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This book is dedicated to our fathers, Patrick Colin Carroll
and Walmir Crocce Lopes, who still inspire us to reach for the stars.

Foreword

As I stared out the nine-inch-thick viewport at the unnaturally flat and unblemished plain, I was struck by the sheer remoteness of this place. It was as far from the human world of air and sunlight as one could get, without leaving our planet completely. I had left the warm surface waters of the Pacific, south west of Guam, and journeyed almost 7 miles straight down, into the depths of the Challenger Deep, the deepest place in our world's oceans. After free falling through blackness for two and a half hours, I arrived at this austere, lunar plain —the flat "ponded sediments" at the center of the trench's floor. My vehicle, the Deepsea Challenger, landed in a cloud of silt blown up by its thrusters like a spacecraft settling on the surface of an alien world. And indeed it was an inner-space ship, designed to explore the deepest and remote places in the Earth's oceans. It was functioning well as I took my first sediment sample and began to explore horizontally in a transect to the north, across the seafloor.

But something was bothering me. I had come all this way, not just the vertical 7 miles, but the years of design and construction of the sub, and the months at sea diving deeper and deeper as we refined our hardware and honed our skills prior to this ultimate dive. And now that I was here, I was viewing the world just outside my tiny steel sphere through the eyes of multiple HD cameras. But not with my own eyes. So I unshipped the 5K camera mounted in the viewport, and laboriously moved all the gear, the joysticks, and scrubber canisters and bags of warm clothing that were packed in around me. I moved forward, ducking under the HD monitors and bending painfully so that I could look out the viewport with my own eyes—to bear witness to this landscape that had never known the eyes or lights of Man. Ah, I thought, I'm really here. My breath caught in my throat at the realization of where I was, of how many tens of thousands of feet of water lay above my head, separating me from my wife, my children, the world I knew. I felt a sudden sense of loneliness, of disconnection from my kind and the world I knew. And with that followed the thrill that comes with being in a new and strange place, and knowing that no one else, of the seven billion on our world, had been here before. This is what some future astronaut will feel, looking out across the plains of Mars, the ice of Europa, or the hydrocarbon seas of Titan, having journeyed far to be the witnessing eyes for humanity.

As I stared at that stygian plain, I felt a sense of the vastness of time and space. There was a strong feeling of Deep Time here, of slow tectonic processes grinding relentlessly on through the eons, unwitnessed. It was a place seemingly hostile to life, as there was not a single animal large enough to see, nor even the tracks of creatures who might have wandered blindly across the sediment in decades or centuries past. I had never seen this, despite having dived over 80 times to abyssal depths. There were always at least tracks, if not animals themselves, plying their humble trade on the seafloor ooze. But here—nothing.

I knew intellectually that many species of pressure-adapted bacteria lived in the sediment, hopefully some new to science that would be revealed by the core sample I had just taken. But the impression of being *beyond life* was profound. I felt I was in an extreme place, a place I didn't belong. On prior expeditions, I had seen the seemingly infinite adaptability of life. I'd seen millions of blind albino shrimp swimming inches from geysers of water hot enough to melt lead, swarming happily through clouds of deadly hydrogen sulfide, and in fact living off of those toxic chemicals. I'd seen the scarlet fronds of tube worms six-feet long, swaying in the hot boil from hydrothermal vents while, inside them, long sacks of bacteria made their food for them. I'd seen giant mushroom caps 7 m across formed by the interaction of minerals and bacteria, with upside-down lakes of hot water on their undersides, the terraced pools shimmering like mercury. Nature's imagination is so much richer than our own, and life's ability to adapt is seemingly boundless. But here, on this darkling plain, I felt that life had found a limit. And maybe that's what I was there to witness.

I was struck by the enormity of what we don't know. How limited the headlights of our inquiry are, and how vast the darkness beyond the edge of those lights. Even in this "post-exploration age" on planet Earth, a time when Google Maps allows one to access satellite images of any place on the land surface of our world, there are still so many unseen places, in the depths of the hadal trenches, that all combined they would equal the area of Australia. An unexplored continent waiting down there.

And that is just in the oceans of our own world. What about the oceans of other worlds? Our robotic emissaries have brought us just enough tantalizing information to scientifically imagine those alien seas. And so our minds can voyage there now, but it will be many years before humans can physically venture to those remote shores and bear witness, bringing back the tale of their experience for the rest of us. In the intervening decades, our robotic avatars will send us more pictures and data, perhaps even bring back samples, and that will have to satisfy our relentless monkey curiosity. But eventually, we will have to set foot on those worlds ourselves. Men and women, their breath catching in their throats at the enormity of where they are standing and what they are seeing, must go to those alien shores and push back the boundaries of the unknown.

Imagine standing on the shore of a cryogenic ocean of methane under the dusky orange sky of Titan. Perhaps a hint of the parent planet Saturn, with its ring system blazing diamond-bright in the sunlight, will be visible through a gap in the clouds. A more beautiful, serene, and utterly alien place is hard to conceive.

Imagine standing on the ice of Europa (in your massive radiation-proof hard-suit) as Jupiter's baleful countenance glowers down from above. Water boils up through fissures in the ice nearby, water that might contain life energized by chemosynthesis in the ocean far below.

Imagine standing next to a cryo-volcano on Enceladus, as the ethereal plume of ice crystals towers above you 200 km into the black sky, drifting across the untwinkling stars like ectoplasm. A fairy dust of snow falls around you, sparkling on a plain of ice so cold it's harder than steel. Like an ant next to Old Faithful, you are dwarfed by a manifestation of power and beauty that has gone unwitnessed until your arrival. Now you will bring the images back, halfway across the solar system, for the rest of us.

Imagine standing on the ancient shoreline of the boreal ocean of Mars, leaving bootprints in the dust where the long-vanished surface water once lapped a rocky beach. Was there life in this ocean as well, adapted to the dense brine? Did some creature leave its tracks on this wet sand as it ventured out, bravely, onto that doomed land? Or were those ancient shores trackless and sterile? Is Earth, alone, the only living world? Is there a limit to life? The only way to know is to go.

This book will take you, with words and stunning images, on a voyage of the mind. You will journey far from our blue planet, to the alien seas we now know exist, or once existed, out there on the planets and moons of the solar system. Just as the ocean of our own world mesmerizes us, drawing us to its shores, or to venture forth upon its treacherously fickle surface, and even far beneath it, these alien oceans will compel us to explore and understand them. Their beauty beckons and their danger challenges us. Voyage now, in the pages of this book, just as we will voyage later, with our machine eyes and, someday, our own.

James Cameron

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Our thanks to Springer editor Maury Solomon, who first saw the potential for this subject and then patiently helped us navigate it to safe harbor. Thanks to Alan Gould for Kepler data and concepts. Our appreciation to NSF, the Mount Erebus Volcano Observatory, and Jeffrey Johnson for the spectacular shots of extremophile-infested ice towers. Dale Andersen of the Carl Sagan Center for the Study of Life in the Universe (SETI Institute) supplied us with some very gooey algal mats. Thanks, too, to all the wonderful artists who shared their visions of cosmic seas in our gallery at the back of the book.

Contents

Introduction: Oceans on Earth and Elsewhere

1

Michael Carroll

Samuel Taylor Coleridge's ancient mariner lamented, "Water, water, everywhere, nor any drop to drink." Today, it seems that planetary scientists are faced with the same situation. Drinking aside, the prospect of oceanic planets and moons scattered across the cosmos is brighter than ever. During its first 3 years of operation, NASA's planet-hunting Kepler spacecraft tracked down somewhere in the neighborhood of 100 planet candidates that appear to be in the "habitable zone" around their parent stars. In other words, these planets, or moons circling planets in the case of giant planets, have the capacity to support liquid water on their surfaces.

With some 2,300 candidate planets beyond our own solar system, and counting, these pages cannot hope to cover all that cosmic territory. But seas in many forms await our studies within our home planetary system. There are oceans of water beyond the Earth, below the icy crusts of satellites in the outer solar system. Surface oceans probably existed on Mars in the past, and perhaps on Venus as well. Saturn's planet-sized moon Titan hosts respectable seas of liquid methane or ethane. Truly alien oceans of liquid metallic hydrogen slosh at the heart of outer planets, while seas of sand cast gritty tides across frozen landscapes of ice and rock in other places.

A Short History

Oceans have played an important role in humanity's story, and it's been a tumultuous relationship. Ancient peoples often feared the briny unknown. Many ancients believed that a mysterious, monster-filled ocean surrounded the world. Most ships built in the fertile crescent were not safe on the open seas, as they were designed for travel on rivers or across floodplains. Roman law simply forbade sea travel between November 10 and March 10, as the period was considered too risky. As vessels became more seaworthy and explorers began to venture further into the great oceans, their maps reflected their unease with labels like "Thar Be Dragons" and "Zona Incognita".

Nevertheless, early explorers ventured great distances into the unknown. Asian populations spread through Polynesia and Micronesia. The Vikings set up shop in Iceland and visited several sites in North America. It is possible that many early humans migrated from Siberia to the western hemisphere traveling by small boats, staying close to shore. Some 1,600 years before Christ, the Minoans set sail across the Mediterranean in the largest flotilla of the ancient world, waging war not with weapons but with economics and trade. In fact, ancient Egyptian texts—typically disdainful of foreigners—assigned the Minoans the respectful label "the Sea Peoples".

Though they may at times be terrifying, the Earth's oceans are crucial to life and are thought to be where primitive life originated. The oceans have a profound influence on climate, enabling life to exist in some regions, while sometimes causing havoc in others. Oceanic currents transfer heat from the tropics to polar regions, helping to drive our weather. Changes in currents, such as the famous El Nino effect, cause seasonal shifts in wind, rain and temperature patterns globally. Our oceans play a critical role in climate stability and in the carbon cycle, providing an interface between atmosphere and surface.

But what of seas in the sky? What about seas on the orbs floating in those fuzzy telescopic views? Even through the eyepiece, the Moon's dark plains looked like bays, ponds and seas. Hence, many are named Maria (sea), Lacus (lake), Palus (marsh), and Sinus (bay). Jules Verne sent his cannon-shell-riding passengers around the far side of the Moon while it was in darkness, conveniently. When meteors briefly lit the landscape below, they got a tantalizing glimpse. Could they see rivers? Forested hillsides? Seas? Nearly a century later, Ray Bradbury gave us his chess-piece civilizations in the Martian Chronicles, where we saw a Mars with wine-colored canals and slumbering fossil seas.

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Science Leaps In

Early astronomers added their voices to the literary crowd. The first telescopic observations of Venus frustrated efforts to determine its length of day or the nature of its landscape; what became obvious was that the world was covered in hazes and clouds. Venus is the closest planet to the Earth, and virtually identical in size, leading some observers to guess that the Venusian landscape might be Earthlike: swamp-covered or blanketed in oceans of carbonated water, a planetary Perrier source. Spacecraft laid waste to this Venus version, but have provided some evidence of possible ancient oceans.

While some astronomers looked sunward toward Venus, others cast their gaze outward, in the direction of Mars. Antoniadi, Schiaparelli, and a host of others saw the Martian resemblance to Earth right away. They clocked its days at about 24 h and 40 min. They found a season-producing axial tilt similar to our own, and noted the ebb and flow of its polar ices. Meticulously, observers mapped the "wave of darkening" spreading across the mysterious web of shapes draping the face of the red planet. Rich Bostonian diplomat Percival Lowell set up his own observatory to study the strange world, crafting intricate, canal-filled maps. Reasoning that Mars' apparently straight lines seemed more artificial than natural, Lowell proposed that these dark canals sprang from an artificial source, engineered by what he postulated as a dying, advanced race holding on the last vestiges of long-dead seas. Early observers also guessed that the outer planets might be oceanic, great globes of liquid sloshing under bands of clouds. They were surprisingly close to the truth.

Alien Seas

Alien Seas explores the wonders of distant seas across our solar system. Late-breaking research brings us vistas of seascapes that no one even dreamed of until a few decades ago. Armed with spacecraft data, advanced ground observation tools, and powerful new computer models, researchers are revealing strange, new worlds brimming with truly alien seas.

In our first chapter, NASA astrobiologist David Grinspoon introduces us to the alien seas that may once have lapped against the shores of ancient Venus. In Chap. 2, JPL's Timothy Parker takes us to Mars, where past epochs have left the fingerprints of flood plains, river valleys, and perhaps telltale evidence of beaches lining vast oceans of acidic water. JPL volcanologist Rosaly Lopes takes us farther back in time, where we witness pelagic expanses of lava that covered planets and moons in their formative years. In Chap. 4, more familiar seas of water may meet us within three moons of Jupiter. Robert Pappalardo, also from JPL, tours Europa, Ganymede and Callisto. The Southwest Research Institute's John Spencer delves into the oceans of ice and water blanketing the outer moons, with a focus on Saturn's dramatic erupting satellite Enceladus. Jani Radebaugh of Brigham Young University journeys to a different kind of ocean: seas of sand. Her sixth chapter provides an overview of the bizarre dunes on Venus, Mars and Titan. Titan is also blessed with seas of liquid ethane, as JPL's Karl L. Mitchell shows us in Chap. 7. Kevin Baines (JPL/ University of Wisconsin-Madison) and chemist Mona Delitsky (California Specialty Engineering) team up to go deep in Chap. 8, investigating the hearts of the gas and ice giants, where dense air becomes alien oceans of liquid metallic gases. NASA/Ames' astrobiologist Chris McKay takes a look at Earth's exotic life, and how it might shed light on the possibilities of life in distant oceans. Finally, astrophysicist Jeffrey Bennett rounds out our cosmic sea inventory by honing in on exoplanets near and far, where familiar seas may lap the shores of moons circling gas giants orbiting close to their suns. Join us as we explore alien seas!

Chasing the Lost Oceans of Venus

2

David Grinspoon

Is it deranged to build a good part of a career studying something that may or may not have been? I study the oceans of Venus. Maybe it's the scientific equivalent of an artist who emphasizes negative space—focusing on something that is believed to have existed but is no longer there. And yet I believe. True confession: I've even dreamed about them (Fig. 2.1).

I imagine them timeless, vast and deep, covering most of the planet except where mountains—conical volcanoes and steep rims of giant craters—jut skyward. I picture foaming waves lapping the eroding shores of those scattered highlands, blowing in warm breezes, sometimes raging into terrible storms but completely untroubled by tides.

There's no moon to raise the tides and perhaps no early trauma of a moon-forming collision,[1] without which—all else being equal[2]—Venus may have retained more water but left more of it buried in its less-distressed mantle.

Call me crazy. I've studied them my whole adult life and yet I've never seen them. Maybe I'm better off than a particle physicist who spends her life chasing some strange, charmed anti-gluon that turns out to not even have been a good idea. Or perhaps not much more pathetic than a geophysicist who focuses on Earth's core that nobody has ever seen except in a couple of Hollywood mistakes. But, at least indirectly, we know the core is there. It gives its lurking presence away, like a fetus in the womb, in the attenuation patterns of seismic waves, which allow us to see the core. We can sense its presence indirectly in the Earth's gravitational and magnetic fields.

I would argue that in a similarly indirect sense we can also sense the oceans of Venus. Only it's worse because they are long gone, like the scientists on all those tissue-sample TV shows, we are seeking forensic evidence that is mostly vanished from the scene (Fig. 2.2).

I have friends who study extinct creatures or disappeared civilizations, but they can go and dig up evidence without risking instant death in 900° superpressurized air. In fact we simply can't go look for ourselves[3] so we have to send machines, and we haven't been able to send very many, though not for lack of trying.

So we don't yet know, but in the meantime we've been able to gather some pretty strong circumstantial evidence. The data are still loose enough to allow for a contrarian "Venus was always dry" opinion, but most scientists who have looked at all the evidence and how it fits into what we've learned about the entire solar system believe that almost surely Venus started out as a watery, more Earthlike place—a planet with warm, liquid water oceans (Fig. 2.3).

What were they like? I see them alternately dappled with sunlight and dulled with thick cloud. When the sun does break through it is much closer than on Earth and therefore looks huge, twice as large as what we are used to. But it is also unnaturally pale as the young sun was markedly dimmer. When the clouds scatter, the full sun is 40 % less bright than what we see on Earth today.

That dim Sun[4] is the reason why young Venus, despite her proximity to our star, should have been able to host oceans for eons. Stars like ours start out cooler. As they age, they fuse Hydrogen into Helium, and they gradually brighten. At some point, and we don't yet know when, the warming sun crossed a threshold so that Venus could no longer hold her oceans. More sunlight heated the surface waters, causing evaporation, which fed water vapor into the air. Water vapor is itself a strong "greenhouse gas", so this caused young Venus to heat up further, which caused still more evaporation, and so on. Evaporation causes more greenhouse heating causes more evaporation. A positive feedback. Thus was initiated the runaway greenhouse.

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[1] Or maybe several big hits that, when the plasma and dust cleared, cancelled out and left her spinning retrograde and slow.

[2] Was it? Give me 5 billion dollars and 10 years, then ask me again…

[3] For now.

[4] No not a typo for a Chinese brunch treat.

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Fig. 2.1 A primordial ocean washes across a battered crater rim, as volcanoes in the distance strive to dominate what will eventually become their realm. Any early seas on Venus would have eventually become acidic, boiling into a carbon dioxide sky. The continent of Ishtar Terra rises at left (Painting ©Michael Carroll)

Runaway here refers to the fact that such a feedback loop is unstoppable. Once it started, the fate of those oceans would have been sealed. But it also applies in its other sense, for those oceans did run away—left home for good. When in the form of an ocean, water is gathered tight to a planet and largely protected from solar radiation. But once it enters the air as steam it is vulnerable to the sun's ultraviolet, and the H_2O is split.

The hydrogen drifts off into space and the oxygen chases after it or stays behind to react with minerals, forming rusty rocks and leaving Venus an empty nest, permanently stripped of its potentially life-giving waters.

We don't know when this departure occurred, or how long it took, but we're pretty sure it did happen. Today Venus is drier than Arizona in June. Much. It is ridiculously parched. The tiny trace of water vapor left in the air is about 100,000 times less than the water found on Earth's surface. (although we don't know how much water is trapped inside Earth's interior and even less about any water trapped inside Venus…)

And we see convincing evidence of the watery exodus: like the shoes of refugees forced to leave in a hurry, we see the signs of a thorough evacuation of hydrogen which left behind a strong residue of deuterium—the more massive variant of hydrogen which has a harder time packing up and leaving. The huge build-up of this heavy hydrogen tells us that most of the water has escaped. Not when, or how much, just most.

The loss of water completed an irreversible and dramatic shift in climate. Do not let this happen to your planet! Rocky water worlds like Earth have a built-in thermostat that regulates climate over the long run, keeping it in the range of liquid water (which we carbon-in-water creatures pretty much demand as a minimum condition of residency). If it gets too cold then volcanic CO_2 builds up in the atmosphere, eventually warming the planet. If it gets too hot then the rate at which water dissolves CO_2 and "weathers" silicate rock into carbonate rock increases, drawing down the CO_2 content and cooling the planet. This mechanism has worked over the ages to keep Earth's climate more or less in line. It probably functioned on Early Venus as well. But once the last surface water was lost to the brightening sun, there was no efficient way to make carbonate rocks swiftly enough to counter the runaway warming. At this point the thermostat of Venus broke completely and the thermometer pegged in the red zone- where it has remained ever since (Fig. 2.4).

There are other reasons to believe in the lost seas. Aside from the hydrogenous evidence of mass escape there is our growing understanding of how the planets were made and what the planets were like near the beginning. Many lines of evidence conspire to suggest that Venus and Earth were formed much more alike and evolved in different directions. At times we have entertained theories suggesting that Venus and Earth formed very differently, that somehow materials in the planet-forming nebula segregated themselves and Earth ended up with 100,000 times as much water. But we now understand that planet formation was a violent and random process. The planets accreted in a gathering of material from small to large- from dust to pebbles to boulders and finally

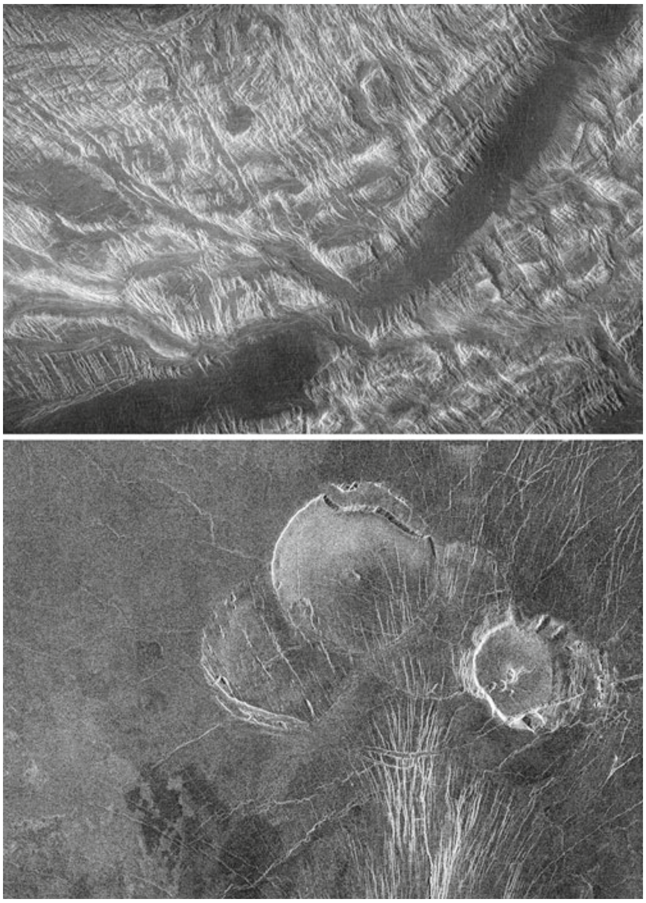

Fig. 2.2 The restless surface of Venus has obliterated geological records of ancient seas. (*top*) Tectonic faults and uplifted crust blanket Ovda Regio, whose surface may be only a few 100 millions years old geologically. (*below*) Volcanic mountains, lava flows, and associated fractures cover nearly 90 % of the Venusian surface (Magellan photos courtesy NASA/JPL)

1,000 mile planetesimals smashed together to make planets. As the planet chunks grew larger, so did the force of their gravitational attraction to each other. This made the final phases chaotic indeed. Collisions were fast and furious and the even more frequent near-misses flung near-planets into wild orbits, setting them up for further collisions or for getting tossed out to the nether regions of the solar system.

It was a hot mess; everything was smashed, melted, vaporized, steamed, churned and mixed together, over and over again. It seems likely that the materials that composed the inner planets were fairly well mixed. In order to somehow form Venus so much drier than Earth they would have to be extremely, absurdly, well unmixed.

You can even, if you'll indulge me, look at it in thermodynamic terms. Say what? I mean in terms of entropy- you know, the second law: it all runs downhill—no matter how many times you clean your room you'll have to do it again. Nature mixes things together. It doesn't randomly make dramatic differences between neighboring spaces- it erases them. So unless some tremendously efficient process dried Venus out completely then it must have started with more water, perhaps even an Earth's oceans worth of water- perhaps ten times this much.

We have also learned that water is common in the solar system (in the whole universe, actually). In most places it's not liquid but any reasonable source material for Earth would have been water-rich—some combination of rocky stuff with water chemically bound in hydrous minerals or icy interlopers from the outer solar system. We also see plenty of signs that Mars, our other neighbor, started out drenched in water, though he too had trouble holding it for different reasons. The planets started out wet, and they were drenched by the same scattershot rain of planet pieces.

So, yes, I don't think I'm delusional, but I do believe in the lost oceans of Venus. And believing is seeing. I see them filling the lowland basins on either side of the great continent-sized upland of Aphrodite Terra. This, I admit is complete fantasy as it doesn't seem likely that Venus has maintained her shape over the billions of years it might have been since she lost her oceanic look. Look at Earth- mountain ranges come and go, riding the slow currents of plate tectonics, moved by the churning heat engine of Earth's interior. In fact it seems quite possible that it is Earth's oceans that enable plate tectonics on Earth. Absent their lubricating effect on crustal motions and mantle flows, Earth's smooth interior engine might seize up. Some model results suggest that if you dry out Earth to Venusian extremes then instead of plate tectonics you get a more constipated type of behavior with bursts of tectonic and volcanic activity separated by 100s of millions of years of relative inactivity. But either way, it seems that Venus has to lose as much heat as Earth and thus, over the long term, probably moves around. We can tell approximately how old the Venusian surface is by counting the craters left from random asteroid and comet impacts. The surface averages less than 1 billion years. The older craters have been covered up by volcanic flows or broken up by Venus-quakes. So what are the chances that the same places where we find highlands and lowlands were the oceans and continents of a Venusian water-world? That depends on how recently Venus could have lost its water. For those of us studying the history of Venus and trying to place our lost oceans accurately in this chronology, the timescales are vexing. We have a pretty good story of how Venus went from ocean to steam, lost hydrogen to space and ended up permanently stuck in a horribly hot and dry condition. But whether the last trickle of water there flowed more than 3 billion years ago, or only a billion years, depends on factors that we still have trouble estimating, like how cloudy the early atmosphere was. We need more data, and better models, to know exactly when the oceans were lost (Fig. 2.5).

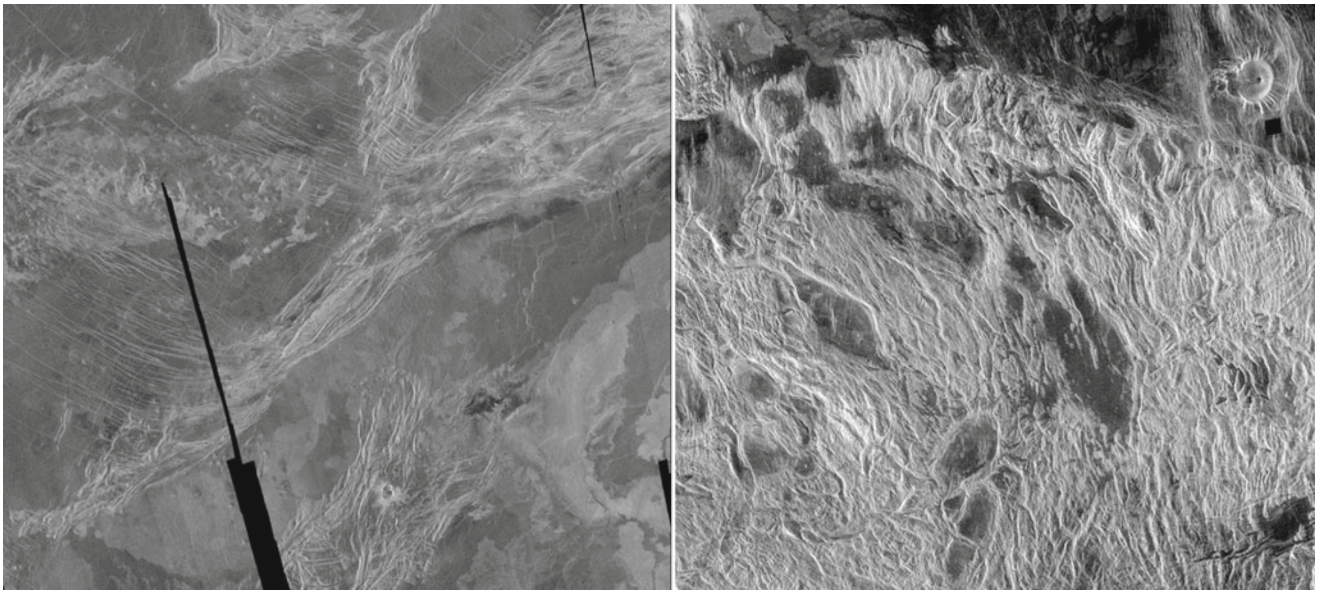

Fig. 2.3 Infrared studies of Venus' highland plateaus have detected the kind of heat signature often associated with granite. Granitic rock on Earth forms in the presence of plate tectonics and oceans. *Left*: Ridges and lava flows cut across Lavinia Regio. *Right*: The highland area Alpha Regio is 1,300 km across (Courtesy NASA/JPL/Magellan project)

Fig. 2.4 Some researchers suggest that Venus has always been a desert world. Today, Venus is thousands of times drier than the most parched regions of Earth (© Michael Carroll)

And, by the way, in my vision those seas are teeming with life?[5] No, seriously—why not? There is a lot we still don't know about the origin of life on Earth but it happened quickly once the remnants from planetary formation ended their deathly pummeling of the planets around 4 billion years ago. This suggests that it might have happened easily or inevitably on planets with the right conditions. Everything we suspect about what those right conditions probably also existed at the same time on Venus.

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[5] Hey this is my dream. If you don't like it, start your own.

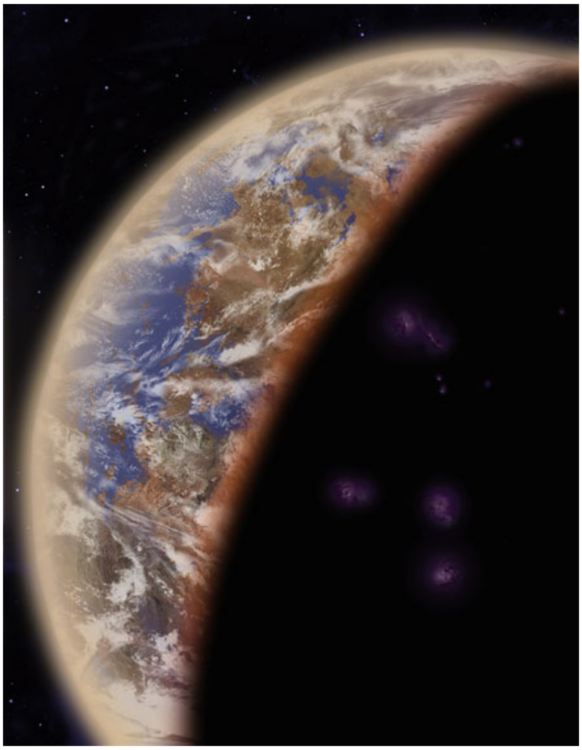

Fig. 2.5 Dying planet: The Venusian ocean is close to the boiling point, held to the surface by skyrocketing humidity. At the terminator near the center of the image, the land mass that will become Tellus Tesera looms out of the darkness. Stretching across the lower portion of the view sprawls the infant continent of Aphrodite Terra, with mountains twisting across Ovda Regio. Fierce lightning flickers across the night side (©Michael Carroll)

Oceans? Check.

Fresh rocky surface? Check.

Volcanic vents on the ocean floor? Lightning? Plenty of organic matter falling from space and forming on the surface? Check. Check. Check.

Earth's oceans were already brimming with primitive critters a couple 100 million years after the great bombardment slowed to an occasional fusillade, and nothing we know about Venus suggests it should have been significantly different.

And also consider this—rocks can get knocked between worlds in large impact events. This we know. We find meteorites from Mars in Antarctica. Such events happened with much greater frequency when the worlds were young. Venus, Earth and Mars were all flinging bits of themselves on each other. And we know that simple life forms like bacteria are very, very hard to kill off and would surely survive an interplanetary trip inside of rocks. So if life formed on any one of these worlds it could have naturally spread to any other, if it landed in a place where it could survive. The early oceans of Venus, Earth and Mars were not isolated and if any of them were populated, chances are they all were. Wait—we KNOW that one of them was populated, so… so, yes lets paint that early Venusian ocean teeming with bacteria and who knows what else.

What happened to that life after the surface dried up and heated up to the point where organic matter cannot be? Just maybe it moved to the sky. This is the opposite of what we suspect about Mars, where when the surface dried the life perhaps moved underground. Today in a sense the clouds are the oceans of Venus—a thick, globally encircling aqueous layer that covers the planet 30 miles up in the sky. Some of us have speculated that there may even be a niche for some kind of cloud-based life up there today. A long shot, perhaps, but remember that we still don't really have a scientific clue about the evolution of life elsewhere so it's important in astrobiology to remain open to exotic ideas.[6]

Perhaps life on Venus today is too much of a stretch. I don't know, but I think that while we explore the planet for all of the other good reasons—to understand how Earthlike planets work and test our climate models—we should at least look. And whether or not Venus is inhabited today, I think there is a very good case to make for creatures that once enjoyed the moonless nights there and swam endless days under that alien sky.

And what color was that sky? Nobody knows (heck we don't even know if the early Earth was a Titanian organic hazy orange, a steamy, cloudy white or a nice blue marble) so I'm going to go with blue, flecked with white. Today Venus is densely clouded- a bright pearl from the outside but a dull red on the surface. I'm betting that the permanently cloudy visage of Venus we see today is not new but not ancient either, that it arose with those same planetary transformations that doomed its once heaving, brackish ocean.

My first introduction to the idea of oceans of Venus came in the 5th grade when I read Isaac Asimov's juvenile sci-fi book *Lucky Starr and the Oceans of Venus*, which featured humans living in giant submarine domed cities which protected them from a global ocean populated with various exotic creatures, some menacing and some harmless (and some just enigmatic, like the telepathic frogs…) (Fig. 2.6).

At the time this was written in the 1950s, this was a scientifically reasonable view of Venus. Historically, the idea of oceans on Venus precedes the space age by centuries. In fact, before the time of spacecraft everyone "knew" Venus had oceans. Of course she did- she's the same size as Earth, a little bit closer to the sun, possessing a thick atmosphere and covered with clouds. It seemed reasonable to imagine her as a slightly warmer and more tropical Earth. After World War II, with the benefit of radar technology developed for the war, the first radio astronomy observations of Venus started

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[6] Without, of course, keeping our minds so open that our brains fall out.

Fig. 2.6 Literature is rife with Venusian monsters on land and sea (©Michael Carroll)

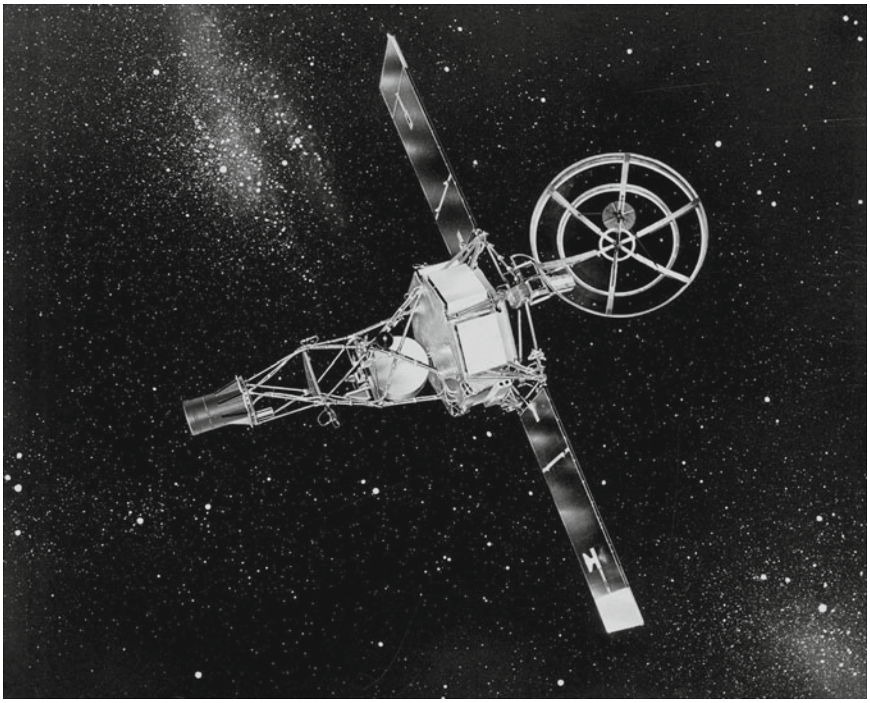

Fig. 2.7 Mariner 2, the first successful interplanetary craft, flew by Venus in 1962. To the left of the wing-like solar panels is the octagonal instrument box (the "bus"), and just to its left is the circular "microwave radiometer" which essentially took the temperature of the planet (Courtesy of NASA/JPL-Caltech)

dropping some hints that all might not be wet and warm in paradise. Speculation on the source of the "anomalous microwave radiation" included several possibilities, including that it might be revealing an extremely hot surface. The first ever successful spacecraft sent from Earth to another planet was Mariner 2 to Venus, launched in August 1962. The most important experiment on Mariner 2 was a "microwave radiometer" designed to find the source of the strange radiation. In the first scientific result ever achieved by interplanetary spacecraft exploration, Mariner 2 showed that the signal was indeed coming from a surface far too hot to support liquid water. We learned then that Venus on the surface is not at all like Earth, that it is absurdly hot and dry (Fig. 2.7).

We've come a long way in the first 50 years of space exploration, but the dramatic questions posed by Mariner 2's first exploration, "How did these 'twins' become so different from one another?" and "What happened to the lost oceans of Venus?" still remain with us.

And as we learn more about the vulnerability of our own planet to climate change, we will have all the more reason to test our knowledge and abilities on a nearby sister world where familiar climate processes have produced a completely alien environment. As we embark on an era of discovering planets that are more and more earthlike in various ways, and as we attempt to reconstruct their stories-the need to more fully understand the planet next door will make this next stage of exploration unavoidable and inevitable. We will soon return to Venus, with orbiters, balloons, probes and landers, and we'll finally solve the mystery of the lost ocean.

Oceans on Mars

3

Timothy Parker

Any past oceans of our solar system have left few clues to their existence. Lava flows, meteor bombardment, weathering, and a host of tectonic forces have conspired to keep evidence of ancient oceans hidden from us. But Mars stands as a unique outpost, with telltale signs of what may be extinct seas etched into its plains and slopes even today (Fig. 3.1).

Across the northern hemisphere of Mars, vast plains form a ring around the north pole. The southern edge of this plains region is peppered with ancient craters and rugged mountains. But at the transition between the more ancient highlands and the low plains, a network of valleys wanders, as if cut by ancient rivers leading to the low basins to the north. These dry river valleys inscribe several other areas on Mars farther to the south, but the extensive plains to the north bear some resemblance in profile to the Earth's ocean basins. And along the border of those low plains, some investigators believe they see signs of long-term wave action, the same kind that is seen along bodies of water here on Earth (Fig. 3.2).

With increased resolution in our orbital data, researchers are revisiting sites along the lowland/upland boundary where landforms interpreted to be shorelines were identified over 20 years ago. We use Geographic Information Systems (GIS) applications to generate an image map of the planet's northern hemisphere, based primarily on images keyed to laser topographic data. Significant improvements over Viking data from the 1970s have been realized from the Mars Global Surveyor (MGS), Mars Odyssey (MO), Mars Express, and Mars Reconnaissance (MRO) orbiters, with their images providing the best regional coverage at high resolution. These data enable the compilation of global maps of proposed shorelines.

The possibility of ancient Martian oceans has been addressed in peer-reviewed publications beginning during the mid 1980s, based primarily on orbiter images of the northern plains. Pioneers like Baerbel Lucchitta, Vic Baker, Ken Edgett, Steve Clifford and others based their work on data acquired by spacecraft preceding the more powerful MGS mission of the late 1990s, chiefly the Viking Orbiters. Their research indicated specific locations where proposed shorelines could be evaluated with high-resolution cameras on board MGS, MO, Mars Express and MRO.

The search for beachfront property is critical to our understanding of the martian past. Early images from Soviet Mars and US Mariner and Viking spacecraft seemed to leave open two possibilities: either ancient Mars was a frigid world with sporadic flash-flooding but no semi-permanent bodies of water, or Mars was warmer and wetter than today, with lakes, rivers, seas and an active water cycle. Perhaps the planet was a combination of the two views, but discovery of shorelines would certainly point to long-standing water. The search was on.

Multiple, "nested" plains unit contacts, terraces, curvilinear ridges, and other features were identified in several locations around the northern plains. After considering the alternate genetic processes that had been suggested for their origin, these features were interpreted as most likely related to highstands of an ancient northern plains ocean. Two of the contacts, one associated with what had been called the "gradational boundary" and a second one plainward of it and described as an "interior plains boundary" were traced to almost complete closure around the northern plains. Investigators traced several others laterally for hundreds of kilometers within a few key regions that appear to be sub parallel to the two global contacts (either between or to either side of them), and a number of others were traced only locally in the highest resolution Viking Orbiter mosaics. The large number of these features necessitated a mapping and naming scheme. Researchers suggested a scheme similar to that used by terrestrial geomorphologists for shorelines in Pleistocene Lake Bonneville basin and used local classical albedo feature names from where the proposed shoreline feature was first identified. Thus, "Contact 1" was renamed "the Arabia Shoreline", and "Contact 2" was renamed "the Deuteronilus Shoreline."

However, the decision to apply the term "shoreline" to these features was unfortunate, as shoreline is a term that

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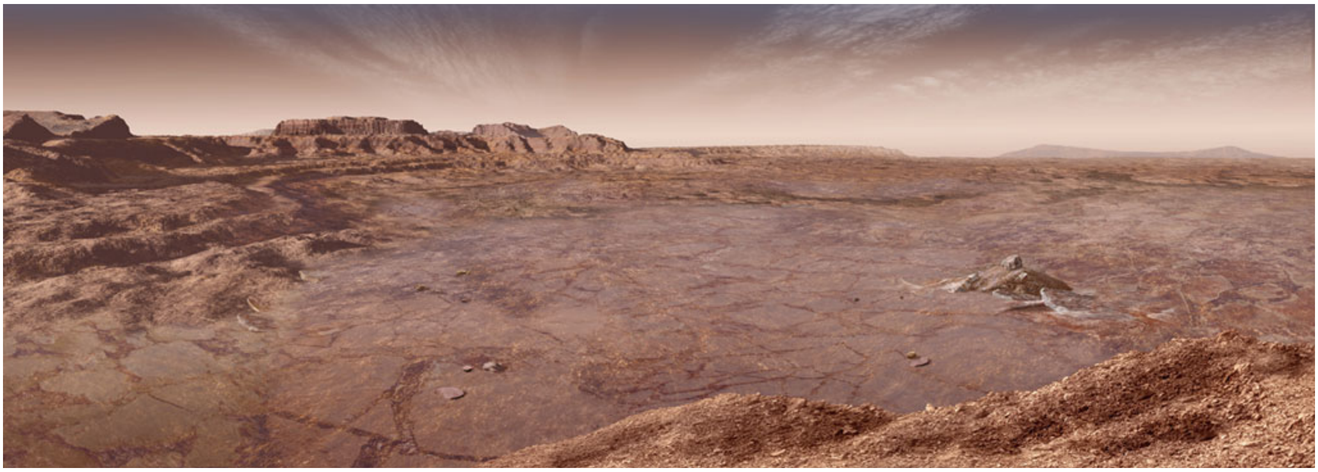

Fig. 3.1 Remnants of a frozen ocean leave their telltale signs as coastal benches (*at left*) and plates of material that echo ancient ice floes (Painting ©Michael Carroll)

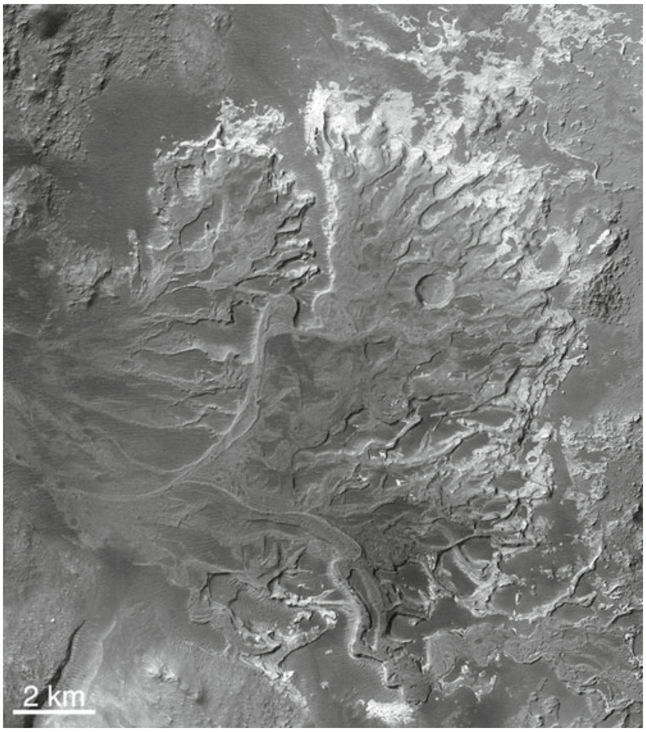

Fig. 3.2 A typical delta system on Mars, this one at the crater Eberswalde (Courtesy of NASA/JPL/Malin Space Science Systems)

implies a specific origin. Selection of a term that does not refer to origin, but is still a precise and descriptive term for these features, is not straightforward. Many are not simple demarcations separating geologic units, and so are not strictly "contacts," but can be expressed as a subtle association of a number of landform types with or without distinct boundaries between them. Referring to them as "contacts" implies that the materials or textures on either side are distinct from one another, but this is not always the case. Some larger martian features do show distinct textural differences between surfaces on either side. One such example is the contact separating the well-known mottled plains from the "thumbprint" terrain in eastern Acidalia Planitia. But the less extensive or smaller-scale features, for the most part, do not exhibit differences from one side to the other. In addition, even the best expressed of these features displays numerous breaks in the available global mosaics (initially, Viking Orbiter, but now including Mars Odyssey's THEMIS daytime IR).

Landforms associated with the proposed shorelines suggest that although they likely do represent marine shorelines, they also resemble debris or lava flow margins. This suggests that an ocean would have been debris- and ice- covered much of the time, with remnants of the debris along the margins to the present day. Mars seems to have endured periods of time in which standing water froze and then flowed, possibly glacier-like, across the landscape.

Investigators look to terrestrial paleolake shorelines as analogs for the proposed martian shores. Some of these earthly formations are simply narrow terraces cut into pre-existing rock, such as an outcrop of basalt, or geomorphic features like alluvial fans. The form of the pre-existing surface is not necessarily altered or obscured, although at very high-resolution, some images seem to show modification of the surface during sea level changes and burial by sediment deposition. Verifying these formations may require imaging with similar resolution to aerial photography—or perhaps even on a scale of field observations at ground level—to verify their coastal origin. Lacustrine (lake-related) landforms can be recognized at smaller scales, provided the lake was present long enough—or the rates of erosion and deposition high enough—to produce changes recognizable from orbit. In the interest of objectivity then, this discussion will refer to the martian features as "levels" (Fig. 3.3).

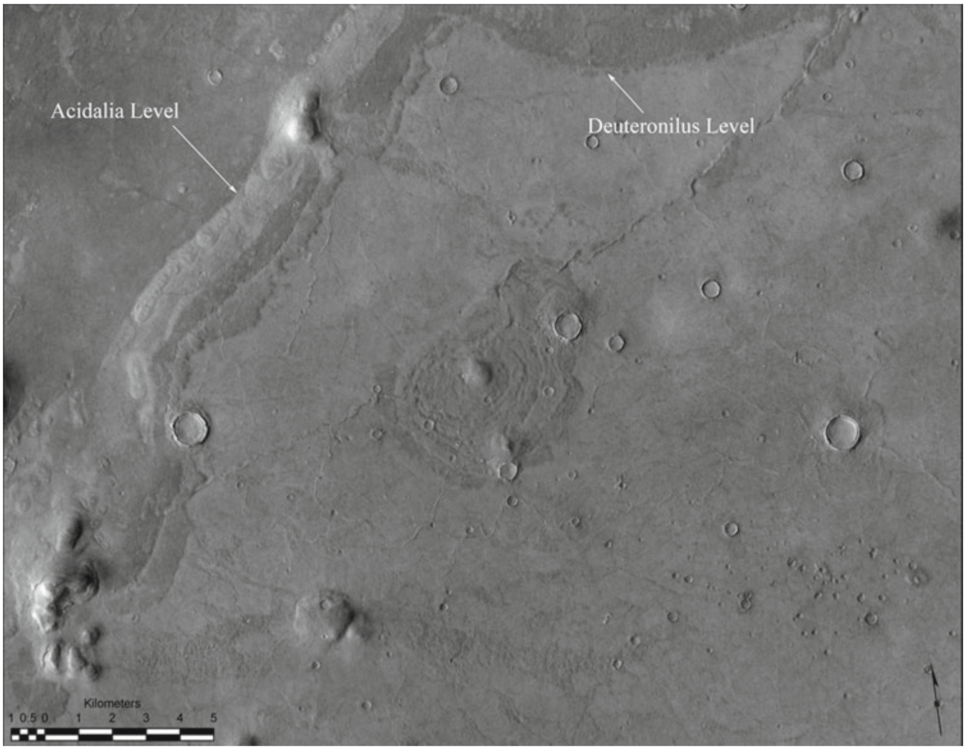

Fig. 3.3 Two critical levels under study, the Deuteronilus and Acidalia, may be remnants of an ancient Martian coastline (Courtesy Tim Parker)

Since MGS began mapping Mars in the late 1990s, other investigators began offering independent tests of the ocean hypothesis, either by directly addressing the question based on results from MGS and later missions, or by considering the hypothesis as one possible explanation for the discovery of coarse crystalline hematite in Meridiani Planum. Early work by James Head and members of the MOLA team seem to support the ocean hypothesis, at least for the Deuteronilus Level, which is fairly level, with two notable exceptions. The first exception is the Arabia Level, which exhibits a much poorer fit to the MOLA topography, deviating from horizontal by more than a kilometer at some localities. Another exception to the rule lies along broad topographic terraces in Utopia that some researchers interpret as additional shorelines below the Deuteronilus Level. Mission planners targeted the MGS's MOC imaging system to examine sites that had been proposed as shorelines prior to MGS, and were unable to equate their observations to the hypothesis that a former ocean had produced them. More recent independent tests of the ocean hypothesis appear to be consistent with the presence of oceans or large seas in the northern hemisphere.

MGS' MOC camera system provided the first very high-resolution images ever taken of Mars—truly comparable to aerial photos in resolving fine detail. MOC imaged only a few percent of Mars' surface, however, so regional coverage of interesting targets often required acquisition of mosaics of overlapping images. Prior to the arrival of Mars Odyssey, Viking Orbiter images still provided the best regional context maps for the MOC Narrow Angle images.

Mars Odyssey arrived at Mars in late 2001 and began its primary mission in early 2002. Odyssey's Camera has two imaging modes. Its Thermal infrared (IR) mode yields a resolution of 100 m/pixel (taken during the day and night portions of the orbit), while its visible portion (called VIS) sees objects at 18 m/pixel during daylight periods. The daytime IR images have been compiled by the Odyssey team into a global mosaic with nearly complete coverage of the planet. The latest version of this map is greater than twice the average resolution provided by the previous global Viking Orbiter mosaics. Any remaining gaps in the daytime IR mosaic can still be filled with Viking mosaic data, where needed.

Shorelines that do not follow a consistent altitude would seem to contradict the ocean hypothesis. But what if the martian surface itself has been uplifted or lowered by tectonic forces, carrying the shoreline along with it? Mars Global Surveyor's laser altimeter (MOLA) yields topography that is orders of magnitude higher in resolution than the Mariner 9 and Viking topography, all that was available for the early work on the ocean hypothesis. All the MOLA data have been compiled into global gridded image products. In addition, the individual data points can be quickly accessed and map projected with the gridded product to determine the quality of the elevation value averaged for a particular grid cell, or to make higher resolution measurements of elevation at points of interest. It is now possible to compare shoreline positions with topography to look for elevation changes that might indicate systematic variations due to "neotectonic" adjustments in the topography or other tectonic changes to support or contradict the shoreline interpretation for the origin of these features.

