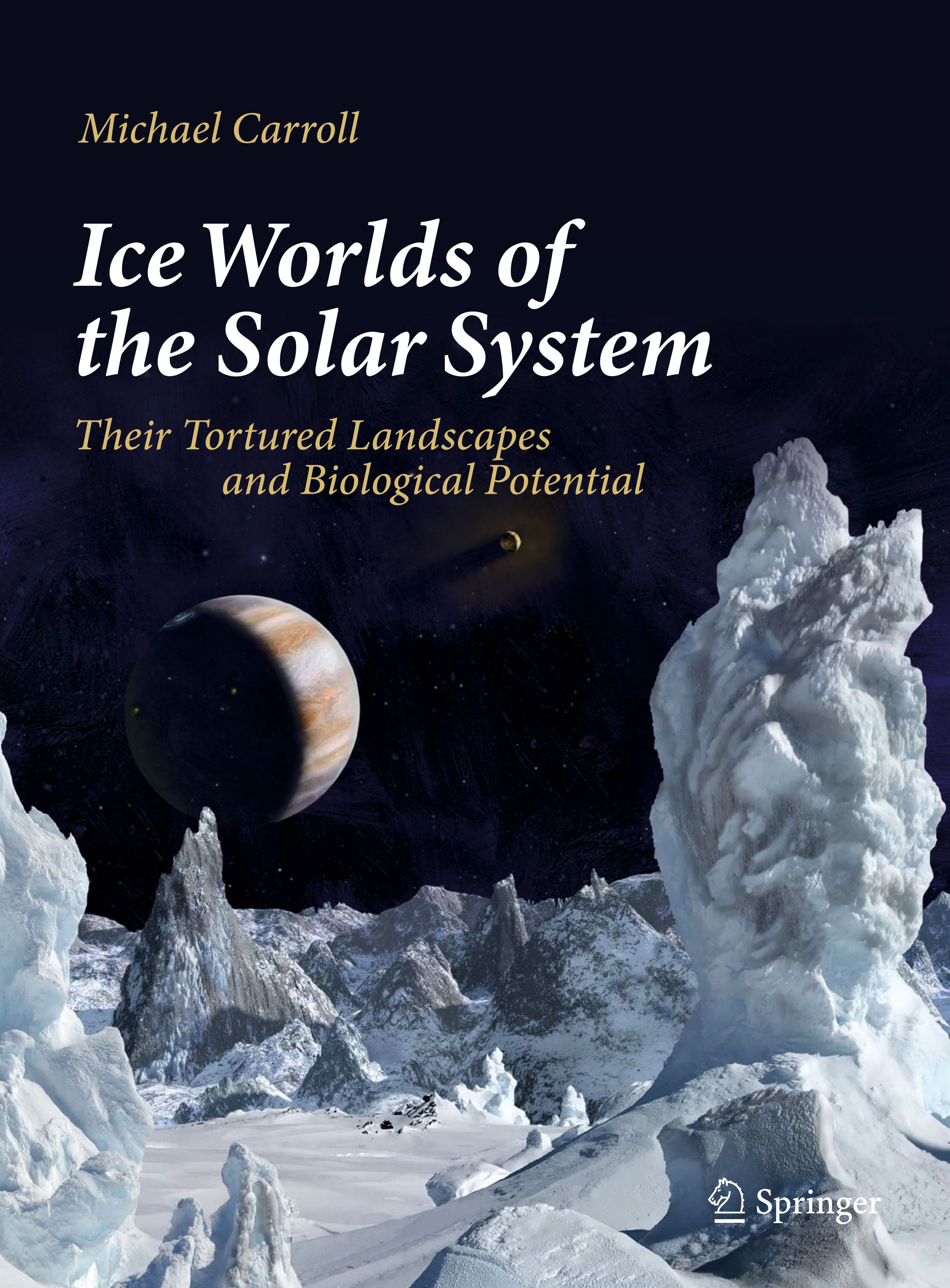
Michael Carroll

Ice Worlds of the Solar System

Their Tortured Landscapes and Biological Potential



Springer

Ice Worlds of the Solar System

Michael Carroll

Ice Worlds of the Solar System

Their Tortured Landscapes and Biological Potential

Springer

Michael Carroll
Littleton, CO, USA

ISBN 978-3-030-28119-9 ISBN 978-3-030-28120-5 (eBook)
https://doi.org/10.1007/978-3-030-28120-5

© Springer Nature Switzerland AG 2019
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors, and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

A Note About This Book

The natural satellites of the Solar System have become individual worlds to us, far more than star-like objects attending their important planetary overseers. But to understand the pattern and overall design of their natures, we have organized them (primarily) by how active they are. After visiting the largest asteroid—the dwarf planet Ceres—we will dive into the details of worlds beyond, beginning with the ones that are the most geologically tame. From them, we'll progress to the most complex planets and moons, the ones with ice crusts covering oceans. This progression from geologic simplicity to complexity will help the reader to understand the ice worlds as an interrelated family within the Solar System's clan of asteroids, comets, icy and rocky moons, terrestrial planets, and gas and ice giants. It's a strange and beautiful realm filled with worlds of frost and fire.

Acknowledgements

First readers are the unsung heroes of good writing. First readers are the unpaid editors, the people who give their precious time, energy, and expertise to an author out of the goodness of their hearts. The good writing in this book is due, in large part, to my trusty first readers Caroline Carroll and Marilynn Flynn. My thanks also go to the wonderful editors at Springer, Maury Solomon and Hannah Kaufman, who have stood by me through many projects and made my work presentable. My thanks to Steve Davidson, Frank Wu, and especially Bill Engle and the estate of Frank R. Paul for the use of the *Amazing Stories* cover.

Special thanks go to all my artistic and otherwise visually oriented friends who not only contributed to this book but who have contributed to the public's knowledge and inspiration for all-things-ice-worlds: Marilynn Flynn, David A. Hardy, and Ted Stryk.

Thanks to the many scientists who enable us to see and understand these remarkable worlds, including Julie Castillo-Rogez, Rosaly Lopes, Ralph Lorenz, Rachel Maxwell (special thanks for Europa fault insights), Chris McKay, William McKinnon, Francis Nimmo, Bob Pappalardo, Carolyn Porco, Louise Prockter, Marc Rayman, Paul Schenk, Peter Smith, John Spencer (with commendation for a fine lunch venue), Alan Stern, Peter Smith, Peter Thomas, and Leslie Young.

As always, my thanks to my friends at *Astronomy Magazine*, who graciously gave me permission to base portions of my text on past articles.

Contents

About the Author

Michael Carroll received the AAS Division for Planetary Sciences' Jonathan Eberhart Award for the best planetary science feature article of 2012, an article based on his Springer book *Drifting on Alien Winds*. He lectures extensively in concert with his various books and has done invited talks at science museums, aerospace facilities, and NASA centers. His two decades as a science journalist have left him well-connected in the planetary science community. He is a Fellow of the International Association for the Astronomical Arts and has written articles and books on topics ranging from space to archaeology. His articles have appeared in *Popular Science, Astronomy, Sky & Telescope, Astronomy Now* (UK), and a host of children's magazines. His twenty-some titles also include *Alien Volcanoe*s (Johns Hopkins University Press), *Space Art* (Watson-Guptill), *The Seventh Landing* (Springer 2009), and *Drifting on Alien Winds* (Springer 2011). His latest book—his eighth from Springer—is in Springer's Science and Fiction series, a novel called Lords of the Ice Moons (2019).

Carroll has done commissioned artwork for NASA, the Jet Propulsion Laboratory, and several hundred magazines throughout the world, including *National Geographic, Time, Smithsonian, Astronomy*, and others. One of his paintings is on the surface of Mars—in digital form—aboard the Phoenix lander. Carroll is the 2006 recipient of the Lucien Rudaux Award for lifetime achievement in the Astronomical Arts.

Beginnings

1

They are out there waiting for us, in the shadows, moving through the chilled void as they have for eons (Fig. 1.1). Hidden from Earthbound eyes by darkness and distance, these worlds are only now yielding their secrets to us. From humble moons to dwarf planets, the ice worlds display a wondrous symphony of geology, texture, and color. Canyons score the faces of worlds such as Ganymede, Enceladus, and Charon. Ridges raise a repeating tempo across the landscapes of Europa, Titan, and Pluto, and great stretches of sand dunes sigh across Titan and Pluto as well. Fanfares of cryogenic volcanoes rumble from Europa, Enceladus, and perhaps Ceres, Titan, Pluto, Ariel, and other small worlds. Some moons and dwarf planets may host oceans to rival the deepest seas on Earth. Internal forces crescendo as mountains thrust into alien skies. Dramatic gorges lay down a baseline deeper than anything seen on our own world. Strange concoctions of salts, methane, and ammonia play harmonies of umbers, ochers and yellows across the ices, colored by a descant of radiation from the Sun and nearby planets. The outer Solar System, once thought to harbor only dead globes of ice, has turned out to be an exhilarating and astonishing cacophony of sound, grace, and fury.

Order from Chaos

At a glance, our planetary system appears to be rocky and dry near the Sun and wetter as we venture away from the inner terrestrial planets. Ice abounds in the outer regions, the area this book focuses on. Water seeds the vast atmospheres of the gas and ice giant planets of Jupiter, Saturn, Uranus, and Neptune and makes up a great deal of the crust and cores of the moons circling them. We find such worlds also within many of the asteroids orbiting between Mars and Jupiter. One of those is the largest asteroid of all, the dwarf planet Ceres.

Beyond the gas and ice giants, a vast donut of icy worlds circles the Sun in the outer darkness. The poster child – and best known – of these is Pluto. To appreciate the lay of the land on an interplanetary scale, to understand the structure and nature of our planetary family, we must look to the Sun's and planets' origins. Like the results of genetic testing at a genealogy lab, we must look to our Solar System's "DNA," and the genetic code that was embedded within a primordial disk of dust and gas known as the solar nebula. With the Sun at its center, all of the planets, rocky asteroids, icy comets and moons issued from this vast cloud.

The early solar nebula, the great cloud of dust and gas from which all planets and moons and other objects came, originally lacked any big planets. The Solar System began as a great cloud of interstellar gas, much like many of the beautiful nebulae we see today. Those nebulae provided clues to early theorists about how our Solar System came together. Among them, Swedish scientist Emmanuel Swedenborg proposed the "nebular hypothesis" in 1734. His theory posited the Solar System arose from a hot globe of material around the infant Sun. German philosopher Immanuel Kant (1755) later enhanced this theory. French astronomer Pierre-Simon Laplace (1796) added even more detail, suggesting that the primordial cloud surrounding the Sun somehow flattened into a disk, eventually leading to the genesis of the planetary system we have today.

Kant and LaPlace had good reason to theorize such a spinning cloud; after all, a flat, spinning cloud of material would limit all the planets to orbiting the Sun in roughly the same plane (as they do), and every major body formed within that disk would tend to turn in the same direction (as they do).

The dynamics of the transformation from a hot, spherical cloud into a flat, planet-forming disk were not well understood, and other theories were constantly being put forward. Soviet theorist Otto Schmidt suggested that the primordial Sun passed through a cosmic cloud of gas, dragging it along in a great tail that ultimately condensed into the planets we see today. In 1917, James Jeans hypothesized that a star passed close to the Sun, pulling material from it. This theory seemed to fit the outline of the planets, as if a donut-shaped cloud surrounding the Sun, thickening toward its outside edge, led to the small terrestrials on one side and the large gas and ice giant planets on its outer perimeter.

M. Carroll, *Ice Worlds of the Solar System*, https://doi.org/10.1007/978-3-030-28120-5_1

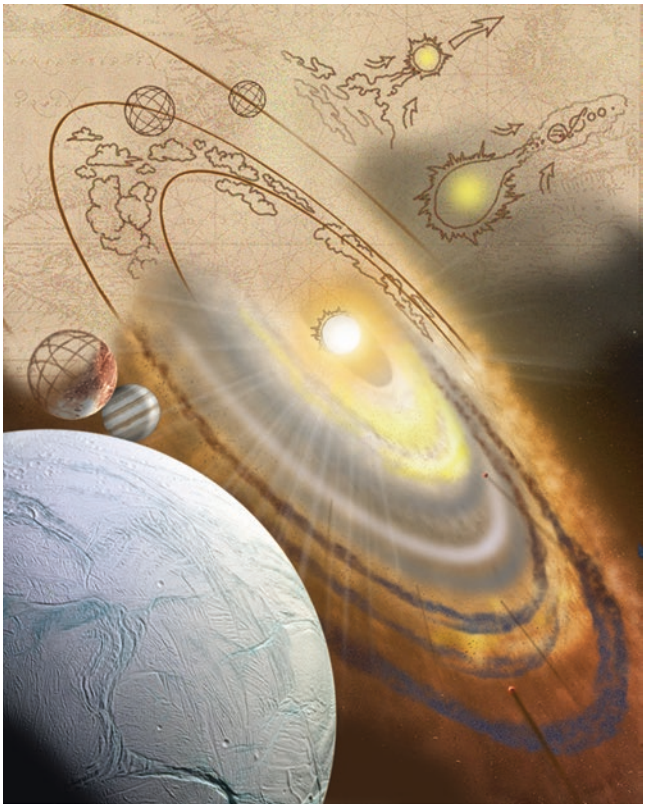


Fig. 1.1 Our sketchy view of the birth of our own planetary system has matured as science reveals the workings of planets and stars around us. Thanks to advanced observatories and computer modeling, our picture of the solar system's evolution is coming into clearer focus

Astronomer Forest Moulton and geologist Thomas Chamberlin proposed that a passing star caused a tidal bulge in the Sun, and that this bulge streamed out into tendrils of material, which mixed with similar trails of material from the passing star. These congealed into small blobs that they called planetesimals, bodies that then merged into larger planets.

Computer modeling and advances in mathematics led astrophysicists to settle on a Solar System formation model much like that of Kant and Laplace. Then, in 1993, the Hubble Space Telescope caught several young star systems in the act of formation, complete with disks of condensing material (known as proplyds) just like those described in Kant's nebular hypothesis.

Today, astrophysicists have a much better understanding of how a solar nebula becomes a system of planets. Shock waves from nearby passing – or even exploding – stars trigger eddies and currents in the cloud surrounding a young sun. As shock waves ripple through the cloud, the cloud condenses and begins to spin, in the same way that an ice skater spins at an increasing rate when pulling her outstretched arms to her sides. Like the clay on a potter's wheel, that rotation flattens the cloud into a great disk, called an accretion disk. Within that foggy disk, matter compresses and condenses into knots of material, each of which grows as it pulls more material to itself. The growth grows into a runaway effect, where the biggest objects grow the fastest because they have the most mass and can grab the lion's share of drifting material around them. This growth continues, and the disk dissipates until there is nothing else from which to grow.

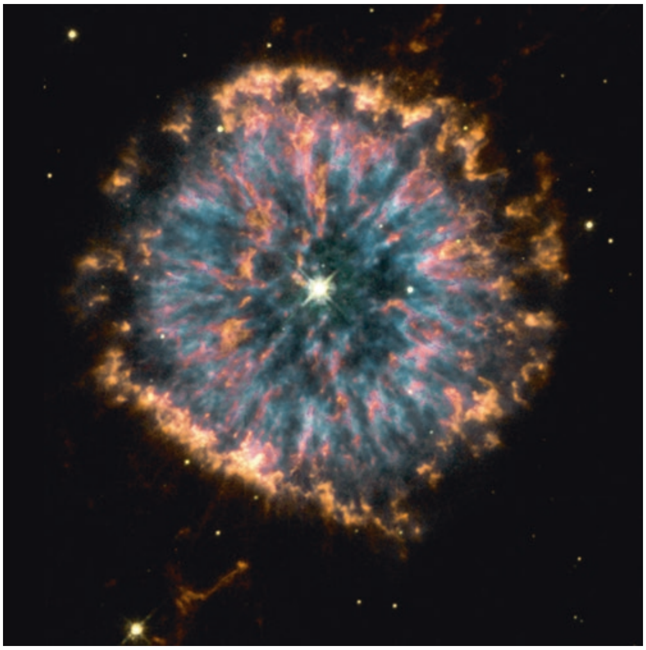


Fig. 1.2 Hubble Space Telescope image of the remnants of an exploding star. The object is NGC 6751 in the constellation Aquila. Shock waves from such an event may have led to our Solar System. (Image courtesy of STScI.)

Many of the objects that are not absorbed by the cores of giant planets are deflected by those cores and flung out of the Solar System. The still-forming protostar at the center begins to shrink, and in doing so develops a rapid spin. The new planets and residual cloud around it, also spinning, drag upon the star, forcing it to slow. When the pressure and temperature within the protostar rises to a sufficient level, reaching several million degrees, the atoms in the core collapse into each other, and nuclear fusion ignites. A star is born (Fig. 1.2).

Planetesimals circling the Sun 4.5 billion years ago had one of two likely fates – either to collide with the growing core of a planet and become part of it, or to be scattered by that core and ejected from the Solar System completely. The ones that bashed into each other were a part of the Late Heavy Bombardment, an epoch of cratering that battered every surface in the Solar System. Craters from this early epoch, if they still exist, represent the most ancient of terrains in the Solar System. Of all the objects that were kicked outward, at least 90% left the Solar System. But a small fraction – not more than 10% of those ejected bodies – were deflected a second time by nearby stars and captured into the Oort Cloud, a distant sphere beyond the main Solar System, at the very fringes of the Sun's gravity.

Initially, material in the Oort Cloud began close in to the Sun, and then those objects were scattered outward. It is likely that parts of the Kuiper Belt were scattered out in similar fashion.

During all this shuffling, the central hub of the cloud grew massive enough to collapse in on itself, triggering nuclear fusion at its core, and the Sun flared to life. The spinning of the disk began to increase as the debris contracted, and the cloud pancaked further.

The flattened cloud of dust, ice, and gas was not uniform in makeup. Eddies and currents within the cloud led to smaller disks, which would eventually coalesce into planets, pulling more material to themselves as their size – and gravity – grew. This phenomenon of material condensing into larger bodies is called accretion.

The great cloud eventually dissipated, due to two processes. The first was the loss of material to interstellar space. As the cloud became less dense, its heat was free to leak away. The cooling material in the nebula condensed into planets, moons, comets and asteroids. The laws of physics dictated this outcome, and nearly every theory about the origin of the Solar System revolves around this concept.

Furious solar winds gusted from the infant star in an energetic period called the T-tauri phase, the second clearing process. A gale of solar wind coursed through the cloud, clearing out the lighter materials from the inner system. What remained near the center were the small, rock-and-metal terrestrial planets and the asteroids. But farther out, lighter material, including hydrogen, helium, and water, were able to remain, settling around the growing planets and moons. The outer realm became a dark kingdom of frozen water and gases.

The Sun's energized T-tauri phase dried out the entire inner Solar System. But the water story was only beginning. Mercury, Venus, Earth, and Mars were left with desiccated landscapes and dry atmospheres. But a second wave of moisture may have come from infalling comets and asteroids. Water makes up a large component of comets, but even the drier asteroids may have brought vast quantities of H_2O to the surfaces of the terrestrial worlds. Early models implied that water delivered in this violent way would vaporize, boiling away into space at the moment of impact. But more modern investigations simulated these primordial impacts[1] using a facility at NASA's Ames research Center called the "Vertical Gun Range." Sharp-shooting researchers used marble-sized pellets of antigorite, a type of mineral common to stones, which may have carried water to the primordial terrestrial planets. Shooting the marbles into baked pumice at 5 km/s, they discovered that rather than vaporizing, some of the antigorite's water fused with the liquefied rock and glass during the impact. The research suggests that asteroids could have added over a quarter of their water to the planetary crusts (Fig. 1.3).

Fig. 1.3 NASA/Ames Vertical Gun Range simulates impacts. (Image courtesy of NASA/Ames)

Drawing Boundaries

Our planetary system is divided in two by a boundary known as the frost line or snow line. This important frontier is defined by temperature. Inside the line – toward the Sun – we find surface temperatures high enough to support liquid water. Outside the snow line, water is forced into its solid form, ice.

Water is not the only volatile changed by temperature. Separate snow lines also exist for gases such as ammonia, methane, and nitrogen. In the case of water, the snow line is at about 5 astronomical units, roughly 700 million km from the Sun. Here, temperatures drop to about –103°C. If water drifts out here in the form of vapor, it will immediately turn to solid ice.

---

[1] *Science Advances*, Vol. 4, Number 4, April 25, 2018.

Well beyond the snow line, the gas giant planets held on to the constituents of the original cloud – mostly hydrogen and helium – while their smaller satellites became reservoirs of volatiles: dry ice, frozen water, and rimes of gases condensed upon their surfaces and within their crusts. Still further out, Uranus and Neptune were able to hold on to more water, becoming the ice giants we see today.

New research proposes that the quartet of giant worlds (Jupiter, Saturn, Uranus, and Neptune) started out not as the great orbs of gas we see today but as "steam worlds." Beginning as hydrogen/helium protoplanets, the four bodies would have settled out of the Sun's accretion disk initially with bulks slightly larger than Earth. Even by today's standards, these would have been alien worlds, ocean planets with deep water vapor atmospheres. As more ice and rock came together, a runaway growth process took over, beginning when the primordial planets reached two to five Earth masses. At that point, the grand size of the gas and ice giants was a fait accompli, with the planets becoming massive within the span of only a few million years.

This view of Solar System formation – of worlds born within clouds of varying constituents – came to be accepted as the "Standard Model." It was a great narrative, but it needed observational backup. Kant's contemporaries tried to find examples of stellar disks, but none could be seen through their telescopes. Even after centuries of searching through the best instruments on Earth, protoplanetary clouds surrounding new stars proved to be elusive. All that changed with the launch and eventual commissioning of the Hubble Space Telescope. HST imaged the cosmos in detail never seen before. Within its images lay the smoking gun, evidence of Kant's ideas. Infant stars thundered to life within vast nebular clouds. Around them swirled flattened disks of dust and gas. These protoplanetary disks are the planetary systems of the future, and there are many.

Making Moons

The formation of the natural satellites of the gas and ice giants is linked to the formation of the planets themselves. The moons of the outer system give us two clues as to their origin. The first is that all the moons tend to orbit their primary planet in the direction of the planet's spin. A second clue to their source is the fact that most of them orbit very near the equatorial plane. These two bits of evidence show us that the moons arose within the same cloud that formed their parent planet.

Like miniature Solar Systems, each planet condensed from a flattened, spinning disk. The moons themselves emerged from that cloud, orbiting and rotating in the same direction of spin. The clearest example is the Jupiter system, with its four large moons, the Galilean satellites. As Jupiter condensed into the king of planets, the cloud around it grew hot at its center. The space surrounding Jupiter became hot enough to drive away the light volatiles, leaving the innermost satellite, Io, as a dense, rocky globe. But farther out, each satellite held on to more and more water. A 100-km-deep ocean surrounds Europa's rocky core, topped by a solid ice crust. Still farther out circles Ganymede, with nearly a third of its formidable sphere as liquid ocean beneath a frozen water crust. The farthest out of the four is Callisto, a dead world of scrambled rock and ice, less dense, overall, than any of the other three Galileans.

The four moons echo the density and architecture of the Solar System, with the inner, rocky terrestrials and the outer, lighter giants. In fact, as Jupiter evolved into a planet, a long train of moons may have come and gone, a great cosmic conveyor belt where moons condensed in the surrounding cloud and then migrated inward, eventually gobbled up by Jupiter itself. As the cloud cleared away, less and less material was available to slow the paths of the moons, until finally Jupiter was left with its four large satellites.

How did the Galileans develop into such different siblings? Once settled into stable orbits around their parent planets, major moons continue to change and evolve into new worlds. Two primary factors affect the outcome: heating (internal and external), and a process called differentiation. These two forces can change an inert, cratered ball of ice and rock into an exciting, energetic world of canyons, mountain chains, volcanoes, and ice floes. For the most part, the moons began with a mix of ice and rock in the same ratio as what was floating around the early Solar System: 60% ice[2] and 40% rock. If a moon forms in the cold emptiness of space, with no heat beyond the background temperature, the ices will not melt, so the building-block chunks of rock and ice will remain mixed throughout the globe, locked in place. But among most of the ice worlds of our Solar System, we see an ice shell surrounding a denser, rocky core. It takes heat to create this "differentiated" layering, and it's cold out there. Ice worlds must get heat from outside sources, and some of those sources are violent ones: impacts from asteroids and comets.

In the early days of the Solar System, the rock and ice fragments throughout the Solar System pummeled the surfaces of planets and moons. Today, a record of this violent time is left on the cratered faces of planets and moons. In general, the more geologically quiet a world is, the more craters it will have. (Earth's moving crust, volcanoes, and weather all contribute to obliterating its ancient craters.) When an asteroid or comet falls to the surface of a solid body, it essentially explodes, with most of its mass turning into vapor or pure heat energy. But astronomers estimate that

---

[2] "Ice" may include water-ice, dry ice (frozen carbon dioxide), and other ices such as ammonia and methane.

less than half of the heat from impacts remains inside the planet, with the rest escaping back into space. This is not enough heat to trigger differentiation. Something else must be at work, and that extra heating element is radioactivity.

The rocky building blocks of the planets and moons included radioactive elements. Our own planet provides insights into what materials heated other worlds as they grew: uranium (^{235}U and ^{238}U), thorium (^{232}Th) and radioactive potassium (^{40}K). All of these elements are isotopes, meaning that they are unstable. In normal atoms, the protons making up the nucleus are in balance with the neutrons circling around them. But if the atom has too many neutrons, it is radiogenic (radioactive). Its nucleus tends to shed those extra, unstable particles. These escaping particles create radioactivity.

If the ice world is large enough, radiogenic materials contribute enough heat for differentiation. In the beginning, rock is distributed throughout the ice, but its radioactivity melts the ice and enables the rock to settle toward the center. Within 2 billion years, rock has formed a core, and a rock/ice combination forms an outer layer. In the case of many satellites, this ice is fairly pristine, lacking rock of any kind.

The interior of an ice world may be heated by another force unknown until a few decades ago. This force is called tidal heating. Tidal heating occurs when the push and pull of gravity from nearby worlds heats the interior. We'll explore this important phenomenon further in Chap. 3.

Within this general origin scenario, more subtle narratives exist. Take, for example, the moons of Saturn. Several scenarios are under study for the origins of Saturn's vast system of moons, which range from Mercury-sized Titan to tiny ring moons a few km across. If Saturn's moons formed in that conveyor-belt style that we find with the Galileans, we would expect to see the most dense satellites nearest the planet, with gradually less densities moving out. But the mid-sized moons of both Saturn and Uranus break this pattern, with a jumbled arrangement of size and density. Instead, these moons seem to follow a different pattern, arranged not by density but by mass. With this revelation, planetary dynamicists have put forth an alternative theory, in which the moons form within the planet's ring system and then migrate out, pulled by the complex gravitational interaction between the planet, its rings, and the nearby moons. The most massive moons in this scenario move out faster than their smaller siblings. If this view of satellite origins is accurate, Iapetus and Titan may have been among the first satellites to accrete (or the sole survivors of the earliest stages of this moon evolution).

Other formation theories have been proposed as well. Moons might form within the disk that formed the planet itself, at the end of the planet-birthing process. As the central planet grows, it becomes large enough to open a gap between itself and the surrounding solar nebula from which all planets and moons eventually formed. Through that gap, the infant planet's gravity pulls streamers of material, including the seeds of what would become moons. These "seeds," nicknamed "pebbles," migrate through the streamers into the growing accretion cloud around the planet, growing in size into moons. The gas surrounding the planet slows the path of the moons, dragging them in toward the central planet. The gas finally clears out, and the inward migration stops. The resulting densities in satellites would decrease with distance, because volatiles such as ices can condense farther out, where it is cooler. However, the satellites of Saturn (and possibly Uranus) show no such gradient, and the richness of ice in the moons suggests that they materialized in a cooler environment than this theory asserts.

Another idea proposes that the rings of Saturn arose from the destruction of a Titan-sized moon, either by a massive impact or by that super-moon drifting into the Roche limit, a region in which moons are close enough to the planet to be gravitationally torn apart. The rocky core of this theorized moon fell into Saturn itself, but its outer icy layers were left behind as extensive rings. The icy moons of Saturn would have issued from the icy residue of the lost moon (Fig. 1.4).

A variation on the theme has Mimas, Enceladus, and Tethys accreting from the ring material, while the moons farther out coalesced from the cloud surrounding the infant Saturn. Presumably, a similar process could occur at Uranus and Neptune. Alternatively, the mid-sized moons may be the leftovers of the meeting of two large moons that resulted in Titan, or from the collision of two Titan-sized moons. The formation of the icy moons among the gas and ice giants is a mystery awaiting a solution. That solution may have to wait for more advanced spacecraft missions (Chap. 11).

Today, elements of our own Solar System's birth cloud drift among the skies and hearts of the giant worlds Jupiter, Saturn, Uranus and Neptune, and within their hundreds of moons, large and small. They are a storehouse, a precious Dead Sea Scroll of the ancient Solar System. With the advent of our robot emissaries, we are just beginning to unroll that parchment. What we see is astonishing. Astronomers supposed that with the building blocks of rock, ice, and frozen atmospheres, the outer Solar System's moons would be inert, cratered, dead balls of ice. But instead, our explorer spacecraft have beheld a wild variety of moons, some of rock and ice, some hiding ocean depths beneath ice crusts, still others washed in alien seas of liquid methane or carpeted by gases turned to frost. Some have been sculpted by the strange melting and refreezing of volatiles, exhibiting bizarre landscapes of ice spires, fractures, hollows, and alien terrains named "cantaloupe" and "bladed." Still others have been cleaved by cryovolcanism, eruptions of cryogenic material welling up from deep inside their ice crusts. The frosty canyons of Enceladus are blanketed in powder from a hundred water jets, while nitrogen geysers drape dark trails across the pink face of Triton. It's a wild, energized Solar System out there in the darkness, one that has lessons to teach.

Fig. 1.4 One of the many theories about how Saturn got its rings: a Titan-sized moon is torn apart by gravitational forces as it wanders too close to Saturn, scattering its debris around the planet. (Sketch by the author)

Dance of the Dwarfs

Among the ice orbs spinning in the outer darkness, astronomers have defined a new class of world, the ice dwarf or dwarf planet. Five have been officially recognized, but hundreds or thousands more are waiting out there. Only one lies inside the orbit of Neptune, and it is the ice dwarf Ceres, largest of the asteroids. The main asteroids form a family of rocky fragments orbiting between Mars and Jupiter. In size, they range from as far across as Ceres, at 476 km, to small piles of material like the humble Itokawa, a rubble pile that's a scant 350 m in average diameter. Beyond the orbit of Neptune lies another asteroid belt-like region, this one rich in water ice. This is the Kuiper Belt.[3] It is the source of short-period comets. The poster child of the Kuiper Belt Objects (KBOs) is Pluto, which holds the distinction of being the largest Kuiper Belt object visited up close by a spacecraft.[4] Its orbit around the Sun is so large that the entire history of the United States has passed during just one Plutonian year, or circuit of the Sun.

Pluto is no longer considered a planet and has now been reclassified as an ice dwarf. The reason is one of numbers. Dozens of KBOs have now been discovered beyond Neptune, and scientists suspect there may be hundreds more, some of which may be larger than the planet Mercury. With the discovery of so many Pluto-like worlds out there, the International Astronomical Union was faced with a dilemma. Should those small worlds join the family of traditional planets, or did they deserve a class of their own?

The IAU finally came to the conclusion that for an object to be a "planet," it must fulfill three prerequisites. First, it must be big enough to have settled into a sphere during formation (a phenomenon known as hydrostatic equilibrium).[5] Second, it must orbit the Sun without orbiting another body. Finally, it must be big enough to clear debris around its orbit. "Dwarf planet" means that the object is large enough to be in hydrostatic equilibrium, orbits the Sun, but is too small to clear debris. To this point, however, the IAU has only a short list of dwarf planets: Ceres, Pluto, Eris, Makemake, and Haumea. All dwarf planets are expected to be icy worlds, with a preponderance of water over rock.

Ice by Any Other Name

The worlds we will visit in this book are ruled by ices both familiar and alien. Many possess shells of frozen water that might make an Arctic explorer feel right at home. But in the outer Solar System, temperature and pressure conspire to

---

[3] More formally known as the Edgeworth-Kuiper Belt.

[4] Aside from several short-period comets, including Giacobini-Zinner, Grigg-Skjellerup, Halley, Hartley 2, Borelly, Tempel, Wild, and 67P/Churyumov-Gerasimenko, and the KBO 2014 MU69.

[5] Note that the planet does not need to have actually settled into a sphere; it just needs to possess enough mass to have the potential of doing so.

change the very nature of ice. In fact, temperature and pressure determine whether a material exists as a gas, liquid, or solid. A familiar substance demonstrates the point.

On Earth, we are surrounded by water. It sloshes around in liquid form in our lakes and rivers, and sits comfortably in our coffee cup. If we're at sea level and that water warms to a temperature above 100°C, it turns to vapor, as we can see with that morning coffee. If its temperature drops below 0°C, it freezes, ready for our soda. But should its temperature and pressure change significantly from those "norms," water morphs into exotic forms.

The local ice cream store carries dry ice, which is frozen carbon dioxide (CO_2). We breathe in CO_2 every day without thinking. Plants breathe it in as they convert it to oxygen. But if the air on Earth could become cold enough, the CO_2 within it would turn to snow and fall to the ground. The polar ice caps of Mars have done just that; they contain a large component of dry ice. It looks like ice, but anyone who has touched it has felt its burn.

The ice cubes in our homes are a crystalline form of water. Unlike many substances, which contract when cold, water actually expands as it freezes. It is a uniquely flexible amalgamation of hydrogen and oxygen, critical to the chemical operations of biology. It is a universal solvent, elixir of life. Its remarkable nature comes from its molecular structure. Water molecules consist of an oxygen atom and two hydrogen atoms. Single atoms of oxygen hold eight pairs of electrons. All of them constantly repel each other. But in a molecule of water, two pairs of those electrons bond with two hydrogen atoms, leaving the other two electron pairs free. The water molecule is left in a form where two hydrogen atoms extend outward, as do two pairs of electrons from the oxygen molecule.

Whether we speak of gases flowing from one region to another seeking equilibrium, or weather driven by a planet's attempt to even out its global temperature, nature is constantly seeking balance. The most balanced arrangement for water molecules is the tetrahedron, with an oxygen atom at center and the pairs of electrons sticking out farthest from each other.

One important aspect of water is that it is "polar." Its pyramid-like structure is arranged with oxygen at one end, which is negatively charged, and hydrogen opposite with a positive charge. Water molecules meet ("bond") at the hydrogen sides, with the negative pole of one molecule linking up with the positive pole of another. When water is in its liquid state, these bonds are weak. They are strongest in the ice form and weakest as a gas (water vapor). As solid ice, the hydrogen in water molecules bonds in a crystalline structure. But in this form, pairs of electrons from neighboring molecules tend to repel, pushing the molecules away from each other. To be stable, the molecules form a crystalline form, depending on the temperatures and pressures surrounding them. As the environment around them changes, the crystalline form shifts to remain stable. Water-ice takes on some 17 of these exotic forms of ice. Each form is called a "phase," and is assigned a Roman numeral in order of when it was discovered.

On Earth, the most common phase of ice is called Ice I, which describes the tetrahedron form of the ice crystal. This is the ice that dusts our mountain peaks and can make Colorado winter driving miserable. Ice I comes in several flavors, depending on conditions.

At higher pressures, approaching 40,000 pounds per square inch, Ice I becomes Ice II, where temperatures hover around –75°C. Ice II is a crystal with a rhomboid shape. But as temperatures plunge below –250°C, the water turns to Ice III, with a tetragonal crystalline form. The ices continue to morph and change with changes in the environment.

In the gloomy outer darkness of our Solar System temperatures drop dramatically. In the vacuum of space, water cannot freeze into a crystalline form because of the lack of air pressure, but rather flash-freezes into a solid with no crystal arrangement. This type of ice, found in all corners of the universe from comets and asteroids to interstellar dust, has no Roman numeral label. As we explore the dramatic landscapes and numbing depths of the ice worlds, we will encounter ice in many forms.

With their wild histories, diverse evolutions, and bizarre conditions, the worlds beyond Mars are not as simple as we had once thought. This new face of the outer Solar System, unexpected and exotic, has been revealed by a flotilla of spacecraft bearing bold names such as Pioneer, Voyager, Galileo, Cassini, and New Horizons. These ambassadors from Earth represent a new chapter in humanity's exploration of far frontiers. But a host of explorers came before them, wearing not solar cells and thermal blankets but rather Parkas and skis. They were the polar explorers, the daring humans who ventured to the icy realms here on Earth.

The Not-So-Neat Solar System

Computer modelers who study the early Solar System began to doubt the "Standard Model" in the decade of the seventies. Sophisticated mathematical simulations showed that objects the size of Uranus and Neptune could not form where those two planets now reside. Earth-sized or smaller objects in that region do not attract each other, but rather scatter each other toward the inner Solar System, where Jupiter's mighty gravity tosses them out of the Solar System. Researchers have put forth several models to better describe the early Solar System. The first, called the *Nice model* (named

(continued)

(continued)

after the French city), portrays Uranus and Neptune forming close to the orbits of Jupiter and Saturn, and then migrating out gradually. The second, named the Grand Tack, sees a more violent early Solar System, where the four giant planets orbited close together until something – perhaps a passing planet or nearby star – disrupted their peaceful coexistence. The four worlds yo-yoed wildly from the inner to the outer Solar System, eventually settling into the orbits we see today.

Some of the smaller ice worlds may shed light on this mysterious, primordial epoch. Not all moons move in the direction of their planetary parent. Neptune's largest moon Triton orbits in a retrograde motion, opposite the spin of the planet and the orbits of the other major moons. Additionally, it does not orbit in the plane of Neptune's equator, as it would have had it issued from Neptune's formative disk. Triton appears to be the product of a violent past – forming somewhere else, likely in the Kuiper Belt outside the orbit of Neptune. The moon was then cast into the orbit of Neptune, where the gravity of the blue behemoth captured it. Other moons follow strange orbits, bearing witness to violent pasts.

2

Terrestrial Explorers Before the Space Age

The First Adventurers

From the first migrations out of northern Africa to the mass trek across the Beringia land bridge into the western continents, humankind has had the longing to move, to expand, to explore. Some migrations came at the hands of drought or famine, but the lure of "just over that horizon" seems to be ingrained in our psyche. Aerospace engineer Robert Zubrin declares that it is a natural, built-in urge for the survival of our species. "Look at nature. Any species that does not expand dies out. It's natural and healthy for humanity to move out into the cosmos."[1] Explorer Robin Hanbury-Tenison said, "It has always been mankind's gift, and curse, to be inquisitive – this is what makes us unlike all other species. Without this curiosity we would all have stayed at home."[2] *Apollo 12* astronaut Alan Bean agreed. "Exploring is part of being human. People have always wanted to know what lies beyond the next mountain or across a faraway river."

Historically, exploration has been fueled by at least one of three main drivers: technology, science and research, or geopolitical considerations (including business and economics). Of these, the latter has been the most prominent in modern times. Columbus did not come to the Americas to document the plants and animals; he came to find a more efficient trade route, and he came at the sponsorship of a politically and economically motivated government. The Apollo project revolutionized both science and technology, but its impetus was primarily geopolitical, a competition to beat the Soviet Union in a technological sprint for national prestige.[3]

Human migrations and explorations have not always been peaceful. Adventurers have battled against the elements, and explorers have contended with other humans for rangeland or resources. The clash of cultures – such as the meeting between Spain's Hernán Cortez and Montezuma of the Aztecs – is rife with tragic consequences.[4]

In the outer Solar System, explorers will face primarily the struggle of humans against the relentless forces of nature. We strive not for high ground, military position, or prime real estate, but rather for knowledge: to know the deep things the cosmos has to teach us about the natural history of the Solar System, about the nature of other worlds, and of what they can teach us about caring for our own planet and people. We stand on the shore of a great ocean of sun-drenched ebony skies and starry depths, an ocean empty of air but full of promise. Our robots stand ready to sail, and after them, the humans will follow. It is a noble trek, and one that echoes those who came before.

After the initial expansion of the human race from its origins in Africa up into Asia and Europe,[5] the "sea peoples," or Polynesians, embarked on a daring journey across unknown seas. They ventured into the vast emptiness of the Pacific in open canoes from Tahiti, Fiji, Samoa, and the Marquesas, traveling across thousands of miles. Captain James Cook – himself a great explorer and seafarer – famously observed, "How could a stone-age people have navigated and explored a third of the Earth's surface without instruments and charts?"

