Astronomers' Universe

Bernard Henin

Exploring the Ocean Worlds of Our Solar System

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To my father

Preface

About 1.2 billion km away from our blue planet, frozen droplets of water orbit Saturn in unison with its majestic rings. These droplets are so abundant that they form a large ring around the planet. Hundreds of thousands of km wide and 2,000 km deep, this ring contains so many frozen water particles that Tethys and Dione, two small moons that happen to lie within the ring, have both developed a blue tint.

By analyzing this ring, the E ring, one of eleven other rings of Saturn (see Chapter 8), we have discovered that the droplets contain traces of sodium chloride (salt) and silicon dioxide (silica), indicating that the body of water from which they originate must be warm, salty, and in direct contact with rocks – very much like our seawater here on Earth. Science tells us that these conditions are favorable for life to develop and flourish, so it doesn't require a big stretch of the imagination to believe that, trapped inside these tiny seawater droplets, we might find microorganisms in the deep freeze – extraterrestrial life.

Scientists recently found the ocean from which these frozen water particles originate, but this ocean is different from the ones we see here on Earth. It is a subsurface ocean that lies many kilometers beneath the surface of one of Saturn's tiny moons, Enceladus. Mighty geysers, powered by the little moon's heating, regularly spout large jets of ocean water into space, where they join the E ring.

We now know that many worlds within our Solar System contain vast subsurface oceans. We call them "ocean worlds," and they are one of the most exciting discoveries in the history of space exploration.

It is remarkable that we live in an age where data collected by robotic space probes allows us to have educated conversations about the possibility of extraterrestrial life. In this book, we'll travel back in time, tracking the discovery of the ocean worlds. Then we'll move through space as we visit each of these worlds, investigating the latest scientific evidence as we contemplate the tricky yet thrilling concept of planetary habitability, the potential to have environments hospitable for life.

The idea of this book germinated more than a year ago during a public outreach event at the Sherwood Observatory in the United Kingdom. It had been a busy yet satisfying event for all of us involved, and as the evening drew to a close, a visitor approached me, as he was eager to share a news article about the newly discovered ocean of liquid water under the surface of Pluto and the possibilities that life might be discovered there by future NASA missions. When he asked for my opinion on this news item, I didn't have good news for him. The existence of a subsurface sea underneath Pluto was, and is still, only suggested by theoretical models, not confirmed by solid evidence as seemed to transpire from the article. In addition, there are much better places for NASA to search for life in our Solar System than Pluto, a far off distant world where, if liquid water existed, it would most likely be rich in ammonia – a powerful antimicrobial agent.

Subsequently, as I gave further public talks at the observatory and interacted with the people attending, I understood that the public was sometimes misled by the press overhyping or grossly distorting the science facts behind the ocean worlds' concept. This was no real surprise here, as anyone taking part in activities aimed at communicating scientific ideas to the public quickly becomes aware how easy it is for the public to misinterpret modern scientific concepts and the intricacies that come with them.

It is in response to these inaccurate interpretations that the book you hold in your hands was conceived, easily accessible by any layperson wanting to know more on subsurface oceans. It aims to guide the reader through the concept of the ocean worlds and provide insights into the latest scientific discoveries, with all the nuances that come along.

In a way, the field of planetary science has always been ripe for misleading interpretations as it involves, more often than not, cutting-edge science where technologies are pushed to their limits, and theoretical models are continuously refined. Add to this mix our never-ending obsession with alien life, and we have a perfect click bait. In this context, it can be difficult for non-experts to separate the wheat from the chaff, and this is where this guide can help.

The book is divided into four parts, each focusing on a specific aspect of the ocean worlds' topic. Part I, consisting of three chapters, aims to cover some basic concepts in planetary science and astrobiology to establish a good foundation upon which we can explore the ocean worlds. Chapter 1 will reveal how the idea of ocean worlds was first introduced through the remarkable journeys taken by NASA's Voyager spacecraft as they visited the outer planets' satellite systems in the last decades of the twentieth century, revolutionizing planetary science in the process. Chapter 2 will cover the origins of water in the universe as well as the processes behind its distribution throughout our Solar System. The possibility of life arising within subsurface oceans and the current approach that is taken in finding it will be described in Chapter 3. In so doing, we will make a slight detour to the planet Mars, where the first ever interplanetary mission to detect alien life was undertaken in the 1970s.

With the essentials covered, our journey to the ocean worlds will start as we move into the second part of the book. There, we will explore in detail the five confirmed ocean worlds of our Solar System, which are in fact moons of Saturn or Jupiter: Ganymede, Callisto, Europa, Titan, and Enceladus. Each one will be covered in a chapter to allow us to explore their history fully, their physical and geochemical properties, and ponder on the prospects of life within their subsurface oceans.

Part III will take us to two moons and two dwarf planets where tantalizing clues suggest that a subsurface ocean or smaller bodies of liquid water could lie under the icy crust but for which we still haven't found definitive proof. Within this part, Ceres and Dione will be covered in Chapter 9, while Triton and Pluto will be explored in Chapter 10. In the following chapter, we will explore numerous planetary objects that could theoretically have hosted a subsurface ocean in the past or might still do so in the present, but for which the limited observational data makes such cases debatable. This category includes, among others, icy moons such as Rhea, Ariel, Titania, and Oberon as well as trans-Neptunian objects (objects lying further than the orbit of Neptune) such as Makemake, Eris, Sedna, and 2007 OR10.

Finally, the last part will review the space missions planned to visit the ocean worlds in the coming decades. In Chapter 12, we will examine the confirmed missions such as ESA's JUICE and NASA's Europa Clipper as well as the proposed ones waiting to be approved, such as the Europa Lander. Given the life-detecting capabilities of these future missions, we will end the chapter, and the book, speculating on the scientific and societal impact if we find evidence of alien life within a subsurface ocean. Ultimately, looking for life forms in these remote and strange habitats is part of a bigger quest, the one for our cosmic origins.

In the appendix section, we will cover Mimas, a small moon of Saturn, which had been previously put forward by some scientists as an ocean world candidate, only to be disproven recently. As such, this moon provides a cautionary tale on the drawbacks in interpreting from a limited set of data. In addition to Mimas, a brief overview of the relic surface oceans of Mars and Venus will complete our investigation of past and present liquid water environments in our Solar System.

What's more, our journey will take us across the entire Solar System to meet numerous objects. From the now-famous Comet 67P/Churyumov-Gerasimenko to the icy surface of Pluto's moon Charon; from Io, the most geologically active object in our Solar System, to some of the remotest objects known, we will venture far and wide, meeting in the process the robotic explorers that unveiled these worlds to us – the spacecraft *Pioneer* 10 and 11, *Voyager* 1 and 2, *Galileo, Rosetta* and *Philae, Dawn, New Horizons*, and *Cassini-Huygens* – and the people that made all this possible. We will also cover the geological and geochemical processes involved in the alteration of planetary bodies such as how water behaves in extreme conditions in Chapter 4 and the external factors that alter a planetary surface exposed to space in Chapter 5. Further processes and concepts will be distilled here and there throughout the chapters.

Key to the approach taken by this book is the fact that planetary science is a comparative science, where we gain much from comparing planetary objects with each other. As such, although it might be tempting to skip chapters and quickly jump to specific parts of the book (e.g., Europa), it is recommended to read in the order the chapters appear, as knowledge on the ocean worlds and the technology used to investigate them builds up progressively. Of course, in the case chapters are read individually, there will be pointers as to where a specific concept or technology has been covered elsewhere in the book.

In keeping with the comparative theme, every ocean world candidate mentioned in this book is presented in an overarching table, located after this preface, where comparisons on fundamental physical properties (such as ratio or mass) and the known characteristics of the subsurface oceans can be made between each candidate. This table should become handy when one wants to quickly check the properties of these objects against what they have read or heard. Furthermore, a schematic diagram establishes where each ocean world candidate is located within the context of the planets and structures of our Solar System, making it easier to locate a given object.

One of the most satisfying aspects of life is sharing with others what you are most passionate about. I genuinely hope you enjoy reading what follows as much as I relished researching and writing it. If anything written herein inspires you to learn more about space or science in general, then I've succeeded in my effort.

Nottingham, UK
April 2018

Bernard Henin

Acknowledgments

As can be expected with a project of such scope and depth, the insights and support of numerous people from around the world have proved indispensable.

To start off with, I would like to thank my publisher, Springer, for giving me this unique opportunity to share my passion for this fascinating topic and to inspire future generations of astronomers, space enthusiasts, and scientists. John Watson, working for Springer in the United Kingdom, proved instrumental in getting this project started and was a guiding hand throughout the course of the book proposal stage. I am incredibly grateful to my editor in New York, Maury Solomon, who was the first, with John, to believe in this project from the outset and entrusted me with its writing. Despite her busy schedule, she always made herself available whenever I required support during the 12 months needed to write this book. Her assistant, Elizabet Cabrera, proved helpful as well.

In addition to my publisher, many people were involved in the making of this book. Taryn from Cape Town was responsible for sharpening my writing skills as well as a contributing factor in getting my book proposal accepted, while Karen from London provided insight into the writing process. Their early encouragements and enthusiasm made it all possible.

I would like to thank Piers Bizony, a successful author of space and science-themed books, for his support and counsel as well as the various members of the Sherwood Observatory, United Kingdom, where the idea of the ocean worlds' book germinated. I especially want to single out all the committee members for their warm welcome and continuous support about this project and in particular, Chris D. and Steve W. who took their time to review my first drafts and point out areas that needed clarity.

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No acknowledgments would be complete without thanking my family, close friends, and everyone else who has supported me during the entirety of this project – you know who you are. To my parents who have always supported me throughout my life, my wife who has had to endure endless hours of me rambling on the ocean worlds, and my daughter for bringing me joy every day.

Contents

About the Author

Bernard Henin fell in love with planetary science when, as a teenager reading *National Geographic,* he came across images of Neptune taken from NASA's spacecraft *Voyager* 2. He was mesmerized by the giant blue planet and found it both exhilarating and liberating to think that entire new worlds could be explored during his lifetime. Since then, he has closely followed humanity's continued exploration of our Solar System.

Henin is a member of the Sherwood Observatory in the United Kingdom (home to the second largest telescope in the country that is freely accessible for public viewing), where he performs regular talks aimed at the members of the Astronomical Society and the public at large. Writing a book on astronomy was the next obvious step in raising awareness of the fascinating Solar System we inhabit.

Originally from Belgium, Henin has lived in the United States, the United Kingdom, and Hong Kong. His previous work has been published in international magazines.

Contributors

I would like to express my most profound gratitude to the scientists listed below who kindly found the time to talk to me and send me material. Without their contributions, making this book would not have been possible. In alphabetical order, they are:

Dr. Penelope Boston, director of NASA's Astrobiology Institute, Mountain View, California.

Dr. Charles Cockell, director of the UK Centre for Astrobiology and professor of astrobiology in the School of Physics and Astronomy at the University of Edinburgh.

Dr. Amanda Hendrix, senior planetary scientist at the Planetary Science Institute, Tucson, Arizona.

Dr. Luciano Iess, professor of aerospace engineering at the Sapienza University of Rome.

Dr. Jonathan Lunine, the David C. Duncan professor in the physical sciences and director of the Center for Radiophysics and Space Research at the Cornell University, Ithaca, New York.

Dr. Chris McKay, planetary scientist at NASA's Ames Research Center, Mountain View, California.

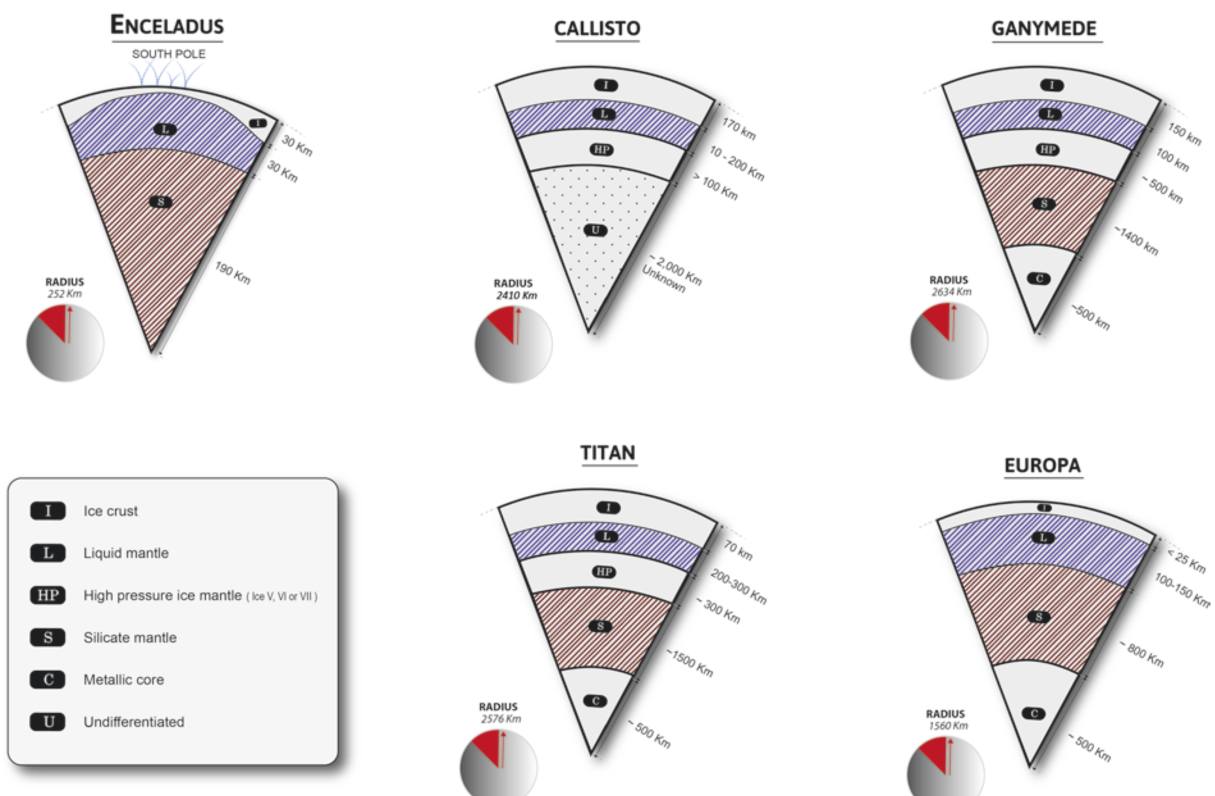
Dr. William B. McKinnon, professor at the Department of Earth and Planetary Sciences, Washington University, St. Louis, Missouri.

Dr. Marc Neveu, astrobiology science assistant at the NASA Headquarters, Washington.

Dr. Olivier Witasse, JUICE project scientist at the European Space Research and Technology Centre, ESA, Noordwijk.

Dr. Steve Vance, lead for the Habitability team of JPL's Icy Worlds Astrobiology group, JPL, Pasadena, California.

Cross section of the five confirmed ocean worlds in our Solar System



Diagrams are not to scale

Confirmed and potential ocean worlds in our Solar System

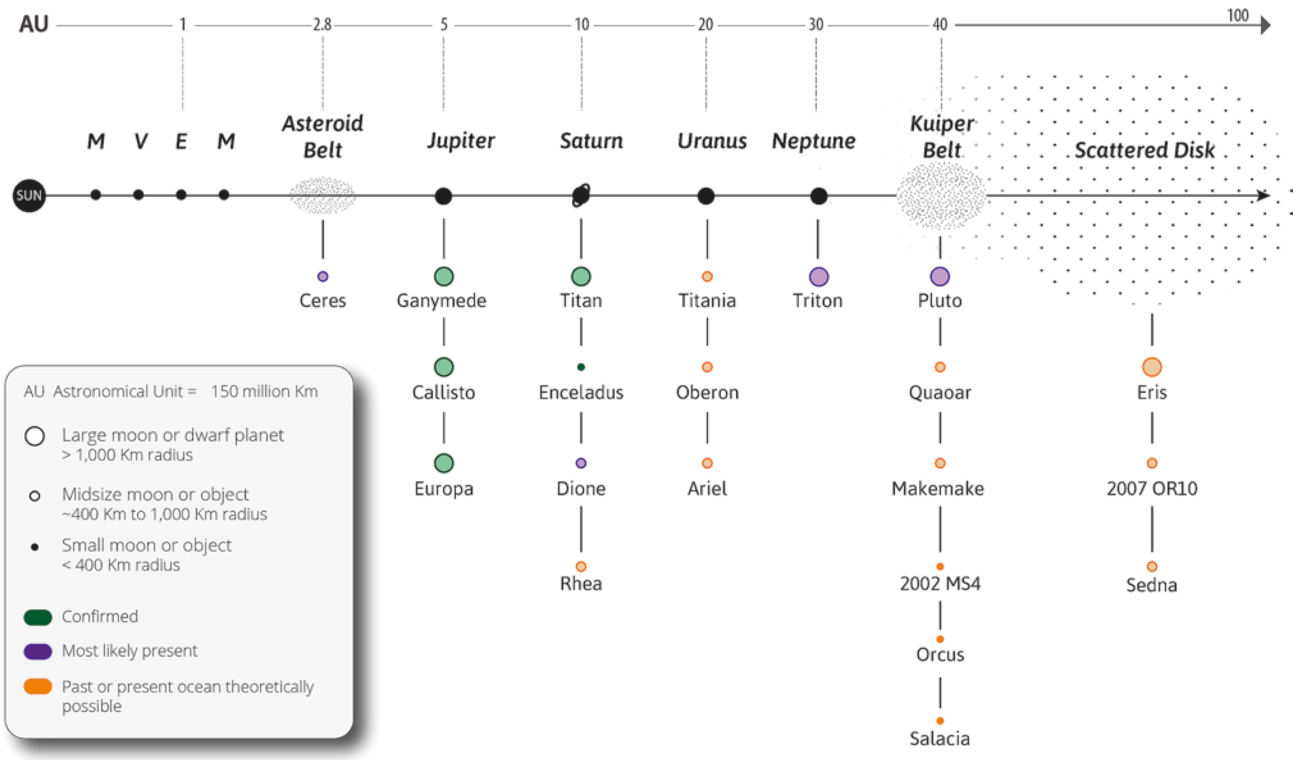


Diagram not to scale

Confirmed or Possible ocean worlds in our Solar System

Name of planetary object	Type of planetary object	Parent planet or Location	Distance from Sun (AU)	Mean Radius (km)	Mass (10^{20} kg)	Mean density (g/cm^3) Water = 1	Subsurface ocean status (past or present)	Lines of evidence of a subsurface ocean	Liquid water adjacent to rocky material	Future missions approved
Ceres	Asteroid, dwarf planet	Asteroid belt	4	473	9	2.16	Likely but unconfirmed	–	Yes	–
Europa	Satellite	Jupiter	5	1,560	480	3.01	**Confirmed**	2	Yes	JUICE, Europa Clipper
Callisto	Satellite	Jupiter	5	2,410	1,076	1.83	**Confirmed**	1	No	JUICE
Ganymede	Satellite	Jupiter	5	2,634	1,482	1.94	**Confirmed**	1	No	JUICE
Enceladus	Satellite	Saturn	10	252	1	1.61	**Confirmed**	+2	Yes	–
Titan	Satellite	Saturn	10	2,575	1,346	1.88	**Confirmed**	2	No	–
Rhea	Satellite	Saturn	10	764	23	1.23	Theoretically possible	–	–	–
Dione	Satellite	Saturn	10	560	11	1.47	Likely but unconfirmed	–	Yes	–
Ariel	Satellite	Uranus	20	579	14	1.59	Theoretically possible	–	–	–
Titania	Satellite	Uranus	20	788	35	1.71	Theoretically possible	–	–	–
Oberon	Satellite	Uranus	20	761	30	1.63	Theoretically possible	–	–	–

(continued)

Name of planetary object	Type of planetary object	Parent planet or Location	Distance from Sun (AU)	Mean Radius (km)	Mass (10^{20} kg)	Mean density (g/cm^3) Water = 1	Subsurface ocean status (past or present)	Lines of evidence of a subsurface ocean	Liquid water adjacent to rocky material	Future missions approved
Triton	Satellite	Neptune	30	1,353	214	2.06	Likely but unconfirmed	–	Yes	–
Makemake	KBO, dwarf planet	Kuiper Belt	40	~720	44	1.4–3.2	Theoretically possible	–	–	–
2002 MS4	KBO	Kuiper Belt	40	~467	–	–	Theoretically possible	–	–	–
Quaoar	KBO	Kuiper Belt	40	~537	~ 14	~2.2	Theoretically possible	–	–	–
Salacia	KBO	Kuiper Belt	40	~425	~4.4	~1.29	Theoretically possible	–	–	–
Orcus	KBO	Kuiper Belt	40	~460	~6.4	~1.5	Theoretically possible	–	–	–
Pluto	KBO, dwarf planet	Kuiper Belt	40	1,188	130	1.85	Likely but unconfirmed	–	Yes	–
Eris	SDO, dwarf planet	Scattered disk	30–100	1,163	166	2.52	Theoretically possible	–	–	–
Sedna	SDO	Scattered disk	80–950	~498	–	–	Theoretically possible	–	–	–
2007 OR10	SDO	Scattered disk	30–100	~751	–	–	Theoretically possible	–	–	–

AU: Astronomical Unit / KBO: Kuiper Belt Objects / SDO: Scattered Disk Objects

Part I
The Origin of Water and Life

> "Equipped with his five senses, man explores the universe around him and calls the adventure Science."
>
> – Edwin Powell Hubble

In Part I, we review the revolution that occurred in planetary science when the *Voyager* space probes visited the outer planets and their satellite systems, bringing back the first hints of ocean worlds in our Solar System. The second chapter deals with the origin of water in space and how it was distributed among the planetary objects orbiting our Sun, while the third chapter deals with the possibility of extraterrestrial life and our attempts to find it.

1. The Voyagers' Tale

Golden Amazons of Venus

The night sky has always been a source of fascination for humankind. Storytellers have turned to it to create fantastic myths and legends for centuries. But it seems that, even within the realms of science fiction, our imaginations are not powerful enough to always uncover truth.

When astronomers first pointed their telescopes at our Moon in the 17th century, they assumed that they were looking at a world awash with liquid water. In fact, our modern lunar maps still feature the watery names Maria (singular mare, Latin for "sea"), Oceanus (singular oceanus, Latin for "ocean"), Lacus (singular lacus, Latin for "lake"), Sinus (singular sinus, Latin for "bay") and Paludes (singular palus, Latin for "marsh"). We now know of course that the Eagle that landed in the 'Sea of Tranquility' 50 years ago landed on struts rather than floats.

Similarly, the discovery of an atmosphere around Venus in 1761 led to speculation that hidden beneath the thick Venusian cloud cover was a lush and humid world. Venus as a 'water world' captured the imaginations of astronomers and science fiction writers alike. A quick browse through some of the science fiction novels written at the time reveals titles such as" Oceans of Venus" by Isaac Asimov, "Swamp Girl of Venus" by H. H. Harmon, and the classic "Golden Amazons of Venus" from J. M. Reynolds. Of course, the last two titles are from the so-called pulp era of science fiction in the 1930s and 40s, when scientific facts were often sidelined by fantastic adventure stories, now referred to as planetary romance.

Alas, the age of Venusian blondes waiting to be rescued by virile Earthlings ended abruptly in 1962 when NASA's *Mariner 2* spacecraft completed the first-ever flyby of the planet (or any planet for that matter). Recording atmospheric temperatures of 500 degrees Celsius (900 degrees Fahrenheit), there was no escaping the fact that the surface of Venus is hot enough to melt lead and that, sadly, there are no seas on Venus of liquid water and no Venusians.

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A similar story followed with Mars, the Red Planet, which has long been a source of intrigue. Mars was first observed through a telescope in 1610 by Galileo Galilei, the father of observational astronomy. Unfortunately, his telescope wasn't powerful enough to reveal the planet's distinct surface features. We had to wait until 1659 when Christian Huygens, a Dutch astronomer, using a telescope he built himself, drew a rudimentary map of Mars, showing darkened surface features.

Convinced that these were signs of vegetation, Huygens published his belief in extraterrestrial life in his influential book *Cosmotheoros*. He was also the first man to see the white south polar cap of the planet, but he didn't recognize it as such. More than a century passed before it was correctly identified as water-ice by Sir William Herschel, a German-born British astronomer who nevertheless postulated that the dark areas on Mars were oceans. Herschel's work on Mars and the realization that the planet showed many similarities to our own gave credibility to the idea that there was liquid water, and therefore life, on the red world. He speculated that Martian inhabitants "probably enjoy a situation similar to our own."

The belief that water was flowing on Mars reached its height in the early 20th century. It was a result of the sloppy translation (Italian to English) of channels that led to the belief that canals built by Martians to irrigate the planet could be seen from Earth. The excitement died down over the course of the century as astronomers gained the ability to see the planet in more detail. The idea was finally laid to rest when the *Mariner 9* spacecraft orbited Mars in 1972 and returned images of a lifeless, utterly dry planet.

Suddenly our Solar System was inhospitable and barren. Gone were the Selenites, Venusians and Martians. Earth, our blue oasis, was the only place that could support life, and science fiction, one of the most imaginative and thought-provoking genres, had reached an impasse. As a result, swashbuckling spacemen moved on to the more promising lands outside of our Solar System with the help of warp engines and other faster-than-light travel methods, while our neighboring planets and moons were shunned.

The Jovian Revolution

As the title of this book gives it away, this would not last. Our understanding of the Solar System changed once again as evidence of liquid water was found in less obvious places – the moons of the outer planets. There, vast oceans of flowing water lie waiting to be explored.

The discovery of these oceans started as the two Voyager spacecraft, ironically conceived in the years when our Solar System was thought to be barren, embarked on long journeys that had, as their first stage, flybys of the Jovian moons. These close encounters would change everything.

In fact, despite their relatively small sizes, the satellites of Jupiter had already been game changers in the past, as they had played a remarkable role in the history of astronomy, science and our understanding of humanity's place within the universe. Described by Galileo Galilei in January 1610 as "three fixed stars, totally invisible by their smallness," they were found to be very close to the giant planet and even moved in a straight line across it. This configuration, and the fact that the 'stars' disappeared behind Jupiter only to reappear once again later, led the Italian astronomer to deduce that these were, in fact, moons. This straightforward yet significant discovery made Galileo the first person to see and understand that objects were orbiting another planet and this led to the unraveling of the Tychonic system (from the ancient Ptolemaic system that Earth was at the center of the universe).

The Italian astronomer, not imprudent, originally named these four moons after his patron, the Medici, and his siblings. Thankfully these names were lost in time, and today, we use the ones chosen by Simon Marius, a German astronomer who named them after Zeus's lovers in Greek mythology: Io, Europa, Ganymede, and Callisto.

Almost 400 years after their discovery, in 1979, Jupiter's moons would once again change our understanding of our Solar System. This time, it wasn't done with the help of Earth-based telescopes similar to Galileo's but with the most advanced technological tools of our modern age. We could now send robotic visitors to the moons.

As such, only twenty years after the Soviets sent the very first artificial object into space, the United States launched not one but two spacecraft: *Voyager 1* and *Voyager 2.* Taking advantage of a favorable alignment of the outer planets of our Solar System (next occurring in the year 2153), these new emissaries embarked on a grand tour, visiting not only Jupiter but Saturn, Uranus, and Neptune, too.

Before the Voyagers' grand tour, the only moon we knew relatively well was our own, whose official name is "Luna." Although magnificent to look at, our Moon is geologically inactive and somewhat dull. This led humankind to make the mistake of assuming that other moons would be like ours – interesting objects to study but much less attractive than a planet. Of course, we had already gathered information about other moons through Earth-based observations, mainly by analyzing their reflected light known as spectra.

These observations revealed not only that specific moons had icy surfaces but that they also displayed albedo and color variations as they rotated (suggesting diverse geological terrains). Because of this, scientists knew that they would encounter different moons. Nevertheless, with only one moon available for close observations – our own – the astronomers' best guesses were just that, guesses.

When the Voyager missions were being conceived, Jupiter's moon Europa (see Chapter 6 for a detailed review of this moon) was thought to be of little importance compared to the other Galilean satellites, as it was the smallest of the four. Io was a far more intriguing subject, with its colorful surface features faintly observed from ground telescopes. Ganymede and Callisto were so big that their size alone was a key attraction. (Let us not forget that Ganymede is bigger than Mercury and almost as big as Mars.) When it came to planning the routes of the Voyagers through the Jovian system, Europa was at the bottom of the list, not warranting a close flyby.

As we now know, scientists were in for a big surprise. When *Voyager 1* first reached the Jovian system in 1979 and flew past Europa, at the intended distance of 2 million km, the low-resolution images returned by the spacecraft were bewildering (Figs. 1.1 and 1.2).

The images returned a bright moon crisscrossed by mysterious intersecting linear features. Furthermore, most scientists expected that small celestial bodies would show a heavily cratered surface (like on our Moon) as they would lack sufficient heat to support active geology that reshapes surfaces and erode or erase craters. Where were the impact craters on Europa? Dark patches could also be seen on the surface, but few scientists had an idea of what these were. Through its density (derived from the mass and volume of the moon) and spectrum, Europa was known to be mainly a rocky moon with a relatively thin layer of water-ice. At first, this led scientists to believe that the lines observed on the surface were deep cracks within the ice crust, caused by unknown tectonic processes. Could it be that Europa was geologically active now?

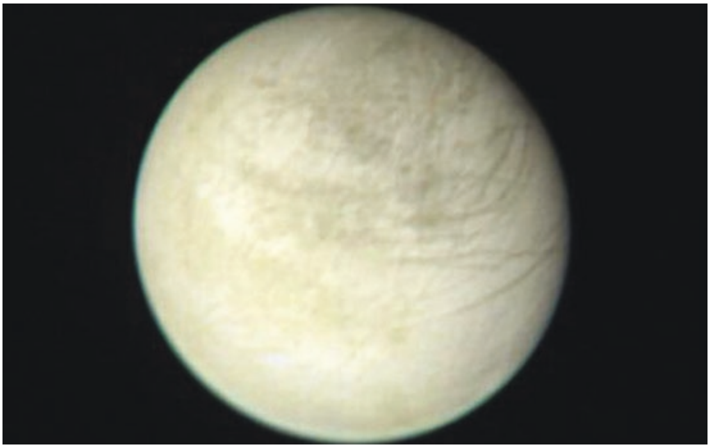

Fig. 1.1. Europa, the icy moon of Saturn, viewed by *Voyager 1* on March 4, 1979. This shot was the best resolution obtained by the spacecraft. We can see bright areas contrasting with dark patches, crisscrossed by long linear structures. (Image courtesy of NASA/JPL.)

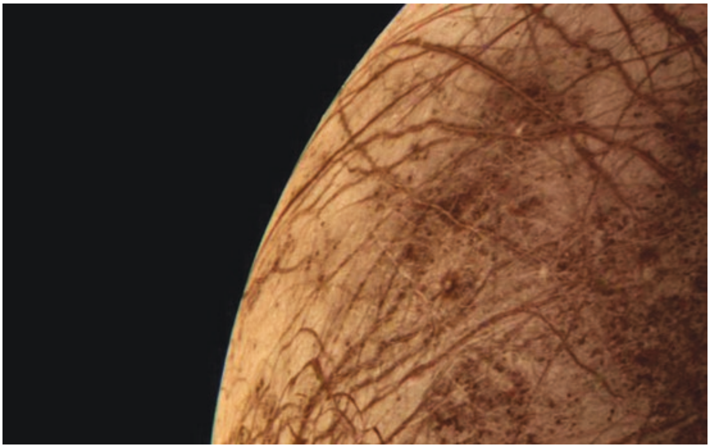

Fig. 1.2. Taken by *Voyager 2* on July 9, 1979. A closer look at Europa revealed few impact craters and a complicated, fractured crust. The lack of any mountains or craters is consistent with a thick ice crust. (Image courtesy of NASA/JPL.)

Fortunately, *Voyager 2* made a closer flyby four months later and returned high-resolution images from the surface.

These images allowed scientists to count the impact craters more precisely and revealed that Europa had very few of them compared to our Moon or the other Jovian icy moons, Callisto and Ganymede. Contrary to most expectations, Europa's icy crust was young – very young – maybe less than 100 million years old, which is a blink of an eye in planetary science. Also, the surface was very smooth, displaying little height variation that can only be explained if a surface is too elastic to keep tall features such as crater rims or cryovolcanoes. Somehow the icy crust wasn't as frozen solid as would be expected from an object lying so far away from the warmth of our Sun. The images returned by *Voyager 2* were unambiguous. Europa was an active moon capable of resurfacing itself.

That Europa, a small icy moon, could retain enough heat to stay active puzzled many scientists, and one hypothesis, tidal heating, proposed a few months before the Voyagers' flybys, soon gained the attention of the scientific community. This process had the potential to melt ices inside a moon, creating vast amounts of liquid water upon which a thick icy crust would rest – in other words, it would form a subsurface ocean. Ultimately heat exchanges between the subsurface ocean and the icy crust could deform and stress the ices, thus creating cracks within the surface. Could this new theory be the cause of the moon's unusual surface features? The scientific community was abuzz.

A New Form of Energy

To understand tidal heating, we must go back to when the Voyagers made close flybys of the moon Io, one of Europa's neighbors, and Jupiter's closest moon. Io had been a priority for the Voyagers, as a visit made five years earlier by another American spacecraft, *Pioneer 11*, hinted at a brightly colored yet undetermined surface. Astronomers were intrigued, and the Voyagers' trajectories were conceived in such a way that close flybys of Io could be performed.

When the high-resolution images from the Voyagers came back (see Fig. 1.3), they also revealed an active world, but this time not of ice but fire. Io was a dream world for volcanologists. The moon was peppered with volcanic calderas and tall mountains, upon which eruption plumes and lava flows, stained yellow and red by oxides of sulfur, would emerge. Remarkably, the surface seemed not to have a single impact crater, suggesting that the moon's surface was continually being renewed by volcanic activity. Io had a lot of energy.

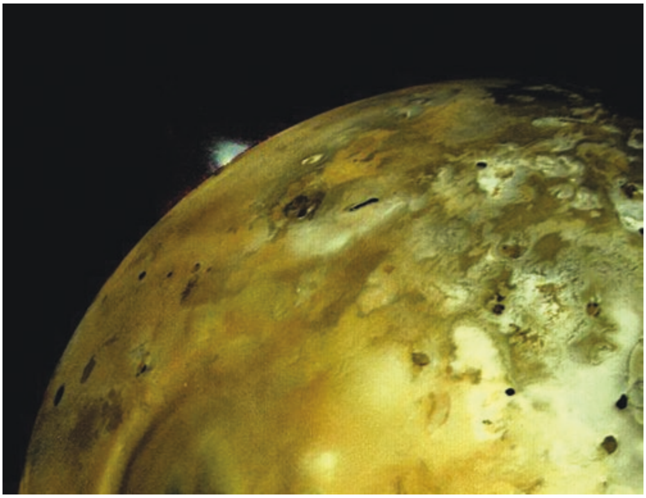

Fig. 1.3. A fiery Io captured by *Voyager 1* on March 4, 1979, the same day that the spacecraft took its best resolution image of Europa. The distance to Io is about 490,000 km (304,000 m). A volcanic explosion can be seen in the upper left ejecting solid material to an altitude of 160 km. (Image courtesy of NASA/JPL.)

Finding such an active world lying far away from the Sun was astonishing and led to a hunt for the source of Io's energy. The explanation came from a paper by Stanton Peale and his colleagues published in the prestigious journal *Science* just a few days before *Voyager 1*'s arrival in the Jovian system. The paper proposed that Io could be experiencing warming as it orbits Jupiter in a non-circular orbit (elliptical orbit), which produces variations in the gravity pull from the giant planet. This process was named tidal heating, and it didn't take long for this new theory to be accepted by the scientific community as the primary heat source driving Io's fiery temper.

What goes on inside Io can be easily demonstrated by using a simple metal wire. If you happen to have one to hand, flex one part of the wire backward and forwards. It doesn't take long for heat to be felt in the bendy part. The explanation is simple. Some of the kinetic energy was transformed into heat through internal friction. A similar process also makes squash balls warm after a match.

The reason behind Io's energy output is its elliptic orbit resulting from a phenomenon known as orbital resonance, which locks each Galilean moon into a specific orbital ratio around

Jupiter. For every two orbits that Io takes around the planet, Europa takes precisely one orbit. Due to orbital mechanics, both moons always come closest to each other at the same location within their orbits, pulling Io closer to Europa, thus making it elliptical instead of circular. (Similarly, for every two orbits that Europa takes, Ganymede makes precisely one orbit. This 4-2-1 sequence dictates the orbital eccentricity of these three Jovian moons, as we shall see in subsequent chapters.) Elliptical orbits are measured by their eccentricity. The greater the eccentricity, the more elliptical the orbit will be and vice versa.

Since Io's orbit around its giant parent planet is not a circular one but an elliptical one, the moon will feel Jupiter's gravitational pull differently along its orbit. This is referred to as tidal forces and is similar to the gravitational effect our Moon has on the seas and oceans of Earth. On Io, the tidal forces will be most influential during the moon's closest approach in orbit (periapsis) than during its furthest point (apoapsis). As it moves from periapsis to apoapsis and back, the tidal forces pull Io at varying intensities, thus creating friction and generating heat as the moon's interior repeatedly distorts and buckles.

Of course, many factors determine how much impact tidal forces can have on an object. The size of the moon in relation to its parent planet as well as the distance of the moon's orbit will be determining factors. As importantly, the composition of the moon itself will dictate how strongly it responds to these distortions. If the object is rocky, like our Moon, it will distort far less than if it is made entirely of ice. The measurement of the rigidity of a planetary body, and the ability of its shape to change in response to a tidal potential, is called the Love number (introduced in the early 20th century by the famous British mathematician Augustus Edward Hough Love).

By analyzing its orbit around Jupiter, astronomers deduced that Io has roughly the same density as silicate rock, which means that the inside of the moon must consist mainly of rocky material. This material is flexible enough to feel the effects of Jupiter's strong gravitational pull, but not so fragile as to be pulled apart by it. Therefore, the rocky core and mantle get stretched and squashed at every orbit, producing vast amounts of heat through friction, which in turn fuels the volcanism observed on the surface.

With Io's power source now well understood, Europa's mysterious heat source was a mystery no more. Due to its resonance with Ganymede and Io, it was also being pulled apart by tidal forces, although not as intensely as Io. Could the heat generated by the tidal forces be capable of melting parts of Europa's thin icy crust and – gasp – create a subsurface ocean? No one could tell for sure, but this was undoubtedly the central thesis proposed to explain the moon's deformed surface. Future investigations would be required to test this idea.

After Io and Europa, scientists turned their attention to Ganymede and Callisto. Ganymede's surface didn't have Europa's pizzazz, but it did show two distinct terrains: one dark and cratered (and therefore old), and the other grooved, with fewer craters (implying recent geological or tectonic activity). Was this a result of tidal heating? Was the moon still generating heat, like Io and Europa were? If so, was this activity sufficient to create and maintain a subsurface body of water? Unfortunately, none of these questions could be answered confidently with the images returned by the Voyagers' flybys. We would have to wait for future missions to start providing some answers. (Chapter 4 reviews Ganymede in more detail) (Figs. 1.4 and 1.5).

Fig. 1.4. This picture of Ganymede was taken on March 5, 1979, by *Voyager 1* at a distance of 272,000 km. The bright areas contain grooves and ridges indicating geological activity, while many older impact craters have been eroded over time. (Image courtesy of NASA/JPL.)

Fig. 1.5. Callisto as seen by *Voyager 2* on July 7, 1979, at a distance of 1 million km. Variations of surface materials can be seen in UV. The moon of Jupiter is the most densely cratered surface in our Solar System. (Image courtesy of NASA/JPL.)

Callisto, the last of the Galilean moons, displayed very little eccentricity in its orbit due to a weaker orbital resonance pattern. For every three orbits Callisto takes around Jupiter, the neighboring Ganymede takes seven. This 'imperfect' orbital pattern, and the fact that Callisto is much further away from Jupiter, means that the moon wouldn't experience much tidal heating. Indeed, images returned from the Voyagers revealed that Callisto was home to the most heavily cratered surface in the Solar System, with no signs of past or present geological activity. Compare this to Io, the most geologically active body in our Solar System, and you find a scale within the Galilean moons. The further away they are from Jupiter, the less energy they gain through tidal heating. Nevertheless, could Callisto also harbor a subsurface body of water? Again, we would have to wait for future missions to answer this question (See Chapter 5 for further details on Callisto.)

The Moons of Saturn

What the Voyagers had discovered in the Jovian system transformed planetary science. With a new energy source capable of heating up the small icy moons of our Solar System, scientists could once again contemplate the existence of flowing liquid water away from planet Earth. And this is precisely what they did, as they anticipated the Voyagers' next destination, the Saturnian system.

The Saturnian system was a rich target. It had a vast weather system, on Saturn many times bigger than Earth's. It had a grandiose set of rings that would require detailed observations. It had Titan, the only moon in our Solar System that was known to support a thick atmosphere. And it had strikingly bright and tiny moons such as Enceladus or Mimas, that were believed to consist mainly of water-ice (Figs. 1.6, 1.7, and 1.8).

Before the Voyagers, *Pioneer 11* had conducted a flyby of the ringed giant in 1979, the first ever to do so. Alas, the low-resolution images weren't detailed enough to observe the surface of Saturn's moons, so little insight was gained during this mission. Luckily, scientists didn't have to wait long: Voyager 1 arrived in the system in 1980, and *Voyager 2* would follow it nine months later.

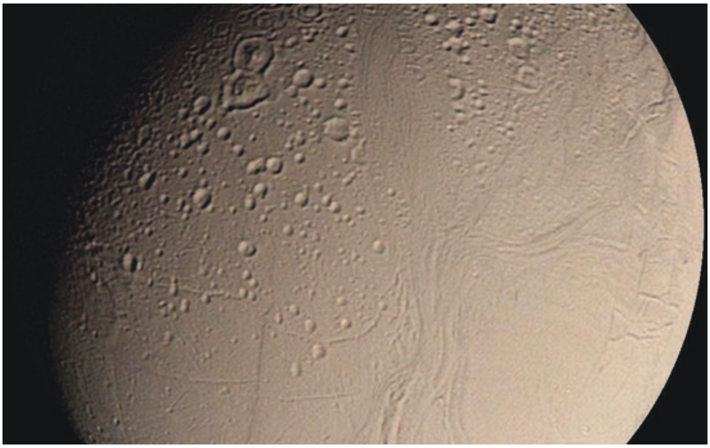

Fig. 1.6. This color image of Enceladus, one of Saturn's icy moons, is a mosaic of *Voyager 2* images taken in August 1981. The moon reflects 90% of incident sunlight, making it the most reflective object in the Solar System. (Image courtesy of NASA/JPL/USGS.)

Fig. 1.7. Taken from 0.5 million km away, this is one of the first pictures of Saturn's moon Mimas, as *Voyager 1* made a flyby on November 12, 1980. The massive crater, approximately 100 km wide and therefore about one-quarter of the satellite's diameter, is named after the 18th-century astronomer William Herschel, who discovered Mimas in 1789. (Image courtesy of NASA/JPL.)

There is no doubt that, after Titan, one of the highlights of the mission to the Saturnian system would include the exploration of Enceladus and its E Ring, which we introduced at the beginning of this chapter. (Further details on Enceladus can be found in Chapter 8). This tiny moon quickly became one of the most tantalizing planetary bodies in our Solar System, and for a good reason. High-resolution images from the Voyagers revealed that the moon had a surface that was unusually smooth, with a small amount of cratering. Could it be that Enceladus was being subjected to the same tidal stresses as Europa and generating a substantial amount of heat?

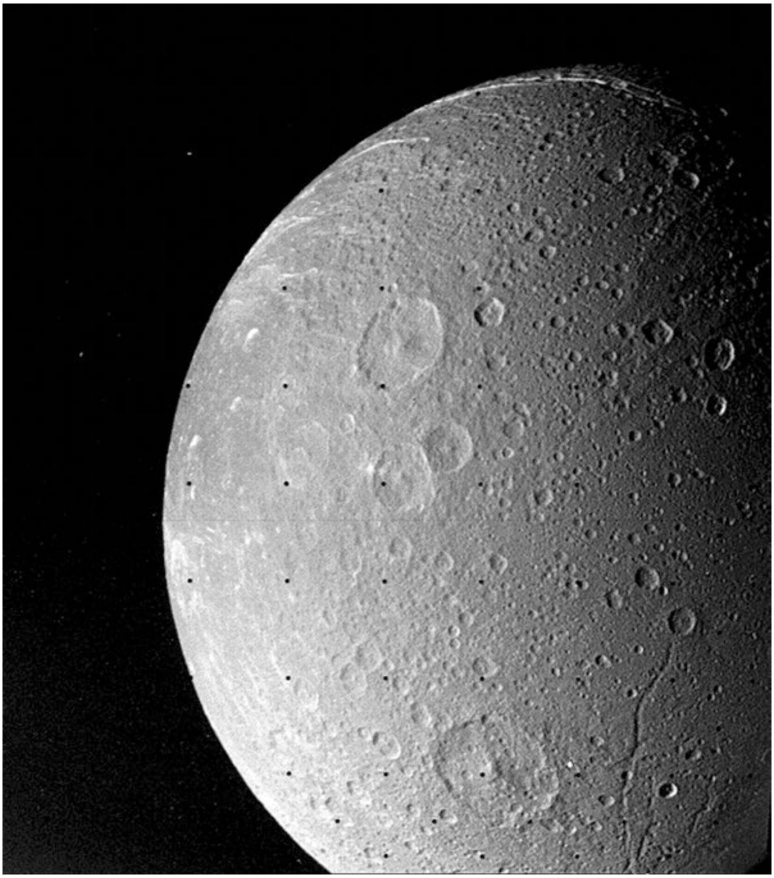

Fig. 1.8. Dione viewed by *Voyager 1* from 160,000 km on November 12, 1980. The wispy material can be seen on the edges of the small moon. (Image courtesy of NASA/JPL.)

The scientific community was once again excited by such possibility, but there was just one problem with this explanation – a major one. Enceladus, with a diameter of 500 km, is six times smaller than Europa and has a relatively low orbital eccentricity, half of what Europa experiences. When scientists applied these factors to their calculations of tidal heating, the results were insufficient to explain the observed energy. Although various proposals were put forth to explain this energy gap, no consensus could be reached, and the source of Enceladus' heat, and therefore its smooth craterless surface was a mystery. It would remain so for many years.

Regardless of these theoretical problems, Enceladus had shown clear signs of activity. Close-up images of the E ring, taken fourteen years earlier during ground-based observations, had revealed that the ring was centered on the moon. And Enceladus' orbit was shown to be at the densest part of the E ring, suggesting that the moon's surface was the source of the particles in the E ring. By then, most scientists speculated that a subsurface ocean could indeed exist on Enceladus, albeit at a much smaller scale than on Europa.

Other Saturnian moons also proved interesting. Mimas, the smallest and innermost of Saturn's major moons, is less than 198 km (123 m) in mean radius, making it the smallest spherical body in our Solar System. It is so tiny that it can barely maintain its shape, although, this wasn't the only thing that made Mimas special. Since the small moon was known to have a more eccentric orbit than Enceladus (four times as much), is closer to Saturn, and consists mainly of water-ice (contrary to Enceladus, which is also made of rock), theoretical models at the time predicted that the moon should have much more tidal heating than Enceladus.

Yet when the Voyagers took close-up shots of Mimas, they revealed one of the most densely cratered surfaces in the Solar System. Now the scientific community was faced with the opposite problem they encountered with Enceladus. They were looking at a solidly frozen surface that had remained unchanged for billions of years. This contradiction didn't prevent optimists from suggesting that liquid water could still exist in the interior of the moon. It was clear, though, that these were early days and that additional scientific data would be required to resolve this paradox. Unfortunately, scientists would have to wait twenty years to learn more. (More details on Mimas can be found in the appendices.)

Another intriguing icy moon revealed by the Voyagers as a possible ocean world was Dione, a bigger sister to Enceladus, although it exhibited a less active history, as surface images showed a wide variety of terrain, from heavily cratered regions to moderate and lightly cratered plains. Mysterious wispy material composed of bright, narrow lines was discovered on the surface, leading some scientists to suggest that these were the result of fresh ice seeping from the interior of the moon.

The team knew that Dione was experiencing an orbital resonance with Enceladus, completing two orbits of Saturn for every single orbit completed by Enceladus. This gave Dione an orbital eccentricity, creating tidal heating. Nevertheless, the moon showed little sign of recent activity compared to Enceladus, making it uncertain whether there was enough heat to maintain a subsurface ocean beneath its icy crust. Regarding geological activity, Dione seemed to be lying between Mimas and Enceladus. Again, only the next mission to Saturn would provide further insight on this moon.

Finally, in March 1979, one of the most awaited events of the entire Voyager mission took place: the Titan flyby of *Voyager 1.* This giant moon hid beneath a shroud of orange atmosphere, and it was uncertain whether its surface details could be seen by a spacecraft. Larger than the planet Mercury, and laced with organic gases, Titan was thought to have a liquid cycle of methane (lakes, rain, and gas). It was such a unique body that scientists had decided early on that *Voyager 1* would be programmed to make a close flyby.

Unfortunately, the constraints in orbital mechanics meant that this flyby would force the spacecraft on an outward trajectory outside of the ecliptic plane, ruling out any visits to further planets. No routes allowed a close pass of Titan while preserving a Uranus flyby option. If this were the case, then *Voyager 1* would be 'lost' after its Titan flyby, and *Voyager 2* would be the only spacecraft to continue exploring the last two gas planets, with no backup plan.

Despite such risks, Titan proved unique enough that the team decided to go ahead with the flyby. In fact, the Voyager mission was planned in such a way that if *Voyager 1* were to fail to complete its objectives at Titan, *Voyager 2* would be required to make the flyby instead, prematurely ending the tour of the outer planets, meaning that neither Uranus nor Neptune would be visited. It is telling that Titan was thought to be more critical from a scientific point of view than two giant planets with their systems of satellites.

Already, a year before *Voyager 1*'s flyby of Titan, *Pioneer 11* had passed within 355,600 km of the moon. Unsurprisingly, it had returned low-resolution images of a featureless orb, since the spacecraft had limited imaging capabilities. Little could be learned from these images, so when, in November 1980, *Voyager 1* passed at 3,915 km, the closest approach any of the Voyager spacecraft would make to a moon or planet, scientists were hoping to learn more from Titan's surface. Unfortunately, the resulting pictures were also disappointing, as they presented a thick, impenetrable atmosphere with no obvious surface features. *Voyager 1* detected a variety of organic compounds in the atmosphere, but the mystery remained. What was hidden below the thick haze?

Voyager 1 nevertheless returned promising scientific data. It was discovered that Titan experienced the strongest orbital eccentricity of all the moons of Saturn and Jupiter and that its density was between that of solid rock and water. The moon's interior probably consisted of a thick layer of ice suspended between a solid crust and a rocky core. Would this layer of water be liquid or icy? The scientists didn't know. Theoretically, Titan could host a subsurface ocean, provided its tidal heating was strong enough to melt sections of the ice layer. But further investigations would be required.

Voyager 1's flyby meant that Titan had the potential to host two entirely different liquid environments: liquid methane on its surface (due to the environmental conditions expected to be present there), and liquid water within its interior (due to tidal heating). Sadly, it would be twenty-four years before another spacecraft would finally begin to reveal the truth behind Titan's liquid promises.

Beyond Saturn

And so, as *Voyagers 1* and *2* left the Saturnian system (the latter on its way to Uranus and Neptune, and the former flying straight out of the Solar System on a trajectory perpendicular to the ecliptic plane), planetary science had been transformed in just a few short years. Instead of a dry, inert, and unexciting set of moons lying far away from the warmth of the Sun, the Voyagers found diverse and geologically active worlds that could host multiple vast subsurface oceans. The Solar System was becoming wet again (Table 1.1).

The cherry on the cake was the discovery that Triton, the largest of Neptune's satellites, had a relatively young surface and was still active, showing evidence of geyser-like volcanic vents that spewed gases and dark particles. This big moon, far away from the Sun and made up of ices and rock, was another addition to the list of possible ocean worlds within our Solar System, although it experiences the smallest eccentricity of any known object in the Solar System (its orbit is almost a perfect circle).

Triton is unique among the big Solar System moons, as it has a retrograde orbit, revealing the fact that it wasn't formed there but was lying further out, much like Pluto, and got 'captured' by Neptune's gravity. Such a capture would have placed Triton on a

Table 1.1 This table represents the exploration of the outer planets since the first voyage of the Pioneer probes in 1973. NASA holds the title of being the only space agency to have sent missions beyond the Asteroid Belt and to the outer planets. The European Space Agency hopes to send a spacecraft in the Jovian system by mid-2020s (JUICE mission). Although Cassini-Huygens was a joint mission (NASA, ESA and the Italian Space Agency) the vehicle itself was designed and built by NASA

Outer planet exploration chart

		Spacecraft	Jupiter	Saturn	Uranus	Neptune	Pluto
NASA	**Launched**	**Pioneer 10**	1973 – flyby				
		Pioneer 11	1974 – flyby	1979 – flyby			
		Voyager 1	1979 – flyby	1980 – flyby			
		Voyager 2	1979 – flyby	1981 – flyby	1986 – flyby	1989 – flyby	
		Galileo	1995–2003 orbiter				
		Cassini – Huygens	2000 – gravity assist	2004–2017 orbiter			
		New horizons	2007 – gravity assist				2015 – flyby
		Juno	2016 – orbiter				
	In development	**Europa clipper**	2024 – orbiter				
ESA		**JUICE**	2030 – orbiter				

highly elliptical eccentric orbit, generating intense tidal heating and certainly melting its interior ice. Despite the fact that the moon has a circular orbit nowadays, having been slowed down by Neptune after billions of years, heat generated from Triton's early days could still be sufficient to maintain a subsurface ocean.

As planetary scientists got ever more enthusiastic about these discoveries, they perfected theoretical models proposing that moons such as Rhea, Charon, Oberon, Titania, and others could also host subsurface oceans if the conditions were right. In particular, Ariel, one of Uranus's moon, seemed to be a promising candidate, especially after *Voyager 2*'s surface images showed it to have experienced resurfacing events in its past.

In the following decades, the success of dedicated orbiters such as *Galileo* around Jupiter (1995–2003), *Cassini* around Saturn (2004–2017), *Dawn* around Ceres (2015–2018) as well as new space probes such as *New Horizons* visiting Pluto (2015), meant that scientific data came pouring in from all over the outer Solar System, providing further evidence to substantiate claims of ocean worlds (See Table 1.1). Indeed we now realize that our blue planet is relatively dry, as from Jupiter onwards our Solar System is awash with water. Callisto and Ganymede have around 50 percent of their mass composed of the stuff while Europa holds two to three times the volume of Earth's oceans under its thick icy crust. In fact, it seems that an outer Solar System object without water is the exception (such as Io), not the rule.

But where did all this water come from?

2. The Frost Line

The Origins of Water

Like many space-related misconceptions that refuse to go away, there is still a widely held belief that our planet is the only place in our Solar System where water exists. This couldn't be further from the truth. Water is abundant in space. We find it everywhere. Break H_2O down into its two main constituents, and you immediately realize that hydrogen and oxygen are respectively the first and third most common elements in space. That's a lot of matter capable of forming water.

Hydrogen, the first and simplest atom in our universe, was formed only 400,000 years after the Big Bang and makes up 75% of all observable matter in the universe. You could refer it as the primary building material in the universe, forming all the stars and gas planets (dark matter notwithstanding). Hydrogen's abundance is why common elements are found in their hydrogenated forms: oxygen as water (H_2O), carbon as methane (CH_4), nitrogen as ammonia (NH_3), and silica as silane (SiH_4), for example.

Oxygen, on the other hand, was not formed by the Big Bang but instead was cooked inside massive stars. When these stars are born, they initially start fusing hydrogen into helium. However, as the hydrogen in their cores gets depleted and temperatures increase, the stars expand into red giants, creating super-dense, super-hot cores. Inside these, a helium fusion process referred to as the CNO cycle (carbon-nitrogen-oxygen cycle) form new elements: beryllium, lithium, carbon, nitrogen, and oxygen. Since oxygen is a light element (atomic number 8), it will be manufactured abundantly. Later on, when a star is at the end of its lifecycle and depletes most of its fuel, these elements (and heavier ones for bigger stars) are dispersed in vast, interstellar molecular clouds called nebulas.

Although far less abundant than hydrogen, oxygen still exists in astronomical quantities. To put this into context, oxygen makes up 0.9% of the Sun's mass (thousands of times the mass of Earth), 49.2% of Earth's crust, and 89% of the world's oceans by mass. Raise your hand and look at it. Two-thirds of your body is made up of oxygen.

B. Henin, *Exploring the Ocean Worlds of Our Solar System*, Astronomers' Universe, https://doi.org/10.1007/978-3-319-93476-1_2

Back in the nebulas, when hydrogen and oxygen meet, on the surface of tiny silica grains, for example, a simple collision impact between them provides just enough energy for these two elements to combine and form the H_2O molecule as ice. As this happens on a grand scale, a lot of icewater gets formed. From a nebula awash with water, a small overdensity appears, and gravitational forces will collapse the cloud, forming a new star and with it a new Solar System.

Where it is cold, water will exist in its solid form as ice. Where it is hot, near a star, for example, water will be in its gaseous form as vapor. Planets, moons, and all Solar System objects will, therefore, have water on them. That must be the reason why we have water on Earth. *Et voila!* Case closed. Well, no, not really. Like many things involving space, the case for water on Earth and other Solar System bodies is not that straightforward.

The Concept of the Frost Line

In Earth science, where scientists gaze less often at the stars, there exists a concept termed the frost line, which is the maximum depth of ground below which soil will not freeze in winter. This is because our planet's rocky crust holds vast amounts of heat regardless of the low temperatures observed on the surface. Below this line, water remains in its liquid form, preserving the organisms located there (and to our relief, often preventing the sewage water pipes from bursting).

Astronomers, being an efficient bunch, poached this term to explain a similar process occurring across our Solar System (albeit without the sewers). In astronomy, the frost line (also referred to as snow line or ice line) is the distance from the Sun where the low temperatures encountered force a volatile molecule (such as water, ammonia, or methane) to revert into its solid state and form ice particles. For the water molecule, the frost line is a little less than 5 AU, or around 700 million km, at which point the average temperature falls below 170 K (−103.15 °C or −153.67 °F). At this location, water in its gaseous state will condense straight into ice. (Water in its liquid state cannot exist in space due to the lack of pressure.)

This change is significant because the state of a molecule will determine how it behaves within its location in the Solar System. Before the frost line, water is in its gaseous state as vapor, and since it weighs very little, it gets blown away by the intense solar radiation. This mainly electromagnetic radiation is emitted continuously by our Sun, pushing away any light molecules, volatile compounds, and small particles that lie in its paths such as water, methane, nitrogen, ammonia, and carbon monoxide. Heavier compounds and elements, such as metals or silica, are too heavy to be nudged by solar radiation and remain where they are.

After the water-frost line, lower temperatures force water vapor to condense into ice, and as a result, newly formed ice grains attract each other and assemble into bigger, heavier chunks. These are now too heavy to be blown away by the solar radiation and can become building blocks, components of the moons and planets formed in this part of the Solar System. For example, Mimas, Saturn's tiny moon, lies far away from the water frost line and consists mainly of water ice, in effect it is like a giant snowball (Fig. 2.1).

Each area of the nascent Solar System will, therefore, contain different condensates for planet formation. The inner nebula will be rich in heavy solid elements, while the outskirts will consist of ice and gases, such as water and ammonia.

You can replicate the frost line by creating your Solar System on your dinner table. Sprinkle a bit of salt and pepper on the table to represent the light, volatile compounds such as water, methane,

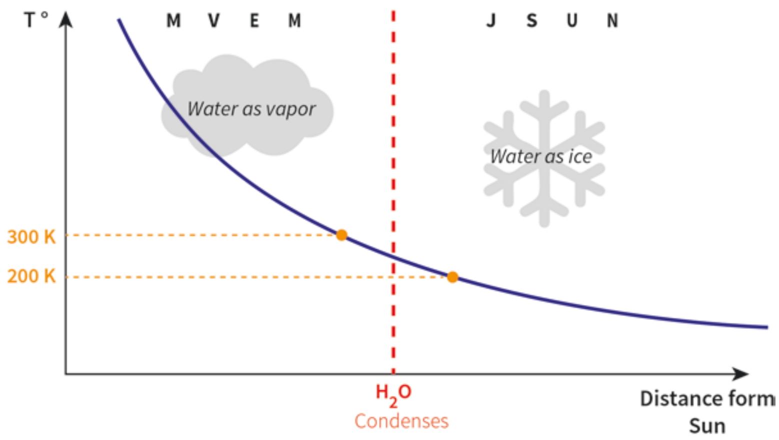

Fig. 2.1. As seen in this simplified diagram, water's frost line is right before Jupiter at a little less than 5 AU or around 700 million km, at which point the average temperature falls below 170 K (−103.15 °C or −153.67 °F). At this location, water in its gaseous state will condense straight into ice

and nitrogen surrounding a nascent star. Next, place more massive objects, such as sugar cubes, paper clips or even small pebbles, on the table to represent the heavier compounds such as silica and iron aggregated into various clumps. Now, sitting at one end of the table, pretend that you are the newly formed Sun emitting intense solar radiation, and blow as hard as you can on the surface of the dinner table (you can use a fan as well). As expected, the heavy compounds will remain on the table, while the lighter ones will have either moved to the far end of the table or been blown to the floor. Pile the heavy items on the table in little mounds, and do the same with the lighter ones on the floor, and you have just made yourself a proto-Solar System. The piles of heavier stuff accumulate into heavy, dense objects lying close to the Sun, while lighter objects form further out. You now have one of the primary explanations for the variances in the densities of Solar System objects.

The four inner, or terrestrial, planets of our Solar System – Mercury, Venus, Earth, and Mars – are the 'dinner table' planets. They are dense, mainly composed of heavy matter, and hold relatively few volatile compounds. In contrast, the four outer planets – Jupiter, Saturn, Uranus, and Neptune – are the 'lighter' planets. They are mainly composed of light compounds, holding relatively small amounts of dense matter such as rock or metal.

Determining density is an important tool within a planetary scientist's toolkit. Density is the mass of the object divided by its volume. We can evaluate the mass of an object by studying how it orbits around the Sun or another planet, while its volume is directly related to the diameter of the sphere (for spheroid objects, at least) which can either be measured directly if the disc is apparent or estimated through the analysis of the light reflected by the object.

For more than a century now astronomers have been hard at work measuring the densities of the objects in our Solar System, as such information can provide valuable insight as to what an object is really made of. Water in its solid state (frozen water) has a density of about 1 gram per cubic cm (g/cc or gm/cm^3), while rock is around 3 g/cm^3. Our planet's density is 5.5 g/cm^3, which implies that something heavier than rock lies inside it; this is the iron core. Saturn's density is less than water at 0.7 g/cm^3. It would float in a swimming pool (if there ever existed one big enough), implying that the giant planet is made up mostly of gas. Pluto's density is around 2 g/cm^3, halfway between rock and ice. Its composition, therefore, will be a mix of these two components. Since the objects that we will investigate are moons and dwarf planets, which are mostly formed of rocks and ices (volatiles), knowing their densities will provide a powerful insight as to the makeup of these objects.

As you can see from Table 2.1, when comparing the densities of the four inner planets and the four outer planets, a clear divide between both categories can be seen.

The frost line explains why the 'lighter' gas planets can't form near a star. It also explains why water constitutes the composition of most of the objects lying further from the line. Moons such as Enceladus and Europa ooze with water, while our Moon has almost none. Giant planets such as Neptune and Uranus hold untold volumes of water within their deep interiors, while Mars has some. The Kuiper Belt is populated by billions of icy objects, whereas the Asteroid Belt has far less in comparison.

You will have noticed that, according to this model, any object formed before the frost line shouldn't have much water on it. However, on Earth, an inner planet lying inside the frost line, our bodies are 65% water, and water is everywhere. We also know that Mars, also located before the frost line, had a very wet past, with a vast ocean covering most of its northern hemisphere. Furthermore, there is evidence that Venus might also have supported oceans in its past before turning into the furnace that we know. Even more striking is the fact that huge quantities of water-ice have been discovered trapped in frozen pits at the north pole of Mercury, the planet closest to the Sun.

Why was water present on all four inner planets (and still is for some), contradicting the frost line concept?

Table 2.1 Mean densities of the eight planets in our Solar System. There is a clear divide between the inner and outer planets. Note that Saturn is lighter than water

Mean density of planets	
Planet	**Mean density (g/cm^3)**
Mercury	5.4
Venus	5.2
Earth	5.5
Mars	3.9
Jupiter	1.3
Saturn	0.7
Uranus	1.3
Neptune	1.6

The Grand Tack Model

The simple answer is that we don't know for sure yet, but we have a good idea as to how this might have happened. A model referred to as the Grand Tack hypothesis postulates that the primordial oceans on Earth, Venus, and Mars consisted of water that formed in the outer Solar System. Indeed, the hypothesis proposes that in the early stages of our Solar System, waterless planetesimals inside the frost line were pummeled by a vast number of water-rich small Solar System objects such as comets and tiny protoplanets that formed beyond the frost line, but were thrown into the inner Solar System. This was the result of Jupiter and Saturn migrating inward towards the Sun, dragging many small objects with them (as well as ejecting or gobbling up many others).

In addition to distributing water to the inner planets, it is predicted that such a migration may have disturbed many objects lying within the inner Solar System and the outer Solar System alike, somewhat mixing them up in the process. Furthermore, the Grand Tack goes a long way in resolving the Mars problem. (Alternative models can't reliably predict the formation of a small planet such as Mars in its current location.)

Until recently, one of the uncertainties with this model was the delivery mechanism for the water. Did it arrive on the terrestrial planets as icy asteroids that had formed just outside of the frost line, or with water-rich comets that lie beyond Neptune's orbit (a long-time favorite candidate)?

An important piece of the puzzle was found on December 10, 2014, when the European Space Agency (ESA) announced the findings of its spacecraft, *Rosetta,* which had been orbiting the duck-like comet called 67P/Churyumov-Gerasimenko. It was a big day for many planetary scientists, as the data from one of *Rosetta*'s scientific instruments, ROSINA (Rosetta Orbiter Spectrometer for Ion and Neutral Analysis), was made public, and they could now start to consider answers to the question of the origin of water on Earth.

Built by the University of Bern in Switzerland, ROSINA is a mass spectrometer that among other things, analyzes the ratio of heavy water. This ratio, acting as a distinctive signature, allows scientists to determine if Earth's water is similar to water found on comets such as 67P. Before we go into the results, let us clarify the concept of heavy water, isotopes, and the context in which the measurements of 67P were made.

The hydrogen atom is composed of a proton as the nucleus and an electron orbiting around it. This form of hydrogen can be referred to as protium, although this term is rarely used. In some instances, a neutron can join the party and sit comfortably within the nucleus alongside the proton, creating a variance of hydrogen called deuterium.

Although neutrons do not have electrical properties, they do have a mass, and this additional particle will make the hydrogen atom heavier, thus changing its properties. Protium and deuterium are isotopes of the hydrogen atom, meaning that they share the same number of protons and electrons but have a different number of neutrons in their nuclei. These isotopes can be denoted like such: protium as 1H (containing no neutron) and deuterium as 2H (1 neutron). More neutrons can be added to the hydrogen atom, forming new isotopes: tritium (3H) containing two neutrons, and so forth, all the way up to an isotope named hydrogen 7 (7H), which unsurprisingly consists of six neutrons. Protium, deuterium, and tritium occur naturally, while isotopes 4H to 7H are artificially created in high-end laboratories and are highly unstable. Protium is by far the most common hydrogen isotope in space, with an abundance of more than 99.98% by mass, followed by deuterium at 0.02%. Tritium is rare and has a very short half-life (12.3 years).

Since a water molecule, H_2O, contains a hydrogen atom, it follows that there could be multiple 'flavors' of water molecules, each made up of the different isotopes of hydrogen. A water molecule such as $1H_2O$ is made up of protium and is referred to as 'light water,' while a water molecule made up of deuterium, $2H_2O$, is called 'heavy water' and has different physical and chemical properties. Tritiated water, $3H_2O$, composed of tritium atoms, is radioactive and is only stable for a limited number of years.

