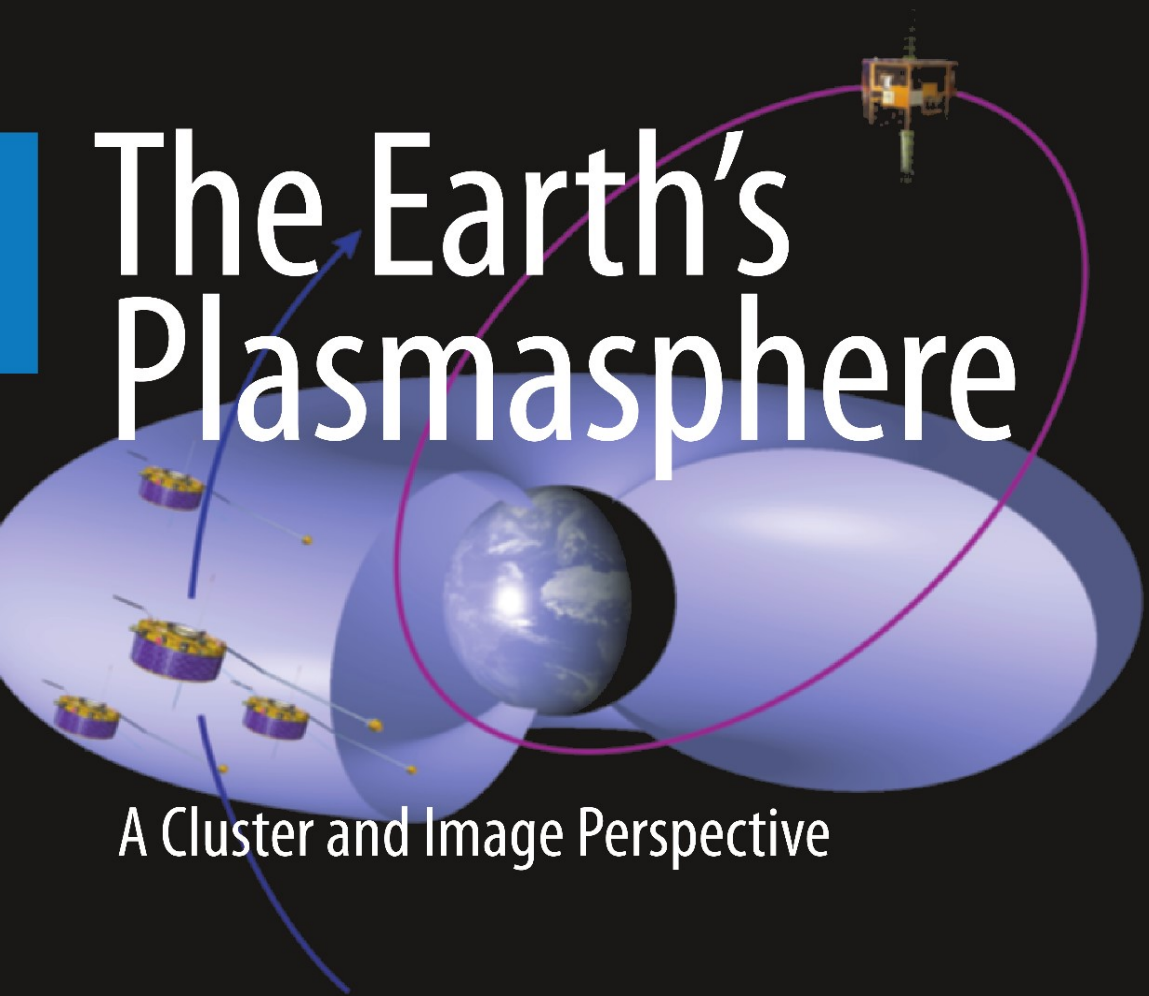


F. Darrouzet
J. De Keyser
V. Pierrard
Editors

The Earth's Plasmasphere



A Cluster and Image Perspective

MyCopy powered by  SpringerLink

F. Darrouzet • J. De Keyser • V. Pierrard
Editors

The Earth's Plasmasphere

A CLUSTER and IMAGE Perspective

Previously published in *Space Science Reviews* Volume 145,
Issues 1–2, 2009

 Springer

F. Darrouzet
Belgian Institute for Space Aeronomy (IASB-BIRA)
Brussels, Belgium

J. De Keyser
Belgian Institute for Space Aeronomy (IASB-BIRA)
Brussels, Belgium

V. Pierrard
Belgian Institute for Space Aeronomy (IASB-BIRA)
Brussels, Belgium

Cover illustration: Artist's rendition of the CLUSTER spacecraft. Credit: European Space Agency. Artist's rendition of the IMAGE spacecraft. Created by Ernest Mayfield of Southwest Research Institute. Artist's rendition of the plasmasphere. Created by Johan De Keyser of Belgian Institute for Space Aeronomy. Composition by Jonathan Brennan of Aptalops and by Fabien Darrouzet of Belgian Institute for Space Aeronomy.

All rights reserved.

Library of Congress Control Number: 2009932141

DOI: 10.1007/978-1-4419-1323-4

ISBN-978-1-4419-1322-7 e-ISBN-978-1-4419-1323-4

Printed on acid-free paper.

© 2009 Springer Science+Business Media, BV

No part of this work may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, microfilming, recording or otherwise, without the written permission from the Publisher, with the exception of any material supplied specifically for the purpose of being entered and executed on a computer system, for the exclusive use by the purchaser of the work.

Contents

Preface	1
J.L. Burch and C.P. Escoubet	
Foreword	3
F. Darrouzet, J. De Keyser, and V. Pierrard	
CLUSTER and IMAGE: New Ways to Study the Earth's Plasmasphere . . .	7
J. De Keyser, D.L. Carpenter, F. Darrouzet, D.L. Gallagher, and J. Tu	
1 Introduction	8
2 History of Plasmasphere Data Interpretation	9
3 The Quest for a More Global View	20
4 New Data Analysis Tools	24
5 Conclusions and Outlook	43
Plasmaspheric Density Structures and Dynamics: Properties Observed by the CLUSTER and IMAGE Missions	55
F. Darrouzet, D.L. Gallagher, N. André, D.L. Carpenter, I. Dandouras, P.M.E. Décréau, J. De Keyser, R.E. Denton, J.C. Foster, J. Goldstein, M.B. Moldwin, B.W. Reinisch, B.R. Sandel, and J. Tu	
1 Introduction	56
2 Sources and Losses in the Plasmasphere	61
3 Overall Plasma Distribution and Plasmopause Position	67
4 Ion Composition	73
5 Plasmaspheric Plumes	76
6 Notches	86
7 Shoulders, Channels, Fingers, Crenulations	90
8 Small-Scale Density Irregularities	91
9 Conclusion	96
Electric Fields and Magnetic Fields in the Plasmasphere: A Perspective from CLUSTER and IMAGE	107
H. Matsui, J.C. Foster, D.L. Carpenter, I. Dandouras, F. Darrouzet, J. De Keyser, D.L. Gallagher, J. Goldstein, P.A. Puhl-Quinn, and C. Vallat	
1 Introduction	108
2 Inner Magnetospheric Electric Fields Measured by CLUSTER	113
3 Inner Magnetospheric Electric Fields From Plasmasphere Images	119
4 SAPS Electric Fields	121
5 Spatial Gradients of the Magnetic Field in the Plasmasphere from CLUSTER .	124
6 Summary and Outlook	129

Advances in Plasmaspheric Wave Research with CLUSTER and IMAGE

Observations 137

A. Masson, O. Santolík, D.L. Carpenter, F. Darrouzet, P.M.E. Décréau,
F. El-Lemdani Mazouz, J.L. Green, S. Grimald, M.B. Moldwin, F. Němec,
and V.S. Sonwalkar

1 Introduction	138
2 CLUSTER and IMAGE Wave Instrumentation	140
3 Kilometric Continuum	141
4 Non-Thermal Continuum	147
5 Z-Mode	156
6 Whistler-Mode Soundings at Altitudes Below ~ 5000 km	164
7 Proton Cyclotron Echoes and a New Resonance	167
8 Chorus	171
9 Hiss	174
10 Equatorial Noise	178
11 ULF Resonances	181
12 Conclusion	183

Recent Progress in Physics-Based Models of the Plasmasphere 193

V. Pierrard, J. Goldstein, N. André, V.K. Jordanova, G.A. Kotova, J.F. Lemaire,
M.W. Liemohn, and H. Matsui

1 Introduction	194
2 The Fluid Approach	195
3 The Kinetic Approach	204
4 Comparison Between MHD and Kinetic Approaches	218
5 Conclusions	221

Augmented Empirical Models of Plasmaspheric Density and Electric Field

Using IMAGE and CLUSTER Data 231

B.W. Reinisch, M.B. Moldwin, R.E. Denton, D.L. Gallagher, H. Matsui,
V. Pierrard, and J. Tu

1 Introduction	232
2 Empirical Equatorial Density Models	233
3 Field-Aligned Density Distributions for Plasmasphere and Plasma Trough	235
4 Field-Aligned Density Distributions in the Polar Cap	244
5 Empirical Models of Electric Field	246
6 Summary	254

Index 263

Bibliography 269

Preface

James L. Burch · C. Philippe Escoubet

Originally published in the journal *Space Science Reviews*, Volume 145, Nos 1–2, 1–2.
DOI: [10.1007/s11214-009-9532-7](https://doi.org/10.1007/s11214-009-9532-7) © Springer Science+Business Media B.V. 2009

The IMAGE and CLUSTER spacecraft have revolutionized our understanding of the inner magnetosphere and in particular the plasmasphere. Before launch, the plasmasphere was not a prime objective of the CLUSTER mission. In fact, CLUSTER might not have ever observed this region because a few years before the CLUSTER launch (at the beginning of the 1990s), it was proposed to raise the perigee of the orbit to 8 Earth radii to make multipoint measurements in the current disruption region in the tail. Because of ground segment constraints, this proposal did not materialize. In view of the great depth and breadth of plasmaspheric research and numerous papers published on the plasmasphere since the CLUSTER launch, this choice certainly was a judicious one.

The fact that the plasmasphere was one of the prime targets in the inner magnetosphere for IMAGE provided a unique opportunity to make great strides using the new and complementary measurements of the two missions. IMAGE, with sensitive EUV cameras, could for the first time make global images of the plasmasphere and show its great variability during storm-time. CLUSTER, with four-spacecraft, could analyze in situ spatial and temporal structures at the plasmopause that are particularly important in such a dynamic system. In addition, IMAGE, using a powerful and sensitive sounder, determined for the first time the plasma density along magnetic field lines, which is key to understanding the refilling of the plasmasphere after an active period. On the other hand, CLUSTER could derive for the first time density and magnetic field gradients at the plasmopause and in the ring current using four-point measurements.

J.L. Burch (✉)

Space Science and Engineering Division, Southwest Research Institute, P.O. Drawer 28510,
San Antonio, TX 78228-0510, USA
e-mail: jburch@swri.edu

C.P. Escoubet

Research and Scientific Support Department, ESA/ESTEC, Keplerlaan 1, 2200-AG Noordwijk,
The Netherlands
e-mail: Philippe.Escoubet@esa.int

Many discoveries and key results are highlighted in this book. While IMAGE obtained global images of He^+ content of the plasmasphere, CLUSTER was able to determine the ratios between H^+ , He^+ , and O^+ . Likewise, the plasma plumes viewed in a global context by IMAGE were seen to have complex spatial structure by CLUSTER. Many smaller scale structures have for the first time been observed, including “shoulders”, “channels”, “fingers” and “crenulations” that together depict the irregular behavior of the plasmasphere. Finally the extensive data sets from both missions have driven a strong modeling effort producing empirical and kinetic models that are absolutely necessary to understand globally the plasmasphere and its interaction with the ionosphere and the magnetosphere. Perhaps the greatest advantage was that both missions were operating simultaneously during many years.

We are grateful to the Belgian Institute for Space Aeronomy, the authors and referees of this book for preparing such comprehensive and detailed review articles that describe the history of plasmaspheric physics and the discoveries and fundamental results that have been obtained with CLUSTER and IMAGE. We hope that many students and scientists will enjoy reading it and find it useful in their research.

Foreword

Fabien Darrouzet · Johan De Keyser · Viviane Pierrard

Originally published in the journal *Space Science Reviews*, Volume 145, Nos 1–2, 3–5.
DOI: [10.1007/s11214-009-9531-8](https://doi.org/10.1007/s11214-009-9531-8) © Springer Science+Business Media B.V. 2009

The Earth's plasmasphere can be regarded as the upward extension of the low- and mid-latitude ionosphere. While being located relatively close to Earth, on closed geomagnetic field lines, this region of the inner magnetosphere has turned out to be enigmatic: It is filled with cold plasma of ionospheric origin that is hard to detect, permeated by variable electric fields, and home to a zoo of plasma radio waves. It is also extremely dynamic as it responds in multiple ways to geomagnetic activity.

Plasmaspheric exploration got a major boost since 2000, when the CLUSTER and IMAGE spacecraft were launched. ESA's four CLUSTER satellites continue to orbit Earth in a coordinated constellation until today, visiting the plasmasphere on each perigee pass and returning correlated multi-spacecraft measurements. NASA's IMAGE spacecraft ceased operations after almost 6 years of discovery by pioneering global imaging and radio sounding techniques. These missions offered a new and different view of the plasmasphere. The past years have therefore been fruitful, and the body of scientific knowledge about the plasmasphere has grown significantly. It was felt, however, that the IMAGE and CLUSTER plasmaspheric science communities did not know each other's instruments and tools well enough, and that further efforts to exploit the data produced by these missions were desirable. This led us to organize the workshop "The Earth's plasmasphere: A CLUSTER, IMAGE, and modeling perspective" at the Belgian Institute for Space Aeronomy in the fall of 2007. This workshop provided an overview of what had been achieved by the two communities, and offered the starting point for writing this book as an integrated collection of six self-contained papers.

The first paper, "CLUSTER and IMAGE: New Ways to Study the Earth's Plasmasphere" reviews old and new techniques for exploring the plasmasphere. Particular attention is paid

F. Darrouzet (✉) · J. De Keyser · V. Pierrard
Belgian Institute for Space Aeronomy (IASB-BIRA), 3 Avenue Circulaire, 1180 Brussels, Belgium
e-mail: Fabien.Darrouzet@aeronomie.be

J. De Keyser
e-mail: Johan.DeKeyser@aeronomie.be

V. Pierrard
e-mail: Viviane.Pierrard@aeronomie.be

to the capability of the IMAGE and CLUSTER instruments to go beyond the traditional scheme of single-point in situ measurements. The paper highlights the novel data interpretation algorithms that are required to do so.

The cold plasma making up the plasmasphere is the subject of the second paper “Plasmaspheric Density Structures and Dynamics: Properties Observed by the CLUSTER and IMAGE Missions”. Plasmaspheric structures with large, medium, and small scales are discussed in the light of the new body of data. The size, topology, composition, and evolution of these structures are underscored.

The magnetic and electric fields dictate the behavior of the plasmasphere, as covered by “Electric Fields and Magnetic Fields in the Plasmasphere: A Perspective From CLUSTER and IMAGE”, the third paper. The electric fields reflect the dynamical response of the inner magnetosphere to the ever-changing solar wind–magnetosphere interaction, and are given particular consideration.

The plasmasphere hosts a large variety of wave phenomena. “Advances in Plasmaspheric Wave Research with CLUSTER and IMAGE Observations”, the fourth paper, shows how CLUSTER and IMAGE help to understand these wave phenomena, but also how these waves help to understand the physical processes.

The final two papers, “Recent Progress in Physics-Based Models of the Plasmasphere” and “Augmented Empirical Models of Plasmaspheric Density and Electric Field Using IMAGE and CLUSTER Data”, deal with our present abilities to model the rich variety of plasmaspheric structures and their evolution, as tested against the IMAGE and CLUSTER observations. These models help us to identify and understand the underlying physical processes. At the same time, they allow us to make predictions about the plasma and field environment in the inner magnetosphere.

Numerous specialists have contributed their time and energy to guarantee that this book provides an up-to-date overview of the state-of-the-art in plasmaspheric research. We hope that it can inspire the field for years to come. We are very much indebted to the CLUSTER and IMAGE project scientists, C. Philippe Escoubet and James L. Burch, for their support. The realization of this book has run smoothly thanks to the dedicated efforts of Harry J.J. Blom, Randy D. Cruz and Fiona Routley at Springer. We feel particularly obliged to all the reviewers who scrutinized the manuscripts to ensure a high quality and without whom this book would never have materialized: Mark L. Adrian, Robert F. Benson, Galina A. Kotova, Mark B. Moldwin, Pamela A. Puhl-Quinn, Mark A. Reynolds, Phillip A. Webb and two anonymous reviewers. We also gratefully acknowledge the financial support by the Belgian Institute for Space Aeronomy and by the Belgian Federal Science Policy Office.



Participants of the Workshop “The Earth’s plasmasphere: A CLUSTER, IMAGE, and modeling perspective” at the Belgian Institute for Space Aeronomy, 19–21 September 2007: 1. Dennis L. Gallagher, 2. Joseph F. Lemaire, 3. Hiroshi Matsui, 4. Viviane Pierrard, 5. František Němec, 6. Iannis Dandouras, 7. Bill R. Sandel, 8. Pierrette M. E. Décréau, 9. Farida El-Lemdani Mazouz, 10. Mark B. Moldwin, 11. Richard E. Denton, 12. Michel Roth, 13. Arnaud Masson, 14. Fabien Darrouzet, 15. Jerry Goldstein, 16. Nicolas André, 17. Bodo W. Reinisch, 18. James L. Green, 19. Johan De Keyser, 20. Donald L. Carpenter. Not present for the picture: John C. Foster

CLUSTER and IMAGE: New Ways to Study the Earth's Plasmasphere

Johan De Keyser · Donald L. Carpenter ·
Fabien Darrouzet · Dennis L. Gallagher · Jiannan Tu

Originally published in the journal *Space Science Reviews*, Volume 145, Nos 1–2, 7–53.
DOI: [10.1007/s11214-008-9464-7](https://doi.org/10.1007/s11214-008-9464-7) © Springer Science+Business Media B.V. 2009

Abstract Ground-based instruments and a number of space missions have contributed to our knowledge of the plasmasphere since its discovery half a century ago, but it is fair to say that many questions have remained unanswered. Recently, NASA's IMAGE and ESA's CLUSTER probes have introduced new observational concepts, thereby providing a non-local view of the plasmasphere. IMAGE carried an extreme ultraviolet imager producing global pictures of the plasmasphere. Its instrumentation also included a radio sounder for remotely sensing the spacecraft environment. The CLUSTER mission provides observations at four nearby points as the four-spacecraft configuration crosses the outer plasmasphere on every perigee pass, thereby giving an idea of field and plasma gradients and of electric current density. This paper starts with a historical overview of classical single-spacecraft data interpretation, discusses the non-local nature of the IMAGE and CLUSTER measurements, and emphasizes the importance of the new data interpretation tools that have been developed to extract non-local information from these observations. The paper reviews these innovative techniques and highlights some of them to give an idea of the flavor of these methods.

J. De Keyser (✉) · F. Darrouzet
Belgian Institute for Space Aeronomy, Ringlaan 3, 1180 Brussels, Belgium
e-mail: Johan.DeKeyser@aeronomie.be

F. Darrouzet
e-mail: Fabien.Darrouzet@aeronomie.be

D.L. Carpenter
Space Telecommunications and Radioscience Laboratory, Stanford University, Stanford, CA, USA
e-mail: dlc@nova.stanford.edu

D.L. Gallagher
NASA Marshall Space Flight Center, National Space Science & Technology Center, Huntsville, AL, USA
e-mail: dennis.l.gallagher@nasa.gov

J. Tu
Center for Atmospheric Research, University of Massachusetts Lowell, Lowell, MA, USA
e-mail: Jiannan_Tu@uml.edu

In doing so, it is shown how the non-local perspective opens new avenues for plasmaspheric research.

Keywords Plasmasphere · CLUSTER · IMAGE · Measurement techniques

1 Introduction

Sixty years ago, Owen Storey inferred the existence of a dispersive medium in near-Earth space in order to explain the propagation of whistler radio waves along the geomagnetic field lines. This medium is now known as the “plasmasphere”. In 1959 Gringauz’ plasma instrument on LUNIK 2 provided an in situ confirmation of its existence. The plasmasphere has been studied ever since. NASA’s Imager for Magnetopause-to-Aurora Global Exploration, IMAGE (Burch 2000), and ESA’s CLUSTER probes (Escoubet et al. 1997) have ushered in a new era of plasmaspheric research through innovative observation strategies. The goal of this paper is to highlight these observation techniques and the new data interpretation methods they require, in order to show how they can advance our scientific understanding of the plasmasphere.

The plasmasphere does not easily reveal its secrets. One of the major difficulties has been the low temperature of the plasmaspheric plasma (a few eV at most). Spacecraft potential control and appropriately biased detectors are required to properly sample this cold population. Separating the photo-electrons from the plasmaspheric electrons is another problem. The inner magnetosphere contains cold plasmaspheric plasma, warm ring current particles, and energetic radiation belt particles, so that a comprehensive study necessitates an instrument suite that covers a wide energy range. The densities of these populations vary over several orders of magnitude and the plasma composition is variable, with important contributions from heavier ions of ionospheric origin.

The plasmasphere is subject to the solar wind induced magnetospheric electric field at high altitude, as well as to the forcing by the ionosphere at low altitude. As a consequence, the plasmasphere undergoes a cyclic evolution. Upon arrival of a solar wind disturbance at Earth, the flank-to-flank electric potential difference across the magnetosphere increases and the roughly dawn-to-dusk electric field becomes stronger, so that the outer regions of the plasmasphere are eroded away. The plasmasphere develops a sharp outer density gradient, known as the plasmopause. If the disturbance is strong enough, the eroded material can form a plume in the afternoon local time sector, sometimes reaching out to the dayside magnetopause. The nightside edge of the plume footpoint appears to coincide with the intense electric fields associated with ionospheric subauroral ion drifts or subauroral polarization streams. As the magnetospheric electric field recovers, the plasmasphere is refilled from the ionosphere on a time scale of hours or even days, thus becoming denser and larger in average radius, and exhibiting a locally less well defined outer boundary. As quieting proceeds, an existing plume may begin to rotate with the Earth, move outward, and eventually disappear.

The plasmasphere is a dynamic system with memory: Its spatial structure bears the imprint of past changes in the magnetospheric electric field, while refilling tends to smooth away all structure. Solar wind perturbations (with varying duration, intensity, and recurrence frequency), as well as variations in the ionosphere as a refilling plasma source, produce a zoo of spatio-temporal structures. Single-spacecraft measurements cannot separate variations in different spatial directions or distinguish spatial from temporal effects. It is especially in this domain that the IMAGE and CLUSTER probes have offered what previous spacecraft could not: a non-local perspective.

The purpose of this paper is to illustrate in what ways IMAGE and CLUSTER can open up new directions of plasmaspheric research. To set the scene, Sect. 2 briefly recalls what we knew about the plasmasphere from ground-based radio sounding and from classical single-spacecraft measurements. Section 3 explains the rationale of the non-local measurement techniques introduced by IMAGE and CLUSTER. In Sect. 4 we discuss new analysis tools for extracting non-local information from the data, without trying to be exhaustive. We focus on a few of those tools in more detail to give an idea of the typical difficulties that are encountered and how they can be solved, and of the potential pay-off of such techniques. Scientific results obtained with these techniques are reviewed in the accompanying papers (Darrouzet et al. 2008; Matsui et al. 2008; Masson et al. 2008; Pierrard et al. 2008; Reinisch et al. 2008, this issue). Section 5 concludes the paper and offers an outlook.

2 History of Plasmasphere Data Interpretation

In this section we illustrate the fundamental modes of data interpretation that have been used prior to IMAGE and CLUSTER, so that the significance of the new analysis methods used in conjunction with those missions can be more fully appreciated. We discuss plasmasphere data interpretation by highlighting a few historical milestones; a more complete account of the history of plasmaspheric research before the IMAGE and CLUSTER missions can be found in the monograph by Lemaire and Gringauz (1998). Other historical reviews are the papers by Gringauz and Bezrukikh (1977), Ganguli et al. (2000), Carpenter (2004), and Kotova (2007).

2.1 Data Interpretation at the Beginning of the Space Age

The discovery of the plasmasphere and its outer boundary, the plasmopause, is itself a nice illustration of the role of different experimental techniques and the associated data interpretation.

The first hint at the existence of the plasmasphere came from remote sensing. In the late 1940s, Storey used observations of whistlers, dispersed radio signals from lightning, to determine that the essentially geomagnetic-field aligned paths of whistlers extended several Earth radii (R_E) into space at the equator (Storey 1953). Theoretical considerations allowed him to conclude that the plasma density at those peak altitudes was $\sim 400 \text{ cm}^{-3}$, orders of magnitude higher than conventional wisdom would predict, based on the assumption of an oxygen-dominated upper atmosphere. Some years later, Carpenter used data from a spatial network of whistler receivers established in 1957–1958 to identify a knee-like drop-off in the range $2 < L < 5$ (L being McIlwain's parameter, approximately the radial distance of the equatorial point on a field line expressed in R_E , McIlwain 1961) in the equatorial profile of electron density (Carpenter 1963). In 1959, Gringauz and his colleagues of the Radio Technical Institute in Moscow placed ion traps on LUNIK 1 and 2, destined for impact on the moon. As the spacecraft were underway, their in situ measurements revealed both a region of plasma density comparable to the one identified by Storey as well as an unexpected falloff in that density at an altitude of $\sim 10000 \text{ km}$ (Gringauz et al. 1960; Gringauz 1963), as shown in Fig. 1. The LUNIK measurements were met with some skepticism, and there apparently was some concern in the Soviet Academy of Sciences about the embarrassment that might attend the publication of an incorrect interpretation of the data (Lemaire and Gringauz 1998). The remote sensing and the in situ data seemed to contradict the theoretical predictions at that time. There remained an undercurrent of disbelief, which dissipated in 1963 when

Fig. 1 Ion densities measured by LUNIK 2 (dots) and equatorial electron density profile from ground-based whistler measurements (solid curve) as a function of geocentric distance. The first line of numbers represents the invariant latitudes of the LUNIK 2 measurements, and the second line their latitudes. (From Carpenter 1965)

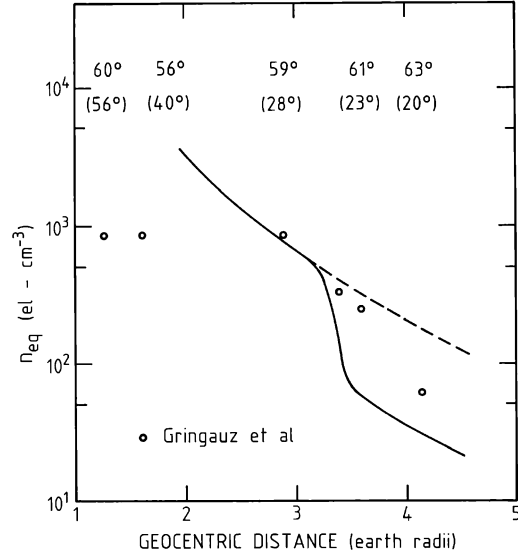
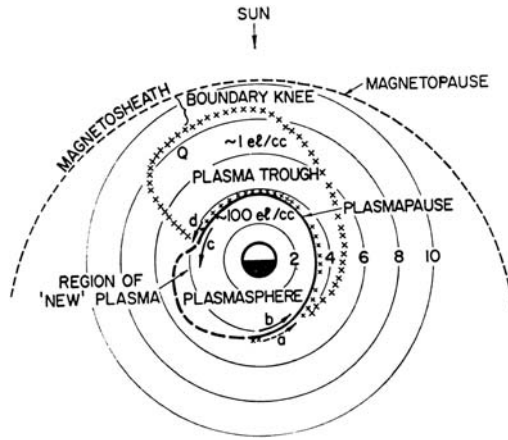


Fig. 2 Average equatorial radius of the plasmasphere during multi-day periods of moderate disturbance following weak magnetic storms ($K_p \approx 6$). The $\times$ -symbols enclose regions most frequently probed by ground-observed whistlers that propagated outside the plasmasphere. Dashed lines indicate an evening sector region where the outer limits of the plasmasphere were not well defined in available whistler data. (From Carpenter 1966)



Gringauz and Carpenter met for the first time and when Fig. 1 was shown, illustrating their mutually consistent results (Carpenter 1965). As of today, the combined analysis of remote sensing and in situ data remains an important way of cross-checking results. In particular, the combination of IMAGE remote sensing and in situ CLUSTER measurements has proven to be very useful (e.g., Darrouzet et al. 2006a).

The whistler measurements were repeated in time, but also in space as more ground stations were deployed. Piecing together the abundant whistler data that became available from Antarctica in the early 1960s, Carpenter (1966) was able to estimate the average shape of what was now called the plasmasphere (Fig. 2). An evening bulge in radius was found. The density knee appeared to develop in the aftermath of magnetic disturbances and its equatorial radius was found to vary inversely with the intensity of the disturbance. Inward displacements of the knee on the night side were observed to correlate with the K_p index during the onsets of several weak magnetic storms, so that K_p became the dominant parameter in performing plasmaspheric studies.

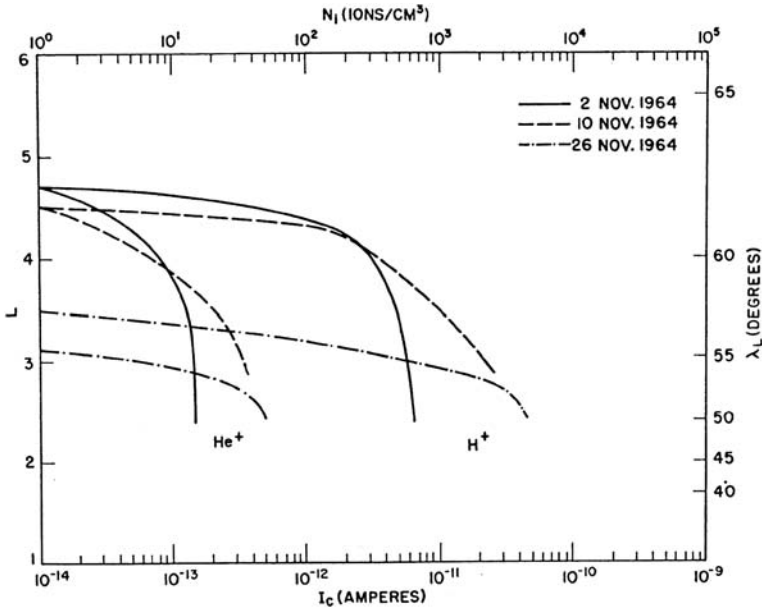


Fig. 3 Profiles of He^+ and H^+ density versus altitude showing steep falloffs between $L = 3$ and $L = 5$, measured by an ion mass spectrometer on board OGO 1. (From Taylor et al. 1965)

Those early days also showed that one had to be very careful with in situ data. The retarding potential electron analyzers on IMP 1 and IMP 3 had found no “knee” in the thermal plasma profile (Serbu and Maier 1967), while the effect was clearly seen by the retarding ion mass spectrometer on OGO 1 (see Fig. 3), (Taylor et al. 1965). A debate on the reality of the knee effect as identified from whistlers was held at the XVth URSI General Assembly in 1966. In the aftermath of the debate, a consensus developed that the retarding potential analyzers had suffered from the effects of an increase in spacecraft potential (Gurnett and Scarf 1967). This interference of the spacecraft potential with cold plasma spectrometer measurements is still a major challenge. Experimenters confront it by means of active spacecraft potential control and/or by biasing the plasma spectrometer; on CLUSTER this is done by means of the ASPOC ion current emitter and by the CIS/CODIF spectrometer’s RPA mode (Escoubet et al. 1997).

Many fundamental questions about plasmasphere dynamics have been addressed by means of extended time series of whistler measurements. A major question was whether the dayside upward fluxes from the ionosphere were sufficient to enable the plasmasphere to act as a night-time reservoir for the decaying ionospheric layers below. Some theorists suggested that a diffusive barrier between the $\text{O}^+ - \text{H}^+$ charge exchange region of the ionosphere and the higher altitude level above which H^+ becomes the dominant constituent would limit the upward H^+ flux to a value less than that required for a replenishment of the night-time ionosphere (e.g., Hanson and Ortenburger 1961). Using electron density data from a library of Antarctic whistlers covering a long magnetic storm recovery period, Park (1970) showed both on a day-to-day basis and during a multi-hour period on a single day that the inferred upward fluxes could account for the drainage fluxes needed to replenish the ionosphere at night.

The interplay between solar-wind induced convection and plasma flow induced by the Earth's rotation was demonstrated at an early point by the evening bulge in the plasmasphere radius (Carpenter 1966). As suggested in Fig. 2, the bulge was not believed to be the result of radially outward drift of plasmas as local time increased in the late afternoon sector, but it was initially interpreted as representing plasma accumulated during the course of sunward convection. Once formed, the bulge was found to vary in terms of the local time at which its westward edge was first detected by a whistler ground station, appearing at earlier local times as magnetospheric disturbance levels increased (Carpenter 1970b). Later it became clear that the bulge as detected by a whistler station represented either a small remnant plume or that part of the westward edge of a plume nearest the main plasmasphere (Ho and Carpenter 1976; Carpenter et al. 1992, 1993, note that these papers did not use the term “plume” yet). The plasmasphere bulge was the impetus for the earliest theoretical efforts to explain the plasmopause phenomenon in terms of large-scale convection (e.g., Nishida 1966; Brice 1967). Dungey (1967) posed a problem about the plasmopause density profile that has persisted to the present day: He suggested that the unsteadiness in convection activity should lead to patchiness in the profile, a patchiness that would be inconsistent with the sharpness of the plasmopause. At the time, the whistler method was capable of identifying an order of magnitude density jump along the outermost detected whistler propagation path in the plasmasphere and the innermost one in the plasmatrough. However, it was not well capable of identifying fine structure near the plasmopause on a scale of $0.1 R_E$ or less, or measuring its distribution as a function of equatorial radius and longitude (e.g., Carpenter 1970a). Detailed study of this structure therefore remained as a challenge to future experimenters.

2.2 More Refined Space Experiments

As noted, particle detectors that measure total plasma density in the plasmasphere and beyond can be subject to problems with instrument calibration and limitations, particularly for the colder or more tenuous plasma components. Nevertheless, such detectors have proven very useful in identifying important plasmasphere features. The increasing sophistication of the detectors has been accompanied by an increasing importance of the data interpretation techniques, for instance to ensure a proper calibration by relating the measured densities to those obtained from the radio detection of local wave resonances, which has proven to be highly accurate over a wide range of density levels.

In situ exploration in the 1960s and 1970s collected a large number of plasmaspheric ion number density profiles, such as those from the Russian satellites ELECTRON 2 and 4 by Bezrukhikh (1970), thereby confirming the reality of the plasmopause density gradient. OGO 1 contributed the first profiles at high altitude of the proton and helium ion concentrations as depicted in Fig. 3 (Taylor et al. 1965), showing that the density gradient appears at the same place for both, with helium ions being less abundant (the density falloffs in Fig. 3 are larger than later studies of plasmatrough levels would support). The ISIS and OGO 2 and 4 polar orbiters gave the first insights into phenomena that were apparently associated with the projection of the plasmopause to ionospheric altitudes. The so-called lower hybrid resonance (LHR) noise band (Brice and Smith 1965) was found to serve as a marker of the plasmopause projection in ALOUETTE satellite measurements of whistler-mode wave activity. It was particularly well defined during periods of moderate to heavy magnetic disturbance and at times of substantial whistler activity. The spectrograms of Fig. 4 show two effects that occurred as ALOUETTE 1 moved poleward in the plasmopause region: (i) a falloff in whistlers propagating on paths through the outer plasmasphere from lightning sources in the conjugate region; (ii) a “breakup” in a noise band, involving a change in smoothness within ~ 1 s and a drop in

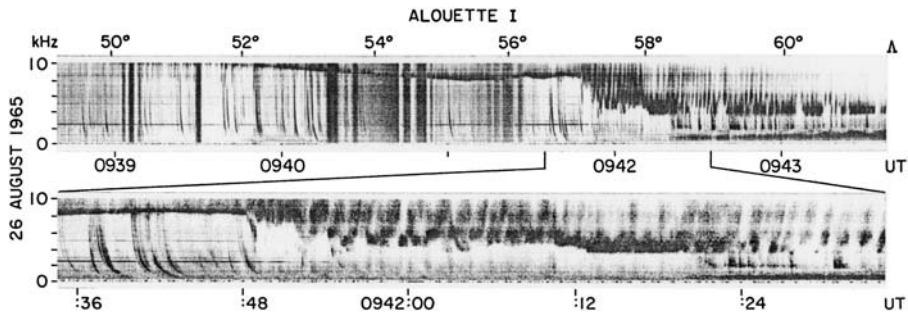


Fig. 4 ALOUETTE 1 broadband VLF spectrograms (0–10 kHz versus time) showing abrupt changes in whistler and noise band activity near $L = 3$ at $\sim 04:40$ MLT. The abrupt changes were attributed to the projection of the plasmapause to 1000 km altitude. (Adapted from Carpenter et al. 1968)

lower cutoff frequency from ~ 8 kHz to 4 kHz within 20 s (Carpenter et al. 1968). A proper knowledge of the behaviour of the waves was indispensable to interpret these changes in the local LHR frequency in terms of a spatial increase in the effective mass of the ions along the satellite orbit. These observations were also consistent with the discovery from OGO 2 of a light ion trough in the ionosphere just poleward of the plasmapause (Taylor et al. 1969), the plasmapause having been identified both by a falloff in whistlers from the conjugate region as well as a latitudinal dropoff in the strength of signals from powerful ground-based very low frequency (VLF) transmitters (Heyborne et al. 1969). Abrupt spatial transitions in whistler-mode wave activity were used as a basis for identifying a thermal linkage between the plasmasphere and ionosphere near the plasmapause (e.g., Carpenter 1971).

Among the more compelling observations of plasmasphere structure projected onto the ionosphere were OGO 4 measurements of a plume-like (using present-day terminology) feature that appeared in conjugate hemispheres just poleward of the main plasmasphere (Taylor et al. 1969). The feature was observed in H^+ density on successive orbits, as illustrated in Fig. 5a, and was interpreted as the ionospheric projection of the plume at high altitude shown in Fig. 5b.

The first evaluation of plasmaspheric ion temperature was made with the LUNIK data (Gringauz et al. 1962), and later on with IMP 2 and OGO 5 (Serbu and Maier 1966, 1970). Those early measurements were neither reliable nor comprehensive enough to describe the thermal structure of the plasmasphere.

The harvest of plasmasphere observations from OGO 3 (Taylor et al. 1968), ELECTRON 2 and 4 (Bezrukikh 1970), and OGO 5 (Chappell et al. 1970), coupled with the ongoing whistler observations (Carpenter 1963, 1967), allowed scientists to use statistical data interpretation techniques successfully. These studies showed clearly that the plasmapause position can vary over a wide range of L values, from ~ 2 to $7 R_E$ (Fig. 6). The datasets from the Russian PROGNOZ satellites helped to infer the overall shape of the plasmasphere. They highlighted the asymmetrical shape of the plasmasphere, depending on the level of geomagnetic activity. Other studies confirmed that the plasmasphere was more extended on the day side than in the post-midnight sector (Bezrukikh and Gringauz 1976). Such studies were, of course, limited by the assumption that the observed structures were really spatial, rather than being due to changes in time: Only geomagnetic activity had been used to sort the data.

GEOS 1 and 2, launched in 1977 and 1978, carried three experiments to measure ion and electron densities: a mass spectrometer, a relaxation sounder, and a mutual impedance

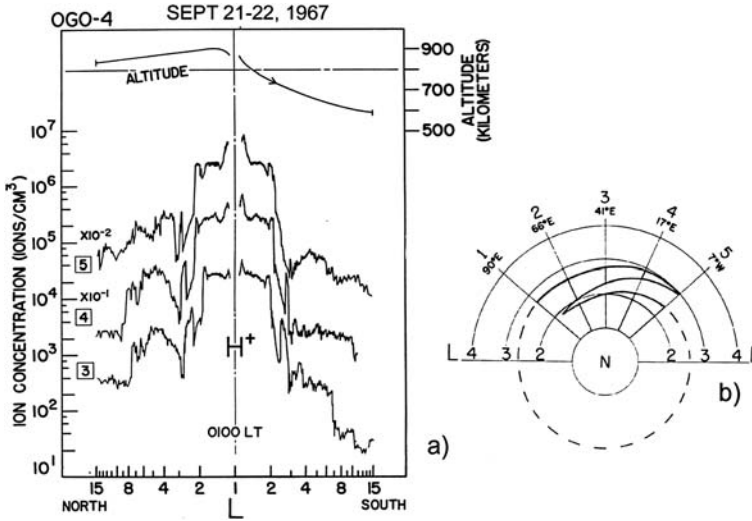


Fig. 5 (a) A sequence of H^+ density profiles acquired by an ion mass spectrometer on OGO 4, showing an inner trough that was detected in both hemispheres and was displaced outward with time. (b) Schematic representation of the plume-like structure derived from the series of five passes ending with those of part (a). The structure indicated is believed to have corotated relative to the essentially fixed local time of the satellite orbit. (From Taylor et al. 1971)

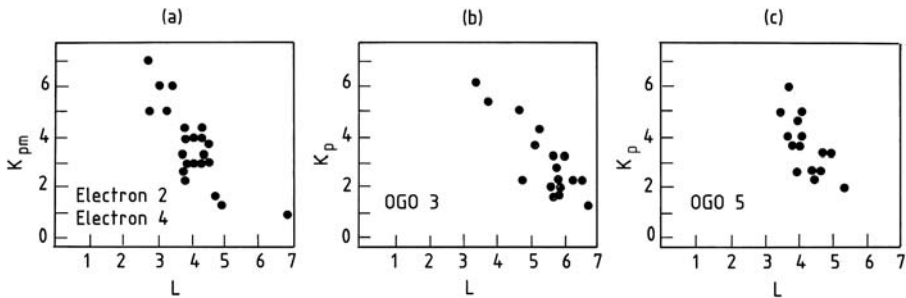


Fig. 6 L position of the plasmapause as a function of the K_p average over the preceding 24 hours: (a) from ELECTRON 2 and ELECTRON 4, after Bezrukikh (1970); (b) from OGO 3, after Taylor et al. (1968); (c) from OGO 5, after Chappell et al. (1970)

experiment. Figure 7 shows results obtained with this last instrument onboard GEOS 1 on a pass beyond $L = 4$ in the post-dusk sector in June 1978 (Décréau et al. 1982). There is a sharp change in density at what is marked as the plasmapause (PP in the figure), as well as an increase in temperature with L , as found with PROGNOZ 5 before. The mass spectrometer onboard GEOS 1 led to the first identification of D^+ , He^{++} , and O^{++} in the plasmasphere (Geiss et al. 1978). The diversity of these measurements reflects the sophistication of the instrumentation and offered a new challenge to data interpretation, in particular with respect to the origin and relative abundance of the heavy ion populations.

The plasma composition experiment on ISEE 1, launched in 1977, measured the H^+ temperature. Statistical studies revealed that the mean temperature increases with L , both on the day and the night side (Fig. 8). On the day side, however, there is a negative temperature

Fig. 7 Electron density and temperature profiles measured by GEOS 1 as a function of L , UT and MLT. The plasmapause is indicated by PP and P_1 and P_2 represent the L^{-4} profiles. (From Décréau et al. 1982)

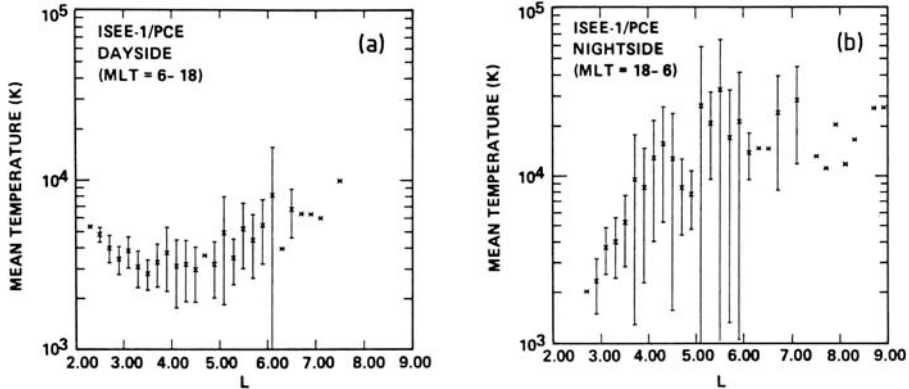
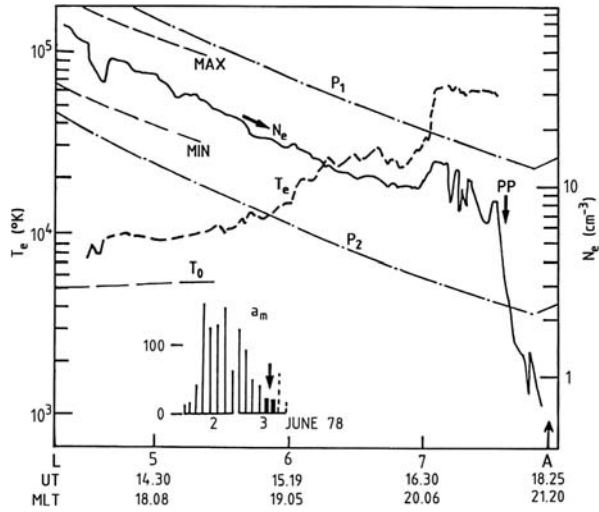


Fig. 8 Mean hydrogen temperature as a function of L for (a) the dayside and (b) the nightside plasmasphere, from observations by ISEE 1. (Adapted from Comfort 1986)

gradient for $L < 3$, an effect that remains unexplained. For $L > 4$, the temperatures are higher at night (Comfort 1986).

Figure 9 shows four typical density profiles (Carpenter and Anderson 1992) obtained by the Passive Wave Instrument (PWI) on ISEE 1. The crossing on day 215 shows a well-defined plasmapause, whereas the crossings on days 217 and 219 show a recovering plasmasphere with a less pronounced plasmapause. The last crossing, on day 224, after some geomagnetic activity, shows a well-defined plasmapause again. These observations illustrate the cyclic pattern of erosion during disturbed periods and recovery thereafter. DE 1 and 2, launched in 1981, helped to define categories of density profiles (Horwitz et al. 1990). For example, Fig. 10 presents different H^+ and He^+ density profiles, some of which feature non-monotonic variations. To which three-dimensional structures these profiles were related, could not be resolved at that time because of the single-point nature of the measurements.

During the later 1980s and the 1990s new missions brought increased observing power. Some highlights include AKEBONO measurements of the parallel drift velocities of various

Fig. 9 Electron density profiles as a function of L for 4 plasmasphere crossings obtained with the Passive Wave Instrument (PWI) on ISEE 1. (From Carpenter and Anderson 1992)

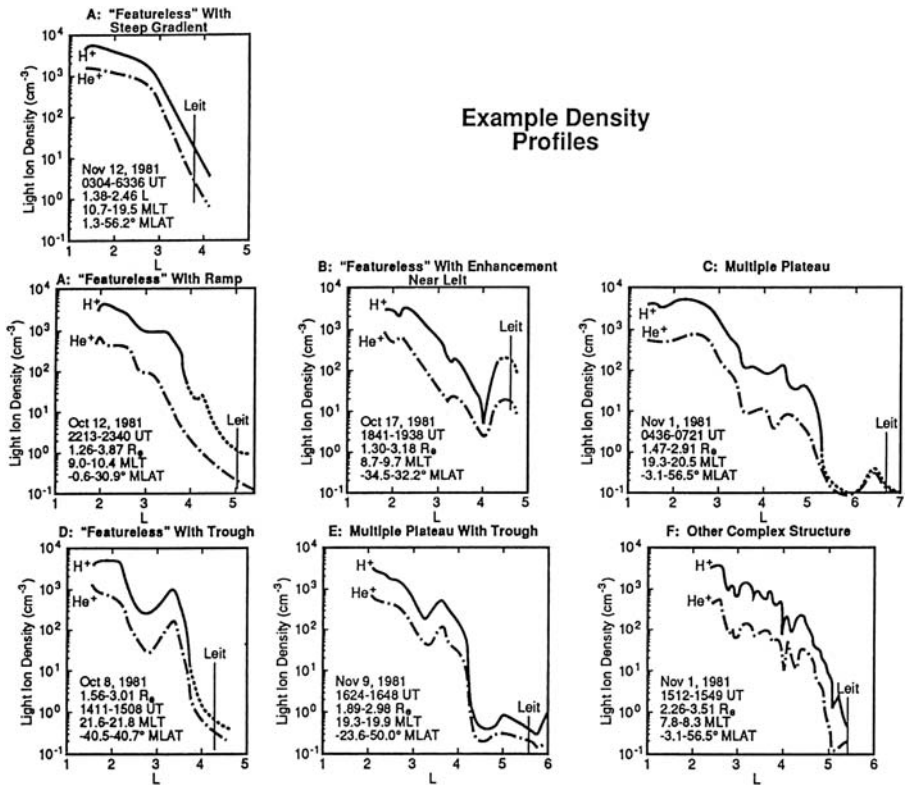
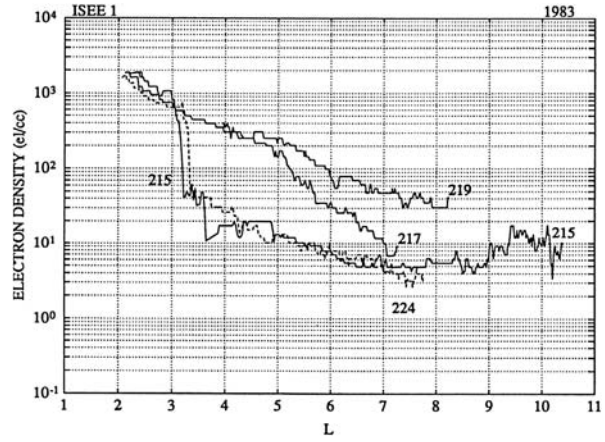


Fig. 10 Classification of hydrogen (H^+) and helium (He^+) density profiles based on DE 1 observations. (From Horwitz et al. 1990)

ions (Watanabe et al. 1992) and of geoelectric field variations with latitude at 10,000 km altitude (Anderson et al. 2001). The Russian INTERCOSMOS 24 and 25 satellites provided information on plasma composition (Afonin et al. 1994) and new results were obtained

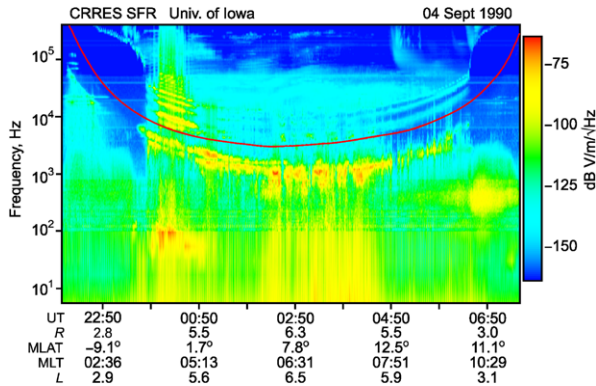


Fig. 11 CRRES sweep frequency receiver data for an orbit on September 4, 1990, with approaches to perigee at far left and right and apogee at ~06:30 MLT. The local gyrofrequency is shown by the *curving line*. The plasmasphere is outlined at upper left and right by the upper hybrid noise band. A noise enhancement associated with the equator appears near 23:30 UT. Below the gyrofrequency, a band of VLF chorus extends throughout the region outside the plasmasphere. In that same region and above the gyrofrequency are several bands of cyclotron harmonic waves, above which there is trapped continuum radiation. Above and to the right are two Type III solar noise bursts, while to the right and inside the plasmasphere there is plasmaspheric hiss near 500 Hz. (Courtesy of R.R. Anderson)

from COSMOS-900 on thermal coupling between the plasmasphere and the ionosphere in the plasmasphere boundary layer (Afonin et al. 1997). The CRRES spacecraft, launched in 1990, proved to be an excellent resource for study of cold electron density profiles both inside and outside the plasmopause (Moldwin et al. 2002) and for detecting complex density structure that develop near the plasmopause (LeDocq et al. 1994). CRRES provided data on electric fields and their enhancements in the dusk sector during periods of enhanced convection (Burke et al. 1998). It also contributed to the study of waves in the plasmasphere by detecting many different kinds of waves over a wide frequency range (see Fig. 11 and, e.g., Anderson 1994). Yet all these missions, however sophisticated their instruments, suffered from the fact that the measurements were made locally. Any measured time variations could be both due to spatial or temporal variations, or both. A partial remedy was offered by the Los Alamos geosynchronous satellites, located at different longitudes, which offered a (relatively crude) way of distinguishing between temporal and longitudinal variations. In particular, the plasma analyzers on these spacecraft provided new information on irregular density structure and the properties of plasmaspheric plumes as those have recently come to be identified (Moldwin et al. 1994; Thomsen et al. 1998), although their measurements were constrained to the radial distance corresponding to geosynchronous orbit, which is often well outside the plasmasphere.

The need to be able to resolve space and time variations with in situ data was recognized and led to the INTERBALL mission, which consisted of two pairs of spacecraft: INTERBALL 1/MAGION 4 and INTERBALL 2/MAGION 5, launched in 1995 and 1996. While testing a number of multipoint data interpretation techniques for the magnetospheric boundary, the multi-spacecraft aspect was not really exploited for plasmaspheric research. Nevertheless, this mission showed that the ion temperature in the plasmasphere increases with MLT from the post-midnight to pre-noon sector in the innermost part of the dawn plasmasphere (Kotova et al. 2008). In the outermost plasmasphere, however, no temperature dependence with MLT was observed. MAGION 2, a subsatellite of INTERCOSMOS 24 (ACTIVNY), found thermal O^{++} density peaks within the plasmasphere (Smilauer et al. 1996).

2.3 Radio Probing from Ground and Space

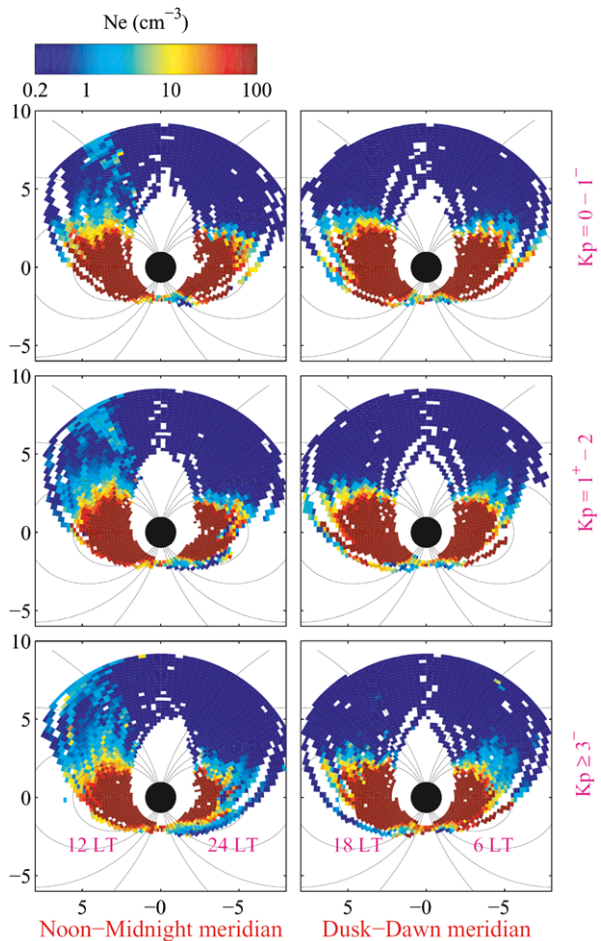
Both ground- and spacecraft-based radio probing have evolved considerably. Much of the ground-based probing work prior to the IMAGE and CLUSTER missions is summarized by Lemaire and Gringauz (1998). While radio probing originally began with the study of whistler-mode waves, other types of emission have gained attention more recently. Useful reviews of whistler-mode waves as diagnostic tools are the papers by Gurnett and Inan (1988), Sazhin et al. (1992), and Hayakawa (1995). The volume by Labelle and Treumann (2006) reviews active probing in space using the Z-mode (Benson et al. 2006), kilometric continuum radiation (Hashimoto et al. 2006), and the influence of plasma density irregularities on whistler-mode propagation (Sonwalkar 2006).

Magnetospheric reflection, in which whistler-mode waves propagate back and forth across the equator after reflecting near locations where the local LHR frequency matches the frequency of the wave, is of considerable geophysical importance (Kimura 1966; Shklyar and Jiříček 2000; Bortnik et al. 2003). Non-ducted propagation of whistler-mode waves and the occurrence of whistler-mode emissions in space were discussed by Smith and Angerami (1968), Matsumoto and Kimura (1971), Sonwalkar (1995), and others. Plasmaspheric hiss has been studied extensively (Thorne et al. 1973; Hayakawa and Sazhin 1992). Important theoretical work was accomplished on the interplay of waves and the hot plasmas of the radiation belts (Kennel and Petschek 1966) and on the possible origin of continuum radiation in a mode conversion process at the plasmasphere boundary layer (Jones 1982). The introduction of the concept of a wave distribution function (Storey and Lefeuvre 1979, 1980) heralded the beginning of efforts to track waves observed on spacecraft to their regions of origin. A lot of work was devoted to the study of non-linear whistler-mode wave–particle interactions using a ground-based transmitter in Antarctica (Helliwell and Katsufakis 1974; Paschal and Helliwell 1984; Helliwell 1988), supported by theoretical modeling (e.g., Nunn 1974; Omura and Matsumoto 1982; Gibby et al. 2008). The loss of radiation belt particles through scattering by whistler-mode waves has been studied by, e.g., Inan et al. (1978), Burgess and Inan (1993), and Abel and Thorne (1994).

The importance of radio measurements is illustrated by the results of the POLAR mission. Launched in 1996, this spacecraft followed CRRES, ISEE 1, and others (Anderson 1994), by providing excellent surveys of wave activity over a wide range of frequencies. At this stage, radio instruments as well as the corresponding data interpretation had evolved into true remote sensing techniques. For instance, POLAR data allowed Laakso et al. (2002) to construct meridional cross-sections of the average electron density distribution in the plasmasphere, and showed that the dawn–dusk asymmetry increases with K_p , presumably due to strong motion of the dawnside plasmopause (Fig. 12). Measurements of local plasma emissions lead to very precise determinations of plasma densities, and have resulted in empirical plasmasphere and plasmatrough density models using the POLAR dataset (Denton et al. 2002).

Currently, global positioning system (GPS) signal propagation delays through the ionosphere are being analyzed to infer ionospheric total electron content (TEC). TEC provides information on the state of the plasmasphere as the ionosphere can be regarded as the downward prolongation of plasmaspheric flux tubes. For instance, so-called “tongues of ionization” observed in the ionosphere are probably the signature of plasmaspheric plumes (Foster et al. 2002). Space-to-space propagation measurements allow one to reconstruct the ionosphere and low-altitude plasmasphere by inversion of the propagation delays (e.g., Heise et al. 2005; Stankov et al. 2005).

Fig. 12 Average electron density in two meridional planes derived from POLAR Electric Field Instrument (EFI) data between 1 April 1996 and 31 December 1999. The *left panels* are for the noon-midnight meridian, and the *right panels* are for the dusk-dawn meridian. The panels from top to bottom are for three different K_p ranges. (From Laakso et al. 2002)



2.4 Theoretical Understanding

Early attempts tried to interpret the plasmapause phenomenon in terms of a separatrix between two flow regimes, or as a region of finite but occasionally steep gradients that was subject to plasma instabilities. Perhaps the boundary was something in between, patchy because of a combination of unsteadiness in the large-scale convection and instabilities on smaller scales. These questions have prompted theoretical studies of the stability of the plasmapause profile (e.g., Richmond 1973; Lemaire 1975), as well as the development of magnetohydrodynamics-based and kinetic models of the plasmasphere and its erosion and recovery (see Pierrard et al. 2008, this issue). Further progress toward understanding the erosion processes would clearly depend upon the ability of the observations to cover larger regions of the plasmasphere boundary so as to elucidate its topology. Typical examples were the “detached plasma elements”, which in current global views are not seen to be physically detached from the main plasmasphere.

Another fundamental, but notoriously difficult problem was the study of plasmasphere refilling. With single-spacecraft measurements it was impossible to obtain solid information on the density profiles along field lines. Such information was needed to be able to establish

the rate of refilling, and how refilling changes with time (see Darrouzet et al. 2008, this issue).

The concept of shielding of the inner magnetosphere was relatively well established, but needed observational support concerning the meso-scale electric field distributions in the inner magnetosphere. This was particularly true for understanding the role of the subauroral polarization stream electric fields and the associated subauroral ion drift, which is a manifestation of the interaction of the cross-tail electric field and the plasma sheet on one hand and the corotation electric field in the plasmasphere on the other hand (see also Matsui et al. 2008, this issue).

Progress on these subjects stalled because of a lack of global-scale observations, coupled with slowness on the part of the magnetospheric physics community to recognize the geophysical importance of what is now called the plasma boundary layer (Carpenter and Lemaire 2004). With CLUSTER and IMAGE and their new observation strategies, and thanks to appropriate data analysis techniques, a new chapter has opened on both the experimental and interpretive sides of this problem.

3 The Quest for a More Global View

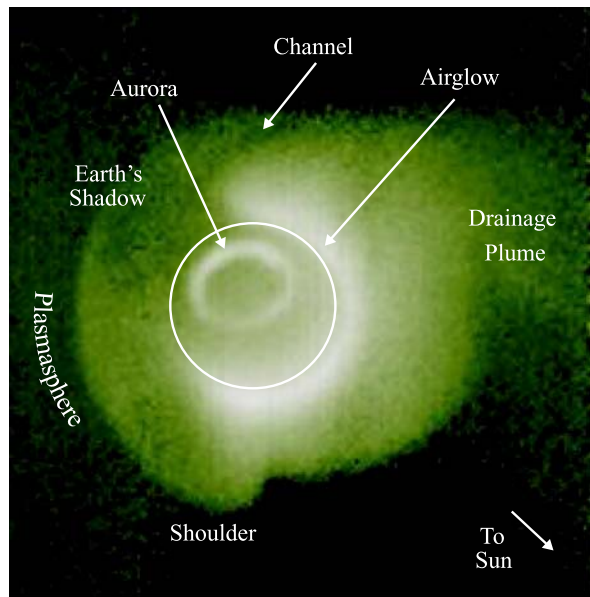
There are two ways to obtain non-local information: either by making in situ observations at a number of different points, which requires multi-spacecraft constellations such as CLUSTER, or by developing remote sensing techniques that are able to detect a proxy for the desired plasma information from a distance, which is the idea behind the IMAGE mission. Both missions were launched in 2000. IMAGE stopped operations at the end of 2005, while the CLUSTER mission has been extended to the end of 2009, at least.

3.1 The Rationale of Global Imaging: IMAGE/EUV Observations

IMAGE's Extreme UltraViolet (EUV) imager (Sandel et al. 2000) observed sunlight resonantly scattered off He^+ ions, producing an emission at 30.4 nm. The plasmasphere contributes much to this emission as it is one of the most dense regions of the magnetosphere, with He^+ densities up to thousands of particles per cm^3 . Useful images are obtained through long exposure times and long line of sight contributions through the optically thin plasma medium. The high latitude initial apogee of the IMAGE orbit ($8.2 R_E$) offered an optimum vantage point for observing the azimuthal structure and dynamics of the plasmasphere. The exposure time was limited because of spacecraft motion. Limitations on the telemetry also prohibited a fast imaging cadence; EUV provided an image every 10 minutes. The instrument has a wide field of view. It consists of three cameras, each with an opening angle of 30° and together covering a fan-shaped field of $84^\circ \times 30^\circ$.

Figure 13 shows a typical EUV image taken near apogee. It shows the ultraviolet glow of the dayside upper atmosphere on the sunlit side of the Earth, the auroral oval encircling the northern magnetic pole in the upper atmosphere, and the plasmasphere as a glowing halo around the Earth. Interpreting such images is not trivial since EUV images record line-of-sight integrated intensities. As EUV looks down on Earth from a vantage point that is not exactly over the pole, geometric corrections must be performed. Actual densities can be obtained by means of image inversion techniques, although simpler heuristics also work well, as discussed in Sect. 4.1. Rescaling the He^+ densities into total densities depends on assumptions concerning the He^+ relative abundance; He^+ density is about 15% of the H^+ abundance in the plasmasphere (Craven et al. 1997). The sensitivity of the instrument corresponds to a lower limit of about 40 cm^{-3} equatorial plasma density (Goldstein et al. 2003c);

Fig. 13 EUV image of the plasmasphere at 30.4 nm at 07:34 UT on 24 May 2000, at a range of $6.0 R_E$ and a magnetic latitude of 73° N. The Sun is to the lower right, and Earth's shadow extends through the plasmasphere toward the upper left. The *bright ring* near the center is an aurora. The *white circle* gives the size of the Earth. Several plasmaspheric structures often visible in such images are indicated. (Adapted from Sandel et al. 2003)



the outer layers of the plasmasphere therefore cannot be seen completely. The spatial resolution is about $0.1 R_E$ when IMAGE is at apogee (Sandel et al. 2000). Other complications arise from the effects of the Earth's shadow, of auroral ultraviolet emission, and of the airglow on the EUV images. Several instrumental issues have to be dealt with, such as image contamination, matching of the data produced by the three detector heads, and aging of the detectors. In spite of these complications, EUV images are a treasure trove of plasmaspheric structures. They have led to a new morphological nomenclature (Sandel et al. 2003, see also <http://image.gsfc.nasa.gov/poetry/discoveries/N47big.jpg>) for various types of spatial structures (Darrouzet et al. 2008, this issue).

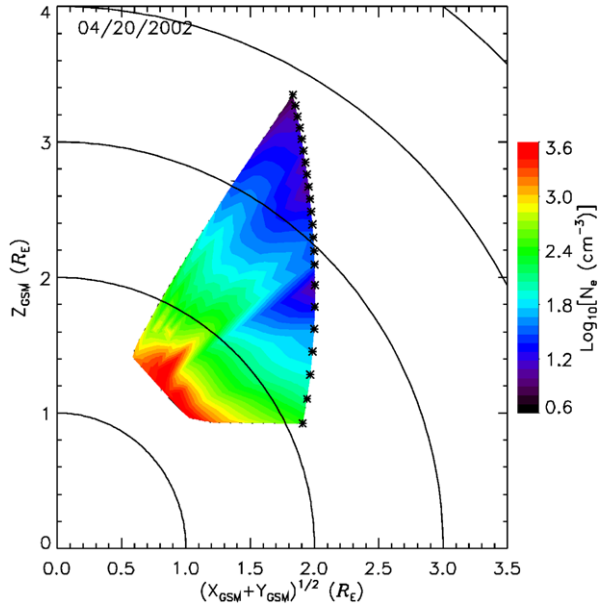
The IMAGE spacecraft also carried other global imaging instruments, the High, Medium, and Low Energy Neutral Atom (HENA/MENA/LENA) imagers (Mitchell et al. 2000; Pollock et al. 2000; Moore et al. 2000). Energetic neutral atom imagers address the distribution of higher-energy particles (10–500 keV/nucleon, 1–70 keV/nucleon, and 10–500 eV/nucleon, respectively). These imagers help to shed light on the dynamical interaction in the coupled ring current–plasmasphere system (Williams et al. 1992; Brandt et al. 2002; Gurgiolo et al. 2005).

3.2 Radio Observations in Space with IMAGE/RPI

The Radio Plasma Imager (RPI) on IMAGE operated in the frequency range from 3 kHz to 3 MHz using three orthogonal antennas, two 500 m long dipoles in the spin plane, and a 20 m dipole along the spin axis. The design and measurement characteristics of RPI have been described in detail by Reinisch et al. (2000).

The RPI instrument alternated between making passive electric field measurements and active radio sounding measurements. Each of those modes of operation are analyzed and displayed differently. In active sounding mode, the RPI emitted coded signals and listened for reflected echoes. The received echoes are plotted in a “plasmagram” with the analysis software known as BinBrowser (Galkin et al. 2004a, 2004b). A plasmagram is a color-coded

Fig. 14 Two-dimensional electron density image projected into the $Z_{\text{GSM}}-r$ plane, where $r^2 = X_{\text{GSM}}^2 + Y_{\text{GSM}}^2$ from RPI measurements on 20 April 2002 when IMAGE flew from the polar cap toward the plasmasphere at ~ 12 MLT. (Courtesy of J. Tu)



display of the signal amplitude as a function of frequency and echo delay time. The echo delay time is usually represented by the so-called virtual range, i.e., half the delay time multiplied with speed of light in free space. If the actual signal propagation speed does not differ much from the speed of light in free space, the virtual range gives an idea of the distance at which the signal was reflected.

When the RPI was sounding inside or close to the plasmapause, there were often discrete echoes forming traces with virtual ranges of up to $7 R_E$ when echoes from the conjugate hemisphere were received. Outside the plasmasphere, the RPI acquired discrete echo traces with virtual ranges of $3-4 R_E$. These traces appear to represent signals that were reflected remotely and propagated along the magnetic field line (Reinisch et al. 2001; Green and Reinisch 2003; Fung and Green 2005). By scaling the traces, i.e., recording the frequency and virtual range pairs, an electron density distribution along the magnetic field line that intersects the spacecraft can be derived (Huang et al. 2004). How trace information can be translated into density profiles will be discussed briefly in Sect. 4.2.1. The measurement of a single field-aligned density profile takes typically 1 minute. Multiple density profiles were obtained along the IMAGE orbit and can be used to construct a two-dimensional electron density image covering a large area of the inner magnetosphere. Figure 14 shows such an image that was constructed from RPI measurements obtained as the IMAGE spacecraft flew over the polar cap, crossed the dayside cusp/auroral oval, and entered the plasmasphere at lower latitudes.

In passive measurement mode, the RPI monitored the natural plasma wave environment around the satellite. Those natural plasma wave signals are displayed in conventional frequency-time electric field spectrograms or dynamic spectra (e.g., Green and Reinisch 2003). Typical features on an RPI dynamic spectrogram are a narrow upper hybrid resonance (UHR) noise band, kilometric continuum (KC) radiation, and the non-thermal continuum (NTC) radiation (see Masson et al. 2008, this issue). The lower cutoff frequencies of the UHR band and the NTC radiation provide an estimate of the electron plasma frequency f_{pe} or, equivalently, electron density $n_e \propto f_{pe}^2$ (e.g., Mosier et al. 1973; Shaw and Gurnett 1980;

Benson et al. 2004). The RPI in its passive mode therefore can be used much like earlier wave instruments (e.g., the Plasma Wave Instrument, PWI, on POLAR) to study the plasma-pause, plasmaspheric troughs, and plumes. The techniques underlying that kind of analysis are discussed in Sect. 4.2.2.

3.3 Disentangling Spatial and Temporal Variability with CLUSTER

The four CLUSTER spacecraft (C1, C2, C3 and C4) fly in a tetrahedral configuration along similar inclined orbits with a perigee of about $4 R_E$. They cross the outer plasmasphere from the southern to the northern hemisphere every 57 hours. Each CLUSTER satellite contains 11 identical instruments. Five of them are of particular relevance to the study of the plasmasphere:

- The magnetic field measurements by the FluxGate Magnetometer (FGM) (Balogh et al. 2001) are very accurate, with a broad dynamic range. The weakest fields are measured with an error below 0.1 nT and a (cross-)calibration down to the same level. These data are therefore well suited for the computation of gradients. The sampling rate can be as high as 67 Hz, but spin-averaged (4 s) data are usually sufficient for plasmaspheric studies.
- The CLUSTER Ion Spectrometry (CIS) experiment (Rème et al. 2001) consists of two detectors, CODIF and HIA. Most useful in the plasmasphere is CODIF in RPA mode, in which the detector potential is biased relative to the spacecraft environment so as to repel photo-electrons and to facilitate capture of the cold (a few eV) ions, but even then a fraction of the cold ion distribution may be missed. Nevertheless, useful data about density variations, composition, and plasma flow can be obtained (see also Darrouzet et al. 2008, this issue). Cross-calibration is difficult since the environment of each spacecraft is different. Note that the PEACE electron spectrometers usually are not operating in the plasmasphere because it is hard to separate plasmasphere electrons from the photo-electron cloud.
- The wave sounder (WHISPER, Waves of High frequency and Sounder for Probing Electron density by Relaxation) (Décréau et al. 2001) observes plasma waves. In its passive mode, the receiver monitors the natural plasma emissions in the frequency band 2–80 kHz. In its active mode, the sounder analyses the pattern of resonances triggered in the medium by a radio pulse. Various types of waves have been observed in the plasmasphere (see Masson et al. 2008, this issue). The resonance signatures in both modes lead to an independent estimation of f_{pe} , which provides a well-calibrated measurement of n_e . Because of WHISPER's frequency limits, the method is applicable for densities between 0.05 and 80 cm^{-3} .
- The Electric Field and Wave (EFW) experiment (Gustafsson et al. 2001) measures the electric potentials of the antenna probes (mounted on two pairs of extended boom wires, with a distance of $\sim 88 \text{ m}$ between each pair of probes) and of the spacecraft body. The instrument provides the spin-plane electric field components, which is interesting for the study of the plasmaspheric convection electric field (see Matsui et al. 2008, this issue), as well as the spacecraft potential. Using a non-linear empirical relation, which depends on the plasma regime, the electron density can be estimated from this potential (Pedersen 1995; Laakso and Pedersen 1998; Moullard et al. 2002; Pedersen et al. 2008). For each plasmasphere traversal the EFW measurements can be calibrated against the WHISPER-derived densities (Pedersen et al. 2001) wherever the density is below 80 cm^{-3} . Unfortunately, extrapolation of the calibration relation to higher densities is not justified.

- The Electron Drift Instrument (EDI) (Paschmann et al. 2001) emits a steerable beam of electrons and detects when it returns to the spacecraft. A controller commands the electron guns to track the return beam continuously. The convection electric field can be derived from the steering signal. This technique works well when there is no strong time variability. EDI returns excellent results in the plasmasphere. EDI and EFW measurements can be combined to provide a comprehensive electric field dataset (see Reinisch et al. 2008, this issue).

Multi-spacecraft missions like CLUSTER require appropriate data analysis techniques to exploit the multipoint nature of the observations. A nice review of multi-point methods can be found in the books edited by Paschmann and Daly (1998) and Paschmann and Daly (2008). Experiences with these methods in the study of the outer magnetosphere are reported by Paschmann et al. (2005). Further development of such methods is an ongoing effort.

Single-spacecraft measurements do not allow for a determination of whether observed variations are due to spatial or temporal changes. The idea behind the CLUSTER mission was to launch four spacecraft into nearby orbits, so that the variations in space and time can be sorted out. Simultaneous measurements at four non-coplanar points allow one to evaluate the spatial gradient (see Sects. 4.3 and 4.4). In order to work properly, the spacecraft must all be embedded in the gradient structure at the same time (the homogeneity condition). The spacecraft separations have therefore been adapted in the course of the mission, varying between 100 km and 10000 km: small separations to study the bow shock and the magnetopause, and larger separations to study the tail. Some difficulties with the homogeneity condition can be overcome by making assumptions about the objects that are being sampled. For instance, if the plasmopause is a locally planar interface, one can use the positions and the relative times at which the spacecraft cross the plasmopause to infer its orientation and speed, without requiring all spacecraft to be inside the plasmopause at the same time (see Sect. 4.5).

4 New Data Analysis Tools

Both the IMAGE and CLUSTER missions pioneer new observational paradigms and therefore require new data analysis techniques. Without the pretension of being complete, we review a number of examples of such methods that are relevant for the study of the plasmasphere so as to give an idea of the flavour of these techniques.

4.1 Analysis of Global Images

In this section, we first give an overview of different techniques that have been used for IMAGE/EUV image analysis. We then focus on one technique in more depth to illustrate some of the issues that must be addressed.

4.1.1 Overview of Methods

Analyzing EUV images typically involves one or more of the following processing steps.

Removal of Noise and Instrument Artifacts Because of the constraints on image acquisition time, detector sensitivity, and the low densities in the outer plasmasphere, and despite the integrated nature of the images along the line of sight, EUV's images can be noisy. An obvious way to improve the signal-to-noise ratio is by accumulating subsequent images

(e.g., Burch et al. 2004). Smoothing and/or binning of the image can reduce noise at the expense of a loss in spatial resolution. Specific noise reduction techniques have been used to suppress random small-level density fluctuations that might hamper correlating subsequent images (Gallagher and Adrian 2007). Binning has been used by Darrouzet et al. (2006a) to detect plasmaspheric plume tips down to relatively low densities. Gurgiolo et al. (2005) use a despeckling algorithm to remove isolated active pixel clusters, which can be regarded as an intelligent form of binning.

Subtraction of the image background largely eliminates the adverse effects of stray-light in the EUV instrument and facilitates further image processing (Gurgiolo et al. 2005; Gallagher and Adrian 2007; Galvan et al. 2008). A quite sophisticated approach is the use of data quality flags to eliminate the Earth's shadow region, the auroral emission, and the seams between the fields-of-view of the three EUV cameras from the analysis (Galvan et al. 2008). Not doing so results in erroneous contributions to the solution in the subsequent image inversion process (Gurgiolo et al. 2005).

Photometric Calibration Intensity variations of the solar flux must be taken into account. A proxy for this flux can be obtained from SOHO instruments (Gallagher et al. 2005; Galvan et al. 2008). The flux dependence is especially important if precise photometric calibration is needed, in particular when one wants to compare several EUV images, or if one wants to compare them to data acquired in situ. Examples include studies of plasmaspheric flux tube content (Sandel and Denton 2007; Galvan et al. 2008) or motion of low-contrast plasmaspheric features (Gallagher et al. 2005; Galvan et al. 2008).

Three-Dimensional Inversion and Projection on the SM Equatorial Plane Images are taken from a specific vantage point, often high above the pole. Because of the varying distance from Earth and the changing viewing direction it is necessary to properly account for the observation geometry.

A full inversion of a plasmaspheric image or of a set of successive images (Williams et al. 1992; Roelof and Skinner 2000; Gurgiolo et al. 2005) should include all relevant observations, as well as the known magnetic field geometry and the physical mechanisms of emission and detection of the radiation. In particular, inversion can benefit from a good field-aligned density model. Depending on the available data, parts of the solution may not be well-constrained, so that regularization assumptions enforcing a certain smoothness are needed. Noise adversely affects the inversion process. The inversion produces the complete three-dimensional density distribution. Inversion is a computationally expensive iterative process; it has therefore been used especially in situations where precise plasmopause positions are required (e.g., Larsen et al. 2007). Note that similar inversion techniques can be applied to the HENA, MENA, and LENA images, although in that case assumptions concerning the isotropy and the energy spectra of the particles have to be made to convert the differential number flux into velocity space distribution densities, which results in the actual densities after integration (Gurgiolo et al. 2005).

If an image is obtained from more or less straight above the pole, the equatorial projection of the plasmopause is simply the plasmasphere silhouette determined as an isophote (e.g., Garcia et al. 2003; Goldstein et al. 2003b). For other viewing directions one can use the "edge algorithm" to compute the equatorial projection of the plasmopause from the viewing geometry and the plasmasphere silhouette in the acquired image, without the need for a full inversion (Roelof and Skinner 2000). The correctness of this approach can be proven under certain simplifying assumptions. A detailed evaluation by Wang et al. (2007) indicates that the algorithm suffers from a number of problems, such as the non-uniqueness of

the radial plasmopause position when a plume is present, and difficulties with certain atypical projection geometries and with image discretization effects. These authors propose a “revised edge algorithm” that addresses some of these issues. Yet another alternative is the minimum- L algorithm (e.g., Gallagher et al. 2005). While not so precise as the edge algorithm, this technique has been shown to be sufficiently accurate in practice, with errors on the radial plasmopause position of a few percent at most, especially if the plasmasphere is observed from a vantage point high above the pole (Wang et al. 2007). The technique is also very general and robust. It is used very often (Brandt et al. 2002; Sandel et al. 2003; Spasojević et al. 2003; Garcia et al. 2003; Goldstein et al. 2003c, 2004; Adrian et al. 2004; Burch et al. 2004; Gallagher and Adrian 2007; Sandel and Denton 2007; Galvan et al. 2008), in part because it can map each image pixel onto the equatorial plane while at the same time converting the line-of-sight integrated density to a pseudo-density by dividing it by an estimate of the line-of-sight distance that contributes most to the intensity in each viewing direction (for more details, see Gallagher et al. 2005). In doing so, this pseudo-density is a fair approximation of the equatorial density that would be obtained from a full inversion. The same rationale is followed by Sandel and Denton (2007) to combine the minimum- L algorithm with the effective pathlengths along the lines of sight to convert the time derivatives of He^+ column density into equivalent volume refilling rates at the equator.

Density Calibration A proper density calibration is needed to relate the inferred He^+ densities to the total density. People often rely on a constant He^+ abundance ratio from an earlier statistical study (Craven et al. 1997) to obtain total densities. Such a rescaling, however, should be performed with caution as the actual He^+ abundance ratio can vary throughout the plasmasphere. This can be an issue, for instance, in studies of refilling (Sandel and Denton 2007). The He^+ distribution resembles the overall total plasma distribution, as has been confirmed by the high correlation between plasmopause and plume positions obtained from in situ IMAGE/RPI total densities and from IMAGE/EUV He^+ densities (Garcia et al. 2003; Goldstein et al. 2003c; Moldwin et al. 2003). More detailed studies suggest an enhancement of the heavy ion populations in the inner plasmatrough during active refilling periods; this enhancement, however, is ascribed to O^+ rather than He^+ (Dent et al. 2006; Grew et al. 2007).

Comparison of Successive Images EUV movies of images at a 10 minute cadence enable studies of the dynamics of plasmasphere structure. Especially when IMAGE had its apogee high above the North Pole, it was able to record long sequences of images.

The time evolution of structures in the plasmasphere can be followed by visual inspection of a movie. Examples include tracking the position of plasmaspheric notches or plumes in order to derive the effective corotation speed (Garcia et al. 2003; Sandel et al. 2003; Spasojević et al. 2003; Gallagher et al. 2005), monitoring the shape of shoulders, notches, plumes and channels to see how they develop (Spasojević et al. 2003; Gallagher et al. 2005), or following the inward and outward motion of the plasmopause at a fixed MLT to monitor plasmasphere compression/erosion and expansion/refilling by relating this motion to the dawn-dusk electric field and its solar wind driver (Goldstein et al. 2003a, 2007). In general, following cold plasma structures reveals information about the magnetospheric convection electric field (Goldstein et al. 2003b, 2005). Visual inspection of EUV movies may also be guided by models (see Pierrard et al. 2008, this issue).

Automated cross-correlation of successive images is particularly useful when analyzing large datasets and/or to avoid subjective effects in feature identification. Burch et al. (2004)

analyze the brightness curve along an annulus to identify the position of notches, while Gallagher et al. (2005) use least-squares fits to describe notch geometry to assist in obtaining more precise notch positions; both studies do this in consecutive images to obtain notch drift velocities and to gain insight as to why sub-corotation is usually observed. Gallagher and Adrian (2007) correlate subsequent images to infer the two-dimensional He^+ flow in the magnetic equatorial plane, from which the global and mesoscale electric fields can be determined. Another highly automated technique is that of Galvan et al. (2008): They use the cross-correlation of the densities in an annulus, as observed in subsequent images, to infer the corotation speed. This allows them to identify the diurnal plasmaspheric density variations that are recorded as one follows individual plasma elements. The up/down flows due to the exchange of plasma between the ionosphere and the plasmasphere throughout day and night can then be computed from these density variations.

Data Accumulation It is always possible to use data accumulation to suppress statistical uncertainties. In their study of refilling rates, Sandel and Denton (2007) use azimuthal binning of their pre-processed data to obtain column abundances over concentric rings at successive L values. To improve their statistics even more, such data are summed over a number of orbits. Galvan et al. (2008) accumulate their set of density changes in flux tubes as a function of time, which are derived from low-contrast changes in the EUV image intensities collected during an orbit, by considering a large set of 128 orbits to maximize the statistical significance of their results and to obtain a complete picture of the diurnal density variations.

Visualization Aids In addition to the specific analysis methods discussed above, various techniques have been used to cope with the high dynamic range of the images, such as: the use of contrast enhancement techniques, rendering the images in false color, using intensity scales proportional to the square root or the logarithm of the image intensity, plotting radial gradients of the data (Sandel et al. 2003) or visualizing the data with various image projection formats such as polar plots or MLT- L diagrams (e.g., Gallagher et al. 2005). Such visualization techniques can sometimes reveal surprising phenomena. For instance, contrast enhancement by differencing of images after a proper amount of rotation ("residue images") has revealed radial brightness variations corresponding to what might be interpreted as a standing global magnetospheric wave pattern (Adrian et al. 2004).

Correlation with Data from Other Spacecraft or Ground Stations An analysis can always benefit from additional information from other sources. In particular, every analysis of plasmasphere data has to take into account the role of geomagnetic activity, for instance, expressed in terms of the K_p index deduced from ground observations. An alternative is to study the relationship between the plasmasphere and the solar wind parameters directly. An attempt in this direction has been made by Larsen et al. (2007), who have used a multiple regression analysis to relate the average plasmopause position derived from EUV image inversion to ACE solar wind parameters. This analysis shows that the time-delayed interplanetary magnetic field B_z , its clock angle θ , and the merging proxy $\phi = vB \sin^2(\theta/2)$, where v and B denote solar wind speed and field magnitude, are the dominant controlling parameters. The time delays are found to be around 200 minutes. Although statistical in nature, and although the MLT-dependence of the plasmopause is not taken into account, this regression analysis gives indications about the physical processes involved in the response of the inner magnetosphere to the solar wind driver. Goldstein et al. (2003a) have studied the direct correspondence between the dawn-dusk electric field computed from time-delayed

ACE data and the plasmaspheric electric field inferred from plasmopause motion in EUV movies, as an illustration of the physical mechanism of plasmaspheric erosion.

Various other correlative studies have been performed with EUV data. EUV densities have been compared to in situ measurements of plasmaspheric densities and plume densities by IMAGE/RPI (Reinisch et al. 2004), by CLUSTER (Darrrouzet et al. 2006a), and by the LANL satellites (Moldwin et al. 2003; Goldstein et al. 2004). EUV data have been correlated to ground magnetometer data and RPI data to infer composition (Dent et al. 2006; Grew et al. 2007). Notch drift velocities inferred from the EUV images have been compared with DMSP ionospheric drifts (Burch et al. 2004; Gallagher et al. 2005) to understand differential rotation. Combined analysis of EUV and HENA and MENA data has contributed to studies of the ring current–plasmasphere interaction and its role in subauroral ionospheric heating (Brandt et al. 2002; Gurgiolo et al. 2005). Variations in EUV-derived plasmopause positions have been related to auroral features visible in IMAGE/FUV auroral keograms (Goldstein et al. 2007). EUV densities have also been compared to GPS-TEC ionospheric density maps and DMSP ionospheric densities and drifts to study the overlap between the subauroral polarization stream and plasmaspheric plumes (Foster et al. 2007).

4.1.2 Example: A Technique for Determining Plasmaspheric Drifts

We describe the technique proposed by Gallagher and Adrian (2007) to determine plasmaspheric convection in more detail. The basic premise is that EUV detects a lot of structure that can be recognized in subsequent images. The technique is based on matching features from one image to the next by cross-correlation analysis. The images are photometrically calibrated and are projected to the equatorial plane first, which is done with the minimum- L technique. Figure 15 displays the pseudo-density projected in the solar magnetic equatorial plane for two successive 10-minute integrated images, centered at 05:45 UT and 05:55 UT on 10 July 2000, using a logarithmic gray-scale to represent the pseudo-densities. A kernel representing a portion of the first image is differenced with the same sized portion of the subsequent image to determine the quality of correspondence. Cross-correlation coefficients are calculated across a range of subimages until the best match is found or until it is determined that no match of sufficient quality can be found. Since any drift must be finite in speed, the number of locations at which the cross-correlations must be computed can be limited. The optimum cross-correlation can be computed for each kernel position and thereby drift speeds across the EUV field of view can be derived.

Not all EUV image intensity variations correspond to features in the He^+ distribution. A single image is composed of three subimages from separate cameras (Sandel et al. 2000), each of which can independently protect itself from the Sun and straylight by lowering the detector high voltage and a roll-off in image intensity. The flat-field correction and composition of the separate subimages still may leave some artifacts along the seams between the subimages. Such systematic effects must be guarded against.

A prominent feature of EUV images is noise. Noise can hide the existing plasmaspheric structures, but it also might create artificial structure. Both effects would compromise the drift analysis. Noise strongly influences the correlation coefficient analysis of image pairs. Figure 16 (left panel) is an example of how noise manifests itself in this analysis for the cross-correlation of the consecutive images shown in Fig. 15. The red arrows indicate the derived plasma flow, where the legend defines the arrow length scaling. The yellow regions mark the overlap between individual EUV imaging sensors. The flow pattern looks much more systematic when a noise mitigation technique is applied first (Fig. 16, right panel). A filter is used here that replaces each pixel by the median value in its surrounding $1 R_E \times$

Fig. 15 Graphical representation of the cross-correlation procedure for determining drift in EUV images. Each panel shows pseudo-density in the solar magnetic (SM) equatorial plane from EUV images on 10 July 2000 at 05:45 UT and 05:55 UT. Pseudo-density increases logarithmically with gray-scale intensity. The dark center is the location of the Earth. The Sun is to the left. (From Gallagher and Adrian 2007)

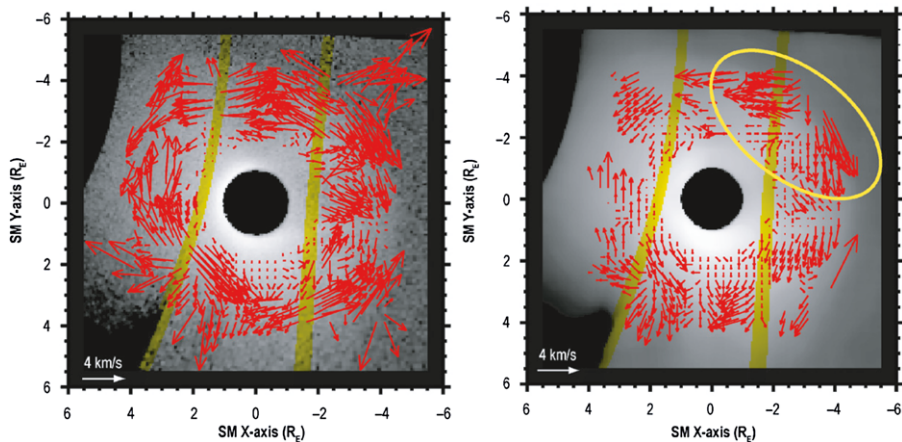
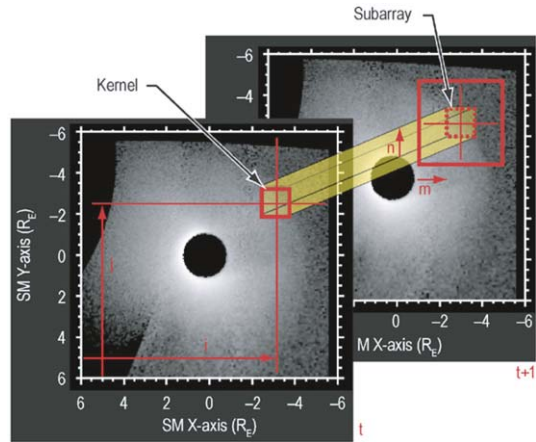


Fig. 16 Cross-correlation-derived plasmaspheric drift vectors (*red arrows*). Two sequential 10-minute integrated EUV images are used in the analysis (see Fig. 15). The *yellow shading* shows where subimages overlap. (*Left*) Derived from the raw images. (*Right*) Derived from images in which noise has been reduced by means of a median filter. The *yellow oval* indicates divergent postmidnight flow. (Adapted from Gallagher and Adrian 2007)

$1 R_E$ spatial box; such a filter preserves edges in images better than linear smoothing filters (see the discussion by Hannequin and Max 2002). An even better treatment of noise is expected from a technique that is based on the properties of Poisson and additive noise, as discussed by Gallagher and Adrian (2007). The challenge is to reduce noise without loss of information.

In the example of Fig. 16, the most pronounced feature is the divergent postmidnight flow (highlighted by the yellow oval) that appears to be real, showing plasmaspheric erosion flows at an early stage. The reliability of the derived drift velocities depends on the errors inherent in the analysis; Gallagher and Adrian (2007) discuss this in some depth and point out that the electric field strengths corresponding to the derived flow velocities are comparable to those derived by an independent technique.

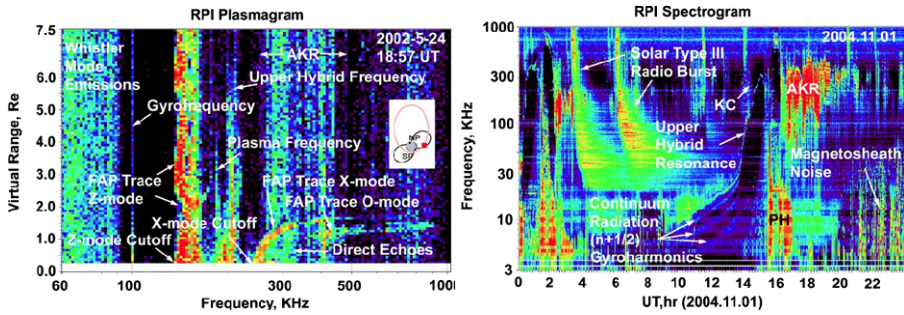


Fig. 17 Sample IMAGE/RPI active and passive measurements, annotated manually. (Left) A plasmagram showing signal reflections from remote plasma locations (*dark traces*) intermixed with stimulated resonances in the local plasma (*vertical lines*) and natural radio emissions (*vertical bands*). (Right) A typical dynamic spectrogram showing different electromagnetic wave signatures: type III solar radio burst, auroral kilometric radiation (AKR), kilometric continuum (KC), and non-thermal continuum radiation, as well as a number of localized plasma wave signatures: plasmaspheric hiss (PH), $(n + \frac{1}{2})$ gyroharmonic and upper hybrid resonances, and magnetosheath noise. (Adapted from Galkin et al. 2008)

4.1.3 Outlook

Techniques for EUV image analysis are still fairly recent. Because of noise, straylight, camera artifacts, Earth's shadow, line-of-sight integration, and so on, any analysis will likely necessitate a healthy degree of skepticism and careful scientific judgment, dependent on finding systematic and coherent behavior in time. Results should be checked against in situ observations or models whenever possible.

4.2 Interpretation of Remote Sounding and Local Radio Observations

Remote sounding with radio waves has become possible with the IMAGE/RPI instrument's active mode. This unique diagnostic tool allows for a quasi-instantaneous determination of the plasma density at various ranges from the spacecraft. Both sounding from above and from within the plasmasphere are possible. Local radio observations, with IMAGE/RPI's and CLUSTER/WHISPER's passive modes, detect natural radio emissions in the Earth's plasmasphere. WHISPER's active mode has been useful in finding the local plasma properties with more precision. The scientific results obtained from wave observations with RPI and WHISPER in the plasmasphere are reviewed elsewhere in this issue.

While the wave data have a rich scientific content, their interpretation is not easy for space physicists outside the radiowave expert community. To facilitate matters, the radio scientists have developed a number of techniques embedded in a suite of software solutions to enable prospecting, analysis, processing, and content annotation of the data (e.g., Rauch et al. 2006; Galkin et al. 2008). As an example, Fig. 17 shows RPI's science products, the plasmagram (for active sounding) and the spectrogram (for passive observations).

4.2.1 Remote Sounding

The left panel of Fig. 17 shows a typical RPI plasmagram. Received signal strength is plotted as a function of echo delay or virtual range (vertical axis) and operating frequency (horizontal axis) of the radar pulses. Radar echoes from remote plasma structures appear as traces on plasmagrams (dark lines observed above 250 kHz in the left

panel of Fig. 17). Discrete thin traces correspond to field-aligned propagation (FAP) of signals that are guided with little attenuation along a field line (Reinisch et al. 2001; Fung et al. 2003). Plasmagram traces are intermixed with vertical signatures corresponding to the locally excited plasma resonances (e.g., intensification near 200 kHz in the left panel of Fig. 17) and various natural emissions propagating in space.

Field-aligned density profiles are obtained in two steps. First, the traces have to be identified in the plasmagrams, i.e., the frequency–virtual range relation has to be extracted for each trace, a procedure called “scaling the trace”. Fitting of the traces can help to suppress digitization errors. A second step consists of the actual inversion of the traces so as to obtain the density profiles. Both steps have been used extensively in the past for interpreting topside ionosphere sounding data (e.g., Huang and Reinisch 1982). The inversion algorithm solves a set of integral equations that relate the virtual range to the group refractive index along the magnetic field line. The group refractive index is a function of signal frequency, electron plasma frequency, and electron gyrofrequency. The solution of this set of integral equations is a set of electron plasma frequencies along the magnetic field line. Thus a magnetic field-aligned electron density profile is obtained (Huang and Reinisch 1982; Huang et al. 2004). Combination of the local and remote active measurements makes it possible to derive an accurate two-dimensional plasma density distribution in the satellite orbital plane (Huang et al. 2004; Tu et al. 2005; Nsumei et al. 2008), as already discussed in Sect. 3.2 and illustrated in Fig. 14.

Through statistical processing of field-aligned density profiles obtained from plasmagrams, it is possible to construct empirical models of these density distributions (Huang et al. 2004). Such models can serve as the baseline for studies of mass loss and refilling of plasmaspheric flux tubes (Reinisch et al. 2004).

Tu et al. (2005) have used the RPI-derived distribution of electron density n_e along field lines, as measured by the s coordinate, in combination with the continuity equation for plasma transport along field lines

$$\frac{\partial n_e}{\partial t} + B \frac{\partial}{\partial s} \left(\frac{n_e V_{\parallel}}{B} \right) = 0$$

to infer the field-aligned electron velocity $V_{\parallel}$; the magnetic field is taken from a model. When there is no significant field-aligned current, $V_{\parallel}$ also represents the mean ion field-aligned velocity. Assuming a quasi-steady situation and ignoring cross-field transport, they obtain the normalized electron velocity $V_{\parallel}/V_{\parallel 0} = n_{e0}B/n_eB_0$, where $V_{\parallel 0}$, n_{e0} , and B_0 are the values at the wave reflection points below the IMAGE orbit. While this analysis does not provide absolute values for $V_{\parallel}$, it clearly shows the upward flow and its acceleration. Different slopes of the density profiles distinguish the plasmasphere from the polar cap. It is even possible to differentiate between the inner plasmasphere where refilling has saturated, and the more outwardly lying plasmasphere where refilling is still ongoing.

Apart from remote sounding, in which the sounder is located outside the plasmasphere, it is also possible to perform sounding from within the plasmasphere. Echoes have been recorded that are the result of ducted propagation in field-aligned plasma density irregularities (Carpenter et al. 2002). The virtual range spreading for such echoes in the plasmagrams is interpreted as being the result of aspect sensitive wave scattering from density irregularities, partial reflection from such irregularities, and propagation in these irregularities. Various characteristics can be derived from the properties of the echoes, such as the transverse size of the irregularities, their extent along the field lines, and the density contrast with their environment. Interpretation of guided echo characteristics is supported by ray-tracing

(Fung and Green 2005). Ray-tracing calculations demonstrate the possible wave propagation paths and establish the conditions for ducted transmission. By performing simulations over the relevant parameter space, insight is gained into the role of duct width, length, and density contrast, and their impact on the appearance of the echoes in a plasmagram.

Detection of stimulated resonances and wave cutoffs in the RPI plasmagrams provides a determination of local plasma density with demonstrated superior accuracy to what conventional density probes can achieve (Reinisch et al. 2001). However, the intricate process of deriving the local plasma density and magnetic field strength values from plasmagram images is known for its high demand of expertise and manual labor. Even greater effort is required to obtain two-dimensional plasma density distributions in the satellite orbital plane using plasmagram traces, as mentioned above. Furthermore, the acquired RPI dataset of 1.2 million plasmagrams incurs a substantial manual expense of data exploration. These considerations warranted development of computer-assisted techniques for data prospecting and interpretation.

Figure 18 shows a screenshot of the RPI BinBrowser software (Galkin et al. 2008) with the plasmagram for 18 January 2001 at 02:37 UT. A resonance matching algorithm (Galkin et al. 2004a, 2004b), with controls on the left side panel of the BinBrowser graphical user interface, was used to match visible resonance signatures in this plasmagram with their theoretical counterparts, resulting in $f_{ce} = 15.57$ kHz and $f_{pe} = 62.25$ kHz, well within 0.5 % of the expert-interpreted values. After the interpretation process is complete, a record of all plasmagram-derived data, together with the expert classification ratings, is added to the RPI Level 2 data repository. This Internet-accessible expert rating service provides a much needed means to tag data by physical content, which makes understanding the plasmagram data an easier exercise to many.

The RPI Level 2 data repository has been used as a testbed for the intelligent data prospecting algorithm CORPRAL (Galkin et al. 2004a, 2004b) that has automatically pre-processed all 1.2 million plasmagrams to search for echo traces. This prospecting algorithm does not provide scientific interpretations of plasmagrams; it merely locates plasmagrams containing echo traces. However, a number of scenarios have emerged that use the number of traces per plasmagram as the database query criterion to restrict data search to relevant data examples. CORPRAL annotations are exploited to find sequences of plasmagrams with traces, corresponding to plasmasphere traversals, for use in calculations of two-dimensional distributions of plasma density in the orbital plane. Also, plasmagrams with a large number of traces can be retrieved to find the most spectacular cases of wave propagation.

4.2.2 Local Plasma Observations

The right panel of Fig. 17 shows a typical RPI dynamic spectrogram, a time history plot of passive measurements of wave intensities as a function of frequency. The RPI detects signatures of various emissions as it orbits the Earth, including intense auroral kilometric radiation (AKR), solar type III radio bursts, plasmaspheric hiss (PH), kilometric continuum (KC), and VLF noise in the magnetosheath. The observed signatures reflect wave generation and propagation mechanisms that are indicative of major physical processes in the Sun–Earth environment.

For illustration, Fig. 19 presents the timeline of RPI passive observations during four days in October 2003, covering the Halloween storm. While these observations do not specifically address plasmaspheric physics, they do illustrate the capabilities of RPI’s passive mode in detecting a plethora of waves over a broad frequency range. The dynamic spectrogram shows two Type III solar radio bursts on 28 October at 11:04 UT and on 29 October at 20:46 UT

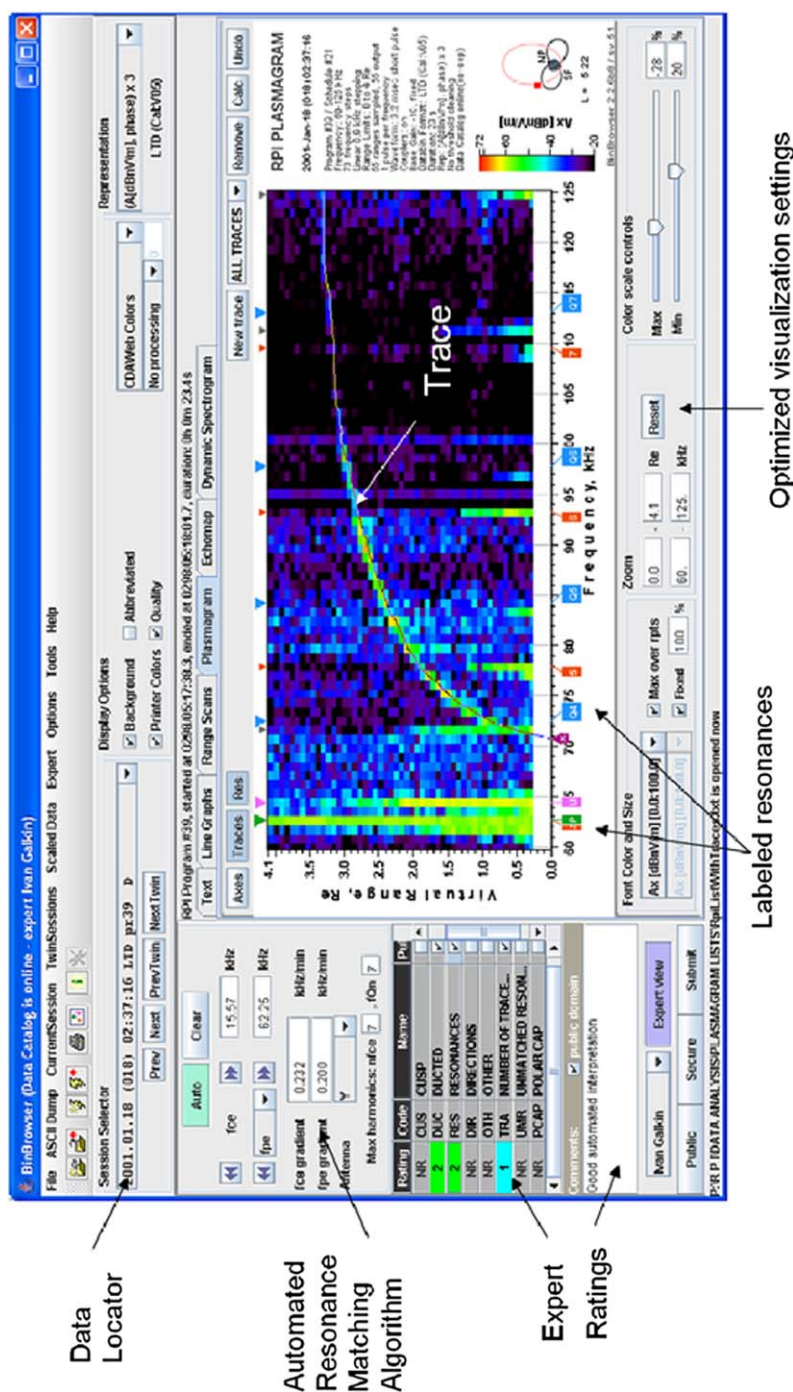


Fig. 18 Screenshot of the RPI BinBrowser software tool showing an active measurement (plasmaprogram) interpreted with the help of a resonance matching algorithm (Galkin et al. 2004a, 2004b). The algorithm detects resonance signatures using image filters and seeks the optimal match between these signatures and a model that accounts for the relation between resonance frequencies and the gradients in the underlying media due to movement of the satellite during the measurement

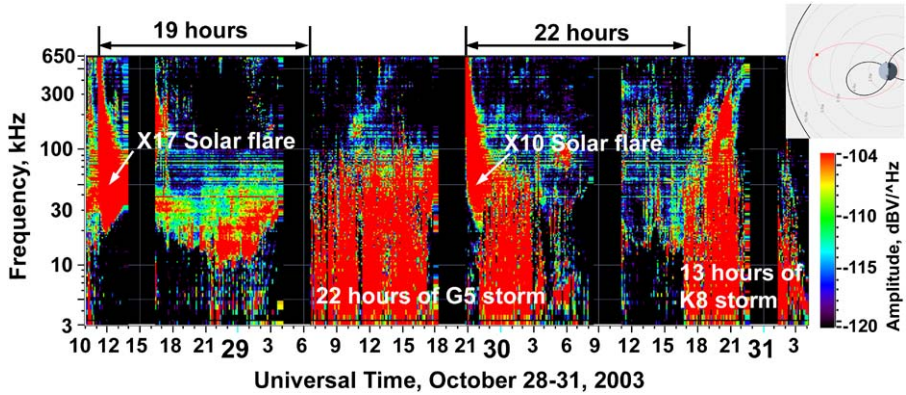


Fig. 19 IMAGE/RPI passive measurements (spectrogram) showing the timeline of the October 2003 Halloween storm. Two solar events causing Type III solar radio bursts on 28 October 2003 at 11:04 UT and on 29 October 2003 at 20:46 UT are responsible for two geomagnetic storms seen in the spectrogram as intense magnetosheath emissions. The *upper right corner insert* shows the typical IMAGE orbit during the events

correspond to X-category flares. Associated coronal mass ejections were ultimately responsible for two geomagnetic storms seen in the RPI spectrogram as intense magnetosheath emissions generated by turbulent plasma flow across the magnetopause. The ability to monitor such major perturbations are obviously relevant for understanding the magnetospheric context of subsequent plasmasphere observations.

The upper hybrid band and the lower frequency edge of the continuum radiation are nearly always visible in the RPI spectrograms. These spectra can be fitted semi-automatically so as to extract the in situ electron plasma frequency f_{pe} from the RPI database for the whole mission, from launch in 2000 to end 2005, as well as the electron density n_e , which can be found from the relation $f_{pe} [\text{kHz}] \approx 9(n_e [\text{cm}^{-3}])^{1/2}$. When an upper hybrid band is present, the fitting technique makes use of the fact that the band extends from the greater of f_{pe} and the electron cyclotron frequency f_{ce} to the upper-hybrid frequency f_{uh} , given by $f_{uh}^2 = f_{pe}^2 + f_{ce}^2$ (Benson et al. 2004). Since IMAGE did not carry a magnetometer, a magnetic-field model is used to obtain f_{ce} in the fitting technique. If the continuum edge is present, fitting the edge with a hyperbolic tangent function can determine f_{pe} . Fitting techniques can be automated so as to apply the appropriate method to either the continuum edge or the upper hybrid band. User interaction can help to assess the quality of the fit. Figure 20 shows a spectrogram obtained during a plasmasphere pass on 1 September 2002, which reveals a plasmasphere with the signature of a plume around 13:50–14:30 UT. The black solid triangles denote f_{pe} calculated from successful fits to the upper hybrid band, while the black solid circles denote f_{pe} obtained from fitting the lower edge of the continuum band. Open black circles and triangles denote manually corrected points. Their number is limited, illustrating that the automatic procedure is very effective. The red open circles indicate the f_{ce} values computed from the Tsyganenko T96 magnetic field model (Tsyganenko and Stern 1996). Open magenta symbols denote values that have been discarded by the automatic fitting routine. The figure shows that the model f_{ce} delimits the upper frequency extent of the low frequency whistler noise band. Also visible are multiple $n + \frac{1}{2}$ emission bands (Benson et al. 2001) between the continuum edge and the whistler noise band, which occur at approximately $(n + \frac{1}{2})f_{ce}$ where $n = 1, 2, \dots$

The CLUSTER/WHISPER wave sounder uses an approach that is slightly different from the IMAGE/RPI, mainly because of its more limited frequency band 2–80 kHz. In its passive

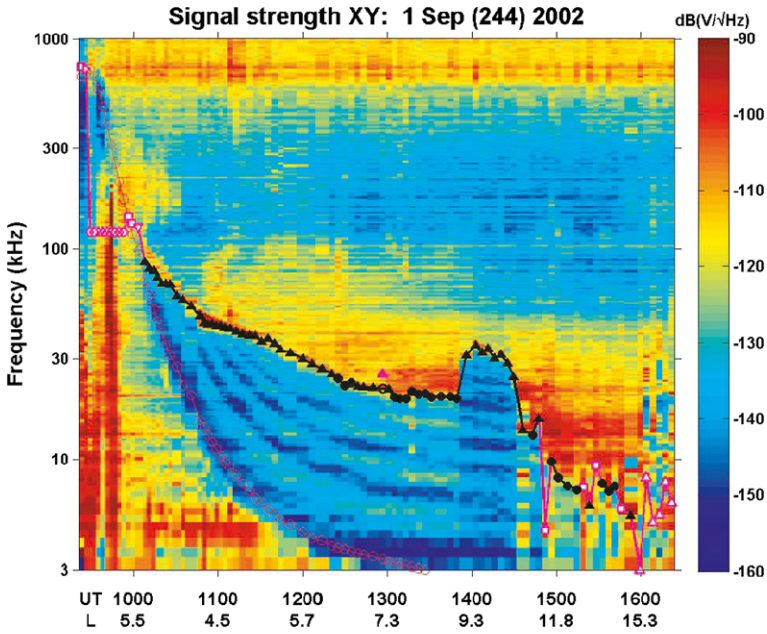


Fig. 20 IMAGE/RPI passive measurements (spectrogram) for a plasmasphere crossing on 1 September 2002, showing a plasmaspheric plume around 13:50–14:30 UT. *Black solid triangles* denote f_{pe} values from fitting the upper hybrid band, while *black solid circles* denote f_{pe} obtained from fitting the lower edge of the continuum band. *Open black circles and triangles* represent manually corrected points. *Open red circles* indicate f_{ce} values computed from the T96 magnetic field model. *Open magenta symbols* denote discarded points. (Courtesy of Phillip Webb, GSFC)

mode, the receiver monitors natural emissions in that frequency band. Particular wave signatures lead to an independent estimation of f_{pe} from local wave cut-off properties (Canu et al. 2001). In its active mode, the sounder analyzes the pattern of resonances triggered in the medium locally by a radio pulse. This also allows for the identification of f_{pe} (Trotignon et al. 2001, 2003). As the plasma resonance signal often is stronger, the precision tends to be higher. Because of WHISPER's frequency limits, this method is useful only in the outer plasmasphere for densities between 0.05 and 80 cm⁻³.

These radio measurements provide only a local characterization of the plasma. Of course, a radial density profile is obtained during a spacecraft pass through the plasmasphere, but that does not provide a global picture, except in a statistical sense (e.g., Goldstein et al. 2003c). To obtain non-local results, in situ data from several spacecraft must be combined. This can be done with CLUSTER by means of general multipoint analysis techniques, such as timing certain events visible in the spectrograms of all spacecraft, or computing gradients of wave data (of f_{pe} or the derived plasma density, of wave intensities in a particular spectral range, ...). Such general techniques are discussed in Sects. 4.3–4.5. Another way of using local data in a global analysis is to relate the local data to remote sensing data. Examples of this approach are correlated studies between EUV global images and RPI or WHISPER local f_{pe} observations, for instance, for studying plasmaspheric plume densities (Garcia et al. 2003; Darrouzet et al. 2006a). Both types of observation are complementary: The local measurements give a detailed picture, avoiding line-of-sight integration effects, while the global data provide the context of those measurements.

A specific radio data analysis technique is multiple direction-finding. Direction-finding is an established technique that exploits the fact that the spacecraft are spinning: If the wave is electromagnetic, propagating in the ordinary (O) mode (quasi-circular polarization) and coming from a fixed and limited source, the spin modulation can be used to determine the projection of the direction of propagation onto the antenna spin plane (Gurnett 1975; Gough 1982; Calvert 1985; Kasaba et al. 1998; Reinisch et al. 1999; Décréau et al. 2004). As the antennae on board the CLUSTER satellites rotate in the $X_{\text{GSE}}Y_{\text{GSE}}$ plane, the WHISPER instrument measures the E_{xy} projection of the wave electric field onto that plane. Considering the general case of elliptic polarization (with circular and linear polarization as particular cases), E_{xy} will describe an ellipse whose major axis gives the intensity of the wave electric field. Since the $\mathbf{k}$ -vector is perpendicular to the wave plane, the wave propagation direction in the spin plane is obtained when the antennae are parallel to the minor axis, i.e., when the lowest value of the electric field is measured. To be useful, it should be easy to differentiate the minor axis from the major axis, so situations where the wave polarization is linear and where the wave plane is perpendicular to the spin plane are preferred. The CLUSTER satellites have a 4 s spin period. As the electric field rotates much quicker, many E_{xy} rotation cycles are measured at a given position of the antennae. The measured signal is therefore modulated and can be modelled by

$$E_{\text{antennae}}^2 = E_0^2[1 + \alpha^2 \cos(2\omega t - \phi)]$$

where E_0 is the maximum amplitude measured, ϕ denotes the angle between the antennae and the X_{GSE} axis, ω is the angular velocity of the antennae, and α is the modulation index factor ($0 \leq \alpha \leq 1$). Using a minimum variance method, it is possible to fit the data and to determine E_0 , α , and ϕ , i.e., the direction of propagation of the wave projected into the spin plane. The multi-spacecraft aspect of multiple direction finding consists of combining the direction-finding results from several spacecraft observing waves from the same source. Plotting the directions of propagation obtained from two spacecraft in a diagram, two lines are obtained that intersect at the projection of the source position in the spin plane. The source of the wave is then located somewhere in a column parallel to the Z_{GSE} axis and crossing the point of intersection. In practice, a third and/or fourth satellite are needed to confirm the result. Further, it must be noted that if one finds a modulation index close to 1, the wave has linear polarization and the source is limited in size and remains at a fixed position. For lower modulation factors, the wave is not linearly polarized, or the source might be moving and/or extended in space. Results obtained with this technique on CLUSTER are reported by Grimald et al. (2007). Especially interesting in this context was the tilt manoeuvre operated on one of the spacecraft: With the spin axis of one spacecraft of a closely spaced pair tilted by about 45° , it is possible to test the validity of the hypotheses made in the direction finding method, and sometimes to derive the ellipticity of the observed electric field. In addition, a three-dimensional ray path can be derived.

Another illustration of a multi-instrument (but not really multipoint) technique is the combination of plasmaspheric electron number density profiles from RPI and mass density profiles obtained from ground magnetometer networks through cross-phase determination of the field line resonance frequencies: The result is the computation of an effective “ion mass factor” that measures the admixture of H^+ , He^+ , and O^+ ions (Dent et al. 2006). Enhanced heavier ion admixtures have been found immediately outside the plasmopause during refilling periods, most likely due to O^+ . Similar work has been done using EUV-derived densities (Grew et al. 2007).

4.3 Classical Gradient Computation and the Curlometer

It was already possible in the past to estimate spatial gradients from single-spacecraft data, but only if a number of assumptions were made. For instance, assuming a planar boundary with fixed orientation, one can estimate the gradient with single-point measurements, but the results strongly depend on the orientation of the boundary, which can in principle be obtained by minimum variance analysis (see Sonnerup and Scheible 1998, and references therein), and on the speed of the spacecraft relative to the boundary, which can be estimated from the measured plasma velocity if the interface is a tangential discontinuity. Consequently, it is also possible to estimate the current density. On rather rare occasions, two-spacecraft observations have been used to examine boundary gradients (e.g., Berchem and Russell 1982; Sibeck et al. 2000). The most thorough way of obtaining spatial gradients, without the need for too many assumptions, however, is by making measurements at four non-coplanar points in space as CLUSTER is doing.

4.3.1 Principle

The classical spatial gradient method has been introduced by Harvey (1998). The spatial gradient of a scalar quantity $f(x, y, z)$ is computed at the centre of the CLUSTER tetrahedron from simultaneous measurements f^α , $\alpha = 1, \dots, 4$ of that quantity. Its components ($i = x, y, z$) are given by

$$\frac{\partial f}{\partial i} = \frac{1}{32} \sum_{j=x,y,z} \left[\sum_{\alpha=1}^4 \sum_{\beta=1}^4 (f^\alpha - f^\beta) (r_j^\alpha - r_j^\beta) \right] \times \mathbf{R}_{ji}^{-1}, \quad (1)$$

where the $\mathbf{r}^\alpha$ are the spacecraft positions and $\mathbf{R}$ is the volumetric tensor

$$\mathbf{R}_{ji} = \frac{1}{4} \sum_{\alpha=1}^4 x_j^\alpha x_i^\alpha,$$

which describes the geometrical properties of the tetrahedron. The properties of the spacecraft configuration can be expressed in terms of its eigenvalues and eigenvectors, or in terms of three equivalent geometrical parameters: the characteristic size L , the elongation E , and the planarity P , together with corresponding direction vectors (Robert et al. 1998). The tetrahedron is regular when $E = P = 0$. When $P = 1$, the satellites are coplanar, whereas when $E = 1$, they are colinear. In such cases $\mathbf{R}$ is singular so that not all gradient components can be computed.

For vector quantities, the gradients can be computed component-wise. For the magnetic field, for instance, the evaluation of the current density vector $\mathbf{j} = \nabla \times \mathbf{B} / \mu_0$ (at least if time-variability does not play a role) is based on the component gradients. This technique is called the “curlometer” (Chanteur 1998; Chanteur and Harvey 1998; Dunlop and Woodward 1998; Robert et al. 1998; Dunlop et al. 2002; Dunlop and Eastwood 2008). One can also evaluate $\nabla \cdot \mathbf{B}$ to verify to which extent it is zero; this can give an idea about the precision of the obtained gradients.

4.3.2 Error Determination

Equation (1) yields an average gradient over the spacecraft separation scales, which coincides with the actual gradient only if the gradient is essentially constant over the tetrahedron: The spacecraft have to be embedded in the same structure at the same time. This is

the so-called spatial homogeneity condition. Within the context of the method itself, it is not possible to estimate the error due to the fact that the gradient in reality might not be constant. A priori knowledge about the quantity f can guide scientific judgment about the realism of the obtained gradients.

A second observation is that (1) involves differences of the measured data values, which can lead to large numerical errors. This is especially true for small spacecraft separation distances, a condition often required to satisfy the homogeneity condition. Gradient computation can therefore only be performed successfully if the measurement errors are small. In particular, the data must be properly cross-calibrated.

The classical gradient computation as defined by (1) is a linear operator acting on the measurements f^α . The measurement errors will therefore propagate according to the same operator. As the computation involves the inverse of the volumetric tensor $\mathbf{R}$, small eigenvalues of this tensor lead to strong error propagation in the corresponding eigenvector direction. Therefore, if the tetrahedron degenerates into a plane or even a line, the errors become excessive. Expressions for the error propagation in terms of L , P , and E have been given by Darrouzet (2006).

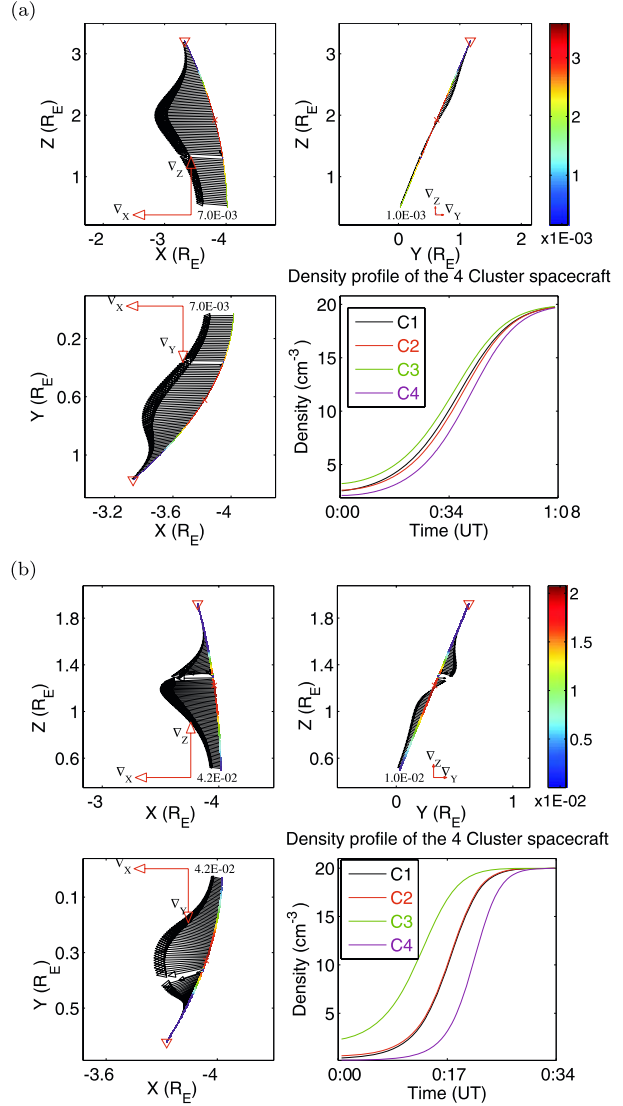
We have already pointed out how sensitive gradient computation is to the errors on the data, since it is based on computing differences. Computing the curl and the divergence of a vector field poses another level of difficulty. As the divergence and each of the components of the curl are sums of terms of the same order of magnitude, but possibly with opposite sign, the relative error on the result can be larger than the relative errors on the individual gradient components, which themselves already carry a significant uncertainty.

The precision of the gradient also depends on the uncertainty on the spacecraft positions. In the context of plasmaspheric studies, which are usually done with medium to large spacecraft separations, this error contribution can be neglected. Similar errors can arise due to imperfect knowledge of the exact time of measurement, owing to uncertainties in spacecraft clock synchronization and instrument cycling or scanning during the data acquisition time (organized in frequency scans in wave instruments, or according to spin for plasma spectrometers); in the plasmasphere such error sources do not matter either.

4.3.3 Applications

While the propagation of measurement errors can be evaluated analytically, it is much more difficult to assess the consequences of the homogeneity condition. One can therefore perform some numerical experiments. Figure 21 shows the gradients computed for a simulated crossing by the four CLUSTER spacecraft through an artificial planar density boundary perpendicular to the X_{GSE} -axis, given by $n^\alpha(t) = n_1 + n_2 \tanh(\mathbf{r}_x^\alpha(t)/C)$, where n_1 and n_2 are given densities and C the characteristic size of the boundary. In these experiments, real CLUSTER orbits were used (26 February 2001, 00:00–01:30 UT) characterized by a rather regular tetrahedron with $P < 0.5$ and $L \approx 0.75$ with a spacecraft separation S (along X_{GSE}) of ~ 1000 km. Figure 21a corresponds to $C = 9S$, a structure larger than the separation distance, while Fig. 21b corresponds to $C = S$. Each part of the figure displays the projections of the gradient vectors onto the $X_{\text{GSE}}Y_{\text{GSE}}$, $Y_{\text{GSE}}Z_{\text{GSE}}$ and $X_{\text{GSE}}Z_{\text{GSE}}$ planes along the trajectory of the centre of the tetrahedron, as well as the artificial density profiles for the four spacecraft as a function of time. Figure 21a shows that for $C > S$ the density gradient has both a correct orientation (pointing along X_{GSE} only) and magnitude, with an error of around 5%. When $C = S$, the spatial gradient has spurious components in the Y_{GSE} and Z_{GSE} directions, mainly near the edges of the transition. The error attributable to the homogeneity

Fig. 21 Artificial density gradient computed for the four CLUSTER orbits on 26 February 2001, 00:00–01:30 UT, crossing an artificial density boundary perpendicular to X_{GSE} . The spacecraft separation was around 1000 km. The panels show the gradients computed along the trajectory of the center of the tetrahedron and projected onto the $X_{GSE}Y_{GSE}$, $Y_{GSE}Z_{GSE}$, and $X_{GSE}Z_{GSE}$ planes, as well as the artificial density profiles at the four spacecraft, for spatial structure (a) on a 9000 km scale, and (b) on a 1000 km scale. The gradient vectors are indicated by black arrows, the color scale encodes the gradient magnitude, and the red cross and triangle indicate the middle and the end of the trajectory. (Adapted from Darrouzet 2006)



condition is now estimated to be around 10 %. For even smaller structures ($C < S$), the gradient technique is no longer valid. In conclusion, the homogeneity condition indeed plays a decisive role.

Darrouzet et al. (2006a, 2006b) have applied the classical gradient computation technique to plasmaspheric densities derived from the WHISPER f_{pe} data. The discrete frequency scale on WHISPER has a half-step of 163 Hz. For densities around 10 cm^{-3} , this implies a relative error of $\sim 1 \%$, or 0.1 cm^{-3} . A typical density difference between simultaneous measurements of 2 cm^{-3} then leads to a relative precision on the density gradient of typically 5 %. In addition, one has to consider the error due to the homogeneity condition, which varies from event to event.

The curlometer based on the classical gradient computation has been applied to CLUSTER magnetic field measurements in the plasmasphere by Vallat et al. (2005), thereby detecting a westward ring current near the equator and field-aligned currents at the plasma sheet boundary.

Gradient techniques, and the curlometer in particular, have been extensively used in the CLUSTER community for studying the magnetopause current layer (e.g., Dunlop and Balogh 2005; De Keyser et al. 2005; Dunlop et al. 2006). These studies, mostly involving the smallest spacecraft separations, lead to results that are consistent with a Chapman-Ferraro current, often showing signatures of magnetospheric surface waves, of reconnection, or of flux transfer events. Current densities have also been computed successfully in the magnetotail current sheet. Other applications include measuring the current density in the heliospheric current sheet (Eastwood et al. 2002).

4.4 Least-Squares Techniques for Gradient Computation

The validity of the classical gradient computation depends on the spatial homogeneity requirement. A recent generalization, least-squares gradient computation, is based on homogeneity in space–time. This improved gradient technique can provide a total error estimate on the result (De Keyser et al. 2007; De Keyser 2008).

4.4.1 Principle

Least-squares gradient computation collects all measurements in a space–time region in which the gradient is essentially constant. Consider a scalar field $f(\mathbf{x}, t)$ that is sampled N times, at positions and times $\mathbf{x}_i = [x_i; y_i; z_i; t_i]$. The measurements f_i have known random error variances $\delta f_{\text{meas},i}^2$. To illustrate the idea, consider the 2-dimensional situation sketched in Fig. 22. We want to compute the gradient at $\mathbf{x}_0$ from measurements $\mathbf{x}_i$ made by several spacecraft. The field f can be locally approximated by a Taylor expansion around $\mathbf{x}_0$. With $\Delta\mathbf{x} = \mathbf{x} - \mathbf{x}_0$, and denoting the function value, the gradient, and the hessian at $\mathbf{x}_0$ by f_0 , $\mathbf{g}_0 = \nabla_{\mathbf{x}t} f_0$, and $\mathbf{H}_0 = \nabla_{\mathbf{x}t} \nabla_{\mathbf{x}t}^\top f_0$, this expansion gives

$$f(\mathbf{x}) = f_0 + \Delta\mathbf{x}^\top \mathbf{g}_0 + \frac{1}{2} \Delta\mathbf{x}^\top \mathbf{H}_0 \Delta\mathbf{x} + \dots \quad (2)$$

This expansion can be truncated after the linear term, thus defining the approximating function $f_{\text{approx}}(\mathbf{x}) = f_0 + \Delta\mathbf{x}^\top \mathbf{g}_0$ and the approximation error $\delta f_{\text{approx}}(\mathbf{x}) = \frac{1}{2} \Delta\mathbf{x}^\top \mathbf{H}_0 \Delta\mathbf{x} + \dots$. Requiring that the approximation matches the measurements,

$$f_{\text{approx}}(\mathbf{x}_i) - f_i = 0, \quad (3)$$

results in a system for f_0 and $\mathbf{g}_0$ with N equations, one for each measurement. The number of unknowns, M , is 5. In practical situations in the plasmasphere, this system is overdetermined ($N \gg M$); it can be solved in a least-squares sense.

Approximation (2) is valid in a region around $\mathbf{x}_0$ that can be described by a 4-dimensional ellipsoid in space–time (dark shaded ellipse in the 2-dimensional analog of Fig. 22); this ellipsoid reflects the homogeneity conditions. It is uniquely specified by a set of four mutually orthogonal unit vectors (the homogeneity directions) and by the associated homogeneity length and time scales. The approximation error δf_{approx} grows with distance from $\mathbf{x}_0$, measured with a norm based on the homogeneity lengths and directions. The total error on each measurement can then be estimated as $\delta f_i^2 = \delta f_{\text{meas},i}^2 + \delta f_{\text{approx},i}^2$.

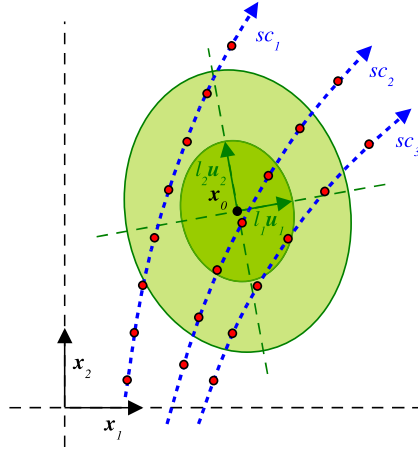


Fig. 22 The least-squares gradient algorithm uses data from a set of points in space-time, represented here as a 2-dimensional space (x_1, x_2) . The data are obtained along the trajectories of several spacecraft (*red dots on the dotted lines*). The homogeneity condition is expressed by associating with each data point an error that grows with distance from x_0 , the point where the gradient is computed. This distance is measured in the frame $(l_1 u_1, l_2 u_2)$. Points inside the inner ellipse correspond to small distances and a small error, points between both ellipses are less relevant, and points outside the outer ellipse are considered irrelevant. (Adapted from De Keyser 2008)

System (3) is treated as a weighted least-squares problem, with the weights being $1/\delta f_i$. The system that is actually solved is

$$(f_0 + \Delta \mathbf{x}^\top \mathbf{g}_0 - f_i)/\delta f_i = 0, \quad (4)$$

which is equivalent to minimizing the least-squares problem

$$\chi^2 = \sum_{i=1}^N \frac{(f_0 + \Delta \mathbf{x}^\top \mathbf{g}_0 - f_i)^2}{\delta f_i^2}.$$

We refer to De Keyser et al. (2007) for a description of the solution procedure. The choice of the weights $1/\delta f_i$ makes sure that measurements with a large total error do not contribute much to the solution. In particular, data acquired well outside the homogeneity domain do not add information.

The gradients of the individual components of a vector field can be obtained by treating each component as a separate scalar field under the simplifying assumption that the approximation errors are not correlated. The number of unknowns at each point is $M = 3 \times 5 = 15$. Since the least-squares method can easily handle constraints, magnetic field gradient computations impose the condition $\nabla \cdot \mathbf{B} = 0$ (so that $M = 14$), thus leading to an improved curlometer.

In situations of strong time-variability the homogeneity time scale is short and one can only use simultaneous measurements. The overdetermined system then is simplified: The time derivatives can be removed from the system, so that $M = 4$ for the gradient of a scalar field, $M = 12$ for a vector field, and $M = 11$ for a divergence-free vector field. If exactly four simultaneous measurements are available and if the four points are well within the spatial homogeneity domain (giving them identical δf_i), the method effectively reduces to the classical algorithm (as demonstrated in detail by De Keyser et al. 2007).

4.4.2 Error Estimates

The effect of the measurement and approximation errors on the result is described by the singular values of the weighted system (4): Small singular values imply strong error propagation. The singular values offer a convenient generalization of the tetrahedron geometric factors (Robert et al. 1998) and allow one to diagnose when the problem is ill-conditioned. As a result, the least-squares gradient algorithm provides reliable total error estimates on the computed gradient.

4.4.3 Applications

One of the practical benefits of this technique is its robustness. It can handle short data gaps, something that is problematic for the classical gradient algorithm. A particular advantage of the technique is that it may be applied in situations with less than four instruments if constraints are imposed. It can also exploit data from more than four spacecraft. In fact, the actual number of spacecraft does not matter; what is important is the space–time distribution of the measurement points.

While the gradients obtained with the new method typically do not differ much from those obtained with the classical gradient method, one now obtains a quantitative estimate of the total error on the results. The reliability of this estimate depends on the specified homogeneity properties. De Keyser et al. (2007) assume that the homogeneity parameters are all given. While suitable values can be chosen based on physical considerations, this may not be easy to do in practice. It appears possible to introduce heuristic techniques to estimate at least some of the homogeneity properties automatically, so that each gradient can be computed with the optimal set of data points; the error estimates on the gradient then are more realistic (De Keyser 2008).

The homogeneity scales reflect the physical structures to be studied. Whatever the scales, the least-squares method will always produce a result, but whether the computed gradients are accurate depends on the nature of the data and the quality of the space–time sampling. With CLUSTER in the plasmasphere, a good gradient can be obtained when the homogeneity scales are on the order of, or larger than, the spacecraft separations in space and time. Homogeneity lengths of a few hundreds of kilometers and a time scale of 1 minute are usually fine, although finer-scale plasmaspheric structures may be formed more rapidly when geomagnetic activity is stronger, necessitating smaller homogeneity scales. Some CLUSTER applications of the technique are described elsewhere in this issue (Darrouzet et al. 2008; Matsui et al. 2008).

4.5 Time-Delay Analysis with Multiple Spacecraft

The limitations of the homogeneity condition can be overcome by making certain assumptions about the objects that are observed. For a magnetospheric interface, for instance, one can perform an analysis of the time delays between the consecutive interface crossings by the four CLUSTER spacecraft in the assumption that the interface is planar.

4.5.1 Method

The basic assumption is that the interface is locally planar, that it moves at a constant speed, that its orientation does not change, and that its characteristic evolution time is longer than the time between the consecutive crossings. The time-delay analysis takes as input the time

delays $t_\alpha - t_\beta$ between the crossing of the interface for all spacecraft pairs (α, β) as well as the position differences $\mathbf{r}^\alpha - \mathbf{r}^\beta$. The method determines the orientation of the interface, as given by its normal direction $\mathbf{n}$, and its speed, V_n , in the normal direction. The method is based on the following set of relations:

$$\frac{1}{V_n} (\mathbf{r}^\alpha - \mathbf{r}^\beta) \cdot \mathbf{n} = t_\alpha - t_\beta$$

for all distinct pairs. For the case of CLUSTER, there are 6 such pairs, of which (at most) 3 are independent. There are also 3 unknowns: 2 independent components of $\mathbf{n}$ (which is a unit vector) and V_n . There may be degenerate spatial configurations for which no solution can be found.

4.5.2 Applications

The important advantage of time delay analysis is that it does not require all spacecraft to be within the transition at the same time. This makes the technique peculiarly interesting for intrinsically thin interfaces, such as the bow shock and the magnetopause, for which more evolved versions of the technique have been developed (Haaland et al. 2004). But even for interfaces that are not really thin, this tool can help in situations where the spacecraft separation is simply too large.

Attractive targets for this method in the plasmasphere are density interfaces, such as the plasmopause itself, the edges of a plasmaspheric plume, or density irregularities. The conditions of slow dynamic evolution, planarity, constant orientation, and constant speed are often likely to be satisfied, except perhaps for smaller-scale density irregularities. Darrouzet et al. (2004, 2006a) have applied the technique to plasmaspheric density irregularities and plume interfaces.

5 Conclusions and Outlook

The new observational strategies of IMAGE and CLUSTER have already resulted in a number of scientific advances in plasmaspheric research.

The detection of rich detail in IMAGE/EUV global images provides a better understanding of plasmasphere structure. We have reviewed the most frequently used data processing tools, including image inversion and the approximate technique of minimum- L projection and pseudo-density determination. We have highlighted one example of the added value that new tools can bring: By cross-correlating details in subsequent images, the overall plasma convection pattern in the inner magnetosphere can be inferred, from which the convection electric field can be deduced. Such global scale results should be helpful for studying the global and mesoscale electric fields that are responsible for plasmasphere dynamics, including the magnetospheric electric fields responsible for subauroral polarization streams observed in the ionosphere (Goldstein et al. 2003b), and for studying the coupling to the ring current and the ionosphere (Goldstein et al. 2002; Khazanov et al. 2003; Gallagher et al. 2005; Liemohn and Brandt 2005). Interesting in this respect are studies that combine EUV global images with global images from the HENA and MENA neutral atom imagers to investigate the ring current–plasmasphere interaction (Gurgiolo et al. 2005).

The IMAGE/RPI wave instrument provides a picture of its environment by active radio sounding, thereby discovering, for instance, wave ducts of finite extent along the magnetic field lines. With the emitter inside the structures under study, the radio wave echoes can

reveal a lot of detail of the spacecraft environment. The interpretation of the various wave echoes can be ambiguous; a proper understanding of the types of plasma radio waves and their propagation characteristics is indispensable, as techniques for automated identification of traces and resonances rely on the different wave characteristics. Also noteworthy is the use of ray-tracing algorithms in understanding the plasmagram signatures of wave propagation effects. An interesting application has been the measurement of field-aligned total densities that have permitted renewed study of the microphysics of plasmaspheric refilling (Reinisch et al. 2004; Tu et al. 2005). Data mining tools facilitate searching through the plasmagram database. Local radio measurements by IMAGE/RPI and by CLUSTER/WHISPER have both been exploited using automated plasma resonance recognition algorithms to produce reliable ambient plasma density measurements (Rauch et al. 2006; Galkin et al. 2008). Of particular importance are the multi-spacecraft direction-finding techniques for determining the source location of certain waves (Grimald et al. 2007).

The study of the plasmasphere with CLUSTER multi-spacecraft measurements is only starting to gather momentum. An important aspect is the use of the curlometer technique to compute the current density in the plasmasphere (Vallat et al. 2005; De Keyser et al. 2007). Initial results have been reported concerning the density and field gradients in the plasmasphere (Darrouzet et al. 2006b). Studies of the form and evolution of plasmaspheric plumes confirm and extend IMAGE findings, such as plasmaspheric plumes that span more than 6 hours in local time, and the outward motion of plume tips while moving azimuthally at sub-corotation speed (Darrouzet et al. 2006a). The availability of improved gradient computation techniques will certainly help in situations where the spacecraft separations are not small. Especially in combination with empirical models for the field-aligned density distribution, radial and azimuthal gradients could be computed in many more cases than they are now. As the behavior of the CLUSTER instrumentation in space becomes better understood, their intercalibration is improving so that gradients of quantities other than the FGM magnetic field and the WHISPER densities might be computed as well.

Explaining the morphology of plasmaspheric plumes or notches as revealed by these non-local observations (Darrouzet et al. 2008, this issue) challenges current models for the plasmasphere's dynamic evolution. We refer to Pierrard et al. (2008, this issue) for a review of the state-of-the-art in physics-based plasmaspheric models.

Non-local measurements are very well suited for the construction of empirical models (Reinisch et al. 2008, this issue). IMAGE and CLUSTER have contributed to empirical models of the plasma density in the inner magnetosphere and of the electric field that drives the convection. Empirical models of the broad variety of plasma waves that have been recorded by both missions are being constructed for assessing the effect of wave-particle interactions on the time-evolution of the radiation belts.

As in the past, combining data from various spacecraft and/or on the ground, as well as model simulations, help scientists to arrive at a more global picture of the state of the plasmasphere. Interesting conjunctions between individual spacecraft have been rather rare. The pictures offered by IMAGE/EUV, however, provide the global context for in situ measurements without requiring a conjunction. In particular, combined data analysis with CLUSTER and IMAGE data has turned out to be rewarding (e.g., Darrouzet et al. 2006a).