Of course, the Polynesian sea captains used maps of a different kind. They charted the stars using mats of twine and

---

[1] Personal interview, 16th Annual International Mars Society Convention, Boulder, Colorado, August 2013

[2] *Explorers' Sketchbooks: the Art of Discovery & Adventure* by Lewis-Jones and Herbert (Chronicle Books, 2017)

[3] For more on human exploration of the icy worlds beyond Mars, see this author's *Living Among Giants: Exploring and Settling the Outer Solar System* (Springer, 2015)

[4] Contact usually comes with mixed results, some negative, some positive. Cortes, for example, founded the Hospital de Jesus in what is now Mexico City.

[5] The "Recent African Origin" model, also called the "Out of Africa" or "Recent Single-Origin Hypothesis," suggests that modern humans migrated north and east from Africa beginning 70,000 years ago, spreading south along the Asian coasts and across Oceania by 50,000 years ago. The migration through the Pacific islands took place over 20,000 years later.

M. Carroll, *Ice Worlds of the Solar System*, https://doi.org/10.1007/978-3-030-28120-5_2

sticks; they watched the swells of the waves to catch telltale signs of distant shores. They kept an eye out for billowing cumulus clouds that tended to stack up above atolls and rocky islands. Even the birds gave them clues; shore birds went to sea in the morning and returned to land at night. Their flight pointed the way to shores just over the horizon.

The peoples who sailed in their double-hulled reed boats eventually came ashore on the Hawai'ian island chain. Archeological evidence from the island of Hawai'i suggests that the first landfalls were made by expeditions from the Marquesas around A.D. 800. The Polynesians learned, incrementally, how to make longer and longer voyages, in much the same way that our robotic spacecraft and astronauts have moved from suborbital flights to regular routes into low Earth orbit and beyond. But before travelers ventured off the planet, they honed humankind's exploration skills in places of rock and ice. Climbers summited the highest peaks of the Himalayas, the Andes, and the Alps. Explorers mapped the desolate wilds of Siberia, Canada, and Alaska.

Exploration of Earth's icy wilderness regions continued on both poles. Aside from knowledge and adventure, the North Pole had another appeal: navigators yearned for a northwest passage, a link between the eastern and western hemispheres.

Into the North

The vast plains of sea ice covering deep oceans remind today's researchers of moons such as Europa, Enceladus, and Ganymede, ocean worlds with an ice crust (see Chap. 6). Nineteenth-century explorers were first to face these frigid wastelands up close and personal. Norwegian adventurer Roald Amundsen was first to cross the Northwest Passage, announcing his success by telegram from the tiny village of Eagle, Alaska. Although Amundsen had made it through, he found that the route was too shallow for practical shipping lanes.

In 1825, William Edward Parry lost his ship, the H. M. S. *Fury,* to the ice near Baffin Island. Two years later, Parry tried for the pole again, making it to 82°45′ N, the farthest north at the time. A more northern locale was not reached until 1871 during a polar attempt by Charles Francis Hall's Polaris expedition, sponsored by the U. S. government. The crew of the *Polaris* came close to mutiny on several occasions, due to poor leadership. It made it farther north than Parry had, but could not achieve the pole itself. As the *Polaris* crew progressed northward from a wintering site on the Greenland coast, Hall left the ship and went ahead by sledge. Upon his return, he fell critically ill and accused his crew of "poisoning" him. At the time of Hall's death, no charges were filed against the crew. In 1968, his body was exhumed and an autopsy revealed high levels of arsenic.

The U. S. Navy's Jeanette expedition (1879–1881), commanded by George DeLong, attempted the pole from the Pacific side, winding its way through the Bering Strait. But the *Jeanette* found herself trapped in the ice. DeLong led his crew by boat and sled to the Lena River Delta in Siberia, but in the course of doing so, more than half of the crew – including their leader – died of cold or starvation before rescue.

Despite its loss, the *Jeanette* would figure into future Arctic exploration. The ship provided famed Norwegian explorer Fridtjof Nansen with a novel way to achieve the pole. During a 3-year voyage from 1893 to 1896, Nansen allowed his ship, the specially designed *Fram*, to become icebound in the eastern Arctic, at the New Siberian Islands. From there, Nansen planned to let the trapped ship drift in the pack ice, with the Arctic's own sea ice carrying it to the pole. His inspiration was the wreckage of the ship *Jeanette*, which appeared to have drifted across the North Pole before being discovered on the southwest coast of Greenland. Nansen's ship drifted slowly for 18 months, and the Norwegian explorer became impatient. He set out with a colleague for the pole on foot, with the aid of a team of dogs. The two did not reach their destination, but they did survive the trip back from the farthest northern point yet explored, at the latitude of 86° 13.6′ N.

First to the North Pole may have been Admiral Robert Peary, who claimed to reach the top of the world on April 6, 1909. Peary traveled using dogsleds, and set up three successive support teams along the way. But his claim is in dispute. Unlike other explorers, Peary did not submit his charts and documentation to international authorities, but rather presented them to the National Geographic Society. As the society had sponsored his trip, some doubted their thoroughness in confirming his assertion. Peary's notes lacked some critical navigational records, and his progress across the ice also seemed to vary considerably. Others also claimed to have reached the pole, most notably Frederick Cook, whose claim was rejected by the Danish authorities.

Roald Amundsen was part of a 1926 expedition to fly over the pole in a dirigible, a foray which recorded the pole's first undisputed sighting (Amundsen was also first to attain both poles). The flight was carried out by Italian aviator and engineer Umberto Nobile aboard his dirigible, the *Norge.* At the time, the American explorer Admiral Richard Byrd was drawing plans to reach the pole as well, but Amundsen was interested in more. He planned to do a survey of the entire region, referring to the pole as "merely a station on the way." The *Norge* drifted over the pole at 1:25 a.m. on May 12, 1926.

Two years later, the French government backed Nobile in a second series of polar flights. Nobile's airship *Italia* departed on the first of five planned flights in 1928. The *Italia* was similar to the *Norge* in design, spanning a length of 145 m (348 feet), with a diameter of 19 m (64 feet).

It carried a crew of twenty. After bad weather aborted the first attempt, the second flight of the *Italia* charted 4000 km of Arctic terrain. But the third flight became the most famous.

The *Italia* departed Greenland on May 23, 1928, cruising along the coast of Greenland to the North Pole. Two days out, the weather turned. Ice buildup and mechanical problems caused the *Italia* to crash on the sea ice, tearing the gondola from the gas envelope of the dirigible. Six of Nobile's comrades were trapped in the envelope as it drifted away on the wind. The wreck marooned ten of the crew in the shattered gondola on the sea ice. One of them died from the impact. The other nine erected a tent using silk from their supplies and sections of the ruined envelope. They dyed the tent red using the dye from glass "dye-bombs" used to measure the ship's altitude during flight. Chief Flight Engineer Ettore Arduino, seeing the men left behind on the ice, tossed as many supplies as he could to them as the dirigible's envelope carried him and the rest of the crew away in the gale. Arduino undoubtedly saved their lives, but those trapped inside the envelope were never seen again.

Five countries carried out aerial searches after a Soviet amateur radio operator heard the crew's SOS. Eventually, all but one of the men in the gondola were rescued in a series of flights and the arrival of the Soviet icebreaker ship *Krasin.*

In one of history's great ironies, after a lifetime of daring exploration, careful planning and successful triumphs to both poles, Roald Amundsen vanished while attempting to rescue Nobile's *Italia*. Amundsen and a French crew of five disappeared on June 18, 1928. Their loss underscores the high stakes that exploration brings.

The excursions in the northern Arctic, both successful and tragic, taught explorers how to navigate polar terrain. Although some explorers continued north, adventurers were also assaulting the continent of Antarctica.

Antarctica

Perhaps the bleakest of Earth's frozen wilds is Antarctica. The "Harsh Continent" has engendered the spirit of exploration as no other.

Antarctica is probably the place on Earth most like the icy moons of the outer Solar System. Pressure ridges and fissures heave across sea ice flows, superficially resembling features found on Jupiter's moon Europa or Saturn's Enceladus. Wind and water carve jagged valleys into the same kinds of shapes that methane rains have created along the shorelines of Saturn's moon Titan. Antarctic glaciers find counterparts at the boundaries of Pluto's Sputnik Planitia, in ice floods on Saturn's Enceladus, or within the furrows of Neptune's Triton. Sastrugi (parallel ice ridges in polar regions and open frozen lakes) echo the form of methane ice dunes that ripple at the foot of Pluto's peaks.

A summit crater crowns Antarctica's active volcano, Mount Erebus, reminding geologists of cryovolcanic calderas on ice worlds. Erebus also provides insights into Saturn's geyser-ridden moon Enceladus, as well as to other volcanically active ice worlds that vent gases into their skies. Possible cryovolcanic sites may include Saturn's Titan, Neptune's Triton, Uranus' Miranda and Ariel, and Pluto.

For the first explorers venturing into southern waters, the ice worlds did not enter into their strategies. The moons and dwarf planets of the outer system were unknown quantities when British explorer Captain James Cook sailed south in search of the theorized southern continent, commonly referred to as Terra Australis. Cook circumnavigated the globe in the far southern latitudes from 1772 to 1775. At one point, his ship reached a latitude of 71° south before turning back from the ice pack. Half a century after Cook, mariners finally glimpsed the shoreline of Antarctica. Russian seafarer Fabian Gottleib von Bellingshausen is one of three who may have seen it first. Bellingshausen, an admiral in the Russian navy, commanded the ships *Vostok* and *Mirny*. In November of 1820, Bellingshausen's crew sighted the islands of Peter I and Alexander I. This may have been the first solid land seen within the Antarctic Circle.

Another early sighting of the mainland resulted from a search for new seal hunting grounds. On November 17, 1820, several sealers ventured into Antarctic waters, most notably the Englishman James Wedell. Wedell made it as far as 74° S, a record that was to stand for 80 years. Another sealer, American Nathaniel Brown Palmer, made landfall in Antarctica while in search of seal rookeries. Today, the coast and several islands on this part of western Antarctica bear his name.

Exploration of the great southern wilderness began to gel with the voyage of British Royal Naval officer Edward Bransfield, who was commissioned to sail the two-masted brig *Williams* south from Chile to survey the newly discovered South Shetland Islands. The Shetlands scatter across the ocean near the Antarctic peninsula. Bransfield made his way farther to the southwest, finally spying the Trinity peninsula. Its prime head is the northernmost limit of the Antarctic continent proper. He recorded "high mountains covered with snow."

At the beginning of the nineteenth century, a host of European explorers descended upon Antarctic shores. One of the most influential was James Clark Ross, who led two remarkable expeditions. Ross set out on the *Erebus* and the *Terror* (commanded by Francis Crozier) in 1839 (see Fig. 2.1). His choice of ships was a wise one. The two munitions vessels had been constructed with reinforced hulls, making them the ideal option for a voyage through sea ice. Ross's expedition aimed to set up magnetic observatories at several sites to monitor Earth's magnetic fields, ultimately setting up a permanent station in Tasmania. Ross's team ventured south in search of the center of Earth's magnetic south pole.

Fig. 2.1 The H. M. S. *Erebus* and H. M. S. *Terror* in Antarctica. British marine painter John Wilson Carmichael rendered this painting in 1847. Armored sailing ships such as this one opened great possibilities for polar exploration. The *Terror* carried the James Ross expedition to Antarctica in 1839, along with the H.M.S. *Erebus.* Two volcanoes on Ross Island are named after the ships. (Image from https://en.wikipedia.org/wiki/Ross_expedition#/media/File:HMS_Erebus_and_Terror_in_the_Antarctic_by_John_Wilson_Carmichael.jpg.)

The *Erebus* and *Terror* mapped hundreds of miles of Antarctic coastline. The Ross Ice Shelf is named after him, as is Ross Island, home of the active volcano Mount Erebus, named after Ross's ship. An adjacent extinct volcano is named after Ross's second ship, the *Terror*. Unlike many of the map-making forays before him, his voyage had a strong science component. Ross' expeditionary force included artists and scientists, and was a true voyage of discovery.

Antarctic exploration had also fired the American imagination. In 1838, at about the time of Ross's expedition, the U. S. Congress funded an Antarctic voyage led by Charles Wilkes. Congress's mandate was to "aid commerce and navigation," but lawmakers included a clause about extending general knowledge. The Wilkes expedition ventured into Antarctica in two stages, in 1839 and 1840, during the austral summers. Team members carried out geological surveys and collected zoological and anthropological specimens from some of the islands.

A quarter century after the Wilkes expedition, the H.M.S. *Challenger* became the first steam-powered ship to enter the seas of Antarctica. *Challenger* was tasked with carrying out the first global oceanographic research mission, a cruise that would cover 68,900 miles of the world's seas. The ship was equipped with laboratories and a darkroom for developing photographs. In fact, the *Challenger* expedition was the first to make extensive use of photography as a research tool. Engineers also installed a steam-powered dredging system for bringing up samples from the abyss. A globe with a hole on the side could also be lowered to the seafloor, dragged, and reeled back in for retrieving seafloor samples.

Building on the rich return of specimens by Wilkes, the *Challenger* crew, and others, polar science flourished. Norwegian Carl Larsen's expedition excavated fossils in Antarctica, constituting the first evidence that Antarctica may have enjoyed a warmer climate in its past. Swedish and German researchers soon followed. Pioneer explorer Carsten Borchgrevink was first to collect plant life in Antarctica in the form of lichens. Welsh-Australian geologist Douglas Mawson led the Australasia Antarctica expedition with the goal of charting 3000 km of Antarctic coast. Mawson also championed magnetic field studies, visiting the south magnetic pole during the trip. Ernest Shackleton carried out several of the first wide-ranging explorations of the Harsh Continent. Taking part in three British missions, Shackleton first attempted to find the South Pole with Robert Falcon Scott on Scott's *Discovery* Expedition of 1901–04. Edward Wilson accompanied Scott and Shackleton. The Discovery Expedition set up a permanent hut, now known as Discovery Hut, near the site of what is, today, McMurdo Base today. Shackleton's 1907 *British Antarctica expedition (*also known as the *Nimrod Expedition)* carried out extensive exploration of Ross Island, ascending Mount Erebus for the first time. On the same expedition, Douglas Mawson gathered valuable scientific data throughout. The Japanese joined the scientific journeys, mounting their first expedition to survey the King Edward II Land and the nearby Alexandra mountains.

Although science was often an important element of various polar expeditions, it was the poles themselves that called many. The North and South poles of the planet marked specific, unmovable, compelling locations in which to plant a nation's flag. Nationalistic pride often carried these expeditions, with personalities and fame associated with voyages. The *cause celebre* of polar exploration earned the period the name of "The Heroic Age." Its nationalistic, geopolitical spirit echoed through explorations nearly a century later, as the first explorers carried out voyages to Tranquility and the Lunar Apennines.

Many polar explorers, though financed by political forces, carried a true interest in the research side of their journeys into new wildernesses. The pursuit of knowledge may, in fact, have been a factor in the loss of Robert Falcon Scott's expedition to the South Pole. Scott had been to Antarctica once already on Britain's *Discovery Expedition* (1901–1904). But Scott received news that Shackleton's group had narrowly failed to reach the South Pole, and Scott was ready to try again.

The Terra Nova expedition (more officially known as the British Antarctic expedition) was backed by the Royal Geographic Society and privately funded. Scott's party set out across the Harsh Continent with 65 men. His group carried out an extensive scientific program, led by chief scientist Edward Wilson. Their studies included zoology, meteorology, physics, and geology. While Scott's men settled on McMurdo Sound in their prefabricated "Discovery Hut," waiting for the winter to end, they got word that Amundsen had arrived down the coast, planning an assault on the pole as well.

Amundsen, who had spent so much time in the Arctic learning the ways of the Inupiat and Inuits, traveled with only four compatriots, reaching the South Pole on skis on December 14, 1911. Amundsen took an untried route that required only 57 days of travel. The Norwegian used dogsleds, skis, and sledges to achieve the pole, along with colleagues Bjaaland, Wisting, Hassel, and Hanssen. While the voyage was, at times, grueling, all members survived to return home.

Robert Scott's party followed a different route, covering more territory. His team consisted of himself and four others: Edward Wilson, Edgar Evans, Henry Bowers, and Lawrence Oates. Storms battered the British team, subjecting them to some of the lowest temperatures on record. Using ponies for the initial part of their journey, the quartet reached the pole arduous weeks after Amundsen, only to see the Norwegian flag flying before them. Amundsen had also left letters for the British team, along with a letter addressed to King Haakon of Norway. Scott's group perished on their return journey. Nevertheless, Robert Falcon Scott stands alongside Amundsen as a titan of Antarctic exploration. A memorial to those lost in the Terra Nova expedition was erected in 1913 on Observation Hill, which today overlooks McMurdo Base. The deprivations and frustrations encompassed in the Heroic Age's explorations of the Arctic and Antarctic were perhaps best summed up by Scott's last diary entry, found beneath his body a year after his team were lost. He said, "Great God! This is an awful place and terrible enough for us to have labored to it without the reward of priority."

The Heroic Age of exploration was drawing to a close, but explorers were not finished with Antarctica. Ernest Shackleton followed the Nimrod expedition with the Imperial Trans-Antarctic expedition, from 1914 to 1917. Shackleton's vision was daring: send two parties to opposite coasts of Antarctica. One team, the Ross Sea party aboard the ship *Aurora*, would land at McMurdo Sound. From the base of operations there, they would lay supply depots across the ice and up the Beardmore Glacier. Meanwhile, Shackleton's team would take the ship *Endurance* to make landfall at Vashel Bay on the opposite side of the continent. Shackleton's men would then trek across the entire continent to the South Pole towards the Ross Sea, using the depots left by the Ross sea party.

The Ross sea party successfully deployed the supply caches, but a storm ripped the *Aurora* from its anchor, marooning the sledding parties on shore. Aurora drifted for over 6 months before breaking free of the ice, stranding more of the crew. The *Aurora* had a damaged rudder and was forced to return to New Zealand for repairs before a rescue could be attempted. All but three of the stranded crew were eventually rescued, despite extreme weather and illness. Crew members were still able to carry out their mission, laying the depots for Shackleton's party.

However, on the other side of the continent, the tall ship *Endurance* also became icebound. The shifting floes crushed the *Endurance*, and it sank. Shackleton's 28 members survived in improvised camps on the ice for months, finally setting out to sea in three lifeboats. They arrived at the bleak Elephant Island in the South Shetlands, which afforded little more shelter than they had before. Realizing that their chances of being rescued from the out-of-the-way island were slim, Shackleton and five other brave men set out in one of the three lifeboats, the *James Caird*. In this 6.9-m (22.5 foot) open boat, they braved 800 miles (1290 km) of open sea before reaching South Georgia Island, where they assembled a search party and rescued every member of the rest of Shackleton's crew.

Shackleton and his team might have expected a hero's welcome upon their return, but timing is everything. World War I had broken in Europe, and their arrival was barely noted. Still, Shackleton's expedition is equated with bravery, ingenuity in the face of the harshest of conditions, and, appropriately enough, endurance. These days, the *James Caird* lifeboat is on exhibit at Dulwich College in London, Shackleton's old school, on a bed of stones from Antarctic shores.

As with most other groups, the Shackleton endeavor included unique approaches to travel and research. With each foray into the polar wastes, voyagers learned new tactics in transportation, new strategies of study. Sir Raymond Priestly summed up the diverse approaches to polar exploration well when he said, "For scientific leadership, give me Scott; for swift and efficient travel, Amundsen; but when you are in a hopeless situation, when there seems to be no way out, get on your knees and pray for Shackleton."

Shackleton's expedition marked the end of the Heroic Age of exploration, but as is often the case, it paved the way for future ventures. U. S. Rear Admiral Richard E. Byrd brought mechanized travel to the great southern continent in 1928, when he used airplanes, aerial photo reconnaissance, Ford-built snowmobiles, and a network of communications devices to an extent unmatched to that point. Byrd's group was the first in Antarctica to carry out regular wireless communications with the outside world. Douglas Mawson led a large team from Australia, Britain, and New Zealand on a project known as BANZARE (for British, Australian, and New Zealand Antarctic Research Expedition). BANZARE involved two separate trips, in 1929 and 1930.

Many expeditions followed, but public interest in funding single expeditions was waning. The stage was set for exploration on a larger scale, exploration that could only take place with the cooperation and resources of many nations. In 1958, modern Antarctic research arrived under the auspices of the International Geophysical Year (IGY), which took place in 1957–1958. The international scientific community proposed the IGY as a comprehensive global study of geophysical phenomena and their relationships to solar activity. Although research was to be carried out on a global scale, the poles (and in particular, Antarctica) were considered areas of prime importance. Twelve nations participated in IGY Antarctic programs.

The first step was to establish coastal research bases, which they did in the summer of 1955–56. Inland stations were set up just before the official IGY opening on July 1, 1957. IGY carried out a total of 18 months of intensive research, and built the first infrastructure for exploration of Antarctica, including the largest base at McMurdo Sound. In all, 67 countries established outposts across the continent.

The IGY ushered in a new era of international cooperation, resulting in a nearly globally accepted ban on military, mining, and oil drilling activities. The only drilling that takes place on the white continent is ice core drilling for research into past climate and geologic history. Science takes place unencumbered by national politics, as no one country can "own" Antarctic real estate.[6] Science teams often help each other and share logistics for carrying out work in the field. The southern continent serves – at least in theory – as a noble model for future planetary exploration.

Testbed for the Higher Frontiers

The hub of civilization on Antarctica is McMurdo Station. Surrounded by the extremes of polar wilderness, glacial floes, and some exotically deadly environments, McMurdo is a settlement where people recognize the hostile nature of their home. McMurdo's buildings, dormitories, laboratories, and science facilities must be structured to stand against the harsh elements of the polar extremes. Their architecture and day-to-day operations give them elements common to scenarios for future Martian colonies and, by extension, human outposts further out in the Solar System. Entries and exits are all arranged like airlocks, with outer and inner accesses. Inner doors are not open until the outer ones are sealed. Door handles are the horizontal type used on freezer doors, because winds can reach hurricane force and accesses must seal securely. The difference with these freezer doors, of course, is that the cold is being kept out, not in (Fig. 2.2).

Human explorers to other planets will set up staging areas that will serve extended exploration of the Martian or Europan wilderness. From a central, safe location, astronauts will depart for the poles, the great canyons, and the soaring volcanoes of the Red Planet, the tiger-stripe canyons, cryovolcanic summits, or vast fractures in the icy moons and dwarf planets. McMurdo, too, is the home base for an assortment of field camps and distant outposts. From the glacial valleys of the Transantarctic Mountains to the ice plateau surrounding the South Pole, remote camps and science stations dot the continent's landscape. Caches and fuel depots stand in strategic locations, lifelines between the outposts and the relative civilization of major bases such as the U. S. McMurdo, New Zealand's Scott, and Argentina's Belgrano bases.

---

[6] Although several countries lay claim to some locations.

Fig. 2.2 "Mac Town." MacMurdo base is, at its summer height, a bustling outpost of over 700 people. (Photo by the author)

Fig. 2.3 Scientists camp out on the slopes of Antarctica's active volcano, Mount Erebus, named after one of the Terra Nova ships. (Photo by the author)

Large bases such as McMurdo serve as the staging arena for many deep field camps, supporting research on the vast ice plains where meteorite hunts take place, on satellite camps of the South Pole, and in the famous McMurdo dry valleys, some of the most Mars-like places on Earth. The stations also function as training centers for anyone destined to go to those camps or to the South Pole Amundsen-Scott Station. One day, these lessons will be turned skyward as humans take to the outer Solar System (Fig. 2.3).

Modern Exploration

Polar research continues today, and much of it impacts – directly or indirectly – on the study of the ice worlds in the outer Solar System. Eventually, we will explore ice worlds with orbiters and landers, and both Europa and Enceladus have oceans that may be accessible by submarine probes (Titan certainly does; see Chap. 11).

Britney Schmidt, Assistant Professor at Georgia Tech's Earth and Atmospheric Sciences department, has been studying Antarctica and its surroundings as a testing ground for future exploration of ice worlds.

"For Europa and some of the other ice moons," Schmidt says, "the strongest similarities are deep under the ice. There is no perfect analog [on Earth] for what's going on in the ice moons. Ice in Antarctica is produced by compaction of snow, which we don't have on Europa. There, we have stuff that's growing from below, so the bottom of the ice is the most important."

Schmidt and her colleagues study the underside of the ice shelf, where the ice and water interact. They observe how the ice builds up, and the processes involved in its melting. And though the pressure ridges and fissures in sea ice may resemble the fractured surface of Europa or Enceladus, Schmidt suggests that Earth's sea ice is breaking up due to different forces. Terrestrial sea ice is comparatively thin, and it is filled with brine channels that weaken it. Schmidt explains, "It's not breaking up mechanically in the same way that the ice on Europa is. On Europa, the ice is at least 3 km thick, and probably more like 30. The 1- or 2-m thickness that sea ice is doesn't really begin to describe that. Just because it's shaped like stuff you've seen before doesn't mean it's the same."

Schmidt points to Europa's chaos regions, where ice has broken into rafts that have drifted and then frozen into place again. "What's happening in the chaos regions is a lot closer to ice shelf breakup. Those are pretty rare on Earth. Europa's case is really like iceberg calving, where thick ice is breaking because of fractures. On Earth, the interaction of fractures and a little bit of water is why that breaks up, but it's driven by the fact that it's melting, which is just not possible on Europa."

In other ways, the ice pressure ridges (outside of Scott Base, for example) are more similar, because the sea ice is shearing. The frozen sheet breaks, pushes up, and piles upon itself. Although we have no imagery of Europa with enough detail to see those kinds of features, Schmidt points out that, "We've seen Enceladus up close, and it looks really different from those. If you really look at it and measure it, you can see that it's completely different. You don't see these huge cliffs in the sea ice, you don't see boulders like you do on Europa. So you may see big patterns that look similar, but there's always something missing."

Far from being disappointed in those differences, outer planet experts are happy to have them as contrast between ice worlds and Earth's own processes. Differences can be as informative as similarities, and those differences continue to inform researchers on the nature of icy worlds.

Although the terrestrial oceans serve as a model for some outer planet sites, other modern explorers investigate regions farther inland. Many of the ice worlds lack any substantial rock on their surfaces, but the cliffs and canyons of Antarctica are informing biologists about life in extreme environments. The McMurdo dry valleys, for example, host many sites of interest for those studying life in extreme environments, along with their astrobiological implications. Sarah Stewart Johnson, an Assistant Professor at Georgetown University, brought a team to Antarctica for just such a purpose. Johnson researches the evolution of planetary environments. This work is especially important in the search for life on Mars and how life and its traces persist in extremely harsh environments such as Antarctica's dry valleys. Sarah and her team conducted a series of day trips to the dry valleys to collect samples. The team analyzed samples in the lab back at McMurdo but also in the field.

The team of biologists was interested in whether Antarctica's paleolakes (ancient lakes that are now dry) harbor "microbial seed banks" – caches of viable microbes adapted to past paleoenvironments – that may help transform our understanding of how cells survive over long timescales. The paleolake sites in the dry valleys afforded a perfect opportunity for the team to investigate questions about the persistence of microbial life, because these sites are thought to have remained geologically stable for millions of years. This geologic stability, together with the geographic isolation of the dry valleys and a steady polar climate, mean that biological activity has probably remained fairly stable over the last 1–2 million years.

Sarah and her team collected samples from multiple paleolake sites in the dry valleys. The sampling was exacting and physically taxing work, using sterile techniques at the field site and, back in the lab, extracting DNA from the organic material. Most exciting of all is that the team was conducting, for the first time, DNA sequencing in Antarctica. It brought with it a miniature, handheld DNA sequencer – called a MinION sequencer – from Oxford Nanopore Technologies. As DNA passes through an array of protein nanopores embedded in a special polymer membrane, the sequencer measures changes in current. Any of the nucleotides present will affect the electrical current. The software driving the sequencer operated from a Macintosh laptop.

Findings from their project will be important not only for cell biology and Antarctica microbiology but also for planetary science. Future explorers on a Mars base might be similarly equipped, analyzing organic material from Martian paleolakes. Will they find life? Will the DNA be similar to what we find on Earth?

And what about life within the frozen crusts and subsurface oceans of worlds such as Pluto, Europa, and Titan? Many biologists suggest that Earth's oceans were the cradle of life on this planet, and the ice worlds are awash with subsurface seas. NASA Ames' astrobiologist Chris McKay studies extreme biology in Antarctica, such as algal mats that live in high-pressure, low-temperature lakes. To his Antarctic studies he adds biology in other locations such as the Atacama Desert and Death Valley. He comments, "Earth is the big teacher. Earth teaches us about life. It teaches us about planets. It teaches us about how they work together. And so a lot of my time is spent going to places on Earth that are at the edges of the habitable zone, if you will."

McKay's travels have taken him to the driest deserts, the coldest climes, and the most desolate landscapes of our planet. "Going to the Antarctic dry valleys, going to the driest place on Earth, the Atacama Desert, the top of mountains on the equator, places like that, and trying to understand life on the edge, now, this is the edge literally. Not the cultural edge, but the literal edge of survival." Everything that astrobiologists think about in terms of searching for life, says McKay, "is rooted on the studying of Earth." McKay is singing Sarah Johnson's tune.

What is it, then, that draws the Schmidts, Scotts, and Shackletons to the great white wilderness? The lure is far more than national prestige or even scientific knowledge. The poles are a geographic singularity, a fixed location on a spinning globe. As Ernest Shackleton put it, the polar realms are "the end of the axis upon which this great round ball turns." They offer frozen wastes that are at once bleak and majestic. Even the light is different, a phenomenon that artists describe as the "arctic light."[7] Author Shannon Mullen says, "[T]he light is much more intense up here and everything looks different because of it. The Sun hasn't set in a couple of months, and you can see things much more clearly when it is light all of the time."[8] American writer Jon Krakauer agrees: "The thing that is most beautiful about Antarctica for me is the light. It's like no other light on Earth…You get drugged by it."

Today, a new frontier of ice and mountain faces us. It lies beyond the orbit of Mars, and its horizons are far more vast than those of the Harsh Continent. Antarctica and other polar regions have taught us lessons about living on – and under – the ice, in hostile and remote environments. For the short term, we have our eyes on Mars, but the ice worlds await.

---

[7] Not to be confused with polar lights, a term that refers to the aurora or "northern lights" and "southern lights" (aurora borealis and aurora australis).

[8] *See What Flowers* by Shannon M. Mullen, 2018.

A Survey Through Lenses and Spacecraft Eyes

3

Early Thoughts

The first ice worlds seen by a human were Europa, Ganymede, and Callisto. They were observed with their rocky sibling, Io, on January 7, 1610. Jupiter's moons drifted in the eyepiece of Italian observer Galileo Galilei as he studied the king of worlds. In his sketchbooks, Galileo noted that, "On the 7th of January, Jupiter is seen thus…On the 8th thus; it was therefore direct and not retrograde…The spacing of the 3 to the west was no greater than the diameter of Jupiter and they were in a straight line." Galileo was able to estimate the periods of the four moons at 42 h, 3.5 days, 7 days, and 16 days.[1]

His observations were remarkable, considering that the four "Galilean satellites" are barely visible in small modern telescopes or binoculars of 15× magnification. Galileo's telescope had a 20× magnification, but the astronomer's instrument contained optical imperfections in its lenses, including spherical and chromatic aberrations. With these flaws, Jupiter appears out of focus and surrounded by prismatic colors. Galileo was clever, partially alleviating these problems by stopping down his aperture (narrowing his scene). This decreased his field of view but also lessened the problems caused by Jupiter's brightness.

Galileo revealed his findings to the world in his *Sidereus Nuncius* (the "Sidereal Messenger") in March of 1610. The publication displayed some seventy of Galileo's drawings of the Moon's craters and phases, constellation diagrams, and his series of Jupiter and its star-like "attendants."

At almost the same moment in history, German astronomer Simon Maurius may have been peering at the Galilean moons, too. In the autumn of 1608, Maurius ran across an acquaintance who had found a curious artifact in nearby Frankfurt. John Phillip Fuchs, artillery officer and Lord Privy Councilor to the Margraves of Brandenburg-Ansbach, had been to a fair where a Dutch inventor was demonstrating a little tube that made the distant landscape "be seen as though quite near."

Fuchs and Maurius attempted to fabricate a telescope of their own, using lenses from a pair of eyeglasses, but could not get the instrument to focus. A year later, the newfangled inventions were becoming more common – and cheap – so Maurius was able to purchase a telescope for himself. In November or December of 1609, Maurius began to systematically observe Jupiter. He spotted the Galileans, but did not publish the observations right away. In 1614 wrote: "…I was at first much astonished; but by degrees arrived at the following view, namely, that these stars moved round Jupiter, just as the five solar planets revolve round the Sun."

Maurius began to record his observations on December 29, 1609, in the Julian calendar. This date corresponds to the Gregorian calendar date, which Galileo used, of January 8, 1610, which was actually the second night that Galileo documented Jupiter's starry companions.

Galileo mentioned the Jovian moons in an earlier letter dated January 7, so he probably spotted the four large moons at least one night before Maurius. Maurius did not publish his findings for several years. When he finally did, he gave recognition to Galileo, saying, "The first discovery of these stars in Italy is deservedly assigned to Galileo and remains his." Nevertheless, Maurius's 1614 writings are the first to detail the specific movement of the moons, and it was Maurius who first suggested the names that are now assigned to them, names of lovers of Jupiter.

Even as telescopes grew more powerful, the true nature of the Galileans eluded scientific inquiry. At its closest, the Jovian system is 588 million km away – nearly four times as far from us as Earth is from the Sun – and its moons are so small that no detail could be made out. But over time, astronomers crafted better telescopes, and patience paid off incrementally. Over 300 years after Galileo's discovery, Lucien Rudaux, director of the Meudon Observatory in Paris, wrote, "One sees that the principal satellites are bigger than our Moon and can rival in dimension certain planets.

---

[1] *Siderius Nuncius,* pp. 118–119.

M. Carroll, *Ice Worlds of the Solar System*, https://doi.org/10.1007/978-3-030-28120-5_3

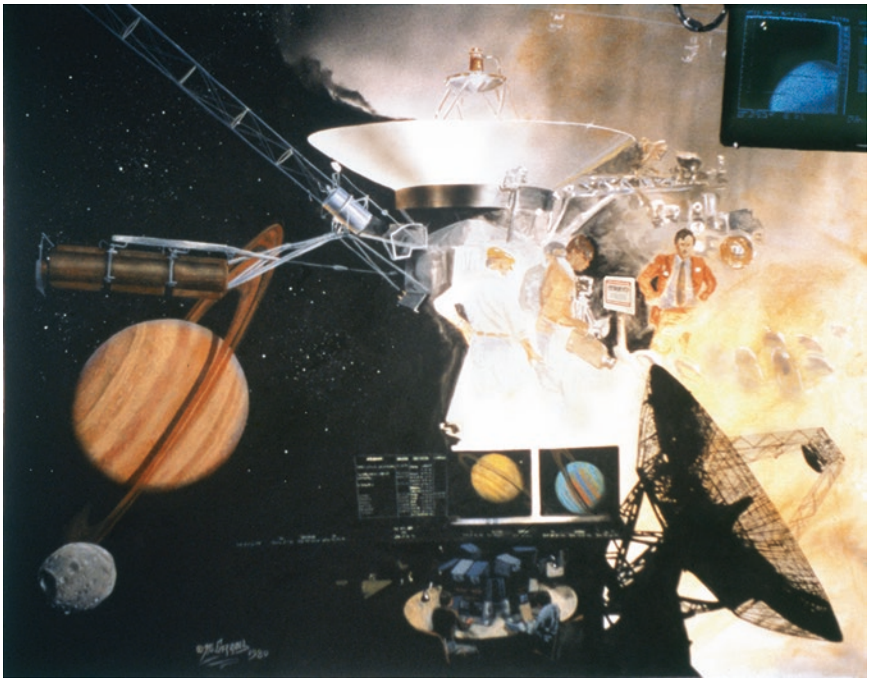


Fig. 3.1 *Two Worlds of Voyager*. Voyager 1 fades from the exotic environs of Saturn to a full-scale mockup at JPL's Von Karmann Auditorium in Pasadena, CA, where the control center for NASA's deep space missions lies. (Painting done from on-site sketches at JPL by the author)

The diameter of Ganymede is almost that of Mars and surpasses that of Mercury, the latter of which is just smaller than [Ganymede]."[2] Rudaux compared the Galileans to the planets neighboring Earth: "…small patches of gray which offer evidence of a naturally varied surface structure…like the Moon and the planets that we can see from Earth… Are we seeing accidents of color? Is it flat or rough? Is it sterile or not? In this regard, it is impossible to have a precise idea."

In addition to being a careful observer, Rudaux was an accomplished oil painter. He could not resist painting Jupiter floating above the landscapes of some of its moons. Like modern astronomical art, these early pieces of space art are constrained by the science of the time, true to the contemporary knowledge of the scientific community.

Early observers noted that the Galileans all orbited Jupiter in the same direction as Jupiter's spin. When viewed from above the North Pole, most major objects in the Solar System orbit the Sun in a counterclockwise direction, and they rotate in the same direction. A planet moving in this direction is said to travel with a prograde motion. The rare examples of large objects moving in the opposite direction have a motion referred to as retrograde.

Even at the turn of the twentieth century, the ice worlds of the outer Solar System had captured the imagination of the popular press. Magazines such as *Amazing Stories, Astounding,* and *Weird Tales* blossomed with stories of explorers braving the jungles of Europa, or of maidens awaiting a rescuing Earth hero to descend on a moon of Saturn. Although scientific accuracy was not a major concern of the editors, they sensed a popular interest in all things of the distant planets beyond Mars.

The Galileans and the First Hints of Ice

Twentieth-century astronomers refined the sizes and masses of the Galilean moons, and their painstaking studies began to yield hints at the nature of Jupiter's four largest satellites. Their orbital motion led to estimates of their masses, and studies of their brightness, combined with mass estimates, yielded some idea of their true sizes and what they might be made of.

In the 1920s, British astronomer Harold Jeffreys was first to realize that Ganymede and Callisto, less dense than the other Galileans, might contain a large component of ice mixed with rock. The inner two, Europa and Io, seemed dense enough – similar in density to Earth's own Moon – to be made mostly of rock and perhaps metals. His insights into the fact that planetary bodies might contain layers of rock and ice opened the worlds to new possibilities. Was it conceivable that some moons out in the darkness were composed mostly of frozen water?

Still, the details were slow in coming. The popular 1958 children's book *Exploring the Planets*[3] could only describe colorful Io as "most likely a rocky globe with metals scattered through it." The book's author, Roy A. Gallant, summed

---

[2] *Sur Les Autres Mons*, or *On the Other Worlds* originally published by Auge, Gillon, Hollier Larousse (Librarie Larousse, Paris) 1937. Reprinted 1990.

[3] *Exploring the Planets* by Roy A. Gallant, Doubleday & Co, 1958.

Fig. 3.2 The distance from Earth to the Moon (240,000 miles/384,400 km) at the same scale as the distance from Jupiter to Io. Below, the distances of all four Galileans to Jupiter, to scale. Io's distance is represented by red, Europa blue, Ganymede green, and Callisto brown. (Art by the author)

up the scant details known of the other Galileans: "Europa… an excellent reflector of the Sun's light [that] sometimes appears to wear a dark belt about its equator and to show light polar regions. Generally the satellite appears white…" Ganymede was seen as resembling Mars, with dark patches, canal-like markings, and bright polar caps. Gallant added, "Like our Moon, Ganymede must be a freezing cold world with an extremely thin atmosphere," a conclusion not far from the truth. Gallant reported that contemporary astronomers assumed that Callisto's dark appearance indicated that the large moon was different from its companions. "Some astronomers regard it as a solid ball of ice. Others say that it is an ice-covered rock core." Well into the 1970s, many researchers thought the surfaces of the Galileans to be cratered and barren. A popular 1965 book declared, "[Ganymede's] terrain is probably very similar to our Moon's…with frozen gases encrusting the rocky plains."[4]

Astronomers had other tools and techniques to add information to their limited view. With increased telescopic power, they were able to estimate the temperatures of the satellites. Temperature could provide insights into the nature and density of surface materials. The way those materials acted in sunshine vs. shadow also afforded clues.

The largest and easiest moon to study was Ganymede. As Jupiter's shadow fell across the moon, temperature changes indicated that the surface was a poor conductor of heat. This, combined with other hints, led some researchers to conclusions outlined in a 1979 book by Werner Von Braun and Fred Ordway. Just months before the Voyager 1 reconnaissance of the Jovian system, the authors made the prescient statement that "the satellite might have a crust of ice covering a satellite-wide ocean of water and ammonia, and below this deep ocean a core of rocks and iron oxide."[5] The idea of a subsurface ocean on Ganymede was confirmed many decades later (see Chap. 6). Further study of Jupiter has unveiled a total of 75 other moons, many of them small, rocky, irregular satellites (Fig. 3.2).

Sights to See

Jupiter's Galileans are among the largest moons in our planetary system. With its diameter of 5268 km, Ganymede is the largest natural satellite, surpassing the planet Mercury. Callisto, Io, and Europa decrease in size, with Europa measuring 3100 km (compared to Earth's own Moon at 3474 km; see Fig. 3.10). Visiting any one of them would afford dramatic

---

[4] *The Moon and the Planets* by Joseph Sadil; published by Paul Hamlyn, London, 1965.