The water that we drink every day is a mixture of light water and heavy water (oxygen isotopes also exist, but they aren't relevant here), although the concentration of heavy water on Earth is extremely low, around 156 molecules of heavy water per million molecules of water, or 0.0156%. Scientists use this figure as the deuterium/hydrogen ratio – also known as the D/H ratio. It is our planet's fingerprint.

Like fingerprints, each planetary body has a unique D/H ratio. The mix of these 'flavors' is dependent on the physical properties where the water molecules formed. It is for this reason astronomers have been busy measuring D/H ratios either in situ or through astronomical observations on a large variety of Solar System objects, including planets, moons, many asteroids, and even eleven comets. (It is important to note, though, that with time atmospheric and geological processes on these planets and moons can alter these ratios. Scientists take this into account when analyzing the raw data.)

Earth and meteorites hailing from the Asteroid Belt (the carbonaceous chondrites type) have very similar D/H ratios and therefore must share the same origin. On the other hand, the four gas planets, as well as long-period comets (originating from the Oort Cloud), have very different D/H ratios implying that even though comets are thought to represent a significant reservoir of icy material, they are not the bearers of water for planetary objects residing in the inner Solar System.

At first, asteroids seemed to be the most likely culprits, yet, as often in space, things aren't that simple. Short-period Jupiter-family comets such as 103P/Hartley 2 or 45P/H-M-P have also shown to have a D/H ratio very much like Earth's, suggesting that they could also be the contributors to Earth's oceans, contrary to their distant cousins the long-period comets.

It is at this point where the short-period Jupiter-family comet 67P/Churyumov-Gerasimenko comes into the story. Like most comets orbiting close to Jupiter, 67P is believed to have originated in the Kuiper Belt, a vast ring of icy objects beyond Neptune's orbit. The comet was then nudged inwards, most likely due to Neptune's interaction and caught by Jupiter's massive gravity, forcing it into a short-period orbit around the giant planet (less than 20 years per orbit). A similar pattern must have occurred for short-term comets 103P/Hartley 2 and 45P/H-M-P. Because of this, most scientists expected that Comet 67P/Churyumov-Gerasimenko would display the same D/H ratio as comets 103P/Hartley 2 and 45P/H-M-P and therefore confirm once and for all that short-term comets (originating from the Kuiper Belt) as well as asteroids were the carriers of water to Earth. ESA even produced in 2014 a short promotional film for the *Rosetta* mission with this theme in mind (see 'Ambition the film').

But the measurements returned by ROSINA took planetary scientists by surprise. The water ratio of 67P was roughly three times higher than that of water on Earth as well as also being very different than that of Oort Cloud comets. It seems that the water within Jupiter family objects has diverse origins. For now, because few comets contain Earth ocean-like water, we have to conclude that most of the water on our planet was delivered by asteroids (carbonaceous chondrites) despite their relatively low water content.

There is no doubt that the formation of our Solar System was a messy thing and the full picture of the origins of water on Earth is likely to be more complicated than our current understanding has it. The Grand Tack model, as appealing as it is, has yet to be proven. Another popular model, termed the Nice Model, also provides much insight as to how small Solar System objects that formed in the outer Solar System were tossed around as Jupiter and Saturn entered a 2:1 resonance, wreaking havoc with the original Kuiper Belt objects roughly 600 million years ago. Like the Grand Tack model, the Nice model seems to fit many observations made but remains to be proven. As further D/H measurements are performed in the coming decades through the continued robotic exploration of asteroids and comets (NASA will send new missions to the asteroids and Jupiter's Trojans by the next decade), we will hopefully get a clearer picture of the origins and distribution of water in our Solar System.

Final Thoughts

There is another aspect of our Solar System's early history that can also shed some light as to why some objects within the frost line contain water. By studying objects within the Asteroid Belt (around 2.7 AU from the Sun), there are hints that the frost line resided in the belt during the early stages of the Solar System and then moved gradually outwards as the Sun got hotter. Ceres, a dwarf planet and the most prominent asteroid within the belt, holds a significant amount of water, as it was most likely formed beyond the frost line (but still within the belt). We investigate Ceres and its potential subsurface water in greater detail in Chapter 9. It is worth pointing out, though, that the Grand Tack model predicts that carbonaceous and water-rich objects migrated from the outer Solar System to the location where the Asteroid Belt now resides, thus providing an explanation for the variances in the composition of the Asteroid Belt.

Finally, let us not forget that water isn't the only substance to have a frost line, as each volatile substance has its own. Therefore, it is necessary to specify which material's frost line is being discussed. Due to the inherent nature of the water molecule, it is the first volatile substance to condense as we move further out from the Sun and the temperatures drop, therefore making it the first frost line we encounter. However, the further outwards we go, the colder it gets, turning more volatile compounds into icy particles massive enough not to be nudged by solar radiation. These then become the building blocks for planetesimals and other small Solar System bodies forming in this part of space. Nitrogen's frost line is at 63 K (–210 °C or –346 °F), which is roughly within Saturn's orbit, while methane's frost line is at 41 K (–231 °C or –385 °F), before Uranus's orbit. Neptune's moon Triton, or the dwarf planet Pluto, where methane ice is present on the surface, have a pinkish coloring, whereas surfaces dominated by water-ice have a white or grayish coloring depending on what else has accumulated on the surface. *NOTE: The detection of ammonia (NH3) and methane (CH4) in marginal quantities on the surface of a planetary body such as Ganymede or Callisto, which are located within their frost lines, is not implausible as these gases can be trapped in complex molecular structures.*

Therefore by knowing where each volatile condenses in our Solar System, we can extrapolate the composition of the objects formed there. Europa is mainly composed of rocks and water-ice as we are still too close from the Sun for other volatiles such as ammonia and methane to condense. Further out, Titan, the most prominent moon of Saturn, is composed of rock as well as water and nitrogen ice. (It also has liquid methane on its surface, as we haven't reached the temperatures required to freeze methane; this is developed further in Chapter 7). On Pluto, located far out from the Sun and where volatile compounds have condensed into icy particles, ices from the original nebula are present: water, nitrogen, methane, and carbon monoxide (Table 2.2).

Table 2.2 Abundance of the major ices resulting from the gas nebula. After water, methane and ammonia make up most of the ices

Ice species	Formula	n_x / n_{H_2O}
Water	H_2O	1
Methane	CH_4	0.38
Ammonia	NH_3	0.14
Carbon monoxide	CO	0.054
Hydrogen cyanide	HCN	0.014
Nitric oxide	NO	0.0014
Nitrogen gas	N_2	0.00035

Now that we have understood where the water in our Solar System comes from and how it is distributed, the topic of our next chapter will look at the life that lives in it. Indeed, before starting our tour of the ocean worlds, it would be useful for us to review the most recent notions of astrobiology – the study of life on Earth and in space. These will be helpful as we scrutinize in great detail each ocean world and try to make educated guesses as to their habitability.

3. Life on Earth and in Space

Although this book is devoted to subsurface oceans of our Solar System and the potential for life to arise in such environments, a detour to the arid plains of Mars is recommended, as unique experiments related to extraterrestrial life were performed there. The search for life on the Red Planet is a fascinating tale, and we do it no justice by covering it here in a few paragraphs since entire books have been written on this subject alone. Regardless, such a story provides a sense of perspective, as well as insights that will prove helpful as we speculate about the possibility of life within the subsurface oceans of our Solar System.

The Vikings Are Coming

The year was 1976. This could have been a year that would have changed our perception of life as we know it, and ultimately our history. It turned out not to be. The emissaries that were sent out to complete this accomplishment returned ambiguous data that at best confused scientists as well as the general public that ultimately funded these missions. Disillusionment settled in, and the budget approvers took note. Over the next forty years, no further mission with a similar scope was flown again and thus ended humanity's first real endeavor into the search for extraterrestrial life in our Solar System.

We are, of course, referring to NASA's Viking missions, which successfully landed two spacecraft on the surface of Mars, a remarkable feat in its own right, and revealed a barren and apparently lifeless world. Much has been said and written about these missions that seemed, in many ways, ahead of their time. This shouldn't detract us from the fact that these missions were a product of their era, the Cold War, where a powerful combination of national prestige and the need for displaying one's technological prowess was synonymous to bold ideas and, to attain them, seemingly limitless budgets.

B. Henin, *Exploring the Ocean Worlds of Our Solar System*, Astronomers' Universe, https://doi.org/10.1007/978-3-319-93476-1_3

The following figures will speak for themselves. Roughly 1 billion U. S. dollars were spent in the 1970s on the Viking program, equivalent to $11 billion nowadays. To put things in perspective, in fiscal year 2017, NASA received a total of $19.5 billion, or the equivalent of 0.5% of the entire U. S. federal budget, which allows it to fund four different directorates: Human Exploration and Operations; Aeronautics; Science; and Space Technology. The Planetary Science division, which is responsible for the robotic exploration of our Solar System that the Viking missions would be part of, sits within the Science Directorate and received only $1.8 billion in the fiscal year 2017 (and that was a good year).

Flagship NASA missions in this division take a considerable portion of the annual budget and are therefore few and far between. The Cassini-Huygens mission to Saturn launched in 1997 cost in its entirety $3.26 billion. The Curiosity rover launched in 2011 to investigate the past habitability of Mars was done with an overall budget of $2.4 billion, while its newer sibling, the Mars 2020 rover, will hit the $2.5 billion mark when it launches for the Red Planet. Moreover, the coming Europa Clipper that will investigate Jupiter's icy moon is planned for a 2024 launch and will be around the $2 billion mark (although this might go up). To put it plainly, NASA wouldn't have the money to carry out the Viking missions today regardless of their potential to 'change the world.'

Various factors can explain why the cost of the Viking mission was so exorbitant. One of them was the doubling down of spacecraft. In the early years of space exploration, NASA would build two spaceships per mission to guarantee success due to the high failure rate experienced at the time. *Mariner 1* and *2* were launched to do the first survey of Venus, *Mariner 3* and *4*, *6* and *7*, and *8* and *9* were all Mars flyby missions sent in tandem. There were also two Voyager spacecraft and two Mars rovers (launched decades later, though). Nowadays this mode of operating isn't favored by NASA, in large part due to budget constraints, and is also attributable to the high level of engineering competency gained throughout decades of launching missions into space. NASA, through its famous Jet Propulsion Laboratory (JPL) development center in Pasadena, has now produced an uninterrupted succession of successful missions over two decades, reaching a level of reliability that doesn't require the need to duplicate spacecraft anymore.

Furthermore, to understand why the U. S. government was willing to throw so much money at the Viking missions, we need to understand the space race. In the 60's and 70's, the USSR and the Americans were trying to outpace each other technologically, and one of the areas pursued was the newly gained ability to robotically explore of the Solar System. As such, multiple spacecraft were sent to the Moon, Venus, and of course Mars. There, over the course of a decade, the Soviets launched well over a dozen attempts, including flybys, orbiters, and landers. Sadly, apart from two spacecraft (Mars 2 and Mars 3) that successfully orbited Mars in 1971 but weren't able to perform their mapping operations due to the presence of a global dust storm, they all failed. As can be seen from Table 3.1, other leading space agencies have sent missions to the Red Planet with varying success.

The Americans had more luck. The Viking missions, similar to the Apollos, were meant to demonstrate the country's technological superiority, and they did so remarkably by successfully landing the first spacecraft on Mars – twice (the USSR's *Mars 3* did land on the surface in 1971 but failed to operate), and were also the first to send back surface images, the first to study the Martian soil and weather, and of course the first to investigate the possibility of life on the Red Planet or any planet for that matter (Table 3.2).

After the Vikings, the USSR threw in the towel and abandoned any further missions to Mars in the following two decades. (The failed Phobos missions launched in 1988 were meant to study Deimos and Phobos, the moon of Mars.) However, the American government soon lost interest in the program, and as soon as the Vikings had demonstrated the country's technological might, the political will to fund more costly missions to the Red Planet disappeared and there were no new missions for the next fifteen years.

There was also another reason why funding proved elusive after the Vikings: no life on Mars could be found. This was a huge blow for many scientists and the public at large, as they were hopeful that some form of microbial life could have been detected by the landers. Although the results from the Viking experiments proved challenging to interpret, the majority of the scientific community agreed that the missions had been unsuccessful in their attempts to find life.

It would have been tempting to think that the Viking story was over, but scientists are a stubborn bunch. There were enough nuances in the results that some doubts were raised,

Table 3.1 This table shows the successes and failures of the world's leading space agencies to send missions to Mars. NASA leads the pack with 18 successful missions throughout 50 years of exploration

Mars missions successful						
	Europe	**Europe/Russia**	**Japan**	**USA**	**USSR**	
Mission\agency	**ESA**	**ESA/Roskosmos**	**ISRO**	**NASA**	**Soviet Union**	**Grand Total**
Flyby				3		3
Lander				4		4
Orbiter	1	1	1	7	2	12
Rover				4		4
Grand Total	**1**	**1**	**1**	**18**	**2**	**23**

Mars missions unsuccessful							
	China	**Europe**	**India**	**USA**	**Russia**	**USSR**	
Mission\agency	**CNSA**	**ESA**	**ISAS**	**NASA**	**Roskosmos**	**Soviet Union**	**Grand Total**
Flyby				1		5	6
Lander		2		1		5	8
Orbiter	1		1	3	2	7	14
Penetrator			1			1	
Rover						1	1
Grand Total	**1**	**2**	**1**	**6**	**2**	**18**	**30**

Table 3.2 This table shows NASA missions to Mars success rate throughout the years. NASA is on track for having no mission failures in 20 years – a record

NASA mars mission success and failures		
Year	**Mission Name**	**Successful**
2013	MAVEN	Yes
2011	Curiosity	Yes
2007	Phoenix	Yes
2005	MRO	Yes
2003	Spirit	Yes
	Opportunity	Yes
2001	Mars odyssey	Yes
1999	Deep space 2	No
	Mars polar lander	No
1998	Mars climate orbiter	No
1996	Mars global surveyor	Yes
	Mars pathfinder	Yes
	Sojourner	Yes
1992	Mars observer	No
1975	Viking 1 lander	Yes
	Viking 1 orbiter	Yes
	Viking 2 lander	Yes
	Viking 2 orbiter	Yes
1971	Mariner 9	Yes
	Mariner 8	No
1969	Mariner 7	Yes
	Mariner 6	Yes
1964	Mariner 4	Yes
	Mariner 3	No

and, unsurprisingly, given what is at stake here, some scientists interpreted measurements from one of the experiments as tantalizing evidence that life had actually been detected. If all this seems confusing, that's because it is. To get clarity over all this, let's review the Viking experiments and their results in detail.

The Viking Experiments

Since 1971, when *Mariner 9,* the first spacecraft to orbit Mars, took images revealing a barren and lifeless world shaped only by geological activity, scientists were forced to agree that if life still existed on the Red Planet, it would just be microbial. No one honestly expected to find signs of land plants, macrofauna (large worms) or megafauna (vertebrates) – although this didn't stop the American astronomer Carl Sagan from famously joking that lights should be installed next to the cameras of the Viking landers to attract anything that was out there. In case you wondered, there were no lights.

As it seemed Mars was able to support life on the microscopic scale only, in 1971 JPL's director Bruce Murray set out Viking's principal purpose as such: "The primary objective of the mission will be the direct search for microbial life on Mars." Although this might seem straightforward to most, the biology team for this mission was in fact given an incredibly difficult challenge.

For a start, no one knew with certainty what the composition of Mars' surface was. The images taken by *Mariner 9* provided many clues, but with no imaging spectrometer on board and no spacecraft landing on the surface, there were no real certainties as to what the ground was made of. Would the landers rest on solid rocks or capsize in thick layers of dust? No one could say for sure. Some scientists had even speculated that the surface consistency might be like that of shaving cream, which would in effect sink the landers altogether. The biology team had no definitive answers to basic issues such as what was the ground made of, was there soil and if so what was its composition, would we find nitrogen or any element vital for life as we know it on Earth, or even the holy grail, might there be icy water under a thin dusty layer.

Scientists behind the Viking mission had to begin somewhere, though. With the environment so little understood, they had to go back to the fundamentals of life on Earth.

As a starting point, they knew that detecting tiny microorganisms would prove impossible given the technological constraints imposed by a spacecraft. Better to focus on the measurable chemical activity that could betray the microbes' presence. However, sweeping assumptions had to be made as to what chemical activity would be prevalent on the surface of the Red Planet.

On Earth, the sheer diversity of chemical processes generated by terrestrial microorganisms is overwhelming. There are nitrifying bacteria, sulfur-oxidizing bacteria, iron-oxidizing bacteria, sulfate-reducing bacteria (chemotrophs), phototrophic bacteria (generating energy from light), bacteria that use oxygen respiration (aerobic) while others will die in the presence of the gas (anaerobic), etc. And we have even recently found cells that live off pure electricity, bypassing the need for food or chemical reactions altogether. Where should they begin?

The researchers started with the common denominator of all life on Earth: carbon-based organic chemistry. Every biological cell on Earth absorbs, manufactures and expels carbon-based compounds. The reason is simple – carbon atoms have properties that make them extremely versatile. No other element comes close. They can attach themselves to an endless number of configurations and form long chains, providing an incredible variety of molecules upon that life utilizes to adapt and survive.

With this in mind, it was decided that the Viking missions would focus solely on searching for carbon-based chemistry. Of course, other types of chemistry could exist on Mars, and in that case, they would be genuinely alien and we would miss them altogether, but the line had to be drawn somewhere, and as such carbon biology fit with the central principles of the mission brief.

As the scientists continued their long and arduous decision-making process to select the experiments that would go on the Vikings landers, four basic questions emerged:

1. Does anything in the Martian soil exchange gases with the atmosphere?
2. Does anything in the soil release carbon?
3. Does anything in the soil assimilate carbon?
4. Does the soil contain its own carbon-based compounds?

Each one of these questions on its own would not confirm the presence of life, but taken as a whole, if all of them would receive a positive answer, then scientists could conclude that a carbon-based biological process of unknown nature was taking place on Mars. We wouldn't have seen it nor been able to characterize it, but we would have detected its presence through the indirect observation of its metabolism. Such a 'grand-slam' of positive findings would have no doubt fueled a fleet of further missions, and perhaps even seen human footsteps on Mars by now.

Equipped with these four questions, the team then set about on selecting the instruments. Four experiments were selected, each answering one of the questions.

The first of these, 'Does anything in the Martian soil exchange gases with the atmosphere?', would be answered by an instrument called the Gas Exchange Experiment (GEX). The idea was simple. Some Martian soil would be scooped up by the Viking's robotic arm and placed in a hermetically sealed and heated tube, where the atmosphere within would be regularly monitored. Small amounts of water and 'food' to speed up the metabolic processes would gradually be introduced into the chamber. It was assumed that if Martian microbes did exist, they might be living in a state of torpor due to the freezing temperatures present on the planet (averaging −55 degrees C) and the lack of abundant nutrients.

The 'food' consisted of a broth of vitamins, sucrose, lactose, amino acids and other organic compounds on which carbon-based microorganisms should thrive. Once the water and nutrients were added, a gas chromatograph, an instrument capable of identifying simple substances such as oxygen, nitrogen, carbon dioxide, and methane, would analyze the atmosphere on a regular basis. Any changes in the atmosphere's composition due to metabolic reactions would be quickly detected.

The decision to add such a broth was not universally accepted, and only two of the experiments would use this supplement in their processes: GEX and LR (see below). The primary concern for some scientists was that organic nutrients could create false positives by triggering life-like reactions from existing inorganic compounds. This is why the fourth experiment, 'Does the soil contain organic compounds?', was crucial to the entire biology package, as it would validate any positive results from the other three experiments.

The second question 'Does anything in the soil release carbon?' would be answered by the Labeled Release (LR) experiment. This experiment was designed to detect any signs of organic processes coming from the Martian soil as water and nutrients containing carbon-14 atoms would be added. If microorganisms metabolized the nutrients with the traceable carbon-14, they would theoretically release these carbons as waste gas into the atmosphere of the container. Any gas laced with carbon-14 could then be easily detected by Geiger counters, thus providing indirect evidence that some organic process had taken place within the soil.

To answer the third question, 'Does anything in the soil assimilate carbon?,' the Pyrolytic Release (PR) experiment (or carbon assimilation experiment) was conceived to detect signs of life in the complete absence of water and organic nutrients. No food would be added. Instead, the assumption taken by Norman Horowitz, the principal investigator for PR, was that if life on Mars currently existed on the surface, it would be able to metabolize without additional liquid water or nutrients, whose introductions would only create further complications to an already complicated experiment. It could also potentially stress the organisms that have evolved to live without such quantities of water and food.

Once again soil would be collected from the robotic arm and placed into a container. This time, carbon monoxide and dioxide gases with carbon-14 would be added to the atmosphere and left there for five days. (There is a slight caveat in that Horowitz had found that ultraviolet light could create organic compounds in the presence of carbon monoxide, water vapor, and certain types of soil. With this in mind, he filtered out all ultraviolet light that was created by the arc-lamp simulating the Martian sunshine.)

The sample would be gently heated, and after 120 hours of incubation, the atmosphere would be pumped out using a neutral gas (helium), and the remaining soil would be subjected to temperatures of about 625 °C to break down (pyrolize) any organic matter into volatile compounds that could easily be detected. Any traces of carbon-14 in the sample after pyrolization would indicate that something in the soil had captured the carbon monoxide or dioxide in the initial atmosphere and used it for its metabolic processes.

Finally, the last question, 'Does the soil contain its own organic compounds?', would be answered by the Gas Chromatograph/Mass Spectrometer (GC/MS) experiment. Martian soil would be placed into one of three chambers (sample ovens) and heated gradually to 500 °C (each oven could be heated up to this temperature in eight seconds), breaking down in stages any organic compound, such as a Martian microorganism, present in the soil. The resulting vapors generated would be filtered through a gas chromatograph, which in this experiment would act like a granular filter separating out the organic molecules according to their complexity. The simpler, lighter molecules would pass through the chromatograph at a faster pace than the heavier, more complex ones. The resulting gases would then go through a mass spectrometer, a sophisticated instrument that would bombard these passing gases with charged particles, ionizing the organic molecules in the process. These molecules, in turn, would be subject to a magnetic field that deflected them according to their mass, the lighter organic molecules being more affected than the heavier, more complex ones. Finally, electronic detectors would measure the degree of deflection for each molecule, and results could be compared with similar experiments done on Earth using organically derived vapors. The GC/MS was a unique state-of-the-art piece of engineering that required an incredible amount of ingenuity.

In theory, the GC/MS experiment would be the only one to directly detect organic compounds, while the GEX, PR, and LR tests would follow a life-detection approach. It is important to note that the Viking GC/MS wasn't meant to detect life but would instead provide additional data to interpret the biological experiments.

Klaus Biemann, who designed the GC/MS experiment, stated in 2007 in an article in the *American Chemical Society* journal: "The thing that gets me annoyed is that people think we were looking for life. We calculated that we would need 1 million microorganisms per gram of soil to be able to detect the organic material that they represent." Due to later criticism of the GC/MS experiment, which we will review a bit later, Biemann replied "And still people say that we couldn't have detected microorganisms – of course we couldn't because we weren't looking for them! In fact, if NASA had asked me to fly an experiment for life detection, I would have said, 'Go to someone else.'"

And so it was from these four experiments that the first mission to investigate the possible existence of extraterrestrial life on another Solar System body was designed. The Vikings would also characterize Mars' surface geological composition and its weather and atmosphere with additional scientific instruments placed on the lander and orbiter (Fig. 3.1).

More than 40,000 pieces for Viking spacecraft were assembled, many miniaturized and all rigorously tested to withstand the harshness of space travel, making, at the time, the two most complex spacecraft ever built. Hundreds of leading scientists, engineers, and planners working tirelessly to meet the launch date of 1975, which was only a few years away. No space agency today would contemplate setting up such an ambitious and complex mission within the tight deadlines imposed on the Viking teams. No doubt, geopolitics were at play as the Soviets had already sent

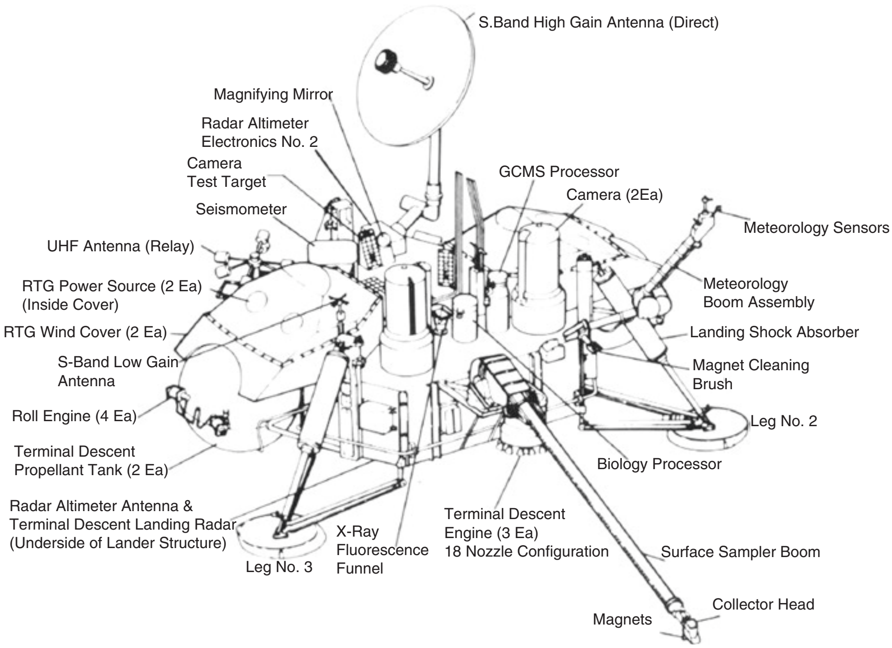

Fig. 3.1. The Viking lander (diagram)

13 missions (all unsuccessful) to the Red Planet by the time the Viking spacecraft were being developed. But, unknown to the Americans, with such a long string of failures the Soviet's dreams for exploring Mars had run out of steam. No further missions to the planet would be launched until the end of the following decade.

It was inevitable, though, that despite the vast resources allocated to the Viking missions, the tight schedule had a detrimental impact on its preparation. For example, there had been no time to calibrate all four experiments with each other, meaning that the data collected by the entire group might be difficult to interpret. Also, due to technical constraints, the GC/MS experiment would analyze separate soil samples from the one feeding the GEX, PR and LR experiments, making the comparison of the results even more prone to ambiguity. And, of course, there was no time to send a preceding mission to analyze the Martian soil and determine its chemical composition and general properties, which would have significantly helped the scientists to tailor their experiments to best suit the Martian environment. But the clock was ticking, and any mission was still preferable to none in the eyes of many.

All that the scientists had to do now was to hope that at least one of the landers would come to rest safely and all four experiments would work as designed. At this early stage of space exploration, this was not a given, as more missions to Mars had failed than succeeded. And indeed, there were some hair-raising moments.

For example, in 1972, *Mariner 9* (the first spacecraft to orbit another planet) had taken more than 7000 images of the Martian surface, which the Viking team had scrupulously analyzed to find the best landing sites for the two landers. On June 19, the *Viking 1* orbiter inserted itself around Mars and started sending back high resolution images of the initial landing sites. Upon looking at these new images, the Viking team quickly realized that the landing sites were not perfect, and with less than a month to go before landing, they hurriedly searched for new locations.

Thankfully, they found one in time for the *Viking 1* lander, and it safely touched down on July 20, hundreds of kilometers north of its intended primary site. The *Viking 2* lander had a similar fate. It touched down on September 3 in an area a third of the way around Mars from the initial landing sites. For both landers, scientists and engineers only had had only a few weeks to analyze vast amounts of data being returned from the Viking orbiters to select new sites. If it would have been possible to allow more time to review the new images, better landing sites might have been found.

Regardless, when the *Viking 1* lander safely touched down in western Chryse Planitia (making it the first American spacecraft to land on another planet), and the *Viking 2* lander did the same in Utopia Planitia, there was immense relief among the scientific community, the public, and also the politicians that had funded this mission. America had done it first once again.

The Viking Results

As expected, the first images sent back by the landers showed no lifelike plants among the rocks strewn on the barren plains. No hard-shell bug was seen running in the foreground as well. It was bleak and lifeless (Fig. 3.2).

The experiments started straightaway and lasted for weeks at a time, although they were slowed down due to various technical problems such as the jamming of the robotic arm used

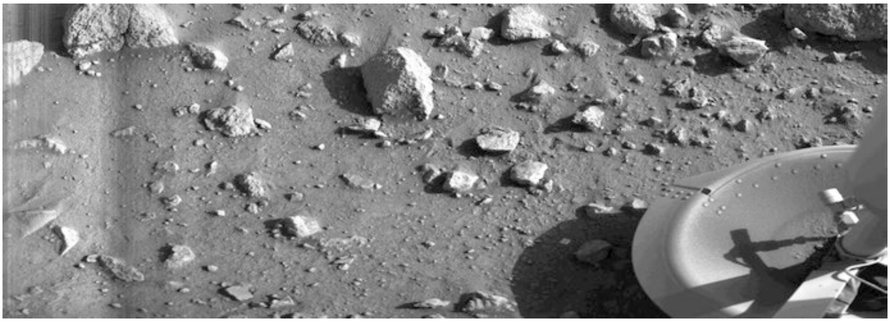

Fig. 3.2. Taken by the *Viking 1* lander shortly after it touched down on Mars, this image is the first photograph ever taken of the planet's surface. It shows an arid and rocky world (Image courtesy of NASA)

to collect soil samples and a leakage of radioactive gas within the chamber used by the PR experiment on *Viking 1* (this unfortunate event required adjustments in the data to compensate for the loss). Remarkably though, all the instruments worked out pretty much as was expected, and the results were sent back to Earth (although a few months apart as the landers had not arrived at the same time).

Alas, the results proved very confusing from the start. Only one of the three biological experiments yielded a seemingly positive outcome, while the two GC/MS instruments saw only carbon dioxide and water. It seemed that the Martian soil wasn't ready to give up its secrets so quickly. Here are the details.

On both landing sites the GEX experiment (does anything in the Martian soil exchange gases with the atmosphere) started first and immediately experienced a sudden surge in oxygen and carbon dioxide when the nutrients and water were introduced to the soil (although the experiment on *Viking 2* detected only a quarter of the oxygen measured with the *Viking 1* experiment). The quick rise in oxygen and carbon dioxide seemed too sharp for a biological explanation and even more troubling for the 'pro-lifers' camp; both gases tailed off after 50 hours of exposure to fresh food and water.

Such a result was in contradiction with our understanding of life. If Martian microorganisms were present in the soil, why would they suddenly stop feeding on the nutrients we were sending them? Instead, as any chemistry teacher will tell you, the quick bursts and the eventual drop in oxygen production had the telltale marks of a chemical reaction. A culprit was quickly advanced: peroxides seemed the best candidate in explaining the GEX results. Peroxides are molecules, such as hydrogen peroxide (H_2O_2) that are highly reactive with water and metals and release oxygen as a byproduct of the reactions. Although this hypothesis wasn't universally accepted by all Viking scientists, it provided a non-biological explanation for the results.

The results from the PR experiment (does anything in the soil assimilate carbon) proved intriguing as well. Minute traces of carbon-14 were picked up by the Geiger counters at both sites (after the gases were introduced and the sample pyrolyzed), implying that something in the soil had captured the carbon-14. The data could be interpreted as the result of less than a thousand bacteria cells within the sample using the radioactive carbon dioxide or monoxide as part of their metabolic processes, making it a surprisingly small number if this turned out to be true. To put this figure in perspective, on Earth, a single teaspoon (1 gram) of garden soil can hold up to a billion bacteria.

This result wasn't proof that life existed on Mars, but it was showing that something was going on, since a lifeless sample should have produced no count whatsoever. However, to confuse the scientists even more, a control soil sample sterilized by heat before it was put in contact with the radioactive gases also proved to have minute traces of carbon-14 in the soil, albeit at a level much smaller than the ones detected in the non-sterilized soil samples. If any life was present in the ground, it should have been destroyed by the sterilizing process, and no trace of carbon-14 should have been detected at all. This result implied that a non-biological explanation as a chemical reaction would be the most likely culprit to explain these results.

Of all the experiments that were run by the Viking landers, the LR experiment (does anything in the soil release carbon) proved to be the most promising in showing lifelike results. Once the water and nutrients were in contact with the soil in the sealed compartment, the Geiger counter in both Viking landers were able to detect carbon-14 in the air above the soil. The *Viking 1* experiment measured 9000 blips over the course of seven days while *Viking 2* had even more blips. This startled Gilbert Levin, the scientist behind the LR experiment.

To remove the possibility of getting positive results that could be associated with the effect of ultraviolet radiation hitting the surface of Mars, the landers collected soil underneath a rock, which again tested positive. Levin then set up few control tests. One test had the soil sterilized at 160 °C, which produced no results. He then heated another sample at 50 °C and found that there was much less activity. Finally, a sample was kept in the dark for two months at 10 °C, and this returned a negative result. Whatever was doing the metabolizing had been damaged.

Levin and his team claimed that the LR experiment had found evidence that life was present in the soil of Mars, since it absorbed the carbon-14 and released it. The other Viking scientists weren't convinced by the results and suggested non-biological explanations such as oxidants (peroxides were proposed as a possible explanation for the GEX results). Oxidants are molecules that can react to the organic matter present within the nutrients and by breaking them down will release volatile compounds containing the traceable carbon-14. There were various problems with these suggestions, though, so the case was still open for a biological origin.

The results of the final experiment, the GC/MS (does the soil contain its own carbon-based compounds) were the most striking. As a reminder, if the GC/MS's results failed to detect carbon-based compounds in the soil, then none of the positive results from the three other experiments would hold up.

With this in mind, everyone was eager to get examine the GC/MS data returned from the landers. As it turned out, it became the biggest disappointment of the mission. At neither landing site did the GC/MS detect any traces of organic material in the soil. The instrument was working, as it detected the cleaning solvents used before the launch, but despite numerous repeats, no organic compounds were discovered. This was a surprise to everyone, as organic compounds could commonly be found in space, on asteroids, on moons, in comets – even in vast clouds of interstellar gas. It was expected that the Martian surface would also be covered with them. The fact that the GC/MS returned blank was a mystery.

As the year came to a close, the mood in the Viking team soured. Although the LR results were promising, the GEX and PR results didn't support the life-on-Mars hypothesis, while the GC/MS hadn't found the building blocks necessary for life. Something was not adding up, and different interpretations emerged from the ambiguous data. Levin claimed that the GC/MS experiment wasn't sensitive enough to detect small traces of organic compounds. In the other camp, scientists claimed that Levin's experiment discovered a new form of non-biological reaction that had nothing to do with life. The biology team was divided, and no clear answers were to be found.

NASA was in a muddle and quickly released an official statement claiming that the results neither proved nor disproved the existence of life on Mars – hardly an acceptable outcome for politicians who had agreed to fund billions of dollars for the mission. With the public disappointed and scientists split into camps, politicians in Washington took note. In the coming years, the budget for planetary science evaporated like water on the surface of Mars. There would be no further spacecraft to the Red Planet for the next twenty years, and no mission to seek the existence of life on another world would be approved until the agreement to fund the 2020 Martian rover.

And yet, the outcome could have been different.

A less complicated experiment was initially proposed to be part of the Viking biological hardware but wasn't selected for budgetary reasons. Designed by Wolf Vishniac, an American microbiologist and subsequently named the Wolf trap, the experiment consisted of suspending a sample of Martian soil in an aqueous solution that contained nutrients. If any Martian microorganisms did grow in the solution, they would quickly turn the liquid cloudy, which would be detected by a light sensor and change the solution's acidity that would be measured using a PH meter. The experiment wouldn't provide any information on the exact nature of the microorganism found, just that something living had grown in the solution.

The Wolf trap had been tested with many samples from Earth and showed that for some strains of microorganisms, it was a surprisingly accurate means of detecting life forms. The only caveat was that this was the least Mars-like environment that the soil samples would be subjected to. It didn't seem to matter. Trials done using extremely arid and cold Antarctic soil, similar to the conditions expected on the Martian surface, and supposedly sterile of life, returned positive results from a few microorganisms that are now classed as extremophiles, able to live in what we would consider extreme conditions. It seemed that rather than stemming the growth of these extremophiles, which had evolved to withstand extreme environments, the Wolf trap was doing the opposite and accelerating their metabolism.

It is worth mentioning, though, that not all microorganisms experience growth within such a medium. Therefore, the danger in using such experiment is that a negative result would not necessarily imply that life on Mars doesn't exist – just that life capable of growing in such medium isn't present within the soil sample.

Nevertheless, because of the simplicity of its design (all you need is a container, some amino acids, and water) and the potential for a positive detection, astrobiologists such as Charles Cockell, director of the UK center for astrobiology, still see merit in this experiment. Alas, the Wolf trap never flew to Mars with the Vikings or any other spacecraft. It is anyone's guess where we would be now if the Wolf trap experiment had been part of the Viking biological package as initially planned.

Post Viking Blues

Much speculation has been made throughout the following decades on the data returned by the Viking landers. Since then, many landers and rovers have added to our scientific understanding of the Red Planet, although much is still unknown. It has become clear though that the Viking missions, ambitious as they were, occurred far too early within the context of a Mars exploration strategy.

For the non-biological camp, the discovery of perchlorate in 2008 by NASA's Phoenix mission, which landed in the northern polar region, could explain the LR experiment results as the breakdown of the nutrients that released the molecules laced with carbon-14. On the other hand, the pro-life camp claimed that those same perchlorates could, when heated up in the Viking experiments, break down any organic compounds contained within the soil sample, therefore resulting in the lack of positive result from the GC/MS experiment. Also, the perchlorate would produce chloromethane and dichloromethane, which is what the Viking landers had detected. Pro-lifers also pointed out that none of the strong oxidants proposed over the years by the non-biological camp exhibit the thermal profiles as established by the LR experiments.

In 2012, Joseph Miller, an associate professor of cell and neurobiology at the Keck School in the United States and mathematician Giorgio Bianciardi, of Italy's University of Siena, used a data analyzing technique called cluster analysis, which groups together similar-looking datasets, to review the entire dataset from the LR experiment. The computer program analyzed the raw data and established that the results of two of the LR experiments were clustered in the biological group with the control experiments while the rest were found in the non-biological group. The same Joseph Miller had previously published a paper putting forward the possible detection of circadian rhythms in the results from the LR experiments. These rhythms are internal clocks present in every life form on Earth that help them time their biological processes such as waking or sleeping as well as temperature regulation. Miller's interpretation seems too good to be true and would require further work to be validated. It is just an interpretation among many.

A breakthrough came in 2014, with the detection, by the Mars Science Laboratory Curiosity rover, of organic molecules in Gale Crater – the first detection of such molecules on the planet's surface. Curiosity was using a method that prevented the perchlorates from being involved in the process as opposed to the Viking experiments. This discovery has raised further doubts on GC/MS's ability to detect organic compounds on the Martian surface, as the heating up of the samples before the analysis was most likely the cause for the non-detection of organic material.

Further analysis and discoveries will undoubtedly continue to keep the results from the Viking missions relevant in the years ahead. Unfortunately, there is no denying the fact that, in the immediate post-Viking era, the search for life in our Solar System took a step back from these bold beginnings, as it took decades for NASA to get back to Mars.

Almost twenty years after the initial launch date for the Vikings, NASA set up the Mars Exploration Program (MEP) as a means to make a comprehensive study of the geology and atmosphere of the planet with the help of a fleet of orbiters, landers, and rovers. This marked a definite transition in the exploration of Mars, as it put the search for Martian life on the back-burner. Instead, the focus for MEP in the last thirty years has been to understand the geology of the planet well enough to determine if habitable environments have existed or still exist on Mars, the 'Follow the water' strategy.

This approach culminated in 2012 by the landing in Gale Crater of the highly specialized Curiosity rover, which had for its mission the understanding of the planet's geological and geochemical processes to determine if Mars could have supported life. Such a concept is often referred to as habitability, a term widely used in geoscience and defined as the ability of an environment to support the activity of at least one known organism. (This concept can be further broken down into either instantaneous habitability, the conditions at any given time in a given environment required to sustain the activity of at least one known organism; or continuous planetary habitability, the capacity of a planetary body to sustain habitable conditions on some areas of its surface or within its interior over geological timescales.)

In short, Curiosity is a habitat detector. And after years of studying Gale Crater, we now know that at some point in Mars' distant past, it was a habitable place for carbon-based life as we know it. Whether any life forms were present, that is another matter altogether, one which will hopefully be answered by the upcoming Mars 2020 rover designed by NASA and the Exomars rover by ESA. Indeed, after decades of probing and sensing the Red Planet with orbiters, landers, and rovers, space agencies are once again confident in funding life-detection missions and will carry on the quest first started by the Vikings fifty years ago.

The instruments both rovers will carry bear no resemblance to the ones brought to Mars forty years earlier. There will be no nutrients to give away as snacks and no water to be drizzled. Instead, these new missions will use, among other tools, powerful instruments such as X-ray fluorescence spectrometer or Raman spectrometers that can quickly provide a chemical composition analysis and the mineralogy of any rock or object on the planet. On both rovers, the suite of instruments has been carefully selected so as to complement each other and insure that the interpretation of a sample that is being analyzed can be accepted with confidence.

The aim of these missions will not be to look for the hypothetical metabolic reaction of Martian microorganisms in the presence of external stimuli but instead to carry out the hunt for specific organic molecules or detect patterns in the mineralogy that can only have a biological origin. The rovers will also be equipped with powerful cameras (PIXL for the 2020 Rover and CLUPI for ExoMars) that will take images of rocks and unconsolidated material at the micrometer scale to search for changes in textures and chemicals that could be left behind by ancient microbial life. In other words, if fossils big enough to be detected (such as stromatolites) are present on the surface, these cameras will be able to visualize them.

The search for life on Mars is a fascinating tale, and we do it no justice by covering it in a few paragraphs here (entire books have been on this subject alone). It nevertheless can provide much insight as we speculate about the plausibility of life within the subsurface oceans of our Solar System.

The approach taken by the major space agencies regarding potential life in ocean worlds is not the one used by the Viking mission, defined by the technological and scientific limitations of the time, but instead involves the precise and careful characterization of subsurface environments and their habitability for carbon-based life forms.

Defining Life

Before we go into further detail on the ocean worlds of our Solar System and the missions planned to study them, there is one aspect of the Viking mission that we need to delve into, and that is the surprisingly tricky exercise of defining life. Indeed the Viking scientists broadly defined life in terms of something producing a metabolic reaction (the GEX, LR and PR experiments were set up this way). However, as we shall see, this is an insufficient definition.

It is often remarked that biology is the only science in which there is no general agreement on the object of its study. What is life? How to define it? This simple, yet profound, question seems much harder to answer than it sounds. Is a virus alive? How about the strawberry you picked up yesterday at your local supermarket? Is it alive? Go to your nearest university and talk to the scientists in the biology department, and you will most likely find that there is no simple consensus on these questions. It turns out there is no official definition of life, as it is not a scientific term, to begin with. It's a popular term, similar to planets and continents in that scientists have really struggled to come up with a satisfactory scientific definition.

So where do we start? There are various ways to approach this thorny issue. Some scientists like to list characteristics, while others prefer focusing on processes.

Throughout the years, though, many attributes have been put forward to define life. These are complexity (life seems to bring about organization), metabolism (chemical reactions occurring in an organism), homeostasis (the ability to regulate one's internal environment), growth (ability to increase in size and complexity), contains a system of storing data (DNA or RNA), reproduction (ability to multiply sexually or asexually), response to external stimuli, and capable of Darwinian evolution.

Most of these aren't genuinely satisfactory, though, as various non-biological processes can replicate them while some biological ones can't. For example, a snowflake can be seen as having complexity; crystals can even experience growth if the conditions are right. Fire seems to reproduce as it jumps from tree to tree in a forest fire, while computer programs can evolve yet no one would consider them alive. On the other hand, the fact that your neighbor's neutered cat can't reproduce or that a person is not reacting to external stimuli due to a temporary coma doesn't imply that he or she is not alive.

A definition of life that has gained much attention among scientists was proposed in 1992, at an Exobiology Discipline Working Group set up by NASA and comprised of various academics (including Gerald Joyce, a professor in biological studies). The definition is the following: *Life is a self-sustaining chemical system capable of undergoing Darwinian evolution.* Each term in this definition has been carefully chosen as we see below.

The term "chemical system" supports the notion that the transformation of matter is the bedrock on which life exists. We can't have life from nothing. (The expected arrival of artificial intelligence in the coming future, which according to this definition would not be considered as life, will most likely require some changes to these terms. Given the context of this book though, the definitions discussed here will be from a biological point of view only.)

The term "Darwinian evolution" implies many attributes often associated with life, such as self-replication or reproduction, mutability, heritability and metabolism (without which you can't replication). Darwinian evolution also entails adaptability properties such as locomotion, photosynthesis, chemosynthesis, energy storage, etc. Furthermore, it is a way for complex entities to maintain themselves, not as individuals but as a system, continuously evolving to adapt to environmental change. The "capable" term brings about the idea of the population or living system in contrast to the individual, as many individuals are needed to make the system capable of Darwinian evolution, not just one.

Finally, we have "self-sustaining," which implies that all of the information necessary for a system to undergo Darwinian evolution must be present within the collective system. In other words, the system should work without the need for an external factor. In this case, a virus isn't alive, as it doesn't have all the information required for it to undergo Darwinian evolution. A virus with a host cell might be called alive, but this requires an external intervention (the arrival of the host cell).

While this isn't the official working definition of life at NASA or any other official organization, it is very close to what we should look for.

To demonstrate how this definition can help scientists to confirm the evidence of extraterrestrial life, here is an interesting thought experiment proposed by Lin Chao, professor at the University of California at San Diego, using a reenactment of the Labeled Release (LR) experiment from the Viking mission. As you may recall, the experiment added water and labeled nutrients to the Martian soil, which in turn released labeled gas in a lifelike manner. The LR experiment, which focused primarily on a metabolic reaction, is inadequate on its own in revealing the presence of life, since a positive result is necessary, but not sufficient, as inorganic processes mimicking biological reactions could be at play here.

To overcome this, Chao suggested that the LR experiment be modified to focus on other attributes of life, such as reproduction or evolution. Surprisingly this can be easy to implement.

First, we can incorporate into the LR experiment one of the leading attributes of life, reproduction. The experiment starts as initially set up by placing a sample of Martian soil into a container. Water and labeled food are added, and as we have seen a reaction occurs with gas being released. The experiment then continues. We transfer a small portion of the same soil sample into a new container containing food and water and track any changes in the air above the soil. If the agent causing the reaction were of biological origin and is still active within the soil, labeled gas would be emitted once again, with results equivalent to the original experiment if sufficient time is allowed.

If, instead, the agent causing the reaction was inorganic, the amount of gas produced in the second container should be less than in the original experiment. The repeating of this process could even reveal predictability in the amount of gas reduced as the original sample gets diluted. However, if the causative agent was organic, it should be able, with time, to compensate for the dilution by reproducing and generate a similar level of gas released each time the soil is transferred to a new container.

Simple. However, it's not enough. There are autocatalytic reactions that could mimic such a pattern, resulting in a false positive.

Autocatalytic reactions occur when a compound 'A' comes in contact with a substrate 'B' and produces a reaction that generates twice as many 'A's and a byproduct 'C.'

$$A + B \Rightarrow 2A + C$$

The byproduct 'C' could be the release of gas, therefore mimicking the reproduction pattern of the LR experiment, since such a reaction will cause an increasing amount of 'C' despite having started with a smaller amount of 'A' (through dilution). Various non-biological autocatalytic reactions are known. Fire is the most famous of all.

Such reactions, therefore, requires us to focus on the second attribute of life, evolution.[1]

Bacteria can be shown to evolve in a laboratory as they are transferred from one culture to another for many hundreds of generations and become better adapted to the given environment (substrate, temperature, etc.). Parameters such as density, growth rate, and lag time can be measured to determine the increased adaptability of the microorganism. Within a month a bacteria will be able to enhance its ability to metabolize within the given environment.

This can be replicated in the LR experiment by allowing for a large number of generations to be produced through multiple transfers. If evolution is occurring, monitoring the release of labeled gas for each generation will be sufficient for its detection as the total amount of gas released per container should increase with time. This pattern is exclusively the realm of the living as far as we can tell; therefore the chances of having a false positive using this experiment are most likely null. If such an analysis landed on Mars and yielded positive results, we would be more confident in our assertion that a process similar to life, and therefore life itself, has been found.

Lin Chao's study provides a compelling insight on the difficulties scientists face when interpreting the Viking results as well as the many pitfalls inherent in experiments focusing exclusively on metabolic processes. It is little wonder that space agencies do not consider similar experiments for future life-detection missions. Instead, they have implemented a broad strategy of identifying past and present habitable environments within our Solar System and are now in the next phase of investigating them for

[1] Darwinian evolution is the process by which organisms change over time as a result of changes in heritable physical or behavioral traits. The changes which increase the chances of survival in a given environment will be more likely to pass on to the next generation. Unfortunately, Darwinian evolution is often misunderstood by the general public, which sometimes confuses it for the defunct Lamarckism theory that supports the idea that an organism passes on the attributes that it has acquired throughout its life to its offspring. For example, it was thought that a neck of a giraffe would grow from generation to generation because the giraffe uses this part of his body most throughout his lifetime. This has since then been proven to be false.

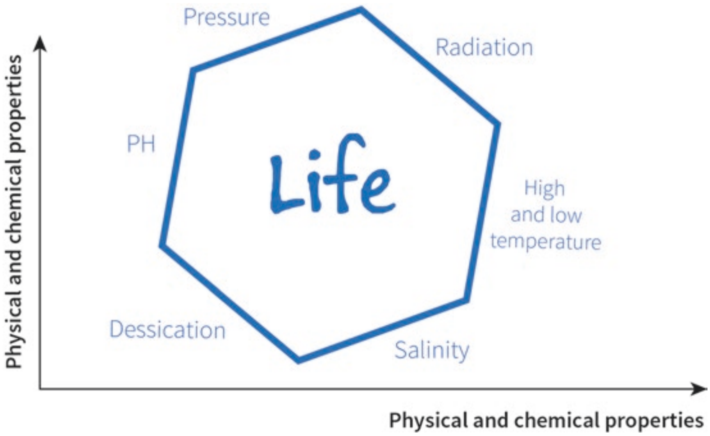

Fig. 3.3. The habitability of our planet is delimited by physical and chemical properties (Diagram courtesy of Charles Cockell)

biosignatures, as we have seen with the 2020 rover and Exomars. In Chapter 12, we review future planned and proposed missions for the search of life within subsurface oceans.

Pushing the Boundaries of Life

There is a catch, though. By defining the chemical and physical properties of a habitable environment, we are hopelessly biased towards the examples of habitable environments on Earth. Our planet can be thought of as an enclosure surrounded by a fence of six physical and chemical extremes: pressure, high and low temperature, salinity, radiation, PH, and desiccation.

As you can see from Fig. 3.3, all known life resides inside this enclosure that has been pushed further out numerous times throughout the decades as we discovered microorganisms able to survive in extreme conditions. The most remarkable and, rightly so, famous example of such discovery occurred in 1977, when hydrothermal vents were found at the bottom of the Pacific Ocean. These vents are fissures occurring on the oceanic floor from which water heated geothermally escape sustaining independent and unique ecosystems of very complex life forms, ranging from microorganisms to tube worms and crabs. We have since found many such vents at the bottom of our oceans.

Less famous, but still striking nonetheless, is the discovery of extremophiles living happily within the most extensive natural asphalt lake in the world, Pitch Lake on the Caribbean island of Trinidad. Oil samples from the lake contained bubbles of entrapped water droplets of 1 to 3 µl (microliters) where bacteria were found. On the other side of the world, Lake Whillans, a body of freezing water located 800 m under the surface of a glacier in western Antarctica has also been found to harbor a thriving ecosystem, although the lake has been sealed from the surface for more than 120,000 years.

Recently, scientists in Europe were stunned to discover multicellular animals capable of living in the anoxic environment of the Atalante Basin, a brine lake at the bottom of the Mediterranean Sea, where only bacteria, archaea, and viruses were known to survive. Microorganisms have also been found deep in Earth's outer crust – the layer just before the mantle – forming unique biospheres. Biologists are even considering that life might also be present in Earth's mantle (which starts 6 km under the seafloor on average), and excavations done in 2015 in the Atlantis Massif, a rocky region situated on the western side of the Mid-Atlantic Ridge, suggest that this might indeed be the case. Future expeditions to drill into the mantle itself (a first) are planned for 2030 at the latest; these have the potential to uncover new ecosystems. (Life's ability to thrive in Earth's outer crust, and possibly its mantle, might open the door to an ecosystem in the context of Mars exploration.) That simple and complex life manages to survive in these habitats would have seemed unthinkable a few decades ago, and yet we now know that life is present there.

As such, the boundaries of life has continued to expand as we have discovered life on almost every surface on the planet, from high up in the tenuous atmosphere to deep within the crust itself. It now seems that life can withstand a wide range of environments, and, importantly for us, some of these might also be similar to other parts of our Solar System.

Indeed, when we try to characterize the habitability of an environment such as Mars' surface or Enceladus' subsurface ocean, we are in fact searching for an overlap with the known habitats on Earth. If such overlap does exist, then life might have appeared as well and thrived, thus providing a strong case to investigate it. The good news is that we are continuously discovering extremophiles in places where we thought life couldn't take hold, thus increasing the range where an overlap might be possible with alien environments.

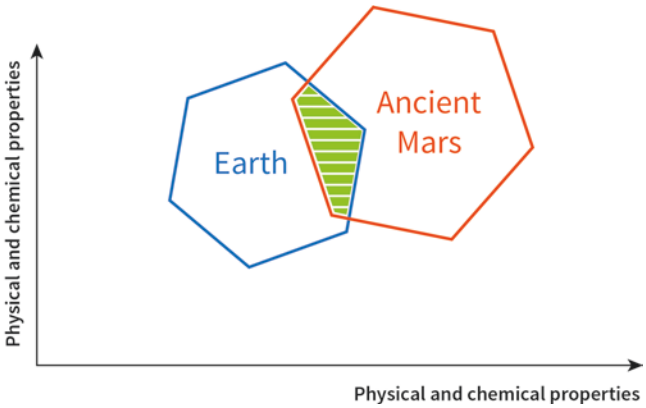

Fig. 3.4. Understanding the nature of the habitability zones in our Solar System that overlap with the ones on Earth is crucial in search of life in space. In this example, we compare early Mars with today's Earth (Diagram courtesy of Charles Cockell)

As you can see from Fig. 3.4, the investigation from Curiosity rover has revealed that the habitability zone of ancient Mars has overlapped with our habitability zone on Earth, raising the prospect that life could have been present there in the past.

The Three Ingredients for Life

Embedded at the very heart of the habitability concept lies the conditions required for life to emerge. Although bacteria and archaea can survive in extreme environments such as Pitch Lake, these microorganisms didn't live inside the hydrocarbons themselves but rather in tiny bubbles of water.

As such, scientists often list three conditions essential for life: liquid water, an energy source and access to nutrients and organic compounds (the building blocks of life). For complex life, another condition is required: time. Let us review each of these conditions in the context of the subsurface oceans that lie within our Solar System.

Water, as everyone knows, is the primary constituent of living things. It is essential to make a distinction, though, between water in its liquid state and its solid (ice) and gas (vapor) states. The reason is simple; we have never discovered an organism that has been proven to survive without water in its liquid state. There are of course extremophiles that can survive (just barely) in nearly waterless environments (think of the arid valleys of Antarctica), but eventually, even these extraordinary microorganisms will require a minimum of liquid water to function, sometimes having to wait thousands of years for them to do so.

Without liquid water, life on Earth as we know it wouldn't exist. This is because water molecules have this unique ability to act as a medium for organic compounds, mixing them in the process. As a matter of fact, liquid water is known as the perfect universal solvent, as it can dissolve more substances than any other liquid. This characteristic is due to its simple polar arrangement of hydrogen (positive electrical charge) on one side and oxygen (negative electrical charge) on the other, which can disrupt the attractive forces that usually keep other molecules together.

One of the other essential characteristics of water is that, because it is a polar substance, polar compounds are more soluble in it than non-polar ones (e. g., long chain alkanes). This means that compounds with hydrophobic tails and hydrophilic heads (amphiphiles) can 'clump' together to form micelles. (It's how soap dissolves fat – the tails dissolve in the fat and the heads in the water.) This is thought to be a mechanism for the early formation of cell membranes. In addition, being able to dissolve most substances means that wherever it goes, water will carry with it valuable nutrients and minerals, making it an ideal method of transportation within the medium into which an organism appears but also within the organism itself as it grows in size and complexity.

Liquid water also acts as a physical barrier, shielding potential life-bearing habitats from harmful solar radiations, highly charged particles and other nasty stuff coming from deep space.

Some scientists consider dismantling the boundaries of an Earth-centric approach by suggesting other forms of solvents for life. Ammonia, NH_3, springs to mind. Liquid ammonia can become a medium for many compounds, although its downside are the extremely cold temperatures at which it only exists as a liquid, between −33.3 °C and −77.7 °C, where it then solidifies into a mass of white crystals. This temperature range makes it difficult for metabolic reactions to occur.

Other solvents proposed are liquid hydrocarbons, such as methane or ethane, which form lakes on the surface of Titan, Saturn's giant moon. Theoretically, life forms could exist in waterless habitats by using hydrogen and acetylene as an energy source. A silica-based life could also grow in a liquid methane habitat, since methane is a suitable solvent for silanes (SiH_4) and polysilanes (compounds of multiple silanes), thereby mimicking the liquid water and organic chemistry association found on Earth.

These suggested substitutes for water are highly speculative, though, since such life forms have never been found on Earth. The only certainty we have for now is that without liquid water, carbon-based life forms as we know them cannot exist. Hence why our search for life in the Solar System involves searching for bodies of liquid water, either on Mars or within the depths of icy moons.

The next essential condition for life is energy, which can be roughly defined as a property that can be stored or transferred to an object that will give it heat or allow it to do work. Energy can take many forms, such as kinetic energy (motion), electrical energy, radiant energy (light), thermal energy (heat), nuclear energy, chemical energy, gravitational potential energy, etc. Without energy, molecules and atoms become inert (cold), preventing any reactions whatsoever. Although the requirement for liquid water as a critical condition for life might be too Earth-centric for some, the need for an energy source is universally accepted.

This should come as no surprise, as an energy source is required to keep the temperatures of a habitat within the range in which life operates: from 121 °C to −25 °C (although salts can lower the freezing point of water, which is why we put salt on roads, and life has been found to manufacture antifreeze compounds to survive in very cold environments). Within the context of icy moons and dwarf planets, we can imagine hydrothermal vents, occurring at the intersection between a rocky mantle and icy crust, radiating enough heat to melt small pockets of frozen water. But it is doubtful that life could appear in such limiting environments. We should better consider vast bodies of water such as the liquid mantles found under Europa or Enceladus or the hypothetical broad sea under Pluto, where the chances for life to appear are better.

Because such bodies represent a considerable volume of water, only a few processes can provide enough energy to melt them: primordial heat, radiogenic heat and tidal heating.[2]

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[2] Surface regions can also receive additional forms of energy, such as the electromagnetic radiation given off by the Sun (sunlight); however this is only relevant for planetary bodies that lie within the 'Goldilocks zone,' an area in the Solar System where the surface temperatures could theoretically allow liquid water to exist.

(Asteroids and comet strikes can also provide heat, although only localized heat. Collisions with planetary bodies were very common in the early history of our Solar System, but this form of heating isn't pertinent to oceans locked under thick layers of ice.)

Primordial heat is the residual heat trapped inside a planetary body as it was being formed in the early days of the Solar System and consists of two forms of heating. The first is accretion heat, which is generated by the conversion of the kinetic energy of impacting bodies to thermal energy. We are still benefiting today from the energy unleashed by a massive collision between Earth and a protoplanet, which resulted in the birth of our Moon. The second form of heat is referred to as gravitational release, which occurs when a planetary body has accumulated enough mass and heat to go through differentiation – the separation of different constituents of a planetary body. As denser material moves towards the center, such as iron, friction is created between the moving masses and converted to heat. (Phase transitions, such as when water vapor turns to rain, can release a lot of latent heat as well. An example is the case of Saturn, which is found to be warmer than it should be from solar gain alone, and this is thought to be due to 'helium rain' falling towards the center, releasing heat as it goes.)

Accretion heat generates a positive feedback loop, as the melting of icy and rocky material add further energy into the system. Once differentiation has occurred, this form of heating comes to a halt. However, the energy it has released will be stored within the interior of a planetary body for a very long time.

On Earth, primordial heat still represents half of the total energy released by our planet even though it is 4.5 billion years old. For bodies of smaller densities and volumes, such as small moons, this form of energy will more often than not dissipate quickly, leaving little leftover heat.

Another type of energy is radiogenic heat, which is generated from the decay of the nuclei in radioactive isotopes (radioisotopes), unstable elements that dissipate their excess energy by emitting radiation in the form of alpha, beta, and gamma rays. These isotopes are very present in the mantle and crust of planetary bodies (lithosphere) and warm these parts uniformly. The thicker the mantle and crust are, the more it warms up. As an example, Earth's radiogenic heat is responsible for the other half of the total heat produced by our planet. Mercury, on the other hand, has smaller layers of crust and mantle, which in turn reduces the amount of energy it receives from radiogenic heating. However, due to its small size, it should take less time to heat it up. The problem with smaller bodies though is that of absolute size, the surface area goes up with the square of the radius, but the volume goes up with the cube. Therefore smaller objects cool faster.

Regardless, due to the relatively small sizes of their lithosphere, some moons have little to no radiogenic heating. Nevertheless this form of heating can last for a very long time due to the presence of long-lived radioisotopes whose half-lives are counted in hundreds of millions or billions of years.

Tidal heating, introduced in Chapter 1, has its roots in the gravitational pull of one or more planetary bodies on a moon. The variation in heating depends on the severity of the gravitational pull as well as the internal composition of the moon itself (icy or rocky). Like most things in life, moderation is best. Too much and you end up like fiery Io scarred with constant volcanic activity, too little and you barely have enough energy to melt hard ice.

Tidal heating has two significant advantages over the other sources of energy. First of all, it can last almost indefinitely once the orbits of celestial bodies are locked. Io, Europa, and Ganymede have been subjected at varying degrees to tidal heating for billions of years. This is more than enough time for things to get interesting as far as life is concerned. Not every orbit is stable, though, and in that case, tidal heating can occur for a shorter period (but still within hundreds of millions of years). The Saturnian satellite system comes to mind as the small icy moons seem to drop in and out of resonance with each other throughout their formation.

The second advantage of tidal heating is that, depending on the circumstances, the energy can be focused towards a specific region inside the planetary body. The heating then becomes localized. Therefore an icy moon might not receive enough tidal heat to melt its entire ice mantle, but it could still host a body of liquid water confined to a particular area within it.

We shall revisit these three forms of energy as we explore one by one the confirmed ocean worlds or the planetary bodies which we suspect might host a subsurface ocean. Let us now move to the last condition we believe life requires to get started: the presence of organic chemistry.

Organic Chemistry for Dummies

The assembly of complex organic compounds forms the foundation of all life on Earth and can only occur if two prerequisites are met. Firstly, simple organic compounds need to be accessible to assemble the molecular structures that life requires, and secondly, an external energy source that life can use to drive metabolic reactions needs to be present (which on Earth will either be sunlight or redox reactions). Organic chemistry is the study of these two prerequisites.

The good news with the first prerequisite is that a rich variety of simple organic compounds can be found in the interstellar medium, planetary atmospheres and surfaces, comets, asteroids and meteorites, and interplanetary dust particles. These include carboxylic acids, sulfonic acids, sugars, urea, aliphatic and aromatic hydrocarbons, ketones, ammonia, alcohols, purines, and pyrimidines just to name a few. (More than 70 different amino acids have been identified in meteorites alone.) The building blocks of life lie everywhere we look. In September 2017, ESA announced, after studying at length the data returned by the Rosetta mission as it investigated Comet 67P Churyumov-Gerasimenko ('Chury'), that organic matter made up 40% (by mass) of Chury's nucleus and proposed as its origin interstellar space instead of within our Solar System. Comets like Chury must have delivered vast amounts of organic matter to Earth through the early bombardment phases of our Solar System, and actually, they still do so today.

Furthermore, organic compounds, and therefore life, are formed mostly by using only six essential elements. An easy catchword has been created to label them: CHNOPS (or SPONCH), with the letters representing carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur. The four major classes of organic molecules; carbohydrates, lipids, proteins, and nucleic acids can be built entirely from these CHNOPS.

That organic compounds are found everywhere in space comes to no surprise as these six elements constitute the most common matter our universe (see Table 3.3). Hydrogen, formed at the Big Bang, makes up three-quarters of all the mass in our observable universe, followed by oxygen (3rd most common element), carbon (4th), nitrogen (6th), sulfur (10th) and not seen on this table, phosphorus (19th). Life didn't rise from rare elements that were difficult to combine. No. Instead, it used accessible stuff that could also be easily assembled.

Table 3.3 Chemical elements ranked by their relative abundance in space. Five of the six essential elements for life to come into existence are part of the ten most abundant chemical elements in space. Phosphorus (P) is the 19th most abundant element

Abundance of chemical elements in our Universe					
Rank	**Symbol**	**Elements**	**Universe**	**Sun**	**Earth**
1	H	Hydrogen	92%	94%	0.20%
2	He	Helium	7.10%	6%	
3	O	Oxygen	0.10%	0.06%	48.80%
4	C	Carbon	0.06%	0.04%	0.02%
5	Ne	Neon	0.01%	0.00%	
6	N	Nitrogen	0.02%	0.01%	0.00%
7	Si	Silicon	0.01%	0.01%	13.80%
8	Mg	Magnesium	0.01%	0.00%	16.50%
9	Fe	Iron	0.00%	0.00%	14.30%
10	S	Sulfur	0.00%	0.00%	3.70%

Let us review these six elements and see what molecules they form as we combine them.

We will start with the carbon atom, the heart of organic chemistry. Carbon is a remarkable element. Carbon has different forms in nature, from graphite, the softest form of carbon, to diamond, one of the hardest substances known to us. Being tetravalent, each atom of carbon has four electrons capable of forming multiple bonds. This and the atom's small size makes it one of the most versatile elements, which explain why the Beilstein database, the most extensive database in the field of organic chemistry, contains almost 10 million organic compounds identified so far.

By adding hydrogen atoms to a carbon atom, a hydrocarbon is formed. This is the simplest of the organic compounds. The smallest hydrocarbon is methane (CH_4), which is composed of one carbon atom and four hydrogen atoms. Ethane (C_2H_6) has two carbon atoms linked to each other surrounded by six hydrogen atoms. Propane (C_3H_8) has three carbon atoms connected to each other surrounded by eight hydrogen atoms, while butane (C_4H_{10}) has four carbon atoms surrounded by ten hydrogen atoms, and so forth. As we add more carbo atoms and hydrogen atoms to the hydrocarbon, the chain gets longer and are then called polymers. When the chain of hydrocarbon is between five to nine carbon atoms long, it is named gasoline. At about a dozen carbon atoms long, it is diesel, and around twenty carbon atoms long, it becomes motor oil. Carbon has the unusual ability to form polymers at the temperatures commonly encountered on Earth, making it an ideal element to build molecular structures with.

If we insert oxygen between carbon and hydrogen, methane becomes methanol ($CH_4 \rightarrow CH_3OH$), ethane becomes ethanol (C_2H_5OH), propane becomes propanol (C_3H_7OH), and so forth. These are all known as alcohols. (Vast clouds of methanol have been found in space.) However, you can also make another class of organic compound with these three common elements by replacing the two remaining hydrogen atoms of the carbon belonging to the alcohol by a single oxygen atom. These form the carboxylic acids. They are called acids because the hydrogen bonded to the oxygen will then tend to come off easily, making it quick to react with other elements (more precisely the proton from a hydrogen atom will leave the organic compound while the electron of the same atom stays). Formic acid (CH_3OH becomes COOH), created by some ant species, is the smallest of these acids and is formed when an oxygen atom replaces a hydrogen atom in methanol. Acetic acid (CH_3COOH), also known as vinegar, is derived from ethanol and is created when an oxygen atom replaces another hydrogen atom. Butyric acid (C_3H_7COOH) appears when butter goes rancid.

Now, if you combine alcohols and organic acids (casting off one molecule of water in the process), a new class of organic compound is formed, the esters. These form one of the main classes of lipids (animal fats and vegetable oils) and are the basis for fragrances (for example ethyl butyrate has pineapple flavor). It is worth pointing out that alcohols (such as methanol), carboxylic acids (such as acetic acid) and esters (such as ethyl formate) have been found in space within large interstellar clouds.