The acquisition of non-local data, by remote sensing from a single spacecraft as with IMAGE or by combining in situ data from spacecraft constellations as with CLUSTER, has revolutionized space plasma physics. Current and future magnetospheric missions will heavily use these techniques: China's CHANG'E and KUAFU-B spacecraft will use extreme ultraviolet imagers similar to those on IMAGE, and the CROSS-SCALE and WARP missions proposed in the frame of ESA's Cosmic Vision program, as well as NASA's THEMIS and MMS missions, use a multi-spacecraft configuration.

Future plasmasphere missions would have to carry a sufficiently broad suite of experiments that is able to measure the plasma environment, from the cold plasmaspheric populations over the warm ring current plasma to the energetic radiation belt particles. Such missions should study the interactions between all these plasma populations and the fields to further elucidate the dynamical response of the inner magnetosphere at times of disturbed geomagnetic activity. Electron content data routinely inferred from the propagation of radio signals between spacecraft or between spacecraft and the ground undoubtedly will play an important role as well. Practical benefits of such research would include improved predictability of the state of the ionosphere and of the reliability of GPS-based applications, and a more thorough understanding of radiation belt ionization hazards to spacecraft and human crew.

Acknowledgements J. De Keyser and F. Darrouzet acknowledge the support by the Belgian Federal Science Policy Office (BELSPO) through the ESA/PRODEX CLUSTER project (contract 13127/98/NL/VJ (IC)). This paper is an outcome of the workshop "The Earth's plasmasphere: A CLUSTER, IMAGE, and modeling perspective" organized by the Belgian Institute for Space Aeronomy in Brussels in September 2007.

References

- B. Abel, R.M. Thorne, Electron scattering loss in Earth's inner magnetosphere. 1. Dominant physical processes. *J. Geophys. Res.* **103**(A2), 2385–2396 (1994)
- M.L. Adrian, D.L. Gallagher, L.A. Avanov, IMAGE EUV observation of radially bifurcated plasmaspheric features: First observations of a possible standing ULF waveform in the inner magnetosphere. *J. Geophys. Res.* **109**, A01203 (2004)
- V.V. Afonin, K.V. Grechnev, V.A. Ershova, O.Z. Rosté, N.F. Smirnova, Y.A. Schul'chishin, Y. Smilauer, Ion composition and temperature of the ionosphere obtained from the Intercosmos 24 satellite ("Aktivnyi" project) at the maximum of the 22nd solar activity cycle. *Cosmic Res.* **32**(2), 189–198 (1994)
- V.V. Afonin, V.S. Bassolo, J. Smilauer, J.F. Lemaire, Motion and erosion of the nightside plasmopause region and of the associated subauroral electron temperature enhancement: Cosmos-900 observations. *J. Geophys. Res.* **102**(A2), 2093–2103 (1997)
- P.C. Anderson, D.L. Carpenter, K. Tsuruda, T. Mukai, F.J. Rich, Multisatellite observations of rapid subauroral ion drifts (SAID). *J. Geophys. Res.* **106**(A12), 29585–29599 (2001)
- R.R. Anderson, CRRES plasma wave observations during quiet times, during geomagnetic disturbances, and during chemical releases, in *Dusty and Dirty Plasmas, Noise, and Chaos in Space and in the Laboratory*, ed. by H. Kikuchi (Plenum Press, New York, 1994), pp. 73–96
- A. Balogh, C.M. Carr, M.H. Acuña, M.W. Dunlop, T.J. Beek, P. Brown, K.-H. Fornacon, E. Georgescu, K.-H. Glassmeier, J. Harris, G. Musmann, T. Oddy, K. Schwingenschuh, The Cluster magnetic field investigation: Overview of in-flight performance and initial results. *Ann. Geophys.* **19**(10), 1207–1217 (2001)
- R.F. Benson, V.A. Osheroovich, J. Fainberg, A.F. Vinas, D.R. Ruppert, An interpretation of banded magnetospheric radio emissions. *J. Geophys. Res.* **106**(A7), 13179–13190 (2001)
- R.F. Benson, P.A. Webb, J.L. Green, L. Garcia, B.W. Reinisch, Magnetospheric electron densities inferred from upper-hybrid band emissions. *Geophys. Res. Lett.* **31**, L20803 (2004)
- R.F. Benson, P.A. Webb, J.L. Green, D.L. Carpenter, V.S. Sonwalkar, H.G. James, B.W. Reinisch, Active wave experiments in space plasmas: The Z mode, in *Geospace Electromagnetic Waves and Radiation*, ed. by J.W. Labelle, R.A. Treumann. Lecture Notes in Physics (Springer, Berlin, 2006), pp. 3–35
- J. Berchem, C.T. Russell, The thickness of the magnetopause current layer - ISEE 1 and 2 observations. *J. Geophys. Res.* **87**(A4), 2108–2114 (1982)
- V.V. Bezrukh, Results of the measurements of the concentration of charged particles in the plasma cloud of the Earth carried out on board of Elektron 2 and Elektron 4. *Kosm. Issled.* **8**, 273–277 (1970)
- V.V. Bezrukh, K.I. Gringauz, The hot zone in the outer plasmasphere of the Earth. *J. Atmos. Terr. Phys.* **38**, 1085–1091 (1976)
- J. Bortnik, U.S. Inan, T.F. Bell, Frequency-time spectra of magnetospherically reflecting whistlers in the plasmasphere. *J. Geophys. Res.* **108**(A1), 1030 (2003)
- P.C. Brandt, D.G. Mitchell, Y. Ebihara, B.R. Sandel, E.C. Roelof, J.L. Burch, R. Demajistre, Global IMAGE/HENA observations of the ring current: Examples of rapid response to IMF and ring current-plasmasphere interaction. *J. Geophys. Res.* **107**(A11), 1359 (2002)

- N.M. Brice, Bulk motion of the magnetosphere. *J. Geophys. Res.* **72**(21), 5193–5211 (1967)
- N.M. Brice, R.L. Smith, Lower hybrid resonance emissions. *J. Geophys. Res.* **70**(1), 71–80 (1965)
- J.L. Burch, IMAGE mission overview. *Space Sci. Rev.* **91**(1–2), 1–14 (2000)
- J.L. Burch, J. Goldstein, B.R. Sandel, Cause of plasmasphere corotation lag. *Geophys. Res. Lett.* **31**(5), L05802 (2004)
- W.C. Burgess, U.S. Inan, The role of ducted whistlers in the precipitation loss and equilibrium flux of radiation belt electrons. *J. Geophys. Res.* **98**(A9), 15643–15665 (1993)
- W.I. Burke, N.C. Maynard, M.P. Hagan, R.A. Wolf, G.R. Wilson, L.C. Gentile, M.S. Gussenhoven, C.Y. Huang, T.W. Garner, F.J. Rich, Electrodynamics of the inner magnetosphere observed in the dusk sector by CRRES and DMSP during the magnetic storm of June 4–6, 1991. *J. Geophys. Res.* **103**(A12), 29399–29418 (1998)
- W. Calvert, DE-1 measurements of AKR wave directions. *Geophys. Res. Lett.* **12**(6), 381–384 (1985)
- P. Canu, P.M.E. Décréau, J.G. Trotignon, J.L. Rauch, H.C. Séran, P. Fergeau, M. Lévêque, P. Martin, F.X. Sené, E. Le Guirrec, H. Alleyne, K. Yearby, Identification of natural plasma emissions observed close to the plasmapause by the Cluster-Whisper relaxation sounder. *Ann. Geophys.* **19**(10), 1697–1709 (2001)
- D.L. Carpenter, Whistler evidence of a “knee” in the magnetospheric ionization density profile. *J. Geophys. Res.* **68**(6), 1675–1682 (1963)
- D.L. Carpenter, Whistler measurements of the equatorial profile of magnetospheric electron density, in *Progress in Radio Science 1960–1996, III, The Ionosphere*, ed. by G.M. Brown (Elsevier, Amsterdam, 1965), pp. 76–91
- D.L. Carpenter, Whistler studies of the plasmapause in the magnetosphere, 1. Temporal variations in the position of the knee and some evidence on plasma motions near the knee. *J. Geophys. Res.* **71**(3), 693–709 (1966)
- D.L. Carpenter, Relations between the dawn minimum in the equatorial radius of the plasmapause and *Dst*, *K_p*, and local *K* at Byrd Station. *J. Geophys. Res.* **72**(11), 2969–2971 (1967)
- D.L. Carpenter, Remarks on the ground-based whistler method of studying the magnetospheric thermal plasma. *Ann. Geophys.* **26**(2), 363–370 (1970a)
- D.L. Carpenter, Whistler evidence of the dynamic behavior of the duskside bulge in the plasmasphere. *J. Geophys. Res.* **75**(19), 3837–3847 (1970b)
- D.L. Carpenter, OGO 2 and 4 VLF observations of the asymmetric plasmapause near the time of SAR arc events. *J. Geophys. Res.* **76**(16), 3644–3650 (1971)
- D.L. Carpenter, Remote sensing the Earth’s plasmasphere. *Rad. Sci. Bull.* **308**, 13–29 (2004)
- D.L. Carpenter, R.R. Anderson, An ISEE/Whistler model of equatorial electron density in the magnetosphere. *J. Geophys. Res.* **97**(A2), 1097–1108 (1992)
- D.L. Carpenter, B.L. Giles, C.R. Chappell, P.M.E. Décréau, R.R. Anderson, A.M. Persoon, A.J. Smith, Y. Corcuff, P. Canu, Plasmasphere dynamics in the duskside bulge region: A new look at an old topic. *J. Geophys. Res.* **98**(A11), 12943–12971 (1993)
- D.L. Carpenter, J. Lemaire, The plasmasphere boundary layer. *Ann. Geophys.* **22**(12), 4291–4298 (2004)
- D.L. Carpenter, R. Walter, R.E. Barrington, D.J. McEwen, Alouette 1 and 2 observations of abrupt changes in whistler rate and of VLF noise variations at the plasmapause—A satellite-ground study. *J. Geophys. Res.* **73**(9), 2929–2940 (1968)
- D.L. Carpenter, A.J. Smith, B.L. Giles, C.R. Chappell, P.M.E. Décréau, A case study of plasma structure in the dusk sector associated with enhanced magnetospheric convection. *J. Geophys. Res.* **97**(A2), 1157–1166 (1992)
- D.L. Carpenter, M.A. Spasojević, T.F. Bell, U.S. Inan, B.W. Reinisch, I.A. Galkin, R.F. Benson, J.L. Green, S.F. Fung, S.A. Boardsen, Small-scale field-aligned plasmaspheric density structures inferred from the radio plasma imager on IMAGE. *J. Geophys. Res.* **107**(A9), 1258 (2002)
- G. Chanteur, Spatial interpolation for four spacecraft: Theory, in *Analysis Methods for Multi-Spacecraft Data*, ed. by G. Paschmann, P.W. Daly. ISSI SR-001 (ESA Publications Division, 1998), pp. 349–369
- G. Chanteur, C.C. Harvey, Spatial interpolation for four spacecraft: Application to magnetic gradients, in *Analysis Methods for Multi-Spacecraft Data*, ed. by G. Paschmann, P.W. Daly (ESA Publications Division, 1998), pp. 371–393, ISSI SR-001
- C.R. Chappell, K.K. Harris, G.W. Sharp, A study of the influence of magnetic activity on the location of the plasmapause as measured by OGO 5. *J. Geophys. Res.* **75**(1), 50–56 (1970)
- R.H. Comfort, Plasmasphere thermal structure as measured by ISEE-1 and DE-1. *Adv. Space Res.* **6**(3), 31–40 (1986)
- P.D. Craven, D.L. Gallagher, R.H. Comfort, Relative concentration of He⁺ in the inner magnetosphere as observed by the DE 1 retarding ion mass spectrometer. *J. Geophys. Res.* **102**(A2), 2279–2289 (1997)
- F. Darrouzet, Etude de la magnétosphère terrestre par l’analyse multipoint des données de la mission CLUSTER. Contributions à la caractérisation des frontières et de la magnétosphère interne, Ph.D. thesis, University of Orléans, France (2006). http://www.aeronomie.be/plasmasphere/pdf/Darrouzet_PhDThesis_UniversityOrleans_20060607.pdf

- F. Darrouzet, P.M.E. Décréau, J. De Keyser, A. Masson, D.L. Gallagher, O. Santolík, B.R. Sandel, J.G. Trotignon, J.L. Rauch, E. Le Guirriec, P. Canu, F. Sedgemore, M. André, J.F. Lemaire, Density structures inside the plasmasphere: Cluster observations. *Ann. Geophys.* **22**(7), 2577–2585 (2004)
- F. Darrouzet, J. De Keyser, P.M.E. Décréau, D.L. Gallagher, V. Pierrard, J.F. Lemaire, B.R. Sandel, I. Dandouras, H. Matsui, M. Dunlop, J. Cabrera, A. Masson, P. Canu, J.G. Trotignon, J.L. Rauch, M. André, Analysis of plasmaspheric plumes: CLUSTER and IMAGE observations. *Ann. Geophys.* **24**(6), 1737–1758 (2006a)
- F. Darrouzet, J. De Keyser, P.M.E. Décréau, J.F. Lemaire, M.W. Dunlop, Spatial gradients in the plasmasphere from Cluster. *Geophys. Res. Lett.* **33**(8), L08105 (2006b)
- F. Darrouzet, D.L. Gallagher, N. André, D.L. Carpenter, I. Dandouras, P.M.E. Décréau, J. De Keyser, R.E. Denton, J.C. Foster, J. Goldstein, M.B. Moldwin, B.W. Reinisch, B.R. Sandel, J. Tu, Plasmaspheric density structures and dynamics: Properties observed by the CLUSTER and IMAGE missions. *Space Sci. Rev.* (2008, this issue)
- J. De Keyser, Least-squares multi-spacecraft gradient calculation with automatic error estimation. *Ann. Geophys.* **26**(11), 3295–3316 (2008)
- J. De Keyser, F. Darrouzet, M.W. Dunlop, P.M.E. Décréau, Least-squares gradient calculation from multi-point observations of scalar and vector fields: Methodology and applications with Cluster in the plasmasphere. *Ann. Geophys.* **25**(4), 971–987 (2007)
- J. De Keyser, M.W. Dunlop, C.J. Owen, B.U.O. Sonnerup, S.E. Haaland, A. Vaivads, G. Paschmann, R. Lundin, L. Rezeau, Magnetopause and boundary layer. *Space Sci. Rev.* **118**(1–4), 231–320 (2005)
- P.M.E. Décréau, C. Beghin, M. Parrot, Global characteristics of the cold plasma in the equatorial plasmapause region as deduced from the GEOS 1 mutual impedance probe. *J. Geophys. Res.* **87**(A2), 695–712 (1982)
- P.M.E. Décréau, C. Ducoin, G. Le Rouzic, O. Randriamboarison, J.L. Rauch, J.G. Trotignon, X. Vallières, P. Canu, F. Darrouzet, M.P. Gough, A. Buckley, T.D. Carozzi, Observation of continuum radiations from the CLUSTER fleet: First results from direction finding. *Ann. Geophys.* **22**(7), 2607–2624 (2004)
- P.M.E. Décréau, P. Ferreau, V. Krasnosels'kikh, E. Le Guirriec, M. Lévêque, P. Martin, O. Randriamboarison, J.L. Rauch, F.X. Sené, H.C. Séran, J.G. Trotignon, P. Canu, N. Cornilleau, H. de Féraudy, H. Alleyne, K. Yearby, P.B. Mörgensen, G. Gustafsson, M. André, D.A. Gurnett, F. Darrouzet, J. Lemaire, C.C. Harvey, P. Travnicek, Early results from the Whisper instrument on Cluster: An overview. *Ann. Geophys.* **19**(10), 1241–1258 (2001)
- Z.C. Dent, I.R. Mann, J. Goldstein, F.W. Menk, L.G. Ozeke, Plasmaspheric depletion, refilling, and plasmapause dynamics: A coordinated ground-based and IMAGE satellite study. *J. Geophys. Res.* **111**, A03205 (2006)
- R.E. Denton, J. Goldstein, J.D. Menietti, Field line dependence of magnetospheric electron density. *Geophys. Res. Lett.* **29**(24), 2205 (2002)
- J.W. Dungey, The theory of the quiet magnetosphere, in *Proceedings of the 1966 Symposium on Solar-Terrestrial Physics*, ed. by J.W. King, W.S. Newman (Belgrade, 1967), pp. 91–106
- M.W. Dunlop, A. Balogh, Magnetopause current as seen by Cluster. *Ann. Geophys.* **23**(3), 901–907 (2005)
- M.W. Dunlop, A. Balogh, K.-H. Glassmeier, Four-point Cluster application of magnetic field analysis tools: The discontinuity analyzer. *J. Geophys. Res.* **107**(A11), 1385 (2002)
- M.W. Dunlop, J.P. Eastwood, The curlometer and other gradient based methods, in *Multi-Spacecraft Analysis Methods Revisited*, ed. by G. Paschmann, P.W. Daly. ISSI SR-008 (ESA Communications, 2008), pp. 17–25
- M.W. Dunlop, T.I. Woodward, Multi-spacecraft discontinuity analysis: Orientation and motion, in *Analysis Methods for Multi-Spacecraft Data*, ed. by G. Paschmann, P.W. Daly. ISSI SR-001 (ESA Publications Division, 1998), pp. 271–306
- M.W. Dunlop, A. Balogh, Q.-Q. Shi, Z. Pu, C. Vallat, P. Robert, S. Haaland, C. Shen, J.A. Davies, K.-H. Glassmeier, P. Cargill, F. Darrouzet, A. Roux, The curlometer and other gradient measurements with Cluster. *Proceedings of the Cluster and Double Star Symposium, 5th Anniversary of Cluster in Space, ESA SP-598* (2006)
- J.P. Eastwood, A. Balogh, M.W. Dunlop, C.W. Smith, Cluster observations of the heliospheric current sheet and an associated magnetic flux rope and comparisons with ACE. *J. Geophys. Res.* **107**(A11), 1365 (2002)
- C.P. Escoubet, C.T. Russell, R. Schmidt (eds.), *The Cluster and Phoenix Missions* (Kluwer, Dordrecht, 1997)
- J.C. Foster, P.J. Erickson, A.J. Coster, J. Goldstein, F.J. Rich, Ionospheric signatures of plasmaspheric tails. *Geophys. Res. Lett.* **29**(13), 1623 (2002)
- J.C. Foster, W. Rideout, B. Sandel, W.T. Forrester, F.J. Rich, On the relationship of SAPS to storm-enhanced density. *J. Atmos. Sol.-Terr. Phys.* **69**(3), 303–313 (2007)
- S.F. Fung, R.F. Benson, D.L. Carpenter, J.L. Green, V. Jayanti, I.A. Galkin, B.W. Reinisch, Guided echoes in the magnetosphere: Observations by radio plasma imager on IMAGE. *Geophys. Res. Lett.* **30**(11), 1589 (2003)

- S.F. Fung, J.L. Green, Modeling of field-aligned guided echoes in the plasmasphere. *J. Geophys. Res.* **110**(A1), A01210 (2005)
- I. Galkin, B.W. Reinisch, G. Grinstein, G. Khmyrov, A. Kozlov, X. Huang, S. Fung, Automated exploration of the radio plasma imager data. *J. Geophys. Res.* **109**, A12210 (2004a)
- I. Galkin, B.W. Reinisch, X. Huang, R.F. Benson, S. Fung, Automated diagnostics for resonance signature recognition on IMAGE/RPI plasmagrams. *Radio Sci.* **39**(1), RS1015 (2004b)
- I.A. Galkin, G. Khmyrov, A. Kozlov, B.W. Reinisch, Intelligent resident archive for RPI Level 2 data, in *Radio Sounding and Plasma Physics*, ed. by P. Song, J. Foster, M. Mendillo, D. Bilitza. AIP Conf. Proc., vol. 974 (2008), pp. 111–117
- D.L. Gallagher, M.L. Adrian, Two-dimensional drift velocities from the IMAGE EUV plasmaspheric imager. *J. Atmos. Sol.-Terr. Phys.* **69**(3), 341–350 (2007)
- D.L. Gallagher, M.L. Adrian, M.W. Liemohn, Origin and evolution of deep plasmaspheric notches. *J. Geophys. Res.* **110**, A09201 (2005)
- D.A. Galvan, M.B. Moldwin, B.R. Sandel, Diurnal variation in plasmaspheric He^+ inferred from extreme ultraviolet images. *J. Geophys. Res.* **113**, A09216 (2008)
- G. Ganguli, M.A. Reynolds, M.W. Liemohn, The plasmasphere and advances in plasmaspheric research. *J. Atmos. Sol.-Terr. Phys.* **62**(17–18), 1647–1657 (2000)
- L.N. Garcia, S.F. Fung, J.L. Green, S.A. Boardsen, B.R. Sandel, B.W. Reinisch, Observations of the latitudinal structure of plasmaspheric convection plumes by IMAGE-RPI and EUV. *J. Geophys. Res.* **108**(A8), 1321 (2003)
- J. Geiss, H. Balsiger, P. Eberhardt, H.P. Walker, L. Weber, D.T. Young, H. Rosenbauer, Dynamics of magnetospheric ion composition as observed by the GEOS mass spectrometer. *Space Sci. Rev.* **22**(5), 537–566 (1978)
- A.R. Gibby, U.S. Inan, T.F. Bell, Saturation effects in the VLF triggered emission process. *J. Geophys. Res.* **113**, A11215 (2008)
- J. Goldstein, R.W. Spiro, P.H. Reiff, R.A. Wolf, B.R. Sandel, J.W. Freeman, R.L. Lambour, IMF-driven overshielding electric field and the origin of the plasmaspheric shoulder of May 24, 2000. *Geophys. Res. Lett.* **29**(16), 1819 (2002)
- J. Goldstein, B.R. Sandel, W.T. Forrester, P.H. Reiff, IMF-driven plasmasphere erosion of 10 July 2000. *Geophys. Res. Lett.* **30**(3), 1146 (2003a)
- J. Goldstein, B.R. Sandel, M.R. Hairston, P.H. Reiff, Control of plasmaspheric dynamics by both convection and sub-auroral polarization stream. *Geophys. Res. Lett.* **30**(24), 2243 (2003b)
- J. Goldstein, M. Spasojević, P.H. Reiff, B.R. Sandel, W.T. Forrester, D.L. Gallagher, B.W. Reinisch, Identifying the plasmopause in IMAGE EUV data using IMAGE RPI in situ steep density gradients. *J. Geophys. Res.* **108**(A4), 1147 (2003c)
- J. Goldstein, B.R. Sandel, M.F. Thomsen, M. Spasojević, P.H. Reiff, Simultaneous remote sensing and in situ observations of plasmaspheric drainage plumes. *J. Geophys. Res.* **109**, A03202 (2004)
- J. Goldstein, J.L. Burch, B.R. Sandel, Magnetospheric model of subauroral polarization stream. *J. Geophys. Res.* **110**, A09222 (2005)
- J. Goldstein, B.R. Sandel, H.U. Frey, S.B. Mende, Multiple plasmopause undulations observed by the IMAGE satellite on 20 March 2001. *J. Atmos. Sol.-Terr. Phys.* **69**(3), 322–333 (2007)
- M.P. Gough, Non-thermal continuum emissions associated with electron injections: Remote plasmopause sounding. *Planet. Space Sci.* **30**(7), 657–668 (1982)
- J.L. Green, B.W. Reinisch, An overview of results from RPI on Image. *Space Sci. Rev.* **109**(1–4), 183–210 (2003)
- R.S. Grew, F.W. Menk, M.A. Clilverd, B.R. Sandel, Mass and electron densities in the inner magnetosphere during a prolonged disturbed interval. *Geophys. Res. Lett.* **34**, L02108 (2007)
- S. Grimald, P.M.E. Décréau, P. Canu, X. Suraud, X. Vallières, F. Darrouzet, C.C. Harvey, A quantitative test of Jones NTC beaming theory using Cluster constellation. *Ann. Geophys.* **25**(3), 823–831 (2007)
- K.I. Gringauz, The structure of the ionized gas envelope of the Earth from direct measurements in the USSR of local charged particle concentrations. *Planet. Space Sci.* **11**(3), 281–296 (1963)
- K.I. Gringauz, V.V. Bezrukhikh, Plasmasphere of the Earth (Review). *Geomagn. Aeron.* **17**(5), 523–533 (1977)
- K.I. Gringauz, V.G. Kurt, V.I. Moroz, I.S. Shklovsky, Results of observations of charged particles observed out to $R = 100,000$ km with the aid of charged-particle traps on Soviet space rockets. *Astronomicheskii Zhurnal* **37**, 716–735 (1960)
- K.I. Gringauz, V.V. Bezrukhikh, V.D. Ozerov, R.E. Rybchinskii, The study of interplanetary ionized gas, high-energy electrons and corpuscular radiation of the Sun, employing three-electrode charged particle traps on the second Soviet space rocket. *Planet. Space Sci.* **9**(3), 103–107 (1962)
- C. Gurgiolo, B.R. Sandel, J.D. Perez, D.G. Mitchell, C.J. Pollock, B.A. Larsen, Overlap of the plasmasphere and ring current: Relation to subauroral ionospheric heating. *J. Geophys. Res.* **110**, A12217 (2005)

- D.A. Gurnett, The Earth as a radio source: The nonthermal continuum. *J. Geophys. Res.* **80**(19), 2751–2763 (1975)
- D.A. Gurnett, U.S. Inan, Plasma wave observations with the Dynamics Explorer 1 spacecraft. *Rev. Geophys.* **26**(2), 285–316 (1988)
- D.A. Gurnett, F.L. Scarf, Summary report on session on new developments, in *Progress in Radio Science, 1963–1966* (International Union of Radio Science, Brussels, 1967), pp. 1106–1107
- G. Gustafsson, M. André, T. Carozzi, A.I. Eriksson, C.-G. Fälthammar, R. Grard, G. Holmgren, J.A. Holtet, N. Ivchenko, T. Karlsson, Y. Khotyaintsev, S. Klimov, H. Laakso, P.-A. Lindqvist, B. Lybekk, G. Marklund, F. Mozer, K. Mursula, A. Pedersen, B. Popielawska, S. Savin, K. Stasiewicz, P. Tanskanen, A. Vaivads, J.E. Wahlund, First results of electric field and density observations by Cluster EFW based on initial months of observations. *Ann. Geophys.* **19**(10–12), 1219–1240 (2001)
- S. Haaland, B.U.Ö. Sonnerup, M.W. Dunlop, A. Balogh, H. Hasegawa, B. Klecker, G. Paschmann, B. Lavraud, H. Rème, Four-spacecraft determination of magnetopause orientation, motion and thickness: Comparison with results from single-spacecraft methods. *Ann. Geophys.* **22**(4), 1347–1365 (2004)
- P. Hannequin, J. Max, Statistical and heuristic image noise extraction (SHINE): A new method for processing Poisson noise in scintigraphic images. *Phys. Medicine Biol.* **47**, 4329–4344 (2002)
- W.B. Hanson, I.B. Ortenburger, The coupling between the protonosphere and the normal F region. *J. Geophys. Res.* **66**(5), 1425–1435 (1961)
- C.C. Harvey, Spatial gradients and the volumetric tensor, in *Analysis Methods for Multi-Spacecraft Data*, ed. by G. Paschmann, P.W. Daly. ISSI SR-001 (ESA Publications Division, 1998), pp. 307–322
- K. Hashimoto, J.J. Green, R.R. Anderson, H. Matsumoto, Review of kilometric continuum, in *Geospace Electromagnetic Waves and Radiation*, ed. by J.W. LaBelle, R.A. Treumann. Lecture Notes in Physics, vol. 687 (Springer, Berlin, 2006), pp. 37–51
- M. Hayakawa, Whistlers, in *Handbook of atmospheric electrodynamics*, ed. by H. Volland, vol. II (CRC, Boca Raton, 1995), pp. 155–194
- M. Hayakawa, S.S. Sazhin, Mid-latitude and plasmaspheric hiss: A review. *Planet. Space Sci.* **40**(10), 1325–1338 (1992)
- S. Heise, N. Jakowski, D. Cooke, Ionosphere/plasmasphere imaging based on GPS navigation measurements from CHAMP and SAC-C, in *Earth Observation with CHAMP: Results from Three Years in Orbit*, ed. by C. Reigber, H. Lühr, P. Schwintzer, J. Wickert (Springer, Berlin, 2005), pp. 471–476
- R.A. Helliwell, VLF wave stimulation experiments in the magnetosphere from Siple Station, Antarctica. *Rev. Geophys.* **26**(3), 551–578 (1988)
- R.A. Helliwell, J.P. Katsufakis, VLF wave injection into the magnetosphere from Siple Station, Antarctica. *J. Geophys. Res.* **79**(16), 2511–2518 (1974)
- R.L. Heyborne, R.L. Smith, R.A. Helliwell, Latitudinal cutoff of VLF signals in the ionosphere. *J. Geophys. Res.* **74**(9), 2393–2397 (1969)
- D. Ho, D.L. Carpenter, Outlying plasmasphere structure detected by whistlers. *Planet. Space Sci.* **24**(10), 987–994 (1976)
- J.L. Horwitz, R.H. Comfort, C.R. Chappell, A statistical characterization of plasmasphere density structure and boundary locations. *J. Geophys. Res.* **95**(A6), 7937–7947 (1990)
- X. Huang, B.W. Reinisch, Automatic calculation of electron density profiles from digital ionograms. 2. True height inversion of topside ionograms with the profile-fitting method. *Radio Sci.* **17**(4), 837–844 (1982)
- X. Huang, B.W. Reinisch, P. Song, J.L. Green, D.L. Gallagher, Developing an empirical density model of the plasmasphere using IMAGE/RPI observations. *Adv. Space Res.* **33**(6), 829–832 (2004)
- U.S. Inan, T.F. Bell, R.A. Helliwell, Nonlinear pitch angle scattering of energetic electrons by coherent VLF waves in the magnetosphere. *J. Geophys. Res.* **83**(A7), 3235–3253 (1978)
- D. Jones, Terrestrial myriametric radiation from the Earth's plasmopause. *Planet. Space Sci.* **30**(4), 399–410 (1982)
- Y. Kasaba, H. Matsumoto, K. Hashimoto, R.R. Anderson, J.-L. Bougeret, M.L. Kaiser, X.Y. Wu, I. Nagano, Remote sensing of the plasmopause during substorms: Geotail observation of nonthermal continuum enhancement. *J. Geophys. Res.* **103**(A9), 20389–20405 (1998)
- C.R. Kennel, H.E. Petschek, Limit on stably trapped particle fluxes. *J. Geophys. Res.* **71**(1), 1–28 (1966)
- G.V. Khazanov, M.W. Liemohn, T.S. Newman, M.-C. Fok, R.W. Spiro, Self-consistent magnetosphere-ionosphere coupling: Theoretical studies. *J. Geophys. Res.* **108**(A3), 1122 (2003)
- I. Kimura, Effects of ions on whistler-mode ray tracing. *Radio Sci.* **1**, 269–283 (1966)
- G.A. Kotova, The Earth's plasmasphere: State of studies (a review). *Geomagn. Aeron.* **47**(4), 409–422 (2007)
- G.A. Kotova, V.V. Bezrukh, M.I. Verigin, J. Smilauer, New aspects in plasmaspheric ion temperature variations from INTERBALL 2 and MAGION 5 measurements. *J. Atmos. Sol.-Terr. Phys.* **70**(2–4), 399–406 (2008)

- H. Laakso, A. Pedersen, Ambient electron density derived from differential potential measurements, in *Measurements Techniques in Space Plasmas: Particles*, ed. by R.F. Pfaff, J.E. Borovsky, D.T. Young. Geophysical Monograph Series, vol. 102 (American Geophysical Union, Washington, 1998), pp. 49–54
- H. Laakso, R. Pfaff, P. Janhunen, Polar observations of electron density distribution in the Earth's magnetosphere. 1. Statistical results. *Ann. Geophys.* **20**(11), 1711–1724 (2002)
- J.W. LaBelle, R.A. Treumann (eds.), *Geospace Electromagnetic Waves and Radiation*. Lecture Notes in Physics, vol. 687 (Springer, Berlin, 2006)
- B.A. Larsen, D.M. Klumpar, C. Gurgiolo, Correlation between plasmopause position and solar wind parameters. *J. Atmos. Sol.-Terr. Phys.* **69**(3), 334–340 (2007)
- M.J. LeDocq, D.A. Gurnett, R.R. Anderson, Electron number density fluctuations near the plasmopause observed by the CRRES spacecraft. *J. Geophys. Res.* **99**(A12), 23661–23671 (1994)
- J.F. Lemaire, The mechanisms of formation of the plasmopause. *Ann. Geophys.* **31**, 175–190 (1975)
- J.F. Lemaire, K.I. Gringauz, *The Earth's Plasmasphere* (Cambridge University Press, New York, 1998)
- M.W. Liemohn, P.C. Brandt, Small-scale structure in the storm time ring current, in *Inner Magnetosphere Interactions: New Perspectives from Imaging*, ed. by J.L. Burch, M. Schulz, H. Spence. Geophysical Monograph Series, vol. 159 (American Geophysical Union, Washington, 2005), pp. 167–177
- A. Masson, O. Santolík, D.L. Carpenter, F. Darrouzet, P.M.E. Décréau, J.L. Green, S. Grimald, F. El-Lemdani Mazouz, M.B. Moldwin, F. Němec, Advances in plasmaspheric wave research with CLUSTER and IMAGE observations. *Space Sci. Rev.* (2008, this issue)
- H. Matsui, J.C. Foster, D.L. Carpenter, I. Dandouras, F. Darrouzet, J. De Keyser, D.L. Gallagher, J. Goldstein, P.A. Puhl-Quinn, C. Vallat, Electric fields and magnetic fields in the plasmasphere: A perspective from CLUSTER and IMAGE. *Space Sci. Rev.* (2008, this issue)
- H. Matsumoto, I. Kimura, Linear and nonlinear instabilities and VLF emissions in the magnetosphere. *Planet. Space Sci.* **19**(6), 567–608 (1971)
- C.E. McIlwain, Coordinates for mapping the distribution of magnetically trapped particles. *J. Geophys. Res.* **66**(11), 3681–3691 (1961)
- D.G. Mitchell, S.E. Jaskulek, C.E. Schlemm, E.P. Keath, R.E. Thompson, B.E. Tossman, J.D. Boldt, J.R. Hayes, G.B. Andrews, N. Paschalidis, D.C. Hamilton, R.A. Lundgren, E.O. Tums, P. Wilson, H.D. Voss, D. Prentice, K.C. Hsieh, C.C. Curtis, F.R. Powell, High energy neutral atom (HENA) imager for the IMAGE mission. *Space Sci. Rev.* **91**(1–2), 67–112 (2000)
- M.B. Moldwin, L. Downward, H.K. Rassoul, R. Amin, R.R. Anderson, A new model of the location of the plasmopause: CRRES results. *J. Geophys. Res.* **107**(A11), 1339 (2002)
- M.B. Moldwin, B.R. Sandel, M.F. Thomsen, R.C. Elphic, Quantifying global plasmaspheric images with in situ observations. *Space Sci. Rev.* **109**(1), 47–61 (2003)
- M.B. Moldwin, M.F. Thomsen, S.J. Bame, D.J. McComas, K.R. Moore, An examination of the structure and dynamics of the outer plasmasphere using multiple geosynchronous satellites. *J. Geophys. Res.* **99**(A6), 11475–11481 (1994)
- T.E. Moore, D.J. Chornay, M.R. Collier, F.A. Herrero, J. Johnson, M.A. Johnson, J.W. Keller, J.F. Laudadio, J.F. Lobell, K.W. Ogilvie, P. Rozmarynowski, S.A. Fuselier, A.G. Ghielmetti, E. Hertzberg, D.C. Hamilton, R. Lundgren, P. Wilson, P. Walpole, T.M. Stephen, B.L. Peko, B. Van Zyl, P. Wurz, J.M. Quinn, G.R. Wilson, The Low Energy Neutral Atom imager for IMAGE. *Space Sci. Rev.* **91**(1–2), 155–195 (2000)
- S.R. Mosier, M.L. Kaiser, L.W. Brown, Observations of noise bands associated with the upper hybrid resonance by the IMP 6 radio astronomy experiment. *J. Geophys. Res.* **78**(10), 1673–1679 (1973)
- O. Moullard, A. Masson, H. Laakso, M. Parrot, P.M.E. Décréau, O. Santolík, M. André, Density modulated whistler mode emissions observed near the plasmopause. *Geophys. Res. Lett.* **29**(20), 1975 (2002)
- A. Nishida, Formation of plasmopause, or magnetospheric plasma knee, by the combined action of magnetospheric convection and plasma escape from the tail. *J. Geophys. Res.* **71**(23), 5669–5679 (1966)
- P.A. Nsumei, B.W. Reinisch, P. Song, J. Tu, X. Huang, Polar cap electron density distribution from IMAGE/RPI measurements: The relative importance of solar illumination and geomagnetic activity. *J. Geophys. Res.* **113**, A01217 (2008)
- D. Nunn, A self-consistent theory of triggered VLF emissions. *Plan. Space Sci.* **22**(3), 349–378 (1974)
- Y. Omura, H. Matsumoto, Computer simulations of basic processes of coherent whistler-mode wave-particle interactions in the magnetosphere. *J. Geophys. Res.* **87**(A6), 4435–4444 (1982)
- C.G. Park, Whistler observations of the interchange of ionization between the ionosphere and the protonosphere. *J. Geophys. Res.* **75**(22), 4249–4260 (1970)
- E.W. Paschal, R.A. Helliwell, Phase measurements of whistler mode signals from the Siple VLF transmitter. *J. Geophys. Res.* **89**(A3), 1667–1674 (1984)
- G. Paschmann, P.W. Daly (eds.), *Analysis Methods for Multi-Spacecraft Data*. ISSI SR-001 (ESA Publications Division, Noordwijk, 1998)

- G. Paschmann, P.W. Daly (eds.), *Multi-Spacecraft Analysis Methods Revisited*. ISSI SR-008 (ESA Communications, Noordwijk, 2008)
- G. Paschmann, J.M. Quinn, R.B. Torbert, H. Vaith, C.E. McIlwain, G. Haerendel, O.H. Bauer, T. Bauer, W. Baumjohann, W. Fillius, M. Förster, S. Frey, E. Georgescu, S.S. Kerr, C.A. Kletzing, H. Matsui, P. Puhl-Quinn, E.C. Whipple, The Electron Drift Instrument on Cluster: Overview of first results. *Ann. Geophys.* **19**(10–12), 1273–1288 (2001)
- G. Paschmann, S.J. Schwartz, C.P. Escoubet, S. Haaland (eds.), *Outer Magnetospheric Boundaries: Cluster Results*. Space Science Series of ISSI, vol. 20 (Springer, Dordrecht, 2005)
- A. Pedersen, Solar wind and magnetosphere plasma diagnostics by spacecraft electrostatic potential measurements. *Ann. Geophys.* **13**(2), 118–129 (1995)
- A. Pedersen, P. Décr  au, C.P. Escoubet, G. Gustafsson, H. Laakso, P.-A. Lindqvist, B. Lybekk, A. Masson, F. Mozer, A. Vaivads, Four-point high resolution information on electron densities by the electric field experiments (EFW) on Cluster. *Ann. Geophys.* **19**(10–12), 1483–1489 (2001)
- A. Pedersen, B. Lybekk, M. Andr  , A. Eriksson, A. Masson, F.S. Mozer, P.-A. Lindqvist, P.M.E. D  cr  au, I. Dandouras, J.-A. Sauvaud, A. Fazakerley, M. Taylor, G. Paschmann, K.R. Svenes, K. Torkar, E. Whipple, Electron density estimations derived from spacecraft potential measurements on Cluster in tenuous plasma regions. *J. Geophys. Res.* **113**, A07S33 (2008)
- V. Pierrard, J. Goldstein, N. Andr  , V.K. Jordanova, G.A. Kotova, J.F. Lemaire, M.W. Liemohn, H. Matsui, Recent progress in physics-based models of the plasmasphere. *Space Sci. Rev.* (2008, this issue)
- C.J. Pollock, K. Asamura, J. Baldonado, M.M. Balkey, P. Barker, J.L. Burch, E.J. Korpela, J. Cravens, G. Dirks, M.-C. Fok, H.O. Funsten, M. Grande, M. Gruntman, J. Hanley, J.M. Jahn, M. Jenkins, M. Lampton, M. Marckwordt, D.J. McComas, T. Mukai, G. Penegor, S. Pope, S. Ritzau, M.L. Schattenburg, E. Scime, R. Skoug, W. Spurgeon, T. Stecklein, S. Storms, C. Urdiales, P. Valek, J.T.M. Van Beek, S.E. Weidner, M. Wuest, M.K. Young, C. Zinsmeyer, Medium Energy Neutral Atom (MENA) imager for the IMAGE mission. *Space Sci. Rev.* **91**(1–2), 113–154 (2000)
- J.L. Rauch, X. Suraud, P.M.E. D  cr  au, J.G. Trotignon, R. Led  e, G. Lemerrier, F. El-Lemdani Mazouz, S. Grimald, G. Bozan, X. Valli  res, P. Canu, F. Darrouzet, Automatic determination of the plasma frequency using image processing on WHISPER data. *Proceedings of the Cluster and Double Star Symposium, 5th Anniversary of Cluster in Space*. **ESA SP-598** (2006)
- B.W. Reinisch, G.S. Sales, D.M. Haines, S.F. Fung, W.W.L. Taylor, Radio wave active Doppler imaging of space plasma structures: Arrival angle, wave polarization, and Faraday rotation measurements with the radio plasma imager. *Radio Sci.* **34**(6), 1513–1524 (1999)
- B.W. Reinisch, D.M. Haines, K. Bibl, G. Cheney, I.A. Galkin, X. Huang, S.H. Myers, G.S. Sales, R.F. Benson, S.F. Fung, J.L. Green, S. Boardsen, W.W.L. Taylor, J.L. Bougeret, R. Manning, N. Meyer-Vernet, M. Moncuquet, D.L. Carpenter, D.L. Gallagher, P. Reiff, The Radio Plasma Imager investigation on the IMAGE spacecraft. *Space Sci. Rev.* **91**(1–2), 319–359 (2000)
- B.W. Reinisch, X. Huang, P. Song, G.S. Sales, S.F. Fung, J.L. Green, D.L. Gallagher, V.M. Vasyliunas, Plasma density distribution along the magnetospheric field: RPI observations from IMAGE. *Geophys. Res. Lett.* **28**(24), 4521–4524 (2001)
- B.W. Reinisch, X. Huang, P. Song, J.L. Green, S.F. Fung, V.M. Vasyliunas, D.L. Gallagher, B.R. Sandel, Plasmaspheric mass loss and refilling as a result of a magnetic storm. *J. Geophys. Res.* **109**, A01202 (2004)
- B.W. Reinisch, M.B. Moldwin, R.E. Denton, D.L. Gallagher, H. Matsui, V. Pierrard, J. Tu, Augmented empirical models of plasmaspheric density and electric field using IMAGE and CLUSTER data. *Space Sci. Rev.* (2008, this issue)
- H. R  me, C. Aoustin, J.M. Bosqued, I. Dandouras, B. Lavraud, J.A. Sauvaud, A. Barthe, J. Bouyssou, Th. Camus, O. Coeur-Joly, A. Cros, J. Cuvido, F. Ducay, Y. Garbarowitz, J.L. M  d  le, E. Penou, H. Perrier, D. Romefort, J. Rouzaud, C. Vallat, D. Alcaidy  , C. Jacquey, C. Mazelle, C. d'Uston, E. M  bius, L.M. Kistler, K. Crocker, M. Granoff, C. Mouikis, M. Popecki, M. Vosbury, B. Klecker, D. Hovestadt, H. Kucharek, E. Kuenneth, G. Paschmann, M. Scholer, N. Sckopke, E. Seidenschwang, C.W. Carlson, D.W. Curtis, C. Ingraham, R.P. Lin, J.P. McFadden, G.K. Parks, T. Phan, V. Formisano, E. Amata, M.B. Bavassano-Cattaneo, P. Baldetti, R. Bruno, G. Chionchio, A. Di Lellis, M.F. Marcucci, G. Pallochia, A. Korth, P.W. Daly, B. Graeve, H. Rosenbauer, V. Vasyliunas, M. McCarthy, M. Wilber, L. Eliason, R. Lundin, S. Olsen, E.G. Shelley, S. Fuselier, A.G. Ghielmetti, W. Lennartsson, C.P. Escoubet, H. Balsiger, R. Friedel, J.-B. Cao, R.A. Kovrazhkin, I. Papamastorakis, R. Pellat, J. Scudder, B. Sonnerup, First multi-spacecraft ion measurements in and near the Earth's magnetosphere with the identical Cluster ion spectrometry (CIS) experiment. *Ann. Geophys.* **19**(10–12), 1303–1354 (2001)
- A.D. Richmond, Self-induced motions of thermal plasma in the magnetosphere and the stability of the plasmopause. *Radio Sci.* **8**(11), 1019–1027 (1973)
- P. Robert, A. Roux, C.C. Harvey, M.W. Dunlop, P.W. Daly, K.-H. Glassmeier, Tetrahedron geometric factors, in *Analysis Methods for Multi-Spacecraft Data*, ed. by G. Paschmann, P.W. Daly. ISSI SR-001 (ESA Publications Division, 1998), pp. 323–348

- E.C. Roelof, A.J. Skinner, Extraction of ion distributions from magnetospheric ENA and EUV images. *Space Sci. Rev.* **91**(1–2), 437–459 (2000)
- B.R. Sandel, M.H. Denton, Global view of refilling of the plasmasphere. *Geophys. Res. Lett.* **34**, L17102 (2007)
- B.R. Sandel, A.L. Broadfoot, C.C. Curtis, R.A. King, T.C. Stone, R.H. Hill, J. Chen, O.H.W. Siegmund, R. Raffanti, D.D. Allred, R.S. Turley, D.L. Gallagher, The Extreme UltraViolet imager investigation for the IMAGE mission. *Space Sci. Rev.* **91**(1–2), 197–242 (2000)
- B.R. Sandel, J. Goldstein, D.L. Gallagher, M. Spasojević, Extreme ultraviolet imager observations of the structure and dynamics of the plasmasphere. *Space Sci. Rev.* **109**(1), 25–46 (2003)
- S.S. Sazhin, M. Hayakawa, K. Bullough, Whistler diagnostics of magnetospheric parameters: A review. *Ann. Geophys.* **10**(5), 293–308 (1992)
- G.P. Serbu, E.J.R. Maier, Low-energy electrons measured on IMP 2. *J. Geophys. Res.* **71**(15), 3755–3766 (1966)
- G.P. Serbu, E.J.R. Maier, Thermal plasma measurements within the magnetosphere, in *Space Research VII*, vol. 1, ed. by R.L. Smith-Rose, S.A. Bowhill, J.W. King (North Holland, Amsterdam, 1967), p. 527
- G.P. Serbu, E.J.R. Maier, Observations from OGO 5 of the thermal ion density and temperature within the magnetosphere. *J. Geophys. Res.* **75**(31), 6102–6113 (1970)
- R.R. Shaw, D.A. Gurnett, A test of two theories for the low-frequency cutoffs of nonthermal continuum radiation. *J. Geophys. Res.* **85**(A9), 4571–4576 (1980)
- D.R. Shklyar, F. Jiříček, Simulation of nonducted whistler spectrograms observed aboard the MAGION 4 and 5 satellites. *J. Atmos. Sol.-Terr. Phys.* **62**(5), 347–370 (2000)
- D.G. Sibeck, L. Prech, J. Safrankova, Z. Nemecek, Two-point measurements of the magnetopause: Interball observations. *J. Geophys. Res.* **105**(A1), 237–244 (2000)
- J. Smilauer, V. Truhlík, J. Boskova, P. Triska, J. Schultchishin, Observations of thermal O^{++} ions in the outer ionosphere. *Adv. Space Res.* **17**(10), 135–140 (1996)
- R.L. Smith, J.J. Angerami, Magnetospheric properties deduced from OGO 1 observations of ducted and non-ducted whistlers. *J. Geophys. Res.* **73**(1), 1–20 (1968)
- B.U.Ö. Sonnerup, M. Scheible, Minimum and maximum variance analysis, in *Analysis Methods for Multi-Spacecraft Data*, ed. by G. Paschmann, P.W. Daly. ISSI SR-001 (ESA Publications Division, 1998), pp. 185–220.
- V.S. Sonwalkar, Magnetospheric LF-, VLF-, and ELF-waves, in *Handbook of Atmospheric Electrodynamics*, vol. II, ed. by H. Volland (CRC, Boca Raton, 1995), pp. 407–462
- V.S. Sonwalkar, The influence of plasma density irregularities on whistler-mode wave propagation, in *Geospace Electromagnetic Waves and Radiation*, ed. by J.W. LaBelle, R.A. Treumann. Lecture Notes in Physics, vol. 687 (Springer, Berlin, 2006), pp. 141–183
- M. Spasojević, J. Goldstein, D.L. Carpenter, U.S. Inan, B.R. Sandel, M.B. Moldwin, B.W. Reinisch, Global response of the plasmasphere to a geomagnetic disturbance. *J. Geophys. Res.* **108**(A9), 1340 (2003)
- S.M. Stankov, N. Jakowski, S. Heise, Reconstruction of ion and electron density profiles from space-based measurements of the upper electron content. *Planet. Space Sci.* **53**(9), 945–957 (2005)
- L.R.O. Storey, An investigation of whistling atmospherics. *Phil. Trans. R. Soc. (Lond.)* **246A**, 113–141 (1953)
- L.R.O. Storey, F. Lefeuvre, The analysis of 6-component measurements of a random electromagnetic wave field in a magnetoplasma. I. The direct problem. *Geophys. J. R. Astron. Soc.* **56**(2), 255–269 (1979)
- L.R.O. Storey, F. Lefeuvre, The analysis of 6-component measurements of a random electromagnetic wave field in a magnetoplasma. II. The integration kernels. *Geophys. J. R. Astron. Soc.* **62**(1), 173–194 (1980)
- H.A. Taylor Jr., H.C. Brinton, C.R. Smith, Positive ion composition in the magnetoionosphere obtained from the OGO-A satellite. *J. Geophys. Res.* **70**(23), 5769–5781 (1965)
- H.A. Taylor Jr., H.C. Brinton, M.W. Pharo III, Contraction of the plasmasphere during geomagnetically disturbed periods. *J. Geophys. Res.* **73**(3), 961–968 (1968)
- H.A. Taylor Jr., H.C. Brinton, D.L. Carpenter, F.M. Bonner, R.L. Heyborne, Ion depletion in the high-latitude exosphere: Simultaneous OGO 2 observations of the light ion trough and the VLF cutoff. *J. Geophys. Res.* **74**(14), 3517–3528 (1969)
- H.A. Taylor Jr., J.M. Grebowsky, W.J. Walsh, Structured variations of the plasmapause: Evidence of a corotating plasma tail. *J. Geophys. Res.* **76**(28), 6806–6814 (1971)
- M.F. Thomsen, D.J. McComas, J.E. Borovsky, R.C. Elphic, The magnetospheric trough, in *Geospace Mass and Energy Flow: Results from the International Solar–Terrestrial Physics program*, ed. by J.L. Horwitz, D.L. Gallagher, W.K. Peterson. Geophysical Monograph Series (American Geophysical Union, Washington, 1998), pp. 355–369.
- R.M. Thorne, E.J. Smith, R.K. Burton, R.E. Holzer, Plasmaspheric hiss. *J. Geophys. Res.* **78**(10), 1581–1596 (1973)

- J.G. Trotignon, P.M.E. Décr  au, J.L. Rauch, O. Randriamboarison, V. Krasnosels'kikh, P. Canu, H. Alleyne, K. Yearby, E. Le Guirriec, H.C. S  ran, F.X. Sen  , P. Martin, M. L  v  que, P. Fergeau, How to determine the thermal electron density and the magnetic field strength from the CLUSTER/WHISPER observations around the Earth. *Ann. Geophys.* **19**(10–12), 1711–1720 (2001)
- J.G. Trotignon, P.M.E. Décr  au, J.L. Rauch, E. Le Guirriec, P. Canu, F. Darrouzet, The Whisper relaxation sounder onboard Cluster: A powerful tool for space plasma diagnosis around the Earth. *Cosmic Res.* **41**(4), 369–372 (2003)
- N.A. Tsyganenko, D.P. Stern, Modeling the global magnetic field of the large-scale Birkeland current systems. *J. Geophys. Res.* **101**(A12), 27187–27198 (1996)
- J. Tu, P. Song, B. Reinisch, X. Huang, J.L. Green, H.U. Frey, P.H. Reiff, Electron density images of the middle- and high-latitude magnetosphere in response to the solar wind. *J. Geophys. Res.* **110**, A12210 (2005)
- C. Vallat, I. Dandouras, M. Dunlop, A. Balogh, E. Lucek, G.K. Parks, M. Wilber, E.C. Roelof, G. Chanteur, H. R  me, First current density measurements in the ring current region using simultaneous multi-spacecraft CLUSTER-FGM data. *Ann. Geophys.* **23**(5), 1849–1865 (2005)
- C. Wang, T.S. Newman, D.L. Gallagher, Plasmopause equatorial shape determination via the Minimum L Algorithm: Description and evaluation. *J. Geophys. Res.* **112**, A12201 (2007)
- S. Watanabe, B.A. Whalen, A.W. Yau, Thermal ion observations of depletion and refilling in the plasmaspheric trough. *J. Geophys. Res.* **97**(A2), 1081–1096 (1992)
- D.J. Williams, E.C. Roelof, D.G. Mitchell, Global magnetospheric imaging. *Rev. Geophys.* **30**(3), 183–208 (1992)

Plasmaspheric Density Structures and Dynamics: Properties Observed by the CLUSTER and IMAGE Missions

**Fabien Darrouzet · Dennis L. Gallagher · Nicolas André · Donald L. Carpenter ·
Iannis Dandouras · Pierrette M.E. Décréau · Johan De Keyser · Richard E. Denton ·
John C. Foster · Jerry Goldstein · Mark B. Moldwin · Bodo W. Reinisch ·
Bill R. Sandel · Jiannan Tu**

Originally published in the journal *Space Science Reviews*, Volume 145, Nos 1–2, 55–106.
DOI: [10.1007/s11214-008-9438-9](https://doi.org/10.1007/s11214-008-9438-9) © Springer Science+Business Media B.V. 2008

Abstract Plasmaspheric density structures have been studied since the discovery of the plasmasphere in the late 1950s. But the advent of the CLUSTER and IMAGE missions in 2000 has added substantially to our knowledge of density structures, thanks to the new

F. Darrouzet (✉) · J. De Keyser
Belgian Institute for Space Aeronomy (IASB-BIRA), 3 Avenue Circulaire, 1180 Brussels, Belgium
e-mail: Fabien.Darrouzet@oma.be

J. De Keyser
e-mail: Johan.DeKeyser@oma.be

D.L. Gallagher
Marshall Space Flight Center (MSFC), NASA, Huntsville, AL, USA
e-mail: dennis.l.gallagher@nasa.gov

N. André
Research and Scientific Support Department (RSSD), ESA, Noordwijk, The Netherlands
e-mail: andre@rssd.esa.int

D.L. Carpenter
Space, Telecommunications and Radioscience Laboratory (STAR), Stanford University, Stanford, CA, USA
e-mail: dlc@nova.stanford.edu

I. Dandouras
Centre d'Etude Spatiale des Rayonnements (CESR), CNRS/Université de Toulouse, Toulouse, France
e-mail: Iannis.Dandouras@cesr.fr

P.M.E. Décréau
Laboratoire de Physique et Chimie de l'Environnement (LPCE), CNRS/Université d'Orléans, Orléans, France
e-mail: Pierrette.Decreau@cnrs-orleans.fr

R.E. Denton
Physics and Astronomy Department, Dartmouth College, Hanover, NH, USA
e-mail: richard.e.denton@dartmouth.edu

capabilities of those missions: global imaging with IMAGE and four-point in situ measurements with CLUSTER. The study of plasma sources and losses has given new results on refilling rates and erosion processes. Two-dimensional density images of the plasmasphere have been obtained. The spatial gradient of plasmaspheric density has been computed. The ratios between H^+ , He^+ and O^+ have been deduced from different ion measurements. Plasmaspheric plumes have been studied in detail with new tools, which provide information on their morphology, dynamics and occurrence. Density structures at smaller scales have been revealed with those missions, structures that could not be clearly distinguished before the global images from IMAGE and the four-point measurements by CLUSTER became available. New terms have been given to these structures, like “shoulders”, “channels”, “fingers” and “crenulations”. This paper reviews the most relevant new results about the plasmaspheric plasma obtained since the start of the CLUSTER and IMAGE missions.

Keywords Plasmasphere · CLUSTER · IMAGE · Plasma Structures

1 Introduction

From the discovery of the plasmasphere and its outer boundary, the plasmapause, in the 1950s (Storey 1953; Gringauz et al. 1960; Carpenter 1963) to the start of the CLUSTER (Escoubet et al. 1997) and IMAGE (Imager for Magnetopause-to-Aurora Global Exploration) (Burch 2000) missions in 2000, many studies of plasmaspheric density structures have been done with in situ measurements and ground-based observations (for more details, see the monograph by Lemaire and Gringauz 1998). However, those two missions completely changed the view of this region, thanks to their new capabilities: multipoint in situ measurements by CLUSTER and global imaging by IMAGE.

1.1 Before IMAGE and CLUSTER

Before the IMAGE and CLUSTER missions, structures in the plasmasphere with both large- and small-scale number density variations had been observed by OGO 5 (Chappell et al.

J.C. Foster

Haystack Observatory, Massachusetts Institute of Technology (MIT), Westford, MA, USA
e-mail: jfoster@haystack.mit.edu

J. Goldstein

Southwest Research Institute (SwRI), San Antonio, TX, USA
e-mail: jgoldstein@swri.edu

M.B. Moldwin

Institute of Geophysics and Planetary Physics (IGPP), University of California, Los Angeles, CA, USA
e-mail: mmoldwin@igpp.ucla.edu

B.W. Reinisch · J. Tu

Center for Atmospheric Research, University of Massachusetts-Lowell (UML), Lowell, MA, USA

B.W. Reinisch

e-mail: Bodo_Reinisch@uml.edu

J. Tu

e-mail: Jiannan_Tu@uml.edu

B.R. Sandel

Lunar and Planetary Laboratory (LPL), University of Arizona, Tucson, AZ, USA
e-mail: sandel@arizona.edu

1970b), by CRRES near the plasmopause (LeDocq et al. 1994), by geosynchronous satellites (Moldwin et al. 1995), and by various other ground-based and spacecraft instruments (see the review by Carpenter and Lemaire 1997).

Among those plasmaspheric density structures, large-scale features have been observed close to the plasmopause and to the plasmasphere boundary layer, PBL (Carpenter and Lemaire 2004). These structures are usually connected to the main body of the plasmasphere, and extend outwards. In the past they have been called “plasmaspheric tails” (e.g., Taylor et al. 1971; Horwitz et al. 1990) or “detached plasma elements” (e.g., Chappell 1974), since their topological relation to the main plasmasphere was not clear from single-satellite measurements. Those structures are now known as “plasmaspheric plumes” (e.g., Elphic et al. 1996; Ober et al. 1997; Sandel et al. 2001). Plumes have commonly been detected in the past by in situ measurements on satellites such as OGO 4 (Taylor et al. 1971), OGO 5 (Chappell et al. 1970a), ISEE-1 (Carpenter and Anderson 1992), CRRES (Moldwin et al. 2004; Summers et al. 2008), and several at geosynchronous orbit (Moldwin et al. 1995; Borovsky et al. 1998), but also by ground-based instruments (Carpenter et al. 1993; Su et al. 2001). Plumes were predicted on the basis of various theoretical models. When geomagnetic activity increases, the convection electric field intensifies, as the electric potential across the magnetosphere increases, driven by the interaction between the solar wind and the Earth’s magnetosphere. The outer layer of the plasmasphere is stripped away, and the plasmasphere shrinks (Grebowsky 1970; Chen and Wolf 1972; Chen and Grebowsky 1974). This process is known as plasmaspheric erosion. The eroded plasma provides the material to form plasmaspheric plumes, which extend sunward. During storm recovery plumes become entrained in corotational motion, rotating eastward into the nightside inner magnetosphere. Numerical simulations using the Rice University model and the Magnetospheric Specification and Forecast Model reproduced the formation and motion of plumes (Spiro et al. 1981; Lambour et al. 1997). The interchange instability mechanism also predicts the formation of plasmaspheric plumes (Lemaire 1975, 2000; Pierrard and Lemaire 2004; Pierrard and Cabrera 2005).

Earlier in situ observations revealed a host of complex density structures at medium-scale (e.g., Horwitz et al. 1990; Carpenter et al. 2000). However, it was difficult to understand those structures without the context afforded by global imaging and multi-satellite missions. Small-scale density irregularities have also long been observed. In the early 1960s, the existence of narrow density irregularities extended along geomagnetic field lines was established (e.g., Smith 1961; Helliwell 1965). The irregularities were usually not detected directly, but instead were studied indirectly through their transmission properties as wave ducts or guides. Later satellite measurements revealed concentrations of cross-field density irregularities in the vicinity of the plasmopause, for example with the LANL geosynchronous satellites (Moldwin et al. 1995) or the CRRES spacecraft (Fung et al. 2000). Several mechanisms have been suggested to explain those small-scale density structures, like the drift wave instability (e.g., Hasegawa 1971), or the pressure gradient instability (e.g., Richmond 1973). Irregular density profiles are also predicted by plasmaspheric models that simulate the convection (erosion) and refilling processes, like the Convection-Driven Plasmaspheric Density Model (Galperin et al. 1997) and the Rice University model (Spiro et al. 1981). Theoretical modeling of plasmaspheric refilling was also found to produce density irregularities in the equatorial region (Singh 1988; Singh and Horwitz 1992). Turnings and changes of strength of the interplanetary magnetic field (IMF) influence the convection and might be responsible for the formation of density irregularities (Goldstein et al. 2002; Spasojević et al. 2003). Plasma interchange motion was shown to be able to create density irregularities (Lemaire 1974, 2001).

With new experimental perspectives come new physical insights. The IMAGE and CLUSTER missions have fundamentally changed our knowledge about plasmaspheric density structures. IMAGE has made remote, global observations with the Extreme UltraViolet (EUV) instrument (Sandel et al. 2000) and the Radio Plasma Imager (RPI) instrument (Reinisch et al. 2000), from points both outside and within the plasmasphere (e.g., Carpenter et al. 2002; Sandel et al. 2003). The CLUSTER satellites are making detailed and coordinated multipoint measurements in the outer plasmasphere using the WHISPER (Waves of High frequency and Sounder for Probing Electron density by Relaxation) instrument (Décréau et al. 1997) and other instruments (e.g., Darrouzet et al. 2004; Dandouras et al. 2005; Décréau et al. 2005).

1.2 IMAGE Observations of Density Structures

From its initial high-latitude apogee the IMAGE spacecraft (Burch 2000) provided an excellent platform for remotely observing the azimuthal distribution of plasmaspheric plasma with the EUV instrument. Designed to detect solar-origin extreme ultraviolet light at 30.4 nm resonantly scattered by thermal He^+ , EUV provided the first global images of the plasmasphere. At a time cadence of 10 minutes, EUV images were able to repeatedly follow plasmaspheric dynamics from storm onset and erosion through recovery and refilling. The resulting global view provided a new context for more than 40 years of in situ and ground observations. One of the first results led to a refinement in our descriptive language for plasmaspheric structures, which is presented in Fig. 1. The six EUV image panels provide examples of plumes, notches, shoulders, fingers, channels and crenulations. The shadows and aurora are not features of the plasmasphere, but are routinely present in the images. The brightness in these images is proportional to the line integral of the He^+ abundance along each pixel's line of sight.

Like for EUV, the RPI instrument provides an entirely new perspective on thermal plasma density structures. RPI measured inner magnetospheric electron densities both actively and passively. The passive electric field measurements are used to observe natural radio noise and to derive electron densities local to the spacecraft as has been done with all previous in

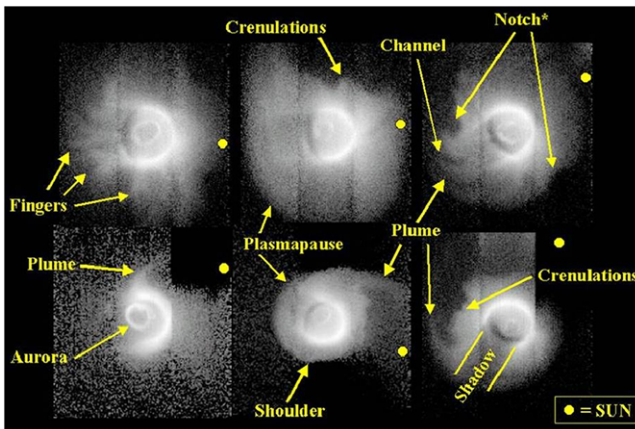


Fig. 1 Structures observed by the EUV instrument onboard IMAGE and new morphological nomenclature: examples of shoulders, plumes, fingers, channels, crenulations and notches. The direction to the Sun is shown as a yellow dot for each image. (From <http://image.gsfc.nasa.gov/poetry/discoveries/N47big.jpg>)

situ plasma wave instruments, except with greater sensitivity due to the long 500 m cross dipole antenna in the spacecraft spin plane. A 20 m tip-to-tip antenna was deployed along the spin axis to complete the 3-axis electric field antenna system. RPI actively broadcast digitally coded signals from 3 kHz to 3 MHz in order to quantitatively sample remote electron densities from about 0.1 to 10^5 cm^{-3} through the returned echoes. Thousands of plasma-pause crossings and field-aligned density distributions with resolution better than 1 minute in time, $0.1 R_E$ in range, and 10% in density have been obtained and are still being analyzed.

Those instruments and related tools are described in more detail elsewhere in this issue (De Keyser et al. 2008).

1.3 CLUSTER Observations of Density Structures

In contrast with IMAGE, which provides global two-dimensional (2-D) views of the plasmasphere in a large domain of local time (LT) and geocentric distance (R), CLUSTER provides a meridian view of plasmaspheric density, by way of four orbital sweeps placed within a limited range in LT and R , as the four CLUSTER spacecraft (C1, C2, C3, C4) cross the plasmasphere near perigee around 4 Earth radii (R_E) every 57 hours from southern to northern hemisphere (Escoubet et al. 1997). Figure 2a displays a three-dimensional (3-D) view of the CLUSTER orbits during such a crossing. Each spacecraft provides a density profile versus s , the curvilinear distance along track. The two main parameters, latitude λ and McIlwain L parameter (McIlwain 1961), are explored in a coupled way along the orbit. More precisely, electron density n_e is obtained from the WHISPER instrument (D  cr  au et al. 1997, 2001), which in its active mode, unambiguously identifies the electron plasma frequency f_{pe} (Trotignon et al. 2003), directly related to n_e . f_{pe} can also be inferred from WHISPER passive measurements by estimating the low frequency cut-off of natural plasma emissions (Canu et al. 2001). WHISPER operates between 2 and 80 kHz, with a frequency resolution of 163 Hz. This corresponds to densities between 0.05 and 80 cm^{-3} , with a relative precision that varies from 16% for low densities to 0.4% for high densities. The time resolution of density measurements is $\lesssim 3 \text{ s}$, corresponding to a distance along the orbit of $\Delta s \lesssim 15 \text{ km}$. More precisely, the WHISPER instruments deliver four density profiles,

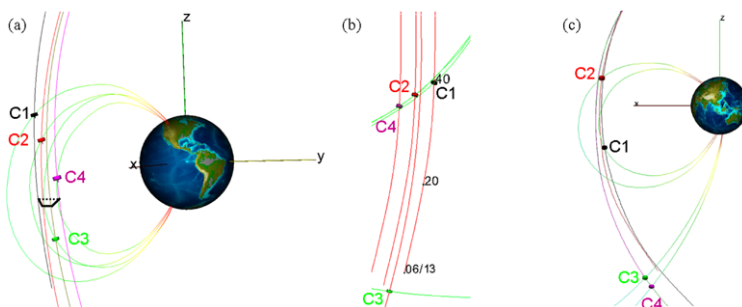


Fig. 2 **a** Instantaneous view of the four CLUSTER satellites during the $\sim 5000 \text{ km}$ separation season (September 2002). The section of the tube limited by the four orbital paths is outlined. **b** “Field-aligned” configuration in a tail season (June 2001). For the trio C1–C2–C4, the largest separation distance is $\sim 2000 \text{ km}$ along field lines, the smallest being $\sim 200 \text{ km}$ across field lines. C3 is placed at $\sim 9000 \text{ km}$ from the trio. **c** Multi-scale configuration in a tail season (August 2005). Figure produced with the Orbit Visualisation Tool (OVT, <http://ovt.irfu.se>)

$n_e^i(s_i)$, i from 1 to 4, versus respective distances s_i along orbits. This provides a spatio-temporal sampling of the region explored, as s_i depends on universal time (UT) and position (LT, L , λ).

Such density profiles obtained from single-satellite missions like GEOS, ISEE, DE and CRRES, have generally been analyzed by focusing on one variable, mostly L (e.g., Carpenter and Anderson 1992), sometimes λ (e.g., Décr  au et al. 1986), or LT for geosynchronous satellites, by assuming either uniformity of density over the explored range of the three other quantities, or by using other models of spatio-temporal density variations. CLUSTER provides new perspectives in plasmasphere observations, not only thanks to an unprecedented spatial resolution and to accurate density measurements by WHISPER, but also because density profiles can be compared to each other in order to test models and to study the 3-D view and the lifetimes of density structures.

In addition to plasma density, the multipoint measurements performed by the CLUSTER spacecraft in the plasmasphere provide other parameters such as the plasma composition and 3-D ion distribution functions measured by the Cluster Ion Spectrometry (CIS) experiment (R  me et al. 2001), or the electric field measured by the Electric Field and Wave (EFW) instrument (Gustafsson et al. 2001) and the Electron Drift Instrument (EDI), (Paschmann et al. 2001). Those instruments and related tools are described in more detail elsewhere in this issue (De Keyser et al. 2008).

The changes in the CLUSTER configuration (spacecraft separation varies from 100 to 10000 km) and the evolution of its orbit over the years, coupled to the natural dynamics of the plasmasphere, enable a variety of scientific questions to be addressed. Small spacecraft separations (100 km) allow small-scale structures to be resolved (D  cr  au et al. 2005; Darrouzet et al. 2004, 2006a), while large ones (5000 km), which are associated with larger time shifts, can be used to assess lifetime of structures or to address global dynamics (Darrouzet et al. 2008). All constellations are elongated along the orbit track, a property which can be turned into an advantage, since many of the smallest-scale structures are field-aligned. Spacecraft can be magnetically conjugate, either in a loose way (Fig. 2a), where C2 in the northern hemisphere and C3 in the southern hemisphere are at close transverse distance (~ 500 km) from the same magnetic field line, or in a more tight way (Fig. 2b), where three satellites are grouped along the same magnetic field line, at small transverse distances (~ 200 km). Lastly, the multi-scale configuration (Fig. 2c) can be used to study small-scale evolutions in a context simultaneously explored at a larger scale.

1.4 Outline of the Paper

The purpose of this paper is to survey the results obtained with CLUSTER and IMAGE on plasmaspheric density structures. Section 2 presents a new vision of the erosion and refilling processes, and new results about the plasmaspheric wind. The overall plasma distribution in the plasmasphere and several studies about the plasmopause are described in Sect. 3. Section 4 presents various results on the ion composition of the plasmasphere. The four following sections are devoted to studies of specific types of density structures, from large-scale to small-scale: plasmaspheric plumes in Sect. 5, notches in Sect. 6, other medium-scale density structures in Sect. 7, and small-scale density irregularities in Sect. 8. Section 9 concludes the paper and offers an outlook.

2 Sources and Losses in the Plasmasphere

It is well known that the plasmasphere is very dynamic, constantly in a state of change, contracting and eroding in a few hours in response to increasing geomagnetic activity and refilling over a period of a few days in quiet times. Both processes received much experimental and theoretical attention (e.g., Lemaire and Gringauz 1998), but the advent of the CLUSTER and IMAGE missions played an important role in the study of those processes, which contribute to the sources and losses of plasma in the plasmasphere.

2.1 The Disturbed Plasmasphere: A New Look at Refilling

Dynamic exchange typifies the ion populations of the plasmasphere and ionosphere and this flux is an important aspect of their coupling. Roughly speaking, the daylit portion of ionosphere supplies material to the plasmasphere, while the flow direction is into the dark ionosphere. This diurnal variation is often overwhelmed by more pronounced sinks of plasmaspheric ions, such as erosion of the entire outer plasmasphere. Following erosion events, the dominant trend in the plasmasphere is towards increasing densities and this trend is termed refilling.

Refilling of the plasmasphere has been studied for many years using ground-based and in situ techniques, but this section focuses on new results based on IMAGE data. Sandel and Denton (2007) developed a global view of refilling, using EUV observations taken on-board IMAGE. They studied the azimuthally-averaged change of He^+ column densities and equatorial abundances during an unusually quiet period extending for about 70 hours. Geomagnetic conditions during this time suggest that losses of plasmaspheric material due to erosion were minimal, leading to measurements of refilling that were expected to be largely uncompromised by confounding effects. By computing azimuthal averages of summed EUV images, Sandel and Denton (2007) derived radial profiles of He^+ column abundance at six times during the study interval corresponding to six consecutive IMAGE orbits. These profiles showed an orderly increase in column abundance with time, which slowed near the end of the period.

Instead of doing a global study of refilling, Gallagher et al. (2005) studied a small region of particular interest. They reported the first measurements of refilling using EUV observations. They were particularly interested in the physics governing the formation and evolution of plasmaspheric notches, so their measurements of refilling were made in such a feature. By tracking a notch over three IMAGE orbits, they avoided errors that could have been introduced by deviations from perfect corotation (see Sect. 6). Binning in radial distance yielded measurements at three L -positions at the single azimuth defined by the notch, which drifted relative to corotation. Geomagnetic conditions varied during the interval of their study, leading to increasing He^+ abundance during two of the orbits and decreasing abundance during the intervening orbit. Considering only the times and distances for which refilling was unambiguous, Gallagher et al. (2005) found averaged refilling rates at the equator of $3.8 \text{ He}^+ \text{ cm}^{-3} \text{ h}^{-1}$ at $L = 2.75$ and $2.7 \text{ He}^+ \text{ cm}^{-3} \text{ h}^{-1}$ at $L = 3.25$. These rates represent a limited sample of space and time, but are higher than would be expected on the basis of many other measurements, which for comparison often must be extrapolated in L and further are at best an indirect measure of the He^+ refilling rate.

Whereas the fundamental quantity measured by EUV was the change in He^+ column abundance with L and time, measured or modelled refilling is usually reported in terms of volume rates. For more direct comparison with these measurements and models, Sandel and

Denton (2007) used the method described by Gallagher et al. (2005) to convert He^+ column abundances to equatorial volume abundances; then converting to volume refilling rates was straightforward. The inferred refilling rate at the equator, averaged over the 69-hour study period, decreases with L , from $1 \text{ He}^+ \text{ cm}^{-3} \text{ h}^{-1}$ at $L = 2.3$ to $0.07 \text{ He}^+ \text{ cm}^{-3} \text{ h}^{-1}$ at $L = 6.3$. The rates determined in this way are generally a factor of 3–4 lower than those inferred by Gallagher et al. (2005) at corresponding values of L . This difference is not surprising given that the determination of Sandel and Denton (2007) uses averaging over a much longer time, and consequently includes the slower approach to saturation.

Further, other measurements and models refer to species other than He^+ , such as electron densities or total ion mass. For comparing with these determinations, Sandel and Denton (2007) used estimates of the variation of the ratio α between the He^+ density and the H^+ density with L (Craven et al. 1997), and, where necessary, neglected the contribution of heavier ions to the plasmaspheric mass density. With these approximations, they found their measurements to have a radial dependence similar to that inferred from earlier measurements and models, but their absolute values for refilling rates were generally higher by a factor of 4. They mention two factors that may contribute to this difference: (i) extrapolating the radial dependence of the ratio α outside the domain over which it was originally defined; (ii) possible interspecies variations in the refilling rate with time and L .

In spite of the uncertainties that arise when using observations of He^+ as a proxy for plasmaspheric particle populations, the global view provided by remote sensing offers advantages over more traditional techniques. These include sensing all LT and radial distances simultaneously, and avoiding errors possible when density changes driven by, i.e., departures from corotation are interpreted as purely temporal.

Galvan et al. (2008) used EUV to investigate the diurnal variation in He^+ column abundance, thus extending refilling studies to shorter timescales. Their work is unique in investigations of the diurnal variation, in that it relates to heavy ions rather than electrons or protons, and that by tracking brightness features in the plasmasphere they were able to account for departures from corotation to accurately follow a specific volume element of plasma. Their analysis of over 1000 EUV images from 128 IMAGE orbits revealed a consistent picture of the diurnal variation: (i) a general increase in He^+ abundance from dawn to dusk, peaking shortly after dusk at a level higher than dawn by a factor of 1.5–2; (ii) a region near noon where abundances remain constant or decrease slightly. They report similar behaviour in relative rates at $L = 2.5$ and 3.5 . The absolute rates of change in abundance at the two distances were consistent with the difference in flux tube volume, assuming similar rates of supply from the ionosphere at the two latitudes. The measured variations show no dependence on geomagnetic activity, but were consistent with the idea that the diurnal variation in He^+ abundance is dominated by upflow from the sunlit ionosphere and downflow into the night ionosphere.

Complementary to line-of-sight global measurements of the EUV instrument, sounding measurements from the RPI instrument provided field-aligned electron density profiles that are almost instantaneously obtained. Multiple field-aligned density profiles were sometimes available along an extended portion of the IMAGE orbit. As a consequence, 2-D electron density images can be constructed (Tu et al. 2005). It allows to infer plasma dynamics from RPI 2-D density profiles, such as plasma refilling in the outer plasmasphere and plasma acceleration in the aurora/cusp region. Those density profiles provide the first true magnetospheric electron density gradient along magnetic field lines, which has not previously been practical using in situ measurements. If the local production and loss of the charged particles are assumed small (true for the plasmasphere and subauroral trough), if plasma transport across magnetic field lines is neglected, and assuming quasi-steady conditions, the electron number

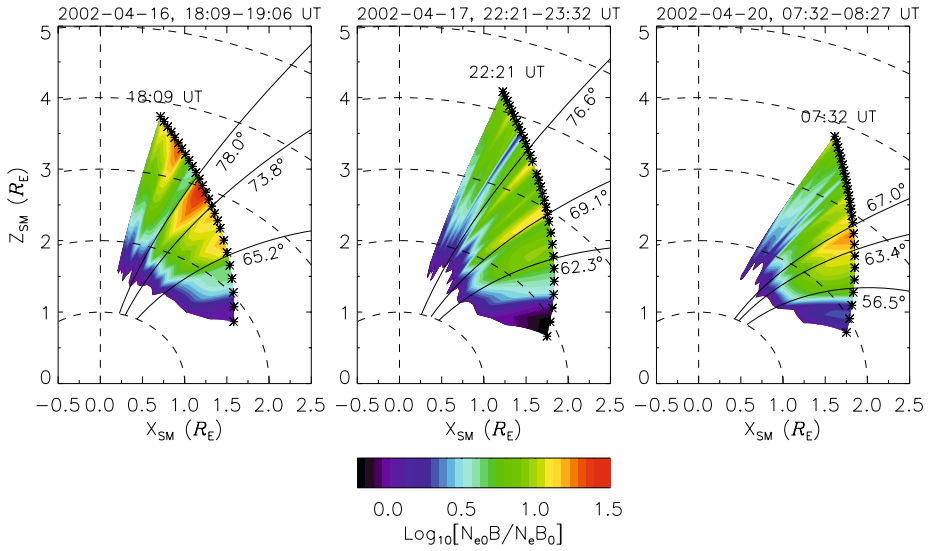


Fig. 3 Two-dimensional images of the normalized field-aligned electron velocity, projected onto the solar magnetic (SM) X_{SM} - Z_{SM} plane and derived from the field-aligned density profiles measured by RPI on three different days. The stars on each orbit segment indicate the locations from which the field-aligned density profiles were measured. Three field lines (solid) are plotted with the corrected geomagnetic coordinate (CGM) latitude labeled. The field line of lowest latitude indicates the plasmapause, while the two other delimit a density depletion region. (Adapted from Tu et al. 2005)

flux is conserved along magnetic field lines. Variations of the electron velocity parallel to magnetic field lines can thus be derived. Figure 3 displays for three different days 2-D images of this velocity normalized by the electron velocity at the base of the individual electron density profiles. Several regions of different velocity characteristics can be identified from this figure. In the inner plasmasphere the normalized electron velocity is almost constant along field lines. Beyond the plasmapause, in the trough region, the normalized velocities rapidly increase along the field lines at altitudes above about $1 R_E$, indicating a possible plasma acceleration above this altitude.

2.2 The Quiet Plasmasphere

Attention is most often paid to the striking plasmaspheric density structures produced during disturbed geomagnetic conditions. Plasmaspheric plumes, notches, and plasmapause undulations dominated our studies of plasmaspheric physical processes. Unlike the slow, multiple day process of plasmasphere refilling, these processes unfold in minutes to hours. The consequence is that other, more subtle physical processes have often been overlooked. However, the PLANET-B, IMAGE, and CLUSTER missions recently led to discoveries that have significant implications for the modelling of the quiet plasmasphere, providing us with new opportunities to study the mechanisms of plasmapause formation, in particular when there are no confounding effects associated with disturbed geomagnetic periods (e.g., Yoshikawa et al. 2003; Tu et al. 2007).

Extended quiet periods, i.e., when the geomagnetic activity index K_p is low (such as $<1^+$), are required to allow refilling to significantly proceed, especially at geosynchronous orbit and beyond where refilling times are expected to be many days. Such periods are most likely to exist during solar minimum. Reynolds et al. (2003) recently listed the yearly

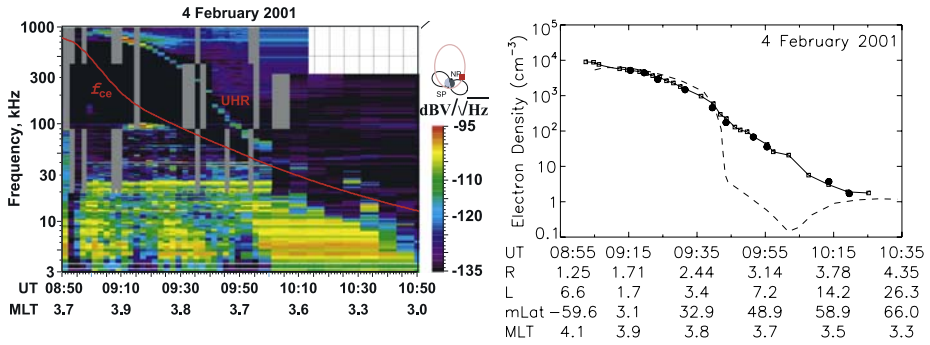


Fig. 4 (Left) Electric field spectrogram measured by RPI showing an upper hybrid resonance (UHR) band. The red line is the electron gyrofrequency determined from the Tsyganenko and Stern (1996) model. The gray strips indicate frequencies and times when no passive data were measured from RPI. The IMAGE orbit configuration is displayed on the upper right corner. (Right) Electron densities derived from the lower frequency cutoff of the UHR band along the IMAGE orbit. The dashed line represents electron densities from the empirical model of Gallagher et al. (2000). The solid dots are in situ electron densities derived from the available sounding measurements. (Adapted from Tu et al. 2007)

occurrence frequencies of various lengths of quiet periods for the entire 69-year history of recorded K_p values (from January 1932 to December 2000). It can be seen from their study that quiet time periods longer than two days with $K_p \leq 0^+$ occur rarely, but periods with $K_p \leq 2^-$ occur approximately 14 times per year.

The plasmasphere rarely appears filled to saturation, i.e., in diffusive equilibrium with the ionosphere. Tarcasai (1985) reported that the day-to-day filling of the plasmasphere after magnetic disturbances continues several days without exhibiting saturation levels corresponding to diffusive equilibrium, even for radial distances deep inside the plasmasphere. More recent observations found significant refilling in less than 28 hours near $R = 2.5 R_E$ (Reinisch et al. 2004), but still insufficient to reach saturation levels. Reynolds et al. (2003) compared locally measured plasma densities with theoretical predictions obtained from a multispecies kinetic model. The observed density level was at most only 25% of saturation density, and the density still appeared to increase even after three days of very quiet geomagnetic activity. In addition, according to the Carpenter and Anderson (1992) empirical model for saturated equatorial densities, the averaged slope of the logarithmic density is found to be independent of radial distance inside $8 R_E$, which does not correspond to that expected for a plasmasphere in diffusive equilibrium (see Fig. 8 in Pierrard et al. 2008, this issue). Beyond the limited time permitted for the plasmasphere to reach saturation, some researchers suggest refilling is slower than expected due to an additional process at work.

After many days of very quiet geomagnetic conditions, a distinct plasmopause boundary may not be found, particularly on the dayside of the Earth. Such a boundary is expected as a consequence of the continued presence of solar wind induced convection at high latitudes. Nevertheless, prolonged quiet-time observations have found smooth plasmasphere density variations extended to about $L = 7$ or beyond (e.g., Chappell 1972; Carpenter and Anderson 1992; Tu et al. 2006), implying an extended plasmasphere with either the plasmopause located beyond $L = 7$ or a smooth density transition to the subauroral region without a clear plasmopause signature. Such a smooth transition is possible if magnetospheric convection is very weak so that corotation dominates to a large radial distance. Tu et al. (2007), using passive measurements from RPI, present cases of a smooth electron density transition from the plasmasphere to the subauroral region without a signa-

ture of the plasmapause. Figure 4, as an example, displays a smooth transition as represented by the smooth frequency variations of the upper hybrid resonance (UHR) noise band (left panel) and the corresponding derived electron density (right panel). Such smooth transitions can occur at various MLT and were observed after geomagnetic activity had been quiet for 2 or more days, with K_p primarily less than 3 for the cases examined. The survey of the RPI database indicates that such events occurred about 10% of the time.

2.3 New Evidence for a Plasmaspheric Wind

The unexpectedly long time for refilling and lack of a distinct plasmapause could be explained if the plasmasphere experiences a slow outward drift in addition to corotation and convection. Lemaire and Schunk (1992, 1994) noted that it would then take more time to refill a flux tube when it is lost through an outward drift across magnetic field lines in the form of a plasmaspheric wind. This concept is based on the result of plasma interchange motion, which is driven by an imbalance between pressure gradient and gravitational, centrifugal and inertial forces (André and Lemaire 2006). This outward drift is also controlled by the height-integrated Pedersen conductivity of the ionosphere.

Global imaging recently demonstrated that plasmaspheric losses from the plasmaspheric wind are as significant as ionospheric refilling, for populating the region just outwards of the plasmapause, even under quiet/moderate geomagnetic condition (Yoshikawa et al. 2003). At the plasmapause, the smooth electron density transition from the plasmasphere to the subauroral region observed by RPI was interpreted by Tu et al. (2007) as additional indirect evidence for a plasmaspheric wind.

A recent analysis of ion distribution functions acquired in the outer plasmasphere by CIS revealed a significant anisotropy in the particle fluxes. Systematically more ions are going outwards than inwards in the plasmasphere at all LT. This may constitute the first direct evidence for a continuous escape of plasma from the plasmasphere, the plasmaspheric wind (Dandouras 2008). The contribution of this plasmaspheric wind to plasma populations outside the plasmasphere is not negligible, with preliminary estimates indicating that it could be of the same order as the solar wind input to the magnetosphere under quiet geomagnetic conditions.

2.4 Erosion of the Plasmasphere

The storm-time loss of plasma in the outer plasmasphere, or plasmaspheric erosion, is one of the oldest known properties of the plasmasphere (Gringauz et al. 1960; Carpenter 1962). Early on, the location of the plasmapause was associated with the last closed equipotential resulting from the superposition of the corotation and convection electric fields. Its erosion or inward motion was found to occur with increased geomagnetic activity and was modeled by a corresponding increase in the convection electric field (Nishida 1966). An inward motion of plasma and steepening of the plasmapause has also been associated with the consequences of the dynamic balance between centrifugal and other forces (Lemaire 1974, 1985).

Global images have revealed the morphology of the plasmaspheric response to changes in convection. IMAGE observations show that the overall erosion process starts with a slight initial indentation in the plasmasphere near midnight that widens and spreads eastward and westward, encompassing the entire nightside plasmasphere within a few hours (Spasojević et al. 2003; Goldstein et al. 2003a; Goldstein and Sandel 2005; Gallagher and Adrian 2007). The basic pattern of erosion and formation of the plasmaspheric plume is illustrated using

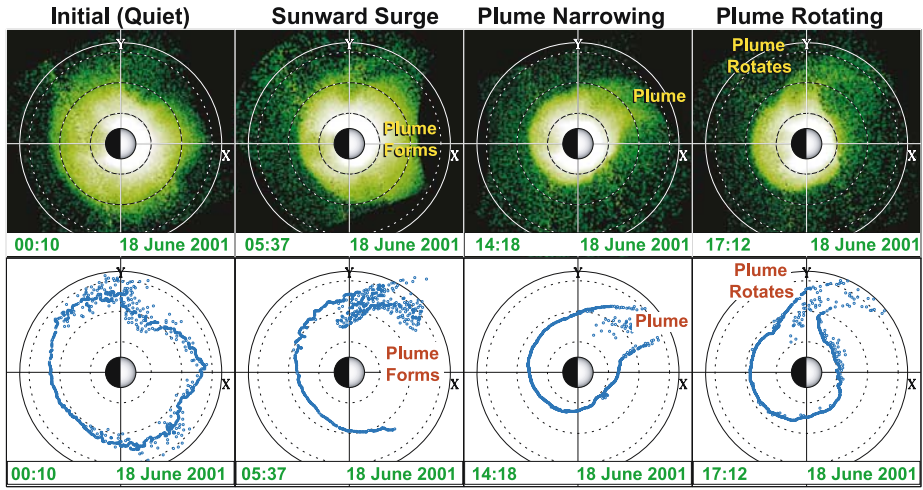


Fig. 5 (Top row) EUV plasmasphere images on 18 June 2001, depicting erosion of the plasmasphere and formation and rotation of a plume. Each panel displays the equatorial plasmaspheric He^+ distribution versus X and Y (in SM coordinates). Color indicates column abundance (in arbitrary units). The Sun is to the right (positive X) and the Earth is the half-shaded circle in the center. Dotted circles are drawn at $L = 2, 4$, and 6 ; the solid circle indicates geosynchronous orbit. (Bottom row) The blue circles are manually extracted points from the EUV image directly above, showing the outer boundary of the plasmasphere. (Adapted from Goldstein 2006)

EUV observations in Fig. 5. Erosion for this 18 June 2001 event follows a southward turning of the IMF. It shows the typical pattern of initial night-time plasmaspheric loss and broad dayside plume formation, followed by a narrowing of the plume as erosion nears an end and associated with its rotation eastward (see Goldstein 2006). Driven by an enhanced solar wind electric field, the onset of erosion requires 10–30 minutes to propagate from the magnetopause to the inner magnetosphere through the ionosphere (Goldstein et al. 2003a; Murakami et al. 2007). RPI observations also demonstrate the dramatic loss of plasma along magnetic field lines (Reinisch et al. 2004). Outer plasmaspheric flux tubes lost more than two thirds of their plasma in less than 14 hours during the 31 March 2001 storm. Later recovery of the plasmasphere by refilling occurred over a period of 10 days.

In this process, removal of plasma occurs at different times for different MLTs, so that the effects of erosion propagate with a finite speed, eastward and westward from the initial MLT where erosion is first observed. This finite propagation effect has been observed in every erosion event for which EUV data have been analyzed (Spasojević et al. 2003; Goldstein et al. 2003a; Goldstein and Sandel 2005). A similar finite propagation effect occurs during transient disturbances of the plasmopause, such as the so-called plasmopause undulations produced by bursts of convection associated with substorms (Goldstein et al. 2004a, 2005a, 2007). A plasmopause undulation event is part of a chain of interconnected electrodynamic and plasma phenomena. First, substorm dipolarization injects plasma into the ring current, inflating the geomagnetic field, inducing an electric field which pulls the plasmopause outward to form a $1\text{--}2 R_E$ bulge. Ionospheric closure of the partial ring current then generates a westward subauroral polarization stream (SAPS) flow that removes the $1\text{--}2 R_E$ bulge. The net global effect is an outward-then-inward motion that propagates westward along the plasmopause. This westward-moving undulation, accompanied by a smaller, subtler eastward-moving ripple, can be correlated with corresponding intensifications of the aurora to a greater or lesser degree (Goldstein et al. 2005a, 2007).

3 Overall Plasma Distribution and Plasmapause Position

As discussed above, the IMAGE and CLUSTER missions provided us with a new appreciation of the plasmasphere through global and multipoint plasmaspheric observations. The overall geometry and context of the time varying distribution of plasmaspheric plasma has been revealed in ways not previously possible.

3.1 Overall View from EUV

The global images obtained from EUV onboard IMAGE provide an overall view of the plasmasphere. They can be used to infer the plasmapause position, by looking at the He^+ edge, i.e., the outermost sharp edge where the brightness of He^+ emissions drops abruptly (Goldstein et al. 2003b). On EUV images, many density structures appear as seen in Fig. 1. Successive images illustrate the spatial and temporal evolution of such structures. For example, undulations of the plasmapause can be observed and an equatorial azimuthal speed of such structure can be deduced: $4 R_E h^{-1}$ at $L = 4$ in a case event analysed by Goldstein et al. (2004b).

3.2 Plasma Density in the Plasmasphere

The sounding measurements from RPI onboard IMAGE provided field-aligned electron density profiles that are almost instantaneously obtained (Reinisch et al. 2000). 2-D electron density images along the satellite orbit can be constructed with those multiple density profiles. Such images proved to be useful to differentiate various plasma regions in the near Earth magnetosphere and to provide insights to the plasma dynamics in those regions. Tu et al. (2005) presented case studies of three electron density images obtained before, during and after a magnetic storm. Figure 6 displays the images on three separate days of field-aligned electron density divided by r^{-5} , where r is the radial distance along individual field

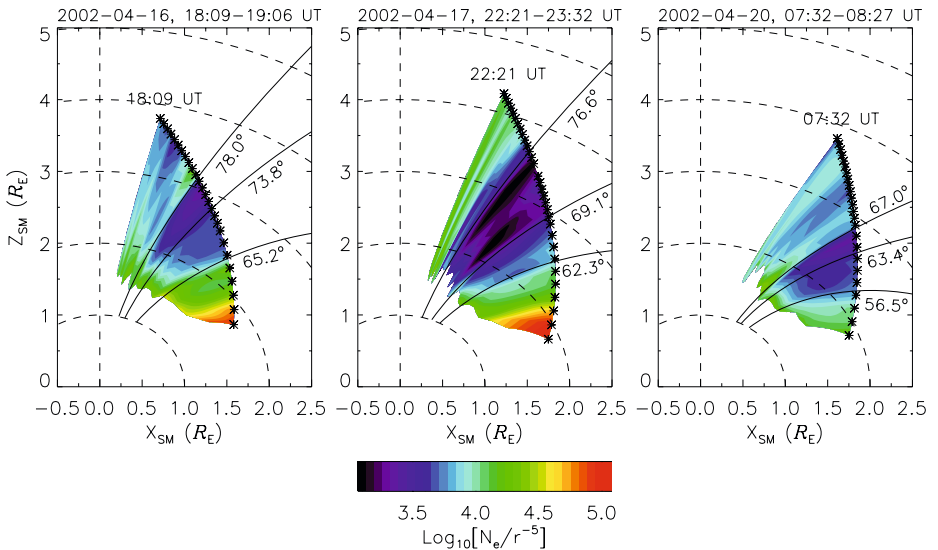


Fig. 6 Same format as Fig. 3 but for electron density images divided by r^{-5} , where r is the radial distance (in R_E) along individual field lines. (Adapted from Tu et al. 2005)

lines. Such normalization is useful since the densities in different plasma regions have a distinct radial distance dependence; it helps to better differentiate the plasma regions relative to the polar cap. The RPI observations allow plasma regions to be identified more reliably because their 2-D spatial extent can be seen. Furthermore, the difference in the radial dependence of the densities along field lines in these regions can be determined using the near instantaneously measured field-aligned density profiles. The plasma regions, namely, the plasmasphere, plasmatrout, V-shaped density depletion region, cusp, and polar cap are clearly differentiated in the images because the polar cap density variations along field lines are nearly proportional to r^{-5} (Nsumei et al. 2003, 2008), as demonstrated by Fig. 6. For example, the plasmasphere is shown consisting of two layers: the high-density region mentioned above, and a high- L region with lower densities.

3.3 Overall Density Gradients in the Plasmasphere

Darrouzet et al. (2006b) and De Keyser et al. (2007) analyzed a plasmasphere pass by CLUSTER to study the overall geometry of the plasmaspheric density structure, using gradient computation techniques. Such a study is only possible with high precision data, which is achieved with the electron density n_e determined from WHISPER. Techniques to compute the gradients along the trajectory of CLUSTER are described elsewhere in this issue (De Keyser et al. 2008). A fundamental requirement for these methods is the hypothesis that the satellites are close enough to each other, so that all spacecraft are embedded in the same structure at the same time (homogeneity condition).

Darrouzet et al. (2006b) analyzed the plasmasphere pass on 7 August 2003, at 14:00 LT and between -30° and $+30^\circ$ of magnetic latitude $MLAT$. The maximum value of K_p in the previous 24 hours was 2^+ . The spacecraft separation was small and the tetrahedron geometric factors are satisfactory. Figure 7a illustrates that the WHISPER density differences between the four satellites vary as a function of time. The density gradient ∇n_e on the inbound crossing is generally towards Earth, with some azimuthal deviations. During the outbound crossing, ∇n_e behaves less regularly. Interesting insights can be gained by analysing the angle $\alpha_{B, \nabla n_e}$ between the magnetic field vector $\mathbf{B}$ and the density gradient ∇n_e at the center of the tetrahedron (see Fig. 7b). The global orientation of the density gradient can also be described by its latitude $\theta_{\nabla n_e}$ (blue curve in Fig. 7c) and its azimuth relative to the spacecraft azimuth angle $\phi_{\nabla n_e} - \phi_{sc}$ (red curve in Fig. 7c). Figure 7 displays those angles obtained with the classical gradient method (Darrouzet et al. 2006b); comparable results have been found with the least-squares gradient method (De Keyser et al. 2007).

In regions A, C and E, the density changes rather slowly (Fig. 7a) and the three angles displayed on Figs. 7b–c demonstrate that the density structures are largely cylinder-symmetric, but with the presence of azimuthal ripples, which are similar to the structures described by Bullough and Sagredo (1970). When the spacecraft observe markedly different densities at a given time (regions B and D on Fig. 7a), the density gradients are definitely stronger. This is due to the presence of field-aligned density structures, i.e., steep density changes across field lines (as illustrated by the angles displayed on Figs. 7b–c). The corresponding geometry in the equatorial plane is sketched in Fig. 8: The density gradient is inward during the inbound crossing; it points azimuthally duskward for much of the outbound one. The thicknesses of these density steps (500 to 1000 km) are sufficiently large so that the homogeneity condition is satisfied: The gradient computation produces correct results.

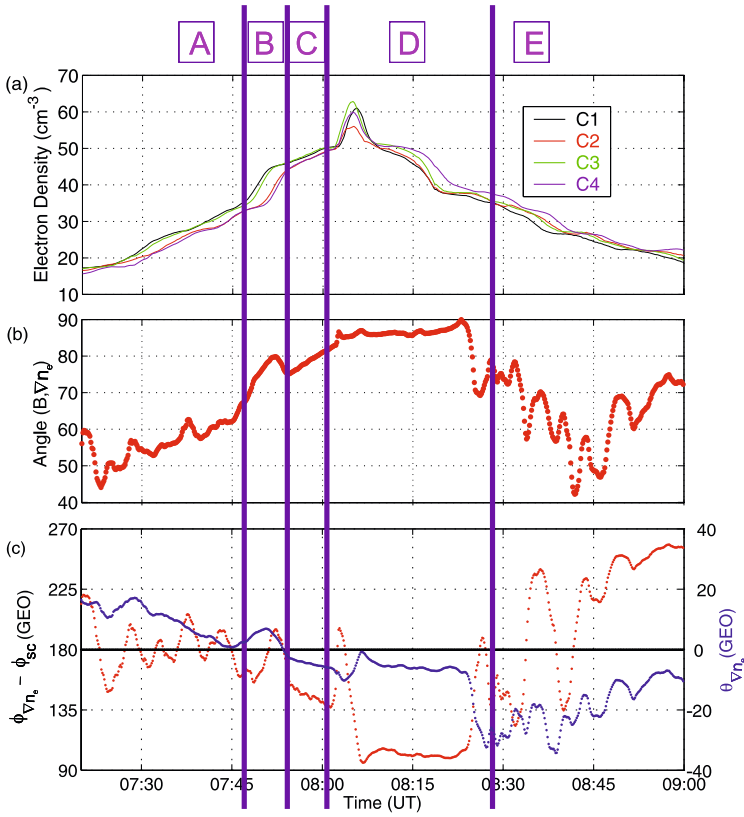
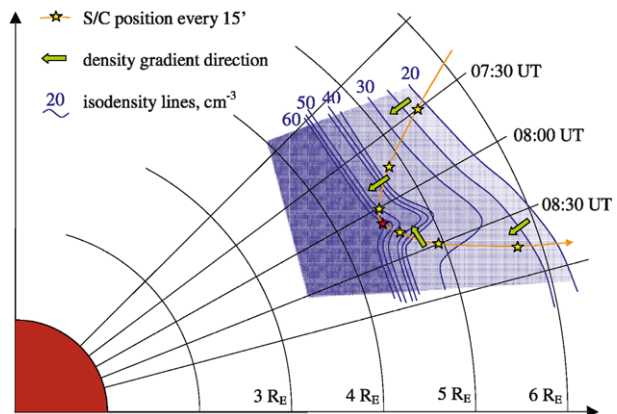


Fig. 7 **a** Electron density from WHISPER for the four CLUSTER spacecraft, **b** angle $\alpha_{B, \nabla n_e}$ between the magnetic field vector B and the density gradient ∇n_e , **c** latitude angle $\theta_{\nabla n_e}$ (blue curve), and azimuth angle of ∇n_e relative to the spacecraft azimuth, $\phi_{\nabla n_e} - \phi_{sc}$ (red curve), as a function of time during the plasmasphere pass on 7 August 2003. The angles are known up to about 9° . (Adapted from Darrouzet et al. 2006b)

Fig. 8 Sketch of the plasmasphere pass on 7 August 2003 projected onto the equatorial plane in a corotating frame, chosen so that the perigee pass (at about 08:00 UT) corresponds to the LT at perigee (about 14:00 LT). (Adapted from Darrouzet et al. 2006b)



3.4 The Plasmapause Seen by CLUSTER

3.4.1 Introduction

The structure of interest at the largest scales is the plasmasphere itself, and its outer boundary, the plasmapause. In the past, many studies focused on the equatorial plasmapause radial position as a function of LT and geophysical conditions (Lemaire and Gringauz 1998). From a CLUSTER perspective, a systematic study on this topic has yet to be undertaken. Three combined difficulties are encountered: (i) the range in L values when at small latitudes ($<20^\circ$) is narrow (a window $\Delta L \approx 2$ at a central value decreasing from $L \approx 5$ at the start of the mission down to $L \approx 3.5$ at the end of the mission); (ii) the density range measurable by WHISPER ($0.25\text{--}80\text{ cm}^{-3}$) is below values encountered at inner plasmapause boundaries; (iii) the plasmapause is located inward from CLUSTER perigee in a number of events encountered during the first half of the mission. The second and third difficulties are less problematic in the day and dusk sectors, where the plasmasphere extends further outward, and can thus be crossed more often by the CLUSTER spacecraft at densities within the sounder's range. Clear plasmapause density gradients are regularly encountered in those sectors. Examples of such plasmapause crossings are visible in Fig. 9a, obtained in the noon sector at 5000 km spacecraft separation during a quasi-steady event (configuration displayed in Fig. 2a). Spectrograms display plasma frequencies (light blue emissions) measured by each of the four WHISPER instruments. The behaviour of the four density profiles corresponds to cuts of the plasmasphere at increasing geocentric distances from C4 to C3, C2 and C1, leading to decreasing time intervals spent by the respective satellites inside the inner plasmasphere (when f_{pe} is above the 80 kHz threshold), and increasing latitudes where the boundary is encountered. For this event, seven clear-cut plasmapauses associated with sharp

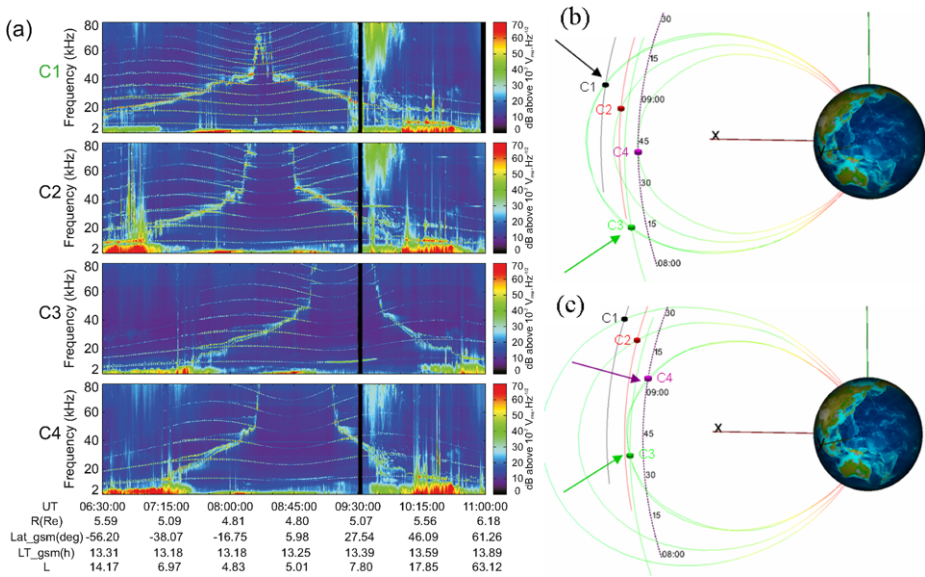
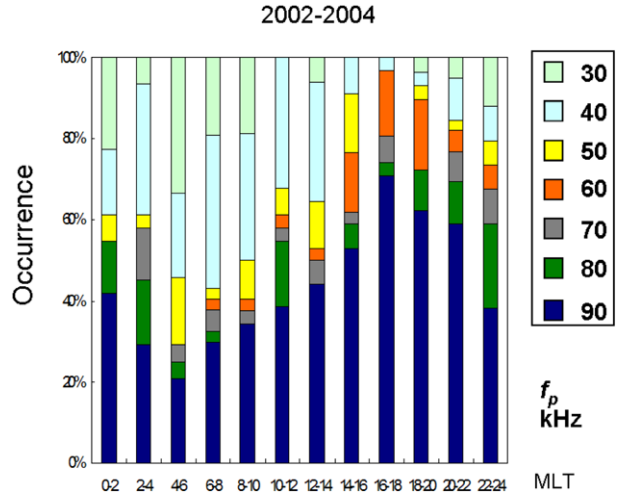


Fig. 9 a Time–frequency electric field spectrograms measured by the WHISPER instruments onboard the four CLUSTER satellites during a plasmaspheric pass on 15 August 2002 with a spacecraft separation around 5000 km. The orbital parameters correspond to C1. Examples of magnetic conjunction, b at 08:45 UT in the outer plasmasphere for C1 and C3, c at 09:06 UT in the inner plasmasphere for C3 and C4

Fig. 10 Relative occurrence of equatorial plasma frequency values measured by WHISPER onboard CLUSTER in the different MLT sectors. (Adapted from El-Lemdani Mazouz et al. 2008)



local density gradients are observed with a plasma frequency increasing from ~ 50 kHz (or a density $\sim 30 \text{ cm}^{-3}$). Those plasmopause crossings are seen by all spacecraft, except during the outbound pass of C1, which is associated with large-scale density fluctuations that complicate the identification of the plasmopause. All seven clear plasmopause crossings are placed within a narrow interval of L values (4.67 ± 0.10). Spacecraft are magnetically conjugate on six successive pairs during such events, at various latitudes (see examples in Figs. 9b–c), providing useful information about instantaneous latitudinal profiles. A full latitudinal density profile can further be obtained by a best fit with an empirical density model (Denton et al. 2008).

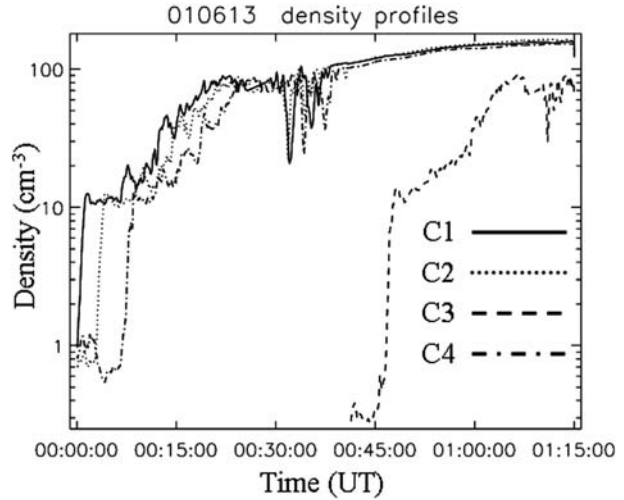
3.4.2 Statistical Study of the Plasmopause Distance

Despite the above quoted limitations of WHISPER density measurements, a systematic study of the plasmopause position in the equatorial plane has been conducted with CLUSTER, based on observations in years 2002–2004 (El-Lemdani Mazouz et al. 2008). Instead of searching for plasmopause boundary positions, the strategy has been to focus on the plasma frequency observed at the equator crossing on each CLUSTER orbit, a crossing located within a narrow geocentric window ($4.2\text{--}4.7 R_E$). By comparison with the empirical model of the plasmopause position given by Carpenter (1970), this plasma frequency gives a qualitative empirical estimate of the plasmopause distance to perigee. Figure 10 results from a study of 387 perigee events well distributed as a function of MLT. The plasma frequency figure is what has been measured (in bins of 10 kHz wide), except for the 90 kHz figure, indicating cases where the equatorial plasma frequency is higher than the upper range measurable by WHISPER. The highest occurrence of low frequencies is observed in the dawn (02:00–04:00 MLT) sector, while the high frequencies are observed mostly in the dusk (16:00–18:00 MLT) sector. This study is thus consistent with the expected dawn-dusk asymmetry of the plasmopause.

3.4.3 Plasmopause Dynamics: Position and Velocity

In the event of 15 August 2002 presented above (Fig. 9), a total of seven plasmopause positions have been identified within a narrow interval of L values, $\Delta L = 0.1$. Those measure-

Fig. 11 Density profiles at the inbound perigee pass on 13 June 2001 determined by WHISPER onboard the four CLUSTER satellites. The plasmopause boundary (density step from 1 to 10 cm^{-3}) is crossed successively by C1, C2, C4 and C3. (Adapted from Décr  au et al. 2005)



ments are spread over a time interval of 90 minutes, indicating that this boundary is quasi-stationary during the duration of the interval, within the MLT sector considered (around 13:00 MLT). In this example, the crossing points are placed at large distances from each other, over a large latitude interval.

When the crossing points are at close distance from each other ($< 0.2 R_E$), the plasmopause boundary can be considered locally as a magnetic shell of large curvature radius ($> 1 R_E$). In this case it is possible to evaluate its orientation and velocity with the time delay method (De Keyser et al. 2008, this issue). The velocity of the “frozen-in” material itself cannot be tracked in this way, but only that of the locally planar plasmopause surface. Figure 11 displays the four density profiles versus time in the inbound pass of 13 June 2001 (Décr  au et al. 2005). Crossings of an external plasmopause knee occur between 00:00 and 00:10 UT for the trio C1–C2–C4 and about 40 minutes later for C3. The CLUSTER constellation, displayed in Fig. 2b, is elongated (largest spacecraft separation $\sim 10\,000 \text{ km}$), but the size of the tetrahedron formed by the four crossing positions is significantly smaller (largest distance between positions $\sim 1000 \text{ km}$). The tetrahedron centre is located near 18:00 MLT and $MLAT = -35^\circ$. Timing analysis indicates a planar boundary containing the magnetic field vectors measured onboard, as expected from a magnetic shell surface, but with an orientation (nearly facing the Sun) twisted from the expected global shape of the plasmopause. In summary, the plasmopause boundary is observed to be almost motionless during ~ 45 minutes. The measured orientation is compatible with the magnetic field orientation. It is, however, still somewhat questionable, as the assumption of a constant drift velocity over the total time interval is idealized.

3.4.4 Statistical Study of the Plasmopause Position and Thickness

A statistical analysis of the plasmopause position and thickness has been done with 264 CLUSTER plasmopause crossings using time-delayed values of K_p depending on the MLT of the point of measurement (Darrouzet 2006). The plasmopause has been identified by the innermost sharp density gradient, with a density drop of at least a factor of 5 over a radial distance of $1 R_E$, or less. In order to facilitate inter-comparison of the CLUSTER density profiles, the parameter R_{equat} is introduced. It corresponds to the geocentric distance of the

magnetic field strength minimum along a field line, and is expressed in units of R_E (for more details see Darrouzet et al. 2004). The results are in agreement with general trend from earlier studies: For example the plasmopause forms closer to the Earth when the level of geomagnetic activity increases. It is difficult to say more, because of the limited coverage of the sample in term of MLT and K_p . Indeed, the sample contains very few plasmasphere passes corresponding to $K_p \geq 4$. This bias in the sample results from the relatively small orbital time spent by the CLUSTER spacecraft in the plasmasphere, and the rather low probability for high level of activity. Furthermore, for high K_p the plasmopause forms closer to Earth, i.e., below the perigee of CLUSTER ($\sim 4 R_E$). The thickness of the plasmopause region can be determined from the equatorial density profiles. It decreases when K_p increases in all MLT sectors and has a maximum around 09:00 MLT and in the dusk sector. This result should however be taken with caution, because the database is not equally distributed in MLT (less data in the noon sector). Because of the precession of the CLUSTER orbits, the satellites cross the plasmasphere in the same MLT sector every year at the same period of the year. Therefore seasonal effect could also influence those results.

4 Ion Composition

Combining ground-based measurements with space-based remote sensing (IMAGE) and in situ measurements (CLUSTER) can capitalize on the complementary natures of these techniques. Such investigations elucidate the general question of the plasmaspheric ion composition and provide an overview of typical composition and variability.

4.1 Ion Composition from IMAGE

Dent et al. (2003) combined observations of mass densities from ground magnetometers, electron abundances from whistler measurements and from RPI, and He^+ column abundances from EUV, all taken on a geomagnetic quiet day. The shapes of radial profiles determined using these techniques were consistent with one another. Dent et al. (2003) found that, if all heavy ions are accounted for by a single species (unlikely to be true for either species they consider), the ratios by number are 35–64% for He^+ alone or 7–13% for O^+ alone for $L < 3.45$. For $L > 3.45$, their techniques suggest that relatively few heavy ions are in the outer plasmasphere. This study demonstrated also the presence of azimuthal density structures in the outer plasmasphere.

Clilverd et al. (2003) analyzed almost simultaneous determinations at $L = 2.5$ of the mass density from ground measurements of geomagnetic pulsations, the electron abundance at the same location from ducted-mode whistlers, the in situ electron abundance from RPI, and the remotely-sensed He^+ abundance from EUV. They used measurements that referred to a single geomagnetic field line and longitude, whereas Dent et al. (2003) used measurements at a specific time from different locations. Further, they include observations during two days of moderate geomagnetic disturbance. For the earlier day, Clilverd et al. (2003) inferred a He^+ abundance ratio of $\sim 3.8\%$ by number relative to H^+ from ground magnetometer measurements. They derived a value of 3–4% for the same ratio using EUV and VLF measurements. They further noted that the L -dependence of He^+ column abundance near $L = 2.5$ has the same shape as the electron column abundance computed by integrating RPI electron measurements along EUV lines of sight. This implies that the ratio He^+/H^+ is approximately constant at this time and place, in contrast with the statistically decrease with L derived by Craven et al. (1997). The ratio He^+/H^+ is also somewhat lower than the

value of $\sim 10\%$ found in Craven et al. (1997). For the second day, Clilverd et al. (2003) inferred the presence of ions heavier than He^+ , and suggested O^+ as a likely candidate. By comparing the mass density and VLF-derived electron abundance, they found a ratio of 20% He^+ by number, assuming charge neutrality and a plasma whose only ions are H^+ and He^+ . Although EUV gives a column abundance of He^+ higher than the first day's by a factor of 1.6, this is insufficient to account for much of the discrepancy in mass density, leading to the conclusion that heavier ions must be present.

Building on these techniques, Grew et al. (2007) used measurements of mass density from field line resonances, electron abundance from whistler measurements, and He^+ abundance from EUV, to study a 8-days interval of prolonged geomagnetic disturbance. By combining all measurements on a field line at $L = 2.5$, Grew et al. (2007) were able to solve simultaneous equations for the abundances of H^+ , He^+ , and heavier ions (taken to be O^+) under the assumption of charge neutrality. During their study interval, the plasmapause moved inward and outward, and also showed substantial azimuthal structure, so that the $L = 2.5$ location sampled conditions both inside and outside the plasmasphere. They found that, for most times, composition ratios were roughly similar both inside and outside the plasmasphere. For $\text{H}^+:\text{He}^+:\text{O}^+$, they found $\sim 82:15:3$ by number. An interesting deviation from this norm occurred just outside the plasmasphere, when the inferred O^+ proportion reached $\sim 60\%$. This value suggests the presence of an O^+ torus consistent with the findings of Fraser et al. (2005) and the results of Clilverd et al. (2003).

4.2 Seasonal Variations

The seasonal variation has been known for some time, having been first detected in whistler measurements of the electron abundance (see, for example, the discussion in Clilverd et al. 1991). Using CRRES measurements of electron abundance, Clilverd et al. (2007) demonstrated that this variation is manifest as a maximum in equatorial electron abundance in December and a minimum in June that occurs in the longitude range of approximately -180°E to $+20^\circ\text{E}$, with a maximum variation near -70°E . Outside this range of longitudes the seasonal variation is much weaker. They attribute the variation to the offset and tilt of the geomagnetic dipole, which leads to differing amounts of illumination, and hence ionization, at the foot-points of plasmaspheric flux tubes. A contributing factor is differences in thermospheric winds at high latitudes, which tend to drive the ionospheric plasma up field lines. In addition to the complete azimuthal coverage in electron abundance afforded by the CRRES measurements, Clilverd et al. (2007) included a determination of the corresponding variation in equatorial He^+ abundance. These data were extracted from summations of many EUV images acquired in June and December 2001, that is, approximately one solar cycle after the CRRES observations. The amplitude and phase of the variation in He^+ abundance match the variation in electron abundance from CRRES quite well in general, while showing some small-scale differences. Even though comparing the absolute values of the two abundances inferred from measurements of different species separated in time by a decade is of dubious value, such a comparison yields $\text{He}^+/\text{H}^+ \approx 0.25$. This value is higher than typical, yet not unreasonable.

4.3 New Methods of Studying Ion Composition in the Plasmasphere

Radio sounding in the whistler- and Z-modes by RPI onboard IMAGE led to the identification of two new methods of studying ion composition in the important altitude range between the O^+ dominated ionosphere and the H^+ dominated plasmasphere: (i) Z-mode sounding

at altitudes in the 2000–5000 km range to detect a minimum in the altitude profile of the cutoff frequency for Z-mode propagation along geomagnetic field lines. The detection of this minimum and remote sensing of its altitude can provide information on the altitude variation of ion composition. (ii) Whistler-mode sounding, primarily in a frequency range below 12 kHz, in which the variation in echo range with frequency provides information on both the distribution of total plasma density along the field line below the satellite (typically operating at 3000 km altitude) and the effective ion mass both at the satellite and along the field line between the satellite and points below ~ 1000 km altitude. Those methods are outlined elsewhere in this issue (Masson et al. 2008).

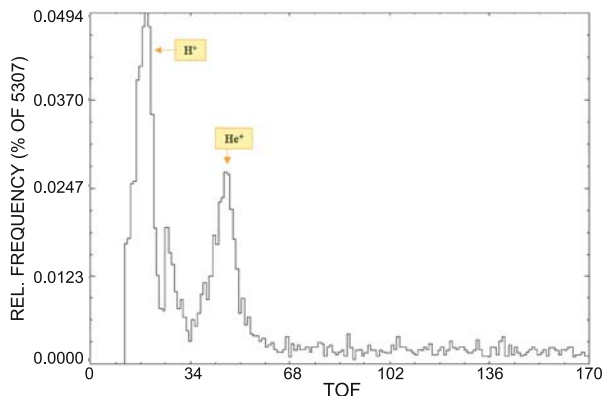
4.4 Ion Composition from CLUSTER

Data provided by the CIS experiment onboard the CLUSTER spacecraft, when operating in the Retarding Potential Analyzer (RPA) mode, allow accurate measurements of the ion distribution functions and composition in the approximate energy range 0.7–25 eV/q (with respect to the spacecraft potential), covering the plasmasphere energy domain. Figure 12 displays a typical ion mass spectrum, obtained by CIS during a plasmasphere pass in the nightside sector, close to the magnetic equator, on 18 March 2002. The magnetospheric conditions during this event were quiet ($K_p = 1^+$). The characteristic peaks of H^+ and He^+ are clearly present. He^{++} , if present, would be almost “washed-out” by the tail of the H^+ distribution (spillover). The height of the H^+ peak is not proportional to the relative abundance, because a different sampling law was used for the other ion species (sampling law change at channel 26). Figure 12 indicates no O^+ ions above the measurement background. The small background present over all time-of-flight channels is due to penetrating particles from the radiation belts.

Dandouras et al. (2005) studied a plume crossing on 31 October 2001 in the morning sector (08:45 MLT), during quiet magnetospheric conditions. The plume was observed after exit from the main plasmasphere, in the outbound leg of the orbit. No background is present, and the spectrum exhibits the characteristic peaks of H^+ and He^+ . It also shows the absence of O^+ ions, at a significant level. An upper limit of about 0.04 cm^{-3} for the O^+ density in the plume has been estimated. This value has to be compared to 0.8 cm^{-3} for the H^+ density and 0.14 cm^{-3} for the He^+ density. Note that these are partial density values, in the energy range covered by CIS in RPA mode.

Dandouras et al. (2005) performed a systematic survey with CIS data to search for low-energy O^+ ions, during the period July 2001–March 2003. Those observations are outside

Fig. 12 Time-of-flight spectrum for the ions detected by CIS onboard C3 on 18 March 2002 between 10:40 and 10:50 UT. The *abscissa axis* is the time-of-flight channel number (inversely proportional to the ion velocity) and the *ordinate axis* is the number of particles in a given channel, with two different sampling laws above and below channel 26



the main plasmasphere, and most of them correspond to upwelling ions, escaping from the ionosphere along high-latitude magnetic field lines. For few of these events, the O^+ distributions are bi-directional and indicate detached plasma, originating from deeper in the plasmasphere and having an outward expansion velocity towards higher L -shell. For example, C4 observed on 2 October 2001 in the morning sector (09:45 MLT, $L \approx 6$) detached plasma, including O^+ ions, with symmetric bi-directional distributions and an outward expansion velocity of $\sim 3 \text{ km s}^{-1}$. Note, however, that O^+ ions were never observed in the main plasmasphere, above instrument background, at CLUSTER altitudes (perigee $\sim 4 R_E$).

4.5 Average Ion Mass from Alfvén Waves

Additional information about ion composition can be determined from the frequencies of toroidal (azimuthally oscillating) Alfvén waves observed in space (Denton 2006) or on the ground (Waters et al. 2006). From the frequencies of observed Alfvén waves, the total mass density ρ_M can be determined from a solution of the wave equation (Denton 2006). If the electron density n_e is independently available, like from plasma wave measurements (LeDocq et al. 1994), the average ion mass M can be determined. Assuming that the plasma consists predominantly of H^+ , He^+ and O^+ , M is:

$$M \equiv \frac{\rho_M}{n_e} \simeq 1 + 3 \frac{n_{He^+}}{n_e} + 15 \frac{n_{O^+}}{n_e}. \quad (1)$$

Equation (1) provides a constraint on the relative He^+ and O^+ densities. Furthermore, there are indications that the He^+ density is not nearly as sensitive to geomagnetic activity as is that of O^+ (Craven et al. 1997; Krall et al. 2007). This suggests that if M is significantly greater than unity, n_{O^+}/n_e is approximately equal to $(M - 1)/15$.

Recently, Denton et al. (2008) used Alfvén frequencies measured by CLUSTER to determine ρ_M with unprecedented accuracy for two events at perigee ($L = 4.8$). By combining the values of ρ_M with n_e determined by the WHISPER instrument, Denton et al. (2008) found $M = 4.7$ when $n_e = 8 \text{ cm}^{-3}$ (28 October 2002, 02:33 UT), and $M = 2.9$ when $n_e = 22 \text{ cm}^{-3}$ (10 September 2002, 12:07 UT). These values imply approximate relative O^+ concentrations of 25% and 13%, respectively. Note that both cases are for the low densities characteristic of the plasmatrough. The CIS instrument was also used to determine the O^+ ring current density, but was limited to particle energies $>40 \text{ eV}$, because CIS was not operating in the RPA mode at these orbits. The amount of O^+ measured by CIS was not negligible, but was still not nearly enough to account for the inferred ρ_M . This indicates that the bulk of the O^+ density is cold particles that are not measured by CIS, when not operating in the RPA mode. For the 10 September 2002 event, Denton et al. (2008) used the four CLUSTER spacecraft to infer the distribution of electron density. They assumed a model distribution and adjusted the parameters of the model to minimize the difference between the observed and modeled density. Figure 13 displays ρ_M and n_e for the 10 September 2002 event, along with H^+ and O^+ densities assuming a H^+/O^+ plasma. The results suggest that there is a trapped equatorial distribution of O^+ .

5 Plasmaspheric Plumes

The plasmasphere often exhibits a feature that extends beyond the main plasmapause towards the dayside magnetopause (e.g., Moldwin et al. 2004). This feature, named the plasmaspheric plume, has been routinely observed by the EUV imager onboard IMAGE, but also

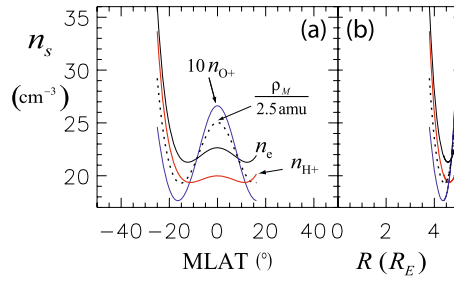


Fig. 13 Field line distribution of species s density n_s versus **a** magnetic latitude $MLAT$ and **b** geocentric radius R on 10 September 2002. The solid black curve is the electron density n_e found using the four CLUSTER spacecraft, the dotted black curve is the mass density ρ_M divided by 2.5 amu based on Alfvén frequencies measured by C1. The red and blue solid curves are the H^+ and O^+ densities consistent with n_e and ρ_M assuming a H^+/O^+ plasma (the O^+ density has been multiplied by 10). (Adapted from Denton et al. 2008)

by the four CLUSTER spacecraft or both. Plasmaspheric plume signatures have also been detected in the ionosphere, in particular with measurements of the total electron content (TEC) by global positioning system (GPS) satellites. The combination of those different dataset facilitates a great deal of progress in understanding the genesis and evolution of plumes in response to ever-changing levels of geomagnetic activity.

5.1 Overall Plume Formation

Global images obtained by EUV onboard IMAGE revolutionized the community's system-level picture of the plasmaspheric response to storms and substorms. EUV images demonstrate conclusively that plumes form in a series of phases that are directly driven by geomagnetic conditions. Figure 14 illustrates those phases during the plasmaspheric erosion event on 18 June 2001. During quiet conditions, the plasmasphere expands in size in response to filling of flux tubes with ionospheric plasma (Fig. 14a). A strong negative solar wind electric field (shown on Fig. 14m), corresponding to strong geomagnetic activity, initiated a sunward surge of plasmaspheric plasma (Figs. 14b–d): The nightside plasmopause moves inward, and the dayside moves outward to form a broad, sunward-pointing plume. Under the influence of continued high activity the dayside plume maintains its sunward orientation but becomes progressively narrower in LT (Figs. 14e–h). Finally, the waning of geomagnetic activity relaxes the plume's sunward orientation, and the plume begins rotating eastward with the rest of the plasmasphere and Earth (Figs. 14i–l). These phases (sunward surge, plume narrowing, plume rotating) are a consistent part of the plasmasphere's response to changes in geomagnetic activity, as confirmed in numerous studies using EUV data, either alone or in combination with in situ measurements (Sandel et al. 2001, 2003; Goldstein et al. 2003a, 2004b, 2005b; Goldstein and Sandel 2005; Spasojević et al. 2003, 2004; Abe et al. 2006; Kim et al. 2007). These global observations of plasmaspheric phases provide context for many in situ plume studies that have been performed (Garcia et al. 2003; Chen and Moore 2006; Darrouzet et al. 2006a; Borovsky and Denton 2008; Darrouzet et al. 2008). A brief discussion of plasmaspheric phases, in the context of physics-based models, is contained elsewhere in this issue (Pierard et al. 2008).

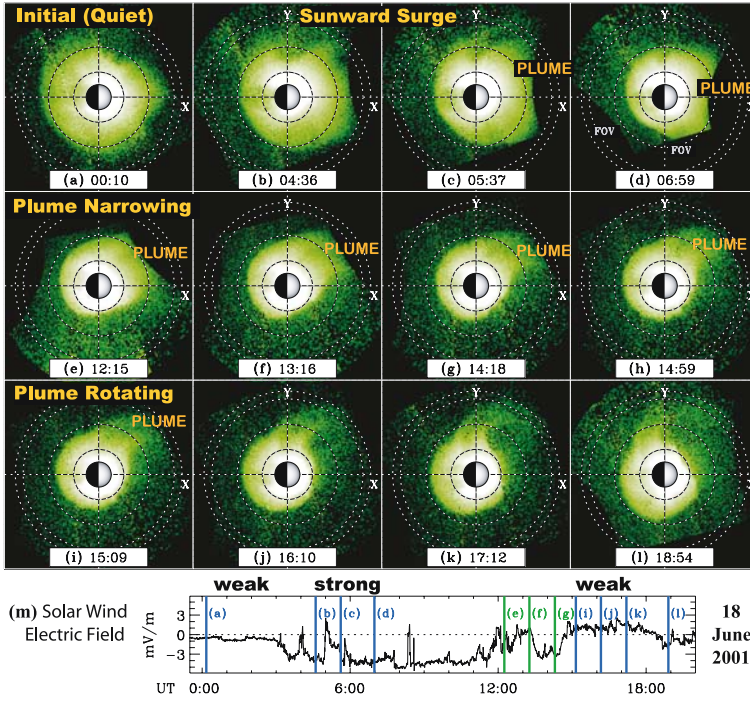


Fig. 14 a–l Plasmasphere EUV images, mapped to the magnetic equatorial plane (in SM coordinates), with the Sun to the right and dashed circles at $L = (2, 4, 6, 6.6)$. The field of view (FOV) edges are indicated in panel d. m Downward solar wind electric field (in geocentric solar magnetospheric, GSM, coordinates), defined as the product between the solar wind speed and the IMF B_Z , so that this electric field is negative when the IMF is southward. (Adapted from Goldstein and Sandel 2005)

5.2 Plume Structure and Evolution on Large Scales

5.2.1 Complicated Structure

The CLUSTER mission phase at 5000 km spacecraft separation corresponds to orbit planes exploring the plasmasphere in different LT sectors, at respectively the inbound part of the orbit (southern hemisphere, later LT) and its outbound part (northern hemisphere, earlier LT). Figure 15 displays WHISPER observations in such a case, as well as boundary positions derived from their analysis. The event chosen here, on 5 July 2002, occurs at the end of a period of slightly increasing disturbance (K_p from 1^+ to 4). Several large-scale features are clearly seen on the WHISPER electric field spectrograms (Fig. 15a): (i) the plasmasphere body at the centre of each plot (20:45–22:10 UT for C4); (ii) a plume in the southern hemisphere (20:00–20:30 UT for C4); (iii) a plume in the northern hemisphere (22:30–22:45 UT for C4). Spectrograms for the other spacecraft display similar features, at different times.

Arrows, pointing towards plumes, delimit the time intervals covering the low density channel between each plume and the plasmasphere (see Sect. 7). The positions of satellites at each side of an arrow can be projected along field lines in the equatorial plane, providing the 2-D view displayed in Fig. 15c, where possible motions of the low density channels are ignored, i.e., as if all boundary crossings occurred simultaneously. Several interesting spatio-temporal aspects can be learned by analysing Fig. 15a, which provides the chronology of

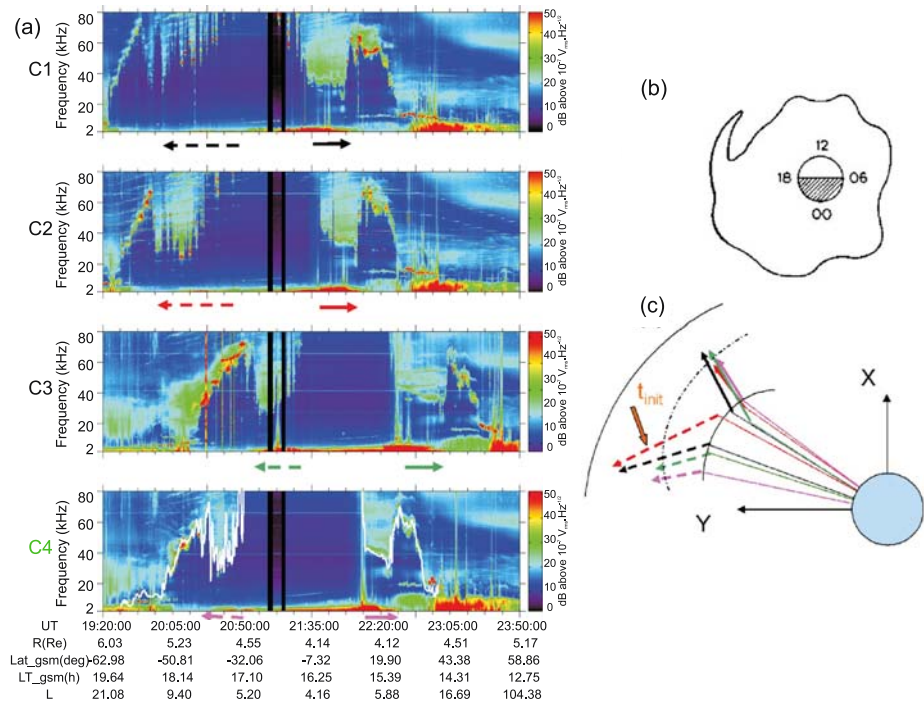


Fig. 15 **a** Frequency–time electric field spectrograms from WHISPER onboard CLUSTER displaying a plume structure observed on 5 July 2002 in both hemispheres. The evolution of the plasma frequency during a pass is plotted in white for C4. The arrows (*dashed* in the southern hemisphere and *solid* in the northern hemisphere), pointing towards the plume, delimit time intervals covering the low density channel between the plume and the plasmasphere. **b** Sketch of a type of spatial irregularity in the equatorial cross-section of the plasmasphere expected during a period of increasing disturbance. (Adapted from Carpenter 1983.) **c** Positions of low density channels observed by the four CLUSTER spacecraft plotted in the equatorial cross-section of the plasmasphere in GSM coordinates

observations, and Fig. 2a, which provides the shape of the constellation: The spacecraft order along the orbit is C1, C2, C4 and C3, and the order in increasing LT is C1, C2, C3 and C4. The feet of the arrows, indicating the plasmopause boundary, are crudely aligned with a quasi-cylindrical shape, except for the C3 northern crossing, which is inward from the others. This could be due to a slight undulation of the plasmopause, as illustrated in Fig. 15b.

The view of Fig. 15c could be modified, in order to take account of large-scale drifts of frozen-in material. The main drift that could be taken account of is corotation (Darrouzet et al. 2008). Out of the eight plasmopause crossings, two of them occur at the same time ($\sim 21:30$ UT): outbound of C1 (foot of the black solid arrow) and inbound of C3 (foot of the green dashed arrow). It is possible to draw a picture at that common time of reference, by assuming that all frozen-in field lines are corotating. In such a picture, the solid arrows would be displaced and rotated westward, up to $\sim 20^\circ$, still placed inside the indicated channel feature. The dashed arrows would be displaced eastward similar amounts. It is clear that corotation is not likely to be a valid assumption at the beginning of the analyzed period. Indeed, the density profiles inside the channels show a striking evolution from the first crossing (C1, inbound), to the last one (C3, outbound). The event can be split in two successive

phases. During the initial hour (19:40–20:40 UT) the low density channel is not well formed, but filled up by a large number of dense, narrow, plumes. C1, located at an earlier LT than C2, sees more material than C2, at roughly the same UT time. The time and space evolution of those blobs is unclear. No one-to-one correlation of density blobs seen respectively on C1 and C2 is apparent. Data from EDI and EFW onboard CLUSTER indicate fluctuations of large-scale electric field at the same time period. The small size plumes progressively disappear (see C2, C4 inbound). During the last part of the crossing (20:50–23:00 UT), the channel structure is well established, cleaned up from small size plumes. It is likely that, during that time period, the assumption of corotation is valid. It is not during the first part.

5.2.2 Global Visualisation of a Plume Crossing

Darrouzet et al. (2008) studied a CLUSTER plasmasphere pass characterized by a very large spacecraft separation (10 000 km). This event on 18 July 2005 between 13:00 and 20:00 UT, is located around 15:00–16:00 MLT, with a maximum value of K_p in the previous 24 hours equal to 5⁺. Plume crossings are seen during the inbound pass in the southern hemisphere (SH), and also during the outbound pass in the northern hemisphere (NH). Lots of differences are seen in terms of the L position of the plume between the four spacecraft. This is logical, as some of the satellites cross the density structure a few hours after the first one; during this time period, the plume rotated around the Earth and moved to higher L values. The inner boundary of the SH plume is seen around $L = 7.0$ by C1, whereas this boundary is crossed 2 hours later by C3 and C4 around $L = 8.3$. Knowing that the MLT position of the plume crossing is quite similar for those three satellites, one can then calculate an average radial velocity of the plume at fixed MLT of the order of 1.2 km s^{-1} , which is consistent with the results by Darrouzet et al. (2006a). For this event, around 15:00–16:00 MLT, this corresponds to a Sunward motion.

The L -width ΔL of the plume is very different between the spacecraft, and also between the inbound and outbound crossings for some satellites. For C1, $\Delta L = 3.2 R_E$ during the inbound pass in the SH, and $2.6 R_E$ during the outbound pass in the NH. This means that the outbound crossing, taking place a few hours after the inbound one, detects a narrower plume. There is a similar trend for the other satellites. Except for C2, the maximum electron density inside the plume is always higher in the inbound pass than in the outbound one. All those characteristics can be explained by plume rotation so that the outbound crossings occur at greater distance along the plume, where the plume is narrower and has lower density.

More information can be deduced if CLUSTER trajectories are projected along magnetic field lines onto the equatorial plane. As the spacecraft separation is quite large and in order to be able to compare the four trajectories and the eight crossings, one can assume that the plasmasphere and its sub-structures are in corotation with the Earth. Figure 16 presents such a projection in a corotating GSM frame of reference. The plasmopause is clearly seen on the trajectories of C1 and C2 at a radial distance of $\sim 5 R_E$, where the color coded density changes from green to yellow. A clear plasmopause is not crossed by C3 and C4. This could be because the plasmasphere is located closer to the Earth at the LT position and UT time of C3 and C4. The inbound plume crossings by the four satellites, and the outbound crossings by C1 and C2, are clearly crossings of the same plume, which corotates as time elapses between successive crossings. The outbound crossing by C3 and C4 (bottom right of Fig. 16) is probably another density structure and/or the effect of strong time variations.

A few other studies analysed plasmaspheric plumes at large-scale with CIS (Dandouras et al. 2005) and WHISPER (Darrouzet et al. 2004; Décr  au et al. 2004).