[5] *New Worlds: Discoveries from Our Solar System* by Von Braun and Ordway. Anchor Press, 1979.

views of the other three, along with Jupiter. In fact, writing for *Science Digest* in 1980, Isaac Asimov went so far as to say that "…if we could imagine ourselves on the surface of any of these worlds and somehow protected from the harsh conditions, it would probably not be the surfaces that would hold our attention most; not the volcanoes, not the craters, not the cracked glaciers. It would be the skies."

Because the Galileans are tidally locked, keeping the same face toward Jupiter at all times (as our own Moon does with Earth), their orbital period around Jupiter is identical to the length of day. Each turns once for every time it circles the parent planet. This tidal locking is common to all large moons and most small ones. (See "How to tidally lock a moon" below.) This has an interesting effect on the view of Jupiter from its Galilean satellites. Wherever Jupiter appears in the sky, it will seem to stay in one place while the Sun, sibling moons and background stars wheel across the firmament. For Callisto, this day cycle lasts 16.69 Earth days. The time from sunrise to sunset stretches for 200 h. And although blindingly bright, the Sun would seem tiny, only a fifth the diameter it appears from Earth. Its brightness drops to 1/25 of what Earth-bound observers see.

From Callisto, mighty Jupiter is 1,885,000 km away, over four times the distance from Earth to the Moon. But the planet is so large that even from Callisto's distance, Jupiter spans a diameter nine times that of a full Moon in Earth's sky. And, as Asimov points out, "Jupiter is not only larger than the Moon from left to right, but from top to bottom as well. Jupiter's area, as seen from Callisto, is therefore nearly 70 times the area of the Moon as seen from Earth." Jupiter's constantly changing belts and zones, its lightning and aurorae, its dramatic billowing storms and violent jet streams would parade constantly across the face of the king of worlds, easily visible to any Callisto traveler.

Jupiter also goes through phases, from crescent to full to gibbous. When the Sun tracks across the side of the sky opposite to Jupiter, Jupiter stands at full phase. As the Sun drifts closer to the planet, Jupiter begins to wane into a gibbous phase, then to a crescent. Finally the Sun will disappear behind the planet in eclipse. At the same time, the other Galileans each move from one phase to another, but because each is in a different part of the sky, their phases vary. Sadly, only half of Callisto gets to see this Jovian show. Because it is tidally locked, one hemisphere stares into space, away from Jupiter. Any inhabitants there would never guess that a gigantic planet existed beneath their feet!

The scene from the farthest Galilean offers a panoramic vista of the entire system of giant moons. The more inner Galilean satellites trundle back and forth, each crossing in front of Jupiter, moving to the far extent of its travel, and then diving back in to disappear behind the planet before reappearing again. The next moon in, Ganymede, appears slightly smaller than a full Earth Moon, with Europa and Io nearly star-like at their farthest distances. But each of the Galileans has its own view of Jupiter and its siblings. In the case of Ganymede, Europa, and Io, the skies are filled with the circling moons, as some appear to move through the sky opposite to Jupiter. And from the Galilean nearest Jupiter, the planet stretches across a span equal to 39 full Moons over Earth (Fig. 3.3). The sky above the Galileans is, as Asimov aptly put it, "enormously impressive, and so fascinating in its variety…"

How to Tidally Lock a Moon

With one exception,[6] all of the major moons in the Solar System rotate once for each time they orbit around their planet. This synchronous rotation means that the satellites keep the same face toward their parent world as they circle it, a phenomenon called tidal locking. A moon becomes tidally locked when its rotation rate is dampened by the gravity of its parent planet. As time goes on, the gravity from the parent planet slows the spin of the moon, so that eventually the moon turns once for each orbit. Earth's Moon is tidally locked, so that we can only see one face from Earth. Our Moon is also acting upon Earth; given enough time, our planet would also be locked to the Moon. We see this case with Pluto and its moon Charon, in which both bodies keep one face continually turned toward the other.

Saturnian Moons

While many observers were beginning to grasp the nature of the Galileans, some were scrutinizing the frozen moons of more distant planets. In the early years of the seventeenth century, Galileo Galilei turned his telescope toward Saturn. In the tiny instrument's eyepiece, he had a difficult time discerning just what he was looking at. Saturn seemed to be bracketed by two blobs of light. Even more baffling, these "appendages" seemed to fade and disappear, then reappear again. Galileo declared these as moons. Others theorized that these objects were extensions of the planet itself, like the handles of a coffee cup. But in 1655, Dutch astronomer Christian Huygens was able to tell that Galileo's "moons" were actually a disk of material surrounding the planet. This disk seemed to fade in and out from Earthly view as Saturn rocked up and down like a spinning top, its rings appearing to open up and then turn edge on, disappearing from our perspective. So these "ears" of Saturn first glimpsed by Galileo were not moons at all but rather a disk of material

---

[6] The exception is Saturn's moon Hyperion, which bobs significantly from side to side as it circles the ringed gas giant. Pluto's minor moons also travel in chaotic orbits, but they are comparatively small.

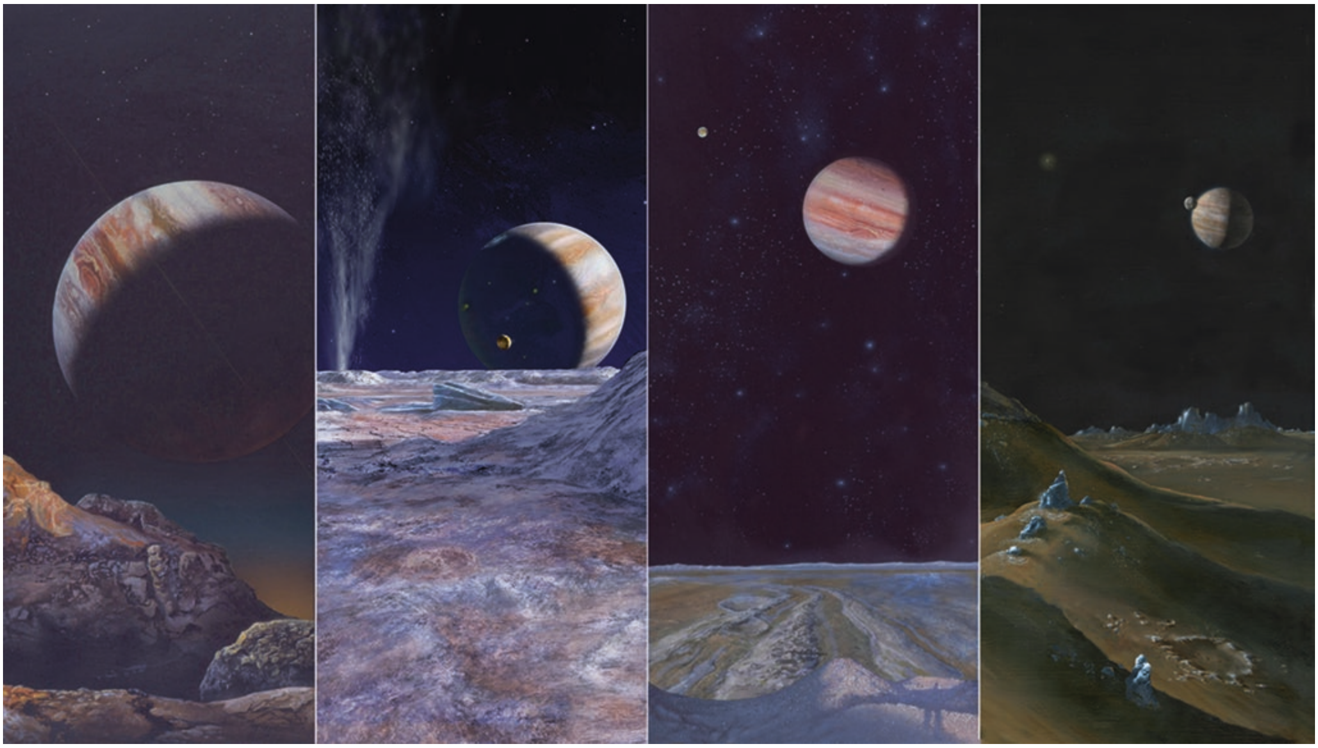


Fig. 3.3 Jupiter seen from the four Galilean satellites. From Io (far left) Jupiter would stretch as far across as 39 full Moons in Earth's sky. The view from Europa shows Io – in front of Jupiter – as about the size of the full Earth Moon. From Ganymede, we see Europa left of Jupiter, and from distant Callisto we see Ganymede on the left edge of Jupiter, with Io to the far left. (Art by the author)

surrounding the planet. Huygens did discover a moon of Saturn – its largest – planet-sized Titan. Huygens spied the moon through a custom-made telescope with an extremely long focal length, the best instrument of its day.

Huygens had been thinking about the moons of the outer system for a long time. In 1698,[7] he conjectured about conditions out there, reasoning that since Earth and Jupiter "have their water and clouds," the other planets should also. But Huygens added: "…this water of ours, in Jupiter or Saturn, would be frozen up instantly by reason of the vast distance of the Sun. Every Planet, therefore, must have its waters of such a temper, as to be proportion'd to its heat." Huygens' statement anticipates the existence of ices other than water ice. In fact, we find frozen forms of methane, carbon dioxide, nitrogen and other super-chilled solids on the moons and dwarf planets of the outer Solar System.

Huygens went on to speculate specifically about the moons of the outer planets.

> [A]ll the Attendants of Jupiter and Saturn are of the same nature with our Moon, as going round them, and being carry'd with them round the Sun just as the Moon is with the Earth.…[W]hatsoever we can with reason affirm or fancy of our Moon (and we may say little of it) must be suppos'd with very little alteration to belong to the Guards of Jupiter and Saturn, as having no reason to be at all inferior to that.

After the discovery of Titan, astronomers began to see other moons circling the Ringed World, and there was something odd about them. Two of Jupiter's Galileans were the size of Earth's Moon (3474 km across), and two were larger, more like Titan (5150 km). But aside from Titan, the moons of Saturn measured much smaller than the smallest Galileans. The next largest to Titan was Rhea, with a diameter of 1532 km. The balance of the seven major moons stepped down to Mimas, whose diameter of 396 km was the smallest of Saturn's primary family.[8] These moons constituted a new class of moon, a "mid-sized" version of what was known before.

Many of Saturn's mid-sized moons were discovered by Giovanni Cassini (who also discovered the ring gap now named after him). From 1671 to 1674, Cassini logged the discovery of Iapetus, Rhea, Dione, and Tethys, all intriguing – and unique – ice worlds. Cassini noticed that the moons had one important thing in common; they seemed to orbit in the same plane, and they all traveled in a prograde motion, as did the rings and Saturn itself. This provided a hint that the moons formed as part of Saturn's system, rather than wandering in from afar. This, coupled with the fact that all the planets circled the Sun in a prograde direction, gave the

---

[7] *The Celestial Worlds Discover'd: or, Conjectures Concerning the Inhabitants, Plans and Productions of the Worlds in the Planets* by Christian Huygens, 1698.

[8] Of Saturn's 62 confirmed moons, 49 have diameters less than 50 km.

French mathematician Pierre-Simon Laplace the idea that all the planets coalesced from one giant disk of gas and dust, a disk that was initially spinning in the same direction. Laplace reasoned that if such a disk cooled and began to condense into clumps, those clumps would tend to spin in the same direction. These primordial knots of material became smaller spinning disks, leading to planets with families of moons orbiting with the same spin. As it turns out, Laplace was right. Not only do our computer models confirm it, but images from observatories such as the Hubble Space Telescope have spotted such clouds surrounding infant stars, planetary systems in the making.

Cassini logged an interesting observation about Iapetus. The moon seemed to get brighter and dimmer as it circled Saturn. It did this in a very regular fashion, with the moon being always dimmest at a certain point in the orbit. Cassini realized that if Iapetus was tidally locked (Cassini had only our Moon as an example), then the leading hemisphere (the portion facing forward in the direction of travel) must be much darker than the trailing hemisphere. He was correct, and the two-toned moon stands as one of the most dramatically hued of any celestial body in the Solar System.

Saturn's mid-sized icy satellites come in pairs. Closest to Saturn, Mimas and Enceladus check in with diameters of roughly 500 km. Next out are Tethys and Dione, measuring about 1000 km. Rhea and Iapetus round out the middle moons at about 1500 km across. Enceladus glistened in the telescopes of astronomers and is the brightest object in the Solar System (aside from the Sun, which burns with its own light). The spectrum of most of these moons[9] shows that their surfaces are covered in water-ice, probably with a few other things (such as ammonia, methane, and carbon monoxide) thrown in for good measure. But aside from these general facts, not much could be discerned until the advent of the Space Age.

Moons in the Outer Darkness

Still better instruments and observational techniques brought more discoveries of tiny satellites orbiting the giant planets. Six years after William Herschel discovered the ice giant planet Uranus, he spotted its two largest moons, Titania and Oberon, on January 11, 1787.[10] As time went on, observers could see that the moons weren't circling the planet as expected. They seemed to be at nearly right angles to the direction that they should have traveled had they been in Uranus' equatorial plane. In fact, they are in the equatorial plane, but Uranus is tipped over in such a way that it "rolls" around the Sun.

The path of the Uranian moons gave astronomers their first evidence of the planet's extreme tilt (at 98°, as compared to Earth's axial tilt of 23.5°). This crazy slant means that the Sun appears directly over the north pole of Uranus and its major moons during one season of the year; half a Uranian year later it looks down directly on the south pole. In spring and fall, Uranian days last 17 h and 14 min, with more Earth-like sunsets and sunrises.

William Lassell found Ariel and Umbriel over 60 years after Herschel's discoveries, in 1851. Nearly a century would pass before the telescope of Gerard Kuiper revealed the existence of a fifth major satellite, Miranda (in 1948). These moons are named after characters in the writings of Alexander Pope and William Shakespeare. The other moons – many of them rocky interlopers captured long ago – showed up during the Uranus flyby of *Voyager 2* in 1986, and later by Earth-based observatories and the Hubble Space Telescope. Uranus has 27 confirmed moons. An inner set of 13 are small and nearly black, and seem to be related to the rings of the planet. They orbit in the same plane and in the same direction, and their composition seems similar. Nine irregular moons orbit at great distances, many in retrograde directions, and are probably captured objects, perhaps from the Asteroid or Kuiper Belts. In between these groups orbit the five major moons, and these are the ice moons of the great ice giant. In size, they are similar to Saturn's mid-sized moons.

At the outer fringes of our planetary system lies azure Neptune. Discovered in the fall of 1846, this second ice giant holds 14 known moons in sway. The largest is a remarkable little world called Triton. Triton is large as moons go. Its size is surpassed only by Earth's Moon, the Galilean satellites and Titan. Even the early observers knew that Triton was special. Although it was as large as the main moons of other worlds, it had a retrograde orbit around Neptune.

Its orbital direction and inclination (tilt) implied that its origin was from more distant realms, perhaps beyond the orbit of Neptune. Years later, astronomers defined the Kuiper Belt, a vast donut of icy comets and bodies, some of which may be larger than Pluto.

Triton is about the size of Pluto, and for some time researchers believed that the two would be quite similar in nature. Nothing could be further from the truth. Humanity finally got to see the remarkable dwarf planet Pluto in 2015 with the reconnaissance of the New Horizons spacecraft. New Horizons revealed a dynamic ice world of glaciers, mountains, canyons, bizarre "bladed" terrain, a complex atmosphere, and perhaps subsurface seas of slush. At about the same time, planetary dynamicists – citing the likelihood of many Pluto-sized worlds in the Kuiper Belt – lobbied for Pluto to become the first of the "ice dwarfs" or "dwarf planets," demoting it from its place among the traditional planets of the Solar System. The debate about Pluto's technical status continues today, but its place among the most vibrant and dynamic ice worlds remains (see Chap. 9).

---

[9] The exception being the dark hemisphere of Iapetus, as we will see…

[10] He also believed he had discovered four more, but it is likely that these were background stars. They do not equate to any of the moons confirmed later.

Arrival of the Robots

The nature of Jupiter's moons seemed sure at the opening of the twentieth century. Our Moon was about the scale of Europa and Io, so it made sense that those distant moons would bear similar faces: cratered, dead landscapes of ice rather than rock. Among planetary modelers, a consensus had grown that the Galileans were a mix of rock and ice, but how that mix settled was under debate. Did these satellites begin with enough heat to differentiate, so that the heavy rock sank to form a stony/metallic core, or were they a more homogeneous mix of rock and ice? If the latter were true, the moons would show little in the way of geologic activity, for example, no canyons, uplifted mountains, or volcanoes. This was largely the view of Earth's own Moon, although with more advanced studies, this view, too, would change (Fig. 3.4).

The idea that the moons of the gas and ice giants are similar to our own Moon carried well into the decade of the 1970s.

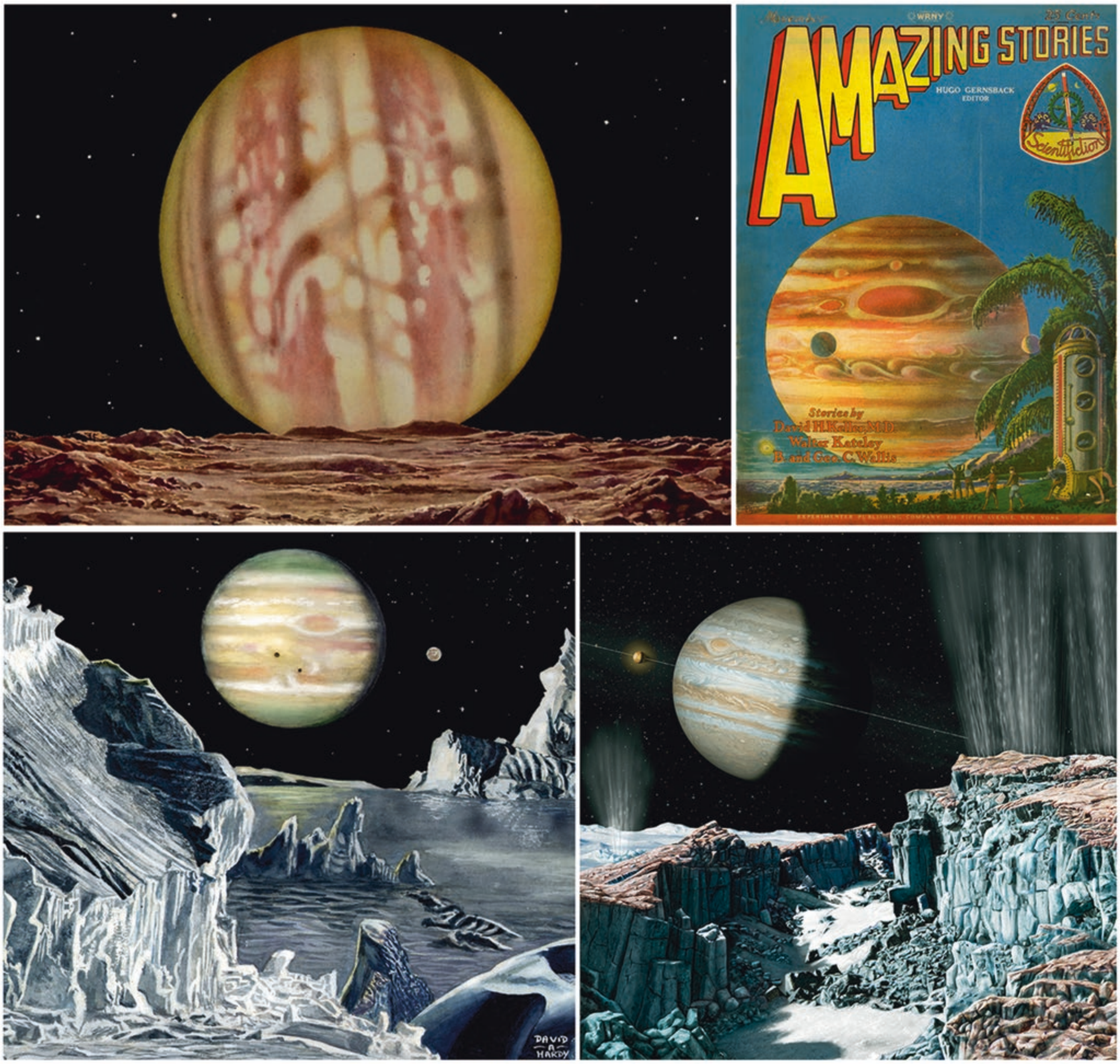


Fig. 3.4 Our changing view of the Galileans: (*top left*). View of Jupiter from one of its moons, painted in the early twentieth century by Lucien Rudaux; (*top right*); 1928 painting of Europa, complete with palm trees, by Frank R. Paul, *Amazing Stories*, Experimenter Publishing Company, LLC (Image used with the acknowledgment of the estate of Frank R. Paul); *Lower left:* the frozen surface of Europa by David A. Hardy, ca. 1952, and *(lower right)* modern view of Europa reflecting recently discovered plumes, by Marilynn Flynn. Unless noted, all art copyright the artist.

The first close reconnaissance of the Jupiter system, by *Pioneers 10* and *11,* shed little light on the Galileans. Flying by in 1973 and 1974, their paths kept the twin spacecraft at great distances from the moons, and their primitive imaging systems were able to resolve only the grossest of details. The Pioneers were spin-stabilized; rather than keeping their orientation with small thrusters, the craft spun like a top to remain stable. This meant that instruments were in constant motion, making high-resolution imaging almost impossible. Because of the spacecraft spin, the images were built up of thin, overlapping strips scanned as the spacecraft turned. A typical color photograph took 30 min to scan. Still, the tiny robots netted the first Galilean close ups, an historical marker.

Pioneer 10 missed the remarkable Io completely, its photopolarimeter temporarily blinded by Jupiter's intense radiation. Months later, *Pioneer 11* was able to image the colorful moon from 327,000 km. Its viewpoint was directly above the orange polar region. The equator appeared to be swathed in a white band. Io continued to perplex researchers, with its brightly hued surface and a complete lack of water in its spectrum. Pioneer's best resolution of the mystery moon was 376 km per pixel. It could not resolve much detail, but did encounter the great Io torus, a donut of gas encircling Jupiter at Io's orbit.

Pioneer 10 returned the only image of Europa. The snapshot shows very little color variation. A dark region blankets the center of the half-illuminated sphere, something Lucien Rudaux had observed at his telescope nearly half a century earlier. Pioneer did reveal a highly reflective surface, confirming preliminary estimates that Europa's surface was covered in water-ice. But in the ultraviolet, *Pioneer 10* spotted something important – a cloud of hydrogen and oxygen molecules at the same distance from Jupiter as the orbit of Europa. This finding bolstered the idea that Europa was covered in ice. Researchers projected that the cloud resulted from the sputtering (blasting from the surface by micrometeorites or solar wind) of molecules from the surface, but future discoveries would afford other possibilities.

The Pioneers transmitted only two images of Ganymede. Their views show a low-contrast, umber color. With a dark circular region slightly off-center and a bright polar cap in the north, Ganymede reminded some of Mars. But the Pioneers could supply only tantalizing hints of surface features. The best resolution of Ganymede came in at 161 km.

Murky Callisto, the darkest of the Galileans, completed the encounter imaging in a distant frame resolving surface objects 391 km across. Small variations in both color and brightness suggested a lighter region near the equator, but not much else. In all, the two Pioneers shuttered over 200 images of the Galilean satellites. Flight engineers also teased out a refined approximation of moon densities, revealing something about their family history stretching back to when Jupiter formed from a vast cloud of dust, ices, and gas. The two Galilean moons closest in to Jupiter, Io and Europa, coalesced in a portion of the cloud ruled most by rocky material. These inner Galileans collapsed into spheres with dense, large rocky cores and, in the case of Europa, a relatively thin water/ice crust. These are Jupiter's version of the terrestrial planets. But farther out, the cloud's makeup shifted to more ice and volatiles. In Jupiter's cool outer cloud, where there was more water, Ganymede and Callisto formed as larger, less dense worlds, apparently with small stony centers and deep ice crusts. These four satellites offer their own echo of our Solar System: inner rocky "terrestrial" worlds and lighter, icy outer ones.

Our understanding of the general nature of Jupiter's major moons was growing. For any surface details, and a better understanding of their internal makeup, scientists would have to wait another 6 years for the Voyager encounters. But before those encounters, Pioneer 11 had one more stop: the icy moons of Saturn (Fig. 3.5).

Pioneering Titan

Pioneer 11's distant glimpse of Titan capped centuries of frustrating observation. Dutch astronomer Christiaan Huygens first spotted the moon as a star-like orange object accompanying the ringed giant. His observations, beginning in March of 1655, yielded enough information to compute the satellite's orbit and to measure its brightness. From these, observers could come to a rough estimate of Titan's size. But although Titan is a behemoth among moons, its distance – over a billion kilometers away – masked much of its nature for some 300 years. Then, in the 1940s, Gerard Kuiper, also Dutch,[11] realized that Titan had an atmosphere. Kuiper carried out a systematic cataloging of the spectrum (of reflected light) of major planets and moons. The spectrum of the gas giants included the "light fingerprint" of methane, and so did Titan. Kuiper concluded that Titan must have an atmosphere. If that atmosphere was dense and foggy, Titan might be smaller than it appeared through the telescope. If it was clear, observers were seeing the surface of the moon, meaning that it spanned a diameter toward the larger estimates.

How much atmosphere enshrouded Titan was anyone's guess, and that was a problem. The detected methane might be on its own, but it was likely mixed with other gases. Estimates ranged from near-vacuum to an Earthlike pressure with a blue sky to a dense blanket like that of Venus.[12] The majority view had Titan's methane air as a low-pressure affair, perhaps akin to the top of Earth's highest mountains.

---

[11] Although he worked in the USA.

[12] More specifically, pressure estimates ranged from 20 millibars to 20 bars (Earth's sea-level pressure is one bar).

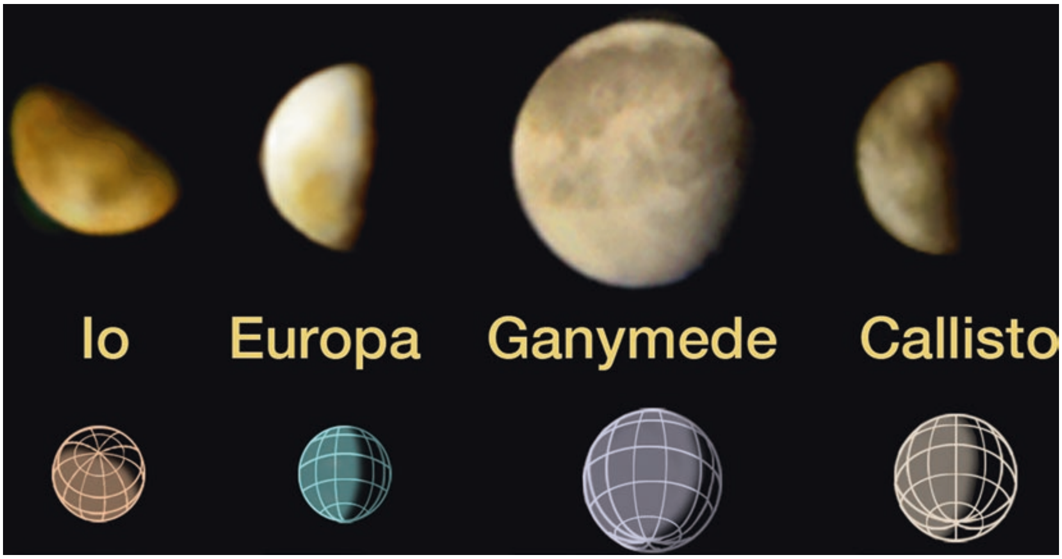


Fig. 3.5 The best images of the Galilean satellites taken by Pioneer 10 and 11. The approximate phase angles of each moon are shown below. (Images courtesy of NASA/Ames. Processed by Ted Stryk.)

The big variable was nitrogen. To study Titan through a telescope, one must look through the atmosphere of Earth, and that atmosphere is mostly nitrogen. Our own air blinds telescopes from detecting nitrogen in the spectrum of other worlds. Could Titan have a large amount of nitrogen, enough to give it a substantial surface pressure? Or were Earth's own gases the only real nitrogen being seen in the mystery moon's spectrum?

Kuiper was not the only one to suspect that one or more of the moons in the outer Solar System might have atmospheres. In the decade of the 1930s, Sir James Jeans estimated that if a moon had sufficient gravity, and its temperatures were low enough to not disturb the molecules of gases, it could maintain a veil of atmosphere over the lifetime of the Solar System. Titan was a perfect candidate, with 1/8 the gravity of Earth and a chilled, quiet environment. Ground-based measurements of Titan's polarization in its atmosphere showed that its skies were filled with more than just gas. Particles floated through its atmosphere. What were they made of? Did they form layers of haze or billow in clouds, or were they evenly mixed throughout?

Observers could tell that Titan weighed in at a class similar to Ganymede and Callisto (in both density and size), but its specific size was in question. How much of its visible disk was fuzzy atmosphere? Titan might be the largest moon in the Solar System, surpassing not only Ganymede and Callisto but also Mercury itself. But it might also be a shrunken dwarf of a world, hiding under an extended blanket of amorphous gases.

By the 1970s, atmospheric scientists had put forth several models of Titan's atmosphere. The one gaining the most traction was offered by the University of Arizona's Donald Hunten. Hunten's working hypothesis assumed an atmosphere dominated by nitrogen, with 7% or less of methane. What intrigued planetary scientists was that if Hunten's model was close, then conditions at the surface of Titan were at the "triple-point" of methane, the point at which methane could exist concurrently as a gas, a liquid, and a solid (ice). If so, methane might play a similar role in Titan's environment to that of water on Earth. Clouds of methane might condense into rainstorms, feeding rivers and even seas of liquid methane. Some estimates even predicted a global ocean of liquid methane covering any solid surface below. But Titan's surface nature depended on its diameter. A small moon beneath all that atmosphere would experience high surface pressure and relatively warm temperatures (warm for an ice moon, that is). A larger moon might be cocooned by a thin, even Mars-like atmosphere. Hunten's numbers gave an estimate of a surface pressure twice that of Earth at sea level, with temperatures hovering around a chilly –186°C.

In the waning days of summer 1979, Pioneer 11 imaged Titan five times. Analysts combined the quintuplet photos to create a synthesized image. Pioneer's distance to the mystery moon was over 100,000 km, and the polarimeter imaging system could not resolve much detail. Additionally, since Titan had never been seen from Pioneer's viewpoint (nearly polar), engineers had no guide from which to estimate its true color. The color image was based on imaging results of Saturn's color, which was well known from telescope observation. Engineers came remarkably close to the reality seen in later missions. Still, as a NASA release[13] put it, "No surface

---

[13] NASA SP-446, 1980.

details are apparent because of the distance of the spacecraft from Saturn. Titan appears to be covered by clouds of which no specific structure or patterns are visible." It was the best that Pioneer technology could do. Scientists eagerly awaited the arrival of Voyager.

Long-Distance Voyagers

After the success of the Pioneers, engineers fashioned two larger Voyager spacecraft. Carrying more advanced experiments, the robots were far more capable than their Pioneer cousins. Rather than spinning for stability, as the Pioneers had, each Voyager was three-axis stabilized, using small hydrazine thrusters to orient itself in three-dimensional space. This enabled the craft to take more detailed images and measurements (although for radiation studies, a spinning platform is actually preferable). Like the Pioneers, the Voyagers were powered by radioisotope thermoelectric generators fueled with plutonium.

The launch of the Voyager duo happened to coincide with a rare planetary alignment. NASA dispatched the advanced craft to the outer Solar System during a narrow launch opportunity at the end of the 1970s. At the time, the alignment of the outer planets enabled the Voyagers to use Jupiter as a gravity slingshot to the other planets of the outer Solar System, cutting flight times by many years. This alignment involving the four giant worlds would not occur again for another 175 years.

Voyager 1 launched on a trajectory that would carry it past Jupiter and on to Saturn. In addition to studying the four Galileans at various distances, its mission featured a close study of Saturn's foggy moon Titan. If the first spacecraft survived, Voyager 2 would be targeted to do a marathon tour of the outer system, passing Jupiter and Saturn before traveling on to Uranus, and perhaps even Neptune, over the course of a long decade.

The Voyagers at Jupiter

The Voyagers fundamentally changed more than our grasp of planetary science; they transformed our general understanding of all the ice worlds. Instead of cold, dead globes of crater and frost, the twin craft revealed diverse worlds of mountains and canyons, volcanoes and tectonic ridges, and discoveries that baffled, entertained, and energized even the most jaded of planetary scientists. What could be energizing these tiny spheres of ice and rock? JPL's Ed Stone said, "[Voyager's initial discoveries were] just a precursor to the kind of discoveries Voyager was going to make, time after time. Suddenly things just changed your whole perspective. Your terracentric view was just that; it was based on things we thought we knew about the Earth, and we extrapolated all that, but it turned out that there was a much broader set of objects out there than our terracentric experience prepared us for." Planetary geophysicist William McKinnon, fellow of the McDonnell Center for the Space Sciences at Washington University, describes the great paradigm shift triggered by the Voyager flights. "Voyager gave us our first look at icy satellites. Simply going out there led us in other directions of thinking."

One of those new directions had to do with a theoretical force called tidal heating – or tidal friction – something never seen in action before (we will discuss this important concept more in Chap. 6). Interior heating of the Galilean satellites was being generated by the gravitational taffy-pull of neighboring moons, and by the gravity of Jupiter itself. The results of tidal heating were more remarkable than projected by theorists, creating a spectacle of geological forms far more varied than the anticipated cratered landscape of dead worlds.

As researchers struggled to understand the strange properties of Io, they began to detect high temperatures on its surface. Voyager instruments indicated that Io has 100 times as much heat flowing from its surface as Earth does. "The piece of the puzzle we were missing was the heating process," says Voyager imaging scientist Torrence Johnson. "Stan Peale suggested tidal heating, but even his team didn't think Io would be cooking enough for active volcanism. Once the data was there, everyone rapidly converged on the 'Voyager era paradigm' (of tidal heating)."

"There had been predictions of tidal heating and what it could do," McKinnon remembers, "but we'd never seen anything like it, and no one had a real appreciation of its power."

That power was first glimpsed by a Voyager navigation officer. The Voyager imaging team (along with all the other instrument teams and flight engineers) had been operating on little sleep and a lot of adrenaline for over a week. The four large moons of Jupiter, expected to be cratered worlds, instead displayed shocking landscapes of fractured ice, flowing rocky plains, multicolored spots and, in the case of Io, absolutely no craters. For the first time in many frantic days, imaging team lead Bradford Smith headed home for some well-deserved rest, his head full of Jupiter's swirling clouds, dancing energy fields, and menagerie of moons.

In a brief lull toward the end of encounter activities, senior engineer Linda Morabito examined several overexposed images of stars designed to aid in confirming Voyager's exact location and trajectory. It was a critical analysis to keep the spacecraft on track for its next destination, Saturn. One of the images happened to include the pizza-colored moon Io. The navigator did a double-take. Io, a moon with no atmosphere, seemed to have a giant cloud hovering above it. Morabito, an astronomer by training, recognized the feature as a probable volcanic plume, but the titanic "cloud" rose over 200 km above Io's surface. Nothing like it had ever been seen.

Fig. 3.6 Concepts of Callisto before (left) and after spacecraft reconnaissance. (Art by the author)

After some soul-searching, Morabito decided the news was too big to wait, so she called the home of her sleeping imaging team leader. Smith rushed back to the Jet Propulsion Laboratory to see the image (in those days, there was no email or cell phone coverage). Over the coming days, team members began searching for other plumes by bumping up the exposure and contrast in images. They found several.

The surface of Io, a rocky moon battered from within by volcanism, dramatically displayed the power of tidal heating. Brad Smith quipped: “I’ve seen better looking pizzas.” But the question was, what would that same force do to the other Galileans, moons ruled more by ice than rock?

Callisto, far from Jupiter, showed a heavily cratered, quiescent face. But next in, Mercury-sized Ganymede had surface features torn by canyons, folded by ridges, and flooded from within. Craters were scarcer, and often faded into “palimpsests,” ghost craters, as the soft ice relaxed and their topography slumped into the surrounding landscape. Europa, pushed and pulled by Jupiter and Io on one side, and mighty Ganymede and Callisto on the other, had been transformed into a crystalline ice ball, one of the brightest spheres in the Solar System. Some images revealed a few small craters here and there, but ridges and furrows cut across vast, smooth ice lowlands. In other places, sea ice-like plains fractured into icebergs before refreezing in the cold vacuum of space. Here, then, was what tidal heating could do to an ice moon. And it was impressive.

Europa gave the appearance of a cracked egg. As the Voyagers passed close to the little moon, Europa’s gravity bent their flight paths. Navigators such as Linda Morabito could carefully chart this bend to model what the interior of Europa was like. The conclusion: Europa’s ice crust hid a deep ocean, perhaps more extensive than any of the seas on Earth. To focus in on the true nature of this complex world, and the other Galileans, planetary scientists would need to carry out a new mission. That mission, already in development for flight nearly a decade later, would be called, appropriately, Galileo. But Voyager’s work was not done (Fig. 3.6).

Among the Moons of Saturn

When Voyager 1 and 2 blazed through the Saturnian system, humankind got its first clear look at the mid-sized ice worlds. Engineers tasked each spacecraft with a different assignment. Voyager 1 was to carry out detailed studies of Titan, Dione, Rhea, and Mimas. Flight planners would send Voyager 2 on a different path, enabling closer surveys of Tethys, Iapetus, Hyperion, and Enceladus. Its flight path also

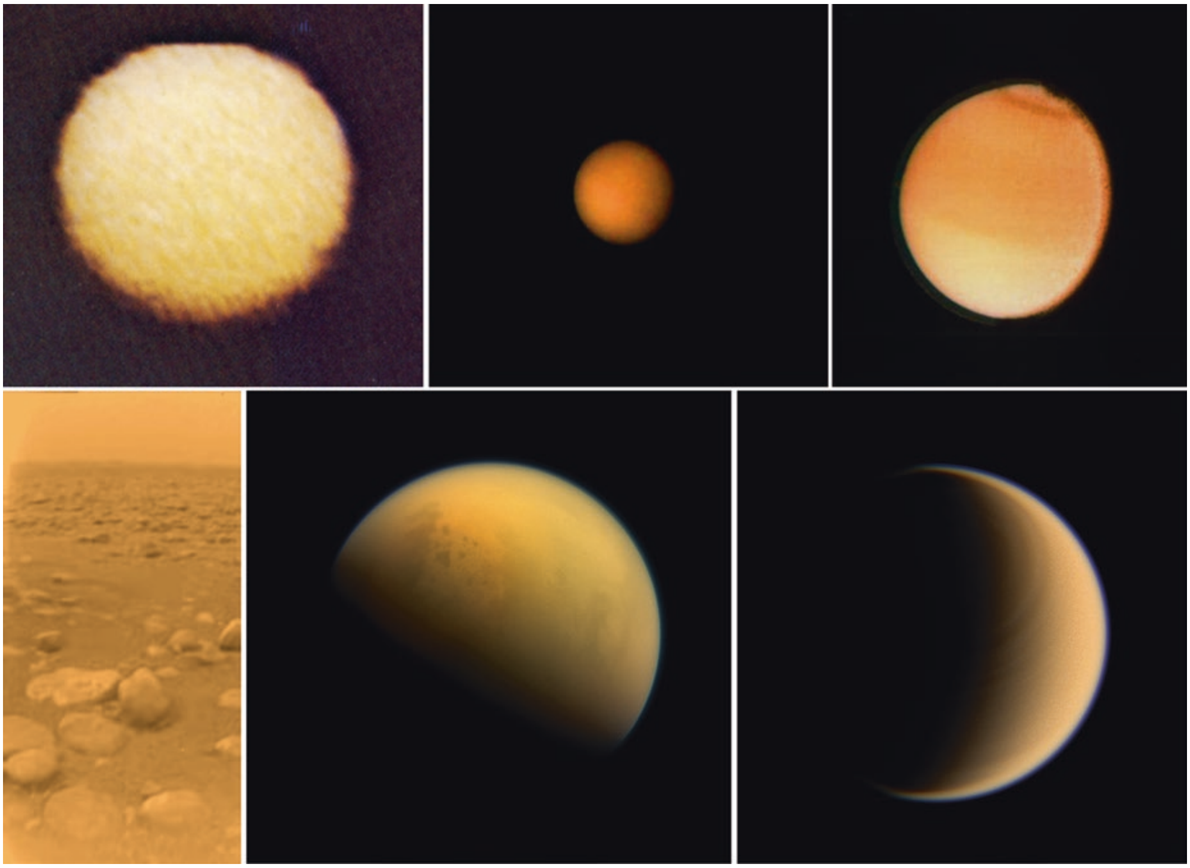


Fig. 3.7 The changing face of Titan. As space missions progressed, our view of Saturn's largest moon came into focus. Clockwise from upper left, views from: Pioneer 11, Voyager 1, Voyager 2, Cassini visible-light image of a crescent Titan (looking down on the pole), Cassini VIMS view "through the haze" with northern methane lakes visible, and ESA's Huygens lander image of the surface. (Images courtesy of NASA/Ames, NASA/JPL, NASA/JPL, NASA/JPL/SSI, NASA/JPL/SSI, NASA/ESA)

allowed for a gravity boost toward the next giant planet, Uranus, should the craft survive the long journey.