Apart from alcohols and carboxylic acids, there is yet another class of compounds that use carbon, oxygen, and hydrogen. These are the carbohydrates. The name, carbohydrates, is a well-chosen here because it indicates the presence of carbon and water. These are utilized by life to form cellulose, starch, sugars, and glycogen.

It's surprising how much you can do with the first, third and fourth most abundant element in our universe, as we still have one last combination left. If you form long chains of a specific type of hydrocarbons (aliphatic compounds to be precise) and add only a handful of oxygen atoms in the form of carboxylic acid, you can create fatty acids useful for energy storage and building cell membranes.

By using only three elements, we have created hydrocarbons, organic acids, fatty acids, esters, lipids, carbohydrates, and alcohols. Not bad. But there's still more.

Let's now add the next element to this already remarkable mix, nitrogen (N). Combine hydrogen to nitrogen and ammonia (NH_3) is formed, a common volatile in our Solar System. If you add acetic acid (vinegar, as seen above) to ammonia, glycine is formed, the simplest of the amino acids. From here new combinations create more complex amino acids, and if you bond these together, proteins are created. Proteins are useful as they allow life to build structures in an organism (keratin for hair, collagen for skin, myosin for muscles, etc.). Throw in the next essential element, sulfur (S), and two more amino acids are formed.

Finally, phosphorus (P), the last essential element to be added to this remarkable mix, will bring about nucleic acids, which form the basis for DNA and RNA, by bonding nucleic bases (based on carbohydrates) together. Our genetic code is written with only five elements; C, H, N, O, and P (Fig. 3.5).

We are lucky. The staggering complexity of life on our planet is mainly derived from only six elements instead of any of the other 92 elements that occur naturally. Such a small set of essential elements makes the quest to find the right conditions

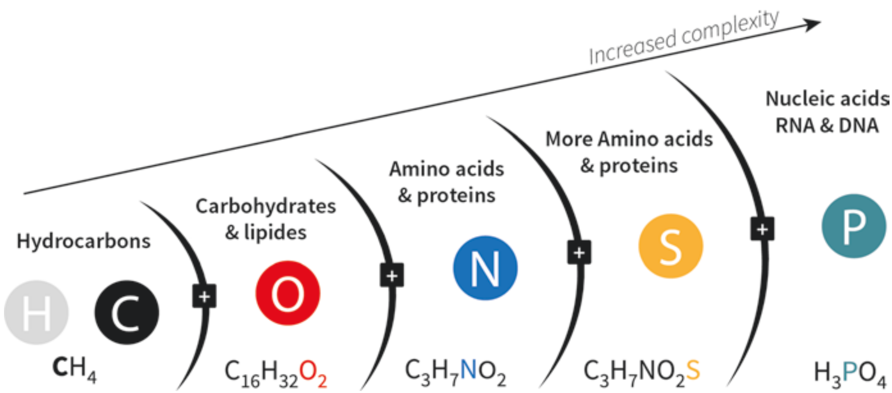

Fig. 3.5. The six elements and how they contribute to the families of organic compounds

for life significantly easier. As an example, within the plumes of Enceladus, four of these elements have already been detected, the CHNO elements, leaving just P and S undiscovered at present.

Food Sources

Now that we have been introduced to the building blocks of life let us see how life sustains itself.

On Earth, light and inorganic chemicals capable of undergoing a chemical reaction provide the two fundamental energy sources for life. (Once organic matter is produced, it becomes the third source of energy as represented by the food chain.) Regardless of their origin, at the heart of all energy sources, we find the electron, the negatively charged subatomic particle. A chemical reaction, called redox-reaction, forces one electron or more to be transferred from one atom to another, and it is this transfer that unleashes energy, making it an energetically favorable chemical reaction. Some of the most common reactions are the Calvin cycle in photosynthesis, hydrogen oxidation, methanogenesis, sulfur reduction and oxidation, iron and manganese reduction, denitrification, and aerobic respiration. (Note that a lot of energetically favorable acid-base reactions are also present in these processes.) Rarer redox-reactions have been found to use uranium, copper, arsenic selenium, and lead.

It is worth remembering that before hydrothermal vents were found at the bottom of our oceans in 1976, life was thought to be entirely dependent on the Sun's energy, enabled by the photosynthesis process. Places where the sunlight was non-existent, such as on distant planetary objects or deep within Earth's crust, was considered off limits to life. The discovery of deep-sea vents represented a breakthrough that turned this idea entirely on its head as biologists now consider these habitats to be conducive to life, not inhibiting it.

Indeed, in the environments created by these vents, a diversity of life thrives undeterred by the superheated plumes gushing out of chimney-like structures. The waters saturated in toxic chemicals and heavy metals can reach up to 250–400 °C and feed rich mats of microorganisms coating the vents. Deep-sea hydrothermal vents are known to support remarkably diverse microbial associations, as thousands of new kinds of marine microbes have been discovered. Clams, snails, and mussels graze upon these mats and become prey for shrimps, anemones, and crabs, who in turn feed bigger crabs and fish as well as octopi. Within such ecosystems, referred to as hydrothermal vent communities, over 300 species of animals have been found, mostly living nowhere else on the planet. Once a vent stops being active, through earthquakes, for example, the microorganisms perish. The rest of the fauna either migrate to a new vent or die as well.

Forming the base of this food chain are the hydrothermal microorganisms (bacteria or archaea) capable of surviving in absurdly hot temperatures. One of these exceptional organisms, Methanopyrus Kandleri, found around chimney walls, can withstand temperatures of up to 122 °C – a record no other organism has beaten yet. But what made these life forms genuinely alien to the biologists at the time was their capacity to harvest chemical energy from the minerals and chemicals that belched out from these vents – a process known as chemosynthesis (as opposed to photosynthesis). Within these vents, life has learned, among other things, to transform hydrogen sulfide, a very poisonous and corrosive gas spewing out from the cracks, into sulfur by causing a redox reaction, thus creating new compounds and energy.

Since the deep-sea vents discovery, many chemosynthesis ecosystems have been found around the world, such as in cold seeps (seafloor depressions, mud volcanoes, gas vents, and brine lakes) or deep within the oceanic crusts where no oxygen or light is available. As long as water is in contact with the rocky material and a heat source is present, life seems to gain a foothold.

Therefore, rocky material (Silicates) is essential for life to sustain itself. For that reason, it is crucial to understand where the rocky material is located within a planetary object. In big moons massive enough to have undergone differentiation, such as Europa or Ganymede, rocks tend to be concentrated within rocky mantles (also known as a silicate mantle). In smaller objects such as the asteroid Ceres, differentiation might not have happened to its fullest, resulting in regions where rocks and ices will be mixed up.

This simple, yet crucial, fact has significant consequences for the possibilities of life existing in subsurface oceans. If a body of water lying within an icy moon is not in direct contact with the rocky mantle (or with significant amounts of rocky material), the minerals and chemical reactions required to fuel life will not be present, making the characterization of an ocean world's interior structure key for assessing its habitability.

Ironically, there can be too much of a good thing, as some icy moons contain so much water that the intense weight at the base of their water mantles force liquid water to change into a high-pressure crystalline form of ice, and will consequently, seal off a subsurface ocean from the vital rocky mantle below. In effect, the subsurface ocean will be contained between two layers of ice: the icy crust on top and the icy mantle at the bottom. With no apparent source of minerals to feed a possible life living in these entrapped global oceans, life will struggle to take hold.

Or will it? Recent studies seem to indicate that this might not be entirely the case, as we shall see in Chapter 4, where we investigate Ganymede's massive ocean mantle in detail.

Europa on the other hand has a relatively thin layer of water mantle (200 km) resting on top of its large rocky mantle. Even though the pressures encountered at the bottom of this liquid mantle are formidable (as a reminder, Earth's average ocean depth is only around 3.7 km), they aren't enough to form a hard layer of ice at the base. In this context, the surface areas where rock is being exposed to liquid water are extensive. In addition to the vast seabed, many cracks and fissures will most likely be present on the oceanic floor, allowing water to penetrate (sometimes deeply) within the rocky mantle. Relatively warm fluids will flow within the rock fractures, and given the right conditions, will likely bring about serpentinization, a low-temperature process that alters minerals such as olivine (made of magnesium and iron). On Earth, when olivine is exposed to seawater, mineral components in the olivine (forsterite and fayalite) undergo an exothermic reaction that produces hydrogen gas and heat. The hydrogen atoms can then be used as fuel for life. That is why scientists got excited when they found hydrogen in the plume of Enceladus. If we transplanted microorganisms on Earth into a subsurface ocean where serpentinization occurs, they would survive. (This is one reason why strict biosecurity protocols are required for space missions that venture close to Europa or similar objects.)

Even so, concluding that subsurface oceans have conditions that are seemingly compatible with life is very different than claiming that it can arise there in the first place. What life requires to come into existence is still a matter of great debate within the biological sciences, and even though robust theories have been proposed, no consensus has been found yet. Some scientists strongly back the deep-sea hydrothermal vents, where serpentinization occurs, as the ideal habitat for life to appear, whereas others suggest that pools of freshwater or hydrothermal volcanic fields located on Earth's surface (such as geysers and hot springs in Iceland and Yellowstone National Park) are more likely habitats.

For example, a paper entitled "Can Life Begin on Enceladus? A Perspective from Hydrothermal Chemistry," published in 2016 by David Deamer and Bruce Damer, researchers in biochemistry and biomolecular engineering, both at the University of Santa Cruz, suggests that life may require cycles of hydration and dehydration in environments similar to hydrothermal fields located on the surface of a landmass where an atmosphere is present. If this proves to be correct, Enceladus or Europa would be habitable but lifeless. (Interestingly, such conditions seemed to be present on early Mars, as we have found traces of shallow oceans and hydrothermal activity.)

Given the current uncertainty, three scenarios present themselves.

- Life started from hydrothermal vents at the bottom of the oceans, in which case, whatever life we find in the subsurface oceans of Europa or Enceladus will have a different origin than life on Earth and be different.
- Life started from hydrothermal fields on the surface of landmasses, in which case, we will not find any life in subsurface oceans.
- Panspermia (life piggybacking from one space rock to another) is common in our Solar System, in which case, whatever life we find in the subsurface oceans of Europa or Enceladus will be similar to life on Earth.

As life is a complex, unsolved puzzle, it might be that all three of these scenarios prove to be correct at the same time – life could arise from hydrothermal vents that are situated at the bottom of the sea as well as on the surface of landmasses and also get reshaped by cross contamination. With this in mind, the view taken by this book is that if a subsurface ocean proves to be habitable, then life might have arisen from it.

The next question we will be faced with is when, exactly, could it have happened?

Time and the Complexity of Life

We have seen throughout this chapter that life requires liquid water, organic compounds, and energy sources to generate heat and provide nutrients.

Once these conditions are met, how long does it take for life to start? Ten million years? A hundred? This is a hard question to answer given our lack of evidence on what exactly gave rise to life on Earth in the first place. Scientists have nevertheless been delving deep into the blurry past of our genesis, where much uncertainty remains, and a clearer yet still fuzzy picture has started to emerge following recent discoveries.

After an intense period of bombardment by asteroids and other space rocks, Earth formed around 4.6 billion years ago with the rest of the Solar System, thus starting the Hadean era, the first geological era of our planet, which lasted a little over 500 million years. Earth was still very hot as it had absorbed enormous energy from accretion and the abundance of short-lived radioactive elements. The surface was mainly composed of molten rocks, and an atmosphere was slowly starting to appear due to the existence of volatiles. During the Hadean, our planet would be pummeled occasionally with rocks from space, but nothing compared to the sheer intensity and scale as the initial accretion period. That is, except for two catastrophic events: the formation of our Moon and the Late Heavy Bombardment phase.

The formation of our satellite is still poorly understood. Some theories put the event at just a few tens of millions of years after the formation of our planet, while others place it at 150 to 200 million years, still very early on in geological and life-forming timescales. Also, it was assumed that the Moon was formed due to an impact on Earth by a single object with a mass similar to Mars; however recent studies seem to refute this model and instead support the idea that dozens of lesser impacts (one to ten masses of the Moon) might have done the trick. Regardless which theory is right, this event would have turned a cooling Earth into a state of fiery chaos and wiped the slate clean.

There was also a period of Late Heavy Bombardment, which occurred at around 500 million years (4.1 billion years ago) after Earth's formation and lasted for hundreds of millions of years, and as its name suggests, inflicted much devastation to our planet's young surface.

For that reason, illustrations of this era often depicted it as a hellish place where bright red lava flows spewed out on a dry and desolate landmass. No one seriously considered that life could appear in these conditions, let alone survive enough time to create a long chain of descendants.

For many years, the first tangible signs of life found were embedded in ancient rocks in South Africa and Australia as microfossils showing cell-like structures. These rocks have been dated at 3.5 billion years old, in the Paleoarchean Era, well after the end of the Hadean Era. Before this period, no signs of early life could be uncovered. Actually, no rocks dating from the Hadean Era could be found, making any claims about this tumultuous period challenging to validate. Nevertheless, it was understood that life couldn't possibly have formed during the violent Hadean Era and that once the dust had settled and the conditions were right, it still took hundreds of millions of years for life to arrive on the stage.

Life was thought to be picky and slow. In other words, it was rare.

However, as is often the case in science, fresh discoveries have forced us to re-evaluate this traditional view. In comes the zircon, a tough mineral with a cool name. Preserved deep within sandstone rocks in western Australia, scientists have found tiny grains of zircon that have been dated as the oldest fragments on Earth ever to be discovered, at 4.4 billion years old, providing a unique window into the Hadean Era before the Late Heavy Bombardment of 4.1 to 3.8 billion years ago. Given the inherent difficulties in interpreting this discovery due to our lack of knowledge of the Hadean Era, there has been much debate as to what these zircons can tell us. Some scientists have proposed that the elements trapped within the crystals reveal a more peaceful period, where a vast water ocean prevailed. Far from the apocalyptic vision we once had, our planet might have cooled down earlier than initially suspected, making it a more hospitable environment for early life. Such a theoretical event is called the Cool Early Earth (also known as CEE). Others have challenged this interpretation, and the debate as to what these oldest zircons can tell us still goes on.

Furthermore, younger zircons, found in western Australia and dated at 4.1 billion years old, contain graphite flecks that could have a biological origin. If this turns out to be true, this would reveal a more hospitable environment, although once again other non-biological interpretations have been put forward.

More promising are the telltale signs found in some of the oldest rock formations on Earth in Isua, Greenland. These have shown intriguing similarities with what appears to be fossilized stromatolites, bulbous formations of sedimentary grains built layer upon layer by bacteria. We know stromatolites well as they can still be found today in extremely saline lagoons. Since these structures were the result of a community of microorganisms displaying some complexity, life would have needed to start much earlier. The Isua rocks are dated at 3.8 billion years old, which if the interpretation of stromatolites is correct, pushes the emergence of life millions of years earlier. Recent studies have also proposed that tube-like structures similar to those found in hydrothermal vents might have been discovered in rocks that are 3.77 billion years old as well as in the Isua rocks.

Although it might appear that life was everything but picky and slow, it is important not to get too carried away with these recent discoveries, as much is still contentious. Trying to deduce the telltale signs of life in material that have been subjected to billions of years of physical and chemical processes can be misleading.

Recently, a novel approach on this topic has brought up new insights that might support the interpretations above. By analyzing DNA databases of thousands of modern species, a new line of investigation called "molecular clock analysis" can trace the earliest points at which specific sequences have been expressed by ancestral cells. Studies using this tool have already suggested that the first animals emerged 1.2 billion years ago, several hundred million years earlier than the oldest fossils found and that eukaryotes (cells containing a nucleus) could have made an appearance much earlier than expected at around 2.3 billion years. Some scientists are now using this tool to go even further back in time to estimate when life first appeared and preliminary results have put it at around 4 to 4.1 billion years ago, which seems to support the recent fossilized discoveries. Although there is still much to be confirmed it does look that we are moving away from the idea that life was slow to get going. Still, time is crucial, and some astrobiologists list Enceladus below Mars, Titan, and Europa for the likeliest places where a second genesis might have occurred based on the belief that its habitable zone is short-lived.

There is as well the intriguing idea presented earlier that life might not originate from our planet at all but was instead delivered by asteroids and other space rocks. Referred to as the Panspermia theory, this idea implies that we might be descendants of life forms that initially started elsewhere such as in the ancient oceans of Mars, Venus or maybe even deep within Ceres' interior. Regular impact events threw pieces of crusts from Mars or Ceres and carried hypothetical organisms living on it into space only to return to Earth as meteorites. This could have been done frequently enough for life to start as soon as it could.

Regardless of where life originated, the most conservative view is that it requires more than half a billion years to appear once the conditions are right, while the most optimistic view proposes that life needed less than 10 million years to get started. At this point in time, it is anyone's guess as to which side more accurately reflects the reality, and we could do worse than suggesting meeting halfway at 250 million years.

What we do know, though, is that complex life forms took a very long time to appear. Precise estimates will vary depending on sources; nevertheless, they all present the view that after single cells emerged within a liquid environment, it took a staggering 2 billion years (more or less) to evolve into complex cells (Eukaryotes) and roughly another half a billion years to organize themselves as multicellular organisms (e. g., plants or bugs). That life on Earth needed 2.5 billion years to create a modest worm wriggling in a sandy seafloor suggest the need for geological time spans in the creation of complex life forms (the presence of an oxygenated environment seems to have helped as well), although the dangers of focusing on one sample only (life on Earth) in extrapolating life's capabilities are evident. It might very well be that life in subsurface oceans can't occur at all due to a missing set of circumstances that we are not yet aware of. The contrary might be true as well, and complex fish-like life could be thriving in many oceans (although studies tend to suggest that not enough energy is available in subsurface oceans to sustain the energy demands of complex creatures, no matter how romantic the concept might seem). The only way to find out is to explore these worlds.

In this chapter, we introduced why carbon-based life forms require liquid water, organic chemistry (with rocks), energy as a heat source and long periods of time (albeit this is still being debated). It is an exciting possibility that, within the context of subsurface oceans, these four attributes are thought to be present in some icy moons and dwarf planets of our Solar System.

In light of this, each ocean world candidate will be reviewed in detail and their habitability assessed whenever possible against these attributes. We will encounter the five icy moons for which the presence of a subsurface ocean has been confirmed, the four planetary objects (two moons and two dwarf planets) that most likely have a subsurface ocean yet are still waiting to be confirmed, and the numerous other objects that could theoretically host a subsurface ocean (now or in the past) but for which there is little evidence of it at present.

For each icy moon and dwarf planet, we will try to answer questions such as: What are the energy sources involved? What is the composition of the liquid mantle? How cold is the ocean? Are organic compounds present on the surface or in the liquid mantle, and if so which ones? Is liquid water directly in contact with the rocky material? How old can the ocean be? In reviewing the answers to these, questions and assessing other characteristics, we will make educated guesses as to which ocean world candidate should be the next target for extra-planetary life-detecting missions in the coming future.

Now that we have gained a better understanding of the origins of water within our Solar System and the conditions for life to emerge from it, our journey through our Solar System can finally begin. It is time to strap our harnesses and inform mission control that we are ready for lift off.

Part II
Confirmed Ocean Worlds

> "Where there's water on Earth, you find life as we know it. So if you find water somewhere else, it becomes a remarkable draw to look closer to see if life of any kind is there, even if it's bacterial, which would be extraordinary for the field of biology."
>
> – Neil deGrasse Tyson

In this part, we review in detail the five moons that harbor vast subsurface oceans under their icy crust. Some are limited in their ability to support life while others boast the most promising environments for life to arise in our Solar System after Earth. All five are fascinating objects in their own right. Let us visit them one by one.

4. Ganymede

Initial Approach

To visit Ganymede, we need to get up close to the king of planets, Jupiter. On our approach to the Jovian system, we encounter a bow-shock wave where the solar wind is deflected by the planet's magnetosphere, the largest and most dominant in our Solar System after the Sun. Jupiter requires respect. We are also greeted by the Galilean moons. These objects hold together a list of superlatives in our Solar System: the biggest moon (Ganymede), the most geologically active moon (Io), the object with the smoothest surface (Europa), the most densely cratered moon (Callisto) and the only moon to have a magnetosphere (Ganymede).

Io, the closest to Jupiter, is spewing its guts out into open space, tidal heating at its most formidable. Although it is a geologically fascinating place to visit, there are no subsurface oceans there, so best not get near it. The three moons located further out; Europa, Ganymede, and Callisto, will be where we will spend the next three chapters. As an ensemble, they form an excellent case study of subsurface oceans. Europa, the most promising in terms of habitability, contrasts well with Callisto, the least active of the three, while Ganymede, full of potential, lies in the middle.

Ganymede Through the Ages

The first observation of Ganymede might have occurred more than 2,000 years ago in the Far East when, in 385 B. C., a Chinese astronomer named Gan De noted in his records a bright companion to Jupiter. This claim was put forward in the 20th century by Xi Zezong, a prominent Chinese astronomer, as proof that it was the Chinese who first observed the Jovian moon. Gan didn't make any assumptions as to the exact identity of what he was seeing, although, surprisingly, he recorded that it had a reddish tint, which

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isn't Ganymede's color, raising doubts that he observed the moon. To his credit, Gan De made very detailed astronomical observations throughout his life, and there have been various reports in the past of naked-eye observations of a "star" next to Jupiter.

If it were not for its proximity to bright Jupiter, Ganymede (and the other three Galilean moons) would be visible in the night sky. Indeed, during Jupiter's opposition, when Earth passes between Jupiter and the Sun and is, therefore, closest to the Jovian system, Ganymede has a magnitude of 4.5, which puts it well within the range of the dimmest object the human eye can detect (at magnitude 6). The key is to block the intense brightness of Jupiter, which induces spikes and flares in the human eye (a natural optical illusion), hiding any light reflected from the satellites. Gan De used this exact method; his records show that he occluded Jupiter behind a tree limb.[1]

Regardless of who saw Ganymede for the first time with the naked eye, it was Galileo Galilei who was the first to point a telescope towards the Jovian system on that pivotal night of the 7th of January 1610. In doing so, he was the first person to recognize Ganymede as a moon of Jupiter, although there has been some dispute regarding this as Simon Marius, a German astronomer contemporary to Galileo, claimed to have discovered the moons a few months earlier in 1609. Unfortunately for him, as Marius kept no records of his observations, history sided with the Italian astronomer instead.

Nevertheless, we have to thank Marius for utilizing mythological characters for the naming conventions of the moons. (Let us not forget Johannes Kepler, who convinced Marius that his original idea of naming Ganymede the 'Jupiter of Jupiter' was probably not the wisest idea.) Galileo, on the other hand, wanted to name the moons after his patron, Cosimo the Medici, the first of the famous Medici political dynasty, but finally settled on using Roman numerical values such as Jupiter I (Io), Jupiter II (Europa), Jupiter III (Ganymede) and Jupiter IV (Callisto). These became the

[1] Next time you find yourself far from light-polluted areas and Jupiter is high up in the sky, why not repeat the observation that Gan De did 2000 years ago and hide the planet behind a thin object (e. g., a branch) in order to see if you can detect the faint light of our Solar System's biggest moon. Make sure you check the real position of Ganymede afterward with reference material to confirm your observations, as Jupiter could also be passing close to a faint star that might be confused with the moon.

common names of the moons until they were finally replaced by Marius's naming convention in the early 20th century. To this day though, you might still see the moons referred by their Roman numerical values.

As soon as it was discovered, Ganymede was recognized as one of the biggest, if not the biggest, of the known moons in our Solar System. With a radius of 2,634 km, it is the eighth biggest object in our Solar System (excluding our Sun), closely followed by the Saturn's moon Titan (2,575 km), the planet Mercury (2,439 km) and Callisto (2,410 km).

Despite this massive size, very little was known of Ganymede before the advent of the Space Age and the flybys of the Pioneers and Voyagers in the seventies and eighties. Until then, astronomers were constrained by the technical limitations of the time and the vast distances that separated Earth from Ganymede. It was still just a bright speck of light in the world's most powerful telescopes. However, astronomers had ground-based observational tools at their disposal that would allow them to characterize Ganymede and other distant objects. These included spectroscopy, photometry, radiometry, polarimetry, and radar.

Spectroscopy takes the light emitted or reflected by a celestial body and splits it using a prism or similar optical device, thus providing the entire electromagnetic profile of the light, also referred to as the spectra. This profile will contain patterns (of absorption and emission bands) that can be compared with similar patterns created in laboratories and then interpreted into surface and atmospheric characteristics.

In the 1950's and 60's, spectroscopy had finally reached the level of maturity required to analyze the spectra of the Galilean moons, and early spectroscopic observations detected patterns of water-ice on Ganymede and Europa, correctly inferring that water was the main constituent of these moons' crust. It was also concluded back then that the moon's high albedo was caused by 'coherent backscattering in fractured ice'; in other words, the moon was most likely covered with ice. (Europa was thought to be even icier due to an albedo twice as strong). Thanks to unabated technological improvements throughout the following decades, astronomers continued using Earth-based spectroscopy to gain more insight on Ganymede's surface composition and are still doing so today, as a recent study using this technique identified molecular oxygen and hydrated silicates composed of iron on Ganymede's surface.

Photometry is another tool used by astronomers. It measures the amount of sunlight reflected by a surface or atmosphere – also referred to as albedo. For example, water-ice has a high albedo, as it will reflect much of the sunlight back into space, while liquid water traps more light and will have a lower albedo. By using models, we can induce characteristics of a planetary object such as the existence or not of an atmosphere, the degree of topographic roughness (is the surface hilly or flat) or the nature of the material on a surface. Furthermore, in some circumstances, it is possible to observe a planetary body throughout its entire rotation showing albedo (and sometimes color) variations, suggesting different geological terrains across the whole surface. This technique has revealed surface diversity on Europa, Io and Dione. Ganymede didn't show much variety.

Photometry is also used when a celestial body occults another body, in this case, when a moon passes in front of a star. The light captured at successive intervals during the occultation can reveal albedo variations from the surface, providing accurate measurements of the diameter or detecting an atmosphere, as was the case for Titan or Triton. Unfortunately, the attempts to identify Ganymede's more tenuous atmosphere using this technique provided ambiguous results in the 70s that would only be resolved in 1995 with the Hubble Space Telescope. The giant moon does have an atmosphere, but it is a very faint one, leading astronomers to refer it as an exosphere instead.

In addition to photometry and spectroscopy, radiometry is the study of the Sun's heat being absorbed or remitted by planetary objects. In essence, it measures the temperature (which is the radiation at thermal wavelengths). The critical factor here is the distance of the object from the Sun. This distance allows astronomers to theoretically calculate the mean temperature of an object when the absorbed radiation is equal to the emitted radiation. An actual temperature measurement that deviates from this mean can provide some insights into the studied object.

As an example, it was already known, by using this technique, before any spacecraft had visited them, that Titan and Io were radiating more heat than expected. The former was due to the greenhouse effect from its thick atmosphere, while the latter was from volcanic activity. Even better, an ingenious method used with radiometry is the measurement of heat loss as a moon is being eclipsed by its main planet. This is called eclipse radiometry. A rapid heat loss from the surface during an eclipse is indicative of a porous surface that has difficulty in trapping the heat, which is usually created by heavy meteor bombardments. When this technique was applied to the Galilean moons in the early 1970's, it was found that both Ganymede and Callisto lost heat rapidly, leading scientists to presume that these two moons had heavily cratered surfaces. This would be confirmed later on by spacecraft.

Polarimetry, another earth-based observational tool, measures the change in the polarization of sunlight being reflected by a planetary surface. The polarization will vary due to the shape, size, and other physical properties of atmospheric or surface particles. The investigation of Titan's atmosphere has greatly benefited from this technique throughout the decades.

Finally, we have radar observations in which radio waves are targeted towards an object, and the echo is received back. The analysis of this signal can provide information on the diameter of the object as well as some insight into the surface composition. Studies conducted in the 1970's using the Arecibo observatory in Puerto Rico accurately measured Ganymede's diameter and also determined that its surface presented highly diffuse scattering, implying a rough and uneven surface.

As can be seen, these Earth-based observations did provide insights on what to expect from Ganymede, yet with no surface images available; astronomers could only imagine what an ice-covered moon would resemble.

There was therefore great excitement when, in 1972, NASA launched *Pioneer 10,* the first mission to the outer planets, with the aim to explore the Jovian system and do a close flyby of its biggest moons. Being true to its name, the *Pioneer 10* spacecraft had a number of firsts that have been hard to beat ever since: it was the first vehicle placed on a trajectory to escape the Solar System and venture into interstellar space; the first spacecraft to fly beyond Mars; the first to fly through the Asteroid Belt; the first to fly past Jupiter; the first to use an all-nuclear power engine to provide energy to its electrical systems; and the first human-made object to fly beyond the orbit of Neptune, the outermost known planet in our Solar System.

And so, in December 1973, the spacecraft proceeded to the Jovian system, made its closest flyby of Ganymede at 443,000 km, and managed to take two fuzzy pictures of the moon. The quality wasn't optimal, due to the limitations of the spacecraft's rudimentary optical instruments, and very little could be deduced with certainty, but light and dark surface patterns could be implied. We had to wait until 1979 when the more capable Voyager spacecraft sent back pictures revealing a genuinely intriguing world as can be seen in Fig. 1.4 in the first chapter. Upon reviewing these, scientists concluded that the dark areas represented ancient surfaces covered with numerous craters while the lighter ones showed surprising signs of younger (but still old) geological activity with its grooves and ridges. It seemed that the newly discovered tidal heating process had visibly altered the surface of Ganymede but to a much lesser degree than what was observed on Io and Europa.

Between 1996 and 2000, higher resolution images were provided by the Galileo spacecraft, which made six close flybys of the moon. During its closest flyby, the second, the probe passed just 264 km from the surface, returning the most detailed surface images we have of the moon. It is worth mentioning that in addition to imaging instruments, Galileo, the Voyagers, and Pioneers, we also had remote sensing instruments such as spectrometers and photometers, which provided much insight into the surface composition of the moon, which we will detail below. Since then various interplanetary missions have passed through the Jovian system (Ulysses, Cassini-Huygens, New Horizons and currently Juno), yet none have come as close to Ganymede as the Galileo mission did in the late 20th century.

Ganymede's Story

Ganymede, along with the other Jovian moons, formed 4.5 billion years ago from the disk of dust and gas leftover after the giant planet's formation. Due to the disk's decreasing density the further you go out from Jupiter, the more the mass of the Galilean moons decrease outwards as well. The moon Io, the closest to Jupiter, has a density of 3.528 g/cm^3, while Europa, the second closest, is 3.014 g/cm^3; Ganymede, the third closest, is 1.942 g/cm^3, and finally the furthest and least dense is Callisto with 1.834 g/cm^3. As a comparison, Earth's density is 5.5 g/cm^3, which is typical of a rocky planet. Since the density of water is 1 g/cm^3, we can already conclude that Ganymede and Callisto must be composed of a significant amount of water to bring their densities to such low values. And indeed, models currently estimate that water forms 46 to 50% of Ganymede's total mass. That is a significant amount of water for a planetary body that is bigger than Mercury.

Another consequence of the disk's decreasing density is that moons formed away from the giant planet take much longer to clear their orbits and reach their final masses than moons closer to Jupiter. Thankfully, for Ganymede, its distance from Jupiter was still close enough to allow it to form within ten thousand years, relatively fast enough for the moon to retain a substantial amount of primordial heat trapped in its core. Being closer also meant that the moon accumulated additional accretion heat, as the strong gravitational attraction of Jupiter substantially increased the impact velocities of any debris coming from outside the Jupiter system.

On the other hand, Callisto, Ganymede's neighbor lying further out, took much longer to reach its final mass, therefore losing much heat in the process, as well as experienced smaller velocity impacts containing less energy. This will have a significant effect on Callisto, as will be seen in the following chapter.

Returning to Ganymede, it is thought that the energy from the primordial heat, as well as the decay of the radioactive elements present in its rocky constituents, were sufficient enough for the moon to undergo differentiation – the separation of the different components into distinct layers. Also, some researchers have recently speculated that Ganymede might also have acquired additional heat due to the tidal forces it experienced after its formation.

As you might recall from the first chapter, Ganymede's current orbit has eccentricity, although it is tiny at 0.0013 compared to Io with 0.0041 or Europa with 0.009. This leads to a negligible amount of energy produced and minimal tidal heating. It is thought, though, that the orbital eccentricity was much greater in the moon's past, as the three-body resonance with Io and Europa was being shaped, generating significant tidal heating. Once Ganymede was firmly locked into the resonance we see today, tidal heating had less of an impact. If that wasn't enough already, recent studies have also speculated that Ganymede could have benefited from additional amounts of energy due to high intensity cratering in the Late Heavy Bombardment, although this is still subject for debate.

Regardless, we now know that Ganymede is fully differentiated with a solid inner core made of iron, an outer core of liquid iron and iron sulfide, a silicate mantle (where radiogenic heating is still occurring) and a thick outer layer of water in liquid and ice phase estimated to be around 800 km thick and containing up to 39 times as much water as our home planet. The exact way ice and liquid water is divided within the mantle is still up for debate, as various models have been put forward depending on the assumed composition of the water and other elements within the core, of which a few are presented here later.

Ganymede's liquid metallic core was discovered in the late 1990's thanks to the detection of a magnetosphere by the Galileo spacecraft – a real surprise for planetary scientists. Galileo was equipped with two instruments – a magnetometer, which measures the direction and strength of magnetic fields, and the plasma wave spectrometer, which measures variations in electromagnetic waves in the Jovian environment. At the time the mission was being conceived, both these instruments were selected to investigate Jupiter's large magnetosphere only.

However, when the spacecraft approached Ganymede, the plasma wave spectrometer detected an increase in charged particles by a factor of more than 100 and the magnetometer sensed a sudden change in the magnetic field (increasing by fivefold). Scientists concluded that they had just discovered Ganymede's magnetosphere, a first for a moon. There was only one explanation. Deep within the heart of the moon was nestled a liquid iron core with high electrical conductivity. Such a feature could generate the magnetic fields that were being detected.

Since the moon's magnetosphere is completely embedded within Jupiter's magnetosphere, this is the first case of a magnetosphere within a magnetosphere. Even today, Ganymede is still the only moon known to have a magnetosphere. Thanks to this (and its distance from the giant planet) Ganymede receives 450 times less radiation from Jupiter than Io (36 Sv or sieverts) and 68 times less than on Europa (5.4 Sv).

Surface Features and the Exosphere

Ganymede's surface crust is mainly composed of water-ice. Due to this, there are relatively few big features, such as mountains or high crater rims, as ice isn't strong enough to hold the weight of extensive vertical features.

Apart from ice, many non-water materials have also been detected on the surface, such as salts in the form of magnesium sulfate and sodium sulfate, which might be similar to those found in the salty subsurface ocean. In spite of the fact that the thickness of the icy mantle separating the ocean and the surface is considerable, some scientists have speculated that these surface salts could be the result of brine making its way to the surface by eruptions or through cracks, although such active features have not been detected.

Other non-water materials detected on the surface are: organic materials that were most likely deposited by comets and other space rocks and altered by Jupiter's radiation; hydrogen peroxide, which can be attributed to photochemical reactions on the ice; sulfur, whose origin is Ganymede's neighbor, Io; solid carbon dioxide (dry ice); and clays (mineral structures formed by organic matter and water).

As we have seen in Chapter 1, the surface of Ganymede presents a mix of two distinct terrain types, the dark and bright regions. The dark regions, which is comprise of about one-third of the surface, are ancient and heavily cratered. These contain the clays and other tarry organic materials mixed with the surface ice.

The newer, brighter regions are covered with intricate patterns of long, narrow grooves. These grooves lie parallel to each other in sets that can be hundreds of meters deep and extend far out to hundreds of kilometers, many from north to south. The origin of these grooves is still not fully understood – it could be due to either cryo-volcanism or the remnants of past tidal heating. In both cases, though interior convection would have been the culprit as warm, icy currents deep within the moon's interior would have strained the lithosphere, flexing and cracking the hard icy surface.

Although craters can be observed all over the surface, the darker regions contain a higher concentration, implying that they are the oldest parts of the moon's surface. In fact, Ganymede seems to have undergone a heavy bombardment phase similar to what our Moon experienced around 3.5 and 4 billion years ago, so we assume that the darker regions date around from that epoch. In contrast, the brighter areas are thought to be roughly 2 billion years old. In a way, the darker regions resemble Callisto's heavily cratered surface, while the brighter regions are similar to Europa's active young surface, although the number of craters on Ganymede's bright surface is still significantly higher than Europa's.

In addition to the bright and dark surface regions, polar caps composed of water-frost were detected by the Voyager spacecraft. For many years scientists were intrigued by these features, although it is now thought that Ganymede's magnetic field has a significant role to play. Researchers have suggested that by funneling the highly charged particles into the polar regions, Ganymede's magnetosphere had indirectly modified surface ice into layers of ice crystals, which brightens these areas. Since Ganymede is the only moon in our Solar System to have a magnetosphere, no other icy moon supports similar polar caps of bright water-ice.

Ganymede also supports a very tenuous atmosphere, referred to as an exosphere, and is mainly composed of oxygen. It is not the only moon to have such an exosphere, and its origin is now well understood. Water-ice located on the surface gets broken down by ultraviolet radiation (coming from our Sun) and releases hydrogen and oxygen as gases. The former element quickly escapes into space and gets lost, while the later, more massive oxygen is retained by the moon and forms the main constituent of the exosphere. Astronomers have also been able to detect (through spectroscopy) various gases trapped within the porous icy surface such as ozone (O_3), oxygen (O_2), and some small traces of hydrogen, which are most likely the remnants of the broken down water molecules.

In addition to an exosphere, there are also suggestions that Ganymede should support an ionosphere as well, but conflicting data has prevented confirmation of this.

The Subsurface Ocean and Its Habitability

The existence of Ganymede's subsurface ocean as a distinct liquid water mantle was only confirmed in 2015 thanks to the venerable Hubble Space Telescope (Fig. 4.1).[2]

The clue in the detection of Ganymede's subsurface ocean lies in the effects it has on the moon's aurorae. By observing the moon with the instrument sensitive to ultraviolet, HST detected auroras similar to the ones we see on Earth. Aurorae are formed when the moon's magnetosphere forces high-speed subatomic particles from space to slam into the thin exosphere. The position of these aurorae will be determined by the interaction of Jupiter and Ganymede's magnetic fields. Since we have a pretty good idea how these interactions work, we can predict where the aurorae will be at a given time by using different models of the moon's interior.

Interestingly, the only model that fitted Hubble's aurora observations were not the ones where the moon's water mantle was

[2] It is worth pointing out that some unreliable sources have claimed that Ganymede's subsurface ocean had already been confirmed by the Galileo spacecraft in the late 1990's, but that is false. It was speculated, given the nature of the moon and what had been observed from the surface; nevertheless, it had never been confirmed until the recent Hubble observations.

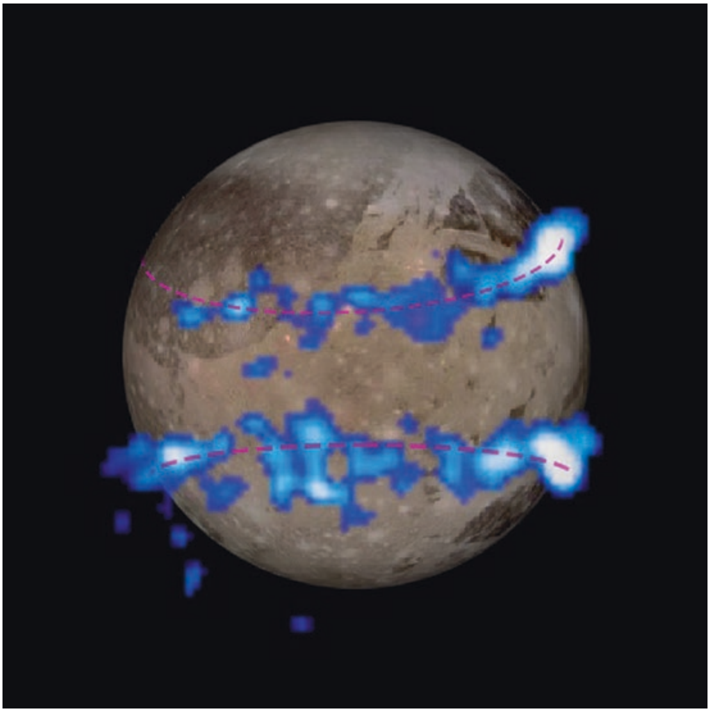

Fig. 4.1. Aurorae on Ganymede. The auroral belts can be seen in blue in this image by the Hubble Telescope. Their position indicates the existence of a salty subsurface ocean. (Image courtesy of NASA/ESA)

entirely made of solid ice but instead had a deep salty subsurface ocean. This is because such an ocean will have its very own magnetic field, albeit a very weak one, which can interact with Ganymede and Jupiter's magnetic field, which in turn influences where aurorae are formed (Fig. 4.2).

It is currently estimated that, to explain the aurora observations, Ganymede needs a globe-circling subsurface ocean that is at least 150 km deep and contains more liquid water than is found on Earth. Also, we know that this ocean has to contain salts, most likely magnesium sulfate and possibly sodium sulfate, as only a salty ocean can create a magnetic field strong enough to influence both Jupiter and Ganymede's magnetospheres. In addition, current models show that the subsurface ocean rests under a very thick icy crust, most likely hundreds of kilometers thick, in effect separating the subsurface ocean from the surface.

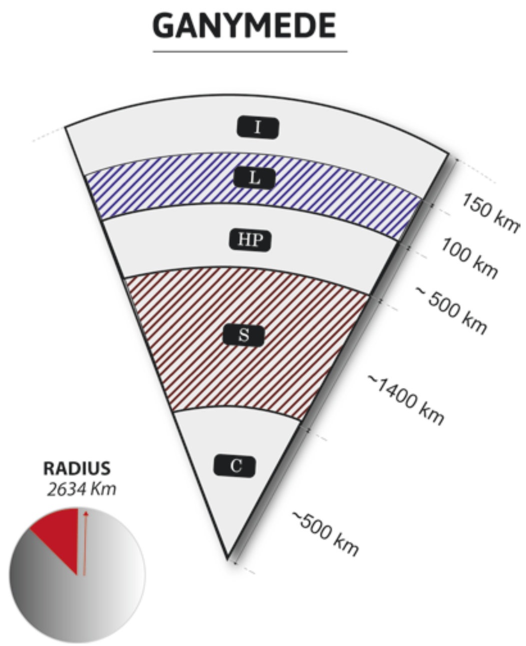

Fig. 4.2. Diagram showing the interior of Ganymede, according to the standard model where the subsurface ocean is sandwiched between two thick ice mantles. The thickness of the mantles is not well known, given the limited information we have on the moon. I Ice, L Liquid, HP High pressure ices, S Rocky, C core. Diagram is not on scale

The observations we have made so far in this chapter holds much promise for the habitability of Ganymede. It has multiple sources of heat (radiogenic heating, primordial heating, and tidal heating), which have continuously warmed up the moon since its inception. It also has a mantle of liquid water in the form of a vast deep and salty ocean circling the globe that has been present as soon as the moon experienced differentiation billions of years ago, more than enough time for life to start. Finally, we have detected organic compounds on the surface that could suggest that these non-ice materials also reside within the moon's interior.

And yet a crucial element is missing – rocks. As you might recall in Chapter 3, for microorganisms to create redox reactions, (through organic chemistry) we need minerals that are found in a silicate mantle or, in this case, the bedrock of the oceanic floor. Is Ganymede's salty subsurface ocean adjacent to a silicate mantle?

For decades now, the standard model of Ganymede's interior accepted by most planetary scientists proposes that the moon's subsurface ocean is sandwiched between the icy shell that forms the crust and another thick layer of ice upon which the ocean rests. This ice layer, in turn, sits on the rocky mantle. Sadly, in this model, rock and liquid water have no chance of interacting.

As unusual as it sounds, the reason why another layer of ice might exist under a subsurface ocean is due to the unique properties of water when exposed to extreme levels of pressure and temperatures. Let us explore this in more detail as this a recurrent theme throughout the models proposed for the ocean worlds.

Temperature and pressure have a significant influence on whether a chemical will exist in a liquid, solid, or gaseous state at any given moment. They directly affect how molecules arrange themselves. In a typical room, such as the one you are sitting in now, where the temperatures and pressures encountered are adequate for our existence, water is in its liquid form. As we all know, it becomes solid (ice) if its temperature is lowered below 273 Kelvin (0 °C or 32 °F) and gaseous (steam/vapor) if its temperature is raised above 373 Kelvin (100 °C or 212 °F) at one atmosphere of pressure.

Whenever water turns into ice, you might think that it exists in only one crystalline form; however, subjected to high pressures and varying temperatures, water-ice can exist in 17 (and maybe more) separate forms known as phases, each one being labeled by a Roman numeral in the order of their discovery. The existence of so many forms of crystalline water-ice is due to the unique properties of water, which no other molecule can match.

Understanding the molecular structure of water (H_20) is critical in understanding its chemical behavior. The oxygen atom carries eight pairs of electrons, all repelling each other regardless if they are shared with other atoms or not. In a water molecule, two pairs of electrons bond with two hydrogen atoms, while the other two pairs of electrons are free. In effect, there are four 'things' sticking out from the oxygen atom, the two hydrogen atoms and the two pairs of electrons from the oxygen atom. The most stable arrangement for this configuration is the tetrahedron, with the oxygen atom at its center and the pairs of electrons furthest apart from each other.

This tetrahedron configuration forms a polar molecule because the oxygen end of the molecule is negatively charged, while the hydrogen end has a partial positive charge. In proximity to another water molecule, these charged ends form hydrogen bonds with each other; the negatively charged pole from one water molecule bonds with the positively charged pole from another and vice versa. The strength of these bonds will depend on the physical properties of the environment in which the water molecules find themselves. They will either form loose bonds (liquid), strong bonds (ice), or little to no bonds (gas).

In its solid ice form, the water molecules contain hydrogen bonded in a crystalline form. However, in this tight configuration, electron pairs from nearby molecules will repel each other and continuously push the molecules apart, creating a need for the molecules to find a stable crystalline form according to the physical properties of the environment. And so, whenever the pressure or temperature conditions change, the water molecules, always seeking for stability, might shift from one crystalline form to another. These forms are known as the 17 ice phases.

By far the most common of these phase found on our planet is called 'Ice Ih,' with the letter I standing for one (Roman numeral) and h for holding for the hexagonal shape of the crystal. This is the one that falls from the sky and brings endless joy to children, as it is ideal for building a snowman. Ice I is the least dense of the water phases, which is why ice cubes float in your drink. (As the pressures increase and the crystalline structures become more compact, the subsequent ice phases become denser and will sink.)

Another form of ice I present on Earth is called 'Ice Ic,' which has a cubic crystalline shape, the letter c standing for a cube. This phase is found in clouds. If pressures increase to 300 MPa and the temperature is at 198 Kelvin, ice Ih changes into another crystalline form referred to as ice II, which has a rhombohedral crystalline form. If ice II gets warmed up to 250 K, it turns into ice III, which has a tetragonal crystalline form. As the physical conditions change, new ice phases will be formed until ice XVI, with each phase having unique properties.

All seventeen ice phases have been created in laboratories on Earth by varying the pressure and temperature to which water is exposed to. We can even create forms of water-ice that exist in temperatures above the boiling point, such as ice X. This is done by compressing the ice at extremely high pressures, compelling it to stay stable regardless of the temperature.

In space, ice doesn't have a crystalline form, as extremely low temperatures forces water-ice to form too quickly. Instead, while still being solid, it is referred to as amorphous ice, as it lacks a crystal structure (it was given no Roman number). This is by far the most common form of ice, as it is found everywhere from interstellar dust to the surfaces of comets, asteroids, planets, and moons.

Returning to Ganymede, the standard model of the moon's interior estimates the global subsurface ocean is 100 km thick and lies under a 150-km icy crust. (As a comparison, the deepest point in our ocean is 10.9 km). The ice phase of this crust is Ice Ih. Models predict that the immense pressures, generated by the ice crust and the subsurface ocean totaling a layer of water 250 km thick, are enough to coerce water under the subsurface ocean to form the ice phase known as 'Ice VI,' a tetragonal crystal. Therefore water reverts to an ice phase not because of the low temperatures encountered in this region but due to high pressures. Unfortunately for us, this results in the presence of an extremely thick mantle of hard ice lying between the salty subsurface ocean and Ganymede's silicate mantle, which prevents any interactions between the liquid water and the rocks and limits any prospect for life as we know it.

Undeterred, scientists have published papers recently showing that magmatic events (such as the movements of hot liquid rocks within the silicate mantle) occurring at the interface between the rocks and the Ice VI mantle could generate pockets of water melts that slowly rise through the high-pressure ice (HP), carrying chemical nutrients and salts to the ocean above. Various characteristics such as the thickness of the ice mantle, the amount of heat exchanged, and the viscosity of the HP ice will affect the likelihood of this process; yet, it does show that HP ices are probably not a barrier to the transport of materials generated by water-rock interactions. They certainly complicate things, though. It might be then that Ganymede's subsurface ocean receives 'drip-feeds' of volatiles and salts from below that would improve its prospect of being a habitable environment. Subsurface oceans sandwiched between two ice mantles might not be as isolated as we initially thought them to be.

Further hope came from a study in 2013 driven by Dr. Steve Vance from Caltech's Jet Propulsion Laboratory. Dr. Vance and his colleagues presented a new model, labeled 'club sandwich,' for the moon's interior that took into account the effects of salt in the water mantles bringing the thermodynamics modeling closer to reality.

What the study suggested is unusual. Ganymede's interior might not be holding a single subsurface ocean layer but instead could be stacked by several layers of ocean separated by multiple layers of ice, hence the sandwich name. These ice layers would each be in different phases depending on the pressures applied to the ice (Fig. 4.3).

The ice crust formed by Ice I would be sitting on a thin layer of liquid water, which itself would be resting on another sheet of ice, this time in the phase Ice III under the form of snow (we will explain what this means shortly). This would in turn also be resting on another thin layer of liquid water, which then would be resting on a layer of Ice V. Also, another thin layer of ocean would separate this layer of ice V to a layer of ice VI further below. At last, a final layer, this time of liquid water would be – hurrah! – resting on the rocky mantle. This model supposes a warm salty subsurface ocean in contact with rocks. In other words; the Holy Grail.

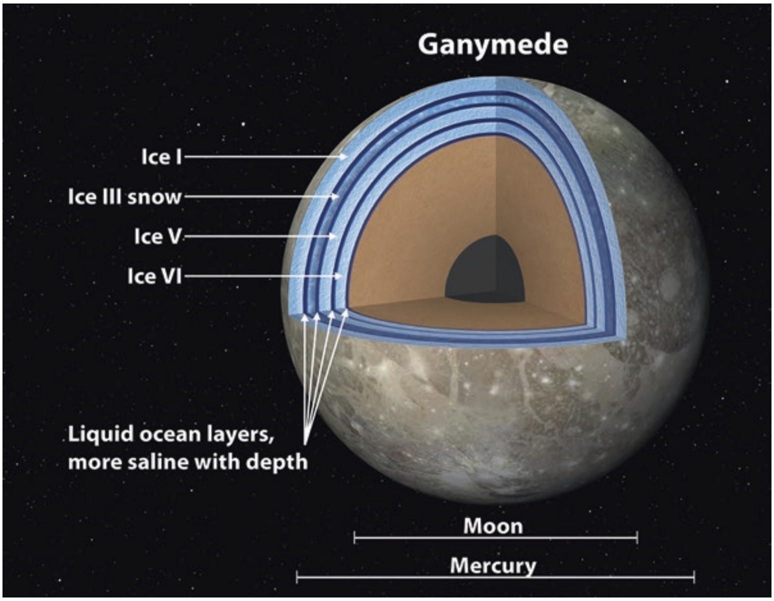

Fig. 4.3. Ganymede's interior as the "club sandwich" model, where multiple layers of liquid water are separated by ices. (Image courtesy of NASA/JPL and Caltech)

Before this new model, previous studies made were deliberately simplified as they didn't take into account the presence of salt within the moon's interior and how it can modify the properties of ice and liquid water. Salt is important, as it increases the density of liquids when exposed to extreme conditions such as those inside Ganymede.

You can make this experiment by yourself. Take a glass of water and add table salt. Contrary to what common sense would assume, the level of the water will decrease. As salt attracts the water molecules, the water at the base of the glass becomes denser, pulling the entirety of the liquid downwards.

In this case, the 'lighter,' less salty, water mantle sits on top while the saltiest and densest water mantle sinks to the bottom, making each liquid layer of ocean more saline with depth. As we go further down, the pressures, temperatures, and densities that can be found at specific depths provide the right conditions for water to turn into ice on multiple occasions, which therefore creates the layering of icy mantles between the liquid mantles.

There is an interesting detail to this model – the emergence of a layer of Ice III in the form of 'snow' between the first and second layer of the liquid mantle. Indeed, ice can appear in cold churning waters such as in the liquid mantle, and when this occurs, salts precipitate out of the water and fall downwards. The leftover 'snow,' being without salt and therefore lighter than the surrounding water, will move upwards, basically snowing upside down.

In this sandwich model, the final layer of water mantle, adjacent to the silicate mantle, is a liquid one – a subsurface ocean. We could reasonably assume that at such great depths, enough heat would be present to induce chemical reactions between the rocks and liquid water, although, given the extreme environment, determining what these reactions are could become difficult.

This model is appealing, but is it conceivable, let alone stable? Can such a multilayered structure last hundreds of millions of years? It seems difficult to answer. The complexities inherent to fluid dynamics make the equilibrium between the different layers challenging to demonstrate at present and may only occur under exceptional circumstances. Additional work is required. Future studies will no doubt provide new insights on the structure of Ganymede's water mantle as mathematical models are refined and new observational data acquired.

In a way, Ganymede has been lucky. It has continuously benefited from the energy generated by primordial and radiogenic heating and most likely also experienced strong tidal heating in its early phase, allowing for a significant melting of the water mantle. Do not be fooled if Ganymede doesn't portray itself as a very active moon compared to its youthful-looking neighbor Europa. The total amount of energy Ganymede holds might not be enough to keep the moon free from old surface craters, but it still offers enough heat to host a warm and extensive subsurface ocean for billions of years.

We are also fortunate, as a new mission aimed at studying Ganymede up close is set for the mid-2030's. Currently being developed up by the European Space Agency, the mission, named JUICE, for Jupiter ICy Moons Explorer, will orbit Ganymede and provide new data for scientists to study. JUICE is presented in detail in Chapter 13.

In the meantime, though, as we consider Ganymede's habitability, we can only make basic assumptions. The standard model, where the moon's subsurface ocean is squeezed between two thick icy mantles, provides a liquid water environment, energy and most probably organic material (although there is currently no evidence for this). As it stands, life as we know it will not thrive in such an environment due to the lack of rocky materials. Nevertheless, this might change if it is regularly fed by minerals and salts from rising pocket melts. Furthermore, as we have seen, the multilayered sandwich model also provides some hope for life in the deepest and saltiest ocean layer adjacent to the rocky mantle.

Regardless of which model is correct, we will most likely never know if any life is present in Ganymede's subsurface oceans due to the extreme depths these are located. We should view this as a blessing since Ganymede is, with Callisto and Titan, one of the most likely locations in our Solar System for future human settlements once humanity has the technological capability to leave Earth for new homes.

Indeed, Ganymede has much to offer: a magnetosphere offering protection from Jupiter's wrath, water in stupendous amounts waiting to be used and converted into hydrogen, a small gravity that is not too strong to make it energetically costly to leave the moon but also not too weak as to make it challenging for its inhabitants, and finally easily accessible minerals (most likely metals) within Jupiter's Trojan asteroids (rocks that share the same orbit as Jupiter). If humanity does step foot there one day, and that is a big if, the subsurface ocean nestled deep inside the giant moon will be completely sealed from the surface, leaving little chance for it to be endangered by human activity.

We shall now leave Ganymede's tarred and fractured icy surface to visit its darker neighbor, Callisto, as this moon also has much to tell.

5. Callisto

Callisto Through the Ages

Callisto is the third biggest moon in the Solar System behind Ganymede and Saturn's moon Titan. As big as the planet Mercury, it nevertheless only has a third of the small planet's mass, as it is mainly made of ices, rocks and metals as opposed to just rocks and metals for Mercury.

As we approach the moon, densely cratered plains are already in full view. Valhalla, a giant impact structure at the heart of many shockwaves deeply embedded within the crust, resembles a planet-scale bulls-eye as the crater radiates its concentric rings for thousands of kilometers (Fig. 5.1).

Upon seeing Valhalla, we cannot help but intuitively feel the immense power generated by the collision of a planetesimal and its effect on Callisto's surface 4 billion years ago, as the solid icy crust stretched and buckled to dissipate the colossal amount of energy generated by the impact.

Callisto, holding the title for the most heavily cratered object in our Solar System, is full of such stories. It is a fascinating world.

Regarding human observations, Callisto shares much of the same history as Ganymede, although there has never been a record of a naked-eye observation throughout history. Detected for the first time by the Italian astronomer Galileo Galilei in 1610, it was referred to as Jupiter IV for hundreds of years until it became known as Callisto, a name from Greek mythology given to it by the German astronomer Simon Marius.

As we have seen in the chapter covering Ganymede, astronomers didn't have much information to work on before the arrival of more powerful observation instruments and techniques in the middle of the twentieth century such as spectroscopy, photometry, radiometry, polarimetry, and radar. In the 50's and 60's, Earth-based observations showed Callisto to be an icy world due to its low density (1.834 g/cm^3), although the brightness observed from the moon's light (its albedo) was much lower than that of Ganymede or Europa, hinting that the moon's icy surface must be

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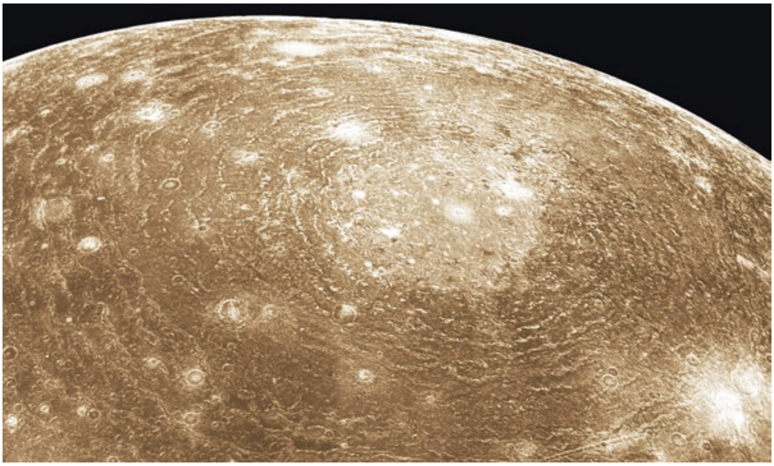

Fig. 5.1. Valhalla Crater, image taken by *Voyager 1* in 1979. The ripples formed in the icy crust by the giant collision can be easily seen across the moon's icy surface. (Image courtesy of NASA)

mixed with non-ice materials to render it darker. Eclipse radiometry performed in the 1970's (see Chapter 4 for more detail) detected a rapid heat loss from the surface during an eclipse, implying that Callisto had a porous surface, most likely due to it being heavily cratered.

When the Pioneer probes visited the Jovian system in the early 1970s, their instruments, unfortunately, returned little information about the moon. As with all the Galilean satellites, it was the two Voyager spacecraft that brought Callisto to life and lifted the veil on this new world.

Images with resolutions of 1 km/pixel revealed a surface covered with innumerable craters from top to bottom, with no trace of any past or present geological activity. It was quickly realized that Callisto must be one of the most heavily cratered objects in the Solar System, as crater density is close to saturation. Any new crater will tend to erase an older one. Apart from impact craters, some fractures, and escarpments, relatively few other surface features can be found. Due to the lack of compelling features such as mountains or valleys and the repetitive homogeneity of an intensely cratered surface, Callisto, the giant moon, suffered from the comparison of its more visually appealing siblings. As such, it has been called the ugly duckling of the Galilean moons, the dead moon, or even the most boring moon of its size (Fig. 5.2).

Fig. 5.2. Callisto in full view taken by the Galileo spacecraft in 2001. The moon's densely cratered surface is apparent in this image. (Image courtesy of NASA/JPL/DLR-Galileo)

The Voyagers returned a limited amount of information as they whizzed by Callisto. As such planetary scientists had to wait an agonizing sixteen years for the next spacecraft, the Galileo probe, to arrive in the Jovian system and complete eight encounters with Callisto from 1996 to 2003. (As a comparison Galileo did eleven encounters with Europa, eight with Ganymede and seven with Io.)

The imaging instruments on Galileo revealed better surface details and a diversity of features unique to the giant moon. It also measured different properties such as gravity and magnetic data. Disregarded as dull after the Voyagers, Callisto was brought back into the light with Galileo's new insights, and it regained its glory as an object of major scientific interest. In 2000, another spacecraft, named Cassini-Huygens, flew by Jupiter on its way to Saturn and viewed Callisto using several of its more capable scientific instruments. Since then much of the new data on the moon has been collected via Earth-based observations.

So what have we learned from these missions? For a start, Callisto took longer to form than the other three Galilean satellites. Estimates range from 100,000 to 10 million years – hardly a precise figure, yet still long enough to suggest that the moon struggled to capture much internal heat from its accretion. To make matters worse, since Callisto is located far away from Jupiter, its formation was mainly done with lower-energy impacts than the other moons. Furthermore, Callisto never experienced much tidal heating, as it lies far from Jupiter's gravitational pull and wasn't locked into a strong resonance with its closer siblings, such as Ganymede or Europa. As a result, Callisto couldn't gather the energy required to undergo full differentiating like its neighbor Ganymede (See Chapter 4 for further insight into Ganymede's interior.)

With all this in mind, instead of being differentiated, we should imagine Callisto's interior as a slush of rocks and ices (and some metals closer to the center) with some areas experiencing partial differentiation as the radiogenic heating from the rocky material would be enough to melt some material. We know this because scientists have devised a simple yet effective way of understanding what goes on under the surface of a planetary object. They measure its gravity.

Indeed, whenever the Galileo spacecraft flew next to Callisto (or any other planetary object for that matter), the Doppler shift of the spacecraft's radio signal would be precisely measured by Earth-based instruments, allowing NASA engineers to track with great precision the changes made in the spacecraft's velocity – the effects of Callisto's gravitational pull – and with this they could extrapolate the mass variations within the moon. Since the mass is directly related to the internal composition of the moon and how it is structured, we can make sound predictions about its interior.

In addition, unlike its bigger sibling Ganymede, no magnetic field has been detected, implying that Callisto lacks a metallic liquid core big enough to generate a magnetosphere, another telltale sign that the rocks and metals in the interior never entirely separated.

Because of this, the moon's interior lacks the geological activity associated with a differentiated interior (such as the heat transfer as convection within the different mantles), which explains why the surface's lithosphere has not changed since its inception. Whereas other icy moons have experienced significant resurfacing events, Callisto has kept large amounts of its crust intact for 4 billion years, apart from the top surface layer, which we shall now investigate.

So what have we found on the surface? Water-ice and rocks. The crust is a buildup of asteroid rocks and comet ices over billions of years. We also detected carbon dioxide ices in younger impact craters, sulfur (from Io's volcanoes) and various unidentified hydrated minerals that are dark and seem to have traces of iron (Fe) as well as clays formed from magnesium. Tholins might have been detected as well (as they fit the absorption bands of 4.57 μm), which could have for origin the irradiation of methane and ammonia gases in the presence of water, carbon dioxide, and ethane ices.

Did these compounds form on Callisto or were they deposited by space rocks? We don't know. It is a possibility that most of the molecules, organic or not, found on the surface of Callisto naturally accumulated after being formed outside of the Jovian system.

In a way, due to its lack of geological activity, the third biggest moon in our Solar System is a time capsule waiting to be explored. However, the top surface has been exposed to the rigors of space and suffered numerous changes brought to it by external agents. Since the surface of icy moons can sometimes provide insight as to what lies below, let us take a small detour to understand how such a surface can be altered through time.

An Ever-Changing Surface

The first external agent involved in the physical changes of an exposed planetary surface is the collision with a space rock or meteorite. Such a strike will form an impact crater that can alter the upper crust depending on the size and composition of the impactor. The more massive the object is, the more material it will attract, and the more energetic and consequential the impacts will be. (The presence of a thick atmosphere on a planet or moon can slow down and even neutralize small to mid-size ranging objects.) As such a giant moon such as Callisto will have brought on itself more bombardments than smaller moons such as Dione or Mimas. And indeed, a quick glance at Callisto's pulverized surface is enough to understand that the moon got its fair share of meteorites. A striking example is Gipul Catena, a long series of impact craters forming a straight line, which was caused by an object that impacted Callisto in a similar way to the disintegrating Comet Shoemaker-Levy 9 striking Jupiter in 1994.

The next agent responsible for modifying Callisto's surface is Jupiter's powerful magnetosphere. Callisto's lack of magnetosphere (unlike Ganymede) exposes its surface to high-energy particles, although in much smaller doses than the other Jovian moons; Callisto receives only 0.1 mSv per day, 800 times less than Ganymede and a whopping 54,000 times less than Europa. Io bears the brunt of Jupiter's lethal magnetic field, as it receives 360,000 times Callisto's radiation. In a way, Callisto has the best of both worlds. The moon's location reduces the strength of Jupiter's magnetosphere significantly while still allowing it to be protected from solar and cosmic radiations that affect most objects in the Solar System unable to hide within a magnetosphere (such as our own Moon).

Nevertheless, over millions of years, high energy particles generated by Jupiter's magnetosphere will modify the surface material in three ways: chemical alterations of surface material, erosion of volatile components (particles within surface material physically ejected by the high energy particles), and the deposition of the magnetospheric ions themselves. As we have seen with Ganymede in Chapter 4, the chemical reactions generated by the high energy particles can break down surface water-ice into oxygen and hydrogen or modify it into H_2O_2 or H_3O. Additionally, oxygen and sulfur atoms start to combine and form SO or SO_2. All these resulting compounds tend to darken Callisto's surface (and in some cases give it a reddish tint). Since a darker surface has the effect of retaining more heat, Callisto has the warmest surface of the icy Galilean moons with an average temperature of 134 K (−139 °C/–218 °F) while Ganymede averages 110 K and Europa, the brightest, hovers between 50 K (poles) to 110 K (equator).

The third agent is photochemistry, which, in this case, are the chemical reactions caused by exposure to high energy ultraviolet photons produced by the Sun. Indeed, our star emits electromagnetic radiation in a wide range of wavelengths, some visible to the human eyes though most are not. The shorter the wavelength, the more energy it contains and consequently the more harmful it can be. A good example is ultraviolet radiation, often just referred to as UV rays, which are lethally short (290 to 400 nm) and carry such a significant amount of energy that it can cause changes to chemical structures of atmospheric and surface compounds as electrons get knocked from their atoms.

As an example, UV rays can create tholins in the presence of nitrogen (ammonia) and methane. The presence of tholins is always an exciting discovery, as these organic polymers can become a source of food for microorganisms given the right habitat. Unfortunately, since the Jovian system is located inside nitrogen's frost line, the stable state of the nitrogen molecule will be gaseous, which limits the creation of tholins on the surfaces of Callisto, Ganymede, and Europa, although as we have seen, some might have been detected on the surface.

Luckily for us, our planet's ozone (O_3) layer shields us from most of these harmful UV radiations but not all; this is why your mother asked you to put suncream when you were a child at the beach. As such, multiple factors will determine how much UV radiation a planetary surface will be exposed to. Some of these include the presence of aerosols in the troposphere, the angle at which the sunlight reaches the surface as well as the elevation and reflectivity of the exposed surface, a thick atmosphere (including an abundant cloud cover), and the existence of an ozone layer in the stratosphere.[1]

Additionally, water (in its liquid and ice forms) offers one of the best protections against these harmful radiations, as water depth rapidly decreases the exposure to UV rays, especially when impurities and sediments are present. Callisto's tenuous atmosphere composed of carbon dioxide and oxygen (resulting from the breakup of water molecules by radiation) doesn't offer much protection, so the top surface gets its fair share of UV radiation, resulting in basic photochemistry resulting in the transformation of organic compounds and other non-ice molecules.