Significant improvements over Viking data have been transmitted by a new generation of orbiters since the 90s and the acquisition of new data continues. The image datasets provide high-resolution views that, when mosaicked and combined with the MOLA gridded topography, enable the compilation of regional and global maps of the proposed shorelines. To produce these maps, GIS (Arcmap) and image processing software are being used to generate an image-based map of the planet's northern hemisphere (incorporating mainly CTX, or context, images) that is georeferenced to the MOLA gridded topography base map provided by the USGS, Flagstaff.

The *follow the water* theme underscores all our current and foreseeable future plans for spacecraft missions to Mars, both orbiters and landers. As a result, it makes sense to take stock of the image data we now have available from past and current missions and assess what these data say about the possibility of an ancient ocean on Mars.

Investigators continue to utilize the new image and topography data, revisiting sites along the lowland/upland boundary where landforms have been interpreted as ocean shorelines. These localities now have extensive high-resolution image coverage from MOC, MO's THEMIS VIS, the CTX and high resolution camera systems aboard Mars Reconnaissance orbiter, called HiRISE. Some of the best examples lie within the west Deuteronilus Mensae region, as well as part of the Arabia Level that was first seen in low resolution Viking images as a prominent albedo boundary. This region of Arabia has since been shown to exhibit terraces and other aspects reminiscent of coastal landforms in the recent very high-resolution images.

Coastlines and Topography

Standing water forms a surface that intersects topography at a fixed elevation around the margin of a depression. Simply stated, modern lakes and ocean shorelines on Earth are level and possess attributes modulated by storms and tides (although Mars would have weaker solar and no lunar tides). By contrast, abandoned shorelines on Earth are seldom level, though they often indicate a planar surface that has been tilted, faulted, or warped due to structural changes, isostatic rebound, or loading. All these effects have been identified in terrestrial paleolakes such as the Pleistocene Lake Bonneville in Utah. Ancient shorelines on Mars should not be precisely level for the same reasons, although it should be possible to recognize systematic changes in elevation along the shoreline due to the geological forces that warp the landscape (Fig. 3.4).

Coastal landforms are often subtle. Some appear quite similar to stratigraphic terraces or fault scarps. Adding to the challenge is the fact that they often extend over vast areas, requiring both high-resolution imaging and regional coverage. For example, on Earth, Landsat MSS data (~80 m/pixel) reveals only the very largest coastal forms in Lake Bonneville,

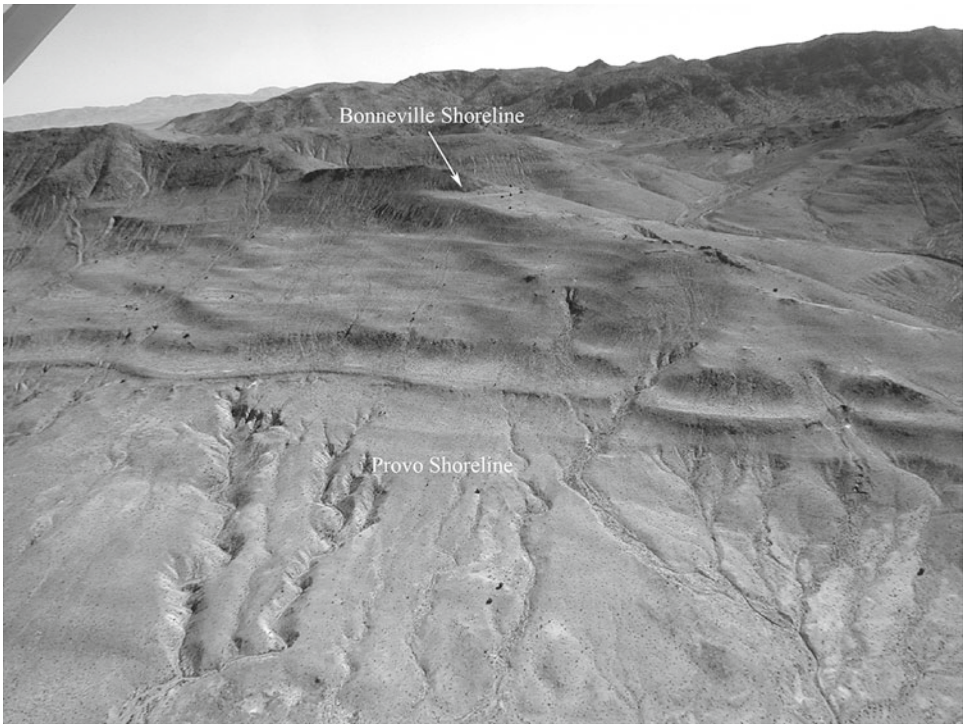

Fig. 3.4 Oblique aerial view of Tule Valley, Utah, showing terraces cut into bedrock and alluvial material at Lake Bonneville. The Provo Level is the prominent terrace crossing the center of the image (Courtesy of Tim Parker)

but provide good regional coverage of the basin. Aerial photographs do much better with the detection and recognition of the smaller features, but even meter-scale aerial photos cannot be relied on for "closure" of a mapped shoreline, for at least two reasons: First, regional coverage is lacking, so placement into context requires large mosaics. Second, post-shoreline degradation by geologic processes after the formation of the feature can subdue it through burial or erosion. At very high-resolution, it is important to consider subsequent, possibly unrelated processes that might dominate the character of a surface, and understand their effects on preservation of pre-existing landforms.

Signs of an Ocean? Proposed "Shorelines" and Related Landforms in the West Deuteronilus Mensae/East Acidalia

Armed with new images and topographic data, investigators have focused on the west Deuteronilus Mensae region for two reasons: First, the features of interest had been identified on the sloping surface of the southern highlands. Here, the topography dips gradually downward to the north into the northern lowland plains west of Deuteronilus Mensae, disappearing into rugged landscapes known as "fretted terrain". Fretted terrain forms a border between ancient and more geologically young areas, and consists of a jumble of canyons, mesas and collapsed cliffs. At typical Viking Orbiter image scales, the fretted terrain of west Deuteronilus Mensae appears incised into the sloping margin of the highlands, resulting in scattered mesas and plateaus that seem to record the former sloping surface. However, a rare, very high-resolution swath of Viking images (7–10 m/pixel) of the wall of one of the easternmost fretted valleys of the Mensae (north Mamers Valles) shows that the prominent boundary features visible on the sloping surface to the west can be traced into the fretted terrain. This suggests that either the erosional forming the fretted terrain exposed stratigraphic contacts (the possible shoreline), or the shoreline was emplaced after the terrain formed. Crater counts for the major geomorphic units in the region show that the terrain becomes progressively younger toward the plains interior and lower elevations. The favored interpretation is that these materials overlay the pre-existing sloping margin and fretted terrain, such that the emplacement of each subsequent plains unit was less extensive than the previous one.

Today, a wealth of high-resolution image data is available in this area, so that we can now describe the levels and their associated landforms in order of their appearance, from topographically highest level (the Arabia Level) to lower levels like the Deuteronilus. We can characterize the landform associations now that they are visible in high-resolution images from across the region.

In their search to verify (or refute) ancient shorelines, investigators identified 7 levels in the Mamers Valles region. Based on the appearance of these features at Viking image scales, and their inferred topographic and age relationships, they were interpreted to be most comparable to wave-eroded shorelines in terrestrial paleolakes (lacking terrestrial-scale oceanic tides). With MOLA topography, these levels were found to indeed approximate level surfaces, or planar surfaces that appear to have been tilted (locally, to the west). However, the higher-resolution image data, beginning with MOC, shows boundary morphology that does not appear to support a shoreline interpretation involving wave erosion and longshore sediment transport (as originally proposed). At very large image scale, many of the best preserved of these features at the lower elevations instead exhibit lobate flow-front morphology suggestive of low-viscosity lava or debris flows. These flows advance uphill across the sloping highland margin from the northern plains. This morphology suggests the material encroaching onto the sloping margin is still present. The Arabia Level does exhibit morphologies at high resolution that are reminiscent of terrestrial paleolake strandlines, however, though unusual accumulations of sometimes relatively thick material at the Arabia Level are present in a number of areas (Fig. 3.5).

All of the levels described and any material deposits associated with them remain elevated with respect to the northern plains interior, even just a few kilometers from the contact defining a particular level, and thus still appear to require withdrawal of vast amounts of some fluid from the northern basin after their emplacement. Deuteronilus Mensae is not alone; it is important to note that many of these features have been identified elsewhere around the martian dichotomy boundary. There is no "other side" of these features somewhere north of Deuteronilus Mensae outside the study area. If these do indeed prove to be shorelines, they are shorelines of an ocean, not a paleolake or sea.

Shores of Arabia?

Across eastern Acidalia and into west Deuteronilus Mensae, the Arabia Level is most easily recognized as a sharp albedo contact separating dark plains surfaces from lighter, rougher surfaces of the highlands to the south. This contrast is evident in all images from the days of Viking through the present day, and is most pronounced in the THEMIS day and nighttime IR data. In daytime IR images, the surface plainward of the Arabia level is dark, whereas in the nighttime IR images, it is brighter than the highlands surface to the south. This suggests that it is comprised of hardened material that is slow to change temperature, relative to the highland materials to the south.

Depending on local slopes, the Arabia Level has two faces. On gentle slopes, a thin, relatively dark mantle over-

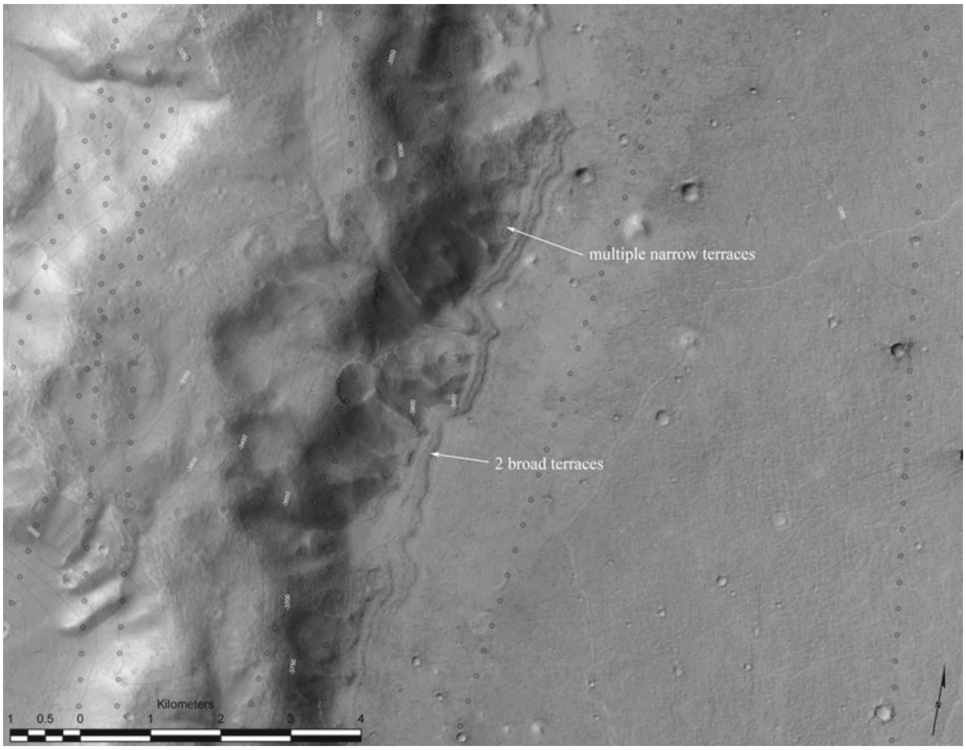

Fig. 3.5 Closeup of crater wall in Cydonia. Note the multiple terraces at the base of the wall, defining the Arabia Level (CTX image courtesy NASA/JPL/UA)

laps the highland margin. On steep slopes, one or more narrow terraces appear approximately level over great distances around elevated topography, such as fretted valley walls and around crater rims and ejecta deposits. These terraces are found within several tens of meters of one another in elevation. In Mamers Valles, the Arabia Level often breaks sharply in slope below an escarpment, with 2 or 3 broad, subdued swales or terraces on the slope between this break and the tops of the debris aprons. These features are reminiscent of terrestrial paleolake shore morphology viewed at high resolution. In southeast Cydonia, multiple terraces along the inner rims of degraded craters along the Arabia Level are strikingly similar in appearance to strandlines in terrestrial paleolakes (Fig. 3.6).

The Viking Orbiters covered much of the Arabia Level between the fretted terrains of Deuteronilus Mensae and southeastern Cydonia Mensae at low resolution (greater than 100 m/pixel). But even at the low resolution of the Viking images, it is apparent that erosion of the highland margin has occurred at this contact. MOLA topography confirms the visual impression that four large craters along this contact have been eroded, rather than being buried. Hundreds of meters of rim material is missing from all four craters and their floors are all at the same elevation. Topography above an elevation of about −3,900 m is degraded, and that below −3,900 m is filled in with dark material, resulting in a ~100 km-wide topographic terrace that can be traced laterally for several 100 km at this elevation.

In the past few years, orbiters have gleaned enough very high-resolution coverage for this part of the Arabia Level that continuous mosaics can be assembled. High-resolution regional mosaics are essential in establishing the regional continuity of what are often very subtle terraces and plains boundaries at the Arabia Level. They are also critical in determining where the albedo contact identified in Viking images actually falls with respect to these terraces and other topographic features. The highest of several identifiable terraces exhibits a sharp albedo boundary that appears to consist of a thin mantle of dark material onlapping topography below about –3,800 m elevation, locally. Similar terraces can be traced around the western edge of these craters. Figure 3.4 is an oblique aerial view of shorelines in the Lake Bonneville basin in Utah. The Provo Shoreline, here representing both erosional and depositional processes by wave activity, is similar in scale to the broader martian terraces.

While small valley networks are relatively less abundant compared to other areas along the highland margin, they are present. Near the Arabia Level, many lie exclusively on the highlands side of the albedo contact and often terminate abruptly at the contact. At least one large valley network lies plainward of the contact at 42°N, 3.5°E. This valley appears draped by the material comprising the plains and is indistinct at either end, suggesting that it was buried or otherwise subdued when the plains were emplaced, but not completely obscured. In addition, there is at least one modest-scale outflow channel in the region. This is a broad, shallowly incised

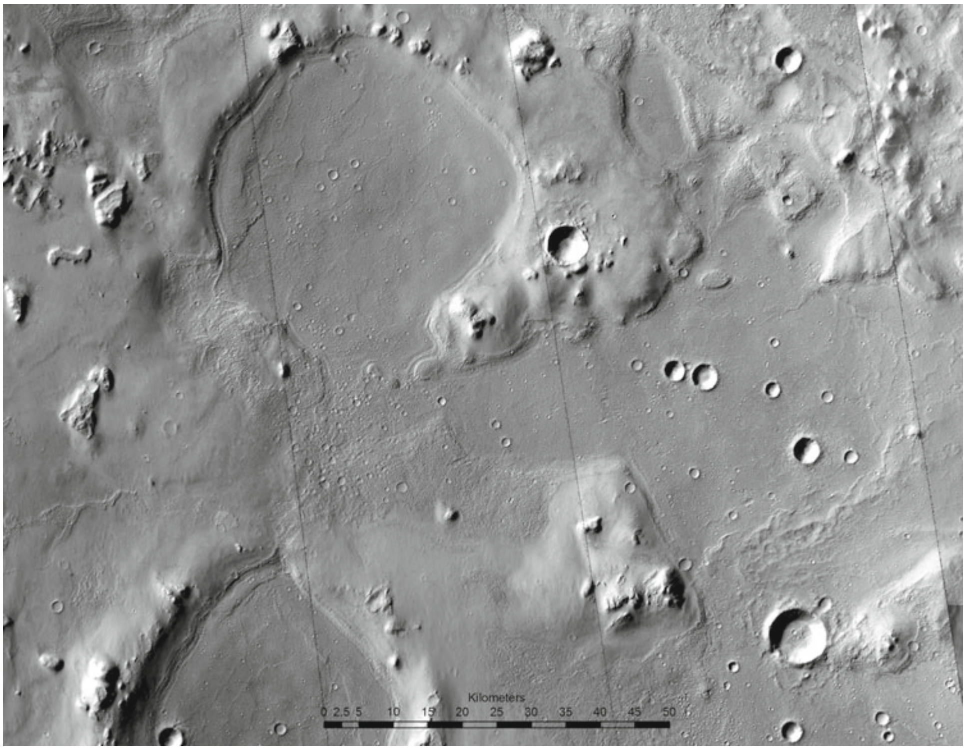

Fig. 3.6 Craters in the Aeolis region exhibit nearly continuous linear terraces (Mars Reconnaissance Orbiter CTX and Mars Odyssey Themis VIS Mosaic. Parallel lines are artifacts. Courtesy of NASA/JPL/ASU/MSSS)

braided system that alternates from sharply defined, where it crosses topographic ridges or encounters other obstacles, to indistinct where it crosses depressions. This channel first appears in an intercrater plains region west of the crater Focas (34°N, 11°E). It bifurcates southwest of Semeykin Crater (40°N, 8°E), with one branch terminating at the Arabia Level on the northwest side of the crater (after first breaching its southwest rim and filling the crater) and the other 80 km west of the crater.

Landforms and their associations with the Arabia Level, using the very high-resolution Viking images of northern Mamers Valles, can now be readily identified throughout the fretted terrain in west Deuteronilus Mensae. The strip of Viking images here had a gap where the Arabia Level intersects the wall of northern Mamers Valles. Investigators inferred that a sharp break in slope near the top of the wall and south of the point of intersection between the Arabia Level and the valley was the continuation of the Arabia Level southward where it was following topography and "veeing" up-valley. As this break was traced southward, the depth at which it appeared below the top of the canyon wall seemed to increase, again suggesting that the break followed the topography as the surrounding terrain climbed to the south. High-resolution post-Viking images verify that the Arabia Level does intersect this valley wall, and several other fretted valleys and mesas to the east, where this break in slope begins until they become lost beneath the ejecta from Lyot Crater. Detailed measurements of MOLA and HRSC-derived elevations of the Arabia Level at these valley intersections do indeed suggest that it defines an approximately horizontal surface, as would be expected if it was water-related (Fig. 3.7).

The next step for scientists was to derive quantitative topographic profiles across northern Mamers Valles. This would bolster the theory that the fretted terrain has been inundated by the material that formed the levels, but that it was not completely obscured by them. If true, this evidence would suggest that the region was partially buried by some material associated with a fluid responsible for the mapped levels, and that fluid has subsequently receded. Viking-era topography was too coarse for making these measurements, so investigators used a technique called photoclinometry. Photoclinometry uses the direction of light and length of shadows to get three dimensional data from a two dimensional image.

With the photoclinometry technique, researchers generated five profiles across the valley. Comparing the results of this method with measurements taken from the MOLA and HRSC DEMs reveals that the depths of the fretted valley were consistently underestimated using photoclinometry, by 10 or 20 % in the northern end of the valley (adjacent to the Deuteronilus Level) and as much as 100 % in the south. The profile shapes appear to be correct, however.

In Mamers Valles and in west Deuteronilus Mensae as far as the Arabia Level to Lyot Crater, debris aprons are only found in association with fretted valley walls and mesa scarps south of where the Arabia Level intersects the walls.

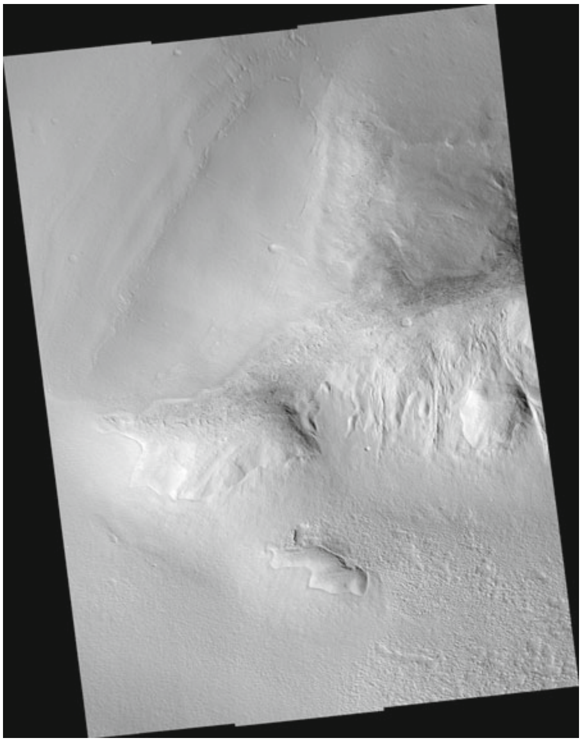

Fig. 3.7 The jumbled landscapes known as fretted terrain form a border between ancient and more geologically young areas (Mars Global Surveyor image. Courtesy of NASA/JPL/Malin Space Science Systems)

This relationship appears to hold east of Lyot Crater as well, though the mesas are smaller and more scattered, so the details are more difficult to ascertain. West of the fretted terrain, the plains interior to these terraces are often polygonally fractured at a scale of a few tens of meters, suggesting a desiccated or frozen sedimentary deposit or a cooled lava lake surface. Locally, this surface is on the order of a few tens of meters lower than the Arabia albedo feature on adjacent slopes (Fig. 3.8).

Stepped massifs are scattered over the plains interior to the Arabia Level. Many of these exhibit prominent terraces or flat-topped aprons around them, particularly in Cydonia Mensae, where they are common. Stepped massifs typically exhibit one prominent terrace that can be attributed to the Deuteronilus Level having been preserved at that location, particularly if it is near enough to make a good correlation based on elevation and morphology. A smaller number exhibit steps that can probably be correlated with either the Ismenius Level or the Acidalia Level, but these are not as pronounced as those at the Deuteronilus Level.

In northern Mamers Valles, the Arabia Level intersects the fretted valley wall at an elevation of approximately −3,600 m. The elevation of the Arabia Level decreases to the west until it is at approximately −3,800 m southeast of Cydonia Mensae. There also appears to be a slope to the surface defined by the Arabia Level that is downward to the northwest. Similar boundary morphology identified in the Acidalia Mensae region (46°N, 334°E) is approximately 600 m lower in elevation than at the point of intersection at Mamers Valles. Similarly, the prominent break in slope below the scarp in Mamers Valles south of this point (43°N in Mamers Valles) is approximately 300 m higher than at the point of intersection with the fretted valley wall.

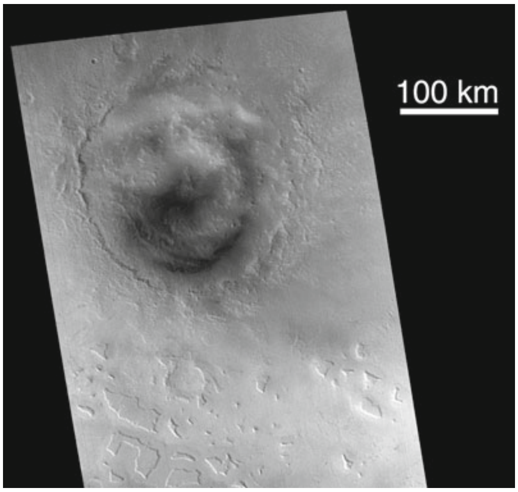

Fig. 3.8 Lyot Crater provides a landmark reference point for the study of possible Martian paleoshorelines (Mars Global Surveyor image. Courtesy of NASA/JPL/Malin Space Science Systems)

Ismenius: Taking It to the Next Level

This Ismenius level is expressed in the very high-resolution Viking Orbiter images of northern Mamers Valles as a local scarp within the plains midway between the Arabia and Deuteronilus Levels. It locally intersects the wall of the fretted valley and vees up-valley, appearing to conform to local topography. It was also identified in high-resolution (~50–75 m/p) Viking Orbiter images west of Mamers Valles as a band of non-branching fluvial rills that were also traced across mesas in the fretted terrain southwest of Lyot crater. In 1989, investigators compared the rills to swash rills on a beach, morphologically, but at a large scale. At the time, this level was simply labeled bench 4, because it was only recognized locally near northern Mamers Valles. Today's extensive high-resolution orbiter images show the break in slope to comprise a discontinuous, faint terrace and scarp within the plains unit between the Arabia and Deuteronilus Levels. The rills appear to terminate at their downslope ends at about the elevation of this terrace, where both features can be identified. The rills are only found immediately above the elevation of this terrace—they never cut terrain at lower elevations,

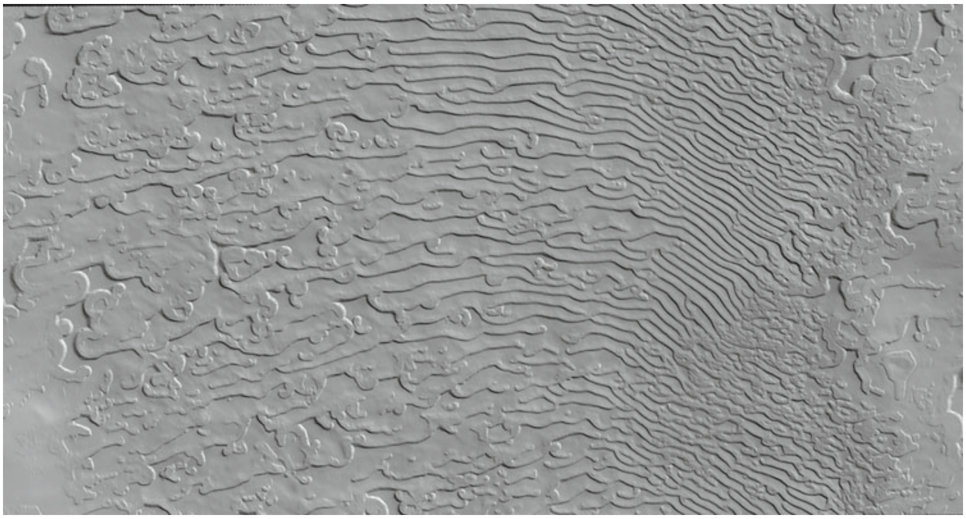

Fig. 3.9 The bizarre "thumbprint terrain" of eastern Acidalia Planitia gives way to mottled terrain in the west. The subtle transition from one terrain type to another may mark an ancient shore level (Mars Reconnaissance Orbiter HiRISE image, LPL. Courtesy of NASA/JPL-Caltech/Univ. of Arizona)

even when they are found in direct proximity to those lower surfaces. In this way, they resemble river valleys that disappear into a lake or sea. Because this terrace and the rills associated with it do appear to define an approximately-level surface that can be traced laterally for more than 1,000 km, it was given a local geographic name, Ismenius Level.

In medium-resolution visible light images, the plains surfaces on either side of the Ismenius Level appear similar, i.e., they appear to be smoother and darker than the surfaces above the Arabia Level and below the Deuteronilus Level. In THEMIS day and nighttime IR, there is a pronounced contrast between the two surfaces at the Ismenius Level, with the daytime IR brightness suggesting the higher plains surface above the Ismenius Level has a higher thermal inertia than the surface below it. This implies that the surface material is more coarse above the Ismenius Level than below it. At visible image resolution above about 50 m/pxl, the two surfaces also appear distinct, with the surface below the Ismenius Level exhibiting polygonal patterned ground on a scale of tens to a few hundreds of meters across, but the surface above appearing comparatively smooth.

The plains surface between the Deuteronilus and Ismenius Levels contains four landforms that were either not described in detail or were not recognized as significant in the earlier, Viking Orbiter-based studies. These are: small mounds or knobs; lobate mounds; platy-fractured plains surfaces; and dark streaks trailing from many of the small knobs. The small knobs have been described since Mariner 9 data became available in the early 1970s. When they occurred in abundance, the surface was often mapped as "knobby terrain." The small knobs tend to be more numerous, and larger, just above the Deuteronilus Level, and smaller and more scattered toward the Ismenius Level. Many of the small knobs are sharply defined, but a number of them feather into the surrounding plains and appear as though draped by plains materials that settled onto pre-existing highs. Similar small knobs seem to be lacking on the plains surface between the Ismenius and Arabia Levels (Fig. 3.9).

Lobate mounds can appear similar to the small knobs at regional scales, such that they were not recognized as morphologically distinct in the earlier Viking-based studies of the region. They tend to occur on the plains surface just upslope from the Deuteronilus Level and within several kilometers of it. A few of these lie in contact with the Deuteronilus Level and appear to be overlain or cut by it. Most have a small peak in the center a few 100 m across, and multiple lobes or concentric ridges and troughs that suggest effusion and flow of relatively dark material from them and thinly overlapping the plains. The lobate mounds tend to be a few to several kilometers across. In daytime IR images, they appear bright relative to the surrounding plains surface, suggesting they are comprised of fine or unconsolidated material with lower thermal inertia than the surrounding plains.

Much of the plains surface between the Deuteronilus and Ismenius Levels exhibits the polygonally patterned ground similar to that found in tundra areas on Earth. The abundance of very high-resolution data available today has revealed a subtle platy-fractured appearance that is similar to—although not as pronounced or large-scale as—the platy flow material described since Viking days in southern Elysium Planitia. In a few cases, these plates and their associated fractures appear near the lobate mounds. Many take a form that suggests the fractures provided pathways for flows that create precursor lobate mounds.

In several places in west Deuteronilus Mensae, a number of dark streaks extend eastward from many of the knobs on these plains. At Viking image scales, they appeared similar to wind streaks, and their confinement to the plains between the Deuteronilus and Ismenius Levels went unnoticed as anything significant. With very high-resolution regional coverage from CTX, they are revealed to not be wind related at all, but more similar to gores in the well-known platy flow crusts in the southern Elysium region where topographic obstacles have torn the crust as it moved past them. The streaks in the west Deuteronilus examples never occur below the Deuteronilus Level, and fade out before reaching the Ismenius Level. The Ismenius Level intersects northern Mamers Valles at an elevation of approximately −3,700 m. As with the Arabia Level, this surface also appears to be tilted westward, from about −3,700 m southwest of Lyot Crater to −3,800 m northeast of Bamberg Crater.

In addition to the Ismenius Level, other terrace-like features were identified in the Viking very high-resolution strip of images of Mamers Valles. These terraces lie at elevations of approximately −3,800, −3,750, and −3,675 m, respectively. An additional, similar feature has been identified upon examining the current very high-resolution orbiter images. This feature lies at an elevation approximately 150–200 m above that of the Arabia Level.

Deuteronilus Level: The Classic Example

This level is probably the best known of the proposed shoreline features. In the east Acidalia and west Deuteronilus region, it separates the thumbprint terrain from the intermediate plains. The Deuteronilus Level is arguably the most pronounced or best preserved of the features interpreted as coastal in origin. It has been traced around the northern plains, where it does appear to define an approximately horizontal surface. Where it embays topography, it often exhibits a lobate, even arcuate plan form. The features resemble the lobate flow fronts related to lacustrine beach ridges. These flow fronts have relief at the margins, although on fretted valley walls it is expressed as a topographic bench (e.g., in Mamers Valles where it was first identified. The lobate fronts suggest a flow direction from the plains interior and up the flanks of the highlands, to about an elevation of −3,850 to −3,900 m in Mamers Valles).

The plains interior to the Deuteronilus Level is the classic "thumbprint terrain" seen in Viking Orbiter images over 30 years ago. The thumbprint appearance of this surface is due to a system of bright, low relief conical mounds—many with shallow summit pits or craters—contrasted against a relatively dark, smooth plains background. Where these mounds are found near the Deuteronilus Level at a sharp contact separating the thumbprint terrain from the intermediate plains. They often lie in chains or arcs that parallel the lobate appearance of the contact, thereby giving it this thumbprint appearance.

The Deuteronilus Level ranges in elevation from −3,800 m southwest of Lyot to about −4,000 m at 0°E. A long lobe of thumbprint terrain bounded by the Deuteronilus Level vees into the fretted terrain by about 250 km at 17.5°E. The elevation difference between the northern and southern expression of this "level" is approximately 100 m, with the tilt downward toward the interior of the northern plains (Fig. 3.10).

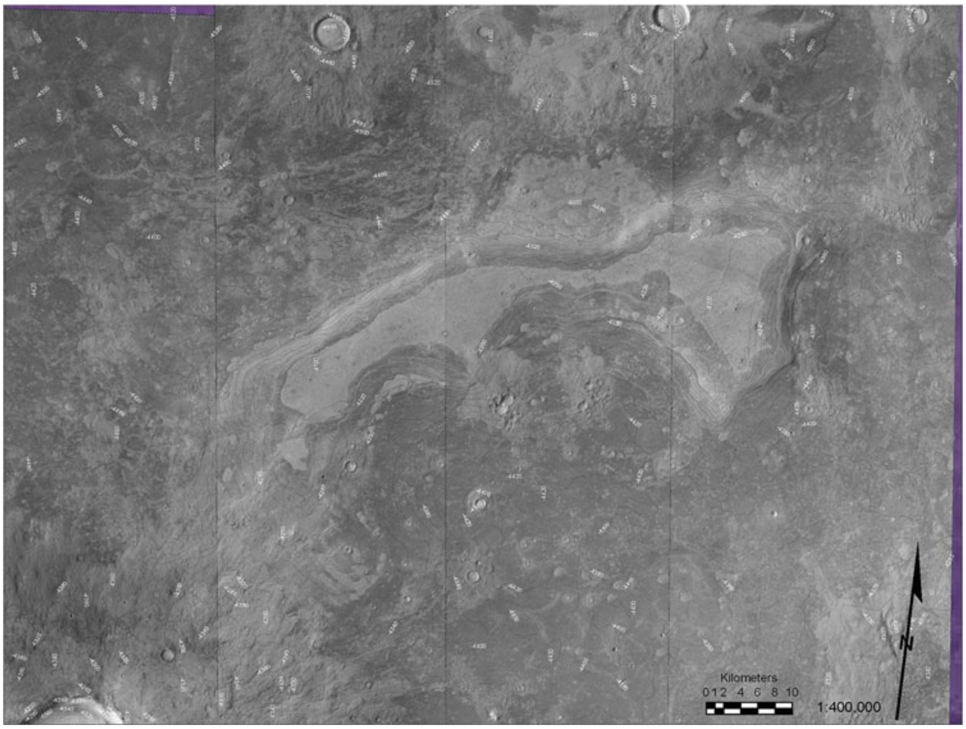

Fig. 3.10 A 200 m-high mesa rises from the eastern plains of Acidalia. The Deuteronilus Level encroaches partway onto the upper surface of the mesa. The Acidalia Level lies on the flanks of the mesa some 50 m farther down. Note the resemblance of some features to pingos in Canada's arctic, inset (Mosaic of CTX data with MOLA topography. The inset is from aerial photos from the Tuktoyaktuk area on the north coast of Yukon Territory, Canada. Courtesy of NASA/JPL/MSSS)

The Acidalia Level

The Acidalia Level is very similar in appearance to the Deuteronilus Level, although the flow fronts and terraces are in general subtler in this region. Yet, it may be more pronounced and exhibit textures that strongly resemble lava flows to the west in Cydonia Mensae. The Acidalia Level typically lies about 50 m lower in elevation than the Deuteronilus level and separates the thumbprint terrain from the mottled plains identified in Viking Orbiter images back in 1984. The Acidalia Level has been mapped in east Acidalia over about 500 km in a southwesterly direction from about 48°N, 11.3°E. Across this distance, it maintains an elevation of about −4,050 m. The mottled plains surface appears relatively dark in daytime IR images, comparable to that of the plains between the Ismenius and Arabia Levels. In west Deuteronilus, the Acidalia Level is at an elevation of −3,950 to −4,000 m.

Perhaps the most-imaged example of both the Acidalia and Deuteronilus Levels is a dramatic 200 m-high mesa east of Cydonia Mensae. It was first imaged at moderate resolution early in the Viking mission. Very high-resolution images have been acquired of this feature since, beginning with transects by MOC, and now Themis VIS, CTX, HiRISE, and HRSC, with CTX providing a continuous mosaic of the entire feature at 6 m/pixel (Fig. 3.11). The mesa lies about 250 km plainward and 200–300 m lower in elevation than the contiguous Deuteronilus and Acidalia Levels along the sloping highland margin, suggesting a plainward tilt of these levels (similar to that measured at Acidalia Mensae for the Arabia Level). The Deuteronilus Level encroaches onto the top edges of this mesa, nearly inundating it completely. The Acidalia Level comes partway up the flanks of the mesa on all sides. The bright, conical mounds characteristic of the thumbrint terrain surface between the two levels is evident on the flanks of the mesa, and the mottled plains surface below the Acidalia Level comprises the plains around the mesa. On the south side of the mesa, the conical mounds appear to rise from thin, level plains material, as if the plains material was not high enough to cover the mounds. In at least one location, a series of mounds appear to be bisected at the contact, suggesting erosion of pre-existing mounds as the plains associated with the Acidalia Level were emplaced (Fig. 3.11).

Putting It All Together

Early Mars explorers revealed a host of features that seemed to be telltale signs of an ancient ocean on the red planet. Some investigators reasoned that if these features were, in fact, ancient beaches, they would indicate paleoclimate conditions that allowed liquid water to remain stable at the surface long enough for wind-driven waves to produce the features through wave refraction and longshore sediment

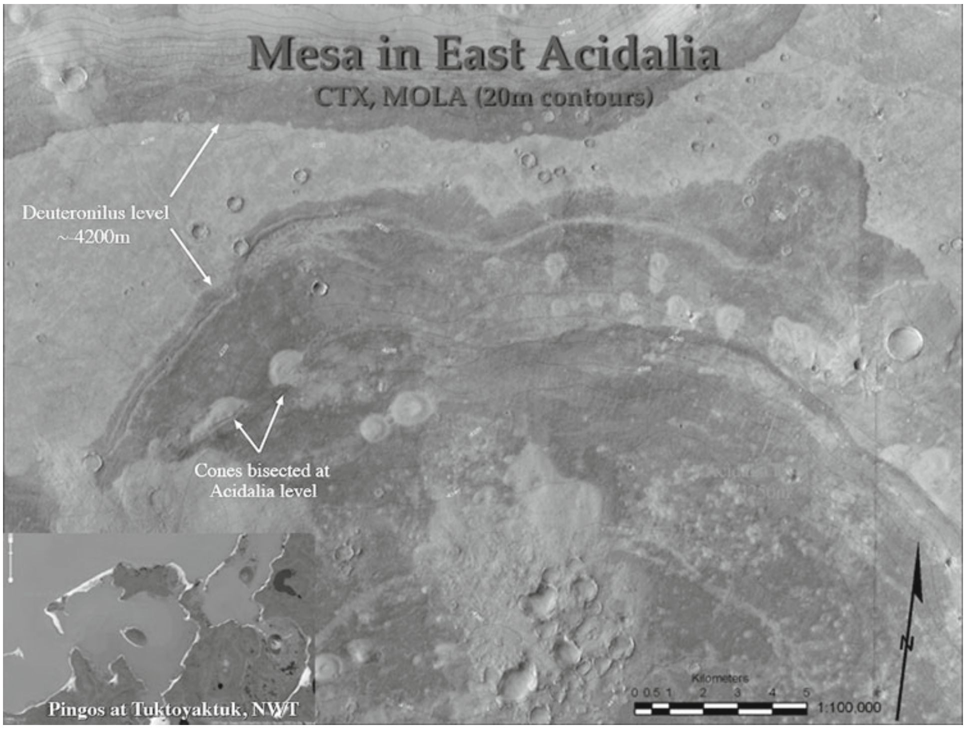

Fig. 3.11 Some mounds between the Ismenius and Deuteronilus levels resemble mud volcanoes (CTX, Courtesy of NASA/JPL/MSSS)

transport. While the Arabia Level does exhibit terracing in the most recent very high-resolution images that is reminiscent of strandlines in terrestrial paleolakes, most of the other mapped levels in this region do not. Instead, boundary morphology at the prominent Deuteronilus Level exhibits lobate flow fronts and textures that resemble low-viscosity lava or debris flows. Still, the MOLA-based topography does verify the earlier impression that the contacts are elevated by hundreds of meters to kilometers with respect to the northern plains interior, which does suggest that millions of cubic kilometers of material receded after the levels were emplaced at the margins of the plains.

Some evidence may be showing us that at one time, Mars held a cooling climate which enabled the planet to host marine conditions. Proponents of the Mars ancient sea scenario point to several lines of evidence:

Starting at the Arabia Level and working plainward, plains textures transition from "smooth plains" between the Arabia and Ismenius Level; to small-scale polygonally-patterned ground between the Ismenius and Deuteronilus Levels; to thumbprint terrain (with bright conical hills interpreted as pingos) between the Deuteronilus and Acidalia Levels; to mottled plains below the Acidalia Level. They reason that smooth plains formed in cold climate conditions that ensued after the shoreline had receded and plains had been desiccated. In this case, small-scale polygons may be ice-wedge polygons formed by thermal cycling in a cold climate with water or ice present in the near surface.

Secondly, "one-off" pingos formed in a permanently cold climate after shoreline recession as near-surface groundwater water froze. This scenario may have been plausible based on the limited resolution data from Viking, but other morphologies discovered with more advanced spacecraft need also be considered in formulating a testable hypothesis based on the most recent, very-high resolution image data. These newly discovered landforms might also be consistent with a cooling marine environment, but may suggest that the initial conditions were never more clement than terrestrial arctic environments. In other words, if Mars had oceans, the observed morphologies may suggest that they were covered with thick ice, and the flow front morphology seen along the Deuteronilus Level may indicate ice-shoving due to a short-lived transgressive event caused by channel activity elsewhere into the northern plains. However, for the morphology to be preserved at the surface at these latitudes today, the ice cover would either need to be dirty or itself be mantled with other material, such as eolian debris, impact ejecta, or lava flows—all of which suggest the long-term presence of subsurface ice and water in the northern plains (Fig. 3.12).

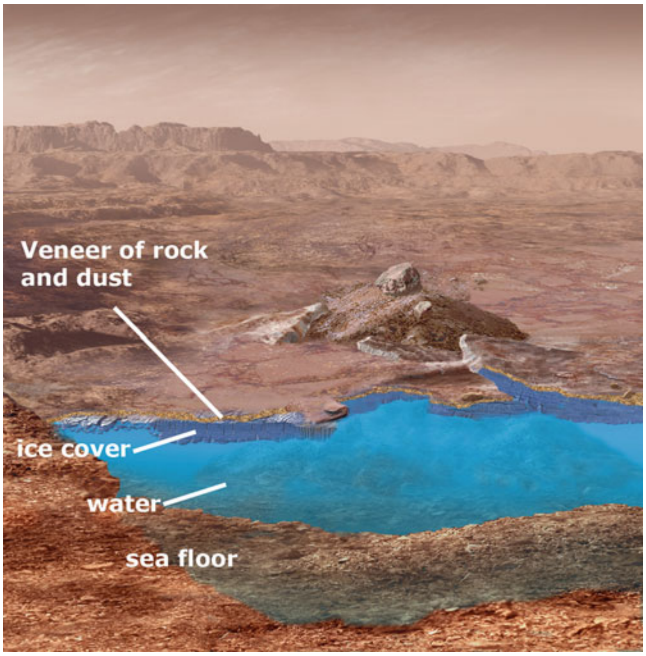

Fig. 3.12 Ancient Martian seas may have survived under a cover of ice and regolith for extended periods. As they drained, the morphology of sea-ice patterns could have been left behind for today's planetary scientists (©Michael Carroll)

Newly-identified landforms at the Deuteronilus and Ismenius Levels may give us the clearest view of what the "seaside" conditions were like on ancient Mars. The landscape in the area hints at brief disruptions of a thick debris and ice covered ocean. A series of fluvial rilles snake across the region, punctuated by lobate mounds and dark streaks. Platy flow-textured plains spread between the Ismenius and Deuteronilus levels. For the sake of argument, let's assume that an ice and debris-covered ocean is present at about the elevation of the Ismenius Level, but that it is gradually receding due to loss via sublimation and redistribution elsewhere on Mars. The ice cover is frozen to the substrate at the edges, but floating as the topography drops off toward the northern plains interior. The fluvial rills could have formed due to a catastrophic disruption of this ice cover—perhaps due to an impact or landslide into the ocean. The dark streaks might also have formed at this time, their orientations with respect to the small knobs and bends in the streaks themselves indicating the direction of motion of the ice cover over underlying topography. In this scenario, the dark streaks represent tears in the ice cover as the ice was pushed past the immovable knobs. Subsequent re-freezing and sublimation of the water from the debris/ice cover at the Ismenius Level has permanently preserved the tears as pseudomorphs of the earlier setting. When the ocean had receded to about the Deuteronilus Level, floods into the northern plains triggered a minor transgression to produce the lobate flow fronts and mounds at the Deuteronilus Level. The mounds resemble mud volcanoes on Earth, and may have formed as water and sediment under pressure broke through the debris/ice cover that had once again frozen to the substrate at the margins.

Following cessation of the floods, the disrupted cover re-froze, this time producing pingos (and thumbprint terrain) as the debris/ice cover froze.

There may be oceans across the outer solar system today, on and under the surface of moons and in the hearts of planets. But these oceans are truly alien seas of methane, ammonia and liquid metal. But what of the kind of seas that lap at the shores of our own world? It seems possible that frigid Earth-like seas existed for some time on the red planet just next door.

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Seas of Molten Rock

4

Rosaly Lopes

The surfaces of the terrestrial planets were, long ago, glowing with hot lava, the frozen remains of which we still see today. When we look at the Moon and see smooth dark patches, we are looking at what, some 3 billion years ago, were seas of lava. In fact, they look so much like seas that they were named Maria by early astronomers. Our own Earth had vast seas of lava long before oceans covered most of its surface. Venus has volcanic features covering some 90 % of its surface, recent results from the *MESSENGER* mission revealed Mercury's volcanic past, Mars has vast plains of frozen lavas as well as the largest volcanoes in the solar system. Jupiter's Io is the most volcanically active body in the solar system today, its colorful surface entirely covered by volcanic materials and its interior likely harboring a magma ocean. As we explore other worlds we find evidence that volcanism played a major role in shaping the planetary surfaces we see today (Fig. 4.1).

The surfaces of the solid planets and their moons resulted from the interplay of four major geologic processes: volcanism and tectonism are the internal ones, while impact cratering and erosion are driven by external forces. The faces of the Earth and Moon are so remarkably different largely because the Earth had both plate tectonics and erosion, and these processes erased the evidence of ancient impact craters and volcanic seas. Our closest neighbor, however, remained pretty much frozen in time. We still see the bright, cratered highlands that were formed during the period of heavy bombardment some 4 billion years ago, and the dark seas of frozen lava that were last active about a billion years before spacecraft revealed the outlines of its ancient lava flows.

Volcanism is how planets lose their primordial heat. Volcanoes can be thought of as windows into the interior of a planet, revealing clues to their formation and evolution and, especially, to the composition of materials that lie beneath. Understanding the diversity of volcanism in our solar system is important for numerous reasons, among them understanding how planets formed from the solar nebula, how planets around other solar systems might form and evolve and, in a more directly applicable way to us, understanding the physics of volcanic processes. We can think of other planets as natural laboratories—how does a volcano behave given different factors such as gravity, internal composition, presence or absence of an atmosphere, and so on.

When we compare how volcanism has affected our solar system's planetary bodies, we see striking similarities but some key differences as well. The Earth is the only body so far where we know plate tectonics operates. If we had never ventured outside Earth, we might have been well-justified in thinking that plate tectonics existed also on Venus, Mercury, Mars, and other bodies. Why does the process of plate tectonics happen only on Earth? Water is a factor as it provides lubrication for the moving plates. Most likely it is also related to a particular thickness of crust relative to the size of the planet. If the crust is too thin, it will crack into small pieces, if it is too thick, it won't break up into plates. Earth just happens to be at the Goldilocks point on this one. The giant volcanoes that built up on Mars, such as Olympus Mons, were able to get to their size due to the relatively thick Martian crust and the lack of plate tectonics. Olympus Mons is a shield volcano similar to those on Hawaii but so much larger. While Mauna Loa is 4.2 km above sea level, Olympus Mons is about 24 km high and 600 km in diameter. The Hawaiian volcanoes were built from the bottom of the sea due to a "hot spot"—a region in the middle of the Pacific Plate where magma comes up. However, the plate moves slowly to the northwest, hence the hot spot will start building another volcano to the southeast. While island volcanoes are relatively common on Earth (think Hawaii, Iceland, the Azores, Tenerife) most of our planet's active volcanoes are hidden under the sea, dotting the boundaries of tectonic plates. There are oceans of lava under our seas! On land, we have about 600 volcanoes considered active—meaning that they have erupted within the last 10,000 years. Whether they

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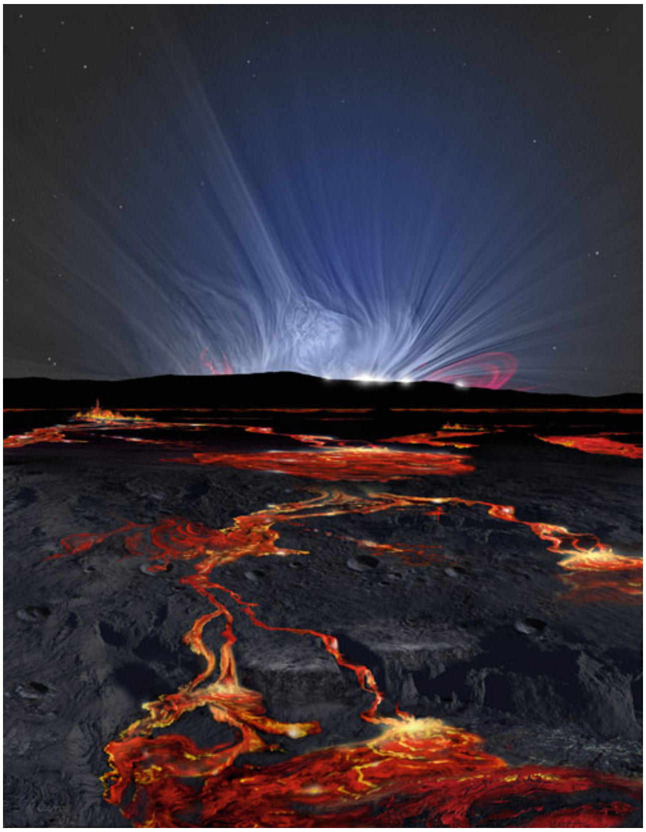

Fig. 4.1 The first "seas" in the solar system were probably seas of molten rock. All terrestrial planets suffered through a phase such as this one on primordial Mercury. Here, we see twilight, as Mercury's sky is bathed in the light of the Sun's corona. Neon-pink flares loop above the horizon in the moments before sunrise (Painting ©Michael Carroll)

are underwater or on land, the location of volcanoes on Earth is controlled by plate tectonics. Most eruptions occur along the boundaries of tectonic plates, where they are spreading apart (the mid-oceanic ridges) or being pushed together (subduction zones). Beneath the plates lies the mantle, covering the hot interior. Molten hot rock (magma) rises through zones of weaknesses in the crust, most often the plate boundaries. Mid-plate volcanoes like the Hawaiian islands and Yellowstone are the exception—they are examples of hot spot volcanism.