Voyager 1 took a path that brought it close to Titan, the mysterious, fog-enshrouded moon. Because it dove across the pole, it continued on high above the Solar System. This trajectory meant that it could not visit more distant worlds; it would be too far out of the ecliptic, the disk around the Sun in which all planets travel (Fig. 3.7).

Voyager 1 sailed by Titan in November of 1980, passing within 4000 km (2485 miles) of the surface. The spacecraft trained all of its instruments on the moon, measuring temperatures, composition of the atmosphere, assessing the size of particles in the air, and trying desperately to tell us something about the surface. The spacecraft narrowed Titan's diameter to 5150 km (3200 miles), slightly larger than the planet Mercury but shy of Jupiter's Ganymede. Titan's mass indicated that it has a heart of stone and perhaps metal, enshrouded by a thick water-ice crust. If Titan had canyons, mountains and plains, they would all consist of nearly pure water-ice frozen rock-solid. Had Voyager actually seen the ground, it could have spotted formations just 10 km across. But its camera system, though far more capable than those of the primitive Pioneers, could not breach the deep orange fog enshrouding Titan.[14] The moon's surface would remain a mystery.

Even so, the Voyagers told us much about what was above that unseen surface. Years before the Voyager flight of discovery, researchers knew that Titan's atmosphere – no matter what it was made of – contained particles of something. How dense and opaque these were was anyone's guess, and even the early images from Voyager showed a thick haze obscuring the moon. The northern hemisphere was markedly darker than the southern, starting at about the equator. The craft revealed an atmosphere dominated by nitrogen, making Titan the only body besides Earth with a substantial nitrogen atmosphere. The second gas, methane, makes up about 5%

---

[14] It turns out that the part of the spectrum covered by the Voyager imaging systems does, in fact, cover that part of light that penetrates through the fog, but only just. Recent studies of Voyager data show subtle variations coming through the fog from the surface. For more, see http://www.lpl.arizona.edu/~rlorenz/voyager.pdf.

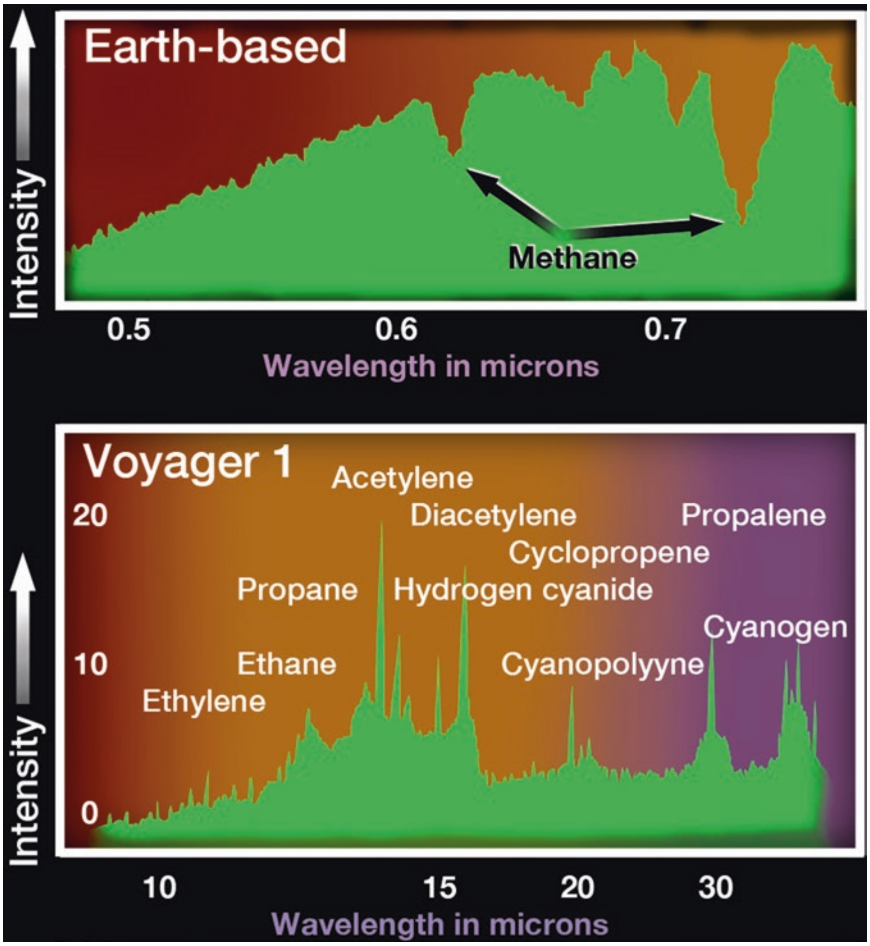


Fig. 3.8 What a difference a billion kilometers makes. *Top:* Spectrum of light reflected by Titan's atmosphere shows two telltale dips indicative of methane (CH_4). (1978 spectrum from the same telescope used by Kuiper in 1944.) *Bottom:* Approximation of infrared spectrum taken by Voyager 1 shows peaks revealing many different gases. (Diagram by the author)

of the total, with ethane and other gases below one percent. On Earth, nitrogen makes up close to 80%, with oxygen filling in about 20%. The big surprise was just how much air there was. At the surface, Titan has half again as much air pressure as Earth does at sea level (Fig. 3.8). Rather than a bulky pressure suit, Titan-exploring astronauts would only need an oxygen mask and something to protect them from the harsh temperatures, which dip to a frigid –179°C (–290°F).

The Importance of Smog

Why was Titan's largest moon enshrouded in such dense fog? What was the orange stuff made of? The particles suspended in the hazy atmosphere of Titan play an important role throughout the entire outer Solar System. The stuff of Titan's upper atmosphere is chemically similar to the smog we see hovering over major cities. It is called photochemical haze, because it is manufactured by the action of light. As sunlight acts upon the methane in Titan's air, it forces simple molecules of methane to combine, forming complex chains of organic material. Those dark organic compounds become a haze layer. They also rain down upon the surface, as another spacecraft discovered decades later.

Titan is not the only moon blanketed by organic material. Many surfaces in the outer Solar System have a dark reddish patina. From the ring particles of Uranus to the dark side of Iapetus, moons, comets and asteroids that contain methane ices are "sunburned," darkened by the Sun's radiation acting upon methane, converting it to the same complex organics that tint Titan its rich orange color. These organics play an important role in the appearance and chemistry of the farthest moons and planets. We will see them making their presence known again and again as we venture across the outer Solar System.

The organic material in Titan's environment intrigued astrobiologists. Was this the stuff of organic "soup" that led to life on Earth? And if Titan was truly at the triple point of methane, was that methane raining down into seas below? The Voyagers – blinded by Titan's organic hazes – could not tell. For answers, we would need to turn to more advanced spacecraft, and one of them, Cassini, was in the early planning stages.

During its survey of the ice moons of Saturn, Voyager 1 snapped an image whose importance was not realized until

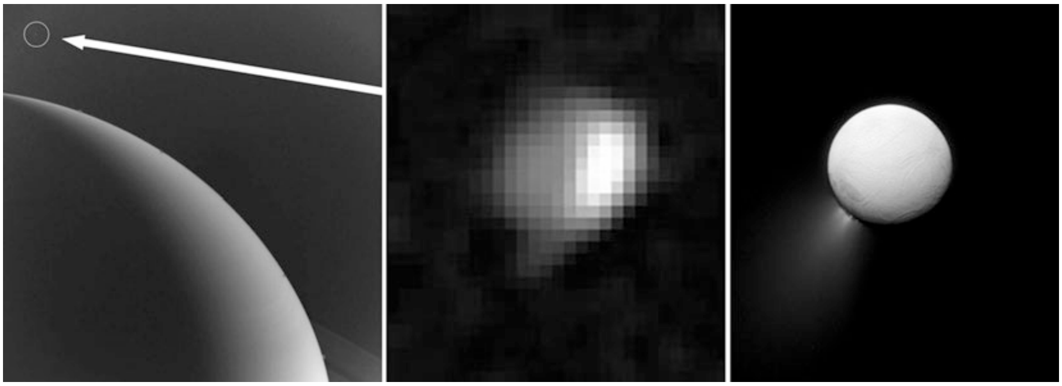


Fig. 3.9 A blurred Voyager image of Enceladus only a few pixels across (center) captures cryovolcanic activity, seen in detail later by the Cassini mission. (*Left:* Courtesy of NASA/JPL-Caltech. *Center:* Courtesy of NASA/JPL-Caltech/Ted Stryk. *Right:* Courtesy of NASA/JPL/SSI)

decades later. In a single, distant view of Enceladus, a smudge extended below its south pole. The low resolution image had captured one of the most important phenomena among the ice worlds: a volcanic plume extending hundreds of kilometers into space (Fig. 3.9).

Voyager 2 at Uranus

While Voyager 1 continued northward, out of the plane of our planetary system, its sister craft continued on toward the mysterious ice giants, Uranus and Neptune. Little was known of the ice moons accompanying these blue/green behemoths. In the late summer of 1986, Voyager 2 opened up the realm of the ice moons to the waiting world.

Voyager had braved extreme cold, blistering heat, and the radiation-filled vacuum of space since its launch nearly a decade earlier. Critical elements had failed and were on backup systems; the craft was old and tired. As the veteran spacefarer approached Uranus, the humble moons of Uranus began to come into focus. Jupiter had displayed its huge Galilean satellites, and Saturn had its great Titan. But Uranus had no such large moons to offer. Still, researchers had learned their lesson at Jupiter and Saturn, that moons are full of surprises. Even the mid-sized moons of Saturn were chock full of revelations for the geologists, and the moons of Uranus promised more to come.

With similar diameters to those of the mid-sized satellites of the Saturn system, engineers expected the moons of Uranus to exhibit similar cratered surfaces, perhaps with a few sites transformed by subtle geological processes. After all, the Voyagers had hinted at past geologic activity on several of Saturn's moons, including Enceladus and Dione. Voyager 2 spotted the fingerprint of past activity at Uranus as well. Most surprisingly, the smallest of the five major moons – Miranda – showed a face warped and torn by forces within or outside of it. Two others, Ariel and Titania, exhibited features that hinted at past epochs of cryovolcanic activity (see Chap. 6).

The Uranus encounter was the most challenging at that time. The spin axis of Uranus is tipped over, so that the southern hemisphere was pointed almost directly at the Sun at the time of the encounter. It was also pointed at Voyager's flight path, so that the craft passed through the system of rings and moons like a dart through a dartboard. This made the reconnaissance of the moons a very quick affair. Instead of visiting one moon after another, as at Jupiter and Saturn, the craft barreled past from top to bottom, passing through the orbits of all the moons at about the same time. Additionally, light levels at Uranus are quite low – about 1/400th the sunlight at Earth – and the spacecraft was traveling at over ten times the speed of a rifle bullet. There were technical challenges as well. The greatest of these was a balky scan platform, the aiming system for all of Voyager's instruments. The platform had jammed in one direction during the Saturn flyby, so instead of moving the camera, the entire vehicle had to be slewed to compensate for long exposures to prevent image smearing.

Flight engineers did a fantastic job, triumphing over the most difficult of circumstances. In addition to surveying the subtle cloud bands and chemistry of the giant green world, and studying the ring system and magnetosphere, the plucky robot reconnoitered the five major moons, Miranda, Ariel, Umbriel, Titania, and Oberon. The craft also searched for – and found – smaller moons in the region, bringing the total known moons of Uranus to 27.[15] The spectrum coming from the five major moons indicated that they were covered in water-ice mixed with a darkening agent of some kind. That darkening is probably similar to the photochemical haze we see at moons such as Iapetus and Phoebe. The mid-sized satellites don't seem to follow the same rules that planets and large moons do.

---

[15] Voyager discovered ten of them.

In light of the bewildering patterns seen among the Saturnian moons, researchers braced themselves for what they might see at Uranus. The surprises continued, and more of the accepted “rules” had to be abandoned. The smallest mid-sized satellite, Miranda, has a completely tortured surface. Ariel, too, has clear evidence of geologically recent activity, while the larger moons appear to be more quiescent and ancient. The pattern goes against the trend of the scientific community’s initial predictions.

Although they are similar in size to Saturn’s mid-sized satellites, the moons of Uranus are denser, with the exception of Miranda. They follow a pattern opposite to that of Jupiter’s Galileans or the planets of our Solar System. The densest ones are farthest from the planet. The two outer moons, Titania and Oberon, have diameters akin to Rhea and Iapetus (about 1500 km). The next two moons in, Umbriel and Ariel, are quite different from each other. They both span roughly 1000 km across, but Umbriel appears to be dark and fairly geologically quiet, while Ariel displays exciting features that may be related to cryovolcanism (see Chap. 6).

Rounding out the quintet of Uranus’s major moons is exotic Miranda. Because of Voyager’s flight path, Miranda was the moon best seen by Voyager’s cameras. As the smallest of the five moons, planetary scientists believed it would also be the most cratered and quiet. But Miranda had its own wonders in store. The tiny world measures a scant 472 km in diameter, but hosts some of the most bizarre terrain found anywhere among the moons and planets.

Voyager’s difficult flyby of the Uranian system was good practice for the next encounter, 3 years later. Neptune awaited.

Swan Song at Neptune

The summer of 1989 brought the intrepid Voyager spacecraft to the last of the ice giants. Neptune provided surprises from the start. Planetary meteorologists were baffled by all the activity on the azure world. After all, Neptune was farther away from the Sun than any of the other giant worlds and received the least solar energy. Should it not be the quietest?

As the resolution improved, it became clear that Neptune refused to play by any preconceptions. The blue giant had the fiercest winds of any world, with cobalt jet streams crowned by glistening white methane cirrus clouds. A great blue storm, reminiscent of Jupiter’s Great Red Spot, was vast enough to swallow an entire Earth. And, like the satellites of Uranus, Neptune’s celebrity was a moon, the large Triton.

Neptune lacks an organized system of mid-sized moons like those of Saturn or Uranus. Voyager’s dash by Neptune revealed six previously undiscovered moons orbiting close in, all with diameters less than 200 km (125 mi). Next out is the substantially larger moon Proteus, measuring roughly 420 km (260 mi) across. Beyond these inner satellites, the entire family of moons seems to have been scrambled by some cosmic catastrophe. The largest of Neptune’s satellites, Triton, ranks among the largest moons of our entire planetary family. Its 2705-km diameter puts it as the seventh in size of all Solar System moons.

The fact that Triton is the only major moon that orbits backwards, in a retrograde direction, suggests that it is an interloper – an outsider. Its exotic water-ice surface is encrusted with pink nitrogen ice concentrated near the southern pole. As with the Uranian satellites, Voyager saw only the south pole of Triton, as the north was in darkness. The polar region is streaked by dark plumes, evidence of a new type of cryovolcanism (see Chap. 6).

Because it had nowhere to go after the Neptune encounter, flight engineers were able to target the craft for an optimum flyby of Neptune and Triton. Voyager raced over Neptune’s north pole at a scant 4950-km altitude. It was the closest planetary flyby of its entire dozen-year mission. The close shave sent the craft on to Triton. That encounter took place at a range of 38,500 km, again proving the prowess of the NASA/JPL flight team. But because of its necessarily close flyby past the Neptunian pole, the craft picked up so much speed that it approached the moon at a breakneck 56,000 km/h. At that speed – and under Neptune’s dim lighting conditions – the closest images would be impossibly smeared. Voyager 2 had to settle for approach images of the southern hemisphere. As with the Uranian system, Triton’s north was cloaked in darkness. Voyager’s instruments recorded surface temperatures on Triton’s nitrogen ice-covered plains at –235°C, the coldest of any icy body visited to that time. Frozen nitrogen blanketed 55% of the surface, while water-ice came in at between 15 and 35%. Carbon dioxide ice (or “dry ice”) rounded out the landscape, with traces of methane and carbon monoxide ices.

Next out from Triton is Nereid, Neptune’s last major moon, with a diameter of about 350 km. Voyager was able to image Nereid only from a distance of nearly 5 million km, revealing only a few amorphous, but tantalizing, details. The imaging system was not able to resolve any surface features, but it did clarify Nereid’s size and rough shape. Voyager 2 also confirmed the presence of water-ice on the surface. Nereid has the most eccentric orbit of any planetary satellite yet found.

Although Nereid’s orbit is prograde (in the same direction as Neptune’s spin), its elliptical path implies that it, like Triton, is a captured object. But there is a problem with this theory. Its surface is as dark as the darker intermediate moons of Uranus, but it lacks the red photochemical color seen on comets or dark asteroids that are considered wanderers from the Kuiper Belt. An alternate explanation for its odd path is that the small moon was disturbed during the event that led to the capture of Triton itself. Nereid is about the same size as Mimas. Five more outer moons orbit at a distance, their natures unknown.

With the encounter at Neptune, the Voyagers completed their reconnaissance of the outer Solar System. They continue to monitor space at the edge of interstellar space. Their plutonium energy sources nearly spent, many systems have now been shut down. Power aboard the Voyagers drops by about 4 watts every year. The energy output from their antennae is less than the average refrigerator light bulb.

Messages from the Voyagers take 16½ h to reach Earth. The twin explorers have now broken through the heliosphere, the Sun's magnetic boundary of influence. Voyager 1 reached this frontier in 2012. Voyager 2 reached it on November 5, 2018, at a distance of 18 billion km. The robots are now sailing through the cosmic void among the stars. However, they have not left the Solar System. That journey is just beginning. The Solar System is surrounded by a vast sphere of comets called the Oort Cloud. The inner edge of this region is thought to start at 1000 astronomical units – Earth-Sun distances –from the Sun. Its outer edge may drift as far as 100,000 AU. The Voyagers will arrive at the inner edge of the Oort Cloud roughly 300 years from now and may not exit until 30,000 years in the future. By then, the silent craft will sail in silence, bearing testament to a creative species that had the urge to explore the farthest and highest frontiers.

The logical step after flyby missions are robots that can do long-term study. At Jupiter, this was to be the task of the Galileo orbiter and atmospheric probe.

Galileo: Return to the King of Worlds

The Galileo mission was designed to take up where the Voyagers left off at Jupiter. While the combined Voyager reconnaissance returned images with resolution of the Galilean moons rarely surpassing 1 km – and with significant gaps in coverage of all four satellites – Galileo was projected to orbit through the Jupiter system for many years, passing within a few hundred kilometers of each of the ice moons. (Io was too enmeshed in Jupiter's radiation for the spacecraft to have more than a few encounters. One of those would be on its inbound leg approaching Jupiter for the first time.)

Galileo was to return complete global maps of Europa, Ganymede, and Callisto down to a few hundred meters resolution, with targeted images coming home at 10- to 100-m resolution. Data on their interior layout, composition, and magnetic fields, if any, would be taken care of by a battery of experiments far more advanced than those aboard Voyager. Movies would be taken as researchers searched for active volcanoes, aurorae, and other phenomena on the ice worlds of Jupiter. All of this precious data would be returned by a huge high-gain antenna that would unfurl en route to Jupiter like a great umbrella.

In a sense, Galileo combined the best of Pioneer and Voyager, with a spinning section to test energy fields and a despun section to scrutinize the clouds and rings of Jupiter and the surfaces of the Galilean satellites and other moons. The craft's unique dual-spin design meant that the main bulk of the spacecraft spun like a top to keep it stable (as the Pioneers had). This section also carried fields and particles experiments, including a magnetometer and a plasma wave spectrometer, which return better data if its field of view sweeps across the sky. Its de-spun section carried the probe and imaging equipment for maximum clarity of photos, with instruments mounted on a steerable platform (as the Voyagers had).

The mission was originally to launch aboard a space shuttle in 1982 with a powerful liquid-fueled upper stage, but various issues caused its delay until 1986. Just weeks before the craft was due to depart, the Challenger disaster occurred, destroying one of NASA's shuttle fleet. All seven astronauts aboard were lost, and the program was put on hold until causes could be ascertained and remedies applied.

Once the shuttles flew again, the liquid upper stage was deemed too dangerous to carry within a shuttle cargo bay. Instead, a less powerful solid rocket, the inertial upper stage, boosted the craft. But it would now be a journey made years longer by the slower speed of Galileo. In order to ramp up its speed enough to get to the king of worlds, this spacecraft – designed to withstand the blistering cold of the outer Solar System – would need to spend time in the hot inner Solar System gaining speed with flybys of Earth and Venus. A Sun shield was fashioned to protect the delicate furled antenna until the craft finally headed out to cooler territory. Sadly, the extended flight time and higher temperatures caused the high gain antenna to jam. Flight engineers worked for years to free the antenna, to no avail. Now, instead of a stream of data 140,000 bits per second strong, Galileo's backup antenna, the size of a coffee can, would transmit at less than 20 bits per second. Galileo would only be able to do a tiny fraction of what it was designed to.

Engineers got to work upgrading the software so that the spacecraft could compress data in new ways. Advances were also carried out on Earth receiving stations. By the time Galileo arrived, it would be able to return about 150 bits per second. It was a spectacular improvement, but a devastating disappointment compared to what we might have learned.

Galileo was tasked with studying two main-belt asteroids en route to Jupiter. It flew by 951 Gaspra in 1991. A stony asteroid, Gaspra orbits along the inside edge of the Asteroid Belt between Mars and Jupiter. Galileo measured Gaspra's arrowhead shape at 20 x 12 x 11 km. In August of 1993, Galileo encountered the asteroid 243 Ida, a mountain of stone and iron. Like Gaspra, Ida is irregularly shaped, measuring 56 x 24 x 21 km. The flyby yielded an important discovery: the first moon of an asteroid. Ida's 1.4-km companion was christened Dactyl.

Fig. 3.10 Despite a fouled high gain antenna (JPL's flight hardware simulation at left), the Galileo mission returned spectacular images of the ice moons of Jupiter (Europa seen at about 12m/pixel, at right). (Images courtesy of NASA/JPL)

Galileo arrived at the Jovian system in December of 1995. After dropping off a 339 kg atmospheric probe – the first to investigate in situ a gas giant planet – the crippled robot explorer got to work. It fired its engines to slow down enough for Jupiter's mighty gravity to snag it. At the time of close approach to Jupiter, the craft was traveling so fast that it could speed from Los Angeles to San Francisco in 11 s. After firing its engines for 49 min, the cartwheeling craft settled into orbit, having slowed down by over 2000 km/h. The intrepid Galileo looped through the Jupiter system from 1995 through 2003. Each successive orbit carried it close to a specific moon, and redirected the next orbit to another encounter. After completing 32 orbits, the craft had logged 4.6 billion km of travel.

Galileo's cameras had the capability to return images with resolutions of meters, and to evaluate surface chemistry, temperature, texture, and other insights using its sensitivity to a wide spectrum of light from infrared to ultraviolet. Its survey of the Jovian system revealed Jupiter's ice moons to be varied worlds. The largest, Ganymede, measured larger than Mercury and had an interior complex enough to qualify it as a planet in its own right. Ganymede's core generates its own magnetosphere, and the moon is differentiated like a planet, with the heaviest materials of rock and metal settled into a central core, and lighter water-ices forming an outer mantle and crust.

Callisto and Europa had their own unique offerings, all recorded by the orbiting craft during its 84 voyage among the rings, moons, and deadly magnetic fields of Jupiter. Flybys of the moons gave flight engineers enough data to measure not only gross mass and densities of the ice worlds but also provided insights into their internal structures. These encounters offered the first conclusive constraints on what oceans might be hiding beneath the surfaces of Europa, Ganymede, and Callisto.

After all of its years in flight, Galileo's tape recorder, critical to the new way of compressing data, became balky and sometimes jammed. Jupiter's intense radiation caused loss of data, too.[16] Scientists were faced with choosing between one experiment and another rather than using Galileo's full battery of investigations (Fig. 3.10).

---

[16] In fact, like the first Io encounter, data from Galileo's closest flyby of Io near the end of the mission was almost completely lost as the computer forced the craft into safe mode during the most critical, and high radiation, moments.

The spacecraft returned between 150 and 180 images during each of its orbits, many only partial. Those images had to include not only the moons but also Jupiter's rings, searches for new moons, and shots of Jupiter itself. Tragically, many of the maps of the Galilean satellites we have today still have gaps, and display wide swaths from the much lower resolution Voyager encounters. Still, the vast majority of our knowledge of the moons' interiors, composition, and topography comes from the Galileo mission. At mission's end, controllers commanded the spacecraft to dive into the atmosphere of Jupiter, where its destruction by fire assured that Galileo could not eventually contaminate Europa or any other moon that might be a host of native life, possibilities that Galileo, itself, had underscored.

Cassini: Settling In at the "Lord of the Rings"

The Cassini/Huygens mission, the most advanced outer planets' spacecraft, was an international affair. Led by NASA/JPL, partners joined from the European Space Agency's 22-member nations. The Italian Space Agency was deeply involved, building the critical high gain antenna system and a synthetic-aperture radar system for mapping Titan. ESA independently designed the Huygens Titan probe, which made landfall on the mysterious moon after charting Titan's complex layers of atmosphere and hazes. Huygens was the first probe to land on an outer planet moon.

To date, the Cassini orbiter is the largest craft to visit the outer Solar System. As large as a school bus, the explorer logged 13 years in Saturn's orbit, studying the golden world's storms, lightning, aurorae, magnetosphere, moons, and rings. Its power-hungry battery of sophisticated instruments required three upgraded RTGs (radioisotope thermoelectric generators, essentially nuclear-powered batteries) designed for the long mission life. Even at the end of the mission, the RTG output was still 700 watts – hefty by interplanetary robot standards.

The orbiter alone weighed 2150 kg. Added to this weight was the piggybacking Huygens probe, checking in at an added 350 kg. No launch vehicle was powerful enough to send Cassini on a direct route to Saturn. Instead, like Galileo before it, Cassini would need gravity slingshots from planetary flybys.

Launched just 2 years after Galileo's arrival at Jupiter (liftoff was in October of 1997), the craft took a circuitous route to the golden giant, carrying out two gravity assist flybys of Venus, one of Earth, and a final sprint by Jupiter. In transit, the spacecraft also encountered the asteroid 2685 Masursky at a distance of 1.6 billion km. At Jupiter, Cassini carried out an imaging campaign of Io, as well as observing the Jovian clouds, rings, and magnetosphere. In all, Cassini's imaging system shuttered 26,000 images. It also studied the Galilean satellites with its visual and infrared mapping spectrometer. The craft imaged aurorae on Io while the volcanic moon was in Jupiter's shadow.

The Saturn-bound spacecraft did not linger in Jovian space. Jupiter's gravitational slingshot added 2.2 km/s of speed, adjusting the pathway of the spacecraft by 12.2 degrees, sending it on to its 2004 appointment with Saturn.

In a rerun of Galileo and its atmospheric probe, 150 days prior to its arrival at Saturn, Cassini set free the European Space Agency's Huygens probe, prodding it onto a slightly different path that would intersect Titan. The separation enabled Cassini to relay data from Huygens to Earth in real time as the probe descended through the complex hazes and clouds of Titan.

On Cassini's final approach before slowing into permanent orbit, the craft glided by the outer icy moon Phoebe. Phoebe is a lonely outpost, orbiting Saturn at a distance of nearly 13 million km. The moon's long, leisurely orbit takes it around Saturn once every 18 Earth months. Cassini's approach was timed specifically so that the craft could encounter this distant moon.

With a diameter of 210 km, Phoebe is one of the darkest objects in the planetary region, as dark as charcoal. It is roughly spherical, and its color and retrograde orbit imply that it came from outside the Saturn system, likely from the Kuiper Belt. Skimming by at a close range of less than 2000 km, Cassini cameras took in views down to a resolution of 12 m/pixel. Cassini's instrument suite (see "How to Tidally Lock a Moon") detected water-ice, minerals containing iron, and carbon dioxide.

After its Phoebe flyby, Cassini's top priority was getting into orbit around Saturn. As with the Galileo flight, its mission would not be easy. The craft had to slow itself enough so that Saturn's gravity would pull it into orbit. The 96-min-long Saturn orbit injection burn went flawlessly, as did most of the mission. All major subsystems worked, and the craft returned prodigious amounts of data.

In terms of mission design, Cassini's primary goals were twofold: to study Saturn and to study Saturn's planet-sized moon Titan. As the mission progressed and geysers were discovered at Enceladus, a mission extension was devised that could carry out further studies of Enceladus. The luxury of adding such a complicated set of observations highlights the importance of an orbital mission.

Cassini's discoveries included the geysers of Enceladus (Chap. 6), the methane seas and great sand dune deserts and mountains of Titan (Chap. 8), and a host of revelations about Saturn's mid-sized moons, new moons, rings, Saturn's aurorae, and magnetosphere. The craft's extended mission enabled observers to witness the change of seasons for essentially half a Saturnian year. Cassini contributed to our fundamental understanding of ice worlds, their wide-ranging surface conditions, and their interiors.

Cassini's Toolbox

Cassini carried instruments more advanced than any to visit the Saturn system. It bristled with an entire suite of experiments; some extended as long whip-like antennae, while others clustered together on a steerable platform for exact aiming. Cassini's experiments consisted of the following:

To study the energy fields, particles and other phenomena related to Saturn's magnetosphere, and to search for magnetic disturbances around moons (which can indicate either a molten core or volcanic activity), Cassini carried:

- Cassini Plasma Spectrometer: CAPS sampled ions and electrons as it swept through Saturn's magnetosphere. Since each of the spacecraft's orbits took a different path, CAPS was able to study the entire structure of Saturn's magnetosphere from near the planet and at a distance. Cassini scrutinized the currents, density, and composition of ions and electrons flowing around Saturn and its moons. One revelation from CAPS was that most of the ions around Saturn emanate from the geysers of Enceladus, which infuse the entire Saturn system with oxygen and other molecules. CAPS played a critical role in revealing the aerosols in Titan's atmosphere, material that contributes to the moon's dunes and lakes.
- Cosmic Dust Analyzer (CDA): As its name implies, the CDA sampled and analyzed dust in Saturn's environs. Particles the consistency of smoke – and down to the size of a virus –were in the sites of the CDA. As particles entered the instrument, their charge, size, and speed were recorded. Then, the particles fractured into smaller parts so the CDA could register their composition. For the ice moons, CDA monitored particles that likely came from meteor impacts or geyser activity. It directly sampled material from Saturn's E-ring, which finds its genesis in the geysers of Enceladus.
- Ion and Neutral Mass Spectrometer (INMS): INMS gathered information on the chemistry, isotopes, and structure of ions and particles in Titan's upper atmosphere, as well as measuring particles in and around Saturn's rings and ice moons. For example, on March 12, 2008, Cassini flew directly through the plume material above Enceladus. INMS detected water vapor, methane, carbon dioxide, carbon monoxide, and a host of simple and complex organics.
- Magnetometer (MAG) sensed the flow of magnetic fields around Saturn, and how that flow interacted with moons (which can indicate internal oceans). It also searched for small magnetic fields coming independently from the moons themselves. MAG was able to confirm that a subsurface ocean of salty water likely exists beneath the surfaces of Enceladus and Titan, and perhaps several other moons.
- Radio and Plasma Wave Science (RPWS): Consisting of a variety of sensors and antennae – including three 10-m-long antennae – the RPWS mapped radio and plasma waves surrounding Saturn and its moons. The instrument suite could also hear lightning in Saturn's clouds and particles impacting the spacecraft itself.

Cassini was able to image a wide part of Saturn's spectrum, including the visible portion. Mounted on its scan platform, Cassini carried out these investigations using:

- Composite Infrared Spectrometer (CIRS): The CIRS was a sort of remote thermometer, able to measure temperatures of moons' surfaces, atmospheres, and Saturn and its rings. CIRS data also provided insights into the chemical compositions of the surfaces it studied. Minerals and other substances have specific markers related to temperature, so CIRS could tease out just what each moon's surface was made of. Other instruments provided checks and also studied other parts of the spectrum in search of the composition of Saturn's moons and other targets.
- Imaging Science Subsystem (ISS): This consisted of sensitive digital cameras hooked up to two different lenses, a wide-angle imager, and a narrow-angle one affixed to a powerful telescope for close ups. Cassini's camera system was able to see in a wider spectrum than off-the-shelf digital cameras, reaching down into the near-infrared and up into the near-ultraviolet. The cameras had a variety of filters that helped them to study solid surfaces as well as atmospheres.
- Ultraviolet Imaging Spectrograph (UVIS): This imaging system "sees" in ultraviolet light, above that which the human eye can sense. UVIS examined Saturn's atmosphere and rings, and studied moon surfaces as well. UVIS was able to observe the nature of atmospheres on the night hemispheres of Saturn and its satellites (especially Titan), and charted starlight and sunlight as it passed through atmospheres and rings during occultations (when a distant object passes behind a closer one). In this way, UVIS returned detailed charts of the structure of atmospheres and rings.
- Finally, the spacecraft was equipped with the Visible and Infrared Mapping Spectrometer (VIMS): This could image Saturn and its family of rings and moons in both visible and infrared light. This meant that VIMS could view things invisible to the human eye. Researchers used the experiment to record the temperatures and constituents of atmospheres, of Saturn's rings, and also satellite surfaces. Although not technically a visual imager, scientists could reconstruct the VIMS light readings to create images. VIMS was able to image the surface of Titan through the dense haze layers that blocked the view from the ISS.

Remote Sensing by Microwaves

Instruments also enabled Cassini to “image” distant surfaces. Using Synthetic Aperture Radar, referred to as SAR, Cassini imaged the surface of Titan beneath its visually impenetrable fog. It also mapped various surfaces on other ice moons, as well as charting particles in the rings and recording structure in the plumes of Saturn.

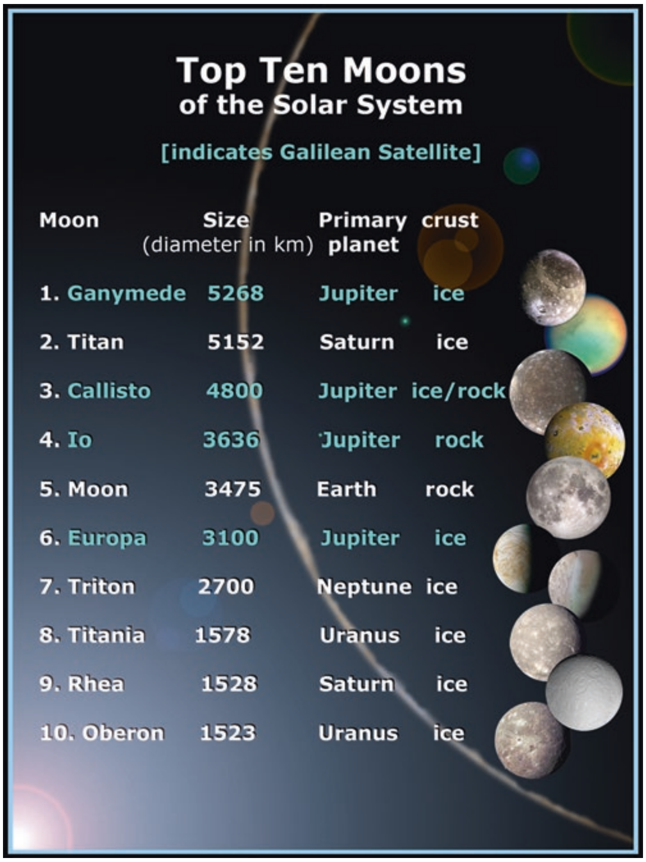
Using its Radio Science Subsystem, the craft determined the mass of moons and charted density and structure in Saturn’s atmosphere. For the RSS, Cassini’s radio signals were the experiment itself. As the craft changed speed, its radio signal shifted, much as the pitch of a horn shifts as a car drives by. Using these changes, investigators could determine the mass of satellites or the density of atmosphere as the air bent the radio waves. Cassini’s radio signals were received at NASA’s Deep Space antennae at Rota, Spain; Canberra, Australia; and the Goldstone receiving station at Goldstone, California.

Huygens Arrives!

Cassini’s fellow explorer, Huygens, arrived at the upper limits of Titan's soupy air on January 14, 2005. Because of Titan's low gravity (1/10th that of Earth's) and dense atmosphere, the probe required much less protection than that of Galileo’s Jupiter probe. Engineers estimated that Huygens would enter the atmosphere at a speed of 13,000 miles per hour, experiencing 12 G’s (12 times that of Earth gravity) of deceleration, compared to Galileo’s whopping 350 G’s.

Huygens recorded a long list of successes. The probe initially descended on a large parachute to slow its descent, but later discarded this for a smaller chute that enabled it to reach the lower atmosphere more rapidly. Its descent had to be timed to coincide with the flyover of the Cassini orbiter, its link to Earth. Huygens was designed to spin beneath its parachute. Images from its DISR imaging system – essentially a slot camera – could be assembled into 360° panoramas (Fig. 3.11). Huygens returned spectacular images from high altitude as well as from the surface after surviving its landing (see Chap. 8).

With the advanced missions such as Galileo and Cassini, planetary scientists are beginning to understand the icy satellites as a cohesive group, an interrelated family of associated bodies. The revelations beamed back from the Voyagers were nearly overwhelming. Says John Spencer: “The idea that the moons of the outer planets were active in recent geologic time was a huge revelation. With Cassini discovering the activity on Enceladus, it really changed so much of what we knew there, but we were already open to that possibility, because of what Voyager had shown us and the fact that we’d seen activity on Io, and we had hints that there might be activity from the Voyager data and other data from Hubble and so on. So it wasn’t completely out of left field the way that finding volcanoes on Io was. We knew that such things were possible.” Voyager unveiled patterns among the icy worlds, and Cassini and Galileo brought us into a deeper understanding of them.



Top Ten Moons
of the Solar System

[indicates Galilean Satellite]

Moon	Size (diameter in km)	Primary planet	crust
1. Ganymede	5268	Jupiter	ice
2. Titan	5152	Saturn	ice
3. Callisto	4800	Jupiter	ice/rock
4. Io	3636	Jupiter	rock
5. Moon	3475	Earth	rock
6. Europa	3100	Jupiter	ice
7. Triton	2700	Neptune	ice
8. Titania	1578	Uranus	ice
9. Rhea	1528	Saturn	ice
10. Oberon	1523	Uranus	ice

Fig. 3.11 Before the space age, the wide variety of form and size among the icy worlds was largely unknown. Not shown is Pluto, whose diameter would put it between Triton and Titania. (Art by the author)

The moons of Uranus and Neptune await the kind of deep, systematic study afforded us by Cassini-class missions, but other ice worlds still loom. The Kuiper Belt, which begins at the orbit of Neptune (30 AU from the Sun) and extends to 50 AU, has a population of perhaps hundreds of ice worlds. These spheres and chunks of primordial ice and rock orbit the Sun in a flattened donut-shaped swarm of cometary material. The disk is vast, with an estimated mass 200 times as great as that of the Asteroid Belt. To date, five ice dwarf planets have been officially recognized by the International Astronomical Union: Ceres, Pluto, Haumea, Makemake, and Eris. The poster child of these is Pluto, and until 2015 it lay unexplored. Then came the New Horizons mission.

New Horizons at the Edge of the Planetary System

As with both Galileo and Cassini, the New Horizons spacecraft required a gravity assist to get out to Pluto. The craft was to carry out the most distant encounter of the space age, and the window of time was critical for two reasons. First, Jupiter was in the correct position for the robot to fly by on its way to Pluto, an alignment that would not come again for a lifetime. Second, Pluto was on its way out, traveling farther from the Sun on its elliptical orbit every day. Researchers calculated that Pluto's atmosphere might become so cold that it would collapse, much as the coma around a comet does as it retreats from the Sun. Now was the time to go if observers wanted to see Pluto's active atmosphere.

New Horizons launched on January 19, 2006. Lofted aboard a powerful Atlas V, the piano-sized craft left Earth at the breakneck speed of 58,536 km/h, making it the fastest moving artificial object in history. It reached Jupiter in February of 2007, picking up more speed and shifting its trajectory. As it passed through Jovian space, New Horizons focused its battery of instruments upon Jupiter and its moons, studying Jupiter's weather, aurorae, and magnetosphere, sampling dust in orbit around the planet, and charting surface compositions and exospheres (extremely thin atmospheres) of the moons in a dress rehearsal for the Pluto encounter 8 years in the future. During most of its cruise, New Horizons was put into hibernation. This conserved energy and cut the overall cost of the mission as well.