Finally, the last agent of surface change is the deposition of the dust and ice coming directly from space. Most of the major moons in our Solar System are tidally locked with their planets (referred to as primaries in this case), which in effect forms two sides to a moon, a leading side and a trailing side. The former, as its name suggests, is the side that is facing forward as moon orbits around its primary while the trailing side is the one facing backwards.[2]

In the same way as a car driving into a cloud of dust will gather more dust particles in the front windshield than in the back, a tidally locked moon will accumulate more space particles on its leading side than on its trailing side. A great visual example is Saturn's moon Iapetus which presents a much darker leading

[1] The formation of the ozone layer around 600 million years ago is one of the reasons why life on Earth was able to leave the protection of water and colonize the land.

[2] There will be no romantic Jupiter-rise for the future colonists on Callisto. You will be either on the near side where Jupiter is always visible or on the far side blanketed by a dark sky.

side in contrast to its brighter trailing side as it orbits Jupiter (due to debris located in its orbit originated from Phoebe, another moon of Saturn). In the case of Callisto, the leading side is indeed darker (its trailing side has a higher albedo) as it receives more micrometeorite bombardments and contains much more sulfur from Io's volcanoes.

Due to all these agents, the top layer of Callisto's ancient surface has been pulverized repeatedly and transformed chemically.

Additionally, there is an agent of change that we have not yet mentioned here due to its negligible impact on Callisto – galactic cosmic radiation, or GCRs. These are particles (mainly protons) that are accelerated to near the speed of light by stellar explosions located within our galaxy. These GCRs are highly energetic and can significantly alter the molecular structure of a compound when struck. Thankfully for Callisto (and the other Jovian moons), Jupiter's powerful magnetosphere acts as a protective shield blocking the vast majority of GCRs.

Now that we have seen how the top surface layer of planetary objects can be modified by external agents, let us investigate endogenous agents.

When, in the late 1990s, astronomers pointed Galileo's powerful cameras on Callisto's surface, they were expecting to see a multitude of impact craters of all sizes, from the tiniest to the biggest. However, few small craters with diameters less than 1 km were detected, leading scientists to come up with two explanations.

Firstly, smaller craters can be buried under a thick coat of ejecta, dark and powdery material generated from meteoritic impacts. In Callisto's case, countless impacts must have resulted in the production of a vast amount of ejecta. And indeed, some regions on the moon show elevated surface features, such as crater rims, poking out from darker ejecta layers.

There is another reason why small craters and surface features are less apparent on Callisto's surface; the ices that lie under its surface. When observing rims and central peaks from the largest craters, bright surfaces are often visible as the ices get exposed after an impact. Once surface temperatures reach 165 K, these exposed ices can sublimate (a process where the ices change directly into a gas), and they either leak into space or fall back, coating high altitude terrains, which become brighter in the process. High-resolution images from Galileo have revealed many imposing pillars of bright ice, often hundreds of meters high, which are being shaped by the steady sublimation of the ices, exposing fresher layers underneath. This process leads to a gradual loss of icy material that weakens surface features and leads to their collapse. Rims and central peaks from small craters contain less material and are therefore quickly erased (relatively speaking) while bigger surface features will be altered. This process, known in geology as mass wasting and ground collapse, has been detected at multiple locations on Callisto. Colder moons will suffer less from such processes.

All these alterations might seem negligible when compared to other icy moons such as Ganymede, Europa or even tiny Enceladus, which have all experienced significant resurfacing events. Interestingly, there have been suggestions that features found in some regions on Callisto's surface could potentially result from tectonic activity.

Five sites have been identified as displaying distinct linear features, such as narrow grooves resembling those found in Galileo Regio on Ganymede. It might then be that Callisto, in its youth, was subject to more tidal heating than what is currently expected, leading to surface alterations, the evidence of which was later erased through mass cratering and mass wasting. This is an intriguing idea, as it could be an indicator that the interior is more differentiated than we currently assume. Or it might be that these grooves are unrelated to tectonic mechanisms and formed through other means. At present, we just don't know.

Also, images taken by Galileo show flat darkish areas of limited scale that might be interpreted as cryovolcanic deposits, although there is currently no evidence for an endogenic process. Regardless, Callisto's simple geological history provides a good reference point for more complex worlds such as Ganymede.

Before exploring the moon's interior, we shall complete this picture of surface features by noting that Callisto has the fourth densest moon atmosphere within our Solar System. (The other three are, in order of thickest, Saturn's moon Titan, Neptune's moon Triton, and Jupiter's moon Io.) Being at fourth place, you might be tempted to imagine Callisto with a thick atmosphere upon which trailing clouds meander quietly, yet this is far from the truth. The atmosphere is very tenuous, being billions of times less dense than Earth's at 26 picobars and offers little to no protection from the outside elements.

However, this density still qualifies it to be an atmosphere as opposed to an exosphere (which is even less dense), as atmospheric molecules will bump into each other more frequently and create what we could call weather. Like Ganymede's exosphere, it is mainly composed of oxygen that forms when water-ice molecules on the surface are split into hydrogen and oxygen atoms. Carbon dioxide is also present but at a very low concentration.

The Subsurface Ocean and Its Habitability

This seemingly uneventful moon is more interesting once we go underground. As surprising as it may sound for a partially differentiated object such as Callisto, we know that a global subsurface ocean resides deep under the icy crust.

This discovery was revealed in the late 1990's and early 2000's when the Galileo spacecraft made flybys of the Jovian moons and detected perturbations in Jupiter's magnetic field around Callisto (and Europa as well, which we shall see in the following chapter).

As you might recall from the previous chapter on Ganymede, the Jovian moons sit inside Jupiter's monstrous magnetosphere and – unless a moon has a magnetosphere of its own like Ganymede – the magnetic fields form a predictable pattern as the magnetosphere tilts up and down in relation to the moon's orbital plane (the lining up of the moons on a conceptualized flat disk). Because of these tilts, Callisto regularly experiences flips of the magnetic field as it orbits the planet. These flips can be predicted very well and were accurately measured by Galileo's magnetosphere. So far so good.

Nevertheless, unpredictable variations of the magnetic fields were observed whenever the spacecraft was near Callisto, much to the surprise of the Galileo team. Something was interacting with Jupiter's magnetosphere, and after much speculation, the culprit was found – moving salt water.

To understand this, we need to remind ourselves of a specific law of electromagnetism: a time-varying magnetic field (such as Jupiter's) will induce an electric field, which in this case causes a current to flow inside Callisto. This, in turn, creates a small magnetic field (whose direction is approximately opposite to the primary magnetic field) referred to as an induced magnetic field. The strength and response of this field can tell us a lot about the conductive medium located under the surface.

In Callisto's case, static icy mantles can't create an induced magnetic field which is responsible for the variability observed in Jupiter's magnetic fields. On the other hand, moving salty water can. Planetary scientists were excited about these results, especially since Europa, which was already known to have a global subsurface ocean, had produced similar types of electromagnetic variations (see the next chapter on Europa). Could Callisto, the so-called dead moon, really have a salty subsurface ocean like Europa?

Feverishly, the scientific community worked on replicating the moon's internal structure through models that took into account the gravity measurements taken by Galileo, thermodynamic properties of the different states of water, high pressured ice as well as meteoritic material (such as ordinary and carbonaceous chondrites, which are thought to be the moon's building blocks).

What came out of all of this research is that models that most closely replicate the variability in Jupiter's magnetic fields host a global subsurface salty ocean. Callisto is therefore an ocean world contrary to what might have been expected from a partially differentiated world.

Recent models suggest that the ocean lies under 170 km of thick icy crust (in an Ice-I phase) and has a depth of at least 10 km but is most likely deeper. Since astronomers believe that Callisto lacks the heat input necessary to create and sustain this ocean, non-water material such as ammonia, salts, and other antifreeze components are thought to be present, as they make it easier to melt water at lower temperatures (although how these antifreeze materials arrived there is subject to debate). The models show that similarly to Ganymede, as we go down within the water mantle, pressures continue to build up and the liquid water changes into a high pressure (HP) ice mantle.

Some models propose that this mantle of HP ice is Ice-V and is estimated to be more than 100 km thick. Underneath the Ice-V mantle lies another layer composed of Ice-VI (mixed with rocks) which itself is resting on an additional layer of Ice-VII (also mixed with rocks). Further down lie mixtures of rocks and metals at the core. Other models suggest a much larger Ice-V mantle which directly rests on the rock and metal layers.

These different outcomes are due to the uncertain nature of the moon's internal composition (its rate of differentiation), so it is important to remember that much remains unknown about Callisto's interior and that these models need to be taken with a pinch of salt (Fig. 5.3).

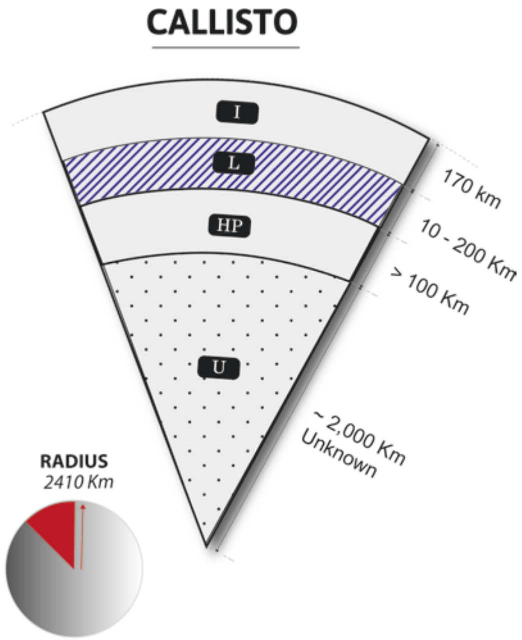

Fig. 5.3. Diagram showing the interior of Callisto where the subsurface ocean is sandwiched between two thick ice mantles. The thickness of the mantles is not well known as well as the extent to which the interior is undifferentiated. I Ice, L Liquid, HP High pressure ices, U Undifferentiated. Diagram is not on scale

Regardless of which HP ices are formed, we know that under Callisto's subsurface ocean there is a thick layer of ice (mixed with some non-ice materials) that seals it off from lower rocky/metal mantles, thus reducing significantly the ocean's habitability.

Furthermore, given the small amount of energy flowing into the Callisto system, there are far fewer chances that pockets of water melts rich in rocky material feed the subsurface ocean such as what might occur on Ganymede. Callisto's subsurface ocean seems to genuinely be sealed off between two very thick ice sheets with not enough heat to stir things up. As such, it is most likely to be an ancient ocean, unchanged and static since its formation billions of years ago.

Callisto is a fascinating world even when placed next to its more exciting siblings such as Ganymede or Europa. It has unique surface features and a surprising liquid interior. It is also the least studied of the Galilean moons, meaning that we still have much to learn and more surprises are likely to come. In truth, we understand far too little about Callisto and Ganymede to have any certainty about the nature of their subsurface oceans. Although it seems safe to assume that Callisto's habitability is very low and that its vast salty ocean is sterile, given the space agency's limited budgets and more promising targets such as Europa or Enceladus, it will be a long time before we know for sure. ESA's JUICE mission (see Chapter 13), which will study Callisto in more detail in the 2030's, is a first step in the right direction.

Ironically, one of the most interesting aspects of Callisto is not its lack of habitability for alien life but instead its potential for supporting human colonists in the far future. Indeed, the giant moon hosts a range of conditions that make it attractive if we ever decide to set up surface habitats in the outer Solar System. In a paper published by NASA in 2003 under the title "Revolutionary Concepts for Human Outer Planet Exploration (HOPE)," seven authors selected Callisto as the best location for an outer Solar System colony due to its location (5 astronomical units from the Sun), its existing gravity (even if it is only 1/8th of Earth's gravity), its surface stability (due to the lack of geological activity), its abundance of water and other non-ice materials necessary for the production of fuel and life support systems, its relatively low exposure to Jupiter's extreme radiation environment, and its proximity to Europa and Ganymede allowing real-time teleoperation of robots to investigate these moons.

It is with this hopeful thought of humanity colonizing our Solar System that we depart from Callisto and visit the last ocean world of the Jovian system and the most promising of all the icy moons within our Solar System, Europa. There is much to explore there, so let's go!

6. Europa

Europa Through the Ages

Arriving at Europa, the sixth biggest moon in our Solar System, we immediately get a sense for why, within the space of a few decades, this moon became as alluring to astrobiologists as the planet Mars. From orbit, Europa is a perfect white sphere. In fact, it is one of the smoothest surfaces of any known solid object in the Solar System. We are far from the heavily cratered surface of Callisto, or the rugged terrains of Ganymede, as the tallest features on Europa are jagged 'blades' of ice that measure in the tens of meters, not hundreds. Standing on its surface, space travelers would observe a uniformly flat horizon everywhere they looked, like being on a giant snooker ball.

Intrepid travelers would nevertheless notice large areas covered with ochre patches and others laced with orangey-brown stripes. Despite these darkish features, Europa's surface is one of the brightest, with an albedo of 0.7. (Ganymede has an albedo of 0.45 and Callisto 0.2.) Only two other icy moons have higher albedos: Enceladus at 0.8 and Triton at 0.76. Since younger surfaces tend to reflect more light than older ones, we can already infer that Europa's surface is very young. A bright surface devoid of large structures can only imply one thing; resurfacing events made possible by recent geological activity. In other words, Europa is an active world.

As with the other Galilean moons detailed in the previous chapters, Europa was discovered in 1610 by Galileo Galilei, the Italian astronomer, and its case as an ocean world wasn't entirely confirmed until Galileo, the spacecraft, characterized it in the late 1990's.

Before Space Age exploration, various properties had already been inferred from Earth-based observations. In 1805, the famed French scholar Pierre-Simon Laplace managed the incredible feat of deducing its mass within 10% of its present value (4.7998×1022 kg). The diameter, far more difficult to establish, was provided in 1859 by Angelo Secchi, a brilliant Italian astronomer, with only a 6% error (present value is 3,100 km).

B. Henin, *Exploring the Ocean Worlds of Our Solar System*, Astronomers' Universe, https://doi.org/10.1007/978-3-319-93476-1_6

With the moon's mass and diameter deduced, academics at the time could have easily calculated its density (mass divided by volume) and therefore made educated guesses about Europa's composition. One of the first to try working out Europa's density was the prolific British amateur astronomer named George Frederick Chambers. Unfortunately, basic errors in his calculations brought up figures that were much lower than they should have been. Not only did he not realize his mistakes, but he also didn't provide any accompanying thoughts on the surprisingly low results.

From 1859 onwards, astronomers tried to infer further properties by observing the variation of the moon's light (photometry – see Chapter 4), yet this method was so imprecise and fraught with errors that it gave way to inaccurate interpretations such as the belief that Europa was highly elliptical due to a fast spinning rate. This theory stayed for half a century before being debunked.

We had to wait until 1908 when American astronomer, Edward Charles Pickering, made a serious attempt to interpret the density and the albedo (luminosity) of the Galilean moons to figure out their composition and structure. Alas, he unfortunately also miscalculated Europa's density, by a third lower, which made him suggest that the moon was composed of 'loose heaps of white sands' or 'dense cloud-laden atmospheres.'

In 1923, a gifted English astronomer and mathematician named Harold Jeffreys first suggested that due to their low densities, Ganymede and Callisto should be composed of icy materials as well as rocks while Io and Europa should be mainly rocky since they had comparable densities to our Moon. Jeffreys' assumptions opened the door to a radical new idea, that rocky moons could be layered with ice, an idea that would become influential for decades.

New observations of Europa came about in 1927 when Joel Stebbins, an American astronomer, used photoelectric photometry, a technique he pioneered, to correctly deduce that Europa and the other Galilean moons were tidally locked with Jupiter, therefore always showing the same side towards the giant planet, just like our Moon.

In the early fifties it was assumed that while Io and Europa were probably rocky bodies, Ganymede was most likely a mixture of rock and ice (composed of either water-ice or carbon dioxide) while Callisto was a chunk of ice. Ironically, few appeared to see a contradiction that while Europa and Io had similar densities to our satellite, the albedos of the two Jovian moons were very different from Earth's Moon, and lumping them into the same category might be misleading.

Fresh ideas introduced in the late fifties and sixties by Gerard Kuiper, the Dutch-American astronomer (considered by many to have revolutionized planetary science), and other astronomers, combined with the arrival of new technologies such as infrared spectral observations, led scientists to conclude that Europa and Ganymede did have water-ice on their surfaces.

Thermal radiation was measured in the seventies for the first time on the Galilean moons, and Europa, unsurprisingly given its high albedo, was found to be the coldest of the four at 120 K. This again confirmed that ices were present in great abundance on its surface, reflecting most of the Sun's heat. More accurate measurements, mainly during satellite eclipses (eclipse radiometry), detected temperature variations between the leading and trailing side, indicative of variance in surface features, as well as the suggestion that the surface was most likely made of low-conductive and porous material.

Around the same time, in 1971, an American astronomer, John S. Lewis, was the first to propose that planetary bodies could host an ocean of liquid water under an icy crust. The theoretical paper he produced was mainly based on the conditions that the water mantles would be rich in ammonia, and that radiogenic heating would be sufficient to provide enough energy (tidal heating had not been conceived yet). Lewis even proposed that detecting such oceans might be possible with the discovery of an induced magnetic field that would prove correct in the following decades (see Chapter 5 on Callisto for more details). At the time, though, all this was highly speculative, as our knowledge on the moons of our Solar system was very limited.

Despite all these advances, Europa was still just a speck of light to the most powerful Earth-based telescopes. And then came 1973.

Space Age Observations

During that year, a new chapter in our exploration of our Solar System opened as NASA's *Pioneer 10* spacecraft was the first human-made object to reach Jupiter and its satellite system, followed closely by its sibling *Pioneer 11* seven months later.

Both spacecraft had for main objectives the measurements of fields and particles within the Jovian system, which was considered at the time to be more scientifically valuable than taking pretty pictures of planetary bodies. Nevertheless, they did carry imaging photopolarimeters that had three roles: analyzing zodiacal dust, gain data on cloud particles in Jupiter's atmosphere, and photometry using red and blue filters. The instruments couldn't independently point at a target, as they were fixed to the chassis and instead slowly scanned over an object by using the spin of the spacecraft. This would often introduce severe distortions that required heavy post-processing.

Furthermore, conceived in the 1960s, the photopolarimeter was limited by the technology of its time and had poor resolution capabilities. For this reason, the first images of the Galilean moons were crude and rudimentary. Also, during *Pioneer 10's* flyby of Jupiter at the end of 1973, Europa was far away in relation to its trajectory, and the probe managed to return just one image of the moon, which was fuzzy and difficult to interpret (see Fig. 6.1 below). Regardless, what had been for centuries a bright light in the sky was now a world to be studied.

The Pioneers also allowed astronomers to measure the mass of the Jovian moons with greater precision than before, forcing the scientists to revise the moons' densities and come to the realization that Io and Europa, with densities of 3.53 g/cm^3 and 2.99 g/cm^3, respectively, couldn't have the same composition and physical

Fig. 6.1. Europa viewed by *Pioneer 10*, the first picture taken of the icy moon. It is very difficult to make out much, but at least the moon was revealed as a disk. (Image courtesy of NASA.)

properties. This was the first time that the two inner moons were thought to be different.

In parallel to the Pioneer missions, theoretical modeling of the moons' formation continued apace due to the increased capabilities of computer simulations. In 1976, John Lewis and his student, Guy Consolmagno, published a seminal paper titled "Structural and Thermal Models of Icy Galilean Satellites," which provided a detailed hypothesis of the interiors of Europa, Ganymede, and Callisto. In the paper, the authors showed how Europa could have an icy crust 70-km thick and a 100-km deep ocean of liquid water directly underneath it. Moreover one excerpt from the paper made a remarkable prediction: "Europa would be more easily punctured by an impact: liquid water could then flow from the mantle onto the surface forming a flat, clean plain….". This was met with much skepticism from the scientific community, and papers were published in response to Lewis and Consolmagno's paper suggesting that subsurface oceans were unlikely.

Nevertheless, some scientists recognized early on the potential for Europa and other icy moons to harbor life if liquid water was present. A significant hurdle had to be overcome, though, as exemplified in a widely reported exchange in 1975 between Consolmagno and the famous astronomer Carl Sagan, where Sagan expressed his skepticism of the idea of life in subsurface oceans, as life on Earth depended entirely on the light from our Sun, a source that was not available in distant oceans covered by kilometers of icy crust. He had a point. At the time, every life form known on Earth was linked one way or another to the Sun's energy output.

Like every good story, though an unexpected twist occurred. In 1977, a team of oceanographers took the scientific community by storm when they discovered on the East Pacific ocean floor the very first chemosynthetic ecosystem, life forms living in total darkness within hydrothermal vents. Life, it seemed, could exist without the energy of the Sun. This major breakthrough led biologists and astronomers alike to consider more seriously the potential of life within hypothetical subsurface oceans.

Thankfully, the scientific community didn't have to wait for too long, as new data from the *Voyagers 1* and *2* arrived in March and July of 1979. Due to orbital constraints, Europa was the least well photographed of the four moons, a reminder that the moon was considered less of a priority during the planning phase of the Voyager missions. Nevertheless, when *Voyager 1* flew past Europa on March 5, it took the very first detailed image of the moon, revealing a world of cracks and the notable red-orange lines criss-crossing the globe named lineae. Most scientists assumed that these were due to plate tectonics, as they were still convinced that the surface was a mixture of ice and rock. The absence of craters was very intriguing as well.

On the July 8, *Voyager 2* made the closest approach to the moon as it passed at just 206,000 km from its surface and managed to return images with a resolution of 2 km per pixel. Although these maps were covering a fraction of the moon's surface, they made scientists realize that they were onto something unexpected as the bright surface was remarkably smooth, contrary to a world shaped by tectonic activity, and showed long linear markings that are similar to fractured sea ice. (See Figs. 1.1 and 1.2 in Chapter 1). The lack of numerous craters or significant surface features implied that the surface was made of 'soft ice' incapable of holding a tall shape, while the linear cracks suggested a hardened crust becoming brittle under tectonic stress. Especially intriguing for the scientists at the time were strange features unique to Europa – the cycloidal ridges (see Fig. 6.2). Found near the moon's south pole, they are symmetric double ridges forming sweeping arcs that run for hundreds of kilometers across the fractured surface. These bizarre features were not understood at the time but most likely had to do with the way the surface was being deformed.

Fig. 6.2. Cycloidal ridges on Europa's surface viewed by the Galileo spacecraft in 1998. (Image courtesy of NASA.)

After taking all these into account, the position taken by the mission scientists was a conservative one. Europa was subjected to episodic heating, due to the newly discovered process of tidal heating (as mentioned in Chapter 1), which occasionally melted parts of the moon's thick icy crust.

The images returned by the Voyagers fascinated everyone, firing the imagination of scientists and science fiction authors alike. Famously, at the time, the renowned science fiction author Arthur C. Clarke was writing the sequel to 2001: A Space Odyssey, and inspired by the Voyagers' recent discoveries, included an indigenous life form on Europa in 2010: Odyssey Two.

This discovery also led to the involvement of NASA's planetary protection officer with the agency's next flagship mission, the Galileo spacecraft planned to orbit Jupiter and visit its moons. The officer's role at NASA focuses entirely on preventing the contamination of terrestrial life forms with the habitable environments in our Solar System (such as Mars and Europa) as well as ensuring that Earth's biosphere is protected in case life exists elsewhere. Even before Galileo arrived at Jupiter, NASA had already made the decision that the spacecraft should be destroyed.

Unfortunately, the story of the development and launch of the Galileo spacecraft is a classic tale highlighting the dangers of politics influencing science. It is also the reason why we still know so little about the Jovian moons despite years of robotic exploration.

Galileo's Tale

Initially labeled as the Jupiter Orbital Probe (JOP), NASA's next flagship to the Jovian system was already being conceived even before the Voyagers launched in the late 1970's to explore the Jovian system. Compared to the multi-planetary missions that were the Pioneers and the Voyagers, JOP had a deceptively simple objective; the detailed study of Jupiter and its moons. Alas, JOP proved to be everything but simple and would become a cautionary tale for future missions.

For a start, JOP required a multidisciplinary approach, as in many ways, Jupiter is like a miniature Solar System in itself with its collection of diverse moons, an intense magnetic field, swarms of dust and charged particles, and the giant planet at its center. In that respect, the Jovian system could offer new clues about our Solar System. There was a catch, though. The study of the giant gas planet, about which so little was known, demanded a very different approach to that of the Galilean moons. Due to this conflict of interest, planning trajectories and deciding what target should be prioritized over another proved challenging for the team.

Another major headache for mission planners was the fact that, due to this multidisciplinary approach, the mission was to be comprised of two spacecraft: the orbiter, which would weigh in at 2.5 tons, and the Jupiter atmospheric probe, which would weigh 339 kg. The scientific instruments planned for the mission would total 16 (as a comparison, both Pioneers and Voyagers had 11), each collecting a fair amount of data even though the storage capacity of the spacecraft's central computer was limited. Indeed, the large amount of data that would be collected by the orbiter and probe had already been identified as a severe bottleneck to the mission due to storage limitations.

An additional challenge was the development of new instruments designed explicitly for JOP, such as the first CCD camera system and the first imaging spectrometer ever to be flown into space. As such, JOP's scientific instruments represented the most capable payload of experiments ever sent to another planet.

A new predicament was added to this project when, in October 1977, it was agreed that the official launch date for JOP – which by then had been renamed the Galileo mission – was for January 1982, using the forthcoming, and still untested, space shuttle launch system. This proved to be an unfortunate decision.

The original plan for Galileo's launch was that once released from the shuttle bay, the spacecraft would use a booster to take it out of low Earth orbit (as the shuttles only reached an orbit of 320 km) and place it on the required trajectory. The chosen booster was the newly developed Centaur-G, which was powerful enough to take the spacecraft on a straight course to Jupiter, ensuring a journey time of two years only. Thus NASA was expecting Galileo to arrive at Jupiter by 1984.

However, plagued by recurring and costly delays, the schedules of the space shuttle launches were continually slipping, and from the initial launch set for 1982, it was pushed back to 1984, then 1985, and finally to that fateful year of 1986, where Galileo spacecraft was supposed to be launched by the space shuttle *Atlantis*.

Tragically, a few months before its planned launch, the space shuttle *Challenger* exploded during take-off, killing all seven astronauts onboard and grounding the shuttle program in the following years. The Galileo probe, already delayed by four years, was forced into a storage facility next to the launch site in Florida and waited for a new launch date. Alas, more delays and problems would plague the mission.

Indeed, the political fallout of the *Challenger* incident forced NASA to improve its safety regulations at all costs. The first victim of this new regime was the Centaur-G booster, which was deemed too risky as it involved carrying several tons of volatile liquid hydrogen and oxygen, which wasn't as tried and tested as solid fuel boosters. Some astronauts refused to fly in the shuttle if a Centaur-G booster would be present in the payload bay.

Faced with no other alternatives, the Galileo mission reluctantly ditched the Centaur-G booster for a smaller, less powerful, but more conventional solid fuel booster named Inertial Upper Stage (IUS), which unfortunately didn't produce enough velocity for the spacecraft to go on a straight trajectory to Jupiter. Instead, a longer flight path had to be chosen that required two flybys of Earth and one of Venus. As opposed to Centaur-G's two years, IUS meant that Galileo would take almost six years to reach Jupiter. Worse was yet to come.

This new course had the spacecraft fly within the vicinity of Venus, much closer to the Sun than what was initially planned, and since Galileo wasn't designed to withstand such high levels of solar radiation (a threefold increase), a total redesign of the spacecraft was required to protect its sensitive instruments.

Thus, Galileo had to be transported back (on a flatbed truck) to the other side of the American continent to the Jet Propulsion Laboratory in Pasadena, California, and stayed there for two years as engineers added thermal shielding and made other modifications. Once the upgrades were completed, Galileo headed back to Florida, again on a flatbed truck.

Sadly, no one had realized that this back and forth cross-country journey on the American freeways caused lubricant on some of the ribs of the spacecraft's primary antenna (the high gain antenna) to wear off completely. So when Galileo finally successfully launched onboard the space shuttle *Atlantis* in 1989, seven years after its intended flight, it was already compromised.

This came to everyone's attention when, on April 11, 1991, after almost two years in space and with the Venus flyby complete, the mission engineers instructed the high gain antenna to unfold its 18 'ribs' out from the central mast, which was designed to open up like an umbrella. Due to the missing lubricant, three or maybe four ribs refused to budge from the mast, and the whole antenna got stuck. It was half opened and tragically useless.

This was a major blow for the Galileo team and NASA. The high gain antenna was supposed to send data back home at a rapid rate to compensate for the computer's limited memory capacity. Without this capability, the mission could be severely compromised. The billion-dollar flagship mission was in serious trouble.

Despite all the attempts made by the engineering team to fix the problem – from spinning the spacecraft at its maximum spin rate of 10.5 rpm or turning on and off the deployment motor over 13,000 times – the high gain antenna refused to cooperate, and the faulty spacecraft was on its way to Jupiter. With no other choice, the orbiter had to use the much smaller low-gain antenna, making Galileo's data transmission rate abysmal. From 134 kilobits per second for the high gain antenna, it had now dropped between 8 to 16 bits per second. And while engineers managed to improve the transmission rate of the low gain antenna to one kilobit per second, through software upgrades and data compression, it still represented only 1% of the data output initially planned. The Galileo team was obliged to compromise even further on the mission objectives to ensure maximum science return.

Irrespective of all the problems described above, another headache was to come in October 1995 while the spacecraft was on its way to Jupiter. The digital tape recorder that stored the data before it was transmitted back to Earth experienced a malfunction that damaged a good length of tape at the end of the reel. For precaution, the engineers sealed off a portion of the recording tape, constraining even further the data-collecting capabilities of the mission. As an example, this led to the decision to scrap planned observations of Io and Europa during the orbit insertion phase to ensure that the tape had enough space to store data collected by the atmospheric entry probe, which would plunge into the Jovian atmosphere.

Of course, we now know with hindsight that the data collected and returned by the Galileo spacecraft during the years it spent in the Jovian system would prove valuable and that the mission was to be considered a success. All these problems left a bitter taste within the planetary science field, though. The irony of this story is that Galileo's hardships could have been easily avoided.

For a start, the critical decision to use road transport instead of air travel to go cross-continent was made to cut down on costs. Had a better risk assessment been made at the time, the antenna fiasco could have been avoided either by choosing to transport the spacecraft in a plane or by checking the integrity of the high gain antenna after the road trips.

More tellingly though, the Galileo mission didn't have to fly on the space shuttle at all. Actually, during the conception phase, most of the Galileo team wanted their spacecraft to ride on Titan, an expendable rocket with a proven track record for sending payloads into space at a fraction of the cost of the space shuttle and without any unnecessary risk placed on astronauts. Even better, the Titan rocket could also carry the Centaur-D booster, making the Titan-Centaur launch system far superior in every way to the shuttle-IUS.

Alas, the politics of the U. S. space program decided otherwise. The development of the ambitious space shuttle program had proven far more costly than anyone would have imagined, and to ensure that it was financially viable, immense pressure was placed on NASA to make the shuttle fly as often as possible, shipping all kinds of payloads into low-Earth orbit regardless if it was the best choice. Indeed, requiring a crew of seven astronauts to put their lives at risk for a mission that a cheaper unmanned rocket could do better was highly questionable, but by then the agency was burdened with the shuttle program.

To be fair, the shuttle program offered a new and promising way to bring payloads into low-Earth orbit and would allow for the construction of a permanent space station that would become the International Space Station. It just simply didn't make any sense to use the reusable launch system for space missions that unmanned rockets could do as well.

And so, a data-starved' spacecraft, old and fitted with 1970's technology, finally arrived in the Jovian system in December 1995, nearly ten years later than initially envisaged. And still, despite all its faults, Galileo is the spacecraft that made the closest approaches to Europa and collected most of the data and images we know of today.

An Ocean World Revealed

In total, the Galileo orbiter executed twelve close encounters (flybys) with Europa during three mission phases. The first three encounters occurred within its prime mission phase, from June 1996 to November 1997. Mission extensions were subsequently approved, allowing for an additional eight flybys during the

Galileo-Europa mission phase (GEM) and a final one during the Galileo Millennium Mission phase (GMM), which ended in 2002. Also, Galileo continued to monitor Europa as it orbited Jupiter, albeit from far greater distances and even though the images returned during these 'non-encounters' were not as detailed, they proved useful as they showed the moon in different angles and phases. During the spacecraft's closest approach, on December 16, 1997, it passed above the surface of the moon at a hair-raising 201 km (lower even than the International Space Station's altitude to Earth!) (Table 6.1).

Table 6.1 Galileo flybys of Europa during prime and extended missions GEM (Galielo Europa Mission) and GMM (Galileo Millenium Mission). (Data extracted from Kurth et al. 2001)

Orbit name	Mission	Date	Altitude (km)
G1	Prime	27-Jun-96	1,56,000
G2	Prime	06-Sep-96	6,73,000
C3	Prime	04-Jan-96	41,000
E4	Prime	19-Dec-96	692
E6	Prime	20-Feb-97	586
G7	Prime	05-Apr-97	24,600
C9	Prime	25-Jun-97	12,00,000
C10	Prime	17-Sep-97	6,21,000
E11	Prime	06-Nov-97	2,043
E12	GEM	16-Dec-97	201
E13	GEM	10-Feb-98	3,562
E14	GEM	29-Mar-98	1,644
E15	GEM	31-May-98	2,515
E16	GEM	21-Jul-98	1,834
E17	GEM	26-Sep-98	3,582
E18	GEM	22-Nov-98	2,271
E19	GEM	01-Feb-99	1,439
I25	GEM	26-Nov-99	8,860
E26	GMM	03-Jan-00	351
G28	GMM	20-May-00	5,93,321
I33	GMM	17-Jan-02	10,03,152

The imaging instrument on the Galileo orbiter, referred to as the solid-state imaging subsystem (SSI), used a Cassegrain telescope with a 176.5-mm (7-inch) aperture narrow-angle telescope that also included image sensors, focal plane shutters, electronics and a filter wheel. It was developed for the needs of studying both the atmospheric motion on Jupiter as well as the Jovian moons. Its wavelength range was from the visible into the near-infrared, allowing it to identify different levels in Jupiter's atmosphere and geological formations on the moons.

The imaging campaigns required meticulous planning, as every image taken would be sent to the tape recorder for temporary storage and then played back off the recorder, compressed by an onboard computer, and sent back to Earth during cruise phases. Since the imaging instrument was a high-data instrument, a not-small part of the storage capacity was being used whenever the spacecraft was taking images, which might limit the data acquisition for other instruments such as the spectrometer, the ultraviolet spectrometer, and the photopolarimeter-radiometer.

Another complexity arose as there were two types of images, regional views and close-ups. Regional views were provided by medium-resolution images that had a few hundred meters per pixel, while high-resolution images at tens of meters per pixel would allow the scientists to examine surface features up close. Ideally, both views would be taken from the same area, as they complemented each other, the regional views giving context to the close-up images. This proved to be a frustrating problem throughout the mission as data limitations forced the imaging team to prioritize close up views over regional views, making it difficult to place the high-resolution images in context.

To add further complications to an already stressful situation, the position of the Sun relative to the moon would show different surface characteristics, as the morphology of the terrain would be more visible in low-Sun angle views while color images and photometry required high-Sun views. With each image being a prime commodity in such a data poor mission, the imaging schedules were the result of lengthy discussions and painful compromises within the Galileo team.

The first high-resolution images of the surface were taken during the prime mission phase (E6) on February 20, 1997, and acquired images of 21 m/pixel. These first-ever close-up images of Europa stunned scientists as they revealed a chaotic terrain full of ridges and displaced ice sheets that could be reconstructed together like a jigsaw puzzle (see Fig. 6.3).

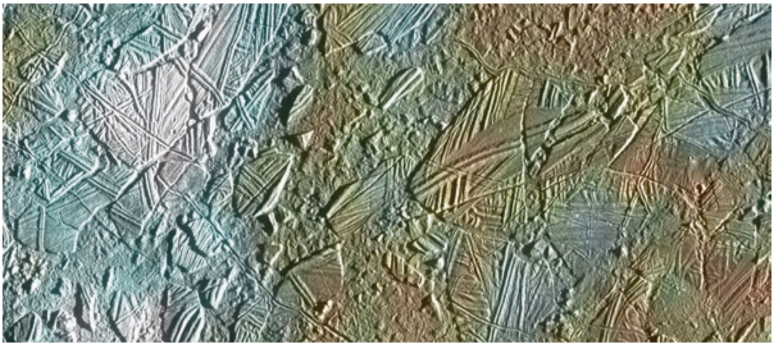

Fig. 6.3. One of Galileo's first high-resolution images of Europa's surface. Broken crustal plates seen here range up to 13 km across. (Image courtesy of NASA.)

The surface was shown to be fractured everywhere, as vast ice sheets jostled with giant titling blocks of ice resting on what seemed to be slush. Some even seemed to float – an impossibility since liquid water cannot exist in the vacuum of space. All this was intriguing.

In chaotic regions such as Conamara Chaos or Thrace Macula, disc-shaped areas were shown to contain 'floating' ice blocks that seemed to be stuck in a matrix of darkened material. It was as if the ice sheet had melted away in these areas, exposing the liquid ocean, but we know this is not possible. So what was going on? At the time, the researchers weren't sure. Some suggested that Europa had a thin icy crust, so that liquid water from below would be very close to the surface, sometimes melting it, while others (the majority) continued to believe the theory that the moon had a very thick crust.

And of course, we should not forget the most compelling surface features, the so-called lineae. These dark streaks covering the entire moon for thousands of kilometers like a vast spider web are giant cracks where younger and brighter material seems to arise from the center, pushing the old darker material to the outer edges (much like oceanic ridges on Earth). This suggests a warming process that brings dirty, fresh slush/ice to the surface. Interestingly, a subduction process has been detected where plates of ice slide onto each other, in effect, analogous to tectonic plates on Earth, making Europa the only other planetary body in our Solar System where such geological activity has been detected.

Another essential characteristic of the lineae is their reddish-brown tint. Scientists weren't sure what to make of the odd coloring, as initial measurements on the nature of this non-ice material were unsuccessful. Still, to this day, various explanations have been put forward. One proposes that they are deposits of salts, coming from subsurface pockets of brine, which are altered by the intense radiation found on Europa's surface. Another explanation for the coloration of the lineae doesn't involve the subsurface ocean at all. As two segments of the icy crust buckle and rub against each other, a process referred to as shear heating occurs, where the two sheets touch, warming up the ice. This, in turn, sublimates the water in these specific areas, leaving enhanced concentrations of darker material that, most likely, would be sulfur from Io (more on this later in the chapter), therefore removing any need for a subsurface ocean contrary to the previous model. It might be that these two models of lineae formation occur at the same time. We currently don't know.

Galileo's first flybys also allowed astronomers to get a better idea of the moon's rocky interior; with an overall density of 3.01 g/cm^3, precisely measured by the orbiter. We know that the moon must be in large part composed of a thick rocky mantle resting on a metallic core. At around 100 to 150 km thick, the water mantle (consisting of the subsurface ocean and the icy crust) is surprisingly thin in relation to Europa's mean radius at 1,560 km and compared to the genuinely humongous water mantles under Callisto or Ganymede.

The Evidence of a Subsurface Ocean

The wealth of scientific data collected during the prime mission phase led the Galileo team to propose a two-year mission extension: the Galileo-Europa mission phase (GEM), whose primary focus was the study of Europa, and to a lesser extent, additional observations of Jupiter and Io. GEM consisted of three phases, each with a clear objective: the Europa campaign labeled "Ice," the Jupiter Water & Torus study labeled "Water," and the Io campaign labeled "Fire." No surprises, then, that GEM was also known internally as the Ice, Water, and Fire mission.

Consisting of eight close flybys, GEM's primary objective for Europa was to find further evidence for a subsurface ocean in the past and determine if it is still in existence today. This two-year extension was approved in 1997 by NASA and Congress (which ultimately holds the purse), yet it was done within the context of a cost-cutting period at NASA (the controversial 'Faster, Better, Cheaper' approach). As a result, GEM was only given $15 million per year, which required trimming spacecraft and ground operations to a bare minimum; mission staff was cut by 80%, operational processes were streamlined and automated whenever possible, and data acquisition was severely restrained (only two days of data would be collected during close approaches of Jupiter or the targeted moons as opposed to a full seven days during the prime mission).

Nevertheless, the extension proved to be a stunning success, as two lines of evidence were found for a subsurface ocean, one from numerous features found on the surface and another, more compelling, from the disturbance in Jupiter's magnetic field. Let us look at both lines of evidence in detail.

The first one is concentrated on Galileo imaging data, where nine surface features were identified as consistent with a liquid water layer underneath the ice: impact morphologies, lenticulae, cryovolcanic features, pull-apart bands, chaos, ridges, surface frosts, topography, and global tectonics. It is important to note, though, that on their own, these geological features were not conclusive evidence, as they could also have been due to processes in warm, soft ice with only localized or partial melting. Nonetheless, once scientists found evidence for an ocean independent from geological interpretation, they could become confident in their understanding that the surface features were also evidence of a subsurface ocean.

The first of this evidence came from the detailed study of the images showing Europa's most prominent impact craters. On any planetary body, a crater's morphology can provide insight into the crust's physical properties – its composition and potential depth. The study showed that the morphology of the biggest craters could only be explained if the icy crust is lying on a low-viscosity material; which in this case would be a layer of liquid water. Also, by analyzing 28 craters with a diameter larger than 4 km, such as Tyre and Callanish, the two biggest craters on the moon, scientists have estimated an average crust thickness of 19 km (as opposed to the crusts of Ganymede and Callisto, which are thought to be ten times thicker).

The second evidence came from the number of impact craters found on the surface. As a general rule, the older a surface gets, the more craters it displays. Determining a precise age using crater counts for objects located in the outer Solar System can be tricky, as there is still much debate regarding the formation of the satellite systems orbiting the outer planets (contrary to the inner Solar System, where we were able to calibrate the major bombardment epochs with precise dates thanks to the Moon rocks returned by the Apollo missions).

This hasn't stopped planetary scientists from working on models to estimate Europa's surface age, which they have put at around 40 to 90 million years. This is incredibly young by geological standards, making it highly improbable for a global subsurface ocean to have entirely frozen since then. Therefore, the ocean must still be active at the present time.

The third study focused on large-scale fractures observed on the icy crust. More than a 100 of these faults were identified and analyzed, and a pattern emerged, as the northern hemisphere is dominated by left-lateral offsets while the southern hemisphere by right-lateral offsets, giving us an clue to the compression forces upon which the icy crust is subjected to through time. When comparing these patterns with computer simulations, the best match is that of the icy crust rotating at a different speed than the interior of the moon itself, an event called slipping in geology. This non-synchronous rotation of the icy crust can only be explained if the crust is lying over a fluid mantle, in other words, a subsurface ocean.

Furthermore, the cycloidal ridges first spotted by Voyager, were now understood to be formed from the tidal stresses generated by Jupiter, causing the subsurface ocean to ebb and flow similar to our tides on Earth. For each orbit, the water mantle experiences the rise and fall of tides by up to 30 m, inducing considerable stresses on the structure of the icy crust and forming arc-shaped cracks due to the orbital eccentricity.

In addition to this list of indirect geological evidence, scientists wanted to build a stronger case for a subsurface ocean, and prior to the last GEM flyby of Europa in February 1999, another mission extension was proposed. Named the Galileo Millennium Mission, or GMM, this extension had only one flyby planned for Europa (E26) while the rest of the focus this time was on the other moons (Io, Callisto, Ganymede, and Amalthea) and the giant planet itself until the demise of the Galileo orbiter in September 2003.

This extension would be operated within the confines of a reduced budget and an even smaller team. But one flyby of Europa in January 2002 was enough for the scientists to finally confirm that, yes, the interference of Jupiter's magnetic field spotted during Galileo's first flyby in December 1996 (the E4 flyby) and additional encounters was genuine.

This interference was proof of an induced magnetic field, generated by the moon in response to the periodic variation of Jupiter's magnetosphere, which could only be explained if a global layer of conductive material was located within the moon. In other words, a salty subsurface ocean had been confirmed on Europa. (See Chapter 5 for more details on induced magnetic fields). Results measured by Galileo are consistent with a global liquid mantle lying 20 km under the icy crust and having a depth of at least 100 km (Fig. 6.4).

Although conductive materials other than salty water exist (graphite comes to mind) these are ruled out due to what we know of Europa's formation and internal composition. Europa's ionosphere was also put forward as an alternative to explain the measurements, yet this was dismissed as being too tenuous to support such strong currents.

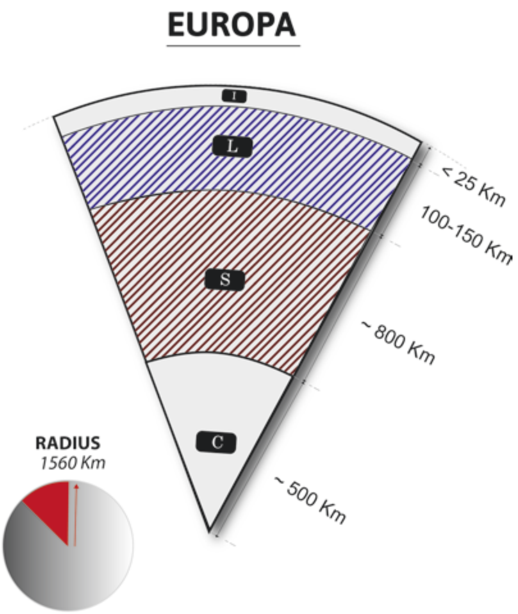

Fig. 6.4. Diagram showing the interior of Europa. The subsurface ocean rests on a silicate mantle where water/rock interactions occur. The thickness of the mantles is not well known. I Ice, L Liquid, S Silicate mantle, C Core. Diagram is not to scale

How salty would this ocean need to be to generate the observed magnetic field? We are not entirely sure, as a range of solutions using different values for ocean depths, the degree of saltiness, and the ice crust thickness can match the measurements. Hopefully, new data from the ESA's JUICE mission and NASA's Europa Clipper mission will allow researchers to estimate the moon's saltiness better. (See Chapter 12 for details on future missions to the ocean worlds.)

The most promising characteristic of Europa's ocean is that due to its relatively low depth and the significant energy generated from tidal heating and radiogenic heating, no icy mantle exist between the subsurface ocean and the silicate mantle below, ensuring direct contact between liquid water and rocks.

Additional properties of the subsurface ocean has been inferred since Galileo's last flyby, mainly thanks to new Earth and space-based observations. We will review these in detail below.

Surface Features

The discovery of the subsurface ocean was only one of many scientific findings made by the orbiter. It also provided data on Europa's surface composition due to instruments such as a near-infrared spectrometer (NIMS), a UV spectrometer (UVS), and a photopolarimeter (PPR).

The results returned from these instruments found evidence that a thin layer of amorphous ice (<1 mm) was predominant on Europa's surface, revealing disruption of the outermost layer of crystalline ice due to the high radiation environment. Given time, radiation will break down ice molecules in a process known as radiolysis and generate radiolytic products such as molecular oxygen (O_2) and hydrogen peroxide (H_2O_2). These molecules can then get trapped inside fluffy looking structures of regolith caused by impact gardening – the accumulation of rocky debris from micrometeorites that hit the top layer of the surface. In addition to these two radiolytic products, the spacecraft found other non-ice material: CO_2, Na, K, SO_2, and elemental sulfur.

The origin of the carbon dioxide is not well defined. It could have been outgassed from the moon's interior or deposited by meteoritic material. On the other hand, the sulfuric material, which is comprised of sulfur dioxide (SO_2) and elemental sulfur, has most likely for origin the volcanoes of neighboring moon Io as these sulfurs are found on Europa's trailing side, implying that they mainly have an exogenous source.

This might seem counterintuitive at first. It is the leading side that faces the forward motion during the moon's orbit around the planet, so you would expect that as the moon plows through the dust and other particles in space, the leading side would be covered with these materials contrary to the trailing side. Callisto and Ganymede are good examples of this process, as they both have a darker leading side compared to their trailing sides. So why is Europa's leading side generally brighter than its trailing side?

The answer is simple: Jupiter's powerful magnetic field. As the giant planet spins on itself every 9.5 hours, its magnetosphere also spins at the same rate and carries with it lots of particles. Europa on the other hand takes 3.5 days to make a full orbit around the giant planet and in the process gets overtaken many times by Jupiter's magnetic field. Similarly, as the Jovian magnetosphere rotates, it sweeps past Europa's neighbor Io and strips away about 1,000 kg (one ton) per second of volcanic gases and other materials, creating a large plasma torus around Jupiter. It is no surprise then that some of the sulfuric material spewed out from Io gets slammed on the trailing side of Europa by the rotating magnetosphere.

Nevertheless, sulfur has also been found to correlate with geological features on the surface, suggesting that some could as well be originated from Europa itself as endogenic salts. Future measurements will be required to confirm this.

Another molecule, sodium (NA), which had already been spotted in 1996 with Earth-based observations, and potassium (K) has been detected in Europa's atmosphere. Scientists believe these elements were initially lying on the surface as salts before being whipped up by Jupiter's radiation and ending up in the atmosphere. The exact origin of these elements is still not precisely known, but here is the main idea: similar to sulfur, Io vents sodium-rich gases into space, which gets slammed into Europa at incredibly high speeds. The sodium particles bore through less than a millimeter into the ice and get trapped inside the fluffy material. After a while, though, the constant bombardment of particles raining on the surface erodes away the material covering the sodium, and it gets released into the atmosphere.

Recent calculations, though, indicate that Io doesn't vent sodium in large enough quantities to explain the rate of detection in Europa's upper atmosphere. Because of this, it does seem that some of the sodium is also generated by Europa itself, most likely through the radiolysis of sodium salts that must have been brought up to the surface as brines. Europa, therefore, joins a select club of planetary objects that includes the Moon, Mercury, and Io; they are a net source of sodium.

Unfortunately, due to the reducing capabilities of its onboard instruments, GEM and GMM weren't able to reveal the nature of the reddish material composing the lineaes and many surface areas. These are most likely hydrated salts even though there are also suggestions that they could be magnesium sulfate or even sulfuric acid. Laboratory experiments done on Earth showed that when certain brines, in this case, water mixed with magnesium and sodium salts, are placed in conditions similar to those we expect to find on Europa's surface, their spectra are similar to what Galileo measured. This doesn't confirm the exact nature of the unknown reddish materials on the surface, but it does indicate that we are on the right track.

For the most part, though, the spacecraft couldn't identify the hydrated components on Europa's surface as the spectroscopic instruments it carried were unable to detect the nature of the substances that were coated with water. Referred to as hydrates (a material that contains water), these elusive substances have been found in various areas on the surface. Earth-based telescopes have since then carried on the investigation of the non-ice components on the surface with some success, as detailed further into this chapter.

Another frustrating element of Galileo's reduced capabilities is the mapping of the moon's surface. Despite performing 12 close flybys of Europa between 1996 and 2000, the surface couldn't be entirely mapped at high resolution. Instead, the majority of the surface was mapped at a resolution of 1 to 4 km per pixel, or even 20 km per pixel, although some regions got lucky and benefited from a 200 m per pixel resolution, and a few selected areas managed to be imaged at 10 to 20 m per pixel. Remarkably, one image reached 6 m per pixel – the highest resolution image Galileo returned – but that is a poor substitute for the fact that too many large areas of the moon's surface were poorly imaged. A global map of Europa provided by the USGS astrogeology science center presents large unresolved swathes of land where the resolution is 20 km per pixel (mainly on the leading side). Compared to the jaw-dropping images of Pluto, Ceres or Enceladus recently returned by modern-day spacecraft, it is frustrating to see that one of the most fascinating moons in our Solar System is still poorly imaged.

Post-Galileo Discoveries

By the end of GMM, the Galileo orbiter was in bad shape. Its two plutonium-powered thermoelectric generators (RTGs) were running out of fuel, and the lethal Jovian radiation environment had significantly weakened the scientific instruments on board. Following a decision made even before Galileo had reached Jupiter, and to prevent any risk from contaminating a potentially habitable environment (the spacecraft had not been sterilized), the orbiter plunged into Jupiter on September 23, 2003, and burned in the upper atmosphere after spending almost 14 years in space. Its last flyby of Europa had been in January 2000. No spacecraft has come as close since.

That hasn't stopped astronomers from persevering in their study of the icy moon. Following Galileo's demise, new observations have been made using Earth-based telescopes, the Hubble Space Telescope and spacecraft passing through the Jovian system as part of a slingshot maneuver on their way to more distant targets within the outer Solar System. An example of this occurred in 2001, while Galileo was still orbiting Jupiter. The brand new Cassini spacecraft flew through the Jovian system to pick up speed on its way to Saturn. In doing so, it observed Europa from a fair distance with its ultraviolet imaging spectrograph (UVIS), which splits ultraviolet light into its component wavelengths, allowing astronomers to identify atmospheric gases on planetary bodies. UVIS' results confirmed that Europa's atmosphere was much thinner than previously thought – 100 times less than what models predicted – reducing the likelihood that hypothetical plumes of water occurred on a regular basis, especially at the time the data was acquired.

In February 2007, another spacecraft, New Horizons, whizzed at neck-breaking speed and reached Jupiter in 13 months (thanks to a powerful launch system combining an Atlas V rocket and a Centaur booster). New Horizons observed in visible and infrared wavelengths the Galilean satellites from a long distance, thus providing images resolutions of only 15 km/pixel. Nevertheless, these new observations showed that light scatters more homogeneously than expected, giving us some indication that Europa has a flatter surface than initially estimated.

In addition to these distant flybys, planetary geologists continuously work on improving their mathematical models for how water-ice behaves in conditions similar to Europa. This led to the publication of a paper in 2011 titled "Active formation of chaos terrain over shallow subsurface water on Europa" that describes in detail how the chaotic terrains on the surface of the icy moon might be formed. The areas that have attracted the attention of scientists are the dark circular matrix of fragmented ice where 'icebergs' seem to be floating. New computer simulations have shown that these chaotic features can form with the rise of solid ice plumes, an upwelling of 'warm' ice behaving similarly to rocky plumes within Earth's mantle.

Indeed, it is best to imagine these ices as a fluid so long as the crust is not too stiff. Hot bubbles of warm ice forming at the base of the ice crust will steadily rise to the top, where its heat will dissipate. This process is known as convection and is an essential mechanism in distributing energy within the interiors of planetary bodies, rocky or icy. Picture a lava lamp. Blobs of warmer material rise, and colder blobs sink. The same process will occur in icy or rocky mantles, although it will take thousands to a 100,000 years for a blob to rise and fall.

Back to Europa. As an ice plume rises through the icy crust, it can bring about substantial alterations to the material lying directly above it. As described in the paper, when a bubble of warm ice reaches a certain height within the crust, it produces enough heat to create an enclosed lake of water melt directly above it, yet 3 km under the surface.

Atop this warm lake, the crust starts to weaken, allowing pressurized liquid water to flow upwards through the cracks, saturating the upper crust with warm water without entirely melting it. This process forms the chaotic terrains as viewed from space, where massive chunks of ice tilt sideways, giving us the illusion that these large structures float on liquid water.

Once the ice plume has lost most of its heat, the enclosed lake and chaotic terrain lying above it freezes up, causing the entire matrix to lift upwards like a dome (liquid water expands when turned to ice). The authors of this model have proposed the chaotic region of Thera Macula to be one of these active regions being formed and that we should observe "noticeable changes between the Galileo encounter and the present day."

Although more observations are required to validate this model and refine it, new images of Thera Macula should be taken by the Europa Clipper in the coming decade; it is at present the theory that comes closest to what we see on the images returned from Galileo.

One last point can be made of these chaotic terrains; they always seem 'dirty' from the non-ice material. This would imply that as the ice plume rises, it brings contaminants from the subsurface ocean that get mixed up with melted water near the surface. If this scenario proves to be correct, we could have direct access to the water coming from the subsurface ocean and the non-ice material it contains, making a strong case for a lander to sample the surface.

In 2013, new discoveries of Europa's surface composition were found using Earth-based telescopes. These discoveries demonstrate the rapid pace of technological innovations that have benefited astronomy since the Galileo spacecraft was built in the 1970s and 1980s.

As such ground-based telescopes have two advantages over orbiters or probes. Firstly, they rarely have constraints on the size of instruments being used (the need to miniaturize scientific instruments for space journeys almost always constrain their capabilities), and secondly, they can be easily upgraded with the latest technology. One such innovation has revolutionized Earth-based observations – adaptive optics. By using lasers to create an artificial point of light in the sky above the observatory and shaping the telescope mirrors in real time to render it as clear as possible, this tool compensates for atmospheric aberrations that are occurring in the sky. The results are remarkable.

The 2013 spectroscopic observations made from Earth detected traces of magnesium sulfate ($MgSO_4$) on Europa's surface. This molecule had never been detected previously on the moon's surface, which made the discovery an unexpected one. Furthermore, magnesium is an element that occurs in rocks. Earth's oceans contain trillions of tons of magnesium, which it gets directly from the rocky mantle upon which it rests (it is the eight most abundant element there). Therefore, discovering magnesium sulfate on Europa implies that the subsurface ocean is interacting with rocky material, dissolving the magnesium and bringing it to the surface through the yet-to-be-confirmed convection process within the icy crust. Once deposited on the surface, the magnesium interacts with the sulfur wherever it is present and forms magnesium sulfate.

One crucial element to support this theory is that magnesium sulfate has only been found on the trailing side, where sulfur is abundant or has enough energy to form the bond with magnesium. Because there is little to no magnesium sulfate on the leading side, we can assume that the compound wasn't created in Europa's interior or else it would be present everywhere on the surface.

The discovery of magnesium sulfate on the trailing side also leads to another speculation. Due to its chemical properties, magnesium is never found unbound in nature. The magnesium transported from the subsurface ocean to the surface has to be combined with another element. What could this be? Sulfur is a candidate, since it is also contained within rocks and gets dissolved in contact with water.[1] However, the lack of magnesium sulfate on the leading side does imply that there just isn't enough sulfur present within the water (and therefore the rocky mantle) to combine with the magnesium in the subsurface ocean.

With the sulfur out, what another candidate could bind with the magnesium present within the subsurface ocean? In all likelihood, we should expect it to be chlorine. This element also generally present in rocks, is quickly dissolved (it is abundant in Earth's oceans) and can combine with magnesium to form the salt $MgCl_2$.

Furthermore, as we saw earlier, previous observations have shown that sodium and potassium have also been detected on Europa. It is therefore highly likely that these two elements originated from within the moon, bound to the chlorine as salts, and were transported to the surface as sodium chloride – plain old table salt – or NaCl and potassium chloride or KCl.

Following this theory, we would expect the subsurface ocean to contain at least three salts, $MgCl_2$, NaCl, and KCl, and that chlorine would be present on the surface. Unfortunately, the inherent difficulties of detecting chlorine using remote-sensing instruments have prevented scientists from making much progress on this theory. We will have to wait for future observations made with Earth-based telescopes or with the Europa Clipper to finally confirm or not the existence of chlorine on the surface.

In the meantime, the discovery of magnesium sulfate, with all its implications, has opened up real possibilities that non-water material present within the subsurface ocean does indeed bubble

[1] Earth has a sulfur cycle of its own.

up to the surface, where it could be sampled by a robotic lander. The simple idea has placed Europa as one of the best locations to search for extraterrestrial life. Another potential discovery could make it even easier for scientists to sample the moon's subsurface ocean.

Europa's Hypothetical Plumes

Motivated by the discovery in 2005 of the existence of plumes at Enceladus' south pole (see Chapter 8), a team of scientists pointed the Hubble Space Telescope towards Europa and, to their surprise, spotted what they interpreted as an active plume located near the south pole of Europa. After additional observations, they proposed in a paper published in 2013 that the material venting out from the plume was water (inferred through studying the auroras on the moon) and calculated that the plume reached an altitude of 201 km before falling back down to the surface due to Europa's gravity (as opposed to Enceladus' plumes that are for the most part ejected directly into space).

The evidence of these jets was suggestive at best, and most within the planetary science community were skeptical. This is because the plumes are very faint, and the Hubble Space Telescope doesn't 'see' them but instead, used a transit technique to infer their presence. Whenever Europa passes in front of Jupiter, the planet's ultraviolet light is precisely measured by Hubble. If something is dense enough to block such light, such as a plume of water venting off from the rim of an icy moon, then there will be a drop in the ultraviolet light at that specific location. It is such a drop that was detected by the observation made in 2012 and published in 2013.

Further detections were required, though, as the likelihood that the observation was a false positive was high (due to instrument defect, etc.). It is with this in mind that researchers analyzed the raw data collected by the Cassini spacecraft as it flew by the Jovian system a decade earlier but found no detection of water in Europa's atmosphere or around the moon, excluding any plume activity at the time. If the plume phenomenon was genuinely occurring, then it was intermittent. Luckily more Hubble observations followed, and in 2014 and 2016 what seemed to be additional plumes were detected, this time from a region where the large Pwyll impact crater is located (Fig. 6.5).

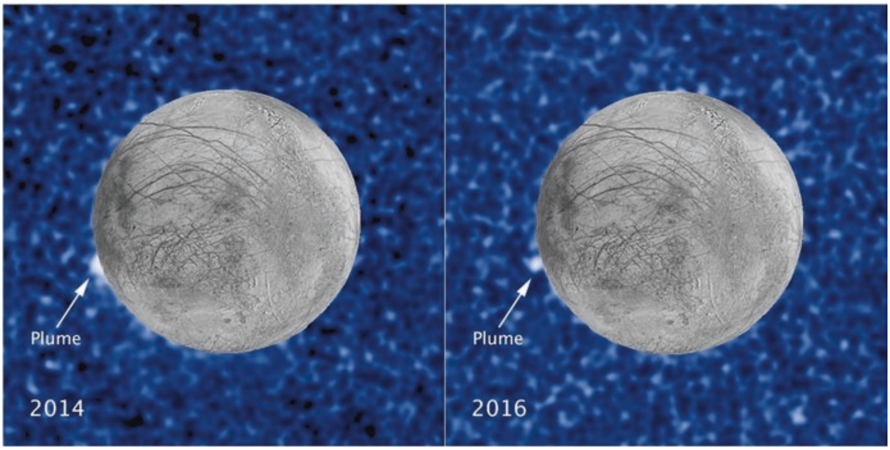

Fig. 6.5. Potential plumes on Europa detected by the Hubble Space Telescope in 2014 and 2016. (Image courtesy of NASA, ESA, W. Sparks (STScI), and the USGS Astrogeology Science Center.)

Indeed, in ten separate occurrences spanning fifteen months, the team observed the icy moon passing in front of Jupiter, and on three occasions, they saw ultraviolet light being blocked in a way that strongly suggests the existence of plumes. Once again, these seem to rise up to around 200 km before falling back down to the surface.

Two elements from these recent observations have reinforced the case for plumes. The first is that the 2014 and 2016 detections were made at the same location on the moon, the region of Pyrll Crater, which statistically reduces the likelihood that these measurements happened by chance (such as an instrument fluke). The second is that this specific region on the surface was observed by Galileo two decades ago through thermal imagery and was identified as a 'hotspot,' an area that is hotter than it should be. The combination of a hotspot at the same area where ultraviolet light is being blocked strengthens the case for a plume. Either warm water from the subsurface ocean is venting out or ice water from the plumes fall back on the surface and alter its structure, making it better at retaining heat. Either way, these latest discoveries strongly suggest the existence of plumes without confirming it.

Further mapping of Europa's surface is currently being made using the high precision Atacama Large Millimeter/submillimeter Array (ALMA) based in Chile. (This is the most expensive ground-based telescope, consisting of sixty-six 12-m and 7-m diameter radio telescopes.) When combined with complex thermal models, the quality of the ALMA observations has the potential to rival Galileo's observations, although, at the time of writing, this wasn't the case yet.

If future observations do confirm the existence of water plumes, the implications for the study and exploration of Europa will be substantial. Future spacecraft will be able either to fly through the plumes and analyze the ocean water at a safe altitude or land on the surface where the plumes have rained back down. This eventuality in addition to the direct sampling of the chaotic regions, as mentioned earlier, removes any need to drill through Europa's icy crust to study its habitability.

Assessing Europa's Habitability

In terms of habitability, Europa seems to have many ingredients necessary for life – a vast salty subsurface ocean as ancient as the moon itself (around 4.5 billion years old) and resting on the rocky mantle that steadily diffuses heat through radiogenic heating. In addition, the moon's eccentric orbit in resonance with Io and Ganymede generates inexhaustible amounts of tidal heating, and a young and thin icy crust allows the transportation of non-ice material to and from the surface, some of which originate from neighboring Io.

Of course, our knowledge of Europa is still very limited. If minerals are indeed being diluted into the ocean through the rock/water interface (more on this below), then the subsurface ocean should be composed of many more minerals than have been suggested so far. To illustrate such possibilities, an interesting study published in 2016 and led by Steve Vance from NASA's Jet Propulsion Lab, found that, chemical cycles within the moon could actually generate hydrogen and oxygen without the need for volcanic hydrothermal activity.

Indeed hydrogen could be formed through a process called serpentinization, where salty water from the ocean seeps into the cracks within moon's crust and produce, via a chemical reaction, hydrogen and heat. Models have shown that Europa's rocky mantle could have cracks as deep as 25 km, providing extensive surface areas for such reactions to take place around the entire moon.

Oxygen, on the other hand, is produced not deep within the subsurface ocean but instead on the surface. As we have seen earlier, water-ice located on the surface is split by radiation into oxygen and hydrogen (which escapes into space). The study has shown that the oxygen can be cycled back into the subsurface ocean through the convection processes thought to be occurring within the icy crust. Calculations have shown that oxygen could be produced at a rate ten times higher than hydrogen and might even reach levels that exceed Earth's oceans.

Would such an abundance of oxygen be suitable for life? Not necessarily. Oxygen is an oxidant, a substance that tends to take molecules apart, so structures vital for life would have a hard time assembling themselves in an oxygen-rich environment. On Earth, oxygen was introduced (slowly) into the environment allowing more complex life forms to evolve to tolerate it.

Furthermore, given the ubiquitous nature of organic compounds in asteroids and comets, and the likely ability of Europa's thin crust to transport surface material to the subsurface ocean, there is a very high probability that such compounds can be found in the ocean as well.

Given all the above, it is not surprising that many scientists believe that life could have emerged at some point during the 4.5 billion years that Europa's subsurface ocean has existed, although geological processes would have changed the properties of the ocean through time, probably making it more habitable at one period and less at another.

A few more points are worth exploring here. First of all, a big unknown for astronomers is, where does the energy produced by tidal heating operate within Europa's interior? It might be that all the energy is concentrated on the icy crust and the top of the ocean, warming the ocean and crust leaving the seafloor static. Or the energy could instead be directed towards the seafloor, where rocks would be heated up and chemically react with liquid water – such as what occurs in a hydrothermal vent. Of course, it could also lie halfway in between, mainly warming the ocean.

Until we have a good idea as to where the heat from tidal heating is operating, we must work with the assumption that if life does exist on the moon, it could be located anywhere, from the ice crust to the bottom of the ocean floor. It might even be that life thrives in the top layer of the upper crust, protected from the harsh radiation by a thin layer of water-ice (10 cm of depth would suffice to block most of the radiation), although the extremely low temperatures encountered there – 133 K (–140 °C) on average – prohibits the growth of life as we know it.[2]

Another point worth mentioning is that although there is much hope for the existence of hydrothermal vents operating on Europa's seafloor, there is no certainty that life could have started there. Indeed, even if these hot vents are one of the candidates for the origins of life on Earth, given the extreme pressures encountered at the base of the Europan ocean floor – five times more than that at a mid-ocean ridge on Earth – the chemical reactions taking place within a hydrothermal vent will be balanced unfavorably for life. For example, methanogenesis (the biological production of methane) is prominent within the vents on Earth, as microorganisms have found a way to combine the carbon dioxide and hydrogen outgassed by the vents and form methane and water. This reaction (an equilibrium) can be written like this:

$$CO_2\left(aq\right)+4H_2\left(aq\right)\rightleftharpoons CH_4\left(aq\right)+2H_2O \qquad (6.1)$$

At high temperatures such as those encountered within the vents, the equilibrium tends to be located to the left of this reaction, where most of the carbon is trapped as carbon dioxide. Methanogenic life forces this equilibrium to be shifted towards the right, where carbon forms methane, and in doing so, some energy is released. Microorganisms feed on this.

This shift from left to right occurs naturally at lower temperatures. On the other hand, a vent on Europa's ocean floor, crushed under a colossal column of water, will encounter pressures large enough to force this equilibrium to the right making carbon dioxide less available. In such conditions, it would be difficult for life to sustain itself with this energy source.

[2] The coldest environment on Earth where active microbes have been found is 252 K (–20 °C) in the north Arctic. Most cellular reproduction stops after this.