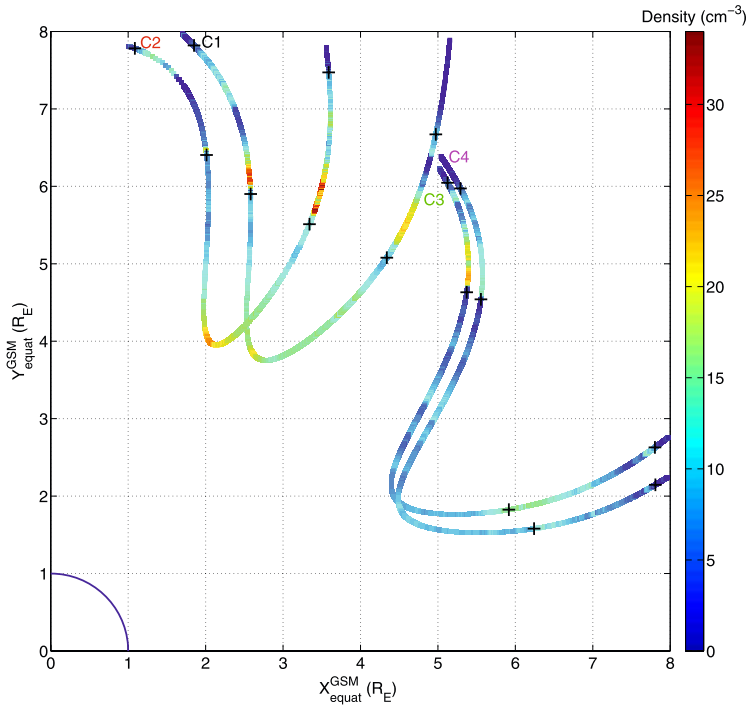


Fig. 16 Electron density plotted along the trajectories of the CLUSTER satellites and projected along magnetic field lines onto the equatorial plane in a corotating GSM frame of reference (chosen such that C4 was at 15:30 MLT at 18:00 UT), during the plasmasphere pass on 18 July 2005. The density is plotted with the color scale on the *right*. The plasmasphere passes start at the label of each satellite (on the *left*), and end on the *right* side. The crosses give the times of the plume crossings computed from the spectrograms. (Adapted from Darrouzet et al. 2008)

5.3 Plume Structures on Small Scales

Darrouzet et al. (2006a) studied three plume crossings by CLUSTER at times of small spacecraft separation, for which multipoint analysis tools can be used. One of the events is on 2 June 2002, between 12:00 and 14:30 UT, in the dusk sector (18:00 MLT) and with moderate geomagnetic activity. A very wide plume is seen in SH and NH on all four spacecraft. The electron density profiles of the plume as determined from WHISPER and EFW (for the part above 80 cm^{-3}) are displayed in Fig. 17. Both structures have the same overall shape. This indicates that these are crossings of the same plume at southern and northern latitudes of the plasmasphere. This also suggests that the plume did not move much over the 2 hours between both plume crossings. To confirm this global statement, one can compute the equatorial normal velocity of the plume boundaries V_{N-eq} , by using the time delay method described elsewhere in this issue (De Keyser et al. 2008). Those velocities, given on the figure for several plume boundaries, are quite small for the inbound plume crossing (larger at the outer edge than at the inner one). From those boundary normal velocities, Darrouzet et al. (2006a) derived an azimuthal plasma velocity V_{P-eq} . They found that for the outer boundary of the inbound crossing, $V_{P-eq} = 6.9 \pm 1.2 \text{ km s}^{-1}$, which is much higher than the corotation velocity (between 3.6 and 2.8 km s^{-1} at these spacecraft

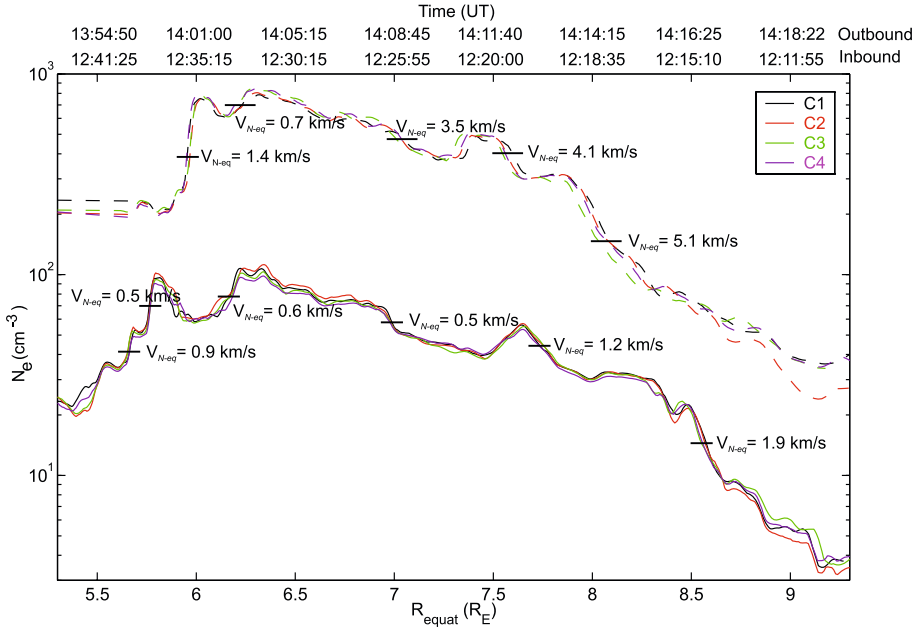


Fig. 17 Electron density profiles as a function of R_{equat} for the two plume crossings by the four CLUSTER satellites on 2 June 2002. The *lower curves* correspond to the inbound pass and the *upper curves* (shifted by a factor 10) to the outbound pass. The magnitude of the normal boundary velocity V_{N-eq} derived from the time delay method and projected onto the magnetic equatorial plane is indicated on the figure. (Adapted from Darrouzet et al. 2006a)

positions). This could also be compatible with a lower azimuthal speed if there is an outward plasma motion as well. The velocity is also higher than the corotation velocity at the inner edge, $V_{p-eq} = 4.0 \pm 1.2 \text{ km s}^{-1}$. For the outbound crossing, there are also deviations from corotation. By computing the average radial velocity of the plume edges, Darrouzet et al. (2006a) demonstrated that the plume is thinner in the NH pass than in the SH pass, and that its inner edge is at a larger equatorial distance. They prove also that the instantaneous measurements are in agreement with long term motion of the plume. EDI measures a drift velocity of the order of the corotation velocity, mainly in the azimuthal direction but with a radial expansion of the plume.

To check those results, it is very useful to combine in situ data with global data from IMAGE. On an EUV image taken at 12:33 UT (close to the time of the inbound plume crossing by CLUSTER), a very large plume is observed in the post-dusk sector, with its foot attached to the plasmasphere between 17:30 and 22:00 MLT (Darrouzet et al. 2006a). This is consistent with the WHISPER observations. As the plume is observed on EUV images during several hours, the motion of the plume can be determined. The foot of the plume (at $3.7 R_E$) moves at a velocity of $1.6 \pm 0.1 \text{ km s}^{-1}$, close to the corotation velocity 1.7 km s^{-1} . The extended part of the plume is clearly moving slower than the foot and away from the Earth.

LANL geosynchronous satellites confirm the presence of the plume: LANL 97A observes a large density structure as it orbits Earth from 12:00 to 22:00 MLT. This is consistent with the plume seen by IMAGE between 17:30 and 22:00 MLT and observed by CLUSTER at 12:30 UT and at $R_{\text{equat}} = 6.5 R_E$.

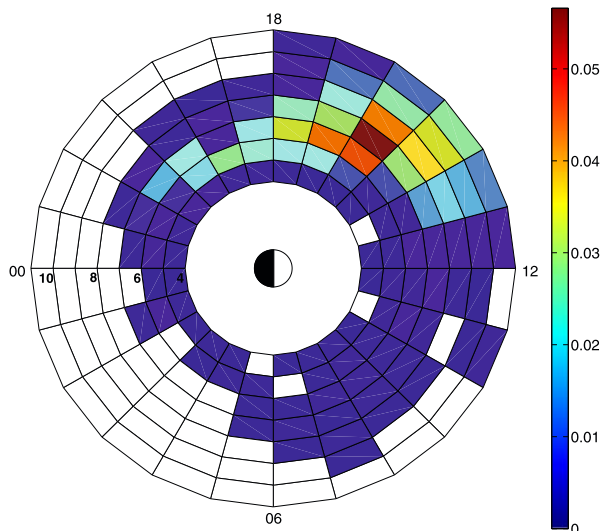
5.4 Statistical Analysis of Plasmaspheric Plumes

Darrouzet et al. (2008) performed a statistical analysis of plasmaspheric plumes with a very large CLUSTER database starting in February 2001 and covering exactly five years, to ensure equal coverage of all MLT sectors. Due to the polar orbit of CLUSTER, the spacecraft usually cross the plumes only at great distance from the foot attached to the plasmasphere. The dataset contains 5222 plasmasphere passes with data (85% of the total number of passes) and offers global coverage of all MLT sectors, above $L = 4$ (perigee of CLUSTER). 782 plume crossings have been observed, which corresponds to 15% of the plasmasphere passes with data. More plumes are found at low and middle L values ($5\text{--}8 R_E$), in the afternoon and pre-midnight MLT sectors (see Fig. 18). Some plumes are observed at high L , especially in the afternoon MLT sector and there are very few plumes in the post-midnight and morning MLT sectors.

The dataset used by Darrouzet et al. (2008) contains passes for almost all K_p values, but mostly for low to moderate geomagnetic activity. There are only a few plasmasphere passes with high activity, mainly because the plasmasphere is closer to the Earth in this case, and therefore not crossed by the CLUSTER satellites. No plumes are observed for the highest K_p , the highest am and the lowest Dst . In such case the plasmasphere moves closer to the Earth, sometimes below the perigee of CLUSTER ($4 R_E$), and if there would be a plume, it would be difficult to unambiguously identify it (because of the absence of a crossing of the main plasmasphere). In such case, CLUSTER could also miss a plume because it narrows quickly in MLT during times of high activity and the spacecraft have to pass through perigee in the appropriate MLT to see it.

Plumes are found to have all possible density variations in the range accessible to WHISPER (up to 80 cm^{-3}), but with more events with small density variations ($<30 \text{ cm}^{-3}$). Plumes do not appear to have a preferred maximum density value. There are more plume crossings with a short time duration. The L -width ΔL of the plumes varies up to $6 R_E$, but with more events at smaller values (the characteristic value is $1.2 R_E$). The broadest plumes are observed in the afternoon MLT sector and at high L , while the narrowest ones are seen at small L ($<7 R_E$) and mostly in the afternoon and pre-midnight MLT sectors. Less dense

Fig. 18 Probability of being inside a plume for each $[L, \text{MLT}]$ bin, normalized by the distribution of all the trajectories. L varies between 4 and $11 R_E$. (From Darrouzet et al. 2008)



plumes are observed at all L distances (mostly $>7 R_E$) and mainly in the afternoon MLT sector. Denser plumes ($>40 \text{ cm}^{-3}$) are observed especially at small L ($5\text{--}7 R_E$) and in all MLT sectors (except morning), although mostly in the afternoon and pre-midnight MLT sectors.

Pairs of plume crossings, during the inbound and outbound plasmasphere passes, make it possible to examine the transformation of a plume on a time scale of a few hours and the corresponding change in LT. Darrouzet et al. (2008) computed the apparent radial velocity of the inner boundary of a plume crossed in both hemispheres, assuming that both crossings are observed approximately at the same MLT. This velocity ranges between -1.5 and $+1.5 \text{ km s}^{-1}$, due to the large diversity of the plume database, but with values mostly positive, which shows an apparent outward motion of the plume towards higher L values. The mean apparent radial velocity is around 0.25 km s^{-1} , in agreement with a previous study by Darrouzet et al. (2006a).

5.5 The Plasmasphere–Ionosphere Connection

In the last few years, the importance of plasmaspheric plumes in magnetospheric dynamics has been emphasized with simultaneous observations of ring current and cold plasmaspheric plasma by IMAGE, and with global ionospheric maps from GPS-derived TEC data. These observations indicate that plasmaspheric plumes play a crucial role in mid-latitude ionospheric density enhancements (Foster et al. 2002; Yizengaw et al. 2006), polar ionization patches (Su et al. 2001) and are strongly correlated with the loss of ring current ions (Burch et al. 2001b; Brandt et al. 2002; Mishin and Burke 2005). Plumes are also associated with enhanced wave growth that can lead to pitch-angle scattering and energization of particles (e.g., Spasojević et al. 2004).

Foster et al. (2002) showed that storm-time density enhancements observed in TEC and incoherent radar studies map to plasmaspheric plumes, which are observed with unprecedented detail with EUV. Figure 19 presents an example of a mid-latitude ionospheric density enhancement observed with GPS receivers over North America, and its comparison with the plasmopause location as determined by EUV. During strong storms, a long-lived region of

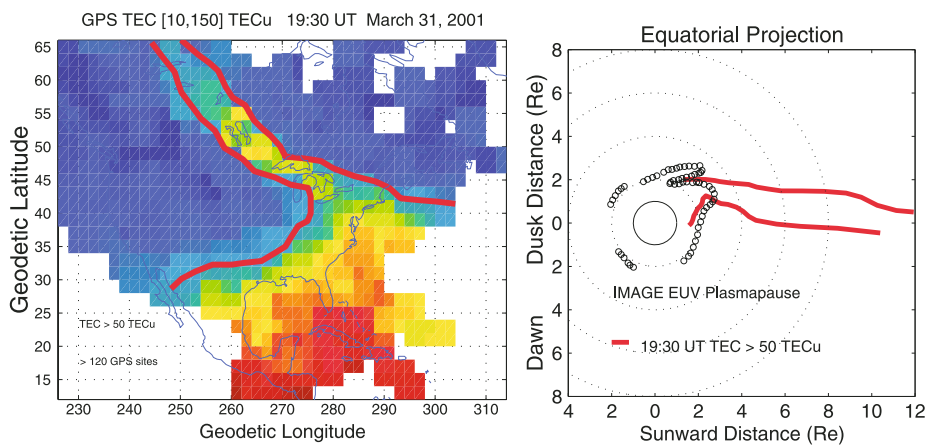


Fig. 19 (Left) A ground-based GPS TEC observation of a mid-latitude ionospheric plume. (Right) The plume extent mapped to the corresponding EUV deduced plasmopause. The red lines map the contour of $>50 \text{ TECu}$. (Adapted from Foster et al. 2002)

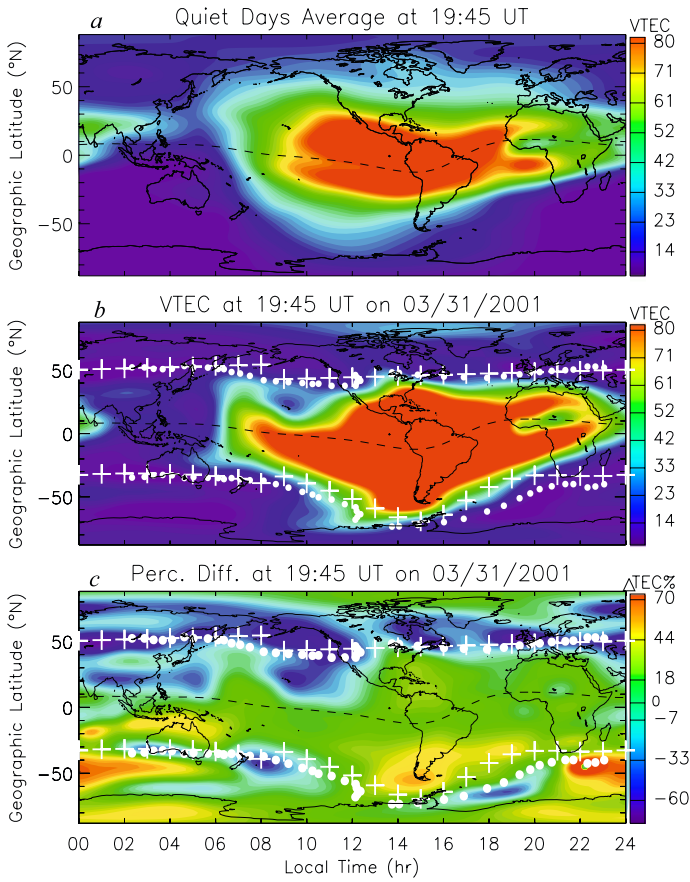


Fig. 20 15-minutes average global contour maps of GPS TEC: **a** six quiet days average, **b** data on 31 March 2001 and **c** percentage difference between data on panels **a** and **b**. The *white dots* and *plus sign* in panels **b** and **c**, respectively, depict the plasmapause locations extracted from EUV and the empirical positions of the mid-latitude trough. (Adapted from Yizengaw et al. 2005)

elevated TEC forms in the vicinity of Florida near dusk at the foot of the erosion plume and persists into the night sector. Foster et al. (2005) combined ground-based and in situ observations in the topside ionosphere, to suggest that this enhancement results from a poleward redistribution of low-latitude ionospheric plasma during the early stages of a strong geomagnetic disturbance. Simultaneous EUV observations of the plasmasphere co-locate the low-latitude TEC enhancement with a brightening and apparent bulge in the inner plasmasphere. The enhanced features, seen both from the ground and from space, corotated with the Earth once they were formed. These effects are especially pronounced over the Americas and Foster et al. (2005) suggested that this results from a strengthening of the equatorial ion fountain due to electric fields in the vicinity of the South Atlantic Anomaly.

Yizengaw et al. (2008) demonstrated that EUV observes plumes at all longitudes, but that TEC signatures of plumes are more common in the North American sector, though weaker plume signatures are seen over Europe and Asia. This study and many earlier demonstrate that plumes are most often observed in the aftermath of enhanced geomagnetic activity (not just geomagnetic storms as defined by some minimum *Dst* value) and that they tend to ap-

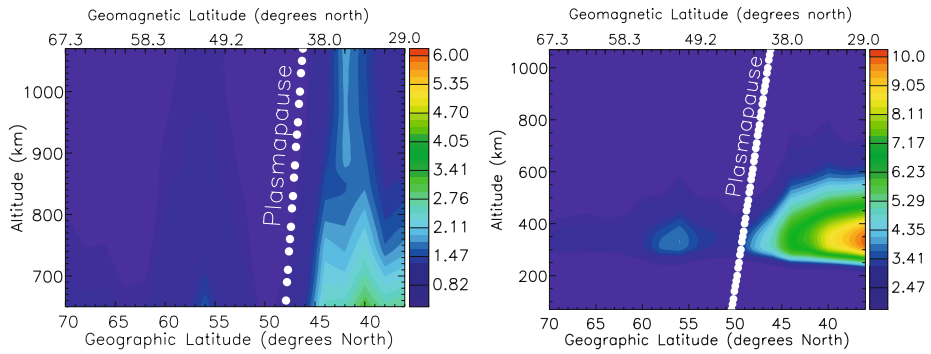


Fig. 21 Tomographically reconstructed electron density of (*left*) topside and (*right*) F-layer ionosphere, performed on 31 March 2001 using multi-direction ground-based GPS TEC from meridionally (at 16°E geographic) aligned GPS receivers. The *vertical white dots* are plasmapause positions as determined from EUV. (Adapted from Yizengaw and Moldwin 2005)

pear at earlier LT with an increase of geomagnetic activity. Garcia et al. (2003) demonstrated that the plume density enhancement exists at high geomagnetic latitude, by combining RPI wave data and EUV plume images.

In addition to plumes, ionospheric electron density exhibits complicated latitudinal structure mainly during periods of increased solar activity. The associated disturbances often result in large TEC gradients. Figure 20a displays global TEC maps showing an average quiet day distribution. The main features include the day-night asymmetry and the latitudinal structure of the low and mid-latitude ionosphere including the clear Appleton anomalies in the afternoon/dusk sector. Figure 20b displays the TEC behaviour during enhanced geomagnetic activity and Fig. 20c is a difference plot of the disturbed time compared to the average quiet time. There is a close correspondence of the mid-latitude trough and the ionospheric projection of the plasmasphere. The plume, especially in the northern hemisphere, is clearly identified in these TEC maps.

Recently, tomography has been used to establish that the altitude extent and structure of the topside ionosphere at the equatorward-edge of the ionospheric trough maps along the inferred location of the plasmapause as determined from EUV (Yizengaw and Moldwin 2005). Figure 21 presents results of the comparison of tomographic reconstruction of topside (left panel) and F-region ionosphere (right panel) during a geomagnetic storm, with the mapped location of the plasmapause as determined from EUV. The close correspondence of the mid-latitude trough and plasmasphere demonstrates the power of GPS tomography in tracking the magnetospheric-ionospheric coupling.

6 Notches

One of the recently named plasmaspheric density structures identified by EUV are notches. It is one of the largest density structures in the plasmasphere after the plume. Notches are also observed by CLUSTER but are often difficult to distinguish from other types of density structure. The observation of the evolution of notches reveals departures from corotation in the plasmasphere.

6.1 Observations of Notches

Notches are characterized by deep, mostly radial density depletions in the outer plasmasphere that can extend inward to $L = 2$ or less (Sandel et al. 2000; Gallagher et al. 2005). The MLT-width ranges from ~ 0.1 to ~ 3 hours MLT and the notch shape can be maintained for several days as it refills with ionospheric plasma. Notches are likely included among the features previously referred to as density cavities inside the outer plasmasphere (Carpenter et al. 2002). Figure 22 illustrates a plasmaspheric notch seen by EUV on 31 May 2000. In this case the notch is a broad density cavity at dusk. Notches sometimes include a central prominence of enhanced plasma density.

Notches have also been observed by CLUSTER, in particular with the WHISPER instruments. It can be seen as a decrease of the density inside the plasmasphere. However, it is often difficult to distinguish from a plume or another structure. When available, this can be resolved with global images of the plasmasphere from EUV onboard IMAGE. Figure 23 presents a notch crossing observed by WHISPER onboard C4 on 9 July 2001. Notches are very often associated with both continuum radiation features over the high end of the WHISPER frequency range, and intense electrostatic emissions thought to be primary sources of

Fig. 22 Pseudodensity image from EUV taken onboard IMAGE at 10:27 UT on 31 May 2000 and projected in the SM equatorial plane. A plasmaspheric notch is observed in the dusk side

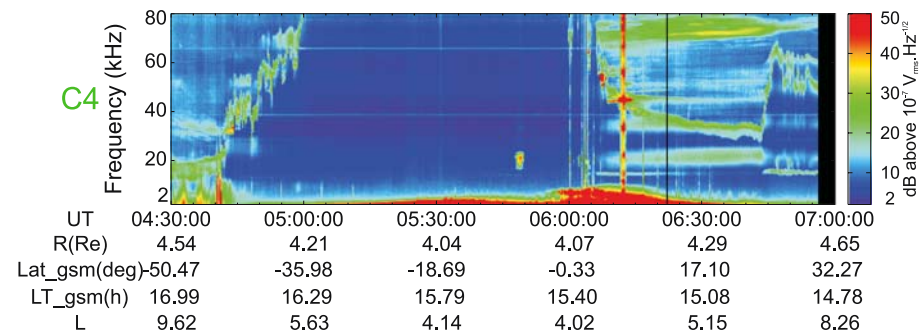
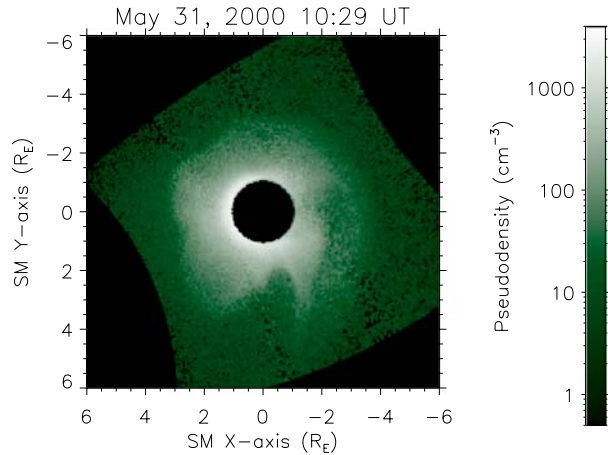


Fig. 23 Time–frequency electric field spectrogram measured by WHISPER onboard one CLUSTER spacecraft, C4, during a plasmasphere pass on 9 July 2001. The magnetic equator is crossed around 05:45 UT, and a notch between 06:05 and 06:45 UT. Continuum radiations are observed during this time interval between 65 and 80 kHz. (Adapted from Décreau et al. 2004)

continuum (Décréau et al. 2004). Using IMAGE data, Green et al. (2004) demonstrated that a notch structure is typically a critical condition for the generation of kilometric continuum radiation, but that notches do not always provide the conditions necessary for the generation of the emission. More details on waves related to notches can be found elsewhere in this issue (Masson et al. 2008).

6.2 Departures from Corotation

Sandel et al. (2003) reported the first evidence that the cold plasma comprising the main body of the plasmasphere does not always corotate with Earth. They tracked notches, persistent distinctive lower-density regions seen in EUV images of the plasmasphere, to infer the motion of particular volume elements of plasma. They defined the parameter ξ , which is the ratio of the observed angular rate to the angular rate of Earth's rotation. Thus $\xi = 1$ for corotating plasma. For $\xi < 1$, the plasma lags corotation, and therefore moves westward relative to Earth, and for $\xi > 1$, the plasma moves eastward relative to Earth.

The thirteen episodes used in this initial study by Sandel et al. (2003) had durations of 15 to 60 hours; the average duration was 31 hours. The average value of ξ was 0.88, and ξ ranged between minimum and maximum values of 0.77 and 0.93 when averaged over the full duration of the episode. During some of the intervals, the westward drift rate was uniform (ξ was constant) but in other cases the drift rate varied and in some episodes and times during the interval of observation, ξ was near 1. Figure 24 illustrates an example of a long-lasting notch that was used to determine ξ . Over the 60 hours that it was distinguishable from background plasma, the notch initially seen at about 07:30 MLT in Fig. 24b moved at a nearly constant rate of $\xi \approx 0.90$. Notches of large radial extent sometimes maintained their shape for many hours, implying that at these times shearing motions, such as might be expected to arise from any L -dependent variations in ξ , were absent.

Burch et al. (2004) argued that departures from corotation in the plasmasphere are driven by corresponding motions of plasma in the ionosphere, where departures from corotation are often observed. In a study of one of the episodes of sub-corotation reported by Sandel et al. (2003), they compared DMSP measurements of ionospheric ion drifts to the motion of a notch in the plasmasphere observed by EUV at the same time. The ion drift measurements came from the same longitude range as the notch, and from latitudes corresponding to the position of the notch in L . Over the 60 hours of the episode, the motion of the notch in the plasmasphere was consistent with that expected on the basis of the azimuthal

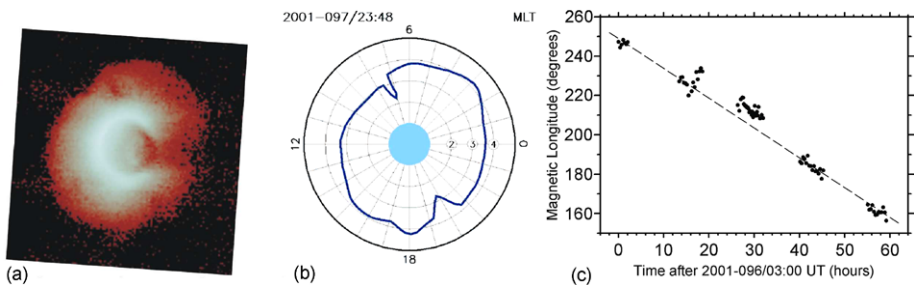


Fig. 24 **a** EUV image at 23:48 UT on 7 April 2001, illustrating two notches separated by $\sim 180^\circ$ in azimuth. **b** Mapping of prominent brightness gradients to the plane of the magnetic equator in $[L, \text{MLT}]$ space. **c** Magnetic longitude of the notch observed near 07:30 MLT in panel **b** as a function of time; the dashed line corresponds to an angular velocity that is 90% of the corotation velocity. (Adapted from Sandel et al. 2003)

ionospheric drifts if the two populations moved together, i.e., assuming that the MHD approximation applies. Burch et al. (2004) suggested that ionospheric corotation lag arises from the ionospheric disturbance dynamo (Blanc and Richmond 1980). Heating of the auroral ionosphere by currents and precipitating particles drives transport towards the equator. As the winds move to lower latitudes, conservation of angular momentum leads to a departure from corotation that takes the form of a westward drift.

A recent study by Galvan et al. (2008) found that the plasmasphere on average sub-corotates at 85% of corotation, with intervals of both sub-corotation and super-corotation. Gallagher et al. (2005) studied the azimuthal motion of 18 notches seen in EUV images. For most of the notches, they derived values of ξ in the range of 0.85 to 0.97. They report one instance of $\xi = 1$, and two much smaller values of $\xi = 0.44$ and 0.74. For 12 of the 18 observations, Gallagher et al. (2005) found that DMSP Ion Drift Meter measurements were available at the relevant locations and times, and they used these measurements for a more comprehensive test of the hypothesis advanced by Burch et al. (2004). For most of the 12 cases tested, they found consistency between the rates of ionospheric and plasmaspheric drifts. However, for 2 cases the ionospheric drift rate was smaller than the plasmaspheric rate at the $>3\sigma$ level. No inconsistencies in the opposite sense ($\xi > 1$) were found. These two instances of significant differences between ionospheric and plasmaspheric drift rates suggest that, at least at some times, effects other than those described by Burch et al. (2004) may be important.

As a possible contributor to this apparent added complexity, Gallagher et al. (2005) propose a different mechanism that may lead to sub-corotation. They suggest that a dawn-dusk asymmetry in the electric potential, which results from gradients in Hall conductance at the terminators, can drive a net sub-corotational drift whose amplitude depends on storm phase. Both the ionospheric and plasmaspheric effects would be similar to those expected in the scenario described by Burch et al. (2004), so distinguishing between the two mechanisms in a way that permits establishing their relative importance proved to be elusive.

Burch et al. (2004) note that azimuthal drifts in the ionosphere have long been known, so corresponding motions in the plasmasphere should not be surprising. However, contemporary models of terrestrial magnetospheric convection do not take this effect into account. They further call attention to one specific result, namely that convection paths in the inner magnetosphere will be distorted. In particular, the boundary between open and closed convection paths will be closer to Earth than for a corotating plasmasphere. From a practical point of view, in situ and ground-based observations, which often must be interpreted using the implicit assumption of strict corotation, may wrongly attribute spatial variations to temporal variations. For example, pre-existing density structures carried into the “field of view” of ground-based measurements would look like a temporal variation to an observer not taking into account the possibility of plasma drifts from other longitudes.

It is finally interesting to note that large corotation lags are also observed in the magnetospheres of Jupiter and Saturn. These lags result from plasma mass loading in the vicinity of strong equatorial plasma sources present deep inside these magnetospheres and from the subsequent outward plasma transport via the centrifugal interchange instability that operates in these environments (Hill 1979). Despite their obvious differences, the same physical mechanism, the conservation of angular momentum (or equivalently the Coriolis force) of plasma elements transported outwards (mainly in the ionosphere of the Earth but also in relation with the plasmaspheric wind or in the equatorial plane of the giant planet magnetospheres), is important to the corotation lags in all three magnetospheres (Burch et al. 2004).

7 Shoulders, Channels, Fingers, Crenulations

Many other medium-scale density structures exist in the plasmasphere, but could not be clearly distinguished before data from the global imaging mission IMAGE and the four-spacecraft mission CLUSTER became available. New terms have therefore been given to those structures, like shoulders, channels, fingers and crenulations.

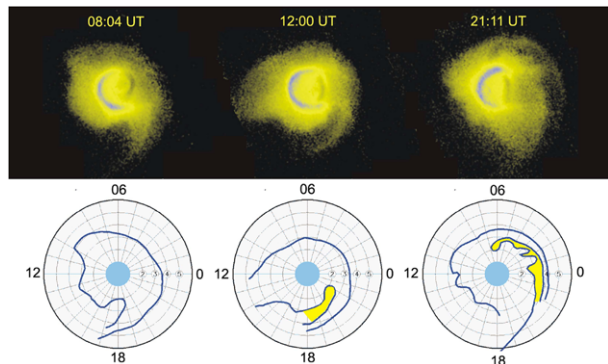
An example of previously unknown phenomena first detected by IMAGE is the shoulder (Burch et al. 2001a, 2001b). A shoulder appears as a sharp azimuthal gradient, which forms following sharp increases in activity. The shoulders are caused by the residual shielding of the convection electric field following the sudden weakening of convection when the IMF turns from southward to northward (Goldstein et al. 2002).

From a study on the evolution of a plume, Spasojević et al. (2003) demonstrated that the differential rotation of the western edge of a plume in L and the stagnation of the eastern edge, led to the wrapping of the plume around the main plasmasphere and to the formation of a low-density channel located between the plasmasphere and the plume. Figure 25 gives an example of such channel development on 10 June 2001 in the pre-midnight sector, when a plume wrapped around the main body of the plasmasphere (Sandel et al. 2003). A channel can extend over a few hours in MLT, with a width of $\sim 0.5 R_E$.

Though the concept of plasmaspheric (or plume) phases is remarkably useful in providing a global context for data interpretation, this concept is far from a complete picture of plasmaspheric dynamics. On smaller scale, many stormtime features have yet to be explained; for example, crenulations are a few-tenths- R_E modulation of the plasmopause location that are often seen between the dawnside terminator and the westmost edge of a plume (Spasojević et al. 2003; Goldstein and Sandel 2005). Other complex structures appear during quiet conditions, but also remain without firm explanation. This unpredictability reflects an incomplete understanding of both inner magnetospheric electric fields and the quantitative influence of ULF waves and plasma instabilities on the distribution of cold plasma (Pierrard and Lemaire 2004).

Prior to 2000, several studies had noted the increased likelihood for medium-scale spatial structure during quieter intervals (Chappell 1974; Moldwin et al. 1994, 1995). This same tendency was also observed in data from IMAGE (Spasojević et al. 2003) and CLUSTER (Dandouras et al. 2005). Goldstein and Sandel (2005) suggested that the increase in structural complexity during early and deep recovery could be explained by consideration of flow streamlines: When flows are strong, streamlines are closer together, leading to a decreased scale size transverse to the flow. This would lead to a steeper plasmopause density gradient, and a more laminar plasmopause shape. On the other hand, the streamlines

Fig. 25 (Top) EUV images on 10 June 2001 scaled to a common range and rotated so that the Sun is to the left. (Bottom) Mapping of the prominent brightness gradients onto the geomagnetic equator plane in $[L, \text{MLT}]$ space; the yellow fill marks the channel. (Adapted from Sandel et al. 2003)



from weaker flows would be more widely spaced, and the transverse size of medium-scale structures would be larger, allowing for a more lumpy plasmopause. Even more puzzling are deep quiet features called fingers that have only tentatively been explained as arising from some resonance of ultra-low frequency waves (Adrian et al. 2004), but which also might be explained by interchange physics. Explaining medium-scale density features both inside and at the plasmopause is one of the major remaining challenges to closure in studies of plasmaspheric dynamics.

8 Small-Scale Density Irregularities

Field-aligned density irregularities have been observed since the discovery of the plasmasphere. But the IMAGE mission, and in particular the RPI instrument, made it possible to more precisely characterize those density structures. Note that the EUV instrument onboard IMAGE does not observe density structures less than its spatial resolution of about $0.1 R_E$. Thanks to the high resolution, in space and time, of the WHISPER instrument, the CLUSTER mission gives also new results on the morphology, dynamics and occurrence of small-scale density irregularities.

8.1 Earlier Work

8.1.1 Field-Aligned Density Irregularities

The existence of field-aligned density irregularities capable of guiding whistler-mode waves for long distances in the magnetosphere has been known since the early 1960s (e.g., Smith 1961; Helliwell 1965), becoming well established through ground-based whistler observations at a wide range of latitudes. Propagation of whistlers between conjugate hemispheres along multiple discrete paths was found to occur regularly at some longitudes even under prolonged quiet conditions, but tended to be poorly defined or undetectable during the highest levels of disturbance. The apparent lifetimes of individual paths could be as long as several hours and the instantaneous distributions of paths in latitude or L value, as determined from ground whistler stations, tended to be unchanged on a time scale of a few minutes (see Hayakawa 1995). Meanwhile, also in the 1960s, topside sounders showed clear evidence of field-aligned propagation of free-space-mode waves back and forth between the sounder and reflection points in the conjugate hemisphere (e.g., Muldrew 1963; Loftus et al. 1966).

The irregularities involved in both ground-based and satellite studies were not usually detected directly, but instead were studied indirectly through their transmission properties as wave ducts or guides. Theory as well as limited experimental evidence indicated that the irregularities involved step-like changes or local enhancements in the range 1–30% with respect to the average density background (e.g., Smith 1961; Booker 1962; Strangeways and Rycroft 1980; Platt and Dyson 1989). For whistler propagation, density enhancement ducts, capable of internally trapping and guiding waves, were inferred to be of order 10 to 20 km in cross section near the ionosphere (e.g., Helliwell 1965). On a rare OGO 3 satellite pass, Angerami (1970) found evidence of whistlers that were trapped within ducts as well as of whistler wave energy escaping from ducts at frequencies above the local electron gyrofrequency. The observations suggested that the equatorial duct cross sections near $L = 4$ were several hundred kilometers.

The origin of the magnetospheric irregularities guiding whistler and sounder waves within the plasmasphere has not been well established. Proposed mechanisms for whistler ducts include irregular electric fields that give rise to flux tube interchange (Cole 1971; Thomson 1978) and thundercloud electric fields (Park and Helliwell 1971).

8.1.2 Irregular Density Structures in the Outer Plasmasphere

Satellite in situ density measurements, for example by LANL (e.g., Moldwin et al. 1995) and CRRES (e.g., Fung et al. 2000), revealed concentrations of irregularities in the plasmopause region, some of which appear to trap and guide whistler-mode waves (Koons 1989). These structures appear to vary widely in cross section, ranging from 50 km upward. Due to limitations on spatial sampling rates, the bulk of the reports made thus far concern features with cross sections of order hundreds of kilometers. Observed peak to valley density ratios for these features vary from ~ 1.2 to 5 or more.

The presence in the middle to outer plasmasphere of density variations with scale widths of thousands of kilometers has been known from whistler studies since the 1970s (e.g., Park and Carpenter 1970; Park 1970). On occasion, such irregularities are seen in a belt in the outer plasmasphere that terminates abruptly about $1 R_E$ inward from the plasmopause (Carpenter and Lemaire 1997). Within such a belt the peak densities tend to reach the quiet plasmasphere level while the minima may be lower than the peaks by factors of as much as 5. Longitudinal variations in density by factors of up to 3 in longitude have been found to arise in the aftermath of magnetic disturbances (Park and Carpenter 1970). Little is known of the occurrence rates and distributions on a global scale of these types of irregularities in the outer plasmasphere.

A number of instabilities have been suggested to explain the irregular density structures observed in the plasmasphere: the drift wave instability (e.g., Hasegawa 1971), the Rayleigh Taylor instability (e.g., Kelley 1989), the pressure gradient instability (e.g., Richmond 1973), and the gravitational interchange instability (e.g., Lemaire 1975).

8.2 Remote Sensing of Density Irregularities by the RPI Instrument

8.2.1 Comments on RPI Observations

The IMAGE mission provided the first opportunity to study the response of the plasmasphere to high power radio sounding by RPI. In planning for the IMAGE mission, it was expected that irregular density structure would be encountered, particularly in the plasmopause region. However, it was not anticipated that the plasmasphere boundary layer (PBL) would consistently appear as a rough surface to the sounder. It was not anticipated that sounder echoes received near or within the plasmasphere would fall into two quite different categories: Discrete echoes that had followed magnetic field-aligned paths and diffuse or “direct” echoes that had propagated generally earthward, in directions not initially aligned with the magnetic field (Carpenter et al. 2002).

Figure 26 illustrates these points by a series of six “plasmagrams”, obtained 4 minutes apart as IMAGE approached and then penetrated the plasmasphere along the orbit shown schematically on the right of the figure. The plasmopause was estimated to be at $L = 4.1$. The records display echo intensity on a gray scale in coordinates of virtual range (0.3 to $4.2 R_E$, assuming propagation at velocity c along ray paths to reflection points) versus sounder frequency (40 to 600 kHz). Two different types of echoes are observed on those plasmagrams: the “field-aligned echo” and the “plasmasphere echo”. Field-aligned echoes

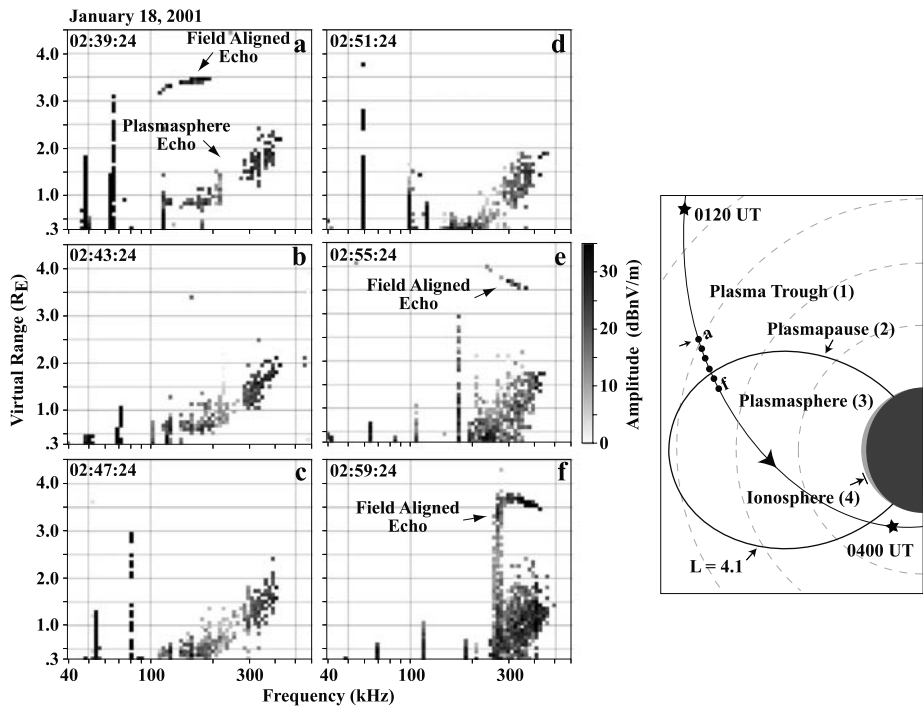


Fig. 26 A series of six soundings by RPI showing range spreading of echoes interpreted as evidence of irregular density structure in both the PBL and outer plasmasphere. The soundings were performed as IMAGE approached and penetrated the plasmasphere along the orbit shown schematically on the right. (Adapted from Carpenter et al. 2002)

were seen both outside the plasmasphere (panel a) and just inside the plasmopause (panels e and f), while a direct echo appears during each sounding. The striking differences in range-versus-frequency form between the former and the latter reflect the differences in the electron density profiles along the respective propagation paths. The field-aligned echo pulses encountered smooth density profiles and small initial gradients while propagating along relatively long paths of order $4 R_E$ in length. Meanwhile, the direct-echo pulses encountered gradients from the PBL inward that were steeper by comparison. Those pulses returned from closer turn-around points, and from the PBL inward encountered widespread field-aligned irregularities. The irregularities gave rise to scattering along the entire path from the near vicinity of IMAGE (so-called “zero range” scattering) to the most distant turning point. Hence the returning echoes tended to be widely spread in range at each frequency.

Within the plasmasphere at $L \geq 2.5$, diffuse echoes were observed on essentially every sounding. The upper frequency limit for zero range echo components increased from a typical value of ~ 200 kHz in the outer plasmasphere to ~ 800 kHz near $L = 2.5$ in the inner plasmasphere. Discrete, field-aligned echoes were observed, but not on every sounding. Within the plasmasphere at $L < 2.5$ the non field-aligned or direct echoes tended to exhibit less range spreading than at $L > 2.5$.

8.2.2 Interpretation of RPI Observations in Terms of Density Structure

The plasma trough along high-latitude field lines appears to contain sufficient field-aligned structure to guide discrete X-mode waves over distances of 4 or $5 R_E$ down to lower alti-

tudes. When this filamentary structure is present, it is found over extensive regions exterior to the PBL. The plasma trough under most conditions appears to be a smooth medium at wavelengths in the vicinity of 200–800 m, which corresponds to the half wavelength of the waves that propagate across the magnetic field in the region without giving rise to detectable echoes.

The PBL regularly contains embedded irregularities that are distributed both in equatorial radius and, more importantly, in longitude, thus giving rise to aspect sensitive scattering of RPI pulses and very possibly to tunneling. The echoes can extend in range beyond a well defined minimum by as much as $1 R_E$ when coherent signal integration is used. RPI confirmed earlier suggestions that density irregularities tend to be concentrated in the PBL and showed that such concentrations nearly always exist.

Strong scattering in the plasmasphere, particularly of the zero range type, presumably occurs in the presence of irregularities that are about half the probing wavelength in size. Hence it is found that the outer plasmasphere, beyond $L \approx 2.5$, is regularly permeated by field-aligned irregularities with scale widths in the range 200–800 m. The plasmasphere beyond $L \approx 2.5$ also exhibits a class of field-aligned irregularities that have been identified from evidence of propagation within irregularities rather than at large angles to the magnetic field. The inferred scale widths vary from 1 to 10 km, based on the assumption that structures several wave lengths across are needed to trap and guide the field-aligned X-mode echoes that are frequently observed from RPI. Earlier studies (noted above) of the conditions for trapping of such waves (or whistler-mode waves) by or within such field-aligned density irregularities found that the density levels within the irregularities remained within a range 1–30% of the nearby background.

8.3 In situ Observations of Small-Scale Density Structures

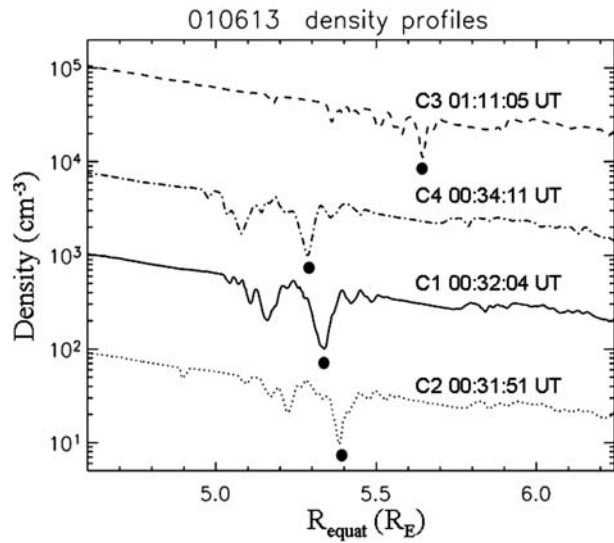
CLUSTER observations confirmed that small-scale density structures, or density irregularities, are often present in the outer plasmasphere, near the Roche Limit surface associated with hydrodynamic instability (Décréau et al. 2005). It is, however, quite difficult to assess the shape of a density irregularity or its relative motion with respect to the background, even with a four-spacecraft constellation.

8.3.1 Morphology

Are density irregularities field-aligned? What is their size along and across magnetic field lines? CLUSTER observations can address those questions directly. Décréau et al. (2005) considered one event (13 June 2001, meridian cut around 17:00 MLT) with three spacecraft near the same modelled magnetic field line (CLUSTER constellation as in Fig. 2b). The same complex specific signature is recognized in density profiles (shown versus R_{equat} in Fig. 27) measured from the three conjugate spacecraft, C2, C1 and C4 within a 2.5 minutes time interval. A remnant form of the signature is encountered 40 minutes later by the fourth satellite, C3: The main density dip (black circle) can be correlated with a similar feature seen in each of the C2, C1 and C4 signatures.

Those observations can be interpreted in the framework of a rigid plasmasphere. The common structure (the main dip) would in that case extend up to the longitude of C3 (C2, C4, C1 and C3 are placed at increasing respective longitudes, within 1° total). Features correlated only on C2, C1, C4, like the two small bumps seen just above the main dip (i.e., at higher R_{equat}), would be restricted to the longitude range of the trio. Subtle differences observed between the conjugate spacecraft (like a small dip at $R_{\text{equat}} = 4.9 R_E$ seen only

Fig. 27 Density profiles from WHISPER are shown as a function of R_{equat} for a structure crossed around 00:35 UT during the plasmasphere pass on 13 June 2001 (same event as in Fig. 11). The density values have been multiplied by factors, respectively 8, 64 and 512 for C1, C4 and C3. (Adapted from Décr  au et al. 2005)



on C2) could be attributed to small filamentary structures which are not encountered by all spacecraft.

Alternatively, the different morphology of the structure observed by C3, as compared to the one observed by C2, C4 and C1, could be attributed to a time effect. In particular, interchange velocity values at work in hydrodynamic instability are proportional to the depth (or amplitude) of a density irregularity (see Lemaire and Gringauz 1998, p. 263). The main dip would then travel faster and reach higher geocentric distances than small bumps part of the structure, leading thus to the observed shape.

8.3.2 Dynamics

The time delay method provides the orientation of a given density structure, as well as its velocity along its normal, assuming this structure to be locally planar (De Keyser et al. 2008, this issue). It is possible to apply this method in the outer plasmasphere when the spacecraft are configured at 100 km separation. In practice, the configuration is elongated along the orbit, the largest distances respectively along and transverse to the orbit are ~ 300 km and ~ 60 km. Three event studies used the time delay method to explore motions of density structures in the outer plasmasphere.

The first event (Décr  au et al. 2005) is located in the dusk region, where corotation and convection are competing (inducing velocities in opposite directions). The authors present a detailed shape of a density structure observed at $L \approx 6$ during this event. The estimated velocity components ($-2, 0.7, 0.5$ km s $^{-1}$ in geocentric solar ecliptic, GSE, coordinates) indicate that corotation dominates, in this case. Magnetic activity is actually low during the day preceding and including the event ($Dst \approx -10$ nT), which explains why the plasmasphere is expanded and its outer edge corotating.

The second event (Darrouzet et al. 2004) is located in the pre-midnight sector. A plasmaspheric plume is seen in the inbound and outbound passes, and many small-scale density structures are visible inside the plasmasphere. By combining density gradient analysis and time delay method, the authors found that the major component of the boundary velocity of a density irregularity corresponds to corotation.

In the third event (Décréau 2008, personal communication), multiple density structures are encountered in the post-midnight sector on 8 February 2002 near perigee. Most irregularities are present on the four density profiles. Focusing on a double structure at the start of the time interval, the time delay method gives the velocity components associated to the first outer density peak. Those values are consistent with velocity components derived by the EDI instrument, indicating that in this case the plasma and its boundary move at comparable velocities.

8.3.3 Occurrence

In an analysis of 264 plasmasphere passes, Darrouzet et al. (2004) identified density irregularities by a density depletion ratio of at least 10%. This survey suggests that there are more density irregularities in the dawn, afternoon and post-dusk MLT sectors. Two of these sectors correspond to the sectors where the plasmopause tends to be thicker. The transverse equatorial size and density depletion ratio distributions of density irregularities are exponential with a characteristic size of 365 km and a characteristic density ratio of 20%. The larger ones (in size) are observed when K_p is small. This is in part due to the fact that large ones simply cannot exist when the plasmasphere is small for high K_p . As expected, there are more density irregularities during and after periods of high geomagnetic activity, suggesting that they are generated near dusk by variations in the convection electric field. But this sample has few cases with high K_p and is therefore biased in this respect.

9 Conclusion

The CLUSTER and IMAGE missions provide a new and non-local view of the plasmasphere, thanks to the new capabilities of those missions: global imaging with IMAGE and four-spacecraft in situ measurements with CLUSTER. Using advanced imaging techniques and radio sounding, IMAGE provided new results for the global density structure and behaviour of plasma in the plasmasphere, while multipoint tools applied to CLUSTER data gave new opportunities to analyse the geometry and motion of plasmaspheric density structures. Refilling has been studied in detail, new results on ion composition have been derived, and new views of plasmaspheric structures have been obtained and analysed in new ways.

9.1 Sources and Losses in the Plasmasphere

Sandel and Denton (2007) updated our view of refilling by analysing IMAGE data during a 70 hours quiet period. They found an orderly increase in He^+ column abundance with time, which slowed near the end of the period. Gallagher et al. (2005) quantitatively obtained the He^+ refilling rates at the equator. Tu et al. (2005) demonstrated that the parallel electron velocity is almost constant along field lines in the inner plasmasphere. Darrouzet et al. (2006b) found that there is no evidence for sharp density gradients along field lines, such as would be expected in refilling shock fronts propagating along field lines. This extensive body of evidence suggests that refilling of flux tubes is a gradual process as described by Lemaire (1989) and Wilson et al. (1992).

The plasmasphere rarely appears filled to saturation, i.e., in diffusive equilibrium with the ionosphere. Reinisch et al. (2004) found significant refilling in less than 28 hours near $R = 2.5 R_E$, but still insufficient to reach saturation levels. Cases of smooth density transition from the plasmasphere to the subauroral region without a distinct plasmopause have been

observed in 10% of the RPI database (Tu et al. 2007). This long refilling time and this smooth transition could be explained if the plasmasphere experiences a slow outward drift in addition to corotation and convection: the plasmaspheric wind (Lemaire and Schunk 1992). Dandouras (2008) showed with CIS data that systematically more ions are going outwards than inwards in the plasmasphere, at all LT. This could be the first direct evidence of the plasmaspheric wind.

New insights into the plasmaspheric erosion process have been given by IMAGE observations. The typical erosion cycle, including the formation of plumes, are followed through EUV images (Goldstein and Sandel 2005). Dramatic evidence confirming the effects of erosion were provided by RPI observations showing that outer plasmaspheric flux tubes could lose more than two thirds of their plasma in less than 14 hours (Reinisch et al. 2004).

9.2 Overall Plasma Distribution and Ion Composition

The global images by EUV improved our understanding of the distribution of plasma in the plasmasphere and the forces that control it. The sounding measurements from RPI provided field-aligned electron density profiles, which allow to build 2-D electron density images along the satellite orbit (Tu et al. 2005). Such images are useful to differentiate various plasma regions in the near-Earth magnetosphere and to provide insight into the plasma dynamics in those regions.

CLUSTER contributed the first systematic determination of spatial gradients of plasmaspheric density (Darrouzet et al. 2006b; De Keyser et al. 2007). This has produced an overall view of the geometry of the electron density distribution in the outer plasmasphere. It allows an evaluation of the relative importance of the dominant density gradients inside the plasmasphere: the increase of density along field lines away from the equator and its decrease away from Earth. The overall density structure is mainly aligned and slowly varying with the magnetic field at low *MLAT*, $\pm 30^\circ$ (see also the IMAGE study by Reinisch et al. 2001), with pronounced transverse density variation.

By combining observations from the ground and He^+ column abundances from EUV, the ratio He^+/H^+ in the plasmasphere has been derived. Clilverd et al. (2003) inferred a ratio of $\sim 3.8\%$ for an event with moderate geomagnetic disturbance, while Grew et al. (2007) found a value of $\sim 18\%$ in the case of a prolonged geomagnetic disturbance. The presence of O^+ has also been confirmed. Using CIS data, Dandouras et al. (2005) observed mostly similar density profiles for H^+ and He^+ ions, with the He^+ densities being lower by a factor of ~ 15 . O^+ are not observed as part of the main plasmaspheric population at the CLUSTER altitudes at a significant level. Low-energy (< 25 eV) O^+ are observed as upwelling ions, escaping from the ionosphere along auroral field lines. O^{++} can also be observed in these upwelling ion populations. Low-energy O^+ have been observed in some plasmaspheric plumes, exhibiting symmetric bi-directional pitch-angle distributions and having an outward expansion velocity.

9.3 Plasmaspheric Plumes

EUV images demonstrate that plumes form and develop in three phases (sunward surge, plume narrowing, plume rotating) that are directly correlated with relative increases or decreases in geomagnetic activity (Goldstein and Sandel 2005). This has been confirmed in many studies using EUV data, with and without in situ measurements (Goldstein et al. 2004b; Spasojević et al. 2004; Kim et al. 2007). However, during post-storm recovery and on smaller scales, our predictive capability remains limited.

Plasmaspheric plumes have also been routinely observed by the CLUSTER spacecraft. In the case of large satellites separation, a comparative study between each crossing clearly illustrates the global shape of a plume (Darrouzet et al. 2008). In some situation, CLUSTER observes details of the formation of a large-scale plume, where filamentary density structures are dragged from the near-Earth foot of the plume. Direct, complementary comparison with EUV images can then be done: It gives a consistent picture for radial position and MLT extent of plumes (Darrouzet et al. 2006a).

In the case of small separation between the CLUSTER satellites, multipoint tools can be used to study the geometry and motion of plumes. Darrouzet et al. (2006a) found the foot of the plume attached to the plasmasphere and nearly corotating, but with the extended plume moving outward and lagging further behind corotation. From a comparative study between the inbound and outbound plume crossing Darrouzet et al. (2008) found the plume rotated eastward and moved to higher L values. Between both passes CLUSTER was displaced outward along the plume, which narrowed and lowered in density. The mean apparent radial velocity was found to be $\sim 0.25 \text{ km s}^{-1}$.

From a statistical point of view, plasmaspheric plumes are found to be a common feature observed in the outer plasmasphere, mainly in the afternoon and pre-midnight MLT sectors (Darrouzet et al. 2008). A small increase of geomagnetic activity is sufficient to produce plumes. Denser plumes are observed especially at small L (around $5\text{--}7 R_E$) and in all MLT sectors (except morning), mostly pre-midnight.

Plasmaspheric plume signatures have also been detected in the ionosphere, in particular with TEC measurements (Foster et al. 2002). TEC signatures of plumes are more common in the North American sector, though weaker plume signatures are seen over Europe and Asia (Yizengaw et al. 2008). It has been demonstrated that plumes play a crucial role in mid-latitude ionospheric density enhancements (Yizengaw et al. 2006), polar ionization patches (Su et al. 2001) and are strongly correlated with the loss of ring current ions (Burch et al. 2001b).

9.4 Density Structures at Smaller Scales

Notches are one of the remarkable large-scale structural features of the plasmasphere, only recognized after flight of the EUV instrument. Notches can extend over more than $2 R_E$ in radial distance and 3 hours MLT in the magnetic equatorial plane (Gallagher et al. 2005). They have been observed to persist for periods as long as 60 hours (Sandel et al. 2003). Notches are also observed by WHISPER, very often associated with both continuum radiation and intense electrostatic emissions (Décréau et al. 2004).

Sandel et al. (2003) found that the outer plasmasphere, as traced by notches, rotates at a rate significantly slower ($\sim 10\%$) than corotation. Burch et al. (2004) suggest that this corotation lag is caused by the ionospheric disturbance dynamo. Gallagher et al. (2005) find that additional mechanisms may be needed such as Hall conductance gradients at the terminators that cause a dawn-dusk electric potential asymmetry, which also yields a net sub-corotational plasmaspheric drift.

The IMAGE and CLUSTER missions revealed many other medium-scale density structures in the plasmasphere that could not be clearly distinguished before: shoulders, channels, fingers and crenulations. For example, a shoulder can be formed after a sharp decrease of geomagnetic activity (Pierrard and Cabrera 2005); fingers appear to result from quite-time global magnetospheric oscillations (Adrian et al. 2004); crenulations are seen as a modulation of the plasmopause location (Spasojević et al. 2003).

IMAGE provided the first opportunity to study the response of the plasmasphere to high power radio sounding by the RPI instrument (Carpenter et al. 2002). Two different types

of sounder echoes have been observed: Discrete echoes that have followed geomagnetic field-aligned paths and diffuse echoes that have returned to the satellite along ray paths that extended generally earthward from the satellite. The reflection points of the diffuse echoes are in the PBL or in the plasmasphere interior, while the discrete echoes follow field-aligned density irregularities that are common in low and high-latitude magnetospheric regions. Field-aligned irregularities in electron density are within $<10\%$ of background, with cross-field scale sizes between 200 m and >10 km.

The CLUSTER constellation has also identified field-aligned density structures in the outer plasmasphere. The spatial extent along the magnetic field is larger than the spacecraft separation in that direction. Sizes transverse to the field in a meridian plane are found to range from ~ 10 km to a few 100 km. Those length scales vary with the altitude of observation. Sizes in the third dimension (in longitude) can be very small, down to 20 km (Décréau et al. 2004). Undulations in longitude, a known feature of the plasmopause, are not easily distinguished with the CLUSTER spacecraft, which travel along polar orbits. The primary motion of small-scale density structures is found to be corotation (Darrouzet et al. 2004). From a statistical study, Darrouzet et al. (2004) established that density irregularities are often, though not always, seen in the plasmasphere and at the plasmopause. They have a transverse equatorial size that falls off exponentially with a characteristic value of 365 km and going up to 5000 km. There are more density irregularities when the level of geomagnetic activity is higher. There seems to be an MLT asymmetry in their distribution.

9.5 Perspectives

Much progress in our understanding of plasmaspheric density structures has been made with the CLUSTER and IMAGE missions, but many questions remain unsolved. For example, the coupling between the ionosphere and the plasmasphere through refilling and erosion is not yet completely understood; several mechanisms for the formation of plumes have been proposed, but their relative importance is not yet clear; many medium-scale density structures (like fingers or channels) are not fully explained; the distributions of field-aligned density structures in space and time throughout the plasmasphere are not yet well documented; the mechanisms that create small-scale density irregularities are not yet fully understood.

The CLUSTER mission has been extended until December 2009. Interestingly for plasmaspheric studies, the orbit is changing since June 2007 towards a lower perigee (down to $2.5 R_E$). This will allow the study of the inner plasmasphere. With the new orbit, it should also be possible to observe plasmaspheric plumes extending up to the magnetopause. But, sadly, the IMAGE satellite was lost on 18 December 2005. There is now a lack of global imaging of the plasmasphere, which could be filled in the coming years with China's CHANG'E and KUAUFU missions. More recent multi-spacecraft missions visit the plasmasphere, such as THEMIS, though this region is not their primary goal and their instrumentation is not specifically adapted for studying it. The Canadian ORBITALS (Outer Radiation Belt Injection, Transport, Acceleration and Loss Satellite) mission is a dedicated inner magnetosphere mission, under preparation, and will carry plasma instrumentation for in situ plasmasphere measurements. The ERG (Energization and Radiation in Geospace) project has been proposed to the Japan Space Agency. But, no other dedicated inner magnetosphere mission is on the horizon, although one, WARP, has been proposed in the frame of ESA's Cosmic Vision program.

Acknowledgements The IMF Y and Z components and the K_p and Dst indices were provided by the Space Environment Information System, SPENVIS (<http://www.spENVIS.oma.be>). The am index was provided by the International Service of Geomagnetic Indices, ISGI (<http://isgi.cetp.ipsl.fr>). F. Darrouzet and J.

De Keyser acknowledge the support by the Belgian Federal Science Policy Office (BELSPO) through the ESA/PRODEX project (contract 13127/98/NL/VJ (IC)). F. Darrouzet thanks M. Roth for careful reading of the manuscript. Work at Dartmouth College was supported by U.S. National Science Foundation grants ATM-0632740 and ATM-0120950 (Center for Integrated Space Weather Modeling funded by the Science and Technology Centers Program). Work at The University of Arizona was funded by a subcontract from Southwest Research Institute under NASA contract NAS5-96020 with SwRI, and by NASA Grant NNX07AG46G. This paper is an outcome of the workshop "The Earth's plasmasphere: A CLUSTER, IMAGE, and modeling perspective", organized by the Belgian Institute for Space Aeronomy in Brussels in September 2007.

References

- S. Abe, H. Kawano, J. Goldstein, S. Ohtani, S.I. Solov'yev, D.G. Baishev, K. Yumoto, Simultaneous identification of a plasmaspheric plume by a ground magnetometer pair and IMAGE Extreme Ultraviolet Imager. *J. Geophys. Res.* **111**, A11202 (2006)
- M.L. Adrian, D.L. Gallagher, L.A. Avanov, IMAGE EUV observation of radially bifurcated plasmaspheric features: First observations of a possible standing ULF waveform in the inner magnetosphere. *J. Geophys. Res.* **109**, A01203 (2004)
- N. André, J.F. Lemaire, Convective instabilities in the plasmasphere. *J. Atmos. Sol.-Terr. Phys.* **68**(2), 213–227 (2006)
- J.J. Angerami, Whistler duct properties deduced from VLF observations made with the Ogo 3 satellite near the magnetic equator. *J. Geophys. Res.* **75**(31), 6115–6135 (1970)
- M. Blanc, A.D. Richmond, The ionospheric disturbance dynamo. *J. Geophys. Res.* **85**(A4), 1669–1686 (1980)
- H.G. Booker, Guidance of radio and hydromagnetic waves in the magnetosphere. *J. Geophys. Res.* **67**(11), 4135–4162 (1962)
- J.E. Borovsky, M.H. Denton, A statistical look at plasmaspheric drainage plumes. *J. Geophys. Res.* **113**, A09221 (2008)
- J.E. Borovsky, M.F. Thomsen, D.J. McComas, T.E. Cayton, D.J. Knipp, Magnetospheric dynamics and mass flow during the November 1993 storm. *J. Geophys. Res.* **103**(A11), 26373–26394 (1998)
- P.C. Brandt, D.G. Mitchell, Y. Ebihara, B.R. Sandel, E.C. Roelof, J.L. Burch, R. Demajistre, Global IMAGE/HENA observations of the ring current: Examples of rapid response to IMF and ring current-plasmasphere interaction. *J. Geophys. Res.* **107**(A11), 1359 (2002)
- K. Bullough, J.L. Sagredo, Longitudinal structure in the plasmapause: VLF goniometer observations of knee-whistlers. *Nature* **225**(5237), 1038–1039 (1970)
- J.L. Burch, IMAGE mission overview. *Space Sci. Rev.* **91**(1–2), 1–14 (2000)
- J.L. Burch, S.B. Mende, D.G. Mitchell, T.E. Moore, C.J. Pollock, B.W. Reinisch, B.R. Sandel, S.A. Fuselier, D.L. Gallagher, J.L. Green, J.D. Perez, P.H. Reiff, Views of Earth's magnetosphere with the IMAGE satellite. *Science* **291**, 619–624 (2001a)
- J.L. Burch, D.G. Mitchell, B.R. Sandel, P.C. Brandt, M. Wüest, Global dynamics of the plasmasphere and ring current during magnetic storms. *Geophys. Res. Lett.* **28**(6), 1159–1162 (2001b)
- J.L. Burch, J. Goldstein, B.R. Sandel, Cause of plasmasphere corotation lag. *Geophys. Res. Lett.* **31**, L05802 (2004)
- P. Canu, P.M.E. Décréau, J.G. Trotignon, J.L. Rauch, H.C. Séran, P. Fergeau, M. Lévêque, P. Martin, F.X. Sené, E. Le Guirrec, H. Alleyne, K. Yearby, Identification of natural plasma emissions observed close to the plasmapause by the Cluster-Whisper relaxation sounder. *Ann. Geophys.* **19**(10–12), 1697–1709 (2001)
- D.L. Carpenter, New experimental evidence of the effect of magnetic storms on the magnetosphere. *J. Geophys. Res.* **67**(1), 135–145 (1962)
- D.L. Carpenter, Whistler evidence of a "knee" in the magnetospheric ionization density profile. *J. Geophys. Res.* **68**(6), 1675–1682 (1963)
- D.L. Carpenter, Whistler Evidence of the Dynamic Behavior of the Dusk-side Bulge in the Plasmasphere. *J. Geophys. Res.* **75**(19), 3837–3847 (1970)
- D.L. Carpenter, Some aspects of plasmapause probing by whistlers. *Radio Sci.* **18**(6), 917–925 (1983)
- D.L. Carpenter, R.R. Anderson, An ISEE/Whistler model of equatorial electron density in the magnetosphere. *J. Geophys. Res.* **97**(A2), 1097–1108 (1992)
- D.L. Carpenter, J. Lemaire, Erosion and recovery of the plasmasphere in the plasmapause region. *Space Sci. Rev.* **80**(1–2), 153–179 (1997)
- D.L. Carpenter, J. Lemaire, The plasmasphere boundary layer. *Ann. Geophys.* **22**(12), 4291–4298 (2004)

- D.L. Carpenter, B.L. Giles, C.R. Chappell, P.M.E. Décr  au, R.R. Anderson, A.M. Persoon, A.J. Smith, Y. Corcuff, P. Canu, Plasmasphere dynamics in the duskside bulge region: A new look at an old topic. *J. Geophys. Res.* **98**(A11), 19243–19271 (1993)
- D.L. Carpenter, R.R. Anderson, W. Calvert, M.B. Moldwin, CRRES observations of density cavities inside the plasmasphere. *J. Geophys. Res.* **105**(A10), 23323–23338 (2000)
- D.L. Carpenter, M.A. Spasojevi  , T.F. Bell, U.S. Inan, B.W. Reinisch, I.A. Galkin, R.F. Benson, J.L. Green, S.F. Fung, S.A. Boardsen, Small-scale field-aligned plasmaspheric density structures inferred from the Radio Plasma Imager on IMAGE. *J. Geophys. Res.* **107**(A9), 1258 (2002)
- C.R. Chappell, Recent satellite measurements of the morphology and dynamics of the plasmasphere. *Rev. Geophys. Space Phys.* **10**(4), 951–979 (1972)
- C.R. Chappell, Detached Plasma Regions in the Magnetosphere. *J. Geophys. Res.* **79**(13), 1861–1870 (1974)
- C.R. Chappell, K.K. Harris, G.W. Sharp, The morphology of the bulge region of the plasmasphere. *J. Geophys. Res.* **75**(19), 3848–3861 (1970a)
- C.R. Chappell, K.K. Harris, G.W. Sharp, A study of the influence of magnetic activity on the location of the plasmopause as measured byOGO 5. *J. Geophys. Res.* **75**(1), 50–56 (1970b)
- A.J. Chen, J.M. Grebowsky, Plasma Tail Interpretations of Pronounced Detached Plasma Regions Measured by Ogo 5. *J. Geophys. Res.* **79**(25), 3851–3855 (1974)
- S.H. Chen, T.E. Moore, Magnetospheric convection and thermal ions in the dayside outer magnetosphere. *J. Geophys. Res.* **111**, A03215 (2006)
- A.J. Chen, R.A. Wolf, Effects on the plasmasphere of a time-varying convection electric field. *Planet. Space Sci.* **20**(4), 483–509 (1972)
- M.A. Clilverd, A.J. Smith, N.R. Thomson, The annual variation in quiet time plasmaspheric electron density, determined from whistler mode group delays. *Planet. Space Sci.* **39**(7), 1059–1067 (1991)
- M.A. Clilverd, F.W. Menk, G. Milinevski, B.R. Sandel, J. Goldstein, B.W. Reinisch, C.R. Wilford, M.C. Rose, N.R. Thomson, K.H. Yearby, G.J. Bailey, I.R. Mann, D.L. Carpenter, In-situ and ground-based intercalibration measurements of plasma density at $L = 2.5$. *J. Geophys. Res.* **108**(A10), 1365 (2003)
- M.A. Clilverd, N.P. Meredith, R.B. Horne, S.A. Glauert, R.R. Anderson, N.R. Thomson, F.W. Menk, B.R. Sandel, Longitudinal and seasonal variations in plasmaspheric electron density: Implications for electron precipitation. *J. Geophys. Res.* **112**, A11210 (2007)
- K.D. Cole, Formation of field-aligned irregularities in the magnetosphere. *J. Atmos. Terr. Phys.* **33**, 741–750 (1971)
- P.D. Craven, D.L. Gallagher, R.H. Comfort, Relative concentration of He^+ in the inner magnetosphere as observed by the DE 1 retarding ions mass spectrometer. *J. Geophys. Res.* **102**(A2), 2279–2289 (1997)
- I. Dandouras, Detection of plasmaspheric wind by analysis of ion measurements obtained onboard the Cluster spacecraft. *Geophys. Res. Abstr.* **10**, 5360 (2008)
- I. Dandouras, V. Pierrard, J. Goldstein, C. Vallat, G.K. Parks, H. R  me, C. Gouillart, F. Sevestre, M. McCarthy, L.M. Kistler, B. Klecker, A. Korth, M.B. Bavassano-Cattaneo, P. Escoubet, A. Masson, Multipoint observations of ionic structures in the plasmasphere by CLUSTER-CIS and comparisons with IMAGE-EUV observations and with model simulations, in *Inner Magnetosphere Interactions: New Perspectives from Imaging*, ed. by J. Burch, M. Schulz, H. Spence. Geophysical Monograph Series, vol. 159 (American Geophysical Union, Washington, 2005), pp. 23–53
- F. Darrouzet, Etude de la magn  tosph  re terrestre par l’analyse multipoint des donn  es de la mission CLUSTER. Contributions    la caract  risation des fronti  res et de la magn  tosph  re interne. PhD thesis, University of Orl  ans, France, 2006
- F. Darrouzet, P.M.E. Décr  au, J. De Keyser, A. Masson, D.L. Gallagher, O. Santol  k, B.R. Sandel, J.G. Trotignon, J.L. Rauch, E. Le Guirri  c, P. Canu, F. Sedgemore, M. Andr  , J.F. Lemaire, Density structures inside the plasmasphere: Cluster observations. *Ann. Geophys.* **22**(7), 2577–2585 (2004)
- F. Darrouzet, J. De Keyser, P.M.E. Décr  au, D.L. Gallagher, V. Pierrard, J.F. Lemaire, B.R. Sandel, I. Dandouras, H. Matsui, M. Dunlop, J. Cabrera, A. Masson, P. Canu, J.G. Trotignon, J.L. Rauch, M. Andr  , Analysis of plasmaspheric plumes: CLUSTER and IMAGE observations. *Ann. Geophys.* **24**(6), 1737–1758 (2006a)
- F. Darrouzet, J. De Keyser, P.M.E. Décr  au, J.F. Lemaire, M.W. Dunlop, Spatial gradients in the plasmasphere from Cluster. *Geophys. Res. Lett.* **33**, L08105 (2006b)
- F. Darrouzet, J. De Keyser, P.M.E. Décr  au, F. El Lemdani-Mazouz, X. Valli  res, Statistical analysis of plasmaspheric plumes with CLUSTER/WHISPER observations. *Ann. Geophys.* **26**(8), 2403–2417 (2008)
- J. De Keyser, F. Darrouzet, M.W. Dunlop, P.M.E. Décr  au, Least-squares gradient calculation from multipoint observations of scalar and vector fields: Methodology and applications with cluster in the plasmasphere. *Ann. Geophys.* **25**(4), 971–987 (2007)
- J. De Keyser, D.L. Carpenter, F. Darrouzet, D.L. Gallagher, J. Tu, CLUSTER and IMAGE: New ways to study the Earth’s plasmasphere. *Space Sci. Rev.* (2008, this issue)

- P.M.E. Décr  au, D. Carpenter, C.R. Chappell, R.H. Comfort, J. Green, R.C. Olsen, J.H. Waite Jr., Latitudinal plasma distribution in the dusk plasmaspheric bulge: Refilling phase and quasi-equilibrium state. *J. Geophys. Res.* **91**(A6), 6929–6943 (1986)
- P.M.E. Décr  au, P. Fergeau, V. Krasnosels'kikh, M. L  v  que, Ph. Martin, O. Randriamboarison, F.X. Sen  , J.G. Trotignon, P. Canu, P.B. M  gensen, Whisper Investigators, WHISPER, a resonance sounder and wave analyser: Performances and perspectives for the Cluster mission. *Space Sci. Rev.* **79**(1–2), 157–193 (1997)
- P.M.E. Décr  au, P. Fergeau, V. Krasnosels'kikh, E. Le Guirri  c, M. L  v  que, P. Martin, O. Randriamboarison, J.L. Rauch, F.X. Sen  , H.C. S  ran, J.G. Trotignon, P. Canu, N. Cornilleau, H. de F  raudy, H. Alleyne, K. Yearby, P.B. M  gensen, G. Gustafsson, M. Andr  , D.A. Gurnett, F. Darrouzet, J. Lemaire, C.C. Harvey, P. Travnicek, Whisper experimenters, Early results from the Whisper instrument on Cluster: an overview. *Ann. Geophys.* **19**(10–12), 1241–1258 (2001)
- P.M.E. Décr  au, C. Ducoin, G. Le Rouzic, O. Randriamboarison, J.L. Rauch, X. Trotignon, J.G. Valli  res, P. Canu, F. Darrouzet, M.P. Gough, A.M. Buckley, T.D. Carozzi, Observation of continuum radiations from the CLUSTER fleet: First results from direction finding. *Ann. Geophys.* **22**(7), 2607–2624 (2004)
- P.M.E. Décr  au, E. Le Guirri  c, J.L. Rauch, J.G. Trotignon, P. Canu, F. Darrouzet, J. Lemaire, A. Masson, F. Sedgemore, M. Andr  , Density irregularities in the plasmasphere boundary layer: Cluster observations in the dusk sector. *Adv. Space Res.* **36**(10), 1964–1969 (2005)
- Z.C. Dent, I.R. Mann, F.W. Menk, J. Goldstein, C.R. Wilford, M.A. Clilverd, L.G. Ozeke, A coordinated ground-based and IMAGE satellite study of quiet-time plasmaspheric density profiles. *Geophys. Res. Lett.* **30**(12), 1600 (2003)
- R.E. Denton, Magneto-seismology using spacecraft observations, in *Magnetospheric ULF Waves: Synthesis and New Directions*, ed. by K. Takahashi, P.J. Chi, R.E. Denton, R.L. Lysak. Geophysical Monograph Series, vol. 169 (American Geophysical Union, Washington, 2006), pp. 307–317
- R.E. Denton, P. Décr  au, M.J. Engebretson, F. Darrouzet, J.L. Posch, C. Mouikis, L.M. Kistler, C.A. Cattell, K. Takahashi, S. Sch  fer, J. Goldstein, Field line distribution of density at $L = 4.8$ inferred from observations by CLUSTER. *Ann. Geophys.* (2008, submitted)
- F. El-Lemdani Mazouz, J.L. Rauch, P.M.E. Décr  au, J.G. Trotignon, X. Valli  res, F. Darrouzet, P. Canu, X. Suraud, Wave emissions at half electron gyroharmonics in the equatorial plasmasphere region: CLUSTER observations and statistics. *Adv. Space Res.* (2008, in press)
- R.C. Elphic, L.A. Weiss, M.F. Thomsen, D.J. McComas, M.B. Moldwin, Evolution of plasmaspheric ions at geosynchronous orbit during times of high geomagnetic activity. *Geophys. Res. Lett.* **23**(16), 2189–2192 (1996)
- C.P. Escoubet, C.T. Russell, R. Schmidt (eds.), *The Cluster and Phoenix Missions* (Kluwer Academic, Dordrecht, 1997)
- J.C. Foster, P.J. Erickson, A.J. Coster, J. Goldstein, F.J. Rich, Ionospheric signatures of plasmaspheric tails. *Geophys. Res. Lett.* **29**(13), 1623 (2002)
- J.C. Foster, A.J. Coster, P.J. Erickson, W. Rideout, F.J. Rich, T.J. Immel, B.R. Sandel, Redistribution of the stormtime ionosphere and the formation of the plasmaspheric bulge, in *Inner Magnetosphere Interactions: New Perspectives from Imaging*, ed. by J.L. Burch, M. Schulz, H. Spence. Geophysical Monograph Series, vol. 159 (American Geophysical Union, Washington, 2005), pp. 277–289
- B.J. Fraser, J.L. Horwitz, J.A. Slavin, Z.C. Dent, I.R. Mann, Heavy ion mass loading of the geomagnetic field near the plasmopause and ULF wave implications. *Geophys. Res. Lett.* **32**, L04102 (2005)
- S.F. Fung, R.F. Benson, D.L. Carpenter, B.W. Reinisch, D.L. Gallagher, Investigations of irregularities in remote plasma regions by radio sounding: applications of the radio plasma imager on image. *Space Sci. Rev.* **91**(1–2), 391–419 (2000)
- D.L. Gallagher, M.L. Adrian, Two-dimensional drift velocities from the IMAGE EUV plasmaspheric imager. *J. Atmos. Sol.-Terr. Phys.* **69**(3), 341–350 (2007)
- D.L. Gallagher, P.D. Craven, R.H. Confort, Global core plasma model. *J. Geophys. Res.* **105**(A8), 18819–18833 (2000)
- D.L. Gallagher, M.L. Adrian, M.W. Liemohn, Origin and evolution of deep plasmaspheric notches. *J. Geophys. Res.* **110**, A09201 (2005)
- Y.I. Galperin, V.S. Soloviev, K. Torkar, J.C. Foster, M.V. Veselov, Predicting plasmaspheric radial density profiles. *J. Geophys. Res.* **102**(A2), 2079–2091 (1997)
- D.A. Galvan, M.B. Moldwin, B.R. Sandel, Diurnal variation in plasmaspheric He^+ inferred from extreme ultraviolet images. *J. Geophys. Res.* **113**, A09216 (2008)
- L.N. Garcia, S.F. Fung, J.L. Green, S.A. Boardsen, B.R. Sandel, B.W. Reinisch, Observations of the latitudinal structure of plasmaspheric convection plumes by IMAGE-RPI and EUV. *J. Geophys. Res.* **108**(A8), 1321 (2003)
- J. Goldstein, Plasmasphere response: Tutorial and review of recent imaging results. *Space Sci. Rev.* **124**(1–4), 203–216 (2006)

- J. Goldstein, B.R. Sandel, The global pattern of evolution of plasmaspheric drainage plumes, in *Inner Magnetosphere Interactions: New Perspectives from Imaging*, ed. by J.L. Burch, M. Schulz, H. Spence. Geophysical Monograph Series, vol. 159 (American Geophysical Union, Washington, 2005), pp. 1–22
- J. Goldstein, R.W. Spiro, P.H. Reiff, R.A. Wolf, B.R. Sandel, J.W. Freeman, R.L. Lambour, IMF-driven overshielding electric field and the origin of the plasmaspheric shoulder of May 24, 2000. *Geophys. Res. Lett.* **29**(16), 1819 (2002)
- J. Goldstein, B.R. Sandel, W.T. Forrester, P.H. Reiff, IMF-driven plasmasphere erosion of 10 July 2000. *Geophys. Res. Lett.* **30**(3), 1146 (2003a)
- J. Goldstein, M. Spasojević, P.H. Reiff, B.R. Sandel, W.T. Forrester, D.L. Gallagher, B.W. Reinisch, Identifying the plasmopause in IMAGE EUV data using IMAGE RPI in situ steep density gradients. *J. Geophys. Res.* **108**(A4), 1147 (2003b)
- J. Goldstein, B.R. Sandel, M.R. Hairston, S.B. Mende, Plasmopause undulation of 17 April 2002. *Geophys. Res. Lett.* **31**, L15801 (2004a)
- J. Goldstein, B.R. Sandel, M.F. Thomsen, M. Spasojević, P.H. Reiff, Simultaneous remote sensing and in situ observations of plasmaspheric drainage plumes. *J. Geophys. Res.* **109**, A03202 (2004b)
- J. Goldstein, J.L. Burch, B.R. Sandel, S.B. Mende, P.C. Brandt, M.R. Hairston, Coupled response of the inner magnetosphere and ionosphere on 17 April 2002. *J. Geophys. Res.* **110**, A03205 (2005a)
- J. Goldstein, B.R. Sandel, W.T. Forrester, M.F. Thomsen, M.R. Hairston, Global plasmasphere evolution 22–23 April 2001. *J. Geophys. Res.* **110**, A12218 (2005b)
- J. Goldstein, B.R. Sandel, H.U. Frey, S.B. Mende, Multiple plasmopause undulations observed by the IMAGE satellite on 20 March 2001. *J. Atmos. Sol.-Terr. Phys.* **69**(3), 322–333 (2007)
- J.M. Grebowsky, Model study of plasmopause motion. *J. Geophys. Res.* **75**(22), 4329–4333 (1970)
- J.L. Green, S. Boardsen, S.F. Fung, H. Matsumoto, K. Hashimoto, R.R. Anderson, B.R. Sandel, B.W. Reinisch, Association of kilometric continuum radiation with plasmaspheric structures. *J. Geophys. Res.* **109**, A03203 (2004)
- R.S. Grew, F.W. Menk, M.A. Chilver, B.R. Sandel, Mass and electron densities in the inner magnetosphere during a prolonged disturbed interval. *Geophys. Res. Lett.* **34**, L02108 (2007)
- K.I. Gringauz, V.V. Bezrukikh, V.D. Ozerov, R.E. Rybechinsky, The study of the interplanetary ionized gas, high-energy electrons and corpuscular radiation of the Sun, employing three-electrode charged particle traps on the second Soviet space rocket. *Sov. Phys. Dokl.* **5**, 361–364 (1960). Published again in (1962) in *Planet. Space Sci.*, **9**, 103–107
- G. Gustafsson, M. André, T. Carozzi, A.I. Eriksson, C.G. Fälthammar, R. Grard, G. Holmgren, J.A. Holtet, N. Ivchenko, T. Karlsson, Y. Khotyaintsev, S. Klimov, H. Laakso, P.A. Lindqvist, B. Lybekk, G. Marklund, F. Mozer, K. Mursula, A. Pedersen, B. Popielawska, S. Savin, K. Stasiewicz, P. Tanskanen, A. Vaivads, J.E. Wahlund, First results of electric field and density observations by Cluster EFW based on initial months of observations. *Ann. Geophys.* **19**(10–12), 1219–1240 (2001)
- A. Hasegawa, Drift-wave instability at the plasmopause. *J. Geophys. Res.* **76**(22), 5361–5364 (1971)
- M. Hayakawa, Association of whistlers with lightning discharges on the Earth and on Jupiter. *J. Atmos. Terr. Phys.* **57**(5), 525–535 (1995)
- R.A. Helliwell, *Whistlers and Associated Ionospheric Phenomena* (Stanford University Press, Stanford, 1965)
- T.W. Hill, Inertial limit on corotation. *J. Geophys. Res.* **84**(A11), 6554–6558 (1979)
- J.L. Horwitz, R.H. Comfort, C.R. Chappell, A statistical characterization of plasmasphere density structure and boundary locations. *J. Geophys. Res.* **95**(A6), 7937–7947 (1990)
- M.C. Kelley, *The Earth's Ionosphere: Plasma Physics and Electrodynamics* (Academic Press, San Diego, 1989)
- K.H. Kim, J. Goldstein, D. Berube, Plasmaspheric drainage plume observed by the Polar satellite in the prenoon sector and the IMAGE satellite during the magnetic storm of 11 April 2001. *J. Geophys. Res.* **112**, A06237 (2007)
- H.C. Koons, Observations of large-amplitude, Whistler mode wave ducts in the outer plasmasphere. *J. Geophys. Res.* **94**(A11), 15393–15397 (1989)
- J. Krall, J.D. Huba, J.A. Fedder, Simulation of H^+ and He^+ dynamics during plasmasphere refilling. *Eos Trans. AGU* **88**(52), SM21A–0303 (2007)
- R.L. Lambour, L.A. Weiss, R.C. Elphic, M.F. Thomsen, Global modeling of the plasmasphere following storm sudden commencements. *J. Geophys. Res.* **102**(A11), 24351–24368 (1997)
- M.J. LeDocq, D.A. Gurnett, R.R. Anderson, Electron Number Density Fluctuations near the Plasmopause Observed by the CRRES Spacecraft. *J. Geophys. Res.* **99**(A12), 23661–23671 (1994)
- J.F. Lemaire, The “Roche-limit” of ionospheric plasma and the formation of the plasmopause. *Planet. Space Sci.* **22**(5), 757–766 (1974)
- J.F. Lemaire, The mechanisms of formation of the plasmopause. *Ann. Geophys.* **31**, 175–190 (1975)

- J.F. Lemaire, *Frontiers of the Plasmasphere*. Aeronomica Acta, vol. 298. (Editions Cabay, Louvain-la-Neuve, 1985). ISBN 2-87077-310-2
- J.F. Lemaire, Plasma distribution models in a rotating magnetic dipole and refilling plasmaspheric flux tubes. *Phys. Fluids B* **1**(7), 1519–1525 (1989)
- J.F. Lemaire, The formation plasmaspheric tails. *Phys. Chem. Earth (C)* **25**, 9–17 (2000)
- J.F. Lemaire, The formation of the light-ion-trough and peeling off the plasmasphere. *J. Atmos. Sol.-Terr. Phys.* **63**(11), 1285–1291 (2001)
- J.F. Lemaire, K.I. Gringauz, *The Earth's Plasmasphere* (Cambridge University Press, New York, 1998)
- J.F. Lemaire, R.W. Schunk, Plasmaspheric wind. *J. Atmos. Terr. Phys.* **54**(3–4), 467–477 (1992)
- J.F. Lemaire, R.W. Schunk, Plasmaspheric convection with non-closed streamlines. *J. Atmos. Terr. Phys.* **56**(12), 1629–1633 (1994)
- B.T. Loftus, T.E. Van Zandt, W. Calvert, Observations of conjugate ducting by the fixed-frequency topside-sounder satellite. *Ann. Geophys.* **22**(4), 530–537 (1966)
- A. Masson, O. Santolík, D.L. Carpenter, F. Darrouzet, P.M.E. Décréau, F. El-Lemdani Mazouz, J.L. Green, S. Grimald, F. El-Lemdani Mazouz, M.B. Moldwin, F. Němec, Advances in Plasmaspheric Wave Research with CLUSTER and IMAGE Observations. *Space Sci. Rev.* (2008). This issue
- C.E. McIlwain, Coordinates for Mapping the Distribution of Magnetically Trapped Particles. *J. Geophys. Res.* **66**(11), 3681–3691 (1961)
- E.V. Mishin, W.J. Burke, Stormtime coupling of the ring current, plasmasphere, and topside ionosphere: Electromagnetic and plasma disturbances. *J. Geophys. Res.* **110**, A07209 (2005)
- M.B. Moldwin, M.F. Thomsen, S.J. Bame, D.J. McComas, K.R. Moore, An examination of the structure and dynamics of the outer plasmasphere using multiple geosynchronous satellites. *J. Geophys. Res.* **99**(A6), 11475–11481 (1994)
- M.B. Moldwin, M.F. Thomsen, S.J. Bame, D. McComas, G.D. Reeves, The fine-scale structure of the outer plasmasphere. *J. Geophys. Res.* **100**(A5), 8021–8029 (1995)
- M.B. Moldwin, J. Howard, J. Sanny, J.D. Bocchicchio, H.K. Rassoul, R.R. Anderson, Plasmaspheric plumes: CRRES observations of enhanced density beyond the plasmopause. *J. Geophys. Res.* **109**, A05202 (2004)
- D.B. Muldrew, Radio propagation along magnetic field-aligned sheets of ionization observed by the Alouette topside sounder. *J. Geophys. Res.* **68**(19), 5355–5370 (1963)
- G. Murakami, M. Hirai, I. Yoshikawa, The plasmopause response to the southward turning of the IMF derived from sequential EUV images. *J. Geophys. Res.* **112**, A06217 (2007)
- A. Nishida, Formation of plasmopause, or magnetospheric plasma knee, by the combined action of magnetospheric convection and plasma escape from the tail. *J. Geophys. Res.* **71**(23), 5669–5679 (1966)
- P.A. Nsumei, X. Huang, B.W. Reinisch, P. Song, V.M. Vasyliunas, J.L. Green, S.F. Fung, R.F. Benson, D.L. Gallagher, Electron density distribution over the northern polar region deduced from IMAGE/radio plasma imager sounding. *J. Geophys. Res.* **108**(A2), 1078 (2003)
- P.A. Nsumei, B.W. Reinisch, P. Song, J. Tu, X. Huang, Polar cap electron density distribution from IMAGE radio plasma imager measurements: Empirical model with the effects of solar illumination and geomagnetic activity. *J. Geophys. Res.* **113**, A01217 (2008)
- D.M. Ober, J.L. Horwitz, M.F. Thomsen, R.C. Elphic, D.J. McComas, R.D. Belian, M.B. Moldwin, Premidnight plasmaspheric “plumes”. *J. Geophys. Res.* **102**(A6), 11325–11334 (1997)
- C.G. Park, Whistler observations of the interchange of ionization between the ionosphere and the protonosphere. *J. Geophys. Res.* **75**(22), 4249–4260 (1970)
- C.G. Park, D.L. Carpenter, Whistler evidence of large-scale electron-density irregularities in the plasmasphere. *J. Geophys. Res.* **75**(19), 3825–3836 (1970)
- C.G. Park, R.A. Helliwell, The formation by electric fields of field-aligned irregularities in the magnetosphere. *Radio Sci.* **6**(6), 299–304 (1971)
- G. Paschmann, J.M. Quinn, R.B. Torbert, H. Vaith, C.E. McIlwain, G. Haerendel, O.H. Bauer, T. Bauer, W. Baumjohann, W. Fillius, M. Förster, S. Frey, E. Georgescu, S.S. Kerr, C.A. Kletzing, H. Matsui, P. Puhl-Quinn, E.C. Whipple, The electron drift instrument on cluster: Overview of first results. *Ann. Geophys.* **19**(10–12), 1273–1288 (2001)
- V. Pierrard, J. Cabrera, Comparisons between EUV/IMAGE observations and numerical simulations of the plasmopause formation. *Ann. Geophys.* **23**(7), 2635–2646 (2005)
- V. Pierrard, J.F. Lemaire, Development of shoulders and plumes in the frame of the interchange instability mechanism for plasmopause formation. *Geophys. Res. Lett.* **31**, L05809 (2004)
- V. Pierrard, J. Goldstein, N. André, V.K. Jordanova, G.A. Kotova, J.F. Lemaire, M.W. Liemohn, H. Matsui, Physics-based models of the plasmasphere. *Space Sci. Rev.* (2008, this issue)
- I.G. Platt, P.L. Dyson, MF and HF propagation characteristics of ionospheric ducts. *J. Atmos. Terr. Phys.* **51**, 759–774 (1989)

- B.W. Reinisch, D.M. Haines, K. Bibl, G. Cheney, I.A. Galkin, X. Huang, S.H. Myers, G.S. Sales, R.F. Benson, S.F. Fung, J.L. Green, S. Boardsen, W.W.L. Taylor, J.L. Bougeret, R. Manning, N. Meyer-Vernet, M. Moncuquet, D.L. Carpenter, D.L. Gallagher, P. Reiff, The Radio Plasma Imager Investigation on the IMAGE Spacecraft. *Space Sci. Rev.* **91**(1–2), 319–359 (2000)
- B.W. Reinisch, X. Huang, P. Song, G.S. Sales, S.F. Fung, J.L. Green, D.L. Gallagher, V.M. Vasyliunas, Plasma density distribution along the magnetospheric field: RPI observations from IMAGE. *Geophys. Res. Lett.* **28**(24), 4521–4524 (2001)
- B.W. Reinisch, X. Huang, P. Song, J.L. Green, S.F. Fung, V.M. Vasyliunas, D.L. Gallagher, B.R. Sandel, Plasmaspheric mass loss and refilling as a result of a magnetic storm. *J. Geophys. Res.* **109**, A01202 (2004)
- H. Rème, C. Aoustin, J.M. Bosqued, I. Dandouras, B. Lavraud, J.A. Sauvaud, A. Barthe, J. Bouyssou, Th. Camus, O. Coeur-Joly, A. Cros, J. Cuvido, F. Ducay, Y. Garbarowitz, J.L. Médale, E. Penou, H. Perrier, D. Romefort, J. Rouzaud, C. Vallat, D. Alcaydé, C. Jacquey, C. Mazelle, C. d’Uston, E. Möbius, L.M. Kistler, K. Crocker, M. Granoff, C. Mouikis, M. Popecki, M. Vosbury, B. Klecker, D. Hovestadt, H. Kucharek, E. Kuenneth, G. Paschmann, M. Scholer, N. Scokoppe, E. Seidenschwang, C.W. Carlson, D.W. Curtis, C. Ingraham, R.P. Lin, J.P. McFadden, G.K. Parks, T. Phan, V. Formisano, E. Amata, M.B. Bavassano-Cattaneo, P. Baldetti, R. Bruno, G. Chionchio, A. Di Lellis, M.F. Marcucci, G. Palloccchia, A. Korth, P.W. Daly, B. Graeve, H. Rosenbauer, V. Vasyliunas, M. McCarthy, M. Wilber, L. Eliasson, R. Lundin, S. Olsen, E.G. Shelley, S. Fuselier, A.G. Ghielmetti, W. Lennartsson, C.P. Escoubet, H. Balsiger, R. Friedel, J.-B. Cao, R.A. Kovrazhkin, I. Papamastorakis, R. Pellat, J. Scudder, B. Sonnerup, First multi-spacecraft ion measurements in and near the Earth’s magnetosphere with the identical Cluster Ion Spectrometry (CIS) experiment. *Ann. Geophys.* **19**(10–12), 1303–1354 (2001)
- M.A. Reynolds, G. Ganguli, Y.-J. Su, M.F. Thomsen, The local-time variation of the quiet plasmasphere: Geosynchronous observations and kinetic theory. *Ann. Geophys.* **21**(11), 2147–2154 (2003)
- A.D. Richmond, Self-induced motions of thermal plasma in the magnetosphere and the stability of the plasmopause. *Radio Sci.* **8**(11), 1019–1027 (1973)
- B.R. Sandel, M.H. Denton, Global view of refilling of the plasmasphere. *Geophys. Res. Lett.* **34**, L17102 (2007)
- B.R. Sandel, A.L. Broadfoot, C.C. Curtis, R.A. King, T.C. Stone, R.H. Hill, J. Chen, O.H.W. Siegmund, R. Raffanti, D.D. Allred, R.S. Turley, D.L. Gallagher, The extreme ultraviolet imager investigation for the IMAGE mission. *Space Sci. Rev.* **91**(1–2), 197–242 (2000)
- B.R. Sandel, R.A. King, W.T. Forrester, D.L. Gallagher, A.L. Broadfoot, C.C. Curtis, Initial results from the IMAGE extreme ultraviolet imager. *Geophys. Res. Lett.* **28**(8), 1439–1442 (2001)
- B.R. Sandel, J. Goldstein, D.L. Gallagher, M. Spasojević, Extreme ultraviolet imager observations of the structure and dynamics of the plasmasphere. *Space Sci. Rev.* **109**(1–4), 25–46 (2003)
- N. Singh, Refilling of a plasmaspheric flux tube: microscopic plasma processes, in *Modeling Magnetospheric Plasma*, ed. by T.E. Moore, J.H. Waite. Geophysical Monograph Series, vol. 44 (American Geophysical Union, Washington, 1988), pp. 87–99
- N. Singh, J.L. Horwitz, Plasmaspheric refilling: Recent observations and modelling. *J. Geophys. Res.* **97**(A2), 1049–1079 (1992)
- R.L. Smith, Propagation characteristics of whistlers trapped in field-aligned columns of enhanced ionization. *J. Geophys. Res.* **66**(11), 3699–3707 (1961)
- M. Spasojević, J. Goldstein, D.L. Carpenter, U.S. Inan, B.R. Sandel, M.B. Moldwin, B.W. Reinisch, Global response of the plasmasphere to a geomagnetic disturbance. *J. Geophys. Res.* **108**(A9), 1340 (2003)
- M. Spasojević, H.U. Frey, M.F. Thomsen, S.A. Fuselier, S.P. Gary, B.R. Sandel, U.S. Inan, The link between a detached subauroral proton arc and a plasmaspheric plume. *Geophys. Res. Lett.* **31**, L04803 (2004)
- R.W. Spiro, M. Harel, R.A. Wolf, P.H. Reiff, Quantitative simulation of a magnetospheric substorm. 3. Plasmaspheric electric fields and evolution of the plasmopause. *J. Geophys. Res.* **86**(A4), 2261–2272 (1981)
- L.R.O. Storey, An investigation of whistling atmospherics. *Philos. Trans. R. Soc. (Lond.)* **246A**, 113–141 (1953)
- H.J. Strangeways, M.J. Rycroft, Trapping of whistler-waves through the side of ducts. *J. Atmos. Terr. Phys.* **42**, 983–994 (1980)
- Y. Su, M.F. Thomsen, J.E. Borovsky, J.C. Foster, A linkage between polar patches and plasmaspheric drainage plumes. *Geophys. Res. Lett.* **28**(1), 111–113 (2001)
- D. Summers, B. Ni, N.P. Meredith, R.B. Horne, R.M. Thorne, M.B. Moldwin, R.R. Anderson, Electron scattering by whistler-mode ELF hiss in plasmaspheric plumes, *J. Geophys. Res.* **113**, A04219 (2008)
- G. Tarcasai, Ionosphere-plasmasphere electron fluxes at middle latitudes obtained from whistlers. *Adv. Space Res.* **5**(4), 155–158 (1985)
- H.A. Taylor Jr., J.M. Grebowsky, W.J. Walsh, Structured variations of the plasmopause: Evidence of a corotating plasma tail. *J. Geophys. Res.* **76**(28), 6806–6814 (1971)
- R.J. Thomson, The formation and lifetime of whistler ducts. *Planet. Space Sci.* **26**(5), 423–430 (1978)

- J.G. Trotignon, P.M.E. Décréau, J.L. Rauch, E. Le Guirriec, P. Canu, F. Darrouzet, The whisper relaxation sounder onboard cluster: A powerful tool for space plasma diagnosis around the Earth. *Cosm. Res.* **41**(4), 369–372 (2003)
- N.A. Tsyganenko, D.P. Stern, Modeling the global magnetic field of the large-scale Birkeland current systems. *J. Geophys. Res.* **101**(A12), 27187–27198 (1996)
- J. Tu, P. Song, B.W. Reinisch, X. Huang, J.L. Green, H.U. Frey, P.H. Reiff, Electron density images of the middle- and high-latitude magnetosphere in response to the solar wind. *J. Geophys. Res.* **110**, A12210 (2005)
- J. Tu, P. Song, B.W. Reinisch, J.L. Green, X. Huang, Empirical specification of field-aligned plasma density profiles for plasmasphere refilling. *J. Geophys. Res.* **111**, A06216 (2006)
- J. Tu, P. Song, B.W. Reinisch, J.L. Green, Smooth electron density transition from plasmasphere to the sub-auroral region. *J. Geophys. Res.* **112**, A05227 (2007)
- C.L. Waters, F.W. Menk, M.F. Thomsen, C. Foster, F.R. Fenrich, Remote sensing of the magnetosphere using ground-based observations of ULF waves, in *Magnetospheric ULF Waves: Synthesis and New Directions*, ed. by K. Takahashi, P.J. Chi, R.E. Denton, R.L. Lysak. Geophysical Monograph Series, vol. 169 (American Geophysical Union, Washington, 2006), pp. 319–340
- G.R. Wilson, J.L. Horwitz, J. Lin, A semikinetic model for early stage plasmasphere refilling. 1. Effects of coulomb collisions. *J. Geophys. Res.* **97**(A2), 1109–1119 (1992)
- E. Yizengaw, M.B. Moldwin, The altitude extension of the mid-latitude trough and its correlation with plasmopause position. *Geophys. Res. Lett.* **32**, L09105 (2005)
- E. Yizengaw, H. Wei, M.B. Moldwin, D. Galvan, L. Mandrake, A. Mannucci, X. Pi, The correlation between mid-latitude trough and the plasmopause. *Geophys. Res. Lett.* **32**, L10102 (2005)
- E. Yizengaw, M.B. Moldwin, D.A. Galvan, Ionospheric signatures of a plasmaspheric plume over Europe. *Geophys. Res. Lett.* **33**, L17103 (2006)
- E. Yizengaw, J. Dewar, J. MacNeil, M.B. Moldwin, D. Galvan, J. Sanny, D. Berube, B. Sandel, The occurrence of ionospheric signatures of plasmaspheric plumes over different longitudinal sectors. *J. Geophys. Res.* **113**, A08318 (2008)
- I. Yoshikawa, A. Yamazaki, K. Yamashita, Y. Takizawa, M. Nakamura, Which is a significant contributor for outside of the plasmopause, an ionospheric filling or leakage of plasmaspheric materials?: Comparison of He II (304 Å) images. *J. Geophys. Res.* **108**(A2), 1080 (2003)

Electric Fields and Magnetic Fields in the Plasmasphere: A Perspective from CLUSTER and IMAGE

Hiroshi Matsui · John C. Foster · Donald L. Carpenter · Iannis Dandouras ·
Fabien Darrouzet · Johan De Keyser · Dennis L. Gallagher · Jerry Goldstein ·
Pamela A. Puhl-Quinn · Claire Vallat

Originally published in the journal *Space Science Reviews*, Volume 145, Nos 1–2, 107–135.
DOI: [10.1007/s11214-008-9471-8](https://doi.org/10.1007/s11214-008-9471-8) © Springer Science+Business Media B.V. 2009

Abstract The electric field and magnetic field are basic quantities in the plasmasphere measured since the 1960s. In this review, we first recall conventional wisdom and remaining problems from ground-based whistler measurements. Then we show scientific results from CLUSTER and IMAGE, which are specifically made possible by newly introduced features on these spacecraft, as follows. 1. In situ electric field measurements using artificial elec-

H. Matsui (✉) · P.A. Puhl-Quinn
Space Science Center, Morse Hall, University of New Hampshire (UNH), 39 College Road, Durham,
NH 03824, USA
e-mail: hiroshi.matsui@unh.edu

P.A. Puhl-Quinn
e-mail: pamela.puhlquinn@unh.edu

J.C. Foster
Massachusetts Institute of Technology (MIT), Westford, MA, USA
e-mail: jfoster@haystack.mit.edu

D.L. Carpenter
Space Telecommunications and Radioscience Laboratory (STAR), Stanford, CA, USA
e-mail: dlc@nova.stanford.edu

I. Dandouras
Centre d'Etude Spatiale des Rayonnements (CESR), Toulouse, France
e-mail: Iannis.Dandouras@cesr.fr

F. Darrouzet · J. De Keyser
Belgian Institute for Space Aeronomy (BIRA-IASB), Brussels, Belgium

F. Darrouzet
e-mail: Fabien.Darrouzet@oma.be

J. De Keyser
e-mail: Johan.DeKeyser@oma.be

D.L. Gallagher
NASA Marshall Space Flight Center (MSFC), Huntsville, AL, USA
e-mail: dennis.l.gallagher@nasa.gov

tron beams are successfully used to identify electric fields originating from various sources. 2. Global electric fields are derived from sequences of plasmaspheric images, revealing how the inner magnetospheric electric field responds to the southward interplanetary magnetic fields and storms/substorms. 3. Understanding of sub-auroral polarization stream (SAPS) or sub-auroral ion drifts (SAID) are advanced through analysis of a combination of magnetospheric and ionospheric measurements from CLUSTER, IMAGE, and DMSP. 4. Data from multiple spacecraft have been used to estimate magnetic gradients for the first time.

Keywords Plasmasphere · Electric Field · Magnetic Field · CLUSTER · IMAGE

1 Introduction

The electric field and magnetic field are two basic physical quantities in the plasmasphere. The electric field, which may contain both potential and induced components, is related both to large scale motions (usually known as convection) of thermal plasma near the Earth and to the magnetic field through the equation $\mathbf{E} = -\mathbf{V} \times \mathbf{B}$, where $\mathbf{E}$ is the electric field, $\mathbf{V}$ the convection velocity, and $\mathbf{B}$ the magnetic field. Convection is driven by dynamo processes acting in the outer magnetosphere and in the ionosphere. Because of the high mobility of plasma along the magnetic field, and hence the high electrical conductivity along the magnetic field, the motions of the plasma that occur as a result of the dynamo forces (or instabilities) are bulk motions involving tubes of ionization that are aligned with the magnetic field. A feature such as the plasmopause that arises as a result of either the dynamo forces or instabilities thus tends to form along a magnetic shell. These characteristics of electric fields and magnetic fields in the plasmasphere have previously been investigated using ground-based observations of whistler waves and in situ spacecraft (see Lemaire and Gringauz 1998). Recently, new observational capabilities by the CLUSTER and IMAGE spacecraft have provided fresh perspectives on how the plasmasphere is a part of the larger magnetospheric system. The combination of CLUSTER, IMAGE, and ground-based data together with modeling capabilities has provided invaluable complementary viewpoints. This introduction (Sect. 1) is organized into two parts as follows. First the early use of whistler measurements to derive electric fields (during both substorms and quiet periods) is reviewed. Second, the accomplishments of the more recent CLUSTER and IMAGE missions are summarized as a bridge to the rest of the review paper. Following the introduction are sections devoted to specific topics, including understanding gained from electric fields deduced from CLUSTER and IMAGE (Sects. 2 and 3), the modern picture of SAPS/SAID (Sect. 4), calculation of magnetic gradients by multiple CLUSTER spacecraft (Sect. 5). The paper concludes with a summary section that reviews CLUSTER and IMAGE observations in the context the early whistler measurements, and discusses outstanding scientific questions for future study.

1.1 Whistler Measurements to Derive Convection

In the early era of plasmaspheric exploration (the 1960s and 1970s), whistler mode signals provided a powerful means of measuring electric fields within the plasmasphere. Two prin-

J. Goldstein
Southwest Research Institute (SWRI), San Antonio, TX, USA
e-mail: jgoldstein@swri.edu

C. Vallat
European Space Agency (ESA), Villafranca, Spain
e-mail: Claire.Vallat@sciops.esa.int

cial approaches were used: (i) measurements of the dispersion properties of lightning generated whistlers, and (ii) phase and group path measurements of signals from transmitters.

1.1.1 The Whistler Method of Measuring Cross- L Plasma Drifts

In the early 1960s, it was realized that lightning-triggered whistlers propagate on discrete magnetic-field-aligned paths and that the frequency–time (f – t) properties of a given whistler can be used to estimate the whistler path radius, i.e., the radial coordinate of the equatorial crossing point of the particular whistler path (e.g., Smith 1961; Helliwell 1965, pp. 43–61). The data indicated that a whistler path can retain its identity as a discrete structure (presumably an irregularity representing a few percent density enhancement over the background (e.g., Smith 1961) over periods long compared to the interval between successive excitations by lightning (e.g., Carpenter 1966). Thus it became possible to detect the changes with time of a whistler path radius and therefore determine the cross- L velocity of the path (e.g., Carpenter and Stone 1967; Block and Carpenter 1974). Proceeding on the reasonable assumption that such a path remains an equipotential of the magnetospheric electric field over most of its length from hemisphere to hemisphere (e.g., Gonzales et al. 1980), the path's radial velocity was used as a measure of the bulk motion of the plasma surrounding the duct and hence as a measure of the associated east-west component of the magnetospheric electric field. Thanks to an abundance of whistler activity recorded in 1963 and 1965 near the 75°W meridian in Antarctica, such plasma flow measurements became possible at a time when the substorm phenomenon was first being explored in detail (e.g., Carpenter and Stone 1967; Carpenter et al. 1972).

Initial studies revealed that fast inward drifts in the outer plasmasphere near $L = 4$ began with the expansion phase of a substorm. The corresponding westward component of the electric field was inferred to peak in the range ~ 0.5 – 1 mV m^{-1} . In cases of temporally isolated substorms, the azimuthal component of the electric field was found to change direction, such that cross- L outward flow began as ground magnetometers showed an end to the substorm-associated field aligned currents (Carpenter and Seely 1976). The intensity and duration of the outward flow were such that the plasmasphere, although subject to distortions in shape imposed by the changes in flow direction, did not appear to change substantially in overall size. However, when substorm activity was prolonged, as in the case of several weak magnetic storms that were studied, the return outward flows were not observed and the global size of the plasmasphere, as seen from a single ground station, was found to shrink substantially (Carpenter et al. 1979).

Abundant Antarctic whistler activity on magnetically quiet days made possible tracking of whistler ducts over extended time periods. Figure 1 shows two case studies: (a) from Siple, Antarctica ($L \approx 4.2$) on 7 July 1973, and (b) from Eights, Antarctica ($L \approx 3.9$) on 13 June 1965 (Carpenter and Seely 1976). The figure is plotted in coordinates of L^{-2} versus time, so that the east-west electric field inferred from a series of data points is approximately proportional to the rate of change of observed L^{-2} with time, regardless of the absolute values of L . The data slopes were similar over paths distributed in L value, attesting to the large scale nature of the plasma motions involved. The most clearly identified features in Fig. 1 are pre-noon outward drifts and post-noon inward motions, which were interpreted as evidence of ionospheric dynamo effects (the SQ, solar-quiet-time, geomagnetic daily variation field, current system).

Figure 2 shows 30-minute averages of whistler-path radial drifts in the plasmasphere at $L \approx 4$ during periods of substorm activity (Carpenter et al. 1979). In spite of limitations imposed by the averaging methods used, several features stand out. There was a rather abrupt

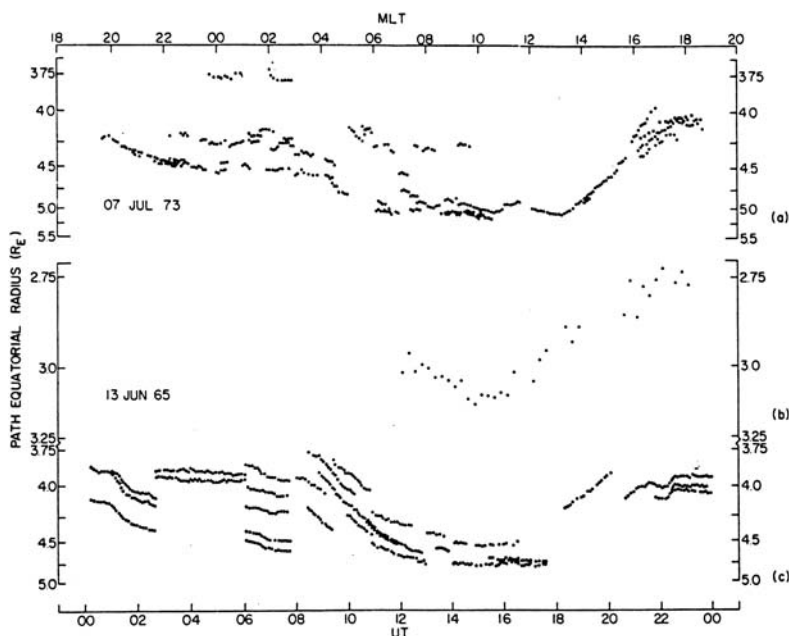
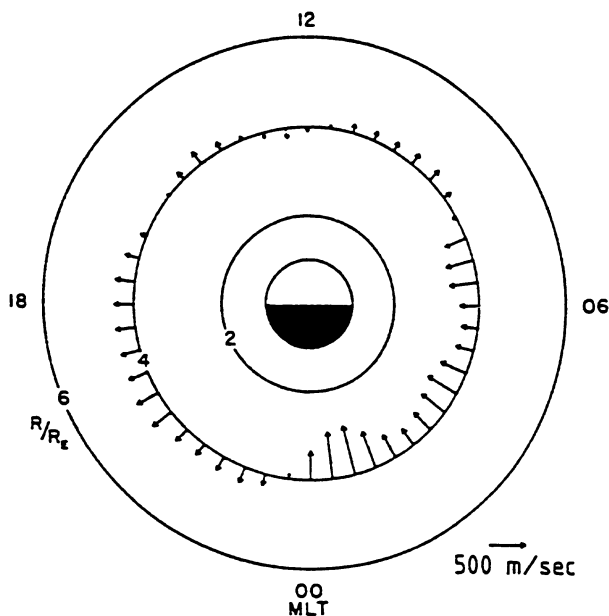


Fig. 1 Whistler path radii time series from two magnetically quiet 24 hour periods showing a strong morning outflow and post-noon inflow, effects that are attributed to an ionospheric dynamo process (the SQ, solar-quiet-time, geomagnetic daily variation field, current system). (Adapted from Carpenter and Seely 1976)

Fig. 2 Average westward electric field in the outer plasmasphere at $L = 4$ during periods of prolonged substorm activity, represented in terms of cross- L flow velocities in the equatorial plane. (Adapted from Carpenter et al. 1979)



transition near midnight from weak outward flow to fast inward flow that persisted into the dawn sector. Moderate outward drifts were observed in the pre-noon sector, followed near noon by weak flows and then later by outward drifts that increased in amplitude near dusk.

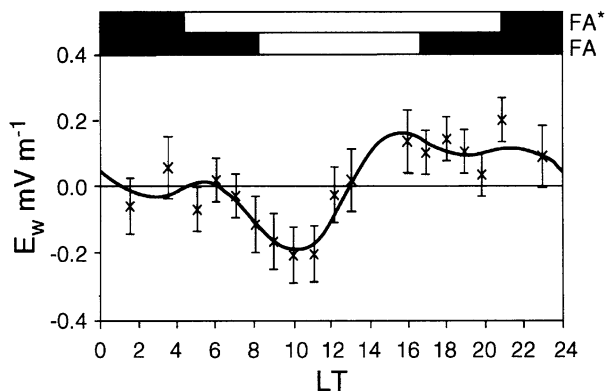
1.1.2 Whistler Estimates of the E_y Electric Field Component Near Dusk

Early whistler data did not show evidence of the type of dusk-side stagnation point in plasma flow envisioned in theoretical models that combined a uniform dawn–dusk convection field with a corotation field (Carpenter 1966, 1970). Instead, there were indications of decoupling of the main plasmasphere from the so-called bulge region of larger plasmasphere radius. That is, there was a fairly rapid spatial transition in the generally radial direction from a region dominated by the Earth's rotation to one strongly dominated by the convection electric field. This outer region (very possibly reflecting the effects of what is now called the SAPS electric field; see Sect. 4) regularly exhibited an abrupt westward edge, which was found by the corotating whistler station to be displaced to earlier (afternoon) or later (post-dusk) local times (LT) as magnetic activity increased or decreased, respectively. Using $L \approx 4.5$ as typical of the outer region, the electric field in the dawn dusk direction (E_y component) was estimated to be $\sim 1\text{--}4\text{ mV m}^{-1}$ during substorms (as seen from the rotating Earth), about 4 times larger than corresponding (essentially westward) values observed in the post-midnight sector using the whistler drift method (Carpenter 1970).

1.1.3 Measurements on Whistler-Mode Transmitter Signals

Phase and group path measurements on transmitter signals began in New Zealand in the late 1960s when it was found to be possible to measure the Doppler shift on signals at 18.6 kHz from the NLK transmitter in Seattle, Washington (McNeill 1967). The Doppler shift was recognized to be a function both of path drift as well as of changes in the path-integrated electron content, and measurements were later performed that allowed separate estimates of the two effects (e.g., Thomson 1976). Successive redesigns of receivers and refinement of methods led to the possibility of identifying the multiple group delays of minimum shift keying (MSK) signals propagating on a set of magnetospheric paths distributed near $L = 2.5$ while also measuring Doppler shifts on the signals (e.g., Thomson 1981). Observations of two transmitter signals simultaneously, namely NSS (21.4 kHz) and NAA (24.0 kHz) at Faraday (Antarctica), made it possible to separately determine for each observed whistler-mode path the L value (determined from small differences in group delay between the two transmitter signals), cross- L drift velocity, and electron coupling flux (Smith et al. 1987). Figure 3 shows the variation with LT of the average westward electric field at $L \approx 2.5$ for nine quiet days in July 1986 (Saxton and Smith 1989). As in the case of the quiet day whistler data of Fig. 1, the field is eastward in the late morning sector and westward in the afternoon.

Fig. 3 The variation with local time of the average westward electric field at $L = 2.5$ for nine quiet days in July 1986, obtained from NAA and NSS whistler-mode observations at Faraday, Antarctica. The white sections above indicate the hours of sunlight for Faraday and its conjugate. (Adapted from Saxton and Smith 1989)



Also in agreement with the whistler work, the quiet day field magnitudes remained below $\sim 0.2 \text{ mV m}^{-1}$. Application of this method at the time of a severe magnetic storm on 11–12 September 1986 indicated that the westward electric field at $L \approx 2.5$ near midnight exceeded 1 mV m^{-1} during a period when K_p reached a maximum of 9 (Balmforth et al. 1994).

1.2 CLUSTER and IMAGE Achievements

The CLUSTER and IMAGE spacecraft were both launched in 2000 with new capabilities (respectively, multi-point and imaging observations) that did not exist in previous missions (Escoubet et al. 1997; Burch 2000; De Keyser et al. 2008, this issue). These new capabilities permitted a deeper investigation of the phenomena discovered by ground whistler measurements. Using four identical spacecraft, CLUSTER performs multi-point in situ measurements with high temporal and spatial resolution, making it possible to derive the electric current by calculating the curl of the magnetic field measured by the FluxGate Magnetometer (FGM) (Balogh et al. 2001). Three of CLUSTER's instruments offer electric field information: the Electron Drift Instrument (EDI) (Paschmann et al. 2001), the Electric Field and Wave (EFW) instrument (Gustafsson et al. 2001), and the Cluster Ion Spectrometry (CIS) instrument (Rème et al. 2001). The IMAGE spacecraft was the first to routinely observe global plasmaspheric behavior, providing a new means of diagnosing the global convection field. The Extreme UltraViolet (EUV) imager (Sandel et al. 2001) was designed to measure 30.4 nm sunlight that is resonantly scattered by the He^+ ions that are an important constituent of plasmaspheric material. Because the relatively cold (1 eV) ions of the plasmasphere are primarily influenced by the electric field (via $E \times B$ drift), observation of the time evolution of plasmaspheric structures such as the plasmopause allows derivation of electric fields. The combination of IMAGE data with that of other spacecraft and ground-based observatories has yielded much new insight.

Together, CLUSTER and IMAGE have substantially increased our knowledge and understanding of both plasmaspheric dynamics and the inner magnetospheric electric field that controls them. Early studies recognized that the interplanetary electric field (generated by the motion of the solar wind past the magnetosphere) drives magnetospheric convection, and that the shape of the plasmasphere is roughly determined by the superposition of the electric fields caused by this convection and by the corotation with the Earth (Nishida 1966; Brice 1967). The convection electric field is not only affected by the immediate interplanetary condition but also by the substorm/storm phases, whose relationship with the interplanetary variation is complicated, especially by the fact that currents and fields generated inside the magnetosphere–ionosphere system can modify substantially the convection generated by the solar-wind–magnetosphere interaction. Thus, quantitative understanding of the relationship between the plasmasphere response and interplanetary (solar wind) parameters remains a major puzzle to be solved. The CLUSTER and IMAGE missions have made it possible to compare plasmaspheric measurements with interplanetary monitors such as ACE and WIND and with geomagnetic indices such as Dst , K_p , and AE , to make progress in the solution to this puzzle.

The mapping of plasmaspheric quantities between high altitude in the magnetosphere and low altitude in the ionosphere emphasizes the important role played by magnetosphere–ionosphere (M–I) coupling in shaping the plasmasphere boundary layer, or PBL (Carpenter and Lemaire 2004). This is also manifested by inter-comparison of data from multiple spacecraft. The new perception of the outer reaches of the plasmasphere as a boundary layer recognizes the unique and important processes found there. The redistribution of plasmaspheric material throughout the coupled magnetosphere–ionosphere system traces out

the convection streamlines and the electric fields associated with a variety of sources and drivers. Features and mechanisms seen for the first time by CLUSTER, IMAGE, and ground-based measurements exhibit a scale size and repeatability, which indicate their fundamental role in the overall system.

In this review, we mainly discuss the following topics.

- The electric field is successfully measured by EDI onboard CLUSTER in the range $L = 4\text{--}10$. Electric fields with various origins are identified: solar wind–magnetosphere interaction, M–I coupling including SAPS, ionospheric dynamo, and ultra low frequency (ULF) waves. The solar wind–magnetosphere interaction is statistically examined in terms of correlation between the Z component of the interplanetary magnetic field (IMF) and inner magnetospheric electric fields. The investigation on IMF B_y dependence reveals the importance of M–I coupling in addition to the solar wind–magnetosphere interaction (Sect. 2).
- Electric fields and flows deduced from sequences of plasmasphere images have provided information about the timing and global phenomenology of erosion during storms and substorms. IMAGE data have been used to study electric fields that arise from ionospheric closure of the partial ring current, including shielding and SAPS, providing quantitative global measurements that have furthered our knowledge of the inner magnetospheric electric field, and helped improve electric field models (Sect. 3).
- SAPS or SAID are examined by multiple spacecraft analysis. IMAGE data show plasmaspheric plumes, which are adjacent to the SAPS channel measured by DMSP. Comparison between magnetically conjugate CLUSTER and DMSP electric field data shows the absence of significant field-aligned potential drops between the two spacecraft, while the field-aligned current comparison suggests partial perpendicular closure between the spacecraft (Sect. 4).
- The CLUSTER mission provides the opportunity to study the plasmasphere with four-point measurements, permitting examination of the geometry and orientation of the overall magnetic field in the plasmasphere. A detailed analysis of a typical CLUSTER pass through the plasmasphere is presented, in which the direction of the gradient is compared with the local field vector. Particular attention is paid to the relative roles of the gradient components along and transverse to magnetic field lines (Sect. 5).

2 Inner Magnetospheric Electric Fields Measured by CLUSTER

Because of their profound influence on the dynamics of particle populations (and particularly upon the cold dense particles of the plasmasphere), measuring or deriving inner magnetospheric electric fields remains an active area of research. Electric fields have been determined indirectly by the shape of the plasmopause (e.g., Maynard and Chen 1975) and the location of the inner edge of the plasmashet (McIlwain 1974), while ground-based measurements are common tools to determine the electric fields (e.g., Carpenter and Seely 1976; Wand and Evans 1981; Foster et al. 1986). Direct in situ measurements have also been provided by the double probe technique (Maynard et al. 1983; Rowland and Wygant 1998) and by the electron drift technique (Baumjohann et al. 1985; Quinn et al. 1999). EDI onboard CLUSTER measures in situ magnetospheric electric fields with high quality and with good data coverage comparable to or better than these previous measurements, which makes it possible to perform comprehensive studies on the inner magnetospheric electric fields.

2.1 EDI Onboard CLUSTER

EDI measures electric fields at the in situ spacecraft location (Paschmann et al. 2001). Electron beams with an energy of 1 keV (and 500 eV for a small number of cases) are emitted from two pairs of guns in the direction perpendicular to the ambient magnetic field. Electron beams subsequently experience cyclotron motion and drift motion, and fractions of the beams return to two pairs of detectors. Drift motions include both $\mathbf{E} \times \mathbf{B}$ and ∇B components, although the latter contribution is much smaller at the above beam energies in the inner magnetosphere. CLUSTER EDI actually measures drift step length during approximately one or multiple gyroperiods by triangulation and/or time-of-flight methods. Here we try to determine two perpendicular components of the electric field from this drift step length.

The EDI tends to work well in the inner magnetosphere, for the following reasons. First, owing to the relatively large magnetic field strength the gyroperiod of electrons in the beam is small, minimizing the parallel (along the magnetic field) dispersion of beams returning to the detectors. Second, inside the plasmasphere there are few natural plasma sheet electrons to contaminate or mask the instrument beams (Quinn et al. 2001). (Note that the EDI instrument data also includes an estimate of the ambient or “background” electrons.) EDI performance suffers in inner magnetospheric regions with significant natural electron fluxes, and during geomagnetically active periods (such as substorms and storms) during which highly variable electric fields make tracking of the electron beams by the onboard controller more difficult. Therefore, electric field data are often not available in these regions/periods. Otherwise, the electric fields are usually measured successfully by EDI. These data are relatively reliable compared to those from the other instruments (Eriksson et al. 2006; Puhl-Quinn et al. 2008). These electric field data have been analyzed by Matsui et al. (2003, 2004, 2005) and by Puhl-Quinn et al. (2007).

The optimal time resolution of the CLUSTER EDI data is 1 second. There are occasional data gaps caused by electron beam tracking difficulties (as noted above). The CLUSTER spacecraft were originally deployed with perigees at $4 R_E$ and apogeas at $20 R_E$ on polar orbits with a period of 57 hours. Analysis of CLUSTER EDI data from this earlier period has been performed for $4 < L < 10$. Modification of CLUSTER’s orbits since 2006 has resulted in a lower perigee, in principle making it possible to study of electric field for $L < 4$, though extension to lower L is beyond the scope of this review. CLUSTER’s pre-2006 orbits covered all magnetic local times (MLT) once per year owing to annual precession as the Earth revolves around the Sun. The CLUSTER spacecraft were launched in summer 2000, and have made available a wealth of data to perform both statistical and case studies. Data from C1 and C3 are available continuously. Data from C2 are available until April 2004, while EDI is not operated on C4. In the work reviewed here the data chosen for analyses have been identified to be of good quality by the ground software.

2.2 Inner Magnetospheric Electric Fields

2.2.1 Case Studies

Matsui et al. (2003) reported electric field observations on 13 April 2002 made by EDI onboard CLUSTER (Fig. 4). The horizontal axis shows the magnetic latitudes (MLAT) between -60 and $+60^\circ$. The results from C1, C2, and C3 are shown by black, red, and green colors, respectively. The three spacecraft measure fairly similar features indicating spatial variation is small compared to the distance between spacecraft examined here (~ 90 – 160 km). Radial

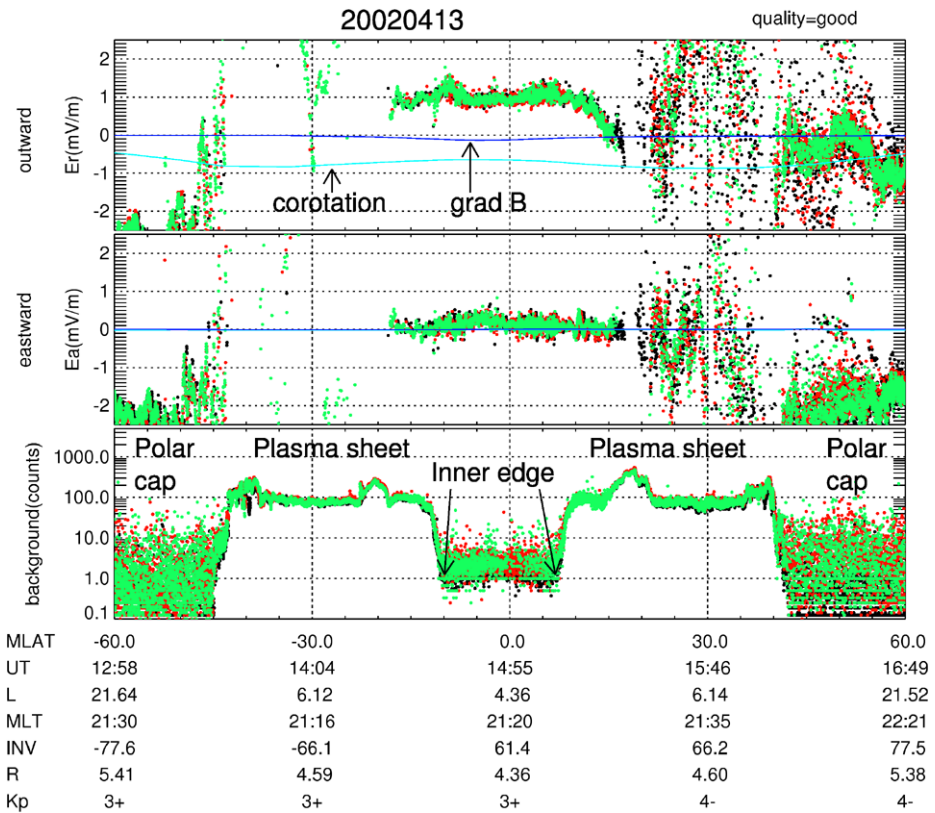


Fig. 4 Example of electric field measured by EDI onboard CLUSTER on 13 April 2002. Outward and eastward components of the electric field and background natural electron counts with an energy of 1 keV and a pitch angle of 90° are plotted from top to bottom. Data from C1 (black), C2 (red), and C3 (green) are plotted. Contributions from corotation (light blue), and ∇B drift (dark blue) are also plotted. Spacecraft plasma regimes are indicated in the bottom panel

and azimuthal components of the electric fields are shown in the inertial frame in the top and second panels, respectively. The electric field caused by corotating drift is shown by light blue lines so that the offset from this value shows the electric field in the corotating frame. The contribution from the ∇B drift is calculated by using the Tsyganenko-02 model (Tsyganenko 2002) and is indicated by dark blue lines: This drift is negligible with a size at most $\sim 0.1 \text{ mV m}^{-1}$. The bottom panel shows counts of ambient electrons with an energy of 1 keV and a pitch angle of 90° , a data product of EDI in addition to the electric field. The spacecraft are located in the polar cap, plasmasheet, and inner edge of the electron plasma sheet in this order from the high geomagnetic latitudes. The electric field is frequently measured inside the inner edge of the electron plasma sheet and in the polar cap, indicating the EDI technique is often useful. At this time, IMF B_Y and B_Z are -1.4 and -3.5 nT, respectively, in geocentric solar magnetospheric (GSM) coordinates as measured by ACE (Smith et al. 1998). The K_p index is varying from 3^+ to 4^- , indicating moderate geomagnetic activity. There is a strong outward component of electric field around perigee causing westward plasma drifts. If measured in the corotating frame, the size is as large as 1.5 mV m^{-1} . Since the location of the spacecraft is at $\sim 21:00$ MLT, this electric field feature corresponds to SAPS (Foster and

Vo 2002) or SAID (Anderson et al. 2001). The detailed analysis of SAID using CLUSTER data is reviewed in Sect. 4.2. It also should be noted that the electric field includes perturbed components caused by ULF waves, for example, in the eastward component at $10\text{--}20^\circ$ of MLAT. The period of these waves is ~ 200 s. This case study demonstrates that common features expected in the inner magnetospheric electric field are actually measured.

2.2.2 Statistical Studies on IMF B_z Dependence

It is possible to analyze the electric field statistically by using data measured by EDI on-board CLUSTER. Here, the period of data used is almost six years between February 2001 and December 2006. As CLUSTER has a polar orbit, the electric fields at spacecraft locations are mapped to the magnetic equator defined as $Z = 0$ in solar magnetospheric (SM) coordinates. The mapping is performed so that the motion of the magnetic field line at the spacecraft location is consistent with that at the magnetic equator. The parallel electric potential drop is assumed to be zero. The magnetic field model used here is the Tsyganenko-02 model (Tsyganenko 2002). Because the mapping calculation becomes increasingly computationally expensive for higher time resolution, and the present interest is on DC phenomena after eliminating contributions by ULF waves, five-minute averages are calculated before applying the mapping procedure. The mapped data are then categorized by spatial bins at $L = 4.5\text{--}9.5$ with $\Delta L = 1$ and full MLT with $\Delta MLT = 1$ hour and also polarity of IMF B_z averaged for 40 minutes. Interplanetary data from ACE (McComas et al. 1998; Smith et al. 1998) are used with propagation delay, which is defined as X component of spacecraft position in GSE coordinates divided by solar wind speed (Matsui et al. 2004). One average value is calculated at each spatial bin for each IMF B_z polarity. After the two-dimensional average electric field patterns are calculated, the electric potential patterns are derived using an inversion technique, as discussed fully in Matsui et al. (2004) and reviewed in Reinisch et al. (2008, this issue).

The calculated potential patterns are shown in the corotating frame in Fig. 5. Panels a and b correspond to the northward and southward IMF cases, respectively. Potential contours for southward IMF are denser than for northward IMF, indicating a strong solar wind–magnetosphere coupling effect on the inner magnetospheric electric field. This feature is consistent with the geosynchronous measurement by Baumjohann and Haerendel (1985). The electric potentials are clearly affected by M–I coupling (Vasyliunas 1970). Closure of partial ring current through the ionosphere via region 2 field aligned currents causes a skewing of equipotential contours from the Sun–Earth line (Cson Brandt et al. 2002). A uniform dawn-to-dusk convection electric field would have equipotential contours that are straight lines parallel to the Earth–Sun line. Instead, for example, the contour originating at $L = 9.5$ and 0 MLT is deflected around the Earth, as is especially noticeable for the northward IMF case. This skewing is part of the global effect of the region 2 current system that generates the shielding electric field in the ionosphere (Jaggi and Wolf 1973). There is a dawn–dusk asymmetry of the strength of the electric field, which is presumably due to the day–night asymmetry of the conductivity (Wolf 1970). Strong outward electric fields (i.e., closely-spaced equipotential contours) are observed in the evening MLT for the southward IMF case, which is consistent with SAPS or SAID structures as shown in the above case studies and by Puhl-Quinn et al. (2007). The ionospheric dynamo effect is another component seen in the pattern for the northward IMF case, at $L \sim 4$ (near perigee). This is inferred by comparing the electric field measured by CLUSTER with that obtained by ground radar at Millstone Hill (Wand and Evans 1981) and an ionospheric spacecraft DE 2 (Heelis and Coley 1992).

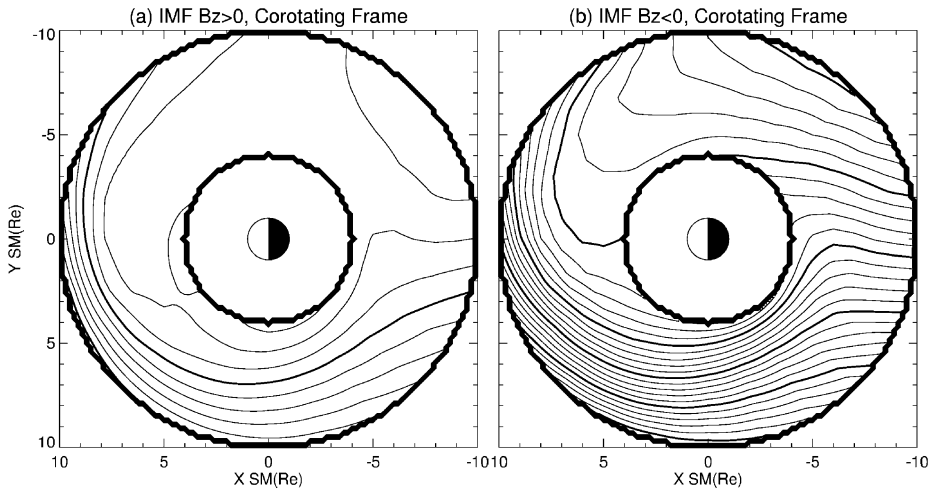


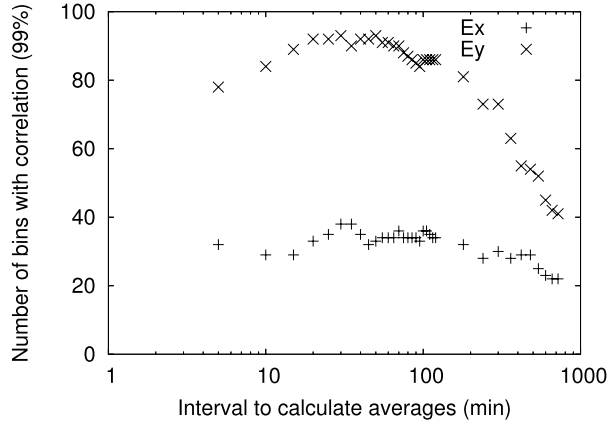
Fig. 5 Electric potential patterns derived from CLUSTER EDI data for almost 6 years. The results for (a) northward IMF and (b) southward IMF are shown in the corotating frame. Contour intervals are 1 and 5 kV for *thin* and *thick* lines, respectively

It should be noted that the standard deviation is often as large as the average values in the above statistics; this can be interpreted as indicating the dynamic nature of the inner magnetospheric electric fields. The motion of cold plasma is therefore expected to be complicated in the plasmasphere including at the PBL. This problem is also discussed by Pierrard et al. (2008, this issue). One factor contributing to this large standard deviation is ULF waves as shown in Fig. 4. Another factor would be the dynamic feature of substorm and/or storm activity such as undershielding and overshielding effects discussed by Huang et al. (e.g., 2006), although EDI tends to not provide data during active periods.

As mentioned above, it is confirmed that electric fields with various origins are observed: solar wind–magnetosphere interaction, M–I coupling including SAPS or SAID, ionospheric dynamo, and ULF waves. The measurement by EDI is reasonable when compared with previous studies at the ionospheric level or those based on theories. Hence, the next step is to create an inner magnetospheric electric field (UNH-IMEF) model, which is described in Matsui et al. (2008), Puhl-Quinn et al. (2008), and Reinisch et al. (2008, this issue). Electric field data measured by double probes are newly introduced to complement EDI data especially to improve data coverage during geomagnetically active periods.

In the above study, the interplanetary parameters introduced are not instantaneous ones but 40-minute averages. Here the correlation between IMF B_Z component and inner magnetospheric electric field is examined to highlight the solar-wind magnetosphere interaction. Figure 6 shows the occurrence rate of 99% correlation between the E_X and E_Y components of inner magnetospheric electric field and IMF B_Z , plotted versus the averaging interval of B_Z in the range 5 minutes to 12 hours. The correlation for E_Y is better than that for E_X because the dawn–dusk component is the primary component merged into the magnetosphere from the same component of interplanetary electric field. A peak of the correlation is obtained for a broad averaging interval of ~ 20 –70 minutes. The number of bins with correlations with averaging intervals > 70 minutes does not decay quickly. More than half of the spatial bins (> 72 bins) have significant level of correlations with averaging intervals up to 300 minutes. This would reflect the operative time

Fig. 6 Number of bins with correlation with a significant level of 99% between inner magnetospheric electric field and IMF B_Z , plotted versus the averaging interval of B_Z . E_X and E_Y components are chosen in the inner magnetosphere for 144 spatial bins (6 radial and 24 azimuthal). IMF B_Z averaging intervals between 5 minutes and 12 hours are plotted



scale of how the interplanetary medium affects the inner magnetosphere. Figure 6 demonstrates that the effect of IMF on the inner magnetospheric electric field has two relevant timescales: a prompt timescale of tens of minutes for the IMF effect to initiate an inner magnetospheric response, and a longer timescale of hours for that response to continue before decaying away. It is useful to compare CLUSTER's results from other studies investigating similar relationships. A prompt response of the plasmaspheric shape to the southward turning of IMF with a delay of a few tens of minutes was reported by Goldstein et al. (2003b). There are other reports on the prompt response ($\lesssim 10$ minutes) of high latitude ionospheric electric field due to IMF B_Z changes (Ridley et al. 1998; Khan and Cowley 1999). These three studies support the response < 1 hour. Other work by Huang et al. (2005) reported substorm recurrence periods of a few hours during continuous southward IMF, which could be related to the long term ($\sim$ hours) effect of IMF. This analysis certainly suggests follow-up analysis to answer significant questions. For example, how would the IMF dependence be different for a limited area in L value and MLT? The combined effects of time delay and averaging should be investigated as well to understand the solar wind–magnetosphere interaction more clearly.

It is possible to evaluate the efficiency of the merging of the interplanetary electric field into the inner magnetosphere, which is defined by E_Y component in the inner magnetosphere divided by the same component in the interplanetary space. When the slope of the relation between the IMF B_Z component and E_Y component in the inner magnetosphere is calculated, the average and standard deviation are -0.05 ± 0.03 (mV m^{-1}) nT^{-1} . If a typical solar wind speed of 450 km s^{-1} is introduced, the efficiency is 0.11 ± 0.07 . This value is comparable to that estimated by Goldstein et al. (2003b) as 0.12 from an IMAGE EUV observation.

2.2.3 Statistical Studies on IMF B_Y Dependence

In addition to the IMF B_Z component, the electric field in the polar cap region is known to be affected by IMF B_Y (e.g., Cowley 1981; Heppner and Maynard 1987) and season (e.g., de la Beaujardiere et al. 1991; Crooker and Rich 1993). Both IMF B_Y and seasonal effects are expected to appear oppositely in the northern and southern hemispheres. For example, the potential pattern with positive IMF B_Y (in June) in the northern hemisphere is the same as that with negative IMF B_Y (in December) in the southern hemisphere. Whether this seasonal asymmetry effect is preserved or canceled near the magnetic equator in the

inner magnetosphere was examined at geosynchronous orbit by Baumjohann et al. (1986). Extending this work, Matsui et al. (2005) compared the electric fields between northern and southern hemispheres and found some north-south disparity, especially on the dawn side, a result consistent with the expectation in the polar region by the Weimer model (Weimer 2001). Thus, the electric field in the region of the inner magnetosphere covered by CLUSTER's orbits is subject to a IMF B_Y dependence that is similar to that found in the polar region. From this result may be inferred a seasonal variation of M–I coupling, a reasonable inference because of the seasonal variation of ionospheric conductivity.

2.3 Summary

Measurement of the inner magnetospheric electric field by EDI onboard CLUSTER has been reviewed in this section, based on studies by Matsui et al. (2003, 2004, 2005). The electric fields show various features such as solar wind–magnetosphere interaction, M–I coupling including SAPS or SAID, ionospheric dynamo, and ULF waves. Analyses of the solar wind–magnetosphere interaction have also been reviewed: IMF B_Z dependence of the potential patterns sorted by its polarity, correlation time scale by averaging IMF B_Z , and efficiency of merging. Observation by CLUSTER of IMF B_Y and seasonal dependence in the inner magnetosphere reflects that the condition of both solar wind and ionosphere can have an effect. Given recent progress in observational characterization of the electric field, the next step should be to develop a convection electric field model. Such a model would be useful for studies of both plasmasphere and ring current dynamics (Reinisch et al. 2008, this issue).