Bristling with science equipment, New Horizons screamed through the Pluto/Charon system in July of 2015, but its imagers had resolved details on Pluto's globe weeks before. The probe skimmed Pluto at a distance of 12,500 km, returning detailed data on Pluto's surprisingly exotic environment. Far from a cratered ice ball, the dwarf planet has been split apart by canyons, painted by organic sludge, and sculpted by sublimating methane and nitrogen across its plains and glaciers. Images revealed bladed terrain unlike anything seen on other ice worlds,[17] and jagged mountain chains dusted in carbon dioxide frost. Plains buckle beneath strange cells of fractured terrain, much like the polygonal ground seen in the Arctic tundra. A vast, heart-shaped region stretches across one hemisphere beneath a blanket of frozen nitrogen, which flows, glacier-like,-from the surrounding mountains.

At the edge of Pluto's more heavily cratered regions lie two rounded mountains with depressions at their summits. These appear to be massive cryovolcanoes. New Horizons also revealed complex haze layers in Pluto's atmosphere, which was far more dynamic than predicted. Rounding out its mission, the spacecraft surveyed all of Pluto's moons, with an emphasis on Charon, a moon with its own evidence of exotic geology. It took New Horizons 15 months to transmit its 6.25 gigabytes of data across the distance to Earth, some 43 AU away.

New Horizons went on to encounter the fascinating Kuiper Belt object 2014MU69 (provisionally known as Ultima Thule) (Fig. 3.12). MU69 is what is known as a contact binary, an object only theorized until New Horizons documented it during its flyby on New Year's morning.[18] Pluto and Ultima Thule are so remarkable that they warrant their own chapter (Chap. 9).

Dawn on Ceres: The In-Between Ice World

In the frenetic study of the moons in the outer Solar System, one ice world had been left behind. Ceres, largest member of the asteroids, constitutes nearly a third the mass of the entire Asteroid Belt. It was the first ice dwarf discovered, although at the time Giuseppe Piazzi glimpsed it, the object appeared as a point source of light, similar to a star. Hence, Ceres and its siblings were given the name "asteroids," from the Greek for "star-like."[19]

Ceres is part of the main Asteroid Belt, a torus-shaped band of rocks and metal circling the Sun between the orbits of Jupiter and Mars. It is large enough to be roughly spherical and bulges at the equator. Although it is a rocky world, it contains much water, the majority of which is probably ice. Ceres, then, is an in-between world, inhabiting a twilight zone between terrestrial, rocky planets and the watery ice globes of the Sun's outer realm. Earthbound observers were able to see hints of water in its spectrum, along with carbon similar to graphite. Charting its orbit revealed that the little orb probably had a large component of water-ice within. Astronomers also noted a mysterious white spot on one hemisphere. Could this be an outcropping of water-ice?

What we know of Ceres comes from a remarkable robot explorer, the Dawn spacecraft. Dawn used solar electric ion propulsion. It was not the first craft to do so, but it used the alternate form of propulsion longer and more efficiently than any before it. Dawn was in powered flight for nearly 6 years. Its ion engines added 41,360 k/h to Dawn's speed, nearly equal to the power delivered by its Delta launcher. After orbiting the asteroid Vesta from 2011 to 2012, Dawn departed to meet Ceres 3 years later. The spacecraft mapped Ceres in

---

[17] Radar studies suggest that some equatorial regions on Europa may host similar formations.

[18] Eastern Standard Time in the United States.

[19] The term asteroid was proposed by either William Herschel, discoverer of Uranus, or by the son of one of Herschel's friends, Charles Burney.

Fig. 3.12 Spacecraft for ice worlds. Dawn fires its ion engine at Ceres. (Image courtesy of NASA/JPL/Caltech) New Horizons at Pluto. (Art by the author)

detail, studying its geology and mineralogy. Dawn established that Ceres has had – and may still have – an active subsurface ocean of salty water and ammonia. This ocean may escape as cryovolcanoes or thick cryolavas (see Chap. 4).

Before the arrival of the Dawn spacecraft, Ceres was indeed a mystery world. Though it was closer than any of the other dwarf planets and icy moons, Ceres was too small to resolve in any but the most advanced telescopes, and even those instruments resolved the face of the largest asteroid as a handful of pixels. Some researchers looked at the scant data and speculated that Ceres was a rocky ball with hidden ice deposits. Others theorized that the dwarf world was covered with a smooth, young surface – perhaps a Europa-like cueball with a hidden ocean beneath a dust-blanketed ice-rink crust. In fact, Dawn revealed that Ceres was none of these, instead encrusted with the chemistry of its ancient seas, salty mineral deposits scattered across its face.

Dawn's mission came to an end in 2018, when its fuel was exhausted. The craft lost lock with Earth and drifted off of its Sun-pointing attitude, finally succumbing to depleted batteries and the cold vacuum of space. Dawn's final resting place, Ceres, is an important dwarf planet, and we will dedicate a chapter to it next.

Although many of our distant planetary explorers have gone silent, from depletion of fuel or failing power, their legacy is rich. Typically, an initial flood of data is scoured as resources permit, while other revelations wait for future scholars to scrutinize the recorded messages from our long-gone robots. Voyager data from Jupiter and Saturn encounters continue to be combined with data from Galileo and Cassini. A flood of data from other missions will require many more years of research to decant, and even more as new techniques for studying the data come to bear.

Human history is marked by moments of greatness, times when peoples of many generations, nations, and interests came together to do something bigger than themselves. These moments leave their physical marks: the pyramids of Giza and Mesoamerica, the temples of Greece and Rome, the

Great Wall of China, and the stone circles on Salisbury. The medieval cathedrals were built by generations who would never see their completion, a finish date scheduled for their grandchildren. But their best efforts went into the spires, sculpted buttresses, and stained glass as a testament that human effort, when worthwhile, will last beyond its own time. Future generations benefited, too, from the explorations of Marco Polo,[20] Leif Erikson,[21] Zheng He,[22] Roald Amundsen,[23] and others. In modern times, our most distant explorations are carried out by our robotic representatives, ambassadors to the new worlds of the high frontier. Encounters like those of Cassini and New Horizons made front-page news and overwhelmed the Internet. Planetary exploration is the Cheops pyramid of a new generation, a temple not to one ruler but to the ingenuity of humanity at large and the beauty of the cosmos around us.

---

[20] Marco Polo's life spanned 1254 to 1324.

[21] Born in Iceland in about 970; died around 1020.

[22] Zheng He lived from 1371 to 1433 or 1345.

[23] July 16, 1872, June 18, 1928 (specific date of death unknown; lost at sea).

Ceres: The First Known Ice Dwarf Planet

4

Ceres is the only dwarf planet inside the orbit of Neptune. Like the traditional planets, the asteroid is differentiated. This means the heavier, rocky elements settled into a core while lighter ices and rock rose to the mantle and crust. The asteroid's surface is a cosmopolitan mix of rock, some water-ices, and hydrated minerals such as clay and carbonates, some of which account for its famous bright spots. And although not much ice is directly observable on the surface, the mass of near-surface rocks (within a few meters of the surface) weighs in at 10% water. This much near-surface ice supports earlier theories that as Ceres differentiated, water separated from rock and metal, forming an ice-rich outer crust. Ceres' surface also contains iron-rich clays, but the core of the dwarf planet is probably composed of rock and metal, like its terrestrial cousins (Fig. 4.1).

A Closer Look

Much of what we know of the asteroid today comes from the Dawn mission. Dawn's first stop was the second-largest of the asteroids, Vesta, where it orbited from July 2011 to September 2012. Then, it was on to Ceres. Dawn arrived at Ceres on March 6, 2015, settling into a high, slow mapping orbit. In doing so, it became the first spacecraft to orbit two bodies. Its assignment: to unveil secrets about the formative years of our Solar System, the dawn of the Sun's family (which is how the craft got its name).

Both Ceres and Vesta are remnants of the earliest epoch in our planetary system, a violent time when the planets coalesced from a primordial cloud of cosmic debris. The two asteroids, planetary building blocks of those ancient times, would – mission planners hoped – provide separate narratives, historical bookends you might say, with rocky Vesta telling a part of the story different from the one chronicled by watery Ceres. Vesta did, indeed, display a record of molten rock, fiery volcanism, and a heated infancy, while Ceres led a cooler, more humid childhood with primordial oceans beneath a rock/ice surface.

As the Ceres component of the mission progressed, flight engineers commanded Dawn to descend into incrementally lower orbits. Its path spiraled closer to the asteroid, and Dawn quickly discovered some 300 bright spots similar to the largest one, seen in Earth observations years before. Dawn's advanced cameras resolved the large bright region into a complex of whitish blemishes on the floor of Occator Crater. The 90-km (56 mile)- wide crater plays host to the brightest and most extensive of the asteroid's bizarre deposits. Most of Ceres is as dark as asphalt, but its bright blemishes range from a dull gray (akin to driveway concrete) to the glaring luster of sea ice in Earth's oceans. The largest deposit, at the center of Occator Crater's 2-mile-deep floor, is called Cerealia Facula. In the heart of the region, white deposits appear atop structures similar to the buttes and mesas found in some desert regions of Earth. Occator itself is young, probably excavated by an asteroid or comet some 80 million years ago (Fig. 4.2).

Second only to Occator in luster is Oxo Crater, spanning some 10 km (6 miles) in diameter. The crater has an irregular rim that slumps into a sunken trough along one side. Bright deposits overflow its odd rim. Another of the brightest craters is the relatively young Haulani, about 34 km (21 miles) across. Extensive deposits of salty material stream down its walls and accentuate lines on the crater's central peak.

Although observers speculated that the "alien acne" consisted of icy outcroppings, Dawn revealed a surprising result: the regions contained mostly hydrated magnesium sulfate, similar to Epsom salts, and sodium carbonate, materials typically left behind as water evaporates. The majority of spots are associated with craters, so their origin may relate to impacts where subsurface water was freed onto the surface. (Oxo's bright outcrops also contain water-ice.) Ceres' spots may point to a primordial ocean that existed for some time beneath its dusty rock surface. Gravity studies of Ceres show that a thin sea – perhaps a mixture of water and mud – may exist under the crust even today. Modern impacts may still expose liquid that sublimates (changes directly from liquid to vapor) into space.

M. Carroll, *Ice Worlds of the Solar System*, https://doi.org/10.1007/978-3-030-28120-5_4

Fig. 4.1 The largest asteroid, Ceres, is dwarfed by our own world and Earth's Moon, at upper left. (Art by the author)

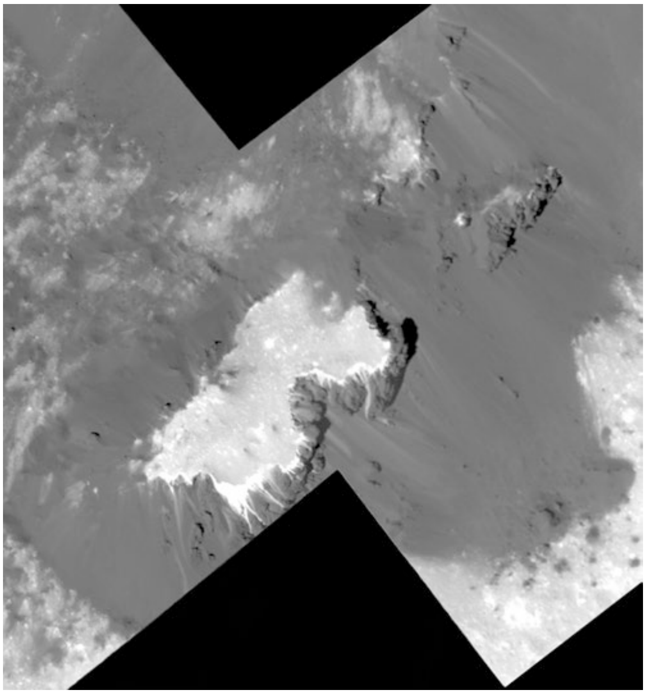


Fig. 4.2 This two-frame image, snapped from an altitude of 34 km (21 miles), is one of the most detailed views of Ceres returned by the Dawn mission. The view covers features on the western side of Cerealia Facula and reveals flat-topped mesa-like formations capped by sodium carbonate. Landslides cut through the darker regions. The light is coming from the upper left. (Image courtesy of NASA/JPL-Caltech/UCLA/MPS/DLR/IDA)

One mode of transporting the salts or condensing water from the interior to the surface is through the eruption of geysers. Ceres' brilliant deposits may represent sites of ancient cryovolcanism, where water vapor has leaked or exploded through the crust, forcing material from subsurface aquifers or even seas. Some activity may continue even now.

Foggy Forecast?

In fact, in 2014 the European Space Agency's Herschel Space Observatory detected clouds of vapor escaping from the asteroid at a rate of 6 kg (13 lbs) each second. This observation was the first confirmation of water plumes in the Asteroid Belt. But the jury is still out on the Herschel observations, which are quite difficult to interpret. Revised assessments of ESA's error uncertainty have called the results into question. For its part, Dawn has not seen enough ice to account for what Herschel seemed to have detected. But if there is subsurface ice, some of it could liberate water molecules that would make their way up through the ground.

Another possibility is that the transient presence of water vapor that Hershel detected is a result of increased solar activity. Dawn's chief engineer and project manager, Marc Rayman, says, "Say the sun produces a coronal mass ejection, so a large number of energetic solar particles impinge on the surface and themselves liberate water molecules."

Dawn carried an instrument to detect solar energetic protons. Observers tried to investigate the possibilities, but the Sun has been uncooperatively quiet. Astronomers had set up a coordinated international campaign between Earth-based telescopes and Dawn, but solar activity was simply at too low a level to demonstrate whether water was being freed by the Sun's activity.

The search continues, Rayman says. "It's a hard problem, because Dawn wasn't made to study that sort of thing. We have instruments designed to study surfaces of airless bodies, and this tentative finding of a haze really pushes the limits of signal-to-noise. You would also need a good explanation for what contains the haze. A haze usually occurs in an atmosphere with something supporting it." In 2016, Dawn flew to an orbit from which two important observations could be carried out: one was of Juling Crater's observed ice, and the other was looking at Occator Crater when it was on the limb, searching for any indication of water vapor. Researchers looked again this year, but with no results.

Nevertheless, the picture we are left with is a rocky world with a wet subsurface that periodically seeps into space in clouds and plumes. Some of Ceres' interior may come to the surface in more violent ways, through volcanic eruptions.

Cryovolcanic Wonderlands?

Our Solar System shimmers with a host of volcanoes. Its erupting menagerie includes forms familiar to us, like the cinder cones and graceful shields of the Martian landscape. The mountains of Venus take on more alien forms in the dense Venusian atmosphere and unique rock chemistry, rising in formations called pancake domes, arachnids, and ticks. Farther out, the volcanoes of Io display violent natures, erupting hundreds of kilometers above the pizza-moon's face. The ice worlds have their own versions of Vesuvius, sending jets of water into the void from such sites as Europa and Enceladus. At Neptune, Triton flaunts its own unique erupters, chilled nitrogen columns wafting into dark skies. And even farther out, we see hints of cryovolcanism atop Pluto's crater-topped mountains, Wright and Piccard Mons.

We thought we'd seen it all. Then came Ceres.

Ceres is large enough to retain substantial heat within. That heat may interact with subsurface briny water. That water, if near the surface, would periodically erupt through the ice/rock crust. If this is the case, Ceres should be peppered with cryovolcanic features. But Dawn's initial survey of the dwarf planet revealed only one large mountain, christened Ahuna Mons.

Ahuna is a strange feature. It's the highest mountain on Ceres, rising like a great pyramid from the cratered landscape. It towers some 4 km on its steepest side. A combination of characteristics convinces researchers that Ahuna is volcanic. Its summit is cracked like the summits of volcanic domes seen on other worlds such as Mars, Venus, and Earth. The mountain's flanks appear to have been scored by rock falls. Ahuna's form indicates that the mountain is geologically young. Ceres has no atmosphere to protect it from meteor impacts, so all of its surfaces are "weathered" by the constant drizzle of micrometeorites, resulting in rounded hills and valleys. But Ahuna has sharp definition with few craters. A final clue to its youth is its color: ice and rock surfaces tend to darken over time with constant solar radiation, but the dome is one of the brightest regions on Ceres. Investigators calculate that the mountain is, at most, 240 million years old, and may be much younger. It is unclear as to whether Ahuna Mons still erupts cryolavas (most likely muddy water) today (Fig. 4.3).

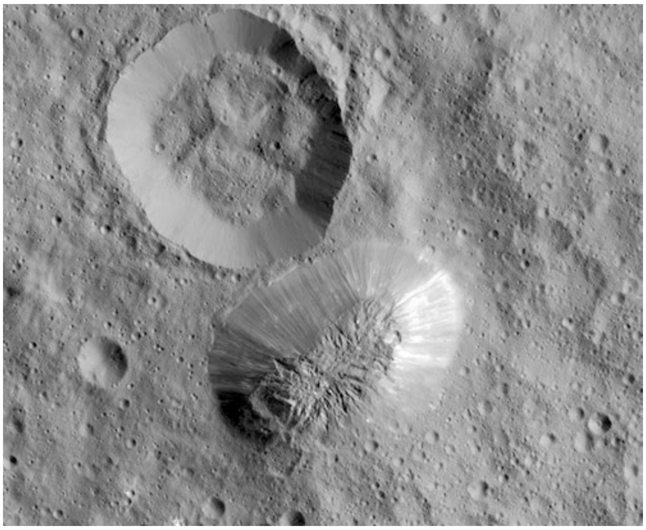


Fig. 4.3 The 4-km-high Ahuna Mons is likely one of many cryovolcanoes on Ceres. Most are dormant or extinct. (Image courtesy of NASA/JPL/Caltech)

In light of Ahuna Mons' geologic activity, researchers began searching for other evidence of past volcanism, but the search was difficult. Most of Ceres' volcanic activity seems to have taken place hundreds of millions of years ago, and may stretch back as far as 2 billion years. Time, impacts, radiation, and micrometeorite erosion have nearly erased much of the ancient eruptions' fingerprints. But they are there. Researchers have identified at least 21 other cryovolcanic domes. They range from 16 to 86 km (10 to 53 miles) across. Investigators compared computer-modeled domes to spacecraft images of the Ceres surface. This research revealed candidate sites that have gradually settled and sunk into the cratered landscape over eons. Temperatures on Ceres are not low enough to make ice strong enough to support a massive structure like a mountain. Ridges, canyons, and peaks tend to relax and sink due to a process called viscous relaxation. Surface features flow slowly, like a glacier, eventually fading into the neighboring landscape.

Researchers played a game of hide-and-seek, searching out rises that fit a model of a tall mountain that had lapsed into its surroundings. "It was looking for objects with similar aspect ratios and sizes," Marc Rayman says. "They're all a kilometer or more in height, and that really stands out on a body like Ceres."

Data indicates that new eruptions of cryovolcanoes have broken out, on average, every million years over the past billion-year span. But the rate at which new material is deposited onto the surface is small compared to terrestrial planets, on the order of 100 to 100,000 times less. Each year, the average of cryolavas on Ceres has been about 9940 cubic meters (13,000 cubic yards), or enough to fill four Olympic-sized swimming pools. This is minor compared to Earth's volcanic activity, which generates 765 cubic meters (1 billion cubic yards) of molten rock annually.

Although these eruptions were probably weak by terrestrial standards, Ceres has no atmosphere. Its low gravity and vacuum could contribute to explosive, violent eruptions. Lava and chunks of rock may be hurled into the airless sky at speeds of 50 to 100 m/s. This is just below escape velocity (the speed at which an object travels fast enough to escape the gravity of its home world).

How old is Ahuna Mons? Researchers can only estimate the age of the summit, but it appears to be between 70 and 240 million years old. The massif may have risen quite quickly, building to its current altitude of 3965 m (13,000 feet) between a few hundred and a few hundred thousand years. The idea that it might have formed in a few hundred years excites scientists such as Rayman. "Even a few hundred thousand years for a structure that's 13,000 feet high, that's pretty fast. Not only that. The structure is more than 70 million years old, and it's still standing with impressively steep slopes."

Ahuna Mon's youth begs the question: Is Ceres still active today? The European Space Agency's Ottaviano Ruesch, whose research includes geology on Ceres and Vesta, says that "making predictions for Ceres' future activity is definitely difficult, and what we can say is only on a speculative basis, but if we consider that cryovolcanism was persistent throughout Ceres' history until geologically recent times [e.g., from a few billions of years ago up to a few hundred million years] there is no reason to exclude events in the upcoming million years."

The Powers That Be

What feeds the volcanic fires of Ceres? On the terrestrial planets (Mercury, Venus, Earth, and Mars), the leftover heat of planetary creation was enhanced by the heat of radioactive elements, such as uranium, at the heart of the planets, in their cores. The larger the planet, the more heat could be retained for longer periods, and the more radiogenic material gathered in the accretion process, the process when a planet pulls more and more material into itself. Radioactive elements heat rock to the melting point, and that magma, or liquid rock, makes its way to the surface in the form of volcanic eruptions. In the case of Earth and possibly Venus – the two largest terrestrials – that volcanism is still alive today. But smaller objects such as moons and asteroids did not have as much radiogenic material to start with. What may be left today has settled into the core, far enough below the surface to have no external effect. Even radioactive elements of Mars may have settled out long ago. It appears that Mars's volcanic era ended roughly 500 million years ago.[1] But Ceres measures only 945 km (588 miles) across. Volcanoes on Ceres and eruptions of water from beneath the crust appear to be young enough that radiogenic heating on its own is not to blame; something else may be afoot.

Another possibility has to do with what's in the water. The melting point of water-ice – which any cryolava on Ceres would consist of – can be lowered by an assortment of materials such as ammonia, methane, and various salts, enabling water to flow even in the chilly temperatures of the Asteroid Belt. Since Dawn has found evidence of carbonates (salts) and ammonia on the asteroid's surface, its observations hint at a subsurface sea laced with these materials. Aside from those high-profile salts, Ceres contains ammoniated compounds. These could also lower the freezing point of water, enabling cryovolcanic eruptions to take place.

As the Voyager missions first revealed, volcanism can be triggered by forces other than radiogenic heating. Triton's alien eruptors – gentle as geysers go – are empowered by the solid-state greenhouse effect. Tidal friction, that gravitational taffy pull between planets and moons, can generate prodigious amounts of internal heat, as we have seen at Io, Europa, and Enceladus. But not at Ceres. The lonely asteroid is not subjected to tidal heating. No objects lurk nearby to force it into stressful orbital gymnastics.

Ceres is a rule-breaker, with its duality of rocky (think inner Solar System) and icy (outer Solar System) natures. The source of its volcanism remains a mystery, but some researchers have suggested that the dwarf planet's volcanoes may also have a divided nature, erupting not only water but also rock, salt, and even magma. One explanation they put forward for the energy behind the eruptions posits that a major impact in primordial epochs penetrated deep into the mantle, excavating radiogenic material up from the core, emplacing pockets of geologically warm material close to the surface in localized sites within the crust, where it triggers cryovolcanism even today. This concept might

---

[1] However, ESA's Mars Express and NASA's Mars Odyssey orbiters have located several hot-spots that may indicate current low-level activity. Locations of these heat anomalies simmer in the Hellas impact basin, and within craters seen on the flanks of the volcano Arsia Mons.

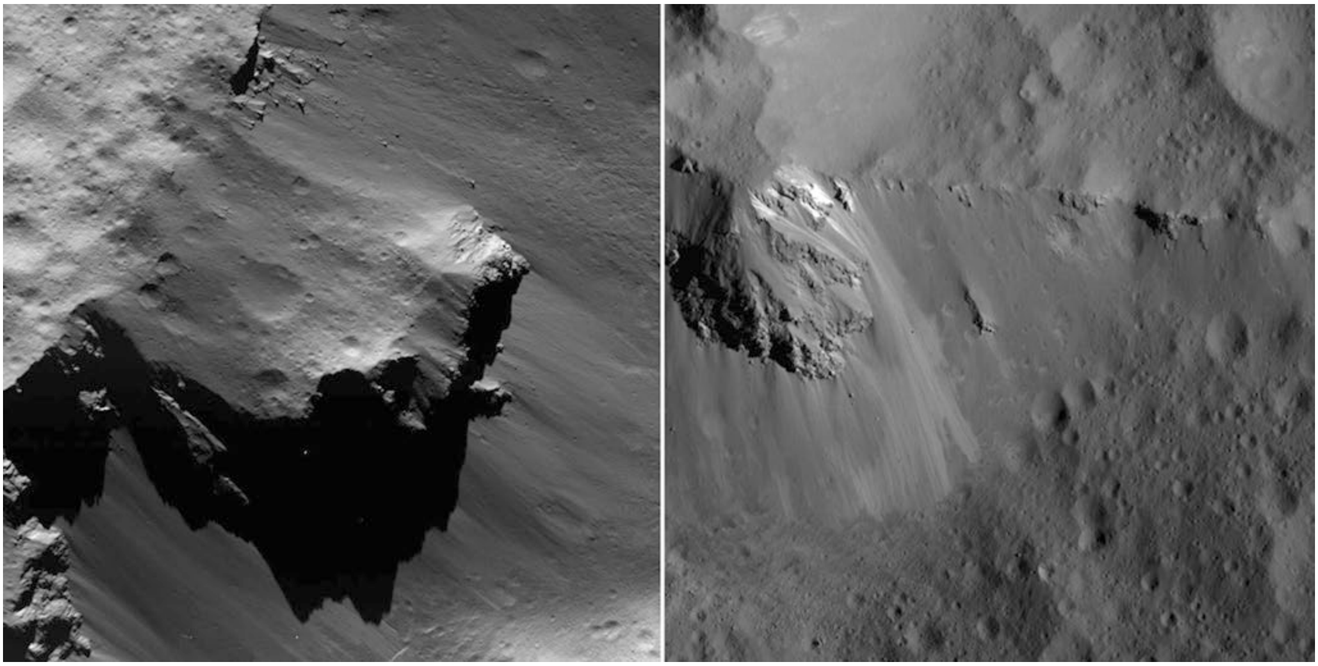


Fig. 4.4 *Left:* This beautiful image of a block separated from the rim of Urvara Crater was taken by the Dawn spacecraft at a range of 55 km (35 miles). Landslides below the massif push down toward the crater floor. Trails from rolling boulders appear at upper right. Their spiraling journey may have been started by the same event that fractured the rim section. *Right:* A similar fragment of wall fallen from another section of Urvara's rim. (Images courtesy of NASA/JPL-Caltech/UCLA/MPS/DLR/IDA)

also explain the activity in some other ice moons not subject to tidal forces.

Whatever their origin, the bizarre sludge volcanoes of Ceres put the small world in good company with exotic Enceladus, Europa, Pluto, and other cryovolcanic worlds of our Solar System.

Cool Customer

Dawn has also detected fresh ice on the dwarf world. The orbiter spotted expanding patches of ice on the walls or floors of several craters, and these morphing patches are attributed to a seasonal ice cycle. Marc Rayman's team has been studying one such crater, named Juling. "Juling is in the southern hemisphere. What happens is that as the seasons progress, in southern hemisphere summer there is greater heating on the floor of that crater, so that warms the ground and releases water vapor. The vapor comes up and condenses on the cold north wall." Observers charted an area of ice that grew by hundreds of acres. "It is water molecules being transported from one location to another," Rayman says. "Ceres is clearly a geologically active world."

Ice has been observed elsewhere on Ceres. Ceres is too close to the Sun for ice to be stable on the surface. When ice is observed, it's a clear indication of some kind of activity. The Dawn team took advantage of being in orbit to take long exposure photos in craters that have persistently shadowed regions. Rayman explains that, "ice has been observed in some of these, so they're acting as cold traps."

The "persistently shadowed craters" lie at the poles, where low Sun-angles year-round[2] shelter the deepest parts from sunlight. Temperatures in such cold traps hover below –143°C, cold enough that much of the ice remains stable – perhaps for as long as a billion years – not sublimating even in the vacuum of the Ceres environment. Similar cold traps have been found at the poles of Earth's Moon and on Mercury.

Extracurricular Activities

There are more sites on Ceres that are symptomatic of geologic activity. Some areas remind geologists of the desert southwest in the United States. Mesas rise from rolling plains, thrusting stony crowns from talus slopes. Events such as collapse and landslides have left their mark on the dwarf planet. Large blocks have broken off of crater walls in several places. A large segment has fractured and separated from the crater rim of Urvara Crater. A similar formation lies within the sodium carbonate regions of Occator Crater. On the western side of Cerealia Facula, a block of dark material has separated, leaving a mesa-like butte with a flat top. Bright sodium carbonate encrusts the capstone of the butte (Fig. 4.4).

---

[2] Ceres' axial tilt is nearly vertical at 4°, so some areas on the poles never see the Sun.

Landslides seem to be ubiquitous across the face of Ceres. This is surprising, since the gravity on Ceres is a scant 1/36 of what it is on Earth. Still, landslides on Ceres appear to be common, and many may be related to ice within the regolith (sterile dirt) of the asteroid, confirming the idea that the layer just below the surface is a mixture of rock and ice. Landslides on Vesta, which has no water in its regolith, have different forms.

Researchers have identified three types of avalanches on Ceres. Type I landslides are extensive, with lobate forms and "toes" at the end similar to rock glaciers on Earth. Type II share characteristics with terrestrial avalanches, longer and thinner than Type I. The third category may be triggered by a flash melting of subsurface ice, where surface debris flows like mud and quickly freezes in place again. Type III landslides are always linked to impact craters. The heat of impact may be responsible for their flow. Similar flows exist on Mars, where much ice lies just under the surface, and Jupiter's icy moon Ganymede (see especially Chap. 8).

The frequency of landslides is shocking – between 20 and 30% of all craters larger than 10 km (6 miles) across have succumbed to landslides along their walls. Using the shape and distribution of the flow features, researchers estimate that the upper few tens of meters of Ceres surface material contain from 10 to 50% ice (Fig. 4.5).

Avalanches have been spotted on other bodies with gravity far weaker than that of Ceres. On Saturn's moon Helene, flows form beautiful fans of rock and sand on slopes between craters. Flows occur even in environments that are nearly weightless. The Messenger orbiter documented several instances of avalanches on the diminutive planet Mercury. Comet 67P/Churyumov-Gerasimenko, which was orbited by the European Space Agency's Rosetta spacecraft, exhibits landslides on several slopes despite the fact that its gravity is about a ten-thousandth that of Earth's. One collapse was actually documented by Rosetta on the face of a scarp called Aswan. A fissure over 200 feet long opened up, exposing fresh ice and generating a torrent of dust and gas. Surface temperatures surrounding the cliff were –140°C, some 50° colder than the coldest temperature ever recorded on Earth. But sunlight illuminated a small section of the rock face, heating it to 50°C. The extremes of temperature probably fractured the rocky promontory, triggering the collapse (Fig. 4.6).

Landslides are not the only evidence of geological activity on Ceres. The Hanami Planum region displays a series of fractures across its cratered plain (Occator Crater is found here). The floors of several major craters are scored by webs of fractures. The Moon has similar floor-fractured craters that were cracked when magma lifted and bowed the crater floors. Ceres may well have undergone a similar process, with cryolavas rather than molten rock, causing uplifting. Outside of Hanami Planum, long lines of cracks and dents form a set of features called the Samhain Catenae. These are not associated with impact craters and may be the result of Hanami's rise as it was forced up by cryomagmas.

Organic Blemishes

One of Dawn's most important discoveries at Ceres – one that has caused buzz in the field of astrobiology – is the detection of organic molecules within the Ernutet Crater. These "building blocks of life" appear to have come from the interior, rather than from deposits of incoming comets or meteors. Their in situ nature means they probably came from the

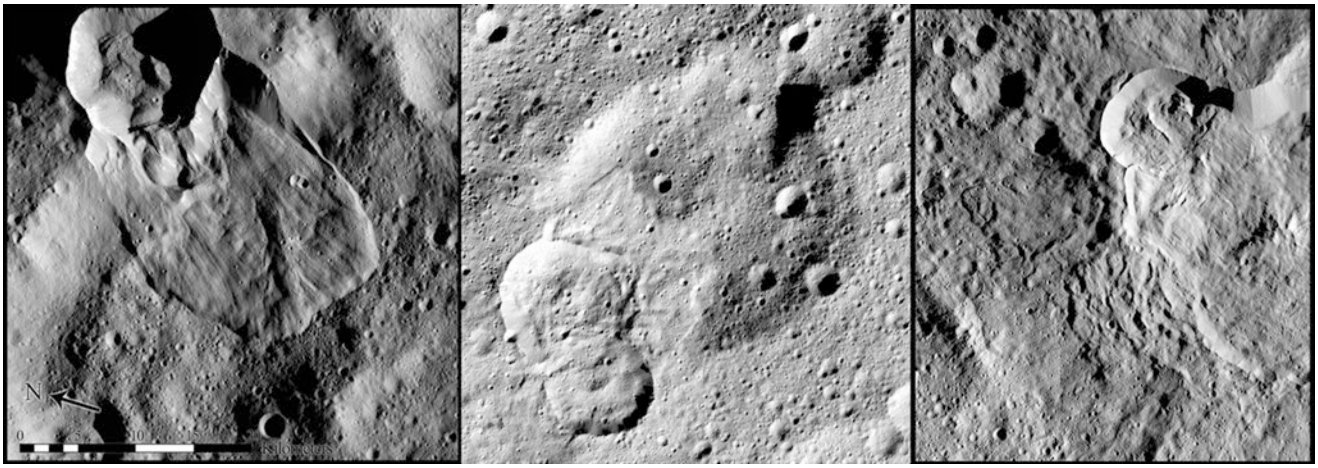


Fig. 4.5 Three types of landslides on Ceres. *Left to right:* Type I slides have rounded edges and raised "toes" at their ends, similar to rock glaciers. Type II landslides are the most common on Ceres, similar to a thin, long avalanche on Earth. Type III landslides are associated with craters, and may be triggered by the heat of an impacting meteor or comet. (Images courtesy of NASA/JPL-Caltech/UCLA/MPS/DLR/IDA)

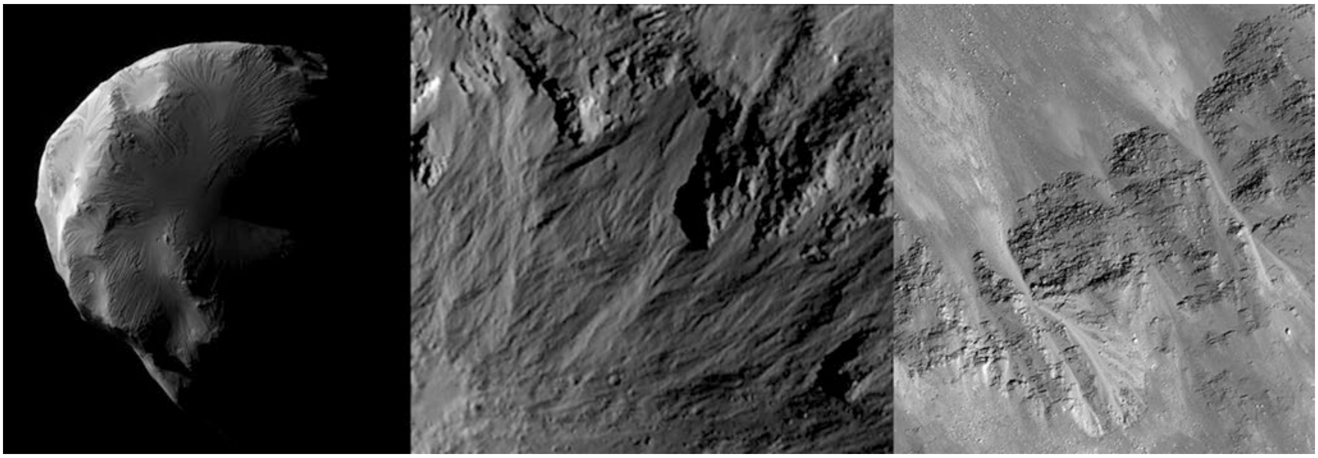


Fig. 4.6 The Saturnian moon Helene (*left*) has a tiny fraction of the gravity of the planet Mercury (*center*). Asteroid Vesta's pull is in between (*right*). All three exhibit flows and landslides. (NASA/JPL/SSI; JHUAPL/NASA; NASA/JPL-CALTECH/UCLA/MPS/DLR/IDA)

interior, and may have been percolating within a subsurface sea for some time. The Dawn spacecraft was not equipped to determine whether the organics formed by biological or geological processes, but the deposits are copious within Ernutet. A Southwest Research Institute statement asserted that the discovery has "broad implications for the astrobiology community," citing Ceres's ammonia-bearing hydrated minerals, water ice, carbonates, salts, and organics as "key ingredients for life." Ceres underscores the ubiquity of organics across the Solar System, and the importance that even ice worlds may play in life's genesis.

Ceres is a remarkable little world, and the most carefully studied of the dwarf planets. But its proximity to the Sun makes it uniquely warm compared to its close cousins in the Kuiper Belt. Scientists are careful when drawing comparisons between the asteroid and the more distant dwarf planets that formed in a very different environment far from the Sun. That environment is a realm where many ices influence the nature of the landscape and interior. But those ices are typically in gas form in the region where Ceres orbits, and Ceres undoubtedly has a greater rocky component than its chilly siblings. The outer realm of darkness is a nursery for very different worlds.

5

The Silent Ice Moons: Callisto, Tethys, Dione, Iapetus, and Smaller Moons of the Outer Giants

The gas and ice giant worlds each have an extensive family of satellites, but with one exception, each has only a handful of large, complex moons (Fig. 5.1). Jupiter has its four Galilean satellites, Uranus has its five major moons (Ariel, Umbriel, Titania, Oberon, Miranda, and Ariel) and Neptune has its trio of moons: Proteus, Triton, and Nereid. In each case, the rest of the moons range from a few to less than 180 km across. The exception is Saturn. Saturn's retinue includes so many major moons that educators have come up with a mnemonic to remember them: MET DR THIP (for Mimas, Enceladus, Tethys, Dione, Rhea, Titan, Hyperion, Iapetus, and Phoebe).

Before the Voyager encounters, we knew of only one moon intimately, the one circling our own planet. Our Moon was a great sphere of rock, cold and dead and battered. True, it had places where lava had flowed in great tidal waves across the cratered plains, and remnants of extinct volcanoes rose from the gunpowder-gray landscape. But the Moon, bludgeoned as it had been by ancient meteors, seemed today to be a calm place silently slumbering in the vacuum of space beneath the Sun's blistering heat. Exploration would reveal to us a far more dynamic world with a rich history, but the quiet Moon was the presumption we carried with us as we took our first, tentative steps into the great outer Solar System. There, we expected entire flotillas of moons as dark, cold, and "dead" as the one that greeted us in our own night skies. In some cases, our presuppositions came close: quiescent moons within the grand family of natural satellites circling the gas and ice giants. But even these show subtle hints of activity stirring within their hearts.

First Visit to a Silent Ice Moon: Callisto

Callisto is the outermost of the Galilean satellites. Its softly rolling, powdery surface bears the scars of billions of years of bombardment, virtually unchanged from within, sculpted by a drizzle of meteoroids, comets, and asteroids since its surface first solidified. From a distance, its surface is bland, sometimes punctuated by eroded craters or large ringed impact basins. But on a human scale there is much more to see. Near sunrise and sunset, long shadows crawl across the cratered plains cast by pinnacles of water-ice, some of them dozens of meters high. Spectral colors may shimmer through those ice towers, rainbows cast in an airless void. Dusty landslides leave tongues of material fanning out from icy mesas. With its own singular beauty, Callisto is at once stunning and austere.

When it comes to geologic activity, Callisto is an underachiever. Its battered face is the most ancient of all the Galileans. Some of its primeval craters probably date back billions of years ago, to a time when the Solar System was finally cleaning up the swarm of rocks and ice that hammered all of its infant planetary retinue. Its pervasive craters point to a fairly quiet interior structure. No internal forces have warped or obliterated the ancient wounds. Callisto seems out of place when compared to its siblings. The giant moon has no traces of Io's erupting fountains, no hint of Europa's wandering ridges or fragmented surface, none of the tortured scoring or folded mountains on the moon next door, Ganymede. But its lack of geologic activity leaves a tabla rasa, a blank slate from which to record the history of Jupiter's neighborhood from primordial times. Callisto is unique.

Callisto lacks the settled internal structure of a classic planet, a structure that its siblings share. All the other Galilean satellites are differentiated. Ganymede, Europa, and Io have all endured formative years in which heavy material sank to create a dense metallic/rocky core, while lighter elements such as water and volatiles rose outward, alighting in the crust. Gravity studies carried out by spacecraft, most notably by the Galileo orbiter, show that Callisto is, instead, a jumbled mix of ice and rock. It is the least dense of the Galileans, with water-ice making up about 60% of its composition and rock roughly 40%. Because of the massive amounts of ice in its makeup, the moon is less dense than Earth's own, creating a gravity field about 6/7 as strong as that of Earth's Moon, or 1/7 Earth gravity.