It is nevertheless possible that other similar equilibrium reactions could be used instead, such as one using ferric iron instead of carbon. As such, more research is required to simulate deep-sea vent environments lying on Europa's ocean floor, but it already seems likely that biological methanogenesis is not the way to go on Europa.

A final element that highlights the difficulties of finding life in a subsurface ocean if it does exist is the existence of a pelagic ocean. On Earth, this refers to the open waterways that are far away from the shore or the seafloor and are characterized by a low density of life. Basically, in a pelagic ocean, life is being diluted to such an extent that discovering an organism would require a ludicrous amount of seawater to be sampled. Since Europa's ocean has a vast seafloor and is far deeper than any ocean on Earth, up to 100 to 150 km, there is a real reason to consider the limitations it could bring to our search for life. One way out of this problem is the existence of a process called bubble scrubbing. On Earth, whenever bubbles created on the seafloor rise to the ocean's surface, they have an effect of concentrating organisms and organic material and depositing them on the ocean's surface. This process could also exist on Europa. It might be that thanks to bubble scrubbing, we could still find microorganisms within the hypothetical plumes in sufficient concentrations to be detected by future instruments.

Given the many uncertainties that remain regarding Europa's interior properties, it might be that most of the estimates presented earlier are off by orders of magnitudes, which could either benefit or hinder life's chances of appearing. Nevertheless, a negative result in a life detection mission on Europa might not necessarily imply that there is no life in the subsurface ocean, just that we need more sensitive instruments.

Regardless, let us imagine that we are lucky and life has indeed arisen somewhere within Europa's subsurface ocean. What life forms could be present there? Simple cell life forms such as extremophiles on Earth (bacteria or archaea) thriving on chemosynthesis is the safest bet. More elaborate life forms such as soft-bodied jellyfish or hard-shelled shrimp would require a series of events such as the apparition of eukaryotic cells, multicellular organisms, oxygen-rich waters, as well as a constant source of energy capable of fueling such creatures. That such events have occurred both on Earth and within the interior of an icy moon seems highly improbable, but the chance remains.

Even bolder, anyone hoping to see whale-like creatures in this ocean will be disappointed. Elaborate ecosystems (large food chains) are required for life to evolve into complex marine animals, necessitating significant amounts of energy for billions of years. Various studies have shown that given what energy sources are known to be available within the moon's interior, complex life forms are highly unlikely. The global ocean within Europa is a silent one.

Of course, nature can surprise us, especially when so little is known. Nevertheless, given our current understanding of biology and the known characteristics of the subsurface ocean, single-cell organisms are what scientists hope to find.

As such, the moon has become once again a prime target for space agencies. NASA's new flagship mission to the outer planets, the Europa Clipper, will be launched within the mid-2020s to investigate via remote sensing instruments the moon's habitability, while ESA's JUICE mission will also visit Europa during two close flybys. (See Chapter 12 to review these missions in detail.) Furthermore, NASA is currently evaluating the possibility of sending a lander, the aptly named Europa lander, to the surface to do contact science and look for biosignatures. (Chapter 12 covers this as well as other proposed missions to the ocean worlds.)

It is now time to leave Jupiter and the Galilean moons, which are without a doubt one of the most fascinating collections of worlds within our Solar System, and visit another system which also has much to offer; the Saturnian system.

Saturn, the second of the giant planets, not only has a majestic set of rings to contemplate, but also hosts a large and diverse satellite system within which three remarkable moons are worth exploring as part of this ocean worlds journey: Titan, Enceladus, and Dione. The next two chapters will be devoted to the confirmed ocean worlds of Titan and Enceladus, thus completing the second part of this book, while Dione will be covered in the third part.

Let's go to Saturn!

7. Titan

The Saturnian System

Surrounded by an abundance of moons and rings, Saturn is home to some of the most awe-inspiring sceneries in our Solar System. Its satellite system is a rich one as it hosts a varied collection of moons, sometimes referred to as the Cronian moons. (Krónos is the Greek name for Saturn.) At the time of writing, a total of 53 had been confirmed so far (another nine are provisional). These include Titan, the second largest moon in our Solar System, and an assortment of mid-size to small icy moons each unique and intriguing, listed here from biggest to smallest: Rhea, Iapetus, Dione, Tethys, Enceladus, and Mimas. Let us also not forget the tiny irregular moons of Hyperion, Phoebe, and Janus. (In contrast Amalthea, Jupiter's fifth biggest moon – the next one after the Galilean moons – is smaller than Janus.)

Because Saturn's orbit lies much further out from the Sun, icy compounds are found in greater abundance. Nothing illustrates this better than the planet's majestic rings, which are made up almost entirely of tiny particles of water-ice. Also, many mid-size and small moons have significant amounts of water (Tethys and Mimas are thought to be made up almost entirely of water-ice) and other antifreeze compounds, making them ideal ocean world candidates (Table 7.1).

The Saturnian system is structured as follows. Closest to the planet lies the classical ring system (with the rings labeled from A to F) and the tiny moons Prometheus and Janus. These are then closely followed by a string of icy moons that increase in size as we move further out from the planet: Mimas, Enceladus, Tethys, Dione, and Rhea. These all sit relatively close to one another and have at times come in and out of resonance with each other. A vast, diffuse ring, the E-ring, is embedded within the orbits of these five moons, with Enceladus for its source. (See Chapters 1 and 8 for more details on this ring.)

B. Henin, *Exploring the Ocean Worlds of Our Solar System*, Astronomers' Universe, https://doi.org/10.1007/978-3-319-93476-1_7

Table 7.1 The main characteristics of Saturn's biggest moons

Properties of Saturn's biggest Moons

Moon	Mean distance from planet 10^3 Km	Orbital period/ Days	Mean radius Km	Mass 10^{20} kg	Density 10^3 kg/m^3	Eccentricity	Discovery year	Discoverer
Mimas	186	0.94	199	0.38	1.15	0.02020	1789	W. Herschel
Enceladus	238	1.37	249	0.73	1.61	0.00470	1789	W. Herschel
Tethys	295	1.89	530	6.2	0.96	0.00010	1684	G. Cassini
Dione	377	2.74	560	10.5	1.47	0.00220	1684	G. Cassini
Rhea	527	4.52	764	23.1	1.23	0.00126	1672	G. Cassini
Titan	1222	15.95	2575	1346	1.88	0.02880	1655	C. Huygens
Iapetus	3561	79.3	718	15.9	1.09	0.02862	1671	G. Cassini

As we move out from the furthest of these inner moons, Rhea, lying roughly half a million kilometers from the planet, we encounter a gap of 700,000 km where no moons or rings can be found until we reach Titan, orbiting at 1.2 million km from Saturn. The giant moon has for a close neighbor tiny Hyperion, which is so small that it can't even form into a spheroid shape. Then, mid-size Iapetus is located at three times the distance Titan is from Saturn, while the next moon after that is Phoebe, located even further at ten times the distance (notwithstanding the two moonlets Kiviuq and Ijiraq as well as the Phoebe ring).

Titan will be examined in this chapter, Enceladus in the next, Dione in Chapter 9, Rhea in Chapter 11 and Mimas can be found in the Appendices section of this book.

Titan's Discovery

The discovery of the second biggest moon in our Solar System is a classic story in the history of astronomy. Discovered by Dutch astronomer Christiaan Huygens on March 25, 1655, it had actually been spotted earlier by the Polish astronomer Johannes Hevelius (who was the first Pole to be made a member of the Royal Society in London and whose second wife, Elizabeth Koopman, is considered to be one of the first professional female astronomers). A patient man, Hevelius had already studied Saturn for 14 years (from 1642 to 1656) and made countless drawings of strange sickle-like shapes around it. These were named 'ansae,' as astronomers at the time didn't recognize them as rings. During his observations, the Polish astronomer would spot now and again a 'star' close to Saturn, but not knowing what to make of it, decided it was of no importance, as it was most likely just another star. (Star charts for telescope observations were rare at the time.)

Huygens, on the other hand, understood very quickly that this 'star' might be something else. A formidable mathematician and an amateur astronomer at the time, Huygens wanted to see for himself Saturns' mysterious ansae that were being reported by astronomers such as Hevelius. He pointed his newly built telescope (which wasn't exceptional by any means) towards the planet and frustratingly saw nothing of these. Unknowingly to him at the time, the planet's position around the Sun had changed since Hevelius' observations, and the rings were now displayed as side-view, making them practically invisible to an observer on Earth.

This circumstance nevertheless proved fortuitous for Huygens, as it had the effect of dimming the brightness of the ansae (rings), making it easier to spot whatever big moon was orbiting Saturn.

Perplexed by the missing ansae, the Dutch astronomer continued to observe Saturn and spotted a 'star' near the planet, at 3 minutes of arc away. Following a hunch, he decided to observe it through multiple nights, and by tracking the motion of the star, Huygens quickly realized that it shared the properties of a moon. Excitedly, he continued tracking it and eventually managed to calculate the time it took for the moon to orbit around Saturn – 16 days. Wasting no time in communicating his observations, Titan's discovery captivated the public, and Huygens became famous overnight.[1]

There was no doubt that Huygens was a bright man with a powerful intuition. In addition to his discovery of Titan, he was also the first to realize that Saturn's mysterious ansae were part of a giant ring orbiting the planet. Ironically, having never seen the ansae himself, he referred to the drawings made from previous observations by Helevius and his contemporaries.

Titan became the sixth known moon (after our Moon and the four Galilean moons discovered fifty years earlier), although it wasn't referred to as Titan at the time since Huygens had decided to simply call it *Saturni Luna,* which means Saturn's moon in Latin. Very soon Saturni Luna proved exceptional as astronomers recognized it to be very big, and was erroneously thought of being even bigger than Ganymede, the biggest of the known moons. Such a mistake was easy to make, as in addition to the presence of a thick atmosphere enwrapping Titan (unknown at the time), which had the effect of extending the moon's apparent size, the difference in radius between Ganymede and Titan is very slim, just 60 km. It would take more than 250 years and the advent of the Space Age for Ganymede to regain its crown as the Solar System's biggest moon.

In the meantime, new companions to Saturni Luna were found by the prolific Italian astronomer Giovanni Domenico Cassini – Iapetus in 1671 and Rhea in 1672. With the existence of these new moons, the name Saturni Luna wouldn't do anymore, and it was quickly changed to Saturn II, following the same nomenclature

[1] In a similar fashion to Helevius, the British astronomer Christopher Wren was also thought to have spotted Titan earlier but had also failed to make the connection between the 'star' and a potential moon.

used in the Jovian system where the moons are ranked by the distance to their planet. As such, Rhea was closer to Saturn and was named Saturn I, while Iapetus, further out, became Saturn III. In 1684, the Italian astronomer, still hard at work, discovered two additional moons, Dione and Tethys, both closer to Saturn than Rhea. Such a discovery pushed Titan's rank to Saturn IV, as Tethys had now become Saturn I, Dione was named Saturn II, Rhea was changed to Saturn III, and Iapetus Saturn V.

Of course, it was only a matter of time before new moons would be seen, forcing the names to be changed once again. This occurred in 1789 when the British-German astronomer William Hershel discovered the smaller moons of Mimas and Enceladus lying even closer to the planet than Tethys (or Saturn I); the nearest moon at the time. Mimas therefore became Saturn I, Enceladus was given Saturn II, Tethys jumped to Saturn III, Dione moved to Titan's previous name Saturn IV, Rhea became Saturn V, Titan was Saturn VI, and Iapetus Saturn VII.

Confused? By that time many people were. Reading through journals and notes made by previous observations became frustratingly tricky as astronomers had to keep track of the name changes throughout the years to make sense of what object they were reading about. To resolve this problem, it was decided that the names of Saturn's moons become permanently frozen regardless if new moons would be discovered – Titan would always be named Saturn VI and Enceladus Saturn II. Such a solution rendered the naming convention rather useless. It is maybe with this in mind that in 1847, Hershel's son, John, proposed new names for Saturn's moons based on Greek mythology. Accepted by the scientific community without much resistance, the moons were quickly renamed, and Saturn VI became Titan, an appropriate name since it was still thought to be the biggest moon of the Solar System.

The Atmosphere

As with many satellites in our Solar System, Titan was a strange curiosity for hundreds of years. Apart from noting that it had an orange tinge, unique among the moons, nothing more could be inferred due to the technological limitations of the times. It would be anyone's guess what Titan might be like. Then, in 1907, the moon came back into the spotlight when the prominent Spanish astronomer Josep Solà claimed to have observed limb darkening (when a planetary body appears darker at its edge or limb), inferring the presence of an atmosphere. This seemed dubious as he had already claimed the same for the Galilean moons as well, which possessed no such atmosphere. Nevertheless, astronomers' interest was piqued, and in 1925, Sir James Jeans, a brilliant British astronomer, worked on the theoretical study of escape processes in atmospheres around planetary objects. The study included Titan as well as the Galilean moons, and he found that despite its weak gravity, Titan could, in theory, have an atmosphere if its surface temperatures were very low, around 60 K to 100 K. He had calculated that at this temperature range, gases that had a molecular weight of 16 or higher would not be able to reach escape velocity (when they can escape the moon's gravity) and therefore form an atmosphere around the moon. These gases included ammonia, argon, neon, nitrogen, and methane.

Furthermore, he predicted that if an atmosphere did indeed exist on Titan, it would be mainly composed of methane, argon, and neon. With methane being more easily detectable through an infrared spectrum than argon and neon (they have weaker absorption bands), he suggested that methane would be the first gas to be detected on Titan once the technology would permit such observations in the decades to come.

To grasp Sir Jeans' remarkable insight, we need to step back and understand the conditions required for atmospheres to form on small planetary bodies.

In Chapter 2, we explained how, during the formation of our Solar System, most gaseous elements close to the Sun couldn't condense due to the star's radiating energy and were blown away by solar wind. Water, methane, nitrogen, and other volatiles got nudged out of the inner Solar System, which explains why the inner planets (Mercury, Venus, Earth, and Mars) are mostly composed of rocks and metals (hence the term terrestrial planets to describe them).

The water and other volatile compounds that currently exist on Earth, Venus, and Mars were not present when these planets were formed but were instead deposited later by comets and ice-rich asteroids. Once the terrestrial planets took stock of their newly added volatile compounds, they hosted surface oceans and were enveloped by thick atmospheres (mostly composed of nitrogen gas). Thankfully for us, Earth's magnetosphere, as well as geological and biological activity present within our planet, helped sustain the oceans and atmosphere throughout billions of years.

Mars and Venus, on the other hand, were unlucky. The nitrogen and other gases in the early Martian atmosphere were blown away by the solar radiation due to the lack of a protective magnetosphere, while Venus suffered the complete opposite, as too much geological activity (volcanism) pumped considerable amounts of CO_2 and sulfur into its atmosphere, heating it up like a pressure cooker. We review the fate of Venus' and Mars' oceans of liquid water and atmosphere in more detail in the appendices of this book.

Moving on to the outer planets, the location within our Solar System of Jupiter and its satellite system seems to inhibit the formation of atmospheres on its moons. Indeed, at 5 astronomical units, we are past the frost line, where it is cold enough for water to condense into ice and become a significant part of the icy moons' composition. However, it is still 'too hot' for the condensation of other volatiles such as nitrogen or methane to occur. With no apparent mechanism to deliver these volatiles once the moons have formed, none of the Galilean moons have a substantial atmosphere. (The tenuous atmospheres found around Callisto, Europa, and Ganymede are so insubstantial that they are regarded as exospheres, or a negligible atmosphere in the case of Callisto.)

The conditions change once we go further out from the Sun. Much like the Jovian system, water is again a significant component of planetary bodies within the Saturnian system.

What is remarkable, though, is that the temperatures found at this location of our Solar System are just about right to allow ammonia, nitrogen, neon, argon, and methane to become an integral part of the moons' composition, depending on the moon's condition.

For Titan, ammonia-ice was present as building blocks from the start and, mixed with water-ice, formed the moon's icy crust. Soon after, nitrogen molecules from the ammonia-ice were converted into gas through the action of various mechanisms such as photolysis or in contact with heat sources. A nitrogen-rich atmosphere was formed. Nowadays, nitrogen makes up over 95% of the atmosphere with argon, methane and other trace gases making up the rest (some of which form thick organic smogs). Remarkably methane and ethane are both found in gas and liquid states, creating cycles of rain and clouds (analogous to Earth's water cycle albeit at lower temperatures averaging 94 K), as well as lakes and seas, which cover 2 percent of the moon's surface. Add simple and complex organic compounds to this mix of hydrocarbons, and you get an excited crowd of astrobiologists eager to send robotic probes to its surface. Yet, if the Saturnian system was located a little further out from our Sun, the colder temperatures would freeze the methane and nitrogen to the ground.

Astronomers (a patient bunch) had to wait for 20 years after Sir Jean's prediction to finally be able to do spectroscopic analysis of Titan's light. The honor went to the famous Dutch-American astronomer Gerard P. Kuiper, who after observing spectroscopically the ten largest satellites of the Solar System as well as the planet Pluto, found that only Titan showed any evidence of an atmosphere. Sir Jeans had been right all along.

Furthermore, Kuiper detected the absorption made by methane in Titan's spectra as predicted by Sir Jeans. This news had a big impact on the science community, and more resources were allocated to find out more about this moon and its atmosphere, yet astronomers were pushing the limits of what technology could realistically achieve at the time, and little progress was made throughout the next two decades.

The status quo was changed in 1973 and 1975 when new measurements from ground-based observations detected thick concentrations of particles within the high altitudes of Titan's atmosphere. This led scientists to propose the presence of hazy clouds formed from condensed methane and complex organic compounds such as oily droplets resulting from the breakdown of the methane by UV light and the recombination of its constituents into polymers. The thought of a moon hosting a thick atmosphere composed of organic compounds was an extraordinary one. With scientists eager to know more, Titan became a top priority in planetary science.

In fact, titan and its mysterious atmosphere proved so crucial to planetary scientists that it became a prime target for the yet-to-be-launched *Voyager 1* and *2* probes, as important as the study of the planets Jupiter and Saturn themselves. As such, *Voyager 1* was deliberately launched on a trajectory to provide the optimum flyby of Titan, and if it had failed its mission, *Voyager 2,* arriving a few months later, would have been requested to do the flyby instead, preventing them from visiting the Uranus and Neptune systems. In other words, two dominant planets and their diverse satellite systems of which we knew next to nothing were judged less important than Titan.

Before the Voyagers' arrival, the plucky *Pioneer 11* reached the Saturnian system by September 1979, the first to do so. (This mission is reviewed in detail in the next chapter on Enceladus.) Titan was listed as a priority target in addition to the giant planet

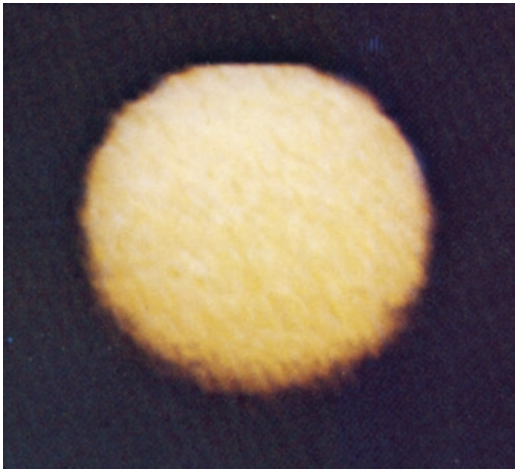

Fig. 7.1. The first image of Titan by *Pioneer 11* taken on September 2, 1979, from a distance of 360,000 million km. It was constructed from five images. The quality is limited due the limited quality of the Pioneer imaging system as well as poor telecommunications at the time of the Titan encounter. (Image courtesy of NASA.)

and its rings, and the spacecraft's trajectory took it as close as possible to the moon, a distance of 360,000 km. There, the first images of Titan were made – five in total – (see Fig. 7.1), and astronomers soon realized upon looking at the fuzzy, indistinct disk that the thick atmosphere would be a severe impediment to the study of the giant moon. *Pioneer 11* did reveal Titan to be a very cold place with an average temperature of almost 93 K (–180 °C), removing any possibility that life as we know it could have arisen there.

Voyager 1 and Cassini-Huygens

A year later, planetary scientists were in high spirits as *Voyager 1* successfully crossed the Saturnian system and made its close encounter with Titan at a distance of only 4,394 km. It was a brief one, lasting just a few hours. It is during this flyby that Titan's diameter was revealed to be slightly smaller than Ganymede, which became once again the largest moon in the Solar System. *Voyager 1's* data also allowed scientists to calculate Titan's density, which was found to be similar to Ganymede's and Callisto's, composed of half water and half rock. At the time, subsurface oceans under the Galilean moons were starting to be considered, although it was too early still for scientists to recognize that such an ocean could exist on Titan as well.

The images returned by *Voyager 1* were a huge disappointment, as Titan's thick atmosphere masked the surface entirely, and no features could be detected. Nevertheless, Titan's atmosphere was found to be almost entirely made up of nitrogen (98% in upper atmosphere), methane (between 2% and 8%), trace amounts of hydrogen, carbon monoxide, carbon dioxide, as well as organic gases such as ethane, propane, acetylene, ethylene, hydrogen cyanide, diacetylene, methyl acetylene, cyanoacetylene, and cyanogen.

Finding nitrogen in Titan's atmosphere hints at a geologically active past. When frozen ammonia (NH_3) is heated up, it turns into vaporized nitrogen, which then gets vented off in the atmosphere by cryovolcanism. There is no doubt, though, that sunlight is partly responsible for the atmospheric nitrogen as it broke down the surface ammonia ice into hydrogen and nitrogen, which bonded to itself to form the inert N_2.

The detection of methane in the atmosphere, although predicted by Sir Jeans, is intriguing since the gas gets broken down by sunlight into hydrogen. Its lifetime is tens of millions of years only. Therefore something must be replenishing the methane in Titan's atmosphere, with the most likely culprit being geological processes, although biological origins can't be excluded. (Only 5% of the methane on Earth is produced by geological processes.)

Scientists also found that once the methane gets broken down, carbon atoms recombine to form complex organic molecules, some of which condense in the atmosphere and precipitate out, forming on the surface thick oily substances referred to as tholins. The idea that organic molecules were raining down on the moon's surface ignited the imagination of the science community and the public at large. There was no other object like it in our Solar System. Titan was unique. We had to go back.

Following the Voyagers' successful flyby and Galileo's spacecraft, NASA and ESA teamed up to build a flagship mission dedicated to exploring the Saturnian system: the Cassini-Huygens orbiter and landing probe. Along with the giant planet and its rings, Titan was the prime scientific objective, and as such ESA built the Huygens probe, whose sole mission would be to fly through the moon's atmosphere and touch down on its surface, a first in the outer Solar System.

Before Cassini-Huygens' arrival in 2004, planetary scientists had taken note of the data returned by the Galileo orbiter confirming the existence of subsurface oceans within the Galilean moons. Using theoretical models based on thermal and mechanical properties of ices and silicates, they argued that a subsurface ocean composed of liquid water might also exist on Titan, similar to the one discovered under Callisto, despite surface temperatures as low as 95 K (−178 °C).

To make this possible, our two usual suspects, radiogenic heating and tidal heating, had gained a new partner; ammonia (NH_3). Indeed, water rich in ammonia has its freezing point lowered considerably, as ammonia freezes at only 196 K (−77.7 °C). The models suggested that depending on the concentration of ammonia (and other volatile gases) present within the primordial liquid layer, the physical conditions were right for a global liquid mantle of water and ammonia to form 350 km under the icy shell. This was an exciting possibility. All that was required now was to prove it.

On its arrival in 2004 until 2017, the Cassini orbiter would perform more than a hundred flybys of Titan and map the moon's surface despite its thick atmosphere while the Huygens lander made a successful touchdown and analyzed the surface in situ. What these intrepid travelers discovered is nothing less than extraordinary: lakes and shallow seas of methane and ethane dot the northern hemisphere, while dunes rich in hydrocarbons cover the equator. Such environments opened up new perspectives in the search for extraterrestrial life, although with surface temperatures dropping to 95 K (−178 °C) life would genuinely be alien, one that bears no resemblance to the one on Earth.

As fascinating as the surface proved to be, planetary scientists were also keen to find pieces of evidence for a water environment deep below the frozen crust. Could a subsurface ocean exist?

Luckily it didn't take long for the first tantalizing clues to appear.

The Evidence of a Subsurface Ocean

On January 14, 2005, the Huygens probe performed the most distant and daring landing of any human-made craft. After a two hours descent through Titan's atmosphere, it touched down on a fluvial basin covered with organic-rich material and dotted with pebbles most likely made up of hydrocarbon coated water-ice (see

Fig. 7.2. Titan's surface as seen by Huygens. This is the first image from a planetary surface within the outer Solar System. Globules (probably made of water-ice) 10 to 15 cm in size lie above a darker, finer-grained substrate in variable spatial distribution. (Image courtesy of ESA/NASA.)

Fig. 7.2). An array of scientific instruments had captured data all the way down, although things didn't go entirely to plan as a misfortunate software error prevented the transmission of half of the images taken by the probe as well as the loss of all the data on wind speed and Doppler radio measurements.

Amid the scientific instruments carried by Huygens was the 'Permittivity, Waves, and Altimetry' sensor (also known as PWA) on the Huygens Atmosphere Structure Instrument (HASI). PWA was meant to measure the ambient electric field in Titan's atmosphere during the descent and could detect extremely low frequencies (ELF) which are radio waves that oscillate very slowly (i.e.: 36 times a second). On our planet, ELFs (often referred to as Schumann resonance) are produced by thousands of lightning bolts taking place each minute within the atmosphere. Earth was the only known planetary object where ELFs had been detected, and since lightning was thought to be prevalent in Titan's atmosphere (A microphone – a first for interplanetary spacecrafts – had been installed on the lander to listen for thunder.), scientists assumed that ELFs could be detected on the moon as well.

Although lightning didn't get picked up, PWA data revealed a narrow-band signal at about 36 Hz during Huygens' descent to Titan. A clear indication that ELFs had been produced despite the absence of lighting. This was a fortunate discovery as ELFs can penetrate deep into the ground and continue until they hit a layer of conductive material which then reflects them back out. On Earth, the ground is highly conductivity and bounces ELFs back as soon as they hit the surface. Titan's surface, on the other hand, has a low conductivity allowing ELFs to pass straight through the top layer until something reflects them back, which is what seemed to have occurred with the ELFs detected by the lander.

In fact, after carefully examination of the data, scientists at ESA determined that Titan's ELFs are trapped in a 'cavity' between the moon's ionosphere (found between 40 and 140 km in altitude) and a lower boundary, some 55 to 80 km below Titan's surface, where a conductive layer exists. The scientists involved with the PWA instrument suggested that a thick layer of liquid water or salts mixed with ammonia could generate the conductivity required to produce the observed pattern. The Huygens team seemed to have discovered a first hint that Titan's subsurface ocean existed, although not everyone was convinced of this interpretation. Today, the Schumann resonance detected by Huygens is seen, at best, as weak evidence in support of a subsurface ocean.

Luckily, stronger evidence for a subsurface ocean was on its way. This proof, which everyone could agree with, came in 2012 when a team led by Luciano Iess of Sapienza of University in Rome, accurately tracked Titan's shape as it orbited Saturn. The moon goes around the planet in 16 days, but like most objects doesn't follow a perfectly spherical orbit but a slightly eccentric one. At its closest to Saturn (periapsis), the planet's substantial mass stretches the moon, elongating it like a rugby ball. At the farthest point (apoapsis), the moon reverts to a more spheroid shape. Since scientists couldn't precisely measure the moon's shape due to its thick atmosphere, an alternative solution was found – minute fluctuations in the spacecraft's velocity could be measured as it went along the moon. Cassini's Radio Science Subsystem sent radio signals at 33,000 and 140,000 bits per second for NASA's Deep Space Network to pick up on Earth. By precisely measuring when these signals arrive, we could determine the spacecraft's velocity at a given time and therefore how it was being influenced by the gravity of the objects close by. In doing so, they detected the gravitational effect due to the variation of Titan's shape and mass along its orbit.[2]

[2] Gravity cannot be directly measured by a spacecraft due to its inherent motion in space (as if in a lift in freefall). Only by interpreting the variations in the radio waves emitted by the spacecraft can we infer the gravity effect on a spacecraft.

Luciano Iess and his team discovered that the moon is shaped by tides of up to 10 m high as it orbits Saturn. These are ten times higher than if Titan's interior was entirely frozen solid, and models show that such variability in the moon's shape can only be explained if a thick icy crust rests upon a flexible mantle of liquid deep down below. This new line of evidence, which has been refined throughout the years, had finally given planetary scientists what they were looking for; Titan's subsurface ocean is a reality.

And so, after Callisto, Europa, Ganymede, and Enceladus, Saturn's biggest moon is the fifth known ocean world in our Solar System. In addition to the organic chemistry occurring on its surface, Titan had become an even more extraordinary planetary object.

(It is worth pointing out that another paper appearing in 2008 reported apparent shifts in surface features, suggesting a variability of Titan's rotation period by about 0.36 degrees, which in turn would hint at a subsurface ocean. This was later disproved as an artifact of early engineering software used to analyze the radar data) (Fig. 7.3).

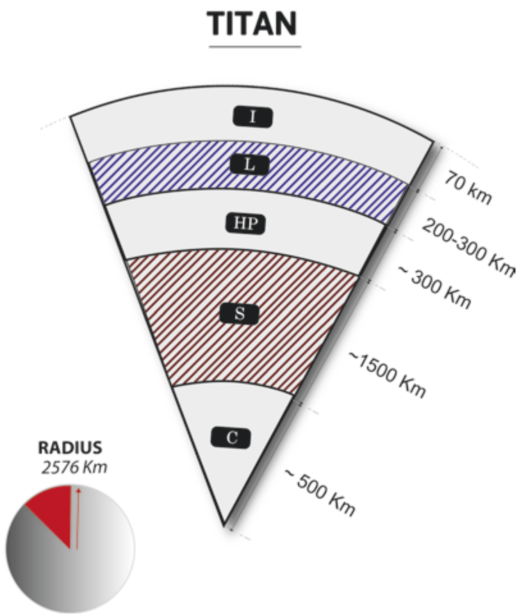

Fig. 7.3. Diagram showing the interior of Titan, where the subsurface ocean lies between two layers or thick ices. The thickness of the mantles is not well known. I Ice, L Liquid, S Silicate mantle, C Core. Diagram is not to scale

The Ocean and Its Habitability

So what can we infer from all these findings?

Titan has a global subsurface ocean a few hundred kilometers thick lying under a de-coupled icy shell (meaning that the icy crust slides on the liquid mantle). This shell, mostly made of Ice Ih and some ammonia, has an average thickness of around 70 km, although recent studies have instead implied that in some areas, it could be as thin as 10 to 50 km. Gravity and topography data collected over ten years of Cassini's flybys found that the subsurface ocean is of high density similar to the saltiest bodies of water on Earth such as the Dead Sea. This suggests that the ocean has to be charged with salts, most likely sulfur, sodium, and potassium. Ammonia should also be present in non-negligible quantities, allowing the ocean to stay liquid at very low temperatures.

This ocean rests on a high-pressure layer of solid ice, most likely Ice VI, although the exact phase of ice is currently unknown. (See Chapter 4 for further details on ice phases). This icy mantle then rests on a rocky mantle a few thousand kilometers in diameter. So, much like the oceans of Callisto and Ganymede, Titan's subsurface ocean is sandwiched between two thick layers of ice – the icy crust at the top and the HP icy mantle at the bottom – sealing it from the rocky material below.

Nevertheless, as we saw in our chapter on Ganymede, this doesn't necessarily imply that the ocean is isolated; in theory, warm bubbles of ice charged with minerals and chemicals originating from the silicate mantle could rise within the HP ice through convection and reach the subsurface ocean – a remote possibility, but a possibility nevertheless. In addition, the Cassini orbiter detected slight traces of argon-40 in Titan's atmosphere, which is intriguing since this isotope of argon is the result of the decay in potassium-40, an element found in rocks, suggestive of past water-rock interaction.

Looking upwards, could there be any exchanges between the subsurface ocean and the organic-rich surface? The thickness of the icy crust is a severe impediment, although one of the most recent finds has been the discovery of cryovolcanoes on the moon's surface. Researchers analyzing topographical data discovered a region called Sotra Facula, where three large volcanic cones (1 to 1.5 km tall) were found to have deep pits. It is very likely that these could have been releasing subsurface materials into Titan's atmosphere in the past, most likely replenishing it with methane.

Also, evidence of resurfacing has been detected in certain places, suggesting past geological activity as well, most likely due to cryovolcanoes. Although these discoveries provide insight into the heat exchanges that might occur within the icy crust, such as bringing material to the surface, the opposite scenario, where organic-rich compounds found on the surface get transported into the icy crust and therefore potentially to the subsurface ocean deep underground, seems very remote.

Titan's subsurface ocean is a truly alien one, an extremely cold mixture of water, ammonia, and salts, with little to no contact with minerals and organic material. The likelihood of life arising in such conditions is extremely low. Alas, given that the ocean is sealed under a thick layer of ice, we most likely will never know what lies within it.

There is one subsurface ocean in our Solar System, though, where this is not the case. Hosting deep cracks within its icy crust and venting seawater directly into space, Enceladus' ocean is the most well understood after Earth's surface oceans. It is time for us to visit the most promising of the confirmed ocean worlds in our Solar System.

8. Enceladus

Following our visit to the giant moon Titan in the previous chapter, the small-scale moon of Enceladus is striking. Ten times smaller than Titan and almost one hundred times less massive, this is a planetary object on a different scale than the giant moons we have been reviewing so far. Another arresting feature of the tiny moon is how bright the surface is. With an albedo of 1.34, Enceladus holds the title for the most reflective object in our Solar System, which suggests a very young surface. Furthermore, the giant fissures located within the south pole, or tiger stripes as they are now called, vent seawater into space, feeding the vast nebulous E-ring surrounding Saturn and the neighboring moons. Enceladus punches in well above its weight.

Flying Through the E-Ring

Enceladus was discovered with Mimas in 1789 (more than a hundred years after Titan) by William Herschel, a British astronomer of German origin, better known for his discovery of planet Uranus. By then four additional moons had already been discovered orbiting Saturn: Iapetus (1671), Rhea (1672), Dione (1684), and Tethys (1684).

Initially, Enceladus was named Saturn II (Mimas was Saturn I, Tethys was Saturn III, Dione was Saturn IV, and so forth) following the naming convention used when the moon was discovered. (We detailed in Chapter 7 how this confusing naming convention evolved with time.) It was Herschel's son, John, who later suggested mythological names for all of Saturn's known moons, giving us the name Enceladus.

Once discovered, astronomers closely followed the orbits of the Saturnian moons and realized that Enceladus and Dione were locked in a 2:1 orbital resonance with each other, meaning that while Enceladus makes two revolutions around Saturn, Dione makes precisely one. At the time, astronomers looked at these resonances more as mere orbital curiosities driven by the peculiarities of space mechanics than anything worth investigating. In fact, before

B. Henin, *Exploring the Ocean Worlds of Our Solar System*, Astronomers' Universe, https://doi.org/10.1007/978-3-319-93476-1_8

the arrival of space probes, knowledge about the orbits of Saturn's moons was very poor, as most measurements dated back from the 1920's and 1930's. The predictions were fraught with errors into the tens of thousands of kilometers. It didn't matter, though. Apart from Titan, the smaller-sized moons were thought to be inert frozen balls of ice and rocks and were mostly ignored.

As soon as Earth-based photometric instruments became capable of providing noteworthy measurements of the Saturnian system astronomers started to pay attention to the moons again. They noted differences in brightness between the leading and trailing hemispheres of Mimas, Enceladus, Tethys, Rhea, and Dione. Interestingly though, the leading sides of Tethys, Dione, and Rhea were brighter than the trailing side, while the opposite was true for Mimas and Enceladus. No explanation could be given at the time for these differences. Furthermore, Enceladus and Thetys displayed high albedos – noteworthy, but not necessarily extraordinary, for icy bodies. Regardless, technological limitations hindered any further studies on these moons and Enceladus for many decades.

All this changed thanks to a picture taken in 1966 at Allegheny Observatory from the University of Pittsburgh. Walter Feibelman, an American astronomer, spotted what seemed to him as a faint whitish halo located within the orbits of the icy moons (further out from Saturn's rings). It was very tempting to suggest that Feibelman had discovered a new ring of Saturn, although due to its diffuse nature there was no consensus on this interpretation. At the time, the ring system was known to be comprised of only three concentric rings, the A ring (outermost), the B ring (middle) and the C ring (closest to Saturn). Feibelman was convinced that he had found a new ring and named it the E-ring. The story could have easily ended there. Yet follow-up observations hinted that the E-ring seemed to be distributed between the orbits of Mimas and Titan, a vast area of space. Furthermore, it appeared unusually thick at the location of Enceladus' orbit. Could it be that this tiny inert icy moon was the source of the hypothetical ring? Eyebrows were raised.

In fact due to the whitish aspect of the E-ring and the icy nature of Enceladus' surface, some speculated that the ring should be composed of water-ice from the moon. However, no geological processes known at the time could explain how surface material from an inactive icy moon would end up in space. The only plausible suggestion put forward was that Enceladus had recently been hit by interplanetary asteroids resulting in the escape of fine debris. Such an idea wasn't without critics due to the apparent lack of similar rings around Mimas or other similar neighboring satellites –

if asteroids were striking Enceladus, why not the other moons? Astronomers were puzzled. Their only hope to solve this mystery was the arrival of the newly developed space probes brought by the advent of the space age. Pioneer 11 would be the first to visit Saturn.

In fact, the seventies saw a resurgence in the study of the Saturnian system in preparation for trail-blazing space probes, expected to reach the ringed planet by the end of the decade and the beginning of the next one, such as Pioneer 11 and the Voyagers. In fact, when Pioneer 11 was launched in 1973, mission planners had less than six years to work out and agree on the precise trajectory the spacecraft would take. By 1975, more accurate measurements of the moons' orbits and the development of a modern theory of motion bolstered by new mathematical tools gave researchers a high level of precision and confidence in their predictions.

Nevertheless, agreeing on the final course *Pioneer 11* would take proved much harder than anyone had anticipated. The initial path advocated by the Principle Investigators (PIs) – the mission scientists responsible for the quality and direction of the scientific research –was to pass between the rings and Saturn itself, a supposedly debris-free space close to the planet's surface. Such a pass would provide invaluable information on Saturn's magnetic field, its radiation belt and the potential interaction between these and the rings. This would be known as the "inside option." Some members of *the Pioneer 11* team even contemplated sending the space probe through the Cassini division, the biggest of the ring gaps separating Rings B and A. Given that this 'gap' would be later found to be populated by particles similar in size to the C ring, albeit at lesser density, it is fortunate that this path wasn't chosen (Fig. 8.1).

Pioneer 11, a twin of *Pioneer 10* (which we referred to in the previous chapters on the Galilean moons), was primarily conceived to investigate particle and field science and had limited capabilities for other science measurements such as imaging. The "inside option" was, therefore, maximizing the science return from the particle and field science instruments. On its own, this made perfect sense since *Pioneer 11* would not visit any more planets after the Saturnian system (which would have constrained the trajectory taken by the probe), and the mission team wanted to go with a bang even if it was a risky maneuver.

Yet, *Pioneer 11* mission was not operating in isolation. In 1972, as soon as the U. S. Congress agreed to fund the "Mariner Jupiter-Saturn" mission (later renamed the Voyager program), *Pioneer 11's* fate was sealed, as it now had a new mission at Saturn, finding a safe path for the Voyagers.

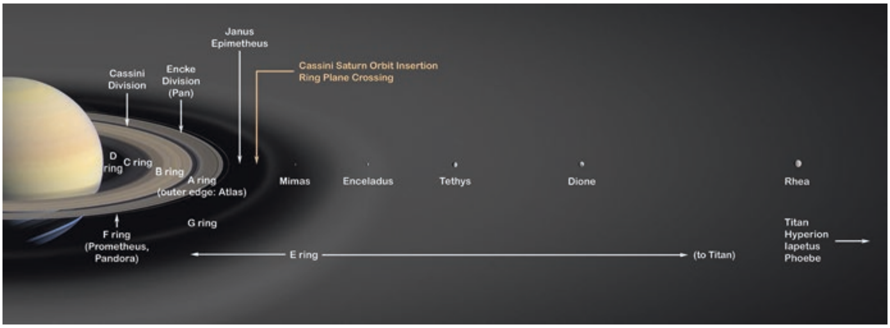

Fig. 8.1. This is an artist's concept of Saturn's rings and major icy moons. Saturn's rings make up an enormous, complex structure although from edge to edge, the ring system would not even fit in the distance between Earth and the Moon. The seven main rings are labeled in the order in which they were discovered. From the planet outward, they are D, C, B, A, F, G, and E. (Image courtesy of NASA/JPL.)

This new approach would prove crucial for the exploration of the outer planets. Although the Congress had initially agreed to fund the Mariner Jupiter-Saturn mission which, as its name indicates, was expected to end in the Saturnian system, scientists secretly hoped that additional funding would be approved subsequently, allowing for the continuation of the mission after Saturn and the visit of Uranus and Neptune – as initially proposed by the Grand Tour program canceled in December 1971 (eaten up by the ballooning costs of the newly approved space shuttle program – see Chapter 6).

If Congress would agree to extend the Mariner Jupiter-Saturn program, one of the spacecraft could use Saturn as a slingshot, placing it on a direct trajectory to Uranus followed by Neptune, thanks to a particular alignment of planets that only occurred once every 175 years. This was an opportunity not to be missed, and ultimately, the renamed *Voyager 2* would be chosen to do such a tour.

As for *Voyager 1,* it had already been decided that the spacecraft would make a close flyby of Titan – one of the prime objectives of the entire mission (see the previous chapter on Titan) – resulting in an upward trajectory out of the ecliptic plane. Due to this, the spacecraft would not visit Uranus and Neptune irrespective of a mission extension.

Also, as the trajectories taken by the Voyager probes within the Saturnian system were being calculated, it was made apparent that, due to the constraints of orbital mechanics, a mission extension to

Uranus and Neptune would require *Voyager 2* to come close to the edge of the A ring, precisely where the E ring was thought to be located (while *Voyager 1* would stay far away from the rings on its path towards Titan). This trajectory for *Voyager 2,* known as the "outside track," became a significant concern for the mission planners.

Astronomers knew that each ring was composed of tens of thousands of individual ringlets, but their exact density was unknown, as was the dust concentration within the gaps themselves. The problem faced by the Voyager team was as such: if the particles were smaller than a millimeter, engineers reckoned that the spacecraft could survive a potential impact and pass through unscathed. Bigger particles, on the other hand, would pose a severe risk, although studies had shown that once the particles became larger than 1 cm, these would become so distant from one another that the chances of an impact would be significantly reduced. Unfortunately, no one knew the average size of the E-ring particles.

To make matters worse, a few years after the apparent discovery of the E-ring (some planetary scientists were still not convinced of the ring's existence at the time), another ring, very faint as well, was found, this time located between the C ring and the planet. It would later be named the D ring. Given these recent discoveries, it was plausible that other diffuse rings could lie around Saturn undetected and be in the path taken by the oncoming spacecraft.

The only way to test if the outside track would be safe for *Voyager 2* was to take advantage of *Pioneer 11's* early arrival and send it first through the E ring. If it passed unscathed, then the passage would be clear for *Voyager 2* to follow.

The drawback was that if both *Pioneer 11* and *Voyager 2* were to follow the outside track successfully, neither would get close enough to Saturn to ensure maximum science return. It was the price to pay for a visit to Uranus and Neptune. If, instead, *Pioneer 11* would suffer any form of damage or even get destroyed, as it forced its way through the E-ring, then the outside track would be deemed unsuitable for *Voyager 2,* preventing it from continuing to the outer planets. In this scenario, *Voyager 2,* unconstrained by a fixed outward trajectory, could visit the Saturnian system on a path better optimized for the study of the giant planet itself.

Time was ticking, and the decision to send *Pioneer 11* on the inside track or outside track had to be made by the middle of 1978 latest. (By then *Voyager 2* had already been launched and was well on its way to the Jovian system.) With both spacecraft built by different teams, *Pioneer 11* by the Ames Research center and *Voyager*

2 by the Jet Propulsion Laboratory (JPL), reaching a consensus for the ultimate path taken by *Pioneer 11* was difficult.

Ames wanted to maximize the science returned by the instruments on their spacecraft – the first ever to visit Saturn – and lobbied for the inside track, while JPL favored the outside track in preparation for *Voyager 2's* arrival. Ultimately, the decision would fall on the director of the Planetary Program at NASA headquarters, held at the time by a brilliant engineer and manager named A. Thomas Young. After carefully examining both options, he sided with strategy supporting the long-term exploration of our Solar System and instructed the *Pioneer 11* team to make the course adjustments necessary to take the outside track, paving the way for *Voyager 2's* trajectory through the E-ring.

Consequently, on September 1, 1979, while *Voyager 2* was on its way to the Saturnian system, *Pioneer 11* crossed the plane of Saturn's rings where the E-ring was located, at a speed nearing 114,000 km per hour. This hair-raising moment lasted just a few seconds, after which the spacecraft successfully carried on its course unharmed, leaving the door wide open for *Voyager 2.* Young had made the right decision, and JPL was contemplating the possibility of exploring Uranus and Neptune.

Ironically, *Pioneer 11* wasn't able to confirm the presence of the E-ring due to technical limitations, but it did nevertheless return great science by detecting two new rings and two new moons, and also studied Titan's atmosphere as well as Saturn's magnetosphere. However, due to the constraints inherent in the given trajectory, the space probe whizzed by Enceladus at a distance of 222,027 km, too far away to take a picture.

And so, as with most of the moons of our outer Solar System, it would be the Voyagers that would bring Enceladus to life.

The Voyagers' Encounter

After its remarkable discoveries at Jupiter (see Chapters 4, 5, and 6), *Voyager 1* was the first to enter the Saturnian system and send back images of Mimas, Rhea, and Tethys within 48 hours. It came closest to Enceladus on November 12, 1980, at a distance of 202,000 km, not much closer than *Pioneer 11*, actually. However, equipped with far more capable imaging instruments the space probe made the first ever picture of Enceladus. It took everyone by surprise. Large areas of the surface were free of craters, contrary to what had been expected, and great grooves and cracks could be found as well. There was no denying that Enceladus had a very young surface, and planetary scientists couldn't help but compare the tiny moon to Europa or Ganymede.

After *Voyager 1's* visit – and before *Voyager 2's* arrival – scientists were hard at work trying to figure out how such a tiny moon could contain enough energy to fuel what seemed to be recent geological activity. Could the tidal heating process newly discovered in the Jovian system be at play here as well?

Furthermore, *Voyager 1* had finally confirmed the existence of the E-ring and revealed that Enceladus was indeed located within its densest part. The icy moon had a direct connection with the E-ring, although scientists still weren't able to determine the process involved in the creation of the ring.

On June 5, 1981, *Voyager 2* whizzed by Enceladus at 87,010 km, returning the first high-resolution images (a few kilometers per pixel) of the surface, more specifically, its trailing hemisphere. These were mesmerizing (Fig. 8.2).

Fault lines, ridges, valleys, plains, and long straight grooves were visible, depicting a highly active world, in fact, the most active of all Saturn's moons. The surface seemed to have melted and frozen multiple times. In addition, the high albedo (the

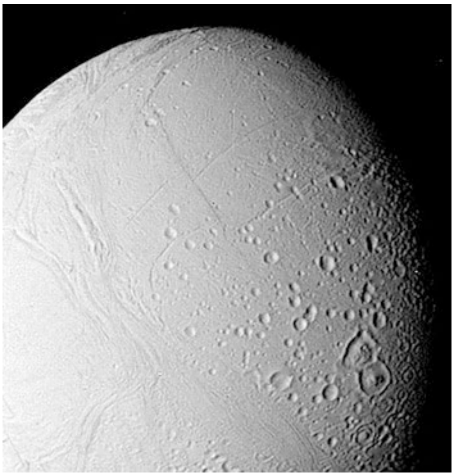

Fig. 8.2. A closeup view of the surface of Enceladus obtained on Aug. 25, 1981, when *Voyager 2* was 112,000 km away. Notice the large surface areas devoid of craters and the strips of young grooved terrains suggestive of interior melting. The largest crater visible is about 35 km across. (Image courtesy of NASA/JPL.)

brightest surface reflection in the Solar System) could be best explained if particles of fresh ice deposited on the surface were vented out by cryovolcanoes (a single cryovolcano would suffice to coat the entire surface, given the moon's small size and gravity), although no trace of present activity could be found. Whatever was happening to the moon's icy crust, it was originating deep within the moon's interior.

The scientific community was electrified. The dust had barely settled with the Voyagers' encounter with Europa than another geologically active moon in our Solar System had been found. Despite the successful acquisition of high-resolution images, though, not everything went as planned.

Voyager 2's predetermined trajectory had it pass behind Saturn, blocking any contact with Earth for 2 hours 20 minutes. This wasn't a problem, as all the data captured by the spacecraft could be stored by the onboard computer until communications could be re-established and transmissions resumed. However, it was during this extended blackout that *Voyager 2* would make the perilous crossing of the E-ring and also perform the close flybys of Enceladus and Tethys. With such a dangerous maneuver, engineers and scientists alike were nervous when they lost contact with *Voyager 2* as it went behind the Ringed Planet.

Luckily the daring spacecraft re-established contact as expected, to everyone's relief, but within thirty minutes of receiving the new data, the mission engineers realized that something wasn't quite right; some of the pictures supposedly taken of the moons were pitch black. As more erroneous images and data came back, the explanation quickly became apparent to the horror of the Voyager team. The camera platform had malfunctioned while the spacecraft went behind Saturn, forcing the cameras to point in the wrong direction. Somehow, the mobile platform upon which the cameras (and other instruments) rested had gotten stuck. By analyzing where the cameras were pointing, engineers quickly worked out that the technical glitch occurred on one of the swivels of the mobile platform 45 minutes after the spacecraft had crossed the E-ring. It was therefore likely that the probe got hit by an icy particle lying further out the E-ring. Ultimately, the cause of the faulty swivel would never be known.

The faulty platform had two consequences, though. The first was that *Voyager 2's* flybys of Uranus and Neptune would have to be reconfigured to take into account this new technical limitation imposed on the spacecraft. The second one, more unfortunate for us, meant that because multiple close-up images of Enceladus were lost, the Voyager mission missed an opportunity to spot the jets of water erupting from the moon's south pole. If the problem had not arisen, such a discovery made in 1981 would have changed the way the Cassini orbiter, launched a decade later, would have been conceived, since the study of these plumes would have become a top priority. Such an eventuality might have already changed our perspective of life in the Solar System. It goes to show that sometimes, all it takes is for a speck of ice to inadvertently lodge itself in intricate machinery for our lives to be altered.

A final note on the Voyagers' flyby of the Saturnian system shows just how close we were in discovering the erupting plumes of Enceladus. In early 2017, a professor in a U. S. college, Ted Stryke, reviewed images taken by the wide-angle cameras of *Voyager 1* as it encountered Saturn thirty-five years earlier. The low-resolution images taken by this camera were used for navigation purposes only (to determine the exact position of the spacecraft) and had limited use for mission scientists. Nevertheless, using modern imaging tools, Stryke processed the low-resolution images whenever Enceladus was viewed by the wide-angle camera, and incredibly, a plume can be seen venting from the south pole. The imaging team of the Voyager mission couldn't have accomplished Stryke's feat for the simple matter that they were unaware that such plumes existed and therefore never actively looked for them.

Cassini's Arrival

Building on the Voyagers' success, NASA and ESA decided to collaborate on the most complex planetary science mission ever conceived; a 6-ton orbiter named Cassini equipped with 12 powerful instruments designed to study in great detail the Saturnian system (and a lander named Huygens to investigate Titan's surface in situ). It would be named the Cassini-Huygens mission in honor of the men who discovered Saturn's main moons.

Launched from Florida in 1997 on a U. S. air force rocket named Titan and a Centaur upper stage launch system, the spacecraft took seven years to reach Saturn, with the help of two gravitational assists from Venus, one from Earth and one from Jupiter. It also made two full loops around the Sun. Far more advanced than the Galileo spacecraft conceived fifteen years earlier, the Cassini orbiter produced vast amounts of scientific measurements thanks to an array of instruments, including four optical instruments, six fields and particles instruments as well as two microwave remote-sensing instruments.

During the prime mission, which lasted from July 2004 until 2008, the orbiter would focus heavily on the planet and its rings, Titan (see Chapter 7), and as many icy moons as possible, including Enceladus. The primary goal at Enceladus was to follow up on Voyager's observations, and either prove or disprove the hypothesis that the moon had an atmosphere or was erupting. Very soon, though, Enceladus turned to be more than an intriguing object to study. It became extraordinary.

Cassini was to do a series of programmed flybys of Enceladus one year after the start of the prime mission. These would take the orbiter to three very close passes. The first one, referred as E0, at a distance of 1,264 km on February 17, 2005, then a second (E1) at 500 km on March 9, and finally the last pass planned (E2) on July 3, was to be a 1,000 km flyby. Further observations by Cassini were to be performed even if the spacecraft wouldn't pass close to Enceladus, and these would be referred to as non-targeted flybys (the greater distances involved could be more than 100,000 km) (Table 8.1).

The first sight of the now-famous plume came just before the probe's first flyby, with images taken by the Imaging Science Subsystem (ISS) in January 2005, showing a very faint plume seeming to emanate from the south polar region, only slightly brighter than the background noise in the image. Given the extraordinary nature of a plume discovery, more observations were required for the mission scientists to be confident in their interpretation.

In February, the spacecraft was positioned in a way to conduct observations during a stellar occultation, illuminating the moon's equator (a stellar occultation occurs when a star passes behind the moon, illuminating areas close to the surface). The UVIS instrument onboard Cassini had been specially designed to conduct science during such an event, and scientists were hoping it could finally shed some light on what was occurring around the tiny moon. The UVIS, or ultraviolet imaging spectrograph subsystem, was a set of telescopes used to measure ultraviolet light from the Saturn system's atmospheres, rings, and surfaces. It could observe fluctuations of starlight and sunlight as the sun and stars moved behind the rings and the atmospheres of Titan and Saturn, allowing it to determine the atmospheric concentrations of hydrogen and deuterium. Yet, the UVIS data showed that there was no

Table 8.1 All Cassini's close flybys of Enceladus during the entirety of the mission. The orbit number refers to Cassini's orbit around Saturn. In total 23 close flybys would be performed over 13 years

Orbit number around Saturn	Encounter name	Date	Distance (km)
3	E0	February 17, 2005	1,264
4	E1	March 9, 2005	500
11	E2	July 14, 2005	175
61	E3	March 12, 2008	48
80	E4	August 11, 2008	54
88	E5	October 9, 2008	25
91	E6	October 31, 2008	200
120	E7	November 2, 2009	103
121	E8	November 21, 2009	1,607
130	E9	April 28, 2010	103
131	E10	May 18, 2010	201
136	E11	August 13, 2010	2,554
141	E12	November 30, 2010	48
142	E13	December 21, 2010	50
154	E14	October 1, 2011	99
155	E15	October 19, 2011	1,231
156	E16	November 6, 2011	496
163	E17	March 27, 2012	74
164	E18	April 14, 2012	74
165	E19	May 2, 2012	74
223	E20	October 14, 2015	1,839
224	E21	October 28, 2015	49
228	E22	December 19, 2015	4,999

atmosphere to discover. Scientists were not surprised – after all, how could such a tiny moon hold on to its atmosphere?

The first flyby, on February 17, allowed the orbiter to take close up images of the surface, revealing regions previously observed by *Voyager 2* that were covered by cracks. Cassini also confirmed the presence of ice water on the surface and identified near the south pole fractures containing simple organics and carbon dioxide. Also, magnetometer observations revealed clear perturbations of Saturn's magnetic field near the moon as it was being deflected around it. In addition, water was identified as a major source of ions for the magnetospheric plasma observed around the moon, revealing that water vapor was being vented into space. In effect, the magnetometer team discovered the vapor component of the plume while the imaging team first discovered the particle component of the plume in January.[1]

All the data pointed at a very light atmosphere or a plume-like feature on Enceladus.

In March, the second closest approach at 500 km located a source of plasma composed of water ions in the southern region but provided no additional insight on the plume itself.

Time was running out fast. The last approach with Enceladus would occur in July with no further flybys planned for the rest of the prime mission. In a 'now-or-never' approach, the Cassini program manager agreed – on the insistence of the magnetometer team – to bring Cassini much closer to the surface during this last flyby; instead of coming within 1,000 km as initially planned, the orbiter would pass at a hair-raising 175 km of the moon's surface. This was no small change, as it would require course corrections (meaning additional fuel) and alterations in Cassini's trajectory around Saturn.

Thankfully, another stellar occultation could be performed during the new flyby ensuring that UVIS would be able to take new measurements of the plume. And so, when Cassini approached Enceladus at its closest on July 3, mission scientists were more eager than ever to analyze the incoming data. What was sent back exceeded their expectations.

For a start, the flyby allowed close up shots of the southern hemisphere with unprecedented image scales of up to 4 m/pixel. The images revealed that the south pole region, starting at around 55 degrees in latitude south, exhibited numerous features formed by recent geological activity such as ridges and fractures with little crater impacts present suggesting a very young age. Also, the albedo of the southern region was brighter compared to the rest of the moon, indicating that it had recently been recently covered with fresh ice. Most intriguing was the presence of long fissures, now known as tiger stripes (the fissures resembled claws

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[1] There have been disagreements within the Cassini team as to which instrument was the first to detect Enceladus' plume with some scientists having publicly taken issue with the official storyline.

marks), embedded in 200-m-high ridges and extending for up to 130 km in length. Each stripe ran parallel to each other at an average distance of 40 km. As of November 2006, each stripe is named after a city named in the *Arabian Nights* folk tale followed by the Latin term *sulcus* (plural, *sulci)*, which means a groove or a ridge. The stripes are: Alexandria Sulcus, Cairo Sulcus, Baghdad Sulcus, and Damascus Sulcus (the latter two being the most active sulci on Enceladus). When *Voyager 2* made its closest approach to Enceladus decades earlier, it had flown over the northern region, where stripes were non-existent.[2]

Particularly notable were the results from the composite infrared spectrometer (CIRS) instrument that measured surface temperatures. CIRS revealed the south polar region to be hotter than the moon's equator (which received the most energy from sunlight), with the highest temperatures found within the tiger stripes themselves (between 114 K and 157 K).

Cassini's instruments also determined the crystallization state of the ice in the southern region and found that pristine, fresh ice was present near the tiger stripes while radiation-damaged amorphous ice could only be found much further away, indicating that the stripes had to be venting fresh ice recently, maybe even less than 1,000 years ago. Light organic compounds, such as methane, were also found near the stripes. Unsurprisingly, the results from two instruments that analyzed particles in space – the cosmic dust analyzer (CDA) and the ion neutral mass spectrometer (INMS) – both detected a considerable increase of water particles within the vicinity of the moon, confirming that Enceladus was indeed the primary source for the E ring.

In addition, the configuration of the orbiter and the moon meant that the light from the occulting star was passing near the south pole, allowing UVIS to collect data from the southern region for the first time. As the plume moved in front of the light emitted by the background star, dips within the spectra were registered by the instrument. Upon seeing these dips, scientists realized that they had detected what seemed like a hazy atmosphere over the south pole. Water vapor was detected as well.

[2] One could only imagine the consequences if Voyager 2 had flown by the south pole instead of the north pole and discovered the tiger stripes in the early eighties.

Although close up images of the southern region would not show the jets of vapor venting out of the ridges due to their tenuous nature, the case for the extraordinary claim that a giant plume was venting out from Enceladus' south pole had been made.

The visual observation that proved without any ambiguity the existence of a plume was taken a few months later on November 28, 2005, during a non-flyby encounter. In preparation for this flyby, the imaging instrument was set with exposures designed to reveal faint atmospheric features and configured with a high phase angle of 148 degrees, a viewing geometry in which small particles become much easier to see. Furthermore, various exposure settings and spacecraft rotations were implemented between each set of images to remove any possibility of image artifacts.

The images sent back showed large towering jets that were ejecting vast quantities of particles into space, forming a giant plume. These visual confirmations of the plume took everyone by surprise. No one was expecting to see a plume of such magnitude and output from this tiny moon. The team calculated that the vents were expelling particles up to 500 km in altitude and at speeds of up to 2,189 km/h, which strongly suggested liquid water as the source of the plume, as it is hard to achieve such velocities without liquids.

And so, remarkably, in 2005 Enceladus had become the latest member of a select group of objects in our Solar System where active volcanism exists: Earth, Io and Neptune's moon Triton.

Enceladus' plume could finally explain a peculiar observation made by the Cassini orbiter on its approach to the giant planet that had puzzled astronomers until then. Oxygen atoms had been detected all over the Saturnian system. The origin of this oxygen was entirely unknown at the time yet, upon seeing the vents, astronomers understood that the water molecules spewing out from the plume was the source of the oxygen, as radiation would eventually break down the water molecules exposing their elemental constituents.

In addition, the discovery of the vents proved without a doubt that Enceladus was indeed generating the E-ring, which by now was shown to be made of icy particles.

Furthermore, it was found that Enceladus was by far the most significant source of dust, neutral gas, and plasma within the Saturnian system, feeding not only the E-ring but also a neutral torus orbiting Saturn. What fiery Io was doing in the Jovian system, Enceladus seemed to be doing something similar in the Saturnian system. What could explain such activity on this tiny moon?

After working out several models, scientists proposed that the vents originated from pressurized warm liquid water lying close to the surface. It was a radical idea as finding evidence of liquid water on Enceladus was totally unexpected.

Flying Through the Plume

The finding of the massive plume and the intriguing tiger stripes at the south pole excited the scientific community. As such, the discoveries made in 2005 proved to be a turning point for the Cassini mission. Enceladus shot straight to the top of the key targets to investigate in the Saturnian system, and Cassini's trajectory was revised accordingly. While the next – and last – planned flyby (E3) during Cassini's prime mission would only occur three years later, on March 12, 2008, it was modified to allow the orbiter to pass at a breathtaking distance of only 47.9 km through the south region (seven times closer than was initially planned).

At its closest approach, Cassini would be traveling at such high speeds (14.4 km/s) and such a narrow vantage point that taking close up shots of the surface would be worthless. Instead, the team had a better idea – to send Cassini straight through the plume and 'taste' it with its particle analyzers. The objective was to analyze the particles and characterize their density, size, composition, and speed while the cameras could provide high-resolution images of the surface whenever possible on the way in and out but not during the closest approach. This was momentous. The Cassini orbiter had never been designed for such feat, and this new trajectory required a complete overhaul of the software and a reassessment of the capabilities of the scientific payload as it would sample the plume. The years running up to the 2008 flyby was frantically spent preparing for this event.

As this new trajectory was being worked out, an extended mission named Equinox was also being proposed. Consisting of seven new flybys of Enceladus between 2008 and 2010, Equinox had a strong focus on the icy moon and was quickly approved. (An additional extension, named Solstice, would ensure the success of the Cassini mission until 2017.) On August 11, 2008, the first flyby within the extended mission (referred to as E4) would pass at 54 km from the surface, while the second one (E5), planned for October 9, would bring Cassini to its closest approach ever during the entire 13-year mission, at only 25 km from the surface.

The last flyby of 2008 (E6), planned for October 31, would bring the orbiter 200 km from the surface.

These three flybys shared a similar trajectory: Cassini would first approach Enceladus over the northern hemisphere, then reach its lowest altitude near the equator before passing through the plume over the southern hemisphere. Because they all followed the same path, different instruments could be activated during the flybys, allowing for a full range of measurements (as the scientific instruments couldn't be activated all at once). Furthermore, these multiple flybys could reveal the moon's dynamism by noticing the changes observed at the surface throughout the months, especially at the fissures near the south pole. Plunging through the plume was still considered hazardous, so all the 2008 trajectories were made so as to not pass within its densest regions, although it was expected that the plume itself might exert some force on Cassini and change its course slightly.

Everyone agreed, 2008 was going to be a big year.

In preparation for these four flybys, a new stellar occultation observation of the plume was made with UVIS in October 2007. This revealed the plume to be composed of four distinct jets, which continued to be tightly concentrated even at an altitude of 15 km, implying that the velocity of the water particles gushing out at the base of the vent had to be at least 2,100 km/h, or else the plumes would have dissipated much earlier.

The team already knew that two types of particles were venting off from these jets. One was composed of pure water-ice, while the other was a mixture of ice and non-ice elements. Most speculated that the non-ice elements were coming directly from the interior of the moon, within the not-yet-confirmed warm subsurface ocean, although this view wasn't agreed to by all. Some scientists suggested that instead, a mixture of gas and ice could be trapped under the icy crust and when exposed to near-vacuum conditions would explode into giant plumes thus removing the need for warm liquid water altogether. The data collected by Cassini during these flybys would prove once and for all the source of the jets.

And so, on March 12, 2008, Cassini opened a new chapter in space exploration by plunging straight through the plume and did so again successfully, flying deeper and deeper through the jets during E4, E5, and E6. What it found during these successive flybys provided much insight as to what lies below Enceladus' icy crust. The ion and neutral mass spectrometer (INMS) measured the plume's composition to be the following: 90% water, 5% carbon dioxide (which suggests that the underground water is carbonated – think fizzy water), 1% ammonia (NH_3), 1% methane (CH_4), traces of argon-40 (resulting from the decay of potassium-40 usually found in rocky material, suggesting a water-rock interaction), less than 1% of hydrogen sulfide (H_2S), methanol (CH_3OH), formaldehyde (H_2CO), and other light organic compounds such as propane, benzene, hydrogen cyanide, and others. The presence of volatiles such as ammonia and methane are important, as these allow water to stay liquid below the freezing point.

In addition to this long list of non-ice components, also detected were salts, such as sodium chloride, sodium carbonate, sodium bicarbonate, and potassium chloride, all at a concentration of 1%, which is equivalent to a tenth of the salinity of Earth's water.

Given that sodium had already been detected in the E-ring particles, finding salt within the plume itself confirmed once more that its source was indeed liquid saline water, making the other alternative explanations less likely. Pressurized saltwater chambers had to be present in the icy crust or underneath it.[3]

In addition to the sampling of the plumes, high-resolution images were taken once again at precise regions of the south pole, and, as expected, these showed signs of change over time, especially around the seemingly very active tiger stripes. Similar to mid-ocean ridges on our planet's seafloor, where new surface material displaces the older crust, the tiger stripes hinted at the presence of significant heat under the icy crust. These close-up images also revealed how old vents could close off and new ones open up, seemingly coinciding with the plume variations observed from month to month. Scientists were beginning to detect a seasonal effect in the plume's behavior, most likely due to the moon's orbit around Saturn.

Using the surface images, scientists tried to infer the ages of the different regions. The north was heavily cratered and appeared to be 4.2 billion years, while the equator was estimated to have regions as young as 170 million and as old as 3.7 billion years. The south polar area, with its active surface, was possibly around 500,000 years if not younger. These figures have to be taken with

[3] Although the pressures encountered within these chambers are far less than what we would expect them to be if a similar process was occurring on Earth, Enceladus is a tiny moon with relatively low gravity, so it doesn't take much pressure to expel material far out into space.

a pinch of salt, though, given the difficulties scientists have in dating objects that lie in environments that aren't static (such as around Saturn; a dynamic planetary system).

Could there be an ocean of liquid water within this tiny moon, While at the time there was still no conclusive evidence that such a body of water existed, a growing number of scientists were optimistic that further proof of its existence would be found.

To better answer this question, the spacecraft, which had already completed 119 orbits around Saturn, was placed on an equatorial orbit allowing for closer and more frequent flybys of the tiny moon. As a result, a total of 13 flybys of Enceladus would be accomplished from 2009 until the end of 2012, by which time Cassini would return to a highly inclined orbit, preventing any close-up observations of the moon for the next three years.

Cassini performed a new flyby (E7) on November 2, 2009. Its closest approach was at 103 km from the surface, although it would plunge far deeper into the heart of the plume this time as the engineers had grown more confident in Cassini's ability to cross the jets safely. Nevertheless, because of the risk associated with this route, engineers decided to use the spacecraft's thrusters to keep it stable throughout the entire flyby as they carefully monitored its behavior within the plume. If all went well, later flybys could be completed without using thrusters, therefore preserving the precious onboard fuel. Scientifically, the flyby would provide further insight into the plume's composition, allow the orbiter to map the heat signatures from the surface and provide additional high-resolution images of the tiger stripes in the hope of detecting changes that occurred after the E6 flyby.