3 Inner Magnetospheric Electric Fields From Plasmasphere Images

3.1 Technique for Deducing Electric Fields From IMAGE

Inspired by earlier work that inferred cross- L drifts by tracking the motion of whistler ducts (Carpenter and Seely 1976), the motion of the plasmopause boundary in IMAGE EUV plasmasphere images has been used to deduce the electric field along the plasmopause (Goldstein et al. 2004b). This technique relies on the assumption that the boundary motion results from the $\mathbf{E} \times \mathbf{B}$ drift of cold plasmaspheric plasma at (or just inside) the plasmopause. For a relatively smooth, featureless plasmopause it is only possible to infer the tangential electric field component. However, convection often produces indentations and bulges whose motion along the boundary can be tracked, allowing a limited capability to obtain two vector electric field components (Goldstein et al. 2004a, 2005b). More recently, some effort has gone into more sophisticated analysis of an entire EUV image, in an attempt to track plasma motion inside the entire plasmasphere (not just at the plasmopause) and obtain a full two-dimensional vector flow (i.e., electric) field (Gallagher and Adrian 2007; De Keyser et al. 2008, this issue).

3.2 Phenomenology of the Erosion Process

Though the electric fields deduced from analysis of EUV images are somewhat crude (both in spatial and temporal resolution) relative to that provided by in situ measurements, global snapshots of the inner magnetospheric electric field have yielded some important observations about the erosion process. Several studies have shown a strong correlation between erosion and southward IMF in the solar wind, but there is a 20–30 minute time delay between the arrival of southward IMF at the dayside magnetopause

and the subsequent onset of erosion (Goldstein et al. 2003a; Spasojević et al. 2003; Goldstein 2006). Different MLT sectors of the plasmapause respond at different times, possibly owing to the finite $\mathbf{E} \times \mathbf{B}$ drift speed of eroding plasma (Larsen et al. 2007). Night-side erosion begins as an initial indentation a few MLT hours wide, centered at or east of midnight; this indentation expands both eastward and westward, widening to eventually encompass the entire nightside (Goldstein et al. 2004b; Goldstein and Sandel 2005; Gallagher and Adrian 2007). The substorm response is similar to that of erosion, but more transient; ripples propagate both eastward and westward from a common initial indentation, but after the passage of a ripple past a given MLT the plasmapause can recover its initial location (Goldstein et al. 2005b). The erosion process is described in more detail elsewhere in this issue (Darrouzet et al. 2008).

3.3 Internal Magnetospheric Electric Fields

The availability of plasmasphere images has facilitated significant progress in understanding electric fields that originate internally in the magnetosphere (as opposed to being directly driven by the solar wind–magnetosphere interaction). These internal electric fields are generated when the stormtime partial ring current is closed through the ionosphere via region 2 field-aligned currents (FAC). Two main types of internal electric fields have been investigated using IMAGE EUV: shielding and SAPS.

In shielding, ionospheric current closure produces an eastward electric field that counters the global dawn-to-dusk solar-wind-driven convection field (Jaggi and Wolf 1973). Images of the plasmasphere during times of changing convection strength indicate that there is generally a dynamic imbalance between convection and shielding (Goldstein et al. 2002, 2003c; Wolf et al. 2005; Sazykin et al. 2005). These images provide a convincing global contextual picture for observations from the inner magnetosphere (earthward of the stormtime ring current) and low-latitude ionosphere (equatorward of the region 2 currents) (Fejer et al. 1990; Fejer and Scherliess 1995; Scherliess and Fejer 1997; Rowland and Wygant 1998; Wygant et al. 1998) that had seemed to refute the idea of a perfectly shielded, quiescent inner magnetosphere.

SAPS is a broad region of westward flow enhancement generated by a poleward Pederson current in the low-conductivity region equatorward of the electron aurora (Anderson et al. 2001; Foster and Burke 2002). The broad SAPS region often contains a sharp intensification of westward flow that is called SAID or polarization jet (PJ); SAID/PJ may be considered a special limiting case of SAPS, although at times (in the literature) SAPS and SAID have been used interchangeably. Stormtime plasmasphere images have provided a means of studying the effects of SAPS on cold plasma. IMAGE observations showed the degree to which SAPS can intensify erosion at the duskside edge of plumes and move the plume location earthward (Goldstein et al. 2003b, 2005c), and enabled the creation of magnetospheric models of the SAPS electric field (Goldstein et al. 2005a, 2005c). During substorms, rapid growth of SAPS electric fields can produce undulatory motion of the plasmapause (Goldstein et al. 2004a, 2007). Extraction of electric fields from plasmapause undulations have provided quantitative global measurements of SAPS in the inner magnetosphere that complement low-altitude measurements by satellites such as DMSP (Goldstein et al. 2004a, 2005b). More about SAPS fields is found in the next section.

4 SAPS Electric Fields

4.1 DMSP and IMAGE Observation

During storms, the effects of magnetospheric electric fields and $\mathbf{E} \times \mathbf{B}$ plasma convection extend deep into the mid-latitude ionosphere producing dramatic effects. At the PBL, strong electric fields associated with storm-time ring current enhancement contribute to the formation of the deep mid-latitude ionospheric density trough and the erosion of the overlying plasmasphere. This process is associated with M–I coupling and ionospheric feedback in the region where magnetospheric FACs attempt to close across the low-conductance subauroral ionosphere. The potential distribution required to satisfy current continuity across this region is adjusted to reflect ionospheric conditions, and maps back into the magnetosphere along magnetic field lines (Nopper and Carovillano 1978).

Foster and Burke (2002) and Foster and Vo (2002) provide a brief description of this process, which is consistent with the model for SAID discussed by Anderson et al. (1993) and others. As disturbance electric fields energize ring-current particles and transport them into the inner magnetosphere, large pressure maxima develop in the nightside magnetosphere. Finite gyroradius effects, intensified by shear flows, may create intense localized transverse electric fields (De Keyser et al. 1998; De Keyser 1999). Misalignments between gradients in plasma pressure and magnetic flux tube volume cause region 2 FACs to flow into/out of the ionosphere evening/morning sector. A fraction of region 2 FACs flow into regions of low ionospheric conductivity at sub-auroral latitudes where large polarization electric fields, needed to maintain current continuity, drive the rapidly drifting streams of storm enhanced density (SED) (Foster 1993) which are the ionospheric signature of the plasmasphere erosion plumes imaged by IMAGE EUV (e.g., Sandel et al. 2001). Within the region of strong plasma drifts frictional heating enhances ionospheric recombination rates (Schunk et al. 1976), accelerating the reduction of ionospheric conductivity in the channel. This, in turn, increases the intensity of the polarization electric fields, leading to still deeper ionospheric troughs and more rapid plasma flow in both the ionosphere and magnetosphere.

Large potential drops imposed on the magnetosphere and polar ionospheres by the solar wind-driven convection electric fields are the ultimate drivers of the SAPS. Region 1 FACs drawn from the interplanetary generator flow near the poleward boundary of the auroral oval; into the ionosphere on the dawn side and out of the ionosphere on the dusk side. The potential distribution required to satisfy Ohm's Law spans the global ionosphere, is adjusted to reflect ionospheric conditions, and maps back into the magnetosphere along magnetic field lines (Nopper and Carovillano 1978).

The SAPS has considerable consequences on the dynamics and redistribution of thermal plasma within the coupled inner magnetosphere/ionosphere system. Anderson et al. (2001) have demonstrated that the SAID electric fields are magnetically conjugate and extend along magnetic field lines into the magnetosphere. The overlap of SAPS with the plasmasphere (see Fig. 7) erodes its outer layers to form the steep disturbed-time plasmopause and spectacular plasmaspheric tails which have been imaged with the EUV detector on the IMAGE satellite (Foster et al. 2002, 2007). Figure 7 and the study of Foster et al. (2007) demonstrate that the SAPS channel, measured at lower altitude by the DMSP satellites in the topside ionosphere, maps upward to the apex of the magnetic field where it accounts for the strong sunward flow which erodes the outer plasmasphere, drawing out the plasmaspheric plumes seen by IMAGE and CLUSTER (Darrouzet et al. 2008, this issue).

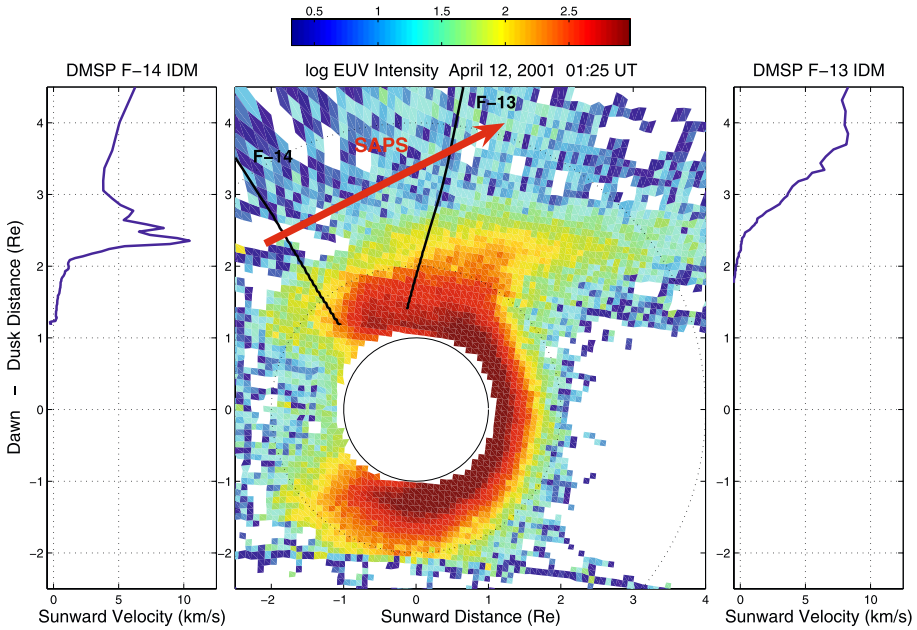


Fig. 7 The IMAGE EUV “snapshot” of the plasmasphere and drainage plume has been mapped to the GSM equatorial plane (Tsyganenko 2002, magnetic field mapping). DMSP passes locate the SAPS channel immediately outside and adjacent to the plasmasphere drainage plume. At dusk, the inward extent of the SAPS sunward convection velocity observed by DMSP F-13 overlaps the outer portion of the IMAGE EUV erosion plume. (Adapted from Foster et al. 2007)

4.2 Multi-Spacecraft Observations of SAID: A CLUSTER Perspective

Conjugate, multi-spacecraft observations of the inner M–I coupling phenomena known as SAID present the opportunity to study how the coupling is created and maintained along entire magnetic flux tubes connecting the southern to the northern ionosphere. Ionospheric observations of SAID are quite extensive, and date back to the mid-1970s (e.g., Galperin et al. 1974; Smiddy et al. 1977; Spiro et al. 1979; Karlsson et al. 1998; Foster and Vo 2002; Figueiredo et al. 2004). Conjugate ionosphere-magnetosphere observations of SAID, however, are relatively rare due to the typical long-period orbit of magnetospheric satellites, which produces a relatively low probability for both the ionospheric and magnetospheric satellites to be in the “right place at the right time”.

4.2.1 SAID Electric Field

Figure 8 summarizes the three known conjugate ionospheric–magnetospheric, multi-spacecraft studies of SAID to date. In the pioneering work of Anderson et al. (2001), conjugate, in situ, magnetospheric and ionospheric observations of SAID were presented for the first time (Fig. 8a). Depicted in this figure is a summary of information extracted from their Fig. 1a. Plotted are peak electric field vectors (arrows) occurring within the SAID channel on 7 February 1990. These electric field vectors are meridional (causing westward drift), and lie within the meridional plane intersecting 21:43 MLT (i.e., the plane of the plot, the X–Z DMS or dipole meridian system plane, is the meridional plane intersecting

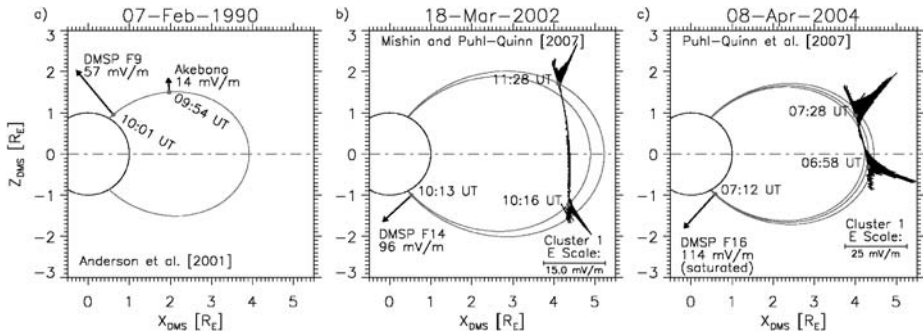


Fig. 8 Multi-spacecraft observations of SAID meridional electric field vectors measured by DMSP, AKEBONO, and CLUSTER. Panels **a–c** show meridional electric field vectors measured by various spacecraft for three events: **(a)** 7 February 1990, **(b)** 18 March 2002 and **(c)** 8 April 2004. From left to right, the X_{DMS} – Z_{DMS} plane is the meridional plane intersecting 21:43, 23:00, and 21:45 MLT, respectively. Dipolar magnetic field lines are drawn for reference. Electric field vectors are drawn either at specific times (for DMSP and AKEBONO) or at several times along the spacecraft orbit (for CLUSTER). Panel **a** shows a summary of information extracted from Fig. 1a of Anderson et al. (2001), where DMSP F9 and AKEBONO were magnetically conjugate at $\sim 10:00$ UT and measured SAID electric fields. Panel **b** summarizes the case study presented by Mishin and Puhl-Quinn (2007), where DMSP F14 and CLUSTER were magnetically conjugate in the southern hemisphere at $\sim 10:15$ UT. Panel **c** summarizes the case study presented by Puhl-Quinn et al. (2007) where DMSP F16 and CLUSTER made conjugate SAID measurements

21:43 MLT). The SAID channel is observed at both DMSP F9 (~ 835 km altitude) and AKEBONO (~ 9400 km altitude). The field-aligned separation of these conjugate observations is ~ 9700 km. A dipolar field line for $L = 3.9$ (invariant latitude, $ILAT = 59.7^\circ$) is drawn to illustrate the magnetic conjugacy of the two spacecraft. The in situ electric field peak at DMSP F9 (AKEBONO) is 57 (14) mV m^{-1} . These values are consistent with the absence of any appreciable field-aligned potential difference between the two spacecraft.

With CLUSTER, we have the opportunity to observe SAID closer to the magnetic equatorial plane. It is fortuitous that typical SAID electric fields at ionospheric heights map to easily measurable electric field magnitudes in the magnetosphere. For example, at $L = 4$ ($ILAT = 60^\circ$), westward ionospheric drifts of 1.0 , 2.0 and 3.0 km s^{-1} , corresponding to poleward-directed electric fields of 38 , 77 and 115 mV m^{-1} , respectively, electrostatically map to the magnetic equator as radially outward electric fields of 2.7 , 5.3 and 8.0 mV m^{-1} , respectively.

Figures 8b and c show multi-spacecraft observations of SAID during the CLUSTER era. The format is the same as that of Fig. 8a, except that the meridional planes depicted in b and c are those intersecting 23:00 and 21:45 MLT, respectively. In both cases, CLUSTER observes the SAID channel in both hemispheres, and DMSP observations are in the southern hemisphere. The field-aligned separation in Fig. 8b between C1 at 10:16 UT and DMSP F14 at 10:13 UT is ~ 25711 km, more than a factor of two larger than that in Fig. 8a between DMSP F9 and AKEBONO. At this time (10:16 UT), C1 is located 15° below the magnetic equator. It was shown in Mishin and Puhl-Quinn (2007) that the electrostatically mapped CLUSTER value of ~ 10 mV m^{-1} agrees to within 10% of the DMSP value of ~ 100 mV m^{-1} , again indicated no appreciable field-aligned potential difference between the magnetospheric and ionospheric locations. The field-aligned separation is extended even further in Fig. 8c, with 27561 km between C1 at 06:58 UT, and DMSP F16 at 07:12 UT. C1 is a mere 4° below the magnetic equator in this case. Nonetheless, a strong SAID signature is observed, indicating the existence of the SAID channel along the entire fieldline. As described in Puhl-Quinn

et al. (2007), a magnitude comparison was not possible, because the DMSP F16 drift meter became saturated within the channel. The strong $\sim 25 \text{ mV m}^{-1}$ fields measured at CLUSTER would electrostatically map to over 300 mV m^{-1} at DMSP altitude, whereas the DMSP drift meter saturated at 114 mV m^{-1} .

4.2.2 SAID Field-Aligned Current

In addition to the coherent SAID electric field channel illustrated in Fig. 8, another large-scale feature of this M–I coupled system is FAC. It has been routinely shown that FAC flows both into and out of the topside ionosphere in the vicinity of SAID (e.g., Rich et al. 1980; Anderson et al. 2001). The ionospheric SAID FAC morphology and strength are quite variable, which is attributed to the dynamic response of the ionospheric conductivity during the initial development and subsequent evolution of the SAID channel. Application of electrical current continuity to the topside ionosphere, under simplifying assumptions, and in the assumed absence of large horizontal conductivity gradients, reveals a possible initial configuration of two, oppositely directed FAC sheets supporting the electric field gradients at the edges of the SAID channel (e.g., Puhl-Quinn et al. 2007). However, this is rarely observed due to the fact that conductivity gradients are relatively quickly formed and serve to support the electric field gradients rather than FAC. The time history of ionospheric SAID FAC morphology relative to the SAID electric field morphology is, in fact, used to formulate hypotheses regarding the magnetosphere's role as a current and/or voltage generator (e.g., Anderson et al. 1993, 2001). More recently, Figueiredo et al. (2004) found that there is evidence to support both types of generator. And Mishin and Puhl-Quinn (2007) used CLUSTER and DMSP data to show that the overall SAID features are consistent with a short circuiting of the substorm injection front over the plasmasphere and subsequent formation of a turbulent overlap region.

Diagnosing the SAID FAC signature at magnetospheric heights was attempted for the first time using CLUSTER data (Mishin and Puhl-Quinn 2007; Puhl-Quinn et al. 2007). The main challenge in the magnetosphere is to successfully isolate the SAID-related current structure, which is embedded in a complex superposition of magnetic perturbations. Using a standard spline/pchip procedure, Mishin and Puhl-Quinn (2007) were able to fit large-scale magnetic components around the channel, and subtract them from the total field in order to isolate the SAID-related FAC structure. Values for in situ SAID FAC within the channel exceed 10 nA m^{-2} for both the 18 March 2002 and 08 April 2004 events. Magnetic lensing of the FAC (assuming $\nabla_{\perp} \mathbf{j}_{\perp} = 0$ along the flux tube) yields values on the order of 1.3 and $0.57 \text{ } \mu\text{A m}^{-2}$ for the 2002 and 2004 events, respectively. The ionospheric in situ values are 0.5 and $0.3 \text{ } \mu\text{A m}^{-2}$, respectively. This trend for the lensed magnetospheric FAC values to be larger than their in situ ionospheric counterparts indicates that partial closure of the FAC occurs between DMSP and CLUSTER altitudes. A more comprehensive and rigorous analysis of several DMSP/CLUSTER conjugations is underway in order to confirm this hypothesis.

5 Spatial Gradients of the Magnetic Field in the Plasmasphere from CLUSTER

The CLUSTER mission allows study of the global orientation of plasmaspheric fields with four-point measurements. Darrouzet et al. (2006) and De Keyser et al. (2007) have analyzed a typical plasmasphere crossing by CLUSTER for this purpose; this work has been limited to computing derivatives of the magnetic field. This also allows the evaluation of $\nabla \times \mathbf{B}$, which is proportional to the electric current density (Vallat et al. 2005; Dunlop et al. 2006), at least if there are no rapid time variations, and to check $\nabla \cdot \mathbf{B}$, which should be zero.

5.1 Datasets and Analysis Technique

The physical quantity used in this study is the spin average DC magnetic field components measured by FGM (Balogh et al. 2001). The uncertainty on those data is less than 0.1 nT. To verify and interpret the results, Darrouzet et al. (2006) have also used a model magnetic field that combines the internal magnetic field model IGRF2000 and the external Tsyanenko-96 magnetic field model (Tsyanenko and Stern 1996).

Techniques to compute the gradients of scalar and vector quantities along the trajectory of the center of the CLUSTER tetrahedron have been introduced by Harvey (1998) (instantaneous spatial gradient computation) and by De Keyser et al. (2007) (least-squares gradient computation), and are described elsewhere in this issue (De Keyser et al. 2008). A prime condition for these methods to work properly is the hypothesis that the satellites are close enough to each other, so that all spacecraft are embedded in the same structure at the same time (homogeneity condition), although this condition can be relaxed somewhat for the least-squares gradient technique. The least-squares gradient technique requires exactly four non-coplanar points to compute the gradient of a scalar quantity or individual vector components. For the magnetic field, the gradients of the field components can be computed, and from them the divergence and the curl, leading to the so-called curlometer method for computing the current density. The least-squares technique imposes strict constraints, such as the divergence-free condition for the magnetic field, thereby leading to an improved curlometer. The technique provides total error estimates on the gradient (and the divergence and the curl).

5.2 A Typical Plasmasphere Crossing

Consider the plasmasphere crossing on 7 August 2003, between 07:00 and 09:00 UT, at 14:00 LT and between -30 and $+30^\circ$ of MLAT during a geomagnetically moderately active regime, which has been analyzed by Darrouzet et al. (2006). At that time, the spacecraft separation was small and the tetrahedron geometric factors are satisfactory. From the measurement errors, and by estimating the approximation error on the gradient (related to the homogeneity condition), the total error on the field magnitude gradient is judged to be about 5%. For the same event, De Keyser et al. (2007) have computed both the gradient ∇B and the gradients of the individual components of $\mathbf{B}$ using the least-squares technique.

In order to study the orientation of the gradient, it is useful to compare its direction to that of the local magnetic field. The angle between the gradient ∇B with respect to the local magnetic field $\mathbf{B}$ (at the center of the tetrahedron) is called $\alpha_{B,\nabla B}$. This angle is always in the range between 0 and 90° , because one is only interested in the orientation of the gradients, and not in their sense, and is known up to a precision of about 3° . The global orientation of the magnetic field strength gradient is also described by its latitude $\theta_{\nabla B}$ and its azimuth relative to the spacecraft azimuth angle $\phi_{\nabla B} - \phi_{sc}$. The precision is 3° on $\theta_{\nabla B}$ and $\phi_{\nabla B} - \phi_{sc}$. In a completely analogous way, angle $\alpha_{B,j}$ can be defined to study the orientation of the current density vector $\mathbf{j}$, which is proportional to $\nabla \times \mathbf{B}$, with respect to the magnetic field. Figure 9a displays the electron density determined by the WHISPER (Waves of High frequency and Sounder for Probing Electron density by Relaxation) instrument (D  cr  au et al. 2001) onboard the four CLUSTER spacecraft as a function of time. Figure 9b gives the angle $\alpha_{B,\nabla B}$. The latitude angle $\theta_{\nabla B}$ and azimuth angle $\phi_{\nabla B} - \phi_{sc}$ of the gradient of the observed FGM magnetic field strength (solid curves) and of the IGRF-Tsyanenko model field strength (dashed curves) are given in Fig. 9c–d.

The magnetic equator is defined as the surface of minimum field strength locations along field lines. It is crossed where $\mathbf{B}$ and ∇B are perpendicular, i.e., when $\alpha_{B,\nabla B} = 90^\circ$. This

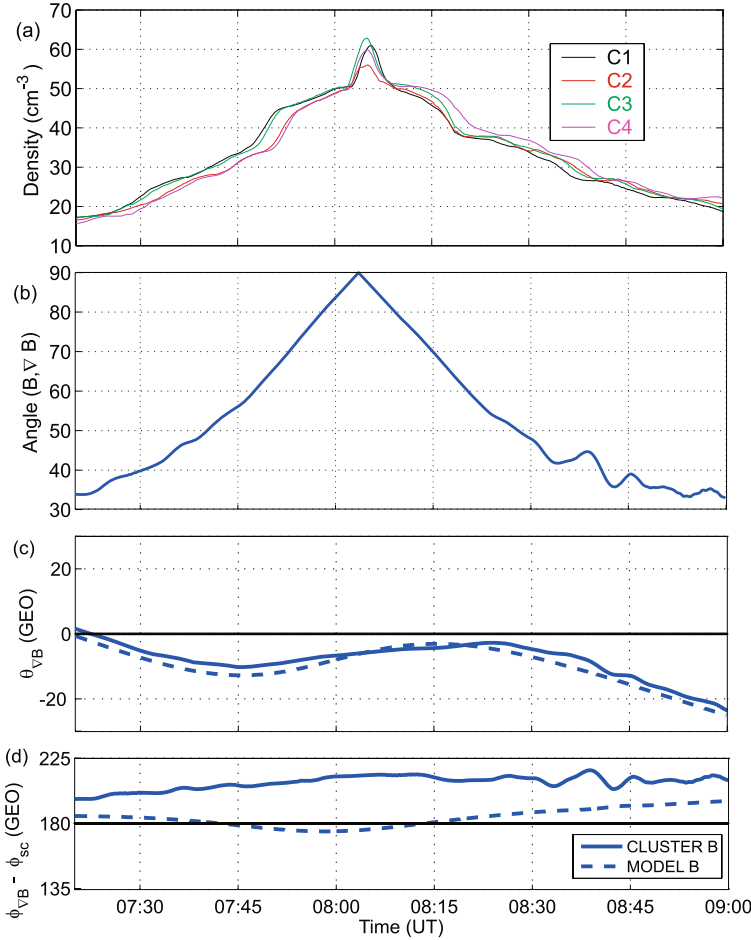


Fig. 9 (a) Electron density from WHISPER onboard the four CLUSTER spacecraft, (b) angle $\alpha_{B, \nabla B}$ between the magnetic field strength gradient ∇B and the local field B , and (c) latitude angle $\theta_{\nabla B}$ and (d) azimuth angle $\phi_{\nabla B} - \phi_{sc}$ of ∇B , as a function of time during the plasmasphere crossing on 7 August 2003. The angles are known up to about 3° . The gradients based on CLUSTER data are represented by the *solid lines*, while gradients computed from the IGRF-Tsyganenko model are drawn with *dashed lines*. (Adapted from Darrouzet et al. 2006)

allows an unambiguous identification of the time of crossing of the magnetic equator in Fig. 9b at 08:03 UT. Note that this in general does not coincide with the time of perigee (08:20 UT) or with the time of maximum density (08:05 UT), but there is not much difference in the present case. Before and after crossing the magnetic equator, the spacecraft sample field lines farther away from the equator and $\alpha_{B, \nabla B}$ decreases as B increases along a field line in the poleward direction in a progressively steeper fashion. Far from the magnetic equator, $\alpha_{B, \nabla B}$ becomes more variable: In the outer fringes of the plasmasphere, the magnetic field strength is smaller and plasma β is higher, which could enhance diamagnetic effects.

For both the observed magnetic field (FGM data) and the model field (IGRF-Tsyganenko), the values of $\theta_{\nabla B}$ are comparable: They vary between 0 and -20° . For a tilted dipole (tilt of 10.3° at 71.7° W longitude in 2003), at 08:03 UT and 14:00 LT, the magnetic equator should be at a latitude of 10° ; the spacecraft encounter the magnetic equator at $\theta_{sc} = 8.5^\circ$. At the magnetic equator of an exact dipole, ∇B would point earthward, so that $\theta_{\nabla B}^{eq} = -\theta_{sc}$; at the actual magnetic equator, the observed value is $\theta_{\nabla B}^{eq} = -6^\circ$.

When the CLUSTER spacecraft cross field lines at higher latitude, the variation of $\theta_{\nabla B}$ depends on how fast B increases away from the magnetic equator. Figure 9b indicates that $\alpha_{B, \nabla B}$ decreases rapidly, so that $\theta_{\nabla B} > \theta_{\nabla B}^{eq}$ just above the magnetic equator and $\theta_{\nabla B} < \theta_{\nabla B}^{eq}$ just below it. But since the field lines are curved towards the Earth farther away from the equator, ultimately $\theta_{\nabla B} \ll \theta_{\nabla B}^{eq}$ at higher latitudes above the magnetic equator and $\theta_{\nabla B} \gg \theta_{\nabla B}^{eq}$ below it. The actual behavior of $\theta_{\nabla B}$ is determined by the geometry of the field lines and by the interplay between the variation of B along field lines ($\nabla_{\parallel} B$) and its variation across field lines ($\nabla_{\perp} B$), offset by the overall dipole tilt.

The azimuth of the observed field strength (FGM data) is $\phi_{\nabla B} - \phi_{sc} \approx 200^\circ$, while it is around 180° for the model field (IGRF-Tsyganenko). If the magnetic field would be a tilted dipole, one would expect $\phi_{\nabla B} - \phi_{sc} = 180^\circ$ at the magnetic equator. The IGRF-Tsyganenko model represents a modified tilted dipole, and indeed has $\phi_{\nabla B} - \phi_{sc}$ close to 180° , i.e., exactly pointing towards Earth. The observed azimuth angle of 200° can only be explained by a deviation from cylinder symmetry around the dipole axis.

These results are confirmed by an analysis with the least-squares gradient computation technique (De Keyser et al. 2007), as summarized in Fig. 10 for a somewhat longer time interval. The magnetic field strength profiles are shown to go through a local minimum near perigee (Fig. 10a). A computation of the angle between $\mathbf{B}$ and ∇B (see Fig. 10b), using realistic input for the error estimates, produces a curve that is very similar to the one of Fig. 9b. The error bars are quite small close to the magnetic equator but they increase significantly away from the equator. There are several reasons: The relative precision of the data is lower there since B is smaller, and the differences between the values measured by the spacecraft are smaller (the gradient itself is smaller). The absence of gradient values in the interval 09:30–09:45 and the very large error bars nearby are due to the bad configuration of the spacecraft: They are nearly coplanar, with the plane containing the spacecraft velocity vector, which is responsible for a bad conditioning of the problem, so that no useful results can be obtained there. For details of the computation, the reader is referred to De Keyser et al. (2007).

Figures 10c and d show the results of a least-squares computation of the gradients of the magnetic field vector components, coupling the three field components through the zero-divergence constraint. The angle $\alpha_{B, j}$ between $\mathbf{B}$ and current density $\mathbf{j}$ (where $\mathbf{j} = \nabla \times \mathbf{B} / \mu_0$ in a steady situation) can vary in principle between 0° and 180° . It is around 90° near the equator, as expected for a roughly symmetric situation. The current density $\mathbf{j}$ appears to be different from zero in the plasmasphere, indicating deviation from a dipolar field, with a field-aligned component inside the plasmasphere (around perigee) and also on auroral field lines (just after 06:00 UT). The relative error is on the order of 5–10% on j near perigee, and 5–10% on $\alpha_{B, j}$, and grows away from the equator for the reasons discussed before. It should be noted, however, that the error bars are drawn at 1 standard deviation and are determined using a rough a priori estimate of the homogeneity properties. A further assessment of the statistical significance of these results is therefore needed. The seemingly erratic values close to the coplanarity interval carry very large error bars and must be ignored. De Keyser et al. (2007) have performed this computation both with and without imposing the condition $\nabla \cdot \mathbf{B} = 0$; they find that this does not affect $\mathbf{j}$ very much, since divergence and curl both involve different derivatives. This conclusion probably depends on

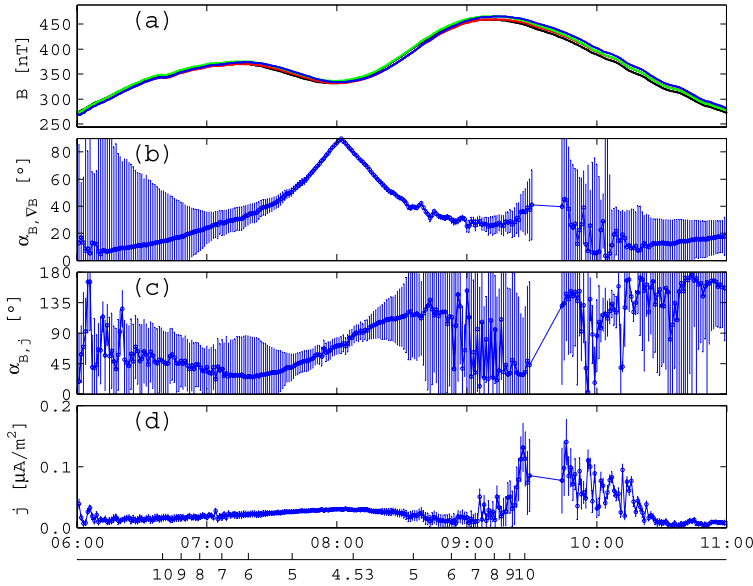


Fig. 10 CLUSTER observations during the inner magnetosphere pass on 7 August 2003, from 06:00 to 11:00 UT, with perigee around 08:03 UT; the bottom scale gives the L -shell position of the center of the CLUSTER tetrahedron (for $L < 10$, elsewhere L cannot be determined accurately). (a) Magnetic field strength B obtained from FGM, reaching a local minimum near perigee, C1—black, C2—red, C3—green, C4—blue. (b) Angle $\alpha_{\mathbf{B}, \nabla B}$ between $\mathbf{B}$ and ∇B (computed with anisotropic homogeneity domain, assuming small-scale fluctuations are present), reduced to $[0^\circ, 90^\circ]$. (c) Angle $\alpha_{\mathbf{B}, \mathbf{j}}$ between $\mathbf{B}$ and current density $\mathbf{j}$ (where $\mathbf{j} = \nabla \times \mathbf{B} / \mu_0$ in a steady situation). (d) Current density magnitude j . The error bars are determined using an estimate of the homogeneity properties, so they are only approximate. (Adapted from De Keyser et al. 2007)

the actual spacecraft separation distance involved, but reflects the typical CLUSTER situation in the plasmasphere.

5.3 Summary and Conclusions

CLUSTER has provided the first systematic spatial gradient results in the plasmasphere, using well-calibrated, unbiased measurements. This produces an overall view of the geometry of the magnetic field in the (outer) plasmasphere. It allows the evaluation of the relative importance between the two effects influencing the spatial gradient of the magnetic field strength inside the plasmasphere: the increase of the magnetic field strength along the field lines away from the equator, and the decrease of this quantity away from Earth.

The variations of the magnetic field strength along the field lines are rather fast, with $|\nabla_{\parallel} B| > |\nabla_{\perp} B|$ (except very close to the magnetic equator). The latitudinal magnetic field structure is found to be roughly compatible with a tilted dipole, but there appear to be significant deviations from cylindrical symmetry. The analysis of electric current density points also toward such a symmetric structure, but the finding of a small, marginally significant nonzero current density indicates again a deviation from the simple tilted dipole model.

It should also be noted that CLUSTER sometimes does observe diamagnetic effects due to the presence of the plasmaspheric plasma, in the form of minor magnetic field strength depressions corresponding to density structure in the outer regions of the plasmasphere, but

it is hard to establish a precise relationship due to the unmeasured contribution of the ring current and radiation belt plasma pressures.

6 Summary and Outlook

Various aspects of plasmaspheric electric fields and magnetic fields have been reviewed in this paper. Ground-based measurements of lightning-generated whistlers and signals from transmitters made it possible to derive electric fields inside the plasmasphere by probing the movement of density ducts. Since the 1960s these whistler studies have provided a context and motivation for later work. Modern observation (e.g., by CLUSTER/IMAGE) of quiet-time, substorm, and SAPS-generated electric fields are entirely consistent with the earlier whistler observations. The CLUSTER and IMAGE missions (launched in 2000) have both improved substantially our capabilities in measuring electromagnetic fields in the plasmasphere. In particular, multiple spacecraft analysis, improved electric field measurements, and tracking the motion of global boundaries were not possible with data from previous missions. The following four points are major achievements from these new satellite measurements.

1. EDI onboard CLUSTER measures electric fields successfully in the inner magnetosphere. Electric fields with various origins are analyzed. In particular, the electric field is examined in terms of the solar wind–magnetosphere interaction.
2. By adapting whistler-based techniques for inferring cross- L drifts, IMAGE EUV plasmasphere images can be analyzed to yield 1- or 2-component electric field information near the plasmopause (and possibly within the plasmasphere). These IMAGE-derived electric fields have helped quantify the temporal (and likely causal) correlation between southward IMF and plasmasphere erosion. Images show that the erosion process is initiated at different times depending on the MLT. Erosion begins as an indentation a few MLT hours wide that widens to encompass the entire plasmopause at all MLTs. During substorms, the starting indentation propagates to other MLTs, but the plasmopause can recover its initial location once the transient disturbance has passed. IMAGE data have also improved our quantitative understanding and models for shielding and SAPS.
3. SAPS or SAID features are observed simultaneously by IMAGE, CLUSTER, and DMSP. This gives a detailed picture of their influence on the PBL. IMAGE/DMSP and ground-based observations have shown that the SAPS convection overlaps the PBL and draws out the erosion plume which forms the outer boundary of the eroding plasmasphere in the dusk sector. Conjugate, in situ CLUSTER/DMSP observations have confirmed that the scale of the electric field and FAC structure within the SAID channel extends from one ionosphere to the other, that there are no appreciable potential drops over this extent, and that partial current closure is expected to exist between DMSP and CLUSTER altitudes.
4. The gradient of the magnetic field is calculated using data from multiple CLUSTER satellites. This will be useful for future field-aligned current and ring current studies.

CLUSTER and IMAGE revealed many dynamic characteristics of the plasmasphere as noted above. It is possible to discuss these results in the context of the whistler measurements introduced in Sect. 1.1. Below, CLUSTER and IMAGE findings are classified into either new findings, confirmation of whistler studies, or further extensions.

Substorm responses of the electric fields are extensively studied using IMAGE data. Ripples or indentations at the plasmopause propagate from nightside toward dusk/dawn MLT, while ground whistler measurements revealed electric field variation first in the westward direction and often subsequently in the eastward direction. Perhaps, both IMAGE and whistler

receivers detect similar phenomena. If this is true, IMAGE has advanced and changed our view on spatial and temporal evolution of substorms from global images.

When the IMF is northward corresponding to small geomagnetic activity, CLUSTER observed electric fields, which are thought to be caused by the ionospheric dynamo effect. This is confirmation of the whistler results. Subcorotation found by IMAGE (Burch et al. 2004) is also interpreted to be caused by the ionospheric dynamo during moderate geomagnetic activity. Further comparison could be made between different instruments at similar geomagnetic activity in future analyses.

The SAPS (or SAID) phenomenon is investigated by IMAGE and CLUSTER. The whistler measurements also reported this large electric field in the duskside. The contribution by IMAGE and CLUSTER studies with combination of DMSP data is to understand the PBL, SED, and M–I coupling through simultaneous measurements at both regions and with various types of instruments. The relationship between the formation of the westward edge of the convection plume and SAPS is new, as well as the apparent close connection between the ionospheric SED and the plume.

Further CLUSTER and IMAGE achievements are to find correlation with IMF and plasmaspheric wind and to extend understanding of undershielding and overshielding effects.

Although various features of plasmaspheric fields are revealed as discussed in this review, further analyses are required to better understand the phenomena. We can identify the following questions guide future directions of research.

1. What are the observational implications on how the electric field is related to other important dynamics in the magnetosphere, such as ring current and radiation belt? The ring current and the electric field are expected to affect each other according to Vasyliunas (1970). What types of mechanisms exactly go on? Quantitative understanding is valuable for this purpose. Radiation belt particles are also related to the background electric fields. For example, the location of the plasmasphere is a parameter that controls the growth rate of ULF and VLF waves and is related to acceleration/deceleration of these particles. Behaviors of trapped particles dependent on the background magnetic field strength suggested by Lemaire et al. (2005) could be investigated in terms of this context as well.
2. What is the physical mechanism, which differentiates between prolonged SAPS and spatially-limited and impulsive SAID? It is necessary to use detailed observations at the ionosphere and magnetosphere combined with modeling studies. Observation of spatial/temporal variability of SAPS with spatially distributed CLUSTER-type instruments would be useful. The dynamics of the PBL would be thus interpreted more consistently.
3. It is important to derive time-dependent inner magnetospheric disturbance electric field models. In particular, the model should be dependent on substorm/storm phases. The developed model is useful to understand the dynamics of the plasmasphere and to compare with simulation results. As these substorms/storms are originally caused by interplanetary parameter changes, this problem is related to the investigation of the Sun–Earth connection. This work complements space weather efforts to achieve better forecasting capabilities.
4. The AC component of the electric field (inductive field and ULF waves) is as large as the DC component. What is the occurrence and distribution of the AC component? Quantitative understanding of ring current acceleration by the AC component and its effect on plasma distribution is a future topic.
5. Field measurements are available at various altitudes from the ground toward the magnetosphere. Combined data analysis between CLUSTER, IMAGE, DMSP, radars, and whistler measurements would lead to a more comprehensive view of the plasmasphere.

Acknowledgements H. Matsui and P. A. Puhl-Quinn acknowledge the support by NASA through grants NNG05GG50G and NNX07AI03G. J. De Keyser and F. Darrouzet acknowledge the support by the Belgian Federal Science Policy Office (BELSPO) through the ESA/PRODEX CLUSTER project (contract 13127/98/NL/VJ (IC)). This paper is an outcome of the workshop “The Earth’s plasmasphere: A CLUSTER, IMAGE, and modeling perspective”, organized by the Belgian Institute for Space Aeronomy in Brussels in September 2007.

References

- P.C. Anderson, W.B. Hanson, R.A. Heelis, J.D. Craven, D.N. Baker, L.A. Frank, A proposed production model of rapid subauroral ion drifts and their relationship to substorm evolution. *J. Geophys. Res.* **98**(A4), 6069–6078 (1993)
- P.C. Anderson, D.L. Carpenter, K. Tsuruda, T. Mukai, F.J. Rich, Multisatellite observations of rapid subauroral ion drifts (SAID). *J. Geophys. Res.* **106**(A12), 29585–29599 (2001)
- H.F. Balmforth, M.A. Clilverd, A.J. Smith, A case study of storm commencement and recovery plasmaspheric electric fields near $L = 2.5$ at equinox. *Ann. Geophys.* **12**(7), 625–635 (1994)
- A. Balogh, C.M. Carr, M.H. Acuña, M.W. Dunlop, T.J. Beek, P. Brown, K.H. Fornacon, E. Georgescu, K.H. Glassmeier, J. Harris, G. Musmann, T. Oddy, K. Schwingenschuh, The Cluster magnetic field investigation: overview of in-flight performance and initial results. *Ann. Geophys.* **19**(10–12), 1207–1217 (2001)
- W. Baumjohann, G. Haerendel, Magnetospheric convection observed between 0600 and 2100 LT: Solar wind and IMF dependence. *J. Geophys. Res.* **90**(A7), 6370–6378 (1985)
- W. Baumjohann, G. Haerendel, F. Melzner, Magnetospheric convection observed between 0600 and 2100 LT: Variations with K_p . *J. Geophys. Res.* **90**(A1), 393–398 (1985)
- W. Baumjohann, R. Nakamura, G. Haerendel, Dayside equatorial-plane convection and IMF sector structure. *J. Geophys. Res.* **91**(A4), 4557–4560 (1986)
- L.P. Block, D.L. Carpenter, Derivation of magnetospheric electric fields from whistler data in a dynamic geomagnetic field. *J. Geophys. Res.* **79**(19), 2783–2789 (1974)
- N.M. Brice, Bulk motion of the magnetosphere. *J. Geophys. Res.* **72**(21), 5193–5211 (1967)
- J.L. Burch, IMAGE mission overview. *Space Sci. Rev.* **91**(1–2), 1–14 (2000)
- J.L. Burch, J. Goldstein, B.R. Sandel, Cause of plasmasphere corotation lag. *Geophys. Res. Lett.* **31**, L05802 (2004)
- D.L. Carpenter, Whistler studies of the plasmopause in the magnetosphere, 1. Temporal variations in the position of the knee and some evidence on plasma motions near the knee. *J. Geophys. Res.* **71**(3), 693–709 (1966)
- D.L. Carpenter, Whistler evidence of the dynamic behavior of the duskside bulge in the plasmasphere. *J. Geophys. Res.* **75**(19), 3837–3847 (1970)
- D.L. Carpenter, J. Lemaire, The plasmasphere boundary layer. *Ann. Geophys.* **22**(12), 4291–4298 (2004)
- D.L. Carpenter, N.T. Seely, Cross- L plasma drifts in the outer plasmasphere: Quiet time patterns and some substorm effects. *J. Geophys. Res.* **81**(16), 2728–2736 (1976)
- D.L. Carpenter, K. Stone, Direct detection by a whistler method of the magnetospheric electric field associated with a polar substorm. *Planet. Space Sci.* **15**(2), 395–397 (1967)
- D.L. Carpenter, C.G. Park, T.R. Miller, A model of substorm electric fields in the plasmasphere based on whistler data. *J. Geophys. Res.* **84**(A11), 6559–6563 (1979)
- D.L. Carpenter, K. Stone, J.C. Siren, T.L. Crystal, Magnetospheric electric fields deduced from drifting whistler paths. *J. Geophys. Res.* **77**(16), 2819–2834 (1972)
- S.W.H. Cowley, Magnetospheric asymmetries associated with the Y -component of the IMF. *Planet. Space Sci.* **29**(1), 79–96 (1981)
- N.U. Crooker, F.J. Rich, Lobe cell convection as a summer phenomenon. *J. Geophys. Res.* **98**(A8), 13403–13407 (1993)
- P. Cson Brandt, S. Ohtani, D.G. Mitchell, M.C. Fok, E.C. Roelof, R. Demajistre, Global ENA observations of the storm mainphase ring current: implications for skewed electric fields in the inner magnetosphere. *Geophys. Res. Lett.* **29**(20), 1954 (2002)
- F. Darrouzet, J. De Keyser, P.M.E. Décréau, J.F. Lemaire, M.W. Dunlop, Spatial gradients in the plasmasphere from Cluster. *Geophys. Res. Lett.* **33**, L08105 (2006)
- F. Darrouzet, D.L. Gallagher, N. André, D.L. Carpenter, I. Dandouras, P.M.E. Décréau, J. De Keyser, R.E. Denton, J.C. Foster, J. Goldstein, M.B. Moldwin, B.W. Reinisch, B.R. Sandel, J. Tu, Plasmaspheric density structures and dynamics: Properties observed by the CLUSTER and IMAGE missions. *Space Sci. Rev.* (2008). This issue

- J. De Keyser, Formation and evolution of subauroral ion drifts in the course of a substorm. *J. Geophys. Res.* **104**(A6), 12339–12349 (1999)
- J. De Keyser, M. Roth, J. Lemaire, The magnetospheric driver of subauroral ion drifts. *Geophys. Res. Lett.* **25**(10), 1625–1628 (1998)
- J. De Keyser, F. Darrouzet, M.W. Dunlop, P.M.E. Décréau, Least-squares gradient calculation from multi-point observations of scalar and vector fields: methodology and applications with Cluster in the plasmasphere. *Ann. Geophys.* **25**(4), 971–987 (2007)
- J. De Keyser, D.L. Carpenter, F. Darrouzet, D.L. Gallagher, J. Tu, CLUSTER and IMAGE: New ways to study the Earth's plasmasphere. *Space Sci. Rev.* (2008). This issue
- O. de la Beaujardiere, D. Alcaide, J. Fontanari, C. Leger, Seasonal dependence of high-latitude electric fields. *J. Geophys. Res.* **96**(A4), 5723–5735 (1991)
- P.M.E. Décréau, P. Ferreau, V. Krasnosels'kikh, E. Le Guirriec, M. Lévêque, P. Martin, O. Randriamboarison, J.L. Rauch, F.X. Sené, H.C. Séran, J.G. Trotignon, P. Canu, N. Cornilleau, H. de Féraud, H. Alleyne, K. Yearby, P.B. Mögensen, G. Gustafsson, M. André, D.A. Gurnett, F. Darrouzet, J. Lemaire, C.C. Harvey, P. Travnick, Early results from the Whisper instrument on Cluster: an overview. *Ann. Geophys.* **19**(10–12), 1241–1258 (2001)
- M.W. Dunlop, A. Balogh, Q.Q. Shi, Z. Pu, C. Vallat, P. Robert, S. Haaland, C. Shen, J.A. Davies, K.H. Glassmeier, P. Cargill, F. Darrouzet, A. Roux, The Curlometer and other gradient measurements with Cluster. *Proceedings of the Cluster and Double Star Symposium, 5th Anniversary of Cluster in Space ESA SP-598* (2006)
- A.I. Eriksson, M. André, B. Klecker, H. Laakso, P.-A. Lindqvist, F. Mozer, G. Paschmann, A. Pedersen, J. Quinn, R. Torbert, K. Torkar, H. Vaith, Electric field measurements on Cluster: comparing the double-probe and electron drift techniques. *Ann. Geophys.* **24**(1), 275–289 (2006)
- C.P. Escoubet, C.T. Russell, R. Schmidt (eds.), *The Cluster and Phoenix Missions* (Kluwer, Dordrecht, 1997), p. 658
- B.G. Fejer, L. Scherliess, Time dependent response of equatorial ionospheric electric fields to magnetospheric disturbances. *Geophys. Res., Lett.* **22**(7), 851–854 (1995)
- B.G. Fejer, R.W. Spiro, R.A. Wolf, J.C. Foster, Latitudinal variation of perturbation electric fields during magnetically disturbed periods—1986 Sundial observations and model results. *Ann. Geophys.* **8**(6), 441–454 (1990)
- S. Figueiredo, T. Karlsson, G.T. Marklund, Investigation of subauroral ion drifts and related field-aligned currents and ionospheric Pedersen conductivity distribution. *Ann. Geophys.* **22**(3), 923–934 (2004)
- J.C. Foster, Storm time plasma transport at middle and high latitudes. *J. Geophys. Res.* **98**(A2), 1675–1689 (1993)
- J.C. Foster, W.J. Burke, SAPS: A new categorization for sub-auroral electric fields. *Eos Trans. AGU* **83**(36), 393 (2002)
- J.C. Foster, H.B. Vo, Average characteristics and activity dependence of the subauroral polarization stream. *J. Geophys. Res.* **107**(A12), 1475 (2002)
- J.C. Foster, J.M. Holt, R.G. Musgrove, D.S. Evans, Ionospheric convection associated with discrete levels of particle precipitation. *Geophys. Res. Lett.* **13**(7), 656–659 (1986)
- J.C. Foster, P.J. Erickson, A.J. Coster, J. Goldstein, F.J. Rich, Ionospheric signatures of plasmaspheric tails. *Geophys. Res. Lett.* **29**(13), 1623 (2002)
- J.C. Foster, W. Rideout, B. Sandel, W.T. Forrester, F.J. Rich, On the relationship of SAPS to storm-enhanced density. *J. Atmos. Sol.-Terr. Phys.* **69**(3), 303–313 (2007)
- D.L. Gallagher, M.L. Adrian, Two-dimensional drift velocities from the IMAGE EUV plasmaspheric imager. *J. Atmos. Sol.-Terr. Phys.* **69**(3), 341–350 (2007)
- Y.I. Galperin, V.N. Ponomarev, A.G. Zosimova, Plasma convection in the polar ionosphere. *Ann. Geophys.* **30**(1), 1–7 (1974)
- J. Goldstein, Plasmasphere response: Tutorial and review of recent imaging results. *Space Sci. Rev.* **124**(1–4), 203–216 (2006)
- J. Goldstein, B.R. Sandel, The global pattern of evolution of plasmaspheric drainage plumes, in *Inner Magnetosphere Interactions: New Perspectives from Imaging*, ed. by J.L. Burch, M. Schulz, H. Spence. Geophysical Monograph Series, vol. 159 (American Geophysical Union, Washington, 2005), pp. 1–22
- J. Goldstein, R.W. Spiro, P.H. Reiff, R.A. Wolf, B.R. Sandel, J.W. Freeman, R.L. Lambour, IMF-driven overshielding electric field and the origin of the plasmaspheric shoulder of May 24, 2000. *Geophys. Res. Lett.* **29**(16), 1819 (2002)
- J. Goldstein, B.R. Sandel, W.T. Forrester, P.H. Reiff, IMF-driven plasmasphere erosion of 10 July 2000. *Geophys. Res. Lett.* **30**(3), 1146 (2003a)
- J. Goldstein, B.R. Sandel, M.R. Hairston, P.H. Reiff, Control of plasmaspheric dynamics by both convection and sub-auroral polarization stream. *Geophys. Res. Lett.* **30**(24), 2243 (2003b)

- J. Goldstein, R.W. Spiro, B.R. Sandel, R.A. Wolf, S.Y. Su, P.H. Reiff, Overshielding event of 28–29 July 2000. *Geophys. Res. Lett.* **30**(8), 1421 (2003c)
- J. Goldstein, B.R. Sandel, M.R. Hairston, S.B. Mende, Plasmopause undulation of 17 April 2002. *Geophys. Res. Lett.* **31**, L15801 (2004a)
- J. Goldstein, R.A. Wolf, B.R. Sandel, P.H. Reiff, Electric fields deduced from plasmopause motion in IMAGE EUV images. *Geophys. Res. Lett.* **31**, L01801 (2004b)
- J. Goldstein, J.L. Burch, B.R. Sandel, Magnetospheric model of subauroral polarization stream. *J. Geophys. Res.* **110**, A09222 (2005a)
- J. Goldstein, J.L. Burch, B.R. Sandel, S.B. Mende, P. Cson Brandt, M.R. Hairston, Coupled response of the inner magnetosphere and ionosphere on 17 April 2002. *J. Geophys. Res.* **110**, A03205 (2005b)
- J. Goldstein, B.R. Sandel, W.T. Forrester, M.F. Thomsen, M.R. Hairston, Global plasmasphere evolution 22–23 April 2001. *J. Geophys. Res.* **110**, A12218 (2005c)
- J. Goldstein, B.R. Sandel, H.U. Frey, S.B. Mende, Multiple plasmopause undulations observed by the IMAGE satellite on 20 March 2001. *J. Atmos. Sol.-Terr. Phys.* **69**(3), 322–333 (2007)
- C.A. Gonzales, M.C. Kelley, D.L. Carpenter, T.R. Miller, R.H. Wand, Simultaneous measurements of ionospheric and magnetospheric electric fields in the outer plasmasphere. *Geophys. Res. Lett.* **7**(7), 517–520 (1980)
- G. Gustafsson, M. André, T. Carozzi, A.I. Eriksson, C.G. Fälthammar, R. Grard, G. Holmgren, J.A. Holtet, N. Ivenko, T. Karlsson, Y. Khotyaintsev, S. Klimov, H. Laakso, P.-A. Lindqvist, B. Lybekk, G. Marklund, F. Mozer, K. Mursula, A. Pedersen, B. Popielawska, S. Savin, K. Stasiewicz, P. Tanskanen, A. Vaivads, J.E. Wahlund, First results of electric field and density observations by Cluster EFW based on initial months of observations. *Ann. Geophys.* **19**(10–12), 1219–1240 (2001)
- C.C. Harvey, Spatial gradients and the volumetric tensor, in *Analysis Methods for Multi-Spacecraft Data*, ed. by G. Paschmann, P.W. Daly. ISSI SR-001 (ESA Publications Division, Noordwijk, 1998), pp. 307–322
- R.A. Heelis, W.R. Coley, East–West ion drifts at mid-latitudes observed by Dynamics Explorer 2. *J. Geophys. Res.* **97**(A12), 19461–19469 (1992)
- R.A. Helliwell, *Whistlers and Associated Ionospheric Phenomena* (Stanford University Press, Stanford, 1965), p. 349
- J.P. Heppner, N.C. Maynard, Empirical high-latitude electric field models. *J. Geophys. Res.* **92**(A5), 4467–4489 (1987)
- C.S. Huang, G.D. Reeves, G. Le, K. Yumoto, Are sawtooth oscillations of energetic plasma particle fluxes caused by periodic substorms or driven by solar wind pressure enhancements? *J. Geophys. Res.* **110**, A07207 (2005)
- C. Huang, S. Sazykin, R. Spiro, J. Goldstein, G. Crowley, J.M. Ruohoniemi, Storm-time penetration electric fields and their effects. *Eos Trans. AGU* **87**(13), 131 (2006)
- R.K. Jaggi, R.A. Wolf, Self-consistent calculation of the motion of a sheet of ions in the magnetosphere. *J. Geophys. Res.* **78**(16), 2852–2866 (1973)
- T. Karlsson, G.T. Marklund, L.G. Blomberg, A. Mälkki, Subauroral electric fields observed by the Freja satellite: A statistical study. *J. Geophys. Res.* **103**(A3), 4327–4341 (1998)
- H. Khan, S.W.H. Cowley, Observations of the response time of high-latitude ionospheric convection to variations in the interplanetary magnetic field using EISCAT and IMP-8 data. *Ann. Geophys.* **17**(10), 1306–1335 (1999)
- B.A. Larsen, D.M. Klumpar, C. Gurgiolo, Correlation between plasmopause position and solar wind parameters. *J. Atmos. Sol.-Terr. Phys.* **69**(3), 334–340 (2007)
- J.F. Lemaire, K.I. Gringauz, *The Earth's Plasmasphere* (Cambridge University Press, New York, 1998), p. 372
- J.F. Lemaire, S.G. Batteux, I.N. Slypen, The influence of a southward and northward turning of the interplanetary magnetic field on the geomagnetic cut-off of cosmic rays, on the mirror points positions of geomagnetically trapped particles, and on their rate of precipitations in the atmosphere. *J. Atmos. Sol.-Terr. Phys.* **67**(7), 719–727 (2005)
- H. Matsui, J.M. Quinn, R.B. Torbert, V.K. Jordanova, W. Baumjohann, P.A. Puhl-Quinn, G. Paschmann, Electric field measurements in the inner magnetosphere by Cluster EDI. *J. Geophys. Res.* **108**(A9), 1352 (2003)
- H. Matsui, V.K. Jordanova, J.M. Quinn, R.B. Torbert, G. Paschmann, Derivation of electric potential patterns in the inner magnetosphere from Cluster EDI data: Initial results. *J. Geophys. Res.* **109**, A10202 (2004)
- H. Matsui, J.M. Quinn, R.B. Torbert, V.K. Jordanova, P.A. Puhl-Quinn, G. Paschmann, IMF B_y and seasonal dependences of the electric field in the inner magnetosphere. *Ann. Geophys.* **23**(7), 2671–2678 (2005)
- H. Matsui, P.A. Puhl-Quinn, V.K. Jordanova, Y. Khotyaintsev, P.-A. Lindqvist, R.B. Torbert, Derivation of inner magnetospheric electric field (UNH-IMEF) model using Cluster data set. *Ann. Geophys.* **26**(9), 2887–2898 (2008)

- N.C. Maynard, A.J. Chen, Isolated cold plasma regions: observations and their relation to possible production mechanisms. *J. Geophys. Res.* **80**(7), 1009–1013 (1975)
- N.C. Maynard, T.L. Aggson, J.P. Heppner, The plasmaspheric electric field as measured by ISEE 1. *J. Geophys. Res.* **88**(A5), 3991–4003 (1983)
- D.J. McComas, S.J. Bame, P. Barker, W.C. Feldman, J.L. Phillips, P. Riley, J.W. Griffée, Solar Wind Electron Proton Alpha Monitor (SWEPAM) for the Advanced Composition Explorer. *Space Sci. Rev.* **86**(1–4), 563–612 (1998)
- C.E. McIlwain, Substorm injection boundaries, in *Magnetospheric Physics*, ed. by B.M. McCormac (Reidel, Dordrecht, 1974), pp. 143–154
- F.A. McNeill, Frequency shifts on whistler mode signals from a stabilized VLF transmitter. *Radio Sci.* **2**, 589–594 (1967)
- E.V. Mishin, P.A. Puhl-Quinn, SAID: plasmaspheric short circuit of substorm injections. *Geophys. Res. Lett.* **34**, L24101 (2007)
- A. Nishida, Formation of plasmopause, or magnetospheric plasma knee, by the combined action of magnetospheric convection and plasma escape from the tail. *J. Geophys. Res.* **71**(23), 5669–5679 (1966)
- R.W. Nopper, R.L. Carovillano, Polar-equatorial coupling during magnetically active periods. *Geophys. Res. Lett.* **5**(8), 699–702 (1978)
- G. Paschmann, J.M. Quinn, R.B. Torbert, H. Vaith, C.E. McIlwain, G. Haerendel, O.H. Bauer, T. Bauer, W. Baumjohann, W. Fillius, M. Förster, S. Frey, E. Georgescu, S.S. Kerr, C.A. Kletzing, H. Matsui, P. Puhl-Quinn, E.C. Whipple, The electron drift instrument on Cluster: overview of first results. *Ann. Geophys.* **19**(10–12), 1273–1288 (2001)
- V. Pierrard, J. Goldstein, N. André, V.K. Jordanova, G.A. Kotova, J.F. Lemaire, M.W. Liemohn, H. Matsui, Recent progress in physics-based models of the plasmasphere. *Space Sci. Rev.* (2008). This issue
- P.A. Puhl-Quinn, H. Matsui, E. Mishin, C. Mouikis, L. Kistler, Y. Khotyaintsev, P.M.E. Décréau, E. Lucek, Cluster and DMSP observations of SAID electric fields. *J. Geophys. Res.* **112**, A05219 (2007)
- P.A. Puhl-Quinn, H. Matsui, V.K. Jordanova, Y. Khotyaintsev, P.-A. Lindqvist, An effort to derive an empirically based, inner-magnetospheric electric field model: Merging Cluster EDI and EFW data. *J. Atmos. Sol.-Terr. Phys.* **70**(2–4), 564–573 (2008)
- J.M. Quinn, G. Paschmann, N. Sckopke, V.K. Jordanova, H. Vaith, O.H. Bauer, W. Baumjohann, W. Fillius, G. Haerendel, S.S. Kerr, C.A. Kletzing, K. Lynch, C.E. McIlwain, R.B. Torbert, E.C. Whipple, EDI convection measurements at 5–6 R_E in the post-midnight region. *Ann. Geophys.* **17**(12), 1503–1512 (1999)
- J.M. Quinn, G. Paschmann, R.B. Torbert, H. Vaith, C.E. McIlwain, G. Haerendel, O. Bauer, T.M. Bauer, W. Baumjohann, W. Fillius, M. Foerster, S. Frey, E. Georgescu, S.S. Kerr, C.A. Kletzing, H. Matsui, P. Puhl-Quinn, E.C. Whipple, Cluster EDI convection measurements across the high-latitude plasma sheet boundary at midnight. *Ann. Geophys.* **19**(10–12), 1669–1681 (2001)
- B.W. Reinisch, M.B. Moldwin, R.E. Denton, D.L. Gallagher, H. Matsui, V. Pierrard, J. Tu, Augmented empirical models of plasmaspheric density and electric field using IMAGE and CLUSTER data. *Space Sci. Rev.* (2008). This issue
- H. Rème, C. Aoustin, J.M. Bosqued, I. Dandouras, B. Lavraud, J.A. Sauvaud, A. Barthe, J. Bouyssou, Th. Camus, O. Coeur-Joly, A. Cros, J. Cuvilo, F. Ducay, Y. Garbarowitz, J.L. Médale, E. Penou, H. Perrier, D. Romefort, J. Rouzaud, C. Vallat, D. Alcaydé, C. Jacquey, C. Mazelle, C. d'Uston, E. Möbius, L.M. Kistler, K. Crocker, M. Granoff, C. Mouikis, M. Popecki, M. Vosbury, B. Klecker, D. Hovestadt, H. Kucharek, E. Kuenneth, G. Paschmann, M. Scholer, N. Sckopke, E. Seidenschwang, C.W. Carlson, D.W. Curtis, C. Ingraham, R.P. Lin, J.P. McFadden, G.K. Parks, T. Phan, V. Formisano, E. Amata, M.B. Bavassano-Cattaneo, P. Baldetti, R. Bruno, G. Chionchio, A. Di Lellis, M.F. Marcucci, G. Pallochia, A. Korth, P.W. Daly, B. Graeve, H. Rosenbauer, V. Vasyliunas, M. McCarthy, M. Wilber, L. Eliasson, R. Lundin, S. Olsen, E.G. Shelley, S. Fuselier, A.G. Ghielmetti, W. Lennartsson, C.P. Escoubert, H. Balsiger, R. Friedel, J.-B. Cao, R.A. Kovrazhkin, I. Papamastorakis, R. Pellat, J. Scudder, B. Sonnerup, First multi-spacecraft ion measurements in and near the Earth's magnetosphere with the identical Cluster Ion Spectrometry (CIS) experiment. *Ann. Geophys.* **19**(10–12), 1303–1354 (2001)
- F.J. Rich, W.J. Burke, M.C. Kelley, M. Smiddy, Observations of field-aligned currents in association with strong convection electric fields at subauroral latitudes. *J. Geophys. Res.* **85**(A5), 2335–2340 (1980)
- A.J. Ridley, G. Lu, C.R. Clauer, V.O. Papitashvili, A statistical study of the ionospheric convection response to changing interplanetary magnetic field conditions using the assimilative mapping of ionospheric electrodynamics technique. *J. Geophys. Res.* **103**(A3), 4023–4039 (1998)
- D.E. Rowland, J.R. Wygant, Dependence of the large-scale, inner magnetospheric electric field on geomagnetic activity. *J. Geophys. Res.* **103**(A7), 14959–14964 (1998)
- B.R. Sandel, R.A. King, W.T. Forrester, D.L. Gallagher, A.L. Broadfoot, C.C. Curtis, Initial results from the IMAGE Extreme Ultraviolet imager. *Geophys. Res. Lett.* **28**(8), 1439–1442 (2001)

- J.M. Saxton, A.J. Smith, Quiet time plasmaspheric electric fields and plasmasphere–ionosphere coupling fluxes at $L = 2.5$. *Planet. Space Sci.* **37**(3), 283–293 (1989)
- S. Sazykin, R.W. Spiro, R.A. Wolf, F.R. Toffoletto, N. Tsyganenko, J. Goldstein, M.R. Hairston, Modeling inner magnetospheric electric fields: latest self-consistent results, in *The Inner Magnetosphere: Physics and Modeling*, ed. by T.I. Pulkkinen, N.A. Tsyganenko, R.H.W. Friedel. Geophysical Monograph Series, vol. 155 (American Geophysical Union, Washington, 2005), pp. 263–269
- L. Scherliess, B.G. Fejer, Storm time dependence of equatorial disturbance dynamo zonal electric fields. *J. Geophys. Res.* **102**(A11), 24037–24046 (1997)
- R.W. Schunk, P.M. Banks, W.J. Raitt, Effects of electric fields and other processes upon the nighttime high-latitude F layer. *J. Geophys. Res.* **81**(19), 3271–3282 (1976)
- M. Smiddy, M.C. Kelley, W. Burke, F. Rich, R. Sagalyn, B. Shuman, R. Hays, S. Lai, Intense poleward-directed electric fields near the ionospheric projection of the plasmapause. *Geophys. Res. Lett.* **4**(11), 543–546 (1977)
- A.J. Smith, K.H. Yearby, K. Bullough, J.M. Saxton, H.J. Strangeways, N.R. Thomson, Whistler mode signals from VLF transmitters observed at Faraday, Antarctica. *Mem. Nat. Inst. Polar Res.* **48**, 183–195 (1987)
- C.W. Smith, J. L'Heureux, N.F. Ness, M.H. Acuña, L.F. Burlaga, J. Scheifele, The ACE magnetic fields experiment. *Space Sci. Rev.* **86**(1–4), 613–632 (1998)
- R.L. Smith, Propagation Characteristics of whistlers trapped in field-aligned columns of enhanced ionization. *J. Geophys. Res.* **66**(11), 3699–3707 (1961)
- M. Spasojević, J. Goldstein, D.L. Carpenter, U.S. Inan, B.R. Sandel, M.B. Moldwin, B.W. Reinisch, Global response of the plasmasphere to a geomagnetic disturbance. *J. Geophys. Res.* **108**(A9), 1340 (2003)
- R.W. Spiro, R.A. Heelis, W.B. Hanson, Rapid subauroral ion drifts observed by Atmospheric Explorer C. *Geophys. Res. Lett.* **6**(8), 657–660 (1979)
- N.R. Thomson, Electric fields from whistler-mode Doppler shifts. *Planet. Space Sci.* **24**(5), 455–458 (1976)
- N.R. Thomson, Whistler mode signals: spectrographic group delays. *J. Geophys. Res.* **86**(A6), 4795–4802 (1981)
- N.A. Tsyganenko, A model of the near magnetosphere with a dawn–dusk asymmetry 1. Mathematical structure. *J. Geophys. Res.* **107**(A8), 1179 (2002)
- N.A. Tsyganenko, D.P. Stern, Modeling the global magnetic field of the large-scale Birkeland current systems. *J. Geophys. Res.* **101**(A12), 27187–27198 (1996)
- C. Vallat, I. Dandouras, M. Dunlop, A. Balogh, E. Lucek, G.K. Parks, M. Wilber, E.C. Roelof, G. Chanteur, H. Rème, First current density measurements in the ring current region using simultaneous multi-spacecraft CLUSTER-FGM data. *Ann. Geophys.* **23**(5), 1849–1865 (2005)
- V.M. Vasyliunas, Mathematical models of magnetospheric convection and its coupling to the ionosphere, in *Particles and Fields in the Magnetosphere*, ed. by B.M. McCormac (Reidel, Dordrecht, 1970), pp. 60–71
- R.H. Wand, J.V. Evans, Seasonal and magnetic activity variations of ionospheric electric fields over Millstone Hill. *J. Geophys. Res.* **86**(A1), 103–118 (1981)
- D.R. Weimer, An improved model of ionospheric electric potentials including substorm perturbations and application to the Geospace Environment Modeling November 24, 1996, event. *J. Geophys. Res.* **106**(A1), 407–416 (2001)
- R.A. Wolf, Effects of ionospheric conductivity on convective flow of plasma in the magnetosphere. *J. Geophys. Res.* **75**(25), 4677–4698 (1970)
- R.A. Wolf, S. Sazykin, X. Xing, R.W. Spiro, F.R. Toffoletto, D.L. DeZeeuw, T.I. Gombosi, J. Goldstein, Direct effects of the IMF on the inner magnetosphere, in *Inner Magnetosphere Interactions: New Perspectives from Imaging*, ed. by J.L. Burch, M. Schulz, H. Spence. Geophysical Monograph Series, vol. 159 (American Geophysical Union, Washington, 2005), pp. 127–140
- J. Wygant, D. Rowland, H.J. Singer, M. Temerin, F. Mozer, M.K. Hudson, Experimental evidence on the role of the large spatial scale electric field in creating the ring current. *J. Geophys. Res.* **103**(A12), 29527–29544 (1998)

Advances in Plasmaspheric Wave Research with CLUSTER and IMAGE Observations

Arnaud Masson · Ondrej Santolík · Donald L. Carpenter · Fabien Darrouzet ·
Pierrette M. E. Décréau · Farida El-Lemdani Mazouz · James L. Green ·
Sandrine Grimald · Mark B. Moldwin · František Němec · Vikas S. Sonwalkar

Originally published in the journal *Space Science Reviews*, Volume 145, Nos 1–2, 137–191.
DOI: [10.1007/s11214-009-9508-7](https://doi.org/10.1007/s11214-009-9508-7) © Springer Science+Business Media B.V. 2009

Abstract This paper highlights significant advances in plasmaspheric wave research with CLUSTER and IMAGE observations. This leap forward was made possible thanks to the new observational capabilities of these space missions. On one hand, the multipoint view of the four CLUSTER satellites, a unique capability, has enabled the estimation of wave characteristics impossible to derive from single spacecraft measurements. On the other hand, the IMAGE experiments have enabled to relate large-scale plasmaspheric density structures with

A. Masson (✉)

Science Operations Department, ESA/ESTEC, Keplerlaan 1, 2201-AZ Noordwijk, The Netherlands
e-mail: Arnaud.Masson@esa.int

O. Santolík · F. Němec

Faculty of Mathematics and Physics, Institute of Atmospheric Physics, Charles University, Praha,
Czech Republic

O. Santolík

e-mail: ondrej.santolik@mff.cuni.cz

F. Němec

e-mail: frantisek.nemec@mff.cuni.cz

D.L. Carpenter

Space, Telecommunications and Radioscience Laboratory (STAR), Stanford University, Stanford, CA,
USA
e-mail: dlc@nova.stanford.edu

F. Darrouzet

Belgian Institute for Space Aeronomy (BIRA-IASB), Brussels, Belgium
e-mail: Fabien.Darrouzet@oma.be

P.M.E. Décréau · F. El-Lemdani Mazouz

Laboratoire de Physique et Chimie de l'Environnement et de l'Espace (LPC2E), CNRS/Université
d'Orléans, Orléans, France

P.M.E. Décréau

e-mail: Pierrette.Decreau@cnrs-orleans.fr

F. El-Lemdani Mazouz

e-mail: mazouz@cnrs-orleans.fr

wave observations and provide radio soundings of the plasmasphere with unprecedented details. After a brief introduction on CLUSTER and IMAGE wave instrumentation, a series of sections, each dedicated to a specific type of plasmaspheric wave, put into context the recent advances obtained by these two revolutionary missions.

Keywords Plasmasphere · CLUSTER · IMAGE · Waves

1 Introduction

Plasma waves play a fundamental role in our geospace environment. In particular, they are key to understand the way mass and energy are transferred from the magnetotail to the plasmasphere, the ionosphere and finally the atmosphere. Particles propagating in the magnetosphere indeed lose or gain energy via wave–particle interactions while waves are amplified or damped. Particles can also be diffused into the loss cone and precipitate to lower altitudes. But how much each type of wave contributes to this process and under which geophysical conditions? In order to answer this difficult question, a complete overview on plasma waves is needed to understand how and under which conditions waves are generated and how they propagate from their source regions.

A key region where such waves are generated is the plasmasphere, either within it or in its near vicinity. Various waves are found in this region from a few mHz to a few MHz, either electrostatic or electromagnetic. Ground-based observatories and space missions since the 1950s have collected a wealth of information about them (e.g., Lemaire and Gringauz 1998, p. 94) but many questions remained open before the launch of the European Space Agency (ESA) CLUSTER and the NASA IMAGE space missions in 2000. A review of whistler-mode type waves observed within the plasmasphere by IMAGE and DE-1 spacecraft can be found in Green and Fung (2005) and Green et al. (2005b).

This paper highlights recent advances obtained by the CLUSTER and the IMAGE missions on plasmaspheric wave phenomena in the medium frequency (MF) range (300 kHz–3 MHz) down to the very low frequency (VLF) range (3–30 kHz), the ultra low frequency (ULF) range (300 Hz–3 kHz) and the extremely low frequency (ELF) range (3–30 Hz). Both missions can be seen as a step forward in our understanding of these phenomena. On one hand, the multipoint view of the four CLUSTER satellites, a unique capability, has enabled the estimation of wave characteristics impossible to derive from single spacecraft measurements.

J.L. Green
NASA Headquarters, Washington, DC, USA
e-mail: James.L.Green@nasa.gov

S. Grimald
Mullard Space Science Laboratory (MSSL), Dorking, UK
e-mail: sg2@mssl.ucl.ac.uk

M.B. Moldwin
Institute of Geophysics and Planetary Physics (IGPP), University of California, Los Angeles, CA, USA
e-mail: mmoldwin@igpp.ucla.edu

V.S. Sonwalkar
Department of Electrical and Computer Engineering, University of Alaska Fairbanks, Fairbanks, AK, USA
e-mail: ffvss@uaf.edu

This includes the first quantitative estimation in three dimensions of the size of wave source regions (Sect. 8), their localizations and beaming properties by triangulation (Sect. 4). On the other hand, IMAGE was the first mission dedicated to remotely study the plasmasphere. The Radio Plasma Imager (RPI) onboard IMAGE was the first radio sounder launched above the plasmasphere enabling the discovery of new wave echoes, the remote derivation of density profiles and the study of field-aligned irregularities in the plasmasphere with unprecedented details (Sects. 5, 6, 7 and 11). Together with RPI, the IMAGE spacecraft carried several imagers including an Extreme UltraViolet (EUV) imager able to capture, for the first time, the entire plasmasphere—distribution of helium ions—in a single shot, every 10 minutes. Thus, EUV enabled for the first time to monitor changes in the plasma distribution of the overall plasmasphere and the size and evolution of large-scale plasmaspheric structures such as notches and plumes. As described in Sect. 3, plasmaspheric notches observed by EUV have been studied with wave measurements made by GEOTAIL to learn more about the source of kilometric continuum. Similarly, CLUSTER data have been combined with observations from the DOUBLE STAR equatorial spacecraft TC-1, which routinely detected chorus emissions, as well as the low altitude DEMETER spacecraft. Recent advances on plasmaspheric hiss have also benefited from measurements of the DE-1 and CRRES satellites (Sect. 9).

This review is the result of a collective effort, gathering the contributions of several scientists. A brief introduction to the CLUSTER and IMAGE instruments related to plasmaspheric wave phenomena is given in Sect. 2 (see also De Keyser et al. 2009, this issue). Then a series of nine sections describes the advances obtained on six waves and three types of sounding echoes. These sections are organized by decreasing frequency of the waves/echoes. Section 3 is dedicated to IMAGE and GEOTAIL observations of kilometric continuum (KC), the high-frequency range of a more general wave phenomenon called non-thermal continuum (NTC). Advances on NTC at lower frequency observed with CLUSTER are detailed in Sect. 4. The next three sections describe what has been learned so far from Z-mode (Sect. 5), whistler-mode (Sect. 6) and proton cyclotron echoes (Sect. 7) received by the RPI instrument. The following three sections are dedicated to VLF and ELF waves impacting the relativistic electron content of the radiation belts, namely: chorus (Sect. 8), plasmaspheric and mid-latitude hisses (Sect. 9), equatorial noise (Sect. 10). The last section (Sect. 11) deals with the determination of the average ion mass in the plasmasphere using ground-based ULF wave diagnostics and electron density profiles derived from RPI soundings. It is worth noting that the locations of the source regions of most of these waves are strongly linked with the position of the plasmopause, itself strongly influenced by large-scale electric fields (Matsui et al. 2009, this issue).

A set of acronyms is used throughout this paper. The Earth radius will be referred as R_E , the magnetic local time as MLT and the magnetic latitude as $MLAT$. The localisation of wave phenomena in the plasmasphere are often expressed in terms of L -shell (McIlwain 1961). For example, “ $L = 4$ ” describes the set of the Earth’s magnetic field lines, which cross the magnetic equator at $4 R_E$ from the center of the Earth. The plasmasphere boundary layer introduced by Carpenter and Lemaire (2004) is often abbreviated as PBL. The acronyms of the main plasma frequencies used in this paper are the following: f_{pe} for the electron plasma frequency, f_{ce} for the electron cyclotron frequency also called electron gyrofrequency, f_{uh} and f_{lh} for the upper and lower hybrid frequencies. Finally, the acronyms of the CLUSTER satellites are C1, C2, C3 and C4, conventionally color-coded as black, red, green and magenta respectively.

2 CLUSTER and IMAGE Wave Instrumentation

2.1 CLUSTER Wave Instruments

The four CLUSTER satellites carry eleven identical instruments to measure the electric field, the magnetic field and the electron and ion distribution functions (Escoubet et al. 1997). Three of them are particularly suited to study wave phenomena within or in the vicinity of the plasmasphere (see Sects. 4, 8, 9 and 10):

- The Spatio-Temporal Analysis of Field Fluctuations (STAFF) instrument measures the magnetic field between 8 Hz and 4 kHz with a three axis search coil magnetometer. Its spectrum analyzer performs auto- and cross-correlations between the three magnetic components estimated by the search coil and the two electric components measured by the Electric Field and Wave (EFW) experiment (Gustafsson et al. 2001). From auto-correlations, the energy densities of electric and magnetic components are inferred, together with the electrostatic/electromagnetic nature of the observed waves. The cross-power spectra are needed to estimate the polarization characteristics of electromagnetic waves. The time resolution varies between 0.125 s and 4 s. For a complete description of STAFF, see Cornilleau-Wehrin et al. (2003).
- At higher frequencies (2–80 kHz), radio wave signals are continuously monitored by the active soundings and passive measurements of the Waves of HIGH frequency and Sounder for Probing of Electron density by Relaxation (WHISPER) instrument. The hardware of WHISPER mainly consists of a pulse transmitter, a wave receiver and a wave spectrum analyzer. Electric signals are acquired by the EFW electric antennas and only the onboard calculated fast fourier transform of the digital electric waveforms acquired are transmitted to the ground. A passive spectrum is recorded every 2.2 s and an active one every 52 s in normal mode for a frequency resolution of 162 Hz. Unlike a passive receiver, such a relaxation sounder enables to trigger plasma resonances when the medium does not show them naturally. For a detailed description of WHISPER, see Décr  au et al. (2001).
- The Wide-Band Data (WBD) experiment consists of a wide-band passive receiver, which provides electric waveforms with high time resolution in three possible frequency bands: 100 Hz to 9.5 kHz, 100 Hz to 19 kHz and 700 Hz to 77 kHz. The first frequency band is the one mostly operated to study plasmaspheric wave phenomena. It provides continuous waveforms with a 27.4 kHz sampling rate. When no soundings are performed, WBD electric data may be seen as high resolution zooms of WHISPER spectra. For a complete description of WBD, see Gurnett et al. (2001).

2.2 IMAGE Wave Related Phenomena Instruments

IMAGE (Imager for Magnetopause to Aurora Global Exploration) was the first satellite dedicated to imaging the Earth's inner magnetosphere (Burch 2000). It was equipped with six instruments, which use neutral atom, ultraviolet and radio imaging techniques. Two of these instruments have been particularly used to study wave phenomena in the plasmasphere (see Sects. 3, 5, 6, 7 and 11):

- The Extreme UltraViolet (EUV) imager was able to picture the entire plasmasphere in a single “snapshot”. It captured the helium ion (He^+) distribution outside Earth's shadow by measuring their emission line at 30.4 nm. He^+ is the second most abundant ion species in the plasmasphere accounting for roughly 20% of the plasma population while hydrogen ion (H^+), the most abundant one, has no optical emission. Because the plasmaspheric

He^+ emission is optically thin, the integrated column density of He^+ along the line-of-sight through the plasmasphere is directly proportional to the intensity of the emission. Moreover, the 30.4 nm emission line is the brightest ion emission from the plasmasphere and is spectrally isolated with a negligible background. For a full description of EUV, see Sandel et al. (2000).

- The Radio Plasma Imager (RPI) was a low-power radar with three dipole antennas. The two spin plane antennas were of lengths 370 m and 470 m tip-to-tip (Benson et al. 2003) while the one along the spin axis was 20 m long (spin rate: 0.5 rpm). The spin plane antennae are so far the longest ever deployed in space for such an instrument. RPI was able to locate regions of various plasma densities by observing radar echoes from the plasma. These echoes were reflected when the radio frequency was equal to the plasma frequency. By stepping the transmitted signal frequency through a wide frequency range (3 kHz–3 MHz), features of various plasma densities were observed. Derived densities, from those locations returning radio sounding echoes, were combined with line-of-sight images captured by EUV to infer quantitative, global distributions of plasmaspheric plasma. For a full description of RPI, see Reinisch et al. (2000).

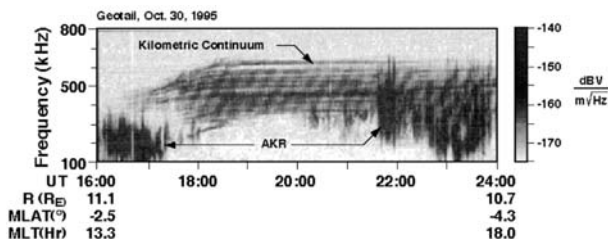
3 Kilometric Continuum

3.1 Previous Observations

Low frequency non-thermal continuum radiation has been observed extending from ~ 15 kHz to as high as ~ 300 kHz although it is rarely observed above ~ 90 kHz. However, Hashimoto et al. (1999) discovered a type of high frequency continuum radiation that is observed in the 100–800 kHz frequency range and as such, will escape the magnetosphere once it has been generated. These authors named this emission kilometric continuum (KC) due to the fact that the emission closely resembles the discrete emission band structure of the lower frequency non-thermal continuum in frequency–time spectrograms, has many other similar characteristics, and is probably generated by the same mechanism. It is important to note that KC is always observed without an accompanying lower frequency trapped component. The discovery of this high frequency KC emission has sparked considerable interest in further understanding various aspects of this radiation, what makes it different from its lower frequency counterpart, and the relationship with the plasmasphere and the plasmopause.

The spectrogram on Fig. 1 clearly shows the discrete emissions bands of KC extending from 17:00 to 24:00 UT. The frequency range for KC is approximately the frequency range of auroral kilometric radiation (AKR), but as shown in Fig. 1, there are significant differences that can be used to easily distinguish between these two emissions. KC has a narrow band structure over a number of discrete frequencies with time while AKR is observed to be a broader band emission with emissions extending over a large frequency range sporadically

Fig. 1 A frequency–time spectrogram of KC emissions measured on 30 October 1995 by the Plasma Wave Instrument (PWI) onboard GEOTAIL. (Adapted from Hashimoto et al. 1999)



and can be seen from 16:00 to 17:00 UT and from 21:30 to 24:00 UT in that spectrogram. In order to determine the source of the KC emission Hashimoto et al. (1999) performed direction finding using spin modulation of the emission. The resulting directions (shown in Fig. 4) with time, as correlated with the spectrogram data, indicated that the emission was generated from a very broad source region of the plasmasphere. Due to the high emission frequency of KC and its lack of correlation with geomagnetic activity, the source of KC was originally believed to lie deep within the plasmasphere (Hashimoto et al. 1999). Soon after these results were published, Carpenter et al. (2000) suggested that the source region for KC was coming from plasmaspheric cavities deep within the plasmasphere. From their analysis of over 1764 near-equatorial electron density profiles from CRRES, deep density troughs or cavities were observed on $\sim 13\%$ of the passes (Carpenter et al. 2000).

3.2 IMAGE Observations

It would take new observations of the plasmasphere from the EUV and RPI instruments onboard IMAGE along with simultaneous observations of KC from the Plasma Wave Instrument (PWI) onboard GEOTAIL to understand what plasmaspheric structures are the source region of KC thereby reaching a new understanding of plasmaspheric structure and dynamics. From the perspective of the CRRES observations the results of Carpenter et al. (2000) are compelling and appear to establish cavity-like structures in the plasmasphere. The IMAGE observations show them as plasmaspheric notches, which are the primary sources of KC.

Figure 2 illustrates that the location of the KC source region within a plasmaspheric notch, and the resulting emission cone pattern of the radiation, as shown from ray tracing calculations, is consistent with many of the previous observations. Figure 2a is a frequency–time spectrogram (passive mode) from PWI onboard GEOTAIL showing the banded structure of KC. The slanted vertical emissions are all Type III solar radio bursts. Figure 2b shows the magnetic longitude versus the equatorial radial distance of the plasmopause (derived from the right insert of the EUV image of the plasmasphere) and the GEOTAIL position during the KC observations of panel (a). As observed by EUV, plasmaspheric notch are large “bite-outs” in the plasmasphere in which plasma has largely been evacuated from a nominal plasmopause to somewhere deep within the plasmasphere (see also Darrouzet et al. 2009, this issue). This structure is significantly different than a density cavity of some size and depth within the plasmasphere. Figure 2b, left insert, presents a ray tracing analysis showing that the structure of the plasmaspheric notch has a significant effect on the shape of the resulting emission cone through refraction of the radiation generated from a small source region located at the magnetic equator deep within the plasmaspheric notch. The correspondence of KC observations with plasmaspheric notches, as shown in Fig. 2, is not an isolated instance. Green et al. (2004) found from a year’s worth of observations of GEOTAIL KC measurements and EUV images of plasmaspheric notches that the vast majority (94%) of the 87 cases studied showed this correspondence. Their results also showed that a density depletion or notch structure in the plasmasphere is typically a critical condition for the generation of KC but that the notch structures do not always provide the conditions necessary for the generation of the emission.

If KC source regions were located deep within a plasmaspheric notch, they can be used to further study the properties of the KC emission cone and the depth of notches. From a statistical analysis Fig. 3a shows the number of occurrences of KC observed by PWI onboard GEOTAIL, associated with plasmaspheric notches observed by EUV onboard IMAGE, with the magnetic longitudinal extent of the emission. This analysis assumed that the plasmaspheric notches were corotating with the plasmasphere. From these events the median in the

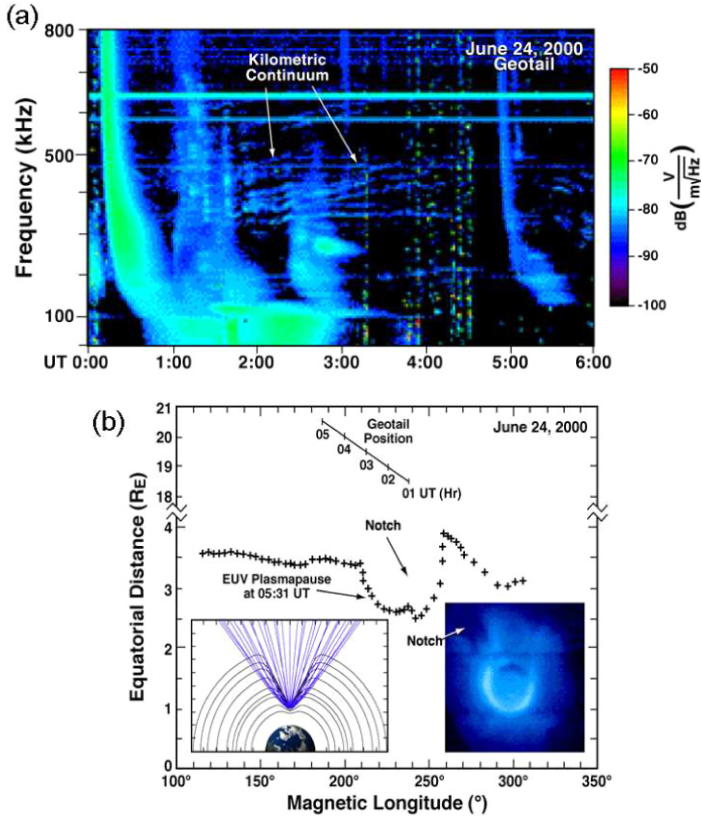
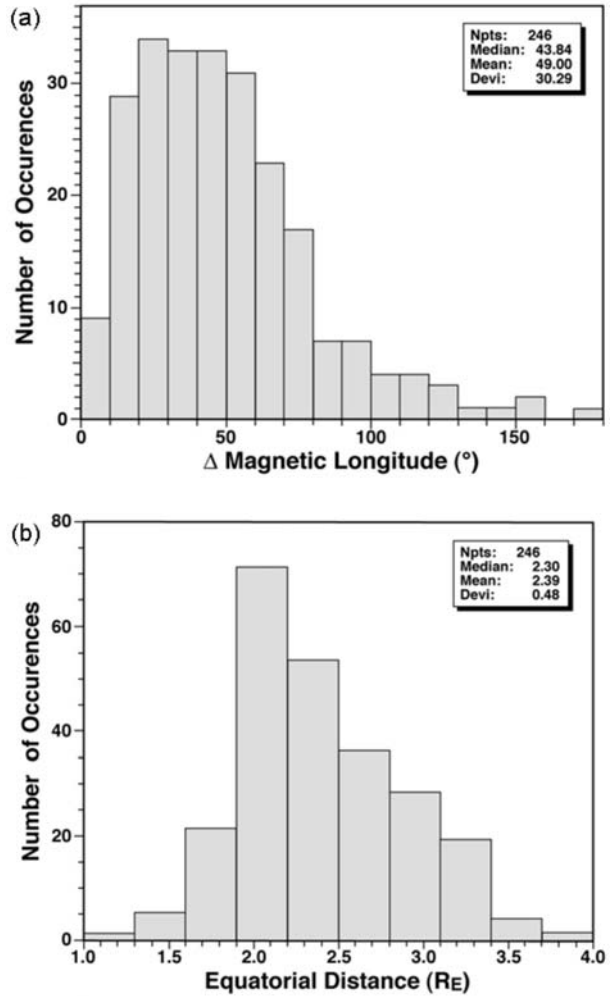


Fig. 2 (a) Kilometric continuum observations from PWI onboard GEOTAIL on 24 June 2000 from 00:00 to 06:00 UT. (b) The location of GEOTAIL during the KC observations and the extracted location of the plasmapause from IMAGE/EUV data are plotted in magnetic longitude versus equatorial distance. Inserted into panel (b) are model ray tracing calculations (*left*) and the EUV image data (*right*). (Adapted from Green et al. 2002, 2004)

longitudinal extent of the KC emission cone is $\sim 44^\circ$. Assuming an average plasmaspheric model and that KC is generated near the upper hybrid frequency an estimation of the depth of notch structures can be determined. Figure 3b shows the number of occurrences of the highest frequency source of the same KC events versus equatorial radial distance as an estimation of the deepest location of the KC source region. The distribution has a large peak with the median and the mean of the distribution at approximately the same equatorial radial distance of $2.4 R_E$.

Observations of the plasmasphere and KC emissions from the IMAGE instruments provide a new perspective in which previous CRRES and GEOTAIL measurements can be interpreted self-consistently to obtain additional insights into plasmaspheric dynamics and structure. Figure 4a shows the direction finding measurements of Hashimoto et al. (1999) indicating an extensive emission region for KC. Figures 4b–f illustrate how a small source region of KC deep within in a plasmaspheric notch can generate an emission cone that is also consistent with the direction finding measurements. The proposed plasmaspheric notch and the corresponding KC emission cone all corotate with the plasmasphere and are shown over the same 12-hour period. GEOTAIL was in the proposed emission cone and ob-

Fig. 3 (a) Number of occurrences of KC (observed by PWI onboard GEOTAIL) associated with plasmaspheric notches (observed by EUV onboard IMAGE) with the magnetic longitudinal extent of the emission. (b) Number of occurrences of the highest frequency source of the same KC events versus equatorial radial distance as an estimation of the deepest location of the KC source



served KC radiation starting at approximately 16:00 UT until 04:00 UT of the next day. During this time, the corotating plasmasphere sweeps the emission cone across and finally past the GEOTAIL spacecraft in a way completely consistent with the direction finding results.

Carpenter et al. (2000) reported significant density variations or cavities in the plasmasphere in which KC at many times were observed. The obvious confinement of KC to a cavity-like structure led those authors to propose that the radiation would be trapped in plasmaspheric cavities at frequencies below the density of the outer cavity wall. With the advent of the IMAGE mission a new interpretation has arisen to these observations as presented by Green et al. (2002). Figure 5a assumes a notch structure, like those that have been observed by EUV, would exist at the time of the CRRES observations (1990–1991). What is also shown is a typical CRRES orbit plotted in the same magnetic longitude and L coordinates. By using magnetic longitude and L coordinates the orbit of CRRES is then presented in the same reference frame as a corotating plasmasphere and notch structure. Figure 5b approxi-

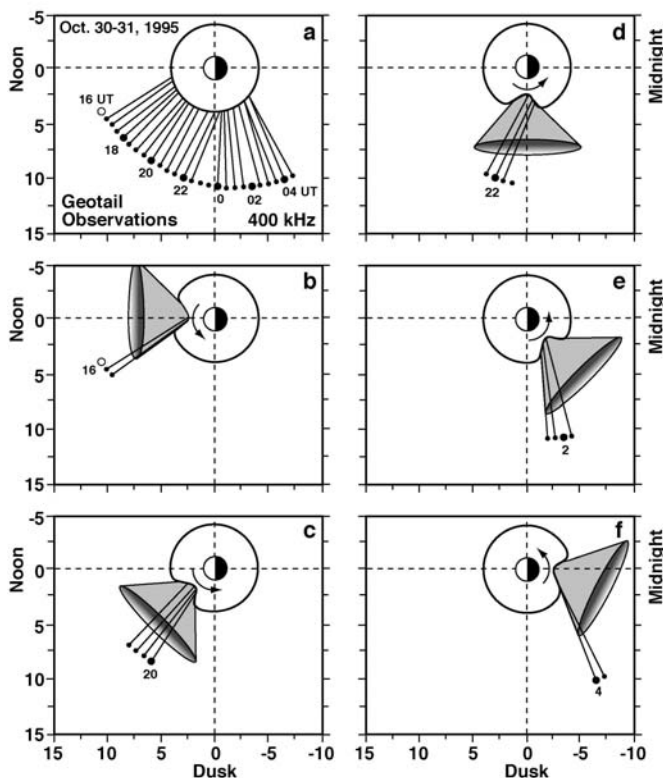


Fig. 4 Direction finding measurement (a) from Hashimoto et al. (1999) of KC at 400 kHz are reinterpreted as being completely consistent with respect to the source of KC emitted from a corotating plasmaspheric notch (b)–(f). (Adapted from Green et al. 2002)

mates the corresponding density structure that would be observed. The resulting qualitative density structure of the plasmaspheric notch, shown in Fig. 5b, is indistinguishable from the density cavities structures reported by Carpenter et al. (2000) and delineated as the upper hybrid resonance emissions. The CRRES observations of the confinement of KC to plasmaspheric cavities, reported by Carpenter et al. (2000) can then alternately be interpreted as KC radiation generated at the plasmopause, at the base of a plasmaspheric notch. Refraction near the source region of the steep density wall of the cavity would then confine the emission to within the notch structure as the ray tracing calculations have shown.

3.3 Conclusions

In summary, recent observations of KC from IMAGE and GEOTAIL have provided a new opportunity to understand plasmaspheric structures and dynamics. KC is always observed without an accompanying lower frequency trapped non-thermal continuum component but is almost certainly generated by the same emission mechanism. Plasmaspheric notches, reported earlier as deep plasmaspheric density cavities, are the source of KC. Much like the lower frequency non-thermal continuum emissions generated at the plasmopause, it is now well established that KC is generated at the newly established plasmopause, deep within a notch structure, near the magnetic equator. From the KC observations, plasmaspheric

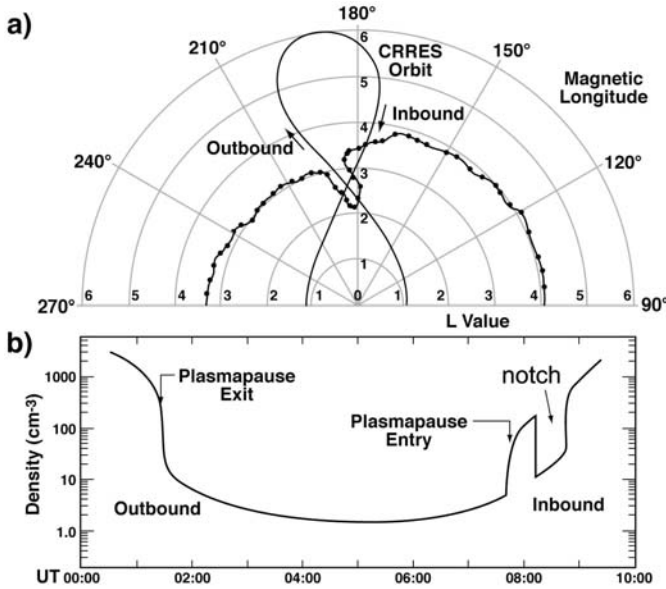


Fig. 5 (a) A typical orbit of the CRRES spacecraft in magnetic longitude and L value plotted over a typical plasmaspheric notch. (b) Approximate variation in density that would be observed assuming that a notch structure like this would exist at the time of CRRES

notches are typically as deep as $\sim 2 R_E$ but can be deeper within the plasmasphere. The average beam width of KC has been found to be $\sim 44^\circ$. The confinement of the KC emission cone, as shown by the ray tracing calculations, due to the steep densities of the walls of the notch structure therefore indicates that the average size of plasmaspheric notches must also be $\sim 44^\circ$ in longitude. Due to the strong relationship between KC and plasmaspheric notches, the long term set of observations of KC by GEOTAIL, extending more than 10 years could now be used to make long-term studies that relate to plasmaspheric notch structure and dynamics.

There are a number of outstanding questions that need to be addressed concerning the generation and propagation of the KC emissions such as:

- Is the motion of the plasmopause inwards coupled with a sufficiently large density gradient necessary and sufficient for the generation of KC? Is the free energy source necessary for the creation of electrostatic waves that are precursors to KC always present, or is the free energy source dependent on the state of the magnetosphere?
- KC often exhibits a banded frequency structure consistent with $(n + \frac{1}{2})f_{ce}$ source, but frequently the structure appears more complex. Can density ducts near the plasmopause explain the more complex structure or do other mechanisms need to be investigated like dynamic motion of the plasmasphere boundary layer?
- For highly disturbed times large changes occur in the inner magnetosphere magnetic field intensity. Can this change be detected remotely in the spectral band spacing of escaping KC? Can the analysis of the frequency structure of escaping KC indicate the state of the plasmasphere and the inner magnetosphere magnetic field?

4 Non-Thermal Continuum

4.1 CLUSTER Observations

4.1.1 Assets of the CLUSTER Mission

The WHISPER instrument measures electric field in a frequency range (2–80 kHz) well adapted to study non-thermal continuum (NTC) waves, both in the trapped frequency band (~ 1 –20 kHz) and in the lowest part of the escaping frequency band (~ 20 –200 kHz). The WBD instrument completes the view by providing high resolution snapshots and wave forms on a similar frequency range (0–77 kHz) when studying NTC waves. The major assets of the CLUSTER observatory about NTC studies are four fold.

- *Orbital characteristics.* The satellites travel from southern to northern hemisphere and cross or skim the plasmasphere around perigee at radial geocentric distances of $\sim 4.3 R_E$. Such orbit configurations provide excellent view points on the radio beams directly emitted at close distances, from equatorial plasmopause sources, when those are placed inward from the orbit, i.e., when the plasmasphere is sufficiently contracted. The polar orbit of CLUSTER near its perigee is comparable to that of DE-1 near its apogee, of geocentric distance $\sim 4.5 R_E$. CLUSTER platforms spin under different conditions than DE-1: Spin axis are normal to XY GSE (geocentric solar ecliptic) plane in CLUSTER case, whereas DE-1 spins in a cartwheel manner with the spin axis parallel to XY GSE plane. CLUSTER offers thus complementary views to those obtained by DE-1 in the past. As a consequence, typical DE-1 observations of NTC beaming properties can be reinterpreted in view of CLUSTER observations, in a similar manner IMAGE views help interpreting CRRES past observations of KC. Away from perigee, CLUSTER offers views at large distances from sources. The electric field measured there results often from a superposition of waves emitted from various and multiple sources. Detailed directivity estimations, made possible thanks to good frequency and time resolutions, help to distinguish each of the main source regions from the others.
- *Instrument performances.* A good time resolution (electric field spectra delivered at a rate of ~ 2 s) allows directivity measurements in 2-D (direction of the wave vector in the spin plane) at successive positions on the orbit (~ 300 km apart).
- *Multipoint observations.* Performances of the constellation vary according to spacecraft separation, which is varied along the mission phase. The spatio-temporal analysis of beam properties is made possible by comparing observations over small time intervals and small distances in space, i.e., during mission phases at small or medium separation (100 to 1000 km). In addition, compared wave vector directions lead to source localization. This can be done via triangulation, either from several spacecraft illuminated by the same beam at the same time (during mission phases at large separation), or from a single drifting spacecraft viewpoint, after stability of the beam has been assessed from compared observations.
- *Plasma diagnostic from a relaxation sounder.* In addition to spectral and geometric analysis of radiated beams, CLUSTER offers the possibility of analyzing intense electrostatic waves, which are potential sources of non-thermal radiations.

This section focuses on observations of NTC radiations (excluding trapped continuum signatures) when CLUSTER is either in the outer plasmasphere or in the polar cap region. The tetrahedron shape achieved at large geocentric distances turns to an elongated shape near perigee. Figure 6a displays the near Earth magnetic field configuration and the orbit

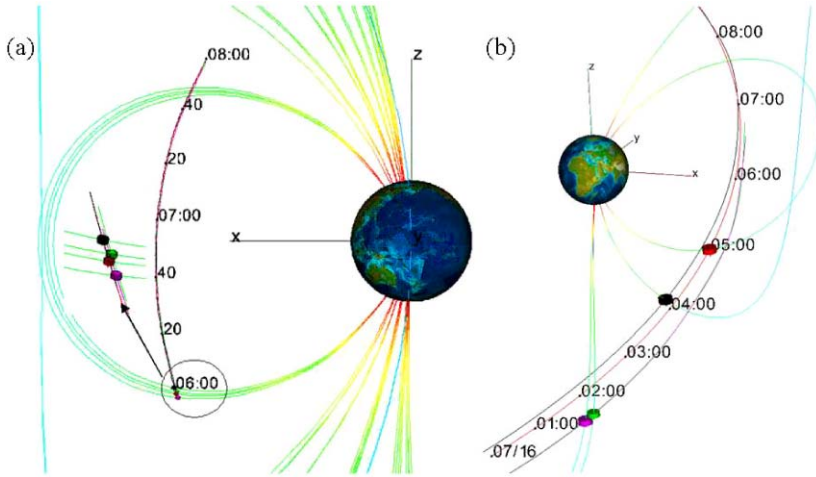


Fig. 6 Orbit tracks and constellation produced with the Orbit Visualization Tool (OVT, <http://ovt.irfu.se>). Magnetic field lines intercepting each satellite are shown, as well as a shell of outermost magnetospheric field lines. The model field is a combination of IGRF internal field model and Tsyganenko 87 external field model. The colour code along field line indicates magnetic field intensity. (a) 26 September 2003, 06:00–08:00 UT, small separation mission phase (200 km), solar magnetic (SM) coordinate system. (b) 16 July 2005, 01:00–08:00 UT, multi-scale mission phase (10 000 km and 1000 km), geocentric solar magnetospheric (GSM) coordinate system

of the four satellites in solar magnetic (SM) coordinates on 26 September 2003. The small spacecraft separation (200 km) does not allow distinguishing the four orbits, nor the four spacecraft, which travel from South to North. From the enlarged CLUSTER configuration shown in an insert, C1 (black) is ahead of C3 (green), C2 (red) and C4 (magenta). Figure 6b illustrates a multi-scale configuration on 16 July 2005, when the pair C3 and C4 (1000 km separation) is in the polar cap. At the same time, C1 is in the outer plasmasphere and C2 near the plasmopause.

4.1.2 Typical Spectral Signatures

Trapped continuum signatures are commonly observed in the low frequency range of WHISPER (Décréau et al. 2004). They present the smooth, large band spectral features already reported from the first observations (Gurnett 1975). It is in the “escaping continuum” frequency range ($> \sim 20$ kHz) that the CLUSTER multi-view offers the best opportunities to improve our understanding of this radio emission. In this range, NTC waves can be classified according to four main types: (i) “equatorial spots”, (ii) “narrow band elements”, (iii) “continuum enhancements” and (iv) “wide banded emissions”. Those names refer to spectral signatures, which depend on two elements: the source on one hand (position, beaming properties and main frequencies) and the observatory on the other hand (position and movement). When the observatory moves rapidly in the vicinity of a source, spectral signatures inform about position and beaming properties of the source. In contrast, a remote observatory can be illuminated by a large region, hence perceive movements of sources via the spectral signatures it records. Visions about time or space in the resulting spectrograms are thus created by one or the other of the protagonists.

The first type of NTC spectral signature, the equatorial spot, is an emission limited in time (~ 30 minutes) and frequency (~ 10 – 30 kHz). In the spectrogram on Fig. 7a, harmonics

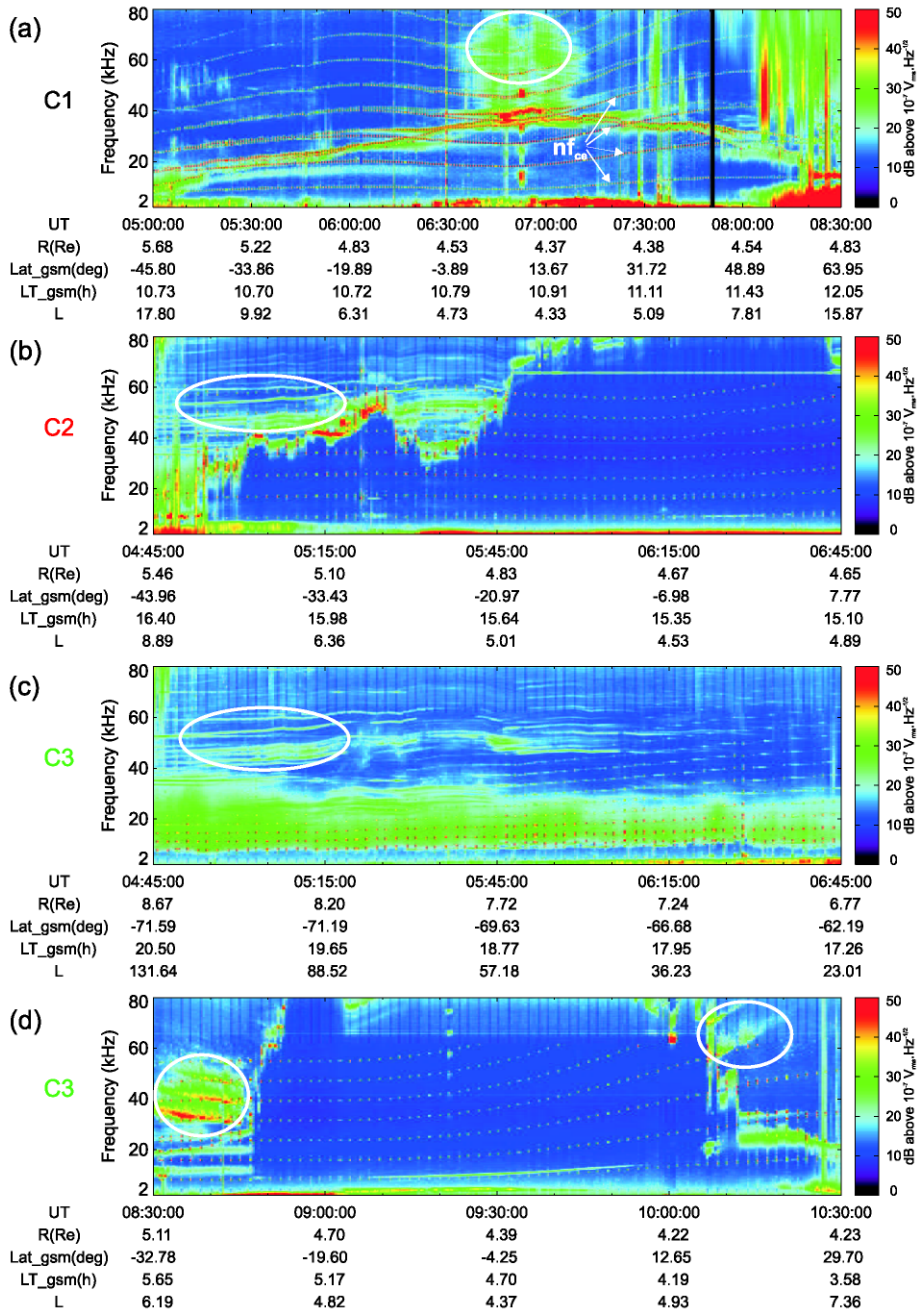


Fig. 7 Three main types of NTC spectral signatures (*white ovals*) observed with CLUSTER near perigee. (a) 26 September 2003, “equatorial spots”; (b)–(c) 16 July 2005, “narrow band elements”; (d) 30 December 2003, “wide banded emissions”. CLUSTER constellation is shown in Fig. 6a for events presented in panels (a) and (d), in Fig. 6b for events presented in panels (b) and (c). L parameter values are calculated from the same magnetic field model than used by the OVT tool producing displays shown in Fig. 6.

of the electron gyrofrequency f_{ce} , triggered by regular sounding operations, appear as intense electrostatic emissions (small red points at $\sim 8\text{--}12$ kHz and harmonics). Other resonant frequencies (red points between electron gyroharmonics) are the electron plasma frequency f_{pe} and the upper hybrid frequency f_{uh} . Their frequency position follows the increase of f_{pe} from 10 to 35 kHz (05:00–06:55 UT), and its decrease from 35 to 15 kHz (06:55–08:30 UT). The magnetic equator, at $\sim 06:55$ UT, can be inferred by brief encounters of natural electrostatic emissions at $(n + \frac{1}{2})f_{ce}$ below f_{pe} . It is worth noting that recent advances on electrostatic wave emissions at $(n + \frac{1}{2})f_{ce}$ in the equatorial plasmasphere have been derived from CLUSTER data and detailed in El-Lemdani Mazouz et al. (2009). NTC emissions (above f_{pe} , in the frequency range 35–80 kHz) are observed on both sides of the equator between 06:35 and 07:10 UT. Time intervals when similar NTC spectral features are observed correspond most often to CLUSTER located near equator. We shall call this type of NTC emissions equatorial spot in short, standing for “near equatorial time-frequency intervals of radio emissions”. This is a case when the observatory moves rapidly in the vicinity of a source region and spectral signatures inform about beaming properties.

The second type is the classical narrow band element form (Kurth et al. 1981), covering about 1 kHz or less. Such emissions appear often in series of waves at frequencies separated by a few kHz from each other, evolving together during time intervals of long duration (up to several hours). Spacing between frequencies f_n of related elements are arranged in quasi harmonic form, $f_n = (n + d)f_{ce}$ with $0 < d < 1$ and n an integer, f_{ce} being interpreted as the gyrofrequency at the source (Kurth 1982; Gough 1982). Figures 7b–c display narrow band NTC elements (40–60 kHz) observed identically and simultaneously (04:45–05:40 UT) by two different CLUSTER spacecraft located at different positions: C2 enters in the plasmasphere, while C3 is placed in the polar cap (see Fig. 6b for the configuration of the constellation).

The third type of NTC spectral form, the continuum enhancement, has been reported for the first time by Gough (1982). It develops after the start of an electron injection event, its spectral shape evolving over duration of one to several hours (Kasaba et al. 1998). Analysis of one example, observed by CLUSTER in the night sector, indicates that a region source of large dimension might be involved (Décréau et al. 2004). This form has not yet been identified by CLUSTER at perigee, either because it travels too fast in comparison to the typical time scale of the event, or because it is not placed at sufficient distance to be illuminated adequately by the various sources, which are likely at play. Indeed, the continuum enhancement scenario proposed by Gough (1982) and Kasaba et al. (1998) involves injection of electrons followed by a plasmopause inward convection. The wave sources (which are where the injection meets the plasmopause) drift likely inward and eastward. This is a case when, in order to be illuminated by the large region engulfing all successive positions of the sources, the observatory has to be remote. Numerous observations of continuum enhancements, often associated with AKR emissions, have been done by CLUSTER on the outermost part of its orbit. Some observations are also available from over the polar cap.

A fourth spectral form, the wide banded emission, has been observed for the first time with CLUSTER (Grimald et al. 2008). It consists of one or several banded emissions with a frequency separation (5–10 kHz) of the order of f_{ce} values encountered at plasmopause. When several bands are observed, they peak at harmonics of the same frequency, interpreted to be the gyrofrequency at the source. For the event presented in Fig. 7d, they appear when the observing satellite approaches the flank of a thick plasmasphere, bounded by a narrow plasmopause. Events of this type have been observed only a few times per year. They are always associated with density steps of large amplitude encountered over short distances. Some are observed on the flanks of a cusp.

4.2 Analysis

4.2.1 Beam Stability

As noted above, the limited time duration of CLUSTER observing the equatorial spots is not due to inherent time duration of the emission, but mainly to the time evolution of CLUSTER view point over the source. Indeed, a satellite observes the radiation only when it is placed inside the illumination cone formed in space by the radiated beams. From a small constellation skimming the outer plasmasphere, compared wave intensities measured at fixed frequency on the four spacecraft indicate most often that the differences observed on intensity versus time profiles are simply due to time shifts between spacecraft progressing along orbit tracks, generally close to each other. When crossing a beam illuminating a limited cone angle in space, each spacecraft observes an increase of intensity followed by a decrease (Fig. 8a). Times of maximum intensity correspond to times when the spacecraft reaches the central part of the beam. When intensities are plotted with respect to *MLAT* (Fig. 8b), their maxima are aligned with each other, indicating that the beam did not move significantly between the first and the last crossing, which are separated by 5–10 minutes. A different behaviour is obtained when time variations at the source are taking place, as illustrated in Fig. 9. For this event, narrow band elements contribute to an equatorial spot observed from $\sim 11:00$ to $11:30$ UT in the 60–80 kHz frequency band. The frequencies of elements are modulated at a time period of about 6 minutes. The bottom panel of Fig. 9, comparing intensities measured by the four spacecraft at 80 kHz, indicates three consecutive increases of intensity observed simultaneously on the four spacecraft in the southern hemisphere. Such a signature indicates a temporal evolution of the radiation properties. In contrast, intensity versus time profiles observed in the northern hemisphere (peak intensities observed as shifted in time) correspond to a beam stable in time and space.

4.2.2 Beam Geometry

The multipoint view obtained from the CLUSTER constellation yields, at least partially, an image of beam contours in space. This capacity enables to test one theory of NTC beam formation, under which the beam geometry is constrained. Indeed, in the frame of the radio window theory examined and proposed by Jones (1980), mode coupling occurs between intense upper hybrid waves produced by a warm loss-cone component of energetic electron distribution and the cold-plasma Z-mode branch of the dispersion relation. Propagation into

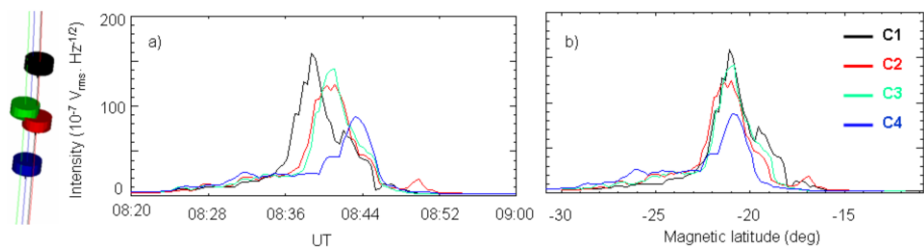


Fig. 8 Compared intensity variations at constant frequency (39.5 kHz), measured respectively by the four CLUSTER spacecraft when progressing along their orbit on 30 December 2003, (a) as a function of UT time, (b) as a function of magnetic latitude (constellation configuration shown at left). The corresponding beam is stable in space. (Adapted from Grimald et al. 2008)

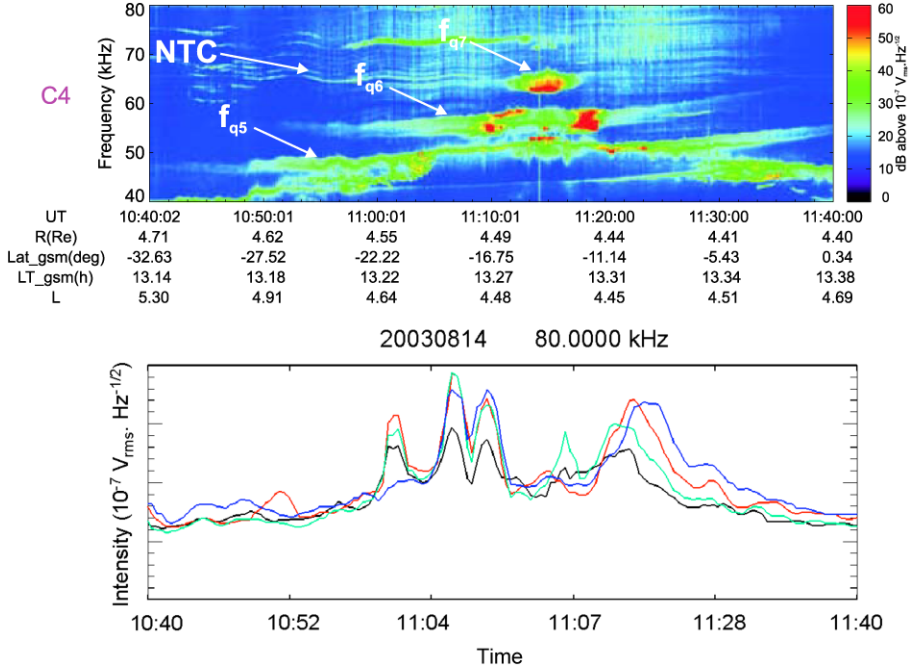


Fig. 9 (Top) Dynamic time electric field spectrogram of C4 for the 14 August 2003 event. Geomagnetic equator is crossed at about 11:15 UT (latitude is not expressed in SM coordinate system). NTC elements (electromagnetic waves) and a local emission (electrostatic Bernstein mode) are pointed with *arrows*. (Bottom) Compared intensity variations at a given frequency with *colour codes* and constellation configuration as for the event shown in Fig. 8

a slowly varying plasma density medium allows direct coupling of energy to L-O-mode waves, which propagate to lower density regions and beam away from the magnetic equator. According to this theory, the inclination angle of the beam with respect to magnetic equator is fixed by the ratio f_{ce}/f_{pe} of characteristic frequencies at the source. The source, placed at the equator (minimum in magnetic field value) radiates two beams, one in each hemisphere. The cone angle attached to each beam is typically $\sim 1\text{--}2^\circ$ large (see Fig. 10a adapted from Jones 1982).

A test of validity of radio window theory (Grimald et al. 2007) has been performed in the case event presented in Fig. 7a, where the equatorial spot NTC form displays two intensity peaks, placed symmetrically to the magnetic equator, a feature, which could be attributed to the symmetrical beams displayed in Fig. 10a. This study could not draw a definitive conclusion about the validity of Jones theory. Indeed, the radio theory is compatible with quantitative observed beaming properties of a selected frequency element when an ad-hoc choice of source position in latitude is made. Although the latitude obtained thus (less than 1° off the equator) is in the expected range, the complete picture does not fit the narrowness of the beam indicated by the theory. Figure 10c displays orientations of the ray path of the 70 kHz NTC wave measured from intensity spin modulation at successive positions of the observing spacecraft on their orbit (curved arrows). Ray path orientations and orbit paths are shown projected onto the XY GSE plane, parallel to the spin plane. One insight in the third dimension is provided by the choice of two different line colours: Ray paths obtained from C4 in southern hemisphere are plotted in blue, whereas ray paths obtained from C2 in

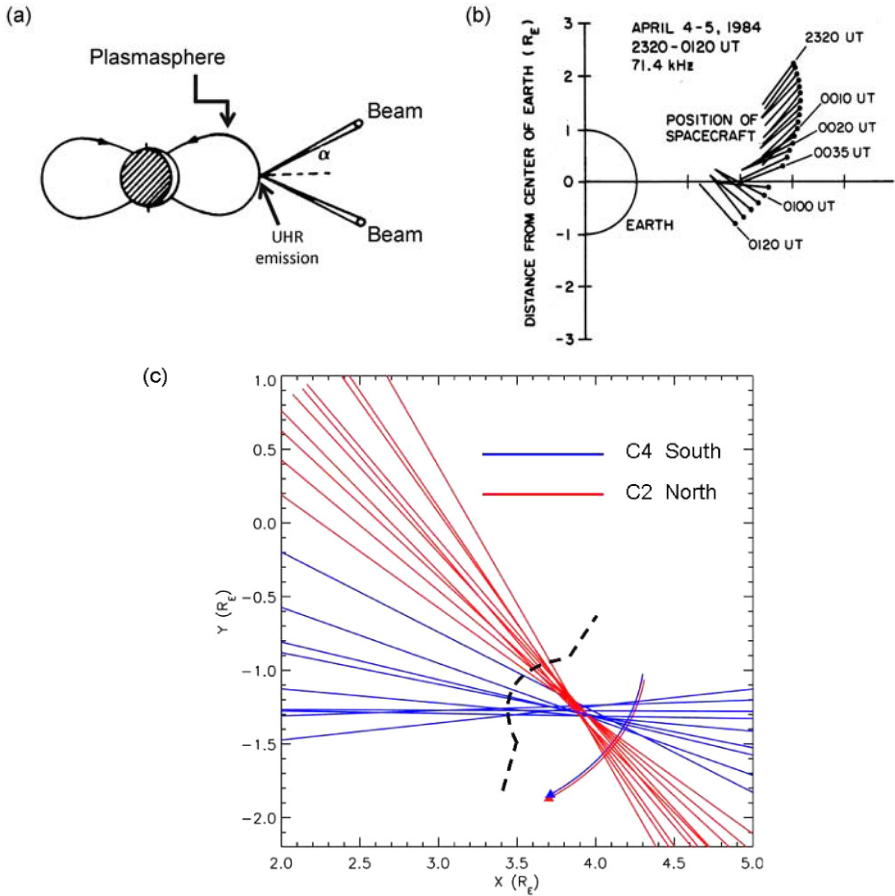


Fig. 10 Beaming properties of NTC waves: (a) configuration of NTC beams expected from the radio-window theory (adapted from Jones 1982); (b) ray path directions in a meridian plane derived from directivity measurements onboard DE-1 (adapted from Morgan and Gurnett 1991); (c) ray path directions of NTC element at 69 kHz derived from CLUSTER and drawn in blue for C4 in the southern hemisphere, in red for C2 in the northern hemisphere (in XY GSE plane); sketch of a possible associated plasmopause shape (dotted line); orbit elements of C2 and C4 shown by the red and blue curves with arrows. (Adapted from Grimald et al. 2007)

northern hemisphere are plotted in red. In this 2-D view, all ray paths point towards the same region, but the point of view drifts from negative ($\sim -4^\circ$) to positive ($\sim +4^\circ$) latitudes along the orbit element considered, which at the same time drifts of about 8° in GSE longitude (but less, below 3° , in SM longitude, corresponding to MLT). As a consequence, the sketch of Fig. 10a, which represents a meridian cut at fixed MLT, cannot be directly compared to observations. Narrow beams (of cone angle $< 1^\circ$) emitted from a single source could not be visible over such a large portion of the orbit. Furthermore, complementary observations detailed in Grimald et al. (2007) indicate that the orbit track is illuminated by several sources of small dimension and various frequencies, placed at different latitudes along roughly the same magnetic field tube, hence concentrated, after projection to the XY GSE plane, within a small area.

4.3 Interpretation

4.3.1 Main NTC Form (*Quasi Equatorial Sources*)

Close up View on Sources Intense electrostatic emissions at NTC frequencies are encountered in the plasmopause region (Kurth et al. 1981). They are thus considered as potential electrostatic sources radiating energy (likely by wave decay or linear conversion) in the form of continuum waves of electromagnetic nature. No simultaneous observations of such a NTC source by one CLUSTER spacecraft and of the beam emitted from that source by another spacecraft has been found. This is due to the 3-D nature of the geometry involved, the small size of sources and the limited extension of the beam near sources. Then, it has not been possible so far to directly test a generation mechanism by comparing wave characteristics at both ends of the process.

The spectrogram of Fig. 9 provides nevertheless an insight on the frequency, size and position of candidate electrostatic sources in the equatorial region. The magnetic equator is crossed at 11:15 UT when f_{pe} (narrow feature in yellow) culminates at ~ 53 kHz. Above that frequency, WHISPER observes banded electrostatic emissions displaying upper frequency cut offs at the Bernstein frequencies f_q characteristic of the harmonic band considered. The intense spots (in red) showing up in the spectrogram of Fig. 9, one at ~ 64 kHz at the equator, and two at ~ 55 kHz on both sides of the equator, belong to the bands associated to Bernstein modes, the $[6f_{ce}-f_{q6}]$ frequency interval in the latter case and the $[7f_{ce}-f_{q7}]$ interval in the former case. These spots are candidate sources, which could participate to the generation mechanism proposed by R  nnmark (1985). Lastly, an event observed on 30 May 2003 by Canu et al. (2006), where NTC frequencies oscillate with time at similar periods than the central frequency of local Bernstein band series, completes this view. The authors interpretation is that Bernstein emissions probably play a role in the generation of NTC radiations.

A striking characteristic of NTC spectral signatures observed near the plasmopause is their splitting in fine structures. This property has been pointed out by detailed analysis of the waves forming the equatorial spots (Grimald et al. 2007). Complex spectral features of NTC observed in Fig. 9 can be interpreted as produced by a superposition of beams emitted from many sources, placed at different locations along the plasmopause and near the equator.

Ray path observations made by DE-1 while skimming the outer plasmasphere (Morgan and Gurnett 1991) can be usefully compared to CLUSTER observations (Grimald et al. 2007). Both views are complementary: DE-1 provides a view in a meridian plane and CLUSTER in the equatorial plane. The ray path directions obtained from DE-1 are more or less parallel to each other during intervals of significant duration, here from 23:20 to 00:20 UT (Fig. 10b). This could be due to sources placed in the equatorial plane at various geocentric distances. An alternative explanation is that the topology observed is due to sources placed at similar geocentric distances but at different latitudes along a single flux tube. The latter interpretation makes better sense in view of CLUSTER observations, which indicate a source region concentrated at a single geocentric distance and emitting beams inside a cone of large longitudinal extent, $\sim 40^\circ$ (Fig. 10c). Such a large extent, similar to longitudinal cone angle of KC radiations (Fig. 4), cannot be envisaged to be produced by a plasmopause boundary smooth in azimuth. This ray path topology is not unique but representative of similar events. It could be due to a particular shape of the plasmopause, known to display density irregularities in azimuth (Darrouzet et al. 2006). In particular, ray paths being likely aligned with density gradients (Jones 1982), a small bite-out structure, sketched

in Fig. 10c, could act as a collimator concentrating radiations. This scenario would be similar to the interpretation of KC emissions proposed by Green et al. (2002) and illustrated in Fig. 2.

Propagation Effects Statistics of occurrence at CLUSTER orbit of equatorial spots and narrow band elements indicate that they are probably signatures of the same phenomena, observed from different perspectives (Grimald 2007). The underlying scenario implies wave propagation. A ray tracing study considers the fate of waves emitted from equatorial plasmapause at a given inclination angle with respect to the equatorial plane, after they have been reflected by the magnetopause density wall (Green and Boardsen 1999). Ray tracing indicates latitudinal confinement of NTC radiation emitted at small inclination angles, since those waves do not move at large distance from the equatorial plane and stay trapped between the plasmapause and magnetopause density walls. In contrast, rays emitted at higher inclination angles bounce at magnetopause, but escape a second bounce at plasmapause as they travel above the poleward plasmasphere regions. Such a scenario explains observations of narrow band elements by C3 during the event of 16 July 2005 (spectrogram in Fig. 7c): C3 is placed above the South Pole, Fig. 6b showing CLUSTER satellites positions at 05:00 UT. At that time, C3 observes a narrow band element at ~ 60 kHz, observed more faintly by C2 at about 40° south latitude (Fig. 7b). Directivity analysis indicates that corresponding ray paths point both towards dayside magnetopause. The interpretation proposed in Grimald (2007) is that a common source placed near equatorial plasmapause emits a 60 kHz wave in a beam of large enough latitudinal cone angle to illuminate the four CLUSTER spacecraft after a bounce at magnetopause (spectrograms for C1 and C4, not shown, display similar narrow band spectral features). This case event demonstrates that narrow band NTC elements can illuminate large regions of the magnetosphere placed at significant distance from the equator without losing their characteristic spectral features. The magnetopause-magnetosheath boundary, populated by complex density structures, could play a role in angle scattering. According to the above scenario, the cohesion in latitude and frequency of the equatorial spots observed in the near equatorial outer plasmasphere is lost during propagation. Only the elements emitted at highest inclination are preserved from being trapped and superposed to radiations from other sources. Among those, only the elements emitted at highest intensity would keep a sufficient level to be observable after propagation.

4.3.2 Wide Banded NTC Emissions

NTC wide banded emissions (Fig. 7d) display a spectral pattern shown in better details in Fig. 11. They present two remarkable characteristic signatures, which, combined, allow

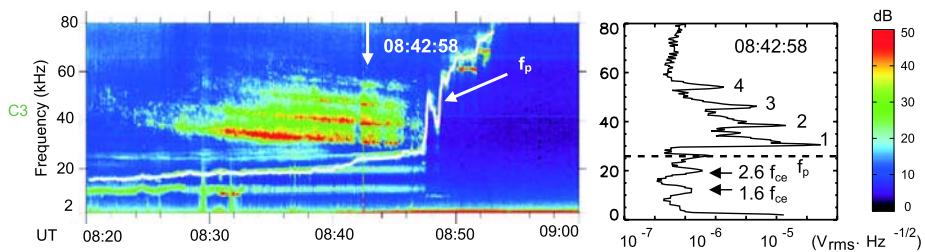


Fig. 11 WHISPER spectrogram on 30 December 2003 and individual frequency spectrum displaying four peaks above plasma frequency. (Adapted from Grimald et al. 2008)

to propose a precise location of the corresponding radio sources. The first characteristic signature is their frequency pattern, peaking at exact harmonics of a fundamental frequency, which is interpreted as the gyrofrequency at the source region. The second characteristic is the evolution of the fundamental frequency with respect to the view point of the observer, indicating that the NTC beams are narrowly collimated. During this event, C3 travels in the outer plasmasphere region, southern hemisphere, from 08:20 to 08:47 UT, at which time it crosses the plasmopause (Fig. 11). The other satellites cross the plasmopause within a few minutes time span. They form together a constellation of small size, C1 and C4 being ~ 1200 km apart. The crossing area is placed at a $\sim 4.85 R_E$ geocentric distance, at $MLAT \approx 20^\circ$ and $\sim 04:36$ MLT. The f_{pe} measured by C3, plotted as a white solid line over the spectrogram, follows large density irregularities at plasmopause crossing, which can thus be better qualified as a structured plasmasphere boundary layer, PBL (Carpenter and Lemaire 2004). NTC emissions, present from $\sim 08:27$ to 08:47 UT, form three clear bands (a fourth one is visible after 08:40 UT). An individual spectrum is shown on the right panel, where peaks of the four bands are labelled from 1 to 4. Compared observations of the four satellites demonstrate that the NTC beams encountered are stable in time and confirm that they are limited to a cone of small angle.

All peaks are placed at exact harmonics of a value df , which slowly decreases with increasing $MLAT$ of observation. The frequency pattern observed contrasts with previous views, where frequencies emitted in a region of gyrofrequency f_{ce} are supposed to satisfy $f_n \approx (n + \frac{1}{2})f_{ce}$ (Kurth 1982), not $f_n \approx nf_{ce}$. An additional experimental fact is the evolution of the NTC fundamental frequency encountered along the orbit element. The frequency df of the spectral pattern is higher than local gyrofrequencies and the difference progressively diminishes, until df meets local gyrofrequency at the plasmopause. This behaviour is the same in all observations of NTC features of the wide banded form. The spectrogram in Fig. 7d shows indeed another example in the northern plasmopause crossing of the same orbit. The interpretation proposed by Grimald et al. (2008) is that sources are placed at the intersection of the plasmopause magnetic shell (at $L \approx 5.5$ in this case) and of iso-gyrofrequency surfaces, leading to source positions at $MLAT \approx 20^\circ$. This latitude is clearly higher than in the generally accepted view of equatorial sources. Together with the uncommon spectral characteristics (wide banded emissions, peaks at exact harmonics), it is possible that the generation mechanism is specific to that particular type of continuum radiation. A theory describing direct generation of electromagnetic O-mode emission at exact electron gyroharmonics, via mildly energetic electron beams in highly dense and warm plasma, has been proposed by Farrell (2001). CLUSTER observations could be related to this mechanism, and thus be a first confirmation of it.

5 Z-Mode

5.1 Active Z-Mode Experiments in Space Plasmas

Many spacecraft have generated Z-mode waves in the ionosphere and magnetosphere using radio sounders, among them the ISIS satellites and the OEDIPUS sounding rockets (e.g., Benson et al. 2006). This work has provided a powerful complement to observations of Z-mode waves of magnetospheric origin performed on rockets and satellites using plasma wave receivers (e.g., LaBelle and Treumann 2002). In this section we describe Z-mode experiments from IMAGE that provide new perspectives on the use of radio sounding at altitudes exceeding those accessible to previous missions and under comparatively more favorable conditions on transmitted frequencies and maximum observable echo delay.

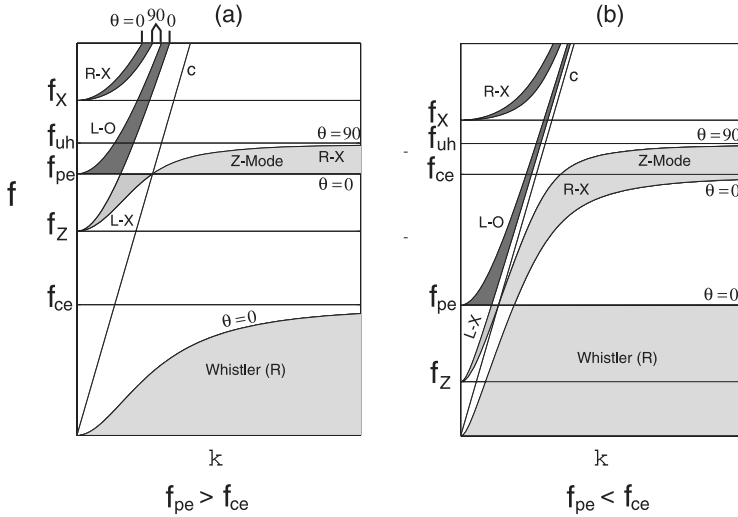


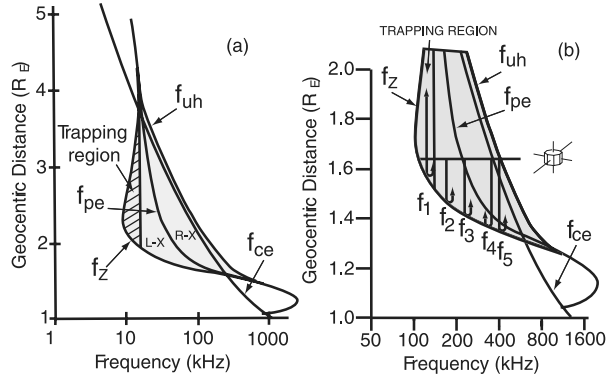
Fig. 12 Dispersion diagrams for waves in a cold plasma illustrating two conditions on the ratio of electron plasma frequency to electron gyrofrequency: (a) $f_{pe} > f_{ce}$ and (b) $f_{pe} < f_{ce}$. (Adapted from Goertz and Strangeway 1995)

By way of introduction to the IMAGE experiments, we show in Fig. 12 a schematic diagram that represents the dispersion relation for waves in a cold plasma, i.e., the scalar relation expressing the angular frequency ω in terms of the propagation vector $\mathbf{k}$, which is related to the refractive index $\mathbf{n}$ by $\mathbf{n} = \mathbf{k}c/\omega$. The diagrams represent two conditions on f_{pe}/f_{ce} , the ratio of electron plasma frequency to electron gyrofrequency. The case of $f_{pe} > f_{ce}$, represented in Fig. 12a, is typical of the plasmasphere above several 1000 km altitude, while the condition $f_{pe} < f_{ce}$, in Fig. 12b, is common at low altitudes poleward of the plasmapause and within a limited altitude range near 2000 km in the mid-latitude topside ionosphere.

5.2 Z-Mode Sounding from IMAGE

When the RPI instrument onboard IMAGE operates at altitudes above $\sim 20\,000$ km, its entire frequency range from 3 kHz to 3 MHz may fall within the domains of the free-space L-O and R-X wave modes (see Fig. 12). However, as the satellite moves to lower altitudes, some part of its operating frequency range begins to fall within the Z-mode and whistler-mode domains, and thus provides the possibility of using those wave modes to probe the plasmasphere and polar regions at altitudes less than $\sim 10\,000$ km. In response to this opportunity, new Z- and whistler-mode probing tools have been developed that complement the operation of RPI at higher frequencies as a conventional sounder. In this section we discuss three basic types of Z-mode echo activity: (i) ducted waves that are presumably constrained by field-aligned irregularities (FAI) to follow the direction of the magnetic field $\mathbf{B}$, (ii) non-ducted or “direct” echoes that follow ray paths extending in generally Earthward directions, (iii) scattered echoes that are believed to return to the spacecraft following interactions with FAI located in directions generally transverse to $\mathbf{B}$ from IMAGE. Comments on use of the echoes as plasma diagnostic tools will follow. We begin with the newly discovered phenomenon of bidirectional sounding along geomagnetic field lines using ducted Z-mode waves (Carpenter et al. 2003).

Fig. 13 (a) Model plot of the variation of key plasma parameters with geocentric distance along polar region field lines, showing by shading the Z-mode propagation cavity or trapping region. (Adapted from Gurnett et al. 1983.) (b) Number of idealized ray paths for Z-mode echoes in a particular case of sounding by RPI near $L = 3$ in the plasmasphere. (Adapted from Carpenter et al. 2003)



5.2.1 Ducted Echoes and the Z-Mode Propagation “Cavity”

Since plasma parameters such as f_{pe} and f_{ce} are known to decrease monotonically with altitude above the peak of the ionospheric F layer, and since the cutoff frequency f_z for Z-mode propagation in a cold plasma is expressed in terms of f_{ce} and f_{pe} as:

$$f_z = (f_{ce}/2) \left[-1 + \left(1 + 4 (f_{pe}/f_{ce})^2 \right)^{\frac{1}{2}} \right], \quad (1)$$

one might expect f_z to decrease monotonically with altitude as well. This is not true, however, as a number of authors have emphasized (Gurnett et al. 1983; LaBelle and Treumann 2002). In an altitude range extending from ~ 1500 km to above 5000 km, a Z-mode propagation “cavity” regularly exists over a wide range of latitudes. Waves originating at frequencies “within” the cavity can return from reflection points both above and below the wave source. This occurs in spite of the fact that the higher altitude reflection takes place in a plasma region less dense than the one at the source.