The landform created by an eruption could be a field of lava, a cone, dome, or mountain. Sometimes lava pours out onto the surface without explosions and just spreads out, with no built-up landform discernible—a true sea of lava. Fluid basaltic lavas often build up a shield volcano (Fig. 4.2), such as those common in Hawaii and Iceland (they were called shield volcanoes because they look like warriors' shields on the ground). When eruptions are explosive, the landforms are different. On volcanoes such as Sunset Crater in Arizona, the exploded fragments of lava that landed close to the vent built a relatively small but steep-sided cone. The combination of lava flows and explosive eruptions over long periods builds tall volcanoes, such as Mount Fuji in Japan and Mayon in the Philippines. Many people consider these the "typical" volcanoes, with their convex-upward shape. Therefore, knowing the shape of a volcano from spacecraft data gives us clues to the type of eruption (and magma).

Why do some volcanoes erupt with a big bang while others have gentle effusions of lava flows? The main reason is gas dissolved in the magma, which on Earth includes water. As the magma rises towards the surface, the temperature and pressure decrease, making it possible for the gases to escape (like taking the top off a bottle of champagne). The way the gases come out of the magma determines how explosive an eruption is. If the magma contains gases but is very fluid, like Hawaiian basalts, the gases can bubble out, frequently forming spectacular lava fountains. However, if the magma is gas-rich and viscous, the gases cannot escape easily and will eventually explode out, ripping the magma to shreds and creating great clouds of gas and ash (think Mt St. Helens in 1980). If the magma is viscous but very low in dissolved gases, it will ooze out slowly, like toothpaste being squeezed from a tube. Lassen Peak is an example of a lava dome caused by this type of magma. Therefore, when we look at the shapes of volcanoes on other planets and the deposits their eruptions have created, we have clues about the type of magma. In terms of chemical composition, the key factor is the amount of silica in the magma, which is found as SiO_2. The magmas that contain the least amount of SiO_2 are also the least viscous, and these are the basaltic magmas (often referred to as basic or mafic). Basaltic magmas originate in the mantle's upper regions. They erupt in a relatively pristine state, often referred to as "unaltered" condition. Other types of magma contain progressively more percentage of SiO_2: andesites, basaltic andesites, dacites, and rhyolites. These magmas are often referred to as silicic, acidic, or evolved magmas. They are not "pristine" like basalts. Basalts come up from the mid-ocean ridges and hot spots such as Hawaii. Evolved magmas come up from subduction zones, where a lot of mixing of old crust and new magma is going on—think of these evolved magmas as "second hand" magmas.

Relating magma composition to eruption style is important for planetary studies, because gathering direct compositional information from spacecraft (for example, using spectrometers) can be tricky—planetary surfaces can be coated by dust, making it difficult to acquire information on the rock that lies beneath. Sample return or sending human field geologists to other planets lies in the future, hopefully not too far.

There are seas of lava under the Earth's oceans, but those we can readily walk upon and compare with the lava seas on other worlds are on land, and mostly happened a long time ago. The Earth had eruptions in its distant past called "flood basalts" which, as the name implies, resulted in copious

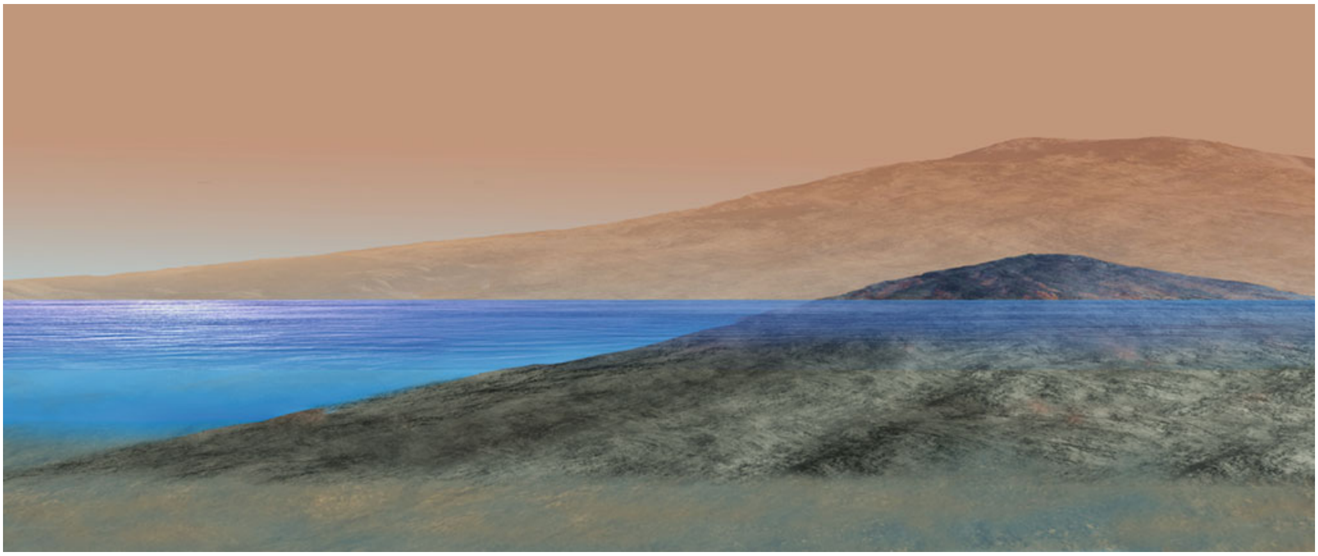

Fig. 4.2 Hawaii's massive shield volcano Mauna Loa is dwarfed by Mars' Olympus Mons (behind). The vertical scale is exaggerated here, but relative heights are to scale (©Michael Carroll)

amounts of low viscosity lavas forming a flood of molten rock. These flood basalts are the Earth's equivalent to the maria or "seas" on the Moon. The Columbia River Basalts in the Western US are an example of flood basalts. The volume of lava on the Columbia River Basalts (or Plateau) is a staggering 170,000 km^3, which flowed between 17 and 15 million years ago. Individual flows are about 20–30 m thick, but can extend hundreds of km. Other well-known examples of flood basalts are the Deccan Traps in India and the Siberian Traps in Russia. The designation "traps" comes from an old Swedish word for staircase. The topography of flood basalts is usually step-like, because the broken-up upper parts of the flows erode more quickly than the more solid lower parts. When this pattern repeats over the lava pile, it looks like steps. Flood basalts were truly catastrophic eruptions because of their volume, and the amount of volcanic gases they put into the atmosphere. Luckily, flood basalts have not happened in modern times. The only recent example of an eruption that can be considered a flood basalt is the eruption of Laki in Iceland in 1783 (Fig. 4.3).

The Laki eruption poured out the largest lava flow in historic times (nearly 15 km^3) and was a major environmental disaster for Iceland. The eruption did not kill anyone directly, but about a third of the population of the country died of starvation. Huge quantities of sulfur dioxide were spewed out and about 100 million tons of sulfuric acid were formed as atmospheric aerosol. The consequences were disastrous for farmland and farm animals and, eventually to humans. The Laki tragic eruption is, however, of great interest to planetary volcanologists, because the flows are possible analogues for flows on Mars, the Moon, Mercury, and Venus.

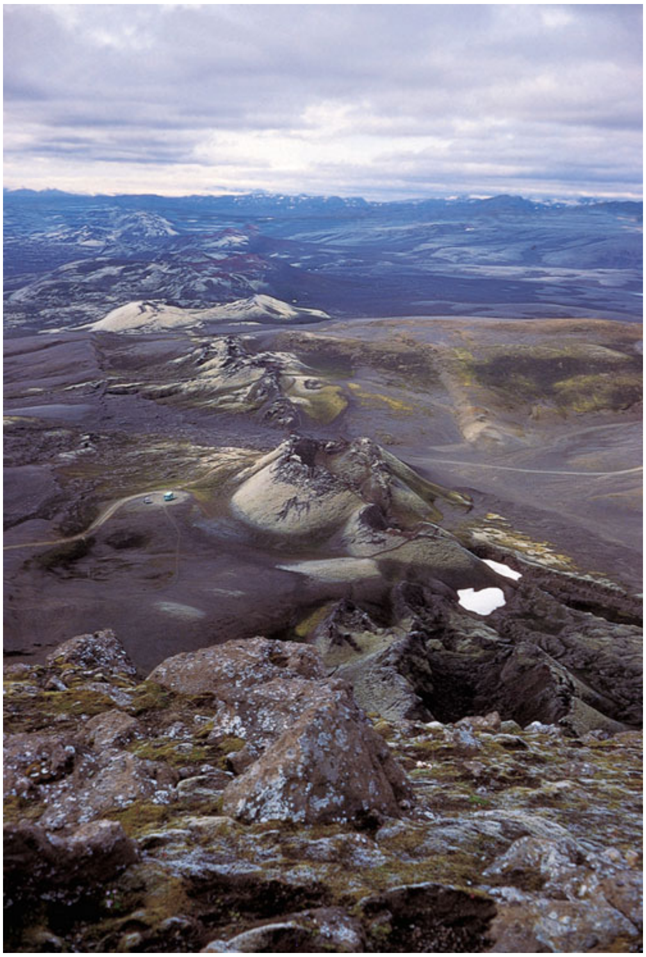

Fig. 4.3 The Laki crater row in Iceland. The Laki eruption of 1783 caused widespread starvation across the island nation (Photo © Rosaly Lopes)

Volcanoes on the Moon, Mercury and Mars

Early in the history of the solar system, volcanoes brought heat and magma from deep within. The surface of the Moon, Mercury, and Mars were aglow in vast seas of lavas. Today we study the remains of their past volcanism and try to piece together the geologic history of these other worlds.

Our Moon once had vast oceans of liquid lava, but today it's volcanically dead—its last eruptions occurred about a billion years ago. It is easy to see the remnants of ancient volcanism on the Moon—just look up on a clear, moon-lit night and you will see the dark patches that once contained flowing lava - the *maria*, or seas, thus named because they looked like seas to early observers. Even before volcanologists could analyze actual rocks, they knew that the Moon's surface once had lava flows, as their outlines are apparent in places such as the Mare Imbrium. Analysis of mare rocks brought back by missions to the Moon showed that the lunar lavas were very fluid basalts which spread relatively quickly to cover vast areas—what an amazing sight this would have been. But there were no tall, Fuji-shaped volcanoes on the Moon, only a few small cones and domes, probably formed in short-lived eruptions of alternating lava and ash. Apollo astronauts collected volcanic glass beads, formed when tiny droplets of magma were erupted into cold space and froze, falling to the surface as round, glassy beads. What caused some lunar eruptions to be explosive? Most likely, small pockets of gases (particularly sulphur and carbon monoxide, traces of which are found on the glass beads) propelled the magma into fountains.

Mercury and the Moon look superficially alike, with impact craters dotting their surfaces. But Mercury has no maria like the Moon. Volcanic activity probably ended on Mercury around 3 billion years ago. Impact craters cover much of Mercury's surface; the *Mariner 10* data showed some smooth plains similar to the lunar maria, with some limited evidence of color differences, possibly indicating lava flows of different compositions. The question of Mercury volcanism remained open until recent results from NASA's MESSENGER spacecraft. Like the Moon, Mercury volcanism appears to have been both explosive and effusive. New insights are coming from *MESSENGER* data, showing additional possible volcanic deposits, most likely composed of basalts but possibly ultramafic volcanism. Ultramafic lavas are high in magnesium and low in silica, which makes them very fluid. This type of lava erupted on Earth millions to billions of years ago. Other than flows, high-resolution images have detected several features that appear to be volcanic, including a shield volcano. *MESSENGER* entered Mercury orbit in March 2011 and we can expect the story of the innermost planet's volcanic history to continue to unfold over the next few years (Fig. 4.4).

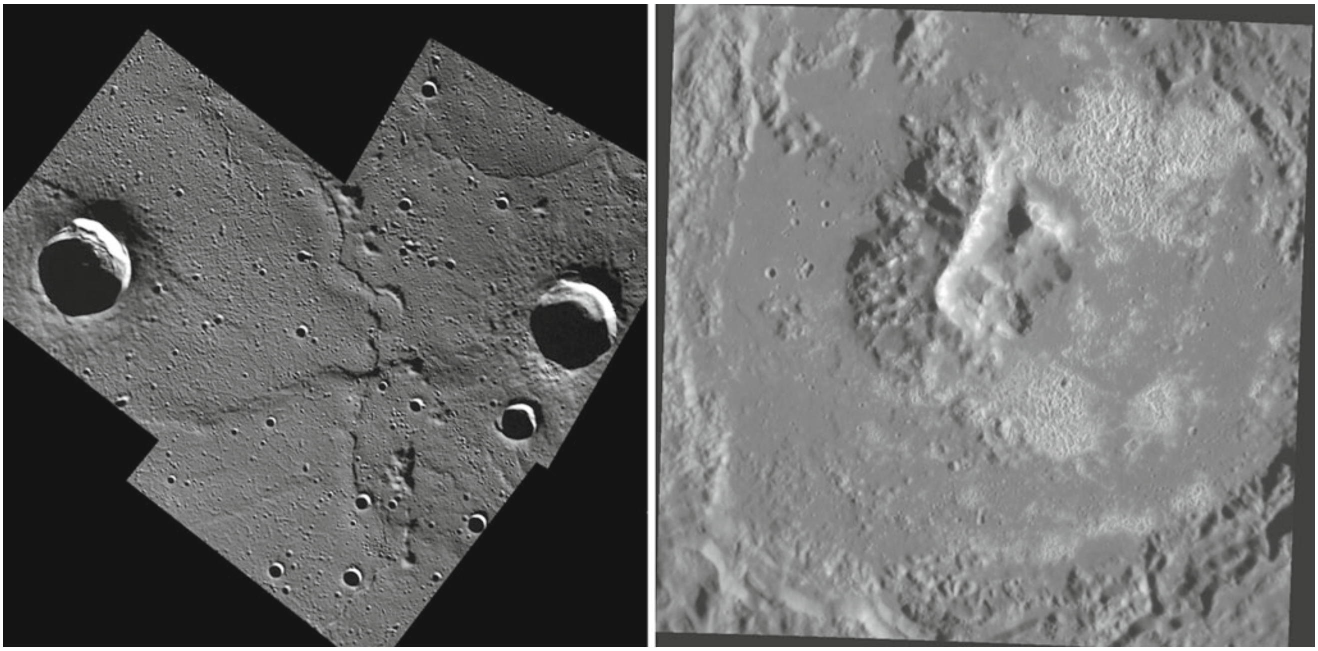

Fig. 4.4 Waves of lava have washed across Mercury's surface in many places, as seen in this image (*left*) from NASA's MESSENGER spacecraft. Lava moved from the west (*left of image*), covering older cratered terrain. The two large impact craters are each ~25 km in diameter. (*Right*) evidence of volcanic venting in hollows in Mercury's Sander crater, which is ~50 km across (Both images courtesy NASA/Johns Hopkins University Applied Physics Laboratory)

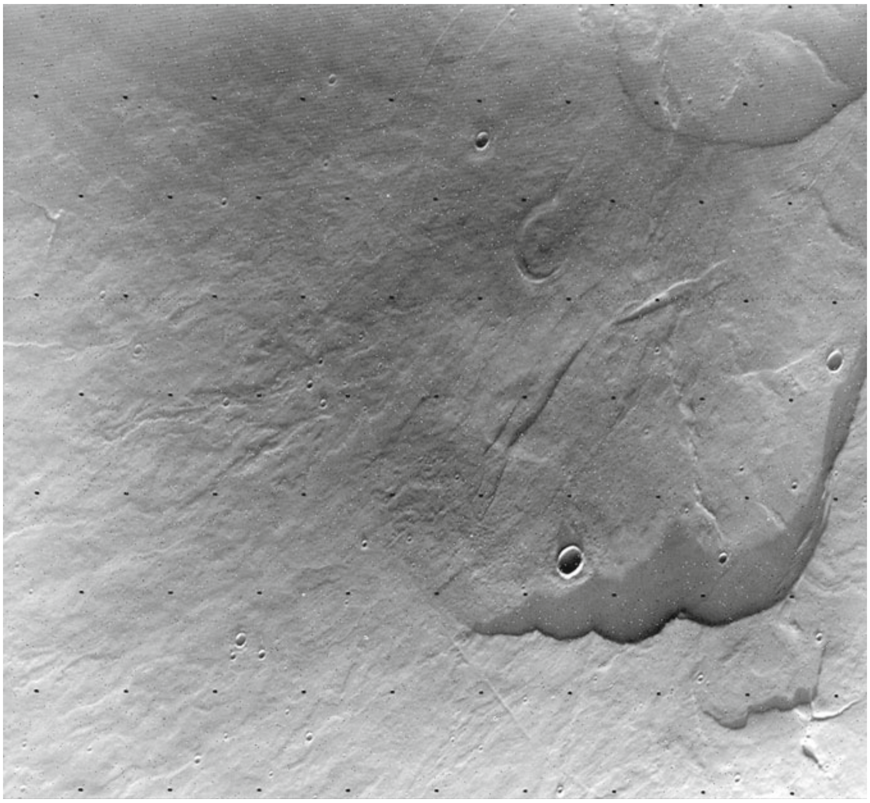

Fig. 4.5 The summit caldera of the martian volcano Alba Patera covers a diameter of ~100 km. Older structures have been partially filled by later lava flowing from lower left (Viking image courtesy NASA/JPL)

In contrast, Mars has been a target of planetary exploration in recent years and we have learnt much about its volcanic history. Because Mars has been the primary focus of planetary exploration since the mid-1990s, and because it has been visited by several spacecraft including orbiters, landers, and rovers, there is a vast quantity of data available on Martian surface geology, including images at resolutions from 30 cm/pixel to several km/pixel, as well as data on surface compositions and the role of volatiles, and atmospheric dynamics and composition. Mars has the largest shield volcanoes in the Solar System, vast plains of lava flows, many lava channels, domes and cones, extensive pyroclastic deposits and considerable evidence of explosive volcanism. Measurements from various orbiters and landers show that most Martian volcanic deposits are similar to terrestrial basalts but some may be of a more viscous type, possibly basaltic andesites, and other compositions may exist which resulted in explosive volcanism. Mars has hundreds of volcanoes and most are much larger than their counterparts on Earth.

Flood basalts make up about 40 % of the surface of Mars, forming vast lava plains mostly on the northern hemisphere. The giant shield volcanoes like Olympus Mons have shallow slopes and would look from the ground like seas of lavas. Even more so is the volcano Alba Patera (Fig. 4.5), an ancient, 1,500 km wide volcanic structure covering an area larger than Olympus Mons. Alba has flank slopes of less than 1° and thus lacks the relief of shield volcanoes. The two giant calderas are surrounded by enormous lava flows, some sheet-like, others having tubes and channels.

Despite the widespread occurrence of volcanic features on Mars, and the number of spacecraft studying the planet, we have not found any conclusive evidence for current—or even very recent—volcanic activity. However, analysis of Martian meteorites that have been recovered on Earth show that the most recent Martian rocks crystallised out of lavas about 170 million years ago, young in planetary terms. High-resolution images from Europe's Mars Express orbiter show few impact craters over some volcanic areas, leading geologists to conclude that some of the lava flows are less than 2 million years old. It's possible that Martian volcanism is not yet dead.

Particularly intriguing are measurements of atmospheric methane (CH_4) gas detected from Earth-based telescopic observations and, later, by measurements from ESA's Mars Express. Given that the atmospheric concentration is only a few parts per billion, measurements are particularly challenging to make. But the presence of methane is very significant, because chemical processes in the Martian atmosphere destroy the gas, so its lifetime is less than a few 100 years—indicating that something is replenishing it. The methane is concentrated in particular locations and the source could be either volcanic gas or biological activity. While many scientists view volcanic gas as more likely, the degassing implies that hot magma still lies below the surface. At the time of writing, results of the measurements from the rover Curiosity, which successfully landed on Gale Crater in August 2012, did not show the presence of methane.

Venus: Land of Volcanoes

Venus is a true volcano planet as at least 90 % of its surface is covered by volcanic materials. In fact, our "evil twin" planet shows more volcanic terrains and edifices than any of the other terrestrial planets. Unlike the other planets, Venus has a thick atmosphere, which made its volcanoes remain largely hidden until the Magellan spacecraft, carrying Synthetic Aperture Radar (SAR), mapped most of the planet in the early 1990s. The Soviet Venera 13 had imaged the surface around the landing site in 1982, revealing a surface interpreted as lava flows. We could say that the Venusian surface is young and hot. Geologically, the Venusian surface is young, as shown by the relatively small number of impact craters. Surface temperatures are more than 700°C, air pressure at the surface is 90 times that of Earth at sea level, and sulfuric acid rains from the clouds. It is not surprising that some of the volcano morphologies on Venus are unusual, with no counterpart elsewhere in the solar system. The Venusian seas of lava are not unusual in planetary terms. There are large plains formed by lava flows across which run long, sinuous channels, some thousands of kilometres long. Although we do not have enough information to be certain of the composition of the lavas, some of the lavas must have been very fluid, to allow them to flow long distances. The Baltis Valley is the longest lava channel in the solar system, about 6,400 km long. As both ends of this channel have been covered by lava flows, it is possible that it is even longer. The chemical composition of the lavas must allow them to flow over long distances. They may be ultramafic lavas, or sulfur-rich or more exotic types. Carbonitite volcanism, such as happens at Ol Doinyo Lengai on Earth, has also been suggested. Carbonitites flow at 490°C, which is close to the surface temperature on Venus, therefore those lavas would be able to stay molten for long periods of time. However, we lack compositional information from Venus, so the question remains open.

The lava seas of Venus are dotted with many different types of volcanoes. Some are similar to Hawaiian-type shield volcanoes on Earth and Mars, while others indicate more viscous lava compositions. There are many shield volcanoes, but they are smaller than those on Mars. Most are 20 km in diameter or less. Some of the shield volcanoes are very large, but there are relatively few of those. For example, Sif Mons is about 350 km in diameter and 2 km high. Large shields on Venus tend to sit atop broad topographic rises, suggesting that they may be over hotspots similar to the Hawaiian volcanoes. These hotspots appear randomly located on Venus, with no alignments that might suggest tectonic plates.

Venus has other types of volcanoes that are different from those found elsewhere in the solar system (Fig. 4.6), and have been given strange-sounding nicknames. "Pancake" domes are steep-sided domes with flat tops that may be similar to silicic domes on Earth, formed by high viscosity lava that is extruded slowly. Some pancake domes appear to have been eroded by landslides, changing their appearance to a strange landform known as "ticks". "Arachnoids" seem to be relatives of ticks. These are volcanic domes surrounded by a cobweb of fractures and crests, possibly the result of upwelling magma that stretched the surface. Soviet scientists first named these features after seeing vast concentric fractures spreading out from volcanic sources in Venera radar images. Continuing the theme of strangely-named volcanoes, Venus also has the "anemone", volcanoes that have lava flows arranged in overlapping flower-like petals extending outward. The lava flows may have come out of fissure eruptions involving a series of elongated vents at the summit. Another type of volcano that appear to be unique to Venus is the corona. Coronas are large (>100 km) circular or oblong systems of fractures and ridges that span hundreds of kilometers. They were probably formed by rising magma bowing up and deforming the surface, producing a ring of concentric ridges. As the magma pushed up against the crust, the surface rose to form a dome. The hot lava spread out under gravity and flattened and, as the area cooled, it sunk and cracked, forming a circular ring around a depression.

The most exciting thing about Venusian volcanoes is that some may still be active. In the late 1970s, NASA's Pioneer Venus spacecraft measured a steady decrease in the amount of sulfur dioxide (SO_2) above the cloud tops. It is possible that a massive volcanic eruption had sent large amounts of sulphur dioxide into the atmosphere and by the time of the *Pioneer* observations, the eruption had ceased and the sulphur dioxide was slowly breaking down. More recently, some exciting results emerged from Europe's Venus Express orbiter. The spacecraft's Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) measures how much energy the surface radiates at a wavelength of about 1 μm. Fluctuations across the surface relate to variations in chemical composition. When scientists correlated VIRTIS data with Magellan radar images and topographic data of the surface, they found that three areas, Imdr, Themis, and Dione Regiones, are anomalously bright. Taken together, these results indicate relatively recent lava flows. The fact that these flows are so pristine is evidence that they are considerably younger than most others on Venus, possibly 250,000 years old or younger—very young in geologic time. Magellan did not find any evidence for surface changes, so if volcanism is still happening on Venus, it is probably not often—but the possibility of detecting an eruption certainly makes future missions to our evil twin exciting.

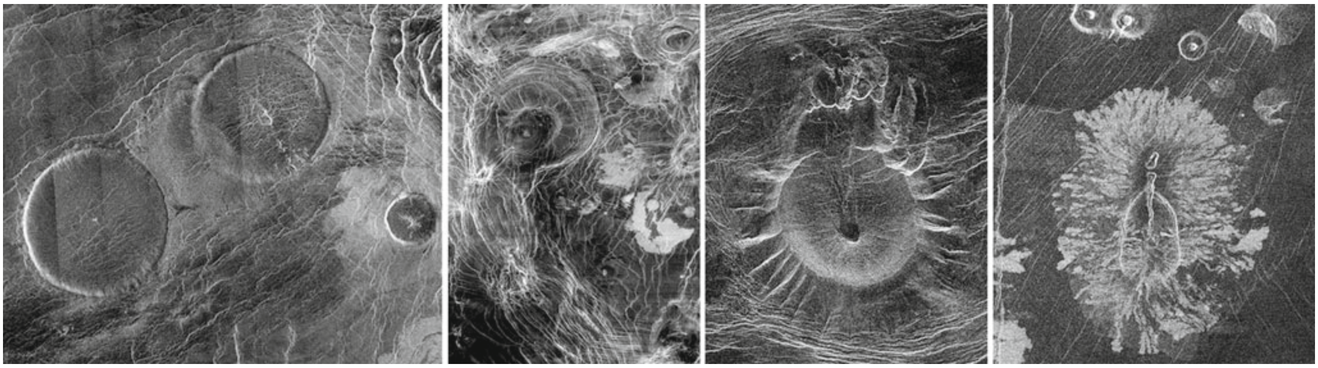

Fig. 4.6 Venus exhibits some truly alien volcanoes. *Left to right*: Pancake domes are approximately 50 km in diameter; concentric and radial fractures spread from arachnoids, giving the appearance of a giant spider. Arachnoids' average diameter is 125 km; this tick volcano in Alpha Regio has a rim ~30 km across; lava flows spread as far as 32 km from the central source of this "anemone" volcanic structure (All Magellan radar images courtesy of NASA/JPL)

Volcanoes on Io

Io is the most volcanically-active body in the solar system and the only place other than the Earth with large-scale silicate volcanism. Its volcanism was, at first, hard to understand because Io is just 5 % larger than our own Moon and it was expected to have cooled and formed a thick crust long ago. However, Jupiter's gravitational pull on Io is so great that it creates a tidal bulge on the crust, while the moons Europa and Ganymede distort the bulge as they pull it towards them. This friction creates heat, which keeps the interior of Io molten. Io's volcanism was predicted on the basis of these orbital interactions shortly before the 1979 Voyager flyby revealed large plumes coming out of volcanoes. Since then we have learnt a lot more about Io's amazing volcanic eruptions, observing them from ground-based telescopes, and the missions Galileo, Cassini, and New Horizons.

Most of Io's surface is covered by sulphur dioxide frost, condensed from the spectacular volcanic plumes, some of which are several 100 km high. The plumes are mostly composed of sulphur and sulphur dioxide gas, with a small percentage of ash. The last spacecraft to fly by Io, New Horizons, captured remarkable images of the plume over the Tvashtar volcano (Fig. 4.7). But scattered on the pizza-like surface of Io are regions of dark materials, which are silicate lavas, still hot and active in many places. Io's volcanoes rarely build structures such as shield volcanoes, but some immense flow fields exist, covering part of the surface in seas of hot lava. The Amirani flow reaches some 300 km in length, and is the largest active flow in the solar system. Repeated imaging of Amirani during the *Galileo* fly-bys allowed eruption rates to be estimated to be 50–500 m^3s^{-1}, which are considered moderate lava effusion rates by terrestrial standards. The ability of the Amirani lava flow field to travel large distances at moderate effusion rates suggests not only that lavas had a low viscosity, but also that they were emplaced as insulated (probably pahoehoe like) flows, so that the cooled crust would insulate the hot material underneath. Thermal profiles along the Amirani flow field, and also along another flow field called Prometheus, and high spatial resolution images from the camera suggest that these large flows were similar to terrestrial pahoehoe flows. They are possibly similar to flood basalt lavas on Earth, which occurred many millions of years ago. Studying Io's volcanism thus gives us a window into Earth's past, as we can study these large eruptions happening on Io (Fig. 4.7).

Some of Io's lava flows create plumes of sulfur dioxide as they move. The best example is Prometheus volcano, also known as the "Old Faithful" of Io because its plume is always present. The "Prometheus type" plumes are relatively small, less than 200 km in height and appear to be caused by the interaction of lava flows with frozen sulfur dioxide in the subsurface. The sulfur dioxide erupts through the distal part of the flow and forms a plume. Perhaps liquid sulfur dioxide from an underground layer is tapped, and keeps feeding the plume. An interesting consequence is that, as the lava flow moves, so does the plume, located near the distal margin of the flow. This caused quite a puzzle for *Galileo* scientists at first, as they noted that the Prometheus plume had shifted some 90 km since the days of *Voyager*, yet its appearance was the same. It turned out that the flow had travelled that distance between the two spacecraft encounters. Since the flow created the plume, the further west the flow moved, the further west the plume erupted from.

Most of Io's volcanoes are caldera-like depressions, referred to as paterae (singular patera, meaning 'saucer-like crater') (Fig. 4.8). Although the origin of paterae is still somewhat uncertain, they are thought to be similar to terrestrial volcanic calderas, formed by collapse over shallow magma chambers following partial removal of magma. Some paterae show angular shapes that suggest some tectonic control, indicating that they may be structural depressions that were later used by magma to travel to the

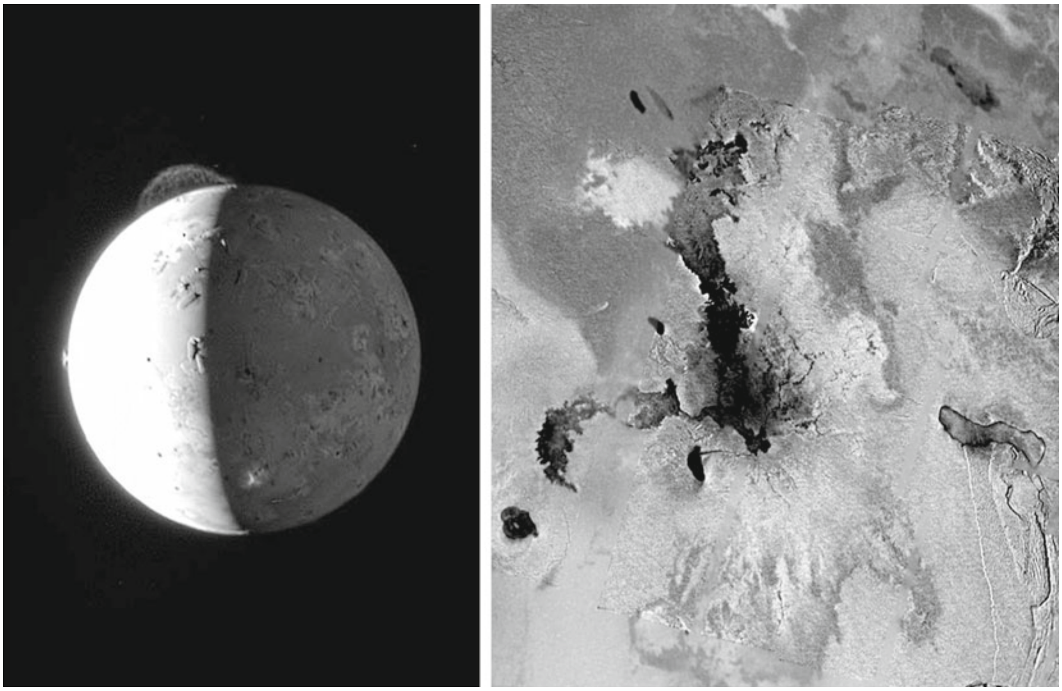

Fig. 4.7 A volcanic plume towers some 330 km above Io's Tvashtar volcano (*left*), seen here through the robot eyes of the Pluto-bound New Horizons spacecraft (JHUAPL/NASA); (*right*) the Amirani lava flow field, over 300 km long, is the longest active lava flow known in the solar system (Galileo image courtesy of NASA/JPL)

surface. At least 400 Ionian paterae have been mapped. Their average diameter is ~40 km but Loki (named after the Norse god of fire) is the largest patera known in the Solar System, over 200 km in diameter. In contrast, the largest caldera on Earth, Yellowstone, is ~80 km by 50 km in size. The larger sizes of the Ionian features probably reflect the much larger sizes of magma chambers, which are thought to be relatively shallow. Loki has been active for decades, observed by Voyager, Galileo, and ground-based observations. It is the most powerful volcano in the solar system, and continuously active (Fig. 4.9).

Inside Loki is a sea of dark lava which may, in fact, be a lava lake, which is perhaps a common type of eruption on Io. *Galileo* infrared observations show an incandescent shore along one edge of the lake, similar to the lava lakes found on Kilauea and a few other places on Earth, such as Erta Ale in Ethiopia. Lava lakes often have a cool crust at the top, but the crust can break up as it collides with the caldera wall, exposing glowing lava cracks. A rather puzzling feature is a gigantic island-like feature covered by frozen sulfur dioxide frost, meaning that the island has not seen any volcanic activity for some time (otherwise the frost would be gone). The island is about the size of Rhode Island, and has not changed in appearance between *Voyager* and *Galileo* observations, meaning that it is most likely anchored and not floating like an iceberg (Fig. 4.9).

Io has some violent explosive eruptions, sometimes called outbursts, such as those that happened at the volcanoes Pillan and Tvashtar. These eruptions typically have a fissure from where a row of fire fountains erupts from, and lava flows follow. They usually have large but often short lived plumes, which leave big rings of plume deposits. The giant 1997 eruption from Pillan, observed by Galileo, produced a large, dark ash deposit. Tvashtar's eruption, observed by Galileo and from the ground in 1999, produced a curtain of glowing lava 22 km long, which erupted from a fracture in the floor of a great caldera. A nearby plume erupted over 100 km above the surface. In 2007, the New Horizons spacecraft flew by Io on its way to Pluto. Tvashtar was still erupting in a spectacular way, with a plume about 300 km high.

These violent eruptions are the best for temperature measurements, since they expose lots of hot materials (lava flows and lakes, in contrast, form cooled crusts quickly). Temperatures detected from these violent eruptions provide the best clues to magma composition, as the temperature at which different types of magma melt depends on their composition. Measurements obtained from the Pillan volcano showed temperatures of about 1,500°C, too high for basalt (basalts on Earth rarely exceed 1,200°C) but consistent with ultramafic lavas. More recent calibration of the same data puts the temperature lower, at around 1,300°C, still unusually high for basalts but possible in some circumstances. The

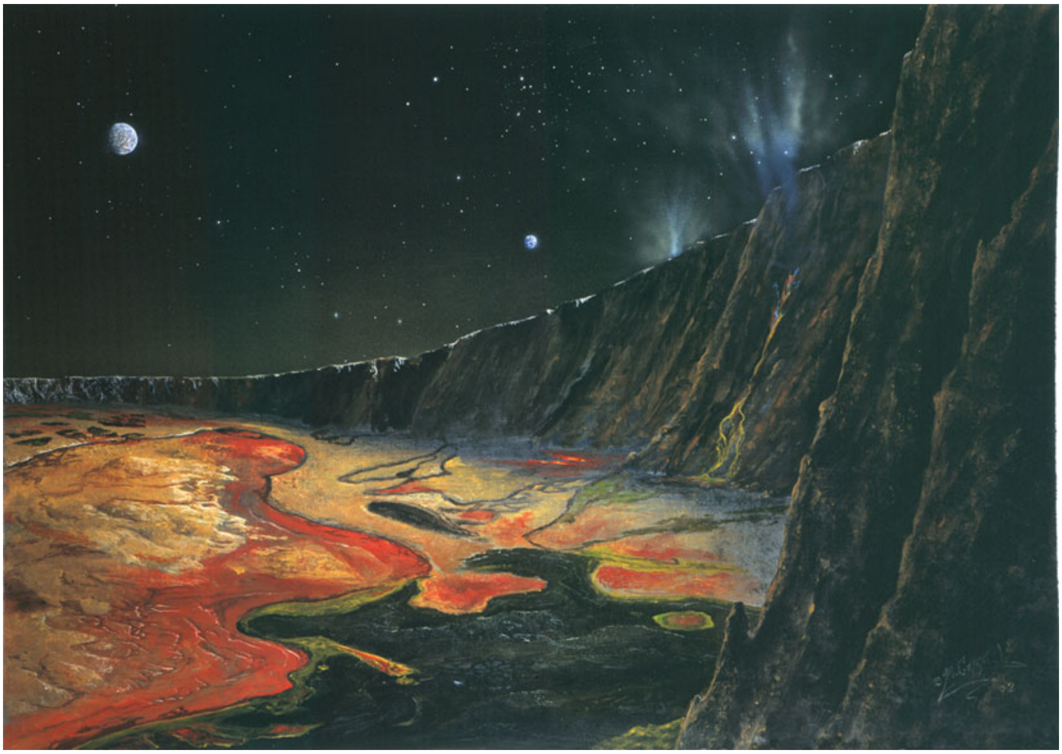

Fig. 4.8 The colorful Tupan Caldera on Jupiter's moon Io spans a diameter of 75 km, and is surrounded by 1,000-m-high cliffs (©Michael Carroll)

Fig. 4.9 Artist's impression of the vast lava lake in the ~200 km diameter Loki caldera on Io. Europa and Ganymede pass overhead at right (©Michael Carroll)

question is still open as to whether Io's magmas are ultramafic, similar to those suggested for Venus and Mercury, and to magmas that erupted on Earth millions to billions of years ago.

How about flows made of sulfur? A major question about Ionian volcanism after *Voyager* was whether volcanic flows were sulfur or silicates. One of the ways of telling apart sulfur from silicate lavas is from their eruption temperature. The highest temperature detected by the Voyager infrared instrument was about 300°C, but most temperatures of hot spots were found to be around 100°C, which is about the melting temperature of sulfur. Basalt melts at around 1,000°C, but cools quickly once erupted, so there was no way of telling if the Io hot spots were sulfur or cooled basalts. The infrared instrument aboard the Voyager spacecraft was not designed to be sensitive to the lower infrared wavelengths, which are best to use to detect high temperatures. The composition of Io's lavas remained undetermined for some time, until telescopic observations from Earth, using infrared instruments, detected temperatures around 700°C—too high for sulfur. By this time, the Galileo spacecraft was already on its way, with instrumentation better equipped to measure temperature of Io's hot spots. Although temperature measurements from *Galileo* clearly showed that many hot spots have temperatures far too high for sulfur, the possibility that some sulfur flows occur on the surface cannot be ruled out. Back in 1979, Carl Sagan argued that the colorful flows around a volcano called Ra Patera were sulfur flows, but unfortunately these flows had been covered over by new eruptions before *Galileo*'s first observations of the area in 1996. However, *Galileo* observations showed other locations that may have sulfur flows. While most Ionian flows appear dark, a few locations show pale yellow or white flows that may well have been molten sulfur. It is possible that rising silicate magma may melt sulfur-rich rock as it nears the surface, producing 'secondary' sulfur flows (as opposed to 'primary' flows that originate from molten magmas at depth). This happened in Mauna Loa, Hawaii, around 1950, and produced a small sulfur flow. So far, the presence of sulfur flows on Io remains open, but it is clear that most of the volcanism is silicate because of the high temperatures detected. There may be some other lava compositions on Io, such as sulfur dioxide. The Near-infrared mapping spectrometer (NIMS) instrument on Galileo mapped a nearly pure sulfur dioxide region topographically confined within a caldera called Baldur. One possibility is that the sulfur dioxide was emplaced as a liquid flow rising from the subsurface. While liquid would normally boil off when exposed to Io's near-vacuum atmosphere, it is estimated that, given sufficiently large quantities, some of the liquid could freeze to form a layer of sulfur dioxide ice inside the caldera. Only a couple of locations have so far been found on Io where sulfur dioxide may have erupted this way, forming rather exotic types of lava "seas".

Results from *Voyager*, *Galileo,* and *New Horizons* missions showed us what a volcanic wonderland Io is, but much remains to be discovered. No doubt the next spacecraft to the Jupiter system, at present a European mission planned to arrive in the 2020 decade, will find some new surprises.

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Jupiter's Water Worlds: Water Lurks Beneath the Surfaces of Europa, Ganymede, and Callisto

5

Robert T. Pappalardo

For nearly four centuries since their discovery, four planet-sized worlds circled the giant planet Jupiter as mysterious points of light. But when the twin Voyager spacecraft cruised past Jupiter in 1979, their robot eyes revealed the astounding diversity of the moons of ice and stone known as the Galilean satellites. The Voyagers revealed the cratered countenance of Callisto, the valleys and ridges of Ganymede, the cracked icy face of Europa, and the spewing volcanoes of rocky Io. But it would take a spacecraft named for Italian scientist Galileo, who first described the moons in 1610, to reveal the true complexity of these worlds and to begin to divulge their interior secrets. Incredibly, the Galileo data strongly suggest that Jupiter's three large icy moons (all but rocky Io) hide interior oceans (Figs. 5.1, 5.2, and 5.3).

Crumbling Callisto

Viewed from afar, Callisto appears heavily cratered, with few signs of internal activity, let alone an internal sea (Fig. 5.4). Debris from asteroids and comets has bombarded its dark surface for billions of years, with the largest early impacts forming giant bull's-eye-like rings. The biggest of these, named Valhalla, was created in a gigantic collision that took place more than 4 billion years ago. As slushy ice flowed inward to fill the enormous hole, Callisto's cold, brittle skin was dragged inward as well, fracturing into a series of concentric arcs.

Up close, Callisto's dark surface appears as a smooth fog that cloaks the moon's contours. Bright knobs poke through the shroud like islands from a dingy sea. Callisto's visible craters run the gamut from fresh to ruined, the latter looking moth-eaten and craggy. Their bright rims resemble the bouldery remains of ancient stone circles; their interiors brim with dark debris.

The process of sublimation, which occurs when solid material turns directly into gas, best explains the origin of this rubbly surface. A mixture of ice and rock delivered by colliding comets and ice-rich planetesimals can sublimate slowly over time, leaving a dusty lag behind. Accumulating dust then trickles downhill. Some tongues of dark debris attest to landslides that have roared downhill into craters. It seems that ice sublimation and downhill sliding are the chisels that sculpted Callisto's landscape, and which are still slowly changing its face today.

Of the Galilean satellites, Callisto's ancient, cratered surface should hold the most pristine and primitive material, the stuff from which the moons were built. The Galileo spacecraft's infrared spectrometer confirmed water ice exists in Callisto's bright areas, and it found carbon dioxide ice residing in some bright, fresh impact craters. Carbon dioxide leaking from dry ice buried just under the surface can explain Callisto's thin atmosphere, which is just several quadrillionths as thick as Earth's.

The spectral fingerprint of Callisto shows a surface with widespread clays. Hints of carbon and nitrogen compounds, the kinds of organic molecules that may have been precursors to life on Earth, are scattered across its landscape. Through the eons, comets and asteroids have rained organic-rich debris onto Callisto, as well as the other jovian moons. This rain was a torrent at first, and has slowed to a trickle at the present time.

Some of the most startling findings about Jupiter's icy moons come from measurements that peered indirectly beneath their skins. Each time the Galileo spacecraft soared by a Galilean moon, mission controllers precisely tracked the spacecraft's velocity by measuring the Doppler shift of its radio signal. Changes in velocity measured the gravitational pull of each moon, which is related, in turn, to the distribution of ice, rock, and metal within. These gravity studies suggest that Callisto is a mix of rock and ice deep

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Fig. 5.1 An eruption of molten lava on the deep, buried rocky core of Ganymede could melt out the surrounding high-pressure ice to form a huge water-filled cavern (© Michael Carroll)

into its interior, with its constituents only partially segregated. This implies that the moon's innards never melted throughout, somehow staying relatively cool as Callisto accreted in the ancient debris cloud around Jupiter.

The magnetic field at Callisto provides another peek beneath the moon's surface and points to an astonishing conclusion: Callisto probably hides a watery subsurface ocean today. Although Callisto does not generate its own magnetic field, Galileo found that the powerful magnetic field of Jupiter triggers one in Callisto. Here's how it works: The jovian magnetic field is tilted slightly to the orbital plane of the satellites, so as the giant planet rotates, Callisto effectively bobs up and down in the jovian magnetic sea. The direction of the jovian field as viewed by Callisto correspondingly changes every 5 hours. As Jupiter's magnetic field effectively flips, it causes Callisto to create an oppositely oriented magnetic field. Existence of this "induced" magnetic field must mean Callisto's interior conducts electricity. Icy innards cannot explain this; instead, the moon almost certainly contains an underground global ocean of salty water.

The decay of radioactive elements left over from Callisto's formation does not generate enough heat to melt pure ice within the moon today, but salts or just a bit of ammonia could play the role of an antifreeze, making it easier for ice to melt within like salt scattered on an icy sidewalk. Also, as pressure increases within Callisto, common ice like that found in our freezers is transformed into more compact forms. This means that Callisto's ocean should lie about 110 miles (170 km) into the moon, at the boundary between commonplace ice that floats on water and stranger forms of ice that sink.

Far beneath its crumbling countenance, the seas of Callisto stir, aided by salt or ammonia, and betrayed by its electrical properties. But this deep ocean will remain forever inaccessible.

Ganymede's Grandeur

The Galilean moon named for a young prince better conveys the turbulent life of an old man, with faults and fractures laid out like creases on its icy skin (Fig. 5.5). The Voyager spacecraft recorded Ganymede's diverse expressions: furrowed dark terrain, bright grooved terrain, and impact craters including ghostly palimpsests. But the moon holds even greater surprises within.

Ganymede's dark terrain is densely pockmarked with impact craters, some nearly as old as the solar system itself. Furrows arc across its countenance, many tracing roughly concentric circles that are reminiscent of the giant, impact-induced bull's-eyes on neighboring Callisto. Close-up images suggest darkening by a clay-rich veneer that drapes a bright icy substrate.

Impact scars on Ganymede take many forms. Some are surrounded by a low pedestal that surged outward from the impact site. Some show a central pit or dome. Others are ethereal bright patches termed palimpsests, named for reused parchment from which older writing has been incompletely erased. Like partially visible ancient text, traces of Ganymede's furrows can be discerned within some. The palimpsests probably formed when ancient, large impacts pierced a thin and brittle icy shell, splashing water and slushy ice onto the surface.

The longer you stand out in the rain, the wetter you will get. Similarly, the more heavily cratered a planetary surface, the older it is, because it has had more time to be smacked by debris that has rained down from space. Compared with its dark terrain, Ganymede's more sparsely cratered grooved terrain sports relative youth. Depending on the uncertain rate at which asteroidal and cometary debris has pummeled Ganymede over time, the grooved terrain may be just hundreds of millions to as many as 4 billion years old.

The parallel ridge and valley sets that comprise grooved terrain crisscross Ganymede's surface in sets, the alternating valleys and ridges resembling furrows in a plowed field. Tens of kilometers wide and hundreds long, these corrugated swaths split the older, dark terrain into polygonal tracts. Their shapes and interrelationships indicate the grooves formed chiefly through stretching of the moon's icy skin.

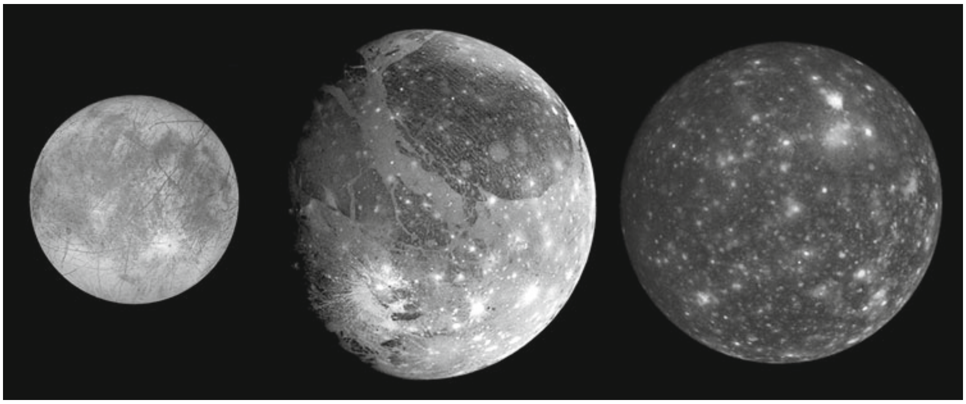

Fig. 5.2 The large icy moons of Jupiter: Europa, Ganymede, and Callisto. Europa, the smallest at 1,939 miles (3,121 km) in diameter, is about the size of Earth's moon. Ganymede, at 3,270 miles (5,262 km) in diameter, is larger than the planet Mercury (Courtesy NASA/JPL-Caltech/DLR, Image NASA PIA00601)

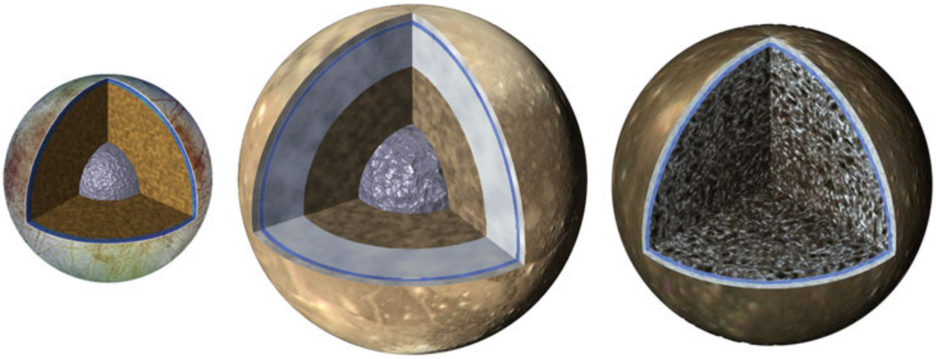

Fig. 5.3 Current understanding of the interiors of Jupiter's large icy moons is that they each have interior ocean layers. Europa's ocean is unique in having an ocean in direct contact with mantle rock. In contrast, the oceans within Ganymede and Callisto are sandwiched between layers of ordinary ice above and high-density forms of ice below. Both Europa and Ganymede both have rocky mantes and deep iron cores, while Callisto's interior is principally a mixture of ice and rock, above a deep rock-rich core (Courtesy NASA/JPL-Caltech)

Unlike contraction, which creates accordion-like folds like those of Earth's Appalachians or Alps, pulling apart can create long valleys and can rotate and tilt slabs into pointed mountains, as has shaped the landscape of Arizona and Nevada.