M. Carroll, *Ice Worlds of the Solar System*, https://doi.org/10.1007/978-3-030-28120-5_5

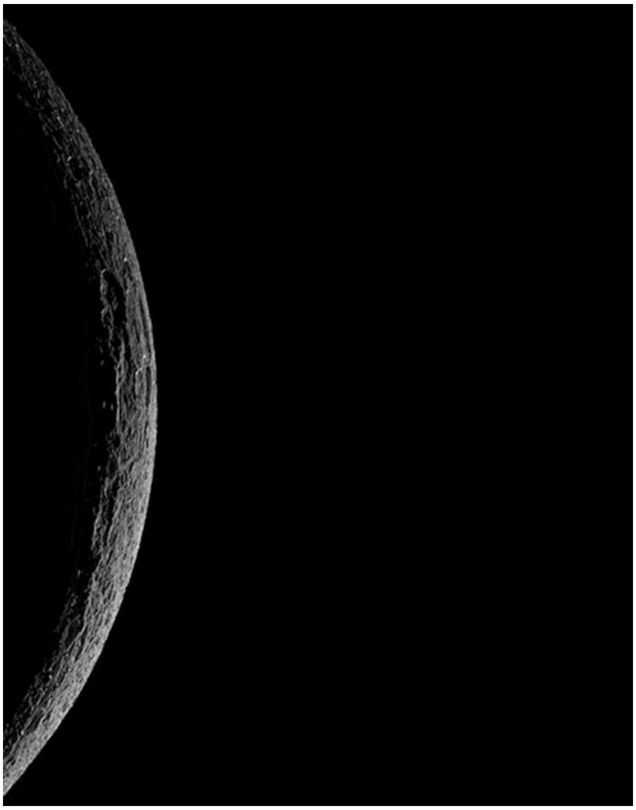


Fig. 5.1 The battered surface of Saturn's moon Dione is typical of the ancient ice worlds. (Image courtesy of NASA/JPL/SSI)

Callisto's well-mixed interior contrasts with the other three Galileans, with neatly layered interiors (see Chap. 7 for a more detailed analysis of Callisto's interior). The difference between Callisto and its siblings is due, in part, to the unique orbital interrelationship between Io, Europa, and Ganymede. Each time that Ganymede orbits Jupiter, Europa circles twice. Io follows a quartet of revolutions in the same time span. This interrelationship means the three moons are in resonance. They are linked to each other in a gravitational dance that heats their interiors. This tidal resonance has, in effect, kept the three siblings young at heart, heating their interiors and triggering active geology on their surfaces.

In the Voyager era, Callisto was seen as the most boring of all the Galilean satellites. But more recent studies have revealed a more complex portrait of the planet-sized moon. Astronomers use the reflected sunlight, the spectrum, to see what materials are present. Light can be split into a rainbow of colors. Within this spectrum, dark lines indicate the absorption of light by the surface materials. In the cases of both Callisto and Ganymede, the spectrum bears the dark absorption bands indicative of water, but also a reddish, rocky component. Callisto's dark surface contains more of this dusty material than Ganymede's does.

Callisto's assortment of craters varies from well-defined, fresh bowls to eroded arenas. Some craters have corroded into pits or soft rings, often blanketed by Callisto's ubiquitous dark dust. In many, frost clings to the crater floors, and bright ice pierces the rims. Landslides and the steady rain of micrometeorites erode features all over the globe. The smallest craters are being systematically obliterated by processes not present on Ganymede, just next door (Fig. 5.2).

Cratered plains sprawl across many regions of the ice moon. They are dark and complex in form. Here, we see some of Callisto's remarkable ice spires, isolated and scattered, lonely pillars rising from a sea of mahogany hills. Across the dark plains, craters are abundant. They range from freshly preserved, well-defined bowls to subtle ghosts of structures barely visible beneath the dust. Their presence shows that whatever process has segregated the dark material from the dark ices was at work long ago. This separation process may no longer be operating (Fig. 5.3).

Some craters come in extraordinary linear arrangements, forming remarkable chains of craters nearly identical in size and shape. Called catenae, they were first seen by the Voyagers' cameras and baffled scientists for over a decade. The lines of craters defied explanation. They could not have been created by conventional cratering, and they were not due to volcanic forces or fracturing. Then came comet Shoemaker-Levy 9, a comet found orbiting Jupiter. After a close pass by Jupiter, the comet had fragmented into a line of small nuclei. As observers on Earth watched, some twenty-two chunks of comet looped around Jupiter one last time, finally blazing into its atmosphere, one after another. The comet's train of ice fragments left a series of giant blemishes in the Jovian atmosphere. The blemishes reminded researchers of the catenae seen by Voyager. When Galileo arrived, it found several more crater chains on both Callisto and Ganymede, impressions left by past comets that wandered too close to the king of planets. Rocky asteroids, less fragile than comets, tend to remain intact until impacting on the surface (Fig. 5.4).

In some areas, Callisto's surface is more heavily eroded than in other areas. The primary agent weathering the features seems to be sublimation. Sublimation is the action of volatiles, such as frozen ice or gas, being driven from the surface by solar energy, turning directly from a solid ice to a vapor. As the ice disappears, the dark dust is left behind. Dusky, soft material banks up against the ice pinnacles, forming a wondrous landscape of buttes and casting rainbows of sunlight across undulating hills.

The genesis of these frozen spires is a quite alien process. The bedrock of Callisto consists mostly of water-ice frozen

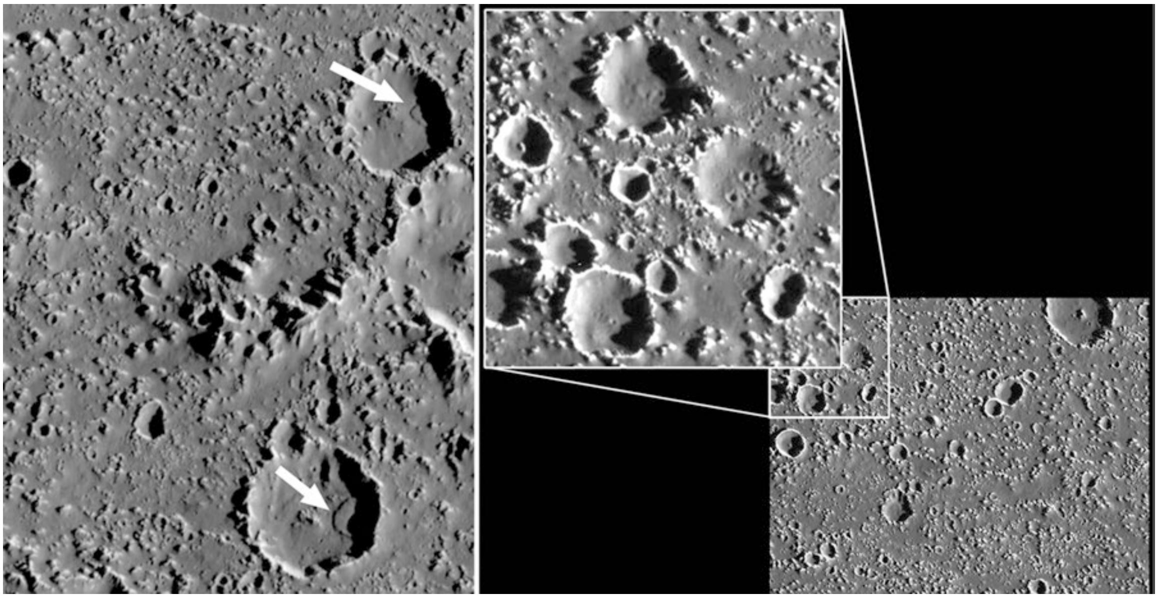


Fig. 5.2 Something is chewing up the crater rims and cliff faces on Callisto. Landslides from collapsing crater rims (seen emerging from shadows in left image) may be partly to blame, while sublimation undoubtedly also plays a part. The landslides run as long as 3.5 km (2 miles). A combination of processes may result in the mangled ice rims seen in the inset at right. (Images courtesy of NASA/JPL-Caltech)

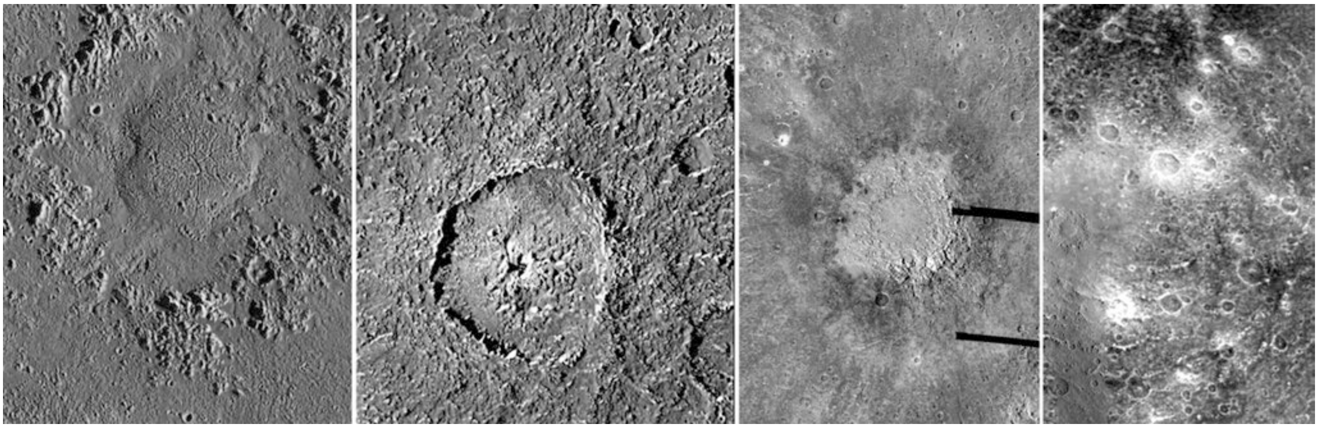


Fig. 5.3 An assortment of craters on Callisto. *Far left:* The crater Doh lies near the center of the Asgard impact basin. Its center is crowned by a large, fractured dome typical of many craters on both Callisto and Ganymede. *Left center:* The crater Tindr is 70 km (43.5 miles) across. Its intricate central pit is scored by fractures and canyons. *Right center:* Massifs ring the flat center of Lofn crater near Callisto's south pole. *Far right:* Bright rayed craters mark impact sites where fresh ice has been blown onto the surface from below. (Images courtesy of NASA/JPL-Caltech)

rock-hard. This ice is mixed with fine stony or organic dust that also blankets Callisto's landscape, along with volatiles such as dry ice (frozen carbon dioxide) and perhaps ammonia or methane. As this "bedrock" is exposed to the vacuum of space, crater rims disintegrate. Icy satellites expert William McKinnon says Callisto appears "as if something has been chewing on the crater rims." The result is a whimsical world, a succession of hundreds of meters-high ice pinnacles or mesas rising from powdery bases, many having an appearance much like the mesas of America's desert Southwest region.

In places, the pinnacle-making process leaves behind a resistant lag of downy powder. The detritus blankets the surface, protecting the ice beneath it from sublimation. The dark stuff leftover from the bedrock has thermal properties similar to talcum powder, along with hydrated minerals (clays). Voyager, Galileo, and some ground-based studies have also detected magnesium, iron-bearing hydrated silicates, and

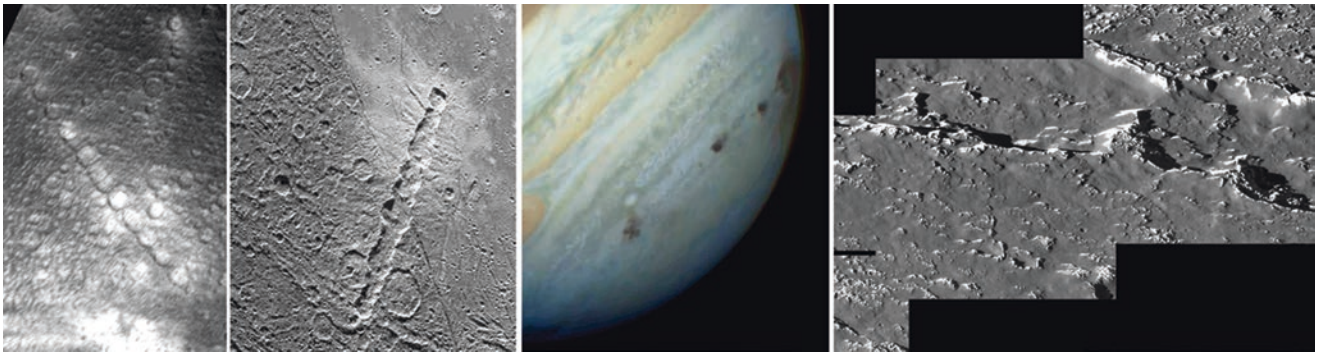


Fig. 5.4 *Left:* A chain of craters called Gipul Catena, on Callisto, resembles another on Ganymede, called Enki Catena (left center). *Center:* This shows the trails of impacts on Jupiter's clouds from Comet Shoemaker/Levy 9. *Right:* detail of a Callisto crater chain. (Images courtesy of NASA/JPL-Caltech except for Jupiter image, courtesy Space Telescope Science Institute/NASA)

condensed gases like carbon dioxide, oxygen, and sulfur dioxide, along with organic compounds. Carbon dioxide is often found in younger craters, but it and other compounds may have been implanted by asteroid impacts.

Sublimation may be at least partly to blame for Callisto's lack of small craters. Some process appears to be eroding its smaller impact features at a higher rate than on Ganymede, where fresh, small craters can be seen to the limit of Galileo's resolution. Whatever surface erosion has subdued Callisto's landscape may still be operating today.

In addition to its many craters, vast concentric-ringed structures scar Callisto's face. These basins are the largest structures on the moon, ranging in size up to Valhallah,[1] which spans an area larger than the continental United States. Although they can be found all over the globe, a cluster of them resides near the south pole – south of the 60° latitude – where Callisto's geology is the most complex and its surface is brighter.

Basins in the region include Adlinda, the mysterious, poorly imaged Heimdall, and Lofn. Lofn is 350 km (220 miles) wide, and is one of the best-preserved, and may be the youngest, impact basin on the moon. Rather than multiple concentric rings, Lofin has a central bright area of almost pure ice encircled by a smooth area within a circle of rugged terrain. Lofn was imaged by the NIMS instrument on Galileo. Results show ice becoming less pristine farther from the center. Secondary craters have brought up fresh ice from below. Lofn lies atop the more ancient multi-ring basin Adllinda. It is of similar size, but the two have quite different structures. The Adlinda impact event occurred earlier in Callisto's history, when the crust was thinner, warmer and more brittle. Lofn came along when the crust had thickened and cooled, so it has fewer concentric rings fracturing the surface.

Farther north sprawls the second-largest ringed structure of the moon, Asgard. Measuring some 1600 km (1000 miles) across, the basin would stretch from Paris, France, to Naples, Italy. At its center, the domed impact crater Doh dominates.

The largest of these impact basins, Valhallah, records rippling waves frozen just after a colossal impact blasted the surface. At its center lies a bright ice plain the size of the state of Colorado. The rings of Valhallah tell a tale of titanic forces. An asteroid visited a violent impact on the ice world, triggering tsunamis across thousands of kilometers of dark cratered plains. Fresh ice rose to the surface in the center, but the force of the impact cracked the brittle frozen surface, fracturing it into faults and dramatic cliffs. The explosion pulled the brittle crust – possibly overlaying a warmer, soft ice subsurface – toward its center, leaving behind the concentric scarps. As in some other impact basins, these concentric circles transition from ridges, close to the impact site, to a succession of graben (sunken) and horst (raised) blocks of surface.

Similar, smaller impact features disfigure other regions of Callisto. The Voyager imagery tantalizes us with hints of impact basins in other provinces, but Voyager data is too low resolution to identify them with certainty. Sadly, the Galileo mission, crippled by a jammed antenna, was unable to image many of these sites at higher resolution, so we must wait for future missions to show us the full extent of Callisto's varied features.

Callisto is a world of vertiginous canyons, ragged peaks, and dramatic views of tidal waves frozen in action. The undulating horizon, with its great spires and rounded towers of water-ice rearing up from chocolate-brown plains, give it a landscape unlike any other. For a silent moon, Callisto is spectacular (Fig. 5.5).

---

[1] Features on Callisto are named after gods and heroes of Nordic mythology, along with their homes, such as Valhalla.

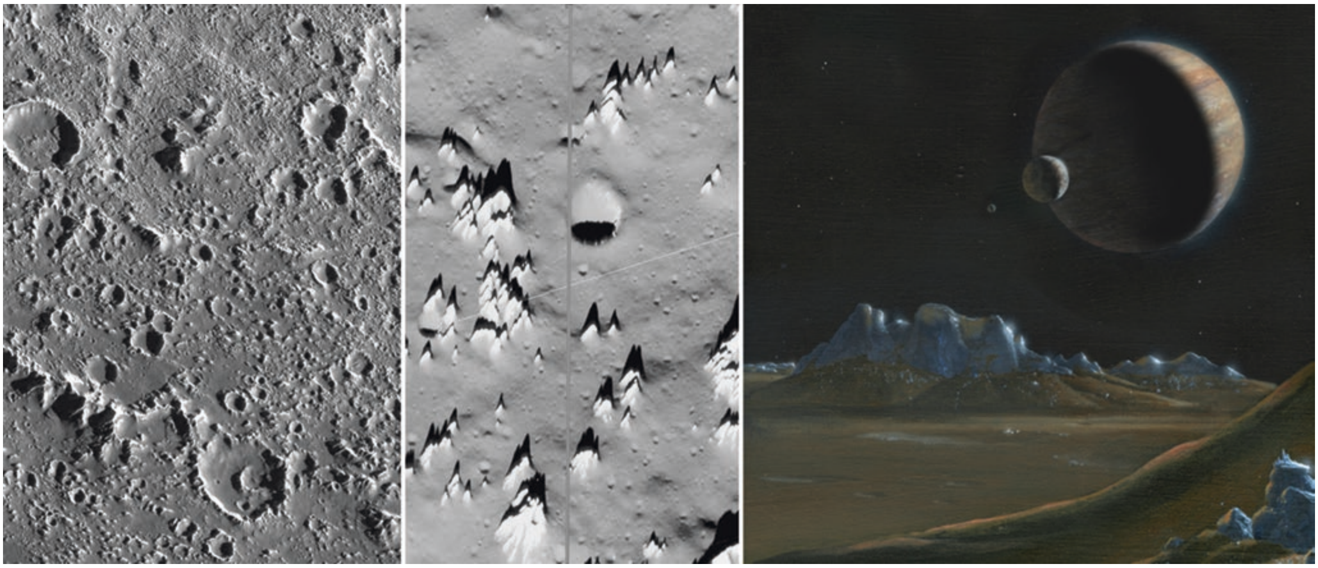


Fig. 5.5 Eroded craters on Callisto (*left*) sometimes disintegrate into ice spires (*center*) that lead to mesa-like formations, seen in artist's reconstruction (*right*). (Cassini images courtesy of NASA/JPL/SSI. Art by the author)

Saturn's Silent Moons

In 1655, Christian Huygens discovered Saturn's planet-sized moon Titan. But it was left to Jean-Dominique Cassini to discover the first four of Saturn's mid-sized moons later that century. Cassini wanted to name them the *Sidera Lodoicea*, the "Stars of Louis," to honor France's King Louis XIV. It was Louis' money that had financed much of Cassini's work to that time. But Saturn's moons ended up with names of the Titans, the sisters and brothers of Kronos (the Greek counterpart of Saturn). British inventor and chemist Sir John Herschel was first to suggest this naming tradition. John was the son of William Herschel, discoverer of the planet Uranus. The younger Herschel joined his father and aunt, comet-hunter Caroline, in the study of the heavens. John's suggested naming convention stuck.[2] And so, Cassini's four Saturnian moons became the moons Dione, Tethys, Iapetus, and Rhea.[3]

There were more moons to be discovered, but we would have to wait for a century before rounding out the MET DR THIP mnemonic. It fell to the elder Herschel – William – to discover little Mimas and its neighbor, Enceladus. Saturn's extended family of companions consists of eight moderately sized moons, along with behemoth Titan and a host of much smaller satellites. In size, Saturn's mid-sized moons come in pairs. Moving out from the planet, small Mimas and Enceladus both span diameters of about 500 km. The next pairing, Tethys and Dione, bridge diameters about twice that. Beyond them, the larger Rhea and Iapetus measure about 1500 km (930 miles) across. Smallest of the major moons are Hyperion, with an irregular diameter of roughly 360 km, and the distant outlier Phoebe, spanning some 220 km.

Like the moons of the other giant worlds, the environs of Saturn imprint personalities on the surfaces of the ice moons. Average daily temperatures rise to a scant 187°C (–305°F). At those cryogenic temperatures, the water-ice crust of these small satellites behaves much like granite. Researchers anticipated that Saturn's family of mid-sized worldlets would present unique features due to their compositions and temperatures. The Voyagers bore out their uniqueness, and NASA's Cassini confirmed it in spades.

Mimas

Smallest of the mid-sized moons is Mimas, with its famous "Death Star" crater. Mimas is also the innermost of Saturn's major moons, skimming just outside of Saturn's magnificent ring system. The outer edge of the G ring encircles Saturn at a distance of roughly 180,000 km,[4] while Mimas orbits just 5500 km further out.

Mimas fits our preconceptions of the ice moons, a cratered surface showing few signs of internal activity to disturb its surface. The surface of Mimas exhibits what is called cra-

---

[2] John Herschel went on to name a total of seven moons of Saturn and four of Uranus.

[3] By this time Titan was already known, having been discovered by Christian Huygens in 1655.

[4] The G ring's inner edge is 15,000 km inside the orbit of Mimas, but its amorphous outer edge varies by some 9000 km.

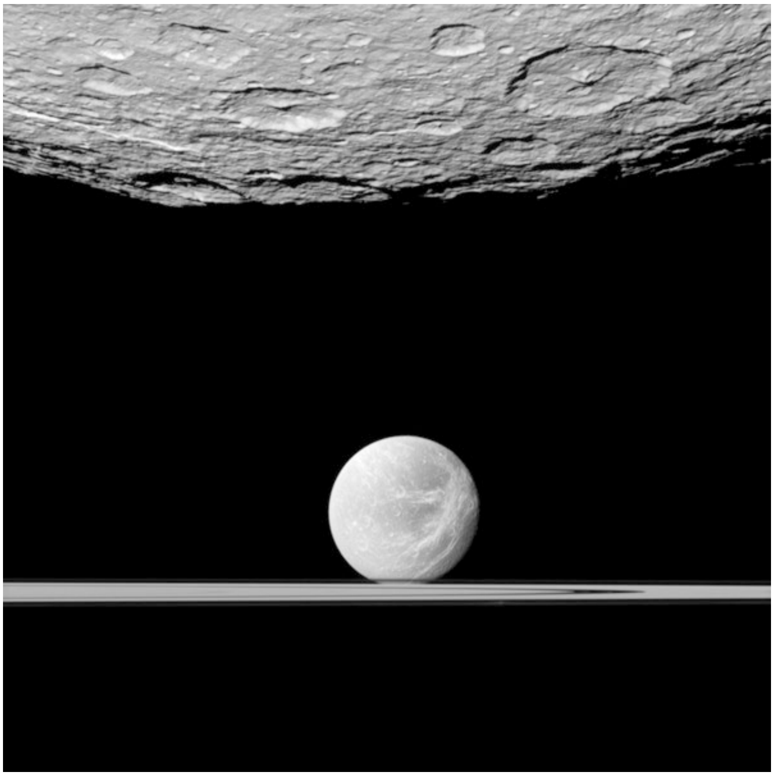


Fig. 5.6 Saturn's rings partially obscure Dione, seen beyond the south pole of its larger sibling, Rhea. (Image courtesy of NASA/JPL/SSI)

ter saturation; each impact event creates as many new craters as the old ones it obliterates. Largest of the impact features on Mimas is the crater Herschel. With a diameter of 140 km, the formation is a third as far across as the entire moon, and likely nearly destroyed it. Herschel's central peak rises as high as Mount Everest, taller than the surrounding crater walls, which rise 5 km from the average surface. The deepest part of this majestic crater dives down 10 km.

Mimas is barely large enough to have achieved hydrostatic equilibrium. In fact, it is the smallest body in the Solar System to have done so. Despite its small size, Mimas has a profound effect on Saturn's rings, clearing a path around the planet called the Cassini division. This division forms a break between the A ring and the dense B ring. Particles floating in this gap region are in a 2:1 resonance with Mimas, meaning that for every orbit of Mimas, they travel around Saturn twice. Mimas' gravitational pull upon them is subtle, but it adds up to dramatic features within Saturn's vast ring system.

Mimas may not be a frozen solid ice ball. Like all moons, it librates, or rocks back and forth, as it circles Saturn. But scientists examining images taken by Cassini have discovered that the libration of Mimas is exaggerated in one region, leading some to suspect that an interior ocean exists within the little moon. The sea may be localized or global. But other experts point out that Mimas shows no evidence of internal heating. It lacks tectonic features that often point to a subsurface layer of water. It seems more likely that Mimas has a non-hydrostatic core of rock, loosely coupled to the outer ice crust and mantle. Its surface has no relapsed craters of the sort seen on Enceladus, implying that very little heat has flowed to the surface. Although the little moon must have been in resonance in its infancy, Mimas today is a cold, static world (Fig. 5.6).

A Pummeled Trio: Tethys, Dione, and Rhea

The existence of a hidden ocean is no longer in doubt for the next moon out, Enceladus. Its violent cryovolcanism earns it a separate chapter (Chap. 6), but seas may exist within some of the silent moons of Saturn.

Innermost of these is Tethys, a glistening world of frost and crystal. Brightest of the silent moons, Tethys is much less dense than its adjacent siblings. Its density suggests that the moon may consist of nearly pure water-ice. It is the brightest of all Saturnian moons except Enceladus. Its surface is less heavily cratered than Dione and Rhea, suggesting that internal heat kept its surface pliable until after most early craters formed. This internal heating may have been tidal, coming from a resonance with other moons, although Tethys is free from such gravitational influences today. External forces contribute to its brightness: particles from the E-ring – a donut of icy dust encircling Saturn – sand-blast the surface, polishing Tethys to its lustrous sheen.

Some impurities taint the glistening face of Tethys. Whatever material is mixed in is a good match for the dark materials found on Saturn's darker moons, especially Iapetus and Hyperion, possibly some form of organic substance.

Tethys has two dramatic geologic features. In a nod to Mimas' "Death Star" formation, Tethys hosts the massive crater Odysseus, some 445 km (275 miles) across. The crater spans 2/5 the diameter of Tethys itself. Like Herschel on Mimas, its formation may have been nearly powerful enough to destroy the moon. Unlike Mimas, Tethys is large enough that the floor of its mega-crater filled in with icy slag after the impact, taking on the same curve as the rest of the moon's surface. This fact provides another clue that Tethys had a warm interior at the time of the event. If Tethys had been solid ice all the way to its core, the impact might well have fragmented the moon into a new ring around Saturn.

The other dramatic geologic structure of the glittering globe is a vast canyon system called Ithaca Chasma. The great canyon straddles ¾ the circumference of Tethys. From rim to rim, the gorge is 100 km (60 miles) wide, and its floor drops some 3 km (1.9 miles). At over 2000 km (1250 miles) long, the canyon is nearly ten times the length of the Grand Canyon in the United States.

Researchers originally theorized that the Odysseus impact was responsible for Ithaca, its shock waves fracturing the brittle ice crust. Some studies point to crater counts on Ithaca's floor, which appear to show the canyon to be older than Odysseus. One theory submits that primordial Tethys and Dione orbited Saturn in a 2:3 orbital resonance, triggering tidal heating within both. Eventually, as the orbits of Saturn's infant moons settled down, Tethys and Dione escaped their orbital dance, settling into paths that had no gravitational lock with each other.

As Tethys' interior cooled, its subsurface ocean froze. The ice expanded, rending the surface and leaving Ithaca as a scar of that past era. But another camp asserts that the floor of Ithaca is actually a preserved slice of the original surface that has sunk as the canyon dropped (this is called a graben system). If this is the case, its crater count does not reflect the true age of the canyon. In fact, craters become more frequent in the canyon as it snakes closer to the Odysseus Crater, as if ejecta from that event is blanketing the canyon that was already emplaced. The mysterious origin of the great Ithaca canyon network is still under debate.

Today, the glittering ice moon has settled into its own course around Saturn, undisturbed by any external tidal forces from other moons. Tethys is a quiet place, occasionally visited by meteor impacts but untouched by the gravitational forces of its siblings.

Its closest relative in Saturn's family is the moon just 83,000 km further out, Dione. Unlike Tethys, Dione has not settled into quiet orbital retirement. Since escaping its tidal resonance with Tethys, the moon has wandered into another one with Enceladus. For every time that Dione makes her circuit around Saturn, Enceladus circles exactly twice. This gravitational tryst sets up stresses in both moons, and may contribute to Enceladus' exquisite geyser-like activity. It also may assure Dione of a subsurface sea (see Chap. 7).

Spanning 1122 km, the icy globe is much darker than its near-twin, Tethys. It is also denser, with water-ice making up less than 2/3 of its mass. The rest of its bulk huddles within a core, probably made of silicate rock and perhaps a smaller fraction of metals. Evidence points to a subsurface sea (see Chap. 7).

Dione's face displays regions that are heavily cratered, while other areas have only moderate cratering. Some craters reach 62 miles (100 km) in diameter. Dione's craters are distinctive. Large tracts of Dione's surface are smooth and appear younger than the other moons. The craters have a distinctive shape, as if internal heating has flattened them out. In terms of geological activity, Dione is far quieter than Saturn's geyser-moon, but its surface seems more active and supple than Tethys, Rhea, or Iapetus. Researchers have studied[5] the large mountain ridge Janiculum Dorsa, an 800-km-long ridge that towers 1.2 miles above its surroundings. It is those surroundings that give hints about the interior of the moon. The landscape around Janiculum seems to have sunk under its weight, implying that a subsurface ocean of liquid water or slush lies below. The depressed surface proves that, at the very least, the crust was at one time warmer, and its heat must have come from the ice moon's interior. It is possible that the moon is still geologically active, with an interior liquid ocean. The Cassini spacecraft's magnetometer sensed a weak stream of particles drifting away from the moon.

Dione exhibits a schizophrenic face, a dichotomy common to many moons. Its trailing hemisphere differs from the leading one. Often, a moon's leading hemisphere, the face that points in the direction of travel as it orbits, is more heavily cratered than the relatively sheltered trailing hemisphere. In Dione's case, its trailing hemisphere is not only less cratered but also significantly less bright.

Dione's surface has been jumbled and fashioned by tectonic forces, some of which have resurfaced its older craters during multiple episodes. A vast, smooth plain covers the majority of its leading hemisphere. Craters here are sparser than on other surfaces of the moon.

The reverse cratering density found on Dione suggests to some astronomers that early in Dione's development, it was tidally locked with Saturn, and its leading hemisphere took most of the impacts. Later, a huge impactor may have spun Dione around so that its hemispheres were reversed, resulting in the moon we see today. The fact that it settled into an orientation exactly 180° from its original seems, to some, too coincidental. Scientists are still struggling to understand the conundrum. Dione's high albedo (surface brightness) on its

---

[5] *Icarus*, March 2014.

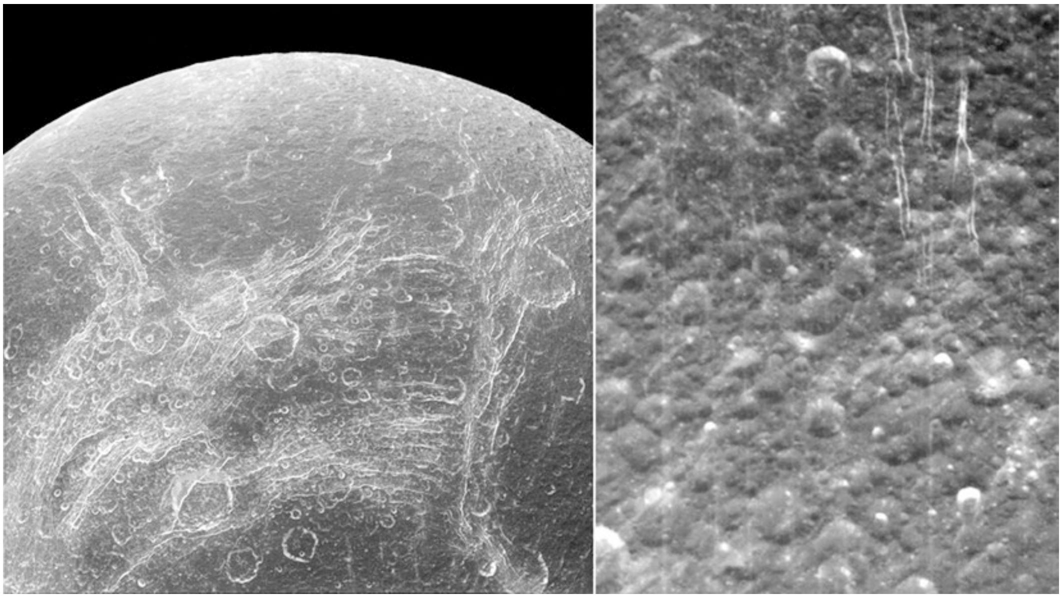


Fig. 5.7 *Left:* Dione's wispy terrain stretches across dark cratered plains, marking the faces of dramatic ice cliffs. *Right:* Dione's "linear virgae" streak across its landscape. (Image courtesy of NASA/JPL/SSI)

leading side suggests that the ice moon has remained in its current alignment for several billion years.

During the Voyager encounters, our first views of Dione revealed what scientists called "wispy terrain." The dark surface of the trailing hemisphere seemed to be lightly brushed with smoky white lines that drifted across the topography. Could these be the traces of cryovolcanism, bright deposits emanating from within? With higher resolution imaging by Cassini a quarter century later, the "wisps" resolved as a remarkable system of ice cliffs. Some of the cliffs tower several hundred meters above the cratered lowlands, stepping up across the cratered plains like a grand staircase. Many cut across craters, showing that the ice walls are a newer feature than many of the impacts (Fig. 5.7).

Lines and Arcs

Dione's cliffs aren't its only bright feature. The moon presents observers with a mystery that has yet to be solved: long, linear striations draped across mountains and craters alike. The bright streaks are called linear virgae. The marks are hundreds of kilometers long, but less than 5 km wide. They seem independent of forces like impacts or faulting of the surface, but rather appear to have been deposited from outside Dione. The virgae are younger than the ancient craters. The streaks may be related to Saturn's ring material, infalling material from nearby moons Helene or Polydeuces, or even material deposited by a passing comet.

Similar linear features on Tethys are tinted a similar reddish hue. The color is also found within a few craters on Dione, but not elsewhere. Jupiter's Europa has reddish tones on its trailing hemisphere, where ices are bombarded by radiation from Jupiter, but the Tethys lines seem to be independent of any radiation-related cause. The arcs cut across older craters and valleys, so they must be relatively younger. How young is unknown. The arcs may result from outgassing, from chemical impurities in the ice, or from features too small to detect in the best resolution returned to us by Cassini.

The arcuate stains may be only skin deep, a thin coloring on Tethys' crust. If this is the case, space weathering such as radiation and micrometeorites may make them short-lived phenomena, which means they are being actively replenished.

The lines on Dione are of a different, more linear form, although their source may be the same as the bizarre arcs of Tethys. Dione's stripes differ from linear features on other moons. Enceladus' tiger stripes, the sites of the little moon's famous jets, are deep fractures that lead to subsurface water. The valleys wander at the whim of surface terrain.

Dione's lines are unaffected by the terrain they cross. On Ganymede and Callisto, long crater chains called catena form when a comet is pulled apart in Jupiter's mighty gravity. The comet's nucleus breaks apart into many pieces, each of which impacts the surface adjacent to the last, leaving a line of attached craters. But Dione's lines are far more consistent than cometary chains of impacts. On Earth's moon and several asteroids, downhill grooves mark the path of rolling boulders. But these lines are less than 10 km long and follow undulations in the terrain. Dione's lines must be something else. Their source continues to baffle researchers.

The answer may need to wait for a new Saturn mission that can provide higher resolution images.

Dione and Tethys are not alone in their linear virgae. Another moon shares these features: Rhea. As far as Saturn's moons go, Rhea is a behemoth, second only to Mercury-sized Titan. Like Titan, it is an ice globe containing about 25% rock. Rhea's interior may be similar to Callisto's, a jumble of ice and rock evenly mixed, but this is by no means certain. Computer analysis and gravity mapping leave room for a well-mixed moon or a differentiated moon with a small stone core.

Rhea's size and mass may actually prevent it from geological activity. The moon is not in resonance with any other moon, so any surface changes from internal forces would rely on energy from radiogenic heating. Since there is no core to collect and preserve all that heat, it must have been evenly distributed throughout. Rhea must have cooled gradually. As it did, interior ice became denser and the globe shrank, compressing the surface and shutting down any early cryovolcanism. Like the wrinkles on a raisin, Rhea's ridges and cliffs may be the result of such a process.

Like Dione, Rhea has a maimed surface, but it has fewer craters on its trailing hemisphere, as is the general rule found throughout the Solar System. In fact, Rhea is one of the most blasted moons in the Solar System. It has far more craters per square kilometer than the other mid-sized Saturnian satellites. Many of its regions exhibit saturation cratering. A preponderance of craters less than 20 km across pepper other regions. This second population of impacts may have come from within the Saturnian system itself, blown from the surfaces of nearby moons. One candidate is the outer moon Hyperion, as we will see.

Rhea's polar and equatorial regions have smaller – and fewer – craters than other parts of the globe. Some sort of global event may have resurfaced the moon while later craters were still forming. Of its many impact sites, Rhea has two large basins, both on the side facing away from Saturn. The largest is called Tirawa. Tirawa is about the same size as Odysseus on Tethys, but it has not been imaged in as much detail (Fig. 5.8).

Rhea's trailing hemisphere also plays host to ice cliffs similar to those seen in Dione's "wispy terrain." They are not as extensive, but they are tectonically formed chasms with similar form and structure to those on Dione.

As for the linear virgae, Rhea's lines are more subtle than those on Dione or Tethys, but they are there, and they cut across smooth and rugged terrain just as the virgae on the other ice moons do. A faint ridge of material also runs along the equator, perhaps deposited by leftovers of the debris that led to the moon in the first place.

Rhea's equatorial ridge may be a telltale sign of something remarkable. In 2008, scientists announced that Rhea may have its own ring system. If so, it would be the first moon ever discovered to have one. Rhea's proposed rings are tenuous, denser close to the moon. Data indicates that the rings may actually exist as three separate bands. The rings were not directly imaged but rather were inferred by changes in Saturn's magnetic fields and how they interact with the moon and nearby environs. The existence of the rings was bolstered by the discovery of ultraviolet-bright spots in a trail along the equator. These may be deposits of ring material. However, the Cassini spacecraft made several directed searches to find any rings or geyser activity at Rhea, all to no avail. For now, the potential rings of Rhea are a mystery waiting to be solved.

Of this triad of quiet moons (Tethys, Dione and Rhea), one may be less quiet than the others. Dione shows signs not only of a subsurface sea but also of ancient cryovolcanism, as we will see in later chapters.

Iapetus: A Moon of a Different Color

The mysterious nature of Iapetus made itself evident to its discoverer, Giovanni Cassini, almost from the start. In 1671, the year Cassini first spotted the moon, the astronomer noticed that Iapetus seemed to brighten and fade away as it circled Saturn. Cassini saw a pattern to this dimming and brightening: when Iapetus was on one side of Saturn, it was brightest, and on the opposite it was so dim that it nearly disappeared from his telescope. Cassini knew that our own satellite is tidally locked, keeping one face toward Earth. He recognized that if Iapetus was tidally locked with Saturn, its trailing hemisphere would be the brightest face, while the leading hemisphere would be darkest. This could explain Iapetus's strange pulsating light. What he couldn't explain was why. Why would a moon have two such different visages?

The orbit of Iapetus is the most inclined of the regular satellites; only the irregular outer moons such as Phoebe and the smaller – probably captured – satellites have more inclined orbits. Of the mid-sized moons, Iapetus is the most distant from Saturn. In size, Iapetus is a near twin to Rhea, just 88 km less in diameter. But the moon is less dense, with only 20–30% of it made of rock. The rest is ice, and the rocky component is likely distributed loosely within rather than forming a core. Its surface is also much more ancient than that of Rhea, with more large impact basins than Rhea. This is significant, as Rhea has probably endured more impacts over time. It is closer to Saturn with its large gravity well. Rhea's surface was able to erase its older craters, where silent Iapetus could not.