Figure 13 illustrates the cavity effect by altitude profiles of two frequencies, f_z and f_{uh} , which (as shown in Fig. 12) locally delimit Z-mode propagation in a cold plasma. Also plotted versus geocentric distance are models of the plasma parameters f_{ce} and f_{pe} . The left-hand diagram was used in a study of natural wave activity in the auroral region, while the right-hand diagram represents conditions encountered by RPI during sounding operations at middle latitudes. It is clear that the curve for f_z undergoes a minimum with altitude and that the minimum is reached within an altitude range in the topside ionosphere where the ratio f_{pe}/f_{ce} falls to a minimum value near or below unity. In Fig. 13a, hatching shows a range of frequencies at each altitude for which locally launched waves could be expected to return after reflection from points both above and below the source. Figure 13b shows schematically the propagation paths of a sequence of waves launched by RPI over a range of frequencies f_i from f_z to f_{uh} . Waves at frequency f_1 , just above f_z , remain within the cavity and are reflected from both above and below RPI. In contrast, frequencies f_2 , f_3 , and f_4 exceed the upper frequency limit of the cavity and the corresponding waves reflect only at points below the spacecraft (assuming propagation in the general direction of $\mathbf{B}_0$).

Two examples of propagation within a cavity are illustrated in Figs. 14a–b on plasma-grams. On both records there is a band of no electromagnetic propagation at the lower frequencies, followed by a broad belt of noise that is attributed to a combination of scattering of RPI Z-mode pulses from irregularities located in directions generally transverse to $\mathbf{B}_0$.

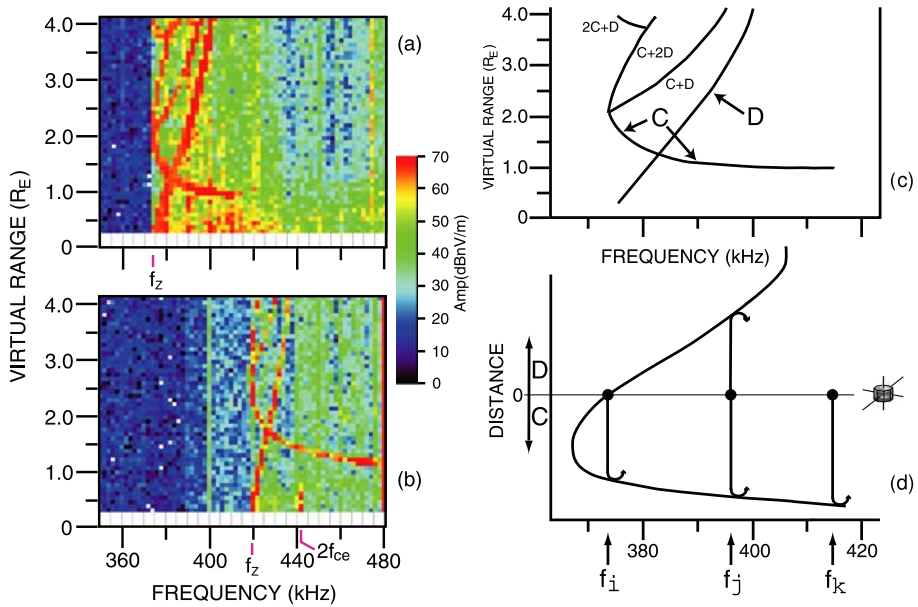


Fig. 14 (a)–(b) RPI plasmagrams from 28 July 2001 showing echo intensity in coordinates of virtual range (echo range at an assumed propagation velocity of c) versus transmitted frequency. Multicomponent Z-mode echoes are detected within the plasmasphere on successive soundings 2.5 minutes apart. (c)–(d) Interpretive model of the echoes of panel (a) for the case of a sounder location above the minimum in Z-mode cutoff frequency with altitude. The horizontal scale has been expanded by a factor of ~ 2 to facilitate comparisons of echo delays. (Adapted from Carpenter et al. 2003)

(Muldrew 1969; Sonwalkar et al. 2004) as well as Z-mode noise from distant sources (Benson and Wong 1987; Benson 1993). The local Z-mode cutoff f_z is found to be at or near the low-frequency edge of this band. Clearly outlined against the background noise are patterns of discrete echo traces that begin at f_z .

An interpretation of the propagation paths of the discrete echoes shown in Fig. 14a is presented in Figs. 14c–d. Panel (c) is a rescaled tracing of the echo observed in Fig. 14a, while panel (d) shows on the same frequency scale the variation with altitude of f_z in a postulated propagation cavity. The sounding is assumed to have taken place at an altitude above the minimum value of f_z in the cavity. The upward and downward directions of propagation are identified as D and C, respectively. As the sounder frequency steps upward and reaches f_z at ~ 372 kHz, an echo f_i is received from a reflection altitude below IMAGE, forming the first elements of what becomes the down-sloping C echo trace. As the sounder continues above f_z , echoes such as f_j begin to return from both higher and lower altitudes. The D echo forms near zero range and extends rapidly towards longer delays because of the small spatial gradients in f_z encountered in the upward direction. Finally, the sounder frequency exceeds the peak value reached by f_z above IMAGE, after which echoes such as f_k can return from below only.

The remarkable clarity of the echo traces suggests that the signals involved were guided or ducted by geomagnetic FAI, a phenomenon that has been found necessary to explain ground-observed whistler-mode signals (Smith 1961; Helliwell 1965). Ducting has recently been invoked to explain discrete O- and X-mode propagation from RPI (Reinisch et al. 2001; Fung et al. 2003) and was earlier identified from observations with ISIS satellites (Muldrew

1963; Loftus et al. 1966). The existence of a single discrete propagation path passing through the satellite position is indicated by the additional components in Fig. 14a identified as $C+D$, $C+2D$, and $2C+D$ in Fig. 14c. Each of the higher order components consists of some combination of the measured delays along the original C and D paths.

When RPI launches Z-mode waves from an altitude below the minimum of a Z-mode cavity, a quite different echo pattern is detected, but again there are well defined echo components from upward and downward directions as well as combinations of the two in the manner of Fig. 14c. Thus it was concluded that an explanation of events such as that of Fig. 14a requires the existence of both a propagation cavity as well as the occurrence of ducted propagation along the magnetic field (Carpenter et al. 2003).

5.2.2 Remote Sensing of Density Profiles Along the Geomagnetic Field Lines Above IMAGE

The propagation cavity is of geophysical interest for a number of reasons. In the case of the D component in Fig. 14c, representing upward propagation along the geomagnetic field from IMAGE, an inversion technique can be applied to determine the electron density profile along the path up to the altitude limit reached by the measured D component (for the conditions of Fig. 13a, that limit was predicted to be $\sim 4 R_E$). The inversion method, described in Carpenter et al. (2003) was applied in the cases of Fig. 14a and Fig. 14b with the results shown in Fig. 15 on a plot of plasma density versus $MLAT$ for $L = 2.1$ and 2.3 . Density is shown from the position of IMAGE upward to a point ~ 5000 km above IMAGE along $\mathbf{B}_0$. For comparison, we show a profile for $L = 2.3$ from an empirical model obtained by Huang et al. (2004), based on X-mode sounding by RPI along multiple field-aligned paths on 8 June 2001. This profile (dashed curve) was scaled by a factor of 0.8 in order to show how well

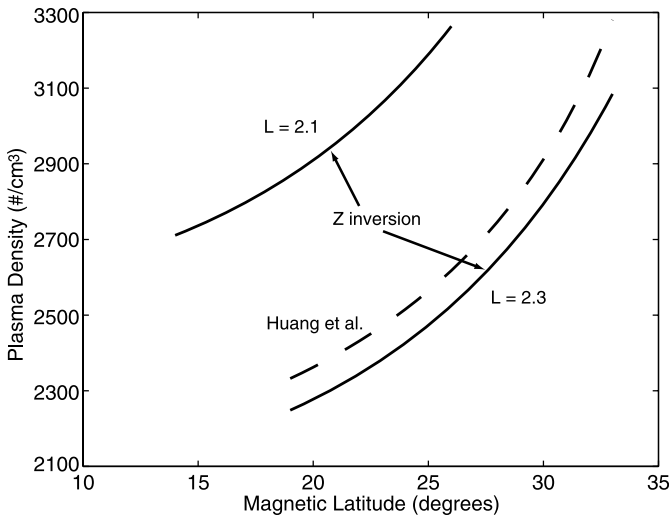


Fig. 15 Plots of electron density versus $MLAT$ at $L = 2.1$ and 2.3 , inferred from the upward propagating Z-mode signals illustrated in Figs. 14a–b and identified as component D in Figs. 14c–d. The *dashed curve* is for $L = 2.3$ from the Huang et al. (2004) model for a different date. That model is based upon inversion of free-space mode echoes that propagated to RPI along multiple field-aligned paths. (Adapted from Carpenter et al. 2003)

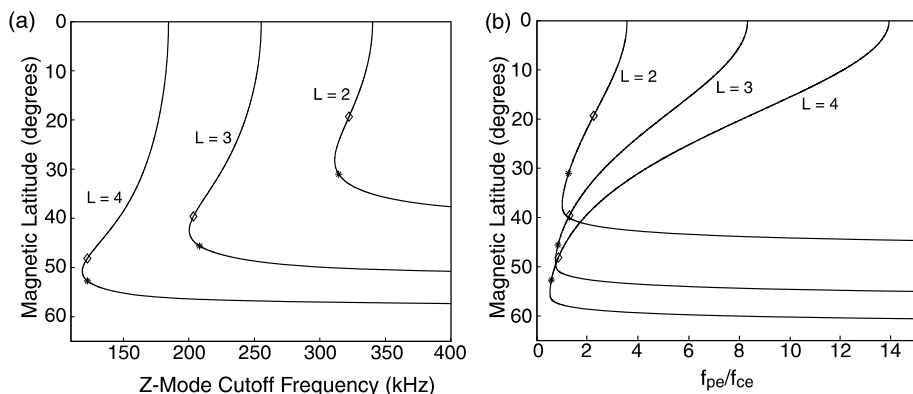


Fig. 16 (a) Plot of calculated Z-mode cutoff frequency f_Z versus $MLAT$ along geomagnetic field lines at $L = 2, 3$, and 4 , illustrating the widespread occurrence of a low-altitude minimum in f_Z within the plasmasphere. A dipole magnetic field model and a diffusive equilibrium density model were assumed. Marks along the curves show the locations of the 3000 km and 5000 km altitudes, respectively. (b) Corresponding plot for the ratio f_{pe}/f_{ce} . (Adapted from Carpenter et al. 2003)

the curves for $L = 2.3$ agree. Geomagnetic conditions relevant to the X (downward) and Z (upward) measurements ranged from calm (X profile) to quiet (Z profile) similar (near $L = 2.3$, variations of 20–30% in the scale factor of the field-aligned electron density distribution with time, longitude, and disturbance levels are common (Carpenter and Anderson 1992)).

5.2.3 Remote Sensing of Plasma Composition Along the Geomagnetic Field Lines

The f_Z profile with altitude may be used as a diagnostic of plasma composition along $\mathbf{B}_0$ in the topside ionosphere region. If one assumes a three-component plasma in diffusive equilibrium above a reference altitude, a small positive electron temperature gradient along $\mathbf{B}_0$, and a known value of electron density at the magnetic equator, one then finds that in order to place a minimum in the f_Z profile in the 3000–5000 km altitude range where it has been observed, there are important constraints on the ion composition at the reference level.

Figure 16a is a plot of calculated f_Z profiles along $\mathbf{B}_0$ at three L values (2, 3, 4), with $MLAT$ plotted on the vertical scale. In Fig. 16b are shown corresponding plots for the ratio f_{pe}/f_{ce} . Using the empirical model of electron density at the equator of Carpenter and Anderson (1992), an assumed ratio of He^+ to H^+ of 0.05 to 0.1 at the equator, an assumed value of 2 for the ratio of the electron temperature at the equator to the same temperature at the 1000 km reference level, it was found that a distribution of 82% O^+ , 17% He^+ and 1% H^+ at the reference level would predict the profiles of Fig. 16a, which exhibit an f_Z minimum in the observed 3000–5000 km altitude range (Carpenter et al. 2003). The altitude of the minimum appeared to be sensitive to the choice of composition at the reference level, thus suggesting that further observations of this kind could be used to investigate the poorly known distribution of ions in the coupling region between the ionosphere and the plasmasphere.

Since little is known of the variations of the plasma properties along the geomagnetic field lines at altitudes below 5000 km, Z-mode probing of the kind described here can become a valuable adjunct to conventional radio sounding. The RPI data offer many as yet unexploited opportunities for application of the new method.

5.3 Additional Diagnostics Uses of Z-Mode Echoes

5.3.1 Non-Ducted or “Direct” Earthward Propagating Z-Mode Echoes

When IMAGE operated in the plasmasphere at $L < 3$ near 3000–4000 km altitude, the ratio f_{pe}/f_{ce} was frequently > 1 but not $\gg 1$, and RPI was found to produce discrete, non-ducted echoes that followed ray paths extending generally Earthward from the satellite. Ducted echoes of the kind described above could also be present (as often happened in the outer plasmasphere in the case of simultaneous direct and ducted X-mode echoes). The direct Z-mode echoes represent low to medium altitude versions of phenomena familiar from topside sounding work (Carpenter et al. 2003).

Two examples of direct echoes recorded on 6 July 2001 are shown in Figs. 17a–b. They were recorded, respectively, at 3100 km altitude, $L = 2.4$ and at 4100 km altitude, $L = 2$. On both panels, a vertical spike identifies the local f_{pe} . There are two discrete Z-mode echoes, labeled Z and Z'. The Z' trace begins at local f_{pe} , while the main Z trace rises slowly in travel time (range) from an origin at f_Z , inferred to be off scale to the left. The Z trace finally crosses over the Z' trace and the two echoes then extend towards asymptotically long delays at a maximum frequency below f_{uh} . This maximum is associated with a limit on vertical incidence propagation (Jackson 1969).

5.3.2 Diagnostic Uses of Direct Z-Mode Echoes

The Z' trace, as observed on topside sounders, was interpreted by Calvert (1966) as having propagated obliquely between the satellite and the O-mode reflection level at $f = f_{pe}$. The occurrence of two distinct Z-mode echo traces at $f > f_{pe}$ is a consequence of the anisotropy of the medium, such that ray paths involving two different initial wave normal angles can lead back to the satellite. The Z' trace was explained by Calvert (1966) in terms of non-vertical propagation in a horizontally stratified ionosphere. The “reflection” does not occur at a Z-mode cutoff, but is in fact the result of refraction such that the ray path reverses direction at a level where $f = f_{pe}$. The Z' trace can be expected to provide information that is independent of results obtained from inverting the regular Z-mode echo. Note that the trace delays are substantially longer than those of an O echo at common frequencies, accentuated by a Z-mode transition at f_{pe} from a fast mode to a slow mode. These traces are therefore more useful (given the minimum 3.2-ms RPI pulse length and receiver sampling frequency) than the O- and X-modes of the transitional altitude region. Analysis of Z and Z' traces for particular RPI echo observations remain to be performed. However, the information on local f_{pe} provided by the Z' trace is particularly helpful for plasma diagnostics at altitudes near 3000–5000 km in the plasmasphere, where the condition $f_{pe}/f_{ce} \approx 1$ is common and thus where estimates of f_{pe} based upon measurements of f_{uh} by passive probing may not provide desired accuracy.

5.3.3 Scattered Z-Mode Echoes

In the plasmasphere at altitudes such that the Z-mode frequency domain was broad enough to occupy a significant range of frequencies below f_{uh} , a background of diffuse Z-mode echoes was almost always present, whether or not discrete echoes were received. When discrete echoes were present, they were typically ~ 20 dB above the levels of the diffuse background, as illustrated in Figs. 17a–b.

Plasmagrams from the low altitude polar regions where $f_{pe}/f_{ce} < 1$ regularly exhibited diffuse echoes with the forms illustrated in Figs. 17c–d. Distinctive features included:

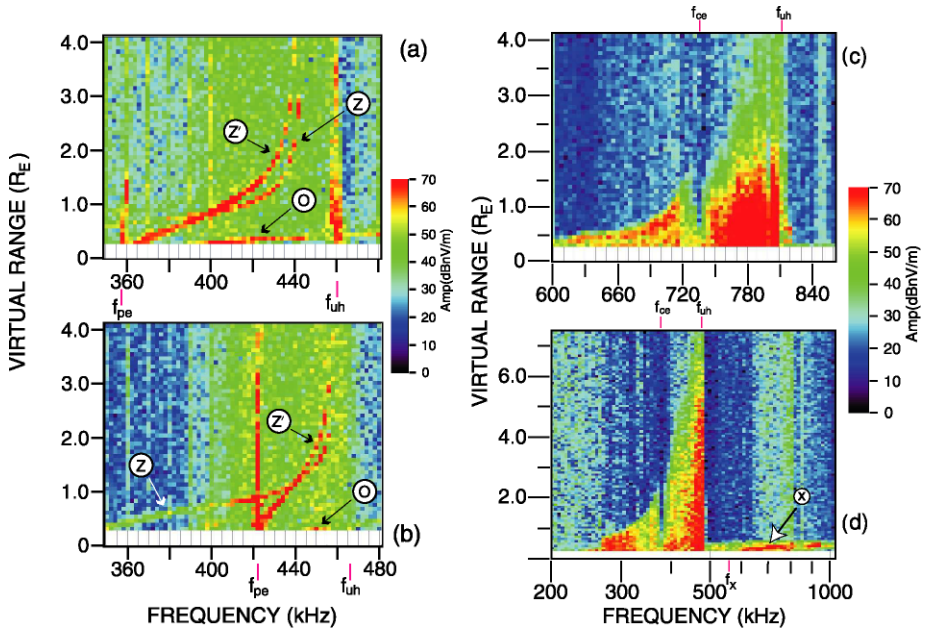


Fig. 17 (a)–(b) RPI plasmagrams illustrating Earthward propagating discrete Z and Z' echoes seen against a background of diffuse Z-mode noise. (c)–(d) RPI plasmagrams typical of low altitude polar regions showing diffuse Z-mode echo activity useful for determining f_{ce} and f_{pe} . (Adapted from Carpenter et al. 2003)

(i) echoes with ranges substantially longer than those of order $0.5 R_E$ to be expected for Earthward propagating O- and X-modes, (ii) echo activity extending from the lowest detectable range to a maximum value that increased with sounding frequency, (iii) a gap or weakening of the echoes at an intermediate frequency, and (iv) a relatively abrupt upper frequency limit, inferred to be f_{uh} .

Sonwalkar et al. (2004) performed a ray tracing analysis of diffuse echo events such as those of Figs. 17c–d, finding that for Z-waves below f_{ce} , Earthward propagation to turning points in the general $\mathbf{B}$ direction could not be excluded, but such propagation could not explain the wide time spreading of the Z echoes and would in any case tend to be masked by them. The authors pointed out that because of the variation with altitude of the Z-mode refractive index surface, at any given frequency f below the local f_{ce} , Z-mode waves can spread out in all directions. Some of these waves, in particular those propagating in directions from IMAGE that are approximately perpendicular to $\mathbf{B}_0$ are scattered by FAI and can return to the satellite. Meanwhile, for frequencies between f_{ce} and f_{uh} , Z-mode propagation is allowed within a resonance cone that permits propagation in the direction roughly perpendicular to $\mathbf{B}_0$. These waves can also lead to echoes after scattering from FAI, as has been documented by topside sounders (e.g., Muldrew 1969; James 1979).

5.3.4 Diagnostic Uses of Scattered Z-Mode Echoes

In a case study similar to those of Figs. 17c–d, Sonwalkar et al. (2004) found that the observed echo delays could be explained by irregularities located within ~ 20 to 3000 km

from IMAGE. The overall distribution of time delays was consistent with propagation theory. For frequencies above f_{pe} (true of most of the observed echoes in Figs. 17c–d) we have a slow Z-mode, with group velocity decreasing and time delay increasing with frequency for any given wave normal direction. Above f_{ce} and close to f_{uh} , the Z-mode becomes quasi-electrostatic and much longer time delays are expected, as observed. The weakening of the echoes at a frequency corresponding to local f_{ce} (Carpenter et al. 2003) is believed to be related to the change in refractive index surface from a closed to an open topology at f_{ce} , as discussed by Gurnett et al. (1983) and LaBelle and Treumann (2002).

In the polar regions at altitudes in the 1000–4000 km range, where f_{pe}/f_{ce} is typically <1 , f_{uh} as observed through passive scanning may no longer be a useful source of information on f_{pe} , being dominated by the value of f_{ce} , and also because of interfering auroral noise that may be present near 1 MHz. In such cases, Z-mode echoes such as those in Figs. 17c–d can provide a useful means of measuring local f_{pe} through f_{ce} , indicated by the gap in echoes, and by the upper hybrid resonance spike, which is often marked by an abrupt drop in intensity by ~ 40 dB on its high frequency side.

6 Whistler-Mode Soundings at Altitudes Below ~ 5000 km

New whistler-mode (WM) tools for probing at altitudes below ~ 5000 km have been developed during work on data from the RPI sounder onboard IMAGE (Reinisch et al. 2000). These tools are based upon various physical mechanisms involved in the reflection and return propagation to IMAGE of WM waves transmitted by RPI. As described by Sonwalkar et al. (2009), these mechanisms include: (i) magnetospheric reflection (MR) at locations where the wave frequency is less than or equal to the local f_{lh} , (ii) specular reflection (SR) from the steep density gradients at the bottom side of the ionosphere, and (iii) multipath propagation and scattering due to the presence of density irregularities that are often field-aligned. In most cases, MR- and SR-WM echoes are distinguished by the distinct upper and lower limits on their frequencies, limits that depend on the value of the lower hybrid resonance at the altitude of the satellite. The two echo types also differ widely in terms of their frequency-versus-time properties, which can be separately explained through ray tracing in models of the plasma environment below ~ 5000 km. Preliminary descriptions of echoes attributed to specular reflection, multipath propagation and scattering have been provided by Sonwalkar et al. (2009). Here we limit ourselves to a brief description of the various echoes and their apparent diagnostic potential.

6.1 Spreading of RPI Whistler-Mode Echoes in Time Delay

Sonwalkar et al. (2009) report that the spectra of all types of WM echoes detected by RPI are sensitive to the presence of FAI, and that they manifest this sensitivity on plasmagrams by various amounts of spreading in travel time, varying from 5–10 ms for the most discrete cases to 40 ms and more for the most diffuse events. The spreading can be occasioned by propagation on multiple paths through irregular regions with cross- B_0 scale sizes of the order of 1–10 km or by forward and backward scattering from irregularities with scale sizes of the order of 10–100 m. Scattering may involve changes in group velocity at the time of coupling between a predominantly electromagnetic wave and a quasi-electrostatic wave at an irregularity boundary. For convenience, MR- and SR-WM echoes have been further classified by Sonwalkar et al. (2009) as either discrete, multipath or diffuse according to the amount of travel time spreading.

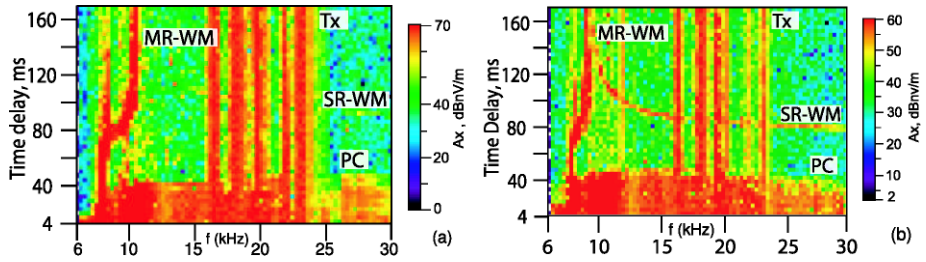


Fig. 18 (a) RPI plasmagram showing an MR-WM echo recorded on 23 October 2005 at 10:22:46 UT. Fixed frequency transmitter signals (Tx) are present, as well as a cluster of proton cyclotron (PC) echoes at delays < 40 ms. (b) RPI record on 26 October 2005 at 09:32:42 UT with MR-WM echo and a well defined SR-SW echo, as well as Tx and PC echoes. (Adapted from Sonwalkar et al. 2009)

6.2 Examples of Magnetospherically Reflected and Specularly Reflected Whistler-Mode Echoes

Examples of MR- and SR-WM echoes are shown on RPI plasmagrams in Fig. 18. These records plot echo travel time in ms versus RPI transmitter frequency, which was stepped each 250 ms in 300 Hz increments from 6 to 63 kHz (only the range 6–30 kHz is displayed). In Fig. 18a, recorded at ~ 2650 km and $L \approx 2.4$, a discrete MR-WM echo appears between ~ 7.5 and ~ 11 kHz. At ~ 7.5 kHz the echo begins at the shortest delay displayed (~ 4 ms) and extends with decreased amplitude to the top of the record. Beginning at a delay of ~ 80 ms, the echo branches towards higher frequencies and extends to an undefined limiting delay at ~ 11 kHz. Meanwhile, ground-based transmitter signals (Tx) appear between 16 and 23 kHz, extending over the full time-delay range available. Also present at frequencies above 8 kHz and at delays less than ~ 40 ms is a band of proton cyclotron (PC) echoes (see Sect. 7), which are attributed to excitation of ambient protons in the antenna sheath by the leading edge of each 3.2-ms transmitter pulse (Carpenter et al. 2007).

Figure 18b, recorded at ~ 2550 km and $L \approx 2.3$, also shows an MR-WM event, in this case with delimiting frequencies of ~ 7 and ~ 9 kHz. Transmitter signals are again present, although those near 16 and 23 kHz exhibit less spreading in frequency than those in Fig. 18a. A highlight of this record is a discrete SR-WM echo, which exhibits delays near 80 ms between ~ 20 and 30 kHz but curves towards longer delays as it approaches the 9 kHz high frequency limit of the MR-WM echo.

Although examples of discrete, multipath, and diffuse SR-WM echoes were shown previously by Sonwalkar et al. (2004), RPI WM-echoes have now been observed much more extensively and categorized much more completely as a result of sounding operations at frequencies below 60 kHz in 2004 and 2005 (Sonwalkar et al. 2009).

6.3 Specularly Reflected Whistler-Mode Echoes

RPI soundings at WM frequencies regularly exhibit echoes that extend over a wide range of frequencies and are interpreted as having reflected from the steep density gradients at the bottom side of the ionosphere (Sonwalkar et al. 2004). Such SR-WM echoes often accompany MR-WM echoes, as illustrated by the example of Fig. 18b. Since an SR-WM echo provides an integral measure of the electron density between IMAGE, say at ~ 3000 km, and the ionosphere at ~ 100 km, it is particularly sensitive to density levels at altitudes below those reached by a simultaneous MR-WM event (~ 1500 km). Thus its dispersion properties

may be used to constrain the density/plasma composition model that is found most consistent with the MR-WM event.

6.4 Magnetospherically Reflected Whistler-Mode Echoes and the Lower Hybrid Resonance

It may be seen in Fig. 12 that the Z-, O-, and X-mode dispersion diagrams each exhibit low frequency cutoffs, at which the refractive index goes to zero and the wave is reflected. That type of cutoff does not occur for WM waves. When the presence of ions is taken into account, the dispersion of WM is modified (not included in Fig. 12) such that WM waves, propagating at high wave normal angles with respect to $\mathbf{B}_0$ can undergo magnetospheric reflection at altitudes where $f \approx f_{lh}$. For an electron, H^+ , He^+ , and O^+ plasma, f_{lh} is given by the following equation:

$$\frac{1}{m_{\text{eff}}(m_p/m_e f_{lh}^2)} = \frac{1}{f_{pe}^2} + \frac{1}{f_{ce}^2}, \quad (2)$$

where m_p/m_e is the proton/electron mass ratio and the effective ion mass m_{eff} is defined as:

$$\frac{1}{m_{\text{eff}}} = \frac{\alpha}{1} + \frac{\beta}{4} + \frac{\gamma}{16}, \quad (3)$$

where α , β and γ are, respectively, the fractional abundances of H^+ , He^+ and O^+ .

The magnetospheric reflection is actually a refraction caused by a topological change and decrease in the size of the refractive index surface as the WM wave at large wave normal angle propagates from a region where $f_{lh} < f$ to a region where $f_{lh} > f$. When $f_{lh} < f$, the refractive index surface is “open”, with a so called resonance cone (delimiting an angular region of no propagation), and when $f_{lh} > f$, it is “closed”, such that the propagation is allowed at all angles with respect to $\mathbf{B}_0$ (Kimura 1966).

MR-WM echoes may exhibit a variety of discrete or diffuse spectral forms. MR-WM echoes with clearly identifiable forms, such as those illustrated in Fig. 18, tend to present a nose-like shape on plasmagrams because of extended time delays at the form’s minimum and maximum frequencies. Those limiting frequencies, usually separated by a few kHz, are associated, respectively, with f_{lh} at the location of the satellite (the lower frequency), often near 6 kHz, and the maximum value of f_{lh} along the field line extending Earthward from IMAGE (the upper frequency), often in the range 9–12 kHz.

Key formative elements in the MR-WM echo phenomenon are believed to be: (i) propagation of RPI WM waves at high wave normal angles, near the so called resonance cone around the direction of the magnetic field; (ii) reflection of the waves near an altitude where the wave frequency is lower than but close to local f_{lh} ; (iii) in the case of multipath or diffuse MR-WM echoes, refraction or scattering of the waves through encounters with FAI such that the echoes reach the satellite with varying time delays.

6.5 The Diagnostic Potential of Magnetospherically Reflected and Specularly Reflected Whistler-Mode Echoes

The time-delay-versus-frequency properties of MR-WM echoes provide a measure of f_{lh} along the field line passing through the satellite. The lower cutoff frequency of MR-WM echo, f_{lh} at the satellite, provides a measure of m_{eff} at that higher altitude where H^+ and He^+ may be dominant. The upper frequency cutoff of the MR-WM echo provides a measure

of the m_{eff} of the plasma in the important transition region (~ 1000 – 1500 km) between the O^+ dominated lower ionosphere and the H^+ dominated region at higher altitudes. This can be seen from expressions of (2) and (3) for f_{lh} and m_{eff} , respectively. It is clear that within altitude ranges over, which the r.h.s. of (2) does not change appreciably, the value of f_{lh} will be sensitive to changes in m_{eff} (by as much as a factor of 16) associated with altitude variations in ion composition.

Ray tracing simulations of the dispersion properties of simultaneously observed MR- and SR-WM echoes may be used for remote sensing of the ion composition and total electron density along a field line between the bottom of the ionosphere and the position of IMAGE (Sonwalkar et al. 2009). As noted, the MR-WM echo provides measures of the local m_{eff} and of m_{eff} at the altitude of the maximum f_{lh} below the satellite (in the vicinity of 1000 km). Meanwhile, the SR-WM echo, because of its noted sensitivity to the ionospheric electron density profile, provides an important constraint on the overall plasma density model used in the ray tracing simulation. Assuming a diffusive equilibrium model for magnetospheric density (see also Pierrard et al. 2009, this issue), Sonwalkar et al. (2009) developed a ray tracing method that determines the diffusive equilibrium model parameters such that the MR- and SR-WM dispersion and frequency cutoffs calculated from ray tracing simulations agree with those observed within experimental uncertainties. Applying this method in two specific instances, including the case shown in Fig. 18b, Sonwalkar et al. (2009) determined within 10% the electron and ion (H^+ , He^+ , O^+) densities along $\mathbf{B}_0$ ($L \approx 2$) passing through the satellite between 3000 km and 90 km.

7 Proton Cyclotron Echoes and a New Resonance

At altitudes ranging from ~ 1500 km to 20000 km in the plasmasphere, the RPI instrument onboard IMAGE can couple strongly to protons in the immediate vicinity of the satellite as it transmits 3.2-ms pulses and scans from 6 to 63 kHz or 20 to 326 kHz. Those soundings also give rise to a new resonance at a frequency $\sim 15\%$ above f_{ce} (Carpenter et al. 2007). The coupling to protons is revealed in echoes that arrive at multiples of the local proton gyroperiod t_p . Lower-altitude (< 4000 km) versions of several of these proton cyclotron (PC) echo forms were observed in the topside ionosphere by sounders in the ISIS satellite era, among them discrete echoes in the WM domain below f_{ce} and in the nominally non-electromagnetically propagating domain above f_{ce} (e.g., Oya 1978; Horita 1987; Muldrew 1998). Also seen on ISIS satellites were spur-like broadenings of resonances such as the one at f_{pe} (e.g., King and Preece 1967; Benson 1975; Horita 1987).

7.1 The f_{ce}^+ Echo

Figure 19a shows an example of what has been called an f_{ce}^+ echo, a phenomenon often observed in the plasmasphere by RPI at frequencies from ~ 10 to 20% above f_{ce} (Carpenter et al. 2007). The plasmagram presents time delay from ~ 40 to 100 ms versus frequency from 20 to 50 kHz. IMAGE was at $L \approx 3.7$, well inside an extended plasmasphere at an altitude of ~ 14000 km and in the mid-afternoon sector. The local electron density was $\sim 560 \text{ cm}^{-3}$. The local value of f_{ce} is well defined at ~ 30 kHz by a resonance spike, a type of response that is regularly present on sounder records from the topside ionosphere (Benson 1977, and references cited therein). A band of WM noise extends upward in frequency to a relatively sharp cutoff at ~ 26 kHz. This band is attributed to multi-path propagation and scattering of a variety of WM signals, including naturally occurring wave emissions, WM emissions

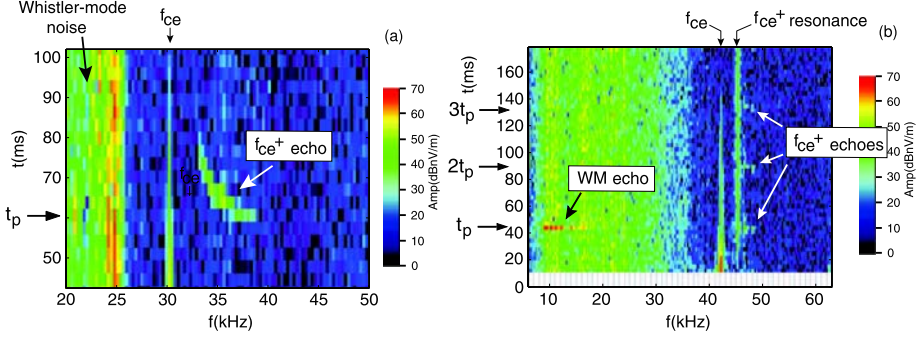


Fig. 19 (a) Portion of an RPI plasmagram showing a well defined proton cyclotron (PC) echo that exhibits extended delays at frequencies just above f_{ce} and then approaches a constant delay at the local value of the proton gyroperiod t_p . (b) RPI plasmagram illustrating three effects, a PC echo in the WM domain, a resonance at a frequency just above f_{ce} , and discrete echoes at multiples of t_p . (Adapted from Carpenter et al. 2007)

triggered by lightning, and multiple WM signals from ground-based transmitters. In the figure, the f_{ce}^+ echo first appears at ~ 33 kHz, ~ 3 kHz above f_{ce} , and extends to 39 kHz. It exhibits a time-delay-versus-frequency form something like that of a hockey stick, at first falling steeply in delay with increasing frequency and then curving to reach a constant delay of ~ 61 ms. That delay corresponds closely to the local $t_p = 1836/f_{ce}$. On IMAGE the occurrence rates of PC echoes above f_{ce} were highest during periods when the angle ϕ between the spacecraft velocity vector and the geomagnetic field $\mathbf{B}_0$ was small, near 20° , but on occasion such echoes were detected when ϕ approached 90° .

7.2 The f_{ce}^+ Resonance

A new phenomenon, called the f_{ce}^+ resonance, has been observed at a frequency $\sim 15\%$ above f_{ce} (Carpenter et al. 2007). This resonance is apparently confined to altitudes above ~ 7000 km. It is illustrated by the plasmagram of Fig. 19b, which displays time delay from 0 to 178 ms versus frequency from 6 to 63 kHz. At the time of the figure, IMAGE was at $L \approx 3.6$ and at an altitude of $\sim 12\,000$ km, well inside the plasmasphere. Three echo forms appear, a WM echo, multiple f_{ce}^+ echoes, and an f_{ce}^+ resonance. The WM echo, extending from ~ 9 to 17 kHz at a constant delay of ~ 45 ms, appears as a discrete intensity enhancement within the usual WM noise background. The value of f_{ce} is well marked by a tapered resonance spike at ~ 42 kHz. Approximately 3 kHz above f_{ce} is an f_{ce}^+ resonance. This resonance differs from the spike at f_{ce} in that it extends to the top of the record and (in this case) is not clearly defined in the first ~ 30 ms after the beginning of the transmitter pulse. Along the high-frequency side of the f_{ce}^+ resonance are f_{ce}^+ echoes that arrived at multiples of t_p , the first at ~ 44.5 ms, the second at ~ 89 ms, and the third at ~ 133 ms. There are differences in amplitude among the echo forms illustrated in Fig. 19b: Portions of the WM echo near 10 kHz are ~ 10 – 15 dB stronger than the f_{ce}^+ resonance or f_{ce}^+ echoes.

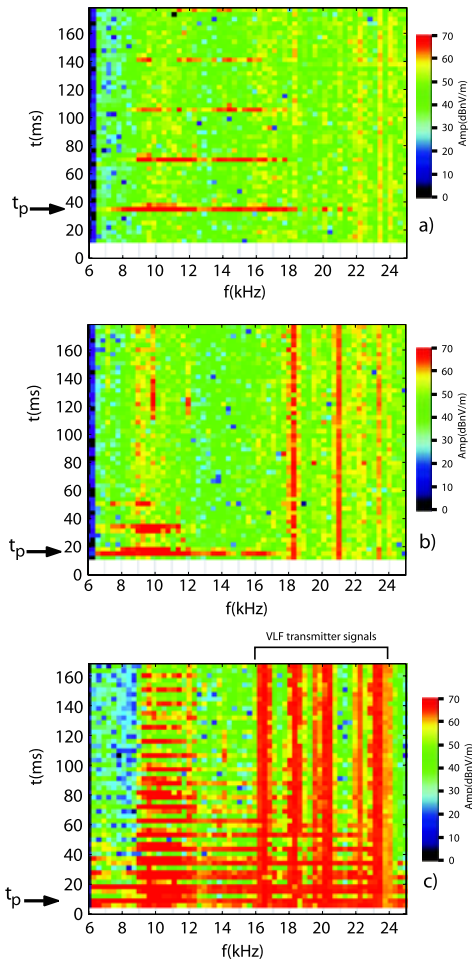
7.3 Whistler-Mode Proton Cyclotron Echoes

Of special interest are exceptionally strong echoes in the WM domain near 10 kHz (Carpenter et al. 2007). On a given orbit, these invariably appeared at altitudes ~ 5000 km and below

and could be detected at altitudes up to $\sim 12\,000$ km. In some cases, the echoes appeared on plasmagrams showing other PC echo activity (see Fig. 19b). Most of the WM echoes observed thus far were found within the plasmasphere or the PBL, at $MLAT$ between -60° and $+60^\circ$. They were evident on occasion at higher latitudes and over the polar regions, but tended to be obscured there by strong natural WM noise with power spectral density 10 dB or more above the noise levels in the plasmasphere. Samplings showed strong WM echo activity at several widely spaced MLT, suggesting that such echoes may occur in all local time sectors.

At each frequency during a given sounding, WM echoes tended to repeat at time delays that were multiples of t_p . Figure 20 displays such effects on plasmagrams recorded on three different orbits at altitudes $\sim 10\,700$, ~ 7700 , and ~ 4200 km, respectively. As altitude decreased, the inter-echo time delay decreased accordingly. In the stronger magnetic fields below ~ 3000 km altitude, the time interval at each frequency between successive high-order echoes fell below 6.4 ms, the minimum interval allowing separation of echoes by one 3.2-ms time delay pixel, and individual echoes could no longer be resolved. In such cases, the echoes formed a “continuous” response extending to multiple values of t_p . When

Fig. 20 RPI plasmagrams showing PC echoes in the WM domain, repeating at multiples of the local t_p . The examples were recorded on three different orbits at altitudes $\sim 10\,700$ km (a), ~ 7700 km (b), and ~ 4200 km (c). The vertical lines between 16 and 24 kHz in panel (c) represent WM transmissions from ground transmitters. (Adapted from Carpenter et al. 2007)



the angle ϕ was near a local minimum of order 10° , WM echoes were observed to repeat at multiples of t_p up to 15 or more. The data indicate that WM echo detection near 10 kHz was largely confined to a region of radius ~ 300 m around the field line of excitation, and that the peak excitation of the protons occurred as a transient event at the beginning of each radio frequency (rf) pulse.

7.4 Comments on Physical Mechanisms of Proton Cyclotron Echoes

Carpenter et al. (2007) suggest that PC echoes and the new resonance are driven by a variety of mechanisms. Time delay measurements of WM echoes near 10 kHz indicated that the energization of the protons by a given 3.2-ms sounder pulse was essentially a transient process that occurred at the beginning of the pulse, and to that extent did not involve replication of the rf pulse by the echo. It was inferred that there is spatial bunching of accelerated protons during the initial formation of an electron sheath around the positive-voltage antenna element. The gyrating protons then produce a series of electrostatic pulses at multiples of t_p . Tight bunching of accelerated protons does not occur during the remainder of a 3.2-ms pulse, since ambient electrons never again appear close to the antenna during this period (due to the acceleration of protons during negative half cycles, protons near the antenna have a wide distribution of energies and thus are not subject to tight bunching during subsequent positive half cycles).

Most WM echoes were observed when IMAGE moved at low angles to $\mathbf{B}_0$ and was within a distance of ~ 300 m transverse to the field line of original excitation of the plasma. The echoes showed no measurable WM propagation delay from a source, which is consistent with the inferred electrostatic nature of the echoes and the closeness of the antenna to the source field lines. The high intensity of the lower-order WM echoes, which regularly saturated the RPI receiver near 10 kHz, as well as the lack of detectable WM echo activity above 12 000 km altitude, were attributed in part to the fact that proton energization at the leading edge of the sounder pulse was at maximum levels when the rf of the pulse was below, but near, the local proton plasma frequency $f_{pp} = f_{pe}/43$. f_{pp} reaches a maximum of ~ 13 kHz at the lower IMAGE altitudes, but falls below 6 kHz (the lowest sounder operating frequency) above 12 000 km.

In contrast to WM echoes, f_{ce}^+ echoes occurred at frequencies well above f_{pp} and were thus outside the range where significant transient energization was expected. Also in contrast to WM echoes, f_{ce}^+ echoes appeared to replicate the sounder pulse frequency and in so doing experienced large frequency-dependent increases in travel time as f_{ce} was approached from above. This dispersion as well as a year-to-year decrease in f_{ce}^+ echo activity with increasing separation of the antenna from the “excited” field lines, is consistent with an explanation of f_{ce}^+ echoes observed in the ISIS satellites in terms of thermal-mode propagation from a perturbed proton distribution (Muldrew 1998). A possible source of energy for the comparatively weak f_{ce}^+ echoes is the quasi-static electric field that exists in the ion sheath that surrounds each antenna element in the immediate aftermath of an rf pulse, as discussed in Carpenter et al. (2007).

The new resonance above f_{ce} suggested the existence of a ringing phenomenon in the plasma that is unique to altitudes above ~ 7000 km. The resonance mechanism appears to operate independently of the f_{ce}^+ echo mechanism, although both phenomena were found within a similar range of frequencies above f_{ce} . The long enduring nature of the resonances, lasting at times for at least 300 ms, suggests that the perturbed plasma environment in which the ringing occurred was carried with the spacecraft a kilometer or more beyond the ~ 300 m transverse distance within which the WM echoes were found. The collapse of the ion sheath

following an rf pulse may provide energy for the ringing process. This collapse may on occasion delay the onset of the detected resonance, in the manner proposed by Muldrew (1972), who argued that in the case of certain ionospheric resonances, the antenna sheath may temporarily exclude very short wavelength stimulated waves.

Previously suggested processes that were considered relevant to PC echoes above f_{ce} and to the new resonance include: (i) coupling between an excited Z-mode wave and longitudinal plasma waves (Benson 1975), (ii) accumulation of negative charge on an electric antenna during an rf pulse (Oya 1978), and (iii) Bernstein-mode propagation to an antenna from an excited proton population (Muldrew 1998).

8 Chorus

8.1 Observations of Whistler-Mode Chorus Emissions by CLUSTER

Whistler-mode (WM) chorus emissions are electromagnetic waves in a frequency range from a few hundreds of Hz to several kHz. Chorus was first observed on the ground (Storey 1953) but spacecraft observations in the Earth magnetosphere are also frequent. Chorus often contains many distinct short-duration wave packets, which change their frequency at time scales of a fraction of 1 s (see reviews by Sazhin and Hayakawa 1992; Omura et al. 1991). The generation mechanism of chorus is not yet well understood. It is most often accepted that chorus is generated by a nonlinear process (Nunn et al. 1997; Trakhtengerts 1999; Trakhtengerts et al. 2004), which involves the electron cyclotron resonance of WM waves with energetic electrons.

WM chorus emissions are receiving an increased attention in connection with the acceleration of energetic electrons in the radiation belts (e.g., Horne et al. 2005). Important new results on chorus has been obtained with wave and particle instruments onboard CLUSTER as well as with the DOUBLE STAR spacecraft, which routinely detects chorus emissions, and with the low altitude DEMETER spacecraft. This research provided us with tests of the existing theories of the chorus source mechanism and particle acceleration, and further motivated theoretical work. In the next two subsections we discuss results, which can have implications for plasmaspheric physics, i.e., results on position and size of the chorus source region and on propagation of chorus from its source region.

8.2 Position and Size of the Chorus Source Region

During the period of very close separation distances of the CLUSTER spacecraft (of the order of hundreds of km), very similar chorus emissions were observed in their generation region close to the magnetic equatorial plane at a radial distance of $4.4 R_E$ (Fig. 21). Both linear and rank correlation analysis have been used by Santolík and Gurnett (2003) and Santolík et al. (2004a) to define perpendicular dimensions of the sources of lower-band chorus elements below $\frac{1}{2} f_{ce}$. Correlation was significant in the range of separation distances of up to 260 km parallel to the field line and up to 100 km in the perpendicular plane. At these scales, the correlation coefficient was independent on parallel separations and decreased with perpendicular separation. This characteristic perpendicular scale varied between 60 and 200 km for different data intervals inside the source region. This variation was consistent with a simultaneously acting effect of random positions of locations at which the individual coherent wave packets of chorus were generated. The statistical properties of the observations were consistent with a model of the source region assuming individual sources of separate wave packets

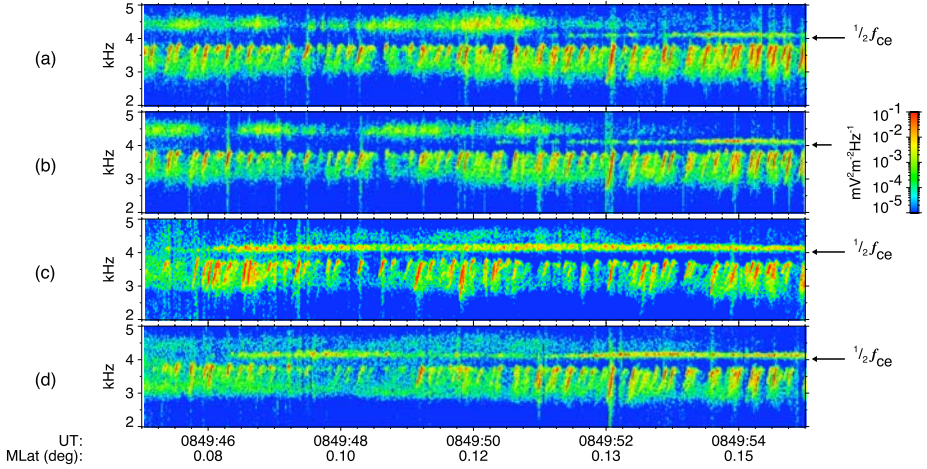


Fig. 21 Detailed time–frequency power spectrograms of electric field fluctuations in the source region recorded by the WBD instruments onboard the four CLUSTER spacecraft on 18 April 2002. Panels (a)–(d) show data from C1–C4, respectively. Arrows indicate local $\frac{1}{2}f_{ce}$ for each spacecraft. MLAT is given on the bottom for C1. Radial distance is $4.4 R_E$, and MLT is 21:01 during this interval. (Adapted from Santolík and Gurnett 2003)

as Gaussian peaks of power radiated from individual active areas with a common half-width of 35 km perpendicular to the magnetic field (Santolík et al. 2004a). This characteristic scale was comparable to the wavelength of observed WM waves.

Central position of the source region from multipoint measurement of the Poynting flux is located close to the magnetic equatorial plane (Parrot et al. 2003; Santolík et al. 2003, 2004b, 2005a). Observed spatio-temporal variations of the direction of the Poynting flux consistently show that the central position of the chorus source fluctuates at time scales of minutes within a few thousands of km of the magnetic equator (Fig. 22). The typical order of magnitude of the speed of this motion is 100 km s^{-1} . Note that this is a global speed of motion of the central position of the entire source region. It has been determined from the Poynting flux measurements where we always average propagation properties of several chorus wave packets. This speed is thus different from the speed of motion of individual sources discussed by Inan et al. (2004), Platino et al. (2006), Breneman et al. (2007) and Chum et al. (2007). Estimates of the electromagnetic planarity can be used to characterize the extent of the source in the direction parallel to the field line, obtaining at a radial distance of $\sim 4 R_E$ a source extent of 3000–5000 km (Santolík et al. 2004b, 2005a). This is consistent with theoretical results (Trakhtengerts et al. 2004) and with recent numerical simulations (Omura et al. 2008).

Santolík et al. (2005b) used the first measurements of the STAFF/DWP instrument on the DOUBLE STAR TC-1 spacecraft to investigate radial variation of intensity of WM chorus for L between 4 and 12. The chorus events showed an increased intensity at $L > 6$, consistent with intensifications of chorus, which were previously observed closer to the Earth at higher latitudes.

8.3 Propagation of Chorus From its Source Region

The four CLUSTER spacecraft observed that intense chorus waves propagate away from the equator simultaneously with lower-intensity waves propagating towards the equator (Parrot

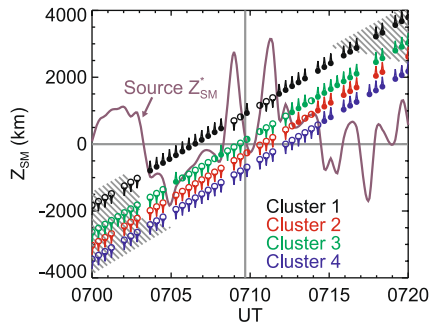


Fig. 22 Z_{SM} coordinate of the four CLUSTER spacecraft during the geomagnetic storm on 31 March 2001 as a function of time. Sign of the parallel component of the Poynting flux is shown by downward arrows attached to the open symbols, and by upward arrows with the solid symbols, for southward and northward components, respectively. The half-filled symbols with no arrows indicate that the sign cannot be reliably determined. Horizontal grey line is at the magnetic equator, vertical grey line shows the time when center of mass of the four spacecraft crosses the equatorial plane. Shaded areas bound the regions of low values of the electromagnetic planarity. Purple line shows the calculated position where the Poynting flux changes its sign. (Adapted from Santolík et al. 2004b)

et al. 2004a, 2004b). Using the observed wave normal directions of these waves, a backward ray tracing study predicts that the lower-intensity waves undergo the lower hybrid resonance (LHR) reflection at low altitudes (Parrot et al. 2004a). The rays of these waves then lead us back to their anticipated source region located close to the magnetic equator. This source region is, however, located at a different radial distance compared to the place of observation. The intensity ratio between magnetic component of the waves coming directly from the equator and waves returning to the equator has been observed between 0.005 and 0.01. The observations also show that waves returning to the equator after the magnetospheric reflection still have a high degree of polarization, even if they started to lose the coherent structure of the chorus elements (Parrot et al. 2004b).

Chum and Santolík (2005), Santolík et al. (2006) and Bortnik et al. (2007) showed that chorus can propagate to low altitudes towards the Earth if it is generated with Earthward inclined wave vectors. This result can be used to explain observations of low-altitude electromagnetic ELF hiss at subauroral latitudes. Santolík et al. (2006) reported observations of a divergent propagation pattern of these waves: They propagate with downward directed wave vectors, which are slightly equatorward inclined at lower *MLAT* and slightly poleward inclined at higher latitudes. Reverse ray tracing using different plasma density models indicated a possible source region near the magnetic equator at a radial distance between 5 and 7 R_E by a mechanism acting on highly oblique wave vectors. Additionally, waveforms received at altitudes of 700–1200 km by FREJA and DEMETER showed that low-altitude ELF hiss contains discrete time–frequency structures resembling wave packets of WM chorus. Detailed measurements of the CLUSTER spacecraft gave the time–frequency structure and frequencies of chorus along the reverse raypaths of ELF hiss, which are consistent with the hypothesis that the ELF hiss is a low-altitude manifestation of WM chorus. This propagation pattern applies mainly to the most frequently occurring dawn and dayside chorus. As noted in the following section these waves can also be considered as a possible additional candidate for the embryonic source of plasmaspheric hiss.

9 Hiss

The last comprehensive review on plasmaspheric and mid-latitude hiss was done by Hayakawa and Sazhin (1992). The following two sections are not an update to that work, but rather tries to put into context recent advances obtained on these natural waves thanks to the CLUSTER and IMAGE satellites.

9.1 Plasmaspheric Hiss

Plasmaspheric hiss is an electromagnetic emission confined to the plasmasphere. It occurs at all local times but is more intense on the dayside, and further intensifies with geomagnetic activity (Dunckel and Helliwell 1969; Russell et al. 1969; Thorne et al. 1973). Its spectral characteristics are similar to audible hiss: structureless and banded in frequency between ~ 100 Hz and several kHz. Statistically, its intensity peaks near 500 Hz and is one order of magnitude more intense below than above 1 kHz (Fig. 23).

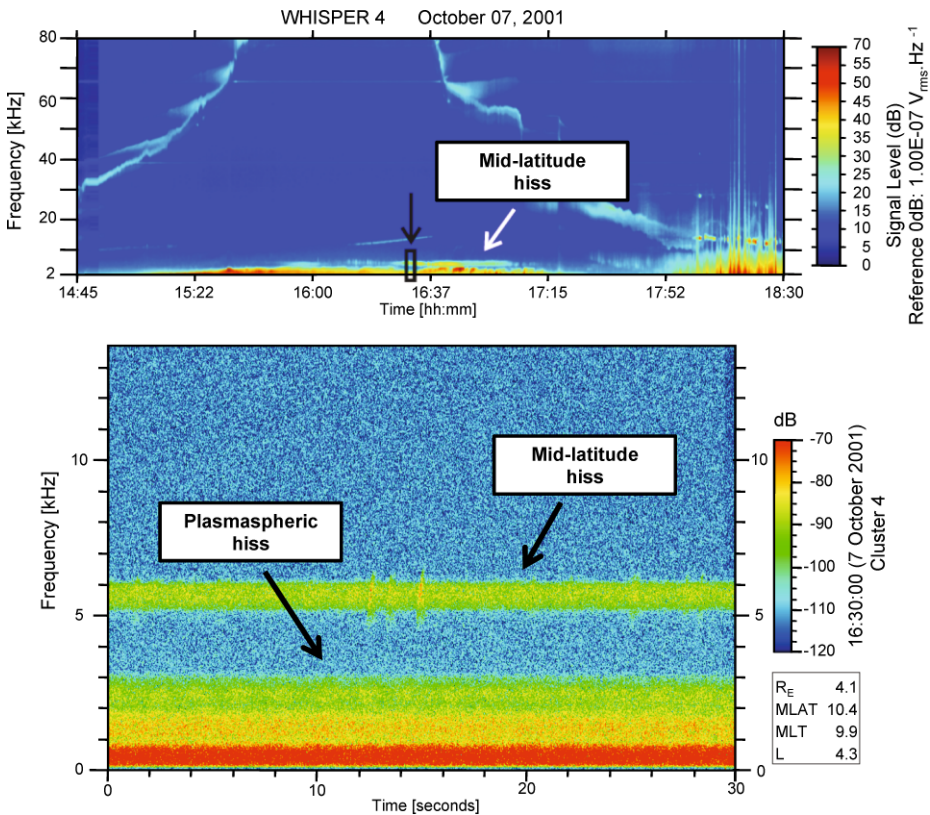


Fig. 23 (Top) WHISPER electric field spectrogram from C4 on 7 October 2001, from 14:45 to 18:30 UT. A banded hiss emission is observed from 16:25 to 17:04 UT (white arrow). The black box (black arrow) symbolizes the time period and the frequency range of the enlargement displayed in the bottom panel. (Bottom) High-time resolution WBD electric field spectrogram measured by C4 on 7 October 2001, during 30 s from 16:00:00.024 UT. The mid-latitude hiss emission is observed just above 5 kHz, while plasmaspheric hiss is observed from 100 Hz to 3 kHz with maximum spectral intensity below 700 Hz. (Adapted from Masson et al. 2004)

Plasmaspheric hiss has been studied since the late 1960s using observations from various satellites flying across the plasmasphere (Hayakawa and Sazhin 1992). It was found in particular that this emission plays a key role in the precipitation of relativistic electrons from the plasmasphere into the atmosphere (Sect. 9.1.1). However, even four decades after its discovery, its source location and generation mechanism remain controversial topics. As shown in Sect. 9.1.2, significant progresses have been made in recent years on these issues, thanks to data collected by several satellites including CLUSTER and IMAGE.

9.1.1 Impact on the Radiation Belts

The Van Allen radiation belts are two roughly concentric belts of energetic particles (>100 keV) encircling the Earth. The inner belt is characterized by a fairly stable population of high-energy protons (~ 10 – 100 MeV), trapped between $L = 1.25$ and $L = 2$. The outer belt encircles the inner belt ($3 < L < 7$) and is characterized by a population of relativistic electrons (>1 MeV) and various ions (~ 10 keV– 10 MeV). However, the content of the outer belt fluctuates widely with regards to the geomagnetic activity. Between the inner and the outer belts ($2 < L < 3$), the population of relativistic electrons drops down by a factor of 10 to 100 (e.g., Brautigam et al. 2004). However, during very strong geomagnetic storms, this slot region can be filled with energetic particles. The slot region subsequently reforms on a timescale of days to weeks.

Theoretical work by Kennel and Petschek (1966) showed that natural waves propagating in the whistler mode are able to gain energy from a gyroresonance interaction with radiation belt relativistic electrons near the magnetic equator, causing them to change pitch angle and precipitate. Several types of WM waves exist in the plasmasphere (e.g., Green et al. 2005a) but plasmaspheric hiss was shown to be the dominant emission responsible for the electron scattering in the slot region (Lyons et al. 1972; Thorne et al. 1973; Abel and Thorne 1998). Plasmaspheric hiss was also found to be an important loss mechanism inside plasmaspheric plumes (Summers et al. 2008), the outer radiation belt (Meredith et al. 2007) and the upper part of the inner belt (Tsurutani et al. 1975) during magnetically disturbed periods.

Therefore understanding the origin of plasmaspheric hiss is of fundamental importance to forecast the distribution of relativistic electrons and dynamics of the radiation belts electrons.

9.1.2 Origin of Plasmaspheric Hiss

Over the years, two theories have emerged as the most likely candidates to explain the origin of plasmaspheric hiss. One of them considers the in situ growth and amplification of background electromagnetic turbulence in space, driven by unstable energetic electron populations (Thorne et al. 1973). Unfortunately, typical wave growth rates estimated in the plasmasphere are too weak to locally generate the hiss emissions with its observed power. However, once hiss is generated, its power can be maintained thanks to the presence of these anisotropic energetic electrons in the outer plasmasphere, via a physical process known as cyclotron resonant instability (Church and Thorne 1983).

The other theory considers terrestrial lightning strikes as the main energy source of plasmaspheric hiss (Dowden 1971; Sonwalkar and Inan 1989; Draganov et al. 1993; Bortnik et al. 2003). Lightning strikes trigger the emission of impulsive signals that can reach the plasmasphere. As they propagate, they undergo dispersion as lower frequencies travel slower than higher ones, sounding like a whistler when turned to audio. Several of these lightning-generated whistlers can finally merge into a broadband signal that becomes plasmaspheric hiss as originally suggested by H.C. Koons according to Storey et al. (1991).

Using a new statistical wave-mapping technique on data collected by DE-1 and IMAGE, Green et al. (2005a) showed that the distribution of hiss emissions in the plasmasphere at 3 kHz is similar to the geographic distribution of lightning strikes. In particular, the observed emissions are stronger over the continents than the oceans. The 3 kHz frequency was chosen since it is the lowest frequency of the IMAGE/RPI instrument. They claim that geographic control of a portion of the hiss spectrum exists to some extent above ~ 500 Hz, although the DE/PWI data below 1.2 kHz were only examined in a qualitative manner (Green et al. 2006). They concluded that lightning is the dominant source of plasmaspheric hiss. But this conclusion has been called into question by Thorne et al. (2006) arguing in particular that the intensities of the waves above 1 kHz are much smaller than the intensities of plasmaspheric hiss below 1 kHz.

Meredith et al. (2006) subsequently analyzed the geographic distribution of hiss over a wider frequency range (0.1–5.0 kHz) using CRRES data. They found that the waves between 1.0 kHz and 5.0 kHz are most likely related to lightning-generated whistlers, confirming the results obtained by Green et al. (2005a) at 3 kHz. However, they found that the waves at lower frequencies (0.1–1.0 kHz) are independent of lightning activity. Since the emission power of plasmaspheric hiss below 1 kHz is statistically an order of magnitude higher than above 1 kHz, lightning strikes are not responsible for the bulk of the wave power of plasmaspheric hiss. As electron loss via pitch angle scattering is proportional to the wave power, this suggests that lightning strikes is not the dominant energy source, which maintains the slot region in the radiation belts during quiet to moderate geomagnetic activity. In other words, both leading models for the origin of plasmaspheric hiss are not fully backed up by observations.

An alternative explanation for the generation of plasmaspheric hiss was proposed by Chum and Santolík (2005) who discovered that chorus, a well-known intense electromagnetic emission generated outside the plasmasphere, can fill the plasmasphere and might be one of the possible sources of plasmaspheric hiss (see Sect. 8). They also found that the wave-normal angles of these waves stay far from resonance and therefore effects of Landau damping can be excluded. Additionally the wave normals are nearly field-aligned inside the plasmasphere, consistent with previous observations of plasmaspheric hiss. This makes possible further amplification of these waves by the cyclotron resonance (e.g., Santolík et al. 2001). Equatorward reflected ELF hiss at low altitudes that is also most probably related to chorus emissions might represent another simultaneously acting embryonic source (Santolík et al. 2006). The results of Chum and Santolík (2005) were reproduced and confirmed by Bortnik et al. (2008) who obtained the same effect and who verified the absence of Landau damping. According to this study, plasmaspheric hiss is driven by chorus emissions. By modeling the propagation of chorus to lower altitudes, Bortnik et al. (2008) are able to reproduce the main features of plasmaspheric hiss including its observed spectral signature, incoherent nature and day-night asymmetry in intensity.

9.2 Mid-Latitude Hiss

9.2.1 Mid-Latitude Hiss and Auroral Hiss

Mid-latitude hiss (MLH) emissions are natural radio waves that usually appear as a band-limited white noise with a central frequency contained between 2 and 10 kHz and a spectral bandwidth of 1 to 2 kHz (Fig. 23). Such hiss emissions were first discovered by ground-based observatories located at mid-latitudes (30 – 60°) in the 1950s and 1960s (Watts 1957; Laaspere et al. 1964; Helliwell 1965). When converted to audio range, these VLF waves (3–30 kHz) have a characteristic “hissing” sound, hence their name.

The first studies of this natural phenomenon suggested that they were just auroral hiss, sometimes called polar hiss (Ondoh 2006), propagating from auroral latitudes to mid-latitudes within the Earth-ionosphere waveguide. This was shown to be incorrect in the pioneering works by Harang (1968) and Hayakawa et al. (1975). Significant differences between auroral and MLH spectral signatures were found between simultaneous measurements from stations located at mid- (34.5°) and auroral (69°) latitudes (see Hayakawa and Sazhin 1992, for the last comprehensive review on MLH). In particular, the upper limit of MLH spectrum could extend up to 8 kHz while the auroral hiss spectrum could extend up to 500 kHz or even higher.

Since then, hiss events recorded at mid- or even low-latitude stations have been considered to be independent from auroral hiss. Mid- and low-latitude hisses are both named MLH since the maximum of their occurrence was found at middle latitudes, 55° to 65° (Helliwell 1965). This latitudinal range is magnetically connected to the plasmapause location, which explains why MLH is sometimes called narrow-band plasmapause hiss or simply plasmapause hiss (e.g., Ondoh 2006).

Thanks to satellite measurements and theoretical studies, other fundamental differences have been discovered between auroral and MLH, such as their source location and generation mechanism.

9.2.2 Source Location and Generation Mechanism

Ground-based direction finding performed by Hayakawa et al. (1986) revealed that MLH is generated mainly on the inner side of the PBL. For the first time, a survey of MLH events observed close to their source region by the CLUSTER satellites confirmed the presence of MLH around the magnetic equator, in the PBL at around $4 R_E$, i.e., 25 000 km altitude (Masson et al. 2004).

MLH, like chorus, is generated near the magnetic equator and propagate via the whistler mode. Chorus often accompanies MLH and the upper cutoff of the combined band of hiss and chorus is found to be proportional to the equatorial gyrofrequency (Dunckel and Helliwell 1969). Both type of waves are believed to be generated by the electron cyclotron instability, sometimes called the whistler-mode instability. Combined ground-based and satellite measurements reveal that mid-latitude/plasmapause hiss waves are excited around the equatorial plasmapause by the cyclotron instability of electrons with energy of a few keV convected from the magnetotail (e.g., Hayakawa and Sazhin 1992; Ondoh 2006, and references therein).

Unlike MLH, auroral hiss emissions are broad, intense electromagnetic emissions, which occur over a wide frequency range from a few hundred Hz to several tens of kHz. At low frequencies, auroral hiss occurs in a narrow latitudinal band, typically only $5\text{--}10^\circ$ wide, centered on the auroral zone ($70\text{--}80^\circ$). At high frequencies, the emission spreads out over a broad region, both towards the polar cap, and to a lesser extent towards the equator. The anisotropic character of whistler-mode propagation causes this spreading at high frequencies.

Satellite data, such as those from POLAR, also revealed that auroral hiss is emitted in a beam around an auroral magnetic field line located between $L = 2$ and $L = 4$. Downward propagating auroral hiss emissions are closely correlated with intense, downgoing 100 eV to 40 keV electron beams precipitating from the plasmasheet boundary layer in geomagnetic quiet and disturbed periods (Gurnett and Franck 1972). Upward propagating auroral hiss is correlated with upgoing ~ 50 eV electron beams.

All these facts confirm ground-based initial measurements: Auroral hiss and MLH are two distinct natural phenomena.

9.2.3 Geomagnetic Activity Impact

Several physical characteristics of MLH are affected by geomagnetic activity, starting with their duration. During quiet geomagnetic conditions, such a band-limited white noise usually lasts for an hour. However, during active periods, MLH can last for several hours showing amplitude fluctuations on a time scale of tens of minutes (see page 427 of Sonwalkar 1995).

According to Ondoh (2006), the occurrence rate of MLH is maximum under geomagnetic quiet conditions ($30 \text{ nT} < AE < 200 \text{ nT}$) while the occurrence rate of auroral/polar hiss is much larger in the substorm period ($200 \text{ nT} < AE < 924 \text{ nT}$). This statistical study is based on 65 MLH and 74 polar hisses observed by the ISIS-2 satellite (1400 km altitude, polar circular orbit) under various geomagnetic conditions.

Close to the source region, in the vicinity of the magnetic equator at $4 R_E$, Masson et al. (2004) showed that the central frequency of MLH (f_0) is correlated with the K_p index: the higher K_p , the higher f_0 . One possible explanation suggested in this paper assumes that these waves are generated in the vicinity of the plasmapause, near the magnetic equator, in a given f/f_{ce} frequency bandwidth. At the equator near the plasmapause f_{ce} is proportional to $1/L_{pp}^3$, where L_{pp} is the geocentric radial distance of the plasmapause. When geomagnetic activity is high, the plasmasphere is compressed, the plasmapause location gets closer to the Earth, and so L_{pp} decreases. In this case, f_{ce} will increase, hence f_0 increases too, according to our assumption (f_0/f_{ce} constant). This explanation is in agreement with theoretical predictions (Sazhin 1989; Hayakawa and Sazhin 1992) and with early ground-based measurements, which revealed that the central frequency of hiss usually increases with decreasing latitude (Laaspere et al. 1964). This behaviour is similar to plasmaspheric hiss, whose wave frequencies just inside the plasmapause increase with increasing K_p (Thorne et al. 1973).

10 Equatorial Noise

10.1 Introduction

Emissions called “equatorial noise” are electromagnetic waves (the term “fast magnetosonic waves” is also sometimes used, e.g., Horne et al. 2000 2007) observed close to the magnetic equator (within $\sim \pm 3^\circ$) at frequencies between f_{ce} and f_{lh} and at radial distances $R = 2\text{--}7 R_E$. They propagate in the fast magnetosonic mode coupled to the whistler mode with wave vectors nearly perpendicular to the ambient magnetic field ($\mathbf{B}_0$), with magnetic field fluctuations linearly polarized in the direction of $\mathbf{B}_0$. Electric field fluctuations are elliptically polarized with a low ellipticity (from 0.02 to 0.11, see Santolík et al. 2002), major polarization axis being oriented along the wave vector. CLUSTER observes emissions of this type during perigee passes through the equatorial region ($R \approx 4 R_E$).

Figure 24 shows an example of equatorial noise emissions recorded by C4 on 17 February 2002 within approximately $\pm 30^\circ$ of magnetic equator. Panels (a) and (b) represent frequency–time spectrograms of power-spectral densities of the magnetic and electric field fluctuations, respectively. Equatorial noise is the intense electromagnetic emission seen on both panels close to the center of the time interval, within a few degrees from the magnetic equator. In the frequency domain it appears as two main peaks at about 30 Hz and 70 Hz. The emission is confined below the upper estimate of f_{lh} , calculated as the geometric average of the proton gyrofrequency f_{cp} and f_{ce} (solid line at ~ 300 Hz). Frequency–time spectrogram of ellipticity of polarization of the magnetic field fluctuations is shown

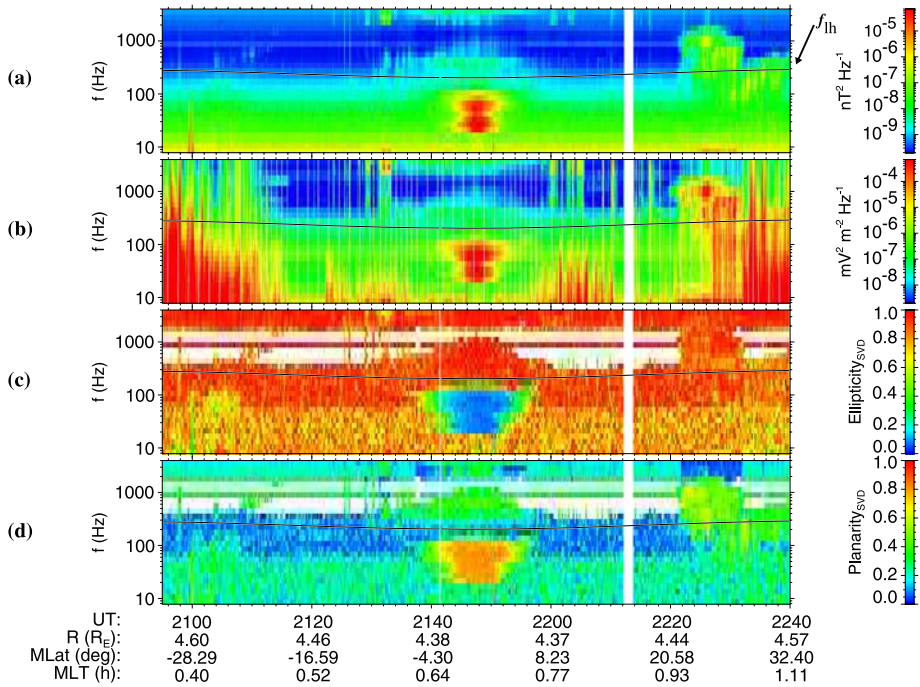


Fig. 24 STAFF data collected by C4 on 17 February 2002: (a) sum of the power-spectral densities of the three magnetic components, (b) sum of the power-spectral densities of the two electric components, (c) ellipticity and (d) planarity determined using the singular value decomposition of the magnetic spectral matrix. Maximum possible value of f_{lh} is plotted over the panels (a)–(d). The data in panels (c) and (d) are not shown for weak signals below $10^{-9} \text{ nT}^2 \text{ Hz}^{-1}$. (Adapted from Santolík et al. 2004c)

in panel (c). It varies between 0 (linear polarization) and 1 (circular polarization). Equatorial noise can be easily distinguished by its polarization close to linear, as it was first described by Russell et al. (1970). Panel (d) represents the frequency–time spectrogram of planarity of magnetic field fluctuations. A value close to 1 represents a strict confinement of the magnetic field fluctuations to a single plane, which is obviously also true for the linear polarization.

10.2 CLUSTER Observations

Santolík et al. (2002) performed a multipoint case study of equatorial noise by using both STAFF and WBD instruments onboard CLUSTER. Frequency–time spectrograms of the analyzed electric field data measured by WBD instruments are shown in Fig. 25. Dipole equator and min- B equator calculated from a Tsyganenko-IGRF model (which is about 1° northward from the dipole equator) are marked. It can be seen that what appears like a noise in a low resolution data is in fact a set of many spectral lines (Gurnett 1976) some of which follow a harmonic pattern. However, all the possible fundamental frequencies were significantly different from the local f_{cp} and they did not match the cyclotron frequencies of heavier ions either. The authors bring observational evidence that the waves propagate with a significant radial component (on average the waves propagate at $\sim 45^\circ$ between the radial and azimuthal directions, but the wave power spreads in a large angular interval) and can thus propagate

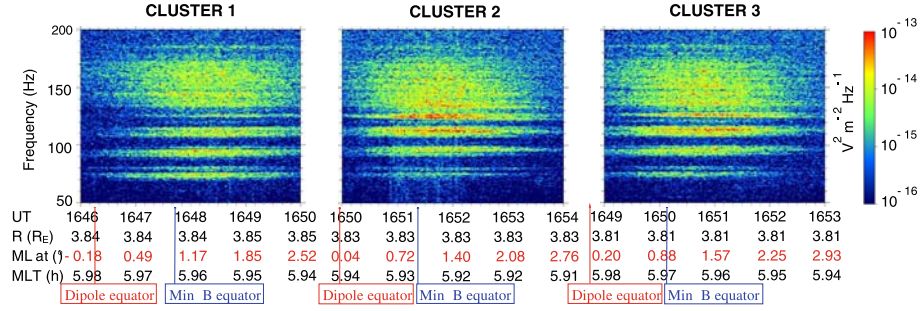


Fig. 25 Frequency–time spectrograms of electric field data recorded by the WBD instrument onboard three CLUSTER spacecraft on 4 December 2000. (Adapted from Santolík et al. 2002)

from a distant generation region located at different radial distances where ion cyclotron frequencies match the observed fine structure.

Santolík et al. (2004c) performed a systematic analysis of 2 years of STAFF data measured by CLUSTER during their perigee passes through equatorial region. A visual inspection has revealed the presence of equatorial noise in 398 of the 671 analyzed passes (each spacecraft has been treated separately), which corresponds to about 59%. They have selected 16 frequency channels between 8 Hz (the lowest frequency analyzed by the STAFF instrument) and 300 Hz (the upper estimate of the maximum f_{ih} throughout the dataset) and with the time resolution of 4 s evaluated the wave parameters within $\pm 30^\circ$ of geomagnetic latitude (altogether, about 1.4×10^7 frequency–time intervals). They have shown that a value of 0.2 is a reasonable upper estimate of the ellipticity of magnetic field fluctuations of equatorial noise and that equatorial noise has the largest power spectral density of magnetic field fluctuations among all the natural emissions in the given interval of frequencies and latitudes.

Němec et al. (2005) have used the same dataset, but limited to only $\pm 10^\circ$ of geomagnetic latitude. Following Santolík et al. (2004c) they selected the 16 lowest frequency bands and only the frequency–time intervals during which the ellipticity was lower than 0.2. Then they calculated average power-spectral density from the selected data in the selected frequency channels and found parameters λ_c (central latitude) and Δ (full width at half of maximum, FWHM) of a Gaussian model of the power-spectral density as a function of geomagnetic latitude. The resulting parameters were found to be about the same for magnetic and electric power spectral densities. Most of the central latitudes occur within 2° from the magnetic equator with the FWHM lower than 3° . From the original frequency-dependent data, they calculated a time-averaged spectral matrix over the time interval where the spacecraft was located inside the latitudinal interval from $\lambda_c - \Delta$ to $\lambda_c + \Delta$ and obtained the probability density of frequencies of equatorial noise emissions normalized to the local f_{cp} . It has been shown that the most probable frequency of emissions is between 4 and 5 local f_{cp} , with probability density slowly decreasing towards the higher frequencies. Finally, multipoint measurements performed by CLUSTER were used to demonstrate that variations of the ratio of amplitudes of equatorial noise increase with time delay between measurements in an interval from tenths to hundreds of minutes, but these variations do not seem to increase with separations up to $0.7 R_E$ in the equatorial plane.

Němec et al. (2006) performed the similar analysis, but used an improved magnetic field model to determine the min-B equator (instead of a dipole magnetic field model used in the previous study). They concluded that central latitudes of equatorial noise seem to be

located exactly at the true magnetic equator and that the observed deviations can be most probably explained by the inaccuracies in the model. They also used cold plasma theory to calculate the number density from the ratio of magnetic and electric power spectral density. The estimated values vary from units to hundreds of particles per cubic centimeter and are in a rough agreement with the densities obtained from the measurements of the spacecraft potential.

10.3 Generation Mechanism of Equatorial Noise and its Effects

A generation mechanism of equatorial noise (fast magnetosonic waves) is discussed by Horne et al. (2000). They conducted a ray-tracing analysis using a density model, which includes a plasmasphere, a plasmopause, and a radial variation in the plasma density outside the plasmasphere, as well as the proton distribution with a thermal spread of velocities taken from spacecraft observations, and a realistic plasma sheet electron distribution to represent conditions outside the plasmopause. Supposing ring distribution functions (ring velocity v_R) with a thermal spread of velocities, they showed that magnetosonic waves can be generated just outside the plasmopause and propagate well inside the plasmopause without substantial absorption. Peak growth occurs for very large angles of propagation, and thus the waves are confined in latitude to a few degrees about the magnetic equator. The instability analysis shows that a good “rule of thumb” for growth of magnetosonic waves at large angles of propagation ($\sim 89^\circ$) is $v_R > v_A$ for growth $f > 30 f_{cp}$, and $v_R > 2v_A$ for growth $f < 30 f_{cp}$ (f is the frequency of wave, v_A is the Alfvén speed).

In a recent paper Horne et al. (2007) discussed potential implications of fast magnetosonic waves for electron populations in Van Allen radiation belts and demonstrated that the fast magnetosonic waves can accelerate electrons between ~ 10 keV and a few MeV inside the outer radiation belt. The acceleration occurs via the Landau resonance, and not Doppler shifted cyclotron resonance, due to the wave propagation almost perpendicular to the ambient magnetic field. Pitch angle and energy diffusion rates are comparable to those obtained for WM chorus. This suggests that the magnetosonic waves are very important for local electron acceleration and could play an important role in the process of energy transfer from the ring current (where ion ring distributions are formed during magnetic storms as a result of losses due to slow ion drift) to Van Allen radiation belts. Finally, since magnetosonic waves do not scatter electrons into the loss cone, the need for a continuous supply of low energy electrons is not as stringent as it is for their acceleration by chorus, and these waves, on their own, are not important for loss to the atmosphere.

11 ULF Resonances

11.1 Historical Description

The attempt to use pulsation data to remotely sense plasmaspheric mass properties has a long history (Troitskaya and Gul’Elmi 1969; Lanzerotti and Fukunishi 1975; Webb et al. 1977; Takahashi and McPherron 1982). A variety of methods have been developed to identify inner magnetospheric field line resonances, which can arise from a driving impulse. These include complex demodulation (Webb 1979), methods of evaluating the spectral matrix (Arthur 1979), such as state vector analysis techniques (Samson 1983), meridional geomagnetic gradient evaluation (Baransky et al. 1985), cross phase analysis techniques (Waters et al. 1991), and dynamic spectrum techniques (Menk 1988). It is not always easy to determine the resonant frequencies because the pulsation spectrum can be dominated by the source mechanism

(Kurchashov et al. 1987). The “gradient method” was developed by Baransky et al. (1985) to separate the mixed driving and resonant power. Field line resonant theory predicts that the wave power peaks at the resonant frequency and the spatial profile of the phase at the resonant frequency changes roughly 180 degrees across the resonant L -shell (Tamao 1964; Chen and Hasegawa 1974; Southwood 1974). Using data from two magnetometers located on the same magnetic longitude and closely separated in latitude, one can compare the wave phase or amplitude seen at both stations and obtain the eigenfrequencies of the field line midway between the two stations. The cross phase spectral technique developed by Waters et al. (1991) was used by Menk et al. (1994, 1999) to monitor the temporal evolution of plasmaspheric properties. This is done by identifying the maximum interstation phase difference between two closely spaced stations (few hundred km) to identify the eigenfrequencies of the local field line. With this diagnostic technique variations in plasmaspheric plasma parameters (such as equatorial plasma density) can be monitored and using a latitudinal array of stations, the location of the plasmopause can be determined. The techniques of Schulz (1996) and Denton and Gallagher (2000) are used to derive the equatorial mass density from the inferred eigenfrequency of the field line (Berube et al. 2003). The techniques are analogous to identifying the mass of a string by determining the sound frequency of the plucked note. By knowing the string length (field line length), string tension (strength of magnetic field line) and the frequency of oscillation, the density of the string (plasma) can be inferred. Under the usual Alfvénic travel time approximations, the eigenfrequencies can be expressed as:

$$\frac{\omega_n}{2\pi} \approx \frac{n\Delta\omega}{2\pi} \approx n \left(\int \frac{ds}{v_A} \right)^{-1}, \quad (4)$$

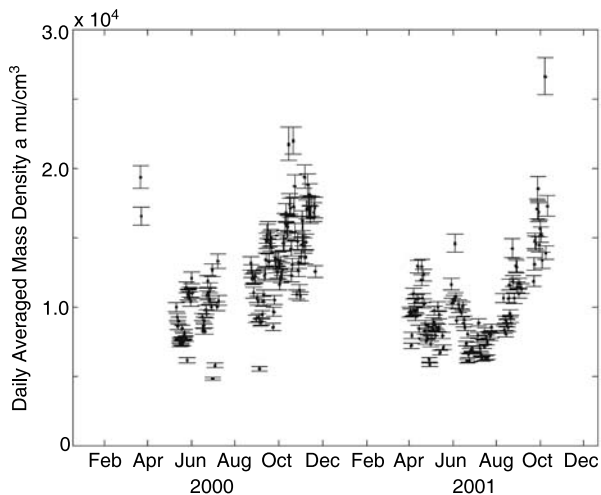
where v_A is the Alfvén speed, n is the harmonic number, and s is the coordinate that measures the arc length of the field line. The measure eigenfrequency is representative of the equatorial mass density because of the slow Alfvén speed there. The ability to uniquely identify the flux tubes eigenfrequency depends on having a solar wind or magnetospheric driving wave. On the dayside of the Earth, ULF waves are almost continuously present due to upstream waves impinging on the magnetopause (e.g., Yumoto 1986). These driver waves excite the field lines resonance frequency that can be separated out from the driving frequency using such methods as the cross phase technique. Therefore one limitation of using ULF waves at the present time is that inner magnetospheric mass densities can only be routinely measured during the daytime.

Figure 26 shows daily plasma mass density averages inferred from ULF resonances during 2000–2001 at $L = 1.74$. The daily averages are made from hourly estimates of the eigenfrequency. The error bars shown are representative of the variation of the mean of the hourly estimates. The December densities are 2–3 times higher than the June densities for both years. Typical uncertainties in determining the ULF resonant frequency, and hence mass density is $\pm 25\%$ (e.g., Berube et al. 2003, 2005). Annual variation of the electron density has also been observed at low latitudes using VLF measurements (e.g., Clilverd et al. 1991).

11.2 IMAGE Observations

The mass density of the inner plasmasphere is difficult to measure and the few satellites capable of making measurements did not sample the inner magnetosphere well. An exception are measurements from DE-1 (e.g., Horwitz et al. 1984). Most studies found that the relative abundances of heavy ions in the plasmasphere vary greatly. Craven et al. (1997) using data

Fig. 26 The equatorial mass densities at $L = 1.74$ computed by a ULF resonance method. Note the seasonal difference in mass density. (Adapted from Berube et al. 2003)



from DE-1 found He^+ to H^+ ratios in the plasmasphere of $\sim 0.03\text{--}0.3$, implying He^+ abundances of $\sim 3\text{--}23$ percent by number, assuming no other heavy ions are present. Horwitz et al. (1984) found that in the aftermath of a storm, O^+ density could become comparable to H^+ density in the plasmasphere. The first empirical model of the equatorial mass density of the plasmasphere was proposed by Berube et al. (2005) using ground-based ULF wave diagnostics. Plasmaspheric mass density between $L = 1.7$ and $L = 3.2$ was determined using over 5200 hours of data from pairs of stations in the MEASURE array of ground magnetometers. The least squares fit to the data as a function of L shows that mass density falls logarithmically with L . Average ion mass as a function of L was also estimated by combining the mass density model with plasmaspheric electron density profiles determined from IMAGE/RPI instrument. Additionally, the RPI electron density database was used to examine how the average ion mass changes under different levels of geomagnetic activity. Berube et al. (2005) report that average ion mass is greatest under the most disturbed conditions. This result indicates that heavy ion concentrations (percent by number) are enhanced during large geomagnetic disturbances. The average ion mass was also found to increase with increasing L (below 3.2), indicating the presence of a heavy ion torus during disturbed times. Heavy ions must play an important role in storm-time plasmaspheric dynamics. The average ion mass was also used to constrain the concentrations of He^+ and O^+ . Estimates of the He^+ concentration determined this way is useful for interpreting IMAGE/EUV images. More details on empirical models can be found elsewhere in this issue (Reinisch et al. 2009).

12 Conclusion

CLUSTER and IMAGE are pioneer space missions with regards to plasmaspheric wave phenomena thanks to their new experimental capabilities. Some of the results highlighted in this paper were considered among the science objectives of these missions such as the source location of waves (Sects. 3 and 8) or the remote sensing of density profiles along geomagnetic field lines (Sect. 5). Now, CLUSTER and IMAGE have also brought or led to a wealth of unforeseen results, just like pioneer missions do.

For instance, the database of plasmaspheric density profiles measured by IMAGE, together with ground-based ULF wave diagnostics, has helped determining the average ion

mass as a function of L under different levels of geomagnetic activity. Thanks to a better knowledge of this key physical parameter, heavy ions were found to play an important role in storm-time plasmaspheric dynamics (Sect. 11).

Similarly, the IMAGE/EUV imager uncovered the presence of density bite-outs of the plasmapause named notches. Together with local wave observations, these EUV images have enabled to identify these notches as the source of kilometric continuum (KC); recall that KC is the high-frequency range of a more general wave phenomenon known as the non-thermal continuum (NTC) radiation. As KC emission cone is constrained by the geometry of these density cavities, KC observations provide back information on this plasmaspheric structure and its dynamics (Sect. 3).

Such a link between density irregularities in azimuth and longitudinal beaming properties of radiations is likely applicable to NTC radiations at lower frequency, linking them with irregularities of smaller size (Sect. 4). CLUSTER observations in the NTC range have also revealed a new class of radio sources, emitting from the mid-latitude plasmapause boundary while new radio echoes have been discovered by IMAGE (Sects. 6 and 7).

Another striking example concerns chorus emissions. The multipoint view of CLUSTER near perigee has enabled a better understanding of the source location and size of these waves and their propagation properties from their source region (Sect. 8). This new knowledge has triggered ray-tracing studies that led to an unforeseen conclusion: Chorus is an embryonic source of plasmaspheric hiss, the dominant emission responsible for the scattering of MeV electrons in the electron slot region (Sect. 9).

As usual, scientific discoveries lead to more questions than answers. For instance, CLUSTER data strongly suggest that equatorial noise plays, like chorus, a role in the acceleration of electrons in the outskirts of the plasmasphere (Sect. 10). However, a crucial limitation of this conclusion lies in the limited range of radial distances of equatorial perigee passes ($3.9\text{--}5 R_E$). A full assessment of the importance of these waves requires detailed analysis of the occurrence rate of their power as a function of L , MLT and latitude.

Overall, both missions have helped to better relate plasmaspheric wave phenomena with plasmaspheric density structures, derive electron density profiles and heavy particles content of the plasmasphere, better locate the source of waves and how they propagate. They have also increased our knowledge on how electrons of magnetotail origin are accelerated up to MeV range and how these killer electrons get scattered by waves. Last but not least, these missions have linked wave phenomena together: Several waves are now considered as embryonic sources of other waves and no more studied as distinct phenomena. In other words, IMAGE and CLUSTER have helped putting the puzzle pieces together.

But the puzzle is far from being complete. Upcoming inner magnetospheric missions will all orbit the magnetic equator and carry appropriate wave instrumentation. These missions are the NASA's Radiation Belt Storm Probes (RBSP) composed of two satellites (launch planned in 2012), the ERG (Energization and Radiation in Geospace) single satellite project from Japan and the ORBITALS (Outer Radiation Belt Injection, Transport, Acceleration and Loss Satellite) project led by Canada. Up till the launch of RBSP and hopefully ERG and ORBITALS, three of the NASA's THEMIS spacecraft launched in 2007 and equipped with search coil magnetometers will survey the inner magnetosphere together with particle instrumentation. In other words, the future looks bright for plasmaspheric wave research.

Acknowledgements O. Santolík and F. Němec acknowledge grants GAAV A301120601 and ME842. F. Darrouzet acknowledges the support by the Belgian Federal Science Policy Office (BELSPO) through the ESA/PRODEX project (contract 13127/98/NL/VJ (IC)). This paper is an outcome of the workshop "The Earth's plasmasphere: A CLUSTER, IMAGE, and modeling perspective", organized by the Belgian Institute for Space Aeronomy in Brussels in September 2007. Figures 1, 2, 4, 8, 10b, 11, 13, 14, 15, 16, 17, 18, 19,

20, 21, 22, 25, 26: Copyright (1999, 2002 and 2004, 2002, 2008, 1991, 2008, 2003, 2003, 2003, 2003, 2009, 2007, 2007, 2003, 2004, 2002, 2003), with permission from American Geophysical Union (AGU). Figure 10a: Copyright (1982), with permission from Elsevier. Figures 10c, 23, 24: Copyright (2007, 2004, 2004), with permission from European Geosciences Union (EGU). Figure 12: Copyright (1995), with permission from Cambridge University Press.

References

- B. Abel, R.M. Thorne, Electron scattering loss in Earth's inner magnetosphere 1. Dominant physical processes. *J. Geophys. Res.* **103**(A2), 2385–2396 (1998)
- C.W. Arthur, Digital techniques for ULF wave polarization analysis. *Ann. Telecommun.* **34**, 166–178 (1979)
- L.N. Baransky, J.E. Borovkov, M.B. Gokhberg, S.M. Krylov, V.A. Troitskaya, High resolution method of direct measurement of the magnetic field lines' eigen frequencies. *Planet. Space Sci.* **33**(12), 1369–1374 (1985)
- R.F. Benson, Ion effects on ionospheric electron resonance phenomena. *Radio Sci.* **10**(2), 173–185 (1975)
- R.F. Benson, Stimulated plasma waves in the ionosphere. *Radio Sci.* **12**(6), 861–878 (1977)
- R.F. Benson, Elusive upper hybrid waves in the auroral topside ionosphere, in *Auroral Plasma Dynamics*, ed. by R.L. Lysak. Geophysical Monograph Series, vol. 80 (American Geophysical Union, Washington, 1993), pp. 267–274
- R.F. Benson, H.K. Wong, Low-altitude ISIS 1 observations of auroral radio emissions and their significance to the cyclotron maser instability. *J. Geophys. Res.* **92**(A2), 1218–1230 (1987)
- R.F. Benson, V.A. Oshervovich, J. Fainberg, B.W. Reinisch, Classification of IMAGE/RPI-stimulated plasma resonances for the accurate determination of magnetospheric electron density and magnetic field values. *J. Geophys. Res.* **108**(A5), 1207 (2003)
- R.F. Benson, P.A. Webb, J.L. Green, D.L. Carpenter, V.S. Sonwalkar, H.G. James, B.W. Reinisch, Active wave experiments in space plasmas: The Z mode, in *Geospace Electromagnetic Waves and Radiation*, ed. by J.W. LaBelle, R.A. Treumann. Lecture Notes in Physics, vol. 687 (Springer, Berlin, 2006), pp. 3–36
- D. Berube, M.B. Moldwin, J.M. Weygand, An automated method for the detection of field line resonance frequencies using ground magnetometer techniques. *J. Geophys. Res.* **108**(A9), 1348 (2003)
- D. Berube, M.B. Moldwin, S.F. Fung, J.L. Green, A plasmaspheric mass density model and constraints on its heavy ion concentration. *J. Geophys. Res.* **110**, A04212 (2005)
- J. Bortnik, U.S. Inan, T.F. Bell, Frequency-time spectra of magnetospherically reflecting whistlers in the plasmasphere. *J. Geophys. Res.* **108**(A1), 1030 (2003)
- J. Bortnik, R.M. Thorne, N.P. Meredith, O. Santolík, Ray tracing of penetrating chorus and its implications for the radiation belts. *Geophys. Res. Lett.* **34**, L15109 (2007)
- J. Bortnik, R.M. Thorne, N.P. Meredith, The unexpected origin of plasmaspheric hiss from discrete chorus emissions. *Nature* **452**(7183), 62–66 (2008)
- D.H. Brautigam, K.P. Ray, G.P. Ginat, D. Madden, Specification of the radiation belt slot region: Comparison of the NASA AE8 model with TSX5/CEASE data. *IEEE Trans. Nucl. Sci.* **51**(6), 3375–3380 (2004)
- A. Breneman, C.A. Kletzing, J. Chum, O. Santolík, D. Gurnett, J. Pickett, Multispacecraft observations of chorus dispersion and source location. *J. Geophys. Res.* **112**, A05221 (2007)
- J.L. Burch, IMAGE mission overview. *Space Sci. Rev.* **91**(1–2), 1–14 (2000)
- W. Calvert, Oblique z-mode echoes in the topside ionosphere. *J. Geophys. Res.* **71**(23), 5579–5583 (1966)
- P. Canu, P.M.E. Décréau, S. Escoffier, S. Grimald, Observations of continuum radiations close to the plasmopause: Evidence for small scale sources, in *Planetary Radio Emissions VI*, ed. by H.O. Rucker, W.S. Kurth, G. Mann (Austrian Academy of Sciences Press, Vienna, 2006)
- D.L. Carpenter, R.R. Anderson, An ISEE/Whistler model of equatorial electron density in the magnetosphere. *J. Geophys. Res.* **97**(A2), 1097–1108 (1992)
- D.L. Carpenter, J. Lemaire, The plasmasphere boundary layer. *Ann. Geophys.* **22**(12), 4291–4298 (2004)
- D.L. Carpenter, R.R. Anderson, W. Calvert, M.B. Moldwin, CRRES observations of density cavities inside the plasmasphere. *J. Geophys. Res.* **105**(A10), 23323–23338 (2000)
- D.L. Carpenter, T.F. Bell, U.S. Inan, R.F. Benson, V.S. Sonwalkar, B.W. Reinisch, D.L. Gallagher, Z-mode sounding within propagation “cavities” and other inner magnetospheric regions by the RPI instrument on the IMAGE satellite. *J. Geophys. Res.* **108**(A12), 1421 (2003)
- D.L. Carpenter, T.F. Bell, D. Chen, D. Ng, C. Baran, B.W. Reinisch, I. Galkin, Proton cyclotron echoes and a new resonance observed by the Radio Plasma Imager instrument on the IMAGE satellite. *J. Geophys. Res.* **112**, A08208 (2007)

- L. Chen, A. Hasegawa, A theory of long-period magnetic pulsations, 1. Steady state excitation of field line resonance. *J. Geophys. Res.* **79**(7), 1024–1032 (1974)
- J. Chum, O. Santolík, Propagation of whistler-mode chorus to low altitudes: divergent ray trajectories and ground accessibility. *Ann. Geophys.* **23**(12), 3727–3738 (2005)
- J. Chum, O. Santolík, A.W. Breneman, C.A. Kletzing, D.A. Gurnett, J.S. Pickett, Chorus source properties that produce time shifts and frequency range differences observed on different Cluster spacecraft. *J. Geophys. Res.* **112**, A06206 (2007)
- S.R. Church, R.M. Thorne, On the origin of plasmaspheric hiss: Ray path integrated amplification. *J. Geophys. Res.* **88**(A10), 7941–7957 (1983)
- M.A. Clilverd, A.J. Smith, N.R. Thomson, The annual variation in quiet time plasmaspheric electron density, determined from whistler mode group delays. *Planet. Space Sci.* **39**(7), 1059–1067 (1991)
- N. Cornilleau-Wehrin, G. Chanteur, S. Perraut, L. Rezeau, P. Robert, A. Roux, C. de Villedary, P. Canu, M. Maksimovic, Y. de Conchy, D. Hubert, C. Lacombe, F. Lefeuvre, M. Parrot, J.L. Pinçon, P.M.E. Décréau, C.C. Harvey, P. Louarn, O. Santolík, H.S.C. Alleyne, M. Roth, T. Chust, O. Le Contel, STAFF team, First results obtained by the Cluster STAFF experiment. *Ann. Geophys.* **21**(1–2), 437–456 (2003)
- P.D. Craven, D.L. Gallagher, R.H. Comfort, Relative concentration of He^+ in the inner magnetosphere as observed by the DE 1 retarding ions mass spectrometer. *J. Geophys. Res.* **102**(A2), 2279–2289 (1997)
- F. Darrouzet, J. De Keyser, P.M.E. Décréau, J.F. Lemaire, M.W. Dunlop, Spatial gradients in the plasmasphere from Cluster. *Geophys. Res. Lett.* **33**, L08105 (2006)
- F. Darrouzet, D.L. Gallagher, N. André, D.L. Carpenter, I. Dandouras, P.M.E. Décréau, J. De Keyser, R.E. Denton, J.C. Foster, J. Goldstein, M.B. Moldwin, B.W. Reinisch, B.R. Sandel, J. Tu, Plasmaspheric density structures and dynamics: Properties observed by the CLUSTER and IMAGE missions. *Space Sci. Rev.* (2009, this issue)
- J. De Keyser, D.L. Carpenter, F. Darrouzet, D.L. Gallagher, J. Tu, CLUSTER and IMAGE: New ways to study the Earth's plasmasphere. *Space Sci. Rev.* (2009, this issue)
- P.M.E. Décréau, P. Ferreau, V. Krasnosels'kikh, E. Le Guirriec, M. Lévêque, P. Martin, O. Randriamboarison, J.L. Rauch, F.X. Sené, H.C. Séran, J.G. Trotignon, P. Canu, N. Cornilleau, H. de Féraud, H. Alleyne, K. Yearby, P.B. Mögensen, G. Gustafsson, M. André, D.A. Gurnett, F. Darrouzet, J. Lemaire, C.C. Harvey, P. Travnicek, Whisper experimenters, Early results from the Whisper instrument on Cluster: an overview. *Ann. Geophys.* **19**(10–12), 1241–1258 (2001)
- P.M.E. Décréau, C. Ducoin, G. Le Rouzic, O. Randriamboarison, J.L. Rauch, X. Trotignon, J.G. Vallières, P. Canu, F. Darrouzet, M.P. Gough, A. Buckley, T.D. Carozzi, Observation of Continuum radiations from the CLUSTER fleet: first results from direction finding. *Ann. Geophys.* **22**(7), 2607–2624 (2004)
- R.E. Denton, D.L. Gallagher, Determining the mass density along magnetic field lines from toroidal eigenfrequencies. *J. Geophys. Res.* **105**(A12), 27717–27725 (2000)
- R.L. Dowden, Distinction between mid latitude VLF hiss and discrete emissions. *Planet. Space Sci.* **19**(3), 374–376 (1971)
- A.B. Draganov, U.S. Inan, V.S. Sonwalkar, T.F. Bell, Whistlers and plasmaspheric hiss: Wave directions and three-dimensional propagation. *J. Geophys. Res.* **98**(A7), 11401–11410 (1993)
- N. Dunckel, R.A. Helliwell, Whistler-mode emissions on the OGO 1 satellite. *J. Geophys. Res.* **74**(26), 6371–6385 (1969)
- F. El-Lemdani Mazouz, J.L. Rauch, P.M.E. Décréau, J.G. Trotignon, X. Vallières, F. Darrouzet, P. Canu, X. Suraud, Wave emissions at half electron gyroharmonics in the equatorial plasmasphere region: CLUSTER observations and statistics. *Adv. Space Res.* **43**(2), 253–264 (2009)
- C.P. Escoubet, C.T. Russell, R. Schmidt (eds.), *The Cluster and Phoenix Missions* (Kluwer, Dordrecht, 1997)
- W.M. Farrell, Direct generation of O-mode emission in a dense, warm plasma: Applications to interplanetary type II emissions and others in its class. *J. Geophys. Res.* **106**(A8), 15701–15709 (2001)
- S.F. Fung, R.F. Benson, D.L. Carpenter, J.L. Green, V. Jayanti, I.A. Galkin, B.W. Reinisch, Guided echoes in the magnetosphere: Observations by Radio Plasma Imager on IMAGE. *Geophys. Res. Lett.* **30**(11), 1589 (2003)
- G.K. Goertz, R.J. Strangeway, Plasma waves, in *Introduction to Space Physics*, ed. by M.G. Kivelson, C.T. Russell (Cambridge University Press, Cambridge, 1995), pp. 356–399
- M.P. Gough, Non-thermal continuum emissions associated with electron injections: Remote plasmopause sounding. *Planet. Space Sci.* **30**(7), 657–668 (1982)
- J.L. Green, S.A. Boardsen, Confinement of nonthermal continuum radiation to low latitudes. *J. Geophys. Res.* **104**(A5), 10307–10316 (1999)
- J.L. Green, S.F. Fung, Advances in inner magnetosphere passive and active wave research, in *The Inner Magnetosphere: Physics and Modeling*, ed. by T.I. Pulkkinen, N.A. Tsytganenko, R.H.W. Friedel. Geophysical Monograph Series, vol. 155 (American Geophysical Union, Washington, 2005), pp. 181–202

- J.L. Green, B.R. Sandel, S.F. Fung, D.L. Gallagher, B.W. Reinisch, On the origin of kilometric continuum. *J. Geophys. Res.* **107**(A7), 1105 (2002)
- J.L. Green, S. Boardsen, S.F. Fung, H. Matsumoto, K. Hashimoto, R.R. Anderson, B.R. Sandel, B.W. Reinisch, Association of kilometric continuum radiation with plasmaspheric structures. *J. Geophys. Res.* **109**, A03203 (2004)
- J.L. Green, S. Boardsen, L. Garcia, W.W.L. Taylor, S.F. Fung, B.W. Reinisch, On the origin of whistler mode radiation in the plasmasphere. *J. Geophys. Res.* **110**, A03201 (2005a)
- J.L. Green, S.F. Fung, S. Boardsen, H.J. Christian, Distribution and origin of plasmaspheric plasma waves, in *Inner Magnetosphere Interactions: New Perspectives from Imaging*, ed. by J. Burch, M. Schulz, H. Spence. Geophysical Monograph Series, vol. 159 (American Geophysical Union, Washington, 2005b), pp. 113–126
- J.L. Green, S. Boardsen, L. Garcia, S.F. Fung, B.W. Reinisch, Reply to “Comment on “On the origin of whistler mode radiation in the plasmasphere” by Green et al.” *J. Geophys. Res.* **111**, A09211 (2006)
- S. Grimald, Etude de l'émission et de la propagation du continuum terrestre à partir des données des satellites Cluster. Ph.D. thesis, University of Orléans, France, 2007
- S. Grimald, P.M.E. Décreau, P. Canu, X. Suraud, X. Vallières, F. Darrouzet, C.C. Harvey, A quantitative test of Jones NTC beaming theory using CLUSTER constellation. *Ann. Geophys.* **25**(3), 823–831 (2007)
- S. Grimald, P.M.E. Décreau, P. Canu, A. Rochel, X. Vallières, Medium-latitude sources of plasmaspheric non-thermal continuum radiations observed close to harmonics of the electron gyrofrequency. *J. Geophys. Res.* **113**, A11216 (2008)
- D.A. Gurnett, The Earth as a radio source: The nonthermal continuum. *J. Geophys. Res.* **80**(19), 2751–2763 (1975)
- D.A. Gurnett, Plasma wave interactions with energetic ions near the magnetic equator. *J. Geophys. Res.* **81**(16), 2765–2770 (1976)
- D.A. Gurnett, L.A. Franck, VLF hiss and related plasma observations in the polar magnetosphere. *J. Geophys. Res.* **77**(1), 172–190 (1972)
- D.A. Gurnett, S.D. Shawhan, R.R. Shaw, Auroral hiss, Z mode radiation, and auroral kilometric radiation in the polar magnetosphere: DE 1 observations. *J. Geophys. Res.* **88**(A1), 329–340 (1983)
- D.A. Gurnett, R.L. Huff, J.S. Pickett, A.M. Persoon, R.L. Mutel, I.W. Christopher, C.A. Kletzing, U.S. Inan, W.L. Martin, J.-L. Bougeret, H.S.C. Alleyne, K.H. Yearby, First results from the Cluster wideband plasma wave investigation. *Ann. Geophys.* **19**(10–12), 1259–1272 (2001)
- G. Gustafsson, M. André, T. Carozzi, A.I. Eriksson, C.-G. Fälthammar, R. Grard, G. Holmgren, J.A. Holtet, N. Ivchenko, T. Karlsson, Y. Khotyaintsev, S. Klimov, H. Laakso, P.-A. Lindqvist, B. Lybekk, G. Marklund, F. Mozer, K. Mursula, A. Pedersen, B. Popielawska, S. Savin, K. Stasiewicz, P. Tanskanen, A. Vaivads, J.-E. Wahlund, First results of electric field and density observations by Cluster EFW based on initial months of observations. *Ann. Geophys.* **19**(10–12), 1219–1240 (2001)
- L. Harang, VLF-emissions observed at stations close to the auroral zone at stations on lower latitudes. *J. Atmos. Terr. Phys.* **30**, 1143–1160 (1968)
- K. Hashimoto, W. Calvert, H. Matsumoto, Kilometric continuum detected by Geotail. *J. Geophys. Res.* **104**(A12), 28645–28656 (1999)
- M. Hayakawa, S.S. Sazhin, Mid-latitude and plasmaspheric hiss: A review. *Planet. Space Sci.* **40**(10), 1325–1338 (1992)
- M. Hayakawa, Y. Tanaka, J. Ohtsu, The morphologies of low-latitude and auroral VLF “hiss”. *J. Atmos. Terr. Phys.* **37**, 517–529 (1975)
- M. Hayakawa, N. Ohmi, M. Parrot, F. Lefeuvre, Direction finding of ELF hiss emissions in a detached plasma region of the magnetosphere. *J. Geophys. Res.* **91**(A1), 135–141 (1986)
- R.A. Helliwell, *Whistlers and Associated Ionospheric Phenomena* (Stanford University Press, Stanford, 1965)
- R.E. Horita, Proton cyclotron echoes and spurs observed on Alouette II and ISIS II. *Radio Sci.* **22**(4), 671–686 (1987)
- R.B. Horne, G.V. Wheeler, H.S.C.K. Alleyne, Proton and electron heating by radially propagating fast magnetosonic waves. *J. Geophys. Res.* **105**(A12), 27597–27610 (2000)
- R.B. Horne, R.M. Thorne, Y.Y. Shprits, N.P. Meredith, S.A. Glauert, A.J. Smith, S.G. Kanekal, D.N. Baker, M.J. Engebretson, J.L. Posch, M. Spasojevic, U.S. Inan, J.S. Pickett, P.M.E. Décreau, Wave acceleration of electrons in the Van Allen radiation belts. *Nature* **437**(7056), 227–230 (2005)
- R.B. Horne, R.M. Thorne, S.A. Glauert, N.P. Meredith, D. Pokhotelov, O. Santolík, Electron acceleration in the Van Allen radiation belts by fast magnetosonic waves. *Geophys. Res. Lett.* **34**, L17107 (2007)
- J.L. Horwitz, R.H. Comfort, C.R. Chappell, Thermal ion composition measurements of the formation of the new outer plasmasphere and double plasmopause during storm recovery phase. *Geophys. Res. Lett.* **11**(8), 701–704 (1984)

- X. Huang, B.W. Reinisch, P. Song, J.L. Green, D.L. Gallagher, Developing an empirical density model of the plasmasphere using IMAGE/RPI observations. *Adv. Space Res.* **33**(6), 829–832 (2004)
- U.S. Inan, M. Platino, T.F. Bell, D.A. Gurnett, J.S. Pickett, Cluster measurements of rapidly moving sources of ELF/VLF chorus. *J. Geophys. Res.* **109**, A05214 (2004)
- J.E. Jackson, The reduction of topside ionograms to electron-density profiles. *Proc. IEEE* **57**(6), 960–975 (1969)
- H.G. James, Wave propagation experiments at medium frequencies between two ionospheric satellites, 3. Z mode pulses. *J. Geophys. Res.* **84**(A2), 499–506 (1979)
- D. Jones, Latitudinal beaming of planetary radio emissions. *Nature* **288**, 225–229 (1980)
- D. Jones, Terrestrial myriametric radiation from the Earth's plasmapause. *Planet. Space Sci.* **30**(4), 399–410 (1982)
- Y. Kasaba, H. Matsumoto, K. Hashimoto, R.R. Anderson, J.-L. Bougeret, M.L. Kaiser, X.Y. Wu, I. Nagano, Remote sensing of the plasmapause during substorms: Geotail observation of nonthermal continuum enhancement. *J. Geophys. Res.* **103**(A9), 20389–20405 (1998)
- C.F. Kennel, H.E. Petschek, Limit on stably trapped particle fluxes. *J. Geophys. Res.* **71**(1), 1–28 (1966)
- I. Kimura, Effects of ions on whistler-mode ray tracing. *Radio Sci.* **1**(3), 269–283 (1966)
- J.W. King, D.M. Preece, Observations of proton gyroeffects in the topside ionosphere. *J. Atmos. Terr. Phys.* **29**, 1387–1390 (1967)
- I.P. Kurchashov, I.S. Nikomarov, V.A. Pilipenko, A. Best, Field line resonance effects in local meridional structure of mid-latitude geomagnetic pulsations. *Ann. Geophys.* **5**(6), 147–154 (1987)
- W.S. Kurth, Detailed observations of the source of terrestrial narrowband electromagnetic radiation. *Geophys. Res. Lett.* **9**(12), 1341–1344 (1982)
- W.S. Kurth, D.A. Gurnett, R.R. Anderson, Escaping nonthermal continuum radiation. *J. Geophys. Res.* **86**(A7), 5519–5531 (1981)
- T. Laaspere, M.G. Morgan, W.C. Johnson, Chorus, hiss, and other audio-frequency emissions at stations of the whistlers-east network. *Proc. IEEE* **52**(11), 1331–1349 (1964)
- J. LaBelle, R.A. Treumann, Auroral radio emissions, 1. Hisses, roars, and bursts. *Space Sci. Rev.* **101**(3), 295–440 (2002)
- L.J. Lanzerotti, H. Fukunishi, Relationships of the characteristics of magnetohydrodynamic waves to plasma density gradients in the vicinity of the plasmapause. *J. Geophys. Res.* **80**(34), 4627–4634 (1975)
- J.F. Lemaire, K.I. Gringauz, *The Earth's Plasmasphere* (Cambridge University Press, New York, 1998)
- B.T. Loftus, T.E. Van Zandt, W. Calvert, Observations of conjugate ducting by the fixed-frequency topside-sounder satellite. *Ann. Geophys.* **22**(4), 530–537 (1966)
- L.R. Lyons, R.M. Thorne, C.F. Kennel, Pitch-angle diffusion of radiation belt electrons within the plasmasphere. *J. Geophys. Res.* **77**(19), 3455–3474 (1972)
- A. Masson, U.S. Inan, H. Laakso, O. Santolík, P. Décréau, Cluster observations of mid-latitude hiss near the plasmapause. *Ann. Geophys.* **22**(7), 2565–2575 (2004)
- H. Matsui, J.C. Foster, D.L. Carpenter, I. Dandouras, F. Darrouzet, J. De Keyser, D.L. Gallagher, J. Goldstein, P.A. Puhl-Quinn, C. Vallat, Electric fields and magnetic fields in the plasmasphere: A perspective from CLUSTER and IMAGE. *Space Sci. Rev.* (2009, this issue)
- C.E. McIlwain, Coordinates for mapping the distribution of magnetically trapped particles. *J. Geophys. Res.* **66**(11), 3681–3691 (1961)
- F.W. Menk, Spectral structure of mid-latitude Pc3–4 geomagnetic pulsations. *J. Geomagn. Geoelectr.* **40**(1), 33–61 (1988)
- F.W. Menk, B.J. Fraser, C.L. Waters, C.W.S. Ziesolleck, Q. Feng, S.H. Lee, P.W. McNabb, Ground measurements of low latitude magnetospheric field line resonances, in *Solar Wind Sources of Magnetospheric Ultra-Low-Frequency Waves*, ed. by M.J. Engebretson, K. Takahashi, M. Scholer. *Geophysical Monograph Series*, vol. 81 (American Geophysical Union, Washington, 1994), pp. 299–310
- F.W. Menk, D. Orr, M.A. Clilverd, A.J. Smith, C.L. Waters, D.K. Milling, B.J. Fraser, Monitoring spatial and temporal variations in the dayside plasmasphere using geomagnetic field line resonances. *J. Geophys. Res.* **104**(A9), 19955–19969 (1999)
- N.P. Meredith, R.B. Horne, M.A. Clilverd, D. Horsfall, R.M. Thorne, R.R. Anderson, Origins of plasmaspheric hiss. *J. Geophys. Res.* **111**, A09217 (2006)
- N.P. Meredith, R.B. Horne, S.A. Glauert, R.R. Anderson, Slot region electron loss timescales due to plasmaspheric hiss and lightning-generated whistlers. *J. Geophys. Res.* **112**, A08214 (2007)
- D.D. Morgan, D.A. Gurnett, The source location and beaming of terrestrial continuum radiation. *J. Geophys. Res.* **96**(A6), 9595–9613 (1991)
- D.B. Muldrew, Radio propagation along magnetic field-aligned sheets of ionization observed by the Alouette topside sounder. *J. Geophys. Res.* **68**(19), 5355–5370 (1963)
- D.B. Muldrew, Nonvertical propagation and delayed-echo generation observed by the topside sounders. *Proc. IEEE* **57**(6), 1097–1107 (1969)

- D.B. Muldrew, Electrostatic resonances associated with the maximum frequencies of cyclotron-harmonic waves. *J. Geophys. Res.* **77**(10), 1794–1801 (1972)
- D.B. Muldrew, Topside sounder proton-cyclotron echo generation from a plasma memory process and electron Bernstein-wave propagation. *Radio Sci.* **33**(5), 1395–1411 (1998)
- F. Němec, O. Santolík, K. Gereová, E. Macúšová, Y. de Conchy, N. Cornilleau-Wehrlin, Initial results of a survey of equatorial noise emissions observed by the Cluster spacecraft. *Planet. Space Sci.* **53**(1–3), 291–298 (2005)
- F. Němec, O. Santolík, K. Gereová, E. Macúšová, H. Laakso, Y. de Conchy, M. Maksimovic, N. Cornilleau-Wehrlin, Equatorial noise: Statistical study of its localization and the derived number density. *Adv. Space Res.* **37**(3), 610–616 (2006)
- D. Nunn, Y. Omura, H. Matsumoto, I. Nagano, S. Yagitani, The numerical simulation of VLF chorus and discrete emissions observed on the Geotail satellite using a Vlasov code. *J. Geophys. Res.* **102**(A12), 27083–27097 (1997)
- Y. Omura, H. Matsumoto, D. Nunn, M.J. Rycroft, A review of observational, theoretical and numerical studies of VLF triggered emissions. *J. Atmos. Terr. Phys.* **53**(5), 351–368 (1991)
- Y. Omura, Y. Katoh, D. Summers, Theory and simulation of the generation of whistler-mode chorus. *J. Geophys. Res.* **113**, A04223 (2008)
- T. Ondoh, Latitudinal changes of polar hiss and plasmopause hiss associated with magnetospheric processes. *Adv. Space Res.* **37**(3), 581–591 (2006)
- H. Oya, Generation mechanism of proton cyclotron echoes due to pulsed radio frequency waves in space plasma. *J. Geophys. Res.* **83**(A5), 1991–2008 (1978)
- M. Parrot, O. Santolík, N. Cornilleau-Wehrlin, M. Maksimovic, C.C. Harvey, Source location of chorus emissions observed by Cluster. *Ann. Geophys.* **22**(2), 473–480 (2003)
- M. Parrot, O. Santolík, N. Cornilleau-Wehrlin, M. Maksimovic, C. Harvey, Magnetospherically reflected chorus waves revealed by ray tracing with CLUSTER data. *Ann. Geophys.* **21**(5), 1111–1120 (2004a)
- M. Parrot, O. Santolík, D.A. Gurnett, J.S. Pickett, N. Cornilleau-Wehrlin, Characteristics of magnetospherically reflected chorus waves observed by CLUSTER. *Ann. Geophys.* **22**(7), 2597–2606 (2004b)
- V. Pierrard, J. Goldstein, N. André, V.K. Jordanova, G.A. Kotova, J.F. Lemaire, M.W. Liemohn, H. Matsui, Recent progress in physics-based models of the plasmasphere. *Space Sci. Rev.* (2009, this issue)
- M. Platino, U.S. Inan, T.F. Bell, J.S. Pickett, P. Canu, Rapidly moving sources of upper band ELF/VLF chorus near the magnetic equator. *J. Geophys. Res.* **111**, A09218 (2006)
- B.W. Reinisch, D.M. Haines, K. Bibl, G. Cheney, I.A. Galkin, X. Huang, S.H. Myers, G.S. Sales, R.F. Benson, S.F. Fung, J.L. Green, S. Boardsen, W.W.L. Taylor, J.-L. Bougeret, R. Manning, N. Meyer-Vernet, M. Moncuquet, D.L. Carpenter, D.L. Gallagher, P. Reiff, The Radio Plasma Imager investigation on the IMAGE spacecraft. *Space Sci. Rev.* **91**(1–2), 319–359 (2000)
- B.W. Reinisch, X. Huang, D.M. Haines, I.A. Galkin, J.L. Green, R.F. Benson, S.F. Fung, W.W.L. Taylor, P.H. Reiff, D.L. Gallagher, J.-L. Bougeret, R. Manning, D.L. Carpenter, S.A. Boardsen, First results from the Radio Plasma Imager on IMAGE. *Geophys. Res. Lett.* **28**(6), 1167–1170 (2001)
- B.W. Reinisch, M.B. Moldwin, R.E. Denton, D.L. Gallagher, H. Matsui, V. Pierrard, J. Tu, Augmented empirical models of plasmaspheric density and electric field using IMAGE and CLUSTER data. *Space Sci. Rev.* (2009, this issue)
- K. Rönmark, Generation of magnetospheric radiation by decay of Bernstein waves. *Geophys. Res. Lett.* **12**(10), 639–642 (1985)
- C.T. Russell, R.E. Holzer, E.J. Smith,OGO 3 observations of ELF noise in the magnetosphere, 1. Spatial extent and frequency of occurrence. *J. Geophys. Res.* **74**(3), 755–777 (1969)
- C.T. Russell, R.E. Holzer, E.J. Smith,OGO 3 observations of ELF noise in the magnetosphere, 2. The nature of the equatorial noise. *J. Geophys. Res.* **75**(4), 755–768 (1970)
- J.C. Samson, The spectral matrix, eigenvalues, and principal components in the analysis of multichannel geophysical data. *Ann. Geophys.* **1**(3), 115–119 (1983)
- B.R. Sandel, A.L. Broadfoot, C.C. Curtis, R.A. King, T.C. Stone, R.H. Hill, J. Chen, O.H.W. Siegmund, R. Raffanti, D.D. Allred, R.S. Turley, D.L. Gallagher, The Extreme Ultraviolet imager investigation for the IMAGE mission. *Space Sci. Rev.* **91**(1–2), 197–242 (2000)
- O. Santolík, D.A. Gurnett, Transverse dimensions of chorus in the source region. *Geophys. Res. Lett.* **30**(2), 1031 (2003)
- O. Santolík, M. Parrot, L.R.O. Storey, J.S. Pickett, D.A. Gurnett, Propagation analysis of plasmaspheric hiss using Polar PWI measurements. *Geophys. Res. Lett.* **28**(6), 1127–1130 (2001)
- O. Santolík, J.S. Pickett, D.A. Gurnett, M. Maksimovic, N. Cornilleau-Wehrlin, Spatiotemporal variability and propagation of equatorial noise observed by Cluster. *J. Geophys. Res.* **107**(A12), 1495 (2002)
- O. Santolík, D.A. Gurnett, J.S. Pickett, M. Parrot, N. Cornilleau-Wehrlin, Spatio-temporal structure of storm-time chorus. *J. Geophys. Res.* **108**(A7), 1278 (2003)

- O. Santolík, D.A. Gurnett, J.S. Pickett, Multipoint investigation of the source region of storm-time chorus. *Ann. Geophys.* **22**(7), 2555–2563 (2004a)
- O. Santolík, D.A. Gurnett, J.S. Pickett, M. Parrot, N. Cornilleau-Wehrin, A microscopic and nanoscopic view of storm-time chorus on 31 March 2001. *Geophys. Res. Lett.* **31**, L02801 (2004b)
- O. Santolík, F. Němec, K. Gereová, E. Macušová, Y. de Conchy, N. Cornilleau-Wehrin, Systematic analysis of equatorial noise below the lower hybrid frequency. *Ann. Geophys.* **22**(7), 2587–2595 (2004c)
- O. Santolík, D.A. Gurnett, J.S. Pickett, M. Parrot, N. Cornilleau-Wehrin, Central position of the source region of storm-time chorus. *Planet. Space Sci.* **53**(1–3), 299–305 (2005a)
- O. Santolík, E. Macušová, K.H. Yearby, N. Cornilleau-Wehrin, H.S.C. Alleyne, Radial variation of whistler-mode chorus: first results from the STAFF/DWP instrument on board the Double Star TC-1 spacecraft. *Ann. Geophys.* **23**(8), 2937–2942 (2005b)
- O. Santolík, J. Chum, M. Parrot, D.A. Gurnett, J.S. Pickett, N. Cornilleau-Wehrin, Propagation of whistler mode chorus to low altitudes: Spacecraft observations of structured ELF hiss. *J. Geophys. Res.* **111**, A10208 (2006)
- S.S. Sazhin, Improved quasilinear models of parallel whistler-mode instability. *Planet. Space Sci.* **37**(6), 633–647 (1989)
- S.S. Sazhin, M. Hayakawa, Magnetospheric chorus emissions: A review. *Planet. Space Sci.* **40**(5), 681–697 (1992)
- M. Schulz, Eigenfrequencies of geomagnetic field lines and implications for plasma-density modeling. *J. Geophys. Res.* **101**(A8), 17385–17397 (1996)
- R.L. Smith, Propagation characteristics of whistlers trapped in field-aligned columns of enhanced ionization. *J. Geophys. Res.* **66**(11), 3699–3707 (1961)
- V.S. Sonwalkar, Magnetospheric LF-, VLF-, and ELF-waves, in *Handbook of Atmospheric Electrodynamics*, ed. by H. Volland, vol. II (CRC, Boca Raton, 1995), pp. 407–462
- V.S. Sonwalkar, U.S. Inan, Lightning as an embryonic source of VLF hiss. *J. Geophys. Res.* **94**(A6), 6986–6994 (1989)
- V.S. Sonwalkar, D.L. Carpenter, T.F. Bell, M. Spasojević, U.S. Inan, J. Li, X. Chen, A. Venkatasubramanian, J. Harikumar, R.F. Benson, W.W.L. Taylor, B.W. Reinisch, Diagnostics of magnetospheric electron density and irregularities at altitudes <5000 km using whistler and Z mode echoes from radio sounding on the IMAGE satellite. *J. Geophys. Res.* **109**, A11212 (2004)
- V.S. Sonwalkar, D.L. Carpenter, A. Reddy, B.W. Reinisch, Magnetically reflected (MR), specularly reflected (SR), and backscattered (BS) whistler mode (WM) echoes observed on the IMAGE satellite: Whistler-mode sounding of electron density, ion composition (H^+ , He^+ , O^+), and density irregularities along the geomagnetic field line. *J. Geophys. Res.* (2009, submitted)
- D.J. Southwood, Some features of field line resonances in the magnetosphere. *Planet. Space Sci.* **22**(3), 483–491 (1974)
- L.R.O. Storey, An investigation of whistling atmospherics. *Phil. Trans. R. Soc. (Lond.)* **246A**, 113–141 (1953)
- L.R.O. Storey, F. Lefeuvre, M. Parrot, L. Cairó, R.R. Anderson, Initial survey of the wave distribution functions for plasmaspheric hiss observed by ISEE 1. *J. Geophys. Res.* **96**(A11), 19469–19489 (1991)
- D. Summers, B. Ni, N.P. Meredith, R.B. Horne, R.M. Thorne, M.B. Moldwin, R.R. Anderson, Electron scattering by whistler-mode ELF hiss in plasmaspheric plumes. *J. Geophys. Res.* **113**, A04219 (2008)
- K. Takahashi, R.L. McPherron, Harmonic structure of Pc 3–4 pulsations. *J. Geophys. Res.* **87**(A3), 1504–1516 (1982)
- T. Tamao, The structure of three-dimensional hydromagnetic waves in a uniform cold plasma. *J. Geomagn. Geoelectr.* **16**(1), 89–114 (1964)
- R.M. Thorne, E.J. Smith, R.K. Burton, R.E. Holzer, Plasmaspheric hiss. *J. Geophys. Res.* **78**(10), 1581–1596 (1973)
- R.M. Thorne, R.B. Horne, N.P. Meredith, Comment on “On the origin of whistler mode radiation in the plasmasphere” by Green et al. *J. Geophys. Res.* **111**, A09210 (2006)
- V.Y. Trakhtengerts, A generation mechanism for chorus emission. *Ann. Geophys.* **17**(1), 95–100 (1999)
- V.Y. Trakhtengerts, A.G. Demekhov, E.E. Titova, B.V. Kozelov, O. Santolík, D. Gurnett, M. Parrot, Interpretation of Cluster data on chorus emissions using the backward wave oscillator model. *Phys. Plasma* **11**(4), 1345–1351 (2004)
- V.A. Troitskaya, A.V. Gul’Elmi, Diagnostics of the parameters of the magnetosphere and of the interplanetary space by means of micropulsations, in *Low-Frequency Waves and Irregularities in the Ionosphere*, ed. by N. D’Angelo. Astrophysics and Space Science Library, vol. 14 (1969), pp. 120–136
- B.T. Tsurutani, E.J. Smith, R.M. Thorne, Electromagnetic hiss and relativistic electron losses in the inner zone. *J. Geophys. Res.* **80**(4), 600–607 (1975)
- C.L. Waters, F.W. Menk, B.J. Fraser, The resonance structure of low latitude Pc3 geomagnetic pulsations. *Geophys. Res. Lett.* **18**(12), 2293–2296 (1991)

- J.M. Watts, An observation of audio-frequency electromagnetic noise during a period of solar disturbance. *J. Geophys. Res.* **62**(2), 199–206 (1957)
- D.C. Webb, The analysis of non stationary data using complex demodulation. *Ann. Telecommunic.* **34**, 131–137 (1979)
- D.C. Webb, L.J. Lanzerotti, C.G. Park, A comparison of ULF and VLF measurements of magnetospheric cold plasma densities. *J. Geophys. Res.* **82**(32), 5063–5072 (1977)
- K. Yumoto, Generation and propagation mechanisms of low-latitude magnetic pulsations—A review. *J. Geophys.* **60**, 79–105 (1986)

Recent Progress in Physics-Based Models of the Plasmasphere

**Viviane Pierrard · Jerry Goldstein · Nicolas André ·
Vania K. Jordanova · Galina A. Kotova · Joseph
F. Lemaire · Mike W. Liemohn · Hiroshi Matsui**

Originally published in the journal *Space Science Reviews*, Volume 145, Nos 1–2, 193–229.
DOI: [10.1007/s11214-008-9480-7](https://doi.org/10.1007/s11214-008-9480-7) © Springer Science+Business Media B.V. 2009

V. Pierrard (✉) · J.F. Lemaire
Belgian Institute for Space Aeronomy (IASB-BIRA), 3 Avenue Circulaire, 1180 Brussels, Belgium
e-mail: viviane.pierrard@oma.be

J.F. Lemaire
e-mail: lemaire@astr.ucl.ac.be

V. Pierrard · J.F. Lemaire
Center for Space Radiations (CSR), Louvain-La-Neuve, Belgium

J. Goldstein
Space Science and Engineering Division, Southwest Research Institute (SwRI), San Antonio, TX, USA
e-mail: jgoldstein@swri.edu

N. André
Research and Scientific Support Department (RSSD), ESTEC/ESA, Noordwijk, The Netherlands
e-mail: nandre@rssd.esa.int

V.K. Jordanova
Space Science and Applications, Los Alamos National Laboratory (LANL), Los Alamos, NM, USA
e-mail: vania@lanl.gov

G.A. Kotova
Space Research Institute (RSSI), Russian Academy of Science, Moscow, Russia
e-mail: kotova@iki.rssi.ru

M.W. Liemohn
Atmospheric, Oceanic, and Space Sciences Department, University of Michigan, Ann Arbor, MI, USA
e-mail: liemohn@umich.edu

H. Matsui
University of New Hampshire (UNH), Space Science Center Morse Hall, Durham, NH, USA
e-mail: hiroshi.matsui@unh.edu

Abstract We describe recent progress in physics-based models of the plasmasphere using the fluid and the kinetic approaches. Global modeling of the dynamics and influence of the plasmasphere is presented. Results from global plasmasphere simulations are used to understand and quantify (i) the electric potential pattern and evolution during geomagnetic storms, and (ii) the influence of the plasmasphere on the excitation of electromagnetic ion cyclotron (EMIC) waves and precipitation of energetic ions in the inner magnetosphere. The interactions of the plasmasphere with the ionosphere and the other regions of the magnetosphere are pointed out. We show the results of simulations for the formation of the plasmopause and discuss the influence of plasmaspheric wind and of ultra low frequency (ULF) waves for transport of plasmaspheric material. Theoretical models used to describe the electric field and plasma distribution in the plasmasphere are presented. Model predictions are compared to recent CLUSTER and IMAGE observations, but also to results of earlier models and satellite observations.

Keywords Plasmasphere · Models · Fluid · Kinetic · CLUSTER · IMAGE

1 Introduction

The satellites IMAGE (Imager for Magnetopause to Aurora Global Exploration) and CLUSTER have notably provided global views of the plasmasphere and electron density profiles that are especially useful in the study of plasmopause formation (De Keyser et al. 2008, this issue). Since the limit of the plasmasphere was discovered (Gringauz et al. 1960) and named plasmopause by Carpenter (1966), different mechanisms have been suggested to explain this sharp boundary, as recalled in Pierrard and Stegen (2008). Dynamical simulations of the plasmasphere have been developed beginning with simple simulations in a spatially constant electric field (Grebowsky 1970) and have since become more sophisticated.

Recent progress in plasmasphere and plasmopause simulations is described using the fluid and the kinetic approaches. This paper is divided in three main sections: The first describes the recent improvements in fluid models related to CLUSTER and IMAGE observations, the second describes such improvements in kinetic models, and the third compares the two approaches and show recent developments based on other satellite observations. Such models concern also the density distributions along the magnetic field lines and refilling processes.

In the fluid section, Sect. 2.1 describes the influence of the inner magnetospheric electric potential on the plasmasphere. The couplings of the plasmasphere with the ionosphere and the magnetosphere play important roles that are described in Sects. 2.2 and 2.3.

In the kinetic section, the mechanisms of plasmopause formation are described in Sect. 3.1. The postulated existence of the plasmaspheric wind and its implications are discussed in Sect. 3.2. The global transport of plasmaspheric material by ULF waves is presented in Sect. 3.3. Models of electrostatic potential and field aligned distribution of the plasma in an ion-exosphere are respectively described in Sects. 3.4 and 3.5. The refilling processes are studied in Sect. 3.6, as well as the Coulomb collisions and implications of Monte Carlo simulations.

Finally, Sect. 4 discusses the comparison between the kinetic and magnetohydrodynamic (MHD) approaches for time-dependent models.

The empirical plasmasphere models directly based on satellite observations are presented elsewhere in this issue (Reinisch et al. 2008). In the present paper, we focus mainly on the physical processes implicated in the plasmaspheric models. The basic plasmaspheric

theoretical concepts and ideas that flourished during the past forty years have been discussed in research articles and review papers that are listed by Lemaire and Gringauz (1998) and in more recent reviews like that by Kotova (2007). Some theoretical concepts are recalled but we mainly emphasize in the present paper the progress obtained from the IMAGE and CLUSTER missions.

2 The Fluid Approach

2.1 Inner Magnetospheric Electric Potential

Progress has been made recently in using plasmaspheric simulations (as well as simulations of the ring current and its coupling to the ionosphere) to understand and quantify the electric potential pattern and evolution during magnetic storms. This progress has been achieved via a series of simulation studies, ranging from simple test particle simulations to full fluid simulations, employing a variety of electric potentials, both parametric and self-consistent. Comparison of simulation results with global images obtained by the IMAGE spacecraft (Burch 2000) has played a key role alongside in-situ observations.

Decades of simulation work, beginning with simple test particle simulations in a spatially constant electric field (Grebowsky 1970; Chen and Wolf 1972; Chen et al. 1975) and followed by numerous more sophisticated fluid treatments (Spiro et al. 1981; Elphic et al. 1996; Lambour et al. 1997; Weiss et al. 1997) all predicted that plasmaspheric plumes form and evolve in response to enhanced convection. Plumes are described in detail elsewhere in this issue (Darrouzet et al. 2008). Nonetheless, the predictions of models such as these were not universally accepted (e.g., Chappell 1972; Lemaire and Gringauz 1998), and the existence of plumes was not conclusively proven until the advent of global images by the IMAGE Extreme UltraViolet (EUV) imager (Sandel et al. 2000) that clearly showed global plume development in so-called “phases” in accord with the early models (Goldstein et al. 2003c; Spasojević et al. 2003; Goldstein and Sandel 2005). However, though the plumes recorded by EUV images did follow the predicted phases in a global sense, on a sub-global scale numerous storm-time behaviors and density features remained unexplained such as plasma-pause “crenulations” (Spasojević et al. 2003) and azimuthally-localized “notches” spanning several L -shells (Gallagher et al. 2005). Most studies of these (and many other) density features concluded that knowledge of the inner magnetospheric electric field, (especially on sub-global scale sizes) remains inadequate, though a parallel line of investigation suggested that plume formation is primarily driven by forces other than convection that in principle can explain some of the novel density features (Lemaire 2000).

Inner magnetospheric shielding (Jaggi and Wolf 1973) was proposed long ago as a mechanism whereby the influence of solar-wind-driven convection would be lessened earthward of the region 2 current system linking the ring current to the ionosphere; however, for decades the influence of shielding was difficult to quantify. Using fluid simulations with an empirical inner magnetospheric potential whose parameterization was based on earlier self-consistent results of the Rice Convection Model (RCM), shielding was shown to have a palpable effect on the recovery-phase plasmopause structure, producing shoulder-shaped bulges 0.5 Earth radius (R_E) or larger (Goldstein et al. 2002, 2003d). That these models agreed with EUV images was taken as proof of at least partial shielding of the inner magnetosphere, but self-consistent RCM runs also illustrated the almost complete breakdown of shielding during the strongest storms (Sazykin et al. 2005).

On the other hand, ring-current-ionosphere coupling via region 2 currents can also intensify the radial electric field especially in the dusk-to-midnight local time (LT) sector, producing a radially-narrow, azimuthally-directed flow channel (Galperin et al. 1974; Smiddy et al. 1977; Burke et al. 1998; Anderson et al. 2001) that in recent years has come to be known as the sub-auroral polarization stream (SAPS) (Foster and Burke 2002). Used in test particle simulations, empirical models of SAPS have achieved reasonable success at reproducing the plasmopause and plume locations observed by IMAGE EUV and Los Alamos National Laboratory (LANL) geostationary satellites (Goldstein et al. 2003a, 2005a, 2005b). Nonetheless it is clear that only a self-consistent formulation with realistic ring current pressure distributions, region 2 currents, and ionospheric conductivities can hope to truly capture the dynamical development -both global and local- of SAPS or, for that matter, shielding.

Illustrating this point, Liemohn et al. (2004, 2005, 2006) conducted a series of studies comparing plasmaspheric simulation results against observations, using a variety of electric field descriptions and calculational formulations, in order to decipher the true electric field dynamics during the storm events. The plasmaspheric model used in these studies is the Dynamic Global Core Plasma Model (DGCPM) of Ober et al. (1997). This code solves a continuity equation for the flux tube content of cold “thermal” ions, using second-order accurate numerical schemes to convect the ions from one grid cell to another. The code is flexible and modular, capable of using any magnetic or electric field specification and written in subroutine format for easy coupling to other codes. For Liemohn et al. (2004, 2005, 2006) studies, the DGCPM was linked with the Ring current Atmosphere interaction Model (RAM) (Jordanova et al. 1996a; Liemohn et al. 2001) along with the ionospheric electric potential solver of Ridley and Liemohn (2002). The two-way coupling between these codes allows for the ring current to alter the inner magnetospheric electric field, which in turn changes the plasmaspheric morphology, which then collisionally interacts with the ring current. Field-aligned currents (FACs) are calculated from the RAM hot plasma distribution, and these are mapped along the magnetic field to 120 km altitude where they are used as current sources and sinks for the ionosphere potential solver. The resulting potential then mapped back to the magnetosphere for use in the next time step of RAM and DGCPM. To obtain a local density at a particular place within the magnetosphere from the total content values calculated by DGCPM, a field-line density distribution must be assumed. This distribution is usually taken to be $n/B = \text{constant}$ where n is number density and B is magnetic field strength, although any relationship could be chosen.

Liemohn et al. (2004) examined the electric potential structure and resulting plasmaspheric morphologies for three electric field descriptions: a simple two-cell convection pattern (McIlwain 1986; Liemohn et al. 2001), the Weimer empirical model (Weimer 1996), and a self-consistent potential model (Ridley and Liemohn 2002) driven by field aligned currents closing the partial ring current (as calculated by a simultaneously-running ring current model). The storm on 17 April 2002 was chosen for this investigation because it is a simple “single-dip” event caused by a shock-sheath passage ahead of a magnetic cloud (which caused a subsequent storm on 18 April).

They compared the DGCPM results against plasmopause locations extracted from snapshots from the EUV instrument onboard the IMAGE spacecraft. Figure 1 shows the method of data-model comparison. In the EUV image (Fig. 1a), a sharp intensity decrease can be seen where the thermal plasma density suddenly drops. This is interpreted as the plasmopause and its location is manually recorded. In the DGCPM equatorial density results (Fig. 1b) using a self-consistent electric field, it is often hard to distinctly identify such a boundary, and therefore the density gradient is numerically calculated (Fig. 1c). This quantity clearly shows the sharp drop in plasmaspheric density, and the peak gradient along any

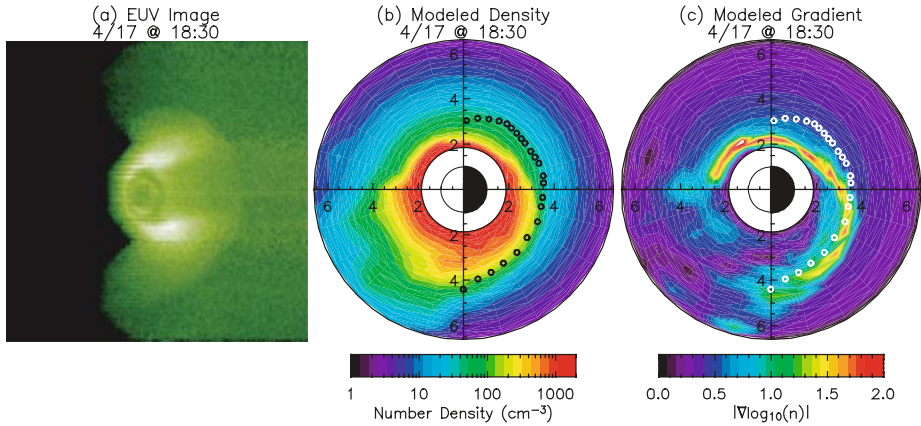


Fig. 1 Example data-model comparison (at 18:30 UT on 17 April 2002) between an IMAGE EUV snapshot and a DGCPM plasmasphere result. Shown here is **a** an EUV image (count rates per pixel) on a linear green-shade color scale, **b** DGCPM equatorial plane cold plasma densities on a logarithmic color scale, and **c** the magnitude of the gradient of the logarithm of the density from DGCPM on a linear color scale. In the EUV image, the view is over the North Pole with the Sun off to the left and slightly downward, as indicated. In the model results, the view is over the North Pole with the Sun directly to the left, and distances are given in R_E . In the image, the plasmopause is the steep drop in intensity from light green to darker green. The extracted plasmopause from this image is shown in the model results as *circles*. (Adapted from Liemohn et al. 2005)

given radial slice is designated the plasmopause. These two radial distances can then be directly compared (as a function of LT and universal time UT).

It was found that the selected two-cell convection model (McIlwain 1986; Liemohn et al. 2001) is good at predicting the nightside plasmopause location, particularly in the post-midnight sector. However, the small electric fields on the dayside from this model yield incorrect dayside morphologies for the stormtime plasmasphere, at least during the recovery phase of the storm. The Weimer electric field model (Weimer 1996) yields a better day-side description of the plasmopause, particularly regarding the shape of the plasmaspheric plume relative to that produced by the modified McIlwain description. The electric fields are somewhat too strong in the inner magnetosphere, though, resulting in a systematically smaller plasmasphere than those extracted from the observations. The self-consistent electric field model yielded the best comparison with the observed plasmaspheric plume location. However, a too low imposed conductance in the post-midnight region led to a modeled plasmopause that was inward of that observed in this magnetic local time (MLT) quadrant.