The grooved terrain's brightness can be explained if water erupting from volcanic vents once covered up and erased tracts of the dark, ancient surface. However, watery "magma" would be denser than ice, so it should sink into Ganymede rather than rise. But just as a shaken soda bottle froths when opened, dissolved gases might drive a bubbly slurry upward to erupt, or perhaps warm glacial ice under the grooved terrain was able to rise buoyantly toward the surface.

The ubiquity of Ganymede's grooves implies that the entire moon expanded during its adolescent years. Grooved terrain tells of a fierce internal strife, perhaps the imprint of heating and separation of interior components to cause expansion. The grooved terrain seen today is the frozen vestige of a violent past.

Like Callisto, the Galileo spacecraft detected an induced magnetic field at Ganymede, pointing to a salty ocean within the moon today. But quite distinct from Callisto, Ganymede also has a stronger internally generated magnetic field, created by the churning of a partially molten iron core. Its strength is only about 1 % of Earth's magnetic field, but it is strong enough for Ganymede to carve out its own magnetospheric bubble within Jupiter's much larger magnetosphere. This makes Ganymede unique among the solar system's moons: Ganymede is the only moon known to have an internally generated magnetic field. Galileo's gravity measurements reinforce this narrative, indicating that much of Ganymede's mass is concentrated in a central metallic core.

From this, we can reassemble a tumultuous history for Ganymede. Intense heating once melted Ganymede's icy

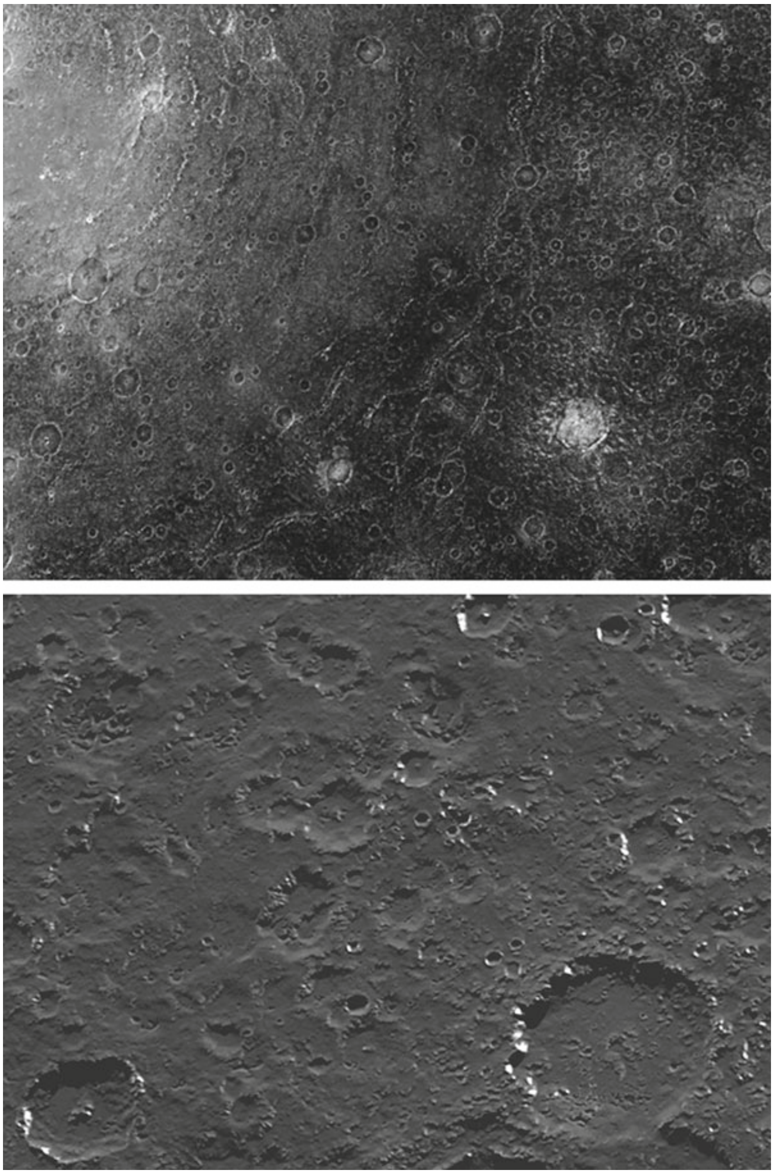

Fig. 5.4 Callisto's dark, impact-strewn surface. In the top image, 620 miles (1,000 km) across, concentric rings radiate like a bull's-eye from the central bright region that marks the Asgard multi-ringed impact structure. In the bottom image, 60 miles (100 km) across, old impact craters are buried in dark debris, and just a few bright icy slopes are visible (Courtesy NASA/JPL-Caltech/DLR, Image NASA PIA00743)

innards. In a process called *differentiation*, the moon's ice matrix released its rock, which sank down to form a stony mantle, while water and slurry floated up and chilled into an icy skin. The moon's rocky interior heated so much that metal melted out and sank further downward to form an iron-rich core. Ganymede's internal magnetic field tells us that the iron core has not yet completely cooled off from its period of intense activity. Ganymede's induced magnetic field signals that an interior ocean persists beneath the outmost layer of ice—as at Callisto, probably sandwiched between ice layers above and below, perched about 110 miles (170 km) beneath the surface.

Ganymede's intense heating and differentiation must have occurred relatively late in solar system history, ending only about a billion years ago, judging from the remnant heat that maintains the molten iron core and Ganymede's internal ocean. Such relic heat could also trigger melting within Ganymede's interior rocky mantle. Perhaps volcanoes erupt onto the "surface" of that mantle, melting some of the ice in contact immediately above, to create giant water caves forever hidden some 560 miles (900 km) below Ganymede's visible icy surface.

But what has caused this heating? And why are the appearances and histories of Ganymede and Callisto so different? Data from Galileo indicate that the disparities between Ganymede and Callisto are much more than skin deep: the gravity data show that their interiors are very different as well, with Ganymede having a strongly differentiated internal structure indicative of momentous heating, while Callisto is weakly differentiated. The fundamental

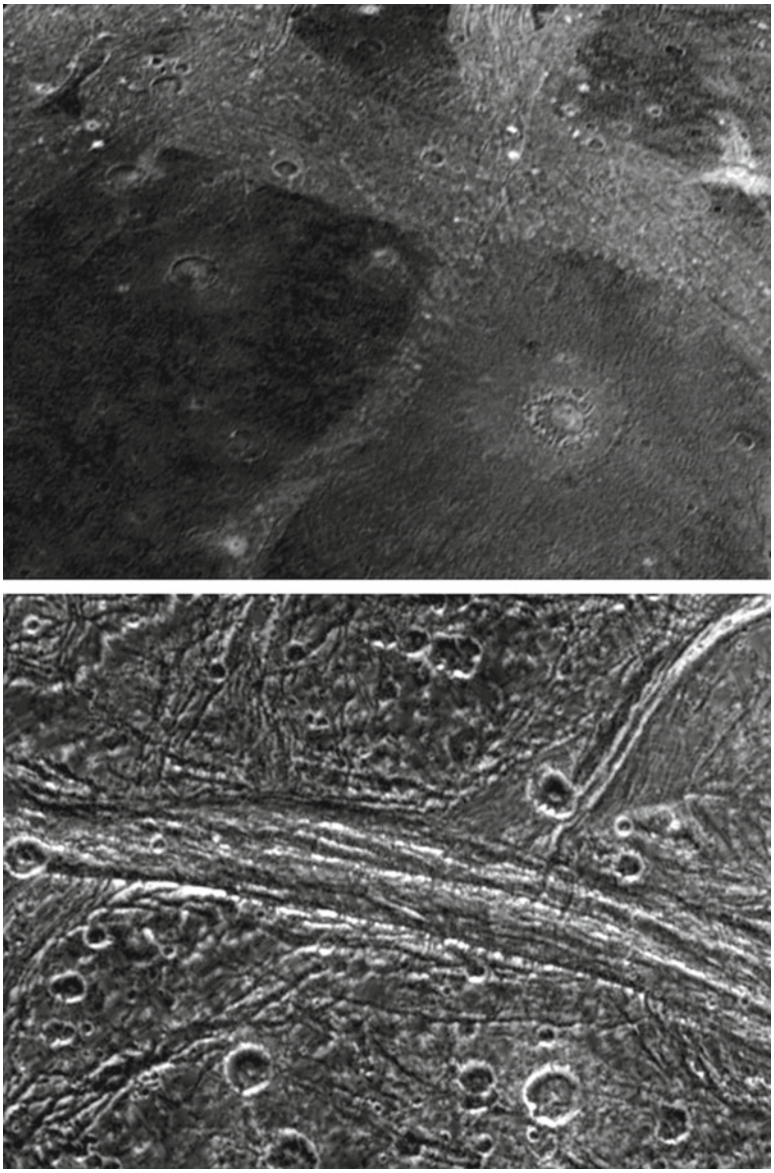

Fig. 5.5 Ganymede's dark and grooved terrains. In the top image, 620 miles (1,000 km) across, lanes of bright grooved terrain criss-cross older dark terrain, and both are splashed by ejecta tossed from a crater that shows a central dome. In the bottom image, 60 miles (100 km) across, intricate fractures cut the heavily cratered dark terrain, and parallel grooves typify the bright grooved terrain (Courtesy NASA/JPL-Caltech/DLR, Image NASA PIA00743)

difference between the two moons seems to be the related processes of heating, melting, and differentiation—which induced wide-scale geological activity on Ganymede but essentially none on Callisto.

Tidal heating most likely explains the divergence of these sibling moons. Giant Jupiter raises tides in the body of each of the four Galilean satellites, but the orbits of the three inner moons—Io, Europa, and Ganymede—are locked together. Each time Ganymede orbits around Jupiter once, Europa orbits twice, and Io orbits four times. This linked orbital dance of the three inner moons keeps their orbits non-circular, so they are constantly squeezed and deformed as they move slightly closer and then farther from Jupiter with each orbit. As bending a paperclip back-and-forth generates heat, this flexing creates heat, which powers the continuous volcanic eruptions on Io and probably maintains a liquid ocean within Europa.

Ganymede does not receive significant tidal heating today, but its characteristics tell planetary scientists that something must have been different in the past. The orbits of the Galilean satellites may have evolved over time, such that past tidal heating triggered Ganymede's intense heating and differentiation. However, Callisto sits out of the orbital dance and so has never been significantly tidally heated. Apparently, the orbital push and pull of their other siblings, Io and Europa, have driven Ganymede and Callisto onto distinct evolutionary paths, lining Ganymede's face while leaving Callisto's to slumber under a hail of asteroidal and cometary debris.

The Galileo Mission

The most ambitious planetary mission of the 1990s was the Galileo orbiter and atmospheric probe. The orbiter was an intensional hybrid of previous spacecraft. Galileo's spin-stabilized body was preferred for instruments that measure fields and particles and saved fuel over the long mission, while a despun section carried remote sensing instruments (including the camera) that need to point stably toward their targets.

The space shuttle Atlantis carried Galileo to Earth orbit, where it received a boost from an Inertial Upper Stage to leave the bounds of Earth. The Jupiter-bound craft took a roundabout route, flying by Venus once and Earth twice to receive additional boosts from the gravity of these inner planets. On its journey, it flew past two asteroids, discovering that asteroid Ida has a tiny moon of its own. Galileo carried the only scientific instruments with a direct view of the impacts of the comet Showmaker-Levy 9 shards as they crashed onto Jupiter in 1994.

En route to Jupiter, Galileo's umbrella-like main antenna jammed. Despite efforts to alternately heat and cool it, and even to jostle and hammer it open, the antenna wouldn't budge. Instead of using a high gain antenna 16 ft (5 m) across, Galileo now had to rely on its tiny low gain antenna the size of a pie pan. The data rates for transmission to Earth were drastically reduced and some experiments had to be curtailed. But thanks to the creativity of the Galileo flight engineers and scientists, the mission proceeded, completely fulfilling most of its scientific objectives. Software engineers taught Galileo's computer to compress data in clever new ways, and encounters with Jupiter and its moons were redesigned to be more streamlined.

Galileo was equipped with an impressive array of instruments. The Solid State Imager returned detailed photos in parts of the spectrum along the visible realm. A Near-Infrared Mapping Spectrometer determined the composition of the moons and of Jupiter's atmosphere. Galileo's Photopolarimeter-Radiometer could see heat reflected off moon surfaces from sunlight, and heat coming from Jupiter and Io. An Ultraviolet Spectrometer examined the aurorae and molecules in Jupiter's upper atmosphere and ices on the moons. Flight engineers carefully recorded radio signals each time the spacecraft flew past a moon, telling of the moon's gravity field, and when it flew behind a moon of Jupiter, to determine atmospheric properties. A Magnetometer measured the magnetic field and related perturbations due to Jupiter and its moons. Other instruments observed the radiation and dust in the jovian environment.

Galileo lasted about three times longer than its planned lifetime. In 2003 it was commanded to plummet into the atmosphere of Jupiter where it burned up. This ensured that Galileo would never accidentally crash into Europa, which would risk contamination of that moon's ocean by Earthly microorganisms that might have hitched a ride to the Jupiter system.

Enigmatic Europa

Europa's surface is woven with a complex patchwork of fractures, ridges, bands, and spots (Fig. 5.6). The moon's enigmatic landscape tells of a dynamic interior beneath a frigid skin of ice, and of the globe-girdling ocean that is believed to lie beneath.

As Europa travels in its eccentric orbit, it moves closer to and farther from Jupiter with the rhythm of its 3.55-day orbit. Its icy shell is stretched and released, stretched and released. This tidal tugging distorts Europa's icy surface to the point where it cracks. From the complex pattern of markings on the moon, planetary scientists can deduce how Europa has been molded, and that an ocean is a central player in the story.

Ridges are Europa's most ubiquitous features—and its least understood. These unique ridges are stitched across the surface in pairs, with a narrow valley running down the center. Long fractures also scratch the surface, and it seems they are related to the double ridges. But how? One idea holds that tidal flexing as Europa orbits Jupiter pumps water and icy slush from deep fractures onto the surface, like glue squirting between repaired pottery pieces. Perhaps the fractures reach all the way down to an ocean, the presumed source of the watery ooze. In some areas, rinds of dark material stain the surface surrounding the fractures, suggesting escaping liquid from below.

Another model invokes shallow, warm ice that rises along a crack. Like a tree root pushing up an asphalt sidewalk, the ice slab warps the surface into a double ridge. This scenario requires a crack to reach relatively warm, glacially flowing ice, but not all the way down to water. However these bizarre ridges formed, they certainly point to a geologically dynamic moon.

The most bizarre of Europa's landscape menagerie are ridges that are shaped like a set of repeating bow-shaped arcs. The Voyager spacecraft discovered these mysterious ridges, and Galileo found many more. For 20 years, how they formed remained a mystery. Then, Randy Tufts and Greg Hoppa of the University of Arizona realized that Europa's tidal flexing

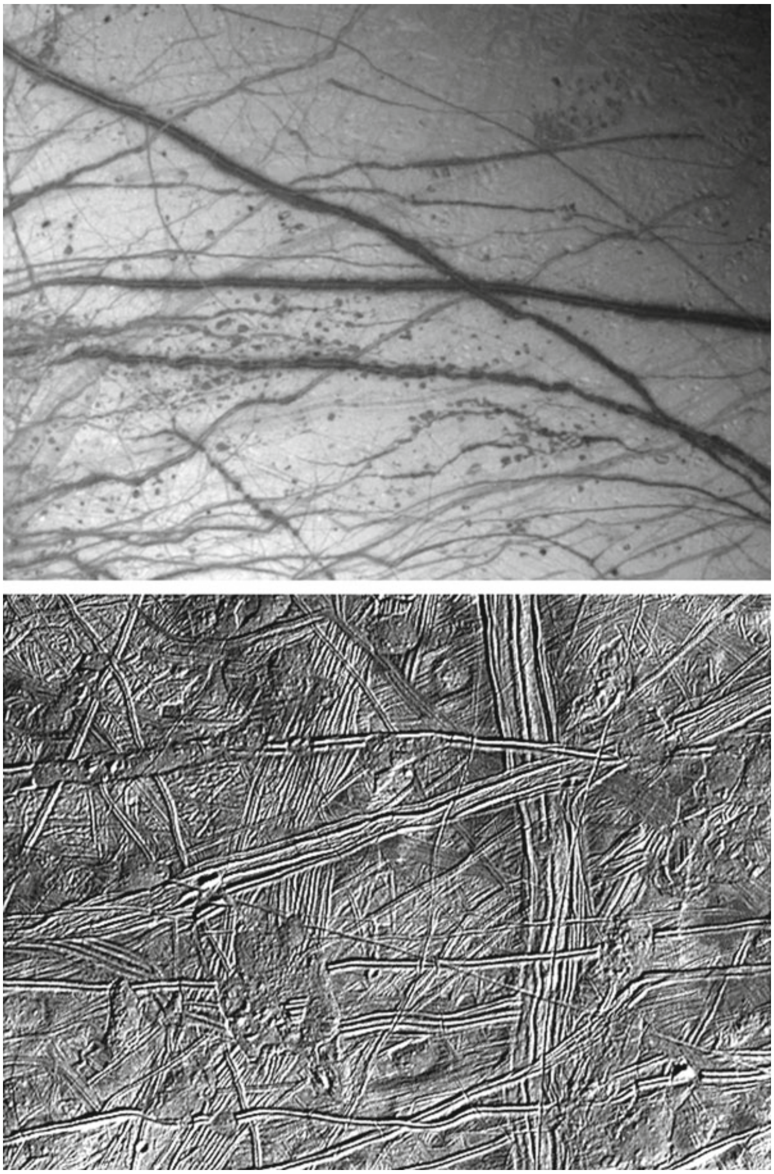

Fig. 5.6 Europa's lineated icy surface. In the top image, 620 miles (1,000 km) across, dark lines and curves look like doodles upon the bright icy surface. In the bottom image, 60 miles (100 km) across, these lines are seen to be sets of ridges and grooves; in places, pits and splotches pockmark the surface (Courtesy NASA/JPL-Caltech/DLR, Image PIA00743)

can explain these cycloidal shapes. As Europa orbits Jupiter, the rise and fall of the moon's tidal bulge bends and stretches the icy shell to the point where it cracks. While this is happening, the direction in which the tides pull changes continuously. Some cracks follow a curved path instead of a straight line, tracing out one arc with each Europan orbit. With this model, Tufts and Hoppa could reproduce the shapes of Europa's arcuate ridges almost perfectly.

These ridges are the call of a hidden ocean. If Europa's interior were solid ice, then Jupiter's gravity should raise a tide only 3 ft (1 m) high, and the small amount of stress would not be enough to make the surface crack. But if Europa hides an inner ocean, the moon's icy rind should rise and fall by 100 ft (30 m) during each orbit around Jupiter. An ocean facilitates the formation of cycloidal cracks and ridges, so their very existence argues for a sub-ice ocean.

In addition to the tidal tugging, scientists can decipher the pattern caused by nonsynchronous rotation. Like Earth's Moon, most of the solar system's large satellites rotate synchronously—each with a gaze of one hemisphere affixed toward its parent planet. But Europa seems to be a rare exception, its icy surface slipping forward very slowly relative to Jupiter's direction, with one full rotation taking as little as 10,000 years or as long as 1 billion years. This can happen only if something lubricates the moon's icy shell, such as a subsurface ocean. The seemingly random doodlings on Europa's complex surface nicely match the fracture pattern scientists predict from nonsynchronous rotation.

Splintered patterns of Europa's dark bands loosely resemble the floes and leads of Earth's frozen-over polar seas. These bands may be places where crustal ice has been pulled and stretched apart and the gaps filled with darker material.

If so, the subsurface must have been mobile and warm, either liquid water or relatively warm flowing ice.

In many places, pits, spots, and domes freckle Europa's face. Some encrust places where the surface has been warped, as if pushed from below by a giant thumb. Other spots appear dark and disrupted. One puddle-like spot is ice-rink smooth, presumably the result of water flowing onto Europa's surface sometime in the past. This means the moon's interior had to be warm enough to melt ice, which offers the clearest sign of volcanism on any icy Galilean satellite. Although the surface of an icy satellite is unimaginably cold, if radioactive or tidal heating warms interior ice, the warmer ice tends to rise like blobs of wax in a Lava Lamp. Such rising blobs, called *diapirs*, probably explain the spots that freckle Europa.

Topping the list of Europa's most enigmatic places are areas of jumbled ice blocks appropriately termed *chaos* regions. Icy plates appear to be tilted there, like icebergs calved into a slushy sea. The matrix between the plates is a rough and jumbled expanse. Scientists have attempted to reconstruct the icebergs to their original positions in jigsaw-puzzle fashion, but half the puzzle pieces are missing—somehow destroyed—and there's no box to show how the picture should look when it's finished. These chaos areas are thought to have formed atop huge lakes within the ice shell of Europa, some as big as Lake Superior on Earth, with huge blocks of ice shaken loose by tectonism and heat related to formation of the lake below.

Galileo's infrared instrument showed abundant water ice on Europa, as expected. But in Europa's darker and redder regions, such as the chaos areas, the compositional fingerprints are skewed. This may be evidence that Europa is the solar system's largest storehouse of Epsom salt. Less attractive to future bathers in the outer solar system, sulfuric acid—better known as battery acid—is another possibility.

Although battery acid is colorless, it could provide an important clue as to why Europa's dark areas appear reddish. The harsh, charged particle radiation that envelops Europa would kill a human in minutes, ripping apart cell walls and life-sustaining chemical bonds. Unwary molecules of sulfuric acid likewise would be torn into their constituent parts, liberating sulfur, which, in turn, can combine with other materials to form long molecular chains. These sulfur chains are a ruddy ocher color, which possibly explains Europa's blush. Sulfuric acid itself could be a product of radiation bombardment, formed by the breakdown and recombination of ice and sulfur dioxide (SO_2), a frost that has been detected on Europa. Irradiation of ice (H_2O) also creates *oxidants* at Europa—including oxygen (O_2), hydrogen peroxide (H_2O_2), and other simple electron-accepting compounds—which could serve as fuels for life, as we'll see below.

The paucity of large craters shows Europa's surface to be remarkably young. From predictions of the number of comets that should have hit Europa over time, the moon has been completely repaved in the past 60 million years. All the satellite's ridges, bands, and chaos regions have formed in the brief time since dinosaurs disappeared from Earth. While a lot can happen in 60 million years, this is a blink of an eye by planetary standards.

Close-up photos of Europa's Tyre impact site show a central, smooth patch surrounded by concentric rings, much like a miniature version of Callisto's Valhalla. The impact blast that made Tyre must have penetrated through the cold near-surface ice into a weaker layer below. Considering the depth to which the Tyre impact could have dug, the liquid or weak slushy layer must be only about 13 miles (20 km) deep within Europa.

Galileo's gravity measurements indicate Europa probably has an outer layer of H_2O about 60 miles (100 km) deep above a thick rocky mantle and a central iron-rich core, but gravity data cannot tell scientists whether any of the H_2O layer is liquid. If most of the water layer is liquid, its volume would be more than twice that of all Earth's oceans combined.

Confirmation of this idea comes from magnetic measurements, like those made at Callisto and Ganymede. As with Callisto and Ganymede, the fingerprint of an induced magnetic field enshrouds the moon, and betrays the presence of an ocean. But unlike the deep oceans of Callisto and Ganymede, Europa's ocean lies probably within 15 miles (25 km) of the surface. This is shallow enough that its contents could be made known by analyzing the surface.

Abodes of Life?

The Galileo spacecraft was not designed to divine subsurface water. Thanks to both unexpected discoveries and clever scientific analyses, the weight of the evidence suggests that all three of the icy Galilean moons possess oceans within. The oceans of Ganymede and Callisto are probably vestiges of warmer pasts, gradually freezing closed today. But Europa's ocean may be eternal and warm, maintained by the ceaseless power of Jupiter's gravitational tug.

On Earth, everywhere there is water, there is also life. If clues point to brackish water beneath the surfaces of Jupiter's large icy moons, we might stretch our imaginations far enough to ask whether life might have arisen within these briny depths. If so, such could be possible not only in Jupiter's realm, but within icy moons of Jupiter-like planets throughout the universe.

Understanding whether the oceans of these moons could contain life requires identification of the three necessary "ingredients" for life: liquid water, bioessential elements, and chemical energy. Liquid water is probable at all three moons, though future spacecraft observations are required to confirm this, by directly measuring their tidal signatures, or in the case of Europa by using radar waves to penetrate through its relatively thin ice layer and down to water. Bioessential elements can leach from rock into water, which

Fig. 5.7 In places, Europa's ridged surface is torn asunder to create chaotic terrain, consisting of icy blocks that have been jostled about, and rough ruddy regions that have a chemistry suggestive of Epsom salts and/or battery acid. This view of Conamara Chaos is 55 miles (88 km) across (Courtesy NASA/JPL-Caltech/DLR)

is expected to be a more active process at Europa, where its ocean floor contacts rock, than at Ganymede and Callisto, whose oceans are sandwiched between ice layers.

The third ingredient is the least certain. In the complete absence of photosynthesis beneath an ice cover, chemical energy is required to power metabolism within an icy satellite ocean. Such implies chemical disequilibrium within the ocean. Can radiation-produced oxidants from a moon's surface get into a subsurface ocean to power life? At Callisto and Ganymede, the ice shells are far too thick for surface-ocean exchange to occur today. But at Europa—where harsh radiation pounds the icy surface to produce abundant oxidants, and geological processes are believed to actively stir the relatively thin ice shell—surface oxidants might make their way to Europa's watery depths, so the strong possibility for life exists.

Europa's ocean seems the most probable extraterrestrial biome in the solar system today. Future examination of this moon is required to confirm its ocean, to characterize its chemistry, and to better understand the types and rates of geological processes. Exploration of Jupiter's watery moons has the potential to bring about a revolution in our understanding of the universe not experienced on this planet since Galileo turned his telescope skyward and first spied the moons that bear his name.

Missions to the Galilean Moons

Before the 2012 budget cuts decimated NASA's planetary program, US scientists and engineers had their eyes on a "flagship mission" to Jupiter's moon Europa. Flagship missions are once-per-decade complex, expensive, science intensive missions involving international partners. NASA was calling its potential Europa flagship mission the Jupiter Europa Orbiter (JEO). The plutonium-powered JEO was to drop into orbit around Jupiter as early as 2025. After several close passes of Io, the craft was to shift into an orbit around Europa, using radar to plumb the depths of its ice, confirm and characterize its subsurface ocean with gravity and magnetic measurements, map the surface and sniff the thin atmosphere to investigate the moon's composition, and image the bizarre fractured surface in unprecedented detail.

JEO was to be a full partner, exploring the Jovian system in concert with an ESA orbiter called Laplace. Laplace would be searching for another ocean, beneath the ice crust of the largest moon in our solar system, Ganymede. It was envisioned that the two spacecraft would observe the entire Jovian system in tandem, from the four Galilean satellites to the magnetic fields that intertwine them with Jupiter itself. Complementary instrument packages would have increased scientific return.

But the joint mission was not to be. NASA's goals were considered too ambitious for the current financial environment, and American designers were sent back to the drawing board to come up with something more affordable. If the plan for a Europa mission survives, it must be smaller, and simpler.

With NASA's withdrawal from the joint European–US mission, the European Space Agency scrambled to revamp its Ganymede orbiter as a solo mission. The result was the ambitious JUpiter ICy moons Explorer, or JUICE. Despite Jupiter's distance from the sun, JUICE is sun-powered, sporting 70 square meters of solar panels. JUICE is slated to make two passes of Europa on its way to its ultimate destination in orbit at Ganymede. NASA is contributing some instruments and other hardware to JUICE. The mission is slated to begin with arrival at Jupiter in 2030 and to last for at least 3 years.

Designers envision more advanced probes in the future. NASA is now examining the Europa Clipper concept, a scaled-back mission that would achieve many of the objectives of JEO, but during flybys of

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Europa from orbit around Jupiter, rather than from Europa orbit. Such a mission would be a precursor to a Europa lander, which some day will go to Europa's surface to scoop up and examine the dark red stuff, and possibly to look for life. In the far distant future, a mission might melt its way through the kilometers of Europa ice to dispatch a submarine ocean explorer. Technologies for these landed and submarine missions are years to decades away.

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Oceans at the Outer Limits: Enceladus, Outer Moons, Pluto

6

John Spencer

Ice and Water in the Outer Solar System

Ices of one kind or another dominate the outer solar system. The interiors of the aptly-named “ice giants” Uranus and Neptune may contain more ice than the rest of the solar system put together. Ice also abounds in comets, the icy moons and rings of the giant planets, and the myriad ice-rich worlds of the Kuiper Belt, beyond Neptune. Most of this ice is water ice, not so different from what you’ll find in your refrigerator, but the further out we go from the sun, the more often we find exotic ices too—carbon dioxide on the moons of Uranus, and nitrogen, methane, and carbon monoxide ices on Neptune’s moon Triton, Pluto, and other objects in the Kuiper Belt (Fig. 6.1).

If there’s water ice, plus a heat source to melt it, and enough pressure from an overlying atmosphere or an ice “lid” to prevent it from boiling away, you’ll get liquid water. The previous chapter talked about the water oceans that probably lurk beneath the surfaces of Jupiter’s giant icy moons. Here we’ll search for wetness even further from the sun, focusing on the one place out there where we’re now somewhat confident that liquid water exists- Saturn’s moon Enceladus. But we’ll also survey the other outer worlds, where water or other liquids might be hidden, or might once have been hidden, beneath their hard-frozen surfaces.

Melting ice to make an interior ocean requires a heat source. For some moons this might be tidal- frictional heat generated by the continual distortion of the moon by its parent planet’s gravity, as is the case for Jupiter’s moons Io, Europa, and perhaps Ganymede. But heat from the decay of radioactive elements in the rocky material that makes up a fraction of most ice-rich worlds can also be enough to melt the ice in some circumstances.

It was easier to form oceans back in the old days. The moons were born, in the first few million years after the formation of the solar system itself, by the coming together of debris in the disks that swirled around the growing planets. This was a violent and chaotic process, punctuated by giant impacts that sometimes added material to the nascent moons, and sometimes ripped them apart. Heat from these impacts might have been enough to make temporary lakes or oceans, hidden beneath temporary atmospheres of steam or buried beneath later-arriving debris.

Moreover, the stuff of the young solar system was highly radioactive. Our sun had many siblings, stars born from the same cloud of dust and gas. Some of these were much bigger than the sun, and burned hot and fast, ending their short lives in supernovae- nuclear detonations that cooked up unstable atomic isotopes and flung them back into the birth-cloud. These radioactive atoms were incorporated into the disk surrounding the sun, and then into the still-smaller sub-disks surrounding the forming planets. The most potent isotopes, aluminum-26 and iron-60, would have provided a source of heat, and perhaps melting, for any moon that formed quickly enough to incorporate them. But with half-lives of only about a million years, these isotopes disappeared quickly, and most moons may have formed too late to benefit from their warming influence.

The colder an ocean is, the less heat you need to maintain it. Pure water freezes, of course, at a temperature of 32°F, or 0°C. But as every highway maintenance department knows, if the water is contaminated by salt or other soluble substances, it can stay liquid at lower temperatures. Sufficiently salty water doesn’t freeze till −21°C, and ammonia (not popular with highway maintenance departments for some reason) can push the freezing point all the way down to −97°C. If a moon cools and water within it starts to freeze, impurities will become more and more concentrated in the remaining water so that its freezing temperature drops, prolonging the lifetime of the its ocean. The last drops of liquid may be a frigid and unsavory concentrated brew of ammonia, salt and other compounds.

These are the basic principles governing the presence of liquid water in the smaller worlds of the outer solar system. Now let’s look at some specific places (Fig. 6.2).

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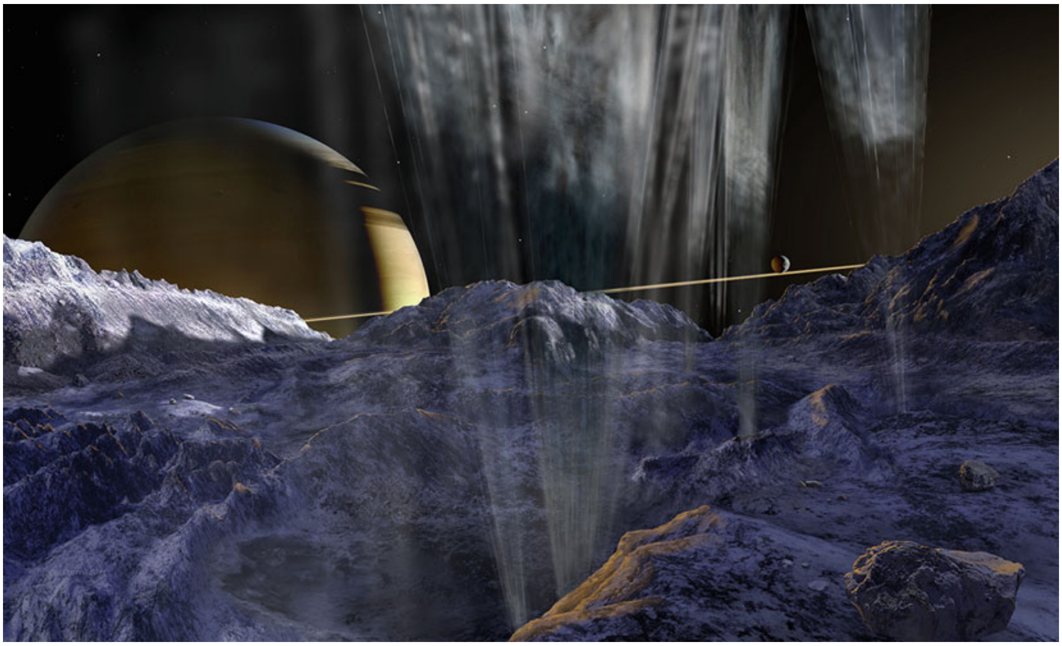

Fig. 6.1 Eruption of geysers from the fissure called Damascus Sulcus on Saturn's moon Enceladus. The moon Mimas is visible against the line of the rings at right (©Michael Carroll)

Saturn's Icy Moons

Saturn's family of moons is very different from Jupiter's. Instead of four big moons there's only one, Titan. But to make up for the deficit of big moons, there are eight mid-sized moons, 130–950 miles across, that are unlike anything in the Jupiter system, plus a host of smaller worlds. The scientists on the Saturn-orbiting Cassini mission that's currently exploring these moons tend to call the eight mid-sized worlds the "icy satellites". This label is convenient even if it's a bit misleading, as it ignores the fact that Titan and the smaller moons are mostly icy too.

These icy moons are fascinating and diverse places, though from the point of view of our quest for liquid water some are definitely more interesting than others. Two of them, Phoebe and Hyperion, are small, irregularly-shaped worlds that have probably never been warm enough to melt-certainly, they have never been soft and deformable enough inside for their relatively feeble gravity to pull them into a spherical shape. Four more, Iapetus, Rhea, Tethys, and Mimas, are more-or-less spherical, so they must have been warm enough for their ice to flow and deform under the force of gravity early in their histories, and might have had subsurface liquid water for a while. Now they are cold, with negligible sources of internal heat, and are probably frozen solid. Their surfaces are all heavily cratered, so not much other than impacts has happened to them for a long time (though the surfaces of Rhea and Tethys are both cut by fractures, and Tethys has some relatively smooth regions). Still, their shapes have interesting stories to tell about their warmer, and probably wetter, younger days.

Iapetus, outermost of the roughly spherical moons, is particularly interesting in this regard. Iapetus is famous for its piebald appearance, black on one side and white on the other-we now think this is probably due to a thin coating of dark material on one side from outer moons like Phoebe, concentrated by the evaporation of surface ice. But of more interest in this chapter is Iapetus' peculiar shape. Iapetus is too far from Saturn to be tidally heated, and contains too little rock for significant radioactive heating now. But it bulges at the equator just as you'd expect for a rapidly-spinning world that had been softened and perhaps melted early in its history, so perhaps Iapetus sported an internal ocean in its youth when it was still warm from the heat of its formation, or from those short-lived radioactive isotopes mentioned earlier. The peculiar thing is that Iapetus' bulge is the size you'd expect if it was distended by the centrifugal force of a 17 h spin period, which is odd because its rotation period is now 79 days, synchronized with its sedate orbital motion around Saturn. Presumably Iapetus was spinning much faster when it froze into its current shape. But if it froze solid when spinning with a 17 h period, it would still be spinning at that rate today- a hard-frozen Iapetus would not have enough friction in its interior to brake its rotation to its present synchronous value. Either the freezing occurred with exquisite timing—fast enough to freeze the 17 h tidal bulge into place, but slow enough to brake Iapetus into synchronous rotation—or we're still missing part of the puzzle.

There remain two more medium-sized spherical moons, Dione and Enceladus. Their histories are linked, because

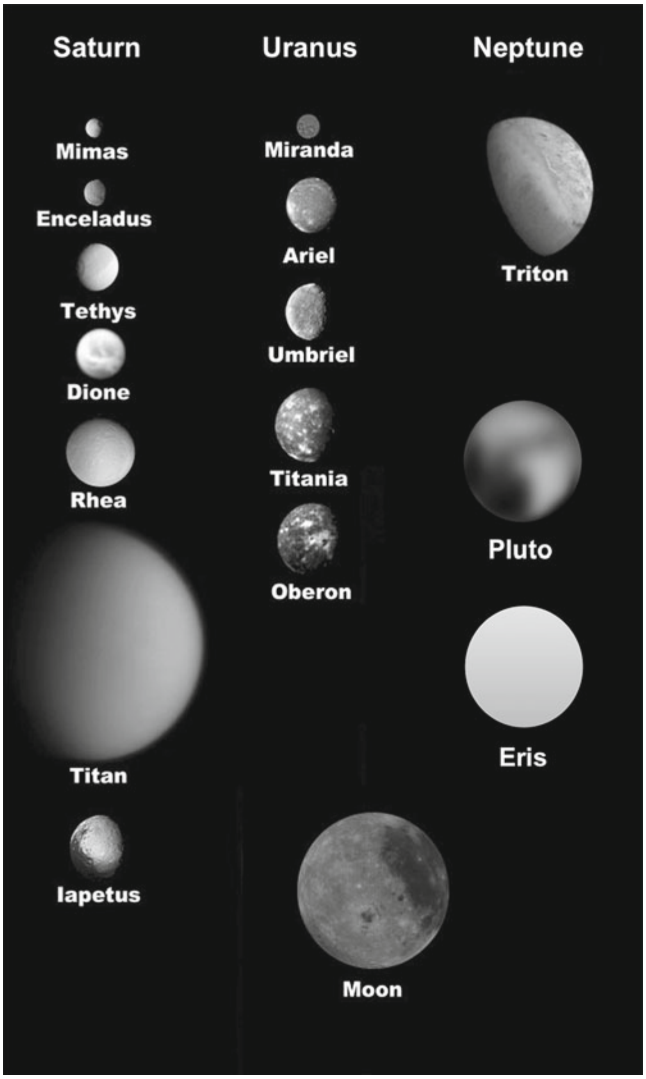

Fig. 6.2 The major satellites of the outer solar system, plus the dwarf planets Pluto and Eris, to scale (Courtesy NASA)

they orbit Saturn locked into a 2:1 resonance in which Enceladus circles Saturn twice for every orbit of Dione, much like the 2:1 resonances between Europa and Io, or Ganymede and Europa. The synchronized gravitational nudges that each moon receives from the other as a result of this resonance keep their orbits from circularizing. The non-circular orbits provide the potential for tidal heating, because of the constantly varying tidal forces from Saturn.

Dione, further from Saturn and with a less eccentric orbit than Enceladus, may have been heated modestly by Saturn tides. It's also more likely to be heated by radioactivity than Saturn's other mid-sized moons because it's fairly rich in rock and is fairly large, so it can retain radioactive heat better than smaller moons. Indeed, Dione has a varied surface that testifies to a restless interior. Some parts of Dione are heavily cratered; others are relatively smooth or laced with peculiar-looking ridges or fresh-looking fractures. Has liquid water, or an exotic, frigid, ammonia-rich slurry, poured out onto its surface at some time in the past, covering up the older craters? Might there still be interior warmth, producing exhalations of gas along those fractures? The Cassini spacecraft continues to search for clues (Fig. 6.3).

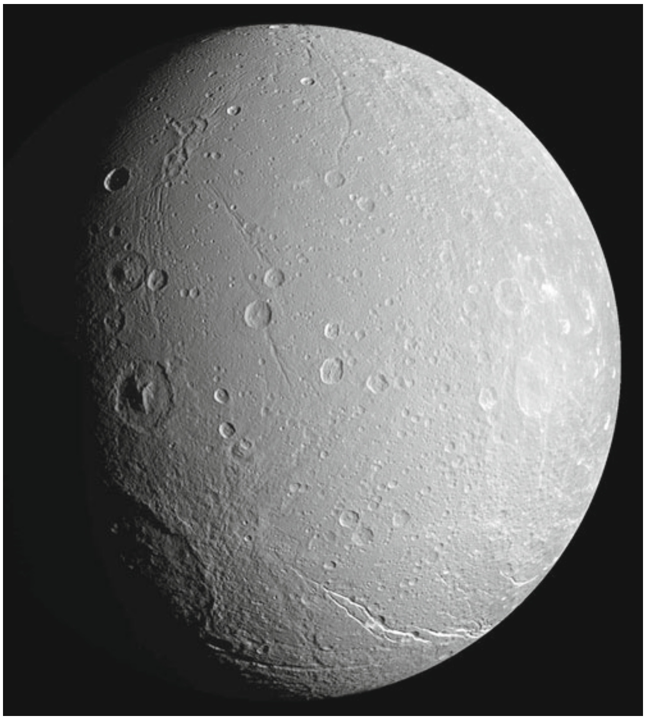

Fig. 6.3 Saturn's moon Dione, heavily cratered in some places but showing smooth areas (*upper left*) and fresh-looking fractures (*lower right*) that testify to an active past (Courtesy NASA/JPL/SSI)

Enceladus

Little Enceladus is in a class of its own. Here, the presence of geological activity is not a matter for speculation: we can actually watch it happen.

Astronomers have known something was odd about Enceladus for several decades. The first hint came in the 1960s, with the discovery of a faint outer ring of Saturn, the E-ring, enveloping the orbits of several of Saturn's moons, well beyond the main ring system that made Saturn famous. In 1980, improved images of the E-ring revealed that its brightness peaked at the orbit of Enceladus, and also showed that the ring was dominated by very small ice particles. Such tiny particles should only last for decades to hundreds of years, so something, perhaps Enceladus, had to be continually replenishing the ring.

Also in the early 1980s, we got the first close-up pictures of Enceladus and Saturn's other moons, from the flybys of

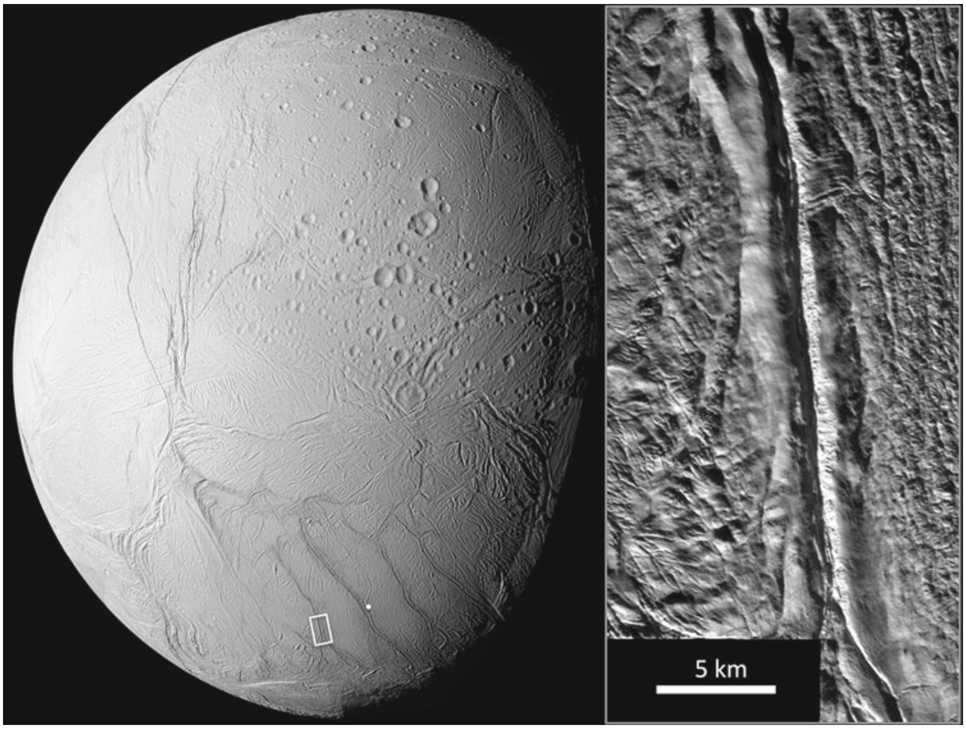

Fig. 6.4 Saturn's moon Enceladus. The four parallel fractures near the bottom of the disk in the left image are the active "tiger stripes". The dot marks the south pole, and the rectangle shows the location of the enlargement of one of the tiger stripes shown on the right

the Voyager 1 and 2 spacecraft. Unlike the other moons, with their ancient surfaces dominated by impact craters, Enceladus' surface was intensely fractured, and in many places almost crater-free. Voyager also revealed that Enceladus had the brightest surface of any known solar system object, reflecting about 80 % of the sunlight that it intercepts. Were Enceladus' peculiar landscapes, the dazzling whiteness of its surface, and the E-ring, somehow connected? Some scientists speculated that tidal heat inside Enceladus might be generating geyser-like eruptions that could generate the E-ring and coat the surface with clean ice. But with the limited data available, there was no way to know for sure.

When the Cassini Saturn orbiter, a joint project of NASA and the European Space Agency, was launched towards Saturn in 1997, Enceladus was a high-priority target, and following Cassini's arrival at Saturn in mid-2004, the small moon came under intense scrutiny. Early data showed peculiar distortions of Saturn's magnetic field near Enceladus, and perhaps a cloud of material near the south pole. Then in a close flyby in July 2005, data from many of Cassini's amazingly capable suite of onboard instruments conclusively demonstrated that Enceladus was the first proven geologically-active ice world. The flyby approach provided a beautiful view of the south polar region, showing that the region was sliced by four prominent parallel troughs, quickly dubbed "tiger stripes", surrounded by an incredibly rugged landscape of overlapping fractures and mountainous ridges. The images showed very few impact craters, so this landscape must have been created very recently, sometime in the last few million years, just yesterday in Enceladus' 4-billion-year history. Infrared maps showed that the tiger stripes were glowing with heat radiation escaping from the interior of Enceladus. Cassini also watched as the ultraviolet light of a star passing behind the moon was blocked by a huge cloud of water vapor above the south pole. Cassini's onboard mass spectrometer reported that the spacecraft had actually flown through the edges of this cloud, and that it contained carbon dioxide, methane, and more complex carbon-rich molecules as well as water vapor. Cassini's payload even includes a dust analyzer, which revealed a cloud of micron-sized particles above the south pole, and dramatic images taken a few months later directly showed multiple jets of these particles erupting from the tiger stripes. The wild speculations of 20 years earlier had proved correct- Enceladus is indeed spewing geyser-like plumes of gas and ice particles into the space around Saturn, generating the E-ring and coating its own surface with white snow (Fig. 6.4).

In the following years, Cassini has flown past Enceladus many more times, skimming the surface at altitudes as low as 20 km, less than twice the height reached by commercial airliners on Earth (but at 70 times the speed). The trajectory and spacecraft orientation during each flyby is optimized for specific science goals- close flybys through the plume for direct sampling, more distant flybys for mapping the surface, and close flybys on a range of trajectories to map Enceladus' gravity field. After its first inadvertent brush through the edge of the gas and ice plume in July 2005, Cassini has ventured deeper and deeper into the heart of the plume. The plume turns out to be safe to fly through because the ice grains in it are so small: even at the high speeds of the Cassini flybys, the blizzard of tiny particles hitting the spacecraft is only a minor annoyance.

The stream of data from Cassini is gradually building a picture of how Enceladus works. For Enceladus, the ultimate engine powering its activity, tidal heating, is not just a theoretical concept- the amount of heating is so large that the heat can be measured directly by Cassini's infrared instrument. The measurement is tricky because Enceladus also radiates heat simply by virtue of being warmed by the Sun, and the solar heating must be estimated and subtracted from the total in order to determine the internal heat. The current best estimate of the internal tidal power is about 16 Gigawatts, eight times the hydroelectric power output of the Hoover Dam-impressive for such a tiny world. In fact the observed power is a bit *too* impressive- calculations based on the orbits of Saturn's moons suggest that Enceladus can only generate about one tenth the observed tidal power on average. Perhaps the power is higher than average right now because Enceladus has been storing heat for a while and is now letting it go in a sudden burst. If so, we are lucky to have arrived at Enceladus while it's in this unusually active state.

Another puzzle is why the activity is so perfectly centered on the south pole. The most plausible explanation is that the heating started in some random location on Enceladus, and that material was transported away from the heated area, perhaps by melting of the ice or even ejection in the plumes. Once a symmetrical spinning object looses mass in one location, the physics governing rotating bodies dictates that its rotation becomes unstable until the spin axis realigns to pass through the less massive region. So maybe that's what happened on Enceladus. The active region could have aligned itself with either the north or the south pole- heads or tails – Enceladus just happened to come up tails.

Cassini's repeated barnstorming of Enceladus has now given us a quite detailed picture of what the plume is made of. Because the plume lets us sample stuff that was inside Enceladus only minutes earlier, it gives us a window into the moon's interior that we don't have for any other ice world. The plume gas is 90 % water vapor and 5 % carbon dioxide, and the rest is a mixture of methane, ammonia, and a wide variety of hydrocarbons, including hints of very complex carbon-rich molecules. So some complicated chemistry is happening, or has happened, beneath Enceladus' surface. Just as intriguing is the composition of the ice particles in the plumes. Most of the particles are 99 % pure water ice, but the remaining 1 % is sodium chloride (ordinary table salt), and other common salts. Salty ice is difficult to make- it's hard to produce except by suddenly flash-freezing salty water. Possibly the plumes are excavating salty ice grains from the frozen spray of some long-dead ocean, but a much simpler, and probably more likely, explanation is that salt water exists not far below the surface of Enceladus right now, and its frozen spray is being incorporated into the plume.

Not only has tidal heating apparently melted the icy crust of Enceladus, but the fact that the water is salty means that the melting isn't just a local aberration. The most likely source for the salt is Enceladus' rocky core, so the water must be extensive and long-enough lived to leach the salt from the core. This requires a subsurface ocean or at least a substantial sea. Further evidence for an ocean comes from the large amount of tidal heat generated by the moon- an ice shell that's floating on an ocean can move much more easily, and thus generate frictional heat more easily, than ice that's frozen solid to the rocky core beneath it. Enceladus is almost certainly an ocean world, now or in the very recent past (Fig. 6.5).