It took the Cassini orbiter less than a minute to fly through the plume, as it was traveling at the neck-breaking speed of 28.8 km/h. The scientific measurements taken during the flyby helped determine that the plume's density was less than half what had been predicted. More importantly, though, the plasma spectrometer (which was initially designed to study Saturn's magnetosphere) measuring the flow velocity and temperature of the ions and electrons within the plume found negatively charged water molecules. This supported the idea of a body of liquid water underneath the surface, as molecules with additional electrons are found when liquid water experiences friction (i.e., a waterfall or crashing waves). Negatively charged hydrocarbons were also detected in the atmosphere, most likely the result of Saturn's magnetic field and the Sun's ultraviolet rays interacting with Enceladus' tenuous exosphere. Organic compounds were again detected in the plume, while close up images of the south pole helped researchers identify areas that had experienced recent change.

The final flyby of 2009 (E8) occurred on November 2 and was a much more distant flyby than the previous five at 1,600 km from the moon's surface. Baghdad Sulcus was a primary focus of the flyby this time, as a detailed thermal map of the fissure revealed heat output throughout the length of the fracture. Temperatures of 180 K were detected (possibly warm enough for liquid water mixed with ammonia to be present below the surface). Also, further high-resolution images of the southern hemisphere were taken as well as a full mosaic of the south pole, where 30 individual jets of different sizes can be seen (see Fig. 8.3).

By then, mission engineers had gained enough knowledge and confidence to fly the spacecraft through the plume without the need to activate the thrusters. Such a configuration provided multiple advantages. When the thrusters were on, the engineers couldn't tell if the spacecraft's motion was coming from the thrusters or

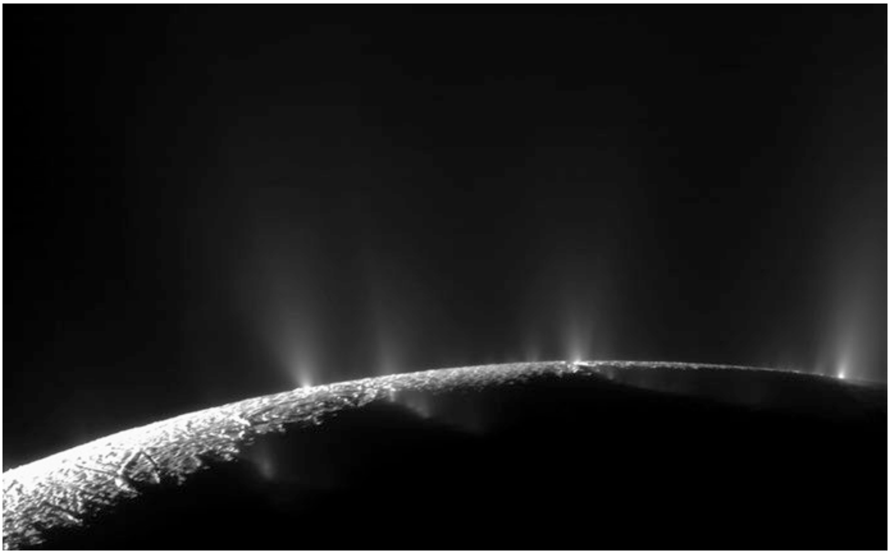

Fig. 8.3. Enceladan south polar vents and plumes captured by Cassini during its close flyby on November 2, 2009. Multiple jets can be seen venting off from the tiger stripes at Enceladus' south pole. From left to right, they trace out Alexandria, Cairo, Baghdad, and, at the extreme right edge, Damascus sulci. Note that this image has been rotated 180 degrees from its original orientation (Image courtesy of NASA/ESA)

Enceladus' gravity. With the thrusters off, they could measure the moon's gravitational pull with high precision by accurately tracking the velocity of the spacecraft during the flyby. The data collected during such a flyby would enable scientists to determine the mass variation under the moon's surface (sometimes called the gravity data).

And so, Cassini flew through the plume without thrusters during the next flyby (E9) which occurred on April 28, 2010. More plume flybys, planned for 2012, would be required to validate the gravity data acquired on the E9 flyby.

The year 2010 saw additional flybys, including an important one on August 13 (E11). During this flyby, new high-resolution images of Enceladus' surface (lit by the sunlight reflecting off Saturn this time) and new infrared data produced the highest resolution heat maps of the tiger stripes yet. This unprecedented set of data revealed warm, complex fractures branching out of Alexandria Sulcus as well as Cairo Sulcus, suggesting that much activity still occurred at the end of the stripes.

Furthermore, temperatures of 190 K were measured within the Damascus Sulcus, which was hotter by 20 K than during the previous measurements made of the same area in 2008. Scientists weren't entirely sure if this was because the fissure was more active or if the 2008 scan, less precise, averaged out the temperature over the area. Regardless, the detection of such high temperatures was suggesting high levels of geological activity under the surface.

Also, the new maps of the Damascus Sulcus showing details as small as 800 m – the highest resolution ever obtained of the fissures – revealed for the first time recently ejected material cooling off next to the central trench. Curved striations along the fissures as well as significant temperature variation on its entire length were observed, adding to its complexity. The dynamism found within Damascus Sulcus placed it as the most active of all tiger stripes.

Plume depositions on the surface were also measured and showed that even in areas far from the vents layers of fine particles were coating the surface at a rate of 1 cm per million years. The areas closer to the tiger stripes resemble snow-covered landscapes on Earth, as thick plume fallouts buried the terrain.

The E11 flyby was an important one as well since winter was settling in the Saturnian system and Enceladus' south pole would be veiled in darkness for several years to come, rendering observations more difficult.

The Evidence for a Subsurface Ocean

In 2011, new studies of the data acquired during the 2008 and 2009 plume flybys confirmed the presence of large grains of ice containing substantial amounts of salt, up to 2% in concentration (in contrast to earlier studies that had suggested smaller icy particles and lower salt levels). Given the known solubility of salt in water, it was assumed that these large icy grains had to originate from a body of salty liquid water, making a case for a subsurface ocean.

The new flybys in 2010 and 2011 would provide additional measurements of the moon's gravitational pull as well as new surface images and further plume sampling. A total of 90 jets varying in size, were identified over the south pole, all sprouting from the tiger stripes. Alas, from 2012, Cassini was placed once again on a highly elliptic orbit, preventing any flybys for the coming three years. Actually, only three close encounters of the moon would be performed in 2015 before the end of the Cassini mission in 2017. In the meantime, scientists were busy analyzing the finer details of the data collected by a multitude of encounters from years of observations.

In 2013, a study linked the changes observed in the plume's activity with Enceladus' position around Saturn. Most planetary orbits are not perfectly spherical but instead have an eccentricity and are therefore elliptical. The study showed that whenever Enceladus was farthest away from Saturn, the intensity of the plume would increase by threefold than when it was closest, leaving no doubt that as the tiny moon does a full orbit of Saturn, the differences of gravity it is exposed to due to the elliptical orbit are enough to squeeze and stretch the icy crust. This, in turn, causes the openings of the south pole fissures to vary. The further the moon distances itself from its primary planet, the wider the openings of the fissures become. As the moon gets closer though, the surface gets tighter, limiting the openings and de facto the amount of material that can be vented out from the jets. This new insight would allow the Cassini team to better plan their future observations of the moon. Interestingly, this pattern might also occur on Jupiter's moon Europa and could help explain why observations of Europa's plumes by the Hubble Space Telescope have been a hit and miss throughout the years.

A more significant story was the publication in 2014 by Luciano Iess of the University of Rome and his colleagues, of what most scientists had been anticipating for years: the evidence a subsurface body of liquid water. This breakthrough came from gravimetric measurements done during three flybys over the south and north poles between 2010 and 2012. Given the substantial depression of the southern region (previously detected through topographic data), the south pole was expected to have a weaker gravitational pull than the north. However, it turned out to be the opposite, as the south pole region was found to have a much stronger pull than expected. The stronger gravity's pull, the more mass lay directly below.

The study revealed that only liquid water (denser than ice) would fit the gravitational observations, therefore confirming the presence of a large body of liquid water under the south pole. Estimated to be the size of Lake Superior in North America, the subsurface sea was though to cover the entire southern region under 30 to 40 km of icy crust and was 8 to 10 km deep. Crucially, the model suggested that the salty sea was resting on the rocky mantle. Therefore water/rock interactions were possible.

And so finally, after years of tantalizing clues and speculations, scientists had once and for all managed to prove that Enceladus was an ocean world even if it was thought of as a regional sea and not a global ocean at the time.

This news captivated the public and scientists alike, since much of what life needs to thrive was present on Enceladus: liquid water, a significant heat source, organic compounds, and the presence of minerals through the water/rock interaction. One unknown parameter was the age of the moon's south polar sea. Contrary to Europa's subsurface ocean, which was estimated to have existed for billions of years, determining how old Enceladus' subsurface sea was difficult at this stage. However, some clues hinted that it was young. For example, the rate of argon-40 spewed out into space by the vents can be measured and compared with the theoretical estimate of the amount of argon-40 generated from the moon's rocky mantle.

Calculations have suggested that at the current venting rate, the reservoir of argon-40 would have only lasted 10 to 100 million years, giving the impression that the plumes might be periodical or that this is a one-off event that we are lucky to observe now.

Mysteries still had the planetary scientists scratching their heads. Given the heat measured within the southern region, estimates had Enceladus' total energy output at 16 gigawatts, which is far more than what the moon receives through radioactive decay and tidal heating. In addition, why was the south pole unusually active compared to the north pole? Tidal heating models depict the heat output as consistent on both poles, yet this isn't the case. There was obviously much more to learn from this moon.

In 2015, after a three-year hiatus, Cassini's orbit around Saturn allowed it to get close to the icy moon once again (although only three targeted flybys would be performed by the end of the Cassini mission). During the second of these close flybys (E21), which occurred on October 28, the probe flew through the plume at a distance of 49 km, the lowest it had ever been at the south pole. E21 would be the last time Cassini would venture into Enceladus' plume itself, as the final flyby, E22, would take another path.

The scientists were looking for two things during this last plume flyby. Firstly, by flying so low within the plume, they would expect Cassini to sample heavier organic compounds, which due to their weight, did not rise to the altitudes attained by the previous flybys. Secondly, it was hoped that molecular hydrogen might be detected in the plume, as this was evidence that hydrothermal activity was ongoing on in Enceladus' seafloor. Also, scientists could extrapolate how much heat is being produced by the hypothetical deep-sea vents, and whether or not these could be conducive to life. The results of the hydrogen investigation would be confirmed a few years later.

While the data from the E21 was being investigated, a new study revealed that tiny particles of silica (nanometer-sized) were found floating freely within Saturn's giant magnetosphere and were thought to have originated from Enceladus' plume. Silica, also known as silicon dioxide (SiO_2), is a major constituent of sand and mostly found in rocks, which in this case must lie at the base of the subsurface sea. Interestingly, hot liquid environments are required for silica particles to be formed, and studies suggest water temperatures at the base of the subsurface ocean to be at least 90 °C (363 K). Since such high temperatures can only be attained through hydrothermal activity, scientists concluded that the silica particles were formed by hot hydrothermal vents at the base of the seafloor. These silica particles were then vented out into space with the water-ice. The case for a warm active seafloor was made.

The same year of 2015 saw the publication of a major study, led by Peter Thomas, a former Cassini imaging team member at Cornell University, Ithaca, New York, which had analyzed seven years' worth of Cassini data on Enceladus and concluded that the subsurface body of water was not confined to the south pole only, but it was actually encircling the entire moon forming a global layer of liquid water. The study had analyzed hundreds of images of the moon's surface taken during the years and mapped the positions of craters with extreme precision. This allowed scientists to accurately measure the way the surface was moving while the moon rotated on its axis. Peter Thomas and his colleagues found that the surface was rotating at a different rate from the interior of the moon itself, which could only occur if a global layer of liquid water was separating the rocky mantle from the icy crust. In effect, the icy crust or shell is decoupled from the moon's interior and rotates independently, wobbling as it orbits Saturn. By carefully tracking this wobble, referred to as libration, and applying it to models we have of the moon's interior, we can extrapolate characteristics of the moon's interior, and early estimates had the ocean at 30 km deep on average (Fig. 8.4).

Two difficult questions remained unanswered, though. How old was this subsurface ocean and, as importantly, how did it arise in the first place, given that the energy output calculated for tidal

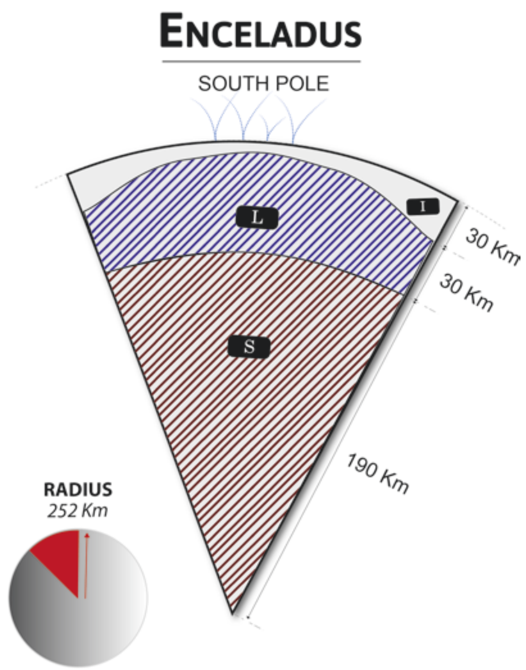

Fig. 8.4. Diagram showing the interior of Enceladus where the subsurface ocean rests on a rocky mantle. The thickness of the icy crust averages 30 km but gets very thin, at 1 km (or even less), at the south pole. I Ice, L Liquid, S Silicate mantle. Diagram is not to scale

heating and radiogenic heating does not seem to produce enough energy for the global ocean to have formed? As scientists pondered about this, additional data piled up.

A few days before Christmas, on December 19, 2015, Cassini performed its final encounter with Enceladus (E22) flying at a distance of 5,000 km from the surface, which placed it at an ideal location to map the southern hemisphere and measured once again the heat flow at the south pole. The Cassini team, saddened by this last rendezvous with this incredible little moon, were nevertheless comforted with the thought that it would take many years to analyze all the data collected by the spacecraft.

As such, in 2016, a study used data from previous years and revised the estimates of Enceladus' ice shell to be around 35 km thick at the equatorial regions and 5 km thick or less at the south pole.

The Discovery of Hydrogen

The most exciting discovery was yet to come. April 2017 saw NASA beat the drums and organize a press event; announcing that hydrogen – gasp – had been detected in the E21 flyby of 2015. In fact, Cassini had already detected hydrogen in the past whenever it had analyzed a plume; however, scientists had been unable to determine if the detected hydrogen had originated from the moon itself or the scientific instrument. Indeed, the spacecraft's ion and neutral mass spectrometer (INMS), which measured the hydrogen, wasn't originally designed to perform under such conditions, as its original purpose was to sample the upper atmosphere of Saturn's moon Titan.

Whenever particles from Enceladus' plume would be sampled, there was always a possibility that they would interact with the titanium walls inside the instrument and produce hydrogen. Due to this uncertainty, the team behind INMS worked hard to reconfigure the instrument and prevent incoming molecules from coming into contact with the titanium walls. The E21 flyby was done with the INMS newly configured. The sample taken by INMS during that flyby took most scientists by surprise, though, as a large amount of hydrogen (1%) was found in the plume. This suggests that a continuous production of hydrogen (H_2) is occurring within hydrothermal vents at the bottom of the subsurface ocean, reaffirming the interpretation made earlier from the presence of silica particles within the plume.

The vents on Enceladus' ocean floor are most likely alkaline hydrothermal systems similar to the "low temperature off-axis hydrothermal systems" present on Earth's ocean floor. These systems are distinctly different from the famous "black smokers" found in Earth's mid-ocean ridge, as they are heated not by volcanic energy but through exothermic reactions between seawater and rocks, called serpentinization, making the vents less hot (40 to 75 °C) and alkaline (pH 9.0 to 9.8). On Earth, carbonate chimneys dominate these low temperature hydrothermal vents, providing vast feeding grounds for dense microbial communities. The heat released by the serpentinization contributes to the circulation of the warm water through the rocks. Furthermore, the rocks undergo a chemical alteration during this process, reducing their density and increasing their volume, which ultimately leads to its break-up from the parent rock. Serpentinization can open up existing fractures and create large surface areas of water/rock interactions.

The other reason why scientists are excited is that hydrogen is one of the essential building blocks for life, as it forms the basis of organic compounds and is a food source for life forms. On Earth, hydrogen is used by microorganisms (methanogens) to produce energy by converting hydrogen and carbon dioxide into methane. As a prominent NASA scientist exclaimed, this discovery is like finding a candy store for microbes. We will explore the implications for the moon's habitability a bit later. Another important find published in June 2018 was the detection within the plume of complex macromolecular organic material with molecular masses above 200 atomic mass units. This suggests the presence of a thin organic-rich film on top of the oceanic water table.

Finally, some ideas were put forward in 2017 to answer the energy conundrum of why is there more energy within Enceladus than we anticipated given the known characteristics of the moon. Two interesting ideas have surfaced recently that might answer this question and at the same time could also start to explain the presence of a subsurface ocean.

The first idea proposes a violent collision of the icy moon by a large rock. Indeed, a recent study published in 2017 by Angela Stickle at Johns Hopkins University in Maryland and John Spencer at the Southwest Research Institute in Colorado, have shown that a significant impact occurring around 100 million years ago could explain the heat output and massive fissures observed at the south pole. They calculated that a strike powerful enough to crack through the 20-km-thick icy crust, thought to exist at the time, would deposit significant amounts of energy within the impact site, ensuring that the ice shell continued to bear the scars of the impact.

The strike didn't necessarily have to have occurred at the south pole, since such an impact would have resulted in a gravity dip at the impact site, forcing the moon to rotate itself so as to migrate the hole to one of the poles (in a case similar to Pluto reviewed in Chapter 9). In this case, the impact site just happened to be closer to the south pole than the north. Intriguingly, new studies have suggested that Saturn's rings (mostly made up of icy particles) could also be around 100 million years old, created by the destruction of a minuscule icy moon. These two hypothetical events might be related.

Another idea for the moon's abundant energy output was proposed in 2017 by Gaël Choblet and Gabriel Tobie, both from the University of Nantes in France. According to their studies, if Enceladus' core was made of unconsolidated and easily deformable porous rock, cold water from the ocean could easily seep into it, gradually warming up through tidal friction (as water rubs the surrounding rocks), and rising back up through convection. Such a heat transfer from the core to the ocean has been shown to produce enough energy to sustain a plume for a billion years, if not more.

Further studies (and most likely additional measurements) will be required to find supporting evidence for these theories. In the meantime, the mystery is unresolved.

Enceladus' Habitability

On September 15, 2017, the orbiter's fate was sealed. Running out of fuel required for adjusting its course, it was purposefully plunged towards Saturn to avoid any risk of contaminating Enceladus or Titan if left unchecked. And so, high up in the planet's upper atmosphere, one of the most successful spacecraft ever to be sent into space disintegrated in a fiery dive.

For more than a decade, the Cassini-Huygens mission characterized Enceladus and its subsurface ocean in great detail. Multiple lines of evidence have revealed the presence of a warm and salty subsurface ocean circumventing the entire globe under a 35-km-thick icy crust, which is much thinner at the south pole, as little as 1 km perhaps. This ocean is on average 30 km deep and in direct contact with a rocky mantle. It contains organic compounds of various lengths such as among others; methane (CH_4), propane (C_3H_8), methanol (CH_3OH), formaldehyde (H_2CO) as well as salts (sodium and potassium chloride), carbon dioxide (CO_2), ammonia

(NH_3) and methane (CH_4) both acting as an antifreeze, hydrogen cyanide (HCN), hydrogen sulfide (H_2S), silica (SiO_2), argon (isotope argon-40) and hydrogen (H_2). Of the six essential elements vital for life as we know it (referred to as CHNOPS as reviewed in Chapter 3). Carbon, hydrogen, nitrogen, and oxygen have already been found so far.

Cassini has also taught us that vast amounts of energy are present at the south pole, although we are not entirely sure why. Such energy fuels around a hundred jets spewing roughly 200 kg per second of ice and non-ice particles through long fissures, aka the tiger stripes. The lightest icy particles reach escape velocity and form the vast E-ring orbiting Saturn. The heaviest particles rain back on the surface.

The presence of low-temperature hydrothermal vents implied by hydrogen's existence in the plume makes Enceladus' ocean one of the most habitable environments in our Solar System (after Earth). Astrobiologists see few problems in imagining methanogen-based microbial ecosystems located at the base of the ocean floor vents. Indeed, methanogens combine the carbon dioxide and hydrogen outgassed by the hydrothermal systems to generate energy, producing in the process methane and water. The reaction is written like this:

$$CO_2\left(aq\right) + 4H_2\left(aq\right) \rightleftharpoons CH_4\left(aq\right) + 2H_2O \tag{8.1}$$

In Chapter 6, we saw how this reaction might not occur on Europa, given the extreme pressures encountered at the bottom of the subsurface ocean (100 to 150 km in depth). On the other hand, the conditions within Enceladus' smaller ocean are favorable for this reaction to take place, ensuring an ample supply of food for the microorganisms.

However, the sheer abundance of hydrogen found in the plume raised eyebrows among the scientific community. Jonathan Lunine, professor at Cornell, has called this observation the "Neglected Pizzeria," bringing forward the image of fresh pizzas stacked up high in a pizzeria. A question quickly comes to mind – why is no one eating them? Indeed, we can argue that too much hydrogen is a sign that life isn't present in Enceladus' subsurface ocean or else it would have consumed it.

Although methanogenesis is one of the simplest and most widespread forms of microbial metabolism using hydrogen, we also know of ecosystems on Earth where hydrogen is present in large quantities yet very little gets touched by life either due to physical constraints limiting its consumption (low amounts of phosphorus curtailing basic life functions) or due to the presence of another food source the microorganisms have evolved to adapt. This is why most astrobiologists don't consider the excess of hydrogen as an argument against life on Enceladus.

There has been, however, another concern, the age of Enceladus and its ocean. The complexity inherent in modeling the formation of the Saturnian system with its rings and multiple moons makes it hard to determine Enceladus' age with certainty. The tiny moon might have formed with Saturn 4.5 billion years ago or much later, around 2 billion years ago. Relying on the number of craters found on the surface exposes us to false interpretations, as the rate of impacts might have varied through time in ways that aren't well known at the moment. For example, Saturn's rings, which were previously thought to be billions of years old, now seem to be only around 100 million years old according to the most recent study.

Furthermore, some scientists suspect that the subsurface ocean itself might be much younger than the moon. Some place it at only 500 million years old, while others put forward even shorter timescales, implying a periodicity in the formation of the subsurface ocean. At present, there are just too many unknowns. It might be hundreds of millions years old or billions of years old. The truth is that we really don't know.

Nevertheless, what do these younger estimates imply for the possibility of life in the subsurface ocean? Although we have seen in Chapter 3 that life did require hundreds of millions years to start off on Earth, some scientists view the young age of Enceladus' ocean as a good thing. If the moon was really old, the serpentinization process that we observe today should have run out, and with it, the nutrients required for life. Given the moon's small size, there might not be enough material to sustain life for significant periods of time. In the case of Enceladus, a younger ocean filled up with nutrients and energy might be a better scenario than an old one where life is now extinct. If the ocean is indeed young and life has found a way to arise from it, it will certainly be simple life forms such as single-cell organisms, as complex cells or multicellular organisms required billions of years to evolve (see Chapter 3).

To detect such life, ambitious missions have been proposed to sample the plume material and analyze them using state-of-the-art laboratories onboard a spacecraft or even to return plume samples back to Earth for extensive analysis in the best laboratories in the world. Ideally, a sample return mission would provide the best scientific return but is fraught with risks. Chapter 12 will explore such missions in detail.

In the meantime, let us imagine that a sample return mission does take place, what implications will arise from such a scientific endeavor? We will be faced with three scenarios: either we find life in the subsurface ocean similar to life on Earth (DNA, RNA, etc.) that would give strong support to the panspermia hypothesis for the origin of life within our Solar System; either we find life to be very different from life on Earth (uses entirely different processes to store information), implying that hydrothermal vents on seafloors are the natural environments for life to arise on planetary bodies; or, finally, we find no life at all within Enceladus' subsurface ocean, in which case life might need additional conditions to arise that Earth can provide (such as an atmosphere). Even if we discover that the third scenario is the right one, it will be truly fascinating. Learning about the boundaries imposed on life will provide much insight into how life appeared on our planet and, ultimately, where we come from. Searching for life within the icy moon of Enceladus is also searching for our own origins.

In the meantime, we are now ready to depart from this captivating and promising moon. Having completed the second part of the journey that took us to the five confirmed ocean worlds in our Solar System – Ganymede, Callisto, Europa, Titan and Enceladus – we will now move on to the third part of the book, where we explore planetary objects that offer tantalizing clues for subsurface oceans or bodies of liquid water but for which we still need further evidence. The two dwarf planets and two moons that will be covered in the next part offer exciting possibilities in increasing the count of habitable environments present within our Solar System. Without further ado, lets us visit Ceres, Dione, Triton, and Pluto.

Part III
Possible New Ocean Worlds

"Somewhere, something incredible is waiting to be known."

– Carl Sagan

In this part, we review the planetary objects that might harbor subsurface oceans (or small bodies of water) but for which we still await confirmation. We will cover a wide range of Solar System objects, from moons to dwarf planets, from Kuiper Belt objects to far away Scattered Disk objects. To highlight the diversity of objects presented in this part, we will start in Chapter 9 by reviewing two very different objects: Saturn's moon Dione and the dwarf planet Ceres, and then follow on in Chapter 10 with Triton and Pluto, which are similar in many ways. In Chapter 11, we will visit the other objects that in theory were capable of hosting a subsurface ocean in their past or might still do today.

9. Ceres and Dione

These two planetary objects – the former a dwarf planet within the Asteroid Belt and the latter an icy moon orbiting Saturn – might not seem to have much in common at first. Nevertheless, they both might host subsurface bodies of liquid water under their icy crusts, making them candidates for the ocean worlds' club whose five members already include Enceladus, Europa, Ganymede, Callisto, and Titan.

Ceres

Discovery and Observations

In 2006, the International Astronomical Union – the organization that represents the majority of professional astronomers around the world (also known as the IAU) – held a conference in the picturesque city of Prague in the Czech Republic. Although this event was famous (or ill-famed depending on your point of view) for demoting Pluto from its status of a planet to a dwarf planet and in the process making millions of schoolbooks and bedroom posters obsolete overnight, news was also made on the change of status of another Solar System body, Ceres (also known as 1 Ceres). Until then, Ceres was known for being the biggest asteroid in the Asteroid Belt, a ring made up of millions of asteroids orbiting the Sun between Mars and Jupiter. Now Ceres also became part of the dwarf planet club alongside four other objects lying further away from Neptune: Pluto, Eris, Makemake, and Haumea.

Ceres was discovered in the early nineteenth century, a period where the enthusiasm for astronomy was flourishing in Europe, as Herschel had discovered Uranus a few decades earlier while the French astronomer Charles Messier had published his famous astronomical catalog. On the first day of the year 1801, Guiseppe Piazza, an Italian priest, mathematician, and astronomer based in Sicily, was observing the night sky searching for a particular type of star when he spotted a "slow-moving star-like object."

B. Henin, *Exploring the Ocean Worlds of Our Solar System*, Astronomers' Universe, https://doi.org/10.1007/978-3-319-93476-1_9

He initially thought it was a comet but had some reservations, since these objects were known at the time to be moving fast throughout the sky. By an ironic twist of fate, the new object the Italian astronomer had found was located exactly where the Titius-Bode law (now a discredited theory) had predicted a planet to exist. Titius and Bode, two German astronomers, were convinced that a distinct pattern existed within the mean distances between the planets and the Sun (known as their semi-major axis), and they had predicted, with the Scottish mathematician Colin Maclaurin, that a small planet should be present between the orbits of Mars and Jupiter. When Piazza's discovery of a new object was announced, astronomers championing the Titius-Bode law were convinced that he had found the missing planet and duly accepted Cerere Ferdinandea, after the Roman goddess of Agriculture, as the name chosen by the Sicilian astronomer.

For half a century, astronomical books and charts showed Ceres as a planet. Nevertheless, it wasn't the only object lying in this particular area, and as observations of the night sky improved, so did new discoveries. By the 1820's, astronomers counted 11 planets in the Solar System: Mercury, Venus, Earth, Mars, Vesta, Juno, Ceres, Pallas, Jupiter, Saturn, and Uranus. In a prelude to the recent demotion of Pluto, by 1847 astronomers came to realize that Ceres and its five siblings were part of a new category of Solar System objects that Herschel termed asteroids (meaning 'star-like' in Latin due to their appearance being indistinguishable from regular stars). The Asteroid Belt was discovered – now known to be comprised of millions of irregular objects made up of rocks, metals, and some ices – and the Solar System reverted back to seven planets once more.

Nestled within this belt, Ceres stands out as being the biggest asteroid, making up almost a third of the total mass of the Asteroid Belt (Vesta makes up 9%, Pallas 7%, and Juno 1%). Astronomers knew that it was big enough for the gravitational pull of its mass to shape it into a ball (a radius of 473 km), yet it was still too small for astronomers to study it properly. Nevertheless, it was suggested that due to its size, Ceres could have experienced differentiation (the separation of the constituents of a planetary body creating distinct layers within its interior) and a large amount of primordial water-ice might be present as an icy subsurface mantle.

As technology improved, plans to study Ceres started in earnest in the 1970's and 1980's, and it was concluded that, based on overall characteristics such as albedo and spectrum in visible and near infrared, Ceres must be similar to carbonaceous chondritic meteorites. This type of meteorite represents primordial matter that has been relatively unaltered by heating during its history. The metal in these meteorites are mainly silicates, oxides, or sulfides, and most contain water and minerals, as well as organic compounds. As a general rule, the outer part of the Asteroid Belt hosts objects such as carbonaceous chondrites that haven't been exposed to the high temperatures present in the early period of the Solar System, while those located in the inner part of the belt (such as Vesta) have undergone significant heating and are comparable to the silicate rocks here on Earth.

As more observations were made, astronomers improved the estimates of Ceres' mass and radius, leading them to calculate its mean density at 1.98 ± 0.03 g/cm^3, halfway between that of water (1 g/cm^3) and the average rock (3 g/cm^3). Given its small density researchers concluded that the giant asteroid must be composed of at least 25% water.

Many questions remained unanswered, such as the composition of Ceres' surface and subsurface layers, the properties of its regolith, and its degree of differentiation. Thankfully, the arrival of powerful new telescopes in the 1990's and 2000's, would bring us closer to answering these questions. Already, in June 1995, the Hubble Space Telescope (HST) – repaired two years earlier – took the first direct albedo maps of Ceres in the hope of detecting a possible polar cap. The images taken in ultraviolet light (see Fig. 9.1) revealed details 50 km across that, despite their fuzziness, suggested the existence of a dark spot 240 km in diameter on the surface, most likely a giant crater.

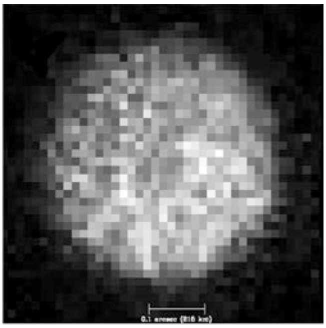

Fig. 9.1. Ceres observed by the Hubble Space Telescope in 1995, the first time the asteroid was seen as a disc. Fuzzy areas show a darkened area in the center. (Image courtesy of HST/NASA/Southwest Research Institute)

Seven years later, ground-based observations from the powerful Keck telescopes provided sharper images and confirmed the presence of the dark spot and a few more darkish areas. More importantly, the Keck observations established that Ceres is an oblate object. Since the shape of a spherical object depends, among other things, on its rotation speed and the mass distribution within its interior, scientists used models to infer that Ceres' interior could be differentiated with an icy mantle resting on a rocky core. Some even went as far as to predict a 100-km thick layer of water-ice. Given this, Ceres was considered to be a large, wet protoplanet.

During this time, the HST required multiple repairs and upgrades by space shuttles missions, significantly improving its capabilities (Shuttle Service Mission 2 in 1997, Service Mission 3A in 1999 and Service Mission 3B in 2002). In effect, new colored images of Ceres in visible and ultraviolet light taken by Hubble in 2003 and 2004 covered a full rotation of the dwarf planet (nine hours) and showed multiple recognizable surface features and mysterious bright spots (Fig. 9.2).

The giant asteroid got even more interesting when in 2005 a study done by Thomas McCord at the Hawaii Institute of Geophysics and Planetology, University of Hawaii, and Christopher Sotin, at the time at the Laboratory de Planetologie et Geodynamique, University of Nantes in France, calculated that the radiogenic heating within the protoplanet would be sufficient to create and potentially sustain a small subsurface ocean if enough differentiation had occurred and an icy mantle was present. (Further studies published in 2010 and 2011 seemed to support the McCord-Sotin interpretation.)

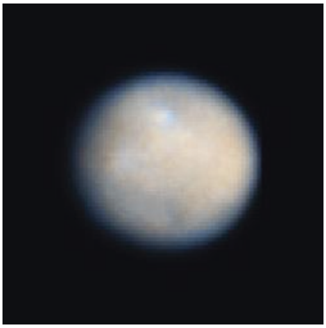

Fig. 9.2. Ceres imaged by the Hubble Space Telescope in 2003 and 2004. (Image courtesy of NASA/ESA/J. Parker [Southwest Research Institute], P. Thomas [Cornell University], L. McFadden [University of Maryland, College Park], and M. Mutchler and Z. Levay [STScI])

At that point, the scientific community was lobbying hard for a spacecraft to visit the dwarf planet and perform close-up studies. Fortunately, the Dawn mission, whose primary objective was to study Vesta and Ceres, was selected in 2001 as part of NASA's discovery program, and, despite multiple false starts and cancelations, was finally launched in 2007.

While Dawn was en route to the Asteroid Belt, a new study published in 2009 by Mikhail Zolotov of Arizona State University proposed that, contrary to having an icy mantle, Ceres might be relatively dry, as its low density could also be explained if it was an undifferentiated body consisting mainly of porous rock increasing in density as we approach the core. The competing theories – dry and undifferentiated versus wet and partially differentiated – would split the scientific community into two camps.

Prior to Dawn's arrival in 2015, observations made a year earlier by ESA's Herschel Space Observatory (a Hubble equivalent in infrared), hinted that water vapor was escaping from two specific areas linked to mid-latitude regions on the surface. Such events could either be due to comet-like sublimation, where ices are transformed into gases, or to cryovolcanism, where internal heat creates ice geysers similar to Enceladus (see Chapter 8). This discovery fired up the scientific community. The year 2015 couldn't arrive soon enough. So when the Dawn spacecraft inserted itself into Ceres' orbit in the spring of that year, a new chapter in the exploration of protoplanets had begun.

The Dawn Revolution

In many ways, Dawn is a groundbreaking mission as it is the first exploratory space mission to use ion propulsion, which allows spacecraft to enter and leave the orbit of multiple Solar System objects. As such, before arriving at Ceres, the spacecraft had already orbited Vesta, another noteworthy protoplanet in the Asteroid Belt. It was also the first spacecraft to visit Vesta and Ceres.

It is also worth mentioning that while Dawn is managed by NASA, two of its three main scientific instruments were provided by Europeans. The framing camera (FC) was built by the German Space Agency, and the visible and infrared spectrometers (VIR) were built by the Italian Space Agency, highlighting the importance of international collaboration in space exploration. The last scientific instrument carried by Dawn is the gamma ray and neutron detector (GraND).

At the time of writing, Dawn had already been studying Ceres for three years, taking over 55,000 pictures and fully mapping its surface. The orbiter has revealed an intriguing world of salty brines, ices, and traces of past activity, such as ancient cryovolcanoes. Here are some of the most striking discoveries.

For a start, astronomers were surprised by the lack of large craters on its surface (none are bigger than 280 km in diameter), as would be expected from a Solar System object with a 4.5-billion-year story. It could either be explained by active geology (i.e., ice volcanoes) resurfacing the dwarf planet, or it could be due to layers of ice or other low-density material (i.e., salt) lying just below the surface, which would smooth surface features over time and erase large craters (Fig. 9.3).

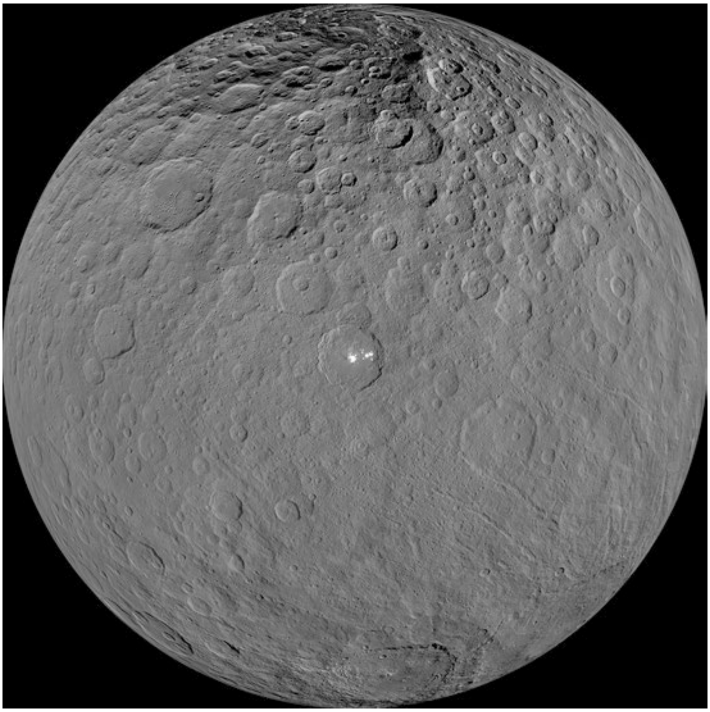

Fig. 9.3. Ceres viewed by the Dawn spacecraft in 2017. A high resolution image taken by Dawn provided a full view of the dwarf planet, with the bright spot clearly visible within the Occator Crater in the middle of the image. Recent studies estimate its age at around a few million years only. (Image courtesy of NASA/JPL-Caltech/UCLA/MPS/DLR/IDA.)

What also became immediately apparent in the first pictures taken by Dawn was the presence of very bright spots (called faculae) standing out on an otherwise coal-dark surface. The spacecraft has now detected over 130 such spots, most of them within craters, with the brightest one lying in Occator Crater, a 90.5-km-wide impact crater formed less than 30 million years ago. Recent measurements estimate the age of the faculae in Occator Crater as being only four million years old, the blink of an eye in geological time.

The nature of the bright spots is not icy material, as was initially suggested, but instead large accumulations of sodium carbonate. In fact, this is the largest deposit of sodium carbonate outside of our planet. Intriguingly, on Earth, this mineral is formed in aqueous conditions linked to a hydrothermal environment. Liquid water is therefore required to bring these minerals up to the surface, most likely in the form of brine. Although this could be suggestive of a very wet subsurface, it is worth pointing out that minimal amounts of moisture within the surface can also generate brines.

Further evidence that Ceres has a wet interior has accumulated, though. Ahuna Mons, an impressive yet lonely 4-km-high ice volcano that appears to be only a few hundred million years old, seemed to have been formed with ices containing substantial concentrations of salts (whose nature is unknown at present). Its origin is thought to be due to hot subsurface brine pouring out to the surface through cracks in the crust and accumulated through time to form the gigantic volcanic dome.

Dawn also confirmed the existence of a transient atmosphere mainly composed of water molecules, which supports the 2014 discovery by ESA's Hershel telescope. This atmosphere seems to be present only during intense solar activity, which seems to warm up and sublimate exposed surface ice within the craters, thus generating a seasonal exosphere. It is similar to what has been observed in comets and provides a direct line of evidence that water-ice is still present on the surface of the dwarf planet.

Additional evidence for the existence of water-ice on Ceres' surface would be published in 2016, as Dawn's gamma ray and neutron detector (GraND) found hydrogen in the uppermost surface, which is indicative of water (mainly frozen). GraND is a clever instrument. It accurately tracks the neutrons escaping from Ceres' surface as it interacts with the galactic cosmic rays (GCR), very high energetic particles from space that strike the surface of the protoplanet. The resulting neutrons do not fly off randomly into space but instead, do so in a pattern determined by the nature of the material hit by the GCRs. By tracking the rate of GCRs the surface is being exposed to and measuring the neutrons generated, one can infer what was hit by the GCRs. Remarkably, GraND can detect neutrons resulting from material lying within a meter under the surface, thus revealing the composition of the surface as well as the immediate subsurface.

Thanks to such capability, GraND detected subsurface water everywhere on Ceres, especially at mid to high latitudes, where temperatures are lower. Such a discovery doesn't necessarily imply that a thick icy crust exists on Ceres (similarly to the ones found within the icy moons of the outer planets), since the measurements could also result from a mixture of water-ice and porous rocky material, thus forming an undifferentiated surface of rocks and ice. In fact, Dawn has detected only a few patches of water-ice lying directly on the surface, although these are located within areas of permanent shadow (such as in crater rims), although the total amount of surface water-ice is marginal compared to the subsurface water detected by GRaND.

Intriguingly, Dawn also found the presence of NH_3 on the surface in the form of ammonia-rich clays and ammonia salts. As ammonia condensed within the outer Solar System, either Ceres was formed in the outer Solar System and then migrated to its current position within the Asteroid Belt or it was formed in the Asteroid Belt yet was subjected to heavy bombardment in its past by outer Solar System objects rich in ammonia. The intriguing idea that Ceres originated in the outskirts of the Solar System is not new, as planetary scientists have suggested for years that the protoplanet bears more resemblance to more distant objects (such as Pluto) than to the asteroids within the belt itself. The early formation of the Solar System was a chaotic one, and it isn't unreasonable to postulate that Ceres migrated from a trans-Neptune orbit to the Asteroid Belt, losing its icy mantle in the process.

It is, however, difficult to explain Ceres' relatively circular orbit and low inclination in respect to the ecliptic plane if the protoplanet had originated from the outer Solar System and migrated inwards. A compromise between these two theories would be to consider Ceres' rocky interior to have originated from the Asteroid Belt and its icy material delivered by distant objects such as comets. Regardless of its mysterious origin, ammonia-bearing objects also contain large amounts of water-ice, so either way, Ceres should have accumulated water.

At the beginning of 2017, NASA made an announcement that took the media by storm: Dawn had detected traces of organic compounds (see Chapter 3) in the dwarf planet's northern hemisphere, more precisely, near Ernutet Crater as well as in Inamahari Crater. Although scientists couldn't accurately determine the exact nature of the compounds, they matched the wavelength absorption of aliphatic organic compounds, similar to hydrocarbons.

What is striking with the discovery concerning Ceres is the fact that the aliphatic organic compounds are thought to have been formed inside the dwarf planet and then flowed onto the surface rather than being delivered in a collision with another object. Indeed the concentration of the organics found on the surface is too high to have been transported by impacts alone, as these tend to dilute the compounds. A more plausible scenario for the origin of such organic material is through hydrothermal processing where warm water and clay minerals catalyze the production of new organic compounds. Such an interpretation not only brings to light the processes that have been active under the surface of Ceres but it also increases the dwarf planet's potential to have in the past a habitable environment.

Water, Rocks, and the Potential for Life

Given all the information collected by Dawn as of today, what can we assume about the dwarf planet?

It is a complex, dynamic world that currently defies a straightforward explanation. Is it a dry undifferentiated world or a wet differentiated one? Neither, since the latest observations and models point towards a middle ground view, whereas the protoplanet is only partially differentiated; ices and rocky material have been separated in some areas – the telltale sign of past heating – while other regions remain undifferentiated.

Our current understanding of Ceres' interior is the following. A solid rocky core at the center of the protoplanet does exist; however, given its density, estimated at 2.46 to 2.90 g/cm^3, and the fact that Ceres hasn't experienced full differentiation, it seems to be partially hydrated. More water and volatiles can be found in the outer layers and crust as their density has been calculated to be around 1.68 to 1.95 g/cm^3, closer to that of water. However, the existence of numerous craters on the surface requires a strong crust, about 30-km thick, able to support such features.

How can the crust be similarly strong yet have a low density? It has been recently proposed that the mixture of rocks, ice, and salts forming the crust might also be composed of clathrate hydrates – water-based crystalline solids that trap gas molecules, giving them an inherent structural strength while having a low density. More research is required to identify the composition of the crust.

Gravity measurements and the lack of large craters also suggest that this ice/rock crust must lie on a weaker material. The most likely explanation is that it is an icy water mantle, and the viscosity required by current observations justifies the presence of pockets of liquid water, probably rich in ammonia and non-ice materials such as salts (which lower the freezing temperature). Therefore there is a possibility that subsurface lakes or even small regional seas might still exist today, although a full subsurface ocean encircling the protoplanet is not envisaged.

The distribution of minerals on the surface indicates extensive alterations, most likely due to past water/rock interaction, while the presence of ammonia point out that some of Ceres' building blocks originate from a colder environment (the outer Solar System). With the discovery of numerous brine deposits, smoother areas due to resurfacing events, and a massive cryovolcano (Ahura Mons), reaching up to 4 km high, there is clear evidence that subsurface water and volatiles have been pressurized through cracks within the crust and released on the surface, bringing with them non-ice material such as salts and minerals. Given what we saw on Enceladus (see Chapter 8), it would be tempting to suggest that a substantial amount of heat could drive such processes, but ironically, it is the opposite that is most likely happening. Indeed, as a pocket of subsurface liquid water freezes over, ice expands within the pocket and puts pressure on whatever liquid brine is left, pushing it through the cracks towards the surface.

Finally, the presence of organic compounds on the surface associated with warm water chemistry builds a strong case for a warm liquid water environment in the past, most likely an ancient subsurface ocean that has now frozen completely, forming the current crust.

All things considered, Ceres presents a unique environment where researchers have the opportunity to directly observe surfaces that have been altered by water/rock interactions, such as what might occur on the ocean floor of subsurface oceans. No other place in our Solar System is comparable.

We have seen that liquid water environments existed in Ceres' past and most likely still exists at this present day in the form of subsurface pockets. The presence of water, warmed by radiogenic heating, and in direct contact with rocky materials, minerals, salts and organic material has led astrobiologists to strongly consider the possibility that microbial life could have arisen during Ceres' past and might still be present today, buried deep down within the water mantle (and so protected from harmful cosmic rays and solar radiation). After all, with surface temperatures of up to –38 °C (235 K), one could land on Ceres and walk on its surface for a short period with only an oxygen mask and a thick jacket.

In addition, Ceres' proximity to Earth and Mars (only 2.8 astronomical units away from the Sun), does make it susceptible to biological cross contamination, whereas microbial life that might have arisen on these planets during the early phases of our Solar System could have been transported, through asteroid strikes, to planetary objects such as Ceres, where a habitable environment could have been present –the panspermia hypothesis.

Some have even raised the idea that this process could have occurred the other way around, that life might have first originated on Ceres and then was delivered to Earth (as well as to early Mars or Venus), where a warmer and wetter environment was present. For all we know, we might all be Cereans.

Needless to say, there is still much to learn from this fascinating object and the data provided by the Dawn orbiter will keep scientists busy for many years to come. After the success of Dawn, the next logical step would be to send a lander to do in situ measurements of the surface material given the unique environment Ceres has to offer. However, with the scant, but real, possibility that life might still be present there, such a mission would present its own set of challenges given the severe restrictions required by planetary protection (see Chapter 6 on Europa for further details on planetary protection).

We will now visit another possible ocean world, lying within the orbit of Saturn, the icy moon of Dione. Although at first glance Ceres and Dione might seem completely different objects, if one could imagine covering Ceres' rock-like crust with a 100-km-thick icy mantle, it would most likely resemble the Dione we see today.

Dione

Discovery and Observations

With our memories still fresh from Ceres' unusual rock-ice surface, we now quickly go back to Saturn's orbit, passing through the tenuous E-ring with tiny Enceladus at its center (see Chapter 8) and arrive at another ocean world candidate, the icy moon of Dione.

At 1,122 km in diameter, the moon is somewhat larger than Ceres by only 200 km. Interestingly, many planetary objects share a similar size as Dione. The moons Charon, Umbriel, Tethys, Ariel, and the dwarf planets Haumea, Quaoar, Senda (and of course Ceres) are all within a 15% diameter range although they differ significantly in their origins and composition. As we make our final approach, one sees that Dione has a distinctive yet familiar surface – smooth plains, cratered terrains, ridges and chasms, to name a few of the features visible from orbit. Surprisingly, the moon's leading side (facing the direction of motion) is bright, contrasting with the much darker trailing side, which hosts a surface feature that astronomers previously referred to as 'wispy terrain.' We will come back to these later. Evidence of past geological activities affecting large surface areas have been found, and some scientists even suggest that Dione might still be active today, although at a much-reduced rate. Even more remarkable, it is possible that a subsurface ocean might still be present under a thick icy mantle, making Dione a candidate for the ocean worlds club whose members already include Ganymede, Callisto, Enceladus, Titan, and Europa.

Dione was discovered in 1684 by the French-Italian astronomer Giovanni Domenico Cassini using the Paris observatory, of which Cassini was the director. In his notes, we learn that Cassini wanted to name the moon (and the three others he had found) as Sidera Lodoicea (Louisian Stars), after King Louis XIV of France, his patron, much like Galileo had done 70 years earlier when he named the four Jovian moons Sidera Medicea (Latin for Medicean stars) in honor of the Medici family of Florence. Cassini pointed out that the names would be by themselves much more lasting monuments to the memory of the French king than those of brass and marble.

Luckily for us, the stars of King Louis didn't catch on, and a terminology similar to the one employed for the Jovian moons was quickly adopted; Dione and her companions were known as Saturn I to VII depending on their presumed distance from the giant planet. Until 1847, when William Herschel's son suggested the name Dione, the moon was known as Saturn IV. (The naming of the Saturnian moons proved to be more complicated than that – see Chapter 7 for more details on this whimsical story.)

Earth-based observations of Dione in the twentieth century proved frustratingly limited due to the moon's small size and distant location. Nevertheless through spectrophotometric observations done in 1975 and 1976, astronomers detected the presence of frost/ice on its surface, the first direct evidence that the moon's crust was composed of water. Further observations made shortly after highlighted a difference in the light reflected by the moon (its albedo) as it orbited Saturn, implying that its sides were not uniform.

As with most planetary objects in the outer Solar System, the Voyager spacecraft transformed what had been until now a speck of light in the dark sky into well-defined worlds. It was *Voyager 1* that took in 1980 the first close-up shots of the moon, revealing both the leading and trailing side while *Voyager 2,* which did not come as near, managed to take images of areas that had been poorly covered by *Voyager 1,* albeit at a lower resolution. The measurements made by the Voyagers allowed astronomers to calculate with high precision the density of Dione, putting it at 1.48 g/cm^3, suggesting that it is most likely composed of a large icy mantle resting on a silicate core.

Upon reviewing the Voyager images, it became clear to mission scientists that Dione, much like Enceladus, had experienced numerous past geological activities. Vast surface areas have few impact craters present (none bigger than 30 km in diameter), indicative of potential past resurfacing events, in contrast to ancient heavily cratered regions with very large craters (more than 100 km in diameter). The moon seemed to be geologically active in its past.

Intriguingly, the leading side showed fewer impact craters than the trailing side, contrary to what might be expected. Indeed, as a reminder, like most of the major moons in our Solar System, Dione is tidally locked to its parent planet, with one side always pointing towards the direction of motion, the leading side, and one towards the opposite, the trailing side. It is assumed the leading side is darker since it gets impacted by more space debris and dust than the trailing side. (Like a car driving on a dusty road, the front windshield will accumulate more dust than the rear windscreen.) To everyone's surprise, Dione was the exact opposite. The only explanation favored by scientists is that the moon was once tidally locked in the opposite direction before a giant impactor hit it with enough energy to change its spin, locking the moon into its new configuration.

Calculations show that due to the moon's small size, an impact large enough to form a 35-km crater could spin it in the opposite direction. Given that the surface shows many craters larger than this, it is tempting to conclude that Dione could have spun multiple times throughout the eons, although such a view is not supported by the cratering pattern observed on the surface, which can only be explained if Dione's current orientation has remained stable for billions of years. Evidently, the origin of the spin is currently not well understood, and it might be that a better idea will be proposed in the future to account for the differences in the leading and trailing side.

Another discovery that puzzled scientists was the presence of 'wispy' features on the trailing side, as seen on the images taken by the Voyagers. These elongated white fuzzy lines were thought to be the deposits from a material that had vented off through linear fractures, although no sign of such activity or fissures were apparent.

As numerous surface features hinted at past activity, planetary scientists envisioned Dione to be much warmer in the past. The combination of radioactive heat generated from the silicate core as well as accretion heat (energy trapped during the moon's formation) could have temporarily melted the icy crust and formed a subsurface ocean that has since then frozen over. Indeed, tidal heating (described in Chapters 1 and 6) was not considered sufficiently strong enough to warm Dione's interior given its current orbit.

The discovery on Dione's surface of chasmata (pl. of chasma), deep and elongated depressions resembling canyons, is important, as these features are thought to be leftover scars following the expansion of the moon's interior water mantle as it froze up, pushing the entire crust upwards. If Dione had a subsurface ocean, it was all frozen up now. Compared to its tiny yet more active neighbor Enceladus, Dione seemed to be a frozen world, lacking in pizzazz. The arrival of the Cassini orbiter would change this view altogether.

Cassini's Results and Dione's Habitability

The Cassini orbiter (see Chapters 7 and 8 for further details on the Cassini mission) flew past Dione only five times during the entirety of its thirteen-years-long mission within the Saturnian system. Enceladus and Titan took the lion's share with almost a hundred and fifty flybys in total between them both. The high-

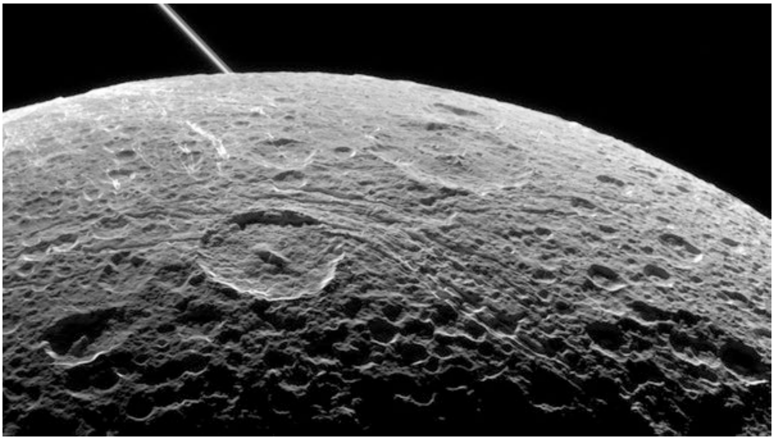

Fig. 9.4. A view of Saturn's moon Dione captured by NASA's Cassini spacecraft during a close flyby on June 16, 2015. The diagonal line in the distance near upper left indicates the rings of Saturn. (Image courtesy of NASA/JPL-Caltech/Space Science Institute)

resolution images captured by the orbiter as well as the remote sensing measurements taken during these flybys renewed the scientists' interest in this icy moon (Fig. 9.4).

The 'wispy' features were found to be huge cracks in the icy crust, exposing very bright cliffs (rather than vent deposits, as was originally perceived). Cutting across hundreds of kilometers of cratered surface, indications were that they had formed much later in the moon's history. The most likely explanation for such giant fissures was the freezing of a past subsurface ocean that, as we have already seen with the chasmata, would have pushed the outer layer upwards, stressing the crust and forming giant fissures. It is thought that cycles of freezing and melting would have contributed to the patterns we observe today, although the properties of the ancient subsurface ocean are poorly understood. For example, there is no clear explanation as to why these cracks have only appeared on the trailing side of the moon. Whatever the cause, it is clear that Dione bears witness to a dynamic past where a mantle of liquid water was present (mixed with ammonia and other volatiles).

Another feature supporting a dynamic past was described in 2013 following the detailed observation of high-resolution surface images (<1 km/pixel) returned from the orbiter's imaging instruments. By carefully analyzing these images, Cassini scientists discovered an area within the leading hemisphere that is entirely free of impact craters, indicative of past flooding by melting ice (or liquid water) or that it was blanketed by fallen material from a nearby cryovolcano, whose location has been suggested but not confirmed. In the south pole, scientists have also identified a surface feature that is very similar to Enceladus' famous tiger stripes (see Chapter 8), although, it is mostly inactive.

Further proof of a past subsurface ocean was found in the topographic anomaly of a mountain range named Janiculum Dorsa, an 800-km-long north-south trending ridge. Rising to an elevation of 1 to 2 km, the mass of this mountain range seems to have deformed and depressed the icy crust underneath it by as much as half a kilometer. This bending of the crust can be best explained if Dione had a warm subsurface ocean at the time of Janiculum Dorsa's formation.

Also, a transient atmosphere of oxygen was confirmed in April 2011 when the RPWS instrument detected a faint trace of ionized oxygen during a close flyby (at 503 km from the surface). This atmosphere is extremely thin, 5 trillion times less dense than Earth's atmosphere at sea level. Therefore it is best to view it as an exosphere instead of an atmosphere. Moons with exospheres composed of oxygen molecules are not uncommon (for example Rhea, a moon of Saturn, has one), and it is assumed that the source of the oxygen are the high energy particles generated by a strong magnetosphere, Saturn's in this case, or solar radiation, which break down the water molecules located on the top layer of surface ice and release oxygen molecules into the exosphere.

Remarkably, though, a discovery contradicts Dione's image of a frozen moon.

In a paper published in 2007, it was revealed that measurements from Cassini's magnetometer and radio and plasma wave science instrument (RPWS) detected plumes of material feeding plasma (ionized gas) in Saturn's rotating magnetosphere and concluded that it originated inside the orbits of Dione and Tethys (an icy moon of similar size). Given what we know of Tethys, scientists strongly suspect that Dione is the source of the plasma; yet Cassini was not able to find traces of a plume despite multiple flybys of the icy moon (and Tethys), leading some scientists to speculate that the venting might be occurring episodically or could, in fact, be too weak to be detected by Cassini's instruments. Future observations will be required to confirm if such venting is indeed occurring.

Given what we know of Dione today, it might be possible that there is still enough heat within the moon's interior for a layer of water mantle to be present. With this in mind, some scientists have tried to find new ways to detect its presence. A study led by Mikael Beuthe of the Royal Observatory of Belgium and published in 2016, used the gravity data from the Cassini spacecraft as it made its flybys of the moon to explore its interior. As seen in the previous chapters, gravity data from the moon is obtained by measuring tiny variations in the gravitational pull generated by the moon as Cassini passes next to it. The spacecraft was continually emitting signals directed towards NASA's Deep Space Network (DSN) that could then be used to measure the exact position and velocity of the probe. With this information, scientists can work out the gravitational forces to which the orbiter was being subjected at specific locations around the moon, thus revealing the differences in masses and providing clues to Dione's interior structure.

This gravity data was processed in a new computer model conceived to simulate the icy shells of Dione and Enceladus. Since the interior of Enceladus is now well understood, we can use it as a benchmark to assess the accuracy of a given model. Indeed, until now, previous attempts at modeling these icy moons failed as they wrongly predicted a very thick icy crust on Enceladus. However, the newest model comes very close to what we currently observe on Enceladus, therefore providing some credibility to its prediction of Dione.

According to the study, a subsurface ocean tens of kilometers thick is predicted and is thought to be located hundreds of kilometers deep under the icy crust. It also predicts that this ocean would rest on the silicate mantle, allowing for rock/water interactions, which are a vital component for assessing the ocean's habitability. It is important to point out though that this latest study isn't conclusive proof that a subsurface ocean exists on Dione. In fact, most planetary scientists consider it to be very weak evidence at best. But it nevertheless suggests that there is a possibility, even if it is remote, that Dione could still host a subsurface ocean.

In summary, Dione had an ancient subsurface ocean whose apparent freezing formed the surface features we observe today, and it might be that Dione could still have enough heat to warm up parts of its frozen interior. However, given the end of Cassini's mission and with no planned or proposed missions set out to explore Dione more thoroughly, Earth-based observations, as limiting as they can be, will be the only source of new data for decades to come. Don't hold your breath on Dione.

From the little we know so far, could life appear and thrive if Dione did have a subsurface ocean? Some characteristics are more favorable for life than others. The fact that the liquid mantle has been predicted to be adjacent to a silicate mantle/rocky core does imply that it will contain dissolved elements essential for life. Furthermore, the ocean will be an ancient one, most likely formed at the same time as the moon itself some 4 billion years ago. Plenty of time therefore for life to arise. However, with little to no tidal heating to warm the moon up, the ocean has to contain a substantial amount of antifreeze compounds to keep it active at low temperatures, and, given the high levels of toxicity, life as we know it would not be able to survive. If Dione still hosts a subsurface ocean today, it will most likely be cold, dark, and sterile.

10. Triton and Pluto

Even before *Voyager 2* had sent back the first images of Triton in 1989, it was commonly accepted that Neptune's moon and Pluto were analogs, most likely sharing a similar origin but had somehow parted during the chaos of the early Solar System. The close observations of both objects have confirmed this interpretation. In this chapter, we will review both worlds, which are listed in different categories (one as a moon and the other as a dwarf planet) purely because of their location.

Triton

Discovery and Observations

To visit Triton, we need to travel further out from Saturn, past the orbit of Uranus with its system of mid-size moons (which we shall explore in the following chapter) to reach the blue gas giant that is Neptune. At such a distance, 4.5 billion km from Earth (or 30 AU), our Sun is just a bright jewel drowned in a sea of darkness. The vast emptiness surrounding us might give the impression that we have reached the edge of the Solar System, yet we couldn't be more wrong. Lying further out from Neptune is the Kuiper Belt at 35 to 40 AU, home to Pluto and many of its siblings.

At 30 AU, it is now cold enough (35 K) for all volatile compounds to turn into ice. The most abundant ices found at this location are water (H_2O), followed by methane (CH_4), ammonia (NH_3), carbon monoxide (CO), and hydrogen cyanide (HCN). These five compounds account for 98% of the ice mass in the region. In effect, the planetary objects found here will be mainly composed of rocky material and ices such as water, methane, nitrogen and carbon monoxide. (This is why the planets Neptune and Uranus are referred to as the 'ice giants'; given their high concentration of icy material, in contrast to the 'gas giants' Jupiter and Saturn).

Incidentally, the high temperatures generated by Neptune's metallic core gives rise to layers of slushy ices composed of water,

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ammonia, and methane upon which rests a thick atmosphere of helium, hydrogen, and gaseous methane, giving the planet its distinctive bluish tint. Smaller planetary bodies such as moons and dwarf planets lack the mass of planet-size objects to sustain the levels of heat required to melt the ices contained within them, so most of them are thought to be frozen solid, although, as we shall see with Triton, this isn't always the case.

Neptune's discovery, almost 200 years ago, represented a turning point in astronomy and the world of science. The fourth largest planet in our Solar System orbits the Sun at such great distances that it cannot be seen with the naked eye. Therefore, it couldn't be detected through serendipitous observations in the way most celestial objects had been found up until then. Instead it was found by way of a new method to look at the world – through mathematical predictions.

At the time, astronomers were puzzled by the peculiarities of Uranus' orbit, and it was the French mathematician Urbain Le Verrier who was the first to prove through mathematics that another hypothetical planet was most likely the cause of such anomalies. Observations were done at the Berlin observatory shortly after by the German astronomer Johann Galle, and he discovered on September 23, 1846, the planet at the precise location as predicted by Le Verrier. Neptune, the eight planet, became a sensation overnight.

Upon receiving the news that French and German astronomers had discovered a new planet, John Herschel, son of the famous William Herschel, who had discovered Uranus sixty years earlier, informed William Lassell, a keen British astronomer (and brewer by profession – those were the days) to immediately search for potential moons around Neptune in order to salvage some British pride in what had been a national embarrassment. Lassell started his observations the following day.

The British felt that Neptune's discovery was 'stolen' from them, as two months before Le Verrier presented his work to the Académie des Sciences at Paris, a young English mathematician, John Couch Adams, had also independently predicted Neptune's orbit. In September 1845, he had contacted the director of the Cambridge observatory as well as the Astronomer Royal at Greenwich, George Biddell Airy, to entice them to start observations and find the new planet. Some confusion remains as to why they didn't follow up on Adam's predictions, most likely because they didn't believe his predictions to be true, and it was only when

Airy got wind of Le Verrier's work in Paris that he understood his mistake of not pursuing the observations. He immediately went to work to catch up on the time lost. The race to find the new planet had begun.

By July 1846, Airy had finally managed to convince the busy and reluctant director of the Cambridge observatory, James Challis, to do a systematic search in the area of the sky where the new planet was predicted to be located in the hope of finding it first. Challis was at the time fully absorbed in the task of diligently tracking down comets and felt that the search for a theoretical planet was not a valuable use of his time. In the meantime, a frustrated Le Verrier had been unable to convince the French astronomers in Paris to point their powerful telescopes to the planet's predicted location, so he got in touch with the more open Berlin observatory instead.

It might be difficult for us to comprehend Challis and the Parisian astronomer's lack of enthusiasm for the discovery of a new planet, but it is important to remember that at the time, predicting the existence of a celestial object through mathematics alone had never been done before.

It was the British that first spotted Neptune. Thanks to the precise calculations made by Le Verrier and Adams, it didn't take long for Challis to detect the planet. By early August he had done so on two occasions and recorded it in his notebook. Incredibly, though, he didn't recognize the importance of his observations and failed to communicate these to Airy, due to a very busy schedule. A month later, Galle in Berlin had also found Neptune in the location predicted by Le Verrier, and contrary to Challis, he immediately published it, making him the official discoverer of the new planet.

Upon realizing that they had lost a once-in-a-lifetime opportunity to find a new planet due to their negligence, Airy became determined to make up for it with the search for a new moon. It was therefore with some relief and a somewhat small consolation that only seventeen days after Galle had discovered Neptune, William Lassell spotted its moon on October 10, 1846. Intriguingly, the brewer did not come up with a name for Neptune's moon, and since it was the only visible object orbiting the planet at the time, it was just known as 'the satellite of Neptune.' Only much later did the French astronomer Camille Flammarion propose the name Triton, which got quickly adopted by the scientific community.

Nitrogen Everywhere

The vast distances separating us from Triton as well as its apparent proximity to Neptune (no more than 17 seconds of an arc) meant that observing the moon was difficult. Even sixty years after its discovery, astronomers had very little to say.

Things started to change in 1930 when Triton's orbit was accurately measured, revealing, to everyone's surprise, that it was retrograde compared with Neptune's spin and orbital motion. In other words, Triton was orbiting in the opposite way to Neptune's orbit around the Sun, the only major moon to do so. This puzzled many astronomers and led them to coming up with various interpretations.

In 1934, Issei Yamamoto, the director of the Kyoto observatory in Japan, suggested that a star had passed close to Neptune, forcing Triton into a retrograde orbit and ejecting Pluto (which was supposed to be a moon of Neptune as well). Another theory was put forward by Raymond A. Lyttleton of England when he proposed in 1936 that a near collision between Triton and Pluto had pushed Pluto out of the Neptunian system as well as radically altered the course of Triton so that it now moved around Neptune in the opposite direction.

Another explanation for Triton's weird orbit was that it didn't form within the Neptunian system after all, but instead, originated elsewhere and got captured by Neptune as it passed much too close to the planet. But when did Triton form? Astronomers couldn't say. Also, in addition to this strangeness, no new objects had been found orbiting Neptune at the time, making it a one satellite system in contradiction to the extensive satellite systems found orbiting Jupiter, Saturn, and Uranus. It was not until more than a hundred years after Triton's discovery that, in 1949, a second moon was detected, the significantly smaller Nereid.

In 1954, the Dutch-American astronomer Gerard Kuiper managed to estimate Triton's diameter at around 3.800 km – a figure 40% higher than its actual size. This early 'erroneous' estimate had the benefit of placing Triton as one of the largest and most massive moons in the Solar System (just between Io and Callisto, the giant moons of Jupiter). Kuiper also managed to detect a mysterious reddish tint in Triton's light, hinting at the possible composition of its surface, but nothing more could be deduced at the time, and Triton remained a curious oddity.

By 1978, technology had finally caught up, and methane ice (CH_4) was detected in Triton's infrared spectrum, two years after a similar detection had been made on Pluto, pointing once again to a similarity between these two objects. The discovery of ice on Triton meant that its surface was more reflective than initially envisioned, forcing astronomers to re-evaluate the moon's size to a smaller value than implied by its apparent brightness making it a similar size to Pluto.