Iapetus' trailing hemisphere is as bright as dirty snow, while its leading side is nearly as dark as asphalt. This dichotomy baffled astronomers for centuries, and the Voyager missions shed little light on the subject. In 1981, Voyager 2

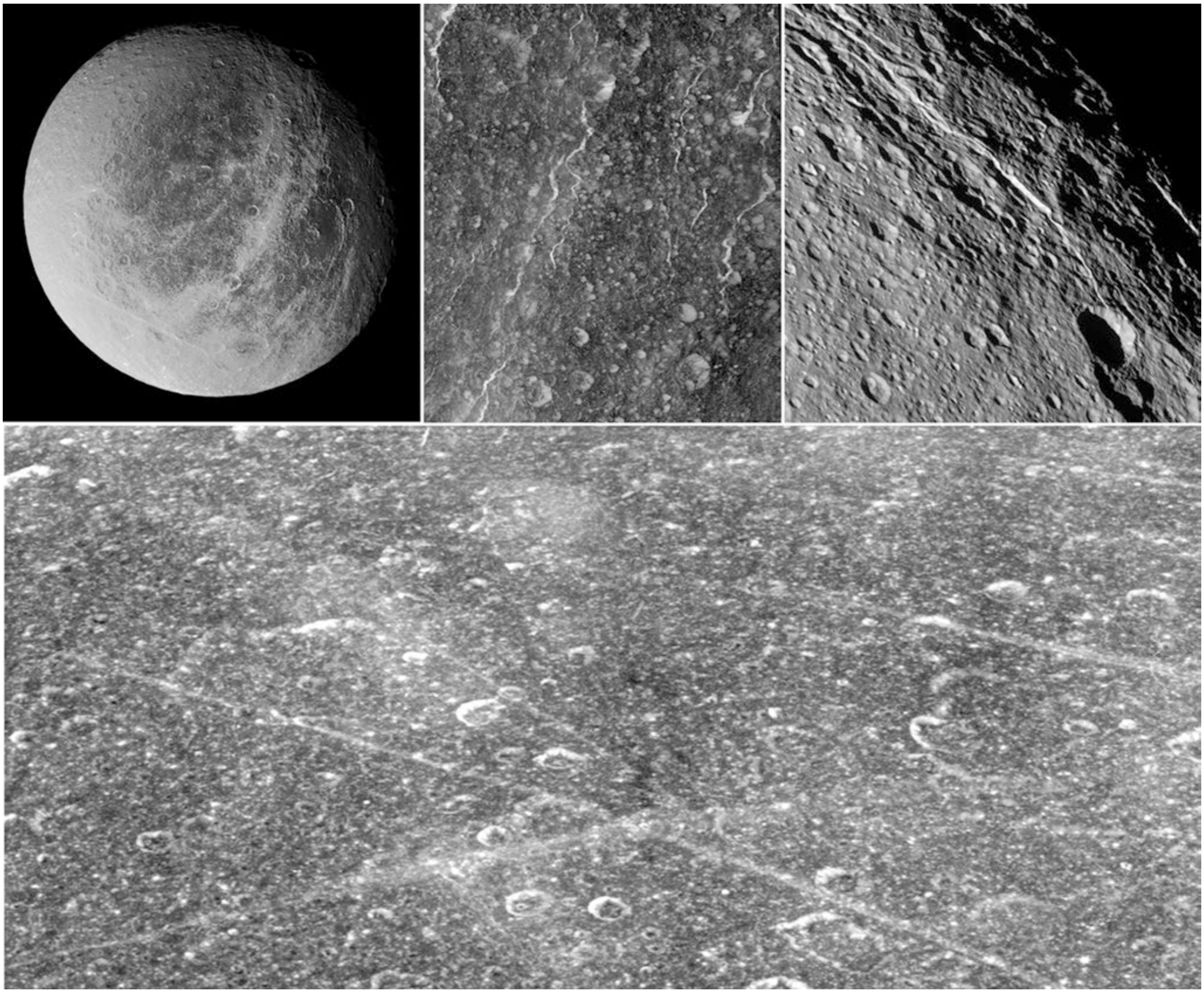


Fig. 5.8 *Top line:* The wisps of Rhea are more subtle than those found on Dione. Three views show the bright features to be ice cliffs. (Image courtesy of NASA/JPL-Caltech/SSI) *Bottom line:* The strange linear virgae seen on Dione are also seen in this view of Rhea, as crisscrossing straight lines. (Image courtesy of NASA/JPL-Caltech/SSI)

flew within 720,000 km of the strange moon. Spacecraft images revealed that both the dark and light hemispheres of Iapetus are heavily cratered. At first glance, the darker material seemed to be welling up inside some craters, as if powered by some type of cryovolcanism. An equally compelling theory, given the dearth of data at the time, advocated a rain of material falling onto the leading side of the moon. Adding to the mystery was that the dark areas were far more reddish than the prime suspect for the rain of dust, the outer moon Phoebe. The boundary between hemispheres was far too sharply defined to have been caused by simple dark "snowfall". But Voyager's distant images could not uncloak the conundrum of Iapetus' bizarre bicameral face.

The Cassini spacecraft was able to image Iapetus at far higher resolution. The first clues to the true nature of the darkened region came from the boundary between it and the lighter ice. In this transition zone, in Cassini's highest resolution shots, the scattered pools and curtains of dark materials fill in valleys and craters. Cassini radar shows that it is a very thin layer, in many places less than a meter deep. Some small impacts have pierced through to bright ice beneath. Scientists have come to the conclusion that a complex set of processes contribute to the piebald nature of the moon, beginning with temperature.

One process at work is called thermal segregation. Water-ice migrates from illuminated, warmer areas, such as Sun-facing crater walls, to nearby shadowed areas that are colder. The ice leaves behind a lag of darker material, while brightening the shadowed terrain. Cassini's thermal instruments showed that the dark material, whether intrinsic to

Iapetus's surface or deposited from the outer moons, is powdery.

The in-falling darkened, fluffy dust appears to come from Phoebe, orbiting farther out than the circuit of Iapetus. In fact, Cassini team members discovered a vast ring of dust encircling Saturn that was coming from Phoebe. The dust is swept onto the surfaces of closer moons, and especially the surface of nearby Iapetus. Over time, the reddish material heats the surface ice, warming it near the equator enough that it evaporates. That ice condenses again at the bright poles and across the trailing hemisphere. The low gravity of Iapetus – just a fifth of the ice moon is rock – enables ice to move freely around the globe, creating one of the most remarkable sites in the Solar System.

The remarkable two-toned face of Iapetus has made the moon famous in popular literature and culture. But Iapetus has another wonder: a titanic ridge that stretches along the equator like the seam on a cheap rubber ball. The ridge reaches heights of some 13 km and spreads up to 20 km wide. The peaks making up portions of the ridge are among the tallest mountains in the Solar System. The great seam branches into three parallel crests on one end. Some of its segments are 200 km long, and other sections break up into isolated peaks. The formation is one of the most perplexing features in the entire Solar System. Three aspects make it unique: it sits exactly on the equator, it is limited to the equatorial region and nowhere else, and nothing like it is found on any other planet or moon.

Some researchers suggest that the ridge resulted from a slowing of Iapetus' rotation. But why did the ridge form only on the equator, unlike the tectonic features found all over Europa and Ganymede due to similar forces?

One theory proposes that as it formed, Iapetus was spinning so rapidly that centrifugal force pushed it up at the equator. As a planet or moon forms, it “spins up” as it condenses and pulls material into it. Presumably Iapetus was spinning much faster when it froze into its current shape. But a body as large as Iapetus would tend to become oblong under such forces, and if it froze solid when spinning with a 17-hour period, it would still be turning close to that rate today. A frozen-solid Iapetus would not have enough friction in its interior to slow its rotation to today’s Saturn-synchronous spin.

Others propose that the ridge was thrust up from forces below, but this would require Iapetus' stiff outer layer to be relatively thin. In fact, the moon’s crust is thick enough that it holds up those tall mountains without deforming around them. The sinking of the crust around a heavy formation is called flexural deformation. This phenomenon can be seen on all the terrestrial planets and many moons that have solid crusts. On Earth, thickening of the crust (for example, a mountain) weighs heavily on the fluid mantle below. The mantle shifts away from the pressure above it, letting the heavy object settle into a balanced shape. Reaching this stable equilibrium is known as isostasy. The crust around the object bends inward toward it. On our own world, this “moat” around the mountain or other structure is quickly filled in with sediment, so is difficult to see. But on a moon such as Iapetus, if the mountain rises up atop a fluid interior, the ground around it should obviously sag. No such moat surrounds the Iapetus ridge, leading analysts to conclude that it did not emerge from the interior, but rather was somehow deposited onto a solid, thick crust.

Ice moon expert William McKinnon and a team of planetary geologists[6] have proposed a theory that explains the ridge’s unique characteristics. Analyzing computer models and Cassini’s most detailed images, the team describes a scenario in which a debris ring around Iapetus – the leftovers of a small moon – gradually collapsed upon the equatorial zone.

Any small moon captured by a larger body settles into an elliptical orbit, but over time tidal forces circularize its path. Depending on its direction of travel, the moon would either work its way out farther or spiral closer to Iapetus.

As Iapetus became tidally locked, turning once for each time it traveled around Saturn in its 79-day orbit, its rotation slowed, as did the orbit of its own small moon, which began to fall toward it. Soon, the gravity of Iapetus pulled the moon apart, scattering it into a thick ring of boulders, gravel, and dust. Eventually, the ring flattened, aligned to the equator just as Saturn’s rings are aligned to its own equator. Because of Iapetus’ low gravity and the dynamics of such a ring, particles would come down at glancing blows and very low speed. Some of this rain of stony debris would create craters, but the majority would build up material rather than excavating craters and destroying the surface.

We may see evidence of a similar process at two of Saturn’s small moons, Pan and Atlas. The two tiny moons share an unusual form, with pronounced ridges extending from their equators. These ridges are thought to be ring material, and this tells us something about their evolution, says Cassini Imaging Team Leader Carolyn Porco. “You have to have them embedded in a thick accretion disk to begin with. Imagine the moon is getting bigger and bigger, and the gap around it is getting bigger and bigger; it’s still accreting stuff on it and it will continue to accrete, even if the ring system around it has gotten flattened. That’s the requirement, that the ring system from which it’s drawing material is flatter than the accretion ring itself. The net result is that gravity accumulates material around the equator, and after a while the moon opens a gap so much that you can truncate the accretion.” The process may have stopped long ago, as the moons’ orbits today are thought to prevent the material around them from settling onto their surfaces now (Fig. 5.9). This timeline is backed up by other examples in the Solar

---

[6] Dombard et al., Abstract P31D-01 presented at 2010 Fall Mtg., AGU.

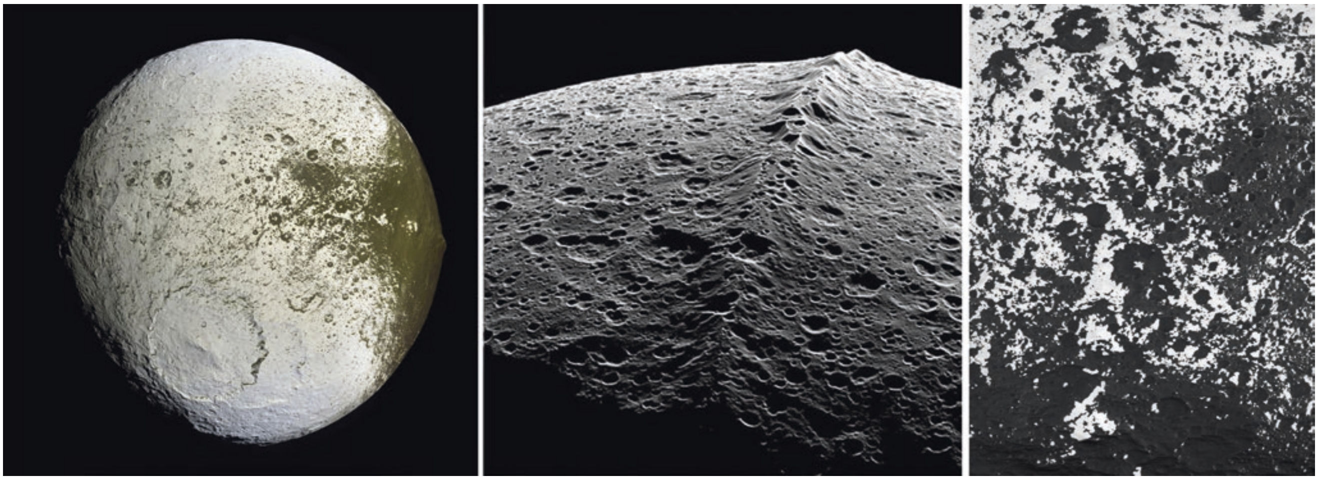


Fig. 5.9 Three views of Iapetus. *Left:* Global view of the exotic moon includes both bright and dark terrain. *Center:* The soaring Iapetus ridge poses a challenge to planetary scientists. How did it form? *Right:* The transition zone between light and dark terrain shows evidence of sorting of materials by "thermal segregation" on the surface of the ice moon. (Images courtesy of NASA/JPL/SSI)

System, says, Porco. "Look at Iapetus's ridge: it looks old, so these ridges can survive for some time."

Skeptics of the theory ask, why have we not seen this on other moons? One explanation may be that most moons orbit near other ones, so gravity disturbs their environment. A ring around most moons would not be stable because of the tidal forces from the planet. But Iapetus is so far out from Saturn that longer-lived rings could be possible. Because of its remote location, the gravity of Iapetus has an uninterrupted influence over large areas of space around it. This wide-ranging influence may have enabled Iapetus to snag a passing asteroid and keep it as a moon that would one day become its exotic equatorial ridge.

The Solar System may offer examples of variations on Iapetus's hypothetical ring. Observers have detected a debris ring around the asteroid 10199 Chariklo, a body orbiting between Saturn and Uranus. This Centaur-class asteroid probably originated as a Kuiper Belt object. It is estimated to be 250–300 km across, or one-third the size of Iapetus. William McKinnon comments, "It is a proof of concept that satellites could have rings, at least for a while."[7]

Clearly, the origin of the great ridge is still a matter of debate, but if the debris theory is correct, we may see a similar formation on another moon that has a comparable gravitational arrangement with its other siblings. That moon is Uranus's Oberon. It will be some time before we have high-resolution data on this moon. Like so many things in planetary science, we will simply have to wait for future revelations.

Outlandish Outliers: Hyperion and Phoebe

Of all the mid-sized satellites, Hyperion may be the most exotic. Its shape is strangely irregular, though the moon is nearly large enough to have reached hydrostatic equilibrium, which should have settled it into a globe. It follows a somewhat irregular path around Saturn that points to a violent past. Hyperion is about 133 km wide – just less than Mimas at its longest – with an unusual honeycombed appearance. Its surface reflects a remarkably porous interior.

Curiously, the moon is not tidally locked. Any irregular moon should point its longest axis toward its parent planet, but Hyperion somersaults dramatically as it circles Saturn. Its tumbling motion is essentially chaotic, something unseen on other bodies of its size except the moons of Pluto. Hyperion is in a 3:4 resonance with Titan, which may also contribute to its wild dance around Saturn.

This strange characteristics suggests that the moon has been chipped away by violent impacts. Its cratered surface looks like a spongy battlefield, and its low density indicates that the spongy appearance is more than skin deep.

Hyperion's craters are unlike craters on other moons. Its impact features seem to have melted, expanding the craters into deep pits. The jagged-edged cavities lie edge to edge, some overlapping or merging into others. Hyperion's low density – just half that of water – and low gravity cause the moon to react in unique ways to impacts. In-falling meteors compress the little moon's surface, rather than excavating it. Instead of forming secondary craters, most of the material from impacts blasts outward and never returns to the surface. An unknown material fills the interiors of many hollows, and landslides collapse the walls of some craters.

---

[7] For a good summary, see "Icy rings found around tiny space rock," *Science News*, May 3, 2014, p. 10.

Although Hyperion is ice, its surface is dingy. The moon's frozen water is mixed with dark, organic material, which seems to gather within its unique craters. The organics on Hyperion may be similar to those that tint nearby Iapetus. In fact, one theory posits that Hyperion was once round and suffered a major impact that peeled off most of its exterior. Hyperion's dark material spewed outward to rain down upon Iapetus, giving it its current yin/yang appearance. The dark floor material seen on Hyperion today is a remnant of the stuff that was blasted from the moon in this theoretical impact. Proponents of the idea point out that if Iapetus flew through a great dust storm, the dust would leave the pattern of deposits visible today.

During its only close flyby of Hyperion, the Cassini spacecraft was shocked – literally – by the little moon. Despite its distance of 2000 km, Cassini received a 200-volt jolt as electrons from the moon moved along the lines of Saturn's magnetosphere. Hyperion gains electrostatic charge, just as does a person walking in stockings across a carpet. The electricity builds because of the ice's exposure to solar ultraviolet radiation. As the charge builds up, a beam of electrons flows through space, following the structure of Saturn's magnetic fields and particles. Cassini happened to fly directly through the beam, sensing it with several instruments. This kind of surface charging happens to other moons as well, but it is not well understood (Fig. 5.10).

Still farther out, orbiting 13 million km from Saturn, coasts the most distant of the mid-sized satellites, Phoebe. Cassini only encountered the moon once, but at close range, as the spacecraft approached the Saturn system for the first time. It was a fast drive by. Phoebe orbits in a retrograde motion, opposite to the rotation of the Saturn system, and also opposite Cassini's direction of travel.

Phoebe is an oddball; it breaks all the rules for a moon of its size. In addition to going around Saturn the wrong way, it is small enough that it should be a solid, irregular shape, but instead seems to be held in a nearly spherical form. And Phoebe seems to be generating its own dust ring around Saturn.

Phoebe's retrograde orbit tells us that it may have flown in from afar, a captured vagabond moon grabbed by the clutches of Saturn's gravity as it glided by in the distant past. Its orbit is also eccentric – not circular – and inclined at an extreme angle. Phoebe takes a leisurely eighteen months to make one circuit of Saturn. These clues point to a capture of the moon early in the evolution of our Solar System. Phoebe came from somewhere else.

The ice moon's history is difficult to reconstruct, and offers several possibilities. Phoebe may be a member of the Centaurs, ice bodies that migrated into the main planetary region from the Kuiper region long ago. Centaurs are not considered to be asteroids or classic Kuiper Belt objects, but

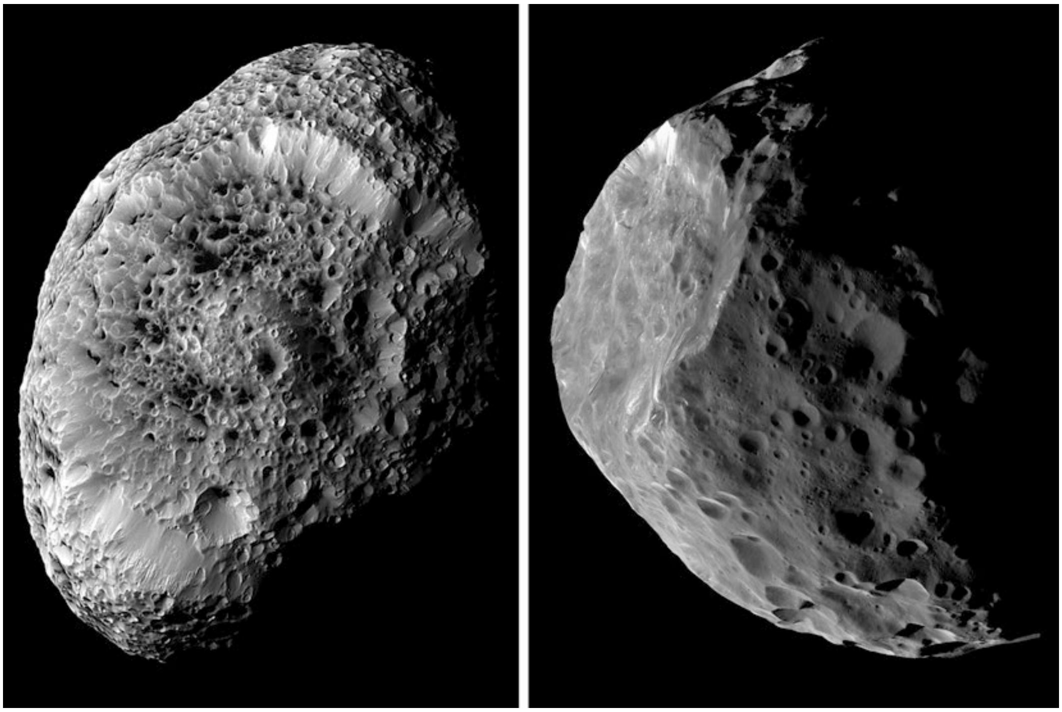


Fig. 5.10 Two oddball moons. *Left:* Hyperion's bizarre sponge-like appearance may be due to its low density. *Right:* Phoebe exhibits some characteristics of a planet. (Images courtesy of NASA/JPL/SSI)

rather make up their own family. Because of this history, Phoebe may be a primordial, very ancient object essentially unchanged from the early formation of the Solar System.

If the moon came from the outer system, its travels from the Kuiper Belt may have taken it closer to the Sun, perhaps as close as Jupiter, before capture. Once in Saturn's vicinity, there may have been even more fireworks. Phoebe may have had a sister.

Computer models show that Phoebe could probably not have been captured gravitationally if it came soaring through Saturn's neighborhood solo. For Saturn to capture Phoebe, planetary dynamicists say a third object would have been necessary. In the encounter, Phoebe's companion would have been ejected, and the lost energy would slow Phoebe enough for capture.

Another intriguing possibility is that Phoebe was a moon of either Uranus or Neptune. In the wild early days of planetary migration (see Chap. 1) one of those planets may have come close enough to Saturn to jettison some of its own natural satellites, perhaps even trading a few with Saturn.

Yet another line of evidence points to Phoebe as an outsider – the nature of its water. Newly calibrated data from Cassini's VIMS reveals the presence of deuterium. Deuterium is an isotope of hydrogen. Isotopes are elements with added neutrons that make them heavier. Normal water is made up of two hydrogen atoms and one oxygen atom, or H_2O. But the hydrogen in Phoebe's water is deuterium, a heavy version of hydrogen. This minor atomic difference in the water is a clue that Phoebe comes from the colder part of the primordial solar disk, where deuterium was more abundant. In contrast, Saturn's rings and other moons have water that is more similar to Earth's.

Phoebe is smaller than the other mid-sized moons, with a diameter averaging 213 km (132 mi). Other moons of similar size are not large enough for their weak gravity to pull them into a sphere. But Phoebe is spherical enough that internal heat may have softened its ices early in its history. Its density is higher than typical icy Saturnian satellites. This suggests that the tiny satellite may be differentiated, with a dense rocky core, making it more planet-like than many of Saturn's other moons.

The shape of Phoebe betrays characteristics of its interior. Phoebe has relaxed into something close to a sphere, meaning it has reached gravitational equilibrium. In other words, its shape is stable under the influence of its internal gravity. The moon must have had internal heating for an extended period, enabling the outer ice layers to settle into a sphere. This fact bolsters the idea that the interior of Phoebe is rocky, perhaps with enough radioactive material early in its history to heat its outer layers.

Phoebe's relaxed surface also affects the shape of its craters. Phoebe's crater rims seem to be composed, in places, of pure ice. Bright downslope streamers mark exposures of underlying ice, as do some bright, rayed craters. The craters themselves are oddly shaped, as if warped by forces from within. Some look as if there were pockets of gas or volatiles that blew the craters out from the inside. Several crater walls seem to have caved in during landslides. Many of Phoebe's craters are cone-shaped, unique among icy worlds in our expeditions seen so far. Additionally, the moon's battered face displays linear ridges, trenches, and chains of pit craters, indicating the influence of internal geologic forces.

Phoebe's landscape is littered with organics. Nearly pristine water-ice lies beneath a blanket of coal-dark surface material, which drapes over crater rims and slides down crater walls. The dark detritus may be 300–500 m deep. It has a composition unlike any yet observed in the inner Solar System. Its complex makeup differs from the rest of the Saturnian system. Cassini's VIMS instrument saw frozen carbon dioxide ("dry ice") on the surface. Phoebe's spectrum also turns toward the UV, which may indicate scattering from iron particles. Some researchers maintain that Phoebe's surface is covered with organic molecules called polycyclic aromatic hydrocarbons. These hydrocarbons contain hydrogen, oxygen, nitrogen, and carbon, the building blocks of life. They assert that these volatiles might provide some evidence for Phoebe migrating in from the outer regions such as the Kuiper Belt, where they may be in abundance (see Chap. 9). VIMS also detected cyanide and another organic compound, nitriles (Fig. 5.11).

There may be a Phoebe/Iapetus connection. We have seen that in-falling dust contributes to the darkened terrain on Iapetus, but where does it come from? If not Hyperion, it may well come from Phoebe, orbiting outside the orbit of Iapetus. In fact, Cassini team members discovered a vast ring of dust encircling Saturn and issuing from Phoebe. This dust tends to drop toward Saturn, and the moons in between get in the way. The dust is swept onto their surfaces, and especially the surfaces of nearby Iapetus. (Hyperion probably gets its share of the dark organic dust, too.) Over time, the dark dust heats the surface ice on Iapetus, warming it near the equator enough that it evaporates. That ice condenses again at the bright poles and around on the trailing hemisphere. The low gravity of Iapetus – only 20% of the ice moon is rock – enables ice to move freely around the globe, creating one of the most remarkable sites in the Solar System, and it all may start at Phoebe.

Saturn's moons constitute a variety of bodies that probably don't come from the same place. Inner satellites formed from the rings of Saturn. Hyperion may be a fragment of another inner body, or a captured object. Iapetus may be original to the system, but its density is not what the models say it should be. Phoebe and other outer satellites are probably captured objects.

With its cone-shaped craters, rich mineralogy, spherical shape, high density, and perhaps great age, Phoebe seems

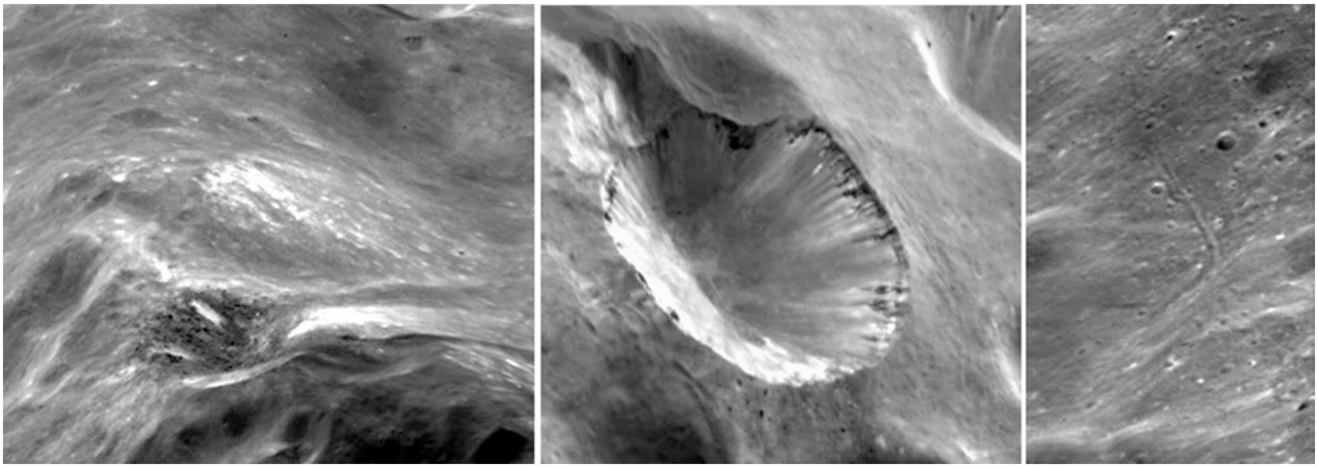


Fig. 5.11 Three views of an icy interloper. *Left:* Dark material overlays bright ice on Phoebe's slopes and crater walls. *Center:* A crater shows rare multiple layers of dark and light material, perhaps laid down by several impacts. *Right:* Chains of pits are visible in several locations. (Images courtesy of NASA/JPL/SSI)

more planet than moon, adding to the mystery and variety of the satellites of Saturn. But more icy moons sulk in the darkness of the outer worlds, the ice giants Uranus and Neptune.

Silent Moons of Uranus

The moons of Uranus may share a similar heritage to those at Jupiter and Saturn. As a gas or ice giant coalesces in the center of its accretion disk, it continues to accumulate gas, rock, and ice from the solar nebula – the cloud of dust and gas around the Sun. The disk of material, orbiting the giant planets in their equatorial planes, begins to ebb and flow, setting up eddies that lead to moons in the planet's own cloud. But the moons don't all form at once. According to several studies, as the proto-satellite cloud condenses around its parent planet and moons form within, the gravity of the newborn moons disrupts the cloud, triggering spiral waves. As the satellites grow, the effect becomes more exaggerated, so that the moons' orbits begin to spiral in toward the planet. As more material flows into the cloud, the inner satellites drop into the planet, one by one, while new ones are born toward the outside of the accretion disk.

At Jupiter, the four Galilean satellites we see today are the last of a conveyor belt of satellites that formed and fell into Jupiter as they migrated in through this disk. As the young Sun matured, it developed a sort of adolescent stage called the T-tauri phase, in which its solar wind blew most of the dust and gas from our planetary system. This stage cleared most of the protoplanetary disk, shutting off the moon-making assembly line. As the T-tauri phase tailed out and the Sun settled down, only a few moons were left behind in stable orbits.

This conveyor-belt mix of satellite birth and destruction keeps the mass of the moons at a constant total. The satellite systems of Jupiter, Saturn, and Uranus are quite different from each other. Jupiter's four Galileans are nearly alike in size, where Saturn has one giant moon along with many mid-sized ones. The satellites of Uranus are somewhat comparable in arrangement to those of Jupiter's. Even so, Jupiter, Saturn, and Uranus have similar ratios between the mass of the planet and the overall mass of the satellite system, with the satellites making up roughly one hundredth of one percent (0.0001) the mass of their parent planet.

As is the case with the gas giants, the satellite system of Uranus may have formed within the ring system or accretion disk in a sort of production line, migrating toward the planet in a long chain. But astronomers estimate that the planet was tipped over early in its formative years. The tilt of Uranus is a wild 98°. Computer simulations at the Observatoire de la Cote d'Azur in Nice, France, suggest that it would have taken several impacts to tilt Uranus into its current angle, the most severe of any planet. As the planet tipped over, the material would have continued to spin around it, trending toward a disk shape in the equatorial plane. This disk then gave rise to a succession of moons that eventually left the five major satellites we see today.

The five mid-sized moons of Uranus range in diameter from Miranda's 300 km to 1500-km Titania. The moons all consist of rock and ices of methane, ammonia, and water. In an opposite arrangement to the Galilean satellites, the moons tend to increase in density with distance from the planet. They are denser than the mid-sized icy satellites of Saturn, implying that they have more rock compared to their ice component. The smallest, Miranda, is the exception, with a very low density. Although water-ice covers all five major Uranian moons, it is mixed with a dark material of some kind. Theories range from carbon monoxide and nitrogen flung out of Uranus from its axis-tipping impacts to surface methane darkened by solar radiation. In any case, all the moons of Uranus are as dark as coal, as is Uranus' ring system.

Despite their small size, some of the Uranian moons show signs of internal activity, and perhaps even cryovolcanism. We will visit two of the recently active ones in Chap. 6. Evaluating the moons of Uranus is difficult, because so little of them have been imaged at high resolution. Because of the orientation of the entire system during the Voyager flyby, only the southern hemisphere of each was illuminated; thus only half of each satellite has actually been seen. And because of the spacecraft's flight path through the bulls-eye arrangement of planet and moons, the outer satellites were imaged only at a distance, providing intriguing but incomplete hints as to their true natures.

As in the Saturnian system, two sets of Uranian moons are twins in size. Distant Oberon and Titania measure roughly half the size of Earth's Moon. Oberon, most poorly imaged of all the moons (resolving objects down to about 12 km large), appears to have a more ancient and battered surface than that of Titania. In the best Voyager images, bright rays and blankets of ejecta radiate from several craters, while others have darkened regions on their floors. This may be due to a dark mantle of material overlaying brighter ice, as we saw at Callisto, Phoebe, and Iapetus.

At the limits of resolution, some images show subtle patterns that may be ridges or curved faults. One chasm has been verified, Mommur Chasma. Oberon's most remarkable feature, however, is a gigantic mountain nearly 14 km high. The peak stands alone on the limb of Voyager's images, with no apparent structures near it. It is by far the tallest feature on the visible terrain of this mystery moon, and is somewhat reminiscent of Ahuna Mons on Ceres. Images are of too low resolution to determine the summit's true character (Fig. 5.12).

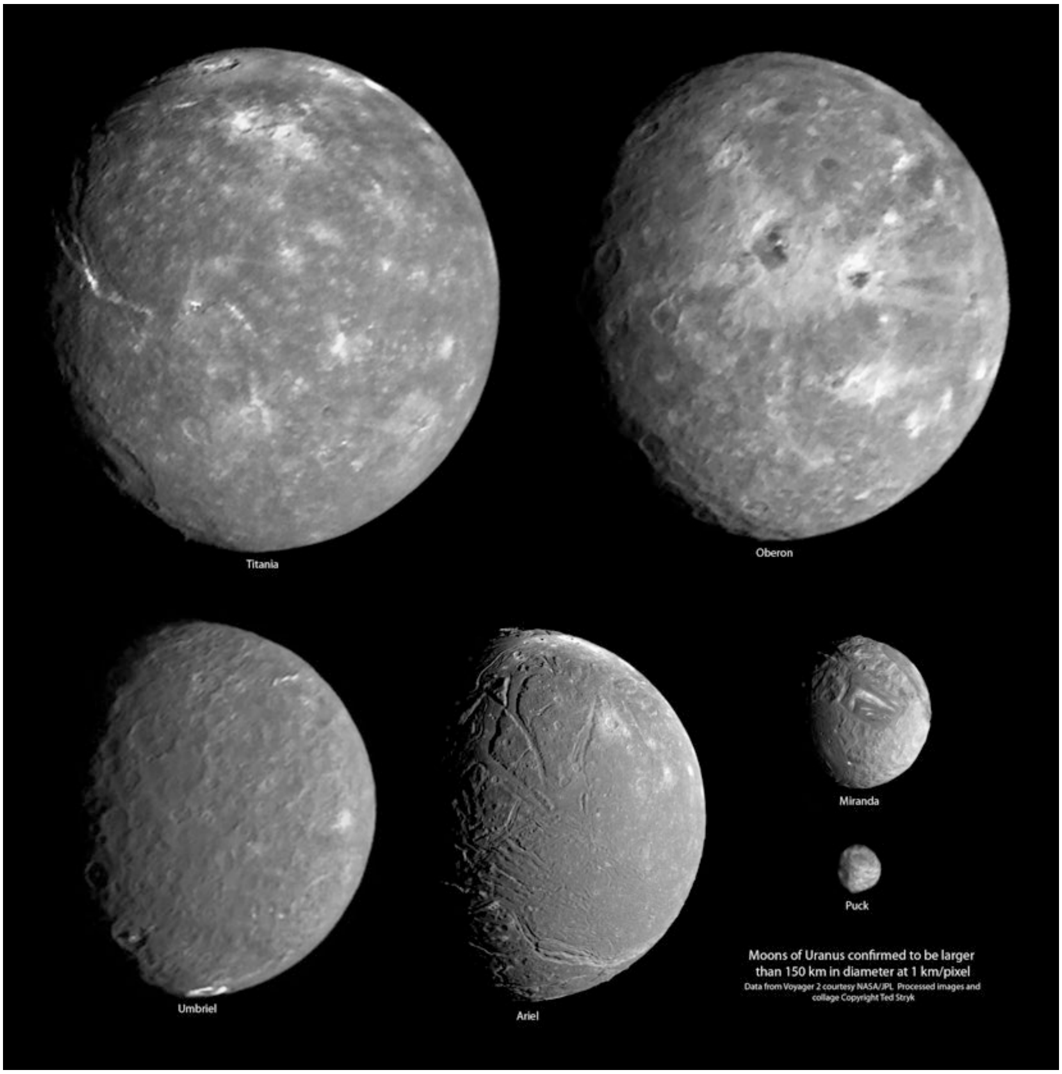


Fig. 5.12 The best Voyager images of the six largest Uranian satellites show a diverse family. (Image courtesy of NASA/JPL; image processed by Ted Stryk)

The second major silent moon of Uranus is Umbriel. Umbriel and Ariel form another pair close in size, each roughly 1150 km across. Although their sizes may be similar, their natures are far different from each other. Umbriel's dark surface appears to be uniformly cratered, with a very primitive face that has changed little from the early days of the moon's formation. This is puzzling, since Saturn's Dione is a near twin in size but has been far more active geologically. Both Umbriel and Oberon have densely cratered surfaces, while the next two moons in, Ariel and Titania, have fresher, less abundant craters. Miranda is the weird one of the bunch and will be visited separately.

Umbriel appears to have few rayed craters or bright outcrops. One glaring exception is a vast impact feature on the limb called Wunda, a 131-km crater with a dazzling ring on its floor. The bright region may be exposed subsurface ice or a deposit of carbon dioxide or other frost. Several other craters have bright central peaks. The moon's leading hemisphere is redder than its trailing one, perhaps from in-falling material. A wavy brightening of the surface at 60° longitude may be a ridge system, but seems to lie in rugged, undefined terrain just at the terminator.

These two of Uranus' five major moons exhibit the most geologically quiescent faces. Resolution is low in our only close ups, and we have seen only a fraction of their globes. It may well be that far from being silent moons, Oberon and Umbriel hold many surprises for geologists of the future.

Smaller Silent Satellites of Neptune

The smaller moons of Neptune suffer from the same low resolutions that the smaller Uranian satellites do. Nevertheless, they have a tale to tell, and their story appears to be one of drama and violence. Aside from Neptune's major moon Triton (Chap. 6), Proteus is the largest, some 420 km across. The moon has not settled into hydrostatic equilibrium, so it is out of round. This may mean that it is a fragment of a larger body. It joins Saturn's Mimas and Enceladus, along with Uranus' Miranda, as a respectable mid-sized moon. Like Mimas (but unlike Enceladus and Miranda), Proteus appears to be a battered ice world little changed from the days of its formation. But Proteus has no similar siblings. Instead, it represents a sort of bookend of a region devoid of mid-sized moons (Fig. 5.13).

In the best Voyager images, half a dozen craters can be clearly identified, along with several crests of ridges and other subtle lineations. Ridges and lineations may all be impact-related, or they may be geologically driven faults and scarps, as we have seen on some of the other small moons.

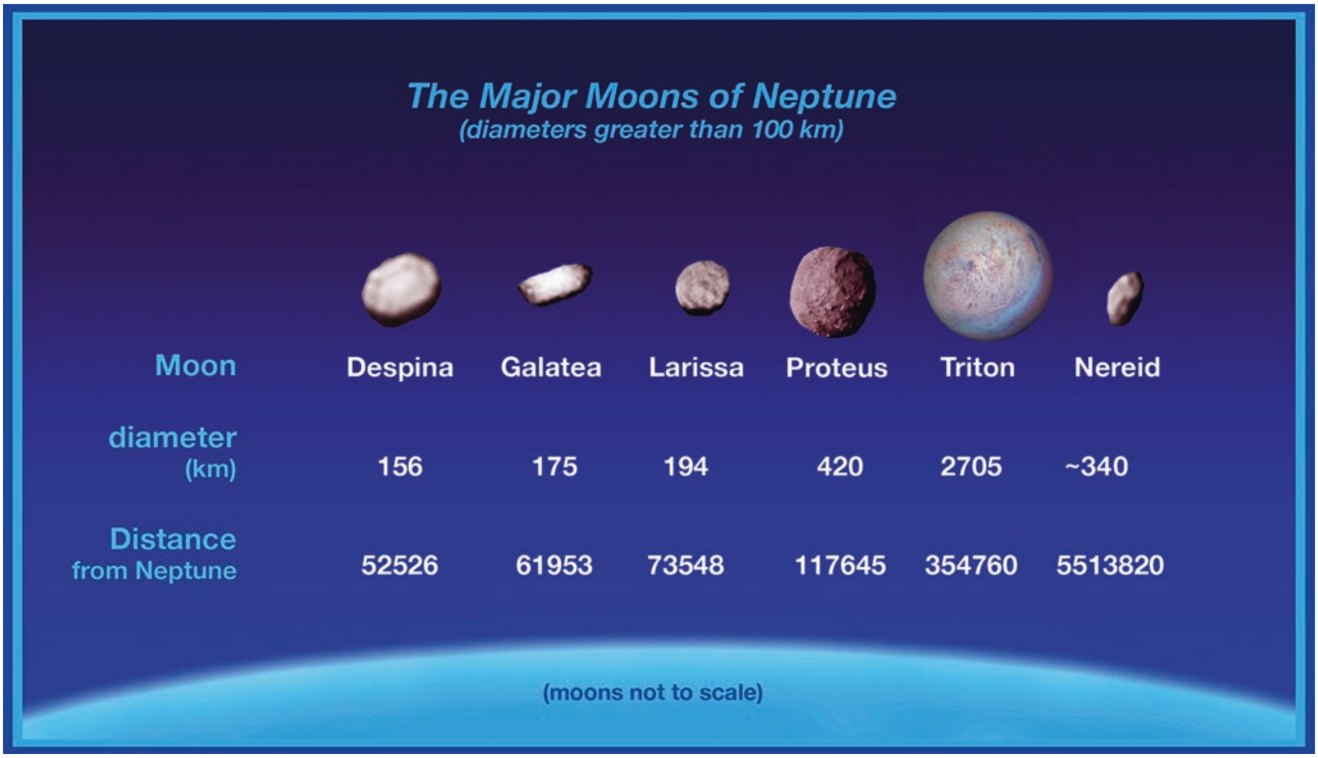


Fig. 5.13 Unlike Saturn and Uranus, Neptune lacks an extensive family of mid-sized satellites. Here, we see the best images to date of the largest Neptunian moons. Both Proteus and Neried show similar diameters to Miranda, Mimas, and Enceladus. The far larger Triton may have been responsible for ejecting other mid-sized moons upon its capture. Images not to scale. (Images courtesy of NASA/JPL)

But Proteus is far enough from the gravitational influence of its sibling moons to make this unlikely. There is a weak 2:1 orbital ratio between Larissa and Proteus that might have some effect, but we will need a closer look to know for sure.