What's most exciting about Enceladus is that with all those complex carbon-rich molecules, and all that salty water lurking beneath its surface, it is one of the most promising habitats in our solar system for extraterrestrial life. Still, it's by no means certain that Enceladus is capable of spawning or supporting life. Liquid water and the appropriate chemical elements are essential ingredients for life as we know it, but there's another essential ingredient that Enceladus might (or might not) have enough of: chemical energy. Life thrives on chemical imbalance. Plants power themselves by photosynthesis, using sunlight to break chemical bonds and generate unstable, energy-rich, molecules that they can feed on. The highly unstable gas oxygen, which is a by-product of that process, is in turn used for power by every animal on Earth, including us. So almost all life on Earth is ultimately powered by sunlight. In case you're thinking "but what about all those creatures living around the 'black smoker' hot springs in the permanent darkness of the deep ocean floor?", even those depend ultimately on sunlight. They would perish but for the oxygen in the surrounding seawater, generated by algae and other plants busily photosynthesizing in the sunlit shallows of the uppermost ocean.

Only a few highly specialized Earth bacteria earn a living completely independent of sunlight. But that's probably the path that any Enceladan life would have to follow, because it's unlikely that sunlight penetrates far enough down the fissures of Enceladus to reach the warm, damp, places beneath. Perhaps geological processes can drag surface materials, containing unstable molecules generated by radiation at Enceladus' surface, down to hungry organisms in the depths. Perhaps Enceladus' core is warm enough to cook up methane that can work its way upwards to power life in the water we think seeps and froths beneath those spectacular geysers. Or perhaps, despite the physical turmoil of the geysers, there's just not enough chemical energy for organisms to

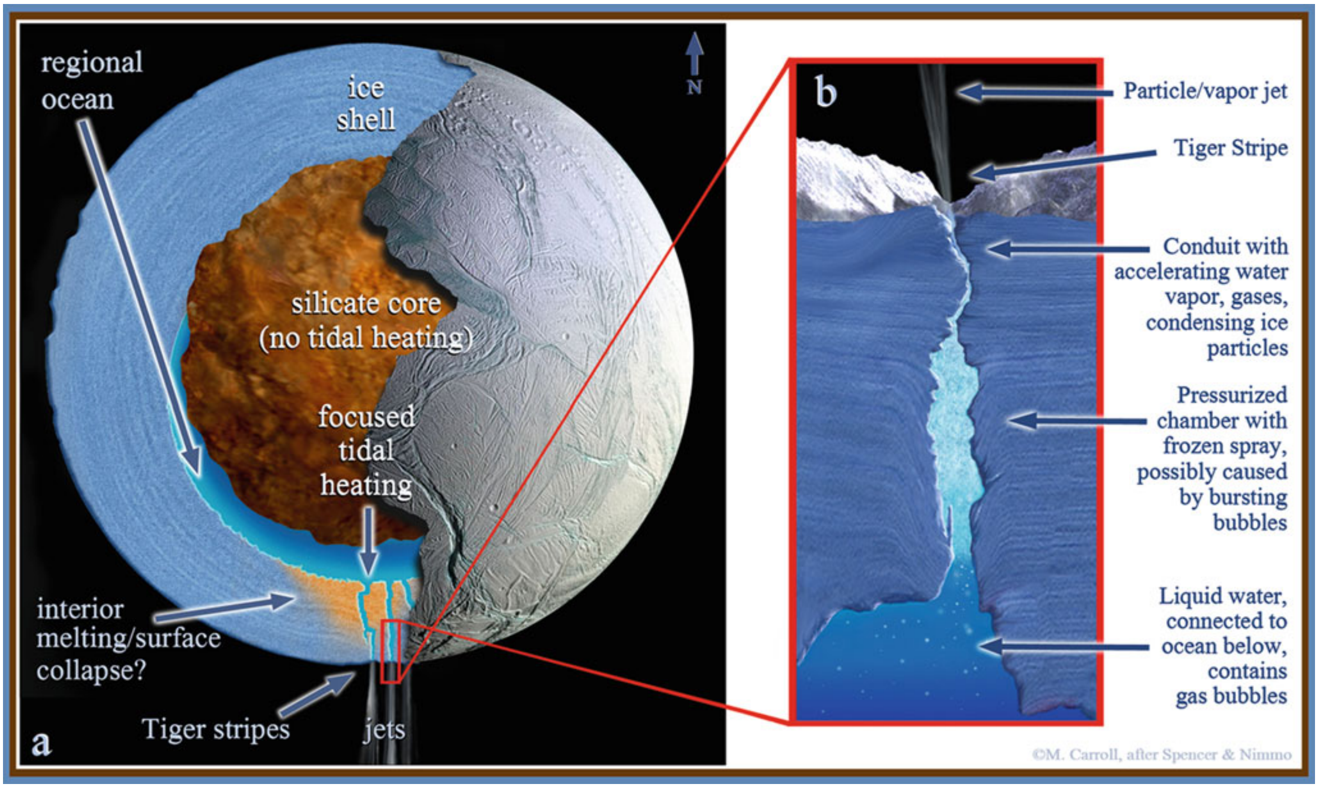

Fig. 6.5 Cartoon of the interior of Enceladus (**a**), including a closeup of the active tiger stripes (**b**). The *dark blue* shows the probable location of liquid water (Spencer, Nimmo and Carroll)

develop and thrive down there, and the only living things to benefit from Enceladus' activity are our own awestruck selves. In any case, if life has indeed gained a foothold on Enceladus, there's a better chance of finding out than in most places. The geysers deliver samples from exactly the regions where life is most likely, directly into the instruments of any spacecraft we send to fly through the plume.

Enceladus will remain a tempting target for exploration even after Cassini's planned demise in 2017, and NASA has conducted several studies of possible future missions. We would love to orbit the moon, thoroughly map its surface, and send much more sophisticated instruments through the geyser plume to analyze its composition in more detail. Perhaps we could even collect plume samples and bring them back to Earth. Then perhaps we will know for sure whether there's water under the surface, and even whether there's anything swimming in that water (Fig. 6.6).

Beyond Saturn

Where can we look for oceans beyond the Saturn system? Uranus has no big moons, but sports a suite of five medium-sized moons (Miranda, Ariel, Umbriel, Titania and Oberon), that are quite similar to many of Saturn's icy moons- they also have water ice surfaces and densities that imply a lot of ice in their interiors, too. We are still very ignorant about these worlds, which we have glimpsed in close-up only once, very briefly, during *Voyager 2*'s flyby of Uranus back in 1986. *Voyager 2*'s pictures do tell us that Miranda, Ariel, and Titania in particular have led restless lives. Interior forces have torn their surfaces with geological faults and have obliterated craters in many regions. But whether liquid water was involved in these convulsions we don't know. We do know that no tidal heating engines are currently operating to warm the interiors of these moons, because none of them share the orbital resonances that are an essential part of any long-term tidal heating. If the geological activity that we see on Uranus' moons is continuing at the present, it must be powered by the small amount of radioactive heat that these small worlds can generate. But perhaps these worlds are now cold and dormant, and their disrupted surfaces speak of an active youth that is now a distant memory. We may have some answers in a decade or two- NASA is studying the possibility of a mission to orbit Uranus and investigate its moons in much more detail (Fig. 6.7).

While the planet Neptune has much in common with Uranus, its satellite system is very different. There are no medium-sized moons at all at Neptune, but there is one big moon, Triton, a world unlike any other moon in the solar

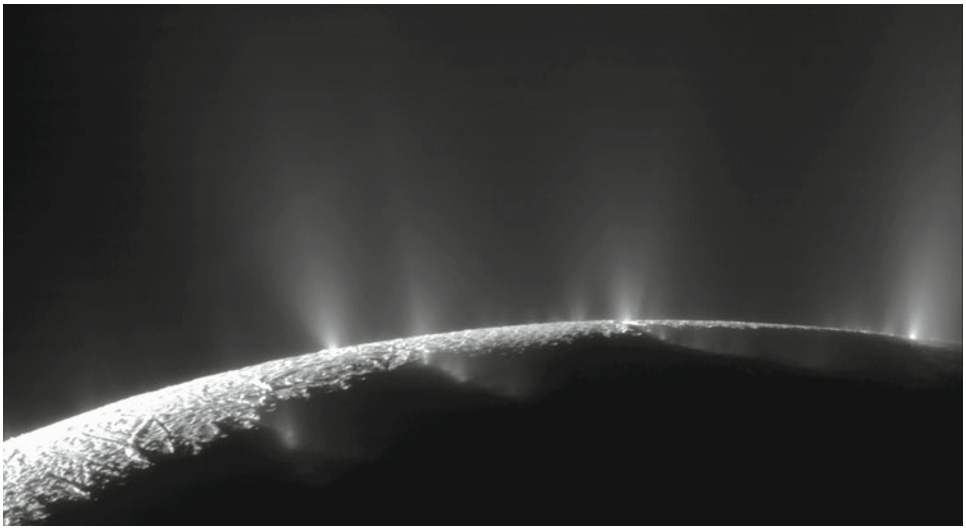

Fig. 6.6 High-resolution Cassini image of multiple plume jets erupting from Enceladus' four south polar tiger stripe fractures. The jets are seen not just off the edge of Enceladus' disk, but also where they rise up into sunlight from sources on the night side of the moon (Courtesy NASA/JPL/SSI)

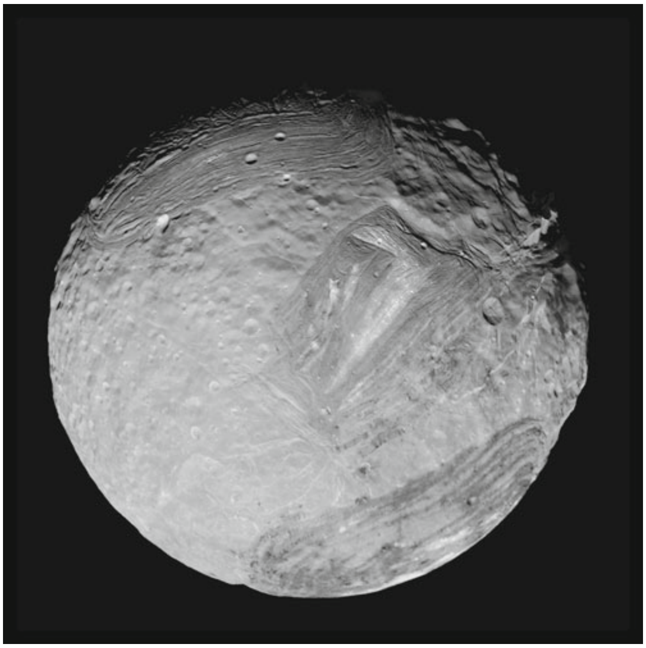

Fig. 6.7 Uranus' remarkable moon Miranda, photographed by Voyager 2 during its Uranus flyby in 1986 (Courtesy NASA/Ted Stryk)

system. Perhaps most extraordinary is its orbit. All other moons in the solar system, with the exception of some tiny outer moons orbiting far from their parent planets, circle their primaries in the same direction as the planet rotates. Triton is the spectacular exception- it's big and it's close to Neptune, but it orbits the planet backwards, in an orbit tilted 24° to Neptune's equator.

The only reasonable explanation for this errant behavior is that Triton did not form around Neptune at all. Instead, it likely began life as an independent world, probably as a member (the largest surviving member, in fact), of the Kuiper Belt.

The Kuiper Belt is the vast swarm of worlds circling the sun not far beyond the orbit of Neptune. From 1930 to 1992 Pluto was the only known object out there, but in the last 20 years about a thousand other Kuiper Belt objects have been discovered. Most are much smaller than Pluto, but not all. Eris, the largest, currently three times further from the sun than Pluto, is about the same size as Pluto and is 25 % more massive. Pluto and Eris are both just a little smaller than Triton, and all three seem to have very similar composition, with surfaces dominated not by water ice, but by frozen nitrogen and methane. These three worlds thus seem to be siblings (Fig. 6.8).

So somehow, sometime, Triton passed very close to Neptune and got captured into orbit around it. We don't know the details, but the process was probably traumatic for Triton. Immediately after capture it must have been in a wildly eccentric orbit, passing very close to Neptune once an orbit and looping far away from it the rest of the time. So the tidal forces from Neptune would have varied hugely during each orbit, producing enormous tidal heating as Triton attempted to adjust its shape to the rapidly varying gravity. The resulting friction would have eventually circularized the orbit, but not before all that heat had thoroughly melted the water ice that we know is abundant in Triton's interior. Triton was therefore almost certainly an ocean world for a while. But the tidal heating was short-lived—with no other satel-

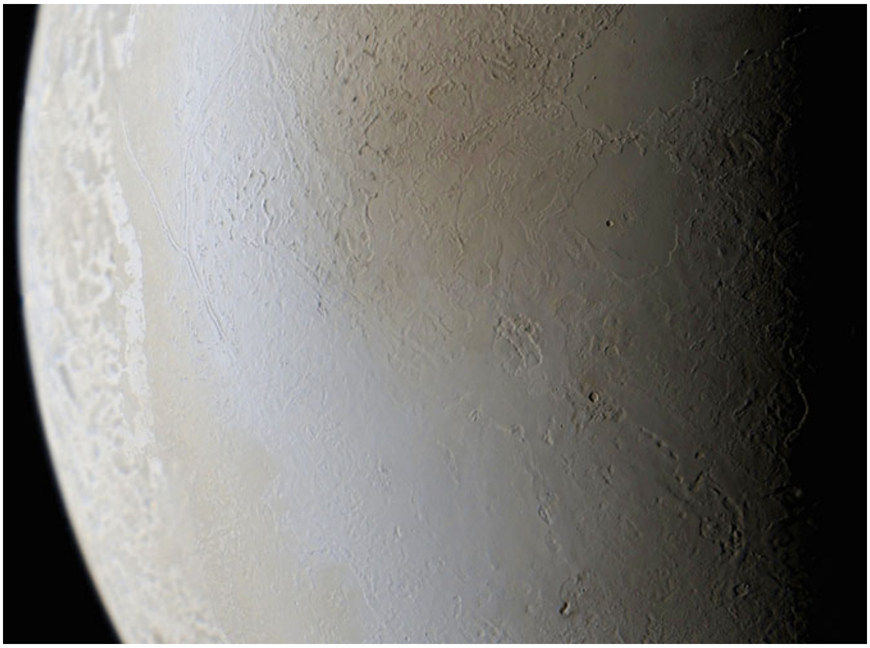

Fig. 6.8 Close-up image of Neptune's moon Triton, photographed by Voyager 2 in August 1989. On the right, the low sun angle picks out a strange landscape that includes features that resemble frozen lakes and ice volcanoes. The blurring of the left edge of the disk is an artifact of the way the image was produced (Courtesy NASA/Daniel Macháček)

lites to perturb it (the capture of Triton probably destroyed or ejected any other large satellites Neptune might have had) Triton's orbit eventually settled into its current perfectly circular shape. A circular orbit means that Neptune's tidal forces on Triton are unchanging, so there's no distortion and no more tidal heat.

It was something of a surprise, then, when *Voyager 2* flew past Neptune in 1989 and returned our only close-up images of Triton, and the pictures revealed a young surface with almost no impact craters. Instead, the surface is covered in a wide variety of wonderful and baffling landforms, some of which look like frozen lakes and flows formed by eruptions of liquid onto the surface. Impacts are inevitable in the solar system, and few impact craters means a surface that has been created very recently in solar system history. Perhaps Triton had been captured by Neptune recently, wiping out any pre-existing craters when Triton was melted by the capture process. However, that's unlikely- capture was much more likely early in solar system history, before the solar system settled down to its current stable arrangement. More likely, another heat source has been keeping Triton warm and producing the geological activity that creates its exotic surface. About the only other option available is radioactivity. But how can radioactive heat keep Triton geologically alive when there are larger worlds (Jupiter's big moon Callisto in particular) that probably have more radioactive elements but seem to be completely dead geologically? Most likely, having formed much further from the sun, Triton incorporated more anti-freeze compounds, such as ammonia, into its makeup. So similar amounts of radioactive heat can soften and stir the interior of Triton, while leaving Callisto frozen. However, even Callisto probably has a subsurface ocean of some kind, so it's quite likely that Triton does too.

Not to be outdone by Enceladus, Triton even has plumes rising from its surface. They are just five or so miles high, appearing as dark streaks rising vertically into its thin atmosphere before being blown away by the tenuous Tritonian winds. But the few pictures we have of them don't tell us much. We don't know whether they are Enceladus-like eruptions from Triton's interior, or jets of nitrogen gas leaking from surface frost as it is warmed by the sun, or even a purely atmospheric phenomenon, like dust devils.

Beyond Triton, in the Kuiper Belt proper, we are truly in terra incognita. Even Pluto, the best-known world out there, has yet to receive a visitor from Earth. The New Horizons spacecraft will change all that in July 2015, and should return spectacular images from what promises to be a very exotic world indeed. Will Pluto look anything like Triton, with a surface that speaks of a restless interior and perhaps a subsurface ocean? It's certainly plausible- Pluto should have a similar radioactive heat source to the one that appears to keep Triton alive, and should contain similar amounts of anti-freeze compounds. But if past experience is any guide, Pluto will be a world all its own, different from anything we

Table 6.1 Large satellites of the outer planets, and other large icy worlds

Primary	Satellite	Distance from Primary (km)	Radius (km)	Density, compared to water	Albedo	Surface composition	Notes
Jupiter	Io	422,000	1,822	3.53	0.6	Sulfur, sulfur dioxide, rock	Intense tidally-driven volcanism, plumes, high mountains
	Europa	671,000	1,561	3.01	0.7	Water ice, salts, acids	Recent complex resurfacing, probable subsurface ocean
	Ganymede	1,070,000	2,631	1.94	0.4	Water ice, salts	Magnetic field, ancient tectonism, probable subsurface ocean
	Callisto	1,883,000	2,410	1.83	0.2	Water ice, Clays?	Partially undifferentiated, heavily cratered, probable subsurface ocean
Saturn	Mimas	186,000	198	1.15	0.6		Heavily cratered
	Enceladus	238,000	252	1.61	1.0	Water ice	Intense recent tectonism, active water vapor/ice plumes
	Tethys	295,000	533	0.97	0.8	Water ice	Heavily cratered, fractures
	Dione	377,000	562	1.48	0.6	Water ice	Limited resurfacing, fractures
	Rhea	527,000	764	1.23	0.6	Water ice	Heavily cratered, fractures
	Titan	1,222,000	2,576	1.88	0.2	Water ice, organics, liquid methane	Dense atmosphere, hydrocarbon hydrological cycle, complex organic chemistry
	Iapetus	3,561,000	736	1.08	0.3	Water ice, dark material	Heavily cratered, extreme albedo dichotomy
Uranus	Miranda	130,000	236	1.21	0.3	Water ice	Complex and inhomogeneous resurfacing
	Ariel	191,000	579	1.59	0.4	Water ice	Limited resurfacing, fractures
	Umbriel	266,000	585	1.46	0.2	Water ice, dark material	Heavily cratered
	Titania	436,000	789	1.66	0.3	Water ice	Limited resurfacing, fractures
	Oberon	584,000	761	1.56	0.2	Water ice, dark material	Limited resurfacing
Neptune	Triton	355,000	1,353	2.06	0.8	Nitrogen, methane, water ice	Captured. Recent resurfacing, complex geology, active plumes
Pluto	–	–	1,170	2.03	0.6	Nitrogen, methane, dark material	Unexplored till 2015
Eris	–	–	1,163	2.52	0.8	Nitrogen, methane	Unexplored

can imagine. Eris, similar in size to Pluto but denser, and thus probably even more enriched in radioactive elements, should be just as active or more so than Pluto, and it is even more likely to conceal an ocean beneath its surface. But no missions are yet planned to Eris, which is so far away that even a New Horizons class spacecraft would take three decades to get there, so it will keep its secrets for a long time to come (Table 6.1).

7

Sand Seas of the Solar System

Jani Radebaugh

> *A great wind-erosion desert has a frightening lack of continuity; no ever-downward valleys, nothing but isolated hills, plateaus, and depressions, with no distinct landmarks visible from afar. Vast areas remain unexplored.*
>
> – R. Bagnold, Sand, Wind, and War, 1990

A discussion of sand may seem out of place in this book mostly about liquids, but the quote above illuminates the ocean-like quality of vast, dune-covered deserts. It is in fact the sheer volume of constantly moving material, the challenge to navigation and survival, and the regular undulations of sand akin to waves on water in oceans that led explorers and scientists to term these regions on Earth "sand seas" (Fig. 7.1).

Sand seas are regions where sand collects in great volumes, made comfortable in its residence by existing in broad basins, where winds converge, and where materials are not removed by processes related to rivers, lakes, or oceans. Sand volumes in sand seas dwarf those of the beaches of the world. Such large amounts of sand are derived from near and far through myriad processes ranging from erosion of granite basement to shoreline processing of quartz pebbles to wind erosion of gypsum accumulations in dry lakebeds. A number of sand seas pepper the face of Earth, often existing on the borders of countries, which indicates their resistance to passage and political taming.

Early explorations of the Great Sand Sea of western Egypt were carefully recorded by the British soldier-scientist Ralph Bagnold (1896–1990). With a small band of soldiers, under post-WWI British peacetime occupation of Egypt, Col Bagnold made tentative forays westward into the foreboding Sand Sea, which stretches from Siwa in northern Egypt, south to the Gilf Kebir, and across western Egypt and eastern Libya, almost 200,000 square miles (500,000 km^2). It is the morphology of dunes in the sand sea—they are almost uniformly linear in form, 1–3 km wide, tens to hundreds of kilometers long, and spaced 1–4 km—that allows passage. Col Bagnold realized if he avoided the soft, actively moving summits and stayed on the low slopes of the dune flanks and in the hard interdunes, with sand, gravel, or basement substrate, that he could wind his way through the massive, 100 m high "distant chains of dunes as yellow airships floating in the sky" (Fig. 7.2).

Exploration of the sand sea carried out by Col Bagnold and his party was much like seafaring voyaging. They traveled light, compact, and in groups, staying alert to ever-changing conditions, taking care to have constant access to water. Accurate navigation was of utmost importance, and they mounted sun compasses on their dash to that end. Storms were crippling and often delayed travel. The similarities in the styles of campaigns on the ocean and into the desert reveal the ever-changing nature of the materials: windblown sand behaves as a fluid. Sand responds to wind by saltating, or leaping off the surface, impacting other particles, and moving downwind. While doing this, the sand self-organizes into dunes, wave-like in shape and regularly recurring, altering orientation around obstacles. From above, sand seas appear as oceans, with wavelike dunes regularly spaced and oriented (Fig. 7.3).

How appropriate, then, it was to immediately christen the vast areas of regularly spaced, alternating light and dark linear features on Titan, seen first by the Cassini spacecraft in 2004, as dunes in sand seas. The features are the same size as linear dunes in sand seas on Earth; they pause briefly or divert around isolated mountain inselbergs, which rise timidly up through the sand deeps, and feather out at the edges of sand seas, much as they do on Earth. Though Titan is larger than Earth's moon, the sand seas here dwarf those on

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Fig. 7.1 The AVIATR (Aerial Vehicle for In-situ and Airborne Titan Reconnaissance) comes to the end of its mission, settling upon a great dune sea on Titan (©Michael Carroll)

Earth. The largest of the three named sand seas, Belet, covers close to 2 million square miles (5 million km^2), about the size of much of the Sahara desert: Egypt, Libya and Algeria together (Fig. 7.4). Although there are separately named collections of sand on Titan, it is difficult to define boundaries between the regions, as materials span the margins and perhaps flow between them. Sands, unfettered in their movement by vegetation or oceans of liquid, wrap around Titan's equator in one large system, covering perhaps a quarter of the body. Dunes are diverted by small obstacles, as on Earth, but halt entirely only at the anomalous (Fig. 7.5).

Dunes on Titan are dark to radar, as they are on Earth, because sands absorb the radar signal, preventing it from reaching the instrument. But dunes on Titan are also dark to visible and near-infrared instruments. This means that if you were standing on Titan's dunes, they would be dark brown or black, similar in color to the small dunes made of volcanic cinders found in the Ka'u Desert on Hawaii's active Kilauea volcano. Their composition, however, is wholly different. At ten times as far from the sun as Earth, Titan's bedrock is water ice, frozen solid. This is covered in sedimentary layers of material derived from atmospheric processing of abundant methane (CH_4). Endless chains of "organics", not originating from life but having chemistry vital for the forming and flourishing of life if it were there, rain or snow out of the atmosphere onto Titan's surface. These could be hardened into sedimentary layers, rained upon by methane rainfall, comfortable as a fluid at Titan's temperatures, and eroded

Fig. 7.2 Dunes of the Egyptian Great Sand Sea are wave-like on several scales. The main linear dune is ~1/2 mile (1 km) wide, 1000 feet (300 m) high and many tens of miles (km) long. Intermediate-sized, seif ("blade"-like) dunes undulate across the summit of the underlying main dune. Finally, small ripples in the foreground are just inches (centimeters) across. All of this can be seen from a car window, as the flanks and interdunes are compacted enough for vehicle travel. Photograph by the author, 9/2010, located approximately 29 04' N, 25 18' E

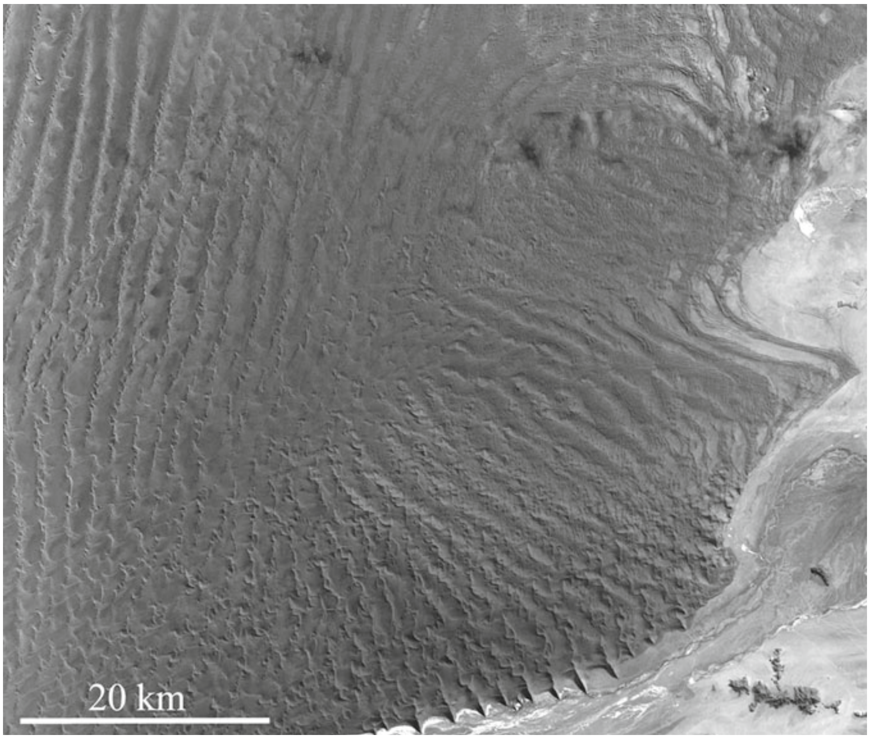

Fig. 7.3 Dunes of the Namib Sand Sea, Namibia. Dunes are dominantly linear in form, and there are vast accumulations of sand in this region, eroded by sandstones and carried by rivers and winds (Image from Cnes/Spot, at 24 S 15 E, courtesy of Google Earth (C) 2013 GeoEye, (C) 2013 DigitalGlobe, (C) 2013 Google)

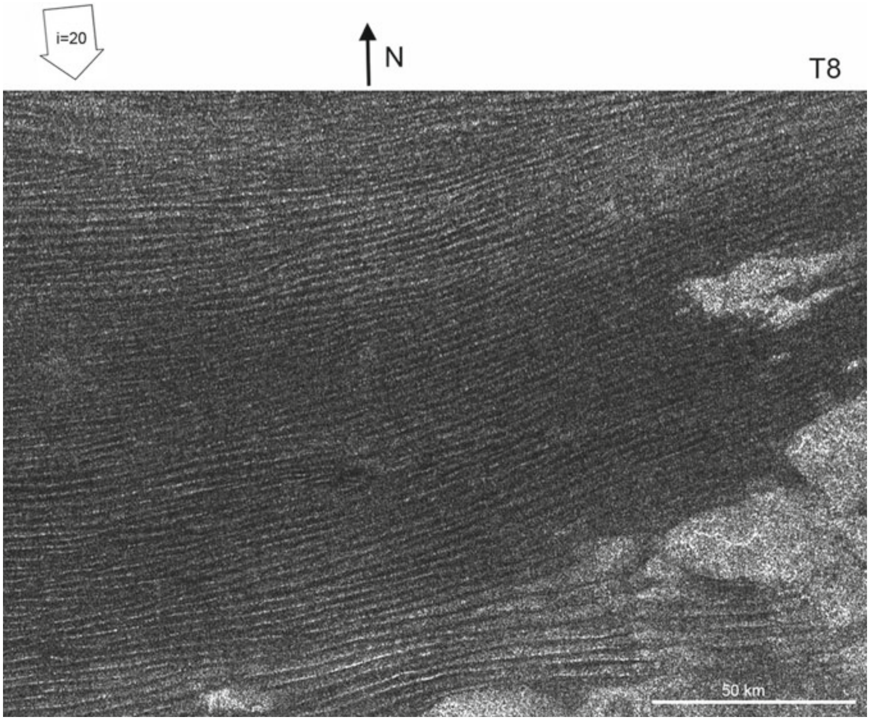

Fig. 7.4 Dunes of the Belet Sand Sea, Titan. Dunes are linear in form here, and are dark to Cassini SAR (Synthetic Aperture Radar) because there are fine particles. They are also dark to the visible/near-infrared because of the composition. *Bright lines* are reflections off the dune crest of the SAR signal. *Inset arrow* describes direction of SAR illumination and incidence angle. Image from Cassini flyby T8, location 8S 240 W. (Courtesy NASA/JPL)

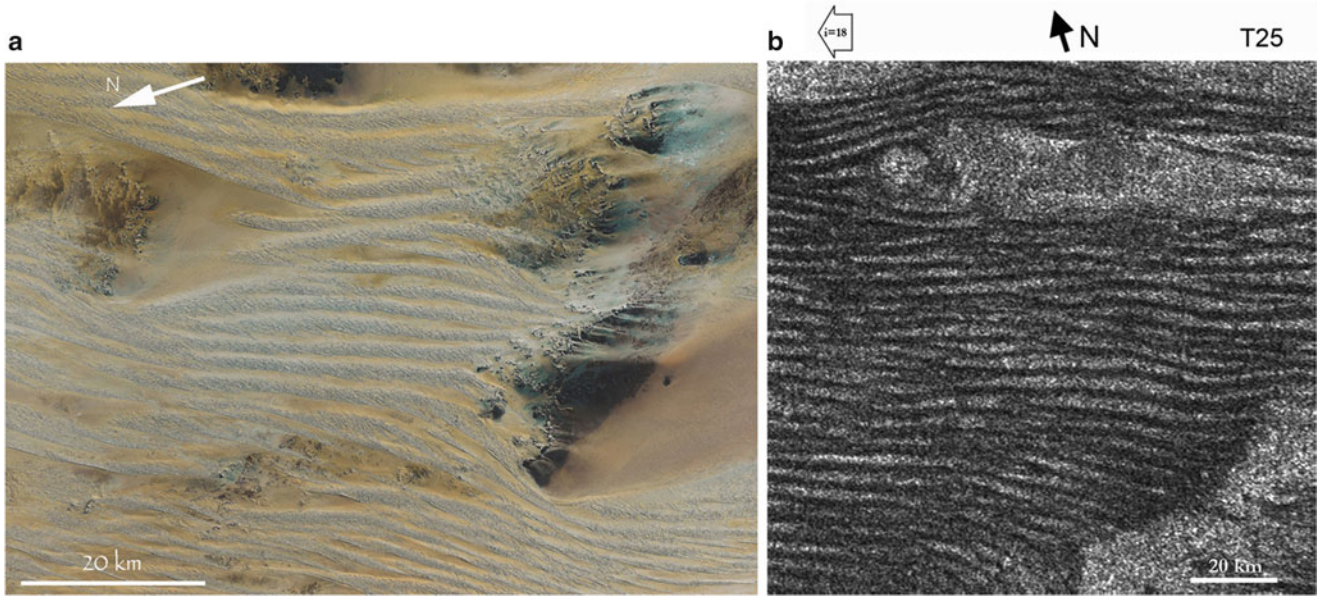

Fig. 7.5 Linear dunes diverge around obstacles in the Libyan sand sea (**a**) and in the Fensal Sand Sea on Titan (**b**). Wind is from the left in both images. Libyan dunes are found at 22 N, 20 E, image from Landsat. (Courtesy of NASA Goddard Space Flight Center and U.S. Geological Survey). Dunes on Titan are at 6 S, 40 W. Image from Cassini SAR (Courtesy NASA/JPL)

into particles small enough to be saltated by winds blowing in Titan's thick atmosphere. The dune sands, trickling through your fingers much like quartz sand in size and character, would be dark in color and more like plastic or coffee grounds in composition.

That such large regions on Titan could be covered in just—sand—was hard to conceive. Other explanations were searched, with solutions ranging from a hardened covering of organic "fallout" to regions unusually smooth and thus dark to radar. But the morphology of the ubiquitous dark lines in radar images, their sizes, their undulatory nature, and their interaction with topography, are unmistakably dune-like (Fig. 7.5).

In addition to Titan and Earth, the other solid bodies in the solar system possessing a substantial atmosphere, Mars and Venus, also have dunes. The requirements for sand dune formation, to have sand free to move, wind, and conditions right for the sand to collect, are all met on these bodies. Sand seas on Venus might have been predicted to exist in force across the surface. After all, there has been plentiful volcanism on Venus, which can generate sand-sized particulates, and there is a dense atmosphere (90 times the pressure of Earth's at sea level) to blow the particles around. Instead, only isolated patches of dunes can be found. The largest dune field, Al-Uzza Undae, nestles in a valley and covers just over 17,000 km^2, slightly smaller than the Qattameya dune field just west of Cairo, a collection of isolated, wispy dunes heralding the approach of the Great Sand Sea to the west. On a 2010 expedition to this dune field, it was only comfortable to cross several of these ¼ mile (0.5 km) wide dunes on foot before succumbing to September heat and dryness. Passage of similar kinds of dunes in Al-Uzza undae, made instead of black basalt sands, would be even more challenging in the 700°C heat of the Venus atmosphere, absolutely devoid of water (Fig. 7.6).

It has been apparent since the early days of Mars exploration that sand is blown around by the unrelenting winds. Sands of unweathered basalt derived from volcanic eruptions of the past collect behind boulders, in dried channels, in crater floors, and behind spunky rovers and landers. Later observations revealed more to the sand story on Mars. Massive, detached sand seas ring the north polar ice cap where sediments are likely derived from the effects of advancing and retreating glaciation on underlying sediments of the exceedingly flat, great northern plains. It is as if an old ocean, thought by some to have once resided in the northern lowlands, has beget a new ocean of sand. The Olympia Undae erg (Arabic for sand sea) covers over 100,000 square miles (300,000 km^2), approaching the size of the Great Sand Sea, and consists of barchan and dome dunes of varying sizes and spacing (Fig. 7.7).

Hundreds of thousands of dunes exist on Mars, and they give the observer the impression that wind is actively moving vast amounts of sand across the planet. However, decades of observations by Mars-orbiting spacecraft revealed very few changes in duneforms over the years. It appeared that the dunes of Mars were anchored firmly in place, probably by interstitial ice deposited seasonally and never fully removed. The dunes were apparently fossils, heralding a time of greater liberality in sand movement, either from stronger

Fig. 7.6 This Magellan Synthetic Aperture Radar image from the southern portion of Venus' Navka region shows a bright-rimmed outflow channel peppered by small volcanic cones. At the end of the channel, where one would expect the smallest particles to be deposited, are specular features which may represent sand dunes. Radar images of sand dunes on earth show similar specular reflections from smooth dune faces. Other evidence for aeolian activity are the dark and bright windstreaks running east to west across the image (Courtesy NASA/JPL)

winds or warmer climes capable of releasing ground ice into the atmosphere. Recently, however, researchers have noted many instances of changing dunes and moving sands on Mars, from the gradual shift of ripples on dune surfaces to the slow migration of large dome dunes. It appears that the surface of Mars is very much alive, and the dunes, like on Titan, may be among the youngest features, responding currently to the effects of the winds.

"How about some piracy on the high desert?" Major Bagnold sealed the argument of the value of a WWII light car patrol in the Libyan desert with the analogy of the desert as a sea. Commander Wavell of Cairo appreciated this from a military point of view and could not resist the tantalizing prospects associated with the request, and the Long Range Desert Group (LRDG) was born. Efforts of this ragtag and tenacious group likely staved off Italian advances on Egypt (Fig. 7.8).

Exploration of sand seas in the solar system, outside Earth, has been done strictly from remote platforms. Mariner orbiters and Viking Landers were first to study Martian dunes in detail. Several dunes near the Viking 1 lander were observed slumping over time, but not migrating. Mars Pathfinder also observed a set of small dunes arranged transverse to the direction of wind. Later surface operations carried out by the MER rovers Spirit and Opportunity investigated a variety of dunes in crater floors and on open plains. In fact, Opportunity was trapped in a dune for 5 weeks. Many dune fields on Mars appear to be active, while some may be "fossilized", hardened in place.

On Venus, Soviet Venera landers saw no evidence of dunes up close, but orbital radar from Veneras 15 and 16 and NASA's Magellan spotted dunes in the lee of craters and mountains. All orbiters used Synthetic Aperture Radar to peer beneath the clouds.

In the case of Titan, radar and imaging systems aboard the Cassini orbiter continue to unveil details in the complex interaction between dunes and atmosphere there. Radar has given us views down to about ½ kilometer resolution. Infrared imaging is considerably less detailed, but has provided context for radar imaging over large areas. The European Huygens probe saw what were probably thin lines of dunes on the distant horizon, and seems to have landed on a sandy area similar to a silty river bed.

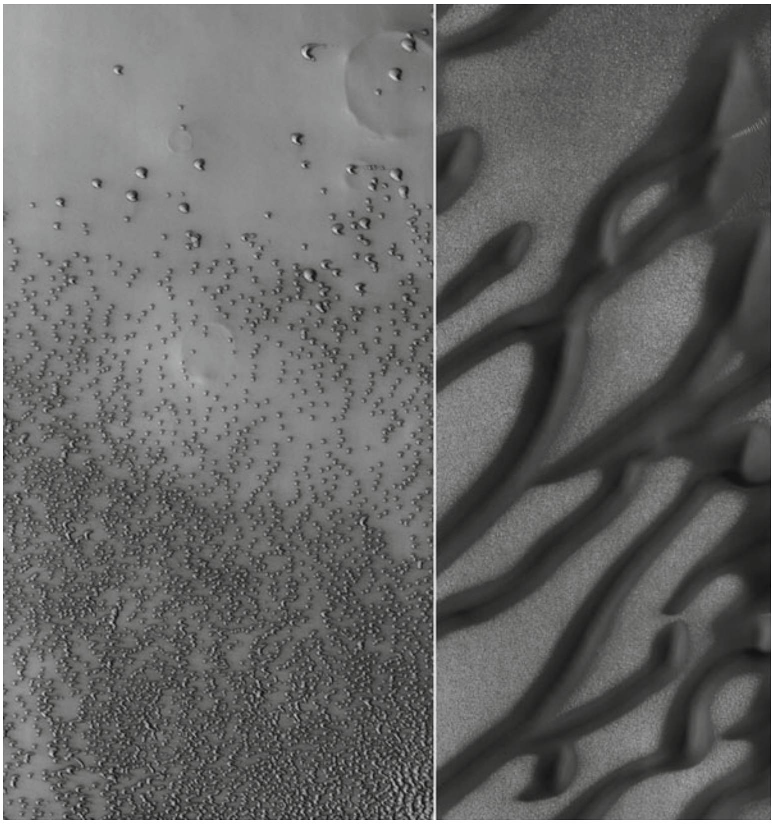

Fig. 7.7 (*left*) Barchan dunes at the edge of the Olympia Undae sand sea, near the north pole of Mars. Though sand quantities are sparse at the edges of the sea, they become more abundant poleward, toward the bottom. Image V27310011 from the THEMIS instrument on Mars Odyssey, centered at 74 N, 308 W, 20 km wide. (Courtesy NASA/JPL/Cornell/USGS/University of Mainz). (*right*) Linear dunes near the north pole of Mars. Dunes are *dark* in color because they are composed of basalt particles. Ripples can be seen near the top right. Image from the HiRISE camera, PSP009739_2580, from 78 N 209 W, and is approximately 1.5 km wide (Courtesy NASA/JPL-Caltech/University of Arizona)

Fig. 7.8 Members of Colonel Bagnold's long range desert group, in North Africa, ca. 1943 (British War Department, public domain)

Even on Earth, sand seas remain among the last incompletely explored terrains, because of the environmental and political challenges in these areas. However, as we press on in our understanding of the evolution of planetary surfaces, we find ourselves driving deeper into the deserts of Earth (Fig. 7.9 and Fig. Fig. 7.10). As we do, we ask questions that require multiple approaches to answer: Why is a sand sea present here? How do winds and climate change affect desert landforms? What can the sand sea say about the past, present and future of the surface? We will continue to do laboratory and numerical modeling to make progress and will analyze images for the wealth of information they contain. But only by getting close to the dunes can we determine the kind and volume of volatiles, such as water, in dunes on Mars. Only by sampling dunes on Venus can we find out the ages and styles of volcanism from a wide region. By flying low over the dunes on Titan we can see if there are active crestlines, which would indicate that this is the largest active dune system in the solar system, and by obtaining a sample we can understand the atmospheric pro-

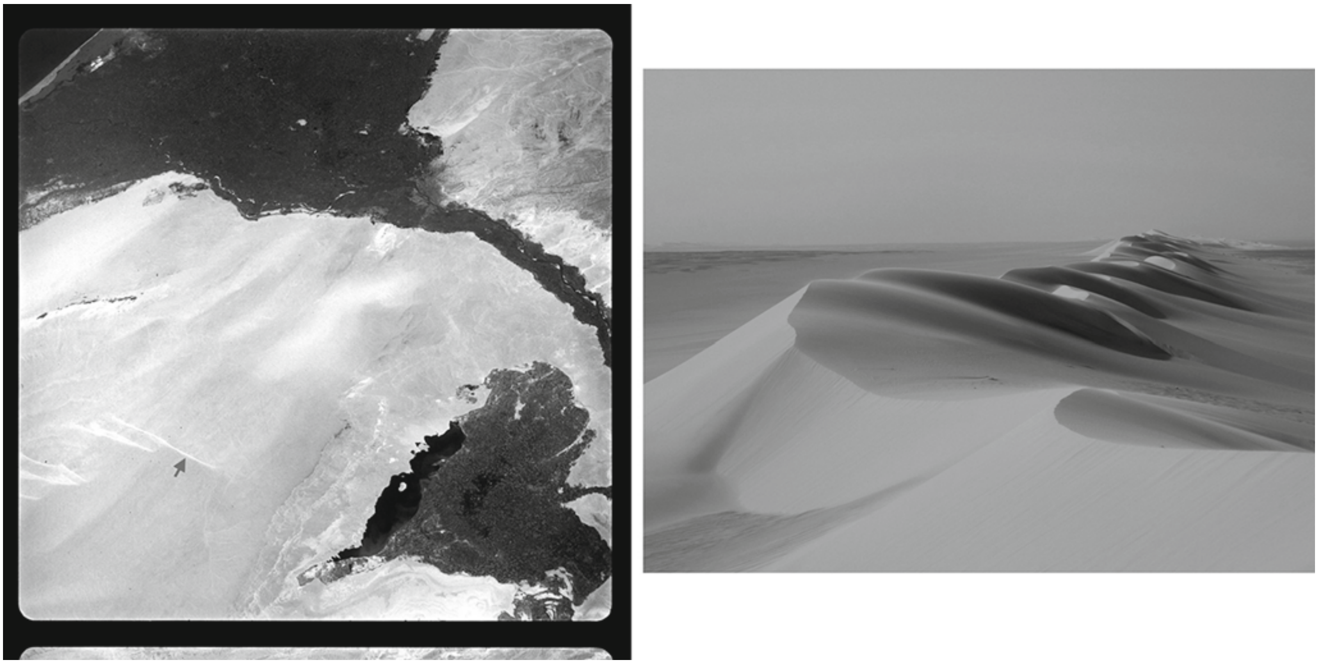

Fig. 7.9 Dunes in the Qattameya dune field, west of Cairo. These have less sand available in the region, so make wispy, widespread dune forms. Image on left obtained by Ed White during the Apollo 8 mission, during the first space walk. The *arrow* indicates the position of the photograph on the right, taken from atop the dune crest by the author in September 2010

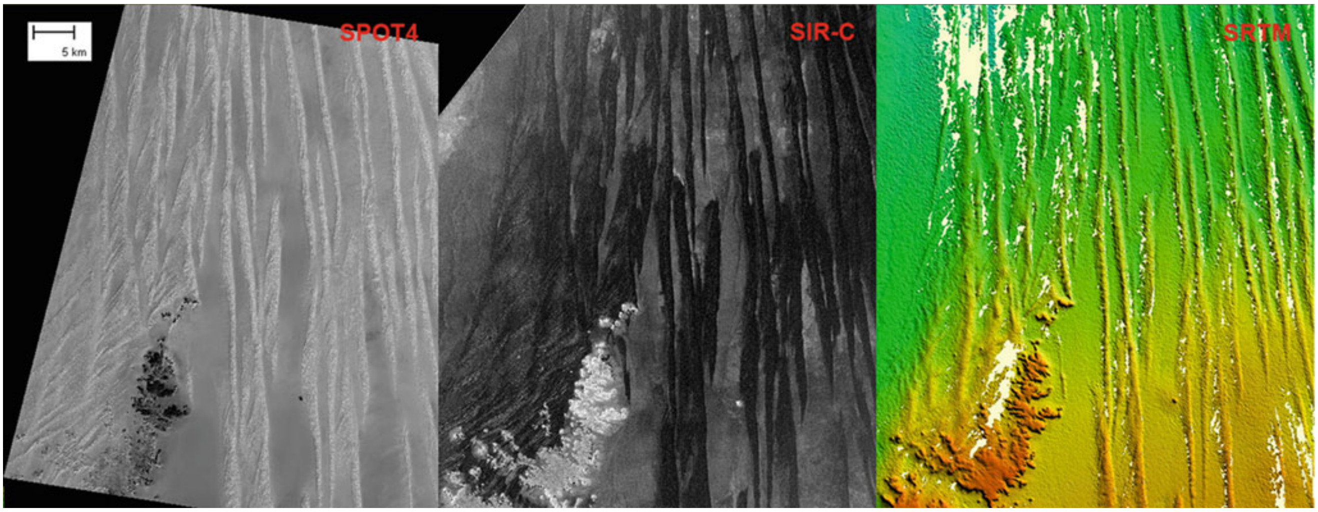

Fig. 7.10 Dunes in the Sahara desert seen at different wavelengths: visual/near-infrared (SPOT4), RADAR (SIR-C, 6 cm) and elevation (SRTM, shuttle RADAR topography mission). The center view is most similar to the images returned by Cassini's radar system (Courtesy CNES/ESA and NASA/JPL)

cesses that result in the unique dune sands of Titan. These efforts require airplanes, balloons, landers, and rovers, all of which are within our reach and capability as explorers. On Earth we are doing this with sturdy trucks and our own two feet, even when the way ahead seems peppered with difficulty. And so we are gradually making headway in our understanding of dunes. When Major Bagnold was asked how he intended to get from Egypt to Libya on his LRDG excursions, he claimed, "Straight through the middle of the sand sea. It's safe because it's believed to be impassable".

Concepts for Future Missions to Titan

If Ralph Bagnold had aircraft instead of cars at his disposal, he might have explored the desert from above. The prospect continues to intrigue mission planners today. The first aerial planetary explorations were carried out by two Soviet/French balloons in the skies of Venus. VEGA 1 and 2, spacecraft bound for Halley's Comet, dropped off two Venera landers at Venus on their way to the comet. Hitchhiking atop each lander was a balloon. Both craft survived buffeting winds and sulfuric acid haze to survive for about 48 h. But plans are on the books to carry balloon technology much farther afield, to the skies of Mars and Titan.

Engineers have seriously considered Mars balloon probes since joint USSR/Planetary Society studies in the 1980s. Balloon expert Jacques Blamont, considered the father of the VEGA balloons, proposed a sealed "superpressure" balloon that would cruise during the warm martian days and settle to the ground at night, where it would sample the soil with a gamma ray spectrometer.

Hot air balloons are under study for an international Titan mission called TSSM (Titan and Saturn System Mission). The ambitious TSSM would involve an orbiter, a nuclear-powered Montgolfier-style hot air balloon, and perhaps a surface science package. Titan's low gravity and dense atmosphere make it a perfect candidate for balloon probes that could circumnavigate the small world on its global winds. The idea is not a new one: in the early 1980s the Science Applications International Corporation studied a probe that would hang beneath a blimp, and later studies were carried out at JPL and several aerospace corporations.

A much less expensive mission recently proposed but not selected is the TiME, or Titan Mare Explorer. As its name suggests, the probe would land in one of Titan's methane/ethane seas.

Titan's environment also lends itself to drone-like aircraft. One such concept is called AVIATR, the Aerial Vehicle for In-situ and Airborne Titan Reconnaissance. The nuclear powered unmanned aerial vehicle (UAV) would have direct atmospheric entry from a delivery craft, would have direct-to-Earth communication, and would fly continuously, making observations and taking data for up to one Earth year. Carrying a near-IR spectrometer and camera, a RADAR altimeter, and atmospheric sensors, it would concentrate on the best science that can be done by aircraft: obtaining observations that would enhance our understanding of global geological processes on Saturn's bizarre dune-covered moon.

Exotic Seas: Liquid Alkanes on Titan's Surface

8

Karl L. Mitchell

Titan Before Cassini

Titan is unique among moons in our Solar System: It is the only one to have more than just a trace atmosphere. Its opaque Nitrogen-Methane blanket, although much colder than those of the atmosphere-laden rocky planets of Earth, Venus and Mars, is nonetheless the second thickest in the Solar System. At 1.5-bar, its surface atmospheric pressure is greater than that of Earth, maintaining the surface at a balmy (by icy satellite standards) 90–95 °C. The existence of an extensive, possibly global ocean—composed primarily of alkanes that can be liquid under these conditions—was proposed in 1983 on the basis of data from Voyager and photochemical modeling. Researchers suggested that bodies of liquid made up principally of ethane and methane, probably containing dissolved nitrogen and some organics, existed on its surface. Put simply, something had to be buffering the atmosphere against losses to space from solar radiation. Some unknown phenomena had to be maintaining the high apparent humidity of the atmosphere, most likely a large surface or sub-surface volatile reservoir, replenishment by outgassing, or a combination of the two (Fig. 8.1).

At around the time of Cassini's arrival in the Saturn system, several studies were underway that revised this concept of Titan as an ocean world. The high relative humidity of methane (close to 100 %) at high latitudes, contrasting with less than 50 % near the equator, led scientists to suggest that high polar rainfall rates near the poles could result in an Earth-like hydrological (or rather alkanological) cycle, with methane playing a similar role to terrestrial water. Furthermore, it was proposed that the observed humidity could result from a global liquid coverage of as little as 0.2–2 % of Titan's surface, and so the possibility of polar lakes was predicted (Fig. 8.2).