The second study in the series (Liemohn et al. 2005) was a systematic analysis of the self-consistent electric field choice. In particular, the ionospheric conductance needs to be specified in the model, and the settings for defining this parameter can be altered within reasonable limits. This conductance model has sources from sunlight on the dayside, starlight (applied everywhere), and a smooth auroral oval of high conductance. The first objective of this study was to conduct a parametric examination of the response in the numerical simulation results to various settings for the nightside ionospheric conductance. The second objective was to compare these results against observations to determine whether (and why) these systematic changes in the conductance bring the simulation results closer to reality. Like Liemohn et al. (2004), this study focused on the 17 April 2002 storm event.

There are five ways in which the conductance was changed between the simulations performed for this study. The first was the amplitude of the oval conductance peak, which

varies in time according to the relation used by Ridley et al. (2004). Because those formulas were developed for region 1 current intensities, a scaling factor was included to account for the known offset in magnitude between region 1 and region 2 currents (e.g., Iijima and Potemra 1976; Weimer 1999). Liemohn et al. (2005) found that a higher multiplier setting (i.e., high conductance) resulted in a smaller plasmasphere.

A second parameter varied in the conductance model was the latitudinal location of the oval peak relative to the RAM-generated FAC peak. The oval is a product of both region 1 and region 2 currents, and RAM is only calculated in the latter, so the oval peak should be shifted poleward of the calculated FAC peak. The data-model comparisons revealed an optimal oval shift of five degrees; too much or too little poleward resulted in a less intense electric field across the dusk sector and a poor plume location in the plasmaspheric model results.

A third parameter was the dawn-to-dusk tilt of the auroral oval. It is known that precipitating electrons are the major contributor to this conductance, and their drift paths bring them closer to the Earth on the dawn side than on the dusk side of the inner magnetosphere. It was found that a symmetric oval (with no tilt) best matched the observations, and moving the dawnside oval equatorward made the plasmopause less distinct across that sector.

The fourth parameter was the choice of the potential description applied at the high-latitude boundary of the Poisson equation. Two models are used for this boundary condition: a ring of potential values extracted from the Weimer model and a sine wave description using only the cross polar cap potential difference from the Weimer model. Not surprisingly, it was concluded that the former choice produced the better fit to the observed plasmopause locations.

The final free parameter that was varied is the baseline conductance value, the so-called starlight Pedersen conductance (Strobel et al. 1974). The baseline (that is, non-auroral) ionospheric conductance at any given place on the nightside is not well known, but it is a function of the illumination from stars and scattered sunlight, from the length of time that part of the atmosphere has been in darkness, transport effects, plasmaspheric downflow, and local heating influences. The influence was small, but increasing this background conductance value resulted in a slightly smaller plasmasphere (similar to the first parameter, the peak conductance multiplier).

The third paper in the sequence (Liemohn et al. 2006) was a large data-model comparison study for two storm intervals (22 April 2001, and 21–23 October 2001). The overall goal of this effort was to determine the state of the inner magnetospheric electric field throughout these two storms. The RAM-DGCPM model combination was run with four electric field specifications, and these results were compared with numerous observations of the plasmasphere and ring current to determine which field selection performed best at which times and places. The specific electric field choices were the Volland-Stern two-cell convection pattern (Volland 1973; Stern 1975), the modified McIlwain two-cell model (McIlwain 1986; Liemohn et al. 2001), and two versions of the self-consistent electric field (Liemohn et al. 2004), with two different peak conductance multiplier values.

In addition to the EUV-DGCPM comparisons conducted in the earlier studies, Liemohn et al. (2006) also included comparisons against in-situ plasmaspheric observations. Specifically, densities and velocities were calculated from the low-energy ion population as measured by the Magnetospheric Plasma Analyzer (MPA) instruments onboard the geosynchronous LANL satellites.

At geosynchronous orbit ($6.6 R_E$ geocentric distance), storm-time plasmaspheric observations are limited to the afternoon LT sector, when the satellites cross the plasmaspheric plume. Figure 2 shows a comparison between the plasmaspheric densities recorded by the

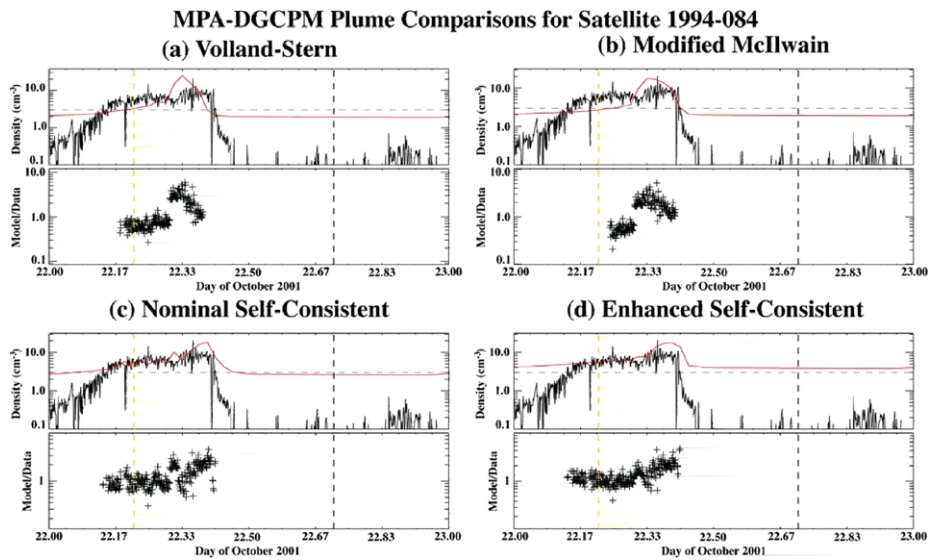


Fig. 2 Four pairs of plots showing a comparison between the low-energy ion density from the MPA instrument on the geosynchronously-orbiting LANL084 spacecraft to corresponding simulated plasmaspheric density values from the runs with four different field descriptions of Liemohn et al. (2006). In each pair, the *upper panel* (a and b) shows the density comparison while the *lower panel* (c and d) shows the ratio of the modeled value to the data value. In the *upper plot*, the data is shown in *black* and the simulation results in *red*. In the ratio plots, values are only shown when both the modeled and the observed density is greater than 3 cm^{-3} . This is an empirically-determined cut-off signifying plasmaspheric plume observations, and therefore trustworthy moment values. This cut-off is marked in the *upper panels* with a horizontal black dashed line. The vertical black and yellow dashed lines indicate local midnight and noon, respectively

LANL 084 satellite with results from the four simulations of DGCPM during the 21–23 October 2001 storm. It is seen that the four numerical results have varying degrees of goodness of fit against the data. In particular, there seems to be two components to the plume, with a slight dip in density at 07:00 UT on 22 October 2001. The self-consistent electric field results produce a similar feature, while the two simplistic two-cell models do not.

Liemohn et al. (2006) found that the self-consistent electric field descriptions did the best at reproducing the data throughout these storm intervals. An interesting result is that the shielded Volland-Stern electric field model, driven with the 3-hour K_p index, also did quite well in the data-model comparisons. In particular, this simple model was excellent at reproducing the main phase plasmopause structure, including the plume location as seen by two different data sets. However, the Volland-Stern model was irregular in its ability to reproduce the observations, often being good against some data sets but off against others.

The two self-consistent field simulations were much more regular with respect to which data sets they obtained excellent agreement, and they matched these data sets throughout the interval (rather than just at certain times and places). The modified McIlwain field consistently produced the worst plasmaspheric data-model comparisons of the 4 field choices, although there were times (particularly the main phase) when it also accurately matched the observed plume characteristics.

2.2 Plasmasphere-Ionosphere Coupling

Another aspect of global plasmaspheric dynamics is the essential mass-exchange interaction between the plasmasphere and ionosphere. Outflow from the ionosphere can gradually fill (or refill) plasmaspheric flux tubes with cold plasma, moving the plasmopause location outward over the course of several hours or days; on the other hand, storm-time “dumping” of plasmaspheric material into the ionosphere can deplete flux tubes well inside the plasmopause. Though some fluid simulations have attempted to include ionospheric refilling (Lambour et al. 1997; Weiss et al. 1997; Goldstein et al. 2002), these treatments have been fairly simple empirical constraints on an otherwise decoupled plasmasphere model. However, the availability of global plasmasphere images has encouraged progress in this area as well.

As an example of this progress, in this section the temporal evolution of plasma density in the equatorial plane of the magnetosphere is studied with a two-dimensional model of the plasmasphere developed by Rasmussen et al. (1993). This model includes the supply and loss of hydrogen ions due to ionosphere-magnetosphere coupling as well as the effects of $\mathbf{E} \times \mathbf{B}$ convection. It utilizes a method for modeling the transport of thermal plasma in the equatorial plane pioneered by Chen and Wolf (1972) that achieves considerable simplification and reduces computer costs. A conservation equation for the total content of a flux tube is obtained by integrating the continuity equation along a flux tube from ionosphere to conjugate ionosphere; the motion of individual flux tubes due to the $\mathbf{E} \times \mathbf{B}$ drift is then followed. Changes of the total tube content due to fluxes of particles entering (or leaving) the plasmasphere from conjugate ionospheres are described with a parametric model, which utilizes the Mass-Spectrometer-Incoherent-Scatter (MSIS) model (Hedin 1987) of the neutral atmosphere and the International Reference Ionosphere (IRI) model (Bilitza 1986). This method is applicable for some types of plasmaspheric studies, including those considering plasmopause formation and the detachment of plasmaspheric plumes, when complete information along a flux tube is not required. In many instances, the convection electric field causes a more rapid variation in density than does any other process. Time scales for advective changes in density can be of the order of one hour or less. This compares to time scales for refilling which are of the order of a few days or longer.

The evolution of the plasmaspheric electron density during 17–19 June, 2001 obtained with the model of Rasmussen et al. (1993) is shown in Fig. 3. During this period there was a moderate geomagnetic storm with minimum $Dst = -61$ nT and maximum $K_p = 5^+$. The plasmasphere model of Rasmussen et al. (1993) was coupled with the RAM (Jordanova et al. 1996a, 2007) and was driven by a high time resolution convection electric field model and a dipole model of the Earth’s magnetic field. For these simulations Jordanova et al. (2007) used the tabulated value of the auroral boundary index (ABI) to control the strength of the convection, by first converting it to an effective K_p (Gussenhoven et al. 1981) and then using a Volland-Stern type electric field with a shielding parameter of 2 (Volland 1973; Maynard and Chen 1975; Stern 1975). During periods of increased convection (larger K_p index) the plasmasphere was eroded on the nightside, and at larger L -shells enhanced densities were confined to the postnoon plasmaspheric plumes.

As the activity level decreased, the plasmasphere corotated and expanded, refilling from the ionosphere. The diamond symbols in Fig. 3 indicate the model plasmopause, i.e., the location of a steep gradient in electron density, identified in the model as the region where the density drops by a factor of 5 or more over a radial distance of $0.25 R_E$. The solid line in Fig. 3 shows the plasmopause identified from IMAGE EUV data as a density drop below the sensitivity threshold of the instrument, estimated to be roughly 40 ± 10 electrons

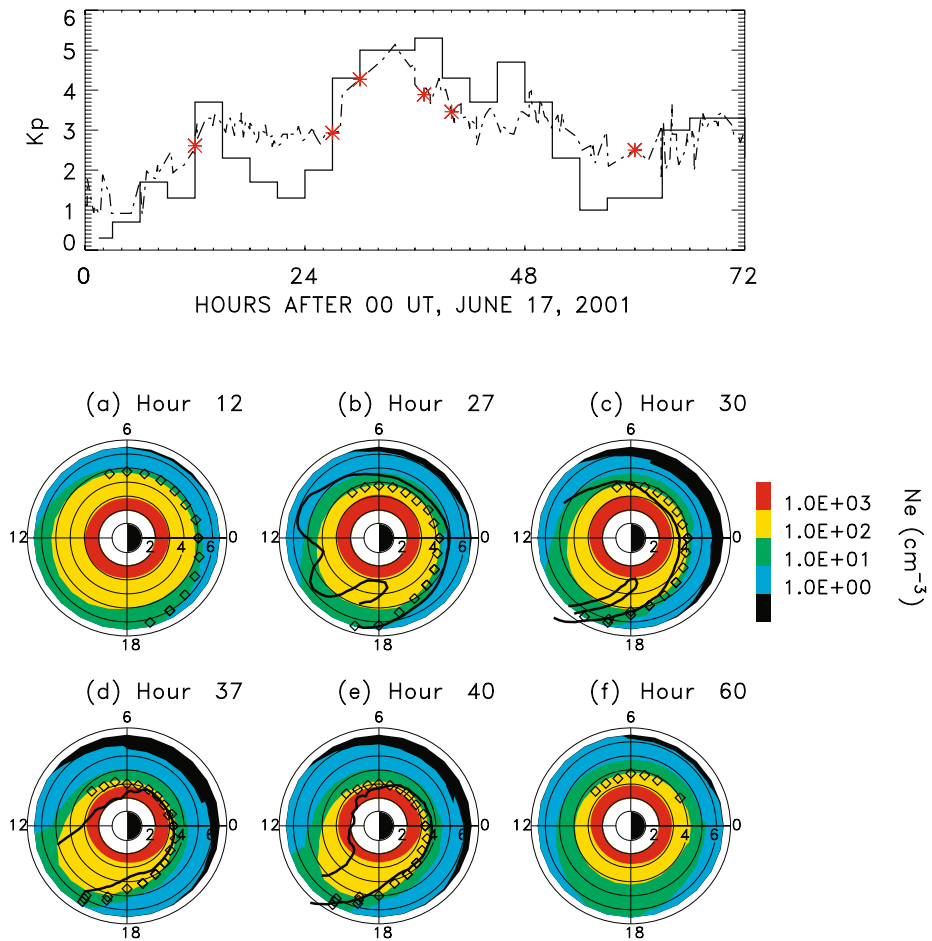


Fig. 3 (Top) The 3-hour index K_p (solid) and the effective K_p determined from the auroral boundary index (dashed-dotted line). **a–f** Equatorial plasmaspheric electron densities (cm^{-3}) at selected hours after 00:00 UT on 17 June 2001 indicated with stars on the K_p plot. The diamonds indicate the model plasmopause (Jordanova et al. 2007) while the solid line indicates the plasmopause location determined from IMAGE EUV data. (Adapted from Jordanova et al. 2007)

cm^{-3} (Goldstein et al. 2003b). These authors showed that the He^+ edge coincides with the plasmopause by comparing the L -shell of steep electron density gradients, extracted from passive mode dynamic spectrograms recorded by the IMAGE Radio Plasma Imager (RPI) with the L -shell of EUV He^+ edges obtained when the satellite is outside the plasmasphere near apogee. The model reproduced well the duskside plasmopause location determined from EUV data on 18 June 2001. However, the model predicted larger densities near 13:00–15:00 MLT than observed by the EUV imager at hour ~ 40 (Fig. 3e). Comparing simulations of the 21 October 2001 large geomagnetic storm using various electric field models, Jordanova et al. (2006) found that the Volland-Stern model produced a plasmopause location closer to that identified from IMAGE EUV data than the model of Weimer (2001). The K_p -dependent version of the Volland-Stern model used by Jordanova et al. (2006) was derived using plasmopause observations to determine the strength of the convection (May-

nard and Chen 1975) and showed indeed very good agreement with IMAGE plasmopause observations.

2.3 Plasmasphere-Magnetosphere Coupling

In this section we discuss the influence of the plasmasphere on the excitation of electromagnetic ion cyclotron (EMIC) waves and precipitation of energetic ions in the inner magnetosphere. In the inner magnetosphere the cold plasmaspheric populations overlap spatially with high-energy plasma forming the ring current and the radiation belts. This is an environment suitable for the amplification of EMIC waves as first predicted by Cornwall et al. (1970) and subsequently investigated by many others (e.g., Anderson et al. 1992; Gary et al. 1995). Scattering by EMIC waves will lead to the precipitation of ring current ions and the excitation of subauroral arcs (Spasojević et al. 2004; Burch et al. 2005). Detached dayside proton arcs have been recently observed with the IMAGE Far UltraViolet (FUV) instrument as subauroral arcs separated from the main oval and extending over several hours of LT in the afternoon sector (e.g., Immel et al. 2002). To study the interplay of hot ring current ions with cold plasmaspheric material during the 23 January 2001 proton arc event, Jordanova et al. (2007) used their kinetic RAM coupled with the plasmasphere model of Rasmussen et al. (1993). The RAM solves numerically the bounce-averaged kinetic equation for the distribution functions of H^+ , O^+ and He^+ ring current ions (from ~ 100 eV to 400 keV) in the equatorial plane for radial distances from 2 to 6.5 R_E and all MLT. Losses due to charge exchange, Coulomb collisions, atmospheric collisions at low altitudes, and drift through the dayside magnetopause are included (Jordanova et al. 1997). The growth rate of EMIC waves is calculated self-consistently by solving the hot plasma dispersion relation with ring current parameters and plasmaspheric densities obtained simultaneously from the coupled models; the wave amplitudes are calculated with an analytical expression derived on the basis of statistical studies. A plasmaspheric ion composition of 77% H^+ , 20% He^+ , and 3% O^+ is assumed for these calculations (Young et al. 1977; Horwitz et al. 1981). Quasi-linear diffusion coefficients from Jordanova et al. (1996b) are used to calculate the pitch angle scattering of ring current ions into the loss cone due to resonant interactions with EMIC waves.

The evolution of equatorial plasmaspheric density, EMIC wave growth, and proton precipitation during 23–24 January 2001 is shown in Fig. 4. Wave-particle interactions are negligible if the integrated wave gain is below 20 dB (the wave amplitudes are below 0.1 nT). Geoeffective plasma waves are thus preferentially excited along the plasmopause or at larger L -shells in regions of enhanced plasmaspheric densities occurring within dayside drainage plumes. The EMIC wave excitation increased after fresh ion injections from the magnetotail and westward ion drift through the duskside magnetosphere. On 23 January 2001 the wave gain reached a maximum in the postnoon MLT sector at $L \approx 6$ between hours 47 and 48 (Fig. 4a), and vanished by hour 49 due to the wave scattering feedback and isotropization of the proton ring current. This indicates that enhanced plasmaspheric density (Fig. 4b) is only one of the factors needed for the excitation of EMIC waves, ring current proton anisotropy is another important factor. The RAM predicted weak proton precipitation from EMIC wave scattering beginning around hour 47 (Fig. 4c); its position matched the observed by IMAGE FUV equatorward edge of the auroral oval. By hour 48 the observed proton arc was well developed, and its projection onto the equatorial plane corresponded to the region of strong proton precipitation from EMIC wave scattering predicted with RAM. Note that in agreement with FAST (Fast Auroral SnapshoT) satellite data (Immel et al. 2002) the 10–40 keV precipitating fluxes were the strongest in the model (Jordanova et al. 2007), indicating

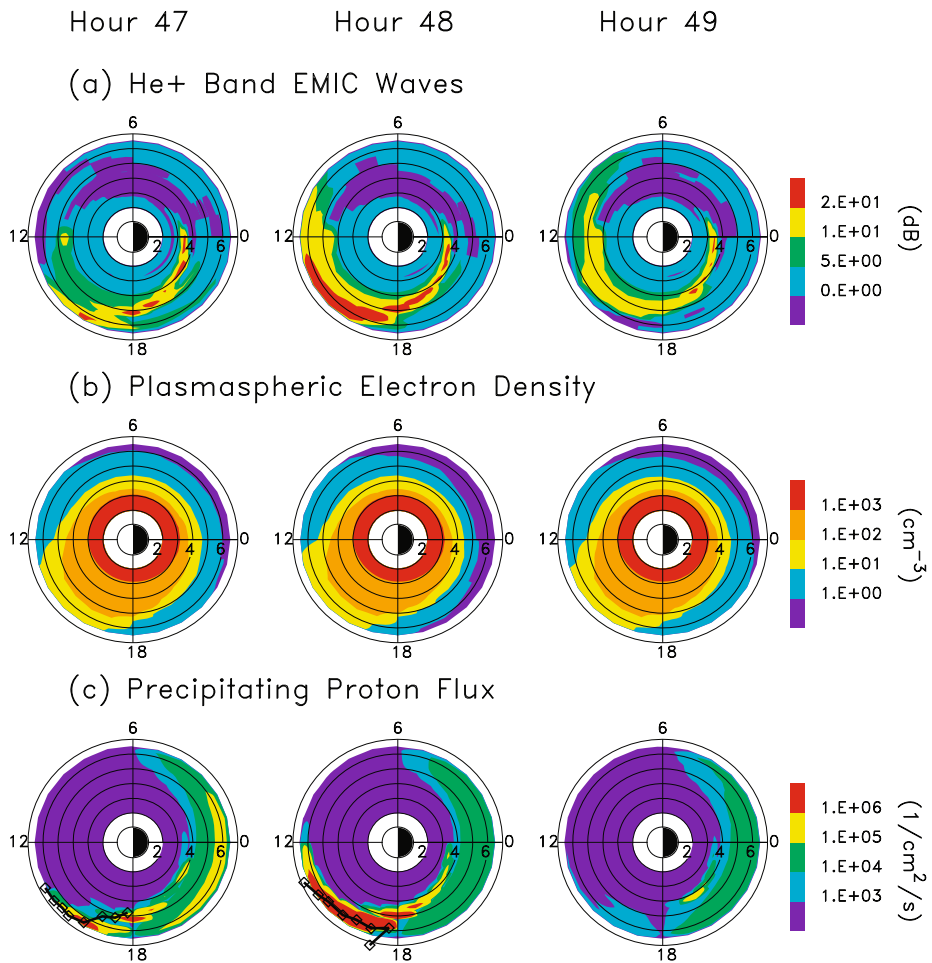


Fig. 4 **a** Calculated wave gain (dB) of He⁺ band (between O⁺ and He⁺ gyrofrequencies) EMIC waves as a function of radial distance in the equatorial plane and MLT at selected hours after 00:00 UT on 22 January 2001. **b** Equatorial plasmaspheric electron densities (cm⁻³). **c** Precipitating 10–40 keV proton number flux (1 cm⁻² s⁻¹); the *diamond line* indicates the low-latitude boundary of IMAGE FUV (Far UltraViolet) images of proton precipitation mapped to the solar magnetic (SM) equatorial plane using the Tsyganenko and Stern (1996) magnetic field model

that the proton arc emission was caused mainly by precipitating ions in this energy range. After hour 48 the observed proton arc receded to higher magnetic latitudes and the emission started to fade. There was no significant precipitation predicted by RAM at hour 49, in very good agreement with these observations. The study of Jordanova et al. (2007) showed the first comparisons of modeled proton precipitation with IMAGE FUV observations and demonstrated that scattering by EMIC waves is a viable mechanism for the generation of detached subauroral proton arcs.

3 The Kinetic Approach

3.1 Plasmapause Formation

The kinetic approach was also used to study the formation of the plasmapause by the mechanism of quasi-interchange instability (Lemaire 1985, 2001). This mechanism causes the peeling off of the plasmasphere as a result of sudden enhancements of the convection velocity associated with substorms in the night side. This enhanced azimuthal convection velocity leads to increased centrifugal acceleration in the outermost layers of the plasmasphere and a reduction of the total field-aligned potential barrier that ions have to overcome to reach the equatorial plane. This prompts the uplift of ions out of the underlying ionosphere. The enhancement of the field-aligned expansion velocity reduces the plasma density at high altitudes along all geomagnetic field lines traversing the zero-parallel force (ZPF) surface. This surface is the locus of points where the components of the gravitational and centrifugal acceleration balance each other in the direction parallel to the geomagnetic field lines. As a consequence of the plasma density diminution at high altitude along the field lines traversing the ZPF surface, a steep density gradient is formed into the plasmaspheric equatorial density profile. This steep plasma density gradient corresponds to a new plasmapause. It is formed where and when the azimuthal component of magnetospheric convection velocity is occasionally raised to values larger than the corotation velocity in the unperturbed core of the plasmasphere. This is how outer layers of the plasmasphere are peeled off and how plasma elements are detached according to the interchange theory for the formation of the plasmapause (Lemaire 2001).

The increased upward ionization flux which is prompted by the lowering of the field-aligned potential barrier depletes the mid-latitude ionosphere in the nightside MLT sector, where and when the eastward component of the convection electric field is suddenly enhanced. This leads to the formation of F-layer ionization troughs in the mid-latitude ionosphere as observed by Muldrew (1965) from ALOUETTE data. As an additional result of the upward H^+ and He^+ ions fluxes along all geomagnetic field lines beyond those which are tangent to the ZPF surface, the concentrations of these light ions are depleted, in both conjugate ionospheric regions. This is how light ion troughs (LIT) are developing beyond the projections of the ZPF surface at low altitudes in the ionosphere (Taylor and Walsh 1972). All these well documented events and features are observed following substorm events. According to Lemaire's theory for the formation of the plasmapause, they are consequences of the field aligned plasma distribution driven unstable by enhanced centrifugal effects at the innermost edge of substorm injection clouds (Lemaire 1974, 1985).

Dynamical simulations have been developed to determine the position of the plasmapause due to the erosion of the plasmasphere by the combined influence of the interchange instability and K_p -dependent electric field distributions (Pierrard and Lemaire 2004). The results predicted by models that include interchange have been compared with success to different IMAGE EUV observations during various periods of time including quiet periods, substorms and storms (Pierrard and Cabrera 2005, 2006; Pierrard 2006). The models predict an extended equatorial plasmasphere during prolonged quiet periods and plumes formation in the afternoon sector when the level of geomagnetic activity suddenly increases. Beside the sunward shift of the dusk-side plasmasphere during episodes of enhancement of the dawn-dusk component of magnetospheric convection electric field, an alternate mechanism of formation of such attached plasmatails or plumes was proposed by Lemaire (2000). Results of the interchange-included simulations have also been compared successfully with CIS (Cluster Ion Spectrometer) (Rème et al. 2001) and WHISPER (Waves of High frequency

and Sounder for Probing Electron density by Relaxation) (Décr  au et al. 2001) observations onboard CLUSTER by Dandouras et al. (2005), Darrouzet (2006) and Sch  fer et al. (2007). Moreover, Sch  fer et al. (2008) studied the spatio-temporal structure of a poloidal Alfv  n wave near the dayside plasmopause based on CLUSTER observations of magnetic and electric fields.

The results of the dynamical simulations based on the inclusion of the interchange mechanism have been compared to the traditional MHD-based convection-only mechanism, in which the plasmopause location is determined dynamically under the influence of a time-dependent potential electric field. The axioms and assumptions of both mechanisms have been recalled in detail in a recent article by Lemaire and Pierrard (2008). The plasmopause positions predicted by these two alternative theories (i.e., convection only and convection plus interchange) have been determined numerically. They have been compared for different empirical electric field models described in this issue by Reinisch et al. (2008): Volland-Stern-Maynard-Chen (VSMC) model, McIlwain's E5D model, and Weimer's model. The predicted positions and overall shape of the equatorial plasmopause cross-section have been compared for these three different electric field models (Pierrard et al. 2008).

The predictions of both alternative kinds of simulations have been compared to whistler-derived densities and global images obtained by EUV, during several storm and substorm events. These simulations confirmed that the presumed plasmopause positions and shapes depend on the variation of the geomagnetic activity level during the preceding days and also on the magnetospheric convection electric field model. When the modeled plasmopause is determined by the combined influence of instability and convection, it is formed slightly closer to the Earth than with the convection only scenario. Plumes are formed in both scenarios and for all electric field models considered in Pierrard et al. (2008) study. Nevertheless, different features are obtained for the plasmasphere structure depending on the simulation scenario and electric field models which had been adopted.

Figure 5 illustrates the differences obtained for the equatorial position of the plasmopause with the different mechanisms (ideal MHD in upper panels, interchange in the bottom left panel) and with for all three electric field models at 21:00 UT, after the magnetic storm of 17 April 2002. The E5D, VSMC and Weimer are used in the three upper panels; only E5D is used in the bottom left panel. The IMAGE EUV observation of the equatorial plasmopause position at 21:07 UT is illustrated in the bottom right panel. VSMC and Weimer models produce a plasmopause closer to the Earth than E5D. In the midnight sector, VSMC and Weimer electric field models lead to a plasmopause position too close to the Earth compared to the EUV observations, while the plasmopause position obtained with E5D corresponds to the EUV observations in this midnight sector. In the noon sector, E5D reproduces EUV observations when the interchange is taken into account.

3.2 Plasmaspheric Wind

The distribution of cold plasma in the Earth's inner magnetosphere depends on the interplay between the corotation electric field, the convection electric field, and plasma instabilities. The corotation electric field is fairly stable but the convection electric field is unsteady and, therefore, the plasma distribution may vary substantially both in space and time during active periods. When there are disturbances in the solar wind, flux tubes outside the corotation region drain their plasma toward the magnetopause under the effect of the duskward convection electric field and a well-defined and sharp density gradient, the plasmopause, is observed. On the contrary, when magnetospheric convection is very weak for a prolonged period, the effect of the plasmasphere corotation with the Earth dominates up to large radial

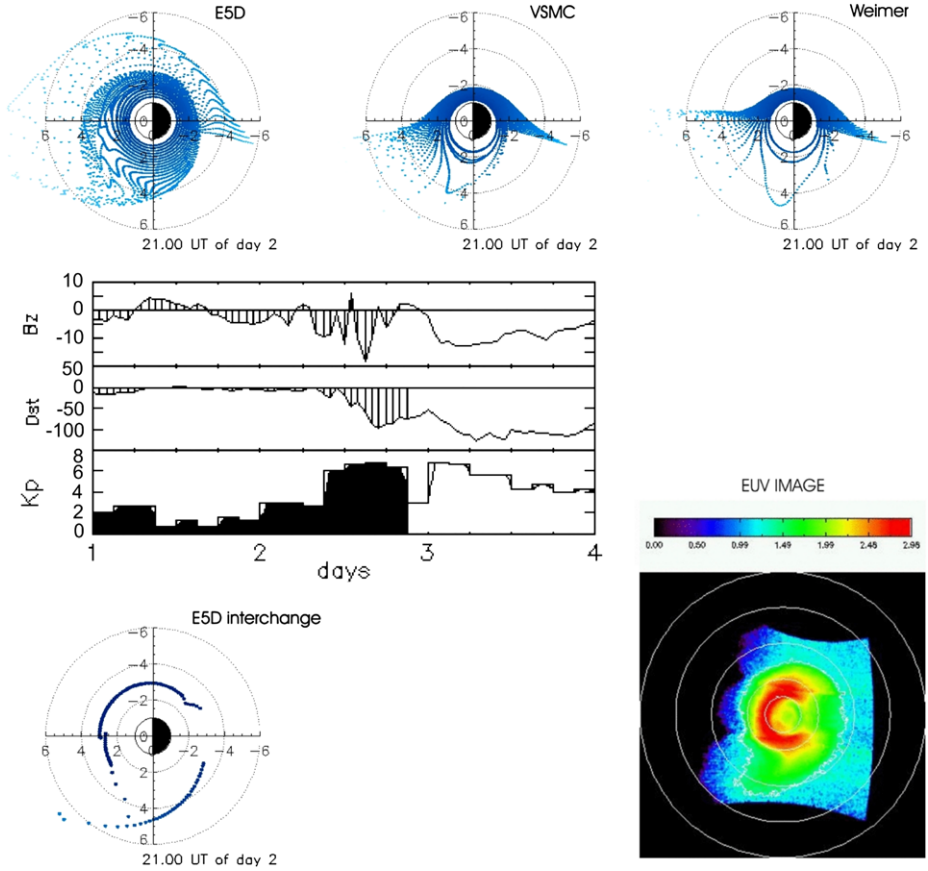


Fig. 5 The equatorial cross section of the plasmasphere after the magnetic storm of 17 April 2002 at 21:00 UT. (*Upper panels*) MHD simulations with E5D (*left*), VSMC (*middle*), Weimer (*right*) electric field models. The Z component of the interplanetary magnetic field (IMF) (B_z), the disturbance storm-time index (Dst) and the geomagnetic activity index K_p from 16 April 2002 0:00 UT up to 18 April 2002 24:00 UT are illustrated below the upper left panel. (*Bottom panels*) Interchange simulations with E5D (*left*) and observations of IMAGE EUV at 21:07 UT (*right*). The white circles correspond respectively to $L = 2, 4, 6$ and 8 . (Adapted from Pierrard et al. 2008)

distances ($< 7 R_E$). The magnetic flux tubes inside the corotation region are supplied with plasma continually flowing up out of the ionosphere, and building up a smooth electron density transition from plasmasphere to the outer subauroral regions as observed RPI onboard the IMAGE spacecraft (Tu et al. 2007). Therefore, the plasmasphere is not always bounded by a steep density gradient as commonly believed.

Noting the systematic differences between theoretical hydrostatic models and the observed density distribution in the plasmasphere, Lemaire and Schunk (1992, 1994) suggested the conceptual existence of continual losses of plasma from the plasmasphere, a plasmaspheric wind, driven by interchange motions. They postulate the existence of a slow and permanent transport of plasma across the magnetic field from the inner to the outer regions of the plasmasphere, even during prolonged periods of quiet geomagnetic conditions when substorm disturbances are absent. This plasmaspheric wind is rather similar to that of the subsonic expansion of the equatorial solar corona. Such a radial plasma transport implies in-

deed that plasma streamlines are not closed, and, therefore, that cold plasma elements slowly drift outward from the inner plasmasphere to the plasmopause along winding up spiral drift paths.

3.2.1 *The Role of Quasi-Interchange Modes*

From a theoretical point of view, the presence of a plasmaspheric wind has been considered to result from a plasma interchange motion driven by an imbalance between gravitational, centrifugal and pressure gradient forces.

Gold (1959) was the first to introduce the concept of interchange of magnetic flux tubes in the magnetospheric context. His so-called strict interchange assumes a one-to-one interchange between magnetic flux tubes enclosing the same magnetic flux and thus leaving the shape of the magnetic field lines unchanged as well as the magnetic energy of the system unperturbed. Cheng (1989) pointed out that this model is at odds with the requirement of total pressure balance, and that a realistic flux tube interchange must be accompanied by a change in field magnitude. The so-called generalized interchange model of Southwood and Kivelson (1987) still assumes that the interchanging flux tubes preserve everywhere the direction of the local magnetic field, but they relax the condition that the energy density of the magnetic field is unperturbed by the interchange. Both models are in fact unphysical, insofar as true interchange motions of plasma elements generally also entail distortions of the magnetic field that preserves the total pressure (plasma plus magnetic pressure). The presence of stratification of the plasmaspheric pressure distribution and of non-electromagnetic forces leads in fact to the destabilizing of a broader category of modes driven by buoyancy forces, known as quasi-interchange modes that trigger transverse as well as translational plasma motions (Newcomb 1961; Ferrière et al. 1999; André 2003; Ferrière and André 2003).

These modes can become unstable in the limit of small parallel wave vector, and fall into two types in the limit of zero parallel wave vector. The type 1 quasi-interchange mode or transverse interchange mode corresponds to plasma motions which are predominantly perpendicular to magnetic field lines and results in the exchange of plasma elements across magnetic field lines. The type 2 quasi-interchange mode or translational mode corresponds to motions of the plasma predominantly along flux tubes.

3.2.2 *Testing the Instability Criteria of Quasi-Interchange Modes in the Plasmasphere*

André and Lemaire (2006) tested the local stability of quasi-interchange modes for various diffusive and exospheric hydrostatic field-aligned density distributions expected to be representative of the equatorial regions of a saturated plasmasphere under very quiet geomagnetic conditions. When the only effect of the centrifugal force due to corotation of the plasma with the angular velocity of the Earth is taken into account, the corotating plasma appears convectively stable inside geosynchronous orbit. However, when the magnetic curvature of the magnetic field lines is properly taken into account, the conclusions obtained in the case of straight field lines are significantly altered since the magnetic curvature is found to have a much larger influence than the effective gravity (including the effect of the centrifugal force) in the Earth magnetosphere. The thermal plasma confined in the Earth's dipole magnetic field cannot remain in magnetostatic equilibrium but becomes convectively unstable much deeper inside the equatorial plasmasphere, at $R = 2 R_E$ and beyond. The type 2 quasi-interchange or translational mode appears to play a more important role than the type 1 quasi-interchange or transverse mode. The type 2 mode appears unstable inside

the geosynchronous orbit for $R < 6.6 R_E$ both in the case of a diffusive equilibrium (DE) model (Lemaire 1999) and in the case of Pierrard and Lemaire (2001) exospheric model for $R > 2.3 R_E$. Since the latter model fits the empirical equatorial density distribution of Carpenter and Anderson (1992), the later conclusion holds also in that case. Similar conclusions are obtained with other empirical models characterized by larger density gradients (e.g., Reinisch et al. 2004). The existence of a static equatorial plasmasphere seems therefore to be questionable, even in a saturated stage following a long period of quiet geomagnetic conditions.

3.2.3 Implications of a Plasmaspheric Wind and Future Refinements

Although the type 2 quasi-interchange or translational mode is considered primarily to lead to plasma motions parallel to the magnetic field line, it should be pointed out that it does not imply strictly parallel motions: The motion necessarily acquires also a transverse component (Ferrière et al. 1999). In that sense, this would be compatible with the concept of plasmaspheric wind introduced by Lemaire and Schunk (1992), consisting of a slow and permanent cross- B transport of plasma from the inner to the outer equatorial regions of the plasmasphere accompanied by a field-aligned upward ionization flow.

Both the diffusive and exospheric models used by André and Lemaire (2006) are oversimplified models, since they assume the plasma distribution to be stationary, i.e., time-independent and with no net mass flow along magnetic field lines, whereas for example asymmetries in the geomagnetic field line geometry and in the boundary conditions at the feet of the flux tube are expected to lead to dynamic inter-hemispheric plasma flows. Their application suffers from large uncertainties due to the use of various simplifying assumptions but interesting conclusions can be drawn from their simplified formulation. Further refinements of their application will have to include, in particular, the coupling of low-energy and high-energy plasma in the plasmasphere, the ionospheric effects arising at the foot of the flux tubes, as well as the observed plasma corotation lag (Burch et al. 2004).

In a recent comparison of measured radial abundance profiles from EUV observations with predicted profiles from the Sheffield University Plasmasphere Ionosphere Model, SUPIM (Bailey et al. 1997) during a period of quiet geomagnetic activity, Sandel and Denton (2007) noted some disagreement between this model and the EUV observations beyond $R = 4 R_E$ that are possibly a signature of physical processes not accounted for in the model. A plasmaspheric wind is one possible process whose inclusion in future magnetospheric convection models might resolve the model-observation disagreement. Recent analysis of cold ion measurements obtained in the plasmasphere by CIS onboard CLUSTER may have provided the first experimental confirmation of such a plasmaspheric wind (Dandouras 2008; Darrouzet et al. 2008, this issue).

3.3 Transport of Plasmaspheric Material Caused by Ultra Low Frequency Waves

The study of transport of plasmaspheric material in plumes is not only important to understand the plasmasphere dynamics but also to understand the physics of the magnetic reconnection at the magnetopause (Borovsky and Hesse 2007). The presence of dense plasma modifies the local reconnection rate by lowering the Alfvén velocity. Some escaping particles could subsequently move toward the magnetotail and subsequently be recirculated into the inner magnetosphere during substorms. Thus the formation of plumes is of vital importance if we are to understand the mass budget in near-Earth space (Chappell et al. 1987).

The formation of a plasmaspheric plume is often discussed in terms of global plasma transport during times of large geomagnetic activity such as substorms and/or storms (Grebowsky 1970; Elphic et al. 1996) including cases with IMF directed southward (negative B_Z) (Goldstein et al. 2002; Chen and Moore 2006). However, observations during quiet and moderate periods of cold plasma in the afternoon sector, well outside the nominal plasmasphere have remained puzzling (Chappell 1974; Carpenter et al. 1993; Matsui et al. 1999; Yoshikawa et al. 2003). Are these cold plasma regions residual density features that linger long after the recovery after storms and substorms? An alternate explanation involves ULF waves, which are often excited by the variation of the solar wind dynamic pressure (e.g., Farrugia et al. 1989) and/or by the velocity shear at the magnetopause (e.g., Engebretson et al. 1995). All current electric field models include a flow stagnation point somewhere on the duskside, where $\mathbf{E} \times \mathbf{B}$ drifts are weak. At this stagnation point (and possibly in a large area on the duskside during quiet conditions), the wave field might exceed the background field, and thus could dominate cold plasma transport. This idea, suggested by Carpenter and Lemaire (2004) as part of the proposed plasmasphere boundary layer (PBL) concept, could help explain the prevalence of cold plasma at large L values in the afternoon sector even during extended quiet conditions. Chen and Wolf (1972) considered time variable electric fields but with longer time scale (8 hours) than ULF waves. Grebowsky and Chen (1976) considered a case applying spatially variable electric fields to examine transport of plasmas. Recently, Adrian et al. (2004) simulated ULF waves related to the formation of radially bifurcated plasmaspheric features.

Matsui et al. (2000) considered this problem with temporally variable electric fields. In this study, a test particle simulation was performed in an idealized mathematical model to examine whether ULF wave fields could cause cold plasma to be transported to the magnetopause. The background electric potential Φ in the inertial frame is given by Volland-Stern model (Volland 1973; Stern 1975) without ionospheric shielding:

$$\Phi = \frac{C_1}{L} - C_2 L \sin \phi, \quad (1)$$

where C_1 is a constant to specify the size of the corotation potential, L is the value of McIlwain's parameter, C_2 is a variable to specify the intensity of the dawn-dusk electric field component, and ϕ is the MLT expressed in radians. In addition, the wave electric potential $\Delta\Phi$ defined by the following equation is added:

$$\Delta\Phi = a \cdot \exp(-br^2) \cdot \sin\left(\frac{2\pi t}{T}\right), \quad (2)$$

where a is the wave amplitude, b is the spatial size of the wave potential taken as $1.0 \times 10^4 R_E^{-2}$, r is the distance from the stagnation point, t is time, and T is the wave period, taken as 300 s. It is assumed that there is no magnetic field perturbation, which is true for the fundamental mode of standing Pc 5 waves. These waves have a typical period of ~ 300 s. The location of the stagnation point is set at $L = 6$ and 18:00 MLT. The particle orbit without perturbation is traced from 15:00 MLT, which leads to the location $L = 5.99$ at 18:00 MLT. The orbit is traced by a Runge-Kutta method with a time step of 0.5 s.

The orbit around the stagnation point is shown in Fig. 6a. This orbit is inside the last closed equipotential (LCE) and rotating around the Earth, although the period is 55.9 hours, longer than 1 day due to a finite convection electric field in the vicinity of the stagnation point. It should be noted that this model is not based on physical processes but mathematical because the calculation relies on the existence of a singular mathematical point. Moreover,

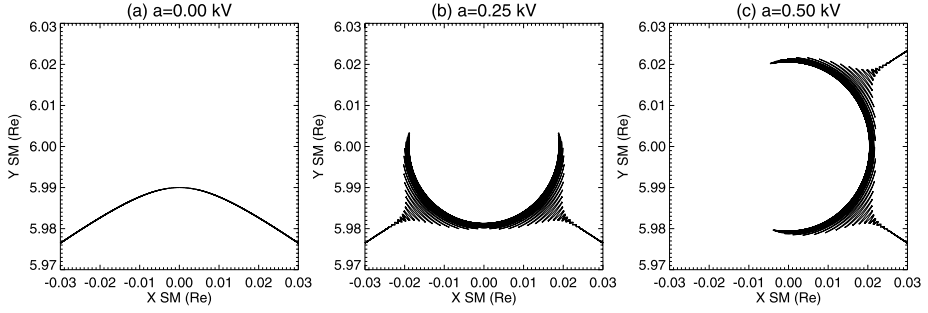


Fig. 6 Particle orbits around the stagnation point $(X, Y)_{SM} = (0.00, 6.00) R_E$ with amplitudes of wave potential: **a** $a = 0.00$ kV, **b** $a = 0.25$ kV, and **c** $a = 0.50$ kV

the wave field essentially assumes coherent waves, which is not necessarily a good description of the turbulence that exists. When a perturbed potential $\Delta\Phi$ with $a = 0.25$ kV is added, the particle orbit starts to deviate at a distance $\sim 0.02 R_E$ from the stagnation point (Fig. 6b). In this case, the perturbation is not large enough to shift the particle orbit from a closed to an open one. After passing near the stagnation point under the influence of waves, the orbit returns to the same as that without perturbation. The orbit is further modified when a larger wave potential $a = 0.50$ kV (Fig. 6c) than the previous case (Fig. 6b) is specified. In this case, the particle orbit is transferred from the original closed orbit to the open orbit and is subsequently transported toward the magnetopause.

The above simple simulation demonstrates that the behaviour of plasmaspheric particles, in particular whether they remain on closed drift paths or are carried toward the magnetopause, can depend on the wave amplitude at the stagnation point. It is often reported that the wave amplitude is comparable to or larger than the background field from various observations such as Equator-S (Quinn et al. 1999), Geotail (Matsui et al. 2000), CLUSTER (Matsui et al. 2003), and LANL geosynchronous satellites (Goldstein et al. 2004). At the stagnation point itself (where the DC electric field is, by definition, zero), the wave component dominates.

In reality, the wave amplitude will not be constant as assumed in the above simulation. LeDocq et al. (1994) reported turbulent behaviour of the density variation, one behaviour expected in the PBL. If this is the case for the electric field variation, the particles at times may be transported to the magnetopause under the dominating influence of ULF waves, and at other times may not. Another open question is the relative importance of this ULF-related mechanism relative to other known mechanisms such as SAPS (Foster et al. 2004), the interchange instability mechanism (Pierrard and Lemaire 2004), or global fields from storms or substorms. Under various conditions, duskside plasma transport could result from various different combinations of the above-mentioned mechanisms.

Finally, it is worth pointing out that the above simulation ignores inductive electric fields created by magnetic variation, and assumes that (barring wave fields) the dominant influence is $\mathbf{E} \times \mathbf{B}$ drift. This latter assumption rules out the possible dominance of the interchange instability or curvature drift (André and Lemaire 2006), which might especially be true near the stagnation point in the $\mathbf{E} \times \mathbf{B}$ field. Ideally, future simulations that include realistic, self-consistent electromagnetic fields (with treatments of all possible mechanisms) would be best suited for comparing the relative importance of the various mechanisms.

3.4 Electric Field in Equilibrium Theory

The first studies of the field aligned plasma distribution in an ion-exosphere considered the case of diffusive equilibrium (DE), in which the plasma velocity distribution function (VDF) is Maxwellian and isotropic (Bauer 1962). The latter studies envisaged the case of exospheric equilibrium (EE), in which the velocity distribution is anisotropic, but without any net inter-hemispheric flow.

Due to the large mean free path compared to the gyroradius of charged particles, they can move longer distances along magnetic field lines than in the direction perpendicular to the magnetic field $\mathbf{B}$. This implies that the motion of charged particles is determined in a co-moving frame of reference where the $\mathbf{E} \times \mathbf{B}$ convection velocity is null. Except during transient flow regimes where electrostatic shocks may be able to propagate downwards or upwards, the plasma density is distributed in a smooth manner along plasmaspheric flux tubes.

When the distribution of plasma is in hydrostatic equilibrium, its field aligned density distribution is determined by the gravitational potential. But besides the gravitational forces, which are proportional to the ion or electron masses, there is always an additional internal force due to a polarization electric field: the Pannekoek-Rosseland electric field (Lemaire and Gringauz 1998). This electric field has non-zero components both perpendicular and parallel to the magnetic field lines. This polarization field exists in all geophysical and astrophysical plasmas as a result of the charge separation created by the difference between the gravitational forces acting on the electrons and on the heavier ions.

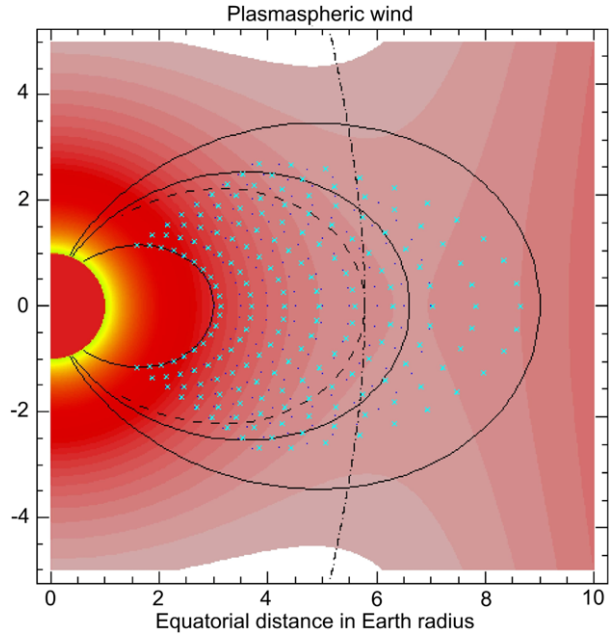
Note that when the plasma is not in hydrostatic equilibrium but has a bulk motion upward or downward (across or along magnetic field lines), the inertial force produces another polarization electric field in addition to the Pannekoek-Rosseland component. Sheared convection velocity distributions, like that existing along magnetic flux tubes in the plasmaspheric wind, creates an additional electric field component, which also has a non-zero parallel component such that $\mathbf{E} \cdot \mathbf{B} \neq 0$. The existence of parallel electric field components in sheared convection velocity distributions has been discussed and modeled by Echim and Lemaire (2005) in the context of plasma elements impulsively injected across the magnetopause. The parallel components of polarization electric fields play also a basic role in interchange motion (Gold 1959) and quasi-interchange motion in magnetospheric plasmas (Newcomb 1961; André 2003; André and Ferrière 2004).

The parallel component of polarization electric fields is of the order of $\mu\text{V m}^{-1}$, which is much smaller than the perpendicular component of magnetospheric convection or of the corotation electric fields (mV m^{-1}), in a fixed inertial frame of reference. The convection and corotation electric fields can be reduced to zero, by changing the frame of reference in which it is measured (by a Lorentz transformation), while this is never the case for the (small) parallel component of $\mathbf{E}$. The relative “smallness” of the parallel electric fields (when compared with the convection electric field intensity) should not be considered as a reason to ignore its effect, nor to justify the postulate that $\mathbf{E} \cdot \mathbf{B} = 0$ everywhere along geomagnetic field lines (Parks 2004).

3.5 Stationary Density Distribution in the Plasmasphere

The centrifugal effects also influence the field-aligned distributions of ions at high altitudes. The centrifugal effect tends to increase the DE densities of ions and electrons at highest altitudes. For $L > 5.78$, the increase of the equatorial number density is very significant when the corotation of the plasmasphere is taken into account. A significant amount of cold

Fig. 7 Number density of a kinetic Maxwellian DE model. Above the ZPF surface located at $L = 5.78 R_E$ for plasma corotation (dot-dashed line), the plasma density distributions become unstable. The blue crosses represent plasma elements displaced from their initial positions originally aligned along the dipole magnetic field lines, due to quasi-interchange plasma motion of type 2 driven unstable by the curvature of geomagnetic field lines



ionospheric plasma can then accumulate in the equatorial potential well beyond the ZPF surface, i.e., the surface where the field aligned components of the gravitational force and pseudo-centrifugal force balance each other.

This accumulation is illustrated in Fig. 7 where the DE equatorial density has a minimum at geostationary orbit: $R = 6.6 R_E$. Beyond this radial distance, the DE density distribution tends to infinity. Since this situation is physically untenable, it must be concluded that the theoretical DE distribution of corotating plasma is convectively unstable. A theoretical accumulation of plasma in the equatorial region can be held off by the continuous radial outward flow of the plasmaspheric wind already discussed above and evacuating the plasma in excess. This excess of plasma is transported away by quasi-interchange plasma motion of type 2 driven unstable not only by the centrifugal effect but mostly by the effect of magnetic tension resulting from the curvature of geomagnetic field lines (André and Lemaire 2006). This sheared convection velocity, the plasmaspheric wind, is illustrated in Fig. 7 showing the displacements of plasma elements (the blue x symbols) from their initial positions (the black dots initially aligned along the dipole magnetic field lines which are represented by the solid lines in Fig. 7).

The amplitude of these unstable type 2 quasi-interchange displacements is largest close to equatorial plane, while the upward field aligned ionization flow out of the ionosphere maximizes at low altitude along the geomagnetic field lines. This plasmaspheric flow is illustrated in an animation available on the Internet,¹ together with other animations of plasmaspheric wind and plasmopause formation.

Although various other field-aligned electron density distributions have been proposed in the analysis of whistler frequency-time spectrograms, DE models were usually adopted for field lines located inside the plasmasphere. In such DE models, the slope of equatorial

¹<http://www.aeronomie.be/plasmasphere/plasmaspherewindsimulation.htm>.

density distributions gradually decreases with radial distances and tends to zero at $6.6 R_E$. However, the slopes of the equatorial ion density profiles measured by OGO-5 are consistently steeper than the theoretical prediction of the DE models. This led Lemaire and Schunk (1992, 1994) to suggest the existence of the plasmaspheric wind. The inadequacy of DE models to describe the plasma distribution inside the plasmasphere is not only demonstrated by the theoretical evidence, but also from an experimental stand point by WHISPER observations onboard CLUSTER (Darrouzet et al. 2008, this issue), as well as by IMAGE RPI observations (Tu et al. 2004).

3.5.1 The Exospheric Equilibrium Density Distributions

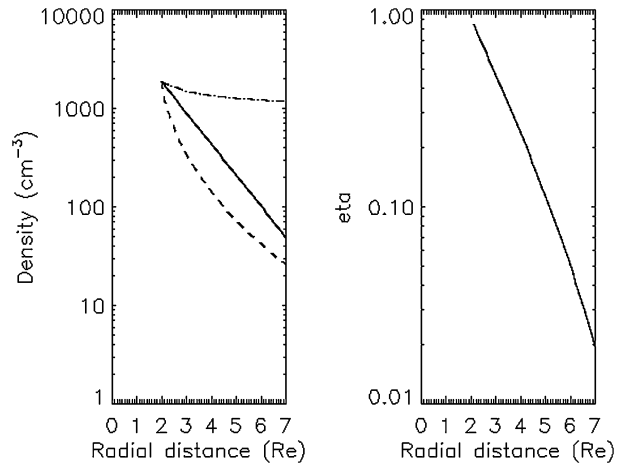
Outside the plasmasphere, the density is more than one order of magnitude smaller than inside the plasmasphere itself, i.e., less than 50 electrons and ions per cm^{-3} at $L = 4$ in the equatorial plane. The free flight time needed for a 0.2 eV proton to move along an $L = 4$ field line from one hemisphere to the conjugate one is 2 hours, if it has not been deflected by Coulomb collisions or wave-particle interactions along its spiraling trajectory (Lemaire 1989). The cumulative number of collisions during their flight from one hemisphere to the other is almost the same for the thermal electrons and H^+ ions (Lemaire 1985, 1989). Therefore, the thermal plasma can be considered as nearly collisionless in the plasmatrough above an altitude of 1000 km, as well as in plasmaspheric flux tubes during the early stages of re-filling phases.

Let's assume that the background plasma density has been reduced to low values in the plasmatrough, after a peeling off event and the formation of a new plasmopause closer to the Earth. Under these transient conditions, the thermal protons and electrons of ionospheric origin can move rather long distances along magnetic field lines without being significantly deflected. Their orbits can be organized into various classes (Lemaire 1976, 1985). These classes are: (e) "escaping" particles, which have enough kinetic energy to go over the total potential barrier; (b) "ballistic" particles, which do not have enough energy to do so; they fall back into the ionosphere. There are also four subclasses of trapped particles (t_1, t_2, t_3, t_4) which have mirror points either in the same hemisphere or in both hemispheres, and those which are trapped in the equatorial potential well for field lines with $L > L_c$ where $L_c = 5.78$. The latter t_3, t_4 classes do not exist for $L < L_c$.

When all these orbits are populated by ions and electrons whose velocity distributions functions are, for instance, Maxwellian and isotropic, the field-aligned density distribution corresponds to the DE model discussed above. Such an ideal state of equilibrium, corresponding to detailed balance between the particles of all these different classes, was assumed to be maintained by Coulomb collisions inside the plasmasphere. However, when one of these classes of orbits is un-saturated (i.e., when for instance the t_3, t_4 trapped particles are missing or under-populated) Coulomb pitch angle scattering will tend to deflect escaping particles as well as trapped particles to fill up the un-saturated classes of orbits. The pitch angle scattering process by Coulomb collisions could be enhanced by the effect of wave-particle interactions, provided that the spectrum of waves and their polarization are adequate and continuously regenerated to feed these additional pitch angle scattering mechanisms; there is not yet definite experimental evidence that this is indeed the case in the plasmasphere and plasmatrough.

The first collisionless (exospheric) models for the plasmasphere were developed by Evitar et al. (1964). Lemaire (1976, 1985) worked out the effect of corotation on the field aligned distribution of thermal ions and electrons, assuming a Maxwellian VDF and empty classes of trapped particles. These kinetic models are labeled EE models.

Fig. 8 (Left) Equatorial density profiles in the plasmasphere obtained by Carpenter and Anderson (1992) from ISEE observations (*thick straight line*). The corresponding equatorial density profiles for DE (*upper line*) and EE (*lower line*) with Kappa distributions with $\kappa = 10$ are shown for comparison. (Right) Fraction η of trapped particles to add to minimum exospheric models ($\kappa = 10$) to recover density profile from (Carpenter and Anderson 1992) corresponding to prolonged quiet magnetic conditions. (Adapted from Pierrard and Lemaire 2001)



A further extension of EE models has been developed by Pierrard and Lemaire (1996) for Lorentzian VDF instead of Maxwellian ones. The tails of the Lorentzian VDF are controlled by a parameter kappa: When kappa is small, there are a large number of suprathermal particles in the tail of the distribution. Conversely, the Lorentzian VDF becomes indistinguishably Maxwellian when the kappa index tends to infinity. Figure 8 (left panel) illustrates equatorial plasmaspheric density profiles for a Lorentzian VDF with a high value of the kappa index. The upper dashed-dotted line in Fig. 8 (left panel) corresponds to the equatorial number density profile in case of DE. The VDFs of the electrons and protons are assumed to be Lorentzian with $\kappa = 10$ and isotropic (Pierrard and Lemaire 2001). Contrary to the DE models with Maxwellian VDFs for which the temperatures of the electrons and ions are uniform, DE models with Lorentzian VDFs have temperatures increasing with altitudes. Positive temperature gradients were first observed in the plasmasphere by Comfort (1986, 1996) and confirmed by the observations in Kotova et al. (2002) and Bezrukhikh et al. (2003).

The lower dashed line in Fig. 8 represents the equatorial density corresponding to EE. In this case, the proton density is formed only of ballistic (b) and escaping (e) particles emerging from below the exobase level. In this model, no trapped particles with mirror points above the exobase are assumed to be present in the ion-exosphere.

The EE distribution can ideally be considered as a sort of minimum density model. Indeed, densities below the values predicted by EE models cannot be maintained much longer than one free flight time of ionospheric ions moving from one hemisphere to the other. Along field lines $L = 4$, this flight time is 2 hours for a proton of 0.2 eV while at $L = 6$ it is four hours (Lemaire 1985, 1989). For example, starting with a hypothetically void magnetospheric flux tube, after four hours the proton density distribution would have recovered to values equal or larger than those corresponding to the EE model. Therefore, EE models or the corresponding distribution obtained for a Lorentzian VDF (Pierrard and Lemaire 1996) are minimum models. They should be considered as initial boundary conditions in dynamical plasmaspheric refilling models like those proposed by Krall et al. (2008) and others. At any time between peeling off event and the long term saturation time, the field-aligned density distributions should be somewhere in between the two extreme EE and DE models.

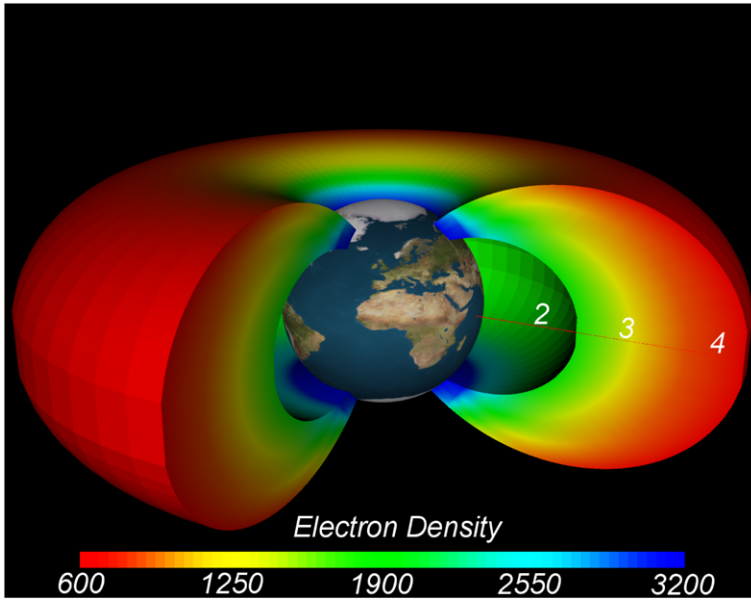


Fig. 9 Kinetic model of the plasmasphere in three dimensions obtained by assuming a fraction of trapped particles so that the geomagnetic equatorial profile corresponds to ISEE observations. The electron density is given in cm^{-3} . (Adapted from Pierrard and Stegen 2008)

3.5.2 Physics Model Constrained by Empirical Data

Pierrard and Lemaire (2001) constructed an intermediate stationary kinetic model of the plasmasphere, where η , the relative abundance of trapped protons and electron populations, was neither equal to 1 as in the DE model, nor null as in the EE model. In this intermediate kinetic model, η is assumed to be a function of L , or of the invariant latitude of the dipole field lines. The values of $\eta(L)$ have been adjusted to recover the statistical equatorial electron density distribution obtained by Carpenter and Anderson (1992) from ISEE observations after prolonged quiet conditions. This observed equatorial density profile is represented by the thick straight line on the left panel of Fig. 8. The right panel of Fig. 8 illustrates how the relative abundance of trapped particles decreases with L in order to recover the Carpenter and Anderson (1992) plasmaspheric density profile in the equatorial region.

It can be seen from the right hand side panel that the required relative fraction of trapped particles, $\eta(L)$, is smaller along the outermost field lines of the plasmasphere, than along the inner region flux tubes, where the average density is larger and consequently where pitch angle scattering of ballistic and escaping particle onto trapped orbits is most efficient.

This stationary kinetic model of plasmaspheric density distribution has recently been extended in three dimensions by Pierrard and Stegen (2008) to also simulate the density distribution outside plasmasphere and in the PBL. This more recent model of the plasmaspheric density distribution is also a function of the level of geomagnetic activity as determined by the K_p index and is illustrated in Fig. 9. This model is in good agreement with satellite measurements, and especially with recent observations of IMAGE and CLUSTER (Pierrard and Stegen 2008).

3.6 Kinetic Process of Plasmaspheric Refilling

In a qualitative refilling scenario proposed by Lemaire (1985, 1989), ballistic and escaping particles from the ionosphere enter empty flux tubes. In less than 4 hours a field-aligned density distribution exceeding that of the EE model is set up along all refilling flux tubes. These ionospheric particles build up a dynamical field-aligned density distribution like that studied in the dynamical refilling model of Krall et al. (2008). The pitch angle distribution of the ions is expected to be initially strongly anisotropic and peaked in the field-aligned direction, i.e., confined to the source and loss cones. For larger pitch angles, corresponding to trapped particles, reduced phase space density are expected during the early phase of the refilling process. However, since Coulomb collision rate is never equal to zero and since it increases rapidly when the total flux tube content increases, the density in the flux tubes is expected to increase rapidly due to the continual accumulation of trapped particles by Coulomb pitch angle scattering and wave-particle interactions.

As time passes, more and more ballistic and escaping particles are scattered onto trapped orbits at larger pitch angles. The particles of lowest energies (subthermal) will be scattered more quickly than the suprathermal ones. Indeed, the Coulomb collision cross section is a rapidly decreasing function of the relative speed between colliding charged particles. Therefore, it is expected that the pitch angle distribution of particles with the lowest energies will become isotropic first. Later on, the pitch angles distribution of suprathermal particles also become more isotropic (Lemaire 1989). The evolution of the pitch angle distribution from a cigar-shaped one to a more isotropic one should take place over a much shorter time scale for the electrons than for the protons of comparable energies.

3.6.1 Coulomb Collisions

Fundamental progress has been done to describe the changes of the particle velocity distribution of the ions in the transition region between the collision dominated ionosphere and the collisionless ion-exosphere. This effort was led by Barakat et al. (1990, 1995), Wilson et al. (1992, 1993) and Barghouthi et al. (1993, 2001). These basic advances in the kinetic theory of the polar wind and post-exospheric models for plasmaspheric refilling are based on Direct Monte-Carlo Simulation method (DMCS); hybrid/semi-kinetic models, fluid/hydrodynamic models and particle-in-cell methods; numerical solutions of the kinetic Fokker-Planck equation have been proposed by Lie-Svendsen and Rees (1996), Pierrard (1996), Pierrard and Lemaire (1996, 1998), Pierrard et al. (1999) and Lemaire and Pierrard (2001). Tam et al. (2007) have recently reviewed the kinetic models of the polar wind.

Monte Carlo simulations of the effect of Coulomb interactions on the velocity distribution function of ionospheric ions streaming in an empty ion-exosphere have been investigated by Barakat et al. (1990) and by Barghouthi et al. (1993). These simulations have demonstrated that, at the exobase, where the mean free paths of H^+ ions become equal to the plasma density scale height, their velocity distribution function changes drastically from a nearly isotropic Maxwellian (in the collision dominated region) to one that is anisotropic and resembles a “kidney bean embedded in a Maxwellian”. Barghouthi et al. (2001) generalized their Monte Carlo simulations to Lorentzian VDFs.

The quantitative DMCS results were confirmed and expanded by Wilson et al. (1992) using a hybrid particle-in-cell model to describe the gradual plasmaspheric refilling process. The plasma accumulation at high altitudes occurs through collisional thermalization and pitch angle scattering controlled by the rate of velocity dependent Coulomb collisions.

Just like Barghouthi et al. (1993), Wilson et al. (1992, 1993) determined the velocity space distribution, $f(v_{\parallel}, v, t)$ for the ions beams. Although different numerical methods

were used in both independent studies, they reached basically the same physical conclusions. Within a few hours after the refilling has started, a significant number of ions from the northern hemisphere return after reflection in the southern hemisphere and vice versa. The gap in phase space between the two counter streaming beams gradually fills from the ionosphere toward the equator. This is due to particles, which are scattered onto trapped trajectories by collisions, with the result that their mirror points has a 50% chance to jump up to higher altitudes getting further removed from the topside ionosphere. Most of these collisions occur at lower altitudes. When the gap is completely filled, the pitch angle distribution has a maximum at 90° . This occurs after about 34 hours for $L = 4.5$.

During the refilling process, the density decreases smoothly toward the equator where the plasma density is minimum, and there is no sign of propagating shock waves. Therefore, according to the kinetic and semi-kinetic or hybrid scenarios proposed, plasmaspheric refilling occurs from the base of the flux tube, and not from top to bottom.

Miller et al. (1993) have modeled field-aligned plasma flows in the plasmasphere using a one-dimensional hybrid particle code to study the interactions between upflowing thermal ions from conjugate ionospheres. They point out that self-consistent modeling of ionosphere-plasmasphere coupling is important and requires information down to an altitude of 200 km. Their kinetic simulations demonstrated that magnetospheric convection and particle injection can change the initial conditions for plasmaspheric refilling on timescales shorter than one hour. But over long timescales (days), this short timescale information is lost.

3.6.2 Monte Carlo Simulations

The effects of magnetic field line divergence and of the external body forces were simulated separately in the study of Barghouthi et al. (1993). In subsequent Monte Carlo simulations, Barakat and Barghouthi (1994) examined the effect of wave-particle interactions on the velocity distribution of polar wind H^+ and O^+ ions flowing out of the ionosphere along magnetic field lines (Barakat et al. 1995). Effects of wave-particle interactions on Lorentzian VDFs were analyzed in Pierrard and Barghouthi (2006). More recently, Barghouthi et al. (2007) analyzed also the effect of finite electromagnetic turbulence wavelength on the high-altitude and high latitude O^+ and H^+ outflows. Barghouthi et al. (2008) showed that altitude and velocity dependent wave-particle interactions lead to the formation of toroids at high altitude for the ion VDFs.

Monte-Carlo simulations have also been employed by Yasseen et al. (1989) and Tam et al. (1995) to determine the velocity distribution of photoelectrons (treated as test particles) moving through a background of H^+ , O^+ , and the bulk of thermal electrons, which all participate in a current-free polar wind type ionization flow. In their latest hybrid simulation, the evolution of velocity distributions of the O^+ and H^+ are also determined by the Monte-Carlo method, while the bulk of thermal electrons is treated as a fluid. Their results agree with observations in various aspects. They demonstrate that a temperature anisotropy develops between upwardly and downwardly moving electrons. They find that upward moving photoelectrons produce an upward heat flux for the total electron population.

Although these Monte-Carlo simulations demand large amounts of CPU-time, they are rather illuminating and useful to test numerical models, which were developed by Lie-Svendsen and Rees (1996) and Pierrard and Lemaire (1998). Both obtain numerical solutions of the Fokker-Planck equation for the H^+ ion velocity distribution moving along diverging magnetic field lines in a background of O^+ ions. Both teams of investigators obtained independently solutions of the Fokker-Planck equations, which are similar to those

of the Monte Carlo simulations, although they employ different boundary conditions at the bottom of the transition layer, as well as different mathematical methods: Lie-Svendsen and Rees (1996) use the finite difference method, while Pierrard and Lemaire (1998) employ a generalized spectral method.

These numerical tools will enable the development of future post-exospheric approximations for ion velocity distributions, which are especially needed in the transition layers between the collision dominated ionosphere and collisionless magnetosphere. Novel numerical methods of this kind, including the Monte Carlo simulation and particle-in-cell method, have opened the door to modern plasma kinetic treatment of plasmaspheric, polar wind and magnetospheric modeling. They are nicely complementing the fluid, moments, and MHD approximations used for decades in space plasma transport theories (see the review by Fahr and Shizgal 1983).

4 Comparison Between MHD and Kinetic Approaches

Numerous theoretical models describing the outflow of ionospheric plasma at polar and mid-latitudes have been based on numerical integration of hydrodynamical transport equations or moment equations. Unlike the case of kinetic models, where plasma is described by the velocity distribution functions of its different particle species, in hydrodynamical models the plasma is described in terms of the total number density or of the partial density of the electrons and different ion species, of their bulk speeds, parallel and perpendicular temperatures, parallel and perpendicular heat flow tensor components or in terms of moments of higher order of the velocity distribution function.

In fluid models, the spatial distributions of these macroscopic quantities (n_i , v_i , $T_i \dots$) are obtained by solving the moment equations for each particle species. These moment equations are obtained by multiplying the Boltzmann equation by various velocity moments and integrating over velocity space. The result is a hierarchy of coupled differential equations—the transport or fluid equations—which describe the spatio-temporal variation of the moments of the velocity distribution functions of the electrons and ions species. In doing so the detailed features of the microscopic VDF are lost (i.e., the existence of non-Maxwellian features in the energy spectrum of particles or asymmetries in their pitch angle distributions). Indeed, there is an infinite variety of VDFs, which share the same values for their lowest order moments (Schunk and Watkins 1979).

The hydrodynamical transport models of varying degrees of sophistication which have been promoted for decades to describe ionospheric and interplanetary space plasmas appear to be easier to integrate than kinetic equations in the case of time dependent situations. By combining the moment equations for the electrons with those for the ions (often all species are assumed to have a common bulk velocity, $\mathbf{v} = \mathbf{E} \times \mathbf{B}/B^2$ as well as the same temperatures), one gets the standard MHD approximation of classical physics.

Furthermore, in the restrictive case of ideal MHD, it is postulated that $\mathbf{E} \cdot \mathbf{B} = 0$, i.e., that the electric field $\mathbf{E}$ has no component parallel to the magnetic field $\mathbf{B}$. To justify this ideal MHD approximation, the electrical conductivity of (almost) collisionless space plasmas should be (almost) infinitely large, so that, according to Ohm's law any small parallel electric field would imply an almost infinitely large value for the field-aligned current (i.e., Birkeland currents). This is based on the postulate that the traditional form of Ohm's law remains applicable even in collisionless plasmas. However, this is not quite the case in nearly collisionless magnetospheric plasma, where a generalized form of Ohm's law has to be used instead of its simplified form, which is only applicable in highly collision dominated plasmas. Wave-particle interactions produce a linear, ohmic type of anomalous resistivity, but

convincing experimental evidence remains to be found to assess their importance in scattering and heating the bulk of cold plasma in the ionosphere and plasmasphere.

Ideal MHD transport equations have been applied with mixed success in the study of a wide variety of space plasma physics problems. The more comprehensive multi-fluid moment equations and hydrodynamic transport equations consist of coupled sets of continuity, momentum and energy equations for each individual particle species separately. Reviews of different approximations for the multi-fluids transport equations used to study the solar wind, the polar wind and the refilling of empty plasmaspheric flux tubes can be found in the papers by Schunk (1988), Gombosi and Rasmussen (1991), Singh and Horwitz (1992) and Guiter et al. (1995).

Comparisons of transport models and kinetic or hybrid (semi-kinetic) models can be found in Holzer et al. (1971), Schunk and Watkins (1981), Demars and Schunk (1986) and Demars and Schunk (1991). These two complementary approaches were also used to model the solar wind and the polar wind (Lemaire and Echim 2008). In the following, we briefly overview how these models have been applied in the past to describe the refilling of plasmaspheric flux tubes that have been emptied or almost during a substorm (Horwitz and Singh 1991; Krall et al. 2008, and references therein).

4.1 Time Dependent Models for Field-Aligned Plasma Density Distribution

Time dependent and three dimensional models of the middle and high latitude ionosphere have been available for several decades (Schunk 1988). The more recent of these models take into account photochemistry, recombination processes and production of various ions due to reactions with the neutral atmosphere. They are based on the transport equations for mass, momentum and energy for the various ions (Singh et al. 1986; Rasmussen and Schunk 1988). Ion flows across magnetic field lines have been taken into account in several time dependent models and simulations for various given convection electric field models. The effects of counter-streaming of H^+ and He^+ along plasmaspheric tubes have been comprehensively studied by Rasmussen and Schunk (1988) and Krall et al. (2008).

The main constituents of the neutral atmosphere at great heights are helium and hydrogen. Hydrogen ions are formed by the charge exchange reaction $O^+ + H \rightleftharpoons O + H^+$. This reaction is accidentally resonant and proceeds at almost the same rate in both directions. Therefore, the main sink for H^+ ions is the reverse reaction. Throughout the F-region, there are sufficient collisions to maintain H^+ in chemical equilibrium. However, in the topside ionosphere where the O^+ density falls below approximately $5 \times 10^4 \text{ cm}^{-3}$, H^+ ions are able to diffuse along magnetic field lines. The direction of the H^+ diffusion velocity depends mainly on the relative densities of the species involved in the charge exchange reaction.

When the plasmasphere is depleted, more H^+ ions are produced by the forward reaction than are removed by the reverse process. This leads to a net upward flow of H^+ into the plasmasphere. However, there is a limit to the rate at which the plasmasphere can be replenished by the upward H^+ flux (Hanson and Patterson 1963). Geisler (1967) indicated that the most important factor limiting the magnitude of the upward H^+ flux is the neutral hydrogen density.

4.2 Time Dependent Refilling Model

The first time dependent plasmaspheric flux tube refilling model was proposed by Banks et al. (1971). It is known as the “two-stage refilling scenario” and has been expanded until in the late 1980s within the framework of various hydrodynamical approximations (Singh

1988). According to this scenario a polar wind like supersonic flow is driven out of the ionosphere by a large pressure gradient parallel to the magnetic field lines. These flows from the conjugate hemispheres collide at the equator. A pair of shocks is formed as a consequence of this collision in the equatorial region. The shocks propagate downward, one in each hemisphere. Between the shocks the plasma is dense and warm, while below the shocks the upward flows are supersonic. This corresponds to the well-known scenario of refilling from “top to bottom”.

Furthermore, it was proposed that when the shocks reach the ionosphere, a second phase of refilling process should follow, with upward subsonic flows lasting for several days. In such single-stream hydrodynamic models, the flux tube refills from top to bottom. So far, however, there is no evidence in CLUSTER and IMAGE observations for this early refilling scenario. As soon as the density becomes high enough, Coulomb collisions are an important factor in thermalizing the plasma flow (Grebowsky 1972; Khazanov et al. 1984; Guiter and Gombosi 1990).

Lemaire (2001) has suggested that the deceleration and deflection of the upwelling plasma streams generate intense electrostatic emissions detected outside the plasmasphere, where geomagnetic flux tubes are refilling. Strong electrostatic emissions sharply confined between $\pm 2^\circ$ of latitude (very close to the geomagnetic equatorial surface) have been observed by WHISPER onboard CLUSTER, on partially depleted flux tubes beyond the plasmopause (El-Lemdari Mazouz et al. 2006). Similarly confined intense electrostatic noise had already been observed in the equatorial region with wave antennae on earlier magnetospheric missions.

No definite picture has yet emerged describing how, when and where the downward or upward propagating shocks would form, if they do so at all. From IMAGE RPI measurements there does not seem to be any evidence for such propagating shocks in the observed field aligned plasma distribution. This supports then the kinetic refilling scenarios of Lemaire (1989), as well as those of obtained with the Monte Carlo simulations described above (Lin et al. 1992; Wilson et al. 1992). No such shocks are formed in the refilling plasmaspheric flux tubes. Moreover, using CLUSTER data Darrouzet et al. (2006) found that there is no evidence for sharp density gradients along field lines, such as would be expected in refilling shock fronts propagating along field lines.

Liemohn et al. (1999) have developed a time-dependent kinetic model to investigate the effects of self-consistency and hot plasma influences on plasmaspheric refilling. The model employs a direct solution of the kinetic equation with a Fokker-Planck Coulomb collision operator to obtain the phase space distribution function of the thermal protons along a field line. Investigations of the effects of anisotropic hot plasma populations on the refilling rates shows that, after a slight initial decrease in equatorial density from clearing out the initial distribution, there is a 10 to 30% increase after 4 hours due to these populations. This increase is due primarily to a slowing of the refilling streams near the equator from the reversed electric field.

4.3 Other Models of the Plasmasphere

Finally, let us mention some other plasmaspheric models. An excellent review of the major advances in plasmaspheric research made just before the launch of CLUSTER and IMAGE spacecraft was presented in Ganguli et al. (2000).

The FLIP (Field Line Interhemispheric Plasma) model (Richards and Torr 1986) is a fluid model that solves the equations of continuity, momentum and energy conservation of the particles in both hemispheres. It has been used to analyze the RPI IMAGE observations

of electron density along field lines (Tu et al. 2003). The calculated densities in the regions far from the equator were much lower than observed values, while good agreement was obtained in the equator.

Another physics-based model of the plasmasphere has been developed by Webb and Essex (2004). Their three-dimensional Global Plasmasphere Ionosphere Density (GPID) model uses a dynamic diffusive equilibrium approach within each magnetic flux tube. This theoretical model constitutes an improvement compared to the purely empirical models of the plasmasphere.

A Multi Species Kinetic Plasmaspheric Model (MSKPM) has been developed by Reynolds et al. (2001). This kinetic model is coupled to a parameterization of a fluid model of the ionosphere at the ion exobase. The hydrogen ion and helium ion density in the equatorial plane are found to exhibit local-time variations that are sensitive to the details of the exobase conditions and the diurnal convection. The theoretical predictions of the kinetic model were also compared with the quiet-time structure of the plasmaspheric density investigated using observations of the LANL geosynchronous satellites (Reynolds et al. 2003).

Note also Maruyama et al. (2005) who have modeled the response to a geomagnetic storm using the Rice Convection Model (RCM) and the Coupled Thermosphere-Ionosphere-Plasmasphere-electrodynamics (CTIPE) model. CTIPE is a global, three-dimensional, time-dependent, non-linear code including three physical components: a code for the neutral thermosphere, an ionospheric convection model and plasmaspheric model (Milward et al. 1996). Maruyama et al. (2005) show that during daytime, and at the early stage of the storm, the penetration electric field is dominant, while at night, the penetration and disturbance dynamo effects are comparable.

SAMI2 is Another low-latitude Model of the Ionosphere developed at the Naval Research Laboratory (Huba et al. 2000). SAMI2 treats the dynamic plasma and chemical evolution of seven ion species in the altitude range of 100 km to several thousand kilometers. The ion continuity and momentum equations are solved for all seven species. It models the plasma along the Earth's dipole field from hemisphere to hemisphere, includes the $\mathbf{E} \times \mathbf{B}$ drift of a flux tube (both in altitude and in longitude), and includes ion inertia in the ion momentum equation for motion along the dipole field line.

A physics-based data assimilation model of the ionosphere and neutral atmosphere called the Global Assimilation of Ionospheric Measurements (GAIM) has been developed by Schunk et al. (2004). GAIM uses a physics-based ionosphere-plasmasphere model and a Kalman filter for assimilating near real-time measurements including in situ density measurements from satellites, ionosonde electron density profiles, occultation data, measurements of the total electron contents (TECs) by Global Positioning System (GPS) satellites, two-dimensional ionospheric density distributions from tomography chains, and line-of-sight UV emissions from selected satellites.

5 Conclusions

The plasmasphere is an active part of a coupled global system. In the decades since the discovery of the plasmasphere and prior to the IMAGE and CLUSTER mission, the prevailing view of the plasmasphere was of a placid, passive component in the larger magnetospheric system. One of the main insights gleaned from plasmaspheric modeling in the era of global imaging observations is that, contrary to the previously prevailing view, the plasmasphere plays a very active role in the dynamics of the rest of the magnetosphere.

The plasmasphere-magnetosphere interaction is two-way. Convection terms, such as shielding and SAPS, produced by the interactions among non-plasmaspheric populations,

such as the ring current and ionosphere, certainly exert a profound and controlling influence upon the dynamics of the plasmasphere. In turn, plasmaspheric dynamics then influence the dynamics of other populations, such as the ring current and radiation belts.

This system-level perspective extends to other populations as well, as illustrated by the need for a self-consistent determination of the inner magnetospheric electric field produced by ring-current-ionosphere coupling. In the post-IMAGE era, we have a deeper understanding of how all the various components of the magnetosphere mesh together into a single system of intimately-coupled plasmas and fields. Moreover, the four CLUSTER satellites provided for the first time highly precise and three-dimensional measurements allowing to better understand the physical mechanisms implicated in the dynamics of the plasmasphere, the formation of the plasmopause and the development of plumes.

Acknowledgements V. Pierrard and J. Lemaire acknowledge the support by the Belgian Federal Science Policy Office (BELSPO) through the ESA/PRODEX CLUSTER project (contract 13127/98/NL/VJ (IC)). Work at Los Alamos was conducted under the auspices of the U. S. Department of Energy, with partial support from the NASA LWS and GI programs, and from a Los Alamos National Laboratory Directed Research and Development grant. This paper is an outcome of the workshop "The Earth's plasmasphere: A CLUSTER, IMAGE, and modeling perspective", organized by the Belgian Institute for Space Aeronomy in Brussels in September 2007.

References

- M.L. Adrian, D.L. Gallagher, L.A. Avakov, IMAGE EUV observation of radially bifurcated plasmaspheric features: First observations of a possible standing ULF waveform in the inner magnetosphere. *J. Geophys. Res.* **109**, A01203 (2004)
- B.J. Anderson, R.E. Erlandson, L.J. Zanetti, A statistical study of pc 1–2 magnetic pulsations in the equatorial magnetosphere 1. Equatorial occurrence distributions. *J. Geophys. Res.* **97**(A3), 3075–3088 (1992)
- P.C. Anderson, D.L. Carpenter, K. Tsuruda, T. Mukai, F.J. Rich, Multisatellite observations of rapid subauroral ion drifts (SAID). *J. Geophys. Res.* **106**(A12), 29585–29599 (2001)
- N. André, Ondes et instabilités basse-fréquence dans un plasma gyrotrope. Application à l'instabilité d'interchange dans les magnétosphères des planètes géantes. PhD thesis, Université Paul Sabatier, Toulouse, France, 2003
- N. André, K.M. Ferrière, Low-frequency waves and instabilities in stratified, gyrotropic, multicomponent plasmas: Theory and application to plasma transport in the Io torus. *J. Geophys. Res.* **109**, A12225 (2004)
- N. André, J.F. Lemaire, Convective instabilities in the plasmasphere. *J. Atmos. Sol.-Terr. Phys.* **68**(2), 213–227 (2006)
- G.J. Bailey, N. Balan, Y.Z. Su, The Sheffield University plasmasphere ionosphere model—A review. *J. Atmos. Sol.-Terr. Phys.* **59**(13), 1541–1552 (1997)
- P.M. Banks, A.F. Nagy, W.I. Axford, Dynamical behavior of thermal protons in mid-latitude ionosphere and magnetosphere. *Planet. Space Sci.* **19**(9), 1053–1067 (1971)
- A.R. Barakat, I.A. Barghouti, The effect of wave-particle interactions on the polar wind O⁺. *Geophys. Res. Lett.* **21**(21), 2279–2282 (1994)
- A.R. Barakat, R.W. Schunk, I.A. Barghouti, J. Lemaire, Monte-Carlo study of the transition from collision-dominated to collisionless polar wind flow, in *Physics of Space Plasmas*, ed. by T. Chang, G.B. Crew, J.R. Jaspers (Scientific Publisher, Cambridge, 1990), pp. 431–437
- A.R. Barakat, I.A. Barghouti, R.W. Schunk, Double-hump H⁺ velocity distribution in the polar wind. *Geophys. Res. Lett.* **22**(14), 1857–1860 (1995)
- I.A. Barghouti, A.R. Barakat, R.W. Schunk, Monte Carlo study of the transition region in the polar wind: An improved collision model. *J. Geophys. Res.* **98**(A10), 17583–17591 (1993)
- I.A. Barghouti, V. Pierrard, A.R. Barakat, J. Lemaire, A Monte Carlo simulation of the H⁺ polar wind: Effect of velocity distributions with Kappa suprathermal tails. *Astrophys. Space Sci.* **277**(3), 427–436 (2001)
- I.A. Barghouti, N.M. Doudin, A.A. Saleh, V. Pierrard, High-altitude and high-latitude O⁺ and H⁺ outflows: the effect of finite electromagnetic turbulence wavelength. *Ann. Geophys.* **25**(10), 2195–2202 (2007)

- I.A. Barghouti, N.M. Doudin, A.A. Saleh, V. Pierrard, The effect of altitude- and velocity-dependent wave-particle interactions on the H^+ and O^+ outflows in the auroral region. *J. Atmos. Sol.-Terr. Phys.* **70**(8–9), 1159–1169 (2008)
- S.J. Bauer, On the structure of the topside ionosphere. *J. Atmos. Sci.* **19**(3), 276–278 (1962)
- V.V. Bezrukhikh, G.A. Kotova, L.A. Lezhen, J. Lemaire, V. Pierrard, Yu.I. Venediktov, Dynamics of temperature and density of cold protons of the Earth's plasmasphere measured by the Auroral Probe/Alpha-3 experiment data during geomagnetic disturbances. *Cosm. Res.* **41**(4), 392–402 (2003)
- D. Bilitza, International reference ionosphere: Recent developments. *Radio Sci.* **21**(3), 343–346 (1986)
- J.E. Borovsky, M. Hesse, The reconnection of magnetic fields between plasmas with different densities: Scaling relations. *Phys. Plasmas* **14**(10), 102309 (2007)
- J.L. Burch, IMAGE mission overview. *Space Sci. Rev.* **91**(1–2), 1–14 (2000)
- J.L. Burch, J. Goldstein, B.R. Sandel, Cause of plasmasphere corotation lag. *Geophys. Res. Lett.* **31**, L02502 (2004)
- J.L. Burch, W.S. Lewis, T.J. Immel, P.C. Anderson, H.U. Frey, S.A. Fuselier, J.C. Gérard, S.B. Mende, D.G. Mitchell, M.F. Thomsen, Interplanetary magnetic field control of afternoon-sector detached proton auroral arcs. *J. Geophys. Res.* **107**(A9), 1251 (2005)
- W.I. Burke, N.C. Maynard, M.P. Hagan, R.A. Wolf, G.R. Wilson, L.C. Gentile, M.S. Gussenhoven, C.Y. Huang, T.W. Garner, F.J. Rich, Electrodynamics of the inner magnetosphere observed in the dusk sector by CRRES and DMSP during the magnetic storm of June 4–6, 1991. *J. Geophys. Res.* **103**(A12), 29399–29418 (1998)
- D.L. Carpenter, Whistler studies of the plasmapause in the magnetosphere, 1. Temporal variations in the position of the knee and some evidence on plasma motions near the knee. *J. Geophys. Res.* **71**(3), 693–709 (1966)
- D.L. Carpenter, R.R. Anderson, An ISEE/whistler model of equatorial electron density in the magnetosphere. *J. Geophys. Res.* **97**(A2), 1097–1108 (1992)
- D.L. Carpenter, J. Lemaire, The plasmasphere boundary layer. *Ann. Geophys.* **22**(12), 4291–4298 (2004)
- D.L. Carpenter, B.L. Giles, C.R. Chappell, P.M.E. Décréau, R.R. Anderson, A.M. Persoon, A.J. Smith, Y. Corcuff, P. Canu, Plasmasphere dynamics in the duskside bulge region: A new look at an old topic. *J. Geophys. Res.* **98**(A11), 19243–19271 (1993)
- C.R. Chappell, Recent satellite measurements of the morphology and dynamics of the plasmasphere. *Rev. Geophys. Space Phys.* **10**(4), 951–979 (1972)
- C.R. Chappell, Detached plasma regions in the magnetosphere. *J. Geophys. Res.* **79**(13), 1861–1870 (1974)
- C.R. Chappell, T.E. Moore, J.H. Waite Jr., The ionosphere as a fully adequate source of plasma for the Earth's magnetosphere. *J. Geophys. Res.* **92**(A6), 5896–5910 (1987)
- S.H. Chen, T.E. Moore, Magnetospheric convection and thermal ions in the dayside outer magnetosphere. *J. Geophys. Res.* **111**, A03215 (2006)
- A.J. Chen, R.A. Wolf, Effects on the plasmasphere of a time-varying convection electric field. *Planet. Space Sci.* **20**(4), 483–509 (1972)
- A.J. Chen, J.M. Grebowsky, H.A. Taylor Jr., Dynamics of mid-latitude light ion trough and plasma tails. *J. Geophys. Res.* **80**(7), 968–976 (1975)
- A.F. Cheng, Magnetospheric interchange instability. *J. Geophys. Res.* **90**(A10), 9900–9904 (1989)
- R.H. Comfort, Plasmasphere thermal structure as measured by ISEE-1 and DE-1. *Adv. Space Res.* **6**(3), 31–40 (1986)
- R.H. Comfort, Thermal structure of the plasmasphere. *Adv. Space Res.* **17**(10), 175–184 (1996)
- J.M. Cornwall, F.V. Coroniti, R.M. Thorne, Turbulent loss of ring current protons. *J. Geophys. Res.* **75**(25), 4699–4709 (1970)
- I. Dandouras, Detection of plasmaspheric wind by analysis of ion measurements obtained onboard the Cluster spacecraft. *Geophys. Res. Abstr.* **10**, 5360 (2008)
- I. Dandouras, V. Pierrard, J. Goldstein, C. Vallat, G.K. Parks, H. Rème, C. Gouillart, F. Sevestre, M. McCarthy, L.M. Kistler, B. Klecker, A. Korth, M.B. Bavassano-Cattaneo, P. Escoubet, A. Masson, Multipoint observations of ionic structures in the plasmasphere by CLUSTER-CIS and comparisons with IMAGE-EUV observations and with model simulations, in *Inner Magnetosphere Interactions: New Perspectives from Imaging*, ed. by J.L. Burch, M. Schulz, H. Spence. Geophysical Monograph Series, vol. 159 (American Geophysical Union, Washington, 2005), pp. 23–53
- F. Darrouzet, Etude de la magnétosphère terrestre par l'analyse multipoint des données de la mission CLUSTER. Contributions à la caractérisation des frontières et de la magnétosphère interne. PhD thesis, University of Orléans, France, 2006. http://www.aeronomie.be/plasmasphere/pdf/Darrouzet_PhDThesis_UniversityOrleans_20060607.pdf
- F. Darrouzet, J. De Keyser, P.M.E. Décréau, J.F. Lemaire, M.W. Dunlop, Spatial gradients in the plasmasphere from Cluster. *Geophys. Res. Lett.* **33**, L08105 (2006)

- F. Darrouzet, D.L. Gallagher, N. André, D.L. Carpenter, I. Dandouras, P.M.E. Décréau, J. De Keyser, R.E. Denton, J.C. Foster, J. Goldstein, M.B. Moldwin, B.W. Reinisch, B.R. Sandel, J. Tu, Plasmaspheric density structures and dynamics: Properties observed by the CLUSTER and IMAGE missions. *Space Sci. Rev.* (2008, this issue)
- J. De Keyser, D.L. Carpenter, F. Darrouzet, D.L. Gallagher, J. Tu, CLUSTER and IMAGE: New ways to study the Earth's plasmasphere. *Space Sci. Rev.* (2008, this issue)
- P.M.E. Décréau, P. Ferreau, V. Krasnosels'kikh, E. Le Guirriec, M. Lévêque, P. Martin, O. Randriamboarison, J.L. Rauch, F.X. Sené, H.C. Séran, J.G. Trotignon, P. Canu, N. Cornilleau, H. de Féraud, H. Alleyne, K. Yearby, P.B. Mörgensen, G. Gustafsson, M. André, D.A. Gurnett, F. Darrouzet, J. Lemaire, C.C. Harvey, P. Travnicek, Whisper experimenters, Early results from the Whisper instrument on Cluster: An overview. *Ann. Geophys.* **19**(10–12), 1241–1258 (2001)
- H.G. Demars, R.W. Schunk, Solutions to bi-Maxwellian transport equations for SAR-arc conditions. *Planet. Space Sci.* **34**(12), 1335–1348 (1986)
- H.G. Demars, R.W. Schunk, Comparison of semi-kinetic and generalized transport models of the polar wind. *Geophys. Res. Lett.* **18**(4), 713–716 (1991)
- M. Echim, J. Lemaire, Two-dimensional Vlasov solution for a collisionless plasma jet across transverse magnetic field lines with a sheared bulk velocity. *Phys. Rev. E* **72**(3), 036405 (2005)
- F. El-Lemdani, M.Z. Mazouz, S. Grimald, J.L. Rauch, P.M.E. Décréau, G. Bozan, G. Le Rouzic, X. Suraud, X. Vallières, J.G. Trotignon, P. Canu, F. Darrouzet, S. Boardsen, Electrostatic and electromagnetic emissions near the plasmasphere. A case event: 27 May 2003, in *Proceedings of the Cluster and Double Star Symposium, 5th Anniversary of Cluster in Space ESA SP-598* (2006)
- R.C. Elphic, L.A. Weiss, M.F. Thomsen, D.J. McComas, M.B. Moldwin, Evolution of plasmaspheric ions at geosynchronous orbit during times of high geomagnetic activity. *Geophys. Res. Lett.* **23**(16), 2189–2192 (1996)
- M.J. Engebretson, W.J. Hughes, J.L. Alford, E. Zesta, L.J. Cahill Jr., R.L. Arnoldy, G.D. Reeves, Magnetometer array for cusp and cleft studies observations of the spatial extent of broadband ULF magnetic pulsations at cusp/cleft latitudes. *J. Geophys. Res.* **100**(A10), 19371–19386 (1995)
- A. Eviatar, A.M. Lenchek, S.F. Singer, Distribution of density in an ion-exosphere of a nonrotating planet. *Phys. Fluids* **7**(11), 1775–1779 (1964)
- H.J. Fahr, B. Shizgal, Modern exospheric theories and their observational relevance. *Rev. Geophys. Space Phys.* **21**(1), 75–124 (1983)
- C.J. Farrugia, M.P. Freeman, S.W.H. Cowley, D.J. Southwood, M. Lockwood, A. Etemadi, Pressure-driven magnetopause motions and attendant response on the ground. *Planet. Space Sci.* **37**(5), 589–607 (1989)
- K.M. Ferrière, N. André, A mixed magnetohydrodynamic-kinetic theory of low-frequency waves and instabilities in stratified, gyrotropic, two-component plasmas. *J. Geophys. Res.* **108**(A7), 1308 (2003)
- K.M. Ferrière, C. Zimmer, M. Blanc, Magnetohydrodynamic waves and gravitational/centrifugal instability in rotating magnetospheres. *J. Geophys. Res.* **104**(A8), 17335–17356 (1999)
- J.C. Foster, W.J. Burke, SAPS: A new categorization for sub-auroral electric fields. *Eos Trans. AGU* **83**(36), 393 (2002)
- J.C. Foster, A.J. Coster, P.J. Erickson, F.J. Rich, B.R. Sandel, Stormtime observations of the flux of plasmaspheric ions to the dayside cusp/magnetopause. *Geophys. Res. Lett.* **31**, L08809 (2004)
- D.L. Gallagher, M.L. Adrian, M.W. Liemohn, Origin and evolution of deep plasmaspheric notches. *J. Geophys. Res.* **110**, A09201 (2005)
- Y.I. Galperin, V.N. Ponomarev, A.G. Zosimova, Plasma convection in the polar ionosphere. *Ann. Geophys.* **30**(1), 1–7 (1974)
- G. Ganguli, M.A. Reynolds, M.W. Liemohn, The plasmasphere and advances in plasmaspheric research. *J. Atmos. Sol.-Terr. Phys.* **62**(17–18), 1647–1657 (2000)
- S.P. Gary, M.F. Thomsen, L. Yin, D. Winske, Electromagnetic proton cyclotron instability: Interactions with magnetospheric protons. *J. Geophys. Res.* **100**(A11), 21961–21972 (1995)
- J.E. Geisler, On the limiting daytime flux of ionization into the protonosphere. *J. Geophys. Res.* **72**(1), 81–85 (1967)
- T. Gold, Motions in the magnetosphere of the Earth. *J. Geophys. Res.* **64**(9), 1219–1224 (1959)
- J. Goldstein, B.R. Sandel, The global pattern of evolution of plasmaspheric drainage plumes, in *Inner Magnetosphere Interactions: New Perspectives from Imaging*, ed. by J.L. Burch, M. Schulz, H. Spence. Geophysical Monograph Series, vol. 159 (American Geophysical Union, Washington, 2005), pp. 1–22
- J. Goldstein, R.W. Spiro, P.H. Reiff, R.A. Wolf, B.R. Sandel, J.W. Freeman, R.L. Lambour, IMF-driven overshielding electric field and the origin of the plasmaspheric shoulder of May 24, 2000. *Geophys. Res. Lett.* **29**(16), 1819 (2002)
- J. Goldstein, B.R. Sandel, M.R. Hairston, P.H. Reiff, Control of plasmaspheric dynamics by both convection and sub-auroral polarization stream. *Geophys. Res. Lett.* **30**(24), 2243 (2003a)

- J. Goldstein, M. Spasojević, P.H. Reiff, B.R. Sandel, W.T. Forrester, D.L. Gallagher, B.W. Reinisch, Identifying the plasmopause in IMAGE EUV data using IMAGE RPI in situ steep density gradients. *J. Geophys. Res.* **108**(A4), 1147 (2003b)
- J. Goldstein, B.R. Sandel, W.T. Forrester, P.H. Reiff, IMF-driven plasmasphere erosion of 10 July 2000. *Geophys. Res. Lett.* **30**(3), 1146 (2003c)
- J. Goldstein, R.W. Spiro, B.R. Sandel, R.A. Wolf, S.Y. Su, P.H. Reiff, Overshielding event of 28–29 July 2000. *Geophys. Res. Lett.* **30**(8), 1421 (2003d)
- J. Goldstein, B.R. Sandel, M.F. Thomsen, M. Spasojević, P.H. Reiff, Simultaneous remote sensing and in situ observations of plasmaspheric drainage plumes. *J. Geophys. Res.* **109**, A03202 (2004)
- J. Goldstein, J.L. Burch, B.R. Sandel, Magnetospheric model of subauroral polarization stream. *J. Geophys. Res.* **110**, A09222 (2005a)
- J. Goldstein, B.R. Sandel, W.T. Forrester, M.F. Thomsen, M.R. Hairston, Global plasmasphere evolution 22–23 April 2001. *J. Geophys. Res.* **110**, A12218 (2005b)
- T.I. Gombosi, C.E. Rasmussen, Transport of gyration-dominated space plasmas of thermal origin 1. Generalized transport equations. *J. Geophys. Res.* **96**(A5), 7759–7778 (1991)
- J.M. Grebowsky, Model study of plasmopause motion. *J. Geophys. Res.* **75**(22), 4329–4333 (1970)
- J.M. Grebowsky, Model development of supersonic trough wind with shocks. *Planet. Space Sci.* **20**(11), 1923–1934 (1972)
- J.M. Grebowsky, A.J. Chen, Effects on the plasmasphere of irregular electric fields. *Planet. Space Sci.* **24**(7), 689–696 (1976)
- K.I. Gringauz, V.V. Bezrukh, V.D. Ozerov, R.E. Rybchinskii, The study of the interplanetary ionized gas, high-energy electrons and corpuscular radiation of the Sun, employing three-electrode charged particle traps on the second Soviet space rocket. *Sov. Phys. Dokl.* **5**, 361–364 (1960). Published again in (1962) in *Planet. Space Sci.* **9**, 103–107
- S.M. Guiter, T.I. Gombosi, The role of high-speed plasma flows in plasmaspheric refilling. *J. Geophys. Res.* **95**(A7), 10427–10440 (1990)
- S.M. Guiter, T.I. Gombosi, C.E. Rasmussen, Two-stream modeling of plasmaspheric refilling. *J. Geophys. Res.* **100**(A6), 9519–9526 (1995)
- M.S. Gussenhoven, D.A. Hardy, W.J. Burke, DMSP/F2 electron observations of equatorward auroral boundaries and their relationship to magnetospheric electric fields. *J. Geophys. Res.* **86**(A2), 768–778 (1981)
- W.B. Hanson, T.N.L. Patterson, Diurnal variation of the hydrogen concentration in the exosphere. *Planet. Space Sci.* **11**(9), 1035–1052 (1963)
- A.E. Hedin, MSIS-86 thermospheric model. *J. Geophys. Res.* **92**(A5), 4649–4662 (1987)
- T.E. Holzer, J.A. Fedder, P.M. Banks, A comparison of kinetic and hydrodynamic models of an expanding ion-exosphere. *J. Geophys. Res.* **76**(A10), 2453–2468 (1971)
- J.L. Horwitz, N. Singh, Refilling of the Earth's plasmasphere. *Eos Trans. AGU* **72**(37), 399–402 (1991)
- J.L. Horwitz, C.R. Baugher, C.R. Chappell, E.G. Shelley, D.T. Young, R.R. Anderson, ISEE 1 observations of thermal plasma in the vicinity of the plasmasphere during periods of quieting magnetic activity. *J. Geophys. Res.* **86**(A12), 9989–10001 (1981)
- J.D. Huba, G. Joyce, J.A. Fedder, Sami2 is another model of the ionosphere (SAMI2): A new low-latitude ionosphere model. *J. Geophys. Res.* **105**(A10), 23035–23053 (2000)
- T. Iijima, T.A. Potemra, The amplitude distribution of field-aligned currents at northern high latitudes observed by Triad. *J. Geophys. Res.* **81**(13), 2165–2174 (1976)
- T.J. Immel, S.B. Mende, H.U. Frey, L.M. Peticolas, C.W. Carlson, J.C. Gérard, B. Hubert, S.A. Fuselier, J.L. Burch, Precipitation of auroral protons in detached arcs. *Geophys. Res. Lett.* **29**(11), 1519 (2002)
- R.K. Jaggi, R.A. Wolf, Self-consistent calculation of the motion of a sheet of ions in the magnetosphere. *J. Geophys. Res.* **78**(16), 2852–2866 (1973)
- V.K. Jordanova, L.M. Kistler, J.U. Kozyra, G.V. Khazanov, A.F. Nagy, Collisional losses of ring current ions. *J. Geophys. Res.* **101**(A1), 111–126 (1996a)
- V.K. Jordanova, J.U. Kozyra, A.F. Nagy, Effects of heavy ions on the quasi-linear diffusion coefficients from resonant interactions with electromagnetic ion cyclotron waves. *J. Geophys. Res.* **101**(A9), 19771–19778 (1996b)
- V.K. Jordanova, J.U. Kozyra, A.F. Nagy, G.V. Khazanov, Kinetic model of the ring current-atmosphere interactions. *J. Geophys. Res.* **102**(A7), 14279–14291 (1997)
- V.K. Jordanova, Y.S. Miyoshi, S. Zaharia, M.F. Thomsen, G.D. Reeves, D.S. Evans, C.G. Mouikis, J.F. Fennell, Kinetic simulations of ring current evolution during the Geospace Environment Modeling challenge events. *J. Geophys. Res.* **111**, A11S10 (2006)
- V.K. Jordanova, M. Spasojevic, M.F. Thomsen, Modeling the electromagnetic ion cyclotron wave-induced formation of detached subauroral proton arcs. *J. Geophys. Res.* **112**, A08209 (2007)
- G.V. Khazanov, M.A. Koyen, Y.V. Konikov, I.M. Sidorov, Simulation of ionosphere-plasmasphere coupling taking into account ion inertia and temperature anisotropy. *Planet. Space Sci.* **32**(5), 585–598 (1984)

- G.A. Kotova, The Earth's plasmasphere: state of studies (a review). *Geomagn. Aeron.* **47**(4), 409–422 (2007)
- G.A. Kotova, V.V. Bezrukhikh, M.I. Verigin, L.A. Lezhen, Temperature and density variations in the dusk and dawn plasmasphere as observed by Interball Tail in 1999–2000. *Adv. Space Res.* **30**(7), 1831–1834 (2002)
- J. Krall, J.D. Huba, J.A. Fedder, Simulation of field-aligned H^+ and He^+ dynamics during late-stage plasmasphere refilling. *Ann. Geophys.* **26**(6), 1507–1516 (2008)
- R.L. Lambour, L.A. Weiss, R.C. Elphic, M.F. Thomsen, Global modeling of the plasmasphere following storm sudden commencements. *J. Geophys. Res.* **102**(A11), 24351–24368 (1997)
- M.J. LeDocq, D.A. Gurnett, R.R. Anderson, Electron number density fluctuations near the plasmopause observed by the CRRES spacecraft. *J. Geophys. Res.* **99**(A12), 23661–23671 (1994)
- J.F. Lemaire, The “Roche-limit” of ionospheric plasma and the formation of the plasmopause. *Planet. Space Sci.* **22**(5), 757–766 (1974)
- J. Lemaire, Rotating ion-exospheres. *Planet. Space Sci.* **24**(10), 975–985 (1976)
- J.F. Lemaire, *Frontiers of the Plasmasphere*. *Aeronomica Acta* **A298** (1985)
- J.F. Lemaire, Plasma distribution models in a rotating magnetic dipole and refilling plasmaspheric flux tubes. *Phys. Fluids B* **1**(7), 1519–1525 (1989)
- J.F. Lemaire, Hydrostatic equilibrium and convective stability in the plasmasphere. *J. Atmos. Sol.-Terr. Phys.* **61**(11), 867–878 (1999)
- J.F. Lemaire, The formation plasmaspheric tails. *Phys. Chem. Earth (C)* **25**, 9–17 (2000)
- J.F. Lemaire, The formation of the light-ion-trough and peeling off the plasmasphere. *J. Atmos. Sol.-Terr. Phys.* **63**(11), 1285–1291 (2001)
- J.F. Lemaire, M. Echim, Kinetic and hydrodynamic models of the solar wind and polar wind. *Eos Trans. AGU* **89**(9), 86 (2008)
- J.F. Lemaire, K.I. Gringauz, *The Earth's Plasmasphere* (Cambridge University Press, New York, 1998), p. 372
- J. Lemaire, V. Pierrard, Kinetic models of solar and polar winds. *Astrophys. Space Sci.* **277**(1–2), 169–180 (2001)
- J.F. Lemaire, V. Pierrard, Comparison between two theoretical mechanisms for the formation of the plasmopause and relevant observations. *Geomagn. Aeron.* **48**(5), 553–570 (2008)
- J.F. Lemaire, R.W. Schunk, Plasmaspheric wind. *J. Atmos. Terr. Phys.* **54**(3–4), 467–477 (1992)
- J.F. Lemaire, R.W. Schunk, Plasmaspheric convection with non-closed streamlines. *J. Atmos. Terr. Phys.* **56**(12), 1629–1633 (1994)
- Ø. Lie-Svendsen, M.H. Rees, An improved kinetic model for the polar outflow of a minor ion. *J. Geophys. Res.* **101**(A2), 2415–2433 (1996)
- M.W. Liemohn, G.V. Khazanov, P.D. Craven, J.U. Kozyra, Nonlinear kinetic modeling of the early stage plasmaspheric refilling. *J. Geophys. Res.* **104**(A5), 10295–10306 (1999)
- M.W. Liemohn, J.U. Kozyra, M.F. Thomsen, J.L. Roeder, G. Lu, J.E. Borovsky, T.E. Cayton, Dominant role of the asymmetric ring current in producing the stormtime Dst*. *J. Geophys. Res.* **106**(A6), 10883–10904 (2001)
- M.W. Liemohn, A.J. Ridley, D.L. Gallagher, D.M. Ober, J.U. Kozyra, Dependence of plasmaspheric morphology on the electric field description during the recovery phase of the 17 April 2002 magnetic storm. *J. Geophys. Res.* **109**, A03209 (2004)
- M.W. Liemohn, A.J. Ridley, P.C. Brandt, D.L. Gallagher, J.U. Kozyra, D.M. Ober, D.G. Mitchell, E.C. Roelof, R. DeMajistre, Parametric analysis of nightside conductance effects on inner magnetospheric dynamics for the 17 April 2002 storm. *J. Geophys. Res.* **110**, A12S22 (2005)
- M.W. Liemohn, A.J. Ridley, J.U. Kozyra, D.L. Gallagher, M.F. Thomsen, M.G. Henderson, M.H. Denton, P.C. Brandt, J. Goldstein, Analyzing electric field morphology through data-model comparisons of the Geospace Environment Modeling Inner Magnetosphere/Storm Assessment Challenge events. *J. Geophys. Res.* **111**, A11S11 (2006)
- J. Lin, J.L. Horwitz, G.R. Wilson, C.W. Ho, D.G. Brown, A semikinetic model for early stage plasmasphere refilling 2, Effects of wave-particle interactions. *J. Geophys. Res.* **97**(A2), 1121–1134 (1992)
- N. Maruyama, A.D. Richmond, T.J. Fuller-Rowell, M.V. Codrescu, S. Sazykin, F.R. Toffoletto, R.W. Spiro, G.H. Millward, Interaction between direct penetration and disturbance dynamo electric fields in the storm-time equatorial ionosphere. *Geophys. Res. Lett.* **32**, L17105 (2005)
- H. Matsui, T. Mukai, S. Ohtani, K. Hayashi, R.C. Elphic, M.F. Thomsen, H. Matsumoto, Cold dense plasma in the outer magnetosphere. *J. Geophys. Res.* **104**(A11), 25077–25095 (1999)
- H. Matsui, M. Nakamura, T. Terasawa, Y. Izaki, T. Mukai, K. Tsuruda, H. Hayakawa, H. Matsumoto, Outflow of cold dense plasma associated with variation of convection in the outer magnetosphere. *J. Atmos. Sol.-Terr. Phys.* **62**(6), 521–526 (2000)
- H. Matsui, J.M. Quinn, R.B. Torbert, V.K. Jordanova, W. Baumjohann, P.A. Puhl-Quinn, G. Paschmann, Electric field measurements in the inner magnetosphere by Cluster EDI. *J. Geophys. Res.* **108**(A9), 1352 (2003)

- N.C. Maynard, A.J. Chen, Isolated cold plasma regions: Observations and their relation to possible production mechanisms. *J. Geophys. Res.* **80**(7), 1009–1013 (1975)
- C.E. McIlwain, A K_p dependent equatorial electric field model. *Adv. Space Res.* **6**(3), 187–197 (1986)
- R.H. Miller, C.E. Rasmussen, T.I. Gombosi, G.V. Khazanov, D. Winske, Kinetic simulation of plasma flows in the inner magnetosphere. *J. Geophys. Res.* **98**(A11), 19301–19313 (1993)
- G.H. Milward, R.J. Moffett, S. Quegan, T.J. Fuller-Rowell, A coupled thermosphere-ionosphere-plasmasphere model (CTIP), in *Solar Terrestrial Energy Program (STEP) Handbook on Ionospheric Models*, ed. by R.W. Schunk (Utah State University, Logan, 1996), pp. 239–279
- D.B. Muldrew, F-layer ionization troughs deduced from Alouette data. *J. Geophys. Res.* **70**(11), 2635–2650 (1965)
- W.A. Newcomb, Convective instability induced by gravity in a plasma with a frozen-in magnetic field. *Phys. Fluids* **4**(4), 391–396 (1961)
- D.M. Ober, J.L. Horwitz, D.L. Gallagher, Formation of density troughs embedded in the outer plasmasphere by subauroral ion drift events. *J. Geophys. Res.* **102**(A7), 14595–14602 (1997)
- G.K. Parks, *Physics of Space Plasmas: An Introduction* (Westview Press, Boulder, 2004), p. 597
- V. Pierrard, New model of magnetospheric current-voltage relationship. *J. Geophys. Res.* **101**(A2), 2669–2675 (1996)
- V. Pierrard, The dynamics of the plasmasphere, in *Space Science: New Research*, ed. by N.S. Maravell (Nova Science, New York, 2006), pp. 83–96
- V. Pierrard, I.A. Barghouthi, Effects of wave-particle interactions on double-hump distributions of the H^+ polar wind. *Astrophys. Space Sci.* **302**(1–4), 35–41 (2006)
- V. Pierrard, J. Cabrera, Comparisons between EUV/IMAGE observations and numerical simulations of the plasmopause formation. *Ann. Geophys.* **23**(7), 2635–2646 (2005)
- V. Pierrard, J. Cabrera, Dynamical simulations of plasmopause deformations. *Space Sci. Rev.* **122**(1–4), 119–126 (2006)
- V. Pierrard, J. Lemaire, Lorentzian ion exosphere model. *J. Geophys. Res.* **101**(A4), 7923–7934 (1996)
- V. Pierrard, J. Lemaire, A collisional kinetic model of the polar wind. *J. Geophys. Res.* **103**(A6), 11701–11709 (1998)
- V. Pierrard, J. Lemaire, Exospheric model of the plasmasphere. *J. Atmos. Sol.-Terr. Phys.* **63**(11), 1261–1265 (2001)
- V. Pierrard, J.F. Lemaire, Development of shoulders and plumes in the frame of the interchange instability mechanism for plasmopause formation. *Geophys. Res. Lett.* **31**, L05809 (2004)
- V. Pierrard, K. Stegen, A three-dimensional dynamic kinetic model of the plasmasphere. *J. Geophys. Res.* **113**, A10209 (2008)
- V. Pierrard, M. Maksimovic, J. Lemaire, Electron velocity distribution functions from the solar wind to the corona. *J. Geophys. Res.* **104**(A8), 17021–17032 (1999)
- V. Pierrard, G.V. Khazanov, J. Cabrera, J. Lemaire, Influence of the convection electric field models on predicted plasmopause positions during magnetic storms. *J. Geophys. Res.* **113**, A08212 (2008)
- J.M. Quinn, G. Paschmann, N. Sckopke, V.K. Jordanova, H. Vaith, O.H. Bauer, W. Baumjohann, W. Fillius, G. Haerendel, S.S. Kerr, C.A. Kletzing, K. Lynch, C.E. McIlwain, R.B. Torbert, E.C. Whipple, EDI convection measurements at 5–6 R_E in the post-midnight region. *Ann. Geophys.* **17**(12), 1503–1512 (1999)
- C.E. Rasmussen, R.W. Schunk, Multistream hydrodynamic modeling of interhemispheric plasma flow. *J. Geophys. Res.* **93**(A12), 14557–14565 (1988)
- C.E. Rasmussen, S.M. Guiter, S.G. Thomas, A two-dimensional model of the plasmasphere: refilling time constants. *Planet. Space Sci.* **41**(1), 35–43 (1993)
- B.W. Reinisch, X. Huang, P. Song, J.L. Green, S.F. Fung, V.M. Vasyliunas, D.L. Gallagher, B.R. Sandel, Plasmaspheric mass loss and refilling as a result of a magnetic storm. *J. Geophys. Res.* **109**, A01202 (2004)
- B.W. Reinisch, M.B. Moldwin, R.E. Denton, D.L. Gallagher, H. Matsui, V. Pierrard, J. Tu, Augmented empirical models of plasmaspheric density and electric field using IMAGE and CLUSTER data. *Space Sci. Rev.* (2008, this issue)
- H. Rème, C. Aoustin, J.M. Bosqued, I. Dandouras, B. Lavraud, J.A. Sauvaud, A. Barthe, J. Bouyssou, Th. Camus, O. Coeur-Joly, A. Cros, J. Cuvelo, F. Ducay, Y. Garbarowitz, J.L. Médale, E. Penou, H. Perrier, D. Romefort, J. Rouzaud, C. Vallat, D. Alcaydé, C. Jacquey, C. Mazelle, C. d’Uston, E. Möbius, L.M. Kistler, K. Crocker, M. Granoff, C. Mouikis, M. Popecki, M. Vosbury, B. Klecker, D. Hovestadt, H. Kucharek, E. Kuenneth, G. Paschmann, M. Scholer, N. Sckopke, E. Seidenschwang, C.W. Carlson, D.W. Curtis, C. Ingraham, R.P. Lin, J.P. McFadden, G.K. Parks, T. Phan, V. Formisano, E. Amata, M.B. Bavassano-Cattaneo, P. Baldetti, R. Bruno, G. Chionchio, A. Di Lellis, M.F. Marcucci, G. Pallochia, A. Korth, P.W. Daly, B. Graeve, H. Rosenbauer, V. Vasyliunas, M. McCarthy, M. Wilber, L. Eliasson, R. Lundin, S. Olsen, E.G. Shelley, S. Fuselier, A.G. Ghielmetti, W. Lennartsson, C.P. Escoubet,

- H. Balsiger, R. Friedel, J.-B. Cao, R.A. Kovrazhkin, I. Papamastorakis, R. Pellat, J. Scudder, B. Sonnerup, First multi-spacecraft ion measurements in and near the Earth's magnetosphere with the identical Cluster Ion Spectrometry (CIS) experiment. *Ann. Geophys.* **19**(10–12), 1303–1354 (2001)
- M.A. Reynolds, D.J. Meléndez-Alvira, G. Ganguli, Equatorial coupling between the plasmasphere and the topside ionosphere. *J. Atmos. Sol.-Terr. Phys.* **63**(11), 1267–1273 (2001)
- M.A. Reynolds, G. Ganguli, Y.J. Su, M.F. Thomsen, The local-time variation of the quiet plasmasphere: geosynchronous observations and kinetic theory. *Ann. Geophys.* **21**(11), 2147–2154 (2003)
- P.G. Richards, D.G. Torr, Thermal coupling of conjugate ionospheres and the tilt of the Earth's magnetic field. *J. Geophys. Res.* **91**(A8), 9017–9021 (1986)
- A.J. Ridley, M.W. Liemohn, A model-derived storm time asymmetric ring current driven electric field description. *J. Geophys. Res.* **107**(A8), 1151 (2002)
- A.J. Ridley, T.I. Gombosi, D.L. DeZeeuw, Ionospheric control of the magnetosphere: conductance. *Ann. Geophys.* **22**(2), 567–584 (2004)
- B.R. Sandel, M.H. Denton, Global view of refilling of the plasmasphere. *Geophys. Res. Lett.* **34**, L17102 (2007)
- B.R. Sandel, A.L. Broadfoot, C.C. Curtis, R.A. King, T.C. Stone, R.H. Hill, J. Chen, O.H.W. Siegmund, R. Raffanti, D.D. Allred, R.S. Turley, D.L. Gallagher, The extreme ultraviolet imager investigation for the IMAGE mission. *Space Sci. Rev.* **91**(1–2), 197–242 (2000)
- S. Sazykin, R.W. Spiro, R.A. Wolf, F.R. Toffoletto, N. Tsyganenko, J. Goldstein, M.R. Hairston, Modeling inner magnetospheric electric fields: Latest self-consistent results, in *The Inner Magnetosphere: Physics and Modeling*, ed. by T.I. Pulkkinen, N.A. Tsyganenko, R.H.W. Friedel. Geophysical Monograph Series, vol. 155 (American Geophysical Union, Washington, 2005), pp. 263–269
- S. Schäfer, K.H. Glassmeier, P.T.I. Eriksson, V. Pierrard, K.H. Fornaçon, L.G. Blomberg, Spatial and temporal characteristics of poloidal waves in the terrestrial plasmasphere: a CLUSTER case study. *Ann. Geophys.* **25**(4), 1011–1024 (2007)
- S. Schäfer, K.H. Glassmeier, P.T.I. Eriksson, P.N. Mager, V. Pierrard, K.H. Fornaçon, L.G. Blomberg, Spatio-temporal structure of a poloidal Alfvén wave detected by Cluster adjacent to the dayside plasmopause. *Ann. Geophys.* **26**(7), 1805–1817 (2008)
- R.W. Schunk, A mathematical model of the middle and high latitude ionosphere. *Pure Appl. Geophys.* **127**(2–3), 255–303 (1988)
- R.W. Schunk, D.S. Watkins, Comparison of solutions to the thirteen-moment and standard transport equations for low speed thermal proton flows. *Planet. Space Sci.* **27**(4), 433–444 (1979)
- R.W. Schunk, D.S. Watkins, Electron temperature anisotropy in the polar wind. *J. Geophys. Res.* **86**(A1), 91–102 (1981)
- R.W. Schunk, L. Scherliess, J.S. Sojka, D.C. Thompson, D.N. Anderson, M. Codrescu, C. Minter, T.J. Fuller-Rowell, R.A. Heelis, M. Hairston, B.M. Howe, Global Assimilation of Ionospheric Measurements (GAIM). *Radio Sci.* **39**(1), RS1S02 (2004)
- N. Singh, Refilling of a plasmaspheric flux tube: Microscopic plasma processes, in *Modeling Magnetospheric Plasma*, ed. by T.E. Moore, J.H. Waite. Geophysical Monograph Series, vol. 44 (American Geophysical Union, Washington, 1988), pp. 87–99
- N. Singh, J.L. Horwitz, Plasmaspheric refilling: Recent observations and modelling. *J. Geophys. Res.* **97**(A2), 1049–1079 (1992)
- N. Singh, R.W. Schunk, H. Thiemann, Temporal features of the refilling of a plasmaspheric flux tube. *J. Geophys. Res.* **91**(A12), 13433–13454 (1986)
- M. Smiddy, M.C. Kelley, W. Burke, F. Rich, R. Sagalyn, B. Shuman, R. Hays, S. Lai, Intense poleward-directed electric fields near the ionospheric projection of the plasmopause. *Geophys. Res. Lett.* **4**(11), 543–546 (1977)
- D.J. Southwood, M.G. Kivelson, Magnetospheric interchange instability. *J. Geophys. Res.* **92**(A1), 109–116 (1987)
- M. Spasojević, J. Goldstein, D.L. Carpenter, U.S. Inan, B.R. Sandel, M.B. Moldwin, B.W. Reinisch, Global response of the plasmasphere to a geomagnetic disturbance. *J. Geophys. Res.* **108**(A9), 1340 (2003)
- M. Spasojević, H.U. Frey, M.F. Thomsen, S.A. Fuselier, S.P. Gary, B.R. Sandel, U.S. Inan, The link between a detached subauroral proton arc and a plasmaspheric plume. *Geophys. Res. Lett.* **31**, L04803 (2004)
- R.W. Spiro, M. Harel, R.A. Wolf, P.H. Reiff, Quantitative simulation of a magnetospheric substorm 3. Plasmaspheric electric fields and evolution of the plasmopause. *J. Geophys. Res.* **86**(A4), 2261–2272 (1981)
- D.P. Stern, The motion of a proton in the equatorial magnetosphere. *J. Geophys. Res.* **80**(4), 595–599 (1975)
- D.F. Strobel, T.R. Young, R.R. Meier, T.P. Coffey, A.W. Ali, The nighttime ionosphere: E region and lower F region. *J. Geophys. Res.* **79**(22), 3171–3178 (1974)
- S.W.Y. Tam, F. Yasseen, T. Chang, S.B. Ganguli, Self-consistent kinetic photoelectron effect on the polar wind. *Geophys. Res. Lett.* **22**(16), 2107–2110 (1995)

- S.W.Y. Tam, T. Chang, V. Pierrard, Kinetic modeling of the polar wind. *J. Atmos. Sol.-Terr. Phys.* **69**(16), 1984–2027 (2007)
- H.A. Taylor Jr., W.J. Walsh, The light-ion trough, the main trough, and the plasmopause. *J. Geophys. Res.* **77**(34), 6716–6723 (1972)
- N.A. Tsyganenko, D.P. Stern, Modeling the global magnetic field of the large-scale Birkeland current systems. *J. Geophys. Res.* **101**(A12), 27187–27198 (1996)
- J.N. Tu, J.L. Horwitz, P. Song, X.Q. Huang, B.W. Reinisch, P.G. Richards, Simulating plasmaspheric field-aligned density profiles measured with IMAGE/RPI: Effects of plasmasphere refilling and ion heating. *J. Geophys. Res.* **108**(A1), 1017 (2003)
- J.N. Tu, J.L. Horwitz, P.A. Nsumei, P. Song, X.Q. Huang, B.W. Reinisch, Simulation of polar cap field-aligned electron density profiles measured with the IMAGE radio plasma imager. *J. Geophys. Res.* **109**, A07206 (2004)
- J. Tu, P. Song, B.W. Reinisch, J.L. Green, Smooth electron density transition from plasmasphere to the sub-auroral region. *J. Geophys. Res.* **112**, A05227 (2007)
- H. Volland, A semiempirical model of large-scale magnetospheric electric fields. *J. Geophys. Res.* **78**(1), 171–180 (1973)
- P.A. Webb, E.A. Essex, A dynamic global model of the plasmasphere. *J. Atmos. Sol.-Terr. Phys.* **66**(12), 1057–1073 (2004)
- D.R. Weimer, A flexible, IMF dependent model of high-latitude electric potentials having “space weather” applications. *Geophys. Res. Lett.* **23**(18), 2549–2552 (1996)
- D.R. Weimer, Substorm influence on the ionosphere electric potentials and currents. *J. Geophys. Res.* **104**(A1), 185–197 (1999)
- D.R. Weimer, An improved model of ionospheric electric potentials including substorm perturbations and application to the geospace environment modeling November 24, 1996, event. *J. Geophys. Res.* **106**(A1), 407–416 (2001)
- L.A. Weiss, R.L. Lambour, R.C. Elphic, M.F. Thomsen, Study of plasmaspheric evolution using geosynchronous observations and global modeling. *Geophys. Res. Lett.* **24**(5), 599–602 (1997)
- G.R. Wilson, J.L. Horwitz, J. Lin, A semikinetic model for early stage plasmasphere refilling 1. Effects of Coulomb collisions. *J. Geophys. Res.* **97**(A2), 1109–1119 (1992)
- G.R. Wilson, J.L. Horwitz, J. Lin, Semikinetic modeling of plasma flow on outer plasmaspheric field lines. *Adv. Space Res.* **13**(4), 107–116 (1993)
- F. Yasseen, J.M. Retterer, T. Chang, J.D. Winningham, Monte-Carlo modeling of polar wind photoelectron distributions with anomalous heat flux. *Geophys. Res. Lett.* **16**(9), 1023–1026 (1989)
- I. Yoshikawa, A. Yamazaki, K. Yamashita, Y. Takizawa, M. Nakamura, Which is a significant contributor for outside of the plasmopause, an ionospheric filling or leakage of plasmaspheric materials?: Comparison of He II (304 Å) images. *J. Geophys. Res.* **108**(A2), 1080 (2003)
- D.T. Young, J. Geiss, H. Balsiger, P. Eberhardt, A. Ghielmetti, H. Rosenbauer, Discovery of He²⁺ and O²⁺ ions of terrestrial origin in the outer magnetosphere. *Geophys. Res. Lett.* **4**(12), 561–564 (1977)

Augmented Empirical Models of Plasmaspheric Density and Electric Field Using IMAGE and CLUSTER Data

Bodo W. Reinisch · Mark B. Moldwin · Richard E. Denton · Dennis L. Gallagher · Hiroshi Matsui · Viviane Pierrard · Jiannan Tu

Originally published in the journal *Space Science Reviews*, Volume 145, Nos 1–2, 231–261.
DOI: [10.1007/s11214-008-9481-6](https://doi.org/10.1007/s11214-008-9481-6) © Springer Science+Business Media B.V. 2009

Abstract Empirical models for the plasma densities in the inner magnetosphere, including plasmasphere and polar magnetosphere, have been in the past derived from in situ measurements. Such empirical models, however, are still in their initial phase compared to magnetospheric magnetic field models. Recent studies using data from CRRES, POLAR, and IMAGE have significantly improved empirical models for inner-magnetospheric plasma and mass densities. Comprehensive electric field models in the magnetosphere have been developed using radar and in situ observations at low altitude orbits. To use these models at high altitudes one needs to rely strongly on the assumption of equipotential magnetic field lines.

B.W. Reinisch (✉) · J. Tu
Department of Environmental, Earth and Atmospheric Sciences, University of Massachusetts-Lowell (UML), 600 Suffolk Street, Lowell, MA 01854, USA
e-mail: bodo_reinisch@uml.edu

J. Tu
e-mail: jiannan_tu@uml.edu

M.B. Moldwin
Institute of Geophysics and Planetary Physics (IGPP), University of California, Los Angeles, CA, USA
e-mail: mmoldwin@igpp.ucla.edu

R.E. Denton
Physics and Astronomy Department, Dartmouth College, Hanover, NH, USA
e-mail: richard.e.denton@dartmouth.edu

D.L. Gallagher
Marshall Space Flight Center (MSFC), NASA, Huntsville, AL, USA
e-mail: dennis.l.gallagher@nasa.gov

H. Matsui
Space Science Center, University of New Hampshire (UNH), Durham, NH, USA
e-mail: hiroshi.matsui@unh.edu

V. Pierrard
Belgian Institute for Space Aeronomy (BIRA-IASB), Brussels, Belgium
e-mail: viviane.pierrard@oma.be

Direct measurements of the electric field by the CLUSTER mission have been used to derive an equatorial electric field model in which reliance on the equipotential assumption is less. In this paper we review the recent progress in developing empirical models of plasma densities and electric fields in the inner magnetosphere with emphasis on the achievements from the IMAGE and CLUSTER missions. Recent results from other satellites are also discussed when they are relevant.

Keywords Inner magnetosphere · Plasmasphere · Empirical models · Plasma density · Electric field · CLUSTER · IMAGE

1 Introduction

Empirical models of plasma density and fields (electric and magnetic fields) play important roles in space plasma studies and space weather prediction. They provide convenient ways to represent the plasma environment around the Earth. Empirical models are important for developing physics-based numeric models as well, since they provide baseline predictions against which to measure their performance (Siscoe et al. 2004) and against which plasma density variations can be evaluated, particularly during magnetic storms (e.g., Reinisch et al. 2004; Tu et al. 2007; Osherovich et al. 2007).

Empirical models of thermal plasma densities in the inner magnetosphere have been developed over many decades. The first efforts were based on the pioneering work by Storey (1953) using ground whistler observations. Using these remote observations, we learned about the existence of the plasmopause and its responses to changing geomagnetic conditions (Pope 1961; Smith 1961; Carpenter 1963; Carpenter and Lemaire 1997; Lemaire and Gringauz 1998; Carpenter 2004). Subsequently, empirical models of the plasmopause position have been derived from in situ measurements such as by the IMP-2, ISEE-1, DE-1, and CRRES satellites (e.g., Binsack 1967; Horwitz et al. 1990; Carpenter and Anderson 1992; Moldwin et al. 2002; O'Brien and Moldwin 2003). Plasmaspheric density models have also been obtained from in situ observations (e.g., Carpenter and Anderson 1992; Gallagher et al. 1998, 2000; Sheeley et al. 2001). Similarly, there have been efforts to develop empirical plasma density models in the magnetospheric polar cap. Based on data from the above mentioned and other satellites Persoon et al. (1983) and Gallagher et al. (2000) developed polar cap density models in which density is shown to vary statistically as a power law with radial distance. The studies of Johnson et al. (2001, 2003) revealed the effects of the solar zenith angle on the plasma density at altitudes up to $4.5 R_E$.

The first model of the magnetospheric electric field was the semi-empirical model of Volland (1973). A similar model was also devised by Stern (1975). Maynard and Chen (1975) then introduced K_p dependence into the Volland-Stern model. Later on more sophisticated models of the electric field were developed based on parameters describing the various geophysical, geomagnetic, solar wind and interplanetary magnetic field (IMF) effects and based on radar or satellite observations (e.g., Heppner 1977; Volland 1978; Heelis et al. 1982; Feldstein et al. 1984; Sojka et al. 1986; Heppner and Maynard 1987; Holt et al. 1987; Papitashvili et al. 1994; Matsui et al. 2004; Ruohoniemi and Greenwald 2005; Weimer 2005).

In this paper, we review advances in the development of empirical models of plasma density and electric field in the inner magnetosphere resulting from the CLUSTER and Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) missions. The results from other missions will be also discussed when they are relevant. The Extreme UltraViolet (EUV)

and Radio Plasma Imager (RPI) instruments on the IMAGE satellite (Burch 2000, 2003) provided the first ever ability to remotely image plasma density structures throughout the inner magnetosphere. The four-satellite constellation of the CLUSTER mission has provided multi-point in situ measurements of plasma density, electric field, and other plasma parameters (Escoubet et al. 1997). The unique measurement techniques of these missions have greatly enhanced our ability to develop empirical models of plasma density and electric field in the plasmasphere or more generally in the inner magnetosphere. More details about the missions are available elsewhere in this issue (De Keyser et al. 2008).

The plasma and field models discussed herein are for the inner magnetosphere. For the purposes of this discussion, the inner magnetosphere extends from above the ionosphere to inside the magnetopause. At low to intermediate latitudes that includes the plasmasphere, the plasmopause, the magnetospheric trough and the plasmaspheric (erosion) plume. At higher latitudes the magnetospheric trough extends into the auroral zone and higher still there is the polar cap, which completes those regions included here as part of the inner magnetosphere.

2 Empirical Equatorial Density Models

The plasmasphere has been studied using low frequency plasma waves from the ground (Carpenter 1966; Park et al. 1978; Clilverd et al. 1991; Loto'aniu et al. 1999; Carpenter 2004) and using spacecraft in many different orbits (polar, geosynchronous, and near-equatorial elliptical) and with a variety of instruments (plasma wave instruments, plasma analyzers, spacecraft potential probes and most recently with imagers and radio sounding) (e.g., Gringauz 1963; Chappell et al. 1971; Décr  au et al. 1982; Horwitz et al. 1986; Carpenter and Anderson 1992; Moldwin et al. 1994; Reinisch et al. 2001a; Sandel et al. 2001; Sheeley et al. 2001). Throughout the years there has been a shared interest in developing empirical models of equatorial thermal plasma distributions as a means of summarizing observed plasma behavior in the inner magnetosphere and to facilitate studies of plasma waves and energetic particle dynamics, which depend on plasmaspheric plasma distributions. The advent of global plasmaspheric imaging with EUV and RPI onboard IMAGE has energized a renewed interest in the development of empirical models both directly through their measurements and in concert with other in situ instrumentation and ground ultra low frequency (ULF) wave observations. While much can yet be accomplished with the IMAGE observations and continued CLUSTER multi-spacecraft in situ measurements, the early studies in this new era are showing the way ahead.

Larsen et al. (2007) have mapped EUV observations into the solar magnetic equatorial plane and correlated the automatically derived plasmopause L -value with solar wind conditions provided by the ACE mission. The direct correlation to the solar wind provides a new look at the state of the plasmasphere as a function of the primary driver of erosion rather than through indirect measures given by geomagnetic indices. The southward component of the IMF B_z , and a magnetic merging proxy, ϕ were most highly correlated with plasmopause location (L_{pp}). The most significant correlation was obtained for separately delayed B_z and ϕ as given in the expression

$$L_{pp} = 0.0374B_{z,155} - 1.05 \times 10^{-4}\phi_{275} + 4.38, \quad (1)$$

where the numerical subscripts refer to the corresponding best fit delays in minutes. The merging proxy is defined by

$$\phi = vB \sin^2(\theta/2), \quad (2)$$

where v is the solar wind speed, B is the total IMF strength, and θ is the solar wind clock angle. A single plasmopause location was obtained from each of the 1356 EUV images used in the correlation analysis. Each plasmopause L -shell location is the average of all plasmopause locations derived from a given EUV image. The delay times (155 min for B_z and 275 min for ϕ) well exceed average propagation time from ACE to the magnetosphere. The predictive capability of the plasmopause location is thus achieved a few hours in advance. The delay time for IMF B_z could reflect the response time of the plasmopause location to the convection after B_z changes. The delay for ϕ longer than B_z is similar to the time scale of the ionospheric shielding indicating a possible relation between shielding and plasmopause motion. Larsen et al. (2007) offers that future work will differentiate the plasmopause location for varying magnetic local time (MLT) as a function of solar wind conditions.

In the course of examining the variation of electron density along magnetic field lines in the plasmasphere and in the magnetospheric trough, Reinisch et al. (2004) and Tu et al. (2006) developed empirical event models using RPI radio sounding data. In both studies, a density profile of L^{-4} in the magnetic equatorial plane reasonably describes the density distribution over the L -shell range of observations ($1.6 < L < 7$) in both the plasmasphere and trough. This radial trough profile agrees with that derived by Sheeley et al. (2001) (where $n_{eq} \propto L^{-4}$), which is more steep than that in Denton et al. (2004) (where $n_{eq} \propto \bar{R}_{max}^{-3.45}$, $\bar{R}_{max} = LR_E$ for a dipole field), but is less steep than that obtained by Carpenter and Anderson (1992) (where $n_{eq} \propto L^{-4.5}$). In contrast, this profile is steeper than that found by Carpenter and Anderson (1992) (where $n_{eq} \propto 10^{-0.3145L}$) in the plasmasphere. Tu et al. (2006) parameterized their plasmasphere and trough models using expressions similar to those used by Huang et al. (2004). Tu et al. (2006) suggested that the functional form used in their study might be of potential for developing a global plasmasphere and trough empirical model that describes both the equatorial plasma distribution and the field-aligned distribution above the topside ionosphere.

Denton et al. (2006a) also demonstrated an approach for developing an event-based empirical plasmaspheric model, except in this case using multiple data sets. They used EUV images to obtain an equatorial plasma distribution, RPI for in situ electron densities, and ground magnetometer field line resonant measurements to obtain mass densities. Functions for L -shell and MLT dependent density distributions were obtained for the inner and outer plasmasphere, for the plasmaspheric plume, for the magnetospheric trough, and for the plasmopause. A mass density model in the inner plasmasphere, outer plasmasphere, and trough was developed and used with the Denton et al. (2002b) field line dependence model. These works clearly illustrate the complexity of accurately representing thermal plasma distributions at any given time.

Berube et al. (2005) have developed the first plasmaspheric, equatorial mass density model using ground-based ULF wave measurements. RPI in situ electron densities derived from natural radio noise resonances and cut-offs were also used to develop an electron density model that when combined with the mass density model was used to infer average ion mass and composition. The electron density model was created using the results of Fung et al. (2001). Equatorial, plasmaspheric electron number densities, n_{eq} , averaged for all RPI derived values independent of geomagnetic activity were represented by the function

$$n_{eq}(L) = 10^{-0.66L+4.89}. \quad (3)$$

A similar functional form was used to fit ULF derived mass densities, ρ_{eq} . The solution for all conditions was

$$\rho_{eq}(L) = 10^{-0.67L+5.1}. \quad (4)$$

Average ion mass was derived as a function of L -shell for quiet and active conditions. Quiet time ion mass is consistent with the He^+/H^+ mass ratio derived by Craven et al. (1997) based on DE-1 measurements. Significantly enhanced O^+ concentrations are inferred for the outer plasmasphere during disturbed times.

3 Field-Aligned Density Distributions for Plasmasphere and Plasma Trough

3.1 Field Line Dependence of Electron Density from in Situ Data

The average field line dependence of electron density has been studied using in situ measurements of electron density based on passive plasma wave data observed by polar orbiting spacecraft. The electron density values are determined either from the upper hybrid noise band (e.g., Benson et al. 2004) or the lower edge of the continuum radiation (e.g., LeDocq et al. 1994). The average field line dependence can be determined from an average of the electron density in latitudinal bins (Denton et al. 2002b). However, a less noisy result is found by assuming that the density values found at low and high latitude crossings of a particular L shell represent the density variation of a single flux tube. This is not exactly correct because the crossings of the same L shell are at different MLT and universal time (UT). In order to reduce the possibility of error, only orbits with smooth variations in electron density are used and the results are averaged over many crossings.

In studies based on data from the POLAR spacecraft (Denton et al. 2002a, 2002b, 2004), a power law dependence was assumed with respect to the geocentric radius,

$$n_e = n_{e0}(LR_E/R)^p, \quad (5)$$

where R is the geocentric radius, n_{e0} is the equatorial electron density and p the power law coefficient. For a dipole magnetic field, this form becomes $n_e = n_{e0}(\cos \lambda)^{-2p}$, where λ is the magnetic latitude MLAT. This equation is similar to the form used by Reinisch et al. (2004) and Huang et al. (2004) to model results from RPI active sounding

$$n_e = n_{e0}(\cos[(\pi/2)(\alpha\lambda/\lambda_{\text{inv}})])^{-\beta}, \quad (6)$$

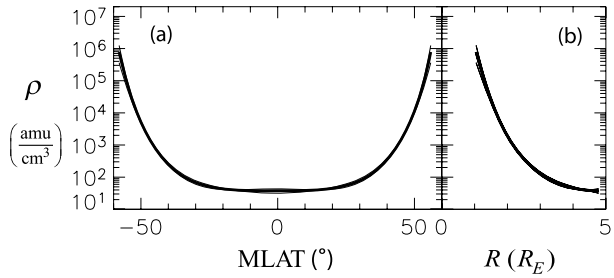
where λ_{inv} is the invariant latitude along the field line of the L -shell. The RPI active sounding results are effective down to an altitude of about 2000 km. Equation (5) is equivalent (for a dipole magnetic field) to (6) if $\beta = 2p$ and $\alpha = \lambda_{\text{inv}}/(\pi/2)$. Denton et al. (2002a, 2004, 2006b) found that the power law coefficient p of (5) was on average 2–3 in the trough and 0–1 in the plasmasphere. In a comparison to results from RPI active sounding, Denton et al. (2002a) showed that in the plasmasphere, the upper value $p = 1$ was more accurate.