The discovery of methane also explained Triton's slightly reddish tint as the Sun's UV radiation can break down methane ice, turning it into red or pink compounds. But there is a catch. When exposed to too much radiation or charged particles, broken down methane gets transformed into a black residue, raising the possibility that if methane was indeed responsible for Triton's color, it had to be continuously replenished. This was a puzzle. Located far away from the Sun, Triton was expected to be one of the coldest objects in the Solar System, and with no alternative energy sources available, there was no reason for it to be geologically active and vent out fresh methane (tidal heating hadn't yet been discovered).

As the Voyagers were making their extraordinary journey past the Jovian and Saturnian systems, further infrared observations detected nitrogen (N_2) in Triton's spectra.[1]

The nitrogen measurements on Triton were so elevated that these could only be explained if the element was not only in its gaseous state but also in its solid or liquid state, giving scientists two distinct models for Triton's surface: one where nitrogen and methane ice formed a stable blanket on the surface, and one, far more exotic, where liquid nitrogen would create a vast ocean with methane icebergs floating on it, an exciting prospect.

Alas, additional studies showed that the moon couldn't sustain the relatively high temperatures required for nitrogen to be stored in its liquid phase (63 K). Nitrogen oceans were out. Astronomers were therefore confident that *Voyager 2* would find, among many other features, large polar caps of nitrogen ice (the source of Triton's tenuous atmosphere of nitrogen).

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[1] The only other place in our Solar System where nitrogen had been discovered on a moon was in Titan's atmosphere, in much smaller quantities than what was being measured on Triton.

Voyager 2's Discoveries

Before Voyager's encounter with Triton in 1989, astronomers learned more about Pluto thanks to the discovery of its moon Charon (see Chapter 11) and stellar occultations. They found that the similarities between Pluto and Triton were striking. Both objects have a similar spectrum of visible and near-infrared light as well as visual magnitudes arguing for bright icy surfaces. They also have almost identical sizes (as big as our Moon), although Triton is 40% denser than Pluto, and share a thin atmosphere. (The composition of Pluto's atmosphere was still not defined at the time, but some scientists suspected it was similar to Triton's.) Because of this, some astronomers proposed that Triton and Pluto were actually from the same family and formed in the same area of our Solar System, the so-called Kuiper Belt (at the time a theoretical doughnut-shaped ring lying further out from Neptune). Somehow Triton escaped the belt and got captured by Neptune, whereas Pluto stayed put. The implications of such a suggestion were profound. If the case for brotherhood was confirmed, not only does Pluto lose its status as a unique object in our Solar System, it also argued that more Pluto-like objects should be present in this part of our Solar System, in effect compromising Pluto's status as a planet. This also meant that learning more about Triton would improve our understanding of Pluto and vice versa.

Because of all this, *Voyager 2's* planned encounter with Triton was considered to be much more than just the study of another intriguing moon in our Solar System. Instead, it was the unveiling of a new type of planetary object that scientists referred to as trans-Neptunian, objects formed beyond Neptune's orbit.

Intriguingly, a study led by geophysicist David G. Jankowski from Cornell University, in April 1989, a few months before *Voyager 2's* highly anticipated flyby, suggested that tidal heating could play an essential role in providing energy to Triton. Such a scenario was dependent on the obliquity of the moon's orbit in relation to the orbit's plane, and the study showed that if the moon had an obliquity of about 100 degrees (a state referred to as the Cassini state 2), it was theoretically possible for Triton to be subjected to large amounts of tidal heating. *Voyager 2's* arrival a few weeks after the publication of this study would determine if Triton had the required obliquity.

And so on August 25, 1989, *Voyager 2* flew by Triton in a once-in-a-lifetime event that has not been repeated since. The good news was that since the Neptune-Triton system was the last one to be visited, mission planners could bring the spacecraft as close as possible to Triton without worrying about the angle of its outward trajectory. Triton would be, rightly so, the fitting capstone in *Voyager 2's* awe-inspiring journey.

On that day, the space probe skimmed Neptune's north pole at only 4,950 km above the atmosphere – the closest approach to any planet during its 12 year journey – and the influence of the planet's strong gravitational pull placed it on a trajectory that took it within 38,500 km from Triton's surface. This was a remarkably precise trajectory after a journey of hundreds of millions of kilometers.

Voyager 2 approached Triton's north pole at a breathtaking 56,000 km/h, far too fast for surface images to be taken. As a result, only the sunlit portion of the southern hemisphere was captured by the camera during the flyby. It showed an icy world, with dark streaks and pink ice reflecting 70% of the sunlight that struck it.

The space probe also measured the surface temperature during the flyby and confirmed that the moon was the coldest in our Solar System, with a mean temperature of –235 °C (38.15 K). As a result, the surface was found to be mainly composed of ices (as opposed to the nitrogen seas, unfortunately). Nitrogen ice was present in large quantities (55%) while water-ice (15 to 35%) and carbon dioxide ice made up the rest (10 to 20%). Surprisingly, only minute traces of methane ice (0.1%) and carbon monoxide ice (0.05%) were found.

What was striking about the images sent back from *Voyager 2* was that part of Triton's southern hemisphere was covered with plains largely devoid of crater impacts such as Cipango Planum. A total of 179 craters were found within the entire set of images returned (representing roughly 40% of the surface of the moon). As a general rule, the smaller the number of crater impacts, the younger a planetary surface is, yet determining the exact age is difficult as the flux of impacting bodies in the Neptune region is poorly known. Some regions of Triton were estimated to be less than 50 million years old, while others were thought to be even younger, at 10 million years, one of the youngest surfaces found in our Solar System. This took everyone by surprise.

The oldest visible terrain on Triton appears to be the "cantaloupe" terrain – as it resembles the fruit that bears its name – although astronomers have struggled to determine its exact age due to the roughness of its surface features, which prevents reliable

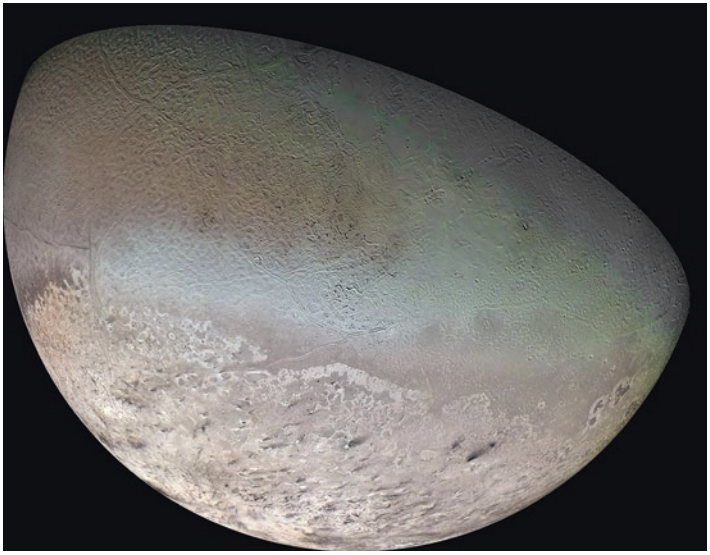

Fig. 10.1. Triton as seen by *Voyager 2.* The "cantaloupe" terrain is clearly visible as well as the south polar ice cap. (Image courtesy of NASA/Jet Propulsion Lab/U. S. Geological Survey)

crater counting. We know that the cantaloupe terrain is older, since younger surface features overlap it (Fig. 10.1).

Within the cantaloupe terrain, vast depressions 30 to 40 km in diameter suggest a process known as diapirism, where warm material rises through the icy mantle, weakening the surface strength in the process. Also, in a similar fashion to Ganymede, Europa, and Enceladus, lanes of grooved terrains representing cracks in the ice, also known as sulci, were found crisscrossing the cantaloupe terrain, the result of strike-slip motion along fault lines embedded within the icy crust. These features, as well as the diapirism, hint at past geological activity where heat was involved.

This interpretation was further supported by the discovery of high plateaus of volcanic origin covering most of the surface visible to the east, where multiple calderas and icy plains of lava could be found. Scientists believe that these plains are most likely composed of a mixture of ammonia and water that gushed out in the past as liquid or slushy ice onto the surface. Indeed, when ammonia is present in rich concentrations, a mixture of water-ice and ammonia can reach a melting point as low as 177 K (–96 °C), making it plausible that such mixtures could be present in a liquid phase under the surface.

In addition, methanol can push the melting point of ammonia water-ice even lower, at around 152 K (−121 °C), and can induce a viscosity similar to the ones that would have created the lava plains. One can easily imagine warm melts (cryolavas) of an ammonia-methanol-water mix spewing onto Triton's surface. Such a scenario implies that the moon was subjected to more heat in its past than it does today and, importantly, raises the possibility that a reservoir of liquid water and antifreeze volatiles was present under the surface.

Further intriguing features were being revealed by the Voyager images. Dark spots, referred to as maculae, were found on the far eastern side of the moon. These smooth, dark patches up to 100 km in diameter are surrounded by bright aureoles as in the Acapura and Zin maculaes. Reddish tints in the center of these spots suggest the presence of methane ice, while the brightness of the surrounding terrain implies nitrogen ice (mixed with some methane ice) similar to the south polar ice cap. The most likely explanation for the maculae is a seasonal one, whereas the polar ice cap melts away in spring, due to the favorable inclination of Triton, and leave behind leftover patches of ice.

More importantly, exciting things were happening within the south polar ice cap itself as images returned by *Voyager 2* revealed four active plumes venting material out from the surface. Each plume consisted of a narrow black geyser rising to 8 km in altitude, at which point the ejected material would form long streaks of dark clouds drifting over 150 km. Incredibly, Triton had become with Earth, Io, and Enceladus, one of the few bodies in our Solar System where active eruptions occurred (Fig. 10.2).

What could be driving such activity? *Voyager 2* confirmed that Triton didn't have the obliquity required for it to be in a Cassini state 2, thus removing the possibility of it benefiting from obliquity tidal heating. Another explanation was required.

Despite Triton's distance from the Sun, scientists now believe that solar heating is generating the plumes (as opposed to tidal heating on Io and Enceladus). It is thought that the moon's south pole is covered by a layer of transparent nitrogen ice roughly a meter thick, through which sunlight penetrates, creating a greenhouse effect that warms up whatever organic material is present underneath the ice. As heat builds up slowly, reservoirs of pressurized gases are formed, which vent off as soon as there is a weakness in the ice above, expelling with it non-ice components such as dark organic-rich material. It is this material that gives the plumes their distinctive black color.

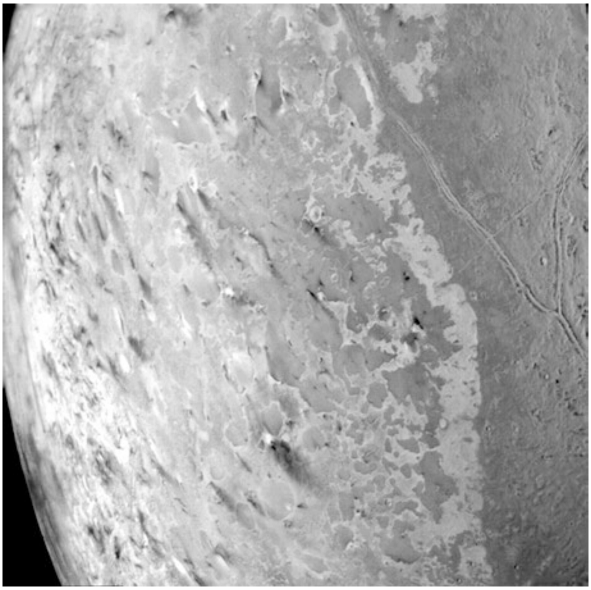

Fig. 10.2. Taken on August 25, 1989, by *Voyager 2,* this image of Triton's south pole reveals traces of dark plumes on the icy surface. It is possible that such vents were driven by seasonal heating of very shallow subsurface volatile deposits. Similarly the winds transporting the particles may be seasonal winds. (Image courtesy of NASA/JPL.)

The Possibilities of a Subsurface Ocean

By precisely measuring Triton's diameter and mass, planetary scientists have calculated the moon's density at roughly 2.06 g/cm^3, indicating that the interior is composed of 65 to 70% rock (and some metals) with the rest made up of ices such as water, ammonia, or methane. Studies tend to support the view that these ices form a 400-km-thick icy mantle sitting on top of the rocky (silicate) mantle. Radiogenic heating from the silicate mantle could provide enough energy to maintain a long-lived ocean beneath an ice shell but is insufficient in causing the multiple features visible on its surface, some of which appear to be as recent as 10 million years.

One convincing model proposed by researchers to resolve this is related to the moon's unusual retrograde orbit around Neptune. It suggests that Triton was once part of a binary system, two objects orbiting each other, which passed far too close to the giant planet forcing, the pair to split. One member of the binary gained orbital energy and was ejected to the outer edges of our Solar System while the other member, Triton, was captured by Neptune. Once this occurred, the new moon found itself in a highly elliptical orbit for more than 100 million years, with the closest point to Neptune (periapsis) only five times the radius of the planet and a semimajor axis 1,000 times the radius. Neptune's strong gravitational pull would have squeezed and stretched the moon as it traveled around the planet, generating significant amounts of tidal heating in the process.

Also, Triton would have disrupted Neptune's original satellite system either by colliding with bodies in it (which adds kinetic energy to the moon) or by disturbing their orbits, forcing them either to plunge into Neptune or to get ejected from the Neptunian system altogether. Astronomers think this is the reason why little is left from the planet's original satellite system, which would have been similar to Uranus'. Today, Triton is the only large moon of Neptune, representing 99.5% of the total mass of Neptune's satellite system.

It has been estimated that the tidal heating experienced by Triton's capture and its subsequent orbital circularization would have produced sufficient amounts of energy to melt the icy mantle for hundreds of millions of years and modify the moon's surface extensively. We don't know exactly when the moon was captured by Neptune, therefore, it is difficult to estimate when the subsurface ocean formed. However, the likelihood that Triton's capture is recent is very low, while the timescale put forward for the circularization of its orbit is most likely less than one billion years old (although such figure is dependent on Triton's interior structure).

If a subsurface ocean was most likely present in Triton's past, could it exist today? Despite the limited amount of tidal heating generated today by the orbit's small eccentricity (0.000016), some models show that radiogenic heating might still be enough to sustain a subsurface ocean today. Furthermore, two recent studies have come forward with new ways to support a current subsurface ocean on Triton.

The first study, published in 2012, used a realistic and sophisticated model of Triton's interior. It revealed that the heat generated from current tidal heating, as little as it is, is concentrated at the base of the ice mantle, especially near the poles. (Contrary to radiogenic heating, which heats up the moon uniformly, tidal heating will tend to be localized at specific areas within the moon's interior.) Such a concentration of heat stops the icy mantle from freezing entirely, leaving a layer of liquid water close to its base, the legacy of a much bigger subsurface ocean that was frozen over time. According to the model, all that is required is for Triton's orbit to vary by only a few kilometers a year to sustain such a layer of heat. The subsurface ocean would also benefit from rich concentrations of ammonia and methane, which have low melting points, although the exact mix is unknown.

If this new model proves to be right and the remnants of a subsurface ocean are indeed protected by a 'heat blanket,' that covering is predicted to be relatively thin (a few tens of kilometers thick) and sandwiched between two icy mantles. The top one would be mainly composed of nitrogen and water-ice (phase Ih) while the bottom one would be expected to be composed of high-pressure water-ice in Phase II or III. (See Chapter 4 on Ganymede for further details on the different phases of water-ice.) Triton is just about big enough for the pressures encountered at the base of the icy mantle to form high-pressure ices (Phase II or III), while Pluto, on the other hand, has a radius 165 km smaller, which places it just under the limit that forms high-pressure ices.

Variations of this model allow the high-pressured icy mantle located at the poles to be thinner due to a more pronounced tidal heating effect there, raising the possibility that liquid water from the hypothetical subsurface ocean might come into direct contact with the silicate mantle.

Another study aimed at solving Triton's energy mystery reassessed the effect of Triton's obliquity tides first predicted by David G. Jankowski in 1989. The research published in 2015 and led by F. Nimmo from the Department of Earth and Planetary Sciences, Southwest Research Institute in Boulder, Colorado, used new models to estimate Triton's heat flux and came to the conclusion that Triton's current inclination should produce obliquity tides large enough to induce convection within the thick ice shell and subsequently form surface alterations similar to those seen by *Voyager 2.* The study reveals that for a 300-km-thick icy mantle, a subsurface ocean could exist and have a temperature as high as 240 K (–33.1 °C) while containing antifreeze compounds such as ammonia. Little else can be extrapolated at present, so we can't characterize Triton's subsurface ocean any further. Although this study isn't proof that a subsurface ocean exists today, it increases the likelihood.

Given what we know so far from Neptune's possible subsurface ocean, could life arise there? It seems doubtful. The low temperatures will significantly slow down biochemical reactions if not stop them altogether, while the possible existence of high-pressure ices under the subsurface ocean will prevent essential interactions between rock and water (although the thinning of the icy mantle at the poles might offer a solution). Ammonia and other antifreeze compounds required to prevent the subsurface ocean from freezing at such cold temperatures add to the problem. It seems that, given what we know so far, Triton's subsurface ocean has little potential for life.

We shall now leave mysterious Triton and the Neptunian system to continue our journey outwards, towards Pluto, another tantalizing world that, surprisingly, has been shown to be as active, if not more so, than Triton.

The Kuiper Belt

We leave the Neptune-Triton system behind and continue to the outer part of our Solar System, a region where objects are aptly referred to trans-Neptunian objects (TNOs). It doesn't take long before we reach the Kuiper Belt, a broad disc located between 30 and 50 AU and populated by remnants of our Solar System. This region is thought to contain over 100,000 small bodies larger than 100 km in diameter and possibly billions of icy objects between 1 and 20 km in diameter, exceeding the mass of the Asteroid Belt by about 20 to 200 times.

First theorized in the 1930's following Pluto's discovery, the Kuiper Belt was named after the renowned Dutch-American astronomer Gerard Kuiper (the discoverer of Titan's atmosphere among many other achievements), misleading many into believing that he was the first astronomer to predict it.

We now know that other astronomers had envisioned the existence of objects neighboring Pluto's orbit earlier than Kuiper. These include the Americans Frederick Leonard and Fred Whipple as well as the Irish astronomer Kenneth Edgeworth. Ironically, the name Kuiper Belt has at its source a 1951 paper written by Kuiper himself, which proposed that no objects should lie within Pluto's orbit or beyond (apart from the Oort Cloud).

Nowadays, many astronomers consider the Uruguayan astronomer Julio Fernández to have accurately predicted in the

1980's the existence of the Kuiper Belt using clear mathematical reasoning. Because of all this, there has been much discussion within astronomy circles on the continued use of the term Kuiper Belt Objects (KBO) to define objects within the disc where Pluto is located. Some astronomers now choose to use alternate names, such as EKO in reference to Edgeworth or just TNO, although this can be misleading since TNOs refers to any objects lying past the orbit of Neptune and includes the scattered disc objects or any other future group of objects lying further out. For the sake of clarity and continuity, we shall use KBO in this book, even though it is now clear that Kuiper's name probably shouldn't have been chosen to define such objects in the first place.

The objects found in the Kuiper Belt are relatively small, mainly made up of rock and icy compounds (such as nitrogen, methane, and water) and benefit from a stable orbit. Up until 1992, Pluto was its only known member (with its moon Charon), but all this was about to change due to the persistence and audacity of a British and Vietnamese astronomer – David Jewitt and Jane Luu, both working at the Massachusetts Institute of Technology at the time.

It took Jewitt and Luu five painstaking years of research to finally discover a second Kuiper Belt object, designated (15760) 1992 QB1. Only 167 km by 108 km in size, this tiny object was not representative of the significance of such a discovery. Prior to (15760) 1992 QB1, very little resources had been allocated for the search of KBOs, as their location within our Solar System prevented them from being included in the two major areas of interest of academia at the time. Planetary scientists were mainly focused on objects that could be easily reached by robotic missions (Mars, Jovian system, etc.), while classical astronomers considered our Solar System to be too close for their interests (stars, galaxies, etc.).

Bucking all trends, Jewitt and Luu proved that KBOs did indeed exist and that given the right resources, a new frontier was waiting to be discovered. Numerous KBOs have been unveiled since, including large objects such as Quaoar (2002), Makemake (2005), and Eris (2005). These last three KBOs, discovered in large part due to the pioneering work by American astronomer Michael Brown, made it evident that Pluto, still a planet then, was only one of many similar objects. This led the International Astronomical Union to downgrade in 2006 the status of Pluto to that of a "dwarf planet." While such a change proved controversial, especially in the United States, where Pluto had been discovered, it was seen as a victory of scientific reasoning over historical and cultural influences. Actually, as we have seen in Chapter 9, a similar event had occurred more than 150 years ago when astronomers at the time discovered four new "planets" (Vesta, Ceres, Juno, and Pallas) orbiting between Mars and Jupiter, only to realize by 1845 that it would be best to rename these objects as asteroids.

Within the Kuiper Belt, Pluto is known to be the biggest member of the plutoids, a class of bodies that are large enough to have attained hydrostatic equilibrium, meaning that they are symmetrically rounded into a spheroid or ellipsoid shape. The dwarf planets Haumea and Makemake are plutoids.

Pluto's Discovery and Early Observations

The discovery, classification, and later demotion of what was for more than 70 years the ninth planet of our Solar System is a classic tale in astronomy involving great wealth, serendipity, and the coming of age of a mighty nation. It all started in 1846 when the planet Neptune was discovered solely by mathematical predictions derived from irregularities in Uranus' orbit, a revolution in those days. This event galvanized the astronomical community into searching for new planets using the same method.

In comes Percival Lowell, a very wealthy American businessman who was also a mathematician and an avid astronomer. Following his mathematical analysis, he was convinced that the orbits of Uranus and Neptune were disturbed by a massive planet lying further out within the Solar System. He termed this object 'Planet X.'

Using his wealth, the American built an observatory in 1894 that bears his name and spent the rest of his life searching for the elusive planet. Ironically, Pluto was spotted by the observatory in early 1915, a year before Lowell's death. However, due to it being much fainter than Lowell's prediction, the object was disregarded as of no importance, and the search for Planet X continued.

Upon his death, Lowell's widow contested the large sums of money left behind by her husband for the observatory, and the search ground to a halt. It took more than ten years of legal battles to resolve the dispute, and in 1929, the observatory finally reopened. Clyde Tombaugh, a young amateur astronomer with a fine eye for detail, was hired in January 1930 with the mission of continuing the painstaking work of searching for Lowell's Planet X (whose estimated brightness had been revised and decreased). The search didn't take long, as by March, Tombaugh had found the new planet (in effect, rediscovering it), and the discovery made headlines around the world. This brought instant fame to a shy young man with little academic background. The search was now on to find a suitable name for this new planet, and Pluto was chosen following the suggestion from Venetia Phaira, an 11-year-old English girl (whose grandfather's brother had already recommended the names Phobos and Deimos for the moons of Mars).

Once again the frontier of our Solar System had expanded. A big planet had been found. Or had it? Many astronomers started to be doubtful of Lowell's calculations, and already by 1931, new estimates had dropped Pluto's mass to around one Earth mass, far lower than what Planet X had initially been predicted to be. Also, by then, Pluto's orbit had been determined, and it was found to be highly inclined and eccentric, as opposed to the four other outer planets. Pluto was an oddity.

Nevertheless, due to the technical limitations of the time, no further insight on Pluto could be gained until 1948, when Gerard Kuiper worked out new estimations of Pluto's mass, which brought it down once again, this time to a tenth of that of Earth's. By then, it was clear to all that Pluto wasn't the Planet X that Lowell had been looking for, as its tiny mass couldn't possibly explain the discrepancies in Uranus' orbit. This prompted astronomers to start the search for Planet X once again.

The 1950s saw drastic improvements in photometry techniques, and Pluto's characteristics started to become apparent. The period of its rotation was calculated to be at 6.4 days, placing it at odds once again with its outer planet neighbors who were all rotating within less than a day. Variations in Pluto's light curve implied differences in surface albedo, and therefore surface features, while its reddish tint hinted at the possible existence of methane, which was later confirmed in 1976 as methane ice. The discovery of such a highly reflective material forced astronomers to reconsider its effect on the planet's apparent albedo and subsequently reduced Pluto's mass to 1% of Earth's, making the planet even less imposing among its peers.

Intriguingly, such a highly reflective surface could only occur if methane ice was fresh, raising the possibility that Pluto's surface might be young. The detection of methane also gave rise to the likelihood of a tenuous methane atmosphere existing on Pluto as the temperatures predicted (around 40 to 60 K) allowed methane vapor to form. Nitrogen would also be found in Pluto's spectra in subsequent observations.

Charon, Pluto's biggest moon, discovered in 1978 allowed even more precise measurement of the planet's mass through its interactions with Pluto. Carrying on a trend that spanned decades now, Pluto's mass was brought down even further to 0.2% of Earth's mass, and its diameter was now estimated to be around 4,400 km. Nevertheless, Pluto's disk couldn't be resolved at the time. (This would change with the work of the Hubble Space Telescope in the 1990's.)

Finally, a stellar occultation in 1980 allowed astronomers to determine Pluto's diameter accurately and found it to be between 2,300 and 2,400 km, making it even smaller than the seven largest moons of our Solar System (Io, Callisto, Ganymede, Europa, our own Moon, Titan, and Triton). The case against Pluto as a planet was slowly building. The diameter allowed astronomers to deduce, with the mass, Pluto's density, which was estimated to be less than 2 g/cm^3, indicating that water was a major component most likely in the form of icy mantles.

Another stellar occultation eight years later confirmed the presence of an atmosphere, although its exact composition and temperature still proved elusive. *Voyager 2's* visit to the Neptune-Triton system in 1989 was a major turning point for scientists studying Pluto, since both objects were thought to be closely related. A visit to Triton was in a way considered to be a visit to Pluto. At least that is what most researchers were hoping for since no mission for visiting distant Pluto was planned at that point.

Voyager 2 found Triton's atmosphere to be dominated by nitrogen, suggesting that Pluto's must be as well, especially since nitrogen had previously been detected on its surface. Furthermore, more accurate measurements of Neptune's mass allowed astronomers to re-evaluate the gravitational pull of the planet on Uranus. It was found that the apparent peculiarities of Uranus's orbit didn't require the existence of a Planet X and that Lowell's calculations had been wrong from the beginning. There had never been a need for a new planet in the outer Solar System, which meant that Pluto's discovery had been the result of pure coincidence and sheer luck.

Shortly after *Voyager 2's* flyby, Jewitt and Luu discovered the first KBO after Pluto, (15760) 1992 QB1. Pluto's days as a planet were now numbered. As technology improved, so did the accuracy in the observations. Atmospheric methane was discovered in 1994, but at very low concentrations (<1%) similarly to Triton; however, Earth-based observations were still unable to resolve Pluto as a disk. Analyzing its reflected light was the best planetary scientists could do until the arrival of the Hubble Space Telescope. In 2002 and 2003, unhindered by the atmospheric distortions lying underneath it, the space telescope produced the first images of Pluto as a disk, using advanced processing techniques even though the surface details were poorly defined, merely suggested. It didn't matter. The New Frontiers program, a new type of space exploration mission funded by NASA; had selected the New Horizons mission for a flyby of Pluto by July 2015.

The New Horizons Revolution

The New Horizons spacecraft launched successfully in 2006, ironically the same year that the IAU demoted Pluto to dwarf planet status (much to the disappointment of the people behind the New Horizon's mission). Benefiting from the latest technology, the space probe had seven instruments which were comprised of three optical instruments, two plasma instruments, a dust sensor, and a radio science receiver/radiometer. All these would allow the spacecraft to characterize, among other things, the geology, temperature, and composition of the surface of the dwarf planet and its moons.

To shorten its journey by three years, the trajectory included a slingshot by Jupiter, where New Horizons returned an impressive set of data on the giant planet and its four Galilean moons, especially Io, where new volcanic plumes were detected. The gravity assist it experienced at Jupiter made New Horizons one of the fastest spacecraft ever, speeding at 13.8 km/s. Despite this, it still took over nine years for it to reach Pluto in July 2015. Apart from a computer glitch that was swiftly dealt with a few days before the flyby, everything went according to plan, and the amount of data collected on the Pluto system during this only flyby was remarkable. A veil had been lifted on a new world (Fig. 10.3).

Before the historic flyby, scientists weren't sure what to expect from Pluto's surface. Some speculated that it could be a homogeneous sphere heavily cratered and with little geological activity, such as Jupiter's moon Callisto (see Chapter 5 for more

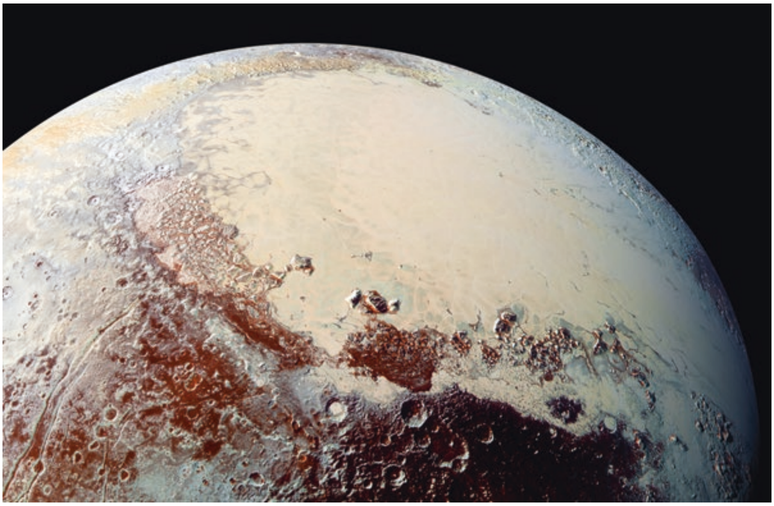

Fig. 10.3. Pluto as seen by New Horizon in 2015. The western lobe of Pluto's famous heart can be seen in this high-resolution picture taken by New Horizons. The lobe, called Sputnik Planitia, is rich in nitrogen, carbon monoxide, and methane ices. (Image courtesy of NASA/JHUAPL/SwRI)

details on this moon), while others suggested Pluto to be a simpler version of Triton, although Pluto's density, already known at the time at 1.86 g/cm^3, hinted at vast quantities of water present in icy mantles. Indeed, given Pluto's mass and size, it was most likely that it had experienced differentiation, forcing the heavier material to settle into a dense core while the lighter icy material rose to the top. The radius of its rocky core was thought to be approximately 850 km, while the rest is made up of ices (water, ammonia, methane, etc.).

On July 14, 2015, New Horizons made its closest approach at 12,500 km from the dwarf planet. High-resolution images showed a surprisingly varied surface composed of mountains of water-ice sliding on plains made of nitrogen ice (mixed carbon monoxide and methane), ancient cryovolcanoes, large resurfacing events, deep ridges extending for hundreds of kilometers, glacial flows, and a few impact craters. Furthermore, terrains colored in deep reds, blacks, browns, and whites could be seen adjacent to each, other suggesting past geological activity. Pluto stunned everyone.

Due to the low temperatures encountered so far out from the Sun (35 to 40 K), water ice on Pluto behaves like rock on Earth, forming solid mountain ranges while nitrogen and carbon monoxide ices, more malleable, will act more like water-ice on Earth and flow on the surface as glaciers. These will create distinctive surface features such as U-shaped valleys and moraines (accumulation of glacial debris), and since water-ice is less dense than nitrogen or carbon monoxide ices, features such as hills or even mountains will seem to 'float' on the heavier ices and be transported across the surface.

Giant basins hold frozen seas of nitrogen, as can be seen in the heart-shaped Sputnik Planitia. This vast basin contains 168 distinctive polygonal features, also known as cells, which have an average diameter of 33 km and are thought to be 3 to 4 km thick. These polygons of nitrogen and carbon monoxide ices are most likely the result of convection, a process where heat from the interior rises to the surface and sinks back when cooled down, a clear sign of geological activity. Such convections cells are young, possibly less than 200,000 years old, which makes Sputnik Planitia one of the youngest areas in our Solar System. As they move around, chunks of mountains located on the edge of the basin get broken up and carried away onto the plain.

Wright Mons and Piccard Mons, two possible cryovolcanoes located in the south of Sputnik Planitia, rise 4 km above the surface, making them the tallest features on the dwarf planet. These mountains are most likely the result of the venting of warm pressurized nitrogen from the interior onto the surface (nitrogen ices turns to vapor faster than carbon monoxide ice) and are thought to be young features, as they display little cratering.

Other fascinating features abound, such as the reddish north polar cap composed of irradiated methane and nitrogen ice, the penitentes (elongated thin blades of frozen ice) found in the Tartarus Dorsa region, the Al-Idrisi montes mountain range of water-ice exhibiting south-facing slopes rich in methane ice, the reddish ancient terrains of the Cthulhu region layered by tens of meters of tholins (complex hydrocarbons), or even Pluto's seasonal atmosphere.

Another discovery has made the dwarf planet even more exceptional than it already is – its potential to host a subsurface ocean.

The Case for Pluto's Subsurface Ocean

Before New Horizons' visit in 2015, some scientists had already put forward the idea that a subsurface ocean might be present on Pluto today if the right conditions were met. These included the differentiation of the dwarf planet, radiogenic heating from the rocky core, the effectiveness of the heat transfer to the surface, as well as the concentration of antifreeze compounds in the water mantle. Scientists found that the existence of potassium within the rocky mantle would be an essential element in generating the required radiogenic heat for the melting of the icy layers. Further studies suggested that the amount of potassium necessary to warm up Pluto would only have to be about a tenth of that found in meteorites hailing from the early Solar System. In theory, a subsurface ocean within Pluto was possible.

Although these conditions might be tricky to assess in a single flyby, mission scientists knew what telltale signs to look for. Sputnik Planitia; the heart-shaped basin 1,050 by 800 km wide, is such a sign. The basin is now thought to be an impact crater formed 4 billion years ago from the collision with a planetary object a few hundreds of kilometers in diameter – unremarkable in its ordinariness.

What makes Sputnik Planitia stand out, though, is its alignment with the Pluto-Charon axis, as the basin is located directly opposite to the side facing Charon. With little chance of such coincidence occurring (calculated at only 5%), the alignment suggests that the impact crater was formed elsewhere on Pluto, possibly northwest from its present location. The impact added additional mass to the basin, forcing the dwarf planet to reorient itself as large bodies in space tend to spin whichever way is easiest, so if there exists an uneven weight distribution, they will be likely to tilt. Models show that the dwarf planet most likely tilted by 60 degrees due to the influence of Charon's tidal interactions.

We know this because Sputnik Planitia has a positive gravity anomaly; more gravity is present than expected in this basin (a hole in the ground), suggesting the presence of high-density material under the surface. Scientists found that only two models could explain this additional mass: either a significant amount of liquid water is located directly underneath the basin (liquid water is denser and therefore heavier than ice), or, instead, a very thick layer of nitrogen ice lies within it. The nitrogen ice model could be explained through the continual accumulation of ices in a local depression, which grows on itself through a positive feedback loop, although recent calculations show that the gravity anomaly would require a 40-km layer of nitrogen ice, which is implausible given our current understanding of Pluto's geology. As it stands, the liquid water model fits best the additional mass found under Sputnik Planitia. However, it requires the presence of a global subsurface ocean, which as we have seen has already been shown to be theoretically possible.

This is what we think happened. When the impactor hit Pluto's surface near what was then the north pole (but still at the region we now call Sputnik Planitia), a counter-reaction generated an upwelling of liquid water from the subsurface ocean located directly under the impact site. The leftover crust at the impact site became thin and weakened, bulging inwards as the liquid water settled underneath it (liquid water holds less volume than ice), thus creating a basin deep by a few kilometers. In itself, this doesn't create the extra mass. What occurs next does, though. Nitrogen in Pluto's atmosphere starts to freeze out within the basin due to increased atmospheric pressure, while nitrogen glaciers formed in the mountainous terrains adjacent to the basin began to flow inside it. Within a relatively short period, Sputnik Planitia became filled with nitrogen ice, providing the extra mass required to reorient Pluto. This model can only be explained if a mantle of liquid water was available globally, ready to interact with the impact site.

How about today? Could the subsurface ocean still be present, or has it completely frozen out? Current models show that Pluto (and other KBOs) could indeed sustain a salty subsurface ocean if it is warmed up by radioactive decay from the rocky core and richly laden with ammonia and other antifreeze compounds such as methanol or ethanol. Ammonia has been found on Charon's surface, so it is most likely present within Pluto as well. At high concentrations (10% to 35%), ammonia reduces the freezing point of the water mantle significantly while making it syrupy (like honey) and hostile for life as we know it. Hydrocarbons (methane, ethane) and more complex molecules formed by carbon, nitrogen, hydrogen, and oxygen have been found on Pluto's surface, so these might also be present in the hypothetical subsurface ocean. Additionally, recent calculations suggest that such ocean could be 100 to 180 km thick and adjacent to the rocky core.

If the subsurface ocean does exist, could life have arisen there? Although extremophiles might be able to find a way to survive such cold temperatures or high concentrations of salt, it is the noxious levels of ammonia that contribute the most in preventing the emergence of life as we know it. If life could arise in Pluto's exotic ocean, it would be very different from life on Earth, alien.

Unfortunately, Pluto isn't located next door, and at 40 AU new missions there are unlikely. However, preliminary proposals have been made for a Pluto orbiter mission, powered by an ion engine such as the Dawn spacecraft has, which could study Pluto and its moons for four to five years using gravity assists from Charon to slingshot itself from one object to another. There have even been calls for such a mission to be launched by 2030, giving it a historical significance, as it would celebrate the 100th anniversary of Pluto's discovery.

It remains to be seen if such a follow-up mission can be launched in time, as a long list of fascinating planetary objects in our Solar System are easier, cheaper, and faster to reach. The planet Mars and the moons of Europa, Enceladus, and Titan quickly come to mind. Triton, as well as the mid-sized moons of Uranus, could also benefit from a new mission. In the following chapter, we shall be exploring other planetary objects that might host a subsurface ocean but for which we know very little.

11. The Possible Others

In the previous seven chapters, we have investigated seven icy satellites and two dwarf planets within our Solar System. Five of those have already been confirmed as ocean worlds, whereas four are very likely to host a subsurface ocean (or at least a subsurface sea in the case of Ceres), but conclusive evidence is still pending. That our Solar System can host so many planetary objects capable of sustaining large amounts of liquid water is remarkable. Still, there is potential for more. In this chapter, we will consider the possibility of subsurface oceans in other icy satellites and trans-Neptunian objects (TNOs) for which we currently have little or no observational data. Some of these objects might be confirmed as ocean worlds in the coming decades, while others might have past subsurface oceans only.

We will start this chapter by going back to the Saturnian system. Throughout Cassini's thirteen-year mission around the Ringed Planet, significant amounts of data were taken of Titan (see Chapter 7) and Enceladus (see Chapter 8), and because of this, we now know that a subsurface ocean lies under both of these moons. Dione (see Chapter 9) also shows potential, although evidence for a subsurface ocean has proven to be frustratingly elusive. However, there is another mid-sized icy moon that might be considered as an ocean world candidate: Rhea.

Rhea

Discovered by Cassini in 1672, Rhea suffers from a lack of personality despite being the second largest moon of Saturn, after Titan. Its leading side has numerous ancient craters, as would be expected from an object orbiting Saturn, while its trailing side displays younger areas, indicative of past resurfacing events and

B. Henin, *Exploring the Ocean Worlds of Our Solar System*, Astronomers' Universe, https://doi.org/10.1007/978-3-319-93476-1_11

fractured terrains. Yet both of these are less pronounced than on other moons. In effect, Rhea pales in comparison with the intriguing Dione and superstar Enceladus.[1]

Due to this, the Cassini spacecraft made only five close flybys of Rhea throughout its 13-year mission around Saturn, during which many of the moon's characteristics were refined. The mean density has been precisely measured at 1.23 g/cm^3, implying that Rhea is mainly composed of water with a quarter rocky material and three-quarters water-ice. Much uncertainty remains as to how these are distributed within its interior though. Differentiation might not have occurred due to the small amount of rocky material available to generate radiogenic heating and the minimal tidal heating present. Either distinct layers of ice and rock exist or these are instead distributed homogeneously throughout the moon. Multiple studies on this topic have reached different conclusions, in part due to errors made while interpreting Cassini's data.

This uncertainty prevents scientists from being confident in their interpretation on how Rhea was formed. It could either have coalesced rapidly, trapping a significant amount of accretion heat in its interior that would allow it to differentiate, or it could have formed slowly, like Jupiter's moon Callisto, thus keeping its interior as a homogenous mass or at least partially differentiated. If Rhea is fully differentiated, it has been estimated that the rocky/iron core would be large enough, about 350 km in radius, to produce enough radiogenic heat – in addition to the leftover accretion heat – to melt the adjacent layer of water-ice creating a liquid mantle in the process. A partially differentiated interior would have a bigger core region with poorly defined boundaries consisting of a rock and ice mix. This could, in theory, allow for pockets of ice to melt, due to the heat generated from radiogenic heating, in a similar manner to Ceres.

Surface features such as young terrains and chasmata do show that there has been past internal activity, although there is no clear indication as to what precisely could have driven this. It might be that, like Dione, a past subsurface ocean was responsible for these features. Whether a liquid mantle still exists under Rhea's ice shell is difficult to determine; however, the latest studies seem to refute such a possibility. More studies are required.

[1] It was thought for a while that Rhea might have a ring system, a first for a satellite, but this has now been discarded due to a lack of evidence.

Apart from Rhea, Iapetus and Tethys are two other mid-size icy satellites orbiting Saturn that have been found to be completely frozen solid, removing all possibility of subsurface oceans occurring. Therefore, the Saturnian system might potentially host four ocean worlds: Titan, Enceladus, Dione, and Rhea.

We shall now leave Saturn and its satellite system to meet other potential ocean worlds orbiting a planet we haven't visited so far; Uranus.

Uranus' Moons

Halfway between Saturn and Neptune lies Uranus, the third biggest planet in our Solar System. Often under-appreciated, it has a ring system much smaller than the majestic rings of its neighbor, a featureless atmosphere that renders the planet somewhat bland, and a set of moons lacking promising attributes at first glance, although this impression is unfair, as they hold many mysteries as well as promises.

Of the 27 icy moons that form Uranus' satellite system, four are mid-size icy moons: Titania, Oberon, Umbriel, and Ariel (in contrast to Neptune that, as we saw in Chapter 10, lost most of its original moons due to Triton). Uranian moons tend to be darker than Saturnian or Jovian moons due to an increased amount of impurities in their icy crust, implying that more non-ice components were present during their formation. They also tend to have bigger rocky cores relative to their sizes that might provide more substantial radiogenic heating.

Voyager 2's quick flyby in 1986 was the only opportunity we had in seeing these moons up close, as no spacecraft has visited the Uranian system since. One limitation *Voyager 2* encountered was that Uranus and its set of moons are tilted by 97.7 degrees, as if lying on their side. Such a configuration makes the satellite system set up like a bullseye for *Voyager 2*, since it had to fly perpendicular through the system as opposed to parallel to it, like with its encounters with the Jovian and Saturnian systems. This reduced the amount of time the spacecraft had for each moon. Of course, Earth-based observations have continued to observe these moons since, returning crucial information through spectroscopy, but the considerable distances involved limit much of what we can learn. As far as we can see, only Titania, Oberon, and Ariel have the potential to host past or present subsurface oceans.

Titania

The biggest and most massive of all Uranian satellites, Titania was discovered by Herschel six years after he had found Uranus. Similar in size to Saturn's moon Rhea, little was known of this world until the arrival of *Voyager 2*, which returned images of a relatively young surface most likely due to past cryovolcanism, although only 40% of the moon's surface has been imaged. Various surface features have been found, such as canyons (chasmata) and scarps (rupes), in other words, cracks in the icy shell. These most likely arose when the interior of the moon cooled down and froze the liquid mantle, expanding the crust in the process.

So far, only two compounds have been detected on the surface: water-ice and carbon dioxide. The latter could be the byproduct of the decomposition of organic material under the constant bombardment of ultraviolet radiation and charged particles. This might also explain the reddish tint detected in some areas of the moon, hinting at the breakdown of carbon compounds.

The moon's density, calculated at 1.71 g/cm^3 (much denser than Saturn's mid-sized moons Dione or Rhea), suggests that it is composed equally of rock and ice. We do not know if Titania's interior has been differentiated, as our understanding of the moon's history is very poor. Nevertheless, if differentiation has occurred, and if ammonia or methane are present in sufficient quantities to act as antifreeze (which seems likely), the moon could, in all likelihood, host a subsurface ocean thanks in part to the radiogenic heat generated by the abundant rocky material.

Such a subsurface ocean would be directly adjacent to the large rocky core and could be as thick as 50 km. The ocean would be very cold, though, with some models predicting temperatures as low as 190 K (−83 °C), a seemingly insurmountable challenge for life. Additionally, the high concentrations of ammonia (and other antifreeze compounds) required for liquid water to exist at such low temperatures would also impede life.

A future mission to Titania is required if we want to know more about the moon's interior. One way such a mission could ascertain the existence of a subsurface ocean would be to measure its influence on Uranus' magnetic field, similar to how Europa's subsurface ocean was detected (see Chapter 6 for further details). NASA is hoping to launch an orbiter to visit the Uranian or Neptunian systems by the mid-2040's, which could have the ability to make such measurements. Until then, though, we can only speculate about Titania and its potential for hosting a subsurface ocean today.

Oberon

Slightly smaller and less massive than Titania, Oberon shares a similar story. Discovered by Herschel on the same day as Titania, Oberon was finally brought to light almost 200 years later thanks to *Voyager 2's* flyby. The spacecraft imaged 40% of its surface, similarly to Titania, revealing that Oberon is more heavily cratered and redder than its bigger sibling, in large part due to it being the outermost large moon of the Uranian system, where it most likely encounters far more small objects (irregular satellites) that roam around the edges of the satellite system. Surface features such as cracks and canyons also appear to have been formed as the moon expanded due to the freezing of a liquid mantle, but these fissures are less prominent than on Titania.

Oberon's density is within the same range as Titania, at 1.63 g/cm^3, leading scientists to believe that it should also have a significant rocky core (480 km in radius) if the interior is differentiated although, like Titania, this is still unknown at present. If differentiation has occurred, models show that the accretion heat and radiogenic heat would have been sufficient to melt the icy mantle as long as the water is rich in ammonia (tidal heating is negligible). Such a liquid mantle would be formed next to the rocky core, although given the extreme conditions (low temperatures and antifreeze compounds), we end up with the same conclusions as we did with Titania, that life as we know it is extremely unlikely. Whether such a subsurface ocean still exists today is something a future mission will have to confirm.

Ariel

Although Ariel is 30% smaller than Titania and Oberon, it is still the fourth largest moon of Uranus. Discovered in 1851 by William Lassell, the British brewer and astronomer who discovered Triton (see Chapter 10), Ariel's orbit has a slight eccentricity to it (0.0012) and is tidally locked with Uranus, always showing the same face to the planet. The pecularities of its orbit is why it is often considered as the Io of Uranus. Indeed, apart from accretion heating and radiogenic heating, the third moon of Uranus benefits from another source of energy, one that we have encountered many times throughout our exploration of the moons of Jupiter and Saturn, tidal heating. Around 4 billion years ago, Ariel was most likely in resonance with Umbriel and Titania, which would have increased significantly the tidal heating experienced by the moon at that time.

Ariel's density, calculated at 1.66 g/cm^3, is similar to Titania's and Oberon's, implying a similar composition of half water-ice and half rocks (as well as other non-ice constituents such as carbonaceous material). Like Titania, carbon dioxide was discovered on its surface, which most likely comes from the breakdown of organic matter by bombardments of ultraviolet radiation and high energy particles. If differentiated, the big rocky core lying at its heart would be 360 km in radius and could have a layer of liquid water adjacent to it, similarly to Titania and Oberon.

Nevertheless, Ariel stands out from its siblings in a remarkable way. Its surface, only mapped at 35% by *Voyager 2,* shows resurfaced areas of smooth plains with few large craters present. Flow-like features forming complex channel networks are also visible, hinting at large cryovolcanic events in the moon's past, where water (rich in antifreeze compounds) must have poured out on the surface multiple times. Actually, after Enceladus, Ariel displays the most active surface of any icy moon in the Saturnian and Uranian systems (Fig. 11.1).

Ariel's active past was also implied by recent studies showing that radiogenic heating from the moon's big rocky core coupled with the tidal heating it experienced as it underwent several

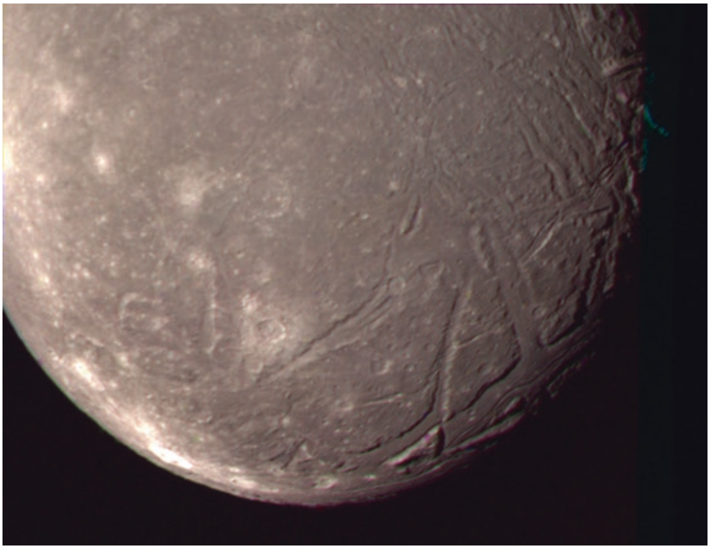

Fig. 11.1. Ariel as seen by *Voyager 2*. Taken on January 24, 1986, this close-up shot of Ariel reveals the moon's southern hemisphere. A complex terrain of large valleys and resurfaced areas can be seen on the bottom right of the image. (Image courtesy of NASA/JPL.)

resonances with Umbriel and Titania was sufficient to melt a substantial part of its icy mantle. This created a warm subsurface ocean for hundreds of millions of years.

It is likely that such an ocean still exists today despite Ariel not being in a strong resonance anymore with other moons. As with most objects so far out from the Sun, such a possibility would require a high concentration of ammonia within the ocean to keep it from freezing.

It is worth pointing out that *Voyager 2's* images of Ariel are of poor quality (low resolution) and only show a third of the moon's surface. A future mission capable of mapping the moon's entire surface at high resolution would most likely provide many surprises and give us a better indication as to what has happened during Ariel's past. In the hope that the moon might still show signs of activity today, there have been attempts to detect a nebulous ring around Ariel's orbit, similarly to Enceladus' E-ring which, as we saw in Chapter 8, was thought to be an inactive moon before the Cassini-Huygens probe arrived. Unfortunately, none has been detected so far.

Given its warm past and the presence of tidal heating, Ariel is, with Triton, the most promising moon within the ice giants to host a subsurface ocean. However, until we send a spacecraft to Ariel once more, little will be known. We can only speculate and wonder if Uranus holds, with its three moons; Ariel, Titania, and Oberon, a collection of ocean worlds similar to Jupiter and Saturn.

The Centaurs

Before we finally depart from the realm of the giant planets and explore the possible ocean worlds inhabiting the Kuiper Belt and beyond, it is worth mentioning that there is a class of Solar System objects that haven't been introduced so far: the centaurs. These small objects can be found wandering between the orbits of Jupiter and Neptune and are known to have unstable orbits, as they only stay for a few million years within the outer planets region before their trajectories take them somewhere else (either out of the Solar System or closer to the Sun).

Overall, not much is known of the centaurs, as they are difficult to spot, being relatively small and dark in color. Nevertheless, it is widely accepted that these objects didn't form at their present location but are instead small TNOs that got dislodged from their original orbit due to an unfortunate encounter. Given that some TNOs are thought to be ocean worlds, could centaurs be potential candidates as well?

It is highly unlikely. The biggest centaur we have discovered so far, Chariklo, has a radius of only 124 km, making it smaller than Saturn's moon Mimas, the smallest spherical known object at 198 km in radius. At these tiny sizes, differentiation can't occur, as not enough heat is trapped to initiate the melting process. Therefore no liquid mantles exist. Even if around 40,000 centaurs larger than one kilometer in diameter are present in our Solar System – and we have only discovered 500 so far – any centaur bigger than Chariklo should have been spotted by now.

Centaurs are just too small to be considered ocean world candidates, but, by being much closer to the Sun than most TNOs, they are still brighter and more accessible. By further studying centaurs, we can better understand TNOs in general, particularly the ones that might host subsurface oceans.

More About KBOs

Located within the outer edge of the planetary system, where the gas densities are too low and the accretion timescale too high for a single dominant planet to form, small planetary objects reside in a doughnut-shaped disk named the Kuiper Belt.

These objects proved extremely difficult to detect – apart from Pluto itself (the biggest object within the belt) – due to their small sizes and the vast distances separating us from them. (see Chapter 10 for our introduction to the Kuiper Belt and Pluto's discovery.)

The largest known KBO is still Triton, captured by Neptune, and until New Horizon's flyby of the Pluto system in 2015, it was the only one that had been closely observed (by *Voyager 2*). Once more KBOs started to be discovered in the 1990's, they proved difficult to study in detail, even with the most powerful telescopes available on Earth, as spectroscopic and photometric studies were of moderate quality and challenging to interpret. Thankfully, with the discovery of larger objects in the last decade (Quaoar in 2002, Makemake and Haumea in 2005, etc.), our understanding has improved. We now have a better grasp as to what processes can affect the surface compositions of these objects, although we still know very little overall. We shall start this tour of the KBOs with a large object that New Horizons visited as well, Pluto's moon Charon.

Charon

Many planetary scientists were intrigued when, in 2015, the New Horizons spacecraft returned images from Charon, Pluto's largest moon. Little was known of the moon at the time, which can be pronounced 'Karon' or 'Sharon.' The latter is preferred by its discoverer, the U. S. Naval Observatory astronomer James Christy, who named the moon in 1978 after his wife, Charlene (Fig. 11.2).

Before the New Horizons' flyby, many suspected Charon to be a frozen world unchanged since its inception and pockmarked with countless craters. As is often the case in planetary science, the moon turned out to be rather different. High-resolution images sent back by New Horizons revealed a diversity of geological features as well as the eye-catching Mordor Macula and Charon's north pole, coated in red, the result of the moon's gravity drawing in Pluto's atmosphere, which freezes and falls onto Charon's

Fig. 11.2. A beautiful composite image of Charon taken by New Horizons on July 14, 2015. One of the most striking features is the reddish north (top) polar region, informally named Mordor Macula. (Image courtesy of NASA/JHUAPL/SwRI.)

surface as nitrogen and methane ice. Solar radiation then breaks down the methane, giving it the distinctive red coloring.

More intriguingly, smooth plains in the southern hemisphere, such as Vulcan Planum, present a relatively young surface, hinting at past resurfacing events most likely from cryovolcanism, where ‘warm’ liquid water (rich in ammonia and other volatiles) spilled out onto the surface. In support of this interpretation, a team of scientists using the Earth-based Gemini observatory in 2007 detected traces of ammonia hydrates and water crystals in Charon’s spectra. The presence of water-ice in its crystalline form hints at recent resurfacing events, since this type of ice usually decays into amorphous ice after a few tens of thousands of years due to solar ultraviolet radiation and cosmic ray bombardment. In other words, there is fresh ice on Charon.

The discovery of ammonia hydrates is also telling, as it suggests that this antifreeze compound is present within the icy mantle below, which could, in the right conditions, contribute to the existence of pockets of water-ammonia slush under the surface. New Horizons showed no sign of active resurfacing events during its flyby, but this isn’t surprising, since these events are thought to occur once every tens of thousands of years only.

Nevertheless, Charon’s surface features reveal deep fissures and rifts, suggesting that the moon had a subsurface liquid mantle in its past. Indeed, although slightly less dense than Pluto at 1.70 g/cm^3, Charon still contains a large proportion of rock to ice (especially when compared to the icy moons of Saturn), and as it differentiated itself and formed a rocky core during its formation, heat generated by radioactive decay and accretion warmed up the moon’s interior, melting the bottom of the icy crust, which most likely formed a subsurface ocean. Unfortunately, the moon’s size wasn’t big enough to sustain the primordial heat, and Charon cooled over time, freezing the subsurface liquid mantle. As frozen water expanded, the crust was lifted up, giving us the surface features we see today. It does seem, though, that given the relatively recent resurfacing events that have been observed by New Horizons, there might still be enough heat to sustain very small pockets of water-ammonia slush under the surface.

Makemake, Quaoar, Salacia, Orcus, and 2002 MS4

That the three large Kuiper Belt Objects we have visited – Triton, Pluto, and Charon – hold much potential as past or present ocean worlds is not as surprising as it seems. Ultimately, KBOs are made of ices and rocks, and the conventional thinking goes that the larger the objects are in the belt, the denser they should get as gravity causes them to compact. If a KBO is massive enough to trap sufficient heat through accretion and radioactive decay, it is very likely that differentiation will have occurred. And if the mix of interior ices is right (presence of antifreeze compounds), part of the water mantle might have melted, thus forming a subsurface ocean in the past.

Unfortunately, there is no easy way to determine at what size/mass limit differentiation occurs, as this will depend on many variable factors, such as the distance from the Sun when the object was formed, the ratio of ice to rock, how fast accretion has occurred or the quantity of radioactive material aggregated (especially Al-26).

For example, we have come to realize that KBOs with a similar radius share very different properties, implying that although it might be theoretically possible for KBOs of a certain size to undergo differentiation and host a subsurface ocean in the past, this needs to be reviewed on a case by case basis. (For example, the KBO 2002 UX25 is both big and porous.)

This being said, we are confident that objects with a radius greater than 1,000 km (Eris, Triton, and Pluto) are massive enough to have formed a subsurface ocean and still sustain it today. The mid-size KBOs, ~400 to 1,000 km that might have formed subsurface oceans in their past, are Makemake, Quaoar, Salacia, Orcus, and 2002 MS4, as they are theoretically large enough to have undergone differentiation. The large dwarf planet Haumea might also be part of this group, but its highly elongated ellipsoid shape resulting from a troubled history (most likely due to an impact that broke part of its icy mantle into fragments) makes it difficult to assess if the right conditions were present for a subsurface ocean.

Currently, the best we can do is characterize the surface chemistry of these objects through their spectra, which is not representative of the entire body. For example, Makemake's surface seems to be dominated by methane ice, while Orcus and Quaoar show strong bands of crystalline water-ice in their spectra, which some have interpreted as evidence for recent resurfacing events. Not everyone is convinced by this interpretation, though, so the presence of crystalline water-ice remains a mystery. Ammonia is most likely present in these objects as well; however, since it is complicated to detect, it hasn't shown up in the spectra yet.

Knowing a KBO's density helps as well. Take Salacia and Orcus for example. Salacia has a slightly bigger radius than Orcus (450 km vs. 400 km), which theoretically should make it more likely to form a subsurface ocean. Orcus is denser (2.3 g/cm^3) and has ice on its surface (higher albedo), so it is most likely differentiated. Salacia, on the other hand, might not be since it has little surface ice (low albedo) and low density (1.1 g/cm^3). Such a difference between similarly sized objects might be due to Salacia being formed later than Orcus, and therefore has aggregated more icy material (similar to what can be found in comets) than denser rocky material.

Given our very limited knowledge of mid-size KBOs, we can't be confident enough in determining if any of these objects had or not a subsurface ocean in the past.

Scattered Disk Objects (SDO)

Further out from the Kuiper Belt lies another group of objects made of rocks and ice that form a large irregular disk referred to as the Scattered Disk. Contrary to KBOs, which hold steady orbits around the Sun, SDOs are home to objects whose orbits are far more irregular, due to Neptune's influence during the early history of the Solar System, leading planetary scientists to conclude that SDOs are the source of short-period comets (the Oort Cloud is where long-period comets reside). Most SDOs have highly elliptical orbits, which for some can extend all the way up to 100 AU, making them the most distant objects observed in our Solar System (even if their eccentric orbit can also pass near Neptune's orbit at their closest approach).

The biggest SDO detected so far is Eris at 1,163 km in radius, slightly smaller than Pluto yet 27% more massive, implying a more rocky composition. (We can measure Eris' mass thanks to its moon Dysnomia.) In fact, Eris is the ninth most massive planetary object directly orbiting the Sun after the planet Mercury, while Pluto is the tenth. (Eris' discovery in 2005 is one of the events that led to Pluto's demotion to a dwarf planet.) Our knowledge of Eris is pretty limited as we have never sent a space probe to investigate it. We know that its surface temperature is between 30 and 56 K (−243.2 °C and −217.2 °C) and that its albedo is far brighter than Pluto or Triton and lacks their distinctive reddish hue derived from the breaking down of organic compounds (tholins). Since methane has been detected in Eris' spectra, it seems likely that it has condensed uniformly over the surface, with the ice making the surface reflect most of the light from the Sun.

With a perihelion of about 37.9 AU, it might be possible for methane ice to sublimate into gas and form a light atmosphere, which in turn might slowly escape into space. If this is the case, the methane would need to be replenished by an active geological process. Furthermore, as Eris is denser than Pluto, models have shown that the radiogenic heating produced by its larger rocky core could be capable of sustaining an internal ocean of liquid water, provided that it is also rich in ammonia. Unfortunately, Eris has almost reached its aphelion at 96 AU, at present making it unlikely that we will be investigating it with a probe anytime soon. (It would take at least 25 years for a spacecraft to reach Eris using conventional methods.)

Another intriguing SDO is a contender for the dwarf planet category, 2007 OR10. At 751 km in radius (similar to Rhea's size), this object is the third largest known trans-Neptunian object after Pluto and Eris, making it slightly bigger than Makemake. (Some scientists consider Haumea to be bigger than 2007 OR10, even though its ellipsoid shape gives it a smaller volume.) It is currently the most massive Solar System object still to be unnamed, mainly because its discoverer, Michael Brown, feels that we don't know enough about it to come up with a name that adequately reflects its properties. Spectra analysis of 2007 OR10 has detected water-ice and methane that, due to its highly eccentric orbit, might form a tenuous atmosphere at its closest approach to the Sun at 33 AU in a few hundred years from now (it is currently at 87.5 AU and speeding towards aphelion at 101 AU.)

2007 OR10's density is poorly known, as its mass hasn't been precisely measured despite the recent discovery of a dark and small moon. Given its size, it is likely to be differentiated with a rocky core and an icy crust made of water-ice and methane, similar to Pluto and Eris. Recent models have shown 2007 OR10 to be capable of sustaining a subsurface ocean, as long as antifreeze compounds are present there. However, not everyone is convinced that 2007 OR10 is big enough to hold onto its heat for billions of years and instead, suggest that if it does have a primordial subsurface ocean, this should be entirely frozen by now. As the performance of Earth-based telescopes increases in the coming decades, more will be learned from this unnamed SDO and its possible subsurface ocean.

That leads us to the final Solar System object, which will be reviewed as a potential ocean world – the enigmatic Sedna. Discovered in 2003, Sedna's orbit is an extremely eccentric one, taking it from 76 AU at its closest to a whopping 936 AUs, far greater than most SDOs. The orbit is so elongated that Sedna takes 11,400 years to go around the Sun. It is intriguing, since Solar System objects don't start off in a highly eccentric orbit. Instead, they tend to have a more circular orbit during their formation, and this is most likely how Sedna started, somewhere around 75 AU from the Sun. However, its orbit was later stretched into its present course by an unknown external agent.

Proposals for the agent include an undiscovered planet lying at 2,000 AU (the hypothetical Planet 9), the effect of a passing star early on in our Solar System's history or, even more radical, that Sedna is a captured extrasolar planetary object. Given the scope of all these plausible explanations, understanding the cause for Sedna's unusual orbit might be the key to understanding our Solar System's origin and evolution.

Sedna's unusual orbit is also a sticking point to some astronomers. They question Sedna's place within the Scattered Disk category, since Neptune's influence is negligible so far out from the Sun, and most SDOs don't exhibit such a highly eccentric orbit. Instead, Sedna could belong to the hypothetical inner Oort Cloud or that the Scattered Disk lies further out than suspected. As such, Sedna could be the first of a new category of planetary objects termed the extended Scattered Disk objects (ESDO) or distant detached objects (DDO). The truth is that, at present, very little is known about this inaccessible part of our Solar System.

We do know, thanks to Earth-based observations, that Sedna has a radius of around 498 km, slightly bigger than Ceres (see Chapter 9). However, its mass is undetermined. Intriguingly, Sedna's reflected light is one of the reddest in the Solar System, suggesting that hydrocarbons such as methane have decayed into tholins due to long exposures of UV radiation and solar particles. This, in turn, implies that resurfacing activities such as icy cryovolcanoes are not present. Furthermore, spectra analysis have detected methane, water, and nitrogen, which should all be present as surface ices, since it is too cold to form an atmosphere. Again, similar to 2007 OR10 and Eris, Sedna could in theory have supported a subsurface ocean in its past if its rocky mantle is large enough and antifreeze compounds are present in sufficient quantities. Whether such ocean is entirely frozen now is anyone's guess. Like all distant Solar System objects, unless a spacecraft is sent to visit Sedna during its closest approach to the Sun at 76 AU in 2075–76, it will most likely continue to be a puzzle. (With an orbital period of over 11,000 years, the 2075–76 passage would be our only realistic opportunity to visit Sedna.) It is not alone, though. With an estimated 40-Sedna size objects populating this distant region of our Solar System, the number of possible ocean worlds is bound to increase.

And so it is with Sedna, the furthest of the candidates, that we end this journey through our Solar System. Thanks to our robotic emissaries, *Pioneer 10* and *11,* the two Voyagers, Galileo, Cassini-Huygens, New Horizons and Dawn, as well as Earth-based ground and space telescopes, the discoveries made within the last 35 years have revolutionized planetary science as well as brought us one step closer in answering this fundamental question: Is there life out there?

What will the next 35 years bring? To start answering this question, it is time for us to return to Earth and see in Chapter 12 what plans are currently being conceived for the exploration of the ocean worlds of our Solar System.

Part IV
Future Missions to the Ocean Worlds

> "Certainly one of the most enthralling things about human life is the recognition that we live in what, for practical purposes, is a universe without bounds."
>
> – James Van Allen

We are living at the beginning of a new age of exploration. The momentum for the investigation of ocean worlds is growing among the public and scientists. In this fourth and last part, we will cover the confirmed missions currently being put in place by ESA and NASA as well as the proposed missions either waiting to be selected or in need of further development.

12. Confirmed and Proposed Missions to the Ocean Worlds

The Exploration of a New Frontier

The last two decades of space exploration have been remarkable. No less than five ocean worlds have been identified in our Solar System, and, as we have seen throughout the last chapters, there is potential for more. Not only is the volume of liquid water currently orbiting our Sun (in moons and potentially dwarf planets) vastly greater than what we have on Earth, the fact that a good proportion of it is in direct contact with rocks and organic compounds is astounding. This represents a shift from how we previously understood our Solar System. If you recall from Chapter 6, it was only in 1971 when astronomer John S. Lewis first proposed that liquid water might exist under the icy crust of small planetary objects such as moons. Even though few supported this idea at the time, these days scientists recognize that instead of being the exception, such water habitats might be the norm within our Solar System.

Such a paradigm shift would not have been possible without significant investments, mainly from the United States, that allowed NASA to send complex missions with exorbitant price tags to the outer planets: two Pioneers, two Voyagers, Galileo, Cassini-Huygens, New Horizons, and Dawn. This is only the beginning, though. Despite how much we have learned in the past decades, our knowledge of the ocean worlds is still limited, mainly due to the vast distances that stand between these worlds and us. More than 50 robotic probes, orbiters, landers, and rovers have visited our neighboring planet, Mars, throughout the last 50 years, and yet, only two spacecraft ever came close to Europa, the poster child for an ocean world if we ever needed one.

This knowledge gap has finally been recognized by the major space agencies (and the lawmakers who ultimately fund them), and we are now experiencing a new age in planetary exploration where, in addition to building spacecraft specifically designed to

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investigate these ocean worlds, the agencies are also investing resources into maturing the technologies required for future missions to these worlds.

As such, both NASA and ESA have a flagship mission, each planned to visit the ocean worlds of Jupiter in the coming decade – NASA with Europa Clipper and ESA with the JUICE mission. And this is just the beginning. Once the potential for life in these ocean worlds becomes more recognized, the public interest will grow stronger and with it, a renewed interest in funding follow-up missions. Already, there have been proposed missions to land on the icy surface of Europa, fly through Enceladus' plume, and visit Triton. Furthermore, in addition to these state-funded programs, very wealthy individuals have been vocal in their interest to support private missions to the ocean worlds as well.