Discovery of Lakes and Seas

The Cassini spacecraft first started observing Titan's surface in 2004, with early imaging at radar, infra-red and optical wavelengths, revealing a dry, desert-like surface at low-to-mid latitudes, with the only seas being massive, dark dune fields, likely consisting primarily of solid organic materials produced in the upper atmosphere. There was ample evidence for liquids, however, from the Huygens lander, which showed a fluvial network during descent and both rounded pebbles and evaporating fluids at the landing site (Fig. 8.3). Furthermore, the Cassini Titan Radar Mapper (RADAR) revealed valleys and channels at numerous locations on the surface, confirming previous predictions of rainfall and a complex hydrological cycle.

Standing bodies of liquids remained elusive until 2006, however, when the first lakes were observed, both by the Image Science Subsystem—which showed a dark expanse near the South pole now referred to as Lacus Ontario—and also by the RADAR instrument, which showed hundreds of small lakes, mostly contained within apparent depressions, in the North polar region. Several lines of evidence supported this interpretation: (1) their morphological similarity with terrestrial lakes and relationship to other fluvial features (channels); (2) the low radar backscatter, implying surfaces that were smooth at the scale of approximately the radar wavelength (2.17 cm); (3) the presence of the liquids in the polar regions being consistent with recent predictions using atmospheric and climatological models; and (4) their radiometric brightnesses, higher by several degrees than the surrounding terrain, were consistent with the high emissivity expected for a smooth surface of liquid alkanes.

Later fly-bys revealed more lakes, some greater in extent than the largest Great Lakes in North America, and both in terms of absolute and fractional coverage of Titan, consistent

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Fig. 8.1 The Titan Mare Explorer (TiME) drifts on a truly alien sea of liquid ethane. Although NASA turned down this discovery-class mission in 2012, craft like it will eventually explore this uncharted territory (©Michael Carroll)

with terrestrial inland seas. Because of their size, these were soon referred to as seas or "Mare" (Fig. 8.4). To date only three have been classified as such. These are, from largest to smallest: Kraken Mare, Ligeia Mare and Punga Mare.

Despite several lines of evidence that the seas of Titan were indeed filled with liquid at present, the initial interpretation as current standing bodies of liquids remained somewhat contentious. An alternative, that the lakes might be dry or muddy and intermittent in nature was suggested, on the basis that the RADAR instrument observed apparent structures, such as buried river channels or valleys, close to the shores within many of the lakes and seas. However, subsequent observations soon demonstrated that this was unlikely, at least in some cases.

The first of these relied on the fact that radar interacts with liquid alkanes in much the same way that optical light interacts with liquid water. In other words, the lakes and seas of Titan are somewhat transparent to the RADAR instrument, but also lossy, and so the more liquid you're looking through, or the deeper the lake, the darker the return. The rate of loss is currently poorly known, but it seems likely that it is possible to see through at least a few meters, possibly more. Where channels were observed within the seas of Titan, it was possible to measure how the radar return varied along their lengths. Because rivers flow downhill, it was expected that if these were indeed drowned river valleys, then the channels would get progressively darker downstream because the spacecraft would observed them through progressively deeper bodies of liquids. This was confirmed soon after (Fig. 8.5).

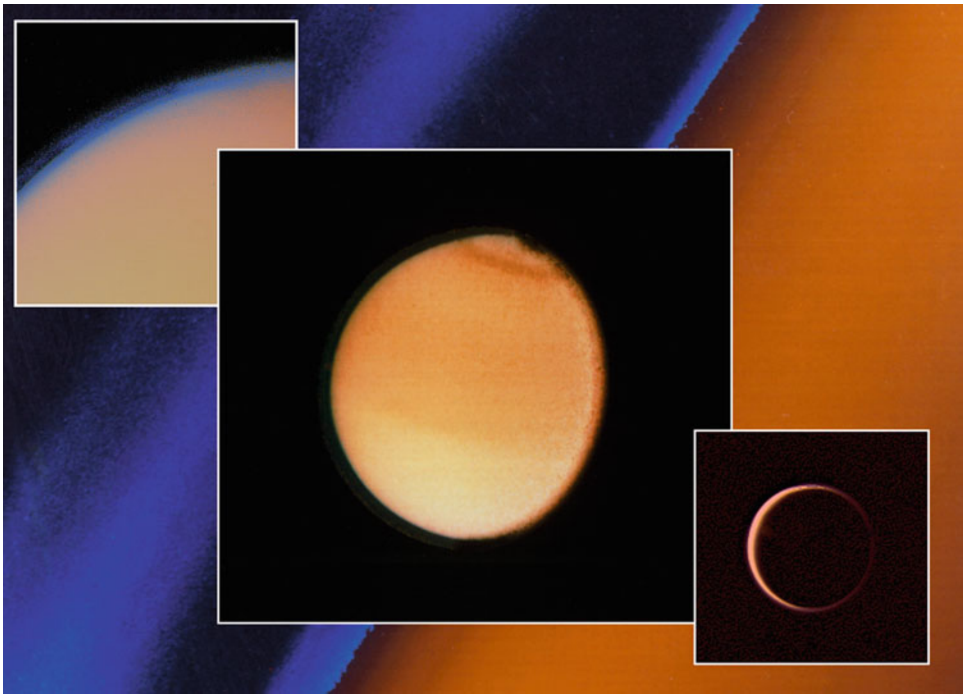

Fig. 8.2 Early images of Titan showed only the layers of haze hiding the surface beneath (Courtesy NASA/JPL Voyager photos)

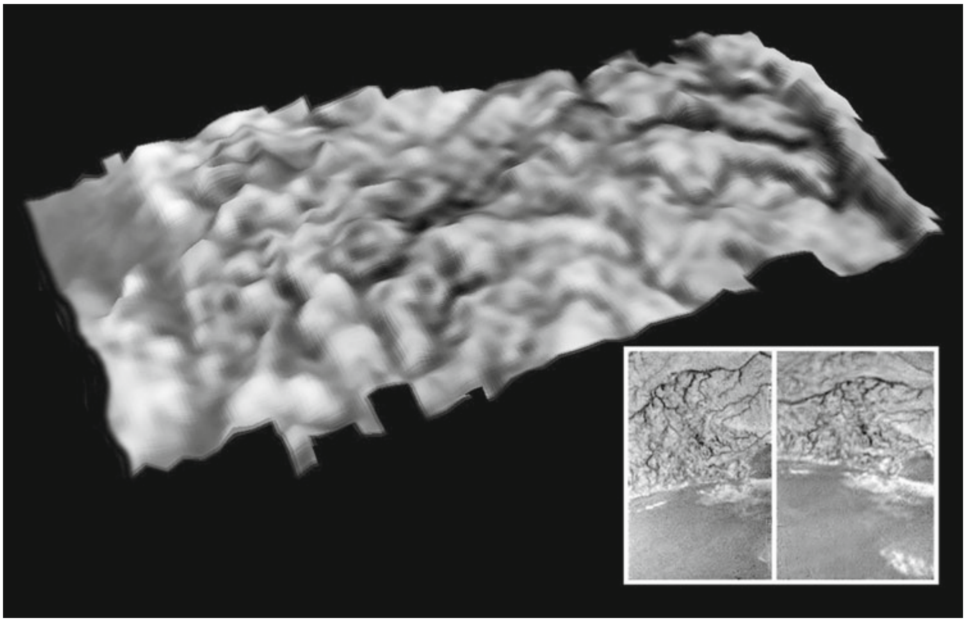

Fig. 8.3 Descent images from ESA's Huygens probe revealed branching tributaries much like rivers on earth (Courtesy ESA/NASA)

Fig. 8.4 Map of the polar seas of Titan. The largest, Kraken Mare is on lower right of image, covers an area equivalent to the Caspian Sea (Courtesy NASA/JPL/K.L. Mitchell)

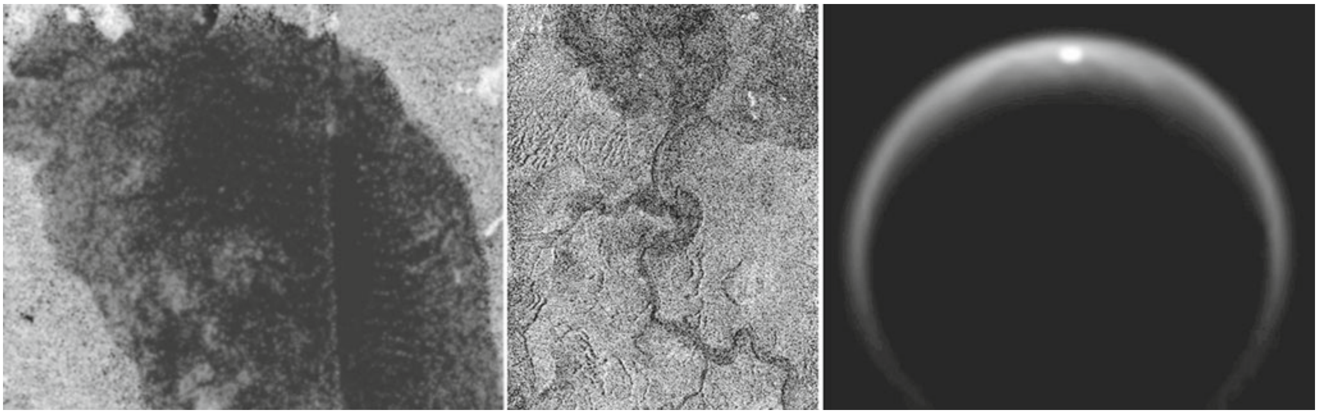

Fig. 8.5 Lines of evidence for liquid in Titan's seas (l to r): translucent or "lossy" quality to the radar images; river-like structures associated with the dark bodies; glint of sunlight off of Kraken Mare (Courtesy NASA/JPL)

Then, in 2009, the Visual and Infrared Mapping Spectrometer (VIMS) observed a glint of sunlight reflected off of one of the seas, Kraken Mare, resolving any remaining doubt (at least in the case of Kraken).

The Nature of Titan's Seas

The lakes and seas vary greatly in size on Titan, from the limits of SAR resolution (typically from 300–1,000 m) up to about 400,000 square km (150,000 square miles) for Kraken Mare. For comparison, North American's Lake Superior is 82,000 square km (31,700 square miles) in extent, and the Black Sea, bounded by Europe and Asia, is 436,400 km^2 (168,500 square miles). Winds, rather than lunar tides, are likely to be the main drivers for waves on Titan, which are not expected to be as great as oceans on Earth. Liquid and air densities affect the growth rate of waves, suppressing the rate on Titan relative to Earth. For a fairly high (for Titan) surface wind speed of 1 m/s (2.2 mph), wave heights could reach about 0.2 m (2/3 ft) with a wavelength of about 4 m (13.3 ft). If such waves with these characteristics were observed by Cassini RADAR, this would most likely cause a fairly significant brightening of the surface, but this has not been observed with any certainty. Significant wave heights as great as 0.6 m (2 ft) might occur in some parts of Titan's seas in the peak of summer when winds are strongest.

There appears to be a distinction both in morphology and size between lakes and seas on Titan, with the larger seas typically having rugged coastlines, in extreme cases reminiscent of fjords or flooded river valleys on Earth. In some cases, the largest of the lakes, e.g. Jingpo Lacus, exhibit some of these features, but most of these are incompletely mapped and may indeed be outliers of the seas. The smaller lakes, however, are mostly circular, quasi-circular or formed from multiple arcuate shores, often with steep rims. These structures have led to the suggestion that the lake basins are actually karstic in nature, the result of dissolution and dissolution-related collapse. Similar lake forms are found in Florida or Minnesota, where depressions have been dissolved into the rock. Given that terrestrial karstic terrain tends to be associated with very porous and/or fractured ground, supporting subsurface groundwater flow, this lends some credence to the suggestion that liquids in the lakes slowly drain into the subsurface and are transported to the lower elevation seas over time (Fig. 8.6).

This may have implications for the chemistries of both the lakes and seas. The exact blend of hydrocarbons in the lakes is unknown, but it is likely predominantly a mixture of ethane (C_2H_6) and methane (CH_4). Although methane rainfall is thought to be about a 100 times greater than that of ethane, its higher volatility on Titan's surface means that the methane will tend to evaporate more quickly, and so over time a standing body of liquids should become gradually enriched in the more stable ethane, probably meaning that ethane dominates. However, a large unknown is how important subsurface flow is to redistribution of liquids on Titan. If many of the smaller lakes are indeed karstic, then it is likely that flow in the subsurface is quite efficient, and the entire polar lake district may be underlain by an extensive aquifer or alkanofer system, connecting lakes to seas via subsurface flow. If the flow is from one general direction, from higher elevation lakes to lower elevation seas, then we might expect the seas to have even greater ethane concentrations, as most of the liquid ethane would end up in the seas, and hence the smaller lakes may consist mostly of liquid methane. In that case, the seas would be thermodynamically very stable, and we are less likely to see any change in their volumes over time. Unfortunately, although it has been possible to detect ethane directly using orbital spectroscopy, Titan's thick methane-rich atmosphere makes spectroscopic determination of the ethane/methane ratio very difficult, and so it seems unlikely that Cassini will be able to directly address most questions about the chemistry of the seas.

Estimating the volume of Titan's lakes has proven difficult, as there are great uncertainties in their depths. Although

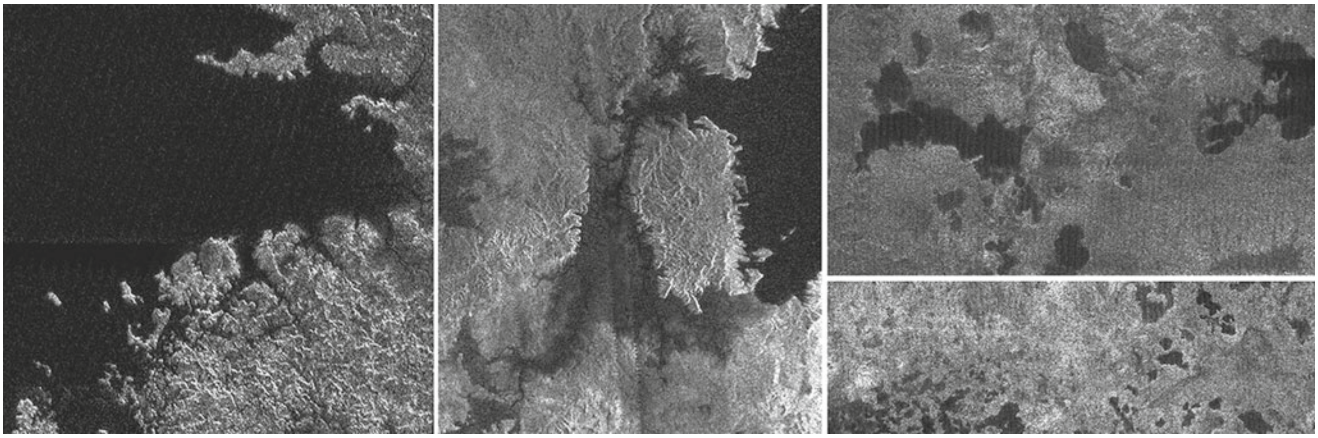

Fig. 8.6 Shorelines of Titan range from rugged coastlines (*left and center*) to karst-like smooth, steep boundaries and rounded bays (Courtesy NASA/JPL)

at least partly transparent to radar, many of the lakes are deep enough that the reflected radar signal is below the noise floor to Cassini's RADAR. Furthermore, the extent of that transparency is unknown, as laboratory studies have been limited, and so scientists cannot yet estimate the depth that this noise floor signifies. On Earth lake depths are generally around 10x less than the height of nearby terrain. If one assumes geometries similar to lakes on Earth, then depths of many 10s of meters, maybe 100s of meters, are plausible. Hence, it seems likely that there is of the order of 10^5 km^3 on Titan, possibly an order of magnitude or so greater, which is both massively smaller than the volume of Earth's oceans (10^9 km^3), but also greater than Earth's natural gas reserves (~10^2 km^3).

Whatever the precise volume, however, the vast volumes in Titan's lakes and seas are important as both a sink and a buffer within Titan's hydrocarbon cycle, which plays a role akin to the terrestrial hydrological cycle. If, as proposed for Mars, there are extensive reservoirs of liquids under the surface, then potentially the volumes involved are greater, and the transport processes may be more complex, including additionally subsurface flow for redistribution.

It is also important to realize that this cycle is a lossy one. Some of the methane (and other hydrocarbons) is constantly lost to space due to high energy ionizing radiation exciting particles in the upper atmosphere. That same radiation can result in a complex series of chemical reactions that convert the methane and ethane into other materials, forming solids that "snow" onto the surface. The volumes of the dunes alone, which are at least mostly derived from such hydrocarbon solids, is thought to be around an order of magnitude greater than the lakes and seas, and this discounts dunes undetected due to resolution limits as well as possibly 100s of meters of immobile solid hydrocarbon deposition over the entire surface. However, the role of such solids is likely to be passive unless there is some way of reactivating them thermochemically (Fig. 8.7).

Looking for Change: The Cassini Solstice Mission

The Cassini spacecraft started touring the Saturn system in 2004, starting just after Saturn's northern winter solstice. However, 1 year in the Saturn system equals 29.7 years on Earth, and so despite observing for many Earth years, barely one season has passed on Titan. The latest extension to Cassini's mission, coined the "Cassini Solstice Mission", will extend the life of Cassini to almost one half a Saturn year, all the way to the northern summer solstice, before crashing into Saturn in 2017. These extra years are particularly important for studies of Titan's lakes, seas and other aspects of its hydrological cycle, as seasonal changes are expected to drive rainfall and evaporation, and hence it is possible that changes to lake levels and coverage might be observed.

Some evidence for change has already been seen. Clouds have been observed throughout the life of the mission, but over the past few years there have also been associated "darkening" effects, suggesting rainfall. Titan's largest south polar lake, Ontario Lacus, has also apparently receded by about 10 km from June 2005 to July 2009, possibly representing a few meters of drop in surface levels. Furthermore, some ephemeral lakes nearby appear to have disappeared between December 2007 and May 2009. However, despite numerous observations, no such changes seem to have been detected in the north polar lakes, and the reasons for this can only be speculated on. Certainly, the north polar lakes are more numerous and appear to have steeper-sided shores in many case. This may mean that a comparable drop in surface levels may only results in an undetectable shoreline retreat. It is also possible that the climate in the north is sufficiently different that transport processes are less at this time in Titan's year (Fig. 8.8).

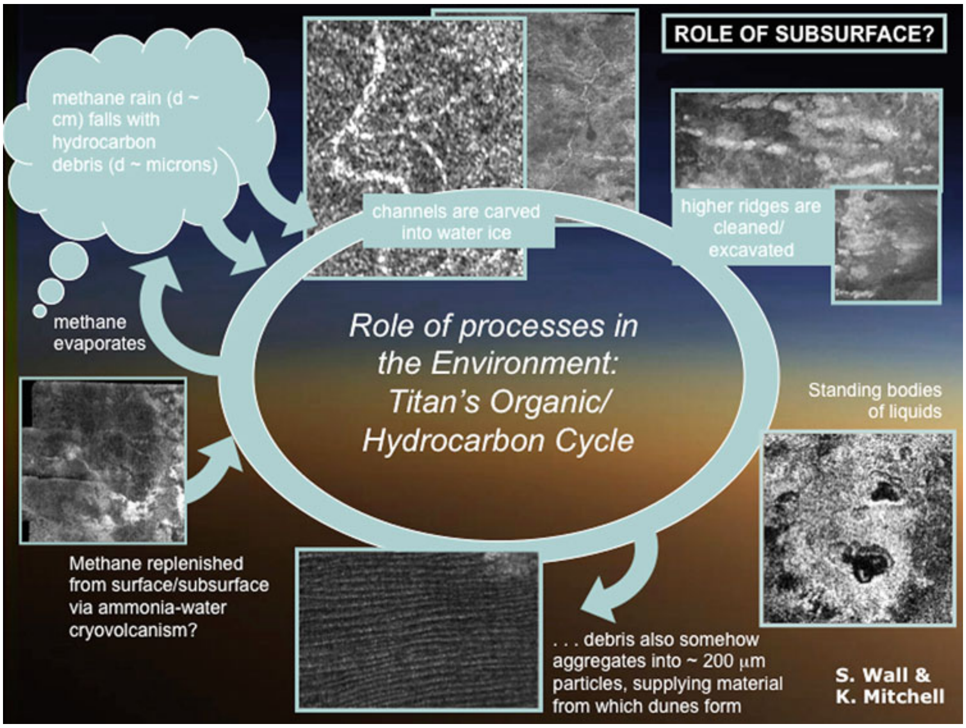

Fig. 8.7 Titan's hydrological cycle is fed by methane and ethane, rather than by water, and plays an important role shaping most of the surface (Courtesy NASA/JPL/S. Wall/K.L. Mitchell)

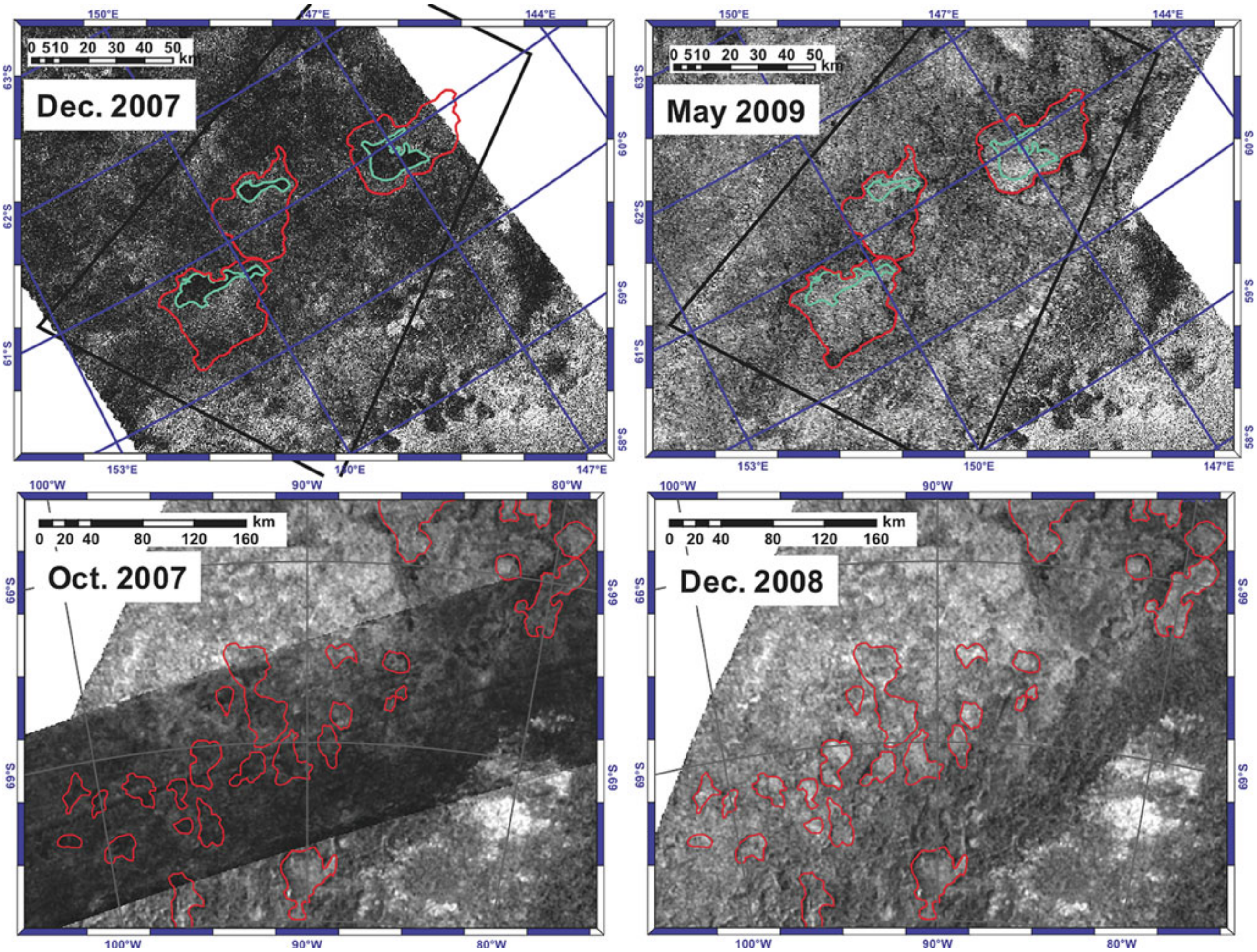

Fig. 8.8 Cassini has documented seasonal changes in Titan's lakes. Outlines show lake basins (in red). In top figure, green outline shows location of assumed liquids not present in a later fly-by. ((Courtesy NASA/JPL) A. Hayes (Cornell University))

Summary

The study of Titan's surface, including its lakes and seas, is in its infancy. Cassini has given us our first glimpses of seas on the surface of an alien world, and over the coming years scientists will continue to analyze the data and make interpretations. It is possible that, much as happened when we first observed Venus' atmosphere, we will learn something about Earth. Mostly, however, as tends to happen, more and better informed questions will be raised, that can only be answered by a future mission. In order to address these questions, sampling the seas should provide the best single-point to understanding chemistry of Titan because, as on Earth, the seas contain a complex smorgasbord of dissolved materials that provide insight into the huge variety of geological, environmental and possibly biological processes.

The first formal proposal to mount such a mission came in the form of the Titan Mare Explorer (TiME), a vessel that would have landed in Ligeia Mare to analyze its composition, surface and shoreline, as well as Titan's atmosphere, over a period of about 3 months. Its mobility would have been achieved simply by following the ocean currents. Although the mission was turned down for funding, a return to Titan, the most unusual of moons, seems inevitable.

Acknowledgment This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

The Seas of Saturn

9

Kevin H. Baines and Mona L. Delitsky

Fluids virtually comprise the Solar System. Indeed, the massive gaseous and liquid oceans inside the four Major Planets—Jupiter, Saturn, Uranus, and Neptune—amount to more than 95 % of all the matter in the solar system outside the Sun. Within each of these planets, fluids extend from their very cores (which themselves are likely to be semi-molten oceans of iron, silicates, and other heavy materials) to the edge of space, altogether encompassing a volume of more than two thousand trillion cubic kilometers, equivalent to the volume of over two thousand Earths. These atmospheric and liquid seas experience an incredibly vast range of environmental conditions, from the near-vacuum of space down several thousand km to Earth-like surface pressures, down another 100 km or so to Earth-like surface temperatures, and then downward many tens of thousands of kilometers to incredibly high pressure and temperature conditions similar to that of the Sun's interior. Indeed, for the colder and smaller Uranus and Neptune, pressures at the bottoms of these oceans exceed more than four million times that found at the Earth's surface while their temperatures exceed 5,000°C (over 9,000°F). Saturn and Jupiter exceed these conditions by several fold, with pressures up to 20 million times that of Earth and temperatures up to 10,000 C and 18,000 C degrees, respectively, more than twice the temperature of the visible face of the Sun (Fig. 9.1).

The fluids comprising these planets are nothing like we experience on Earth. The bulk of the material—80–96 % by number, depending on the planet—is hydrogen, the smallest of the atoms. Most of the remainder is helium, the second smallest atom, used, for example, to float blimps over professional football games and golf tournaments. Together, these materials make up atmospheres on Jupiter and Saturn whose intrinsic mass per molecule is some 14 times lighter than found in our own atmosphere comprised of some 78 % nitrogen, 21 % oxygen and 1 % argon. However, some 14,000 km below the visible clouds within Jupiter, and some 27,000 km within Saturn, the crushing pressure of the overlying atmosphere—two million times the atmospheric pressure at Earth's surface—squeezes this otherwise lightweight air to the density of water, some 800 times the density of the atmosphere at Earth's surface. Indeed, just a few thousand km deeper down the pressures and temperatures are so strong—exceeding three million times the pressure of the Earth (known as three megabar, where a bar is the mean pressure of Earth's surface)—that they pry apart the two atoms making each hydrogen molecule, thus creating an ocean of single-hydrogen atoms. Even more astounding, they compel these atoms to lose control over their own electrons, allowing the resulting sea of electrons to readily flow from one hydrogen atom to another. Thus, the atomic hydrogen ocean behaves as a highly conducting sea of fluid metal, with electrons at the ready to flow throughout the deep interior (Fig. 9.1).

The two outermost planets, Uranus and Neptune, are enriched in heavier materials by more than an order of magnitude compared to Jupiter and Saturn, such that their bulk masses are comprised of carbon (mostly in methane), oxygen (mostly in water-associated molecules) and nitrogen (mostly in ammonia-associated substances). Like hydrogen, water (H_2O) degenerates in the high-pressure environment into ions, most notably OH^- and H_3O^+, while ammonia is converted mostly into NH_4^+. This occurs at much lower pressures and shallower depths than for the ionic hydrogen oceans of Jupiter and Saturn—just 5,000–7,000 km below the visible clouds.

Triggered by convective motions generated by the increasing temperature with depth, electrical currents flow within these ionic seas, creating immense magnetic fields that dominate the space environment for many millions of kilometers into space. Known as the magnetosphere, these regions control the "solar wind" flow of charged particles jetting away from the sun, deflecting a significant fraction to their magnetic poles.

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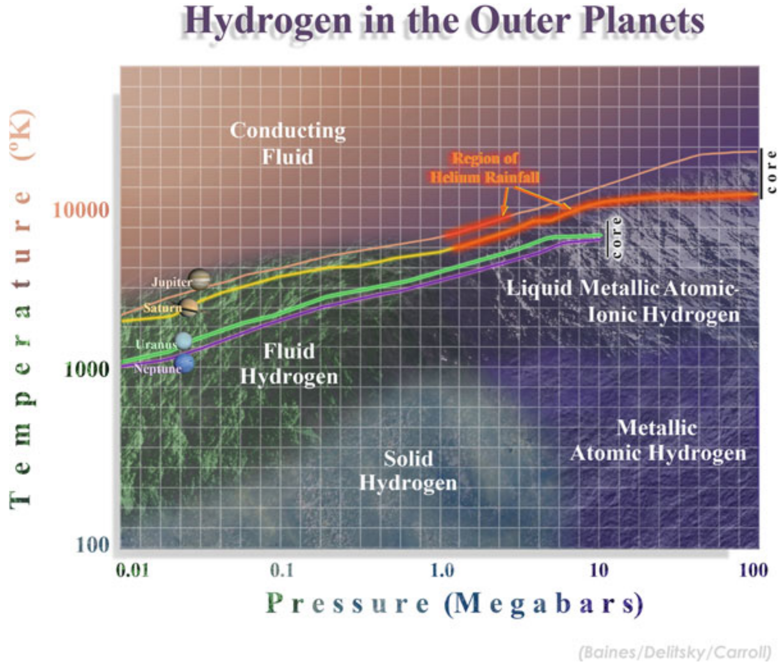


Fig. 9.1 Temperatures and pressures on the Outer Planets shown against the various states of matter for hydrogen and helium, their most prevalent materials. Logarithmic scales are used for both pressure and temperature. Jupiter and Saturn have core pressures and temperatures exceeding 100 Mbar and 10,000 K, while Uranus and Neptune have pressures just 1/10th as great and just one-half the temperature. All the planets have molecular hydrogen (H_2) down to approximately the 3 Mbar level, below which the molecules are torn apart, ionized into their constituent atomic nuclei (protons) and electrons. On Jupiter and Saturn, helium separates from this atomic hydrogen mixture, forming droplets that fall many tens of thousands of kilometers (*thick orange portions of curves*), depleting helium from the upper atmosphere of Saturn in particular while warming its interior. Scientists believe the energy released in the formation and fall of helium rain contributes significantly to Saturn's excess warmth (© Kevin Baines, Mona Delitsky, Michael Carroll). Adapted from Nettelmann et al. (2008, Astrophys. J., 683, 1217–1228)

Particularly on Jupiter and Saturn where, as on Earth, the magnetic poles nearly coincide with the spin poles, the flow of charged particles slamming into the upper atmosphere produce spectacular aurorae extending some 40,000 km (3 Earth diameters) across. These magnetospheres—generated by the trillions of cubic km of exotic seas of electric currents deep within the planets—are, on planetary scales, immense. Indeed, the magnetosphere of Jupiter is the largest single entity in the Solar System, some 11 million km across, encompassing a volume of space more than 500 times the volume of the Sun (Fig. 9.2).

Within the atomic hydrogen sea on Saturn, some 32,000 km below the visible clouds, helium becomes immiscible. Like oil floating on water, helium finds that it cannot stand being mixed with atomic hydrogen and instead separates out into fluid droplets. These droplets, growing to the size of marbles, then rain slowly through the dense atomic hydrogen fluid down to the core. The energy released by the condensation of these droplets from their gaseous state and by the subsequent decades-long fall through tens of thousands of kilometers of fluid causes Saturn to warm up to a much warmer temperature than it otherwise would have, as if it were 1/3 closer to the Sun.

Methane, the next most abundant constituent within the Major Planets, comprises some 0.2–2 % of the number of molecules in the observable portion of the atmosphere. Methane is an especially intriguing material. In the visible and near-infrared spectrum, methane absorbs sunlight from 0.6 to 3.5 μm, thus contributing to the warming of the upper skin of atmosphere. Within the extremely cold upper troposphere and lower stratosphere of Uranus and Neptune near the 0.1-bar level, temperatures as low as 60K (–413C) are found, causing methane gas to condense into wispy, transient clouds. In the comparatively warm depths below these clouds, methane gas is abundant, comprising some 2 % of the atmosphere by number, equivalent to 15–20 % of the atmospheric mass. Yet, mysteriously, despite methane's role as a condensable comprising such a large fraction of the atmosphere, surprisingly few clouds are observed. By comparison, the ~1 % water content of Earth's lower atmosphere produces prevalent clouds that typically cover about one-half of the globe.

Methane makes a surprising mark on Saturn. The intense heat of lightning (typically exceeding 20,000 C) generated in water clouds floating far from view near the 10-bar pressure level vaporizes methane into its atomic constituents of carbon

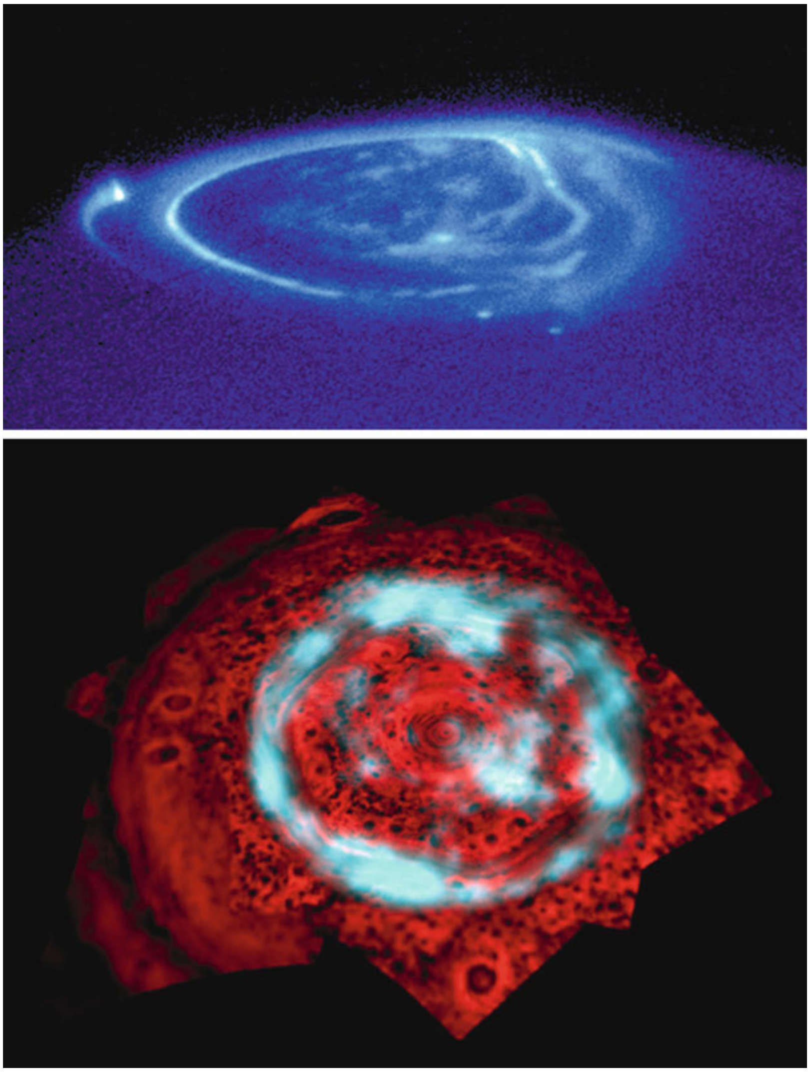


Fig. 9.2 Saturn aurora: Manifestations of an electrified interior. The vast magnetic fields generated by ionized hydrogen and electrons in the deep interiors of the Giant Planets create immense magnetic fields extending millions of kilometers into space. These fields intercept ionized atoms expelled by the sun in the "Solar Wind", redirecting them to the magnetic poles of the planet where they smash into the atmosphere. Collisions with atmospheric molecules create exotic, short-lived species that emit bursts of light as they form and die, resulting in the display of aurorae in the ultraviolet (*upper panel*) and the near-infrared (*lower panel*). These aurorae on Saturn span more than 24,000 km equivalent to two diameters of the earth. In the lower panel, the auroral lights of Saturn near a wavelength of 3.5 μm are seen (*light blue*) against the thermal light generated near the 10-bar level of Saturn at 5.1 μm (*red*). Optically-thick clouds are seen in dark silhouette against this reddish glow. The "Saturn hexagon"—a bizarre six-equal-sided feature centered on Saturn's north pole—can be seen lurking almost directly under the northern aurora (Cassini image courtesy NASA/JPL/University of Arizona)

and hydrogen. As the lightning channel rapidly cools at a rate of about a million degrees per second, the blasted carbon atoms readily find each other to form microscopic soot particles. In the relatively low gravity (less than 40 % of Jupiter) but dense environment at the 10-bar level of their lightning-sparked genesis (nearly twice as dense as the lightning layer in jovian water clouds) soot particles linger for centuries. In subsequent storms, the carbon soot is lofted in powerful updrafts, forming the nucleus of cloud particles comprised of water, ammonium hydrosulfide (NH_4SH), and ammonia (NH_3). As water vapor condenses into droplets, it generates heat in a process similar to what moves thunderstorms on Earth. This heat drives these sooted storm clouds, which rise over a 100 km to the visible upper atmosphere, where they appear as distinctly dark circular splotches against the otherwise bright clouds of Saturn. These distinctive dark formations on Saturn could very well mark something much more important to human destiny: they, and the gases they are immersed in, could be the key to the expansion of our civilization to the outer solar system more than 1.5 billion km from Earth (Fig. 9.3).

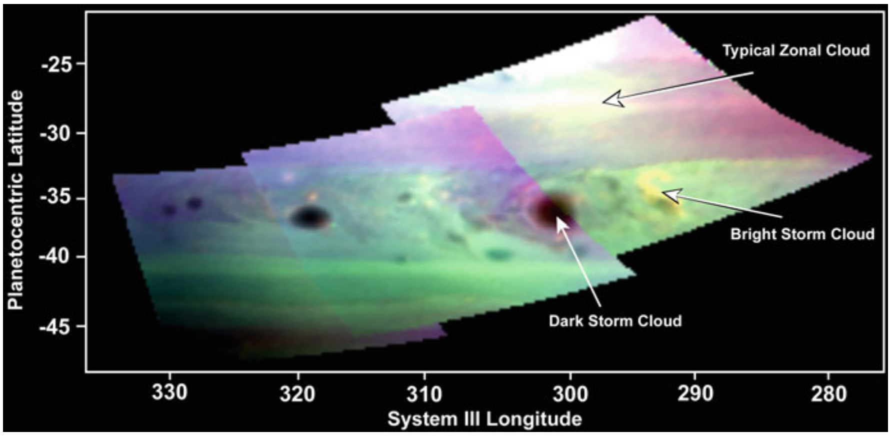


Fig. 9.3 Dark and bright storm clouds on Saturn. Water-powered thunderstorms on Saturn occur in the 10–20-bar level more than 150 km beneath the visible clouds. Convective uplift generated within these deep thunderstorms drive lightning-generated soot and overlying ammonia gas upward, creating both ammonia (NH_3) condensation clouds (yellow features) and dark, soot-impregnated condensates of ammonia hydrosulfide (NH_4SH), ammonia (NH3) and water (brown features). This storm occurred over several months in 2008 in Saturn's "storm alley" near 35° South latitude. Adopted from Fig. 1 of Baines et al., 2009, *Planet. Space Sci*. 57, 1650-1658

Mining Saturn (What Might We See in the Year 2469?)

It's been half a millennium since man first walked on the Moon. The Saturn System, literally a Disneyland of astronomical attractions for scientists as revealed by the two Voyager flyby spacecraft of the 1980s and the Cassini Orbiter/Huygens Titan probe mission of the early twenty-first century, is now being shared with commercial operators. On Titan, robotic factories refine both its hydrocarbon seas—largely comprised of the simple hydrocarbons ethane and methane—and its massive bedrock of water ice to create valuable rocket fuel and oxidizer. As well, when combined, these materials readily provide a key raw ingredient on which vegetation feeds and grows that in turn sustains the Saturn System's growing hoards of explorers and colonists. To wit, the oxidizer and hydrocarbons are unceremoniously burned to produce noxious yet nutritious (if you're a plant) CO_2, thus rather audaciously offending the sensibilities of untold millions of environmentalists back on distant Earth.

On nearby snow-white (literally) Enceladus, scientists are exploring its underground lake and river systems for life. The exotic chemistry fueling the amazingly active and beautiful geyser system, visibly spewing water and hundreds of other constituents several tens of thousands of kilometers into space, is proof that a veritable chemical soup inhabits the interior pools. The water jets out of the moon in liquid form—indicating a vast sea of fluid water underground—and quickly freezes, some of it gently falling back on the low-gravity moon as soft, pure snow, some of the best powder in the Solar System. Varying environmental conditions from place to place in the extensive system of underground, fluid-filled caverns—altogether spanning over several thousands of kilometers in length—means that the conditions for the genesis of life might be found if just the right cavern is explored in just the right way. So far, less than 10 % of the underground system has been probed with deep-sea robotic explorers first developed in the twenty-first century to investigate the oceans of Europa in the Jovian system. Amino acids and other complex organic chemicals have been discovered clinging to cavern walls as well as within surface snows. Scientists throughout the Solar System remain hopeful that conclusive proof of life will be found soon on this little, surprisingly active moon that, with a diameter of just 500 km, is smaller than a number of asteroids.

The skies of both Enceladus and Titan are dominated by the ball of pallid Saturn and its attendant retinue of wonderfully complex, brightly shimmering rings. While giant storms appear across its face about once per decade (Fig. 9.4), most of the time Saturn presents a serene, quiet visage, its most visible characteristic being a broad band of muted clouds encircling the equator. Compared to it dynamic, roiling neighbor—Jupiter—Saturn seems asleep.

Yet, within the depths of Saturn, some 100 km below the clouds, something remarkable is happening. A band of mammoth disc-like floating structures encircle the globe near 35° south latitude, each more than a 100 m across and 10 m high. Suspended in mid-air by a massive balloon more than a 400 m in diameter and 130 m tall, each 14,000 ton "sky station" services dozens of cluster-balloon-like vehicles that periodically visit it (Fig. 9.5).

These cluster mining craft are unlike anything else in the Solar System. The central sphere of each cluster spans some

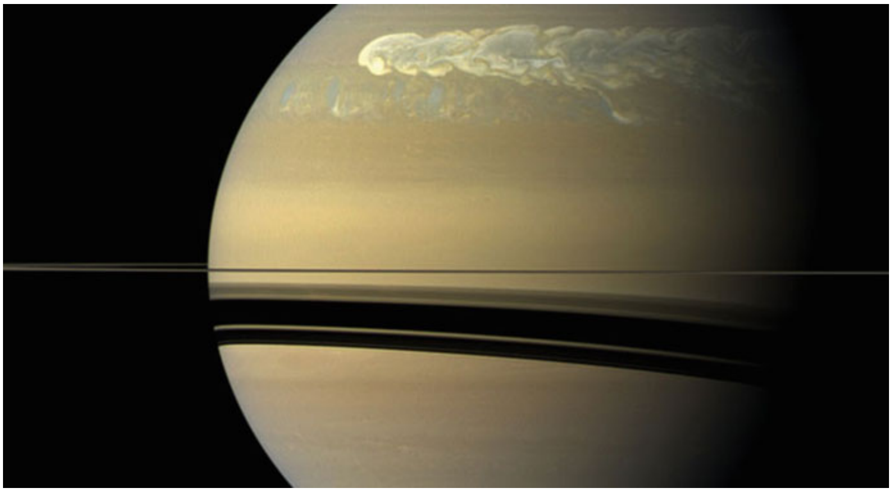


Fig. 9.4 The Major Storm of 2010–2011. The largest storm ever observed in the solar system broke out in December 2010. Within 3 months, a "comet tail" of anvil-tail storm clouds generated by immense thunderstorms at the "comet head" encircled the planet. Hundreds of lightning strikes per minute were recorded in the comet head by Cassini radio instruments, where storm clouds were more than 200 km (660,000 ft) thick (Courtesy NASA/JPL-CalTech/Space Science Institute)

7.5 m. Attached to it are three smaller spheres, each 2.2 m across, arranged in a band about what could be called the bottom portion of the central ball. Altogether, the vehicle is arranged in a tetrahedral, or triangular pyramid, shape, with its four vertices marking the centers of the four spheres. Dazzling in the glow of lights from the service station as they depart, these deep-atmosphere exploration and mining vehicles—each weighing 81 ton, similar to the weight of the American space shuttles of the twenty-first century—plunge tens of thousands of kilometers down into the immense depths of Saturn. Their prime mission: to collect droplets of pure liquid Helium-3, the elusive and immensely valuable isotope of helium that powers, warms, and sustains nearly every device, vehicle, and structure in the outer Solar System.

To avoid thunderstorms and their associated violent up- and down-drafts as well as to enhance the lifting ability of each cubic meter of balloon, the sky stations are located 100 km underneath Saturn's dynamic storm layer (Fig. 9.6). With an outside temperature at an above-boiling 140C (284F) and at a pressure of some 40 bar—equivalent to being 1,200 ft underwater on Earth—these sky stations take advantage of advances in ruggedized, lightweight materials and electronics that have enabled rovers to operate for decades on the hellish (nearly 500 C), high-pressure (94-bar) surface of Venus.

To maintain their floating ability, the sky stations utilize hydrogen syphoned from the surrounding atmosphere and heated to 550 C to create a buoyant gas with half the density of the surrounding air, generating an aerostatic lifting force per cubic meter equivalent to that which buoys blimps near the surface of the Earth. Here again, it is that invaluable ingredient, Helium-3, that is used to create the power needed to warm 15,000 ton of gas by several hundred degrees. Just as the Sun warms the planets by fusing together pairs of hydrogen atoms to release prodigious amounts of radiant heat, the lifting gas is warmed by the fusing together of pairs of helium atoms. However, it is not just everyday helium that is used. Rather in each reaction a pair of the extremely rare isotope Helium-3 is fused together to create two protons used directly to generate electricity and, as its sole waste product, a single normal helium atom, known as Helium-4.

The true magic of Helium-3 is the single neutron within its nucleus, one less than its much more ubiquitous sibling and daughter fusion product, Helium-4. In the process of creating a single Helium-4 atom from a pair of Helium-3's, both parent neutrons end up in the nucleus of the daughter Helium-4. This, quite remarkably, leaves no extra energetic, material-smashing neutrons and secondary radioactive products that typically contaminate and eventually destroy fusion devices, their nearby structures, and—if improperly shielded—any organism that gets too close. Quite happily for the sky station—and for explorers and colonists throughout the outer Solar System—the lack of radioactive waste products eliminates the need for burdensome shielding, resulting in extremely lightweight reactors. This ability of Helium-3—alone among all known substances—to cleanly and directly generate immense amounts of electric power without any radioactive by-products is what makes it the most sought-after material in the Solar System. And deep down in the depths of Saturn, some 32,000 km below—more than halfway to its core—is where it is most efficiently mined.

This is the 100th deep-interior voyage for the Saturn Helium Extraction and Exploration Vehicle (SHEEV) Number 17. With its ceramic skin able to ward off the ravages of an extreme thermal environment—just as its ancestors did for the Space Shuttles of the late twentieth century—and its multiple spherically-shaped cluster of

Fig. 9.5 Massive processing stations, supported by immense balloons, float beneath Saturn's most stormy cloud decks. They await delivery of Helium-3 carried by spherical mining ships returning from Saturn's depths. 81 tons of diamond hull protect the flotilla of SHEEV robotic mining ships from Saturn's titanic pressures, where they have harvested Helium-3 for later shipment to other locales in the Saturn system and beyond

diamond hulls able to withstand pressures up to five million Earth atmospheres, SHEEV 17 is an exquisite representative of the most rugged and arguably the most artistically beautiful ship ever built. If it were on Earth, the scrap value of the diamond hull alone would be worth over $750 billion US dollars, more than the gross national product of all but the eight most productive nations. However, here inside Saturn, it is just one of hundreds of similar vehicles, all created inside the planet from exotic yet, paradoxically, abundant materials found within its depths.

As SHEEV 17 drops from its berth, its 81 ton of 10-cm thick diamond hull structure quickly accelerates the vehicle to its initial terminal velocity of 800 km/h. Within minutes, the sky above darkens to pitch black, a consequence of both the feeble strength of sunlight at Saturn—less than 1 % of that at Earth—and of the significant filtering of what little light there is by the overlying pall of methane gas and dark sooty grit of thunderstorms. But looking below, a faint glow is obvious, growing with every passing minute. Rusty reds, then crimsons, and then oranges slowly surround the craft as it falls. After 100 min, as the probe passes the thousand-bar mark some 1,300 km down, the glow surrounds the spacecraft with a bright orange intensity indicative of the 1,000 C temperature of the gaseous furnace enveloping the ship. From here on down, nothing can be seen with human eyes but the glow of the surrounding inferno, which continues to grow whiter and brighter as the craft descends to ever hotter temperatures, eventually reaching those seen on the surface of the Sun.

As SHEEV 17 descends, the outside air density rises while gravity slightly but steadily lessens, slowing the descent to 700 km/h within 4 h as the craft sinks past a sub-sky-station depth of 3,000 km depth and an immense pressure of 10,000 bar. With an outside temperature above 1,680 C, this is the equivalent point in Jupiter's atmosphere where the Galileo probe melted and vaporized during its suicide descent in December 1995, its titanium structure succumbing to the intense heat as it melted away into the jovian abyss.

Some 18 h into the descent, passing a depth of 8,000 km, the craft stirs into activity. It is still 24,000 km and 4 days from its ultimate destination. But at this incredibly crushing depth of 80,000 bar—equivalent to 90 km underground on the Earth—and subjected to temperatures exceeding 2,700 C, a wondrous material has been forged in the dense atmosphere, something so dear and valuable that it cannot be ignored. It must be collected and brought back.