While this method has been used predominantly for POLAR data, it can also be used with in situ electron density measurements observed by IMAGE or CLUSTER. A database of electron density measurements from passive plasma wave data observed by IMAGE has recently been created (Webb et al. 2007), partly for the purpose of doing such a study.

3.2 Field Line Dependence of Mass Density Based on Spacecraft Observations of Alfvén Frequencies

Magnetospheric magnetic field lines oscillate azimuthally much like a guitar string; this oscillation has quantized (harmonic) frequencies because of the boundary condition that the field lines are “line tied” at the ionospheric boundary. Because Alfvén wave harmonics have

Fig. 1 Mass density ρ versus magnetic latitude MLAT (*left*) and geocentric radius R (*right*) based on solutions for ρ found from Alfvén wave frequencies observed on 28 October 2002. (Adapted from Denton et al. 2009)



differing field line structure, they respond differently to mass-density depending on its field line distribution. For instance, the fundamental mode, with an antinode in the electric field perturbation (radial) and velocity perturbation (azimuthal) at the equator, is slowed down by a concentration of mass density at the magnetic equator, while the second harmonic, with a node for these quantities at the magnetic equator, is not. Thus the ratios of the harmonic frequencies can be used to infer the field line distribution of mass density, determining for instance, the p value for the power law density (5) (Denton 2006).

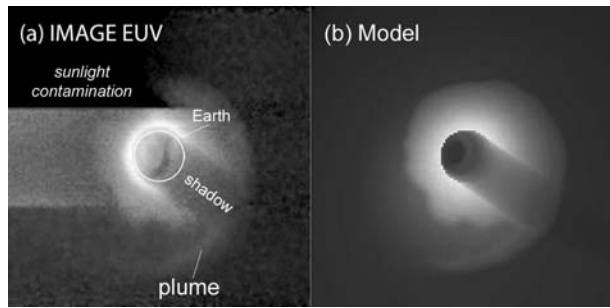
Calculations based on observations by the CRRES and GOES spacecraft indicated that a power law field line variation with $p = 2$ does a good job of modeling the average field line dependence of mass density (at high altitudes above at least $1 R_E$) for $L = 4 - 5$, $p = 1$ is best for $L = 5 - 6$, and at larger L shells there may be an equatorial peak in mass density (nonmonotonic variation between the magnetic equator and the ionosphere) that is largest in the afternoon local time sector at geomagnetically active times (Takahashi et al. 2004; Denton et al. 2002b; Denton 2006). There is evidence from ground-based observations that a larger value of p might be applicable to lower L shells where ionospheric mass loading has a larger effect (Menk et al. 1999; Price et al. 1999; Denton 2006).

Recently, Denton et al. (2009) were able to measure with unprecedented precision the Alfvén wave frequencies of eight harmonics observed by the CLUSTER 1 spacecraft at perigee ($L = 4.8$). Using a polynomial expansion for the field line dependence as a function of a coordinate related to λ , they inferred the field line dependence for mass density shown in Fig. 1. The field line dependence is very flat ($p \approx 1$) out to $|\lambda| = 30^\circ$, but increases steeply as $|\lambda|$ increases. As Denton et al. (2009) showed, the large mass density inferred at low altitude (large $|\lambda|$) is consistent with values from the International Reference Ionosphere (IRI) model (Bilitza 2001). Because the inferred mass density is so large near the ionosphere, the portion of the field line near the ionosphere makes a difference in the Alfvén wave frequency. That is, the Alfvén wave frequency is not merely dependent on the mass density in the equatorial region of the field line.

3.3 Event-Driven Density Model

Denton et al. (2006a) constructed an event-driven model of magnetospheric density for 29 August 2000 using data from IMAGE and ground magnetometers. A map of the plasmapause position was determined from a two-dimensional image of the plasmasphere taken by the EUV instrument on IMAGE using the method of Goldstein et al. (2003). The radial dependence of the electron density in the plasmasphere was determined from in situ electron density measurements from the passive radio wave emissions observed by the IMAGE RPI instrument (Benson et al. 2004). The MLT dependence of the plasmaspheric density was determined from the inferred “pseudodensity” found by inverting the EUV emissions

Fig. 2 **a** IMAGE EUV image of resonantly scattered solar EUV photons (30.4 nm) at 29 August 2000 at 15:19 UT. **b** Simulated EUV image using the model for electron density developed in Denton et al. (2006a). (Adapted from Denton et al. 2006a)



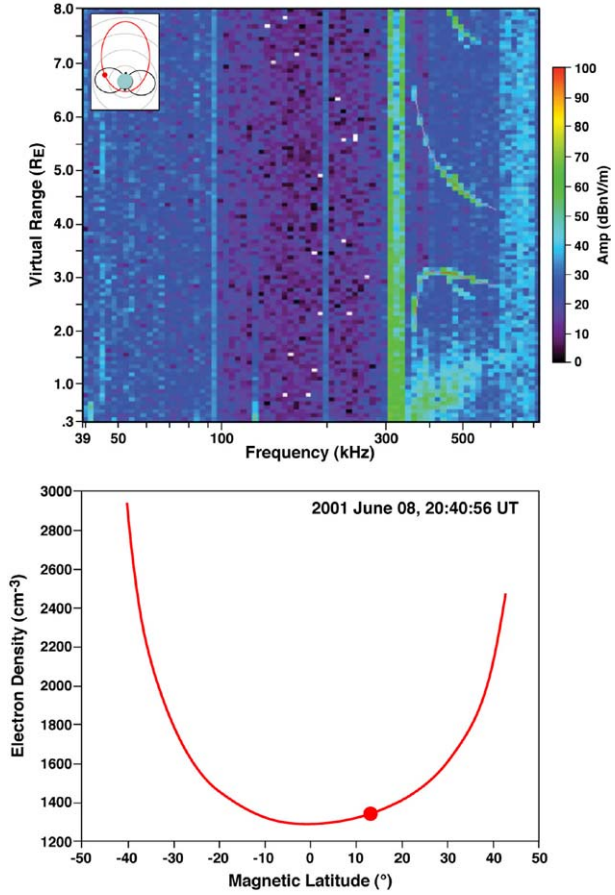
(Gallagher et al. 2005). (In principle, one could use such a pseudodensity to get all the information about the distribution; but in practice, it is better to use all the information available, including the in situ data.) The radial dependence of the density outside the plasmopause in the afternoon local time sector was determined from the inferred mass density based on toroidal Alfvén wave frequencies observed by ground magnetometers (Waters et al. 2006). The field line dependence model of Denton et al. (2002b) was used to extend the equatorial density into a three dimensional distribution and the Gallagher et al. (2000) model was used in the polar cap. Figure 2 shows (a) the EUV image, and (b) a simulated EUV image using the model.

3.4 Field-Aligned Dependence from IMAGE RPI Measurements

RPI onboard IMAGE used the radio sounding technique to remotely measure the electron density in the magnetosphere (Reinisch et al. 2000). The instrument, in active sounding modes, transmitted coded signals with frequencies sweeping from 3 kHz to 3 MHz and listened to the echoes. The received signals are plotted in the form of the plasmagram, a color-coded display of signal amplitude as function of frequency and echo delay time (Galkin et al. 2004). Echoes that experienced the same dispersion during the propagation form a distinct trace in the plasmagram. Under certain conditions (see Reinisch et al. 2001b; Fung et al. 2003; Green and Reinisch 2003; Fung and Green 2005), the echo traces represent the reflected signals that propagated along a magnetic field line threading the satellite. By scaling the traces in a plasmagram and using a new density inversion algorithm, which is based on the ionospheric density inversion technique of Huang and Reinisch (1982), an almost instantaneous (in less than 1 minute) density distribution can be derived along a field line from a single plasmagram. This new algorithm has been discussed in detail in a number of previous publications (Reinisch et al. 2001a, 2001b; Huang et al. 2004; Song et al. 2004). Figure 3 displays, as an example, a plasmagram obtained by RPI in the plasmasphere showing multiple traces (top panel) and the field-aligned electron density profile (bottom panel) derived from the traces shown in the plasmagram. Such true field-aligned density profiles are available only after the launch of the IMAGE satellite. Those electron density distributions provide the most accurate representation of the field-line dependence of the electron density because the multiple point (20 to over 100) measurements were made almost instantaneously (≤ 1 minute) along the individual field lines by RPI (Huang et al. 2004; Reinisch et al. 2001a, 2001b, 2004; Song et al. 2004).

RPI recorded over one million plasmagrams in the plasmasphere, trough, and polar cap. The density inversion technique has been applied to process plasmagrams with echo traces of good quality. The sequence of field-aligned density profiles obtained during one satellite pass allows the construction of the 2-dimensional (2-D) electron density distribution in the

Fig. 3 (Top) Plasmagram recorded inside the plasmasphere displaying the echo amplitude as function of frequency and virtual range. The insert shows the orbit (red line) and location (red square) of IMAGE at the time of the sounding. The field lines of $L = 4$ are shown in black lines. (Bottom) The density profile, as function of magnetic latitude, inverted from the plasmagram shown in top panel. (Adapted from Huang et al. 2004)



plane containing the field lines and the orbit. Figure 4 shows such 2-D distributions projected onto the solar magnetic (SM) X_{SM} – Z_{SM} plane. These density images span the regions of the polar cap, cusp/dayside auroral oval, trough, and the plasmasphere.

With such 2-D density distributions it is possible to construct an empirical model showing the global density distribution in the near-Earth magnetosphere. Huang et al. (2004) has demonstrated, as the first step, the possibility to derive a 2-D plasmaspheric density model. Huang et al. (2004) used seven consecutive density profiles inverted from the RPI sounding measurements, when IMAGE passed through the plasmasphere from $L = 3.23$ to $L = 2.22$ on the morning side on 8 June 2001. Figure 5 displays those field-aligned density profiles. Huang et al. (2004) demonstrated that those density profiles can be well represented by a single functional form as given by

$$\begin{aligned}
 n_e(L, \lambda) &= n_{e0}(L) \left(1 + \gamma \frac{\lambda}{\lambda_{\text{inv}}} \right) \sec^{\beta(L)} \left(\frac{\pi}{2} \frac{\alpha \lambda}{\lambda_{\text{inv}}} \right), \\
 n_{e0}(L) &= A(B/L - 1), \\
 \beta(L) &= C + D \cdot L,
 \end{aligned} \tag{7}$$

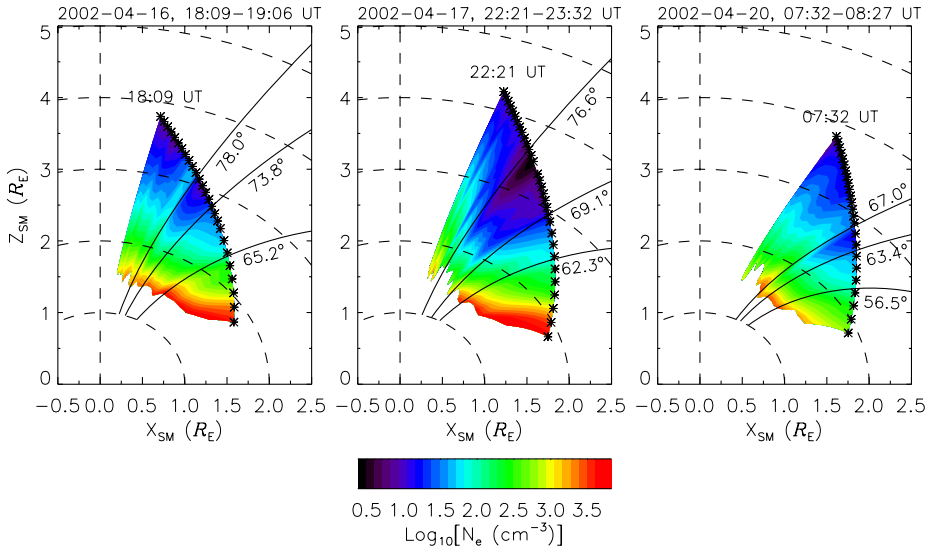


Fig. 4 Two-dimensional (2-D) electron density (n_e) images projected onto the solar magnetic (SM) X_{SM} - Z_{SM} plane. The 2-D images are derived from the field-aligned density profiles measured by RPI from 18:09 to 19:06 UT on 16 April 2002, 22:21 to 23:32 UT on 17 April 2002, and 07:32 to 08:27 UT on 20 April 2002, respectively. The stars on each orbit segment indicate the locations from which the field-aligned density profiles were measured. Also plotted are three field lines (solid) with the corrected geomagnetic coordinate (CGM) latitude labeled. The field line of lowest latitude indicates the plasmapause, while the other two field lines delimit the density depletion region in each panel. (Adapted from Tu et al. 2005b)

where $n_{e0}(L)$ is the equatorial density, γ describes the asymmetry of the north-south distribution around the equator with $\gamma < 0$ ($\gamma > 0$) corresponding to higher density in the southern (northern) hemisphere than at conjugate points in the northern (southern) hemisphere, the power index $\beta(L)$ defines the steepness of the profile at high latitudes, and α specifies the flatness of the profile at low latitudes. The A , B , C , D , γ , and α are fitting parameters. Their values are determined by applying a multi-variant least square fit of (7) to the multiple density profiles. The multi-variant least square fit requires that the square sum of the difference between the measured and modeled electron densities is minimized with respect to six common fitting parameters if using (7), or five fitting parameters if using the functional form modified by Tu et al. (2006) (see (10))

$$\Delta = \sum_i \sum_j [n_{ij}^* - n_{ij}]^2 = \min, \quad (8)$$

where i and j represent the i th field line and the j th point on the i th field line, respectively, and n_{ij}^* and n_{ij} are the measured and modeled electron density, respectively. For the morning sector case on 8 June 2001 shown in Fig. 5, $A = 4833 \text{ cm}^{-3}$, $B = 3.64$, $C = 0.2$, $D = 0.03$, $\gamma = -0.14$, and $\alpha = 1.25$. The fitted density profiles are superimposed on the measured density profiles in Fig. 5 as red dashed lines. With the values of the fitting parameters specified, a 2-D plasmasphere density image can be determined from (7) as shown in Fig. 6. It should be pointed out that the equatorial densities shown as measured in Fig. 5 are in fact generally interpolations from observations. RPI soundings only return echoes from regions with densities higher than that at the spacecraft location. Off-equatorial spacecraft passage through a given L -shell therefore results in a gap in remotely observable electron

Fig. 5 Density profiles on 8 June 2001. The *solid black lines* are inverted from measurements, and the *red dashed lines* are the empirical model. (Adapted from Huang et al. 2004)

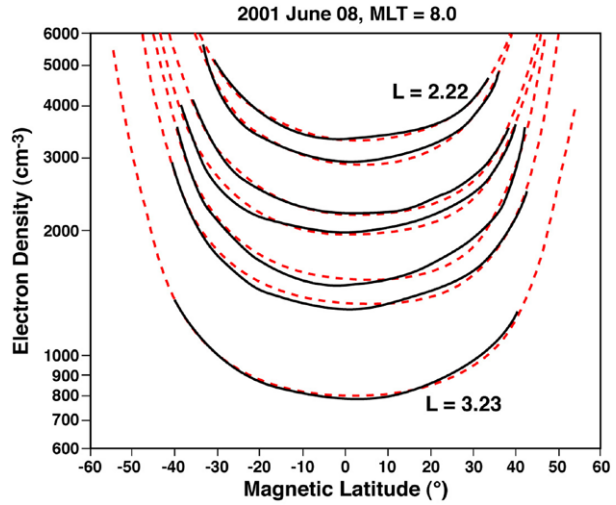
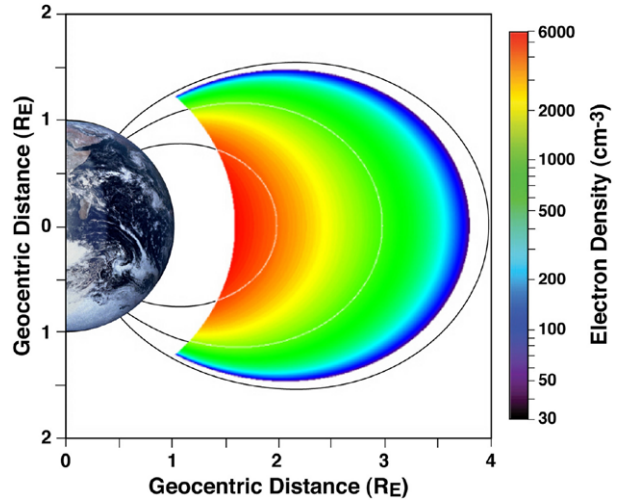


Fig. 6 Empirical model for the 8 June 2001 event at MLT = 8 hours. (Adapted from Huang et al. 2004)



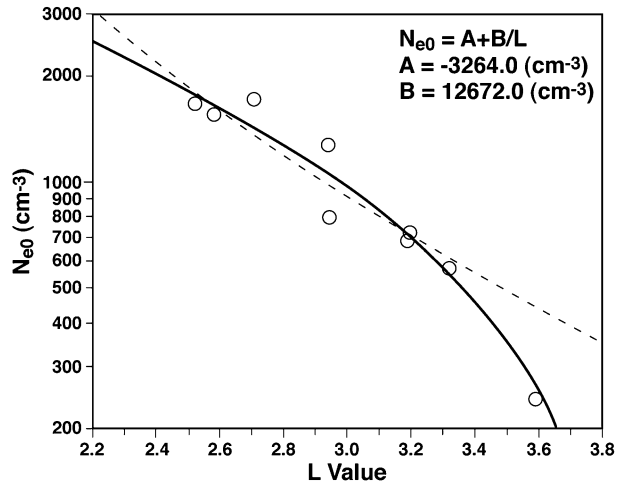
densities at lower magnetic latitudes. Echoes are returned to the spacecraft from both sides of this low latitude region, enabling the direct derivation of densities at higher latitudes in both hemispheres.

In a study of plasmasphere depleting and refilling, Reinisch et al. (2004) applied a similar technique to fit the multiple density profiles obtained by RPI in the noon sector before a great magnetic storm on 31 March–2 April 2001. From the best fit to nine density profiles, the equatorial electron density as a function of L is derived as

$$n_{e0}(L) = 3264(3.88/L - 1). \quad (9)$$

The plasmapause is inferred to be within but near $L = 3.88$ where the model (9) predicts the plasma density to be zero. This function for the equatorial density is plotted as a solid line in Fig. 7. The dashed line depicts the L^{-4} dependence expected for total electron density conservation as flux tubes move radially. Either fit is appropriate in the range from $L = 2.5$

Fig. 7 The equatorial plasma density as a function of L -value from the measurements near 12:00 MLT (*open circles*) before the storm event. The *solid line* shows the best fit hyperbolic function. The *dashed line* is the best fit L^{-4} function as predicted by the conservation of magnetic volume. (Adapted from Reinisch et al. 2004)

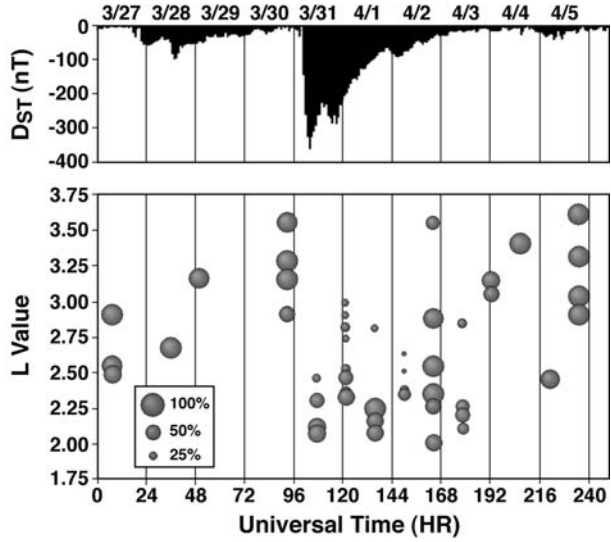


to 3.4, however a significant difference occurs at larger L value between the L^{-4} function and the measured equatorial density.

The modeled equatorial densities (quiet time values) were then used as the reference to assess the plasmasphere depletion and refilling during the course of the magnetic storm. The top panel of Fig. 8 shows the progress of the storm in Dst . The storm started near 06:00 UT, on 31 March 2001 (102 hours in Fig. 8 that starts at 00:00 UT on 27 March 2001), and lasted for about 30 hours. The positions of the “spheres” in the lower panel of Fig. 8 show the L -values and times when the measurements were made. Each column of spheres in the lower panel corresponds to an orbital pass, which occurs every 14.2 hours. To examine the time evolution of the plasma density, the filling ratio is defined as the ratio of the measured equatorial density to the quiet time value calculated from (9) at the same L -value. The size of the sphere in the lower panel of Fig. 8 is proportional to this filling ratio as shown in the legend. Depletion was observed during the storm in the region where $L \geq 2.2$, indicating that the plasmapause moves from $L \geq 3.6$ before the storm to $L \approx 2.2$ during the storm, as shown in lower panel of Fig. 8 after 102 hours. There is apparent refilling of the flux tubes with $L \leq 3$ observed at 20:30 UT on 2 April 2001, which was most likely due to corotating spatial structures (plasmaspheric plume) as suggested by correlating the global images of the plasmasphere from the IMAGE EUV with the RPI observations in the noon sector (Reinisch et al. 2004). The refilling start time cannot be accurately determined because of the 14.2-hour orbit period of the IMAGE spacecraft. However, from the still depleted flux tubes observed at 11:30 UT on 3 April and completely refilled flux tubes at 18:00 UT on 4 April 2001, the refilling time scale is estimated to be less than 31 hours, which is much shorter than that predicted by the theories at those L values (e.g., Singh and Horwitz 1992, and references therein).

Tu et al. (2006) extended this technique to model the RPI density profiles acquired near 00:00 MLT for both plasmasphere and trough. In the study of Tu et al. (2006) the parameter α in (7) is L -value dependent, while the north-south asymmetry of the density profiles is ignored ($\gamma = 0$). The L dependence of α is to account for the different slopes of the profiles in the inner plasmasphere, outer plasmasphere and trough. The modified functional form (based on Tu et al. 2006, (1)) is written as

Fig. 8 Time history of the *Dst* index (*top*), and the filling ratio as function of *L* value and time (*bottom*). The size (area) of the circles in the *bottom panel* is proportional to the filling ratio. The filling ratio is defined as the measured equatorial density normalized by its quiet time value. (Adapted from Reinisch et al. 2004)



$$n_e(L, \lambda) = n_{e0}(L) \sec^{\beta(L)} \left(\frac{\pi}{2} \frac{\alpha(L)\lambda}{\lambda_{inv}} \right),$$

$$\alpha(L) = A + B \cdot L,$$

$$\beta(L) = C + D \cdot L,$$
(10)

where the equatorial density $n_{e0}(L)$ cannot be obtained from the observed density profiles, particularly those in the outer plasmasphere or trough, because they cover only one hemisphere (either northern or southern). $n_{e0}(L)$ is a fitting parameter as are the A , B , C , and D . Three IMAGE passes near the midnight plasmasphere/trough were selected. Along each pass multiple density profiles were inverted from the RPI sounding measurements. The multivariate least square fitting was then applied to the density profiles for each pass using (10).

Shown in Fig. 9 are the observed (solid lines) and fitted (dashed lines) density profiles for three passes corresponding to a storm recovery phase, a prolonged quiet period, and a storm sudden commencement, respectively, from left to right. It is seen from Fig. 9 that in each pass the density profiles along the filled (in the inner plasmasphere) and the depleted (in the outer plasmasphere or trough) flux tubes can be well modeled with the above functional form (the relative error between the modeled and observed densities is $<6\%$). In each panel of Fig. 9 different sets of the values for the fitting parameters, A , B , C , and D , have been used for filled and depleted flux tubes in order to get good fits for two groups of density profiles (Tu et al. 2006). For the three passes examined, the fitting parameter values are not sensitive to the geomagnetic activity for the inner plasmasphere density profiles but vary slightly for the trough density profiles from case to case. The cases examined suggest that there are two different field line dependences of the field-aligned density profiles in the inner filled plasmasphere and trough or depleted outer plasmasphere with steeper density slopes in the latter region.

The equatorial densities $n_{e0}(L)$ from the best fits to the measured density profiles in each case are the extrapolation of the density profiles to the equator, where there were no RPI observations for the three cases. Figure 10 displays the extrapolated equatorial density as a function of L for three cases shown in Fig. 9. The extrapolated equatorial density in the

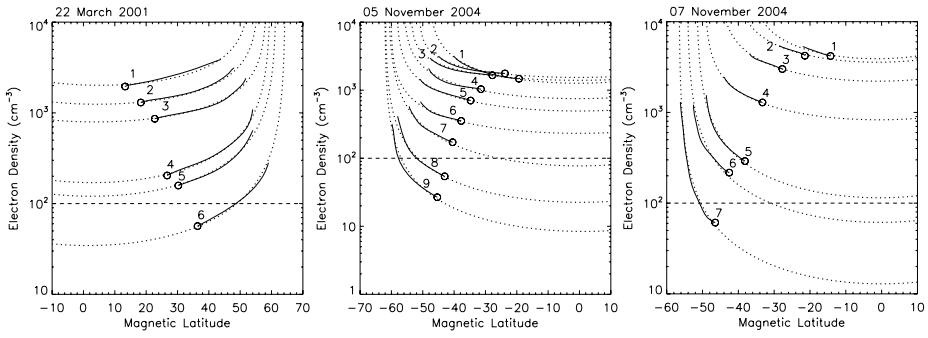


Fig. 9 Field-aligned electron density profiles derived from the RPI sounding measurements made from 01:19–01:43 UT on 22 March 2001 (*left panel*); from 05:33–05:57 UT on 4 November 2004 (*middle panel*); from 14:17–14:35 UT on 7 November 2004 (*right panel*). The *circle* on each profile indicates the satellite location. The profile number is labeled beside each profile. The *dotted lines* are the multi-variant least square fits to the measured density profiles using (7). The *horizontal line* on each panel represents density level of 100 cm^{-3} . (Adapted from Tu et al. 2006)

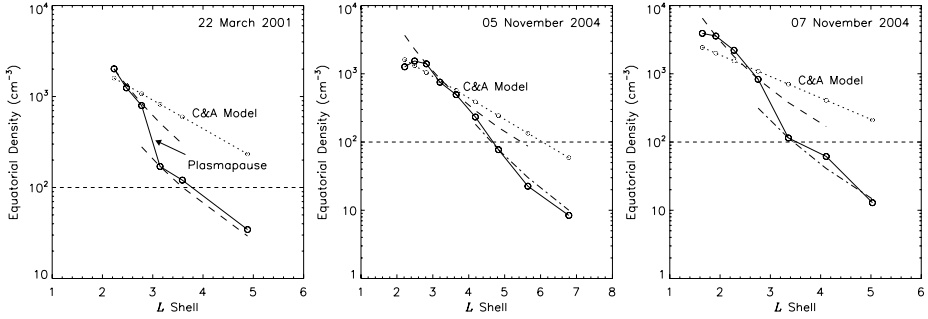


Fig. 10 Equatorial density (*solid line with open circles*) extrapolated from the multi-variant least square fits to the measured density profiles for the 22 March 2001 case (*left panel*), the 5 November 2004 case (*middle panel*), and the 7 November 2004 case (*right panel*). In all panels, the *dashed line* corresponds to a L^{-4} dependence of the equatorial density, while the *dotted line with filled circles* is the filled plasmasphere equatorial density from the Carpenter and Anderson (1992) model. The *dashed-dotted line* in the *middle (right) panel* corresponds to a L^{-6} ($L^{-5.1}$) dependence of the equatorial density. The *horizontal line* on each panel represents density level of 100 cm^{-3} . (Adapted from Tu et al. 2006)

filled flux tubes (in the inner plasmasphere) decreases as L^{-4} (except for the complicated density structure in the 5 November 2004 case), faster than that predicated by the empirical model of Carpenter and Anderson (1992) but consistent with that in the observations of Reinisch et al. (2004). The plasma trough equatorial density (lower three profiles in Fig. 9 for the 22 March 2001 case) also varies with L^{-4} , slightly slower than that predicted by Carpenter and Anderson model ($n_{e0} \propto L^{-4.5}$) but the same as that in the model of Sheeley et al. (2001) and in the observations of Denton et al. (2004). The extrapolated equatorial density of the depleted flux tubes in the outer plasmasphere (lower three profiles in Fig. 9 for the other two days), however, decreases with L much faster, approximately $\propto L^{-\gamma}$ with $\gamma \geq 5$. The difference in the L dependence between the extrapolated equatorial density and the empirical model of Carpenter and Anderson (1992) may be explained by fluctuations of the individual case observations from the average.

Due to the good fits of the functional form in (7) (or (10)) to the RPI density profiles observed in morning, noon, and midnight sectors, it is reasonable to suggest that the functional form has the potential to be used for constructing global empirical plasmasphere/plasma trough models. Particularly, it is feasible to be used to specify the density profiles along the nightside depleted flux tubes for the studies of plasmasphere refilling with appropriately specified fitting parameter values and equatorial densities.

4 Field-Aligned Density Distributions in the Polar Cap

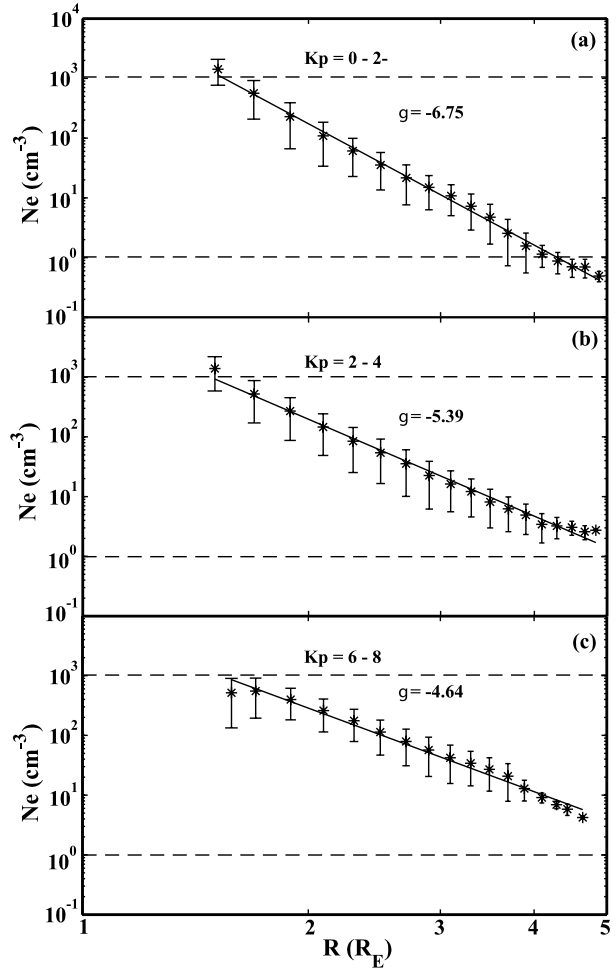
Plasma density distributions in the polar cap (above altitude of 3000 km) have been investigated using the in situ measurements from the S3-3, DE-1 and POLAR, missions (e.g., Mozer et al. 1979; Persoon et al. 1983; Gallagher et al. 2000; Johnson et al. 2001, 2003). Those previous studies established that the statistical dependence of the polar cap density on radial distance follows a power law and revealed the significant effects of solar illumination on polar cap density distributions. Other factors, such as geomagnetic activity, have not been incorporated into the empirical models of polar cap densities.

In a single IMAGE pass, the RPI remote sounding provided multiple measurements that are equivalent to in situ measurements of many passes. Along individual field-aligned density profiles there are typically over 30 density measurements. Therefore, RPI collected a very large number of density measurements during its 5.8-year operation. More importantly, the field-aligned density profiles contain the information of the field-line dependence that allows better statistical description of the density distributions. Using such RPI density profiles, Nsumei et al. (2003) constructed an empirical model for polar cap densities, which has a power law with an exponent of -5.09 ± 0.03 . Furthermore, this model includes dependence on geomagnetic activity as measured by the 3-hour K_p index. The Nsumei et al. (2003) model was developed by using a small database covering the period from June to November 2001.

With a much larger database consisting of 770 RPI density profiles, Nsumei et al. (2008) further developed a polar cap density model. In their study, the relative importance of solar illumination and geomagnetic activity dependences of electron densities in the polar cap was systematically examined. This statistical analysis considered the dynamic nature of the size and shape of the polar cap by using a statistical poleward boundary model of the auroral oval developed by Carbary (2005). The modeled poleward boundary depends on MLT and the K_p index. RPI measurements at invariant latitudes greater than this poleward auroral boundary are designated as polar cap. Such a definition of the polar cap largely avoids contaminations by auroral oval and sub-auroral region density measurements.

The statistical analysis of the RPI electron density distributions not only shows that the electron density distribution within the polar cap depends on the geocentric distance R and geomagnetic activity level, but also reveals that the enhancement of the electron density during periods of increased geomagnetic activity is altitude dependent such that it is most pronounced at higher altitudes and less significant at lower altitudes. The density increase with increasing K_p value can be seen from a comparison of the three panels (for three different K_p ranges) in Fig. 11. The similar density at lower altitudes and different densities at higher altitudes suggest non-local outflow and/or convection across the polar cap associated with changes in geomagnetic activity, particularly at high altitudes. On the other hand, the strong solar illumination control of electron density at lower altitudes, but not at higher, is demonstrated by Fig. 12. It is clear that electron density is higher on the sunlit side than on the dark side. The enhancement in electron density due to solar illumination decreases with

Fig. 11 Log-log plot of average electron density n_e , versus geocentric distance R , in three geomagnetic activity ranges. The RPI data are divided into $0.3 R_E$ bins in geocentric distances and three K_p ranges. The average electron density is computed for each bin. At higher altitudes, the electron density increases more significantly with geomagnetic activity levels measured by the K_p index. The two horizontal lines on each panel represent density level of 1 and 10^3 cm^{-3} , respectively. (Adapted from Nsumei et al. 2008)



increasing altitude. These results are similar to those of Johnson et al. (2003) and indicate decreasing/increasing importance of the solar zenith angle/cleft ion fountain on density with increasing altitude (Tu et al. 2005a).

Based on a statistical analysis of the RPI database, Nsumei et al. (2008) obtained an empirical representation of polar cap densities

$$\begin{aligned}
 n_e(r, K_p, \chi) &= n_{e0}(K_p, \chi) \left(\frac{r}{r_0} \right)^{g(K_p, \chi)}, \\
 n_{e0}(K_p, \chi) &= n_{e00} \exp(\alpha_1 K_p + \alpha_2 \cos \chi), \\
 g(K_p, \chi) &= \gamma_0 + \gamma_1 K_p + \gamma_2 \chi,
 \end{aligned} \tag{11}$$

where $r_0 = 1.4 R_E$ and χ is the solar zenith angle (in degrees) at 300 km altitude of the field line. The coefficients in (11), determined by a multivariate fit of RPI data to the above expressions, are given by: $n_{e00} = 7.29 \times 10^2 \text{ cm}^{-3}$; $\alpha_1 = 0.0747$; $\alpha_2 = 1.8959$; $\gamma_0 = -8.6400$; $\gamma_1 = 0.2601$; $\gamma_2 = 0.0261$. It is interesting to note that χ is a function of UT, local time (LT),

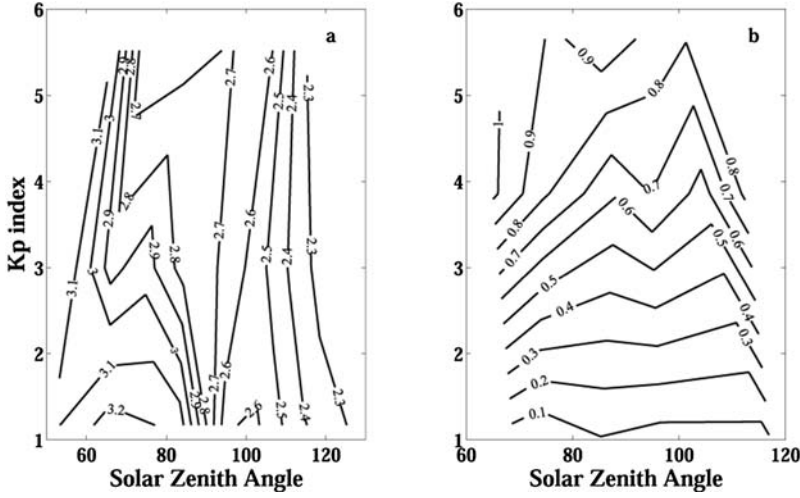


Fig. 12 Contours of the logarithm of average electron density (cm^{-3}) are shown as functions of solar zenith angle and the geomagnetic activity index K_p for two altitude ranges: **a** $R = 1.4 - 1.7 R_E$, **b** $R = 4.0 - 4.4 R_E$. (Adapted from Nsumei et al. 2008)

and latitude. Thus the present empirical model also has dependence on UT, LT, and latitude. Equation (11) was developed from measurements covering geocentric distances from $1.4 R_E$ to a little over $4.5 R_E$, geomagnetic activity from $K_p = 0$ to almost $K_p = 6$, and for solar zenith angles ranging from roughly 70 degrees to 110 degrees. In this study only K_p was used to roughly characterize the noted increase in higher altitude densities with increased activity. Future studies might more directly consider solar wind drivers, such as that found by Moore et al. (1999), where ionospheric high-latitude outflow was found to be correlated with solar wind dynamic pressure.

5 Empirical Models of Electric Field

5.1 The Corotation Electric Field

Close to the Earth, the main source of the magnetospheric electric field is the corotation electric field due to rotation of the Earth along its axis. In the equatorial plane, the potential of the co-rotation electric potential is given by (e.g., Kivelson and Russell 1995)

$$\Phi = -\frac{\omega R_E^2 B_0}{r/R_E} = -\frac{92}{r/R_E} \text{ [kV]}, \quad (12)$$

where $\omega = 7.272 \times 10^{-5}/\text{s}$ is the angular rotation frequency of the Earth, r is the radial distance, $R_E = 6371 \text{ km}$ is the Earth radius and $B_0 = 3.1 \times 10^{-5} \text{ T}$ is the magnetic field strength at the surface of the Earth at the equator.

5.2 Empirical Convection Electric Field Models

The other large-scale source of magnetospheric electric field is the convection electric field, controlled by the solar wind conditions and the level of geomagnetic activity. To determine the global electric field distribution in the whole magnetosphere, various empirical

and mathematical models have been built with various degrees of sophistication. Reviews of convection electric fields were presented in Stern (1977), Lyons and Williams (1984), del Pozo and Blanc (1994), and Ebihara and Ejiri (2002) for instance. The electric field models are empirical or based on the solutions of physical equations, exactly like plasmaspheric models (Pierrard et al. 2008b). Semi-empirical models have also been developed by the pioneer researchers (Nishida 1966), and later the model of Sojka et al. (1986) that is dependent on K_p and on the IMF intensity and direction. We give here first a short overview of empirical electric field models recently used in plasmaspheric research, including a newly developed inner magnetospheric electric field (UNH-IMEF) model using CLUSTER data. Then we discuss the influence of the empirical models on the investigations of plasmaspheric dynamics and plasmopause formation.

5.2.1 Volland-Stern's and Maynard-Chen's (VSMC) Convection Electric Field Model

The Volland-Stern model (Volland 1973; Stern 1975) is a simple mathematical model where a uniform dawn-dusk convection electric potential distribution is applied across the magnetosphere. This magnetospheric electric field derives from a scalar potential which, in a co-rotating frame of reference, is given by

$$\Phi = Ar^2 \sin \phi, \quad (13)$$

where ϕ is the azimuthal angle from noon and the K_p dependent factor

$$A = \frac{0.045}{(1 - 0.159K_p + 0.0093K_p^2)^3} [\text{kV}/R_E^2] \quad (14)$$

determines the convection electric field intensity. The K_p dependence of this empirical model was obtained by Maynard and Chen (1975) by adjusting the last closed equipotential (LCE) of the total electric field in order to favorably compare with plasmopause positions determined by OGO3 and OGO5 satellite observations; this model has been given the acronym VSMC in the following.

5.2.2 McIlwain's E5D Convection Electric Field Model

Another analytical representation of the magnetospheric convection electric potential was derived by McIlwain (1986) from electron and proton dynamical spectra measured at geosynchronous orbit during the ATS-5 and ATS-6 missions. This potential is given by

$$\Phi = [r(0.8 \sin \phi + 0.2 \cos \phi) + 3] \left[1 + 0.3 \frac{K_p}{1 + 0.1K_p} \right] \left[\frac{1}{1 + (0.8R_{ar}/r)^8} \right], \quad (15)$$

where $R_{ar} = 9.8 - 1.4 \cos \phi - (0.9 + 0.3 \cos \phi)[K_p/(1 + 0.1K_p)]$.

The E5D model depends also on the three-hourly geomagnetic activity index K_p . The E5D model was deduced from ATS-5 and ATS-6 particle flux measurements at geosynchronous altitude. The E5D model was derived by fitting the observed positions of the injection boundary.

Figure 13 illustrates the equatorial contour maps of the equipotentials for the VSMC and E5D convection electric field models for $K_p = 6$. The models are quite different from each other. The comparison of Fig. 13 indicates that the E5D electric field model is less sensitive to K_p than the VSMC model. The LCE is everywhere closer to the Earth for the VSMC model than for the E5D one.

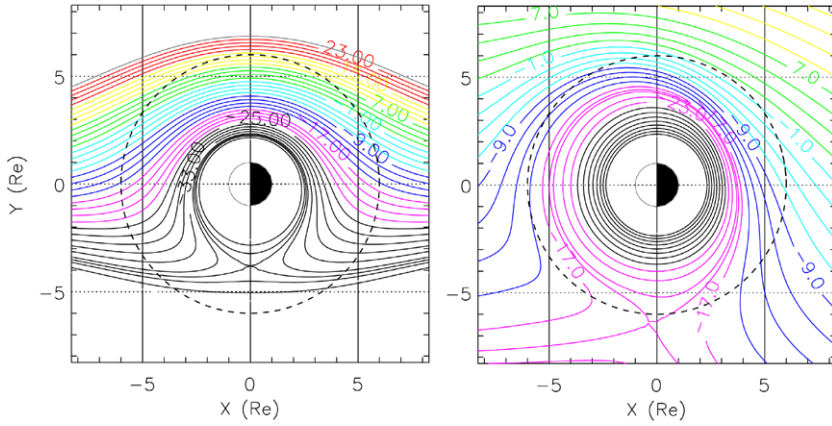


Fig. 13 Equipotential map of the total electric field including convection model and corotation for $K_p = 6$: VSMC (left panel) and E5D (right panel). The values of the potential (in kV) are given on the equipotential contours, which are drawn every 2 kV. The dotted circle corresponds to $L = 6$. (Adapted from Pierrard et al. 2008a)

5.2.3 Weimer's Convection Electric Field Model

Unlike the two previous electric field models, Weimer's (Weimer 1996) electric field model is driven by solar wind parameters: IMF magnitude, solar wind velocity, and dipole tilt angle. It was derived from low altitude ionospheric convection velocity measurements at high latitudes. The electric potential in the Weimer (1996) model, Φ , is given by an expansion in spherical harmonics as a function of the geomagnetic co-latitude θ , the MLT ϕ , and associated Legendre functions P_l^m

$$\Phi(\theta, \phi) = \sum_{l=0}^{\min(l,3)} (A_{lm} \cos m\phi + B_{lm} \sin m\phi) P_l^m(\cos \theta). \quad (16)$$

The A_{lm} and B_{lm} coefficients were derived by a least error fit from multiple satellite measurements of the ionospheric convection velocity.

Figure 14 illustrates the equatorial contour maps of Weimer's convection electric potential including corotation every UT hour from 07:00 UT up to 12:00 UT during the geomagnetic event of 17 April 2002. The LCE has a stagnation point at 18:00 MLT in the dusk sector for VSMC and E5D models, while it is generally located at later MLT, in the post-dusk local time sector, for Weimer's model. Weimer's equipotentials are quite different from those of the E5D and VSMC for the same period. The shielding is often less efficient in the dawn sector than at dusk unlike in E5D. The electric field intensity of the Weimer model is also generally found to be stronger than that of either the E5D or VSMC during geomagnetic storms and substorms.

Other sophisticated ionospheric and magnetospheric electric field models are also available in the literature (Richmond and Kamide 1988; Boonsirirath et al. 2001). These convection electric field models have been compared with observations to study the effects of inner magnetospheric convection on ring current dynamics (Jordanova et al. 2001) and on stormtime particle energization (Khazanov et al. 2004).

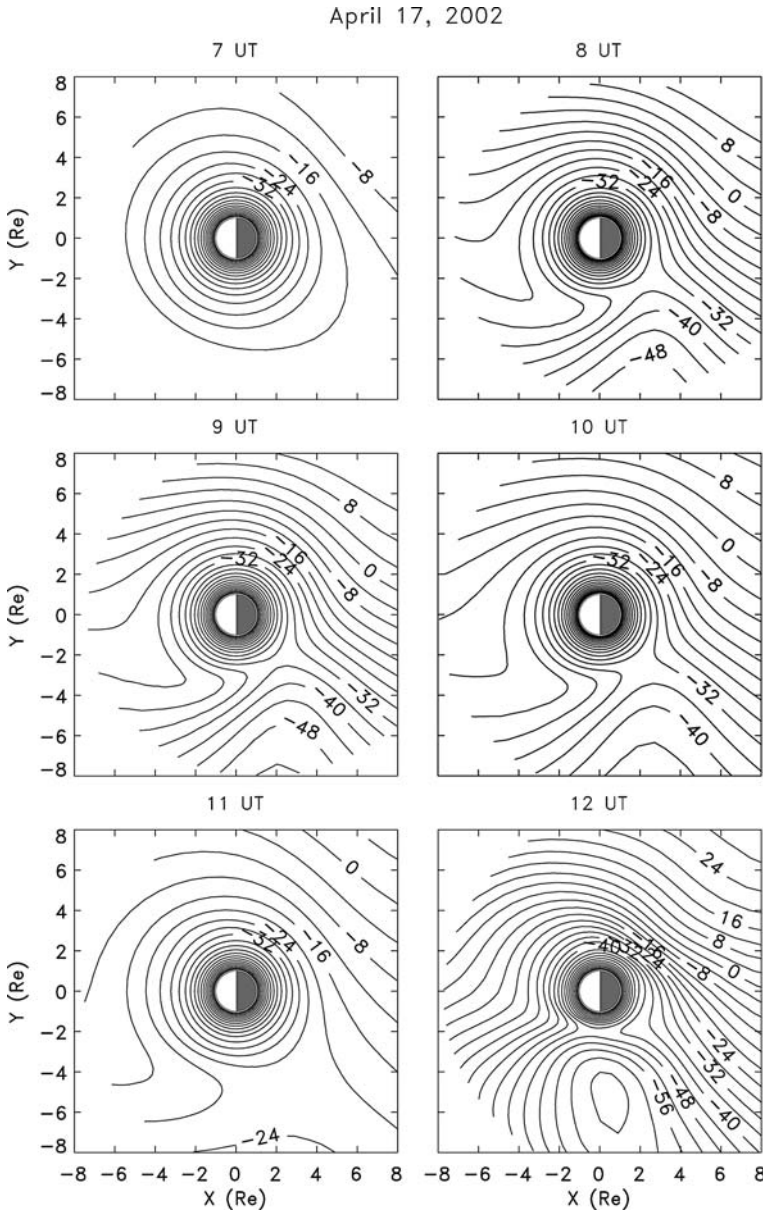
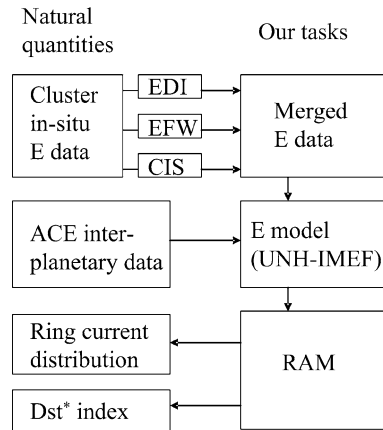


Fig. 14 Equipotential map of the Weimer convection electric field dependent on solar wind conditions on 17 April 2002 with corotation electric field. T96 magnetospheric magnetic field model (Tsyganenko and Stern 1996) is used to map electric potential from the ionospheric altitude to the equator. The values of the potential (in kV) are given on the equipotential contours, which are drawn every 4 kV

5.2.4 Inner Magnetospheric Electric Field (UNH-IMEF) Model

Most of electric field models mentioned above have been developed using measurements at ionospheric altitudes. The application of such models to magnetospheric altitudes strongly

Fig. 15 A block diagram to show the work to be performed. Data set is shown on the *left*, while tasks are shown on the *right*



relies on the assumption that magnetic field lines are equipotentials. This assumption, however, may be violated in regions where field-aligned currents exist and during periods of geomagnetic disturbances. It is thus important to derive an electric field model from in situ measurements made closer to the magnetic equator in the inner magnetosphere in order to mitigate the influence of the field-aligned potentials.

The Electric Drift Instrument (EDI) on each of three CLUSTER satellites provides an excellent opportunity to derive empirical electric field models at higher altitudes. EDI measures particle drift motion, which mostly consists of $\mathbf{E} \times \mathbf{B}$ drift (Paschmann et al. 2001). Matsui et al. (2004) have conducted a statistical study using two years of EDI data obtained in the inner magnetosphere. In that study, electric potential patterns were derived from the average electric field by solving an inverse problem. The statistical data were organized with the southward component of the IMF (B_z), the K_p index, and the Dst index. The derived patterns, however, contained significant statistical errors because of the small database and possibly also due to a data coverage gap corresponding to the nightside MLT.

In order to reduce statistical errors and provide a better description of electric fields in the inner magnetosphere, the merging of over 5 years-worth of EDI measurements with electric field measurements from three other CLUSTER instruments has been proposed (Puhl-Quinn et al. 2008; Matsui et al. 2008). Those instruments are the Electric Field and Wave (EFW) instrument (Gustafsson et al. 2001), the Cluster Ion Spectrometry (CIS) instrument (Rème et al. 2001), and the FluxGate Magnetometer (FGM) instrument (Balogh et al. 2001). EFW is a conventional instrument for measuring electric fields that uses double probes. CIS provides three-dimensional ion distribution functions from which it is possible to calculate the bulk velocity of ions, $\mathbf{V}$. Using the magnetic field, $\mathbf{B}$, as measured by FGM, electric fields can be calculated by $\mathbf{E} = -\mathbf{V} \times \mathbf{B}$. These three types of electric field data will be merged into a single database in order to maximize data coverage. Only the highest quality data will be kept. Figure 15 is a block diagram showing the data sets used to create the database, and the tasks that have been (or will be) performed using the database. The data sets used (or produced) are shown on the left, while tasks are shown on the right.

In order to develop a merged database, Puhl-Quinn et al. (2008) compared EDI and EFW data in three orbits near the magnetic equator (Fig. 16). Electric field data from EDI are shown in black, while that from EFW are shown in red. The electric field component shown in the figure is the X component in the X - Y plane of the despun-satellite-inverted (DSI) coordinates, which are similar to geocentric solar ecliptic (GSE) coordinates. The spacecraft

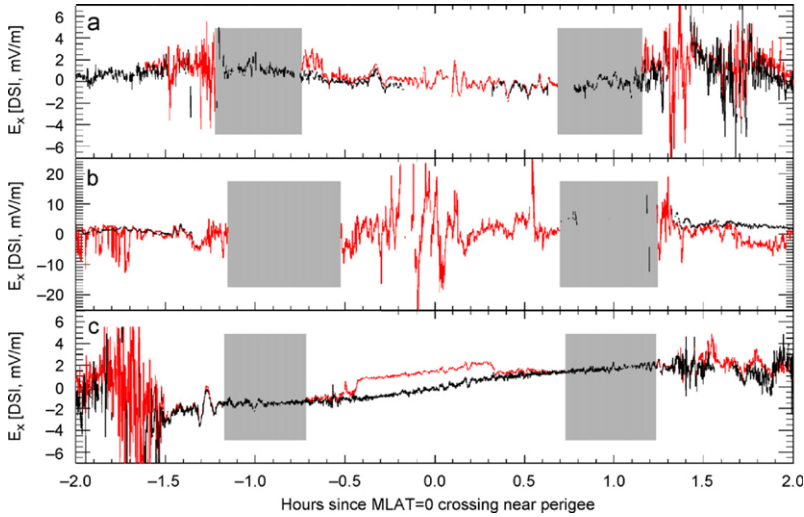


Fig. 16 Comparison of electric fields from EDI (black) and EFW (red). X component of electric field in despin satellite inverted (DSI) coordinates is shown near magnetic equator for three orbits: **a** 2 October 2001, **b** 18 April 2002, and **c** 4 July 2001. Grey areas indicate where the angle between the spin plane and magnetic field direction is $< 15^\circ$. (Adapted from Puhl-Quinn et al. 2008)

spin plane, in which two pairs of EFW double probes lie, is in the X - Y plane of DSI coordinates. The shaded areas in the figure correspond to the region where the angle between the spin plane and magnetic field direction is $< 15^\circ$. In this region, the third component of the electric field cannot be determined reliably by the EFW measurements through the assumption of $\mathbf{E} \cdot \mathbf{B} = 0$. In Fig. 16a (2 October 2001), EDI measurements are available in the shaded region, while EFW data are missing. In contrast, there are many EDI data gaps near CLUSTER perigee, while EFW tends to get data at these times. In this example, the two instruments are complementary. In Fig. 16b (18 April 2002), EDI data are not available, in most part, around the magnetic equator. Nevertheless, EFW worked well during this orbit. This period corresponds to a major storm with sawtooth signatures (e.g., Huang et al. 2005; Ohtani et al. 2007). In Fig. 16c (4 July 2001), both EDI and EFW get data continuously. There are, however, offsets between EDI and EFW data around the magnetic equator. EDI data appear to have smaller errors compared to EFW data. The spurious electric field in the EFW data has a general dependence on the spacecraft potential with the components parallel to the following directions: (i) sunward; (ii) magnetic field; (iii) spacecraft velocity; and (iv) plasma convection. The former two components are related to the photoelectron cloud around the spacecraft. The latter two components are related to wakes created by the relative motion between the spacecraft and the plasma, which was previously reported by Eriksson et al. (2006).

So far an inner magnetospheric electric field model, termed the UNH-IMEF model, has been developed based on a large database merging EDI and EFW data (Matsui et al. 2008). The EDI data are used whenever they are available. If EDI data are missing, EFW data are used by compensating the average offsets between EFW and EDI data for each 5 minutes. The average electric field patterns in two dimensional space sorted by L value and MLT are generated after mapping in situ CLUSTER data at magnetic latitudes within $\sim \pm 50^\circ$ of the magnetic equator. The mapping of the electric field is performed so that plasma motion at in situ spacecraft locations ($> 3R_E$ altitude) is consistent with that at the magnetic equator

on a magnetic field line predicted by Tsyganenko (2002). The equipotential assumption is still the basis for such mapping. The mapping distance between CLUSTER locations and the magnetic equator, however, is smaller than the distance between the ionosphere and the equator so that the reliance on the equipotential assumption is less. The organizing parameter for the inner magnetospheric electric field is the interplanetary electric field (IEF) defined as

$$IEF = vB_z \sin^2(\theta/2), \quad (17)$$

where v is the solar wind velocity, B_z is the IMF z component, and θ is the IMF clock angle defined as $\theta = \tan^{-1}(B_y/B_z)$ with B_y corresponding to the IMF y component. The relation between the electric field pattern and the electric potential pattern is given by

$$\mathbf{e} = \mathbf{A}\boldsymbol{\phi}, \quad (18)$$

where $\mathbf{e}$ is a vector, which consists of electric field vectors from all two-dimensional spatial bins in polar coordinates organized by L values and MLT, $\mathbf{A}$ is an operator to calculate the spatial gradient, and $\boldsymbol{\phi}$ is a vector, which consists of electric potential values from all spatial bins (Matsui et al. 2004). Since the potential is calculated from the electric field, this is regarded as an inverse problem because the electric field is derived from the electric potential in (18). The electric potential is practically estimated by

$$\hat{\boldsymbol{\phi}} = (\mathbf{A}^T \mathbf{A} + \gamma \mathbf{C}^T \mathbf{C})^{-1} \mathbf{A}^T \mathbf{e}, \quad (19)$$

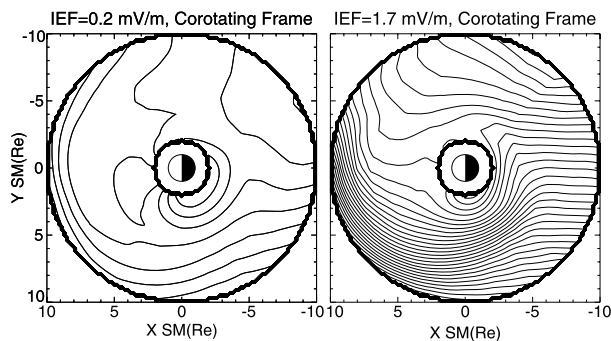
where $\hat{\boldsymbol{\phi}}$ is the estimated potential, γ is a trade-off parameter, $\mathbf{C}$ is a regular matrix, which is a Laplacian operator. If the parameter γ decreases, the equation is close to the original equation (18), although the error is not reduced. If the parameter γ increases, the result is smoothed too much by the Laplacian operator. The criterion for choosing the proper γ is discussed by Korth et al. (2002) and is determined by using the following equation

$$\sigma^2 = \frac{\|\mathbf{A}\hat{\boldsymbol{\phi}} - \mathbf{e}\|^2}{N_e - N_\phi}, \quad (20)$$

where N_e is the number of data points and N_ϕ is the number of model parameters we determined and is given by the trace of the matrix $(\mathbf{A}^T \mathbf{A} + \gamma \mathbf{C}^T \mathbf{C})^{-1} \mathbf{A}^T \mathbf{A}$ (Tarantola 1987). A proper γ is obtained when σ^2 starts to increase.

In the UNH-IMEF model, statistical results are organized by the interplanetary electric field derived from the Advanced Composition Explorer (ACE) spacecraft (see (17)). ACE magnetic field and plasma moment data (McComas et al. 1998; Smith et al. 1998) are used. ACE is located at the L1 point ($\sim 200 R_E$ upstream from the Earth) so that the solar wind at the ACE location typically arrives at the Earth several tens of minutes later. The organization of CLUSTER data by ACE data makes it possible to use the model for prediction. The model is developed using the method proposed in the previous statistical analysis (Matsui et al. 2004) with the larger database merging the EDI and EFW data. The electric field calculated with the UNH-IMEF model is used as an input parameter for the ring current-atmosphere interaction model (RAM) (Jordanova et al. 2003) in order to validate the UNH-IMEF model. The RAM model simulates time evolution of the spatial distribution of ring current particles. The D_{st} index can be reproduced from the ring current distribution by using the Dessler-Parker-Sckopke relation (Dessler and Parker 1959; Sckopke 1966) and can be compared with the measured values. If the simulated and measured values match, the UNH-IMEF electric field model is possibly reliable. There are other ways to validate the model. The

Fig. 17 Electric potential patterns derived in the corotating frame at $IEF = 0.2$ and 1.7 mV m^{-1} . Contour intervals are 1 and 5 kV for *thin* and *thick* lines, respectively



calculated location of the LCE is dependent on the electric field model used. The UNH-IMEF model could be used to predict the location of the LCE, and then comparisons could be made with observations of the plasmapause during extended quiet times when the LCE and plasmapause should coincide.

This version of the UNH-IMEF has been made public (<http://edi.sr.unh.edu/unh-imef/>). Figure 17 shows two examples of potential patterns with $IEF = 0.2$ and 1.7 mV/m in the corotating frame. The electric field strength increases as the IEF increases. The equipotential contours often rotate around the Earth on the dusk-side, indicating ionospheric shielding of the electric field. There are still two points to be checked concerning the performance of the model. The first point is the comparison between the average electric field and the electric field derived from the potential pattern. This is related to the validity of assuming time-stationarity in the above statistical treatment (Faraday's law), which is not always satisfied (Matsui et al. 2004). The second point is the comparison of model results with instantaneous CLUSTER measurements. The model is not yet optimized to include effects of the sub-auroral polarization stream (SAPS). Goldstein et al. (2005) derived a SAPS electric potential model by referring to statistical results on SAPS using DMSP data by Foster and Vo (2002). It would be worthwhile to update the UNH-IMEF model to include SAPS.

5.3 Influence of Electric Field Models on the Plasmapause Position Modeling

The convection electric field appears to be a key factor in the formation of the plasmapause and very different results are obtained depending on the characteristics of the electric field model. Pierrard et al. (2008a) have determined how three magnetospheric electric field models influence the radial distance, the shape and the evolution of the plasmapause during the geomagnetic storms of 28 October 2001 and of 17 April 2002. These models are the VSMC model, the E5D model, and the model of Weimer (1996) described in the previous section. Two different mechanisms proposed for the formation of the plasmapause have been studied: (i) the interplay of magnetospheric convection and plasma corotation with the Earth in which the plasmapause should correspond to the LCE or last-closed-streamline (LCS), if the electric field distribution is stationary or time-dependent respectively (Grebowsky 1970); (ii) the interchange mechanism where the plasmapause corresponds to streamlines tangent to a Zero-Parallel-Force surface where the field-aligned plasma distribution becomes connectively unstable during enhancements of the electric field intensity in the nightside local time sector (Lemaire and Pierrard 2008).

Using the same mechanism for plasmapause formation, the plasmapause is obtained to be further away from the Earth with E5D than with the other models. The plasmapause position obtained with the E5D model and the interchange mechanism is closer to the EUV

observations during the geomagnetic storms of 28 October 2001 and 17 April 2002 than the positions obtained with other electric field models and LCS (interplay between the convection and corotation) simulations. The LCS simulations using the ESD electric field model systematically produce a plasmopause position that is too far away. Results of LCS simulations are improved using the VSMC model, which has been fitted in order to match the LCE with observed plasmopause positions. Although the plasmopause positions of different simulations are found to be quite different, an interesting recent result is that all of the different electric field models account for the formation of plumes during magnetic storms (Pierrard et al. 2008a).

The results of different time dependent simulations were successfully compared with concomitant EUV/IMAGE observations when available (Pierrard and Cabrera 2005, 2006; Pierrard 2006) and also with CIS/IMAGE (Dandouras et al. 2005) and CLUSTER observations (Darrouzet et al. 2006; Schäfer et al. 2007, 2008). Combined with the kinetic model of the plasmasphere developed by Pierrard and Lemaire (2001), dynamic simulations of plasmopause formation give a full description of the plasmasphere in three dimensions (Pierrard and Stegen 2008). The core of this plasmaspheric model is obtained from the kinetic exospheric approach assuming a kappa velocity distribution function for particles. Note that the frequency spectrum of plasma resonances stimulated by the IMAGE/RPI transmissions in the inner magnetosphere, but outside the plasmopause, was consistent with a kappa electron-velocity distribution with a low kappa value (Viñas et al. 2005). The relative abundance of trapped particles is constrained in such way that density profiles correspond to satellite observations. This analytical model is semi-empirical, but incorporates major physical features that determine the density distributions in flux tubes at high altitudes.

Liemohn et al. (2004) have also compared some electric field models and their effects on plasmaspheric morphologies. They used a modified McIlwain electric field model, Weimer model, and another self-consistent electric potential model for the time span of the recovery phase of the 17 April 2002 magnetic storm. These authors found that all these models have certain strengths but also weaknesses in predicting the observed plasmopause position during this storm. They found especially that the electric field intensity of Weimer's model was too strong in the inner magnetosphere, leading to a plasmasphere that was too small. Liemohn's modified McIlwain model (which differs from the original ESD model) has too small an electric field intensity around noon, leading to a plasmopause position that does not correspond to the EUV observations on the dayside, although a good fit was obtained in the nightside.

6 Summary

Previous empirical models of plasma number and mass densities in the inner magnetosphere have been developed by statistical, time-aliased averaging of a large set of in situ measurements. The advent of the IMAGE RPI has added to previous efforts by providing nearly instantaneous measurements of the true field-aligned plasma electron densities, 2-dimensional profiles of density across 20-minute or so orbital passes and repeated transits of inner magnetospheric space over more than 5-years. New, advanced empirical models of plasma density in the plasmasphere and polar cap have resulted. The new plasmaspheric density model not only refines and confirms the radial distance and latitude dependence established using in situ measurements, but has for the first time revealed the density distribution along depleted magnetic field lines. The new polar cap density models are significantly more comprehensive, by refining and going beyond the radial distance density dependence represented in previous empirical models to include latitude and local time dependence through solar zenith angles at ionospheric altitudes. Furthermore, the newly developed polar cap models include

geomagnetic activity dependence, which is found to be stronger with increasing altitude. Further exploration of the RPI sounding data in combination with in situ data provided by the passive measurements of RPI and other satellite instruments can be expected to yield even more comprehensive empirical density models of the inner magnetosphere, organized by location, geomagnetic activity, and solar wind parameters.

The CLUSTER multiple-point and multiple-instrument measurements of inner magnetospheric electric fields have made it possible to develop new electric field models. The assumption of equipotential magnetic field lines has been adopted to map the electric field at magnetic latitudes within $\pm 50^\circ$ of the magnetic equator. Compared to the mapping of the electric field from the ionospheric altitude to the equator, the equipotential assumption has less effects on the equatorial electric fields in the UNH-IMEF model. A large database of CLUSTER EDI and EFW measurements have been merged to create a new empirical model of the inner magnetospheric electric field. Further development of the new electric field model is underway using additional merging of electric fields derived from CLUSTER CIS and FGM measurements.

The electric field distribution is critical in modeling the plasmasphere dynamics. An interesting result is that all of the electric field models that have been obtained account for the formation of plumes during geomagnetic storms. None of the electrostatic field models, however, are capable yet of fully reproducing the magnetospheric electric field distribution. There remains a long way to go before the detailed structures observed in the EUV observations during periods of enhanced geomagnetic activity can be accounted for by an electric field model. These studies point out the need to develop higher time resolution empirical models for the magnetospheric electrostatic field distribution like those developed for the geomagnetic field. The empirical electric field models being developed using the CLUSTER multiple-point and multiple-instrument dataset, such as UNH-IMEF, will hopefully meet this need.

Acknowledgements The work at UML was supported by NASA grant NNX07AG38G, NASA grant via subcontract 83822 from SwRI, NSF grant 0518227, and AFRL contract FA8718-06-C-0072 to the University of Massachusetts Lowell. The work at Dartmouth College was supported by NSF grants ATM-0632740 and ATM-0120950 (Center for Integrated Space Weather Modeling, CISM, funded by the Science and Technology Centers Program). This paper is an outcome of the workshop "The Earth's plasmasphere: A CLUSTER, IMAGE, and modeling perspective", organized by the Belgian Institute for Space Aeronomy in Brussels in September 2007. The use of Figs. 2, 3, 5 and 6 is with the permission of Elsevier.

References

- A. Balogh, C.M. Carr, M.H. Acuña, M.W. Dunlop, T.J. Beek, P. Brown, K.H. Fornacon, E. Georgescu, K.H. Glassmeier, J. Harris, G. Musmann, T. Oddy, K. Schwingenschuh, The Cluster Magnetic Field Investigation: overview of in-flight performance and initial results. *Ann. Geophys.* **19**(10–12), 1207–1217 (2001)
- R.F. Benson, P.A. Webb, J.L. Green, L. Garcia, B.W. Reinisch, Magnetospheric electron densities inferred from upper-hybrid band emissions. *Geophys. Res. Lett.* **31**, L20803 (2004)
- D. Berube, M.B. Moldwin, S.F. Fung, J.L. Green, A plasmaspheric mass density model and constraints on its heavy ion concentration. *J. Geophys. Res.* **110**, A04212 (2005)
- D. Bilitza, International Reference Ionosphere 2000. *Radio Sci.* **36**(2), 261–275 (2001)
- J.H. Binsack, Plasmopause observations with the M.I.T. experiment on IMP 2. *J. Geophys. Res.* **72**(21), 5231–5237 (1967)
- A. Boonsiriseth, R. Thorne, G. Lu, V.K. Jordanova, M.F. Thomsen, D.M. Ober, A.J. Ridley, A semiempirical equatorial mapping of AMIE convection electric potentials (MACEP) for the January 10, 1997, magnetic storm. *J. Geophys. Res.* **106**(A7), 12903–12917 (2001)
- J.L. Burch, IMAGE mission overview. *Space Sci. Rev.* **91**(1–2), 1–14 (2000)
- J.L. Burch, The first two years of image. *Space Sci. Rev.* **109**(1–4), 1–24 (2003)

- J.F. Carbary, A K_p -based model of auroral boundaries. *Space Weather* **3**(10), 10001 (2005)
- D.L. Carpenter, Whistler evidence of a “knee” in the magnetospheric ionization density profile. *J. Geophys. Res.* **68**(6), 1675–1682 (1963)
- D.L. Carpenter, Whistler studies of the plasmapause in the magnetosphere, 1. Temporal variations in the position of the knee and some evidence on plasma motions near the knee. *J. Geophys. Res.* **71**(3), 693–709 (1966)
- D.L. Carpenter, Remote sensing the Earth’s plasmasphere. *Radio Sci. Bull.* **308**, 13–29 (2004)
- D.L. Carpenter, R.R. Anderson, An ISEE/whistler model of equatorial electron density in the magnetosphere. *J. Geophys. Res.* **97**(A2), 1097–1108 (1992)
- D.L. Carpenter, J. Lemaire, Erosion and recovery of the plasmasphere in the plasmapause region. *Space Sci. Rev.* **80**(1–2), 153–179 (1997)
- C.R. Chappell, K.K. Harris, G.W. Sharp, The dayside of the plasmasphere. *J. Geophys. Res.* **76**(31), 7632–7647 (1971)
- M.A. Clilverd, A.J. Smith, N.R. Thomson, The annual variation in quiet time plasmaspheric electron density, determined from whistler mode group delays. *Planet. Space Sci.* **39**(7), 1059–1067 (1991)
- P.D. Craven, D.L. Gallagher, R.H. Comfort, Relative concentration of He^+ in the inner magnetosphere as observed by the DE 1 retarding ions mass spectrometer. *J. Geophys. Res.* **102**(A2), 2279–2289 (1997)
- I. Dandouras, V. Pierrard, J. Goldstein, C. Vallat, G.K. Parks, H. Rème, C. Goullart, F. Sevestre, M. McCarthy, L.M. Kistler, B. Klecker, A. Korth, M.B. Bavassano-Cattaneo, P. Escoubet, A. Masson, Multipoint observations of ionic structures in the plasmasphere by CLUSTER-CIS and comparisons with IMAGE-EUV observations and with model simulations, in *Inner Magnetosphere Interactions: New Perspectives from Imaging*, ed. by J.L. Burch, M. Schulz, H. Spence. Geophysical Monograph Series, vol. 159 (American Geophysical Union, Washington, 2005), pp. 23–53
- F. Darrouzet, J. De Keyser, P.M.E. Décréau, D.L. Gallagher, V. Pierrard, J.F. Lemaire, B.R. Sandel, I. Dandouras, H. Matsui, M. Dunlop, J. Cabrera, A. Masson, P. Canu, J.G. Trotignon, J.L. Rauch, M. André, Analysis of plasmaspheric plumes: CLUSTER and IMAGE observations. *Ann. Geophys.* **24**(6), 1737–1758 (2006)
- J. De Keyser, D.L. Carpenter, F. Darrouzet, D.L. Gallagher, J. Tu, CLUSTER and IMAGE: New ways to study the Earth’s plasmasphere. *Space Sci. Rev.* (2008), this issue
- P.M.E. Décréau, C. Beghin, M. Parrot, Global characteristics of the cold plasma in the equatorial plasmapause region as deduced from the GEOS 1 mutual impedance probe. *J. Geophys. Res.* **87**(A2), 695–712 (1982)
- C.F. del Pozo, M. Blanc, Analytical self-consistent model of the large-scale convection electric field. *J. Geophys. Res.* **99**(A3), 4053–4068 (1994)
- R.E. Denton, Magneto-seismology using spacecraft observations, in *Magnetospheric ULF Waves: Synthesis and New Directions*, ed. by K. Takahashi, P.J. Chi, R.E. Denton, R.L. Lysak. Geophysical Monograph Series, vol. 169 (American Geophysical Union, Washington, 2006), pp. 307–317
- R.E. Denton, J. Goldstein, J.D. Menietti, Field line dependence of magnetospheric electron density. *Geophys. Res. Lett.* **29**(24), 2205 (2002a)
- R.E. Denton, J. Goldstein, J.D. Menietti, S.L. Young, Magnetospheric electron density model inferred from Polar plasma wave data. *J. Geophys. Res.* **107**(A11), 1386 (2002b)
- R.E. Denton, J.D. Menietti, J. Goldstein, S.L. Young, R.R. Anderson, Electron density in the magnetosphere. *J. Geophys. Res.* **109**, A09215 (2004)
- R.E. Denton, J. Goldstein, D.H. Lee, R.A. King, Z.C. Dent, D.L. Gallagher, D. Berube, K. Takahashi, M. Nose, D. Milling, F. Honary, Realistic magnetospheric density model for 29 August 2000. *J. Atmos. Sol. Terr. Phys.* **68**(6), 615–628 (2006a)
- R.E. Denton, K. Takahashi, I.A. Galkin, P.A. Nsumei, X. Huang, B.W. Reinisch, R.R. Anderson, M.K. Sleeper, W.J. Hughes, Distribution of density along magnetospheric field lines. *J. Geophys. Res.* **111**, A04213 (2006b)
- R.E. Denton, P. Décréau, M.J. Engebretson, F. Darrouzet, J.L. Posch, C. Mouikis, L.M. Kistler, C.A. Cattell, K. Takahashi, S. Schäfer, J. Goldstein, Field line distribution of density at $L = 4.8$ inferred from observations by CLUSTER. *Ann. Geophys.* (2009, in press)
- A.J. Dessler, E.N. Parker, Hydromagnetic theory of geomagnetic storms. *J. Geophys. Res.* **64**(12), 2239–2252 (1959)
- Y. Ebihara, M. Ejiri, Numerical simulation of the ring current: Review. *Space Sci. Rev.* **105**(1–2), 377–452 (2002)
- A.I. Eriksson, M. André, B. Klecker, H. Laakso, P.-A. Lindqvist, F. Mozer, G. Paschmann, A. Pedersen, J. Quinn, R. Torbert, K. Torkar, H. Vaith, Electric field measurements on Cluster: comparing the double-probe and electron drift techniques. *Ann. Geophys.* **24**(1), 275–289 (2006)
- C.P. Escoubet, C.T. Russell, R. Schmidt (eds.), *The Cluster and Phoenix Missions* (Kluwer Academic, Dordrecht, 1997), p. 658

- Y.I. Feldstein, A.E. Levitin, D.S. Faermark, R.G. Afonina, B.A. Belov, V.Y. Gaidukov, Electric fields and potential patterns in the high-latitude ionosphere for different situations in interplanetary space. *Planet. Space Sci.* **32**(7), 907–923 (1984)
- J.C. Foster, H.B. Vo, Average characteristics and activity dependence of the subauroral polarization stream. *J. Geophys. Res.* **107**(A12), 1475 (2002)
- S.F. Fung, J.L. Green, Modeling of field-aligned guided echoes in the plasmasphere. *J. Geophys. Res.* **110**, A01210 (2005)
- S.F. Fung, L.N. Garcia, J.L. Green, D.L. Gallagher, D.L. Carpenter, B.W. Reinisch, I.A. Galkin, G. Khmyrov, B.R. Sandel, Plasmaspheric electron density distributions sampled by Radio Plasma Imager on the IMAGE satellite. *Eos Trans. AGU* **82**(47), SM11A–0771 (2001)
- S.F. Fung, R.F. Benson, D.L. Carpenter, J.L. Green, V. Jayanti, I.A. Galkin, B.W. Reinisch, Guided echoes in the magnetosphere: Observations by Radio Plasma Imager on IMAGE. *Geophys. Res. Lett.* **30**(11), 1589 (2003)
- I. Galkin, B. Reinisch, G. Grinstein, G. Khmyrov, A. Kozlov, X. Huang, S. Fung, Automated exploration of the radio plasma imager data. *J. Geophys. Res.* **109**, A12210 (2004)
- D.L. Gallagher, P.D. Craven, R.H. Comfort, A simple model of magnetospheric trough total density. *J. Geophys. Res.* **103**(A5), 9293–9297 (1998)
- D.L. Gallagher, P.D. Craven, R.H. Confort, Global core plasma model. *J. Geophys. Res.* **105**(A8), 18819–18833 (2000)
- D.L. Gallagher, M.L. Adrian, M.W. Liemohn, Origin and evolution of deep plasmaspheric notches. *J. Geophys. Res.* **110**, A09201 (2005)
- J. Goldstein, M. Spasojević, P.H. Reiff, B.R. Sandel, W.T. Forrester, D.L. Gallagher, B.W. Reinisch, Identifying the plasmopause in IMAGE EUV data using IMAGE RPI in situ steep density gradients. *J. Geophys. Res.* **108**(A4), 1147 (2003)
- J. Goldstein, J.L. Burch, B.R. Sandel, Magnetospheric model of subauroral polarization stream. *J. Geophys. Res.* **110**, A09222 (2005)
- J.M. Grebowsky, Model study of plasmopause motion. *J. Geophys. Res.* **75**(22), 4329–4333 (1970)
- J.L. Green, B.W. Reinisch, An overview of results from RPI on Image. *Space Sci. Rev.* **109**(1–4), 183–210 (2003)
- K.I. Gringauz, The structure of the ionized gas envelope of the Earth from direct measurements in the USSR of local charged particle concentrations. *Planet. Space Sci.* **11**(3), 281–296 (1963)
- G. Gustafsson, M. André, A.I. Eriksson, C.G. Fälthammar, R. Grard, G. Holmgren, J.A. Holtet, N. Ivchenko, T. Karlsson, Y. Khotyaintsev, S. Klimov, H. Laakso, P.-A. Lindqvist, B. Lybekk, G. Marklund, F. Mozer, K. Mursula, A. Pedersen, B. Popielawska, S. Savin, K. Stasiewicz, P. Tanskanen, A. Vaivads, J.-E. Wahlund, First results of electric field and density observations by Cluster EFW based on initial months of observations. *Ann. Geophys.* **19**(10–12), 1219–1240 (2001)
- R.A. Heelis, J.K. Lowell, R.W. Spiro, A model of the high-latitude ionospheric convection pattern. *J. Geophys. Res.* **87**(A8), 6339–6345 (1982)
- J.P. Heppner, Empirical models of high-latitude electric fields. *J. Geophys. Res.* **82**(7), 1115–1125 (1977)
- J.P. Heppner, N.C. Maynard, Empirical high-latitude electric field models. *J. Geophys. Res.* **92**(A5), 4467–4489 (1987)
- J.M. Holt, R.H. Wand, J.V. Evans, W.L. Oliver, Empirical models for the plasma convection at high latitudes from millstone hill observations. *J. Geophys. Res.* **92**(A1), 203–212 (1987)
- J.L. Horwitz, S. Menteer, J. Turnley, J.L. Burch, J.D. Winningham, C.R. Chappell, J.D. Craven, L.A. Frank, D.W. Slater, Plasma boundaries in the inner magnetosphere. *J. Geophys. Res.* **91**(A8), 8861–8882 (1986)
- J.L. Horwitz, R.H. Comfort, C.R. Chappell, A statistical characterization of plasmasphere density structure and boundary locations. *J. Geophys. Res.* **95**(A6), 7937–7947 (1990)
- C.S. Huang, G.D. Reeves, G. Le, K. Yumoto, Are sawtooth oscillations of energetic plasma particle fluxes caused by periodic substorms or driven by solar wind pressure enhancements? *J. Geophys. Res.* **110**, A07207 (2005)
- X. Huang, B.W. Reinisch, Automatic calculation of electron density profiles from digital ionograms 2. True height inversion of topside ionograms with the profile-fitting method. *Radio Sci.* **17**(4), 837–844 (1982)
- X. Huang, B.W. Reinisch, P. Song, J.L. Green, D.L. Gallagher, Developing an empirical density model of the plasmasphere using IMAGE/RPI observations. *Adv. Space Res.* **33**(6), 829–832 (2004)
- M.T. Johnson, J.R. Wygant, C. Cattell, F.S. Mozer, M. Temerin, J. Scudder, Observations of the seasonal dependence of the thermal plasma density in the southern hemisphere auroral zone and polar cap at 1 R_E . *J. Geophys. Res.* **106**(A9), 19023–19033 (2001)
- M.T. Johnson, J.R. Wygant, C.A. Cattell, F.S. Mozer, Seasonal variations along auroral field lines: Measurements from the Polar spacecraft. *Geophys. Res. Lett.* **30**(6), 1344 (2003)

- V.K. Jordanova, L.M. Kistler, C.J. Farrugia, R.B. Torbert, Effects of inner magnetospheric convection on ring current dynamics: March 10–12, 1998. *J. Geophys. Res.* **106**(A12), 29705–29720 (2001)
- V.K. Jordanova, A. Boonsiriseth, R.M. Thorne, Y. Dotan, Ring current asymmetry from global simulations using a high-resolution electric field model. *J. Geophys. Res.* **108**(A12), 1443 (2003)
- G.V. Khazanov, M.W. Liemohn, T.S. Newman, M.C. Fok, A.J. Ridley, Magnetospheric convection electric field dynamics and stormtime particle energization: case study of the magnetic storm of 4 May 1998. *Ann. Geophys.* **22**(2), 497–510 (2004)
- M.G. Kivelson, C.T. Russell (eds.), *Introduction to Space Physics* (Cambridge University Press, New York, 1995), p. 594
- H. Korth, M.F. Thomsen, K.H. Glassmeier, W.S. Phillips, Particle tomography of the inner magnetosphere. *J. Geophys. Res.* **107**(A9), 1229 (2002)
- B.A. Larsen, D.M. Klumpar, C. Gurgiolo, Correlation between plasmapause position and solar wind parameters. *J. Atmos. Sol. Terr. Phys.* **69**(3), 334–340 (2007)
- M.J. LeDocq, D.A. Gurnett, R.R. Anderson, Electron number density fluctuations near the plasmapause observed by the CRRES spacecraft. *J. Geophys. Res.* **99**(A12), 23661–23671 (1994)
- J.F. Lemaire, K.I. Gringauz, *The Earth's Plasmasphere* (Cambridge University Press, New York, 1998), p. 372
- J.F. Lemaire, V. Pierrard, Comparison between two theoretical mechanisms for the formation of the plasmapause and relevant observations. *Geomagn. Aeron.* **48**(5), 553–570 (2008)
- M.W. Liemohn, A.J. Ridley, D.L. Gallagher, D.M. Ober, J.U. Kozyra, Dependence of plasmaspheric morphology on the electric field description during the recovery phase of the 17 April 2002 magnetic storm. *J. Geophys. Res.* **109**, A03209 (2004)
- T.M. Loto'aniu, C.L. Waters, B.J. Fraser, J.C. Samson, Plasma mass density in the plasmatrough: Comparison using ULF waves and CRRES. *Geophys. Res. Lett.* **26**(21), 3277–3280 (1999)
- L.R. Lyons, D.J. Williams (eds.), *Quantitative Aspects of Magnetospheric Physics* (Reidel, Dordrecht, 1984), p. 231
- H. Matsui, V.K. Jordanova, J.M. Quinn, R.B. Torbert, G. Paschmann, Derivation of electric potential patterns in the inner magnetosphere from Cluster EDI data: Initial results. *J. Geophys. Res.* **109**, A10202 (2004)
- H. Matsui, P.A. Puhl-Quinn, V.K. Jordanova, Y. Khotyaintsev, P.-A. Lindqvist, R.B. Torbert, Derivation of inner magnetospheric electric field (UNH-IMEF) model using Cluster data set. *Ann. Geophys.* **26**(9), 2887–2898 (2008)
- N.C. Maynard, A.J. Chen, Isolated cold plasma regions: observations and their relation to possible production mechanisms. *J. Geophys. Res.* **80**(7), 1009–1013 (1975)
- D.J. McComas, S.J. Bame, P. Barker, W.C. Feldman, J.L. Phillips, P. Riley, J.W. Griffee, Solar Wind Electron Proton Alpha Monitor (SWEPAM) for the Advanced Composition Explorer. *Space Sci. Rev.* **86**(1–4), 563–612 (1998)
- C.E. McIlwain, A Kp dependent equatorial electric field model. *Adv. Space Res.* **6**(3), 187–197 (1986)
- F.W. Menk, D. Orr, M.A. Clilverd, A.J. Smith, C.L. Waters, D.K. Milling, B.J. Fraser, Monitoring spatial and temporal variations in the dayside plasmasphere using geomagnetic field line resonances. *J. Geophys. Res.* **104**(A9), 19955–19969 (1999)
- M.B. Moldwin, M.F. Thomsen, S.J. Bame, D.J. McComas, K.R. Moore, An examination of the structure and dynamics of the outer plasmasphere using multiple geosynchronous satellites. *J. Geophys. Res.* **99**(A6), 11475–11481 (1994)
- M.B. Moldwin, L. Downward, H.K. Rassoul, R. Amin, R.R. Anderson, A new model of the location of the plasmapause: CRRES results. *J. Geophys. Res.* **107**(A11), 1339 (2002)
- T.E. Moore, W.K. Peterson, C.T. Russell, M.O. Chandler, M.R. Collier, H.L. Collin, P.D. Craven, R. Fitzenreiter, B.L. Giles, C.J. Pollock, Ionospheric mass ejection in response to a CME. *Geophys. Res. Lett.* **26**(15), 2339–2342 (1999)
- F.S. Mozer, C.A. Cattell, M. Temerin, R.B. Torbert, S. Von Glinski, M. Woldorff, J. Wygant, The DC and AC electric field, plasma density, plasma temperature, and field-aligned current experiments on the S3-3 satellite. *J. Geophys. Res.* **84**(A10), 5875–5884 (1979)
- A. Nishida, Formation of plasmapause, or magnetospheric plasma knee, by the combined action of magnetospheric convection and plasma escape from the tail. *J. Geophys. Res.* **71**(23), 5669–5679 (1966)
- P.A. Nsumei, X. Huang, B.W. Reinisch, P. Song, V.M. Vasyliunas, J.L. Green, S.F. Fung, R.F. Benson, D.L. Gallagher, Electron density distribution over the northern polar region deduced from IMAGE/radio plasma imager sounding. *J. Geophys. Res.* **108**(A2), 1078 (2003)
- P.A. Nsumei, B.W. Reinisch, P. Song, J. Tu, X. Huang, Polar cap electron density distribution from IMAGE radio plasma imager measurements: Empirical model with the effects of solar illumination and geomagnetic activity. *J. Geophys. Res.* **113**, A01217 (2008)
- T.P. O'Brien, M.B. Moldwin, Empirical plasmapause models from magnetic indices. *Geophys. Res. Lett.* **30**(4), 1152 (2003)

- S. Ohtani, H. Korth, P.C. Brandt, L.G. Blomberg, H.J. Singer, M.G. Henderson, E.A. Lucek, H.U. Frey, Q. Zong, J.M. Weygand, Y. Zheng, A.T.Y. Lui, Cluster observations in the inner magnetosphere during the 18 April 2002 sawtooth event: Dipolarization and injection at $r = 4.6 R_E$. *J. Geophys. Res.* **112**, A08213 (2007)
- V.A. Osherovich, R.F. Benson, J. Fainberg, J.L. Green, L. Garcia, S. Boardsen, N. Tsyganenko, B.W. Reinisch, Enhanced high-altitude polar cap plasma and magnetic field values in response to the interplanetary magnetic cloud that caused the great storm of 31 March 2001: A case study for a new magnetospheric index. *J. Geophys. Res.* **112**, A06247 (2007)
- V.O. Papitashvili, B.A. Belov, D.S. Faermak, Y.I. Feldstein, S.A. Golyshev, L.I. Gromova, A.E. Levitin, Electric potential patterns in the northern and southern polar regions parameterized by the interplanetary magnetic field. *J. Geophys. Res.* **99**(A7), 13251–13262 (1994)
- C.G. Park, D.L. Carpenter, D.B. Wiggins, Electron density in the plasmasphere: Whistler data on solar cycle, annual, and diurnal variations. *J. Geophys. Res.* **83**(A7), 3137–3144 (1978)
- G. Paschmann, J.M. Quinn, R.B. Torbert, H. Vaith, C.E. McIlwain, G. Haerendel, O.H. Bauer, T. Bauer, W. Baumjohann, W. Fillius, M. Förster, S. Frey, E. Georgescu, S.S. Kerr, C.A. Kletzing, H. Matsui, P. Puhl-Quinn, E.C. Whipple, The Electron Drift Instrument on Cluster: overview of first results. *Ann. Geophys.* **19**(10–12), 1273–1288 (2001)
- A.M. Persoon, D.A. Gurnett, S.D. Shawhan, Polar cap electron densities from DE 1 plasma wave observations. *J. Geophys. Res.* **88**(A12), 10123–10136 (1983)
- V. Pierrard, The dynamics of the plasmasphere, in *Space Science: New Research*, ed. by N.S. Maravell (Nova Science, New York, 2006), pp. 83–96
- V. Pierrard, J. Cabrera, Comparisons between EUV/IMAGE observations and numerical simulations of the plasmopause formation. *Ann. Geophys.* **23**(7), 2635–2646 (2005)
- V. Pierrard, J. Cabrera, Dynamical simulations of plasmopause deformations. *Space Sci. Rev.* **122**(1–4), 119–126 (2006)
- V. Pierrard, J. Lemaire, Exospheric model of the plasmasphere. *J. Atmos. Sol. Terr. Phys.* **63**(11), 1261–1265 (2001)
- V. Pierrard, K. Stegen, A three-dimensional dynamic kinetic model of the plasmasphere. *J. Geophys. Res.* **113**, A10209 (2008)
- V. Pierrard, G.V. Khazanov, J. Cabrera, J. Lemaire, Influence of the convection electric field models on predicted plasmopause positions during magnetic storms. *J. Geophys. Res.* **113**, A08212 (2008a)
- V. Pierrard, J. Goldstein, N. André, V.K. Jordanova, G.A. Kotova, J.F. Lemaire, M.W. Liemohn, H. Matsui, Recent progress in physics-based models of the plasmasphere. *Space Sci. Rev.* (2008b), this issue
- J.H. Pope, An estimate of electron densities in the exosphere by means of Nose Whistlers. *J. Geophys. Res.* **66**(1), 67–75 (1961)
- I.A. Price, C.L. Waters, F.W. Menk, G.J. Bailey, B.J. Fraser, A technique to investigate plasma mass density in the topside ionosphere using ULF waves. *J. Geophys. Res.* **104**(A6), 12723–12732 (1999)
- P.A. Puhl-Quinn, H. Matsui, V.K. Jordanova, Y. Khotyaintsev, P.A. Lindqvist, An effort to derive an empirically based, inner-magnetospheric electric field model: Merging Cluster EDI and EFW data. *J. Atmos. Sol. Terr. Phys.* **70**(2–4), 564–573 (2008)
- B.W. Reinisch, D.M. Haines, K. Bibl, G. Cheney, I.A. Galkin, X. Huang, S.H. Myers, G.S. Sales, R.F. Benson, S.F. Fung, J.L. Green, S. Boardsen, W.W.L. Taylor, J.L. Bougeret, R. Manning, N. Meyer-Vernet, M. Moncuquet, D.L. Carpenter, D.L. Gallagher, P. Reiff, The Radio Plasma Imager investigation on the IMAGE spacecraft. *Space Sci. Rev.* **91**(1–2), 319–359 (2000)
- B.W. Reinisch, X. Huang, P. Song, G.S. Sales, S.F. Fung, J.L. Green, D.L. Gallagher, V.M. Vasyliunas, Plasma density distribution along the magnetospheric field: RPI observations from IMAGE. *Geophys. Res. Lett.* **28**(24), 4521–4524 (2001a)
- B.W. Reinisch, D.M. Haines, R.F. Benson, J.L. Green, G.S. Sales, W.W.L. Taylor, Radio sounding in space: magnetosphere and topside ionosphere. *J. Atmos. Sol. Terr. Phys.* **63**(2–3), 87–98 (2001b)
- B.W. Reinisch, X. Huang, P. Song, J.L. Green, S.F. Fung, V.M. Vasyliunas, D.L. Gallagher, B.R. Sandel, Plasmaspheric mass loss and refilling as a result of a magnetic storm. *J. Geophys. Res.* **109**, A01202 (2004)
- H. Rème, C. Aoustin, J.M. Bosqued, I. Dandouras, B. Lavraud, J.A. Sauvaud, A. Barthe, J. Bouyssou, Th. Camus, O. Coeur-Joly, A. Cros, J. Cuvelo, F. Ducay, Y. Garbarowitz, J.L. Médale, E. Penou, H. Perrier, D. Romefort, J. Rouzaud, C. Vallat, D. Alcaydé, C. Jacquey, C. Mazelle, C. d'Uston, E. Möbius, L.M. Kistler, K. Crocker, M. Granoff, C. Mouikis, M. Popecki, M. Vosbury, B. Klecker, D. Hovestadt, H. Kucharek, E. Kuenneth, G. Paschmann, M. Scholer, N. Sckopke, E. Seidenschwang, C.W. Carlson, D.W. Curtis, C. Ingraham, R.P. Lin, J.P. McFadden, G.K. Parks, T. Phan, V. Formisano, E. Amata, M.B. Bavassano-Cattaneo, P. Baldetti, R. Bruno, G. Chionchio, A. Di Lellis, M.F. Marcucci, G. Pallochia, A. Korth, P.W. Daly, B. Graeve, H. Rosenbauer, V. Vasyliunas, M. McCarthy, M. Wilber, L. Eliasson, R. Lundin, S. Olsen, E.G. Shelley, S. Fuselier, A.G. Ghielmetti, W. Lennartsson, C.P. Escoubet,

- H. Balsiger, R. Friedel, J.-B. Cao, R.A. Kovrazhkin, I. Papamastorakis, R. Pellat, J. Scudder, B. Sonnerup, First multi-spacecraft ion measurements in and near the Earth's magnetosphere with the identical Cluster Ion Spectrometry (CIS) experiment. *Ann. Geophys.* **19**(10–12), 1303–1354 (2001)
- A.D. Richmond, Y. Kamide, Mapping electrodynamic features of the high-latitude ionosphere from localized observations: Technique. *J. Geophys. Res.* **93**(A6), 5741–5759 (1988)
- J.M. Ruohoniemi, R.A. Greenwald, Dependencies of high-latitude plasma convection: Consideration of interplanetary magnetic field, seasonal, and universal time factors in statistical patterns. *J. Geophys. Res.* **110**, A09204 (2005)
- B.R. Sandel, R.A. King, W.T. Forrester, D.L. Gallagher, A.L. Broadfoot, C.C. Curtis, Initial results from the IMAGE Extreme Ultraviolet Imager. *Geophys. Res. Lett.* **28**(8), 1439–1442 (2001)
- S. Schäfer, K.H. Glassmeier, P.T.I. Eriksson, V. Pierrard, K.H. Fornacon, L.G. Blomberg, Spatial and temporal characteristics of poloidal waves in the terrestrial plasmasphere: a CLUSTER case study. *Ann. Geophys.* **25**(4), 1011–1024 (2007)
- S. Schäfer, K.H. Glassmeier, P.T.I. Eriksson, P.N. Mager, V. Pierrard, K.H. Fornacon, L.G. Blomberg, Spatio-temporal structure of a poloidal Alfvén wave detected by Cluster adjacent to the dayside plasmapause. *Ann. Geophys.* **26**(7), 1805–1817 (2008)
- N. Sckopke, A general relation between the energy of trapped particles and the disturbance field near the earth. *J. Geophys. Res.* **71**(13), 3125–3130 (1966)
- B.W. Sheeley, M.B. Moldwin, H.K. Rassoul, R.R. Anderson, An empirical plasmasphere and trough density model: CRRES observations. *J. Geophys. Res.* **106**(A11), 25631–25641 (2001)
- N. Singh, J.L. Horwitz, Plasmaspheric refilling: Recent observations and modelling. *J. Geophys. Res.* **97**(A2), 1049–1079 (1992)
- G. Siscoe, D. Baker, R. Weigel, J. Hughes, H. Spence, Roles of empirical modeling within CISM. *J. Atmos. Sol. Terr. Phys.* **66**(15–16), 1481–1489 (2004)
- C.W. Smith, J. L'Heureux, N.F. Ness, M.H. Acuña, L.F. Burlaga, J. Scheifele, The ACE magnetic fields experiment. *Space Sci. Rev.* **86**(1–4), 613–632 (1998)
- R.L. Smith, Properties of the outer ionosphere deduced from nose whistlers. *J. Geophys. Res.* **66**(11), 3709–3716 (1961)
- J.J. Sojka, C.E. Rasmussen, R.W. Schunk, An interplanetary magnetic field dependent model of the ionospheric convection electric field. *J. Geophys. Res.* **91**(A10), 11281–11290 (1986)
- P. Song, B.W. Reinisch, X. Huang, Magnetospheric active wave measurements. *COSPAR Colloq. Ser.* **16**, 235–246 (2004)
- D.P. Stern, The motion of a proton in the equatorial magnetosphere. *J. Geophys. Res.* **80**(4), 595–599 (1975)
- D.P. Stern, Large-scale electric fields in the Earth's magnetosphere. *Rev. Geophys. Space Phys.* **15**(2), 156–194 (1977)
- L.R.O. Storey, An investigation of whistling atmospherics. *Philos. Trans. R. Soc. (Lond.) A* **246**, 113–141 (1953)
- K. Takahashi, R.E. Denton, R.R. Anderson, W.J. Hughes, Frequencies of standing Alfvén wave harmonics and their implication for plasma mass distribution along geomagnetic field lines: Statistical analysis of CRRES data. *J. Geophys. Res.* **109**, A08202 (2004)
- A. Tarantola, *Inverse Problem Theory* (Elsevier, Amsterdam, 1987), p. 613
- N.A. Tsyganenko, A model of the near magnetosphere with a dawn-dusk asymmetry 1. Mathematical structure. *J. Geophys. Res.* **107**(A8), 1179 (2002)
- N.A. Tsyganenko, D.P. Stern, Modeling the global magnetic field of the large-scale Birkeland current systems. *J. Geophys. Res.* **101**(A12), 27187–27198 (1996)
- J. Tu, J.L. Horwitz, T.E. Moore, Simulating the cleft ion fountain at polar perigee altitudes. *J. Atmos. Sol. Terr. Phys.* **67**(5), 465–477 (2005a)
- J. Tu, P. Song, B.W. Reinisch, X. Huang, J.L. Green, H.U. Frey, P.H. Reiff, Electron density images of the middle- and high-latitude magnetosphere in response to the solar wind. *J. Geophys. Res.* **110**, A12210 (2005b)
- J. Tu, P. Song, B.W. Reinisch, J.L. Green, X. Huang, Empirical specification of field-aligned plasma density profiles for plasmasphere refilling. *J. Geophys. Res.* **111**, A06216 (2006)
- J.N. Tu, M. Dhar, P. Song, B.W. Reinisch, J.L. Green, R.F. Benson, A.J. Coster, Extreme polar cap density enhancements along magnetic field lines during an intense geomagnetic storm. *J. Geophys. Res.* **112**, A05201 (2007)
- A.F. Viñas, R.L. Mace, R.F. Benson, Dispersion characteristics for plasma resonances of Maxwellian and Kappa distribution plasmas and their comparisons to the IMAGE/RPI observations. *J. Geophys. Res.* **110**, A06202 (2005)
- H. Volland, A semiempirical model of large-scale magnetospheric electric fields. *J. Geophys. Res.* **78**(1), 171–180 (1973)

- H. Volland, A model of the magnetospheric electric convection field. *J. Geophys. Res.* **83**(A6), 2695–2699 (1978)
- C.L. Waters, F.W. Menk, M.F. Thomsen, C. Foster, F.R. Fenrich, Remote sensing of the magnetosphere using ground-based observations of ULF waves, in *Magnetospheric ULF Waves: Synthesis and New Directions*, ed. by K. Takahashi, P.J. Chi, R.E. Denton, R.L. Lysak. Geophysical Monograph Series, vol. 169 (American Geophysical Union, Washington, 2006), pp. 319–340
- P.A. Webb, R.F. Benson, R.E. Denton, J. Goldstein, L.N. Garcia, B.W. Reinisch, An inner-magnetospheric electron density database determined from IMAGE/RPI passive dynamic spectra. *EOS Trans. AGU* **88**(52), SM12A–04 (2007)
- D.R. Weimer, A flexible, IMF dependent model of high-latitude electric potentials having “space weather” applications. *Geophys. Res. Lett.* **23**(18), 2549–2552 (1996)
- D.R. Weimer, Improved ionospheric electrodynamic models and application to calculating Joule heating rates. *J. Geophys. Res.* **110**, A05306 (2005)

Index

A

abundance, 14–15, 20, 58, 61–62, 73–75, 166, 182, 183, 208, 215, 254
ACE, 27–28, 115–116, 233–234, 252
active mode, 21, 23, 30–31, 33, 35, 58–59, 140–141, 235, 237
airglow, 21
Akebono, 15, 123
Alfvén wave, 76, 205, 208, 235–242
Alouette, 12–13, 204
auroral zone, 20–22, 121, 158, 177, 197–198, 202, 233, 238, 244
 auroral kilometric radiation (AKR), 30, 32, 141, 150
 auroral oval ultraviolet emission, 20–21, 25

B

bow shock, 24, 43
bulge, 10, 12, 66, 111, 195

C

calibration
 of multi-spacecraft instruments, 23
 of plasmaspheric images, 25
channel, 26, 58, 78–80, 90, 196
chorus, 17, 139, 171–173, 176–177, 181
CLUSTER
 mission, 9–10, 20, 23–24, 36–37, 42–43, 56, 58–60, 108, 112, 114, 138–140, 233–234
 Cluster Ion Spectrometer (CIS), 11, 23, 60, 65, 75–76, 80, 112, 204, 208, 236, 250, 254
 Electric Field and Wave (EFW), 23–24, 60, 80–81, 112, 140, 250–252

Electron Drift Instrument (EDI), 24, 60, 80, 82, 96, 112–119, 250–252
FluxGate Magnetometer (FGM), 23, 112, 125, 127–128, 250
Spatio-Temporal Analysis of Field Fluctuations (STAFF), 140, 179
Waves of High frequency and Sounder for Probing of Electron density by Relaxation (WHISPER) 23, 30, 34–36, 39, 58–60, 68–72, 76–83, 87, 91, 95, 125–126, 140, 147–148, 154–155, 174, 204, 213, 220
Wide Band Data (WBD), 140, 147, 172, 174, 179–180
column abundance, 27, 61–62, 66, 73–74, 141
continuum, *see* kilometric continuum, non-thermal continuum
convection, 12, 17, 19, 28–29, 43, 57, 64–65, 89–90, 246–249, 251, 253–254
corotation, 26–27, 61–65, 79–82, 86–89, 95, 112, 115, 204–207, 211–213, 246–249, 253–254
Cosmos, 17
Coulomb collisions, 202, 213, 216–217, 220
crenulation, 58, 90, 195
CRRES, 17–18, 57, 60, 74, 92, 139, 142–147, 176, 232, 236
curlometer
 classical, 37, 40
 least-squares, 41
current density, 37, 40, 76, 124–128
current system, 195–198
 solar-quiet-time (SQ) current system, 109–110, 116

D

- data accumulation, 27
- data interpretation, 8, 198–199
 - single-spacecraft, 9–14, 18
 - multi-spacecraft, 17
- data mining, 26, 32
- Demeter, 139, 171, 173
- detached plasma elements, 19, 57, 76
- detector potential bias, 8, 11, 23
- diamagnetic effect, 126, 128
- differential rotation, 28, 90
- diffusive equilibrium, 64, 161, 167, 208, 211–214, 221
- direction finding, 36, 142–145, 177
- divergence of a vector field, 38, 41
- DMSP, 28, 88–89, 113, 120–124, 253
- Double Star, 139, 171–172
- ducted wave propagation, 31, 157–160
- dynamic spectrum, *see* spectrogram
- Dynamics Explorer (DE), 15–16, 60, 116, 138–139, 147, 153–154, 176, 182–183, 232, 235, 244

E

- echo
 - delay time, 22, 156, 159–170, 237
 - diffuse echo, 92–93, 162–166
 - discrete echo, 22, 31, 92–93, 159–168
 - echo from conjugate hemisphere, 22, 91
 - echo trace in a plasmagram, 21–22, 30–33, 92–93, 159, 162, 237–240
 - proton cyclotron echo, 165–171
- E-cross-B drift (ExB drift), 27–29, 112, 114, 119–120, 200, 209–210, 221, 250
- edge algorithm, 25–26
- electric field
 - convection electric field, 17, 23–24, 26, 57, 65, 90, 96, 108, 111–112, 116, 119–121, 195–196, 200–201, 204–205, 209, 211, 219, 246–249, 253
 - corotation electric field, 20, 65, 111, 115, 205, 209, 211, 246–249, 253
 - dawn-to-dusk electric field, 8, 20, 26–27, 111, 116, 120, 247
 - interplanetary electric field, 66, 77–78, 112, 117–118, 121, 252
 - ionospheric electric field, 85, 92, 118, 248
 - magnetospheric electric field, 8, 60, 64, 66, 70, 78, 90, 109, 112–121, 232, 246–253
 - meso-scale electric field, 20, 27, 58, 70, 79–80, 87, 90

- plasmaspheric electric field, 28, 129, 196
- polarization electric field, *see* shielding
- electric potential, 8, 23, 57, 89, 116–117, 194–199, 204–205, 209–210, 213, 246–254
- electromagnetic ion cyclotron (EMIC) waves, 202–203
- Electron, 12–14
- empirical model
 - electric field model, 89, 113, 119–121, 194–199, 205, 232–233, 246–247, 250
 - equatorial density model, 64, 161, 183, 194, 208, 215, 233–234, 243
 - field-aligned density model, 25, 31, 221, 234
 - geomagnetic activity dependence, 244, 247
 - inner magnetospheric electric field model, 117, 232–233, 247–252
 - plasma pause model, 253–254
 - plasmaspheric density model, 18, 64, 71, 76, 160, 167, 181, 232, 238–240, 244
 - polar magnetospheric density model, 244–246
 - solar illumination dependence, 244
- equatorial noise, 148–155
- equatorial spots, 178–181
- erosion
 - as a plasma loss, 8, 57, 65–66, 113, 119–121, 204, 233
 - dynamics, 15, 19, 26, 28–29, 58, 77
- exospheric equilibrium, 211, 213–214
- extreme ultraviolet
 - resonant scattering, 20, 58
 - solar flux, 25

F

- field-aligned current (FAC), 31, 40, 120–121, 124, 218, 258
- finger, 58, 90–91
- fluid theory, 195–203, 217–221
- flux tube, 18, 25, 27, 31, 62, 65–66, 74, 77, 92, 121–124, 154, 182, 200, 205–208, 211–221, 235, 240–244, 254
- Fokker-Planck equation, 216–217, 220
- Freja, 173
- frictional heating, 121

G

- geomagnetic activity, 13, 15, 27, 42, 45, 57, 61–62, 65, 73, 76–77, 81, 83, 85–86, 142, 174–175, 178, 183, 215, 234, 242–246
- disturbed time, 15, 45, 61, 63, 85–86, 96, 117, 121, 146, 175, 177, 183, 204–205, 209, 235
- Dst index, 83, 85, 95, 112, 200, 206, 241–242, 250, 252
- geomagnetic storm, 10–11, 32, 34, 57–58, 65–67, 77, 84–86, 89–90, 109, 112–114, 117, 121, 173, 175, 181, 183, 194–201, 206, 221, 240–242, 251, 254
- geomagnetic substorm, 66, 77, 108–114, 117–118, 120, 124, 178, 204–206, 209, 219, 248
- Kp index, 10, 14, 18–19, 27, 63–65, 68, 72–75, 78, 80, 83, 96, 112, 115, 178, 199–201, 204, 206, 215, 232, 244–250
- quiet time, 61–65, 73, 75, 77, 81, 83, 85–86, 90–92, 108–112, 115, 176–178, 208, 241–242
- GEOS, 13–15, 60
- geosynchronous satellites, 17, 57, 60, 82, 116, 119, 198–199, 210, 221, 233, 247
- Geotail, 141–146, 210
- global imaging, 20–21, 24, 35, 43, 56–58, 65–67, 77, 90, 112, 140, 195, 205, 233
- global positioning system (GPS), 18, 28, 45, 77, 84–86, 221
- gradient
 - of density, 8, 12, 19, 38–39, 62, 68–72, 86, 90, 93, 95, 146, 154, 164–165, 196–197, 200–201, 204–208, 220, 252
 - of magnetic field, 23, 108, 113, 125–128
- gradient computation
 - classical gradient computation, 24, 37–40, 68–69, 125–127
 - error estimates, 39, 42, 69, 125–128
 - least-squares gradient computation, 40–42, 68–69, 125–128
 - with single-spacecraft, 37

H

- heavy ions, 14, 26, 36, 62, 73, 182–184, 235
- helium, 11–16, 20, 26–28, 36, 58, 61–62, 66–67, 73–76, 139–141, 161, 166, 173, 201–204, 219, 221, 235

- homogeneity condition, 24, 38–42, 68, 125
- hydrogen, 11–16, 20, 36, 62, 73–77, 140, 161, 166–167, 183, 235

I**IMAGE**

- mission, 8–10, 20–22, 24, 26, 28–31, 34, 43, 56, 58, 108, 112–113, 138–140, 194–196, 232–233
- energetic neutral atom imagers (HENA/MENA/LENA), 21, 25, 28, 43
- Extreme UltraViolet (EUV) imager, 20–21, 24–30, 36, 43, 58, 61–62, 66–67, 73–78, 82, 84–91, 112, 118–122, 139–144, 195–197, 201, 204–206, 208, 232–237, 241, 253–254
- Far UltraViolet (FUV) imager, 28, 202–203
- Radio Plasma Imager (RPI), 21–23, 26, 28–35, 43, 58–59, 62–68, 73–74, 86, 91–94, 139–142, 157–170, 176, 183, 201, 206, 213, 220, 233–245, 254
- image artifacts, 24, 28
- image noise removal, 24–25, 28–29
- IMP, 11, 13, 232
- in situ observation, 8–12, 17, 20, 25–28, 30, 34–35, 56–58, 64, 73, 77, 82, 85, 92, 108, 112–114, 119, 122–124, 195, 198, 221, 232–237, 244, 250–251
- Interball, 17
- interchange, 57, 65, 89, 91–92, 204–208, 210–212, 253
- Intercosmos, 16–17
- interplanetary medium, *see* solar wind
- inversion, 116
 - of GPS signal propagation delays, 18
 - of plasmaspheric images, 20, 25–27, 237
 - of wave echo traces in plasmagrams, 31, 160, 237–238
- ion composition, 8, 16, 23, 28, 60, 73–76, 161, 167, 202, 234–235
- ion mass, 36, 62, 75–76, 166, 183, 234–236
- ionosphere, 8, 11, 13, 17–18, 27, 31, 45, 61–64, 66, 74–77, 84–91, 108, 112, 116, 119–124, 138, 156–158, 161–167, 195–196, 200–201, 204, 206, 212–213, 216–221, 233–236, 252
- ionospheric conductivity, 65, 119–121, 124, 196–198, 218
- ionospheric density trough, 85–86, 121, 204
- ionospheric dynamo, 89, 108–110, 113, 116–117, 119

ionospheric recombination, 121, 219
 ionospheric total electron content (TEC), 18,
 28, 77, 84–86, 221
 ISEE, 14–16, 18, 57, 60, 214–215, 232
 ISIS, 12, 156, 159, 167, 170, 178

K

kilometric continuum (KC), 22, 30, 32, 87–88,
 139, 141–147, 154–155
 kinetic model, 19, 64, 202, 212–213, 215–216,
 218–220, 254
 kinetic theory, 194, 204, 216–220

L

LANL satellite, 17, 28, 57, 82, 92, 196, 198–
 199, 210, 221
 last closed equipotential (LCE), 65, 209, 247–
 248, 253–254
 last closed streamline (LCS), 253–254
 light ion trough, 13, 204
 lower hybrid resonance (LHR), 12–13, 18,
 164, 166, 173
 L-shell, 9, 11, 13–14, 27, 59–64, 66–71, 73–
 76, 78, 80, 83–84, 87–95, 109–114,
 116–119, 123, 128, 139, 144, 146,
 149, 156, 158, 160–162, 165–168,
 172, 175, 177, 182–183, 195, 200–
 202, 206, 209, 211–217, 233–243,
 248, 251–252
 Lunik, 8–10, 13

M

Magion, 17
 magnetic field, 23, 25, 31–35, 37, 40–41, 68–
 69, 72–73, 92, 94, 108, 112–114,
 121–128, 140, 147–148, 152–153,
 157, 161, 166, 169, 172, 178–181,
 196, 205–209, 211, 218, 232, 235,
 246, 250–252
 geomagnetic field, 66, 157, 168, 200, 207,
 255
 interplanetary magnetic field (IMF), 27, 57,
 66, 78, 90, 99, 113, 115–119, 206,
 209, 232
 magnetic field line, 8–9, 19, 22, 31, 43,
 57, 60, 62–66, 73, 75–76, 80–81, 94,
 113, 116, 121, 123, 125–128, 139,
 148, 160–161, 177, 182, 204, 207–
 208, 211–213, 217, 219–220, 234–
 235, 237, 250, 252
 magnetic storm, *see* geomagnetic activity

magnetohydrodynamics (MHD), 19, 89, 205–
 206, 218–219
 magnetopause, 8, 24, 34, 40, 43, 66, 76, 99,
 119, 155, 182, 202, 205, 208–211
 magnetosphere, 24, 57, 65, 67, 89, 91, 108,
 112, 117, 120–124, 141, 146, 155–
 156, 171, 196, 200, 202, 207, 218,
 221, 237–238, 246–247
 inner magnetosphere, 8, 20, 22, 27, 43–45,
 57, 66, 89, 99, 114, 118–121, 128,
 140, 182, 195–198, 202, 205, 208,
 232–233, 250, 254
 magnetosphere-ionosphere (M-I) coupling,
 17, 43, 61–62, 66, 77, 84–86, 89,
 112–113, 116–117, 119, 121–122,
 161, 200–201
 polar magnetosphere, 22, 31, 68, 84, 115,
 118–119, 232–233, 237–238, 244–
 245
 magnetotail, 40, 177, 202, 208
 measurement
 in situ, *see* in situ observation
 multi-point, 24, 56–58, 60, 67, 81, 84, 147,
 151, 172, 179, 180, 233, 237, 255
 multi-spacecraft, 17, 20, 24, 35–36, 40–42,
 44, 57, 59, 81, 99, 122–123, 233, 248
 remote sensing, *see* remote sensing
 single-point, 15, 37, 109
 single-spacecraft, 8, 19, 24, 37, 57, 60
 mid-latitude hiss, 174, 176–178
 minimum-L algorithm, 26, 28
 model
 empirical model, *see* empirical model
 kinetic model, *see* kinetic model
 physics-based model, *see* physics-based
 model
 Monte-Carlo simulation, 216–218
 multi-spacecraft configuration
 coplanarity, 24, 37, 127
 geometric factors, 37, 42, 68, 125
 separation, 24, 37–43, 59–60, 68, 70, 72,
 78, 80–81, 95, 125, 147–148, 171

N

narrow band elements, 148–151, 155
 non-thermal continuum (NTC), 22, 30, 141,
 145, 147–156
 notch, 26–28, 44, 58, 60, 63, 86–89, 142–146,
 195

O

OGO, 11–14, 56–57, 91, 213, 247

oxygen, 9, 11, 14, 17, 26, 36, 73–77, 97, 161, 166–167, 183, 202–203, 217, 219, 235

P

passive mode, 21–23, 30, 32, 34–35, 58–59, 64, 140–142, 235–236

photo-electron, 8, 23, 217, 251

physics-based model, 26, 44, 77, 194, 221, 232, 247

pitch angle, 84, 97, 115, 175–176, 181, 202, 213, 215–216

plasma frequency, 59, 70–71, 79, 139–141, 150, 152, 154–158, 161–164, 167, 170

plasmagram, 21, 30–33, 92–93, 158–159, 162–169, 237–238

plasma pause

characteristics, 9, 12–13, 17, 59–60, 64–65, 70–72, 76, 90–93, 112–113, 119–121, 141–142, 145–150, 153–157, 177–178, 181, 195, 220, 233, 237, 253–254

formation, 8, 12, 15, 19, 63, 65, 108, 194, 199–200, 204–205, 212–213, 232, 247, 253–254

position, 12–14, 25–28, 57, 63–67, 70–73, 79–80, 84–86, 92, 120, 142–143, 177–178, 182, 196–201, 205, 232–236, 239–240, 247, 253–254

thickness, 12, 15, 72–73, 96, 206

undulation, 63, 66–67, 79, 90, 120

velocity/motion, 18, 24, 26, 28, 66, 74, 77, 112, 119–120, 146, 150, 234, 241

plasmasphere

depletion, 142, 239, 241

discovery, 8–9, 194

erosion, *see* erosion

evolution, 8, 26, 44, 61–66, 112, 182, 196, 198, 241, 253

refilling, *see* refilling

topology, 10, 19

plasmasphere boundary layer (PBL), 17–18, 57, 92–94, 112, 117, 121, 146, 156, 169, 177, 209–210, 215

plasmaspheric density

2-D density image, 19, 22, 24–32, 62–63, 67, 215, 238–239

density gradient, *see* gradient

distribution/profiles, 9–18, 22, 25, 31–32, 35, 59–60, 64, 67–70, 72–76, 79, 81,

83, 91, 93–96, 142, 145–146, 155, 160, 167, 183, 194–196, 199–201, 204, 206, 211, 214–217, 219, 221, 232–244, 254

diurnal variations, 11, 27, 61–62

electron density, 8–11, 17–19, 22–23, 31, 34, 59, 62–65, 68–69, 76–77, 80–82, 125–126, 165–167, 182–183, 200, 215, 218, 234–240, 244–246

equatorial density distribution, 9–10, 20, 26–29, 61–62, 64, 73, 81, 161, 182–183, 196–197, 202–204, 208, 211–215, 220–221, 237, 239–244

field-aligned density distribution, 8, 22, 25, 31, 59, 62–63, 67–68, 75, 91, 94, 161, 207, 211–216, 221, 234–237, 239, 242–244

heavy ion density, *see* heavy ions

ion density, 11–15, 20, 26, 62, 75–77, 183, 202, 218–219, 221

irregularities, 17–18, 25, 31, 43, 56–58, 60, 91–96, 109, 144–145, 150, 154, 156, 164, 195

mass density, 36, 62, 73–77, 182–183, 234–237

thermal plasma density, 11, 17, 58, 196, 214, 232

trough, 14, 23, 121, 142

plasmaspheric hiss, 17–18, 30, 32, 173–176, 178

plasmaspheric temperature, 8, 13–15, 17, 161, 214

plasmaspheric wind, 60, 65, 89, 130, 205–208, 212–213

plasmatrrough, 12, 18, 26, 63, 68, 76, 93–94, 213, 233–238, 241–244

plume

characteristics, 17–18, 28, 34–35, 57–58, 63, 66, 75–86, 90, 95, 113, 120–122, 175, 196–198, 202, 233–234, 241

formation, 8, 12, 57, 65–66, 77, 80, 82, 85, 97, 121, 195–200, 204–209, 254

motion/evolution, 8, 13–14, 26, 43–44, 57, 66, 77, 80–82, 84, 120, 241

orientation, 26, 77, 80, 82, 90

POLAR, 18–19, 23, 177, 235, 244

polarization jet (PJ), *see* subauroral ion drift

polar wind, 216–220

Prognoz, 13–14

pseudo-density, 26–29, 87, 236–237

R

- radiation belt, 8, 18, 44–45, 75, 171, 175–176, 181, 202, 222
- radio sounding, 9, 18, 21, 30–31, 64, 67–68, 74–75, 92–93, 141, 156, 161, 233–239, 242–244
- ray tracing, 31–32, 44, 142–146, 155, 163–164, 167, 173, 181
- refilling
 - as a plasma source, 8, 31, 36, 44, 57–66, 200, 216–220, 240–241, 244
 - refilling rate, 19–20, 26–27, 31, 61–66, 241
 - saturation, 31, 64, 241
- remote sensing, 9–10, 18, 20, 35, 44, 62, 73, 75, 92, 160–161, 167, 232–233, 237
- residue image, 27
- resonance, 12, 22–23, 30–36, 74, 140, 145, 163–171, 176, 181–183, 234, 254
- ring current, 8, 21, 28, 43, 45, 181, 195–196, 198, 202, 248, 252
 - determination, 40, 76, 84, 119, 121, 129
 - partial ring current, 66, 113, 116, 120

S

- SAID, *see* subauroral ion drift
- SAPS, *see* subauroral polarization stream
- shielding, 20, 66, 90, 113, 116–117, 120–121, 178, 195–196, 209, 234, 248, 253
- shoulder, 21, 26, 58, 90, 195
- SOHO, 25
- solar wind, 8, 12, 26–27, 64–65, 112, 116, 118–119, 182, 205, 209, 219, 232–234, 246–249, 252
- solar wind-magnetosphere interaction, 8, 12, 26, 57, 112–113, 116–120
- spacecraft potential
 - control, 8, 11
 - effects, 11, 75
 - measurement, 23, 181, 233, 251
- spectrogram, 12–13, 22, 30–35, 64, 70, 78–79, 87, 141–142, 148, 152–156, 172, 174, 178–180, 201, 212
- stagnation point, 111, 209–210, 248
- storm, *see* geomagnetic activity
- storm enhanced density (SED), 121
- straylight (in EUV images), 25, 28, 30
- subauroral ion drift (SAID), 8, 20, 108, 113, 116–124
- subauroral polarization streams (SAPS), 8, 20, 28, 43, 66, 108, 111, 113–122, 196, 210, 221, 253

- sub-corotation, 27, 88–89, 130, 208
- substorm, *see* geomagnetic activity
- super-corotation, 89
- suprathermal particles, 214, 216

T

- TEC, *see* ionospheric total electron content
- THEMIS, 44, 99, 184
- time-delay analysis, 42–43, 72, 81–82, 95–96
- trace, *see* echo

U

- ultra low frequency (ULF)
 - resonances, 181–183
 - waves, 90–91, 113, 116, 119, 130, 208–210, 233–234
- upper hybrid resonance (UHR), 22, 30, 34–35, 64–65, 145, 151, 164, 166, 173, 235

V

- velocity distribution function (VDF), 60, 65, 75, 181, 202
 - Maxwellian, 211–216, 218
 - Lorentzian, 214–217
 - Kappa, 214, 254
- very low frequency (VLF) waves, 13, 17, 32, 73–74, 91, 130, 176, 182
- virtual range, 22, 30–31, 33, 92, 159, 163, 238

W

- wave-particle interaction, 18, 44, 202, 213, 216–218
- wave polarization, 36, 140, 173, 178–179
- whistler-mode wave, 8, 12, 18, 74, 91–94, 108, 157, 175, 178
 - ducts, 31–32, 43, 73, 91–92, 109, 119
 - generation, 9, 109
 - observations, 9–13, 73–74, 108–112, 159, 164–173, 232
 - propagation, 8, 10, 12, 18, 91–92, 109–111, 164–173, 177
 - reflection, 18, 30–31, 75, 164, 166
 - sounding, 9, 164–167
- wide band emissions, 148–150, 155–156

Z

- zero parallel force (ZPF) surface, 204, 212, 253
- Z-mode waves, 18, 74–75, 156–164, 171

Bibliography

- S. Abe, H. Kawano, J. Goldstein, S. Ohtani, S.I. Solov'yev, D.G. Baishev, K. Yumoto, Simultaneous identification of a plasmaspheric plume by a ground magnetometer pair and IMAGE Extreme Ultraviolet Imager. *J. Geophys. Res.* **111**, A11202 (2006)
- B. Abel, R.M. Thorne, Electron scattering loss in Earth's inner magnetosphere 1. Dominant physical processes. *J. Geophys. Res.* **103**(A2), 2385–2396 (1998)
- M.L. Adrian, D.L. Gallagher, L.A. Avannov, IMAGE EUV observation of radially bifurcated plasmaspheric features: First observations of a possible standing ULF waveform in the inner magnetosphere. *J. Geophys. Res.* **109**, A01203 (2004)
- V.V. Afonin, K.V. Grechnev, V.A. Ershova, O.Z. Rosté, N.F. Smirnova, Y.A. Schul'chishin, Y. Smilauer, Ion composition and temperature of the ionosphere obtained from the Intercosmos 24 satellite ("Aktivnyi" project) at the maximum of the 22nd solar activity cycle. *Cosmic Res.* **32**(2), 189–198 (1994)
- V.V. Afonin, V.S. Bassolo, J. Smilauer, J.F. Lemaire, Motion and erosion of the nightside plasmopause region and of the associated subauroral electron temperature enhancement: Cosmos-900 observations. *J. Geophys. Res.* **102**(A2), 2093–2103 (1997)
- R.R. Anderson, CRRES plasma wave observations during quiet times, during geomagnetic disturbances, and during chemical releases, in *Dusty and Dirty Plasmas, Noise, and Chaos in Space and in the Laboratory*, ed. by H. Kikuchi (Plenum, New York, 1994), pp. 73–96
- B.J. Anderson, R.E. Erlandson, L.J. Zanetti, A statistical study of Pc 1–2 magnetic pulsations in the equatorial magnetosphere 1. Equatorial occurrence distributions. *J. Geophys. Res.* **97**(A3), 3075–3088 (1992)
- P.C. Anderson, W.B. Hanson, R.A. Heelis, J.D. Craven, D.N. Baker, L.A. Frank, A proposed production model of rapid subauroral ion drifts and their relationship to substorm evolution. *J. Geophys. Res.* **98**(A4), 6069–6078 (1993)
- P.C. Anderson, D.L. Carpenter, K. Tsuruda, T. Mukai, F.J. Rich, Multisatellite observations of rapid subauroral ion drifts (SAID). *J. Geophys. Res.* **106**(A12), 29585–29599 (2001)
- N. André, Ondes et instabilités basse-fréquence dans un plasma gyrotrope. Application à l'instabilité d'interchange dans les magnétosphères des planètes géantes. Ph.D. thesis, Université Paul Sabatier, Toulouse, France (2003)
- N. André, K.M. Ferrière, Low-frequency waves and instabilities in stratified, gyrotropic, multicomponent plasmas: Theory and application to plasma transport in the Io torus. *J. Geophys. Res.* **109**, A12225 (2004)
- N. André, J.F. Lemaire, Convective instabilities in the plasmasphere. *J. Atmos. Solar-Terr. Phys.* **68**(2), 213–227 (2006)
- J.J. Angerami, Whistler duct properties deduced from VLF observations made with the Ogo 3 satellite near the magnetic equator. *J. Geophys. Res.* **75**(31), 6115–6135 (1970)
- C.W. Arthur, Digital techniques for ULF wave polarization analysis. *Ann. Telecommunic.* **34**, 166–178 (1979)
- G.J. Bailey, N. Balan, Y.Z. Su, The Sheffield University plasmasphere ionosphere model—A review. *J. Atmos. Solar-Terr. Phys.* **59**(13), 1541–1552 (1997)
- H.F. Balmforth, M.A. Clilverd, A.J. Smith, A case study of storm commencement and recovery plasmaspheric electric fields near $L = 2.5$ at equinox. *Ann. Geophys.* **12**(7), 625–635 (1994)
- A. Balogh, C.M. Carr, M.H. Acuña, M.W. Dunlop, T.J. Beek, P. Brown, K.-H. Fornacon, E. Georgescu, K.-H. Glassmeier, J. Harris, G. Musmann, T. Oddy, K. Schwingenschuh, The Cluster magnetic field

- investigation: Overview of in-flight performance and initial results. *Ann. Geophys.* **19**(10–12), 1207–1217 (2001)
- P.M. Banks, A.F. Nagy, W.I. Axford, Dynamical behavior of thermal protons in mid-latitude ionosphere and magnetosphere. *Planet. Space Sci.* **19**(9), 1053–1067 (1971)
- A.R. Barakat, I.A. Barghouti, The effect of wave-particle interactions on the polar wind O^+ . *Geophys. Res. Lett.* **21**(21), 2279–2282 (1994)
- A.R. Barakat, R.W. Schunk, I.A. Barghouti, J. Lemaire, Monte-Carlo study of the transition from collision-dominated to collisionless polar wind flow, in *Physics of Space Plasmas*, ed. by T. Chang, G.B. Crew, J.R. Jaspers (Scientific Publisher, Cambridge, 1990), pp. 431–437
- A.R. Barakat, I.A. Barghouti, R.W. Schunk, Double-hump H^+ velocity distribution in the polar wind. *Geophys. Res. Lett.* **22**(14), 1857–1860 (1995)
- L.N. Baransky, J.E. Borovkov, M.B. Gokhberg, S.M. Krylov, V.A. Troitskaya, High resolution method of direct measurement of the magnetic field lines' eigen frequencies. *Planet. Space Sci.* **33**(12), 1369–1374 (1985)
- I.A. Barghouti, A.R. Barakat, R.W. Schunk, Monte Carlo study of the transition region in the polar wind: An improved collision model. *J. Geophys. Res.* **98**(A10), 17583–17591 (1993)
- I.A. Barghouti, V. Pierrard, A.R. Barakat, J. Lemaire, A Monte Carlo simulation of the H^+ polar wind: Effect of velocity distributions with kappa suprathermal tails. *Astrophys. Space Sci.* **277**(3), 427–436 (2001)
- I.A. Barghouti, N.M. Doudin, A.A. Saleh, V. Pierrard, High-altitude and high-latitude O^+ and H^+ outflows: the effect of finite electromagnetic turbulence wavelength. *Ann. Geophys.* **25**(10), 2195–2202 (2007)
- I.A. Barghouti, N.M. Doudin, A.A. Saleh, V. Pierrard, The effect of altitude- and velocity-dependent wave-particle interactions on the H^+ and O^+ outflows in the auroral region. *J. Atmos. Solar-Terr. Phys.* **70**(8–9), 1159–1169 (2008)
- S.J. Bauer, On the structure of the topside ionosphere. *J. Atmos. Sci.* **19**(3), 276–278 (1962)
- W. Baumjohann, G. Haerendel, Magnetospheric convection observed between 0600 and 2100 LT: Solar wind and IMF dependence. *J. Geophys. Res.* **90**(A7), 6370–6378 (1985)
- W. Baumjohann, G. Haerendel, F. Melzner, Magnetospheric convection observed between 0600 and 2100 LT: Variations with Kp . *J. Geophys. Res.* **90**(A1), 393–398 (1985)
- W. Baumjohann, R. Nakamura, G. Haerendel, Dayside equatorial-plane convection and IMF sector structure. *J. Geophys. Res.* **91**(A4), 4557–4560 (1986)
- R.F. Benson, Ion effects on ionospheric electron resonance phenomena. *Radio Sci.* **10**(2), 173–185 (1975)
- R.F. Benson, Stimulated plasma waves in the ionosphere. *Radio Sci.* **12**(6), 861–878 (1977)
- R.F. Benson, Elusive upper hybrid waves in the auroral topside ionosphere, in *Auroral Plasma Dynamics*, ed. by R.L. Lysak. Geophysical Monograph Series, vol. 80 (American Geophysical Union, Washington, 1993), pp. 267–274
- R.F. Benson, H.K. Wong, Low-altitude ISIS 1 observations of auroral radio emissions and their significance to the cyclotron maser instability. *J. Geophys. Res.* **92**(A2), 1218–1230 (1987)
- R.F. Benson, V.A. Osherovich, J. Fainberg, A.F. Vinas, D.R. Ruppert, An interpretation of banded magnetospheric radio emissions. *J. Geophys. Res.* **106**(A7), 13179–13190 (2001)
- R.F. Benson, V.A. Osherovich, J. Fainberg, B.W. Reinisch, Classification of IMAGE/RPI-stimulated plasma resonances for the accurate determination of magnetospheric electron density and magnetic field values. *J. Geophys. Res.* **108**(A5), 1207 (2003)
- R.F. Benson, P.A. Webb, J.L. Green, L. Garcia, B.W. Reinisch, Magnetospheric electron densities inferred from upper-hybrid band emissions. *Geophys. Res. Lett.* **31**, L20803 (2004)
- R.F. Benson, P.A. Webb, J.L. Green, D.L. Carpenter, V.S. Sonwalkar, H.G. James, B.W. Reinisch, Active wave experiments in space plasmas: The Z mode, in *Geospace Electromagnetic Waves and Radiation*, ed. by J.W. LaBelle, R.A. Treumann. Lecture Notes in Physics, vol. 687 (Springer, Berlin, 2006), pp. 3–36
- J. Berchem, C.T. Russell, The thickness of the magnetopause current layer—ISEE 1 and 2 observations. *J. Geophys. Res.* **87**(A4), 2108–2114 (1982)
- D. Berube, M.B. Moldwin, J.M. Weygand, An automated method for the detection of field line resonance frequencies using ground magnetometer techniques. *J. Geophys. Res.* **108**(A9), 1348 (2003)
- D. Berube, M.B. Moldwin, S.F. Fung, J.L. Green, A plasmaspheric mass density model and constraints on its heavy ion concentration. *J. Geophys. Res.* **110**, A04212 (2005)
- V.V. Bezrukh, Results of the measurements of the concentration of charged particles in the plasma cloud of the earth carried out on board of Elektron 2 and Elektron 4. *Kosm. Issled.* **8**, 273–277 (1970)
- V.V. Bezrukh, K.I. Gringauz, The hot zone in the outer plasmasphere of the Earth. *J. Atmos. Terr. Phys.* **38**, 1085–1091 (1976)
- V.V. Bezrukh, G.A. Kotova, L.A. Lezhen, J. Lemaire, V. Pierrard, Y.I. Venediktov, Dynamics of temperature and density of cold protons of the Earth's plasmasphere measured by the Auroral Probe/Alpha-3 experiment data during geomagnetic disturbances. *Cosmic Res.* **41**(4), 392–402 (2003)

- D. Bilitza, International reference ionosphere: Recent developments. *Radio Sci.* **21**(3), 343–346 (1986)
- D. Bilitza, International reference ionosphere 2000. *Radio Sci.* **36**(2), 261–275 (2001)
- J.H. Binsack, Plasmapause observations with the M.I.T. experiment on IMP 2. *J. Geophys. Res.* **72**(21), 5231–5237 (1967)
- M. Blanc, A.D. Richmond, The ionospheric disturbance dynamo. *J. Geophys. Res.* **85**(A4), 1669–1686 (1980)
- L.P. Block, D.L. Carpenter, Derivation of magnetospheric electric fields from whistler data in a dynamic geomagnetic field. *J. Geophys. Res.* **79**(19), 2783–2789 (1974)
- H.G. Booker, Guidance of radio and hydromagnetic waves in the magnetosphere. *J. Geophys. Res.* **67**(11), 4135–4162 (1962)
- A. Boonsirirath, R. Thorne, G. Lu, V.K. Jordanova, M.F. Thomsen, D.M. Ober, A.J. Ridley, A semiempirical equatorial mapping of AMIE convection electric potentials (MACEP) for the January 10, 1997, magnetic storm. *J. Geophys. Res.* **106**(A7), 12903–12917 (2001)
- J.E. Borovsky, M.H. Denton, A statistical look at plasmaspheric drainage plumes. *J. Geophys. Res.* **113**, A09221 (2008)
- J.E. Borovsky, M. Hesse, The reconnection of magnetic fields between plasmas with different densities: Scaling relations. *Phys. Plasmas* **14**(10), 102309 (2007)
- J.E. Borovsky, M.F. Thomsen, D.J. McComas, T.E. Cayton, D.J. Knipp, Magnetospheric dynamics and mass flow during the November 1993 storm. *J. Geophys. Res.* **103**(A11), 26373–26394 (1998)
- J. Bortnik, U.S. Inan, T.F. Bell, Frequency-time spectra of magnetospherically reflecting whistlers in the plasmasphere. *J. Geophys. Res.* **108**(A1), 1030 (2003)
- J. Bortnik, R.M. Thorne, N.P. Meredith, O. Santolík, Ray tracing of penetrating chorus and its implications for the radiation belts. *Geophys. Res. Lett.* **34**, L15109 (2007)
- J. Bortnik, R.M. Thorne, N.P. Meredith, The unexpected origin of plasmaspheric hiss from discrete chorus emissions. *Nature* **452**(7183), 62–66 (2008)
- P.C. Brandt, D.G. Mitchell, Y. Ebihara, B.R. Sandel, E.C. Roelof, J.L. Burch, R. Demajistre, Global IMAGE/HENA observations of the ring current: Examples of rapid response to IMF and ring current-plasmasphere interaction. *J. Geophys. Res.* **107**(A11), 1359 (2002a)
- P.C. Brandt, S. Ohtani, D.G. Mitchell, M.-C. Fok, E.C. Roelof, R. Demajistre, Global ENA observations of the storm mainphase ring current: Implications for skewed electric fields in the inner magnetosphere. *Geophys. Res. Lett.* **29**(20), 1954 (2002b)
- D.H. Brautigam, K.P. Ray, G.P. Ginat, D. Madden, Specification of the radiation belt slot region: Comparison of the NASA AE8 model with TSX5/CEASE data. *IEEE Trans. Nucl. Sci.* **51**(6), 3375–3380 (2004)
- A. Breneman, C.A. Kletzing, J. Chum, O. Santolík, D. Gurnett, J. Pickett, Multispacecraft observations of chorus dispersion and source location. *J. Geophys. Res.* **112**, A05221 (2007)
- N.M. Brice, Bulk motion of the magnetosphere. *J. Geophys. Res.* **72**(21), 5193–5211 (1967)
- N.M. Brice, R.L. Smith, Lower hybrid resonance emissions. *J. Geophys. Res.* **70**(1), 71–80 (1965)
- K. Bullough, J.L. Sagredo, Longitudinal structure in the plasmapause: VLF goniometer observations of knee-whistlers. *Nature* **225**(5237), 1038–1039 (1970)
- J.L. Burch, IMAGE mission overview. *Space Sci. Rev.* **91**(1–2), 1–14 (2000)
- J.L. Burch, The first two years of Image. *Space Sci. Rev.* **109**(1–4), 1–24 (2003)
- J.L. Burch, S.B. Mende, D.G. Mitchell, T.E. Moore, C.J. Pollock, B.W. Reinisch, B.R. Sandel, S.A. Fuselier, D.L. Gallagher, J.L. Green, J.D. Perez, P.H. Reiff, Views of Earth's magnetosphere with the IMAGE satellite. *Science* **291**, 619–624 (2001a)
- J.L. Burch, D.G. Mitchell, B.R. Sandel, P.C. Brandt, M. Wüest, Global dynamics of the plasmasphere and ring current during magnetic storms. *Geophys. Res. Lett.* **28**(6), 1159–1162 (2001b)
- J.L. Burch, W.S. Lewis, T.J. Immel, P.C. Anderson, H.U. Frey, S.A. Fuselier, J.-C. Gérard, S.B. Mende, D.G. Mitchell, M.F. Thomsen, Interplanetary magnetic field control of afternoon-sector detached proton auroral arcs. *J. Geophys. Res.* **107**(A9), 1251 (2002)
- J.L. Burch, J. Goldstein, B.R. Sandel, Cause of plasmasphere corotation lag. *Geophys. Res. Lett.* **31**, L05802 (2004)
- W.C. Burgess, U.S. Inan, The role of ducted whistlers in the precipitation loss and equilibrium flux of radiation belt electrons. *J. Geophys. Res.* **98**(A9), 15643–15665 (1993)
- W.I. Burke, N.C. Maynard, M.P. Hagan, R.A. Wolf, G.R. Wilson, L.C. Gentile, M.S. Gussenhoven, C.Y. Huang, T.W. Garner, F.J. Rich, Electrodynamics of the inner magnetosphere observed in the dusk sector by CRRES and DMSP during the magnetic storm of June 4–6, 1991. *J. Geophys. Res.* **103**(A12), 29399–29418 (1998)
- W. Calvert, Oblique z-mode echoes in the topside ionosphere. *J. Geophys. Res.* **71**(23), 5579–5583 (1966)
- W. Calvert, DE-1 measurements of AKR wave directions. *Geophys. Res. Lett.* **12**(6), 381–384 (1985)
- P. Canu, P.M.E. Décréau, J.G. Trotignon, J.L. Rauch, H.C. Séran, P. Ferreau, M. Lévêque, P. Martin, F.X. Sené, E. Le Guirrec, H. Alleyne, K. Yearby, Identification of natural plasma emissions observed close