Let us first take an in-depth look at the confirmed missions from the leading space agencies.

Confirmed Missions to the Ocean Worlds

The Emergence of ESA's Jovian Mission

In 2012, the European Space Agency selected the Jupiter Icy Moons Explorer mission (JUICE) as part of its flagship L-class missions group, which will make ESA the second space agency, after NASA, to design and launch a spacecraft to the outer planets. (ESA's Huygens Lander probe really just hitched a ride on NASA's Cassini.) This ambitious mission will have as its primary science objectives the planet Jupiter and the study of its three icy moons – Ganymede, Callisto, and Europa – and their interactions with the planet.

Nevertheless, the star of the show will be the moon Ganymede, as the final stage of the mission will see the JUICE spacecraft orbit the giant moon for nine months to characterize its magnetosphere, atmosphere, surface and internal mass distribution. Such a continued focus will allow scientists to better understand the subsurface ocean that lies beneath its thick icy crust as well as assessing its habitability. Callisto and Europa will also be studied but to a lesser extent, with 12 flybys for the former and only two flybys for the latter.

Ganymede, the most prominent moon of our Solar System, is a fascinating world in its own right (see Chapter 4), and by dedicating its first ever mission to the outer-planets with a thorough study of this moon, ESA demonstrates its confidence in building complex interplanetary missions. One might wonder, though, why Ganymede was selected as the primary target of this mission instead of Europa, a far more promising moon concerning habitability and overall interest.

To answer this question, we need to go back more than ten years, when optimistic plans were being dreamed up by both NASA and ESA. In 2008, both space agencies envisioned a grand joint mission to design and launch a probe to investigate the outer planets. As a result, two destinations were in competition: the Jovian icy moons through the Europa Jupiter System Mission (also known as the EJSM/Laplace mission), whose overarching theme was the study of the emergence of habitable worlds around gas giants as well as understanding the interactions between Jupiter and its satellite system; and Saturn's icy moons, with the Titan Saturn System Mission (TSSM), which was formed by merging NASA's Titan Explorer and ESA's Titan and Enceladus mission (TandEM) proposals.

Ultimately, the mission to the Jovian system was considered more promising, and TSSM was dropped. The two agencies quickly decided that it would be a two-spacecraft mission; NASA would focus on Io and Europa – the two "rocky" moons – with the Jupiter Europa Orbiter (JEO) spacecraft, while ESA would focus on Ganymede and Callisto – the two "icy" moons – with the Jupiter Ganymede Orbiter (JGO) spacecraft. As their names indicate, JEO was planned to orbit Europa in its final mission stage, while JGO would do the same with Ganymede. Additionally, the EJSM/Laplace mission would also investigate Jupiter, its magnetosphere and its interaction with the satellite system (magnetosphere, gravitational coupling, and long-term tidal evolution).

It is worth noting that the Japanese space agency (JAXA) was also interested in joining this joint mission and proposed the Jupiter Magnetospheric Orbiter (JMO) as well as the Jupiter and Trojan Asteroid Explorer (Trojan-JMO). Unfortunately, both were later canceled due to the technical challenge of launching these missions on time with JEO and JGO.

The EJSM/Laplace mission was an ambitious one, requiring a substantial amount of investment, yet both agencies had high hopes that their respective governments would fund it. In that regard, ESA's JGO mission had a significant advantage over NASA's JEO, as the main radiation belts of Jupiter would be avoided during all mission phases of JGO, since the spacecraft would be orbiting the giant planet at a greater distance while NASA's JEO would be spending most of its time in the harsh radiation environment nearer to Jupiter, requiring an entirely different, and more expensive, design. It was estimated that JEO would be exposed to a radiation dose of 2.9 Mrad, an order of magnitude more than JGO's 100 Krad.

More exposure to harsh radiation required the need for additional radiation shielding (such as aluminum and tantalum stack) to protect the sensitive scientific instruments, adding more weight and therefore more fuel (meaning extra weight) to the spacecraft. As a consequence, JEO required two times more shielding (192 kg) than JGO (80 kg), to complete its 2.5 years' mission, adding millions of dollars to its budget.

Furthermore, using solar panels as the primary electrical power system for JEO would be out of the question, as these would quickly degrade from the high radiation levels encountered around Io and Europa. Instead, JEO's energy requirements would need to be provided by five nuclear batteries that reliably converted heat into electricity. These are the multi-mission radioisotope thermoelectric generators (MMRTGs), which form the new generation of the trustworthy RTG (radioisotope thermoelectric generators).[1]

The addition of the MMRTGs led to increased costs and complexity (as well as the depletion of plutonium-238, the scarce fuel used to power the MMRTGs, whose production had stopped entirely at the time).

Finally, all the electronics on the flight systems as well as the scientific instruments required a complete redesign to allow them to operate in a higher radiation environment. This meant that no off-the-shelf electronics could be used, but instead everything would have to be custom made, once more increasing complexity and costs.

All the above, as well as some other cost factors, meant that JEO's estimated price tag shot up to $3.8 billion (for reference, a planetary exploration flagship mission usually lies within the territory of $2 billion). Such a high figure, which ballooned even further to $4.7 billion in a 2011 forecast, proved too hard to swallow for the U. S. government, and the mission was canceled altogether.

This left ESA, who in the meantime had received the green light from the European governments, to go it alone. In the context of the ESJM/Laplace mission, the removal of NASA's JEO led

[1] RTGs have been used on the Apollo missions to the Moon, the Viking and Curiosity missions to Mars, and all the missions to the outer planets: the Pioneers, the Voyagers, Ulysses, Galileo, Cassini-Huygens and New Horizons.

to a reduced science return in the study of Io, Europa, Jupiter's atmosphere and magnetosphere. Having considered this, ESA scientists concluded that JGO would still be relevant to the overarching science objectives put in place by the ESJM/Laplace mission as its chief target, the moon Ganymede, allowed the space agency to study a water-rich world as well as understand its interactions with the surrounding Jovian environment.

Nevertheless, with the cancelation of JEO, there were no plans to visit Europa, a high priority in planetary science. An initial study showed that to fully recover the science return lost from the cancelation of the Europa orbiter, around 50 to 100 flybys of the moon would have to be performed by JGO. This meant sacrificing all of the Ganymede, Callisto, and Jupiter science objectives as well as modifying the spacecraft to withstand exposure to the higher radiation environment and therefore increasing their costs.

It was unanimously agreed that this wasn't a viable option. Instead, ESA concluded that the best way to maximize JGO's science return on Europa without losing focus of its foremost scientific objectives would be to add 2 close flybys of Europa, as well as adjust a flyby of Callisto into a close flyby of Jupiter, allowing the exploration of the Jovian atmosphere and magnetosphere at high-latitudes (30 degrees).

With these new flybys, the spacecraft would dip in and out of the harmful radiation belt, increasing the overall radiation exposure of the mission to 240 Krad. The two Europa flybys would add 25% of the total mission dose, whereas 60% would be accumulated during the Ganymede phase, and the rest of the radiation would come from the various Jupiter and Callisto phases.

Fortunately, the new shielding requirements for the spacecraft were well within the acceptable limits of the mission, and thus the JGO mission was reformulated into JUICE; the JUpiter ICy moon Explorer mission, whose key science goals were redefined as the study of the emergence of habitable worlds around gas giants. A new mission was born.

JUICE

The JUICE orbiter is planned to launch in 2022 on the Ariane 5 launch vehicle and, with the help of multiple gravity assists from the inner planets (Earth, Venus, Earth, Mars, Earth or EVEME), will reach Jupiter in 2030. For the first two years of its mission, it will perform a tour of the Jovian system, with close flybys of Europa, Callisto, and Jupiter before inserting itself into orbit around Ganymede by September 2032, making it the first spacecraft to orbit another moon of our Solar System. There, JUICE will study Ganymede for nine months at ever decreasing altitudes before being disposed of on its surface in June 2033. Orbiting a planetary object as big as Ganymede means that the spacecraft will be eclipsed from the Sun from time to time, which will be a significant constraint on a solar-powered spacecraft. Therefore, JUICE's orbits have been calculated in a way to reduce as much as possible these eclipses (with the longest eclipse lasting for about 45 minutes).

The spacecraft will host a suite of ten scientific instruments that will provide a full range of measurements as seen from the table below (Table 12.1). As with most planetary mission these days, JUICE is a multinational mission, with NASA and JAXA contributing to some of the instruments (Fig. 12.1).

The JUICE payload consists of 10 state-of-the-art instruments plus one experiment that uses the spacecraft telecommunication system with ground-based instruments. This payload is capable of addressing all of the mission's science goals, from in situ measurements of the plasma environment, to remote observations of the surface and interior of the three icy moons, Ganymede, Europa and Callisto, and of Jupiter's atmosphere. A remote-sensing package includes imaging (JANUS) and spectral-imaging capabilities from the ultraviolet to the sub-millimeter wavelengths (MAJIS, UVS, SWI).

The MAJIS instrument will be crucial in determining the nature of the surface compounds and potentially what lies within the subsurface oceans, whereas the UVS instrument is important, too, since ultraviolet is an ideal spectral regime for studying volatiles because many ices and relevant gases exhibit absorptions patterns in this region of the electromagnetic spectrum. Furthermore, atomic emission features are prevalent in the UV. We can also investigate the presence of non-ice contaminants (though they can be more difficult to identify specifically). Much more promising is the fact that during the Cassini mission, the UV imaging instrument named UVIS was used during stellar and solar occultations to study the density and composition of Enceladus' plumes. UVS on JUICE might be able to do the same if a plume on Europa is confirmed (see Chapter 6), although it will be tricky. In the Jovian system, the Hubble Space Telescope has been used to study UV emissions from all four Galilean satellites, helping us to understand those atmospheres. UVS will be able to do the same, with better spatial and temporal resolution.

Table 12.1 A list of the 10 scientific instruments that will be onboard the JUICE spacecraft and their science contribution

Abbreviation	Instrument name	Description and scientific objectives
GALA	Laser altimeter	Tidal deformation of Ganymede; Morphology of moons surface features
3GM	Radio science experiment	Interior state of Ganymede, presence of a deep ocean and other gravity anomalies. Ganymede and Callisto surface properties. Atmospheric science at Jupiter, Ganymede, Europa and Callisto, and Jupiter rings.
RIME	Ice penetrating radar	Structure of the Ganymede, Europa and Callisto subsurface; identify warm ice water "pockets" and structure within the ice shell; search for ice/water interface.
MAJIS	Visible-IR hyperspectral imaging spectrometer	Composition of non water-ice components on Ganymede, Europa and Callisto; State & crystalinity of water ice. On Jupiter: tracking of tropospheric cloud features, characterisation of minor species, aerosol properties, hot spots and aurorae.
UVS	UltraViolet imaging spectrometer	Composition & dynamics of the atmospheres of Ganymede, Europa, and Callisto
JANUS	Narrow and wide angle camera	Local-scale geologic processes on Ganymede, Europa, and Callisto; Io Torus imaging, Jupiter cloud dynamics & structure. 'Global morphology of the Ganymede surface. Global to regional scale morphology of the Callisto and Europa surface
J-MAG	Magnetometer	Ganymede's gravity field and the extent of internal oceans. Ionosphere and upper atmosphere of Jupiter and Ganymede, Callisto and Europa.
PEP	Particle package	Jovian magnetosphere. Interaction between Jovian magnetosphere and Ganymede, Europa and Callisto. Exospheres and ionospheres of the moons.
SWI	Submillimetre wave instrument	Dynamics of Jupiter's stratosphere; Vertical profiles of wind speed and temperature Composition and structure of exospheres of Ganymede, Europa and Callisto.
RPWI	Radio and plasma wave instrument	Ganymede: Exosphere and magnetosphere; Callisto & Europa: Induced magnetic field and plasma environment; Jovian magnetosphere and satellite interactions

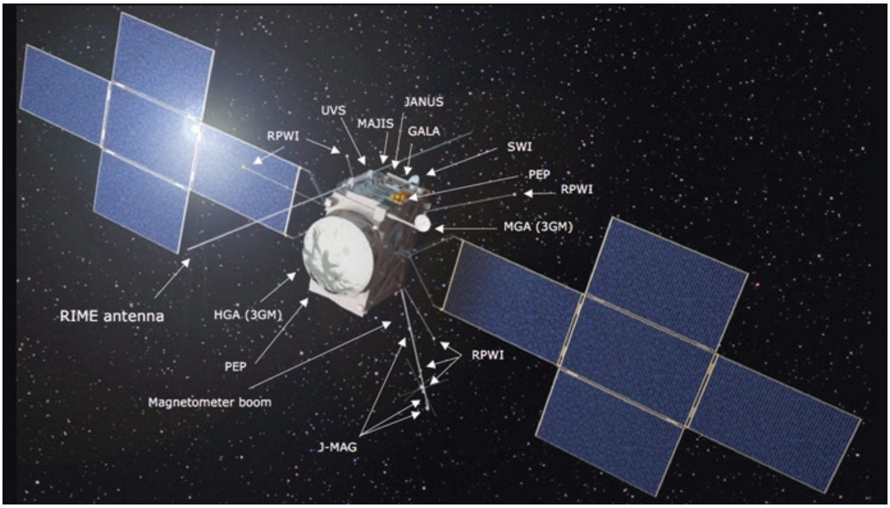

Fig. 12.1. JUICE spacecraft and its host of 10 state-of-the-art instruments. It will be making significant contributions to our understanding of Ganymede, Callisto, and Europa as well as the planet Jupiter and the interactions between all these planetary objects. (image courtesy of ESA.)

A geophysical package consists of a laser altimeter (GALA), which will provide high-resolution maps of the moons' topography and a radar sounder (RIME) for exploring the surface and subsurface of the moons, especially in understanding the structure of the icy crusts. A radio science experiment (3GM), using both the high gain antenna (HGA) and medium gain antenna (MGA) to probe the atmospheres of Jupiter and its satellites and to perform measurements of the gravity fields, should provide powerful insights on the distribution of the moons' interior masses. An in situ package contains a powerful suite to study plasma and neutral gas environments (PEP) with remote sensing capabilities via energetic neutrals, a magnetometer (J-MAG), and a radio and plasma wave instrument (RPWI), including electric field sensors, and a Langmuir probe. An experiment (PRIDE) using the ground-based Very Long Baseline Interferometry (VLBI) will support the precise determination of the spacecraft's velocity and position, with the focus on improving the ephemeris of the Jovian system.

There is no doubt that JUICE is set to revolutionize our understanding of Jupiter's ocean worlds. Current unknowns, such as the structure of Ganymede, Europa, and Callisto's subsurface as well as the composition of non-water-ice components on their surface, will be addressed. Furthermore, Ganymede will be continuously studied for almost a year, a first for a moon in our Solar System (with the exception of our Moon of course).

When it comes to Europa, the spacecraft will perform a close flyby over the northern hemisphere, followed by another over the southern hemisphere, both at very low altitudes (less than 500 km). Although JUICE will most likely not be able to fly through one of Europa's enigmatic plumes due to the constraints of the spacecraft's trajectories and the apparent lack of predictability in the plume's activity, the PEP instruments will be able to analyze any remnants of a hypothetical plume that might linger in Europa's exosphere, thus investigating them indirectly.

The end of the mission will be an unusual one. The spacecraft will run out of fuel during its last orbit around Ganymede and make an uncontrolled crash on the surface of the moon. Ganymede, being a Planetary Protection Category II target, signifies that there is only 'a remote chance that contamination by spacecraft could compromise future investigations.' There is, therefore, no obligation from ESA to determine how or where the spacecraft will be deposited on the surface of the moon (as opposed to Europa or Enceladus, which are Planetary Protection Category III and IV targets). Nevertheless, if the spacecraft is still steerable – which might be doubtful after spending so much time in the harsh Jovian environment – the team might try to force it towards a specific location, such as a flat expanse instead of a region where cracks in the icy crust are apparent.

JUICE's strength is its overarching vision of investigating and understanding the Jovian satellite system as a whole. Planetary science is at its core a comparative science, and by studying the icy moons and their interactions with Jupiter, we will gain far more insight into the ocean worlds located there.

The Europa Clipper

Born from the ashes of JEO, the Europa Clipper is NASA's answer to a frustrated community of planetary scientists who have been requesting for twenty years now that we return to Europa. Surprisingly, warranting a mission to investigate one of the most fascinating objects in our Solar System required more time than what would have been expected for such an endeavor.

As we have seen previously, following the science returned by the Galileo spacecraft in the late nineties, both the American and the European space agencies started independently to study preliminary proposals for an orbiter mission. NASA proposed the Jupiter Europa Orbiter (JEO) for the ESJM/Laplace mission but canceled it following the high cost involved (over $4 billion).

During this time, NASA (with the assistance of the National Science Foundation) developed a better way to set up a comprehensive strategy for the exploration of the Solar System; the Decadal Surveys. These surveys, which can take more than a year to produce and involve a large number of people, try to build a consensus within the planetary science community on where the priorities in the field lie for future robotic exploration missions. Although NASA (and the U. S. Congress, who funds the agency) aren't bound by the recommendations of the Decadal Survey, they understand its value and take it seriously.

In the 2003 Planetary Decadal Survey, "New Horizons in the Solar System," and in the 2011 Planetary Decadal Survey, "Vision and Voyages," NASA is recommended to explore Europa, and such a destination is even listed in the 2011 survey as the second-highest-priority for a new flagship mission after Mars. Therefore, following JEO's cancelation, there was real pressure for NASA to find a way to come up with a Europa mission at lower costs.

On NASA's request, new studies were conducted in 2012 that looked into the feasibility of implementing three types of missions with a firm budget of $2 billion each (the cost of a flagship mission): a lander, an orbiter, and a multi-flyby spacecraft (inspired in part by Cassini's regular flybys of Enceladus and Titan). Although the lander mission quickly turned out not to be due to the limited knowledge of Europa's surface, the study found ways to reduce by half the costs for an orbiter mission (it would spend only 30 days orbiting the moon), making it an attractive proposition. Nevertheless, it was overshadowed by the multi-flyby mission architecture that proved to be the optimal approach to satisfying the science objectives in the most cost-effective, lowest-risk manner, even though the spacecraft would spend less than a cumulative six days around Europa (and therefore limiting its exposure to Jupiter's harmful radiations significantly).

How could a six-day multi-flyby mission outcompete a comparatively longer thirty-day orbiter mission? What tipped the balance is something we have all become familiar with in our day-to-day lives, the ability to be regularly connected to a network. Indeed, the key to the multi-flyby mission is the fact that as the spacecraft gathers large amounts of data during one close flyby of the moon, it has seven to ten days to transmit this data back to Earth as it continues its orbit around Jupiter before a new flyby occurs.

In contrast, the orbiter spacecraft, locked in its orbit around Europa, would be hindered by its regular passages behind the moon in relation to Earth, which effectively blocks all transmission, in addition to the moon also passing behind Jupiter (every 3.5 days), thus interrupting the data transfer. Such a configuration drastically limits the amount of data that can be sent back and therefore stored.

By spending a year orbiting Jupiter and making 34 targeted flybys of Europa, as proposed in the initial study, the multi-flyby spacecraft would transmit three times more data compared to the 30-day period for the orbiter spacecraft. (The data returned by the spacecraft isn't a straight multiple of time, as there are also limitations brought about by the position of NASA's Deep Space Network antennas on Earth at any given time.)

With more data to transmit, the multi-flyby mission opens the door for more data-hungry instruments such as ice-penetrating radar or a shortwave infrared spectrometer, both essential in characterizing the moon's icy shell and surface composition. Further studies showed that with a multiyear mission totaling 45 flybys, the multi-flyby spacecraft would be able to achieve the majority of the scientific goals set out by the initial JEO concept at half the price. The 2012 orbiter concept couldn't match such a feat and was dropped. And thus the multi-flyby mission was aptly rebranded as the Europa Clipper, a name derived from the fast sailing ships of the 19th century, which conveys swiftness and agility.

The Europa Clipper made a lot of sense and received the go-ahead by the U. S. Congress. In 2015 it entered its formulation phase with the objective of launching the spacecraft between 2022 and 2025. Although there are still potential changes concerning some of the details of the mission at the time of writing, the mission's configuration and payload have all been agreed upon. Similarly to ESA's JUICE spacecraft, the Clipper will use solar panels as the primary power source, as it will spend only a limited amount of time within Jupiter's lethal radiation belt, thus reducing the complexity and cost of the mission (Fig. 12.2).

The launch system expected to take the Europa Clipper into space will be the newly developed Space Launch System (SLS) rocket that NASA is currently building as its next heavy launch system. If all goes well, the Clipper should see itself launched on a direct trajectory to the Jovian system at the earliest by 2022, although this date seems too optimistic at the time of writing and will likely slip. The Clipper should take less than three years to reach its target, as opposed to a more conventional but less powerful launch

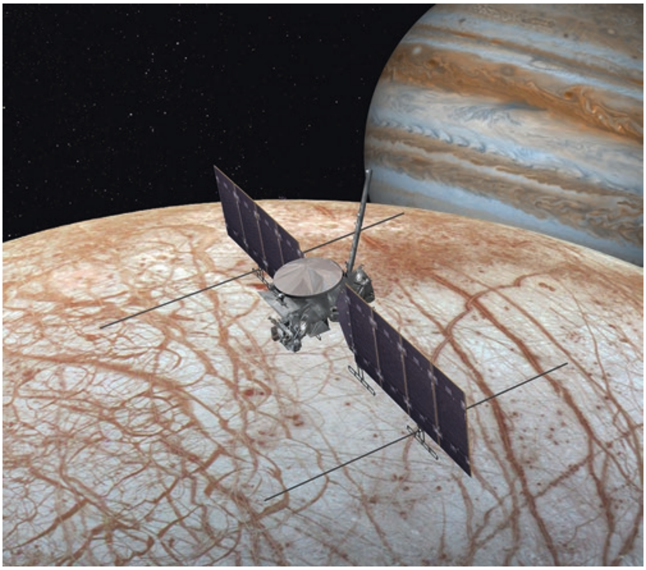

Fig. 12.2 Artist's impression of the Europa Clipper spacecraft as it approaches Europa during one of its orbits around Saturn. The Clipper is set to revolutionize our understanding of the moon. (Image courtesy of NASA.)

system such as the Atlas V rocket, which would require a six-year journey and multiple gravity assists from Earth and Venus. Once arrived at the destination, the Clipper's prime mission would be set to last three years, during which time it would perform 45 flybys of Europa at altitudes ranging from 25 to 2,700 km, ensuring coverage of 90% of the moon's surface.

The Clipper's scientific payload has been chosen explicitly with two objectives in mind: to characterize Europa's subsurface ocean and investigate its habitability. Other areas of focus will be an understanding of the processes involved in the renewal of the icy crust as well as the internal heat budget for the moon. Identifying potential plume activity with the hope of flying into one will be top on the agenda as well. Scientists also hope to model the cycling of essential elements on Europa, such as oxygen, hydrogen, carbon, nitrogen, phosphorous, and sulfur.

As seen in Table 12.2, the payload will include a magnetometer (ICEMAG) to measure the ocean's salinity, an ice-penetrating radar (REASON) to map in detail the icy crust, a thermal camera (E-THEMIS) to look for warm spots near the surface, an infrared spectrometer (MISE) to detect organics on the surface, a wide and narrow-angle camera (EIS) to provide views of the surface in resolu-

Table 12.2 The scientific payload for the Europa Clipper mission

Abbreviation	Instrument name	Description and scientific objectives
E-THEMIS	Europa thermal emission imaging system	The Europa Thermal Emission Imaging System will provide high spatial resolution, multi-spectral imaging of Europa in the mid infrared and far infrared bands to help detect active sites, such as potential vents erupting plumes of water into space.
MISE	Mapping imaging spectrometer for Europa	Imaging near infrared spectrometer to probe the surface composition of Europa, identifying and mapping the distributions of organics (including amino acids and tholins[47][48]), salts, acid hydrates, water ice phases, and other materials.
EIS	Europa imaging system	Visible-spectrum wide and narrow angle camera instrument that will map most of Europa at 50 m (160 ft) resolution, and will provide images of selected surface areas at up to 0.5 m resolution.
Europa - UVS	Europa ultraviolet spectrograph	The Europa Ultraviolet Spectrograph instrument will be able to detect small plumes and will provide valuable data about the composition and dynamics of the moon's exosphere.
REASON	Radar for Europa assessment and sounding: ocean to near-surface	Dual-frequency ice penetrating radar instrument that is designed to characterize and sound Europa's ice crust from the near-surface to the ocean, revealing the hidden structure of Europa's ice shell and potential water pockets within.
ICEMAG	Interior characterization of Europa using magnetometry	Magnetometer that will measure the magnetic field near Europa and in conjunction with the PIMS instrument will probe the location, depth, thickness and salinity of Europa's subsurface ocean using multi-frequency electromagnetic sounding.[48]
PIMS	Plasma instrument for magnetic sounding	The Plasma Instrument for Magnetic Sounding measures the plasma surrounding Europa to characterise the magnetic fields generated by plasma currents. These plasma currents mask the magnetic induction response of Europa's subsurface ocean. In conjunction with the ICEMAG instrument, it is key to determining Europa's ice shell thickness, ocean depth, and salinity.
MASPEX	Mass spectrometer for planetary exploration	The Mass Spectrometer for Planetary Exploration will determine the composition of the surface and subsurface ocean by measuring Europa's extremely tenuous atmosphere and any surface materials ejected into space.
SUDA	Surface dust mass analyzer	Mass spectrometer that will determine the composition of the surface and subsurface ocean by measuring Europa's extremely tenuous atmosphere and any surface materials ejected into space.

tions less than a meter per pixel, an ultraviolet spectrograph (UVS) to detect plumes of saltwater that may spray into space, a plasma instrument (PIMS) to provide further insight into the subsurface ocean, a mass spectrometer (SUDA) specially designed to measure the composition of the small particles ejected from a hypothetical plume and the surface in general, and finally, the mass spectrometer for planetary exploration (MASPEX) to determine the composition of the subsurface ocean and identify the materials ejected into space. SUDA and MASPEX will work in tandem and complement each other.

MASPEX will be making its maiden flight on the Europa Clipper, as it is the next generation of spectrometers to be sent into space. Already more than ten years in development, MASPEX has been designed and built specifically to withstand the rigors of space (harsh radiation environments) as well as sterilization processes required for planetary protection protocols (cooked to 300 °C). Its high-resolution capabilities will allow it to identify small organic compounds as well as noble gases and many volatile isotopes. The hope is that if there are biosignatures currently being spewed out by Europa's hypothetical plumes, MASPEX will sniff them out. These signatures of life could be patterns in the concentration levels of amino acids or fatty acids (used for cellular membranes). If one wishes for unambiguous signs of life, the presence of steroids or hopanoids, which no abiotic process can create, would be sufficient. As importantly, the Europa Clipper mission will be crucial in the preparation for a follow-up mission already being discussed at NASA – the Europa Lander.

Proposed Future Missions to the Ocean Worlds

NASA's Europa Lander

If there ever was a mission that has the potential to change how humanity views itself in the universe, this might be it.

NASA's Europa Lander, which at the time of writing was still in its proposal stage (and didn't have a better name for it), should reach Europa by 2031 (very optimistic, given the difficulties and delays faced by the development of NASA's SLS launch system), land on the icy surface with the help of a sky crane (similar to the Mars Curiosity rover's landing stage), and survive there for 20 to

40 days, where it will conduct the first in situ search for life (or, more precisely, biosignatures) on another world since the Vikings on Mars in the 1970's.

With the help of a robotic arm, it will dig a 10-cm deep trench, collect five samples of icy material beneath the top surface layer, and pass them through a host of microscopic and spectroscopic instruments (i.e., a raman spectrometer and gas chromatograph-mass spectrometer), designed to detect organics at extremely low concentrations (one picomole per gram of sample). If simple life forms (Europan microorganisms) are being deposited on the moon's surface by the hypothetical plumes or brines gushing out from below, the lander will find them. Other recommended instruments include a set of stereo cameras, a seismometer, and a magnetometer to study the physical properties of the ice shell. Due to the intense radiation present on Europa's surface, all the instruments will be held within a protective vault, except the context remote sensing instrument, which will measure the radiation itself.

In addition to detecting life signs, the lander will also prepare the next stages in the robotic exploration of Europa, which might involve melt-probe drilling into the icy crust to analyze pockets of liquid water nestled just below the surface. This is of course a long-term vision, which will take many decades to complete.

The Europa Lander mission is still in its early proposal stages and hasn't been approved. Given its predicted high cost ($3 to $4 billion), which places it on the very top end of a flagship mission, it might actually never come to fruition. Indeed, NASA usually allocates resources to launch a flagship mission in planetary science only once a decade, and the Europa Lander will be directly competing with two highly rated mission proposals, a Mars' sample return mission, which has been set at the highest priority within the decadal surveys and might be composed of two to three flagship missions, and a Cassini-style mission to return to Uranus and its satellite system (Table 12.3).

Another recent concern for the proposed lander was a study published in 2018 suggesting that photopolarimeter observations made of Europa's surface could be explained by an extremely low-density surface, formed by layers of very fine-grained particles with void space greater than about 95%. Such a surface would be less dense than snow, which would see the craft sink. If this is the case, any in situ investigation of the moon's surface would be delayed for decades to come. It is worth noting, though, that these

Table 12.3 Large class missions suggested to NASA by the decadal survey of 2013–2022

Mission	Science objectives	Challenges
Mars Astrobiology Explorer – Cacher (MAX-C)	Perform in situ science on Mars samples to look for evidence of ancient life or prebiotic chemistry. Collect, document, and package samples for future collection and return to Earth	Keeping with MSL design constraints Sample handling, encapsulation and containerization Increased rover traverse speed over MSL and MER
Jupiter Europa Orbiter (JEO) – (author's note : now in development as the Europa Clipper)	Explore Europa to investigate its habitability	Radiation Mass Power Instruments
Uranus Orbiter and Probe (UOP)	Investigate the interior, scructure, atmosphere, and composition of Uranus Observe the Uranus satellite and ring system	Demanding entry probe mission Long life (15.4 years) for orbiter High magnetic cleanliness for orbiter System mass and power

photopolarimeter observations can only probe the outermost layer of the surface, which are less than a mere millimeter thick, leaving the rest of the ice below a mystery. The Europa Clipper will thankfully be able to address this point when it starts its observations of the moon in the next decade.

Enceladus, Titan, and the Others

Following the remarkable success of the Cassini-Huygens mission at the Saturnian system, which among many other things, discovered Titan's methane seas and Enceladus' plumes of salty water, there has been a strong desire to go back and investigate in greater detail these two fascinating moons. With no flagship mission to Saturn planned for the coming decades, any new missions sent there will have to be done within the framework of a medium-class mission: the New Frontiers program for NASA and the M-class mission for ESA.

These medium-size missions can travel far out within our Solar System yet do not require a large payload, as expected by flagship missions, thus keeping their budgets reasonable. It is no surprise then that numerous missions to visit Enceladus and Titan have been proposed under these programs. Out of these, three stand out: Enceladus Life Finder (ELF), Enceladus Life Signatures and Habitability (ELSAH), and the Explorer of Enceladus and Titan (E^2T).

The Enceladus Life Finder was simple in its design. It would orbit Saturn and make precise flybys through Enceladus' plumes in the hope of investigating them using two instruments, MASPEX (similar to the one that will be used for the Europa Clipper) and the Enceladus Icy Jet Analyzer (ENIJA), which is a variant of the SUDA instrument also being developed for the Europa Clipper. Both instruments would have been able to characterize the particles within the plumes and identify the organic materials embedded into them with the hope of spotting biosignatures. To keep the costs and complexity down, there would be no radar, no imager (no photos), and no magnetometer. As attractive as the simplicity of this proposition seemed, it was not selected as a finalist for the fourth New Frontiers mission.

The other proposal for the fourth New Frontiers mission was the Enceladus Life Signatures and Habitability (ELSAH), which included more complex onboard laboratory meant to collect microgram amounts of plume components and then use ultrasensitive biosensors to analyze the sample for biosignatures. Although the mission wasn't selected as a finalist, its principal investigator Chris McKay will receive additional funds from NASA to develop cost effective techniques that limit spacecraft contamination during its construction (to eliminate false positives), with the aim of placing it in a more favorable position for the next round of New Frontiers missions, planned to be selected four to five years from now.

The last proposal, the 'Explorer of Enceladus and Titan,' or E^2T, is aimed at the ESA M5 medium-class mission program, whose launch is scheduled for the 2029–2030 timeframe. As its name indicates, if selected, it would perform multiple flybys of Enceladus and Titan to allow in situ composition investigations and high-resolution imaging. Mass spectrometers would analyze Enceladus' plume and Titan's changing upper atmosphere, while infrared imaging would allow meter resolution measurements of the temperatures found within the fractures on Enceladus' south polar terrain. E^2T's stated goal is to study the origin and evolution of volatile-rich ocean worlds and explore the habitability and potential for life in ocean worlds. At the time of writing, ESA hasn't started the selection process for the M5 mission.

Due to the limitations inherent in space-bound missions where scientific instruments have to be miniaturized and be able to withstand extreme conditions, there has also been a proposal for a sample return mission targeting Europa's plume particles. Submitted in 2014, the Life Investigation For Enceladus (LIFE) mission looked into the use of aerogels to capture particles from the plume in the same way the Stardust mission did with cometary dust back in 2006, and bring them back to Earth, where they could then be studied by the world's best laboratories. Although the LIFE mission wasn't selected by NASA, proposals based on this configuration might be reconsidered in the future. A big unknown with such a mission, though, is the public's reaction once samples potentially containing the remains of frozen alien life forms land back on Earth.

In addition, the billionaire Yuri Milner has expressed interest in funding a life detection mission that would sample Enceladus' plume as part of the Breakthrough Initiatives. Designs for a low-cost mission are currently being studied, although no further information has been communicated so far.

Moving further away from Saturn, many planetary scientists want to return to Uranus and Neptune with a flagship program similar to the Cassini mission. In fact, visiting Uranus and its moons was listed as the third priority on the last decadal survey. If such a mission does occur, it will provide new insights into the possibility of ocean worlds orbiting this ice giant. Ariel immediately comes to mind as a likely candidate worthy of investigating (see Chapter 11 for further details). Visiting Neptune and its moon Triton (see Chapter 10) would also be worthy of a flagship mission.

In addition to sending space probes to visit the ocean world candidates, we should not forget that much can be gained from observing these objects through Earth and space-based telescopes. Indeed, the Hubble Space Telescope has already provided important observations of the Jovian and Saturnian moons, and very soon a new generation of giant telescopes on Earth will be operational, opening up the possibility of observing the hypothetical plumes of Europa or the plumes of Enceladus in greater detail. ESA's Extremely Large Telescope (39.3 m in diameter), the Thirty Meter Telescope (30 m in diameter), and the Giant Magellan Telescope (24 m in diameter) will dwarf the biggest telescopes currently operational, such as the Kecks (10 m in diameter) or the Very Large Telescope (8.2 m in diameter). In addition, NASA's soon to be launched James Webb Space Telescope will use its infrared capabilities to study the ocean worlds of our Solar System. An exciting decade of observations awaits us.

Ocean Worlds Program

Given the number of proposed missions to the ocean worlds being put forward, it might be tempting to believe that somehow, all this is being coordinated by scientists, engineers, budget administrators and lawmakers using a common strategy. Alas, the reality of space politics, the complexities in developing and launching a space mission, and the difficulties in getting a consensus within such a broad and varied group of people means that we currently don't have a clear roadmap in the investigation of the ocean worlds of our Solar System.

The lack of such a strategy is becoming evident within the communities involved, and there is now much talk on the need to establish a program similar to the Mars Exploration Program (MEP), which has been remarkably successful in exploring and characterizing the Red Planet since 1993. MEP has used space probes, orbiters, landers, and rovers in response to a set of clear goals and an overarching vision. There is much to gain from a similar approach for the ocean worlds, although an additional complication would be it being a multi-object program as opposed to visiting just one object, a planet in the case of MEP. Although it can be tempting to think of Europa or Enceladus as stand-alone objects, with missions being developed to visit them that are entirely independent of each other, encapsulating such missions within a comprehensive program makes more sense.

For a start, lessons learned from one set of missions can be applied to future missions elsewhere. A good example is the discovery and observations of Enceladus' plumes by the Cassini mission, which has influenced the development of the Europa Clipper. In addition, technologies and instruments can be developed and matured in accordance with the needs of the entire program (MASPEX or MMRTG are good examples).

Furthermore, due to the long journey times required to visit ocean worlds on medium-class missions – five years for Europa and ten years for Enceladus or Titan – it would make sense to plan the missions to prevent long gaps from occurring between each visit. Interleaving the missions will prevent the scientific community from waiting too long between new datasets – a data-starved scientific community isn't conducive for good science – and provides a more level funding profile, making it more stable in the long term.

Finally, a long-term vision would prevent short-term results from negatively impacting the level of engagement and funding the program requires. The disappointment of not finding any signs of life on one object would not shut off the program entirely but instead allow it to change its focus to the remaining objects. The need for such a strategy was made evident in the case of Mars, when the disappointing results of the Viking landers put a halt to NASA's ability to explore the Red Planet further. (See Chapter 3 for further insights on the Viking mission). It took almost 20 years for the agency to regain the momentum lost. During that time, a whole generation of Mars scientists was neglected.

Although an Ocean Worlds Program has not been officially implemented at NASA, there are hints that the agency is moving towards that line of thought. As seen earlier, it has already started to invest in technologies required for the exploration of the ocean worlds and has also opened up its New Frontiers program to allow for a complex mission to the outer planets, thus giving a chance for missions such as ELF and ELSAH to be proposed. Even more ambitious missions to the ocean worlds will hopefully be put forward in the fifth round of the New Frontiers program.

In the future, alternative technological solutions for the exploration of our Solar System might be studied by an Ocean Worlds Program. One such solution could be the launch of tiny microchips into space (similar to the Starshot initiative currently being studied by the Breakthrough initiatives). Sent in their hundreds or thousands, these microchips could quickly send back crucial scientific measurements on the outer planets' moons as well as distant objects like Eris, 2007 OR10 or even far away Sedna (see Chapter 11 for details on these objects).

The case for an Ocean World Program is strong, and we should remain hopeful that it will most likely see the light of day in the following decade.

The Search for Life and Final Thoughts

The last two decades in the exploration of our Solar System have been remarkable. Although the continued focus on the planet Mars has forced scientists to reduce their optimism of it as a habitable world, we have learned of multiple large moons where warm oceans of salty liquid water exist. Of these, the subsurface oceans of Europa and Enceladus hold the best prospect for carbon-based life to have arisen and are also, luckily for us, the most easily accessible thanks to the existence of plumes (most likely for Europa) as well as the presence of deep fissures and cracks within the icy crust.

As we have seen throughout this book, other ocean worlds populate our Solar System, yet for many of them, their oceans will most likely be rich in volatile compounds such as ammonia or methane, making it much more difficult for life to take hold. Also, tens of – if not more – ocean worlds similar to Pluto or Eris lie waiting to be discovered, suggesting that subsurface oceans might actually be a very common sight within our Solar System and not an exception.

Given the mission proposals to search for signs of life within ocean worlds, what if we do find out that life has taken hold in one of the subsurface oceans? The first line of evidence to inform us of the presence of life within the oceans of Europa or Enceladus (or on Mars for that matter) will be biomarkers, for example, patterns within the concentrations of amino acids or fatty acids indicative of life. Scientists will study a multitude of data points, conclude that something is decreasing the natural entropy within the system, and present this finding to the public.

As the excitement of the discovery lessens, we will need to come to terms with the fact that our understanding of the life we have just discovered will be extremely limited, given the seemingly insurmountable technological challenges required to explore the ocean habitats robotically (for example; melt probes, autonomous submarines capable of powering themselves for weeks, etc.).

In the meantime, people will carry on living their daily lives with the knowledge that one or multiple life forms exist under the icy crust of a moon or dwarf planet with little information about it. Will this knowledge fundamentally change humanity? Maybe, but maybe not.

Our modern popular culture is already sold on the idea that life exists elsewhere in space. At an early age, children are raised up in believing that extraterrestrial life exists, in the same way that Santa, dragons, and princesses do, as numerous storybooks involving aliens sit on the bottom shelves of most libraries. For older kids, it seems that a summer vacation isn't complete without seeing at least one alien-related blockbuster film at the cinema. In fact, some of the most popular films worldwide have extraterrestrials as their main characters: E.T., Star Trek, Aliens or Avatar, just to name a few. This is a thriving genre, which currently sees no end in sight due to its growing popularity. In a way, it is just a return to the historical norm, as in past times, most cultures shared stories of beings living on celestial objects.

On the other hand, from a scientific point of view, such a discovery will prove revolutionary. We will perform comparative studies of the biochemistry and ecology of the alien life. By assessing two biochemical systems capable of sustaining life, we will hopefully start to understand how life appeared on Earth and what universal features we share with alien life. For example, if the life forms on an ocean world are carbon-based, the combinational properties of the carbon molecule suggests that it will most likely use other carbon-based molecules to store its genetic data rather than DNA/RNA. Furthermore, higher level comparisons such as cell structure and organization will have the potential to provide fresh new perspectives on molecular biology and cellular biology, while the study of the alien ecosystem as a whole (by examining how alien organisms interact with their environment) and the processes that produce the diversity of the alien life will prove transformative for evolutionary biology.

One thing is sure, though, if the existence of extraterrestrial life within a subsurface ocean is confirmed, it will have important societal implications, as profound issues regarding our responsibility towards this alien life will be raised. We will most likely choose to abide by the same environmental ethics as we have done on Earth (with varying success) to demonstrate our commitment to enhancing the diversity of life. Currently, international rules for planetary protection exist to prevent scientific missions from contaminating an environment, so as to not jeopardize future biological explorations, not with the aim of protecting such ecosystems or the extraterrestrial organisms. Such legislation will need to change in the light of such discoveries.

Ultimately, we will come to realize that given our technological dominance, as we explore, expand, and someday, we hope, colonize the worlds that form our rich and diverse Solar System; we will have as much responsibility towards life within those worlds as we have towards life on our planet.

Appendix A: Mimas

With a radius of only 198 km, making it 20% smaller than Enceladus, Mimas is ridiculously tiny compared to most ocean world candidates. In fact, it is the smallest known object in our Solar System that is rounded in shape due to its own gravitation. Objects with smaller dimensions start to have potato shapes such as Hyperion (135-km radius) or are half-finished spheres such as Phoebe (106-km radius), both moons of Saturn as well. Mimas is mostly composed of water-ice and has a small rocky core, making it barely massive enough to have an entirely rounded shape, as Saturn's gravity stretches the tiny moon into a slightly egg-shaped ovoid. The diameter facing the planet is longer by 9% than the diameter perpendicular to its orbit (209 × 196 × 191 km).

Mimas is also a densely cratered moon with one side entirely disfigured by a giant impact crater named Herschel after the moon's discoverer. At 139 km across and 5 to 7 km deep, the crater walls rise a further 5 km high, it is one of the biggest craters relative to its parent body in the entire Solar System.

Before the Space Age, Mimas was just a speck of light. This all changed when *Pioneer 11* whizzed past the moon on July 31, 1979, at a distance of 104,263 km, and took an image as it was transiting in front of Saturn. Alas, the image was of poor quality, and planetary scientists had to wait a year later for *Voyager 1's* more capable imaging system to reveal Mimas as we know it now.

Furthermore, *Voyager 1* allowed scientists to accurately calculate Mimas' density at 1.15 g/cm^3, close to that of water, implying that the moon was mainly composed of water-ice contrary to other icy moons of Saturn, which also had a significant rocky core

B. Henin, *Exploring the Ocean Worlds of Our Solar System*, Astronomers' Universe, https://doi.org/10.1007/978-3-319-93476-1

like Enceladus, Tethys, Rhea, Dione, and Iapetus. Mimas was a very different type of moon altogether. Some refer to it as a giant snowball.

Nevertheless, scientists felt compelled to compare Mimas with Enceladus, given their relatively similar sizes and location. In addition, both moons are in resonance with another moon – Mimas with nearby Tethys and Enceladus with Dione – and both display eccentricities in their orbits, with Mimas' eccentricity at 0.0196, making it four times bigger than Enceladus' at 0.0047. This was a surprising find. According to a paper published in 1983, given the parameters above, "Mimas should currently be tidally heated at a rate at least twice that of Enceladus if Mimas' rigidity is like that of rock, and as much as 30 times if its rigidity is the same as Enceladus."

Nevertheless, Mimas shows no evidence of recent tectonic activity. Indeed, *Voyager 1* revealed the moon to be solidly frozen at a temperature of 64 K (–209 °C). This became known as the 'Mimas paradox' or 'Mimas test.' As much as Enceladus' surprisingly active geology required explanation, Mimas' inactivity was as compelling. Any theoretical models put forward to account for Enceladus' characteristics also had to do the same for Mimas and vice versa. This paradox proved to be frustratingly tricky for planetary scientists and would only be solved decades later, thanks to new data from the Cassini spacecraft.

Another surprise from the Voyager flyby was, of course, Hershel Crater. It is not unique within the middle-size icy satellites, as Tethys, Dione, Rhea, and Iapetus also host several large impact basins whose diameters are a substantial fraction of the satellite's diameter. (Enceladus is the odd one out here due to its younger surface.) However, Hershel is the most remarkable. At one-third of the moon's diameter, it is the largest in relation to the size of the moon. In some parts, it is 12 km deep and hosts a central peak which rises to 8 km in height. As craters go, this one is extremely deep.

What's more, large troughs similar to shock waves 10 km wide were found across the moon's surface, suggesting global-scale fractures created from the Hershel impact event. If the impactor had been a little bit bigger or come at a faster speed, it might have broken up the moon, which most likely would have ended up as one of Saturn's ring. With such upheaval and no signs of past or present geological activity, how could this small moon have been considered by some to host a subsurface ocean? Images from the Cassini orbiter would prove intriguing.

Observations from the Cassini orbiter during its 13 years within the Saturnian system gave a better picture of Mimas. For a start, Saturn's satellite and ring system were studied in far more detail than had been possible previously, and it was found that due to its position – and despite its low mass – tiny Mimas was responsible for the Cassini division, a 4800-km wide gap between Saturn's A and B rings. Actually, Mimas is locked in resonances with many objects or features within the Saturnian system, such as the Huygens gap, the G-ring, objects lying between the C and B ring, nearby moons Dione and Enceladus as well as with the larger moon Tethys (2:1 resonance) and the tiny moon Pandora located in the outer F Ring (2:3 resonance).

The precise measurements of all these complex interactions allowed scientists to finally resolve the Mimas paradox. Indeed, the moon's resonance with Tethys, which was initially thought to add tidal heating to Mimas (in a similar way Enceladus is in resonance with Dione), is a different type of resonance and isn't responsible for the tiny moon's eccentricity. Instead, the resonance both moons share is related to the inclination in their orbits, as these are tilted with respect to the orbital planes of Saturn's satellite system. As they orbit Saturn – Mimas orbits twice for each orbit of Tethys – they meet up not at the closest point of Mimas' orbit (periapsis) but instead at multiple locations throughout their orbits. As a result, Tethys doesn't pull Mimas into another orbit and is not responsible for the moon's eccentricity. In fact, when we take into account all the interactions Mimas has with the objects orbiting Saturn, we find no source for the moon's eccentricity, suggesting that it is most likely a leftover process, a fossil from earlier times, when the moons were in different orbits. (Saturn's spin would push the moons further away with time thus altering their orbits.) Recent simulations have shown that around 2 billion years ago, Mimas might have gone through a 2:3 resonance with Enceladus, generating much eccentricity that has decayed ever since.

In addition, the high-resolution images from the Cassini orbiter have also revealed that no surface was left intact by the intense bombardment Mimas experienced throughout the ages. With no internal processes to erode or erase them, the frozen surface has preserved the craters for billions of years. However, by carefully studying the surface craters, it was found that the south pole region hosts craters half the average size (ranging from 20 km in diameter or less), hinting at possible resurfacing processes at some point in the moon's life. (Coincidentally, Enceladus' most active region is also located at the south pole.) In support of such interpretation, the depth of the Herschel Crater and soft features observed on its rims indicates that it formed as a flexible, slushy surface, hinting that the moon's surface and interior might have been much warmer in the past, most likely due to greater orbital eccentricity.

As such, an increased eccentricity must have pumped heat into the moon, softening it and giving it its round shape. Some scientists have therefore speculated that it could have potentially been warm enough to allow its small icy interior to melt and form a small subsurface ocean.

Although Mimas' paltry size and lack of meaningful rocky core meant that it probably couldn't retain a subsurface ocean for long periods of time, this idea raised eyebrows among Cassini mission researchers, as a perplexing pattern in the moon's motion was discovered – Mimas was wobbling. Referred to as libration, this perceived oscillation motion might reveal what lies inside the moon. The properties of a raw and a hard-boiled egg are often used to explain this concept. If you place both eggs on the table and spin them, you will notice that the hard-boiled egg spins evenly and at a fast pace, while the raw egg will be slower and spin unevenly as the white and yolk slosh around inside.

By using images returned from Cassini, initial studies published in 2014 found that Mimas wobbles twice as much as predicted if it had a typical solid interior. The study concluded that this could only be explained by two possibilities: either Mimas contains a frozen interior with a non-spherical elongated core in the shape of a rugby ball or an American football, or it hosts a subsurface ocean (like the sloshed liquid inside a raw egg). Both possibilities have problems, though. Hosting a non-spherical core is not what would be expected from a planetary object billions of years old, as central cores relax into a spherical shape with time. On the other hand, the presumed existence of a subsurface ocean was puzzling as well, since the moon hasn't shown any substantial geological activity on its surface for billions of years, and its tiny size should make it impossible to retain heat for a significant period. The study showed that if a subsurface ocean was indeed present, it should lie within 24 to 31 km below the surface and be global. Although most planetary scientists remained skeptical about this study, some were hopeful that Mimas could be an ocean world candidate.

Alas, all this changed when a new paper published in February 2017 put a blow to the subsurface ocean theory. In this new study, it was calculated that the stresses on Mimas' icy crust induced by a subsurface ocean were much too strong and would produce over time large surface fractures within the crust. Since no fractures could be observed on the moon's surface, Mimas never hosted a subsurface ocean. Instead, the moon's libration was best explained by it possessing a small silicate core that initially started as a sphere but was later pushed askew by a strong impact (such as the one creating Herschel Crater), giving the moon such an asymmetric angular moment.

Given this latest research, it seems therefore that despite Mimas experiencing past tidal heating, a subsurface ocean has most likely never been formed. Future missions to Mimas will hopefully provide conclusive evidence that its libration is indeed induced by an ovoid core.

Appendix B: Relic Surface Oceans

Three Waterworlds

Although the main coverage in this book is of the subsurface oceans in our Solar System, there is a sense of perspective to be gained by reviewing planets that had surface oceans in their past.

As explained in Chapter 2, Earth, Mars, and Venus were bombarded by ice-rich bodies after their formation, allowing them to amass a substantial amount of water on their surfaces. Now, imagine these planets – actually no – imagine three waterworlds all bathed in deep blue oceans and ringed by billowing white clouds drifting high up in their atmospheres. On the first of these waterworlds, two continents rise above the water: Ishtar Terra and Aphrodite Terra. Although the latter is the largest, the former hosts the highest peak, towering 11 km above sea level.

On the second of these waterworlds, the northern hemisphere is entirely covered by water, while the southern hemisphere is a giant continent to itself containing a vast inland sea residing inside the most prominent crater on the planet, Hellas Basin.

And finally, the last of these waterworlds holds a vast ocean upon which a supercontinent lies, waiting to be partitioned in a not too distant future. Planetary scientists have proposed that roughly 500 million years after their formation, Venus, Mars, and Earth enjoyed similar if not identical environments for tens of millions of years, including vast oceans, surface temperatures above freezing, and a rich atmosphere.

Interestingly, there are tantalizing clues that life might have already appeared on Earth during this period (see Chapter 3). Could

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life have started on Venus and Mars as well? It is an intriguing thought. Cross-seeding might have occurred between the three planets through the process called panspermia. We might be Martians or Venusians.

But that was then. Nowadays oceans of water are not what one immediately pictures when we think of our neighboring planets. Venus blanketed with a thick atmosphere, suffers average surface temperatures of 735 K (462 °C or 863 F) and atmospheric pressures 92 times that of Earth's. Think of it as a planet-size pressure cooker, making the planet's surface one of the driest places in the Solar System.

Mars, on the other hand, is the opposite. Lacking a dense atmosphere, low pressures inhibit liquid water on the surface, as it will sublime directly into water vapor. Therefore, most of the planet's water is trapped in polar caps or underground ice. Venus' and Mars' primordial oceans changed with time. On Venus, the water moved into the atmosphere, while on Mars it went underground. Luckily for us, Earth had the right conditions to sustain its surface oceans for billions of years. What happened to our neighbors? Why did they lose their surface oceans? Let us review each one in detail.

Blue Mars

Mars is the most well-understood planet in our Solar System after our own. Although this isn't saying much, since there are still large gaps in our knowledge, it does illustrate how the second smallest planet in our Solar System has fascinated us ever since we looked up at the night sky. The figures speak for themselves; at the time of writing Mars had been visited by 55 spacecraft (taking into account all various flybys and gravity assists), making it the most visited object in our Solar System closely followed by Venus with 43 missions. Out of those 55 missions launched since the 1960s, only 25 succeeded in achieving their primary science goal (see Figs. 3.1 and 3.2 in Chapter 3).

The USSR and subsequently Russia holds the unenviable title for the most failed missions, with a total of 20 out of 22. Ironically, the only two Russian spacecraft that did manage to orbit Mars in the early 1970's did so while an unexpected dust storm raged on the entirety of the planet, rendering most images unusable.

Out of the successful missions, though, we've had twelve orbiters, three flybys, two gravity assists, four landers, and four rovers. NASA holds the lion's share by launching nineteen of these missions, ranging from its first flyby that lasted two days (July 14–15, 1965) to its longest-serving planetary robot, Opportunity, now active for more than fourteen years on the surface (as opposed to its original planned mission duration of only three months).

So what have all these robotic emissaries taught us about Mars' past? We now know that it was wet and remained so for a period. In 2015, NASA's Curiosity rover found evidence that Gale Crater had a long-lived lake. The amount of liquid water and the time this water stayed on the surface is still open for debate among planetary scientists, yet a consensus is slowly starting to emerge in the last few years. It now seems that Mars once had an ocean and maybe two. Let's review the evidence.

To start off with, due to the planet's small size, its interior cooled off rather quickly, which brought to a halt tectonic and volcanic activity. As a consequence, the planet's crust solidified early on in its history, contrary to our planet, which regularly resurfaces the crust every few hundred million years. Therefore, original surface features that were erased a long time ago from Earth's surface remain relatively unchanged on Mars, allowing us to travel back in time and analyze rocks and geological formations that are billions of years old, a rarity on Earth. Given this, you would expect that any claim of the existence of ancient oceans on Mars would be backed up by visible evidence of surface features such as shorelines, deltas, and channels feeding into these oceans as well as evidence of inland rivers generated by falling rain (part of the water cycle caused by a nearby ocean).

When the NASA Viking orbiters sent back detailed images of the planet's surface in the 1970's, some researchers thought they had detected ancient shorelines along the boundary between the northern and southern hemispheres. Not everyone was convinced, though, as the evidence was weak at best and subject to interpretation. Images returned from later orbiters weren't conclusive either, despite unprecedented imaging capability. Frustratingly, traces of ancient shorelines and sea cliffs just couldn't be visible despite new lines of evidence uncovered in the last fifteen years in support of the ocean hypothesis.

One such piece of evidence includes numerous regions within the northern hemisphere where scientists found remnants of deep channels carved by rain as well as the existence of lakes that must have lasted millions of years (similar to the one found in Gale Crater). Such features can only be explained if a large body of water was present for a significant amount of time to bring about the conditions required for cloud formation and rainfall. In addition, many ancient deltas were observed at an altitude where the shoreline was thought to be situated by the ocean hypothesis. These deltas, characteristic of a river entering slow-moving or standing water, suggest that this theoretical yet unseen shoreline remained stable for a long period.

In 2012, the European Space Agency published results collected by the Mars Express orbiter revealing a subsurface blanket of low-density material around the northern polar cap. Contrary to the southern hemisphere, which is comprised of hardened volcanic flows, the presence of low-density material in the northern hemisphere, potentially rocky material mixed with ice, suggests sedimentary material, tens of meters thick. This supports the idea that material was deposited on an ocean floor due to standing water.

What's more, in 2015, after six years of atmospheric observations, scientists found a high ratio of deuterium in the planet's atmosphere indicative that ancient Mars contained much higher water levels than it does today. As you might recall from Chapter 2, deuterium is the hydrogen isotope that forms heavy water molecules. In the past, as these molecules of water evaporated from the surface, they encountered lethal solar radiation high up in the atmosphere and got split in the process. The oxygen dissipated into space while the hydrogen isotope accumulated in the atmosphere, acting like a marker. Measuring its concentration in the current atmosphere not only reveals that water molecules were present in the planet's past but also allows us to extrapolate how much quantity there was. Indeed, since water on Earth and Mars started off with the same D/H ratio, we can measure the difference and calculate how much 'light water' was lost. And the figure is telling.

The concentration of deuterium in Mars' atmosphere is about eight times as much as on Earth. This points to a significant loss of water over time, with some models suggesting that Mars had enough water to cover the planet to a depth of 137 m. All this water must have accumulated in an ocean at the lowest point on the planet, the northern hemisphere. The reason for the disappearance of all this water is one of the areas that is still being researched, but it is commonly agreed that Mars' lack of a protective magnetic field prevented its nascent atmosphere from withstanding the continuous blows from the solar wind, stripping it away during millions of years. This, in turn, reduced the atmospheric pressure that led to the slow but inevitable evaporation of the surface water as well as a substantial drop in the temperature, forcing any remaining freezing water to stick to the ground.

Finally, recent discoveries have also shed new light on the paradox of the perplexing lack of clearly defined shorelines. Thanks to the resolution power of NASA's HiRISE; a powerful telescope orbiting the Red Planet, scientists discovered unique surface formations dotted along the boundary between the northern and southern hemispheres. On Earth, these features are mounds of deposited sediments and are called thumbprint terrain. It was previously thought that they were the result of glaciers or mud moving downhill from volcanoes, but it has now been shown to be a leftover feature of one or multiple tsunamis hitting the shorelines. Finding these thumbprint terrains on Mars has led some scientists to suggest that over 3 billion years ago a giant asteroid hit the planet in what was once the northern hemisphere ocean. An asteroid impact could create multiple tsunamis that would have plowed the coastline of the ancient ocean and buried its shorelines with large deposits. In support of such claim, it has been suggested that the impact site for such an event was Lomonosov Crater, a 120-km wide bowl in the northern hemisphere. Such a hypothesis not only provides further evidence for the existence of an ocean, as tsunamis require vast amounts of water to be created, but it would also finally explain why the ancient shorelines haven't been found.

More scientific data will be collected by future Martian missions, allowing scientists to characterize this possible ocean with much greater certainty and detail, as many questions remain to be answered, such as, was it icy cold and slushy or relatively warm? What was its composition? How did it alter through time? How did it interact with the atmosphere?

This very brief outline of the likelihood that an ancient surface ocean was present on the fourth planet from our Sun doesn't do justice to this fascinating subject. Many intriguing points could be explored (such as the possibility of finding, in the northern hemisphere, substantial amounts of water-ice hidden under a thin layer of dust, the leftover of the frozen ocean). On the other hand, some scientists are not convinced of the ocean hypothesis, as current models have a hard time sustaining an atmosphere capable of supporting a surface ocean for an extended period.

Even though our goal in this book is not to cover this topic in great depth, this brief overview showcases how a systematic and comprehensive exploration program of a planetary body can provide multiple lines of evidence that complement each other; it also highlights the vulnerability of surface oceans, which can be disrupted or even lost, if not by catastrophic events, then by the slow disappearance of a protective atmosphere.

In contrast, subsurface oceans can remain stable for billions of years, making them unique environments within our Solar System. Let's now visit the second planet to the sun, Venus, as it also has a story to tell, one that demonstrates the inherent difficulties of space exploration.

Blue Venus

Imagining an ocean of liquid water on Venus' surface seems ludicrous. Extremely high temperatures prevent any liquid water from lingering at its surface today, yet many scientists are now considering the possibility that the planet had a wetter past lasting for hundreds of millions of years, if not billions of years, even though finding the evidence to support such a hypothesis has to face two inescapable realities.

Firstly, due to the harsh conditions present on the surface, no spacecraft, lander, or rover will be capable of investigating the surface of Venus in a similar way that we have methodically explored Mars throughout the last decades. Although the engineering challenge would be welcomed by many, the astronomical cost of building and sending a robot capable of surviving the Venusian surface for extended periods of time would bring sleepless nights to any financial planners. There will never be a 'Venusian Opportunity rover' busy exploring the surface for more than ten years.

Regardless, such a mission is not required, as – and this is the second point – Venus has a very dynamic geology and experiences regular extensive volcanic activity that resurfaces its crust. In complete contradiction with Mars, which has its past out there in the open for anyone curious enough to investigate, Venus has erased all surface evidence of its distant past, leaving little hope for researchers eager to study such features.

So, if we can't see shorelines, deltas, channels, and sedimentary rocks, what makes scientists confident in their assertion that Venus was once a blue planet? The case for past Venusian oceans derives from our understanding of the formation of our Solar System. In effect, the way we appreciate the planet today has benefited from the comprehensive robotic exploration of the Solar System carried out in the last fifty years by the major space agencies. From studying asteroids, comets, and the inner planets, and establishing theories on how these bodies were formed, we have learned to uncover Venus' past.

In Chapter 2, we explored the idea that most inner planets were pounded by water-rich asteroids (and sometimes comets), and both Mars and Earth held vast amounts of water. Venus was no exception. The fact that it resides a bit closer to our Sun than Earth or Mars doesn't change the fact that it was also composed of the same stuff. Therefore, Venus also had deep oceans in the early part of its history. It was a blue planet.

Luckily, in those early years, our Sun was dimmer, according to the standard model, roughly 40% less bright than it is today. Therefore Venus received less heat from solar radiation, and models show that it could have sustained oceans on its surface for a very long time. For how long? We don't know. Maybe for a few hundreds of millions of years to a billion years. Once our star started to increase its energy output, more sunlight hit Venus' thick atmosphere, trapping an increasing amount of heat, warming it up.

This started an evaporation process that sent huge amounts of water vapor into the atmosphere. With no magnetic field present on Venus, ultraviolet radiation from our Sun collided with the water molecules high up in the atmosphere and broke them apart, resulting in the oxygen molecules being leaked out into space. Little by little, Venusian oceans evaporated into the atmosphere, and some parts were blown away into space. Luckily for us, this process has left a trace in Venus' atmosphere, and we have been able to measure the deuterium ratio, as we have done on Mars. Scientists have found a high D/H ratio within Venus' atmosphere today, a clear indicator that the planet had a much wetter past capable of supporting oceans. More robotic exploration is required if we want to unveil Venus' relic ocean.

Once again, the topic of past Venusian oceans is an intriguing one, worth more than the few pages presented here. Although much remains elusive, it does show once again the vulnerability of bodies of water on the surface of a planetary body.

Conversion Tables

Temperature scales		
Kelvin (K)	**Celsius (°C)**	**Fahrenheit (°F)**
0	−273	−460
173	−100	−148
233	−40	−40
253	−20	−4
255	−18	0
273	0	32
293	20	68
310	37	99
373	100	212
423	150	302
473	200	392
773	500	932
1273	1000	1832
2273	2000	3632

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Distance scales

Kilometers	**Miles**
1	0.6
50	31.1
100	62.1
150	93.2
200	124.3
250	155.3
300	186.4
350	217.5
400	248.5
450	279.6
500	310.7
650	403.9
700	435.0
750	466.0
800	497.1
850	528.2
900	559.2
950	590.3
1,000	621.4
1,100	683.5
1,200	745.6
1,300	807.8
1,400	869.9
1,500	932.1
2,000	1,242.7
3,000	1,864.1
4,000	2,485.5
5,000	3,106.9
10,000	6,213.7

Astronomical unit	
AU	**Kilometers**
1	15,00,00,000
2	30,00,00,000
3	45,00,00,000
4	60,00,00,000
5	75,00,00,000
10	1,50,00,00,000
15	2,25,00,00,000
20	3,00,00,00,000
30	4,50,00,00,000
40	6,00,00,00,000
50	7,50,00,00,000
100	15,00,00,00,000

Glossary

Albedo (meaning "whiteness") The measure of the solar radiation reflected back from a planetary object.

Archaea One of the three great domains in life (bacteria and eukaryotes are the other two), these simple life-forms lack a nucleus to store their DNA. Archaeans include inhabitants of some of the most extreme environments on the planet and may be the only organisms that can live in extreme habitats such as thermal vents.

Astrobiology The study of the origin, evolution, distribution, and future of life in the universe. It lies at the interface between biological sciences and planetary sciences.

Bacteria One of the three great domains in life (archaea and eukaryotes are the other two), these simple life-forms lack a nucleus to store their DNA.

Biosignature Any phenomenon produced by life.

Core The planetary core consists of the innermost layer(s) of a planetary object and may be composed of solid or liquid matter.

Crust The outermost solid shell of a planetary object. It is usually distinguished from the underlying mantle by its chemical makeup; however, in the case of icy satellites or dwarf planets, it may be recognized based on its phase (solid crust vs. liquid mantle).

Differentiation The transformation of a homogenous body into a heterogeneous body. If a planetary body is large enough it will develop a core, mantle, and crust, each of which may be further subdivided. Each layer of Earth has its own set of subdivisions, for example upper, middle, and lower crust.

Eccentricity The orbital eccentricity of an astronomical object is a parameter that determines the amount by which its orbit around another body deviates from a perfect circle. A value of 0 is a circular orbit, values between 0 and 1 form an elliptical orbit, 1 is a parabolic escape orbit, and greater than 1 is a hyperbola.

Extremophile Any organism (particularly microorganisms) that inhabit extremes of chemical or physical conditions.

Frost line (Snow line or ice line) location in our Solar System where it is cold enough for volatile compounds such as water, ammonia, methane, carbon dioxide, and carbon monoxide to condense into solid ice grains.

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Habitability The potential of a planetary body to have habitable environments hospitable to life, or its ability to generate life endogenously.

HP ice or high-pressure ices: As water-ice (1 h at P = 1 atm) is compressed at low temperatures, it undergoes a series of phase transitions between different molecular structures.

Hydrothermal vents Sources of hot, mineral-rich waters located in fractures on deep-ocean submarine ridges. One of the candidates for the emergence of life on Earth.

Late heavy bombardment (LHB) A period from around 4 to 3.8 billion years ago when intense comet and asteroid bombardment occurred.

Mantle The layer between the crust and the outer core. It is often divided into layers of different composition.

Ocean world A planetary object that hosts a subsurface ocean of liquid water (and other non-water components).

Organic chemistry The study of the carbon-based structures, properties, and reactions of matter in its various forms.

Panspermia The theory that life on Earth originated from microorganisms or chemical precursors of life present in outer space and able to initiate life on reaching a suitable environment.

Peroxides Any class of compounds in which two oxygen atoms are linked together by a single covalent bond.

Photochemistry The study of chemical processes that occur because of the absorption of light.

Planetary body A term used to describe planets, satellites, and asteroids.

Planetary protection The prevention of the contamination of other planetary bodies or the contamination of Earth with extraterrestrial organisms.

Serpentinization An exothermic chemical reaction between rocks (rich in magnesium and iron) and water, giving rise to strongly alkaline fluids saturated in hydrogen gas.

Spectra (Pl. of *spectrum*) The full range of all frequencies of electromagnetic radiation.

Subsurface ocean A large body of liquid water lying underneath an icy crust or mantle of a planetary object (mainly in icy satellites or dwarf planets).

Tidal heating Orbital energy dissipated as heat in either a surface ocean or the interior of a planet or satellite.

TNO (Trans-Neptunian Object) Any planetary body in the Solar System that orbits the Sun at a greater average distance (semi-major axis) than Neptune, 30 astronomical units (AU). This includes the Kuiper Belt and the scattered disc.

Tholin Brownish-red substances made of complex organic compounds.

Volatiles Elements or compounds that melt or boil at relatively low temperatures. Examples include hydrogen, helium, methane, and water.

For Further Reading

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