Luckily,—or rather, by design—this material is falling at nearly the same rate as the descending craft, now falling at 400 km/h. Slowly, large porous rakes of ceramic prongs spread out from the equator of SHEEV 17's central sphere and begin to collect the gently settling material. If one could actually see and feel them as they floated by, cloaked in the radiance of the white-hot furnace, one would say the stuff looks like and has the heft of rocks. And indeed, these are rocks, the most valuable in the Solar System, for, being more than 4 cm across on average, they are among the largest natural diamonds ever found. And there are literally thousands of these gems within ready reach of SHEEV's ceramic net.

Like the proverbial manna from above, diamonds perpetually rain down on Saturn, forged from the annoying sun-robbing dark soot produced by thunderstorms. Falling some 8,000 km through the hot atmosphere, these soot particles turn into graphite particles and grow in size, acquiring additional carbon material from hot methane gas as well as by merging in sticky collisions with other soot particles. Centuries after their birth as nanometer carbon particles,

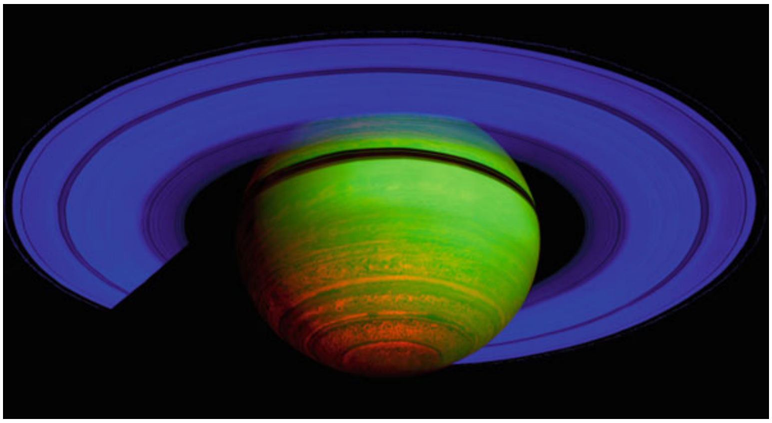
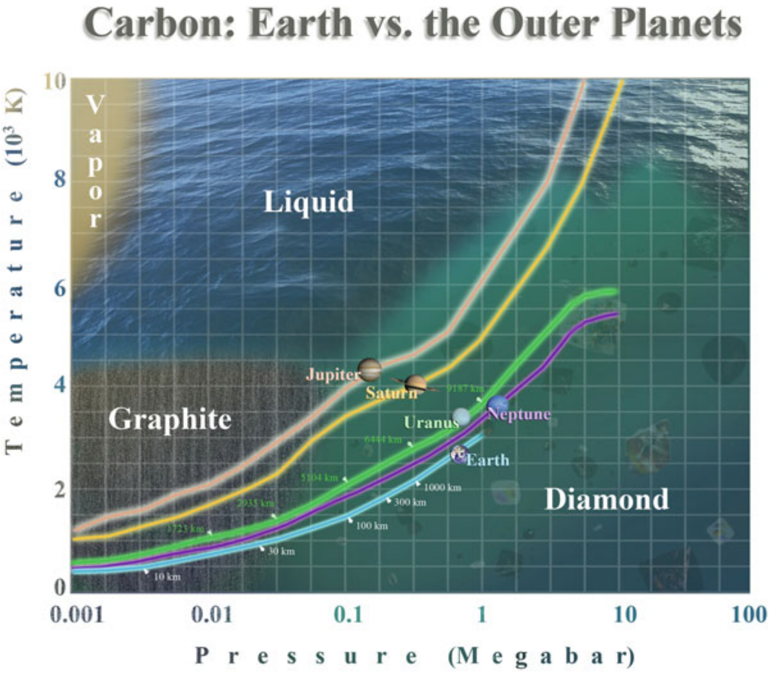


Fig. 9.6 The not-so-pleasant side of Saturn revealed. With its retinue of shimmering rings and pallid appearance, majestic Saturn typically appears regally subdued compared to neighboring Jupiter. But this look by the Visual Infrared Mapping Spectrometer (VIMS) onboard the Cassini spacecraft reveals its true colors: Underneath its languid veil of upper-level hazes (*greenish tint*) that prevents human eyes from seeing deeper than the 1-bar level lies an active caldron of storms, here revealed as darker features observed in silhouette against the red tint of infrared heat escaping the planet. These thick storm clouds can sometimes extend more than 150 km in altitude, becoming visible to human observers as major storms about once per decade. For safety, floating sky stations would be placed well underneath the 10–20-bar level thunderstorm-forming region (Courtesy NASA/JPL/University of Arizona)



(Baines/Delitsky/Carroll)

Fig. 9.7 The state of carbon soot in the Outer Planets. Pure carbon has a variety of forms in planetary interiors, depending on the pressure and temperature conditions. Carbon soot created by lightning in watery thunderstorms near the 10-bar level changes form as it descends, first becoming graphite near 1 kilobar, then turning into diamond at about 80 kilobar in Jupiter and Saturn, and 40 kilobar in Uranus and Neptune. On Earth (*bottom curve*), diamonds can form near 30 km of depth, at temperatures near 1,000 K. At extreme depths and temperatures, near 3.5 Mbar and 8,300 K on Jupiter and 6 Mbar, 8,200 K on Saturn, diamond melts into liquid. On Uranus and Neptune, which never reach such high temperatures, diamonds remain solid as they fall to the core, perhaps accumulating as diamond layers on top of the dense core, or perhaps mixing with it (© Kevin Baines, Mona Delitsky, Michael Carroll). Adapted from Nettelmann et al. (2008, Astrophys. J., 683, 1217–1228)

originally forged in the crucible of lightning which vaporized parent methane gas at the 10-bar weather layer 8,000 km above, the graphite soot finally descends to the crushing, hot depths where they metamorphose into diamond, the hardest, most heat-resistant natural substance known—and the stuff of SHEEV 17 itself (Fig. 9.7).

Fig. 9.8 The first probes explore the depths of a gas giant. At the mind-numbing pressures halfway to Saturn's core, hydrogen becomes a metallic liquid, and a constant drizzle of carbon from the upper atmosphere is compressed into diamonds (©Michael Carroll)

Diamond rains are strongest in three distinct latitudinal bands on Saturn: within 8° of the Equator and within 4° latitudinal bands near 35° latitude in both hemispheres. These are the "Thunderstorm Alleys" of Saturn, the regions where more than 95 % of the huge convective water-powered storms occur that generate the immense lightning strokes required to vaporize methane into carbon soot. Of all these regions, nearly six centuries of observations by Earth-based telescopes and Saturn-orbiting spacecraft have shown that the southern latitude site is the most stormy. It is for this reason that the sky stations and their attendant mining and exploration vehicles are positioned at 35° S. latitude, the most diamond-rich real-estate in the Solar System.

For the next 3 days, diamonds are harvested (Fig. 9.8). The movable ceramic rakes work together to move the precious ocean-forged nodules to one of the small spheres, designed as a cargo hold for the gems. Upon return to the sky station, the 4 t of precious stones—amounting to 20 million carats worth over $40 billion dollars—will be processed with the harvest of 20 other ships to form the hull of another SHEEV.

Nearly 5 days into its descent, SHEEV 17 is 3,000 km from its destination. But the increasing density of the surrounding atmosphere has slowed it to just 120 km/h. Here, some 29,000 km down, and an outside temperature of 6,000C, the craft passes a watershed—literally—for the quasi-gaseous, quasi-liquid fluid outside is now the density of water on Earth. A swimming human here would float in "mid air"—if he could somehow prevent himself from being crushed or vaporized.

As the craft descends another 3,000 km over the next day, exotic new properties infuse the fluid. No longer is the bulk of it comprised of molecules. Instead, the molecules of hydrogen have been wrenched apart, forming a sea of individual hydrogen atoms. And no longer can they hold on to their electrons, which instead slip from atom to atom, flowing as bizarre, uncontrolled currents of electricity through the sea. SHEEV 17 descends, continuing to slow in the ever-thickening ocean, in the midst of a maelstrom of electrical discharges and magnetic bursts.

And then, as SHEEV 17 slows and stops—having reached its destination and neutral buoyancy—another phenomenon appears. It's what SHEEV 17 has travelled all this way to experience: Here at a depth of three million atmospheres, some 32,000 km—more than 2.5 Earth diameters—underneath the ring of floating sky stations above, and with the outside temperature, at 6,500 C exceeding that of the surface of the Sun, marble-sized rain drops splash against the vehicle. SHEEV 17 is being pummeled by the liquid Helium-3 rains of Saturn.

At these depths, with the seas comprised of atomic instead of molecular hydrogen, helium cannot stand being associated with the bulk of materials in its environment. Instead, helium atoms come out of solution and group together as droplets, to fall many thousands of kilometers to the very bottom of Saturn, releasing immense energy that provides significant warmth to the planet. This much scientists of the twenty-first century knew. What they did not know, and were not even suspecting when discovered by the first deep-interior robotic explorers of the late twenty-fourth century, was that droplets of Helium-3 form at slightly higher, cooler, and less pressurized altitudes than Helium-4. The explanation is locked in the quantum mechanics of the helium atom immersed in a dense, hot hydrogen plasma. With just ¾ of the mass of Helium-4, Helium-3 feels the distortion effects of the plasma under somewhat milder conditions. Like a skittish school girl escaping an eager crowd of boys at a junior-high prom, the helium atom seeks refuge with its fellow helium atoms, eventually forming large 1-cm diameter drops of pure helium-3.

Thus, some 32,000 km down, a stratum of Helium-3 droplets forms a mist over 100-km thick. Over the first 40 km or so within it, the droplets grow to the size of grapes, obtaining an average fall speed of 10 cm/s. Some 50-km down, several such large Helium-3 raindrops are found within every cubic meter.

For the next 3 days, SHEEV remains nearly stationary at its 3 mbar float depth, collecting on the dome of its central sphere the helium rain that falls on it from the exotic mist suspended in the atomic hydrogen sea. Ceramic half-pipes spiraling around the dome direct the precious liquid to the second of the three small cargo spheres, eventually accumulating 4 t of the magic fluid that fuels civilization throughout the outer Solar System. Back on Earth, in the early twenty-first century, this bounty would fuel the entire United States for 2 months, or the entire world for 2 weeks, saving $4 billion of fuel costs. As well, this load of Helium-3 would erase untold billions of additional expenses incurred for handling tons of harmful radioactive wastes and megatons of pollutants produced by conventional atomic and fossil-fuel-fed power plants.

Ten days after departing the sky station, with $44 billion worth of diamonds and Helium-3 safely stored within its pair of spherical cargo holds, SHEEV 17 is ready to return. Within the other, third small sphere,—the Command and Control Center—activity hums. Its Helium-3 fusion reactor springs to life, sipping in a bit of the helium harvest. High-voltage current is sent to start powerful expelling motors in the large central sphere above. As the motors spin up, they begin to send back into the ocean the massive load of molecular hydrogen that has been weighing down SHEEV 17 and keeping it at equilibrium with surrounding atomic ocean. Gradually, as the large ball empties slightly more than 10 % of its contents—some 42 t of hydrogen—SHEEV 17 begins to rise. Within an hour, the sphere is empty, at near total vacuum, its 10 cm thick walls preventing it from imploding from the three-million bar of outside pressure. As the mass of the craft is reduced from 487 to 91 ton, and from a mean density of 2.0 to 0.38 gm/cm^3, SHEEV accelerates upward, reaching a vertical speed of 300 m/s in the low viscosity hydrogen ocean.

Under the buoyant lift of the diamond balloon, the craft rises 20,000 km in the next 4 days. Nearing its float level of 240 kilobar, and an outside temperature of 3,700 C, the command sphere signals the central sphere to activate once again the porous diamond-harvesting rakes. But now it is apparent that two sets of rakes are present, one above the other. Each set of rakes deploy and twist some 5° in opposite directions. Both sets of rakes then begin to spin as individual units around the central belt—the equator—of the central ball, also in opposing directions. In essence, these rakes form a pair of counter-rotating propellers that effectively power the craft upward through the sea. Like a twin-engine helicopter, the craft rises and maintains control due to its counter-spinning rotors.

In this manner, the fusion-powered undersea "helicopter" rises another 9,000 km over the next 3 days. To gain more lift during ascent as the effective weight of the craft increases as buoyancy decreases, the twist in the rakes and the rate of rotation are continually adjusted.

As the craft reaches 3,600 bar and the outside air density decreases to 0.05 gm/cm^3—one twentieth of the density of water—more efficient propellers blades are deployed that—at the relatively cool temperature of 1,100 K—maintain their strength. The rate of rotation of these blades increases by a factor of five over the original speed. Over the next 1,600 km, as SHEEV rises to find a sky station, the blades rotate 4.5 times faster still, to a frenetic 2,000 RPM—nearly the speed of aircraft propellers plying the skies of Earth—as the density of the air decreases by another factor of 20.

As the 50-bar level is reached, some 30 km below the sky station altitude, the command sphere begins to signal its presence and listen for a response. Since departing the sky station nearly 3 weeks ago, the winds of Saturn have blown its home sky station some 84,000 km to the east, about ¼ of the way around the planet, too far to go to find it. SHEEV 17 is looking for another port to call home. Within minutes, it locates one, determining both the direction and distance to it from—as Earth's aviators did throughout the mid twentieth century—the direction of maximum signal strength and the radar-like time delay between the ping sent out and the return echo sent back by the receiving sky station. SHEEV 17 only has 5,400 km to go.

SHEEV 17 then actively controls the angle of attack of the rotor blades to home in on its beckoning refuge, elegantly twisting and untwisting each one as it spins. Twenty hours later, SHEEV 17 docks with its new home, the dome of the central sphere nosing into the sky station's docking port from below. Once firmly attached, the rotors are spun down to a stop and stowed again along SHEEV's equatorial belt. The 100th voyage of SHEEV 17 halfway to Saturn's core ends in another success.

Over the next few days, the Helium-3 is refined using relatively rudimentary processes onboard the sky station—in particular to eliminate the noble gas neon.

Some of the resulting pure product is used to maintain the station, but about 80 %—more than $3 billion worth—is sent via balloon-borne rockets, powered by hydrocarbon and oxygen fuel refined from the atmosphere, to orbiting space stations and thence to other destinations via both Helium-3-fusion-powered ion propulsion systems and by conventional rockets using fuels mined from Titan.

All but 1 % of the $40 billion worth of diamonds is used on the sky station to build new SHEEVs and to repair older ones. None leaves the Saturn system. Recognizing the havoc that just one SHEEV payload of diamonds would have on the financial markets back on Earth—more valuable than all the diamonds produced by the world's diamond mines over the past seven centuries—the Earth's trade authorities monitor Saturn closely, to ensure that, while they may be forever, Saturn's diamonds stay forever there.

The Alien Seas of Earth: Astrobiological Implications

10

Chris McKay

Liquid water is the quintessential ecological requirement for all life on Earth. All organisms require liquid water to grow or reproduce. It is not surprising, then, that the search for life beyond the Earth is often characterized by a “follow the water” strategy. Indeed, the link between liquid water and life sometimes leads to the exaggeration that wherever there is liquid water there is life. It is interesting to consider the range of exotic liquid water environments on Earth and the extreme life forms they do, or do not, support (Fig. 10.1).

The most common alteration of liquid water on this planet is the addition of salts—sodium chloride, calcium chloride and other salts. In low concentrations, 3.5 %, seawater is still quite habitable. But as the concentration of sodium chloride goes up to its saturation value (~35 %) only certain types of life can survive. Hypersaline lakes are often found in inland deserts such as the basin that contains the Great Salt Lake. In these locations rain leaches the salt from the surrounding soil and rock and carries it to the lake. If the basin is closed, the only loss of water is evaporation, leaving the salt behind. Over time the accumulation of salt creates a saturated salt solution. Hypersaline ponds are also found near seashores in warm locations where solar driven evaporation concentrates the salt. Sometimes these ponds are artificial, created for salt extraction.

As the sea salt concentration increases, the type of life that can survive there changes. At the extreme salinity of sea salt, only reddish colored halophillic archaea can survive. These extremophiles survive the high salt by actively pumping the salt out of their intracellular fluids. They survive not by adapting to their extreme environment but by protecting themselves from it (Fig. 10.2).

Sea salt is predominantly sodium chloride. But in a few locations on Earth there are ponds composed of other salts. One well-known example is Don Juan pond in the Dry Valleys of Antarctica. Here, the summer melting of the permafrost brings calcium chloride to the bottom of the closed basin. The resulting solution is saturated. Containing a concentration of about 70 % salt and with a freezing point of −50 °C, it stays liquid even in the Antarctic winter. The salt concentration is too high (almost twice the maximum salt concentration of sea salt) for even the halophillic archaea to survive. It is a clear example of liquid water without life.

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Fig. 10.1 A slush of frozen water oozes to the surface on Jupiter's moon Europa. Such areas may be common in chaos regions, and might provide access to samples from the subsurface ocean (©Michael Carroll)

Fig. 10.2 Artificial salt ponds in lower San Francisco Bay. The water is moved from one pond to the next as evaporation gradually increases the salinity. Microorganisms live in the brine and as the brine increase in concentration the type of life changes. In the saltiest solution only the reddish colored halophyllic archaea can survive (Courtesy Doc Searls, Wikipedia Commons)

Getting at the Europans

To many, Jupiter’s moon Europa is the poster child for exobiology. With a 100 km deep briny ocean, and with a continual input on its surface of reactive molecules produced by radiation from Jupiter’s magnetosphere. and—perhaps—volcanoes on its ocean floor, Europa seems a likely candidate for a living biome. But Europa provides an exploratory problem: its ice crust. At Jovian temperatures, the frozen surface of Europa is the consistency of stone, and getting through all that hard ice to any ocean may prove practically impossible. Engineers have tried to design submarine probes that would melt their way through the ice, depositing radio relays as they descend, but to date these tests have not been successful. Drilling through a crust that may be up to 30 km thick is simply not practical. But recent work indicates that Europa itself may solve the problem for us.

Europa’s face is bruised by provinces called chaos regions. At first glance, these areas appear to be collapsed areas in which the surface has broken into icebergs which twist and turn before refreezing. But a 2011 study by Brittney Schmidt and others shows that these regions are actually domed. The jumbled terrain between the icebergs has actually bowed up, filling in the surface around the floating ice chunks. Investigators suspect that water is actively welling up between the icebergs in some areas. The surface profile indicates subsurface lakes the scale of North America’s Great Lakes. These lakes may be sequestered from the ocean below, but they may also be connected to it through networks of fractures. If so, these chaos sites would be perfect targets for future surface probes equipped with coring devices. If our probes cannot go to the oceans, perhaps the oceans will come to us.

The presence of salt can allow water to remain liquid in temperatures well below freezing. Sodium chloride lowers the freezing point to −22°C. Pockets of subsurface salty water known as “cryopegs” are found in permafrost which has a mean temperature of −10°C. Given the tolerance of microbes for salt, it is not surprising that cryopegs have a rich microbial flora. Sodium chloride cryopegs could exist in permafrost as cold as −22°C and cryopegs composed of other salts could have even lower freezing temperatures. However, as the salt concentration gets higher (to allow for the lower freezing point) the possibility for life goes down. Brines on Mars that could be liquid under the present conditions would probably be too salty for any Earth life forms.

In addition to pockets of liquid water in permafrost, salty water is also found emerging from perennial springs in permafrost regions, providing a niche for life. Several of these springs occur in the Canadian high arctic, notably on Axel Heiberg Island. Here, water from briny aquifers percolates through roughly 600 m of permafrost to the surface, where temperatures hover at −15°C. The water is not heated geothermally, but remains liquid because of its high salt content. Microbial communities in these regions may use sulfur compounds for energy. Some sulfur-based bacteria can provide the foundation for an entire ecosystem in environment where there is a complete absence of light.

High temperature can also make liquid water uninhabitable for many life forms. Hot springs that flow from volcanic regions contain specialized life forms known as hyperthermophilles. The adaptation of life to hot water requires that these microorganisms develop specialized forms of enzymes—proteins that enhance chemical reactions—that remain stable at high temperature.

These extreme enzymes have found extensive use in biotechnology. They are used in a vast array of industry, from detergents to biofuels. But up to now, a limiting factor has been temperature: high temperatures tend to break enzymes down, so enzymes found in hyperthermophilles provide stability in processes that typically require extreme heat. Extremophilic enzymes have been used to detoxify radioactive material, aid in DNA fingerprinting, and to genetically diagnose infectious and inherited diseases. They may also have applications in the biofuel industry, where heat-happy enzymes can break down cellulose to make products like ethanol.

At the bottom of the ocean we find another example of extreme liquid water environments: hot, high pressure water from the deep sea vents. At these vents, hot water is driven from the subsurface into the ocean water. The source water is rich in chemicals that can support a diverse vent ecosystem. The temperature of the hottest vents is well in excess of the temperature at which water usually boils (100°C). But due to the high pressure of these deep ocean sites, the water remains liquid and supports life. Laboratory experiments with microorganisms from deep sea vents have shown growth in “pressure cooker” conditions up to 120°C (Fig. 10.3).

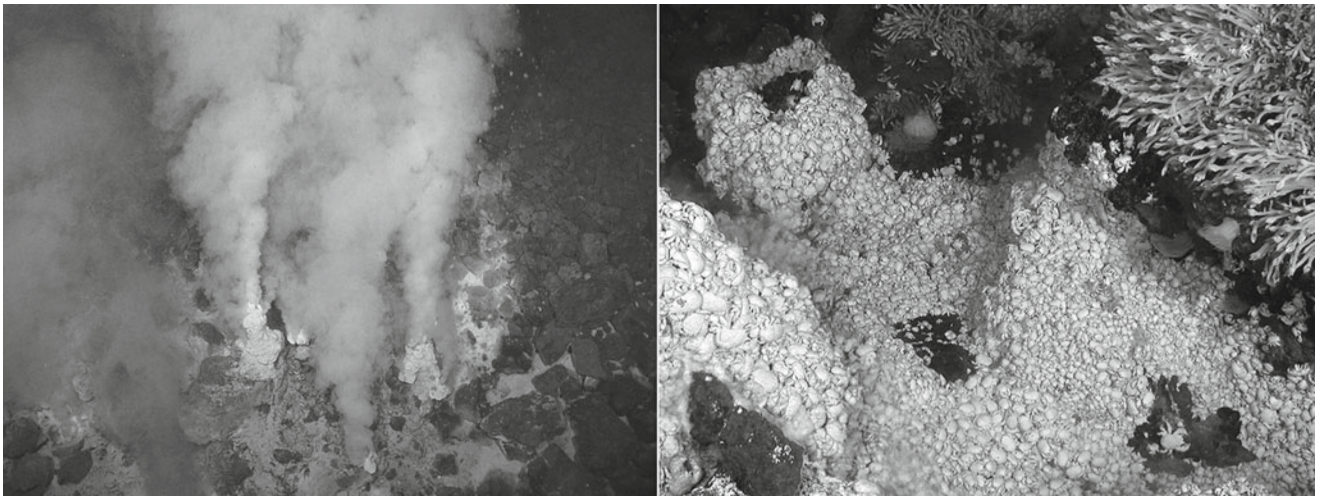

Fig. 10.3 *Left*: "Champagne" deep sea vent. The pressures are so high that water can remain liquid even when the temperature exceeds the normal boiling point of 100°C. Life is good for these organisms as the sources water provide abundant chemical energy and they are well adapted to the environment (Courtesy NOAA). *Right*: At a depth of 2,397 m, extremophiles thrive on the side of a volcanic chimney (Courtesy A.D. Rogers, et al. from PLoS Biology)

Oases Under the Sea

Many deep sea volcanic vents erupt superheated waters high in acid. But in December of 2000, explorers discovered a group of quite different vents along the Mid-Atlantic Ridge, a colossal mountain range on the floor of the Atlantic Ocean. These hydrothermal sources, known as the Lost City vents, arise when mantle rocks react chemically with seawater. Calcium carbonate builds into pillars towering some 60 m (180 ft) above the sea floor.

Minerals pour from the tops and side fissures of the vent columns. The result is a mix of methane and hydrogen, erupting as alkaline water. As hydrogen interacts with carbon dioxide dissolved in the seawater, organic compounds form within the vent. Some biologists think a similar reaction led to early life forms on Earth, and may lead to life on other worlds such as Europa, where submarine vents like those at Lost City are likely to occur.

One of the many curious properties of water is that the solid form is lighter than the liquid water. Hence ice floats. This allows liquid water habitats to persist in regions where the average temperatures are well below freezing. Perennially ice covered lakes are found in many regions of Antarctica that are not covered by the massive polar ice cap. In these areas the summer meltwater flows into the lake under the ice cover. As this liquid freezes it releases heat which diffuses out through the ice cover. This flow of heat is what determines the thickness of the ice cover. These lakes have only microorganisms. No small fish, snails or even insects inhabit them. This is probably due to the remoteness of these Antarctic lakes as well as the thick ice cover. Without animals to graze on them, the photosynthetic microbes that live on the bottom of these ice-covered lakes form interesting structures that resemble the fossil stromatolites of ancient life (Figs. 10.4 and 10.5).

Fig. 10.4 Antarctic ice-covered Lake Untersee. Here the average temperature is well below freezing but liquid water is present below a permanent cover of ice 3 m thick (Courtesy Chris McKay)

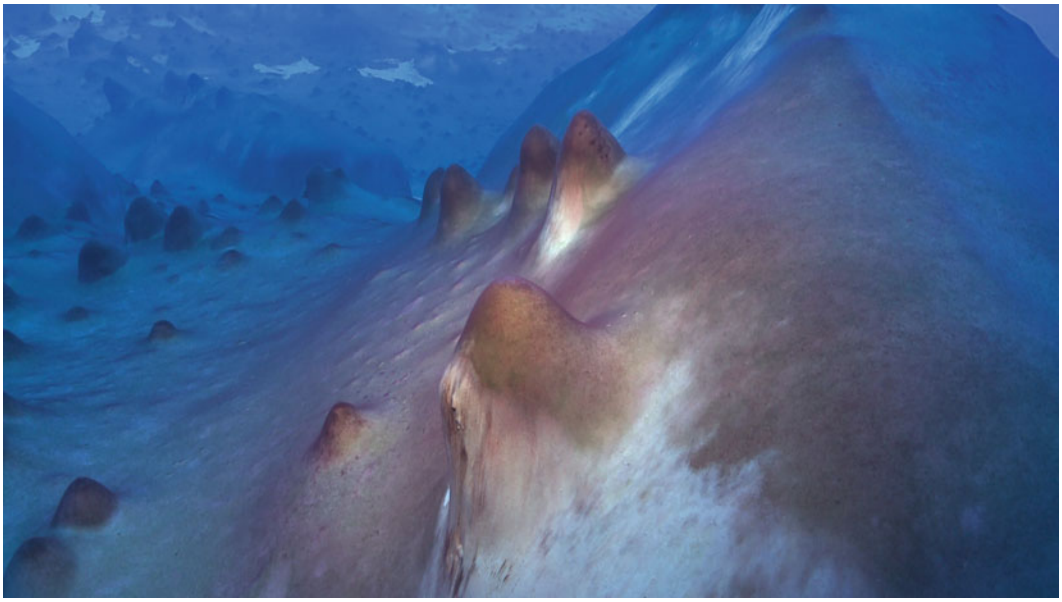

Fig. 10.5 Microbial mounds on the bottom of Lake Untersee. These mats are the only known examples on Earth of living conical stromatolites (Courtesy Dale Andersen/Carl Sagan Center for the Study of Life in the Universe, SETI Institute)

Chillin' with the Microbes

At the base of a surreal ice column 20 m high, in an environment sporting temperatures far below the freezing point of water, a colony of microbes thrive. The ice towers cap the sites of fissures and cracks where hot air escapes from volcanic sources below. Like stalactites in reverse, the towers build, partially collapse, and build again, taking the form of fairytale turrets, misshapen giants, and mythical creatures. This is not some bizarre alien habitation, but rather a site on the slopes of Mt. Erebus, Antarctica's second-tallest volcano (Fig. 10.6).

The icy world of Erebus is quite sterile, but within the immediate surroundings of the volcanic vents, mats of cyanobacteria lay like regurgitated carpet. Beneath them, and in the throats of some of the ice towers, archaea—primitive single-celled life forms whose cells contain no nucleus or membranes around organelles—form colonies. Their biochemistry is unique in the animal kingdom, setting them apart from bacteria or Eukaryotes. What intrigues astrobiologists most is that these microbes may have been lofted to the frozen Antarctic wilderness from the hearts of volcanoes. With frozen and liquid water abounding here, the archaea of Erebus may provide us a glimpse of what forms life may take on the remote ocean worlds beyond.

Fig. 10.6 A researcher perches atop an ice tower on the slopes of Antarctica's Mt. Erebus (Courtesy NSF, Mount Erebus Volcano, Observatory and Jeffrey Johnson)

The liquid water in the lake under thin ice cover is created by summer melting of the outflow of subglacial water. Lakes are also found deep below the thick Antarctic Polar Ice Cap. Here, some 4 km below the surface, the presence of liquid is sustained by geothermal heat. Large lakes, such as Lake Vostok, have been detected by radar but as of yet we do not know the chemistry of these lakes or if there is life in this deep cold liquid water.

Extremophile Rock Stars

In 1976, researchers Imre and Roseli Ocampo Friedmann discovered microbial life living within porous rocks in Antarctica's Ross Desert. These cryptoendoliths survived extremely low temperatures and dessicatingly low humidity, rejuvenating for only brief periods during the Antarctic summer. The Friedmann's rocky picture show was only part of the story. Microbes have been documented at 3 km below the surface, and in rocks on every continent of the world. Known as endoliths, some of the tiny creatures survive by metabolizing iron, sulfur, or potassium.

What do these beasties have to do with our search for alien sea life? Terrestrial oceans do not rest atop the sea floor, but rather continually interact with it, filtering down through cracks and ports within the rock and cycling back up again. Within this twilight zone between sea water and solid rock thrives a community of endolithic life. Up to 1/3 of the earth's entire biomass may be going about its business beneath the floors of our planet's oceans.

How they survive is not always understood. Some of the microbes metabolize oxygen very slowly, and so can exist within porous rock not directly in contact with oxygen. Others oxidize iron for a living, and still others may use chemicals produced by natural radioactivity within their stony environment as an energy source. These exotic life forms demonstrate yet another biome that may be lurking on other worlds.

Liquid water on Earth can be fresh or salty, and its temperature can range from extremely hot to icy. Each set of conditions provides opportunities and challenges for life. Studies of these environments inform us as to the range of possible liquid water habitats on the surface or in the subsurface of other worlds. So far our studies lead us to be optimistic that, for the most part, liquid water environments on or below the surface of Mars, Europa, and Enceladus are likely to be habitable (Fig. 10.7).

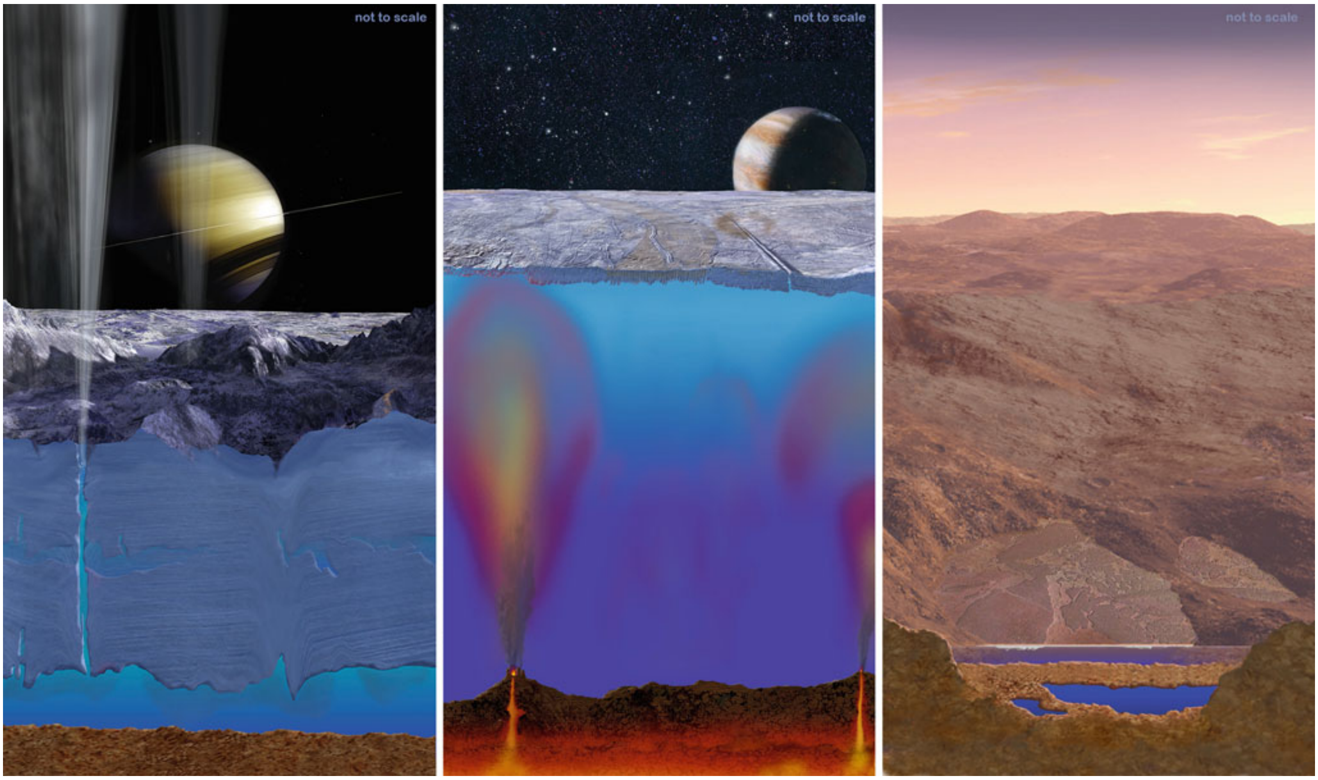

Fig. 10.7 A comparison of three alien seas. From *left to right*: Saturn's moon Enceladus, Jupiter's moon Europa, and Mars. These cutaway views show the subsurface liquid water on these worlds. Liquid water is the quintessential ecological requirement for all life on Earth. The search for life beyond the Earth may involve a "follow the water" strategy for decades to come. Many targets await (©Michael Carroll)

Seas of the Milky Way

11

Jeffrey Bennett

Throughout this book, you have been introduced to a great variety of seas. Hopefully they have both amazed you and opened your mind to the astonishing range of possibilities in nature, possibilities that our species can now explore through the careful and methodical work of science. However, all of these seas share a somewhat dismaying property: A swim in any one of them would mean near-instant death.

The seas of Venus and Mars may once have looked quite tempting, with water lapping at sunlit shores. But they are long gone, and even with a time machine a swim would be far more lethal than it might look. The reason is simple: Like the early Earth, the early Venus and Mars would have had atmospheres with essentially no oxygen at all. Oxygen is a highly reactive gas that requires an active source if it is to remain in an atmosphere. On Earth, the active source is life, which produces oxygen through photosynthesis. However, oxygen is so quickly consumed by chemical reactions that it took billions of years for photosynthesis to build up the atmospheric oxygen concentration to a point at which we could safely breathe. Venus and Mars lost their early oceans (assuming they had them) long before they could have had oxygen atmospheres. So while their early seas may have been pretty, you would have needed a spacesuit[1] to stand on their shores.

The rest of the seas of our solar system are no better for swimming, with their lack of oxygen being accompanied by extremes of temperature, pressure, or toxicity. We are therefore led to a key conclusion for any intrepid swimmer: If you want to go for a swim in an alien sea, you're going to need a starship.

Planets Beyond Our Solar System

Before you set off on an alien beach trip, you'd better figure out where you're going. That's easier said than done, because we have not yet identified even a single extrasolar planet (meaning a planet around a star besides the Sun) that offers a pleasant beach.

In fact, it wasn't so long ago that we did not even know for sure whether planets existed around other stars. Recall that our solar system is thought to have formed from the gravitational collapse of an interstellar cloud of gas and dust, an idea which suggests that planets should form similarly around other stars. However, this idea only gained wide scientific acceptance in the middle of the last century, and it was not until 1995 that scientists found the first clear evidence for planets around stars similar to the Sun. Discoveries have followed at a rapid rate since that time, and at the end of 2012 the number of known[2] extrasolar planets already exceeds 3,000. Moreover, data from the *Kepler* mission (Fig. 11.1) that are still preliminary suggest it may already have found limited evidence for up to another 15,000 planets, and the European Space Agency's *GAIA* mission, slated for launch in October 2013, should in principle be capable of detecting tens of thousands more.

Of course, knowing that a planet exists is not the same as knowing much of anything about it. We know a lot about the planets in our own solar system because we can study them directly. For example, we can take pictures of them through telescopes or visit them with spacecraft. But nearly all known

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[1] The air pressure at that time would have been sufficient for survival, but a lack of oxygen also means a lack of an ultraviolet-absorbing ozone layer, so you would have needed the spacesuit both for oxygen and for protection from solar ultraviolet radiation.

[2] I am including as "known" the planets that the *Kepler* mission calls "candidates," meaning that they seem to have a clear detection in the *Kepler* data, but have not yet been confirmed by other methods. It is possible that a few of these "candidates" will turn out to have been data masquerading as a planet, but statistically at least 90 % of the candidates should prove real. The actual breakdown at the end of 2012 is approximately 800 confirmed planets and 2,300 Kepler "candidates."

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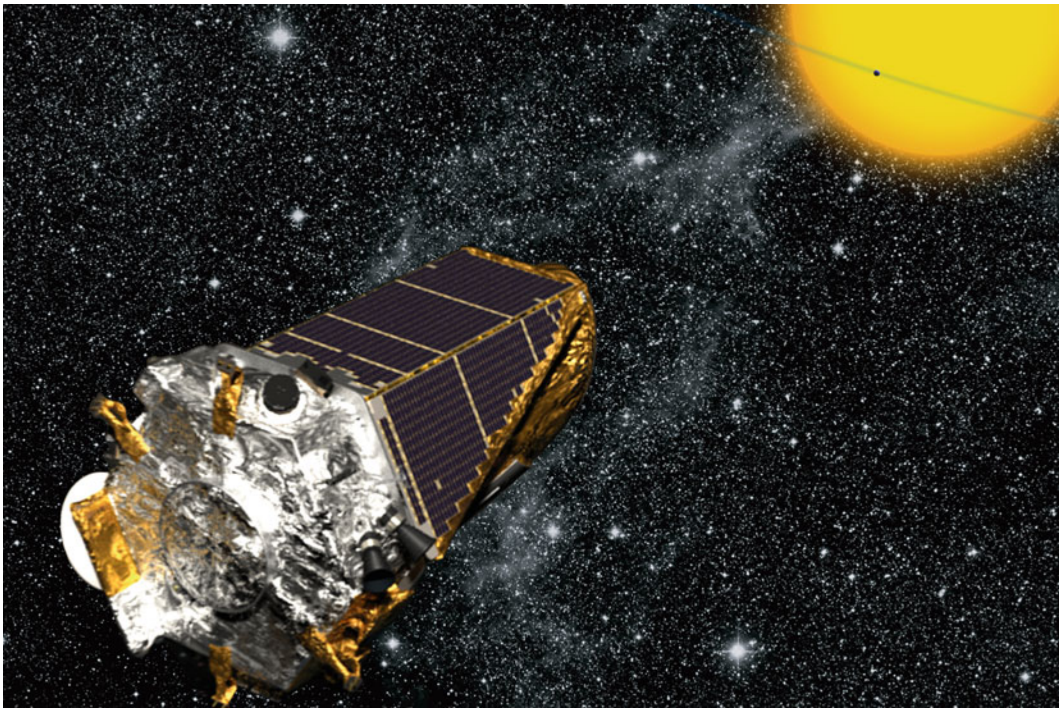

Fig. 11.1 Artist's conception of the *Kepler* spacecraft, launched in 2009, which searches for small changes in a star's brightness that can occur when a planet passes in front of the star. *Kepler* simultaneously monitors about 150,000 stars by keeping its telescope always pointed at the same region of the sky, which happens to be in the constellation Cygnus. *Kepler* has already detected more than 3,000 planets (Courtesy NASA/Kepler mission/Wendy Stenzel)

extrasolar planets have been detected indirectly, meaning that we have detected their influence on the stars they orbit, rather than actually observing the planets themselves.

There are two basic ways to detect a planet indirectly. The first relies on the fact that our usual view of planets orbiting the Sun is actually only an approximation. Newton's gravitational law tells us that orbiting bodies *attract each other* gravitationally, and any pair of bodies will each orbit around their mutual center of mass. For example, if we considered the Sun and Earth in isolation, we'd find that they both orbit once each year around the center of mass between them. The reason we notice Earth's orbit and don't notice the Sun's is because the Sun is so much more massive than Earth (about 300,000 times as massive), and the center of mass of Earth and the Sun is therefore quite close to the center of the Sun. Nevertheless, alien astronomers could in principle learn that Earth exists with careful measurements that would reveal Earth's annual effect on the Sun's position in the sky.[3] In other words, Earth exerts a small gravitational tug on the Sun, which alien astronomers could detect with sufficiently precise measurements. Turning the idea around, we can detect planets around other stars by observing the stars in search of small gravitational tugs.

To date, nearly all detections of gravitational tugs have been accomplished with ground-based telescopes measuring what astronomers call "Doppler shifts" in the spectra of stars (Fig. 11.2). Much as Doppler radar tells the police how fast you are driving, astronomers can use the Doppler effect to detect the motion of a distant star. If the star shows a small back-and-forth motion repeating with a regular period, we can conclude that it is actually moving in a small orbit around a center of mass with an unseen planet.

An alternative way to look for gravitational tugs is with careful observations of stellar positions in the sky. Although the idea is simple in principle, the precision of the measurements needed to detect planet-caused orbital motions has so far proven beyond what we can achieve with ground-based telescopes. That's where the European *GAIA* mission comes in (Fig. 11.3). The mission goal is to measure positions for some one billion stars in our galaxy to a precision that will in some cases be better than 10 microarcseconds. In case you're not yet impressed, consider that a typical human hair held at arm's length has an angular width of about 10 arcseconds, which means *GAIA* will be capable of measuring shifts in a star's position that are *one million times* smaller than this. The primary purpose of these precise measurements is actually to learn the distances of these stars from Earth, but the measurements should have the happy side effect of revealing the existence of vast numbers of planets.

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[3] Of course, before they'd notice Earth's effect, they'd first have to account for the larger effects caused by Jupiter and some of the other planets.

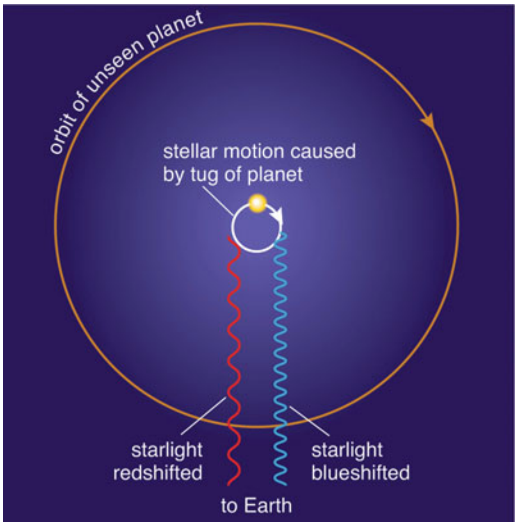

Fig. 11.2 This diagram shows how the gravitational tug of an unseen planet causes its star to make a small orbit around the center of mass between the star and the planet. If the system is oriented so that the star moves alternately toward and away from us as it orbits, then the star's spectrum will show a Doppler shift alternating between a blue shift and a redshift. For a system oriented more face-on as seen from Earth, we can in principle detect the star's small orbit with extremely precise measurements of the star's position in the sky (Reprinted with permission from *The Cosmic Perspective*, 7th Edition by Bennett, Donahue, Schneider, and Voit, Pearson Education, 2014)

With gravitational tugs representing the first general way of detecting planets indirectly, the second general way is to look for slight changes in star's brightness as a planet passes in front of it. This is the approach being used by the *Kepler* mission. The orbits of planets around a distant star can be inclined at any angle to our line of sight, so by random chance, a small fraction of all planets should have orbits oriented in such a way that they pass across the face of their star once each orbit as seen from Earth. Such passages are called *transits*, and the planet blocks a little bit of its star's light when a transit occurs. Therefore, if we watch carefully enough, we can detect a slight dip in the star's brightness during the transit. We may also notice a small dip in the total system brightness as the planet goes behind the star (an *eclipse*), particularly if we monitor the system in the infrared (Fig. 11.4).

Indirect detections are valuable because they tell us that planets exist, but they tell us relatively little about the planets themselves. The only information we get automatically about planets detected through gravitational tugs or transits is their orbital periods, from which we can calculate the average distances at which the planets orbit their stars. Detections by gravitational tugs can also give us a good estimate of a planet's mass, while transits can give us a good estimate of a planet's size (diameter). Beyond that, while scientists have proven amazingly resourceful at extracting bits of extra data from careful indirect observations, we rely mainly on models.

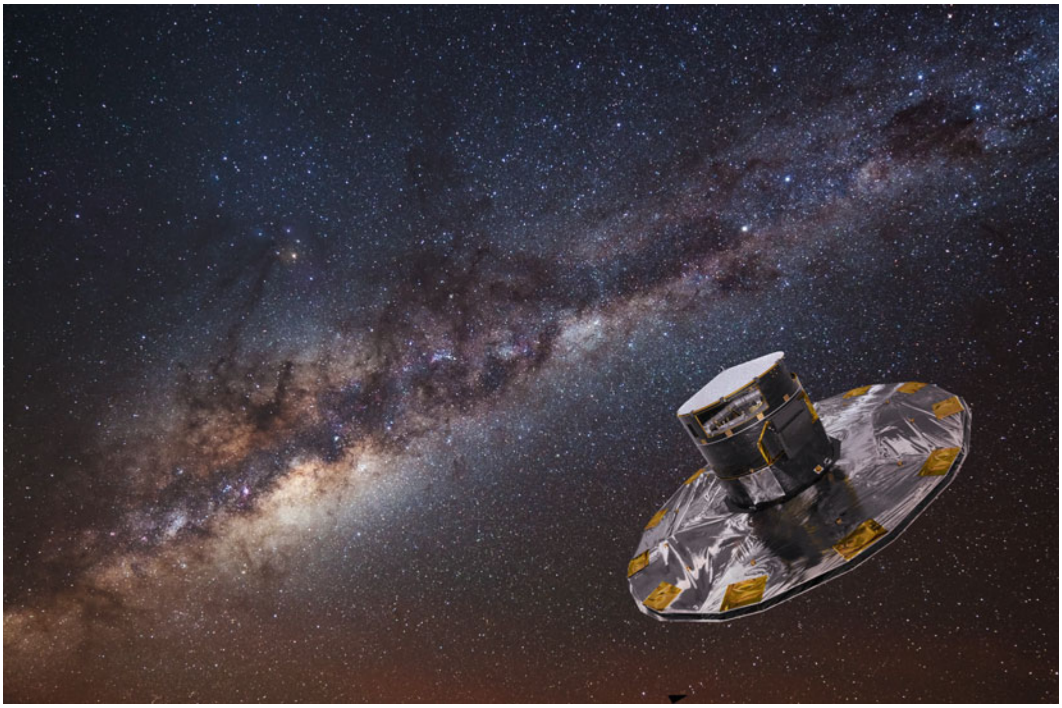

Fig. 11.3 Artist's conception of the *GAIA* spacecraft, which will make extremely precise measurements of star positions in the sky. Among the many scientific returns expected from the mission should be the discovery of tens of thousands of previously unknown planets around other stars (Courtesy ESA-C. Carreau, B. Fugate (FASORtronics)/ESO)

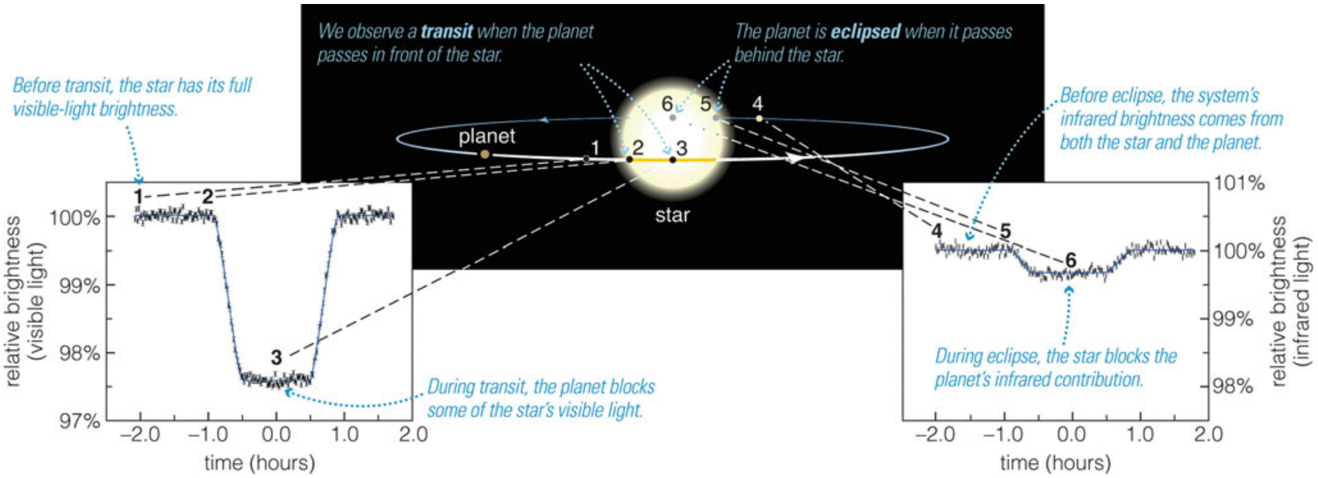

Fig. 11.4 The central diagram shows the geometry of a transit, in which a planet's orbit happens by chance to be oriented so that, from our location, it passes in front of its star once during each orbit. The graphs show data for a star known as HD 189733, which reveal a planet that orbits it every 2.2 days (Reprinted with permission from *The Cosmic Perspective*, 7th Edition by Bennett, Donahue, Schneider, and Voit, Pearson Education, 2014)

For example, if a planet has size and mass similar to Earth or Venus or Mars, we assume it is likewise made mostly of rock and metal, while a planet with a size and mass similar to Jupiter is assumed to have a Jupiter-like composition of hydrogen, helium, and hydrogen compounds (such as water, methane, and ammonia).

Perhaps the greatest surprise to date is that planets apparently come in a much greater variety than we might have guessed from our own solar system (Fig. 11.5). Many extrasolar planets orbit much closer to their star than Mercury orbits the Sun, which means they are expected to be quite hot. Some of these are Jupiter-like in size and mass and have been nicknamed “hot Jupiters” .

We've also found surprising extremes of density, ranging from planets with average density lower than Styrofoam to planets with average density greater than lead. In a few cases, we've found planets with sizes and masses that suggest they may be “water worlds”—planets that may be made mostly of water in the form of either ice, liquid, or steam. In other cases, we've found planets that appear to be rocky like Earth but up to several times as massive, garnering the nickname “super-Earths.”