- to the plasmopause by the Cluster-Whisper relaxation sounder. *Ann. Geophys.* **19**(10–12), 1697–1709 (2001)
- P. Canu, P.M.E. Décréau, S. Escoffier, S. Grimald, Observations of continuum radiations close to the plasmopause: Evidence for small scale sources, in *Planetary Radio Emissions VI*, ed. by H.O. Rucker, W.S. Kurth, G. Mann (Austrian Academy of Sciences Press, Vienna, 2006)
- J.F. Carbary, A Kp -based model of auroral boundaries. *Space Weather* **3**(10), S10001 (2005)
- D.L. Carpenter, New experimental evidence of the effect of magnetic storms on the magnetosphere. *J. Geophys. Res.* **67**(1), 135–145 (1962)
- D.L. Carpenter, Whistler evidence of a “knee” in the magnetospheric ionization density profile. *J. Geophys. Res.* **68**(6), 1675–1682 (1963)
- D.L. Carpenter, Whistler measurements of the equatorial profile of magnetospheric electron density, in *Progress in Radio Science 1960–1966, Vol. III: The Ionosphere*, ed. by G.M. Brown (Elsevier, Amsterdam, 1965), pp. 76–91
- D.L. Carpenter, Whistler studies of the plasmopause in the magnetosphere, 1. Temporal variations in the position of the knee and some evidence on plasma motions near the knee. *J. Geophys. Res.* **71**(3), 693–709 (1966)
- D.L. Carpenter, Relations between the dawn minimum in the equatorial radius of the plasmopause and Dst , Kp , and local K at Byrd station. *J. Geophys. Res.* **72**(11), 2969–2971 (1967)
- D.L. Carpenter, Remarks on the ground-based whistler method of studying the magnetospheric thermal plasma. *Ann. Geophys.* **26**(2), 363–370 (1970a)
- D.L. Carpenter, Whistler evidence of the dynamic behavior of the duskside bulge in the plasmasphere. *J. Geophys. Res.* **75**(19), 3837–3847 (1970b)
- D.L. Carpenter, OGO 2 and 4 VLF observations of the asymmetric plasmopause near the time of SAR arc events. *J. Geophys. Res.* **76**(16), 3644–3650 (1971)
- D.L. Carpenter, Some aspects of plasmopause probing by whistlers. *Radio Sci.* **18**(6), 917–925 (1983)
- D.L. Carpenter, Remote sensing the Earth’s plasmasphere. *Rad. Sci. Bull.* **308**, 13–29 (2004)
- D.L. Carpenter, R.R. Anderson, An ISEE/whistler model of equatorial electron density in the magnetosphere. *J. Geophys. Res.* **97**(A2), 1097–1108 (1992)
- D.L. Carpenter, J. Lemaire, Erosion and recovery of the plasmasphere in the plasmopause region. *Space Sci. Rev.* **80**(1–2), 153–179 (1997)
- D.L. Carpenter, J. Lemaire, The plasmasphere boundary layer. *Ann. Geophys.* **22**(12), 4291–4298 (2004)
- D.L. Carpenter, N.T. Seely, Cross- L plasma drifts in the outer plasmasphere: Quiet time patterns and some substorm effects. *J. Geophys. Res.* **81**(16), 2728–2736 (1976)
- D.L. Carpenter, K. Stone, Direct detection by a whistler method of the magnetospheric electric field associated with a polar substorm. *Planet. Space Sci.* **15**(2), 395–397 (1967)
- D.L. Carpenter, R. Walter, R.E. Barrington, D.J. McEwen, Alouette 1 and 2 observations of abrupt changes in whistler rate and of VLF noise variations at the plasmopause – A satellite-ground study. *J. Geophys. Res.* **73**(9), 2929–2940 (1968)
- D.L. Carpenter, K. Stone, J.C. Siren, T.L. Crystal, Magnetospheric electric fields deduced from drifting whistler paths. *J. Geophys. Res.* **77**(16), 2819–2834 (1972)
- D.L. Carpenter, C.G. Park, T.R. Miller, A model of substorm electric fields in the plasmasphere based on whistler data. *J. Geophys. Res.* **84**(A11), 6559–6563 (1979)
- D.L. Carpenter, A.J. Smith, B.L. Giles, C.R. Chappell, P.M.E. Décréau, A case study of plasma structure in the dusk sector associated with enhanced magnetospheric convection. *J. Geophys. Res.* **97**(A2), 1157–1166 (1992)
- D.L. Carpenter, B.L. Giles, C.R. Chappell, P.M.E. Décréau, R.R. Anderson, A.M. Persoon, A.J. Smith, Y. Corcuff, P. Canu, Plasmasphere dynamics in the duskside bulge region: A new look at an old topic. *J. Geophys. Res.* **98**(A11), 19243–19271 (1993)
- D.L. Carpenter, R.R. Anderson, W. Calvert, M.B. Moldwin, CRRES observations of density cavities inside the plasmasphere. *J. Geophys. Res.* **105**(A10), 23323–23338 (2000)
- D.L. Carpenter, M.A. Spasojević, T.F. Bell, U.S. Inan, B.W. Reinisch, I.A. Galkin, R.F. Benson, J.L. Green, S.F. Fung, S.A. Boardsen, Small-scale field-aligned plasmaspheric density structures inferred from the radio plasma imager on IMAGE. *J. Geophys. Res.* **107**(A9), 1258 (2002)
- D.L. Carpenter, T.F. Bell, U.S. Inan, R.F. Benson, V.S. Sonwalkar, B.W. Reinisch, D.L. Gallagher, Z-mode sounding within propagation “cavities” and other inner magnetospheric regions by the RPI instrument on the IMAGE satellite. *J. Geophys. Res.* **108**(A12), 1421 (2003)
- D.L. Carpenter, T.F. Bell, D. Chen, D. Ng, C. Baran, B.W. Reinisch, I. Galkin, Proton cyclotron echoes and a new resonance observed by the Radio Plasma Imager instrument on the IMAGE satellite. *J. Geophys. Res.* **112**, A08208 (2007)
- G. Chanteur, Spatial interpolation for four spacecraft: Theory, in *Analysis Methods for Multi-Spacecraft Data*, ed. by G. Paschmann, P.W. Daly. ISSI SR-001. ESA Publications Division (1998), pp. 349–369

- G. Chanteur, C.C. Harvey, Spatial interpolation for four spacecraft: Application to magnetic gradients, in *Analysis Methods for Multi-Spacecraft Data*, ed. by G. Paschmann, P.W. Daly. ISSI SR-001. ESA Publications Division (1998), pp. 371–393
- C.R. Chappell, Recent satellite measurements of the morphology and dynamics of the plasmasphere. *Rev. Geophys. Space Phys.* **10**(4), 951–979 (1972)
- C.R. Chappell, Detached plasma regions in the magnetosphere. *J. Geophys. Res.* **79**(13), 1861–1870 (1974)
- C.R. Chappell, K.K. Harris, G.W. Sharp, The morphology of the bulge region of the plasmasphere. *J. Geophys. Res.* **75**(19), 3848–3861 (1970a)
- C.R. Chappell, K.K. Harris, G.W. Sharp, A study of the influence of magnetic activity on the location of the plasmopause as measured by OGO 5. *J. Geophys. Res.* **75**(1), 50–56 (1970b)
- C.R. Chappell, K.K. Harris, G.W. Sharp, The dayside of the plasmasphere. *J. Geophys. Res.* **76**(31), 7632–7647 (1971)
- C.R. Chappell, T.E. Moore, J.H. Waite Jr., The ionosphere as a fully adequate source of plasma for the Earth's magnetosphere. *J. Geophys. Res.* **92**(A6), 5896–5910 (1987)
- A.J. Chen, J.M. Grebowsky, Plasma tail interpretations of pronounced detached plasma regions measured by Ogo 5. *J. Geophys. Res.* **79**(25), 3851–3855 (1974)
- L. Chen, A. Hasegawa, A theory of long-period magnetic pulsations, 1. Steady state excitation of field line resonance. *J. Geophys. Res.* **79**(7), 1024–1032 (1974)
- S.-H. Chen, T.E. Moore, Magnetospheric convection and thermal ions in the dayside outer magnetosphere. *J. Geophys. Res.* **111**, A03215 (2006)
- A.J. Chen, R.A. Wolf, Effects on the plasmasphere of a time-varying convection electric field. *Planet. Space Sci.* **20**(4), 483–509 (1972)
- A.J. Chen, J.M. Grebowsky, H.A. Taylor Jr., Dynamics of mid-latitude light ion trough and plasma tails. *J. Geophys. Res.* **80**(7), 968–976 (1975)
- A.F. Cheng, Magnetospheric interchange instability. *J. Geophys. Res.* **90**(A10), 9900–9904 (1989)
- J. Chum, O. Santolík, Propagation of whistler-mode chorus to low altitudes: divergent ray trajectories and ground accessibility. *Ann. Geophys.* **23**(12), 3727–3738 (2005)
- J. Chum, O. Santolík, A.W. Breneman, C.A. Kletzing, D.A. Gurnett, J.S. Pickett, Chorus source properties that produce time shifts and frequency range differences observed on different Cluster spacecraft. *J. Geophys. Res.* **112**, A06206 (2007)
- S.R. Church, R.M. Thorne, On the origin of plasmaspheric hiss: Ray path integrated amplification. *J. Geophys. Res.* **88**(A10), 7941–7957 (1983)
- M.A. Clilverd, A.J. Smith, N.R. Thomson, The annual variation in quiet time plasmaspheric electron density, determined from whistler mode group delays. *Planet. Space Sci.* **39**(7), 1059–1067 (1991)
- M.A. Clilverd, F.W. Menk, G. Milneviski, B.R. Sandel, J. Goldstein, B.W. Reinisch, C.R. Wilford, M.C. Rose, N.R. Thomson, K.H. Yearby, G.J. Bailey, I.R. Mann, D.L. Carpenter, In-situ and ground-based intercalibration measurements of plasma density at $L = 2.5$. *J. Geophys. Res.* **108**(A10), 1365 (2003)
- M.A. Clilverd, N.P. Meredith, R.B. Horne, S.A. Glauert, R.R. Anderson, N.R. Thomson, F.W. Menk, B.R. Sandel, Longitudinal and seasonal variations in plasmaspheric electron density: Implications for electron precipitation. *J. Geophys. Res.* **112**, A11210 (2007)
- K.D. Cole, Formation of field-aligned irregularities in the magnetosphere. *J. Atmos. Terr. Phys.* **33**, 741–750 (1971)
- R.H. Comfort, Plasmasphere thermal structure as measured by ISEE-1 and DE-1. *Adv. Space Res.* **6**(3), 31–40 (1986)
- R.H. Comfort, Thermal structure of the plasmasphere. *Adv. Space Res.* **17**(10), 175–184 (1996)
- N. Cornilleau-Wehrin, G. Chanteur, S. Perraut, L. Rezeau, P. Robert, A. Roux, C. de Villedary, P. Canu, M. Maksimovic, Y. de Conchy, D. Hubert, C. Lacombe, F. Lefeuvre, M. Parrot, J.L. Pinçon, P.M.E. Décréau, C.C. Harvey, P. Louarn, O. Santolík, H.S.C. Alleyne, M. Roth, T. Chust, O. Le Contel, STAFF team, First results obtained by the Cluster STAFF experiment. *Ann. Geophys.* **21**(1–2), 437–456 (2003)
- J.M. Cornwall, F.V. Coroniti, R.M. Thorne, Turbulent loss of ring current protons. *J. Geophys. Res.* **75**(25), 4699–4709 (1970)
- S.W.H. Cowley, Magnetospheric asymmetries associated with the y-component of the IMF. *Planet. Space Sci.* **29**(1), 79–96 (1981)
- P.D. Craven, D.L. Gallagher, R.H. Comfort, Relative concentration of He^+ in the inner magnetosphere as observed by the DE 1 retarding ions mass spectrometer. *J. Geophys. Res.* **102**(A2), 2279–2289 (1997)
- N.U. Crooker, F.J. Rich, Lobe cell convection as a summer phenomenon. *J. Geophys. Res.* **98**(A8), 13403–13407 (1993)
- I. Dandouras, Detection of plasmaspheric wind by analysis of ion measurements obtained onboard the Cluster spacecraft. *Geophys. Res. Abstr.* **10**, 5360 (2008)

- I. Dandouras, V. Pierrard, J. Goldstein, C. Vallat, G.K. Parks, H. Rème, C. Gouillart, F. Sevestre, M. McCarthy, L.M. Kistler, B. Klecker, A. Korth, M.B. Bavassano-Cattaneo, P. Escoubet, A. Masson, Multipoint observations of ionic structures in the plasmasphere by CLUSTER-CIS and comparisons with IMAGE-EUV observations and with model simulations, in *Inner Magnetosphere Interactions: New Perspectives from Imaging*, ed. by J. Burch, M. Schulz, H. Spence. Geophysical Monograph Series, vol. 159 (American Geophysical Union, Washington, 2005), pp. 23–53
- F. Darrouzet, Etude de la magnétosphère terrestre par l'analyse multipoint des données de la mission CLUSTER. Contributions à la caractérisation des frontières et de la magnétosphère interne. Ph.D. thesis, University of Orléans, France, 2006
- F. Darrouzet, P.M.E. Décréau, J. De Keyser, A. Masson, D.L. Gallagher, O. Santolík, B.R. Sandel, J.G. Trotignon, J.L. Rauch, E. Le Guirriec, P. Canu, F. Sedgemore, M. André, J.F. Lemaire, Density structures inside the plasmasphere: Cluster observations. *Ann. Geophys.* **22**(7), 2577–2585 (2004)
- F. Darrouzet, J. De Keyser, P.M.E. Décréau, D.L. Gallagher, V. Pierrard, J.F. Lemaire, B.R. Sandel, I. Dandouras, H. Matsui, M. Dunlop, J. Cabrera, A. Masson, P. Canu, J.G. Trotignon, J.L. Rauch, M. André, Analysis of plasmaspheric plumes: CLUSTER and IMAGE observations. *Ann. Geophys.* **24**(6), 1737–1758 (2006a)
- F. Darrouzet, J. De Keyser, P.M.E. Décréau, J.F. Lemaire, M.W. Dunlop, Spatial gradients in the plasmasphere from Cluster. *Geophys. Res. Lett.* **33**, L08105 (2006b)
- F. Darrouzet, J. De Keyser, P.M.E. Décréau, F. El Lemdani-Mazouz, X. Vallières, Statistical analysis of plasmaspheric plumes with Cluster/WHISPER observations. *Ann. Geophys.* **26**(8), 2403–2417 (2008)
- F. Darrouzet, D.L. Gallagher, N. André, D.L. Carpenter, I. Dandouras, P.M.E. Décréau, J. De Keyser, R.E. Denton, J.C. Foster, J. Goldstein, M.B. Moldwin, B.W. Reinisch, B.R. Sandel, J. Tu, Plasmaspheric density structures and dynamics: Properties observed by the CLUSTER and IMAGE missions. *Space Sci. Rev.* **145**(1–2), 55–106 (2009)
- J. De Keyser, Formation and evolution of subauroral ion drifts in the course of a substorm. *J. Geophys. Res.* **104**(A6), 12339–12349 (1999)
- J. De Keyser, Least-squares multi-spacecraft gradient calculation with automatic error estimation. *Ann. Geophys.* **26**(11), 3295–3316 (2008)
- J. De Keyser, M. Roth, J. Lemaire, The magnetospheric driver of subauroral ion drifts. *Geophys. Res. Lett.* **25**(10), 1625–1628 (1998)
- J. De Keyser, M.W. Dunlop, C.J. Owen, B.U.Ö. Sonnerup, S.E. Haaland, A. Vaivads, G. Paschmann, R. Lundin, L. Rezeau, Magnetopause and boundary layer. *Space Sci. Rev.* **118**(1–4), 231–320 (2005)
- J. De Keyser, F. Darrouzet, M.W. Dunlop, P.M.E. Décréau, Least-squares gradient calculation from multipoint observations of scalar and vector fields: Methodology and applications with Cluster in the plasmasphere. *Ann. Geophys.* **25**(4), 971–987 (2007)
- J. De Keyser, D.L. Carpenter, F. Darrouzet, D.L. Gallagher, J. Tu, CLUSTER and IMAGE: New ways to study the Earth's plasmasphere. *Space Sci. Rev.* **145**(1–2), 7–53 (2009)
- O. de la Beaujardiere, D. Alcayde, J. Fontanari, C. Leger, Seasonal dependence of high-latitude electric fields. *J. Geophys. Res.* **96**(A4), 5723–5735 (1991)
- P.M.E. Décréau, C. Beghin, M. Parrot, Global characteristics of the cold plasma in the equatorial plasmopause region as deduced from the GEOS 1 mutual impedance probe. *J. Geophys. Res.* **87**(A2), 695–712 (1982)
- P.M.E. Décréau, D. Carpenter, C.R. Chappell, R.H. Comfort, J. Green, R.C. Olsen, J.H. Waite Jr., Latitudinal plasma distribution in the dusk plasmaspheric bulge: Refilling phase and quasi-equilibrium state. *J. Geophys. Res.* **91**(A6), 6929–6943 (1986)
- P.M.E. Décréau, P. Ferreau, V. Krasnosels'kikh, M. Lévêque, P. Martin, O. Randriamboarison, F.X. Sené, J.G. Trotignon, P. Canu, P.B. Mörgensen, Whisper Investigators, WHISPER, a resonance sounder and wave analyser: Performances and perspectives for the Cluster mission. *Space Sci. Rev.* **79**(1–2), 157–193 (1997)
- P.M.E. Décréau, P. Ferreau, V. Krasnosels'kikh, E. Le Guirriec, M. Lévêque, P. Martin, O. Randriamboarison, J.L. Rauch, F.X. Sené, H.C. Séran, J.G. Trotignon, P. Canu, N. Cornilleau, H. de Féraudy, H. Alleyne, K. Yearby, P.B. Mörgensen, G. Gustafsson, M. André, D.A. Gurnett, F. Darrouzet, J. Lemaire, C.C. Harvey, P. Travnicek, Whisper experimenters, Early results from the Whisper instrument on Cluster: an overview. *Ann. Geophys.* **19**(10–12), 1241–1258 (2001)
- P.M.E. Décréau, C. Ducoin, G. Le Rouzic, O. Randriamboarison, J.L. Rauch, X. Trotignon, J.G. Vallières, P. Canu, F. Darrouzet, M.P. Gough, A. Buckley, T.D. Carozzi, Observation of continuum radiations from the CLUSTER fleet: First results from direction finding. *Ann. Geophys.* **22**(7), 2607–2624 (2004)
- P.M.E. Décréau, E. Le Guirriec, J.L. Rauch, J.G. Trotignon, P. Canu, F. Darrouzet, J. Lemaire, A. Masson, F. Sedgemore, M. André, Density irregularities in the plasmasphere boundary layer: Cluster observations in the dusk sector. *Adv. Space Res.* **36**(10), 1964–1969 (2005)
- C.F. del Pozo, M. Blanc, Analytical self-consistent model of the large-scale convection electric field. *J. Geophys. Res.* **99**(A3), 4053–4068 (1994)

- H.G. Demars, R.W. Schunk, Solutions to bi-Maxwellian transport equations for SAR-arc conditions. *Planet. Space Sci.* **34**(12), 1335–1348 (1986)
- H.G. Demars, R.W. Schunk, Comparison of semi-kinetic and generalized transport models of the polar wind. *Geophys. Res. Lett.* **18**(4), 713–716 (1991)
- Z.C. Dent, I.R. Mann, F.W. Menk, J. Goldstein, C.R. Wilford, M.A. Clilverd, L.G. Ozeke, A coordinated ground-based and IMAGE satellite study of quiet-time plasmaspheric density profiles. *Geophys. Res. Lett.* **30**(12), 1600 (2003)
- Z.C. Dent, I.R. Mann, J. Goldstein, F.W. Menk, L.G. Ozeke, Plasmaspheric depletion, refilling, and plasmapause dynamics: A coordinated ground-based and IMAGE satellite study. *J. Geophys. Res.* **111**, A03205 (2006)
- R.E. Denton, Magneto-seismology using spacecraft observations, in *Magnetospheric ULF Waves: Synthesis and New Directions*, ed. by K. Takahashi, P.J. Chi, R.E. Denton, R.L. Lysak. Geophysical Monograph Series, vol. 169 (American Geophysical Union, Washington, 2006), pp. 307–317
- R.E. Denton, D.L. Gallagher, Determining the mass density along magnetic field lines from toroidal eigenfrequencies. *J. Geophys. Res.* **105**(A12), 27717–27725 (2000)
- R.E. Denton, J. Goldstein, J.D. Menietti, Field line dependence of magnetospheric electron density. *Geophys. Res. Lett.* **29**(24), 2205 (2002a)
- R.E. Denton, J. Goldstein, J.D. Menietti, S.L. Young, Magnetospheric electron density model inferred from Polar plasma wave data. *J. Geophys. Res.* **107**(A11), 1386 (2002b)
- R.E. Denton, J.D. Menietti, J. Goldstein, S.L. Young, R.R. Anderson, Electron density in the magnetosphere. *J. Geophys. Res.* **109**, A09215 (2004)
- R.E. Denton, J. Goldstein, D.-H. Lee, R.A. King, Z.C. Dent, D.L. Gallagher, D. Berube, K. Takahashi, M. Nose, D. Milling, F. Honary, Realistic magnetospheric density model for 29 August 2000. *J. Atmos. Solar-Terr. Phys.* **68**(6), 615–628 (2006a)
- R.E. Denton, K. Takahashi, I.A. Galkin, P.A. Nsumei, X. Huang, B.W. Reinisch, R.R. Anderson, M.K. Sleeper, W.J. Hughes, Distribution of density along magnetospheric field lines. *J. Geophys. Res.* **111**, A04213 (2006)
- R.E. Denton, P. Décréau, M.J. Engebretson, F. Darrouzet, J.L. Posch, C. Mouikis, L.M. Kistler, C.A. Cattell, K. Takahashi, S. Schäfer, J. Goldstein, Field line distribution of density at $L = 4.8$ inferred from observations by CLUSTER. *Ann. Geophys.* **27**(2), 705–724 (2009)
- A.J. Dessler, E.N. Parker, Hydromagnetic theory of geomagnetic storms. *J. Geophys. Res.* **64**(12), 2239–2252 (1959)
- R.L. Dowden, Distinction between mid latitude VLF hiss and discrete emissions. *Planet. Space Sci.* **19**(3), 374–376 (1971)
- A.B. Draganov, U.S. Inan, V.S. Sonwalkar, T.F. Bell, Whistlers and plasmaspheric hiss: Wave directions and three-dimensional propagation. *J. Geophys. Res.* **98**(A7), 11401–11410 (1993)
- N. Dunckel, R.A. Helliwell, Whistler-mode emissions on the OGO 1 satellite. *J. Geophys. Res.* **74**(26), 6371–6385 (1969)
- J.W. Dungey, The theory of the quiet magnetosphere, in: *Proceedings of the 1966 Symposium on Solar-Terrestrial Physics*, ed. by J.W. King, W.S. Newman (Belgrade, 1967), pp. 91–106
- M.W. Dunlop, A. Balogh, Magnetopause current as seen by Cluster. *Ann. Geophys.* **23**(3), 901–907 (2005)
- M.W. Dunlop, J.P. Eastwood, The curlometer and other gradient based methods, in *Multi-Spacecraft Analysis Methods Revisited*, ed. by G. Paschmann, P.W. Daly. ISSI SR-008. ESA Communications (2008), pp. 17–25
- M.W. Dunlop, T.I. Woodward, Multi-spacecraft discontinuity analysis: Orientation and motion, in *Analysis Methods for Multi-Spacecraft Data*, ed. by G. Paschmann and P.W. Daly. ISSI SR-001. ESA Publications Division (1998), pp. 271–306
- M.W. Dunlop, A. Balogh, K.-H. Glassmeier, Four-point cluster application of magnetic field analysis tools: The discontinuity analyzer. *J. Geophys. Res.* **107**(A11), 1385 (2002)
- M.W. Dunlop, A. Balogh, Q.-Q. Shi, Z. Pu, C. Vallat, P. Robert, S. Haaland, C. Shen, J.A. Davies, K.-H. Glassmeier, P. Cargill, F. Darrouzet, A. Roux, The curlometer and other gradient measurements with Cluster, in *Proceedings of the Cluster and Double Star Symposium, 5th Anniversary of Cluster in Space ESA SP-598* (2006)
- J.P. Eastwood, A. Balogh, M.W. Dunlop, C.W. Smith, Cluster observations of the heliospheric current sheet and an associated magnetic flux rope and comparisons with ACE. *J. Geophys. Res.* **107**(A11), 1365 (2002)
- Y. Ebihara, M. Ejiri, Numerical simulation of the ring current: Review. *Space Sci. Rev.* **105**(1–2), 377–452 (2002)
- M. Echim, J. Lemaire, Two-dimensional Vlasov solution for a collisionless plasma jet across transverse magnetic field lines with a sheared bulk velocity. *Phys. Rev. E* **72**(3), 036405 (2005)

- F. El-Lemdani Mazouz, S. Grimald, J.L. Rauch, P.M.E. Décr  au, G. Bozan, G. Le Rouzic, X. Suraud, X. Valli  res, J.G. Trotignon, P. Canu, F. Darrouzet, S. Boardsen, Electrostatic and electromagnetic emissions near the plasmasphere. A case event: 27 May 2003, in *Proceedings of the Cluster and Double Star Symposium, 5th Anniversary of Cluster in Space ESA SP-598* (2006)
- F. El-Lemdani Mazouz, J.L. Rauch, P.M.E. Décr  au, J.G. Trotignon, X. Valli  res, F. Darrouzet, P. Canu, X. Suraud, Wave emissions at half electron gyroharmonics in the equatorial plasmasphere region: CLUSTER observations and statistics. *Adv. Space Res.* **43**(2), 253–264 (2009)
- R.C. Elphic, L.A. Weiss, M.F. Thomsen, D.J. McComas, M.B. Moldwin, Evolution of plasmaspheric ions at geosynchronous orbit during times of high geomagnetic activity. *Geophys. Res. Lett.* **23**(16), 2189–2192 (1996)
- M.J. Engebretson, W.J. Hughes, J.L. Alford, E. Zesta, L.J. Cahill Jr., R.L. Arnoldy, G.D. Reeves, Magnetometer array for cusp and cleft studies observations of the spatial extent of broadband ULF magnetic pulsations at cusp/cleft latitudes. *J. Geophys. Res.* **100**(A10), 19371–19386 (1995)
- A.I. Eriksson, M. Andr  , B. Klecker, H. Laakso, P.-A. Lindqvist, F. Mozer, G. Paschmann, A. Pedersen, J. Quinn, R. Torbert, K. Torkar, H. Vaith, Electric field measurements on Cluster: Comparing the double-probe and electron drift techniques. *Ann. Geophys.* **24**(1), 275–289 (2006)
- C.P. Escoubet, C.T. Russell, R. Schmidt (eds.), *The Cluster and Phoenix Missions* (Kluwer Academic Publishers, Dordrecht, 1997)
- A. Eviatar, A.M. Lenchek, S.F. Singer, Distribution of density in an ion-exosphere of a nonrotating planet. *Phys. Fluids* **7**(11), 1775–1779 (1964)
- H.J. Fahr, B. Shizgal, Modern exospheric theories and their observational relevance. *Rev. Geophys. Space Phys.* **21**(1), 75–124 (1983)
- W.M. Farrell, Direct generation of O-mode emission in a dense, warm plasma: Applications to interplanetary type II emissions and others in its class. *J. Geophys. Res.* **106**(A8), 15701–15709 (2001)
- C.J. Farrugia, M.P. Freeman, S.W.H. Cowley, D.J. Southwood, M. Lockwood, A. Etemadi, Pressure-driven magnetopause motions and attendant response on the ground. *Planet. Space Sci.* **37**(5), 589–607 (1989)
- B.G. Fejer, L. Scherliess, Time dependent response of equatorial ionospheric electric fields to magnetospheric disturbances. *Geophys. Res., Lett.* **22**(7), 851–854 (1995)
- B.G. Fejer, R.W. Spiro, R.A. Wolf, J.C. Foster, Latitudinal variation of perturbation electric fields during magnetically disturbed periods–1986 Sundial observations and model results. *Ann. Geophys.* **8**(6), 441–454 (1990)
- Y.I. Feldstein, A.E. Levitin, D.S. Faermark, R.G. Afonina, B.A. Belov, V.Y. Gaidukov, Electric fields and potential patterns in the high-latitude ionosphere for different situations in interplanetary space. *Planet. Space Sci.* **32**(7), 907–923 (1984)
- K.M. Ferri  re, N. Andr  , A mixed magnetohydrodynamic-kinetic theory of low-frequency waves and instabilities in stratified, gyrotropic, two-component plasmas. *J. Geophys. Res.* **108**(A7), 1308 (2003)
- K.M. Ferri  re, C. Zimmer, M. Blanc, Magnetohydrodynamic waves and gravitational/centrifugal instability in rotating magnetospheres. *J. Geophys. Res.* **104**(A8), 17335–17356 (1999)
- S. Figueiredo, T. Karlsson, G.T. Marklund, Investigation of subauroral ion drifts and related field-aligned currents and ionospheric Pedersen conductivity distribution. *Ann. Geophys.* **22**(3), 923–934 (2004)
- J.C. Foster, Storm time plasma transport at middle and high latitudes. *J. Geophys. Res.* **98**(A2), 1675–1689 (1993)
- J.C. Foster, W.J. Burke, SAPS: A new categorization for sub-auroral electric fields. *Eos Trans. AGU* **83**(36), 393 (2002)
- J.C. Foster, H.B. Vo, Average characteristics and activity dependence of the subauroral polarization stream. *J. Geophys. Res.* **107**(A12), 1475 (2002)
- J.C. Foster, J.M. Holt, R.G. Musgrove, D.S. Evans, Ionospheric convection associated with discrete levels of particle precipitation. *Geophys. Res. Lett.* **13**(7), 656–659 (1986)
- J.C. Foster, P.J. Erickson, A.J. Coster, J. Goldstein, F.J. Rich, Ionospheric signatures of plasmaspheric tails. *Geophys. Res. Lett.* **29**(13), 1623 (2002)
- J.C. Foster, A.J. Coster, P.J. Erickson, F.J. Rich, B.R. Sandel, Stormtime observations of the flux of plasmaspheric ions to the dayside cusp/magnetopause. *Geophys. Res. Lett.* **31**, L08809 (2004)
- J.C. Foster, A.J. Coster, P.J. Erickson, W. Rideout, F.J. Rich, T.J. Immel, B.R. Sandel, Redistribution of the stormtime ionosphere and the formation of the plasmaspheric bulge, in *Inner Magnetosphere Interactions: New Perspectives from Imaging*, ed. by J. Burch, M. Schulz, H. Spence. Geophysical Monograph Series, vol. 159 (American Geophysical Union, Washington, 2005), pp. 277–289
- J.C. Foster, W. Rideout, B. Sandel, W.T. Forrester, F.J. Rich, On the relationship of SAPS to storm-enhanced density. *J. Atmos. Solar-Terr. Phys.* **69**(3), 303–313 (2007)
- B.J. Fraser, J.L. Horvitz, J.A. Slavin, Z.C. Dent, I.R. Mann, Heavy ion mass loading of the geomagnetic field near the plasmopause and ULF wave implications. *Geophys. Res. Lett.* **32**, L04102 (2005)

- S.F. Fung, J.L. Green, Modeling of field-aligned guided echoes in the plasmasphere. *J. Geophys. Res.* **110**, A01210 (2005)
- S.F. Fung, R.F. Benson, D.L. Carpenter, B.W. Reinisch, D.L. Gallagher, Investigations of irregularities in remote plasma regions by radio sounding: Applications of the radio plasma imager on IMAGE. *Space Sci. Rev.* **91**(1–2), 391–419 (2000)
- S.F. Fung, L.N. Garcia, J.L. Green, D.L. Gallagher, D.L. Carpenter, B.W. Reinisch, I.A. Galkin, G. Khmyrov, B.R. Sandel, Plasmaspheric electron density distributions sampled by radio plasma imager on the IMAGE satellite. *Eos Trans. AGU* **82**(47), SM11A–0771 (2001)
- S.F. Fung, R.F. Benson, D.L. Carpenter, J.L. Green, V. Jayanti, I.A. Galkin, B.W. Reinisch, Guided echoes in the magnetosphere: Observations by Radio Plasma Imager on IMAGE. *Geophys. Res. Lett.* **30**(11), 1589 (2003)
- I. Galkin, B. Reinisch, G. Grinstein, G. Khmyrov, A. Kozlov, X. Huang, S. Fung, Automated exploration of the radio plasma imager data. *J. Geophys. Res.* **109**, A12210 (2004a)
- I.A. Galkin, B.W. Reinisch, X. Huang, R.F. Benson, S.F. Fung, Automated diagnostics for resonance signature recognition on IMAGE/RPI plasmagrams. *Radio Sci.* **39**(1), RS1015 (2004b)
- I.A. Galkin, G. Khmyrov, A. Kozlov, B.W. Reinisch, Intelligent resident archive for RPI level 2 data, in *Radio Sounding and Plasma Physics*, ed. by P. Song, J. Foster, M. Mendillo, D. Bilitza. AIP Conf. Proc., vol. 974 (2008), pp. 111–117
- D.L. Gallagher, M.L. Adrian, Two-dimensional drift velocities from the IMAGE EUV plasmaspheric imager. *J. Atmos. Solar-Terr. Phys.* **69**(3), 341–350 (2007)
- D.L. Gallagher, P.D. Craven, R.H. Comfort, A simple model of magnetospheric trough total density. *J. Geophys. Res.* **103**(A5), 9293–9297 (1998)
- D.L. Gallagher, P.D. Craven, R.H. Comfort, Global core plasma model. *J. Geophys. Res.* **105**(A8), 18819–18833 (2000)
- D.L. Gallagher, M.L. Adrian, M.W. Liemohn, Origin and evolution of deep plasmaspheric notches. *J. Geophys. Res.* **110**, A09201 (2005)
- Y.I. Galperin, V.N. Ponomarev, A.G. Zosimova, Plasma convection in the polar ionosphere. *Ann. Geophys.* **30**(1), 1–7 (1974)
- Y.I. Galperin, V.S. Soloviev, K. Torkar, J.C. Foster, M.V. Veselov, Predicting plasmaspheric radial density profiles. *J. Geophys. Res.* **102**(A2), 2079–2091 (1997)
- D.A. Galvan, M.B. Moldwin, B.R. Sandel, Diurnal variation in plasmaspheric He⁺ inferred from extreme ultraviolet images. *J. Geophys. Res.* **113**, A09216 (2008)
- G. Ganguli, M.A. Reynolds, M.W. Liemohn, The plasmasphere and advances in plasmaspheric research. *J. Atmos. Solar-Terr. Phys.* **62**(17–18), 1647–1657 (2000)
- L.N. Garcia, S.F. Fung, J.L. Green, S.A. Boardsen, B.R. Sandel, B.W. Reinisch, Observations of the latitudinal structure of plasmaspheric convection plumes by IMAGE-RPI and EUV. *J. Geophys. Res.* **108**(A8), 1321 (2003)
- S.P. Gary, M.F. Thomsen, L. Yin, D. Winske, Electromagnetic proton cyclotron instability: Interactions with magnetospheric protons. *J. Geophys. Res.* **100**(A11), 21961–21972 (1995)
- J.E. Geisler, On the limiting daytime flux of ionization into the protonosphere. *J. Geophys. Res.* **72**(1), 81–85 (1967)
- J. Geiss, H. Balsiger, P. Eberhardt, H.P. Walker, L. Weber, D.T. Young, H. Rosenbauer, Dynamics of magnetospheric ion composition as observed by the GEOS mass spectrometer. *Space Sci. Rev.* **22**(5), 537–566 (1978)
- A.R. Gibby, U.S. Inan, T.F. Bell, Saturation effects in the VLF-triggered emission process. *J. Geophys. Res.* **113**, A11215 (2008)
- G.K. Goertz, R.J. Strangeway, Plasma waves, in *Introduction to Space Physics*, ed. by M.G. Kivelson, C.T. Russell (Cambridge University Press, Cambridge, 1995), pp. 356–399
- T. Gold, Motions in the magnetosphere of the Earth. *J. Geophys. Res.* **64**(9), 1219–1224 (1959)
- J. Goldstein, Plasmasphere response: Tutorial and review of recent imaging results. *Space Sci. Rev.* **124**(1–4), 203–216 (2006)
- J. Goldstein, B.R. Sandel, The global pattern of evolution of plasmaspheric drainage plumes, in *Inner Magnetosphere Interactions: New Perspectives from Imaging*, ed. by J. Burch, M. Schulz, H. Spence. Geophysical Monograph Series, vol. 159 (American Geophysical Union, Washington, 2005), pp. 1–22
- J. Goldstein, R.W. Spiro, P.H. Reiff, R.A. Wolf, B.R. Sandel, J.W. Freeman, R.L. Lambour, IMF-driven overshielding electric field and the origin of the plasmaspheric shoulder of May 24, 2000. *Geophys. Res. Lett.* **29**(16), 1819 (2002)
- J. Goldstein, B.R. Sandel, W.T. Forrester, P.H. Reiff, IMF-driven plasmasphere erosion of 10 July 2000. *Geophys. Res. Lett.* **30**(3), 1146 (2003a)
- J. Goldstein, B.R. Sandel, M.R. Hairston, P.H. Reiff, Control of plasmaspheric dynamics by both convection and sub-auroral polarization stream. *Geophys. Res. Lett.* **30**(24), 2243 (2003b)

- J. Goldstein, M. Spasojević, P.H. Reiff, B.R. Sandel, W.T. Forrester, D.L. Gallagher, B.W. Reinisch, Identifying the plasmopause in IMAGE EUV data using IMAGE RPI in situ steep density gradients. *J. Geophys. Res.* **108**(A4), 1147 (2003c)
- J. Goldstein, R.W. Spiro, B.R. Sandel, R.A. Wolf, S.-Y. Su, P.H. Reiff, Overshielding event of 28–29 July 2000. *Geophys. Res. Lett.* **30**(8), 1421 (2003d)
- J. Goldstein, B.R. Sandel, M.R. Hairston, S.B. Mende, Plasmopause undulation of 17 April 2002. *Geophys. Res. Lett.* **31**, L15801 (2004a)
- J. Goldstein, B.R. Sandel, M.F. Thomsen, M. Spasojević, P.H. Reiff, Simultaneous remote sensing and in situ observations of plasmaspheric drainage plumes. *J. Geophys. Res.* **109**, A03202 (2004b)
- J. Goldstein, R.A. Wolf, B.R. Sandel, P.H. Reiff, Electric fields deduced from plasmopause motion in IMAGE EUV images. *Geophys. Res. Lett.* **31**, L01801 (2004c)
- J. Goldstein, J.L. Burch, B.R. Sandel, Magnetospheric model of subauroral polarization stream. *J. Geophys. Res.* **110**, A09222 (2005a)
- J. Goldstein, J.L. Burch, B.R. Sandel, S.B. Mende, P.C. Brandt, M.R. Hairston, Coupled response of the inner magnetosphere and ionosphere on 17 April 2002. *J. Geophys. Res.* **110**, A03205 (2005b)
- J. Goldstein, B.R. Sandel, W.T. Forrester, M.F. Thomsen, M.R. Hairston, Global plasmasphere evolution 22–23 April 2001. *J. Geophys. Res.* **110**, A12218 (2005c)
- J. Goldstein, B.R. Sandel, H.U. Frey, S.B. Mende, Multiple plasmopause undulations observed by the IMAGE satellite on 20 March 2001. *J. Atmos. Solar-Terr. Phys.* **69**(3), 322–333 (2007)
- T.I. Gombosi, C.E. Rasmussen, Transport of gyration-dominated space plasmas of thermal origin 1. Generalized transport equations. *J. Geophys. Res.* **96**(A5), 7759–7778 (1991)
- C.A. Gonzales, M.C. Kelley, D.L. Carpenter, T.R. Miller, R.H. Wand, Simultaneous measurements of ionospheric and magnetospheric electric fields in the outer plasmasphere. *Geophys. Res. Lett.* **7**(7), 517–520 (1980)
- M.P. Gough, Non-thermal continuum emissions associated with electron injections: Remote plasmopause sounding. *Planet. Space Sci.* **30**(7), 657–668 (1982)
- J.M. Grebowsky, Model study of plasmopause motion. *J. Geophys. Res.* **75**(22), 4329–4333 (1970)
- J.M. Grebowsky, Model development of supersonic trough wind with shocks. *Planet. Space Sci.* **20**(11), 1923–1934 (1972)
- J.M. Grebowsky, A.J. Chen, Effects on the plasmasphere of irregular electric fields. *Planet. Space Sci.* **24**(7), 689–696 (1976)
- J.L. Green, S.A. Boardsen, Confinement of nonthermal continuum radiation to low latitudes. *J. Geophys. Res.* **104**(A5), 10307–10316 (1999)
- J.L. Green, S.F. Fung, Advances in inner magnetosphere passive and active wave research, in *The Inner Magnetosphere: Physics and Modeling*, ed. by T.I. Pulkkinen, N.A. Tsyganenko, R.H.W. Friedel. Geophysical Monograph Series, vol. 155 (American Geophysical Union, Washington, 2005), pp. 181–202
- J.L. Green, B.W. Reinisch, An overview of results from RPI on image. *Space Sci. Rev.* **109**(1–4), 183–210 (2003)
- J.L. Green, B.R. Sandel, S.F. Fung, D.L. Gallagher, B.W. Reinisch, On the origin of kilometric continuum. *J. Geophys. Res.* **107**(A7), 1105 (2002)
- J.L. Green, S. Boardsen, S.F. Fung, H. Matsumoto, K. Hashimoto, R.R. Anderson, B.R. Sandel, B.W. Reinisch, Association of kilometric continuum radiation with plasmaspheric structures. *J. Geophys. Res.* **109**, A03203 (2004)
- J.L. Green, S. Boardsen, L. Garcia, W.W.L. Taylor, S.F. Fung, B.W. Reinisch, On the origin of whistler mode radiation in the plasmasphere. *J. Geophys. Res.* **110**, A03201 (2005a)
- J.L. Green, S.F. Fung, S. Boardsen, H.J. Christian, Distribution and origin of plasmaspheric plasma waves, in *Inner Magnetosphere Interactions: New Perspectives from Imaging*, ed. by J. Burch, M. Schulz, H. Spence. Geophysical Monograph Series, vol. 159 (American Geophysical Union, Washington, 2005b), pp. 113–126
- J.L. Green, S. Boardsen, L. Garcia, S.F. Fung, B.W. Reinisch, Reply to “Comment on ‘On the origin of whistler mode radiation in the plasmasphere’ by Green et al.” *J. Geophys. Res.* **111**, A09211 (2006)
- R.S. Grew, F.W. Menk, M.A. Clilverd, B.R. Sandel, Mass and electron densities in the inner magnetosphere during a prolonged disturbed interval. *Geophys. Res. Lett.* **34**, L02108 (2007)
- S. Grimald, Etude de l’émission et de la propagation du continuum terrestre à partir des données des satellites Cluster. Ph.D. thesis, University of Orléans, France (2007)
- S. Grimald, P.M.E. Décreau, P. Canu, X. Suraud, X. Vallières, F. Darrouzet, C.C. Harvey, A quantitative test of Jones NTC beaming theory using CLUSTER constellation. *Ann. Geophys.* **25**(3), 823–831 (2007)
- S. Grimald, P.M.E. Décreau, P. Canu, A. Rochel, X. Vallières, Medium-latitude sources of plasmaspheric non-thermal continuum radiations observed close to harmonics of the electron gyrofrequency. *J. Geophys. Res.* **113**, A11216 (2008)

- K.I. Gringauz, The structure of the ionized gas envelope of the Earth from direct measurements in the USSR of local charged particle concentrations. *Planet. Space Sci.* **11**(3), 281–296 (1963)
- K.I. Gringauz, V.V. Bezrukhikh, Plasmasphere of the Earth (Review). *Geomagn. Aeron.* **17**(5), 523–533 (1977)
- K.I. Gringauz, V.G. Kurt, V.I. Moroz, I.S. Shklovsky, Results of observations of charged particles observed out to $R = 100,000$ km with the aid of charged-particle traps on Soviet space rockets. *Astronomicheskii Zhurnal* **37**, 716–735 (1960)
- K.I. Gringauz, V.V. Bezrukhikh, V.D. Ozerov, R.E. Rybchinskii, The study of interplanetary ionized gas, high-energy electrons and corpuscular radiation of the Sun, employing three-electrode charged particle traps on the second Soviet space rocket. *Planet. Space Sci.* **9**(3), 103–107 (1962)
- S.M. Guiter, T.I. Gombosi, The role of high-speed plasma flows in plasmaspheric refilling. *J. Geophys. Res.* **95**(A7), 10427–10440 (1990)
- S.M. Guiter, T.I. Gombosi, C.E. Rasmussen, Two-stream modeling of plasmaspheric refilling. *J. Geophys. Res.* **100**(A6), 9519–9526 (1995)
- C. Gurgiolo, B.R. Sandel, J.D. Perez, D.G. Mitchell, C.J. Pollock, B.A. Larsen, Overlap of the plasmasphere and ring current: Relation to subauroral ionospheric heating. *J. Geophys. Res.* **110**, A12217 (2005)
- D.A. Gurnett, The Earth as a radio source: The nonthermal continuum. *J. Geophys. Res.* **80**(19), 2751–2763 (1975)
- D.A. Gurnett, Plasma wave interactions with energetic ions near the magnetic equator. *J. Geophys. Res.* **81**(16), 2765–2770 (1976)
- D.A. Gurnett, L.A. Franck, VLF hiss and related plasma observations in the polar magnetosphere. *J. Geophys. Res.* **77**(1), 172–190 (1972)
- D.A. Gurnett, U.S. Inan, Plasma wave observations with the Dynamics Explorer 1 spacecraft. *Rev. Geophys.* **26**(2), 285–316 (1988)
- D.A. Gurnett, F.L. Scarf, Summary report on session on new developments, in *Progress in Radio Science, 1963–1966* (International Union of Radio Science, Brussels, 1967), pp. 1106–1107
- D.A. Gurnett, S.D. Shawhan, R.R. Shaw, Auroral hiss, Z mode radiation, and auroral kilometric radiation in the polar magnetosphere: DE 1 observations. *J. Geophys. Res.* **88**(A1), 329–340 (1983)
- D.A. Gurnett, R.L. Huff, J.S. Pickett, A.M. Persoon, R.L. Mutel, I.W. Christopher, C.A. Kletzing, U.S. Inan, W.L. Martin, J.-L. Bougeret, H.S.C. Alleyne, K.H. Yearby, First results from the Cluster wideband plasma wave investigation. *Ann. Geophys.* **19**(10–12), 1259–1272 (2001)
- M.S. Gussenhoven, D.A. Hardy, W.J. Burke, DMSP/F2 electron observations of equatorward auroral boundaries and their relationship to magnetospheric electric fields. *J. Geophys. Res.* **86**(A2), 768–778 (1981)
- G. Gustafsson, M. André, T. Carozzi, A.I. Eriksson, C.-G. Fälthammar, R. Grard, G. Holmgren, J.A. Holtet, N. Ivchenko, T. Karlsson, Y. Khotyaintsev, S. Klimov, H. Laakso, P.-A. Lindqvist, B. Lybekk, G. Marklund, F. Mozer, K. Mursula, A. Pedersen, B. Popielawska, S. Savin, K. Stasiewicz, P. Tanskanen, A. Vaivads, J.-E. Wahlund, First results of electric field and density observations by Cluster EFW based on initial months of observations. *Ann. Geophys.* **19**(10–12), 1219–1240 (2001)
- S. Haaland, B.U.Ö. Sonnerup, M.W. Dunlop, A. Balogh, H. Hasegawa, B. Klecker, G. Paschmann, B. Lavraud, H. Rème, Four-spacecraft determination of magnetopause orientation, motion and thickness: comparison with results from single-spacecraft methods. *Ann. Geophys.* **22**(4), 1347–1365 (2004)
- P. Hannequin, J. Max, Statistical and heuristic image noise extraction (SHINE): A new method for processing Poisson noise in scintigraphic images. *Physics in Medicine and Biology* **47**, 4329–4344 (2002)
- W.B. Hanson, I.B. Ortenburger, The coupling between the protonosphere and the normal F region. *J. Geophys. Res.* **66**(5), 1425–1435 (1961)
- W.B. Hanson, T.N.L. Patterson, Diurnal variation of the hydrogen concentration in the exosphere. *Planet. Space Sci.* **11**(9), 1035–1052 (1963)
- L. Harang, VLF-emissions observed at stations close to the auroral zone at stations on lower latitudes. *J. Atmos. Terr. Phys.* **30**, 1143–1160 (1968)
- C.C. Harvey, Spatial gradients and the volumetric tensor, in *Analysis Methods for Multi-Spacecraft Data*, ed. by G. Paschmann, P.W. Daly. ISSI SR-001. ESA Publications Division (1998), pp. 307–322
- A. Hasegawa, Drift-wave instability at the plasmopause. *J. Geophys. Res.* **76**(22), 5361–5364 (1971)
- K. Hashimoto, W. Calvert, H. Matsumoto, Kilometric continuum detected by Geotail. *J. Geophys. Res.* **104**(A12), 28645–28656 (1999)
- K. Hashimoto, J.J. Green, R.R. Anderson, H. Matsumoto, Review of kilometric continuum, in *Geospace Electromagnetic Waves and Radiation*, ed. by J.W. LaBelle, R.A. Treumann. Lecture Notes in Physics, vol. 687 (Springer, Berlin, 2006), pp. 37–51
- M. Hayakawa, Association of whistlers with lightning discharges on the Earth and on Jupiter. *J. Atmos. Terr. Phys.* **57**(5), 525–535 (1995a)
- M. Hayakawa, Whistlers, in *Handbook of Atmospheric Electrodynamics, vol. II*, ed. by H. Volland (CRC Press, Boca Raton, 1995b), pp. 155–194

- M. Hayakawa, S.S. Sazhin, Mid-latitude and plasmaspheric hiss: A review. *Planet. Space Sci.* **40**(10), 1325–1338 (1992)
- M. Hayakawa, Y. Tanaka, J. Ohtsu, The morphologies of low-latitude and auroral VLF “hiss”. *J. Atmos. Terr. Phys.* **37**, 517–529 (1975)
- M. Hayakawa, N. Ohmi, M. Parrot, F. Lefeuvre, Direction finding of ELF hiss emissions in a detached plasma region of the magnetosphere. *J. Geophys. Res.* **91**(A1), 135–141 (1986)
- A.E. Hedin, MSIS-86 thermospheric model. *J. Geophys. Res.* **92**(A5), 4649–4662 (1987)
- R.A. Heelis, W.R. Coley, East-west ion drifts at mid-latitudes observed by Dynamics Explorer 2. *J. Geophys. Res.* **97**(A12), 19461–19469 (1992)
- R.A. Heelis, J.K. Lowell, R.W. Spiro, A model of the high-latitude ionospheric convection pattern. *J. Geophys. Res.* **87**(A8), 6339–6345 (1982)
- S. Heise, N. Jakowski, D. Cooke, Ionosphere/plasmasphere imaging based on GPS navigation measurements from CHAMP and SAC-C, in *Earth Observation with CHAMP: Results from Three Years in Orbit*, ed. by C. Reigber, H. Lühr, P. Schwintzer, J. Wickert (Springer, Berlin, 2005), pp. 471–476
- R.A. Helliwell, *Whistlers and Associated Ionospheric Phenomena* (Stanford University Press, Stanford, 1965)
- R.A. Helliwell, VLF wave stimulation experiments in the magnetosphere from Siple station, Antarctica. *Rev. Geophys.* **26**(3), 551–578 (1988)
- R.A. Helliwell, J.P. Katsufakis, VLF wave injection into the magnetosphere from Siple station, Antarctica. *J. Geophys. Res.* **79**(16), 2511–2518 (1974)
- J.P. Heppner, Empirical models of high-latitude electric fields. *J. Geophys. Res.* **82**(7), 1115–1125 (1977)
- J.P. Heppner, N.C. Maynard, Empirical high-latitude electric field models. *J. Geophys. Res.* **92**(A5), 4467–4489 (1987)
- R.L. Heyborne, R.L. Smith, R.A. Helliwell, Latitudinal cutoff of VLF signals in the ionosphere. *J. Geophys. Res.* **74**(9), 2393–2397 (1969)
- T.W. Hill, Inertial limit on corotation. *J. Geophys. Res.* **84**(A11), 6554–6558 (1979)
- D. Ho, D.L. Carpenter, Outlying plasmasphere structure detected by whistlers. *Planet. Space Sci.* **24**(10), 987–994 (1976)
- J.M. Holt, R.H. Wand, J.V. Evans, W.L. Oliver, Empirical models for the plasma convection at high latitudes from Millstone Hill observations. *J. Geophys. Res.* **92**(A1), 203–212 (1987)
- T.E. Holzer, J.A. Fedder, P.M. Banks, A comparison of kinetic and hydrodynamic models of an expanding ion-exosphere. *J. Geophys. Res.* **76**(A10), 2453–2468 (1971)
- R.E. Horita, Proton cyclotron echoes and spurs observed on Alouette II and ISIS II. *Radio Sci.* **22**(4), 671–686 (1987)
- R.B. Horne, G.V. Wheeler, H.S.C.K. Alleyne, Proton and electron heating by radially propagating fast magnetosonic waves. *J. Geophys. Res.* **105**(A12), 27597–27610 (2000)
- R.B. Horne, R.M. Thorne, Y.Y. Shprits, N.P. Meredith, S.A. Glauert, A.J. Smith, S.G. Kanekal, D.N. Baker, M.J. Engebretson, J.L. Posch, M. Spasojevic, U.S. Inan, J.S. Pickett, P.M.E. Décréau, Wave acceleration of electrons in the Van Allen radiation belts. *Nature* **437**(7056), 227–230 (2005)
- R.B. Horne, R.M. Thorne, S.A. Glauert, N.P. Meredith, D. Pokhotelov, O. Santolík, Electron acceleration in the Van Allen radiation belts by fast magnetosonic waves. *Geophys. Res. Lett.* **34**, L17107 (2007)
- J.L. Horwitz, N. Singh, Refilling of the Earth’s plasmasphere. *Eos Trans. AGU* **72**(37), 399–402 (1991)
- J.L. Horwitz, C.R. Baugher, C.R. Chappell, E.G. Shelley, D.T. Young, R.R. Anderson, ISEE 1 observations of thermal plasma in the vicinity of the plasmasphere during periods of quieting magnetic activity. *J. Geophys. Res.* **86**(A12), 9989–10001 (1981)
- J.L. Horwitz, R.H. Comfort, C.R. Chappell, Thermal ion composition measurements of the formation of the new outer plasmasphere and double plasmopause during storm recovery phase. *Geophys. Res. Lett.* **11**(8), 701–704 (1984)
- J.L. Horwitz, S. Menteer, J. Turnley, J.L. Burch, J.D. Winningham, C.R. Chappell, J.D. Craven, L.A. Frank, D.W. Slater, Plasma boundaries in the inner magnetosphere. *J. Geophys. Res.* **91**(A8), 8861–8882 (1986)
- J.L. Horwitz, R.H. Comfort, C.R. Chappell, A statistical characterization of plasmasphere density structure and boundary locations. *J. Geophys. Res.* **95**(A6), 7937–7947 (1990)
- X. Huang, B.W. Reinisch, Automatic calculation of electron density profiles from digital ionograms 2. True height inversion of topside ionograms with the profile-fitting method. *Radio Sci.* **17**(4), 837–844 (1982)
- X. Huang, B.W. Reinisch, P. Song, J.L. Green, D.L. Gallagher, Developing an empirical density model of the plasmasphere using IMAGE/RPI observations. *Adv. Space Res.* **33**(6), 829–832 (2004)
- C.-S. Huang, G.D. Reeves, G. Le, K. Yumoto, Are sawtooth oscillations of energetic plasma particle fluxes caused by periodic substorms or driven by solar wind pressure enhancements? *J. Geophys. Res.* **110**, A07207 (2005)

- C. Huang, S. Sazykin, R. Spiro, J. Goldstein, G. Crowley, J.M. Ruohoniemi, Storm-time penetration electric fields and their effects. *Eos Trans. AGU* **87**(13), 131 (2006)
- J.D. Huba, G. Joyce, J.A. Fedder, Sami2 is another model of the ionosphere (SAMI2): A new low-latitude ionosphere model. *J. Geophys. Res.* **105**(A10), 23035–23053 (2000)
- T. Iijima, T.A. Potemra, The amplitude distribution of field-aligned currents at northern high latitudes observed by triad. *J. Geophys. Res.* **81**(13), 2165–2174 (1976)
- T.J. Immel, S.B. Mende, H.U. Frey, L.M. Peticolas, C.W. Carlson, J.-C. Gérard, B. Hubert, S.A. Fuselier, J.L. Burch, Precipitation of auroral protons in detached arcs. *Geophys. Res. Lett.* **29**(11), 1519 (2002)
- U.S. Inan, T.F. Bell, R.A. Helliwell, Nonlinear pitch angle scattering of energetic electrons by coherent VLF waves in the magnetosphere. *J. Geophys. Res.* **83**(A7), 3235–3253 (1978)
- U.S. Inan, M. Platino, T.F. Bell, D.A. Gurnett, J.S. Pickett, Cluster measurements of rapidly moving sources of ELF/VLF chorus. *J. Geophys. Res.* **109**, A05214 (2004)
- J.E. Jackson, The reduction of topside ionograms to electron-density profiles. *Proc. IEEE* **57**(6), 960–975 (1969)
- R.K. Jaggi, R.A. Wolf, Self-consistent calculation of the motion of a sheet of ions in the magnetosphere. *J. Geophys. Res.* **78**(16), 2852–2866 (1973)
- H.G. James, Wave propagation experiments at medium frequencies between two ionospheric satellites, 3. Z mode pulses. *J. Geophys. Res.* **84**(A2), 499–506 (1979)
- M.T. Johnson, J.R. Wygant, C. Cattell, F.S. Mozer, M. Temerin, J. Scudder, Observations of the seasonal dependence of the thermal plasma density in the southern hemisphere auroral zone and polar cap at $1 R_E$. *J. Geophys. Res.* **106**(A9), 19023–19033 (2001)
- M.T. Johnson, J.R. Wygant, C.A. Cattell, F.S. Mozer, Seasonal variations along auroral field lines: Measurements from the polar spacecraft. *Geophys. Res. Lett.* **30**(6), 1344 (2003)
- D. Jones, Latitudinal beaming of planetary radio emissions. *Nature* **288**, 225–229 (1980)
- D. Jones, Terrestrial myriametric radiation from the Earth's plasmopause. *Planet. Space Sci.* **30**(4), 399–410 (1982)
- V.K. Jordanova, L.M. Kistler, J.U. Kozyra, G.V. Khazanov, A.F. Nagy, Collisional losses of ring current ions. *J. Geophys. Res.* **101**(A1), 111–126 (1996a)
- V.K. Jordanova, J.U. Kozyra, A.F. Nagy, Effects of heavy ions on the quasi-linear diffusion coefficients from resonant interactions with electromagnetic ion cyclotron waves. *J. Geophys. Res.* **101**(A9), 19771–19778 (1996b)
- V.K. Jordanova, J.U. Kozyra, A.F. Nagy, G.V. Khazanov, Kinetic model of the ring current-atmosphere interactions. *J. Geophys. Res.* **102**(A7), 14279–14291 (1997)
- V.K. Jordanova, L.M. Kistler, C.J. Farrugia, R.B. Torbert, Effects of inner magnetospheric convection on ring current dynamics: March 10–12, 1998. *J. Geophys. Res.* **106**(A12), 29705–29720 (2001)
- V.K. Jordanova, A. Boonsiriseth, R.M. Thorne, Y. Dotan, Ring current asymmetry from global simulations using a high-resolution electric field model. *J. Geophys. Res.* **108**(A12), 1443 (2003)
- V.K. Jordanova, Y.S. Miyoshi, S. Zaharia, M.F. Thomsen, G.D. Reeves, D.S. Evans, C.G. Mouikis, J.F. Fennell, Kinetic simulations of ring current evolution during the geospace environment modeling challenge events. *J. Geophys. Res.* **111**, A11S10 (2006)
- V.K. Jordanova, M. Spasojevic, M.F. Thomsen, Modeling the electromagnetic ion cyclotron wave-induced formation of detached subauroral proton arcs. *J. Geophys. Res.* **112**, A08209 (2007)
- T. Karlsson, G.T. Marklund, L.G. Blomberg, A. Mäkki, Subauroral electric fields observed by the Freja satellite: A statistical study. *J. Geophys. Res.* **103**(A3), 4327–4341 (1998)
- Y. Kasaba, H. Matsumoto, K. Hashimoto, R.R. Anderson, J.-L. Bougeret, M.L. Kaiser, X.Y. Wu, I. Nagano, Remote sensing of the plasmopause during substorms: Geotail observation of nonthermal continuum enhancement. *J. Geophys. Res.* **103**(A9), 20389–20405 (1998)
- M.C. Kelley, *The Earth's Ionosphere: Plasma Physics and Electrodynamics* (Academic Press, San Diego, 1989)
- C.F. Kennel, H.E. Petschek, Limit on stably trapped particle fluxes. *J. Geophys. Res.* **71**(1), 1–28 (1966)
- H. Khan, S.W.H. Cowley, Observations of the response time of high-latitude ionospheric convection to variations in the interplanetary magnetic field using EISCAT and IMP-8 data. *Ann. Geophys.* **17**(10), 1306–1335 (1999)
- G.V. Khazanov, M.A. Koyen, Y.V. Konikov, I.M. Sidorov, Simulation of ionosphere-plasmasphere coupling taking into account ion inertia and temperature anisotropy. *Planet. Space Sci.* **32**(5), 585–598 (1984)
- G.V. Khazanov, M.W. Liemohn, T.S. Newman, M.-C. Fok, R.W. Spiro, Self-consistent magnetosphere-ionosphere coupling: Theoretical studies. *J. Geophys. Res.* **108**(A3), 1122 (2003)
- G.V. Khazanov, M.W. Liemohn, T.S. Newman, M.-C. Fok, A.J. Ridley, Magnetospheric convection electric field dynamics and stormtime particle energization: case study of the magnetic storm of 4 May 1998. *Ann. Geophys.* **22**(2), 497–510 (2004)

- K.-H. Kim, J. Goldstein, D. Berube, Plasmaspheric drainage plume observed by the Polar satellite in the prenoon sector and the IMAGE satellite during the magnetic storm of 11 April 2001. *J. Geophys. Res.* **112**, A06237 (2007)
- I. Kimura, Effects of ions on whistler-mode ray tracing. *Radio Sci.* **1**(3), 269–283 (1966)
- J.W. King, D.M. Preece, Observations of proton gyroeffects in the topside ionosphere. *J. Atmos. Terr. Phys.* **29**, 1387–1390 (1967)
- M.G. Kivelson, C.T. Russell (eds.), *Introduction to Space Physics* (Cambridge University Press, New York, 1995)
- H.C. Koons, Observations of large-amplitude, whistler mode wave ducts in the outer plasmasphere. *J. Geophys. Res.* **94**(A11), 15393–15397 (1989)
- H. Korth, M.F. Thomsen, K.-H. Glassmeier, W.S. Phillips, Particle tomography of the inner magnetosphere. *J. Geophys. Res.* **107**(A9), 1229 (2002)
- G.A. Kotova, The Earth's plasmasphere: State of studies (a review). *Geomagn. Aeron.* **47**(4), 409–422 (2007)
- G.A. Kotova, V.V. Bezrukhikh, M.I. Verigin, L.A. Lezhen, Temperature and density variations in the dusk and dawn plasmasphere as observed by Interball Tail in 1999–2000. *Adv. Space Res.* **30**(7), 1831–1834 (2002)
- G.A. Kotova, V.V. Bezrukhikh, M.I. Verigin, J. Smilauer, New aspects in plasmaspheric ion temperature variations from INTERBALL 2 and MAGION 5 measurements. *J. Atmos. Solar-Terr. Phys.* **70**(2–4), 399–406 (2008)
- J. Krall, J.D. Huba, J.A. Fedder, Simulation of H^+ and He^+ dynamics during plasmasphere refilling. *Eos Trans. AGU* **88**(52), SM21A–0303 (2007)
- J. Krall, J.D. Huba, J.A. Fedder, Simulation of field-aligned H^+ and He^+ dynamics during late-stage plasmasphere refilling. *Ann. Geophys.* **26**(6), 1507–1516 (2008)
- I.P. Kurchashov, I.S. Nikomarov, V.A. Pilipenko, A. Best, Field line resonance effects in local meridional structure of mid-latitude geomagnetic pulsations. *Ann. Geophys.* **5**(6), 147–154 (1987)
- W.S. Kurth, Detailed observations of the source of terrestrial narrowband electromagnetic radiation. *Geophys. Res. Lett.* **9**(12), 1341–1344 (1982)
- W.S. Kurth, D.A. Gurnett, R.R. Anderson, Escaping nonthermal continuum radiation. *J. Geophys. Res.* **86**(A7), 5519–5531 (1981)
- H. Laakso, A. Pedersen, Ambient electron density derived from differential potential measurements, in *Measurements Techniques in Space Plasmas: Particles*, ed. by R.F. Pfaff, J.E. Borovsky, D.T. Young. Geophysical Monograph Series, vol. 102 (American Geophysical Union, Washington, 1998), pp. 49–54
- H. Laakso, R. Pfaff, P. Janhunen, Polar observations of electron density distribution in the Earth's magnetosphere. 1. Statistical results. *Ann. Geophys.* **20**(11), 1711–1724 (2002)
- T. Laaspere, M.G. Morgan, W.C. Johnson, Chorus, hiss, and other audio-frequency emissions at stations of the whistlers-east network. *Proc. IEEE* **52**(11), 1331–1349 (1964)
- J. LaBelle, R.A. Treumann, Auroral radio emissions, 1. Hisses, roars, and bursts. *Space Sci. Rev.* **101**(3), 295–440 (2002)
- J.W. LaBelle, R.A. Treumann (eds.), *Geospace Electromagnetic Waves and Radiation*, Lecture Notes in Physics, vol. 687 (Springer, Berlin, 2006)
- R.L. Lambour, L.A. Weiss, R.C. Elphic, M.F. Thomsen, Global modeling of the plasmasphere following storm sudden commencements. *J. Geophys. Res.* **102**(A11), 24351–24368 (1997)
- L.J. Lanzerotti, H. Fukunishi, Relationships of the characteristics of magnetohydrodynamic waves to plasma density gradients in the vicinity of the plasmopause. *J. Geophys. Res.* **80**(34), 4627–4634 (1975)
- B.A. Larsen, D.M. Klumpar, C. Gurgiolo, Correlation between plasmopause position and solar wind parameters. *J. Atmos. Solar-Terr. Phys.* **69**(3), 334–340 (2007)
- M.J. LeDocq, D.A. Gurnett, R.R. Anderson, Electron number density fluctuations near the plasmopause observed by the CRRES spacecraft. *J. Geophys. Res.* **99**(A12), 23661–23671 (1994)
- J.F. Lemaire, The “roche-limit” of ionospheric plasma and the formation of the plasmopause. *Planet. Space Sci.* **22**(5), 757–766 (1974)
- J.F. Lemaire, The mechanisms of formation of the plasmopause. *Ann. Geophys.* **31**, 175–190 (1975)
- J. Lemaire, Rotating ion-exospheres. *Planet. Space Sci.* **24**(10), 975–985 (1976)
- J.F. Lemaire, Frontiers of the plasmasphere. *Aeronomica Acta A* **298** (ISBN 2-87077-310-2), Editions Cabay, Louvain-la-Neuve (1985)
- J.F. Lemaire, Plasma distribution models in a rotating magnetic dipole and refilling plasmaspheric flux tubes. *Phys. Fluids B* **1**(7), 1519–1525 (1989)
- J.F. Lemaire, Hydrostatic equilibrium and convective stability in the plasmasphere. *J. Atmos. Solar-Terr. Phys.* **61**(11), 867–878 (1999)
- J.F. Lemaire, The formation plasmaspheric tails. *Phys. Chem. Earth (C)* **25**, 9–17 (2000)
- J.F. Lemaire, The formation of the light-ion-trough and peeling off the plasmasphere. *J. Atmos. Solar-Terr. Phys.* **63**(11), 1285–1291 (2001)

- J.F. Lemaire, M. Echim, Kinetic and hydrodynamic models of the solar wind and polar wind. *Eos Trans. AGU* **89**(9), 86 (2008)
- J.F. Lemaire, K.I. Gringauz, *The Earth's Plasmasphere* (Cambridge University Press, New York, 1998)
- J. Lemaire, V. Pierrard, Kinetic models of solar and polar winds. *Astrophys. Space Sci.* **277**(1–2), 169–180 (2001)
- J.F. Lemaire, V. Pierrard, Comparison between two theoretical mechanisms for the formation of the plasma-pause and relevant observations. *Geomagn. Aeron.* **48**(5), 553–570 (2008)
- J.F. Lemaire, R.W. Schunk, Plasmaspheric wind. *J. Atmos. Terr. Phys.* **54**(3–4), 467–477 (1992)
- J.F. Lemaire, R.W. Schunk, Plasmaspheric convection with non-closed streamlines. *J. Atmos. Terr. Phys.* **56**(12), 1629–1633 (1994)
- J.F. Lemaire, S.G. Batteux, I.N. Slypen, The influence of a southward and northward turning of the interplanetary magnetic field on the geomagnetic cut-off of cosmic rays, on the mirror points positions of geomagnetically trapped particles, and on their rate of precipitations in the atmosphere. *J. Atmos. Solar-Terr. Phys.* **67**(7), 719–727 (2005)
- Ø. Lie-Svendsen, M.H. Rees, An improved kinetic model for the polar outflow of a minor ion. *J. Geophys. Res.* **101**(A2), 2415–2433 (1996)
- M.W. Liemohn, P.C. Brandt, Small-scale structure in the storm time ring current, in *Inner Magnetosphere Interactions: New Perspectives from Imaging*, ed. by J. Burch, M. Schulz, H. Spence, Geophysical Monograph Series, vol. 159 (American Geophysical Union, Washington, 2005), pp. 167–177
- M.W. Liemohn, G.V. Khazanov, P.D. Craven, J.U. Kozyra, Nonlinear kinetic modeling of the early stage plasmaspheric refilling. *J. Geophys. Res.* **104**(A5), 10295–10306 (1999)
- M.W. Liemohn, J.U. Kozyra, M.F. Thomsen, J.L. Roeder, G. Lu, J.E. Borovsky, T.E. Cayton, Dominant role of the asymmetric ring current in producing the stormtime Dst*. *J. Geophys. Res.* **106**(A6), 10883–10904 (2001)
- M.W. Liemohn, A.J. Ridley, D.L. Gallagher, D.M. Ober, J.U. Kozyra, Dependence of plasmaspheric morphology on the electric field description during the recovery phase of the 17 April 2002 magnetic storm. *J. Geophys. Res.* **109**, A03209 (2004)
- M.W. Liemohn, A.J. Ridley, P.C. Brandt, D.L. Gallagher, J.U. Kozyra, D.M. Ober, D.G. Mitchell, E.C. Roelof, R. DeMajistre, Parametric analysis of nightside conductance effects on inner magnetospheric dynamics for the 17 April 2002 storm. *J. Geophys. Res.* **110**, A12S22 (2005)
- M.W. Liemohn, A.J. Ridley, J.U. Kozyra, D.L. Gallagher, M.F. Thomsen, M.G. Henderson, M.H. Denton, P.C. Brandt, J. Goldstein, Analyzing electric field morphology through data-model comparisons of the geospace environment modeling inner magnetosphere/storm assessment challenge events. *J. Geophys. Res.* **111**, A11S11 (2006)
- J. Lin, J.L. Horwitz, G.R. Wilson, C.W. Ho, D.G. Brown, A semikinetic model for early stage plasmasphere refilling 2, effects of wave-particle interactions. *J. Geophys. Res.* **97**(A2), 1121–1134 (1992)
- B.T. Loftus, T.E. Van Zandt, W. Calvert, Observations of conjugate ducting by the fixed-frequency topside-sounder satellite. *Ann. Geophys.* **22**(4), 530–537 (1966)
- T.M. Loto'aniu, C.L. Waters, J.C. Fraser, J.C. Samson, Plasma mass density in the plasmatrough: Comparison using ULF waves and CRRES. *Geophys. Res. Lett.* **26**(21), 3277–3280 (1999)
- L.R. Lyons, D.J. Williams, *Quantitative Aspects of Magnetospheric Physics* (Reidel, Dordrecht, 1984)
- L.R. Lyons, R.M. Thorne, C.F. Kennel, Pitch-angle diffusion of radiation belt electrons within the plasmasphere. *J. Geophys. Res.* **77**(19), 3455–3474 (1972)
- N. Maruyama, A.D. Richmond, T.J. Fuller-Rowell, M.V. Codrescu, S. Sazykin, F.R. Toffoletto, R.W. Spiro, G.H. Millward, Interaction between direct penetration and disturbance dynamo electric fields in the storm-time equatorial ionosphere. *Geophys. Res. Lett.* **32**, L17105 (2005)
- A. Masson, U.S. Inan, H. Laakso, O. Santolík, P. Décréau, Cluster observations of mid-latitude hiss near the plasma-pause. *Ann. Geophys.* **22**(7), 2565–2575 (2004)
- A. Masson, O. Santolík, D.L. Carpenter, F. Darrouzet, P.M.E. Décréau, F. El-Lemdani Mazouz, J.L. Green, S. Grimald, M.B. Moldwin, F. Němec, V.S. Sonwalkar, Advances in plasmaspheric wave research with CLUSTER and IMAGE observations. *Space Sci. Rev.* **145**(1–2), 137–191 (2009)
- H. Matsui, T. Mukai, S. Ohtani, K. Hayashi, R.C. Elphic, M.F. Thomsen, H. Matsumoto, Cold dense plasma in the outer magnetosphere. *J. Geophys. Res.* **104**(A11), 25077–25095 (1999)
- H. Matsui, M. Nakamura, T. Terasawa, Y. Izaki, T. Mukai, K. Tsuruda, H. Hayakawa, H. Matsumoto, Outflow of cold dense plasma associated with variation of convection in the outer magnetosphere. *J. Atmos. Sol.-Terr. Phys.* **62**(6), 521–526 (2000)
- H. Matsui, J.M. Quinn, R.B. Torbert, V.K. Jordanova, W. Baumjohann, P.A. Puhl-Quinn, G. Paschmann, Electric field measurements in the inner magnetosphere by Cluster EDI. *J. Geophys. Res.* **108**(A9), 1352 (2003)
- H. Matsui, V.K. Jordanova, J.M. Quinn, R.B. Torbert, G. Paschmann, Derivation of electric potential patterns in the inner magnetosphere from Cluster EDI data: Initial results. *J. Geophys. Res.* **109**, A10202 (2004)

- H. Matsui, J.M. Quinn, R.B. Torbert, V.K. Jordanova, P.A. Puhl-Quinn, G. Paschmann, IMF B_Y and seasonal dependences of the electric field in the inner magnetosphere. *Ann. Geophys.* **23**(7), 2671–2678 (2005)
- H. Matsui, P.A. Puhl-Quinn, V.K. Jordanova, Y. Khotyaintsev, P.-A. Lindqvist, R.B. Torbert, Derivation of inner magnetospheric electric field (UNH-IMEF) model using Cluster data set. *Ann. Geophys.* **26**(9), 2887–2898 (2008)
- H. Matsui, J.C. Foster, D.L. Carpenter, I. Dandouras, F. Darrouzet, J. De Keyser, D.L. Gallagher, J. Goldstein, P.A. Puhl-Quinn, C. Vallat, Electric fields and magnetic fields in the plasmasphere: A perspective from CLUSTER and IMAGE. *Space Sci. Rev.* **145**(1–2), 107–135 (2009)
- H. Matsumoto, I. Kimura, Linear and nonlinear instabilities and VLF emissions in the magnetosphere. *Planet. Space Sci.* **19**(6), 567–608 (1971)
- N.C. Maynard, A.J. Chen, Isolated cold plasma regions: Observations and their relation to possible production mechanisms. *J. Geophys. Res.* **80**(7), 1009–1013 (1975)
- N.C. Maynard, T.L. Aggson, J.P. Heppner, The plasmaspheric electric field as measured by ISEE 1. *J. Geophys. Res.* **88**(A5), 3991–4003 (1983)
- D.J. McComas, S.J. Bame, P. Barker, W.C. Feldman, J.L. Phillips, P. Riley, J.W. Griffée, Solar wind electron proton alpha monitor (SWEPAM) for the advanced composition explorer. *Space Sci. Rev.* **86**(1–4), 563–612 (1998)
- C.E. McIlwain, Coordinates for mapping the distribution of magnetically trapped particles. *J. Geophys. Res.* **66**(11), 3681–3691 (1961)
- C.E. McIlwain, Substorm injection boundaries, in *Magnetospheric Physics*, ed. by B.M. McCormac (Reidel, Dordrecht, 1974), pp. 143–154
- C.E. McIlwain, A Kp dependent equatorial electric field model. *Adv. Space Res.* **6**(3), 187–197 (1986)
- F.A. McNeill, Frequency shifts on whistler mode signals from a stabilized VLF transmitter. *Radio Sci.* **2**, 589–594 (1967)
- F.W. Menk, Spectral structure of mid-latitude Pc3–4 geomagnetic pulsations. *J. Geomag. Geoelectr.* **40**(1), 33–61 (1988)
- F.W. Menk, B.J. Fraser, C.L. Waters, C.W.S. Ziesolleck, Q. Feng, S.H. Lee, P.W. McNabb, Ground measurements of low latitude magnetospheric field line resonances, in *Solar Wind Sources of Magnetospheric Ultra-Low-Frequency Waves*, ed. by M.J. Engebretson, K. Takahashi, M. Scholer. Geophysical Monograph Series, vol. 81 (American Geophysical Union, Washington, 1994), pp. 299–310
- F.W. Menk, D. Orr, M.A. Clilverd, A.J. Smith, C.L. Waters, D.K. Milling, B.J. Fraser, Monitoring spatial and temporal variations in the dayside plasmasphere using geomagnetic field line resonances. *J. Geophys. Res.* **104**(A9), 19955–19969 (1999)
- N.P. Meredith, R.B. Horne, M.A. Clilverd, D. Horsfall, R.M. Thorne, R.R. Anderson, Origins of plasmaspheric hiss. *J. Geophys. Res.* **111**, A09217 (2006)
- N.P. Meredith, R.B. Horne, S.A. Glauert, R.R. Anderson, Slot region electron loss timescales due to plasmaspheric hiss and lightning-generated whistlers. *J. Geophys. Res.* **112**, A08214 (2007)
- R.H. Miller, C.E. Rasmussen, T.I. Gombosi, G.V. Khazanov, D. Winske, Kinetic simulation of plasma flows in the inner magnetosphere. *J. Geophys. Res.* **98**(A11), 19301–19313 (1993)
- G.H. Milward, R.J. Moffett, S. Quegan, T.J. Fuller-Rowell, A coupled thermosphere-ionosphere-plasmasphere model (CTIP), in *Solar Terrestrial Energy Program (STEP) Handbook on Ionospheric Models*, ed. by R.W. Schunk (Utah State University, Logan, 1996), pp. 239–279
- E.V. Mishin, W.J. Burke, Stormtime coupling of the ring current, plasmasphere, and topside ionosphere: Electromagnetic and plasma disturbances. *J. Geophys. Res.* **110**, A07209 (2005)
- E.V. Mishin, P.A. Puhl-Quinn, SAID: Plasmaspheric short circuit of substorm injections. *Geophys. Res. Lett.* **34**, L24101 (2007)
- D.G. Mitchell, S.E. Jaskulek, C.E. Schlemm, E.P. Keath, R.E. Thompson, B.E. Tossman, J.D. Boldt, J.R. Hayes, G.B. Andrews, N. Paschalidis, D.C. Hamilton, R.A. Lundgren, E.O. Tums, P. Wilson, H.D. Voss, D. Prentice, K.C. Hsieh, C.C. Curtis, F.R. Powell, High energy neutral atom (HENA) imager for the IMAGE mission. *Space Sci. Rev.* **91**(1–2), 67–112 (2000)
- M.B. Moldwin, M.F. Thomsen, S.J. Bame, D.J. McComas, K.R. Moore, An examination of the structure and dynamics of the outer plasmasphere using multiple geosynchronous satellites. *J. Geophys. Res.* **99**(A6), 11475–11481 (1994)
- M.B. Moldwin, M.F. Thomsen, S.J. Bame, D. McComas, G.D. Reeves, The fine-scale structure of the outer plasmasphere. *J. Geophys. Res.* **100**(A5), 8021–8029 (1995)
- M.B. Moldwin, L. Downward, H.K. Rassoul, R. Amin, R.R. Anderson, A new model of the location of the plasmopause: CRRES results. *J. Geophys. Res.* **107**(A11), 1339 (2002)
- M.B. Moldwin, B.R. Sandel, M.F. Thomsen, R.C. Elphic, Quantifying global plasmaspheric images with in situ observations. *Space Sci. Rev.* **109**(1), 47–61 (2003)
- M.B. Moldwin, J. Howard, J. Sanny, J.D. Bocchicchio, H.K. Rassoul, R.R. Anderson, Plasmaspheric plumes: CRRES observations of enhanced density beyond the plasmopause. *J. Geophys. Res.* **109**, A05202 (2004)

- T.E. Moore, W.K. Peterson, C.T. Russell, M.O. Chandler, M.R. Collier, H.L. Collin, P.D. Craven, R. Fitzenreiter, B.L. Giles, C.J. Pollock, Ionospheric mass ejection in response to a CME. *Geophys. Res. Lett.* **26**(15), 2339–2342 (1999)
- T.E. Moore, D.J. Chornay, M.R. Collier, F.A. Herrero, J. Johnson, M.A. Johnson, J.W. Keller, J.F. Laudadio, J.F. Lobell, K.W. Ogilvie, P. Rozmarynowski, S.A. Fuselier, A.G. Ghielmetti, E. Hertzberg, D.C. Hamilton, R. Lundgren, P. Wilson, P. Walpole, T.M. Stephen, B.L. Peko, B. Van Zyl, P. Wurz, J.M. Quinn, G.R. Wilson, The low energy neutral atom imager for IMAGE. *Space Sci. Rev.* **91**(1–2), 155–195 (2000)
- D.D. Morgan, D.A. Gurnett, The source location and beaming of terrestrial continuum radiation. *J. Geophys. Res.* **96**(A6), 9595–9613 (1991)
- S.R. Mosier, M.L. Kaiser, L.W. Brown, Observations of noise bands associated with the upper hybrid resonance by the Imp 6 radio astronomy experiment. *J. Geophys. Res.* **78**(10), 1673–1679 (1973)
- O. Moullard, A. Masson, H. Laakso, M. Parrot, P.M.E. Décréau, O. Santolík, M. André, Density modulated whistler mode emissions observed near the plasmapause. *Geophys. Res. Lett.* **29**(20), 1975 (2002)
- F.S. Mozer, C.A. Cattell, M. Temerin, R.B. Torbert, S. Von Glinski, M. Woldorff, J. Wygant, The dc and ac electric field, plasma density, plasma temperature, and field-aligned current experiments on the S3-3 satellite. *J. Geophys. Res.* **84**(A10), 5875–5884 (1979)
- D.B. Muldrew, Radio propagation along magnetic field-aligned sheets of ionization observed by the Alouette topside sounder. *J. Geophys. Res.* **68**(19), 5355–5370 (1963)
- D.B. Muldrew, F-layer ionization troughs deduced from Alouette data. *J. Geophys. Res.* **70**(11), 2635–2650 (1965)
- D.B. Muldrew, Nonvertical propagation and delayed-echo generation observed by the topside sounders. *Proc. IEEE* **57**(6), 1097–1107 (1969)
- D.B. Muldrew, Electrostatic resonances associated with the maximum frequencies of cyclotron-harmonic waves. *J. Geophys. Res.* **77**(10), 1794–1801 (1972)
- D.B. Muldrew, Topside sounder proton-cyclotron echo generation from a plasma memory process and electron Bernstein-wave propagation. *Radio Sci.* **33**(5), 1395–1411 (1998)
- G. Murakami, M. Hirai, I. Yoshikawa, The plasmapause response to the southward turning of the IMF derived from sequential EUV images. *J. Geophys. Res.* **112**, A06217 (2007)
- F. Němec, O. Santolík, K. Gereová, E. Macúšová, Y. de Conchy, N. Cornilleau-Wehrin, Initial results of a survey of equatorial noise emissions observed by the Cluster spacecraft. *Planet. Space Sci.* **53**(1–3), 291–298 (2005)
- F. Němec, O. Santolík, K. Gereová, E. Macúšová, H. Laakso, Y. de Conchy, M. Maksimovic, N. Cornilleau-Wehrin, Equatorial noise: Statistical study of its localization and the derived number density. *Adv. Space Res.* **37**(3), 610–616 (2006)
- W.A. Newcomb, Convective instability induced by gravity in a plasma with a frozen-in magnetic field. *Phys. Fluids* **4**(4), 391–396 (1961)
- A. Nishida, Formation of plasmapause, or magnetospheric plasma knee, by the combined action of magnetospheric convection and plasma escape from the tail. *J. Geophys. Res.* **71**(23), 5669–5679 (1966)
- R.W. Nopper, R.L. Carovillano, Polar-equatorial coupling during magnetically active periods. *Geophys. Res. Lett.* **5**(8), 699–702 (1978)
- P.A. Nsumei, X. Huang, B.W. Reinisch, P. Song, V.M. Vasyliunas, J.L. Green, S.F. Fung, R.F. Benson, D.L. Gallagher, Electron density distribution over the northern polar region deduced from IMAGE/radio plasma imager sounding. *J. Geophys. Res.* **108**(A2), 1078 (2003)
- P.A. Nsumei, B.W. Reinisch, P. Song, J. Tu, X. Huang, Polar cap electron density distribution from IMAGE radio plasma imager measurements: Empirical model with the effects of solar illumination and geomagnetic activity. *J. Geophys. Res.* **113**, A01217 (2008)
- D. Nunn, A self-consistent theory of triggered VLF emissions. *Plan. Space Sci.* **22**(3), 349–378 (1974)
- D. Nunn, Y. Omura, H. Matsumoto, I. Nagano, S. Yagitani, The numerical simulation of VLF chorus and discrete emissions observed on the Geotail satellite using a Vlasov code. *J. Geophys. Res.* **102**(A12), 27083–27097 (1997)
- D.M. Ober, J.L. Horwitz, D.L. Gallagher, Formation of density troughs embedded in the outer plasmasphere by subauroral ion drift events. *J. Geophys. Res.* **102**(A7), 14595–14602 (1997a)
- D.M. Ober, J.L. Horwitz, M.F. Thomsen, R.C. Elphic, D.J. McComas, R.D. Belian, M.B. Moldwin, Premidnight plasmaspheric “plumes”. *J. Geophys. Res.* **102**(A6), 11325–11334 (1997b)
- T.P. O’Brien, M.B. Moldwin, Empirical plasmapause models from magnetic indices. *Geophys. Res. Lett.* **30**(4), 1152 (2003)
- S. Ohtani, H. Korth, P.C. Brandt, L.G. Blomberg, H.J. Singer, M.G. Henderson, E.A. Lucek, H.U. Frey, Q. Zong, J.M. Weygand, Y. Zheng, A.T.Y. Lui, Cluster observations in the inner magnetosphere during the 18 April 2002 sawtooth event: Dipolarization and injection at $r = 4.6R_E$. *J. Geophys. Res.* **112**, A08213 (2007)

- Y. Omura, H. Matsumoto, Computer simulations of basic processes of coherent whistler-mode wave-particle interactions in the magnetosphere. *J. Geophys. Res.* **87**(A6), 4435–4444 (1982)
- Y. Omura, H. Matsumoto, D. Nunn, M.J. Rycroft, A review of observational, theoretical and numerical studies of VLF triggered emissions. *J. Atmos. Terr. Phys.* **53**(5), 351–368 (1991)
- Y. Omura, Y. Katoh, D. Summers, Theory and simulation of the generation of whistler-mode chorus. *J. Geophys. Res.* **113**, A04223 (2008)
- T. Ondoh, Latitudinal changes of polar hiss and plasmapause hiss associated with magnetospheric processes. *Adv. Space Res.* **37**(3), 581–591 (2006)
- V.A. Osherovich, R.F. Benson, J. Fainberg, J.L. Green, L. Garcia, S. Boardsen, N. Tsyganenko, B.W. Reinisch, Enhanced high-altitude polar cap plasma and magnetic field values in response to the interplanetary magnetic cloud that caused the great storm of 31 March 2001: A case study for a new magnetospheric index. *J. Geophys. Res.* **112**, A06247 (2007)
- H. Oya, Generation mechanism of proton cyclotron echoes due to pulsed radio frequency waves in space plasma. *J. Geophys. Res.* **83**(A5), 1991–2008 (1978)
- V.O. Papitashvili, B.A. Belov, D.S. Faermark, Y.I. Feldstein, S.A. Golyshev, L.I. Gromova, A.E. Levitin, Electric potential patterns in the northern and southern polar regions parameterized by the interplanetary magnetic field. *J. Geophys. Res.* **99**(A7), 13251–13262 (1994)
- C.G. Park, Whistler observations of the interchange of ionization between the ionosphere and the protonosphere. *J. Geophys. Res.* **75**(22), 4249–4260 (1970)
- C.G. Park, D.L. Carpenter, Whistler evidence of large-scale electron-density irregularities in the plasmasphere. *J. Geophys. Res.* **75**(19), 3825–3836 (1970)
- C.G. Park, R.A. Helliwell, The formation by electric fields of field-aligned irregularities in the magnetosphere. *Radio Sci.* **6**(6), 299–304 (1971)
- C.G. Park, D.L. Carpenter, D.B. Wiggin, Electron density in the plasmasphere: Whistler data on solar cycle, annual, and diurnal variations. *J. Geophys. Res.* **83**(A7), 3137–3144 (1978)
- G.K. Parks, *Physics of Space Plasmas: An Introduction* (Westview Press, Boulder, 2004)
- M. Parrot, O. Santolík, N. Cornilleau-Wehrlin, M. Maksimovic, C.C. Harvey, Source location of chorus emissions observed by Cluster. *Ann. Geophys.* **22**(2), 473–480 (2003)
- M. Parrot, O. Santolík, N. Cornilleau-Wehrlin, M. Maksimovic, C. Harvey, Magnetospherically reflected chorus waves revealed by ray tracing with CLUSTER data. *Ann. Geophys.* **21**(5), 1111–1120 (2004a)
- M. Parrot, O. Santolík, D.A. Gurnett, J.S. Pickett, N. Cornilleau-Wehrlin, Characteristics of magnetospherically reflected chorus waves observed by CLUSTER. *Ann. Geophys.* **22**(7), 2597–2606 (2004b)
- E.W. Paschal, R.A. Helliwell, Phase measurements of whistler mode signals from the siple VLF transmitter. *J. Geophys. Res.* **89**(A3), 1667–1674 (1984)
- G. Paschmann, P.W. Daly (eds.), *Analysis Methods for Multi-Spacecraft Data*, ISSI SR-001 (ESA Publications Division, Noordwijk, 1998)
- G. Paschmann, P.W. Daly (eds.), *Multi-Spacecraft Analysis Methods Revisited*, ISSI SR-008 (ESA Communications, Noordwijk, 2008)
- G. Paschmann, J.M. Quinn, R.B. Torbert, H. Vaith, C.E. McIlwain, G. Haerendel, O.H. Bauer, T. Bauer, W. Baumjohann, W. Fillius, M. Förster, S. Frey, E. Georgescu, S.S. Kerr, C.A. Kletzing, H. Matsui, P. Puhl-Quinn, E.C. Whipple, The electron drift instrument on Cluster: Overview of first results. *Ann. Geophys.* **19**(10–12), 1273–1288 (2001)
- G. Paschmann, S.J. Schwartz, C.P. Escoubet, S. Haaland, in *Outer Magnetospheric Boundaries: Cluster Results*. Space Science Series of ISSI, vol. 20 (Springer, Dordrecht, 2005)
- A. Pedersen, Solar wind and magnetosphere plasma diagnostics by spacecraft electrostatic potential measurements. *Ann. Geophys.* **13**(2), 118–129 (1995)
- A. Pedersen, P. Décréau, C.P. Escoubet, G. Gustafsson, H. Laakso, P.-A. Lindqvist, B. Lybekk, A. Masson, F. Mozer, A. Vaivads, Four-point high resolution information on electron densities by the electric field experiments (EFW) on Cluster. *Ann. Geophys.* **19**(10–12), 1483–1489 (2001)
- A. Pedersen, B. Lybekk, M. André, A. Eriksson, A. Masson, F.S. Mozer, P.-A. Lindqvist, P.M.E. Décréau, I. Dandouras, J.-A. Sauvaud, A. Fazakerley, M. Taylor, G. Paschmann, K.R. Venes, K. Torkar, E. Whipple, Electron density estimations derived from spacecraft potential measurements on Cluster in tenuous plasma regions. *J. Geophys. Res.* **113**, A07S33 (2008)
- A.M. Persoon, D.A. Gurnett, S.D. Shawhan, Polar cap electron densities from DE 1 plasma wave observations. *J. Geophys. Res.* **88**(A12), 10123–10136 (1983)
- V. Pierrard, New model of magnetospheric current-voltage relationship. *J. Geophys. Res.* **101**(A2), 2669–2675 (1996)
- V. Pierrard, The dynamics of the plasmasphere, in *Space Science: New Research*, ed. by N.S. Maravell (Nova Science Publishers, New York, 2006), pp. 83–96
- V. Pierrard, I.A. Barghouti, Effects of wave-particle interactions on double-hump distributions of the H^+ polar wind. *Astrophys. Space Sci.* **302**(1–4), 35–41 (2006)

- V. Pierrard, J. Cabrera, Comparisons between EUV/IMAGE observations and numerical simulations of the plasmopause formation. *Ann. Geophys.* **23**(7), 2635–2646 (2005)
- V. Pierrard, J. Cabrera, Dynamical simulations of plasmopause deformations. *Space Sci. Rev.* **122**(1–4), 119–126 (2006)
- V. Pierrard, J. Lemaire, Lorentzian ion exosphere model. *J. Geophys. Res.* **101**(A4), 7923–7934 (1996)
- V. Pierrard, J. Lemaire, A collisional kinetic model of the polar wind. *J. Geophys. Res.* **103**(A6), 11701–11709 (1998)
- V. Pierrard, J. Lemaire, Exospheric model of the plasmasphere. *J. Atmos. Solar-Terr. Phys.* **63**(11), 1261–1265 (2001)
- V. Pierrard, J.F. Lemaire, Development of shoulders and plumes in the frame of the interchange instability mechanism for plasmopause formation. *Geophys. Res. Lett.* **31**, L05809 (2004)
- V. Pierrard, K. Stegen, A three-dimensional dynamic kinetic model of the plasmasphere. *J. Geophys. Res.* **113**, A10209 (2008)
- V. Pierrard, M. Maksimovic, J. Lemaire, Electron velocity distribution functions from the solar wind to the corona. *J. Geophys. Res.* **104**(A8), 17021–17032 (1999)
- V. Pierrard, G.V. Khazanov, J. Cabrera, J. Lemaire, Influence of the convection electric field models on predicted plasmopause positions during magnetic storms. *J. Geophys. Res.* **113**, A08212 (2008)
- V. Pierrard, J. Goldstein, N. André, V.K. Jordanova, G.A. Kotova, J.F. Lemaire, M.W. Liemohn, H. Matsui, Recent progress in physics-based models of the plasmasphere. *Space Sci. Rev.* **145**(1–2), 193–229 (2009)
- M. Platino, U.S. Inan, T.F. Bell, J.S. Pickett, P. Canu, Rapidly moving sources of upper band ELF/VLF chorus near the magnetic equator. *J. Geophys. Res.* **111**, A09218 (2006)
- I.G. Platt, P.L. Dyson, MF and HF propagation characteristics of ionospheric ducts. *J. Atmos. Terr. Phys.* **51**, 759–774 (1989)
- C.J. Pollock, K. Asamura, J. Baldonado, M.M. Balkey, P. Barker, J.L. Burch, E.J. Korpela, J. Cravens, G. Dirks, M.-C. Fok, H.O. Funsten, M. Grande, M. Gruntman, J. Hanley, J.-M. Jahn, M. Jenkins, M. Lampton, M. Marckwordt, D.J. McComas, T. Mukai, G. Penegor, S. Pope, S. Ritzau, M.L. Schattenburg, E. Scime, R. Skoug, W. Spurgeon, T. Stecklein, S. Storms, C. Urdiales, P. Valek, J.T.M. Van Beek, S.E. Weidner, M. Wüest, M.K. Young, C. Zinsmeyer, Medium energy neutral atom (MENA) imager for the IMAGE mission. *Space Sci. Rev.* **91**(1–2), 113–154 (2000)
- J.H. Pope, An estimate of electron densities in the exosphere by means of nose whistlers. *J. Geophys. Res.* **66**(1), 67–75 (1961)
- I.A. Price, C.L. Waters, F.W. Menk, G.J. Bailey, B.J. Fraser, A technique to investigate plasma mass density in the topside ionosphere using ULF waves. *J. Geophys. Res.* **104**(A6), 12723–12732 (1999)
- P.A. Puhl-Quinn, H. Matsui, E. Mishin, C. Mouikis, L. Kistler, Y. Khotyaintsev, P.M.E. Décréau, E. Lucek, Cluster and DMSP observations of SAID electric fields. *J. Geophys. Res.* **112**, A05219 (2007)
- P.A. Puhl-Quinn, H. Matsui, V.K. Jordanova, Y. Khotyaintsev, P.-A. Lindqvist, An effort to derive an empirically based, inner-magnetospheric electric field model: Merging Cluster EDI and EFW data. *J. Atmos. Solar-Terr. Phys.* **70**(24), 564–573 (2008)
- J.M. Quinn, G. Paschmann, N. Sckopke, V.K. Jordanova, H. Vaith, O.H. Bauer, W. Baumjohann, W. Fillius, G. Haerendel, S.S. Kerr, C.A. Kletzing, K. Lynch, C.E. McIlwain, R.B. Torbert, E.C. Whipple, EDI convection measurements at 5–6 R_E in the post-midnight region. *Ann. Geophys.* **17**(12), 1503–1512 (1999)
- J.M. Quinn, G. Paschmann, R.B. Torbert, H. Vaith, C.E. McIlwain, G. Haerendel, O. Bauer, T.M. Bauer, W. Baumjohann, W. Fillius, M. Foerster, S. Frey, E. Georgescu, S.S. Kerr, C.A. Kletzing, H. Matsui, P. Puhl-Quinn, E.C. Whipple, Cluster EDI convection measurements across the high-latitude plasma sheet boundary at midnight. *Ann. Geophys.* **19**(10–12), 1669–1681 (2001)
- C.E. Rasmussen, R.W. Schunk, Multistream hydrodynamic modeling of interhemispheric plasma flow. *J. Geophys. Res.* **93**(A12), 14557–14565 (1988)
- C.E. Rasmussen, S.M. Guiter, S.G. Thomas, A two-dimensional model of the plasmasphere: refilling time constants. *Planet. Space Sci.* **41**(1), 35–43 (1993)
- J.L. Rauch, X. Suraud, P.M.E. Décréau, J.G. Trotignon, R. Ledée, G. Lemerrier, F. El-Lemdani Mazouz, S. Grimald, G. Bozan, A. Vallières, P. Canu, F. Darrouzet, Automatic determination of the plasma frequency using image processing on WHISPER data. *Proceedings of the Cluster and Double Star Symposium, 5th Anniversary of Cluster in Space ESA SP-598* (2006)
- B.W. Reinisch, G.S. Sales, D.M. Haines, S.F. Fung, W.W.L. Taylor, Radio wave active Doppler imaging of space plasma structures: Arrival angle, wave polarization, and Faraday rotation measurements with the radio plasma imager. *Radio Sci.* **34**(6), 1513–1524 (1999)
- B.W. Reinisch, D.M. Haines, K. Bibl, G. Cheney, I.A. Galkin, X. Huang, S.H. Myers, G.S. Sales, R.F. Benson, S.F. Fung, J.L. Green, S. Boardsen, W.W.L. Taylor, J.-L. Bougeret, R. Manning, N. Meyer-Vernet, M. Moncuquet, D.L. Carpenter, D.L. Gallagher, P. Reiff, The radio plasma imager investigation on the IMAGE spacecraft. *Space Sci. Rev.* **91**(1–2), 319–359 (2000)

- B.W. Reinisch, D.M. Haines, R.F. Benson, J.L. Green, G.S. Sales, W.W.L. Taylor, Radio sounding in space: magnetosphere and topside ionosphere. *J. Atmos. Solar-Terr. Phys.* **63**(2–3), 87–98 (2001a)
- B.W. Reinisch, X. Huang, D.M. Haines, I.A. Galkin, J.L. Green, R.F. Benson, S.F. Fung, W.W.L. Taylor, P.H. Reiff, D.L. Gallagher, J.-L. Bougeret, R. Manning, D.L. Carpenter, S.A. Boardsen, First results from the radio plasma imager on IMAGE. *Geophys. Res. Lett.* **28**(6), 1167–1170 (2001b)
- B.W. Reinisch, X. Huang, P. Song, G.S. Sales, S.F. Fung, J.L. Green, D.L. Gallagher, V.M. Vasyliunas, Plasma density distribution along the magnetospheric field: RPI observations from IMAGE. *Geophys. Res. Lett.* **28**(24), 4521–4524 (2001c)
- B.W. Reinisch, X. Huang, P. Song, J.L. Green, S.F. Fung, V.M. Vasyliunas, D.L. Gallagher, B.R. Sandel, Plasmaspheric mass loss and refilling as a result of a magnetic storm. *J. Geophys. Res.* **109**, A01202 (2004)
- B.W. Reinisch, M.B. Moldwin, R.E. Denton, D.L. Gallagher, H. Matsui, V. Pierrard, J. Tu, Augmented empirical models of plasmaspheric density and electric field using IMAGE and CLUSTER data. *Space Sci. Rev.* **145**(1–2), 231–261 (2009)
- H. Rème, C. Aoustin, J.M. Bosqued, I. Dandouras, B. Lavraud, J.A. Sauvaud, A. Barthe, J. Bouyssou, T. Camus, O. Coeur-Joly, A. Cros, J. Cuvelo, F. Ducay, Y. Garbarowitz, J.L. Médale, E. Penou, H. Perrier, D. Romefort, J. Rouzaud, C. Vallat, D. Alcaydé, C. Jacquey, C. Mazelle, C. d’Uston, E. Möbius, L.M. Kistler, K. Crocker, M. Granoff, C. Mouikis, M. Popecki, M. Vosbury, B. Klecker, D. Hovestadt, H. Kucharek, E. Kuenneth, G. Paschmann, M. Scholer, N. Scokpe, E. Seidenschwang, C.W. Carlson, D.W. Curtis, C. Ingraham, R.P. Lin, J.P. McFadden, G.K. Parks, T. Phan, V. Formisano, E. Amata, M.B. Bavassano-Cattaneo, P. Baldetti, R. Bruno, G. Chionchio, A. Di Lellis, M.F. Marcucci, G. Pallochia, A. Korth, P.W. Daly, B. Graeve, H. Rosenbauer, V. Vasyliunas, M. McCarthy, M. Wilber, L. Eliasson, R. Lundin, S. Olsen, E.G. Shelley, S. Fuselier, A.G. Ghielmetti, W. Lennartsson, C.P. Escoubet, H. Balsiger, R. Friedel, J.-B. Cao, R.A. Kovrazhkin, I. Papamastorakis, R. Pellat, J. Scudder, B. Sonnerup, First multi-spacecraft ion measurements in and near the Earth’s magnetosphere with the identical Cluster ion spectrometry (CIS) experiment. *Ann. Geophys.* **19**(1012), 1303–1354 (2001)
- M.A. Reynolds, D.J. Meléndez-Alvira, G. Ganguli, Equatorial coupling between the plasmasphere and the topside ionosphere. *J. Atmos. Solar-Terr. Phys.* **63**(11), 1267–1273 (2001)
- M.A. Reynolds, G. Ganguli, Y.-J. Su, M.F. Thomsen, The local-time variation of the quiet plasmasphere: Geosynchronous observations and kinetic theory. *Ann. Geophys.* **21**(11), 2147–2154 (2003)
- F.J. Rich, W.J. Burke, M.C. Kelley, M. Smiddy, Observations of field-aligned currents in association with strong convection electric fields at subauroral latitudes. *J. Geophys. Res.* **85**(A5), 2335–2340 (1980)
- P.G. Richards, D.G. Torr, Thermal coupling of conjugate ionospheres and the tilt of the Earth’s magnetic field. *J. Geophys. Res.* **91**(A8), 9017–9021 (1986)
- A.D. Richmond, Self-induced motions of thermal plasma in the magnetosphere and the stability of the plasmopause. *Radio Sci.* **8**(11), 1019–1027 (1973)
- A.D. Richmond, Y. Kamide, Mapping electrodynamic features of the high-latitude ionosphere from localized observations: Technique. *J. Geophys. Res.* **93**(A6), 5741–5759 (1988)
- A.J. Ridley, M.W. Liemohn, A model-derived storm time asymmetric ring current driven electric field description. *J. Geophys. Res.* **107**(A8), 1151 (2002)
- A.J. Ridley, G. Lu, C.R. Clauer, V.O. Papitashvili, A statistical study of the ionospheric convection response to changing interplanetary magnetic field conditions using the assimilative mapping of ionospheric electrodynamics technique. *J. Geophys. Res.* **103**(A3), 4023–4039 (1998)
- A.J. Ridley, T.I. Gombosi, D.L. DeZeeuw, Ionospheric control of the magnetosphere: conductance. *Ann. Geophys.* **22**(2), 567–584 (2004)
- P. Robert, A. Roux, C.C. Harvey, M.W. Dunlop, P.W. Daly, K.-H. Glassmeier, Tetrahedron geometric factors, in *Analysis Methods for Multi-Spacecraft Data*, ed. by G. Paschmann, P.W. Daly. ISSI SR-001. ESA Publications Division (1998), pp. 323–348
- E.C. Roelof, A.J. Skinner, Extraction of ion distributions from magnetospheric ENA and EUV images. *Space Sci. Rev.* **91**(1–2), 437–459 (2000)
- K. Rønmark, Generation of magnetospheric radiation by decay of Bernstein waves. *Geophys. Res. Lett.* **12**(10), 639–642 (1985)
- D.E. Rowland, J.R. Wygant, Dependence of the large-scale, inner magnetospheric electric field on geomagnetic activity. *J. Geophys. Res.* **103**(A7), 14959–14964 (1998)
- J.M. Ruohoniemi, R.A. Greenwald, Dependencies of high-latitude plasma convection: Consideration of interplanetary magnetic field, seasonal, and universal time factors in statistical patterns. *J. Geophys. Res.* **110**, A09204 (2005)
- C.T. Russell, R.E. Holzer, E.J. Smith, OGO 3 observations of ELF noise in the magnetosphere, 1. Spatial extent and frequency of occurrence. *J. Geophys. Res.* **74**(3), 755–777 (1969)
- C.T. Russell, R.E. Holzer, E.J. Smith, OGO 3 observations of ELF noise in the magnetosphere, 2. The nature of the equatorial noise. *J. Geophys. Res.* **75**(4), 755–768 (1970)

- J.C. Samson, The spectral matrix, eigenvalues, and principal components in the analysis of multichannel geophysical data. *Ann. Geophys.* **1**(3), 115–119 (1983)
- B.R. Sandel, M.H. Denton, Global view of refilling of the plasmasphere. *Geophys. Res. Lett.* **34**, L17102 (2007)
- B.R. Sandel, A.L. Broadfoot, C.C. Curtis, R.A. King, T.C. Stone, R.H. Hill, J. Chen, O.H.W. Siegmund, R. Raffanti, D.D. Allred, R.S. Turley, D.L. Gallagher, The extreme ultraviolet imager investigation for the IMAGE mission. *Space Sci. Rev.* **91**(1–2), 197–242 (2000)
- B.R. Sandel, R.A. King, W.T. Forrester, D.L. Gallagher, A.L. Broadfoot, C.C. Curtis, Initial results from the IMAGE Extreme Ultraviolet imager. *Geophys. Res. Lett.* **28**(8), 1439–1442 (2001)
- B.R. Sandel, J. Goldstein, D.L. Gallagher, M. Spasojević, Extreme ultraviolet imager observations of the structure and dynamics of the plasmasphere. *Space Sci. Rev.* **109**(1–4), 25–46 (2003)
- O. Santolík, D.A. Gurnett, Transverse dimensions of chorus in the source region. *Geophys. Res. Lett.* **30**(2), 1031 (2003)
- O. Santolík, M. Parrot, L.R.O. Storey, J.S. Pickett, D.A. Gurnett, Propagation analysis of plasmaspheric hiss using Polar PWI measurements. *Geophys. Res. Lett.* **28**(6), 1127–1130 (2001)
- O. Santolík, J.S. Pickett, D.A. Gurnett, M. Maksimovic, N. Cornilleau-Wehrlin, Spatiotemporal variability and propagation of equatorial noise observed by Cluster. *J. Geophys. Res.* **107**(A12), 1495 (2002)
- O. Santolík, D.A. Gurnett, J.S. Pickett, M. Parrot, N. Cornilleau-Wehrlin, Spatio-temporal structure of storm-time chorus. *J. Geophys. Res.* **108**(A7), 1278 (2003)
- O. Santolík, D.A. Gurnett, J.S. Pickett, Multipoint investigation of the source region of storm-time chorus. *Ann. Geophys.* **22**(7), 2555–2563 (2004a)
- O. Santolík, D.A. Gurnett, J.S. Pickett, M. Parrot, N. Cornilleau-Wehrlin, A microscopic and nanoscopic view of storm-time chorus on 31 March 2001. *Geophys. Res. Lett.* **31**, L02801 (2004b)
- O. Santolík, F. Němec, K. Gereová, E. Macúšová, Y. de Conchy, N. Cornilleau-Wehrlin, Systematic analysis of equatorial noise below the lower hybrid frequency. *Ann. Geophys.* **22**(7), 2587–2595 (2004c)
- O. Santolík, D.A. Gurnett, J.S. Pickett, M. Parrot, N. Cornilleau-Wehrlin, Central position of the source region of storm-time chorus. *Planet. Space Sci.* **53**(1–3), 299–305 (2005a)
- O. Santolík, E. Macúšová, K.H. Yearby, N. Cornilleau-Wehrlin, H.S.C. Alleyne, Radial variation of whistler-mode chorus: first results from the STAFF/DWP instrument on board the Double Star TC-1 spacecraft. *Ann. Geophys.* **23**(8), 2937–2942 (2005b)
- O. Santolík, J. Chum, M. Parrot, D.A. Gurnett, J.S. Pickett, N. Cornilleau-Wehrlin, Propagation of whistler mode chorus to low altitudes: Spacecraft observations of structured ELF hiss. *J. Geophys. Res.* **111**, A10208 (2006)
- J.M. Saxton, A.J. Smith, Quiet time plasmaspheric electric fields and plasmasphere-ionosphere coupling fluxes at $L = 2.5$. *Planet. Space Sci.* **37**(3), 283–293 (1989)
- S.S. Sazhin, Improved quasilinear models of parallel whistler-mode instability. *Planet. Space Sci.* **37**(6), 633–647 (1989)
- S.S. Sazhin, M. Hayakawa, Magnetospheric chorus emissions: A review. *Planet. Space Sci.* **40**(5), 681–697 (1992)
- S.S. Sazhin, M. Hayakawa, K. Bullough, Whistler diagnostics of magnetospheric parameters: A review. *Ann. Geophys.* **10**(5), 293–308 (1992)
- S. Sazykin, R.W. Spiro, R.A. Wolf, F.R. Toffoletto, N. Tsyanenko, J. Goldstein, M.R. Hairston, Modeling inner magnetospheric electric fields: Latest self-consistent results, in *The Inner Magnetosphere: Physics and Modeling*, ed. by T.I. Pulkkinen, N.A. Tsyanenko, R.H.W. Friedel. Geophysical Monograph Series, vol. 155 (American Geophysical Union, Washington, 2005), pp. 263–269
- S. Schäfer, K.-H. Glassmeier, P.T.I. Eriksson, V. Pierrard, K.H. Fornacon, L.G. Blomberg, Spatial and temporal characteristics of poloidal waves in the terrestrial plasmasphere: A CLUSTER case study. *Ann. Geophys.* **25**(4), 1011–1024 (2007)
- S. Schäfer, K.-H. Glassmeier, P.T.I. Eriksson, P.N. Mager, V. Pierrard, K.H. Fornacon, L.G. Blomberg, Spatio-temporal structure of a poloidal Alfvén wave detected by Cluster adjacent to the dayside plasmopause. *Ann. Geophys.* **26**(7), 1805–1817 (2008)
- L. Scherliess, B.G. Fejer, Storm time dependence of equatorial disturbance dynamo zonal electric fields. *J. Geophys. Res.* **102**(A11), 24037–24046 (1997)
- M. Schulz, Eigenfrequencies of geomagnetic field lines and implications for plasma-density modeling. *J. Geophys. Res.* **101**(A8), 17385–17397 (1996)
- R.W. Schunk, A mathematical model of the middle and high latitude ionosphere. *Pure and Applied Geophys.* **127**(2–3), 255–303 (1988)
- R.W. Schunk, D.S. Watkins, Comparison of solutions to the thirteen-moment and standard transport equations for low speed thermal proton flows. *Planet. Space Sci.* **27**(4), 433–444 (1979)
- R.W. Schunk, D.S. Watkins, Electron temperature anisotropy in the polar wind. *J. Geophys. Res.* **86**(A1), 91–102 (1981)

- R.W. Schunk, P.M. Banks, W.J. Raitt, Effects of electric fields and other processes upon the nighttime high-latitude f layer. *J. Geophys. Res.* **81**(19), 3271–3282 (1976)
- R.W. Schunk, L. Scherliess, J.S. Sojka, D.C. Thompson, D.N. Anderson, M. Codrescu, C. Minter, T.J. Fuller-Rowell, R.A. Heelis, M. Hairston, B.M. Howe, Global assimilation of ionospheric measurements (GAIM). *Radio Sci.* **39**(1), RS1S02 (2004)
- N. Sckopke, A general relation between the energy of trapped particles and the disturbance field near the Earth. *J. Geophys. Res.* **71**(13), 3125–3130 (1966)
- G.P. Serbu, E.J.R. Maier, Low-energy electrons measured on IMP 2. *J. Geophys. Res.* **71**(15), 3755–3766 (1966)
- G.P. Serbu, E.J.R. Maier, Thermal plasma measurements within the magnetosphere, in *Space Research VII*, vol. 1, ed. by R.L. Smith-Rose, S.A. Bowhill, J.W. King (North Holland, Amsterdam, 1967), p. 527
- G.P. Serbu, E.J.R. Maier, Observations from OGO 5 of the thermal ion density and temperature within the magnetosphere. *J. Geophys. Res.* **75**(31), 6102–6113 (1970)
- R.R. Shaw, D.A. Gurnett, A test of two theories for the low-frequency cutoffs of nonthermal continuum radiation. *J. Geophys. Res.* **85**(A9), 4571–4576 (1980)
- B.W. Sheeley, M.B. Moldwin, H.K. Rassoul, R.R. Anderson, An empirical plasmasphere and trough density model: CRRES observations. *J. Geophys. Res.* **106**(A11), 25631–25641 (2001)
- D.R. Shklyar, F. Jiříček, Simulation of nonducted whistler spectrograms observed aboard the MAGION 4 and 5 satellites. *J. Atmos. Solar-Terr. Phys.* **62**(5), 347–370 (2000)
- D.G. Sibeck, L. Prech, J. Safrankova, Z. Nemecek, Two-point measurements of the magnetopause: Interball observations. *J. Geophys. Res.* **105**(A1), 237–244 (2000)
- N. Singh, Refilling of a plasmaspheric flux tube: Microscopic plasma processes, in *Modeling Magnetospheric Plasma*, ed. by T.E. Moore, J.H. Waite. Geophysical Monograph Series, vol. 44 (American Geophysical Union, Washington, 1988), pp. 87–99
- N. Singh, J.L. Horwitz, Plasmaspheric refilling: Recent observations and modelling. *J. Geophys. Res.* **97**(A2), 1049–1079 (1992)
- N. Singh, R.W. Schunk, H. Thiemann, Temporal features of the refilling of a plasmaspheric flux tube. *J. Geophys. Res.* **91**(A12), 13433–13454 (1986)
- G. Siscoe, D. Baker, R. Weigel, J. Hughes, H. Spence, Roles of empirical modeling within CISM. *J. Atmos. Solar-Terr. Phys.* **66**(15–16), 1481–1489 (2004)
- M. Smiddy, M.C. Kelley, W. Burke, F. Rich, R. Sagalyn, B. Shuman, R. Hays, S. Lai, Intense poleward-directed electric fields near the ionospheric projection of the plasmopause. *Geophys. Res. Lett.* **4**(11), 543–546 (1977)
- J. Smilauer, V. Truhlik, J. Boskova, P. Triska, J. Schultchishin, Observations of thermal O^{++} ions in the outer ionosphere. *Adv. Space Res.* **17**(10), 135–140 (1996)
- R.L. Smith, Propagation characteristics of whistlers trapped in field-aligned columns of enhanced ionization. *J. Geophys. Res.* **66**(11), 3699–3707 (1961a)
- R.L. Smith, Properties of the outer ionosphere deduced from nose whistlers. *J. Geophys. Res.* **66**(11), 3709–3716 (1961b)
- R.L. Smith, J.J. Angerami, Magnetospheric properties deduced from OGO 1 observations of ducted and nonducted whistlers. *J. Geophys. Res.* **73**(1), 1–20 (1968)
- A.J. Smith, K.H. Yearby, K. Bullough, J.M. Saxton, H.J. Strangeways, N.R. Thomson, Whistler mode signals from VLF transmitters observed at Faraday, Antarctica. *Memoirs of National Institute of Polar Research* **48**, 183–195 (1987)
- C.W. Smith, J. L'Heureux, N.F. Ness, M.H. Acuña, L.F. Burlaga, J. Scheifele, The ACE magnetic fields experiment. *Space Sci. Rev.* **86**(1–4), 613–632 (1998)
- J.J. Sojka, C.E. Rasmussen, R.W. Schunk, An interplanetary magnetic field dependent model of the ionospheric convection electric field. *J. Geophys. Res.* **91**(A10), 11281–11290 (1986)
- P. Song, B.W. Reinisch, X. Huang, Magnetospheric active wave measurements. *COSPAR Colloq. Ser.* **16**, 235–246 (2004)
- B.U.Ö. Sonnerup, M. Scheible, Minimum and maximum variance analysis, in *Analysis Methods for Multi-Spacecraft Data*, ed. by G. Paschmann, P.W. Daly. ISSI SR-001. ESA Publications Division (1998), pp. 185–220
- V.S. Sonwalkar, Magnetospheric LF-, VLF-, and ELF-waves, in *Handbook of Atmospheric Electrodynamics*, vol. II, ed. by H. Volland (CRC Press, Boca Raton, 1995), pp. 407–462
- V.S. Sonwalkar, The influence of plasma density irregularities on whistler-mode wave propagation, in *Geospace Electromagnetic Waves and Radiation*, ed. by J.W. LaBelle, R.A. Treumann. Lecture Notes in Physics, vol. 687 (Springer, Berlin, 2006), pp. 141–183
- V.S. Sonwalkar, U.S. Inan, Lightning as an embryonic source of VLF hiss. *J. Geophys. Res.* **94**(A6), 6986–6994 (1989)

- V.S. Sonwalkar, D.L. Carpenter, T.F. Bell, M. Spasojević, U.S. Inan, J. Li, X. Chen, A. Venkatasubramanian, J. Harikumar, R.F. Benson, W.W.L. Taylor, B.W. Reinisch, Diagnostics of magnetospheric electron density and irregularities at altitudes <5000 km using whistler and Z mode echoes from radio sounding on the IMAGE satellite. *J. Geophys. Res.* **109**, A11212 (2004)
- V.S. Sonwalkar, D.L. Carpenter, A. Reddy, B.W. Reinisch, Magnetically reflected (MR), specularly reflected (SR), and backscattered (BS) whistler mode (WM) echoes observed on the IMAGE satellite: Whistler-mode sounding of electron density, ion composition (H^+ , He^+ , O^+), and density irregularities along the geomagnetic field line. *J. Geophys. Res.* (2009, submitted)
- D.J. Southwood, Some features of field line resonances in the magnetosphere. *Planet. Space Sci.* **22**(3), 483–491 (1974)
- D.J. Southwood, M.G. Kivelson, Magnetospheric interchange instability. *J. Geophys. Res.* **92**(A1), 109–116 (1987)
- M. Spasojević, J. Goldstein, D.L. Carpenter, U.S. Inan, B.R. Sandel, M.B. Moldwin, B.W. Reinisch, Global response of the plasmasphere to a geomagnetic disturbance. *J. Geophys. Res.* **108**(A9), 1340 (2003)
- M. Spasojević, H.U. Frey, M.F. Thomsen, S.A. Fuselier, S.P. Gary, B.R. Sandel, U.S. Inan, The link between a detached subauroral proton arc and a plasmaspheric plume. *Geophys. Res. Lett.* **31**, L04803 (2004)
- R.W. Spiro, R.A. Heelis, W.B. Hanson, Rapid subauroral ion drifts observed by Atmospheric Explorer C. *Geophys. Res. Lett.* **6**(8), 657–660 (1979)
- R.W. Spiro, M. Harel, R.A. Wolf, P.H. Reiff, Quantitative simulation of a magnetospheric substorm 3. Plasmaspheric electric fields and evolution of the plasmapause. *J. Geophys. Res.* **86**(A4), 2261–2272 (1981)
- S.M. Stankov, N. Jakowski, S. Heise, Reconstruction of ion and electron density profiles from space-based measurements of the upper electron content. *Planet. Space Sci.* **53**(9), 945–957 (2005)
- D.P. Stern, The motion of a proton in the equatorial magnetosphere. *J. Geophys. Res.* **80**(4), 595–599 (1975)
- D.P. Stern, Large-scale electric fields in the Earth's magnetosphere. *Rev. Geophys. Space Phys.* **15**(2), 156–194 (1977)
- L.R.O. Storey, An investigation of whistling atmospherics. *Phil. Trans. Roy. Soc. (London)* **246A**, 113–141 (1953)
- L.R.O. Storey, F. Lefeuvre, The analysis of 6-component measurements of a random electromagnetic wave field in a magnetoplasma. I. The direct problem. *Geophys. J. Royal Astron. Soc.* **56**(2), 255–269 (1979)
- L.R.O. Storey, F. Lefeuvre, The analysis of 6-component measurements of a random electromagnetic wave field in a magnetoplasma. II. The integration kernels. *Geophys. J. Royal Astron. Soc.* **62**(1), 173–194 (1980)
- L.R.O. Storey, F. Lefeuvre, M. Parrot, L. Cairó, R.R. Anderson, Initial survey of the wave distribution functions for plasmaspheric hiss observed by ISEE 1. *J. Geophys. Res.* **96**(A11), 19469–19489 (1991)
- H.J. Strangeways, M.J. Rycroft, Trapping of whistler-waves through the side of ducts. *J. Atmos. Terr. Phys.* **42**, 983–994 (1980)
- D.F. Strobel, T.R. Young, R.R. Meier, T.P. Coffey, A.W. Ali, The nighttime ionosphere: E region and lower F region. *J. Geophys. Res.* **79**(22), 3171–3178 (1974)
- Y. Su, M.F. Thomsen, J.E. Borovsky, J.C. Foster, A linkage between polar patches and plasmaspheric drainage plumes. *Geophys. Res. Lett.* **28**(1), 111–113 (2001)
- D. Summers, B. Ni, N.P. Meredith, R.B. Horne, R.M. Thorne, M.B. Moldwin, R.R. Anderson, Electron scattering by whistler-mode ELF hiss in plasmaspheric plumes. *J. Geophys. Res.* **113**, A04219 (2008)
- K. Takahashi, R.L. McPherron, Harmonic structure of Pc 3–4 pulsations. *J. Geophys. Res.* **87**(A3), 1504–1516 (1982)
- K. Takahashi, R.E. Denton, R.R. Anderson, W.J. Hughes, Frequencies of standing Alfvén wave harmonics and their implication for plasma mass distribution along geomagnetic field lines: Statistical analysis of CRRES data. *J. Geophys. Res.* **109**, A08202 (2004)
- S.W.Y. Tam, F. Yasseen, T. Chang, S.B. Ganguli, Self-consistent kinetic photoelectron effect on the polar wind. *Geophys. Res. Lett.* **22**(16), 2107–2110 (1995)
- S.W.Y. Tam, T. Chang, V. Pierrard, Kinetic modeling of the polar wind. *J. Atmos. Sol.-Terr. Phys.* **69**(16), 1984–2027 (2007)
- T. Tamao, The structure of three-dimensional hydromagnetic waves in a uniform cold plasma. *J. Geomag. Geoelectr.* **16**(1), 89–114 (1964)
- A. Tarantola, *Inverse Problem Theory* (Elsevier Science, Amsterdam, 1987)
- G. Tarcsai, Ionosphere-plasmasphere electron fluxes at middle latitudes obtained from whistlers. *Adv. Space Res.* **5**(4), 155–158 (1985)
- H.A. Taylor Jr., W.J. Walsh, The light-ion trough, the main trough, and the plasmapause. *J. Geophys. Res.* **77**(34), 6716–6723 (1972)
- H.A. Taylor Jr., H.C. Brinton, C.R. Smith, Positive ion composition in the magnetosphere obtained from the Ogo-A satellite. *J. Geophys. Res.* **70**(23), 5769–5781 (1965)

- H.A. Taylor Jr., H.C. Brinton, M.W. Pharo III, Contraction of the plasmasphere during geomagnetically disturbed periods. *J. Geophys. Res.* **73**(3), 961–968 (1968)
- H.A. Taylor Jr., H.C. Brinton, D.L. Carpenter, F.M. Bonner, R.L. Heyborne, Ion depletion in the high-latitude exosphere; Simultaneous OGO 2 observations of the light ion trough and the VLF cutoff. *J. Geophys. Res.* **74**(14), 3517–3528 (1969)
- H.A. Taylor Jr., J.M. Grebowsky, W.J. Walsh, Structured variations of the plasmopause: Evidence of a corotating plasma tail. *J. Geophys. Res.* **76**(28), 6806–6814 (1971)
- M.F. Thomsen, D.J. McComas, J.E. Borovsky, R.C. Elphic, The magnetospheric trough, in *Geospace Mass and Energy Flow: Results from the International Solar-Terrestrial Physics Program*, ed. by J.L. Horwitz, D.L. Gallagher, W.K. Peterson. Geophysical Monograph Series, vol. 104 (American Geophysical Union, Washington, 1998), pp. 355–369
- N.R. Thomson, Electric fields from whistler-mode Doppler shifts. *Planet. Space Sci.* **24**(5), 455–458 (1976)
- R.J. Thomson, The formation and lifetime of whistler ducts. *Planet. Space Sci.* **26**(5), 423–430 (1978)
- N.R. Thomson, Whistler mode signals: Spectrographic group delays. *J. Geophys. Res.* **86**(A6), 4795–4802 (1981)
- R.M. Thorne, E.J. Smith, R.K. Burton, R.E. Holzer, Plasmaspheric hiss. *J. Geophys. Res.* **78**(10), 1581–1596 (1973)
- R.M. Thorne, R.B. Horne, N.P. Meredith, Comment on “On the origin of whistler mode radiation in the plasmasphere” by Green et al. *J. Geophys. Res.* **111**, A09210 (2006)
- V.Y. Trakhtengerts, A generation mechanism for chorus emission. *Ann. Geophys.* **17**(1), 95–100 (1999)
- V.Y. Trakhtengerts, A.G. Demekhov, E.E. Titova, B.V. Kozelov, O. Santolik, D. Gurnett, M. Parrot, Interpretation of Cluster data on chorus emissions using the backward wave oscillator model. *Phys. Plasma* **11**(4), 1345–1351 (2004)
- V.A. Troitskaya, A.V. Gul’Elmi, Diagnostics of the parameters of the magnetosphere and of the interplanetary space by means of micropulsations, in *Low-Frequency Waves and Irregularities in the Ionosphere*, ed. by N. D’Angelo. Astrophysics and Space Science Library, vol. 14 (1969), pp. 120–136
- J.G. Trotignon, P.M.E. Décréau, J.L. Rauch, O. Randriamboarison, V. Krasnosels’kikh, P. Canu, H. Alleyne, K. Yearby, E. Le Guirriec, H.C. Séran, F.X. Sené, P. Martin, M. Lévêque, P. Fergeau, How to determine the thermal electron density and the magnetic field strength from the CLUSTER/WHISPER observations around the Earth. *Ann. Geophys.* **19**(10–12), 1711–1720 (2001)
- J.G. Trotignon, P.M.E. Décréau, J.L. Rauch, E. Le Guirriec, P. Canu, F. Darrouzet, The whisper relaxation sounder onboard cluster: A powerful tool for space plasma diagnosis around the Earth. *Cosmic Res.* **41**(4), 369–372 (2003)
- B.T. Tsurutani, E.J. Smith, R.M. Thorne, Electromagnetic hiss and relativistic electron losses in the inner zone. *J. Geophys. Res.* **80**(4), 600–607 (1975)
- N.A. Tsyganenko, A model of the near magnetosphere with a dawn-dusk asymmetry 1. Mathematical structure. *J. Geophys. Res.* **107**(A8), 1179 (2002)
- N.A. Tsyganenko, D.P. Stern, Modeling the global magnetic field of the large-scale Birkeland current systems. *J. Geophys. Res.* **101**(A12), 27187–27198 (1996)
- J.-N. Tu, J.L. Horwitz, P. Song, X.-Q. Huang, B.W. Reinisch, P.G. Richards, Simulating plasmaspheric field-aligned density profiles measured with IMAGE/RPI: Effects of plasmasphere refilling and ion heating. *J. Geophys. Res.* **108**(A1), 1017 (2003)
- J.-N. Tu, J.L. Horwitz, P.A. Nsumei, P. Song, X.-Q. Huang, B.W. Reinisch, Simulation of polar cap field-aligned electron density profiles measured with the IMAGE radio plasma imager. *J. Geophys. Res.* **109**, A07206 (2004)
- J. Tu, J.L. Horwitz, T.E. Moore, Simulating the cleft ion fountain at polar perigee altitudes. *J. Atmos. Solar-Terr. Phys.* **67**(5), 465–477 (2005a)
- J. Tu, P. Song, B.W. Reinisch, X. Huang, J.L. Green, H.U. Frey, P.H. Reiff, Electron density images of the middle- and high-latitude magnetosphere in response to the solar wind. *J. Geophys. Res.* **110**, A12210 (2005b)
- J. Tu, P. Song, B.W. Reinisch, J.L. Green, X. Huang, Empirical specification of field-aligned plasma density profiles for plasmasphere refilling. *J. Geophys. Res.* **111**, A06216 (2006)
- J. Tu, P. Song, B.W. Reinisch, J.L. Green, Smooth electron density transition from plasmasphere to the sub-auroral region. *J. Geophys. Res.* **112**, A05227 (2007a)
- J.-N. Tu, M. Dhar, P. Song, B.W. Reinisch, J.L. Green, R.F. Benson, A.J. Coster, Extreme polar cap density enhancements along magnetic field lines during an intense geomagnetic storm. *J. Geophys. Res.* **112**, A05201 (2007b)
- C. Vallat, I. Dandouras, M. Dunlop, A. Balogh, E. Lucek, G.K. Parks, M. Wilber, E.C. Roelof, G. Chanteur, H. Réme, First current density measurements in the ring current region using simultaneous multi-spacecraft CLUSTER-FGM data. *Ann. Geophys.* **23**(5), 1849–1865 (2005)

- V.M. Vasyliunas, Mathematical models of magnetospheric convection and its coupling to the ionosphere, in *Particles and Fields in the Magnetosphere*, ed. by B.M. McCormac (Reidel, Dordrecht, 1970), pp. 60–71
- A.F. Viñas, R.L. Mace, R.F. Benson, Dispersion characteristics for plasma resonances of Maxwellian and Kappa distribution plasmas and their comparisons to the IMAGE/RPI observations. *J. Geophys. Res.* **110**, A06202 (2005)
- H. Volland, A semiempirical model of large-scale magnetospheric electric fields. *J. Geophys. Res.* **78**(1), 171–180 (1973)
- H. Volland, A model of the magnetospheric electric convection field. *J. Geophys. Res.* **83**(A6), 2695–2699 (1978)
- R.H. Wand, J.V. Evans, Seasonal and magnetic activity variations of ionospheric electric fields over Millstone Hill. *J. Geophys. Res.* **86**(A1), 103–118 (1981)
- C. Wang, T.S. Newman, D.L. Gallagher, Plasmapause equatorial shape determination via the minimum L algorithm: Description and evaluation. *J. Geophys. Res.* **112**, A12201 (2007)
- S. Watanabe, B.A. Whalen, A.W. Yau, Thermal ion observations of depletion and refilling in the plasmaspheric trough. *J. Geophys. Res.* **97**(A2), 1081–1096 (1992)
- C.L. Waters, F.W. Menk, B.J. Fraser, The resonance structure of low latitude Pc3 geomagnetic pulsations. *Geophys. Res. Lett.* **18**(12), 2293–2296 (1991)
- C.L. Waters, F.W. Menk, M.F. Thomsen, C. Foster, F.R. Fenrich, Remote sensing of the magnetosphere using ground-based observations of ULF waves, in *Magnetospheric ULF Waves: Synthesis and New Directions*, ed. by K. Takahashi, P.J. Chi, R.E. Denton, R.L. Lysak. Geophysical Monograph Series, vol. 169 (American Geophysical Union, Washington, 2006), pp. 319–340
- J.M. Watts, An observation of audio-frequency electromagnetic noise during a period of solar disturbance. *J. Geophys. Res.* **62**(2), 199–206 (1957)
- D.C. Webb, The analysis of non stationary data using complex demodulation. *Ann. Telecommunic.* **34**, 131–137 (1979)
- P.A. Webb, E.A. Essex, A dynamic global model of the plasmasphere. *J. Atmos. Sol.-Terr. Phys.* **66**(12), 1057–1073 (2004)
- D.C. Webb, L.J. Lanzerotti, C.G. Park, A comparison of ULF and VLF measurements of magnetospheric cold plasma densities. *J. Geophys. Res.* **82**(32), 5063–5072 (1977)
- P.A. Webb, R.F. Benson, R.E. Denton, J. Goldstein, L.N. Garcia, B.W. Reinisch, An inner-magnetospheric electron density database determined from IMAGE/RPI passive dynamic spectra. *EOS Trans. AGU* **88**(52), SM12A–04 (2007)
- D.R. Weimer, A flexible, IMF dependent model of high-latitude electric potentials having “space weather” applications. *Geophys. Res. Lett.* **23**(18), 2549–2552 (1996)
- D.R. Weimer, Substorm influence on the ionosphere electric potentials and currents. *J. Geophys. Res.* **104**(A1), 185–197 (1999)
- D.R. Weimer, An improved model of ionospheric electric potentials including substorm perturbations and application to the Geospace Environment Modeling November 24, 1996, event. *J. Geophys. Res.* **106**(A1), 407–416 (2001)
- D.R. Weimer, Improved ionospheric electrodynamic models and application to calculating Joule heating rates. *J. Geophys. Res.* **110**, A05306 (2005)
- L.A. Weiss, R.L. Lambour, R.C. Elphic, M.F. Thomsen, Study of plasmaspheric evolution using geosynchronous observations and global modeling. *Geophys. Res. Lett.* **24**(5), 599–602 (1997)
- D.J. Williams, E.C. Roelof, D.G. Mitchell, Global magnetospheric imaging. *Rev. Geophys.* **30**(3), 183–208 (1992)
- G.R. Wilson, J.L. Horwitz, J. Lin, A semikinetic model for early stage plasmasphere refilling 1. Effects of coulomb collisions. *J. Geophys. Res.* **97**(A2), 1109–1119 (1992)
- G.R. Wilson, J.L. Horwitz, J. Lin, Semikinetic modeling of plasma flow on outer plasmaspheric field lines. *Adv. Space Res.* **13**(4), 107–116 (1993)
- R.A. Wolf, Effects of ionospheric conductivity on convective flow of plasma in the magnetosphere. *J. Geophys. Res.* **75**(25), 4677–4698 (1970)
- R.A. Wolf, S. Sazykin, X. Xing, R.W. Spiro, F.R. Toffoletto, D.L. DeZeeuw, T.I. Gombosi, J. Goldstein, Direct effects of the IMF on the inner magnetosphere, in *Inner Magnetosphere Interactions: New Perspectives from Imaging*, ed. by J. Burch, M. Schulz, H. Spence. Geophysical Monograph Series, vol. 159 (American Geophysical Union, Washington, 2005), pp. 127–140
- J. Wygant, D. Rowland, H.J. Singer, M. Temerin, F. Mozer, M.K. Hudson, Experimental evidence on the role of the large spatial scale electric field in creating the ring current. *J. Geophys. Res.* **103**(A12), 29527–29544 (1998)
- F. Yasseen, J.M. Retterer, T. Chang, J.D. Winningham, Monte-Carlo modeling of polar wind photoelectron distributions with anomalous heat flux. *Geophys. Res. Lett.* **16**(9), 1023–1026 (1989)

- E. Yizengaw, M.B. Moldwin, The altitude extension of the mid-latitude trough and its correlation with plasmopause position. *Geophys. Res. Lett.* **32**, L09105 (2005)
- E. Yizengaw, H. Wei, M.B. Moldwin, D. Galvan, L. Mandrake, A. Mannucci, X. Pi, The correlation between mid-latitude trough and the plasmopause. *Geophys. Res. Lett.* **32**, L10102 (2005)
- E. Yizengaw, M.B. Moldwin, D.A. Galvan, Ionospheric signatures of a plasmaspheric plume over Europe. *Geophys. Res. Lett.* **33**, L17103 (2006)
- E. Yizengaw, Dewar, MacNeil, M.B. Moldwin, Galvan, J. Sanny, D. Berube, B. Sandel, The occurrence of ionospheric signatures of plasmaspheric plumes over different longitudinal sectors. *J. Geophys. Res.* **113**, A08318 (2008)
- I. Yoshikawa, A. Yamazaki, K. Yamashita, Y. Takizawa, M. Nakamura, Which is a significant contributor for outside of the plasmopause, an ionospheric filling or leakage of plasmaspheric materials?: Comparison of He II (304 Å) images. *J. Geophys. Res.* **108**(A2), 1080 (2003)
- D.T. Young, J. Geiss, H. Balsiger, P. Eberhardt, A. Ghielmetti, H. Rosenbauer, Discovery of He^{2+} and O^{2+} ions of terrestrial origin in the outer magnetosphere. *Geophys. Res. Lett.* **4**(12), 561–564 (1977)
- K. Yumoto, Generation and propagation mechanisms of low-latitude magnetic pulsations—A review. *J. Geophys.* **60**, 79–105 (1986)

Copyright permissions for the figures used in the six chapters

The Earth's Plasmasphere: A CLUSTER and IMAGE Perspective

CLUSTER and IMAGE: New Ways to Study the Earth's Plasmasphere

J. De Keyser · D.L. Carpenter · F. Darrouzet · D.L. Gallagher · J. Tu 7

Figures 1, 8: Copyright (1965, 1986), with permission from Elsevier.

Figures 2, 3, 4, 5, 6a, 6b, 6c, 7, 9, 10, 15, 16: Copyright (1966, 1965, 1968, 1971, 1970, 1968, 1970, 1982, 1992, 1990, 2007, 2007), with permission from American Geophysical Union (AGU).

Figures 12, 22: Copyright (2002, 2008), with permission from European Geosciences Union (EGU).

Figure 17: Copyright (2008), with permission from American Institute of Physics (AIP).

Plasmaspheric Density Structures and Dynamics: Properties Observed by the CLUSTER and IMAGE Missions

F. Darrouzet · D.L. Gallagher · N. André · D.L. Carpenter · I. Dandouras · P.M.E. Décréau · J. De Keyser · R.E. Denton · J.C. Foster · J. Goldstein · M.B. Moldwin · B.W. Reinisch · B.R. Sandel · J. Tu 55

Figures 3, 4, 6, 7, 8, 14, 19, 20, 21, 26: Copyright (2005, 2007, 2005, 2006, 2006, 2005, 2002, 2005, 2005, 2002), with permission from American Geophysical Union (AGU).

Figures 10, 11, 27: Copyright (2009, 2005, 2005), with permission from Elsevier.

Figures 13, 16, 17, 18, 23: Copyright (2009, 2008, 2008, 2008, 2004), with permission from European Geosciences Union (EGU).

Electric Fields and Magnetic Fields in the Plasmasphere: A Perspective From CLUSTER and IMAGE

H. Matsui · J.C. Foster · D.L. Carpenter · I. Dandouras · F. Darrouzet · J. De Keyser · D.L. Gallagher · J. Goldstein · P.A. Puhl-Quinn · C. Vallat 107

Figures 1, 2, 8a, 8b, 8c, 9: Copyright (1976, 1979, 2001, 2007, 2007, 2006), with permission from American Geophysical Union (AGU).

Figures 3, 7: Copyright (1989, 2007), with permission from Elsevier.

Figure 10: Copyright (2007), with permission from European Geosciences Union (EGU).

Advances in Plasmaspheric Wave Research with CLUSTER and IMAGE Observations

A. Masson · O. Santolík · D.L. Carpenter · F. Darrouzet · P.M.E. Décréau · F. El-Lemdani Mazouz · J.L. Green · S. Grimald · M.B. Moldwin · F. Němec · V.S. Sonwalkar 137

Figures 1, 2, 4, 8, 10b, 11, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 25, 26: Copyright (1999, 2002 and 2004, 2002, 2008, 1991, 2008, 2003, 2003, 2003, 2003, 2003, 2009, 2007, 2007, 2003, 2004, 2002, 2003), with permission from American Geophysical Union (AGU).

Figure 10a: Copyright (1982), with permission from Elsevier.

Figures 10c, 23, 24: Copyright (2007, 2004, 2004), with permission from European Geosciences Union (EGU).

Figure 12: Copyright (1995), with permission from Cambridge University Press.

Recent Progress in Physics-Based Models of the Plasmasphere

V. Pierrard · J. Goldstein · N. André · V.K. Jordanova · G.A. Kotova · J.F. Lemaire ·
M.W. Liemohn · H. Matsui **193**

Figures 1, 3, 5, 9: Copyright (2005, 2007, 2008, 2008), with permission from American Geophysical Union (AGU).

Figure 8: Copyright (2001), with permission from Elsevier.

Augmented Empirical Models of Plasmaspheric Density and Electric Field Using IMAGE and CLUSTER Data

B.W. Reinisch · M.B. Moldwin · R.E. Denton · D.L. Gallagher · H. Matsui ·
V. Pierrard · J. Tu **231**

Figure 1: Copyright (2009), with permission from European Geosciences Union (EGU).
Figures 2, 3, 5, 6, 16: Copyright (2006, 2004, 2004, 2004, 2008), with permission from Elsevier.

Figures 4, 7, 8, 9, 10, 11, 12, 13: Copyright (2005, 2004, 2004, 2006, 2006, 2008, 2008, 2008), with permission from American Geophysical Union (AGU).