All in all, the great variety of planet types suggests the possibility of a similarly great variety in alien seas around other stars. Here, however, our concern is with finding seas we might swim in, and for that we need to consider more than just the presence of some form of water.

Surface Ocean Zones

If you consider the various types of planets, you'll realize there are at least three general possibilities for water oceans. The first possibility comes from the “water worlds,” which could obviously have oceans, if any of their water is in liquid form. The second possibility concerns terrestrial planets, including the super-Earths and other planets with Earth-like compositions, which should in principle have been born with enough water to make oceans, just as was the case for the terrestrial planets in our own solar system. Jupiter-like planets offer the third possibility, not in the planets themselves—for which water oceans seem unlikely—but perhaps on some of their moons. After all, just as Jupiter, Saturn, Uranus, and Neptune are all orbited by numerous icy moons in our own solar system, we should expect that similar planets in other solar systems would also have many moons, likewise containing vast amounts of ice or water. The major question is whether any of the water on these worlds is in liquid form, rather than frozen solid or in the atmosphere as gas.

This brings us to an important point. There are also two general types of watery seas: surface seas and oceans like we find on Earth, and subterranean seas like those thought to exist on Jupiter's moons Europa, Ganymede, and Callisto. Only surface seas could potentially be swimmable for an oxygen-breathing human being, so we will focus on the search for those.

Based on what we've learned from the planets of our own solar system, the basic requirements for a world (whether planet or moon) to have surface seas are twofold. First, the world must orbit its star at a distance that will allow surface temperatures to be in the relatively narrow range (i.e., 0°C to 100°C) for which liquid water is possible. Planets orbiting at such distances are sometimes said to be orbiting in their star's “habitable zone” or “Goldilocks zone,” but for our purposes you can think of it as the “surface ocean zone”—the zone in which surface oceans are possible. Of course, it's possible to be located in the surface ocean zone and still not have oceans, as our own barren Moon proves (since it is

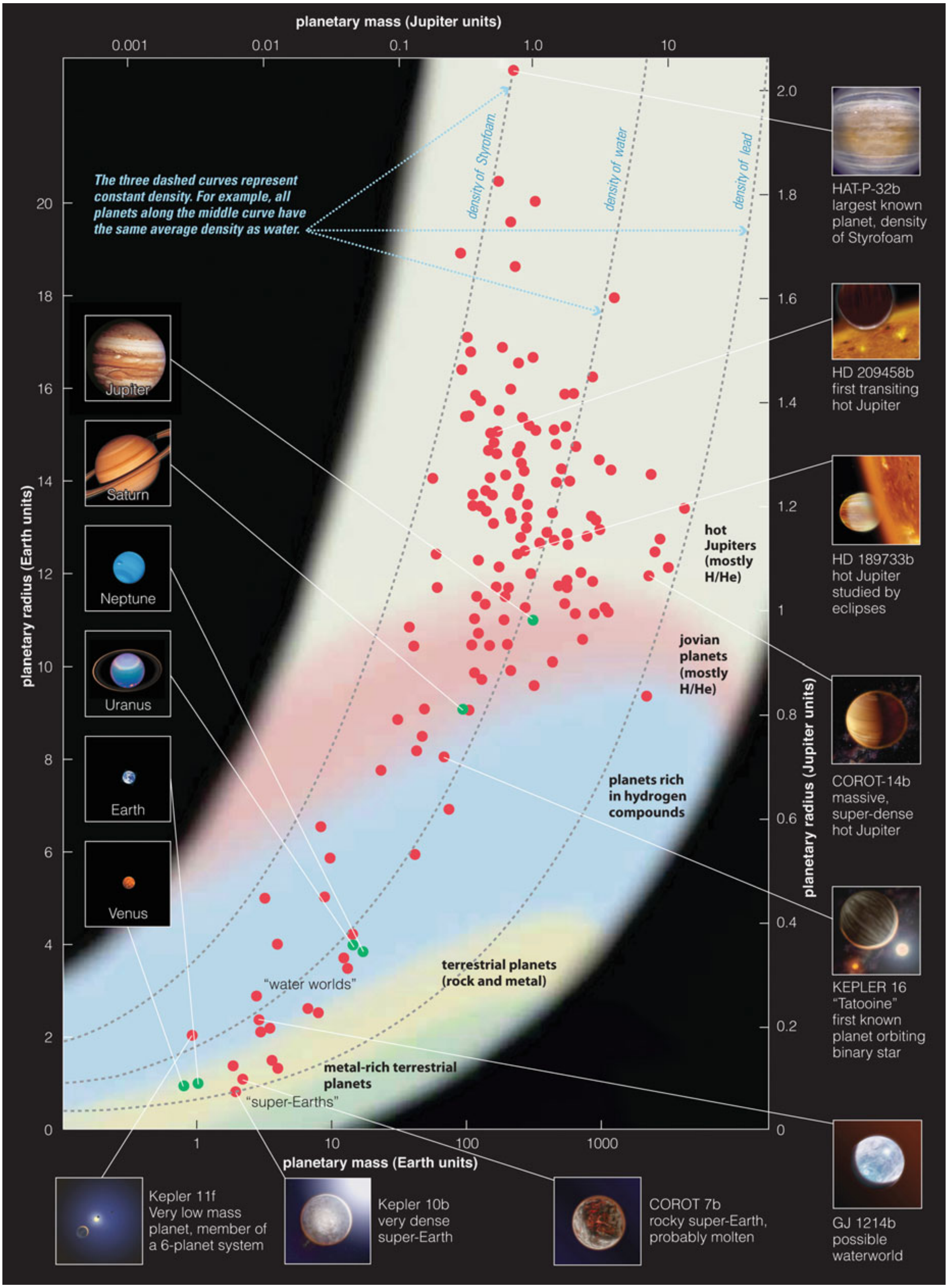

Fig. 11.5 This diagram plots planets by mass and radii for a selection of planets for which both have been measured. Notice that planets come in a much wider range of types than we might have guessed by studying only the planets of our own solar system (Reprinted with permission from *The Cosmic Perspective*, 7th Edition by Bennett, Donahue, Schneider, and Voit, Pearson Education, 2014; planet paintings by Michael Carroll)

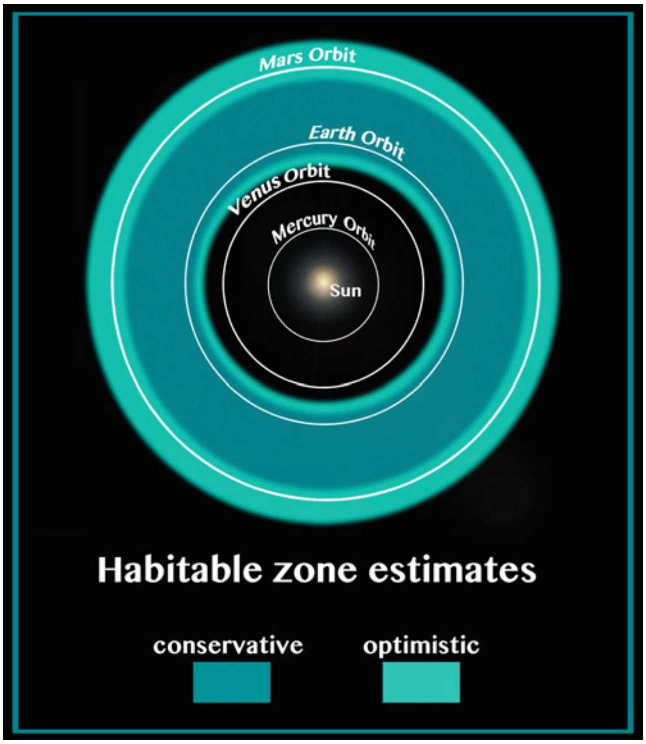

Fig. 11.6 This diagram shows the surface ocean zone in our solar system under both conservative (*narrower*) and optimistic (*wider*) assumptions. Either way it begins somewhere beyond the orbit of Venus and extends to somewhere near the orbit of Mars (After a diagram from *Life in the Universe*, 3rd Edition by Bennett and Shostak, by permission of Pearson Education, 2012)

essentially located at the same distance from the Sun as Earth). The second general requirement for surface oceans is that the world must be large enough so that its gravity has allowed it to retain a substantial atmosphere, because liquid seas can in general exist only if there is sufficient atmospheric pressure above them.

Finding the surface ocean zone around a star is relatively straightforward, since temperatures generally decline with distance from the Sun. There are a few uncertainties because planetary temperature is also greatly affected by atmospheric composition, cloud cover, and other factors. Still, in our own solar system we can say that the ocean zone today extends from somewhere between the orbits of Venus and Earth to some place in the vicinity of Mars (Fig. 11.6). Smaller stars are dimmer and therefore have ocean zones that are smaller and closer in. More massive stars would have ocean zones farther out. However, in the search for oceans and life, we usually don't pay too much attention to stars with masses much greater than the Sun, both because they are relatively rare and because they have relatively short lifetimes that probably do not leave enough time for life to evolve before the stars die.

As of the end of 2012, the *Kepler* mission had already identified more than 50 planets that orbit in their star's surface ocean zone, and other techniques have found dozens more. Many of these planets also seem to be in the right size range to allow for surface seas. So does this mean we have found planets for which you might want to set sail with swim suit in hand?

Perhaps, but perhaps not. We know that finding surface oceans requires both suitable size and being in the surface ocean zone, but we do not yet know whether those are the only factors. Indeed, this is a point of great scientific debate, though my own personal guess[4] is that it will turn out that most of these planets do indeed have surface oceans.

That brings us to the issue of whether these planets might also have life, another point of great scientific debate. Again, my own guess is that the answer will be yes. That is, my own read of current scientific understanding is that if you have a planet with the right composition and temperature to give it surface oceans, then you will find life in those oceans. In that case, at least some of these planets are likely to have life that produces oxygen through photosynthesis, and if the planets are old enough for photosynthesis to have occurred for a few billion years, then by now they should have oxygen atmospheres and teeming life of all kinds. So bring your swim suit, but beware of local wildlife…

Getting There

If you're like almost any kid I've ever met, the next question is "when can we go?" Well, it's not quite time to start packing yet. The problem is that these planets are really far away.

To make the trip as easy as possible, let's consider our nearest neighbor star system, the three-star system known as Alpha Centauri. Astronomers have already detected at least one planet in the Alpha Centauri system, and while this particular planet orbits too close to its star to have surface oceans, it's easy to imagine that there are other planets waiting to be discovered in Alpha Centauri's surface ocean zones. And even if Alpha Centauri does not have any such planets, other nearby stars do. For example, scientists recently announced evidence for a planet in the surface ocean zone of the star Tau Ceti, which is "only" about 12 light-years away. In what must be one of the greatest understatements of all time, several media outlets reported these planets as being "within spitting distance" of Earth.

My favorite way to get a sense of how far away these planets really are is by starting with a scale model of our solar system. If you walk out of the National Air and Space Museum (Washington, DC) on the mall side, you'll find the *Voyage scale model solar system*, the only purely educational exhibit ever approved for the National Mall. (I served

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[4] If you'd like to know the reasons behind my guess, please see my book *Beyond UFOs—The Search for Extraterrestrial Life and Its Astonishing Implications for Our Future* (Princeton University Press, 2008/2011).

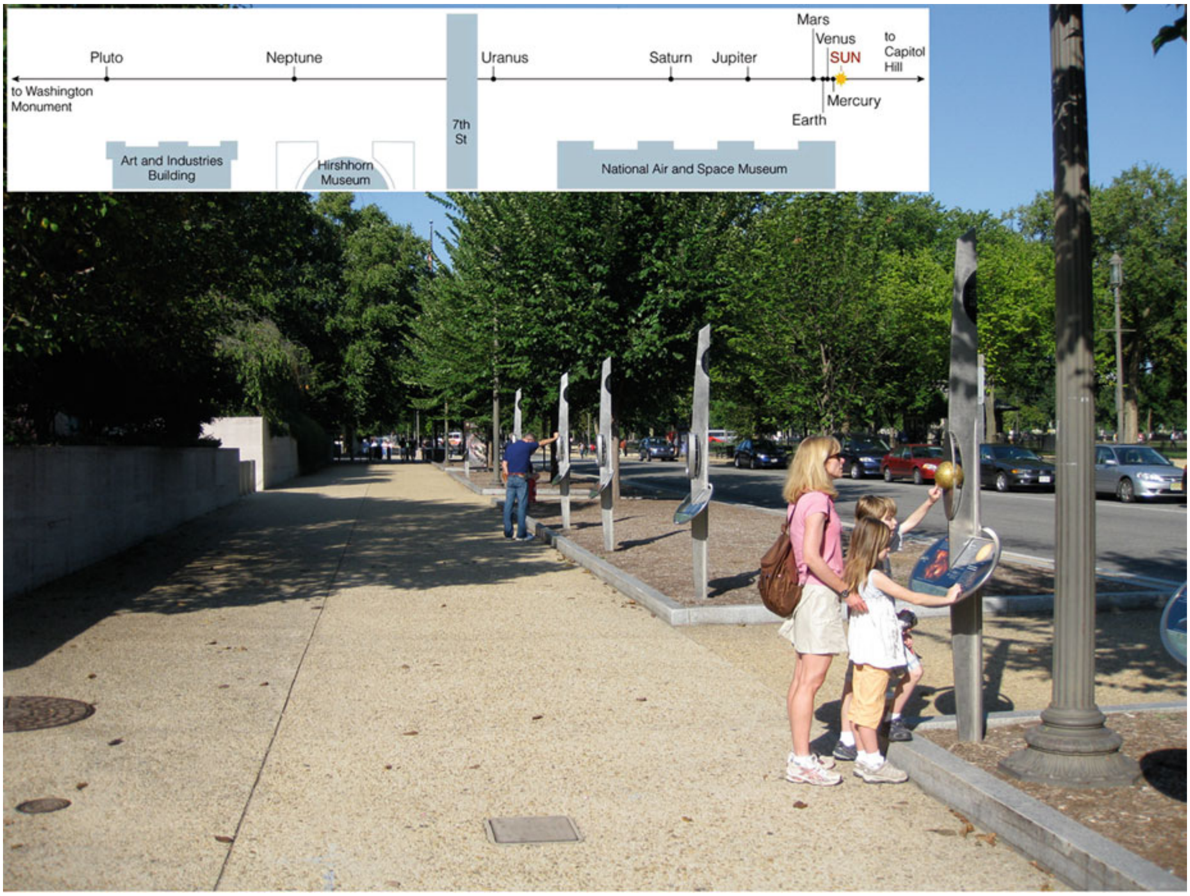

Fig. 11.7 Pedestals housing the Sun (the gold sphere on the nearest pedestal) and the inner planets in the Voyage scale model solar system (Washington, DC). The building at the left is the National Air and Space Museum (© Jeffrey Bennett). Inset: Map of the entire scale model

as co-PI on the project, which was led by my friend and colleague Jeff Goldstein, now with the National Center for Earth and Space Science Education.) The Voyage model shows our solar system on a scale of one to ten billion, which makes the Sun about the size of a large grapefruit (Fig. 11.7). Earth is smaller than the ball point of a pen on this scale, and located about 15 m from the model Sun. The Moon—the farthest a human being has ever travelled—is an even smaller ball point located just 4 cm (1½ in.) from Earth on this scale.

If you start walking from the Voyage model Sun, you'll pass Mars in about 25–30 strides. You'll walk more than that far again to reach Jupiter, which lies on the near side of the National Air and Space Museum steps. Continuing on, you'll reach Saturn on the far side of the steps, then reach Uranus just before you cross 7th Street. You'll encounter Neptune and Pluto (the model was built before Pluto's demotion) near the Arts and Industries building, commonly known as the Smithsonian castle. The entire walk can be completed easily in 10 minutes, though it will take longer if you stop to look closely at each planet.

The obvious next question is, How much farther must you walk to reach Alpha Centauri? Amazingly, the answer is that you would need to walk to California, as the distance to Alpha Centauri on this scale is about 4,400 km, or roughly the distance across the entire United States.

Think about this for a moment. If you place the ball-point Earth in the center of your palm, humans have never yet traveled beyond the edge of your hand on the Voyage scale—yet we'd need to cross a continent to reach even the nearest stars. Clearly, it's a bit more than "spitting distance."

To put it another way, consider the *New Horizons* spacecraft, launched toward Pluto in 2006. It is currently traveling away from Earth at a speed close to 50,000 km per hour, which is about 100 times as fast as a "speeding bullet" and nearly twice the speed at which the fastest satellites orbit Earth. Despite this incredible speed, it's a 9-year journey to Pluto, which *New Horizons* will race past in July 2015. *New Horizons* will ultimately continue heading outward to the stars, but even if it headed directly toward Alpha Centauri, it would need close to 100,000 years to get there.

This fact holds an important lesson about the possibility that we are being visited by aliens in UFOs. If even a small fraction of the many reported UFO sightings are real, then it implies that our alien visitors must be capable of traveling among the stars easily and often. In that case, their technology must be so far beyond ours that it would fall under the dictum of the great Arthur C. Clarke, who said: "Any sufficiently advanced technology is indistinguishable from magic."

Scientifically, we do not yet have any evidence of life beyond Earth, let alone of advanced civilizations. However, I see no reason to think that either life or civilizations should be unlikely, and I consider it well within the realm of possibility that advanced aliens really do make at least occasional visits to Earth. But if this is the case, then our alien visitors must be using technology that to us would look like magic. This means they can hide from us if they want to, and that they won't be suffering accidents that leave metal parts and corpses in the New Mexico desert. It also means that if and when they choose to make themselves known to us, they'll be able to come up with something more clever than drawing circles in wheat fields.

The bottom line is that unless an intelligent civilization suddenly decides to tell us that they are here and share their technology with us, we will not be visiting alien beaches any time soon. For the foreseeable future, our only hope of learning much more about worlds beyond our solar system lies in building ever-more powerful telescopes.

Telescope Technology

Could we actually learn about extrasolar alien seas with telescopes? The idea is not so far-fetched. Our largest telescopes would in principle already be capable of getting crude images and spectra of planets around other stars, except for the fact that the angular separation of the planets and their stars is so small. As a result, the bright light of stars tends to drown out the much dimmer light reflected (or emitted, in the case of infrared light) by any planets that orbit them. To combat this problem, scientists have developed several novel schemes, including using multiple telescopes together in space as an interferometer or using a screen floating thousands of kilometers from a space telescope to block out the central star while a telescope looks at the planets that orbit it.

We could learn a great deal if we actually built such telescopes. Even very crude images—say, a few pixels across—might in principle allow us to detect the presence of oceans and continents, and perhaps to observe seasonal changes. Spectra could tell us the composition of the planet and its atmosphere, and might even reveal the presence of life. For example, as we've discussed, oxygen on Earth is a product of life. Therefore, with careful study to rule out other possibilities, an oxygen detection in a distant planet's atmosphere might allow us to conclude that life is producing the oxygen through photosynthesis.

In fact, the only real obstacle to studying distant planets in search of life or surface seas is budgetary. Both NASA and the European Space Agency have developed concepts for telescopes that could obtain images and spectra of planets around nearby stars, but so far neither agency has succeeded in obtaining funding to build these observatories. Still, it seems only a matter of time until we finally answer the ancient question of whether we are alone in the universe.

Endless Possibilities

Extrasolar alien seas are almost surely out there, and we will eventually begin to learn a little bit about them. What will we find in and around them? The possibilities are almost endless.

We've talked so far about known planets in the thousands, and potential near-term discoveries in the tens of thousands. But this barely scratches the surface of the possibilities.

To get a sense of the reality, consider the fact that our Milky Way Galaxy has several hundred billion stars. By focusing on a small sample of stars nearby, the *Kepler* mission has begun to give us some reasonable statistics on the fraction of stars that have planetary systems, and the results are amazing. So far, we can say with moderate confidence that about one-quarter of all stars have planets, and some of the data suggest that the actual fraction may be upwards of 90%. We do not yet have enough data to do clear statistics on the number of planets in surface ocean zones, let alone on how many of those planets (or moons of Jupiter-like planets) actually have oceans. Still, unless there's some as-yet-unknown factor that would make oceans much rarer than I've presumed, it's easy to imagine that the Milky Way Galaxy could have more than 100 billion planets with surface seas.

The number "100 billion" is easy to say, but it's so literally "astronomical" that it's quite difficult to wrap your head around it. Here's one way to try: Imagine that as you go to bed tonight, you decide to count stars instead of sheep. You might wonder, how long would it take to count 100 billion of them? If we assume a counting rate of one per second, the obvious answer is 100 billion seconds… which turns out to be *more than 3,000 years*. In other words, the Milky Way Galaxy could have so many planets with alien seas that it would take more than 3,000 years just to count them all, and far longer to give the planets names, take telescopic images or spectra of their seas, and determine whether any of the seas have life or if they could be hospitable to human swimmers.

Looking further, there are nearly as many galaxies in the universe as there are stars in the Milky Way, and every reason to think that most of these galaxies would have similar numbers of planets and alien seas. Get this: All in all, there are roughly as many stars in our observable universe—and therefore as many possibilities for alien seas—as there are grains of dry sand *on all the beaches on Earth put together* (Fig. 11.8). The possibilities may not be mathematically "endless," but they are certainly endless in terms of the human imagination.

This brings us back to the starships that might take us to alien beaches. We cannot build such ships today, and even under the most optimistic scenarios it is likely to be centuries before we start sending out ships that would travel to the stars at a fraction of the speed of light. More convenient interstellar travel would require speeds much closer to the speed of light, or science fiction technologies that may not even be possible. Still, human ingenuity is almost as endless as the stars, and I personally have no doubt that if we keep working toward it, our descendants will someday set sail for the stars.

Therein lies the rub: To achieve this incredible future, we must keep working toward it. Sadly, the history of the human race has hardly been a straight line of progress, and today we stand at a point in time at which any number of threats could lead to a rapid downfall for our civilization. There are the obvious threats of nuclear war, increased terrorism, and global hatred. There are also many less obvious but no less ominous threats, including pandemic disease, overpopulation, and global warming. Worse, we face all these threats at a time when our politicians can't even agree on the value of exploration, whether that means exploring the depths of our own seas, building colonies on the Moon and Mars, or launching telescopes that will answer age-old questions about our place in the universe.

We live at the turning point of history. If we make poor decisions today, then a few centuries from now any remaining people will find only the ruins of our civilization. But if we choose more wisely, those same people will be building the starships that will take us to the shores of alien seas (Fig. 11.9).

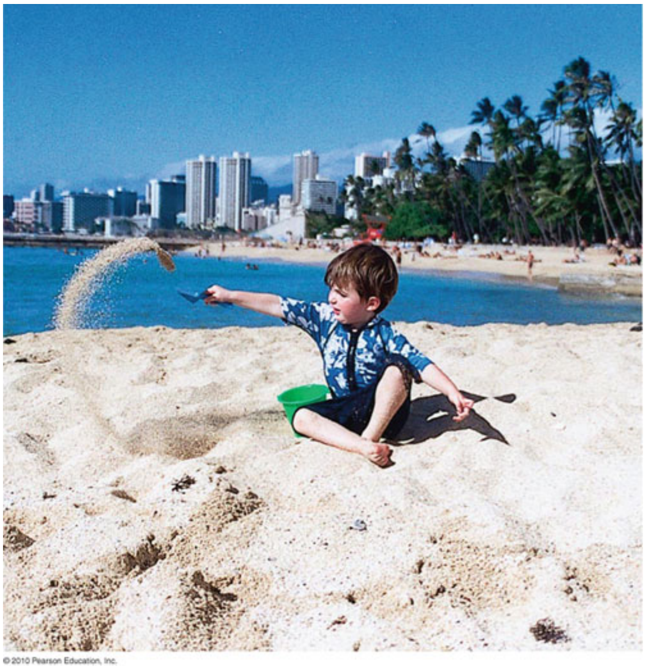

Fig. 11.8 A child demonstrates the fine-grained nature of sand. There are as many stars in our observable universe—and therefore as many possibilities for alien seas—as there are grains of sand on all the beaches on Earth put together (©Jeffrey Bennett)

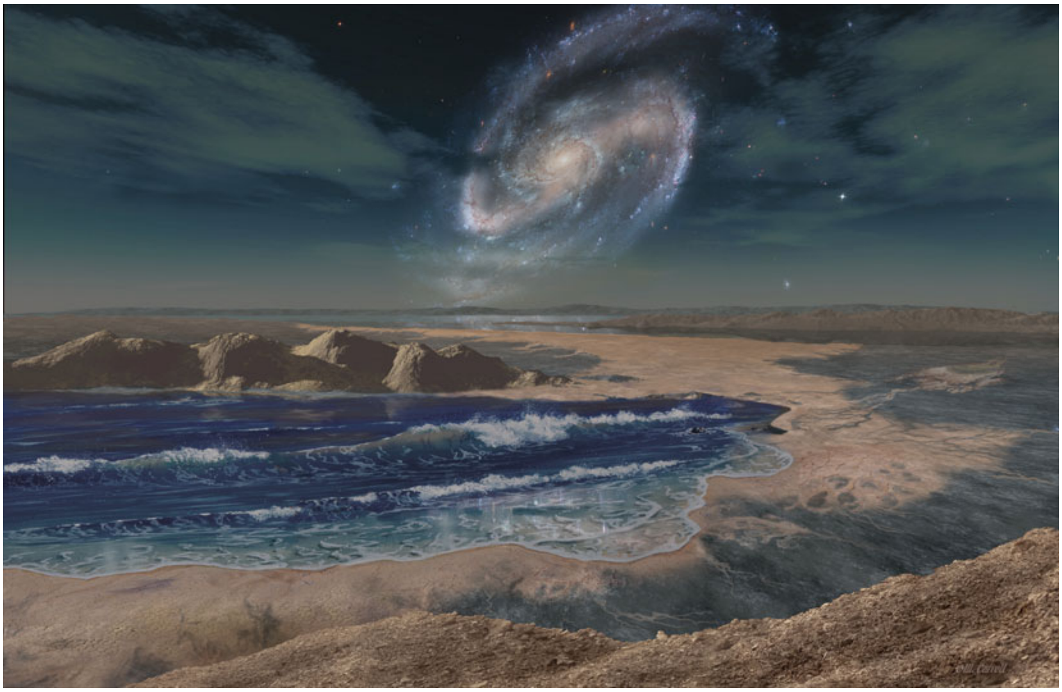

Fig. 11.9 A moonlit night on an ocean-wrapped world. Planetary systems outside of the Milky Way Galaxy would witness spectacular night skies (Painting ©Michael Carroll)

A Gallery of Maritime Planetscapes

12

Michael Carroll

Artists have been imagining alien seas for decades. In the 1950s, Chesley Bonestell envisioned a primordial sea of molten stone on Earth for LIFE Magazine and, later, for the book The World We Live In (Time/Life 1955). Other artists of the time gave us visions of carbonated seas on Venus and dying briny lagoons on Mars. As research advanced, science informed artists in new ways. The next pages offer a visual tour of more recent oceanic vistas on other worlds, beginning with our own and spreading out across the cosmos.

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DOI 10.1007/978-1-4614-7473-9_12,

G01. Moonrise by Don Dixon (© Don Dixon 1996)

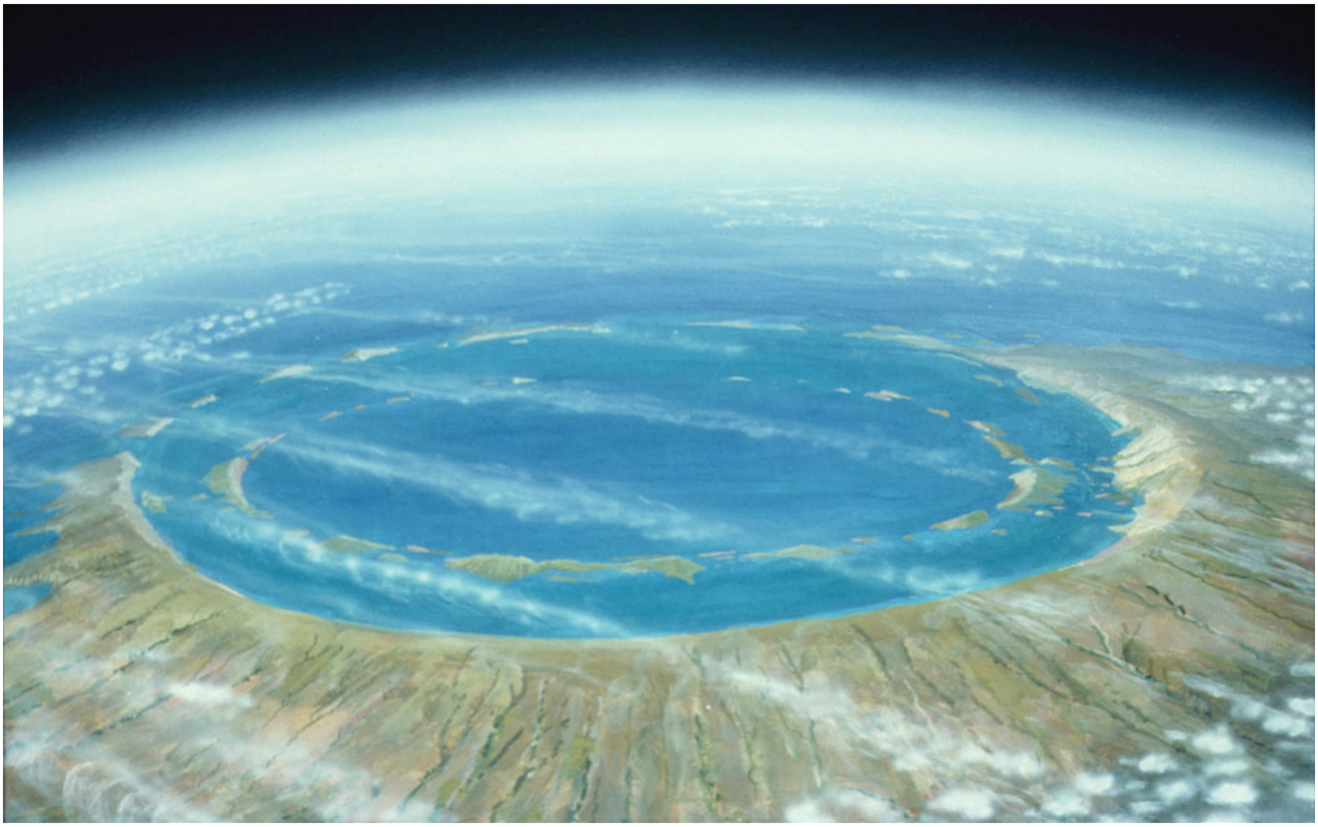
The first lunar tides must have been awesome indeed, if in fact the Moon 3.5 billion years ago was one-third its present distance from Earth. Mountainous waves crashed against the early continents, and friction within Earth's crust may have raised ocean temperatures substantially.

G02. Tidal Pool by Ron Miller (© Ron Miller)

Some 3.8 billion years ago, the Moon began to resemble the one we see in modern skies. On Earth, a dissipating rain of meteors and comets continued to bring organic material and water to the ancient landscape, while volcanoes fed the atmosphere with chemistry important for life. Along the edges of Earth's seas, tidal pools held the first traces of biology.

G03. Early Earth by Don Dixon (© Don Dixon 1993)

As the primordial atmosphere clears and cools, geothermal vents form along tidal basins, contributing a mix of organic chemistry at the base of a new-born food web. Rich colors paint the sides of pools with minerals and primitive microbes.



G04. Chicxulub Impact Basin by William K. Hartmann (William K. Hartmann 1991)

A thousand years after the great impact that ended the dinosaurs' reign, the Chicxulub crater has been flooded with ocean water from the north. The double-ring structure portrayed here has been discovered on many impact craters of similar size on Venus, where gravity and a dense atmosphere provide an accurate analog.

G05. Tylosaur and the KT Event by Julius Csotonyi (© Julius Csotonyi)

A life-filled Cretaceous ocean on the eve of the catastrophic Chicxulub impact, seen in the background. Marine reptiles like this tylosaur became extinct in the Cretaceous period, along with the dinosaurs and many other land and sea species across the Earth.

G06. Nicholson Crater by Kees Veenenbos (© Kees Veenenbos)

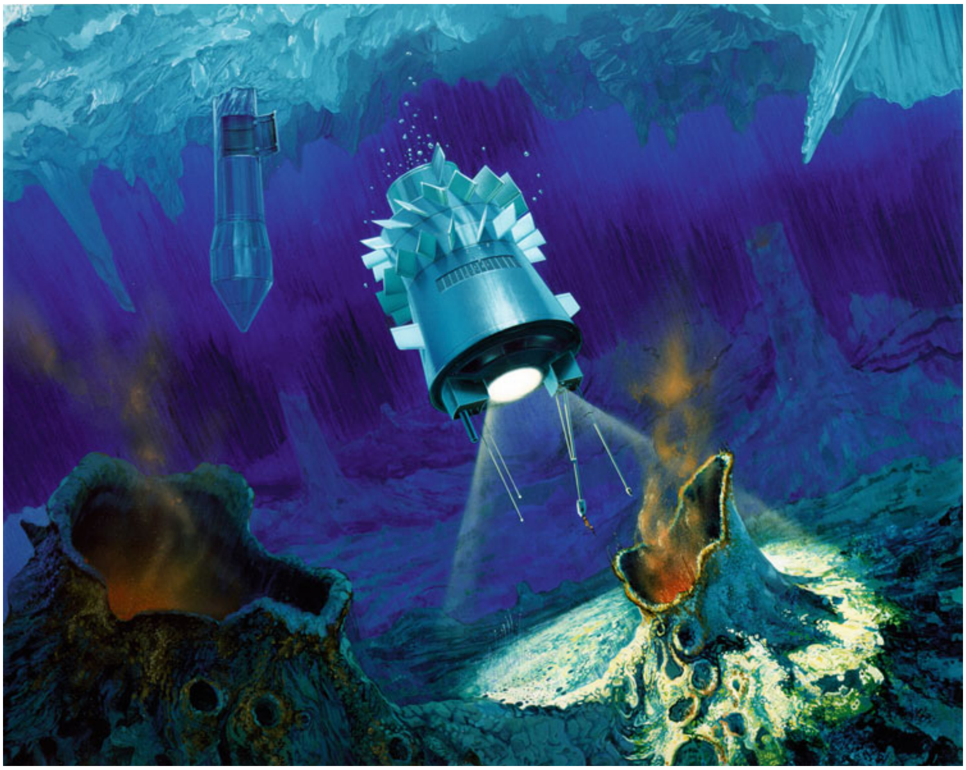
Ancient Martian seas may have lapped against the walls of craters like Nicholson, which lies at the edge of the great northern basin.

G07. Kasei Valles Waters by Kees Veenenbos (© Kees Veenenbos)

As volcanic activity subsided and the atmosphere of Mars drifted away to space, only low-lying areas like Kasei Valles could have retained liquid water. Even these areas eventually dried into the parched landscape we see today.

G08. Early Europa by Don Davis (© Don Davis)

Don transports us back 4 billion years when Jupiter was still a red-hot protoplanet, and Europa's global water ocean was just beginning to cool and freeze. Today, Europa's ocean still exists under the icy shell.



G09. Europabot by Ken Hodges (Courtesy JPL/Ken Hodges)

This painting, done by Jet Propulsion Laboratory artist Ken Hodges, portrayed an advanced concept for the JPL's studies of future exploration of Jupiter's moon Europa. This robotic probe would melt through Europa's ice crust and deploy a miniature submarine into the seas beneath.

G10. Black Smoker by David A. Hardy (© David A. Hardy)

Jupiter peers through a break in the ice as a submarine probe studies life around a hydrothermal vent on Europa. Hydrothermal vents (or black smokers) are found on ocean floors on Earth. They are regions where superheated water erupts from the ocean floor. The towering vents build up as minerals in the water precipitate out as the water cools. On Earth such vents support entire ecosystems. Europa is thought to have an ocean of liquid water beneath its surface crust of ice. If hydrothermal vents were present on its ocean floor, they could presumably support alien life.

G11. Future Europa by Michael Carroll (© Michael Carroll)

In roughly 4 billion years, our sun will swell up to great size as it evolves into a red giant star. Its heat may be sufficient to melt the surfaces of the icy Galilean satellites of Jupiter, recreating the primordial oceanic environments from their pasts.

G12. Titan by Steven Hobbes (© Steven Hobbes)

Vast seas of liquid methane stretch across the northern regions of Saturn's moon Titan

G13. Triton's Nitrogen Sea by Joel Hagen (© Joel Hagen 1983)

Before the Voyager 2 encounter of Neptune in 1989, Neptune's largest moon Triton was thought to have liquid nitrogen on its surface. Surface conditions on the bizarre moon are approximately at the triple point of nitrogen, where nitrogen can exist as a gas, liquid or vapor.

G14. HD 222582b by Lynette Cook (© Lynette Cook)

The exoplanet HD 222582b is a confirmed gas giant orbiting a G5 star. Its highly eccentric orbit of 0.37 AU to 2.31 AU from the star subjects the planet to extreme temperature fluctuations. If rocky moons are present in the system and have water, the regular periods of freezing and melting will create seasonal lakes from the ice and snow.

G15. Azurite Falls by Kim Poor (© Kim Poor)

Liquid can exist in many forms, depending on temperature and pressure. Here, Kim Poor treats us to a scene of a gas giant looming over the torrential waterfalls on a nearby moon. Methane in the atmosphere may tint a sky toward the green part of the spectrum, as we see on Uranus. The waterfalls here are modeled after Godafos in Iceland.

G16. Beach by Dan Durda (© Dan Durda)

Hypothetical moon of a gas giant orbiting in a star's habitable zone.

G17. Ocean Moon by William K. Hartmann (© William K. Hartmann)

An extrasolar super-Jupiter reflects across the waves of an ocean on an Earth-sized moon. While no exo-moons have yet been detected, many super-Jupiters have, and some lie within the habitable zone of their suns.

G18. Haloes by Pamela Lee (© Pamela Lee)

Planets in multiple star systems were once thought rare, but the Kepler Observatory has discovered several. Pam shows us one such world as it might be, with halos cast by four suns. Atmospheric ice crystals composed of different gases (such as water vapor or carbon dioxide) have different refractive properties, and would result in different sizes of haloes. This wide-angle view of 148° shows a halo and sundog display like none seen in Earth's skies.

G19. Ladies of the Lake by Kim Poor (© Kim Poor)

The partially melted surface of a hypothetical ice planet reflects the nearby Pleiades cluster.

G20. Ocean of Space by David A. Hardy (© David A. Hardy)

A night scene on an earthlike planet with an ocean, which has a dramatic view of a close spiral galaxy.

G21. Water, Water Everywhere by Chris Butler (© Chris Butler)

Originally inspired by a trip to a polluted L.A. beach, Butler morphed the beach scene into another water planet, where an astronaut would have to wear a space suit until tests showed no harm would come to him or her from alien bacteria in the water. Body language suggests that the weary space traveler would love to splash around in this vision of home.

About the Authors

Kevin H. Baines is a planetary scientist at the CalTech/Jet Propulsion Laboratory (JPL) in Pasadena, California and at the Space Science and Engineering Center at the University of Wisconsin-Madison. As a NASA-named science team member on the Galileo mission to Jupiter, the Cassini/Huygens mission to Saturn, and the Venus Express mission to Venus, he has explored the composition, structure and dynamic meteorology of these planets, discovering in the process the northern vortex on Saturn, a jet stream on Venus, the first spectroscopically-identifiable ammonia clouds on both Jupiter and Saturn, and the carbon-soot-based thunderstorm clouds of Saturn. He also was instrumental in discovering that the global environmental disaster caused by sulfuric acid clouds unleashed by the impact of an asteroid or comet some 65 million years ago was a root cause of the extinction of the dinosaurs. In 2006, he also re-discovered Saturn's north polar hexagon—last glimpsed upon its discovery by Voyager in 1981—which in 2011 Astronomy magazine declared the third "weirdest object in the cosmos". When not studying the skies and clouds of our neighboring planets, Kevin can often be found flying within those of the Earth as an avid FAA-certified flight instructor, having logged over 8,000 h (nearly a full year) of flight time instructing engineers, scientists and even astronauts in the JPL/Caltech community.

Jeffrey Bennett is an astrophysicist who has taught at every level from preschool through graduate school. He is the lead author of college-level textbooks in astronomy, astrobiology, mathematics, and statistics that together have sold more than one million copies. His books for the general public include *Beyond UFOs* (Princeton University Press, 2008/2011), which was honored by Miami University (Ohio) as the single book chosen in 2008/9 for all incoming students to read and discuss, and *Math for Life* (Roberts & Co, 2012), winner of the 2012 Colorado Book Award for nonfiction and recommended by a reviewer as "should be required reading for all Americans." He is also the author of several award-winning children's books, including *Max Goes to the Moon*, which in 2011 became the first book read aloud from orbit (by astronaut Alvin Drew during the final mission of the Space Shuttle Discovery) and which has also been made into a planetarium show. In addition to his writing, he served 2 years as a visiting senior scientist at NASA headquarters, where he created NASA's "IDEAS" program, started a program to fly teachers aboard NASA's airborne observatories (including *SOFIA*), and worked on numerous educational programs for the Hubble Space Telescope and other space science missions. He also proposed the idea for and helped develop both the Colorado Scale Model Solar System on the CU-Boulder campus and the *Voyage* Scale Model Solar System on the National Mall in Washington, D.C., which is now being replicated for numerous other locations around the world. For more, see his personal Web site www.jeffreybennett.com.

Michael Carroll is the 2012 recipient of the American Astronomical Society's Division of Planetary Science *Jonathan Eberhart award* for best science feature article of the year. In addition to his international magazine articles and 23 science books, Carroll is known for his space art, which has appeared in magazines including *National Geographic, Time, Smithsonian, Scientific American, Sky & Telescope, Astronomy,* and others. One of his paintings is on the

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surface of Mars—in digital form—in a DVD "time capsule" on the deck of the Phoenix lander. He is a Fellow of the International Association of Astronomical Artists and recipient of the Lucien Rudaux award for lifetime achievement in the astronomical arts. In 1991 he also received the "Honorable Tiny Tennies Award" for meritorious bungling.

Mona L. Delitsky is a planetary scientist who has done studies of the chemistry of planetary atmospheres and surfaces. During her 19 years at NASA's Jet Propulsion Laboratory, she investigated the chemistry of the satellites of Jupiter and Saturn and the surface and ionosphere chemistry of Neptune's moon Triton. She was part of the Voyager spacecraft team during its flyby and historic exploration of planet Neptune in 1988–1989 and considers that to be one of the most exciting experiences of her life. She started her own consulting company in 2006 and now works as an freelance scientist/entrepreneur investigating the atmospheres and surfaces of Venus, Saturn, Mercury, Earth and other planets in the solar system.

David Grinspoon is an astrobiologist who studies the possible conditions for life on other planets. He is Curator of Astrobiology at the Denver Museum of Nature & Science, and Adjunct Professor of Astrophysical and Planetary Science at the University of Colorado. He is a frequent advisor to NASA on space exploration strategy, and is Co-Investigator on an instrument that is currently on Mars on the Curiosity Rover. In April of this year, Grinspoon was selected to be the first Chair of Astrobiology at the United States Library of Congress, a 1-year appointment to begin this November, during which he will be researching and writing a book about the human influence on Earth, seen in cosmic perspective. Grinspoon was awarded the 2006 Carl Sagan Medal for Public Communication of Planetary Science by the American Astronomical Society. The citation for this award noted that "like Sagan in his time, Grinspoon is nearly unique in making science truly hip." For these skills, Wired Magazine featured Grinspoon as an "Alpha Geek" in 2008. His first book, *Venus Revealed,* (Perseus Books, 1998) was a Los Angeles Times Book Prize finalist. His 2004 book, *Lonely Planets: The Natural Philosophy of Alien Life* won the PEN Center USA Literary Award for Research Nonfiction. *Entertainment Weekly* called *Lonely Planets* "proof that life on this planet is both intelligent and funny." Grinspoon's writing has appeared in *Slate, Scientific American, Natural History, The Sciences, Astronomy, Seed, the Boston Globe, the Los Angeles Times, the New York Times, Nature, Science,* and *Sky & Telescope* where he is a contributing editor and writes the monthly "Cosmic Relief" column. Dr. Grinspoon has been featured on dozens of television and radio shows. He has given invited talks at international conferences throughout the U.S., Europe, Australia and Japan.

For more, see www.funkyscience.net

Rosaly Lopes is a Senior Research Scientist at the Jet Propulsion Laboratory, California Institute of Technology, Manager of the Planetary Science Section, and Investigation Scientist for the Cassini Titan Radar Mapper on the Cassini spacecraft. She is one of the world's foremost experts on volcanism and geology of the planets. She was born and raised in Rio de Janeiro, Brazil. Her University College London Ph.D. focused on planetary geology and volcanology. During her studies, she became a specialist on the hazards from lava flows and traveled to erupting volcanoes, some of the time as a member of the UK Volcanic Eruption Surveillance Team.

Dr. Lopes has been at JPL since 1989. She was a science team member for the Near Infrared Mapping Spectrometer (NIMS) aboard the Galileo spacecraft, responsible for planning all of the observations of Jupiter's volcanic moon Io using NIMS. During this period, she discovered 71 volcanic hot spots, which landed her a spot on the *Guinness Book of World Records* in 2006 as discoverer of the greatest number of active volcanoes anywhere. She currently researches the geology of Saturn's moon Titan using data from Cassini. She has received many awards, including a *Latinas in Science Award* from the Comision Feminil Mexicana Nacional in 1991, the *Carl Sagan Medal* from the American Astronomical Society in 2005, the *NASA Exceptional*

Service Medal in 2007, and the *Wings Women of Discovery Award* in 2009. She is a Fellow of the American Association for the Advancement of Science, and the 2012–2013 Chair of the Division for Planetary Sciences of the American Astronomical Society.

Chris McKay is a research scientist with the Space Science Division of NASA Ames Research Center. His current research focuses on the evolution of the solar system and the origin of life. He is also actively involved in planning for future Mars missions including human exploration. Chris been involved in research in Mars-like environments on Earth, traveling to the Antarctic dry valleys, Siberia, the Canadian Arctic, and the Atacama, Namib, & Sahara deserts to study life in these Mars-like environments. He was a co-investigator on the Huygens probe to Saturn's moon Titan in 2005, the Mars Phoenix lander mission in 2008, and the Mars Science Laboratory mission in 2012.

Karl L. Mitchell is a scientist at JPL whose research interests include lakes and seas of Titan, cryovolcanism on Titan as evidenced by Cassini Radar, volcanic eruptions on Mars, Titan, Enceladus, Io and Venus, Martian hydrology and remote sensing of planetary surfaces. His studies in geophysical fluid dynamics cover catastrophic flood dynamics, volcanic ascent and eruption dynamics, supersonic flow in explosive volcanic eruptions, and the relationship between volcanic landforms and eruption models. He is currently an associate of the Cassini RADAR team. He has a Ph.D. in Environmental Science from Lancaster University, England.

Robert T. Pappalardo is a Senior Research Scientist in the Planetary Science Section, Science Division, of the Jet Propulsion Laboratory in Pasadena, California.

Pappalardo's research focuses on processes that have shaped the icy satellites of the outer solar system, especially Europa and the role of its probable subsurface ocean. Europa research includes the possibility that solid-state convection has played an important role in the satellite's history, investigation of regions of separation and spreading of the satellite's icy lithosphere, and implications of the surface geology for lithospheric properties and the existence of a liquid water ocean beneath the icy surface. Additional research involves the nature, origin, and evolution of bright grooved terrain on Jupiter's moon Ganymede, specifically the style of tectonism and implications for the satellite's geological history. Also, he is investigating the geological implications of geyser-like activity on Saturn's moon Enceladus, and the level of geological activity on Saturn's moon Titan.

He is the Europa Study Scientist for the development of Europa mission concepts and a member of the National Research Council's Space Studies Board. He has served as the Project Scientist for the Cassini Equinox (Extended) Mission at Saturn, Chair of the Europa Science Definition Team, Co-Chair of the National Research Council's Committee on the Origins and Evolution of Life, and Steering Group member and Large Satellites Panel Vice-Chair for the 2002 Planetary Decadal Survey.

Along the way, he has worked with various science museums and organizations to bring the excitement of astronomy and planetary exploration to the public.

Timothy Parker was the originator of the Mars Ocean hypothesis. He earned his Ph.D. at the University of Southern California in 1994, with a dissertation entitled "Martian Paleolakes and Oceans." His research papers on the subject of ancient aqueous environments on Mars, beginning in 1989, have played a significant role in the development of the "follow the water" theme of Mars exploration and influenced the graduate studies of a number of students around the world. Tim's flight project experience at JPL includes CRAF, Magellan, Mars Pathfinder, Mars Exploration Rovers (MER), and the Phoenix and MSL missions. He is a member of the Athena science team on MER and serves as a Geology Team Group Lead. He played a critical role in landing site selection for Pathfinder, MER and Curiosity, and leads traverse geological assessments for MER and MSL, which involves comparing high resolution HiRISE views of the rover landing sites with overhead projections of images acquired by the rovers on the ground. Continuous updates of these location maps are critical for the successful operation of the rovers. Tim is a team member on the Mastcam, MAHLI and MARDI cameras on MSL.

Jani Radebaugh is a planetary scientist who specializes in landform geomorphology in the solar system. She studies more accessible features on Earth to gain insight into similar landforms and processes on other planets. Her current investigations include dunes, mountains, cryovolcanoes, rivers and lakes on Saturn's moon Titan from Cassini RADAR observations and volcanoes and mountains on Jupiter's moon Io from Galileo, Cassini, and Voyager observations. She has done field work in the Egyptian Sahara, the Ethiopian Afar Rift Valley, Hawaii, the desert southwestern US, and Antarctica. She obtained her Ph.D. in planetary science from the University of Arizona's Lunar and Planetary Laboratory, and she is currently an associate professor of geological sciences at Brigham Young University.

John Spencer is an Institute Scientist at the Southwest Research Institute in Boulder, Colorado. A native of Lancashire, England, he obtained a Bachelor's degree in Geology from the University of Cambridge in 1978, and a Ph.D. in Planetary Sciences from the University of Arizona in 1987. He worked at the University of Hawaii and Lowell Observatory in Flagstaff, Arizona before joining Southwest Research in 2004. He specializes in studies of the moons of the outer planets, using Earth-based telescopes, close-up spacecraft observations, and the Hubble Space Telescope. He was a team member on the thermal mapping instrument on the Galileo Jupiter orbiter, and now works with the Composite Infrared Spectrometer on the Cassini Saturn orbiter, and is a science team member on the New Horizons mission to Pluto. His work has included the first observations of Io's volcanic plumes with Hubble, including the discovery of sulfur gas in those plumes, the co-discovery, using Cassini data, of ice volcanic activity on Saturn's moon Enceladus, and the co-discovery of oxygen on Jupiter's moon Ganymede. He also recently found the probable explanation for the strange black-and-white appearance of Saturn's moon Iapetus. He enjoys living in Boulder with his wife Jane and their dog Maggie.

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