Moving out from the blue ice giant world, the moons are arranged from smallest to largest, with the exception of Nereid. Nereid is closest to Neptune and measures roughly 60 km across. Proceeding outward, we see Thalassa, Despina, Galatea, Larissa, Proteus, and Triton, with Naiad breaking the trend in ascending size, with a diameter smaller than that of Triton or Proteus (see "Neptune's Satellites" below). Moons in the size range of Naiad out to Larissa are undoubtedly too small for internal processes and are probably cratered mountains of dead rock and ice. Larissa was imaged with enough detail to determine its size and shape, but at 4.1 km/pixel no surface features could be discerned. Galatea orbits just inside of Neptune's most conspicuous ring, called the Adams ring. The Adams ring is tightly bound, with edges never wandering farther than 50 km. It is also patchy, with variations in brightness and five ring "arcs" embedded within. Galatea may be a shepherd moon, herding the Adams material into a narrow band.

The other bookend of this region is another mid-sized satellite, this one with a diameter of roughly 350 km. It is the unusual Nereid, Neptune's outermost known moon. The moon orbits Neptune at such a distance that one revolution takes nearly an entire Earth year. Nereid has the most eccentric orbit of any planetary satellite yet found, and its path seems to be related to a cosmic encounter of planetary scale. Therein lies the root of the violent tale of Neptunian moons. The jumbled orbits of Neptune's system of satellites may be the aftermath of a colossal early encounter in which Triton passed near enough to Neptune to be captured. This violent interaction would have left Triton orbiting in its retrograde direction and would have destroyed or ejected many of the major moons from Neptune's system, leaving the remaining satellites in scrambled orbits. Triton's path eventually circularized, settling into the course it takes today and leaving behind a scarcity of the kind of mid-sized moons we see at Saturn and Uranus. In fact, Triton makes up 99.5% of the mass of all Neptunian moons currently in orbit. We'll explore this scenario more when we visit Triton's cryovolcanism (Chap. 6) and possible ocean (Chap. 7).

Aside from Proteus and Nereid, the small survivors left behind all span less than 220 km in diameter. Though their small size implies primitive, geologically quiet natures, the outer Solar System has taught us that they may well be more complex than our scant knowledge suggests. But it will be a very long time before we clearly see the shadowy faces of Neptune's extended family.

Neptune's Satellites

Name	Diameter[a] (km)	Year of discovery	Average distance from Neptune (km)	Orbital period (h) (~same as a moon's "day")
Naiad	58 ± 6	1989	48,227	7.1
Thalassa	80 ± 8	1989	50,075	7.5
Depsina	148 ± 10	1989	52,526	8
Galatea	158 ± 12	1989	61,953	10.3
Larissa	192 ± 7	1981	73,548	13.3
Hippocamp	35	2013	105,280	22.4
Proteus	416 ± 5	1989	117,647	26.9
Triton	2706 ± 2	1846	354,760	141 (retrograde)
Nereid	340 ± 25	1949	5,513,400	8643.1
Halimede	~62	2002	16,111,000	45,096 (retrograde)
Sao	~44	2002	22,228,000	2913
Laomedeia	~42	2002	23,567,000	3171
Psamathe	~40	2003	48,096,000	9074 (retrograde)
Neso	~60	2002	49,285,000	9741 (retrograde)

[a] For comparison, Earth's Moon has a diameter of 3474, and Saturn's Mimas is 396 km across

The silent moons are not boring worlds but rather bodies that offer a rich and important window into the history of the Solar System, as well as its modern nature – seen as systems of planets and moons. But with a little energy from within or from outside forces, even a small or mid-sized satellite can blossom into a wild world full of complexity and dynamism. Much of that energy plays out in the form of cryovolcanism, as we explore in our next chapter.

Cryovolcanoes on Ice Moons

6

Before we continue our tour of ice worlds, we step back and look at two characteristics that may be shared by many of them as a system: cryovolcanoes (in this chapter) and subsurface oceans (Chap. 7). These forces may play an important role in many of the worlds we are about to survey (Fig. 6.1).

For the icy satellites of Jupiter, Saturn, Uranus, and Neptune, water is among the most important constituents, at least at the surface. Although impact craters pepper the icy surfaces of these satellites, there are some apparently young, smooth areas. These areas are thought to have been resurfaced by cryovolcanism, though in some areas other processes – such as ice tectonism (faulting, fracturing, and uplift) or diapirism (the convection of solid ice) all may play a part.

In order to have cryovolcanism, a moon or planet must have liquid water in its interior, and this liquid water or mixture of water and other materials must be able to come to the surface to erupt. Many elements are important variables, including the moon's size and gravity, the amount of internal heating from radiogenic material, and the history of the moon's orbit (whether tidal heating has been operating in the past or is still going on in the present).

Another important factor in cryovolcanism is the composition of the magma, often called "cryomagma." Water alone is not enough, as liquid water is denser than ice. It is difficult for water to erupt through a solid ice crust, because the denser water tends to stay below. Cryomagmas are probably water seasoned with other components, such as ammonia or salts, which can lower their melting point and make them easier to erupt. Anyone who has lived in a cold climate has experienced this phenomenon in action. When temperatures drop and the roads ice up, snow plows deploy to salt the roads with sodium chloride and other chemicals that lower the melting point of the ice.

Additional forces may also be at work. For example, the geysers of Enceladus may be squeezed through fissures as gravitational pull from other moons and Saturn warp its crust.

The composition of cryomagmas varies with the distance of the ice moon from the Sun, because the makeup of the solar nebula – the cloud that the moons and planets condensed from – changed with distance from the Sun. Rock and metals drifted toward the inner Solar System during its formative years, while lighter materials such as ices and gases accumulated in the outer system, away from the Sun's heat and wind (see Chap. 1). Models suggest that methane and ammonia condensed from the solar nebula at the distances of Jupiter and Saturn, so cryomagmas in this region may consist mostly of these mixed with water. All of these intrinsic chemistries lower the boiling point of the cryomagmas. In the outer reaches of the Solar System, carbon monoxide, carbon dioxide, and nitrogen may play an even greater role.

Just as magmas of molten rock on Earth vary in consistency with their composition, the thickness (viscosity) of cryomagmas depends on its mix of water with other materials. Molten water would just flood a surface, filling in topographic lows. But a mixture of water and ammonia will have thicker viscosity, similar to silicate lavas. This means that some cryovolcanoes might exhibit similar forms to terrestrial volcanic landscapes: flows with high margins, shield-shaped mountains such as Mauna Kea or Olympus Mons, and dome-like features so common to Arctic regions on Earth.

Worlds made of cryogenic materials, geographies shaped by alien forces such as vacuum and tidal heating, will undoubtedly have quite alien landscapes. Some terrains will be familiar – rolling hills of ice-sand pocked by craters, looking for all the world like an Apollo landing site. Others will seem quite foreign to the earthly eye. One of the most alien regions may straddle the equator of Jupiter's dazzling ice moon Europa.

Computer simulations reveal that ragged towers of ice may crown Europa's tropical territory, making landings there deadly. Called penitentes, these ice blades may reach as tall as 15 m, the height of a four-story building, and may be arranged in dense rows spread 7.5 m apart. Researchers point

M. Carroll, *Ice Worlds of the Solar System*, https://doi.org/10.1007/978-3-030-28120-5_6

Fig. 6.1 Ice spire "penitents" may blanket Europa's equatorial regions. In this view, the gray areas are not rock but ice, darkened by impurities that have been emitted in Jupiter's strong radiation fields (there is no rock on the surface of Europa). Many strange erosional features may be present in Europa's airless environment, and cryovolcanic sources – if there are any – will undoubtedly take on bizarre forms. (Tradigital painting by the author)

to terrestrial analogs – areas with abundant sunlight and extreme cold temperatures, including ice penitentes found in the Himalayas or on the Chajnantor plain in the Chilean Andes. Penitentes in such areas form through sublimation, when sunlight turns snow and ice directly into vapor without a liquid phase, much as would occur in the vacuum of Europa or Enceladus. Irregularities in the ice surface cause some areas to sublimate more quickly than others, and bowl-like depressions form. Those sunken sites concentrate sunlight like a solar collector, which accelerates the process further. The sublimation carves the ice into blades and spires.

Circumstantial evidence for the equatorial spikes comes from the Galileo mission, which detected unusual temperatures in a band around Europa's middle. During a series of nighttime encounters, the spacecraft detected colder temperatures than expected. Some researchers theorize that the craft may have been reading the frozen tips of the blades, seen obliquely, rather than the warmer surface. Additionally, radar investigations from Puerto Rico's Arecibo Observatory indicate rough terrain there. The odd radar signals may be bouncing among crevasses and towers.

Some researchers are skeptical of the penitente prognosis, citing contaminants in the ices of Europa such as sulfur and salts, but the idea is not one arrived at in a vacuum. The New Horizons spacecraft mapped bladed regions at the terminator of Pluto, scalloped ices referred to as "snakeskin" terrain. And ice spires on nearby Callisto bear striking resemblance to penitentes as well.

Some of the most remarkable landforms issue from volcanic forces. Flows of molten material swirl and bubble into forms that any modern sculptor would envy. Volcanic vents build towers and craters, while subsurface flows cause the ground above them to collapse into serpentine hollows and valleys. Many of these bizarre geologies can be seen best on the human scale. But what have our cruising robotic explorers found?

The Volcanoes Revealed

At the time of the Voyager encounters, volcanoes were known to exist on Mars and the Moon, and astronomers suspected their presence on Venus[1] and Mercury. These were the terrestrial, or Earthlike, worlds, and volcanoes seemed to make sense on all four of these rocky worlds. But what of the colder realm beyond Mars? Could worlds of ice have their own versions of Fuji or Krakatoa?

Though not an ice moon, Jupiter's satellite Io is a chilly world of stone and sulfur, with temperatures well below the freezing point of water. Voyager's discovery of volcanoes at Io marked the first time researchers had been able to see tidal heating in action. The push and pull of Jupiter and the other Galilean satellites heats the interior of the little world, and that energy escapes in the form of Io's savage eruptions. Those volcanoes put researchers on the lookout for signs of tidal heating elsewhere, and they found it in spades.

Among Jupiter's family of Galilean satellites, Io is the innermost, and subject to the most drastic tidal forces. Next out are the icy moons Europa, Ganymede, and Callisto. Strong tidal forces affect both Europa and Ganymede, with Europa subject to the most intense of the two. It shows. Craters on the moon are rare, and its frozen landscape ripples with ridges, domes, and hollows. Upwellings of material from inside stain cracks and fissures with rust-brown materials, salty organics tinted by Jupiter's fierce radiation. In recent years, Europa has even been credited with volcanism of the cryogenic kind: cryovolcanism.

---

[1] Volcanic structures were first confirmed by the radar-mapping Soviet Veneras 15 and 16 in 1983, and by NASA's Magellan in 1994.

Volcanoes of the Chilly Kind

The word "volcano" comes from the Roman god of fire, Vulcan. Vulcan was often depicted as standing over a glowing forge, casting sparks earthward. It seems a fitting image for mountains whose cores rumble with molten rock (magma) and incandescent gases. But though the volcanoes of the inner Solar System and Io may flow with molten rock, magma is not the only recipe for volcanic eruptions. The crusts of the inner planets and Io consist of rock, so their lavas are molten rock. The outer icy satellites have crusts of frozen water – frozen to the consistency of stone – so their lavas will be liquid water. And though we are most familiar with the thundering eruptions of the terrestrial kind, our explorations have revealed alien springs of a very different nature beyond the orbit of Mars. Frigid gases escape from Triton, Europa, and Enceladus. Iceland's mud volcanoes have a cousin on Ceres, where gooey magmas of water have oozed out to form a lonely mountain among the cratered plains (Chap. 4). Strange concoctions trigger eruptions of a very different kind, powered by "magma" of unusual chemistries: super-chilled water mixed with ammonia, methanol, salts, and exotic liquefied gases. These alien eruptions are called cryovolcanism. To power these watery geysers, investigators contend that there must be substantial reservoirs of water beneath the surfaces of icy moons.

Simply put, cryovolcanism is essentially the eruption of liquid or vapor phases of water, with or without solid fragments, of materials that would be frozen solid at the normal surface temperature of an icy world. (One type of cryovolcano breaks this pattern at Triton, which we will discuss later in the chapter.)

The search for volcanoes on an ice moon is not easy. The ice surface behaves differently from rock (even though at the temperatures found in the outer Solar System, ice is nearly as hard as granite). Cryovolcano hunters must search for other evidence among the alien landscapes of ice worlds. There are morphological clues at the surface. These might include ice flows analogous to lava flows on terrestrial worlds. Eruptive sites might also develop familiar forms: steep-sided calderas (volcanic craters), vents, and chains of pits marking subsurface cryolava tubes. Domes or cones may indicate cryovolcanic sources as well (Fig. 6.2). Eventually, landers with seismometers and orbiters with ground-penetrating radar may reveal shifting forces beneath the surface, where cryomagma chambers lead to volcanic throats or fissures (see Chap. 11).

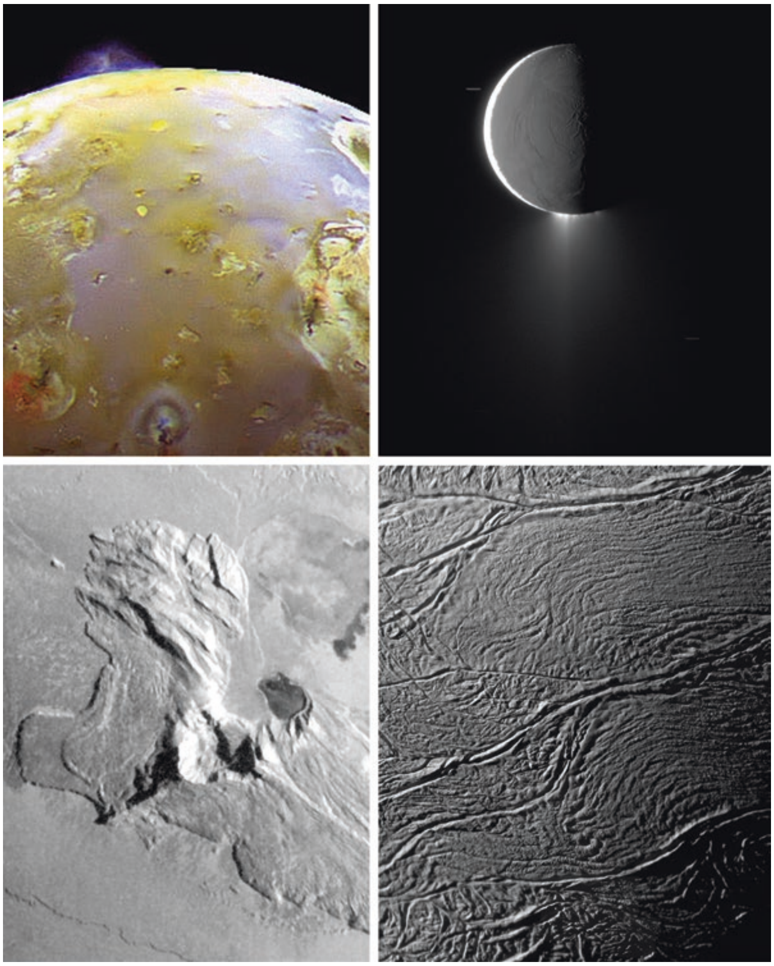


Fig. 6.2 Volcanoes compared. *Left column:* Io's sulfur and silicate volcanoes, seen against the darkness of space, issue from vents or low mounts. *Bottom view*: Volcanic structure Tohill Mons. (Image courtesy of NASA/JPL/Caltech). *Right column:* The geyser-like jets of Enceladus (*top*) issue from fissures called tiger stripes. (Images courtesy of NASA/JPL/Space Science Institute)

We begin our exploration of cryovolcanoes out of order. Rather than examining the moons of Jupiter, we first experience the most fierce and sustained cryovolcanoes known, those of Saturn's tiny moon Enceladus.

Eruptions at Saturn: Enceladus Sets the Stage

Enceladus is the stuff of science fiction. Embedded within Saturn's foggy E ring, its frozen wastelands are torn asunder by fractures and twisting canyons, their ice walls diving down into a glacial-blue darkness. Undulating mountain ridges glisten in the sunlight, powdered by mighty jets of water bursting from the moon's hidden seas.

By any measure, Enceladus is an extraordinary world. All of its surfaces – from ancient cratered terrain to recently formed ridged districts – are exceedingly bright, suggesting that the entire moon is dusted with fresh material. Its granular ice surface is, in places, a tortured jumble of twisted ridges and cracked plains nearly devoid of craters. These plains appear to have been resurfaced, with some areas having a geological age of less than 200 million years. Anything older than that has been obliterated by geologic forces. Still other parts of the surface are heavily cratered, bearing testimony to a more violent past.

A scant 504 km across, the little moon's diameter would span the country of France. Because of its diminutive size, Enceladus' geologically young surface was mystifying. After all, other nearby Saturnian moons had cratered, dead faces, despite the fact that many were larger. Even the most heavily cratered of Enceladan real estate was fresher than the cratered terrains of Rhea, Mimas, and other moons.

Upon Cassini's arrival at the ringed giant in 2004, the robotic explorer immediately felt the effects of the E ring; the environs of Saturn are inundated with atomic oxygen. As Cassini coasted through Saturn's magnetosphere, it detected changes in the magnetic field lines. These changes revealed that ions from Enceladus were shifting the structure and shape of Saturn's magnetic fields, reminding some of Io's interaction with Jupiter. But the source of the disturbances remained a mystery until a trio of flybys the following year (Fig. 6.3).

Cassini's imaging science team first spotted fountains of fine mist casting curtains of light against the starry sky. Magnetometer readings confirmed the discovery, detecting ions streaming from the moon's rarified atmosphere. Enceladus's ion stream emanated from somewhere in the southern hemisphere, just where the geysers are. In some regions, surface flows seemed to divert around low-lying hills. The movement of surface ice sometimes appeared similar to glaciers, although some researchers suggested the frozen streams might be thick cryolavas.

Thanks to the nature of an orbital mission, where the spacecraft is given the luxury of some flexibility in its exploration, flight engineers modified Cassini's orbit. A new course carried the craft within 168 km of the surface on July 14, 2005. Team members wanted detailed data on the magnetic fields and a shot at more detailed geyser images, but they got an unplanned bonus. Cassini sailed directly through

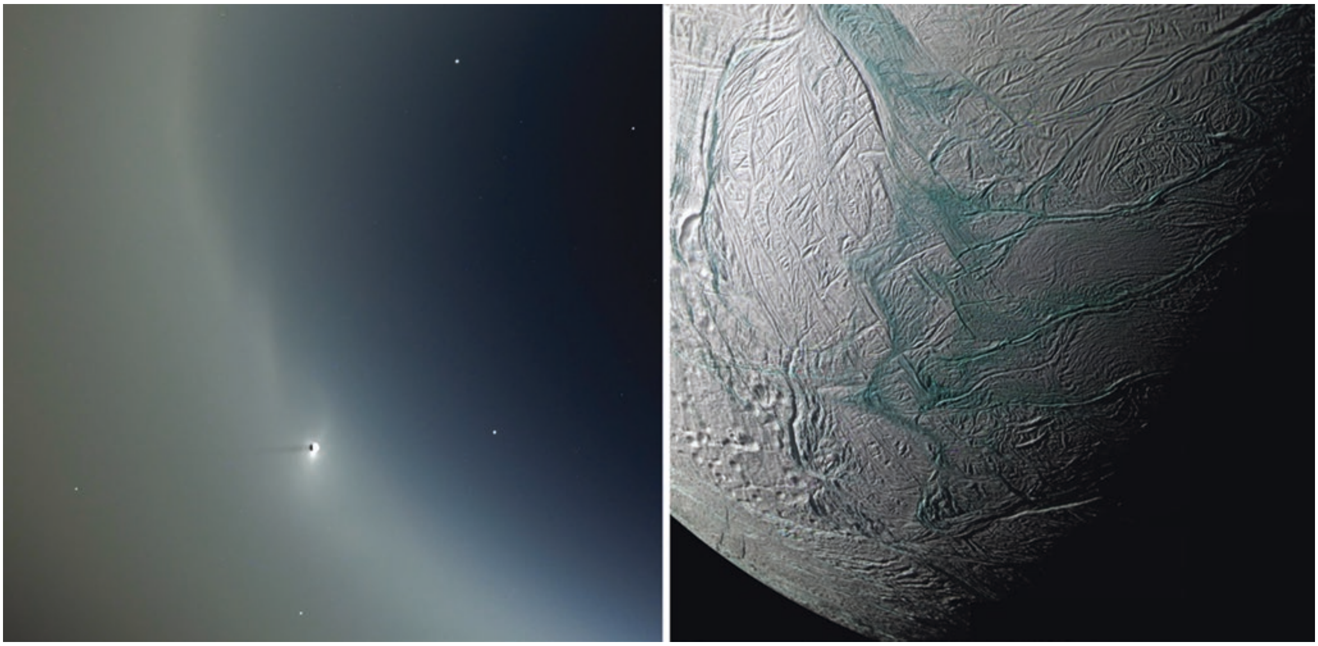


Fig. 6.3 *Left:* The violent water jets of Enceladus feed the E ring in which it orbits. *Right:* Darkened ice paints calligraphy across the volcanic southern provinces, marking the "tiger stripes" where eruptions occur. (Images courtesy of NASA/JPL/SSI)

an extended plume of material. The spacecraft detected 90% water vapor, with traces of carbon dioxide, methane, acetylene, propane, methanol, formaldehyde, hydrogen, hydrogen cyanide, hydrogen sulfide, carbon monoxide, molecular nitrogen, and whiffs of quite intricate carbon-rich molecules. Astrobiologists see six elements as essential for life (for more on this, see Chap. 10). Of these, at least four are confirmed by Cassini: carbon, hydrogen, nitrogen, and oxygen.

Cassini's instruments revealed silicate nanoparticles in the plumes, suggesting that the bottom of Enceladus's ocean could harbor hot spots, with temperatures as high as 100°C. The chemical baking on the seafloor could lead to clathrates (a lattice of water molecules trapping other molecules), which may make up the particles in the plumes (some observations point to clathrates in the ice crust of Europa as well). Something complicated is going on in the chemistry beneath that ice.

Cassini measured temperatures in the plumes as high as –136°F, some 200 degrees higher than the surrounding environment. This temperature is consistent with a mix of water and ammonia, which has long been one proposed mix for cryolavas at Enceladus and other icy worlds. Cassini's repeated visitations have given us a window into the moon's interior that we don't have for any other ice world. In addition to all that chemical excitement, the ice particles in the plumes contain sodium chloride (ordinary table salt) and other salts. Salty ice is difficult to make unless it is flash-frozen from salt water, a likely candidate for the seas of Enceladus. Although the plumes appear to be bringing up salty ice grains from the interior, the frozen spray may come from remnants of a long-dead ocean. But research and models indicate a higher likelihood that salt water exists not far below the surface of Enceladus right now, occasionally rocketing into the airless sky of the glittering ice moon.

The energy involved in this Enceladan geyser factory is prodigious. The concentration of so much energy around the south pole is somewhat baffling. Some one hundred jets send 200 kg of material into the sky each second, some of it ice and some of it mineral. The lighter particles travel so fast that they reach escape velocity, racing off to join the E-ring. Heavier particles of ice and silica rain back down, depositing themselves all over the globe of the remarkable moon.

The spectacular plumes erupt from a series of canyons and ridges bordering a flat region in the southern hemisphere. The entire province lies about half a kilometer below the cratered plains, surrounded by a circumpolar series of southward-facing arcuate scarps accompanied by chains of kilometer-high mountains. The bizarre terrain, extending across an area at roughly 55° south latitude, consists of a frosty plain etched by parallel rifts.

The sunken flats encircle a quartet of darkened gorges called tiger stripes. Ridges 100 m high bracket ravines that drop precipitously some 500 m deep. Each is about 2 km across, and up to 130 km wide. Dark material extends several kilometers to each side. It appears to erupt or seep from the rifts. The tiger stripes are roughly 35 km apart.

The surface textures of Enceladus also provide insights into its cryovolcanic processes. Researchers can tell about the nature of a surface by an effect called thermal inertia, a surface's resistance to change in temperature. Cassini demonstrated that the thermal inertia of the landscape in southern regions is 100 times smaller than that of solid water-ice, suggesting that the landscape is "fluffy," covered in fresh ice or snow. Low-density material blankets the landscapes along the southern valleys. Daylight surface temperatures in the heavily cratered northern hemisphere are consistent with the effect of sunlight on a solid ice surface. They reach highs of –201°C. But the tiger stripe formations reach much higher temperatures, soaring up to the freezing point of water. Heat is concentrated linearly along the tiger stripes. Temperatures are consistent with a heat source roughly 660 m across, which fits well with the highest resolution images of the tiger stripe ravines. The interior chemistry of the chasms fascinates geologists and astrobiologists alike. The majority of Enceladus's face is composed of almost pure water-ice. But in those tiger stripes, as in the plumes, Cassini's instruments detected ammonia, organics, and CO_2.

The specific location of the vents was unclear until Cassini's imaging team was able to lock down the location of several geysers. Carolyn Porco, head of the Cassini CICLOPS imaging team, explains, "Jets appeared to be coming from the south polar terrain, but we had to wait until we got more images to be sure of the locations. The CIRS (composite infra red spectrometer) team determined that the region is warmer than the rest of the moon, and saw several specific hot spots along the tiger stripes." After another encounter, Porco's team had in hand 2 years' worth of images from different angles. By triangulating the snapshots, they were able to pinpoint the sources of the plumes. "We found that every hot spot called out by CIRS has an associated plume," said Porco. "Finally, we have a causal connection."

More than 6.5 years of Cassini data yielded a total of 101 active jets. Although the jet material may not escape at a steady pace, the amount of water in Saturn's environment indicates that the current level of activity has lasted for at least 15 years.

Ice moon experts are faced with a problem in the Enceladus narrative. The tiny moon receives far less energy from tidal heating than can explain its energetic behavior. The orbit of Enceladus is out of round, somewhat like that of Io, so researchers initially assumed that tidal forces might be strong enough to trigger some kind of internal activity that affected the surface. The problem was that the moon next door, Mimas, has a similarly irregular orbit and bears a geologically tranquil facade. Some planetary geologists suggested that the interior of Enceladus might be heated by a wobbling motion of the satellite caused by the tug of nearby moons – tidal heating that we've seen at sites such as Io and Europa, but many experts found this explanation lacking. Most models estimated that there was not enough tidal heating within Enceladus to keep any subsurface water from freezing solid.

The current best estimate of the internal tidal power is about 16 gigawatts, eight times the hydroelectric power output of the Hoover Dam. Though this is impressive, the power output of the little moon is simply too high to be powered by tidal heating alone. Computer models incorporating the orbits of Saturn's satellites indicate that Enceladus can only muster one-tenth the observed tidal power on average. Enceladus may travel in and out of resonances with other moons, so that its output is currently higher than average. Enceladus may have been storing heat for some time and is now enduring one of its periodic active periods.

Tidal heating contributes to the equation, but something else may be adding to the power: solid state friction. As Enceladus travels around Saturn, its crust flexes with the gravitational tug-o-war of its sibling moons and mighty Saturn. Fractures in the ice open and close, alternately triggering geyser activity as water is exposed to the vacuum of space and then shutting down.

The scraping of ice faces against each other also generates interior heat, and may enable subsurface water to make its way upward more easily. This force is called sheer heating. As the solid ice moves back and forth during the Enceladus orbit, friction melts ice, and the resulting liquid escapes explosively.

A new set of models suggests that cryovolcanism may occur without vast subsurface deposits of liquid water. A team led by Sue Kieffer proposes another culprit in the generation of geysers: clathrates. Clathrates are dense compounds of ice that may make up a great deal of the upper crust of Enceladus. Researchers estimate that the clathrates extend to a depth of tens of kilometers, similar in scale to the estimated depth of the tiger stripe fractures. According to coauthor Gustavo Gioia, the advantage of this theory – dubbed "Frigid Faithful" – is that cryovolcanism can remain active at temperatures far below the freezing point of water. "Even a temperature contrast of only 40 degrees could account for the fractures and ridges we see," he explained. "The exposed surfaces of the clathrate-rich ice get heat from the warm heat source at depth. Mostly the heat (i.e., energy) they get is used to dissociate the clathrates."

The Keiffer et al model does have some problems. Skeptics point out that the scenario is only one of several possibilities, and that there are difficulties in getting the model to work with Enceladus as a whole. The reality may be a combination of scenarios. Bill McKinnon summed up the situation this way: "You can line [these theories] up like ducks. They have different plumage, but they all quack."

Another Enceladus enigma is why the geysers are centered on the southern pole. One possible explanation is that the heating started in another location, and that material was transported away from the heated area either by melting of the ice or by loss through eruptions. When a spinning object loses mass in one area, its rotation becomes unstable until the spin axis realigns itself into balance. The active region on Enceladus may have begun somewhere else, and then realigned itself with the pole, becoming stable again. An ice crust that is floating on a sea of liquid water can move much more easily, and generate more frictional heat, than ice that is frozen solid to the rocky core beneath it. The most recent calculations confirm that Enceladus likely has a global ocean with a decoupled crust that freely floats on top. In fact, some observers claim they see patterns like ancient tiger stripes in territory to the north. If true, these structures demonstrate that the eruption-torn southern terrains might migrate to the north over time.

Cornell's Paul Helfenstein has been studying some regions on Enceladus that may be ancient analogs of the currently active region. "The tiger stripes are parallel, with upturned flanks and unique patterns," Helfenstein said in a recent interview. "Enceladus itself shows us an interesting symmetry: Old, cratered terrain forms a band that loops around the poles, interrupted by the cryovolcanic province in the south. Thirty degrees from its center, arcuate scarps form a border between the cryovolcanic plains and cratered terrain. Mountains fold at the ends of the tiger stripes, indicating compression." Similar mountains are seen elsewhere, thirty degrees away from ancient linear features that resemble flattened tiger stripes. Helfenstein calls these "fossils of polar-type provinces."

Two areas bear resemblance to the southern tiger stripe province. Diyar Planitia is bounded by ridges, or dorsae, similar to those seen in the south. Diyar is almost devoid of craters, indicating a young geological age. Farther to the west, Sarandib Planitia shares many of the same formations in more subdued forms, and is modified by more craters. Sarandib appears to be the oldest cryovolcanic province, followed by Diyar. Scientists don't know if all of the provinces erupted at the same time as part of a single global event, with some dying off sooner than others, or if they each formed at different times as distinct geological events and died off sequentially.

Helfstein warns that, "Now, one has to consider a heat source strong enough to shift the diapir," or warm body of subsurface ice. The Jet Propulsion Laboratory's Bob Pappalardo and University of California's Francis Nimmo have been giving the problem some thought. In a paper published in the journal *Nature*, they asserted that the sunken topography of the tiger stripe region stems from a subsurface diapir. The warm ice causes relaxation of the surface above it. The fact that the volcanic province is at the south pole is no coincidence, the authors say. A low density diapir would cause a wobble in the spinning moon until it finds equilibrium at the south pole. An axial reorientation of Enceladus would also explain why craters on the moon do not follow the classic patterns seen on most other satellites, with the familiar difference in cratering density between leading and trailing hemispheres.

The mummies of ancient cryovolcanoes may be found far from the active tiger stripes, fossils of earlier volcanic activity somewhere else (see Fig. 6.4).

The active jets rising from Enceladan canyons make it one of the best targets in the Solar System in the search for prebiotic conditions or even active life, says Cassini's Carolyn Porco. "With Enceladus, whatever it has in its subsurface ocean is there for the asking. We strongly believe the solids are flash-frozen droplets of salty-liquid water that have organics in them, and who knows? They may even have microbes in them. Organics are surely along the tiger stripe fractures."

Across the landscape of Enceladus lies a colorful tapestry of frost, salts, and exotic chemistries. On the human scale, the colors in the Enceladan ice – and indeed on many of the ice moons – may be quite stunning. Although Enceladus is the whitest object in the Solar System, future explorers may see many color subtleties within the Enceladus landscape. Glacial ice on Earth is blue due to scattering of blue light and absorption of red wavelengths. Similar color may be visible on ice moons if their ice is exposed to sunlight in just the right way. Space weathering (micrometeorites, radiation) can cause surfaces to darken over time. For icy bodies, the darkening is likely due to the formation of complex organics, called tholins, from simple molecules such as nitrogen and methane. We see this process on Iapetus and Phoebe, among others. But on Enceladus the surface is new, brightened by the constant dusting from the geysers. Salts may tint the surface ice, changing color due to radiation processing. Some salts, like sodium chloride, change color when exposed to radiation like the Sun's UV light. Sodium chloride turns yellow-orange, and another salt, potassium chloride, turns purple.

Some ice may even come in shades of green, an insight gained from Antarctic icebergs. Icebergs are usually a bright

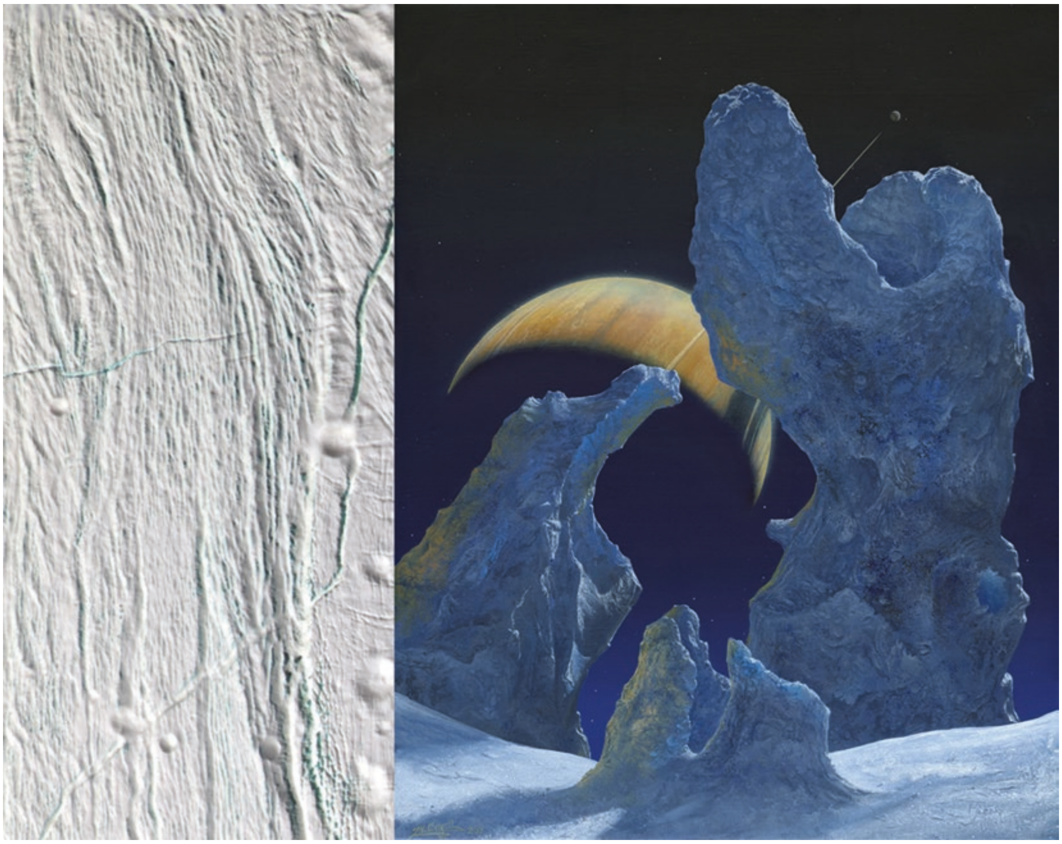


Fig. 6.4 *Left:* Diyar Planitia exhibits formations similar to the south polar volcanic terrain, and may be a fossil of ancient cryovolcanic activity. (Image courtesy of NASA/JPL/SSI) *Right:* Complex tower structures may build around the jets of Enceladus, as they do on active volcanoes in Antarctica. If the decoupled crust of the moon drifts, these formations might be preserved as they settle at locations farther north than the active sources in the southern tiger stripes. (Art by the author)

white as light bounces off air bubbles trapped within. When bubbles or impurities are missing and the ice is dense, it tends toward the blue. But some icebergs near Antarctica are green on their undersides. The striking color comes from iron oxides, which tint the ice with hues of red and yellow. The combination makes for green ice. On moons where there is direct contact between ice and rock, or where the ice has active currents within bringing up material from the interior, green ice may be the order of the day.

Enceladus is clearly one of the most exotic worlds in our Solar System. With its hidden sea, complex organics, and low incoming radiation compared to the Galilean satellites, Enceladus will be a prime target in the search for extraterrestrial life.

With Enceladus under our belt, we now have a yardstick for understanding cryovolcanism throughout the rest of the outer Solar System. Leveraging our knowledge of Enceladus, we now survey the explosive possibilities beyond.

Cryovolcanism at Europa

Even at first blush, Europa stands apart from other moons in our Solar System. Jupiter's fourth-largest moon shimmers with a brilliant white surface, the third-brightest solid object in the Solar System after Enceladus and Triton. Among the Galilean satellites, it is the brightest, shining like the lamp of Diogenes against a dark background of stars. Few craters blemish its radiant water-ice landscape. Its pristine surface is a sign of a very young age, roughly 50 million years by some estimates. Linear and arcuate stripes paint a baffling script across undulating plains, telltale signs of deep fractures and uplift. Early on, it was obvious that gravitational battles with sibling moons had sent frissons through Europa's splintered surface.

A map of Europa is – indirectly – a map of the Jovian magnetosphere. Jupiter takes less than 10 h to rotate once. Europa itself circles the planet once each 3.5 days, always keeping the same face toward the planet. Jupiter's powerful magnetosphere sweeps around the planet as it spins; Jupiter drags its radiation fields and trapped particles around it like the beam from a lighthouse. The strongest wave of the magnetosphere catches up to Europa (and to the other Galileans[2]) each time Jupiter makes one rotation. Even Io, fastest of the Galileans, falls victim to Jupiter's magnetospheric tidal wave of radiation about six times during each of its 42-h days. The moon is continually soaked in radiation, but its deadly levels rise and fall.

Jeff Morgenthaler, Senior Scientist at the Planetary Science Institute, comments, "It is more like Io is always in the ocean and the waves oscillate up and down around it in a fairly predictable (but delightfully complicated) way." Io is being constantly bombarded by plasma in the Io plasma torus, a doughnut-shaped cloud of radiation that rotates around Jupiter within the magnetosphere. "Io never entirely escapes it even as that structure wobbles in Jupiter's magnetic field," Morgenthaler explains. "The torus has a very complicated shape. It is also shifted a bit by some electromagnetic magic of material flowing down the magnetotail (the elongated part of Jupiter's radiation belts, stretched behind the planet by the solar wind). All this structure ends up making a difference for how much of the Io plasma torus material hits Io. There are waves on waves." The primary surge occurs approximately when Jupiter's magnetic field crosses Io's orbit at Io's position.

On Europa, which orbits outside of the torus but well inside the magnetosphere, fierce radiation bombards the trailing hemisphere, darkening impurities in the surface ice. The leading and trailing hemispheres of Europa are dramatically different from each other because of millions of years of this magnetospheric barrage. The radiation falling across the trailing hemisphere is brutal, but the leading hemisphere is sheltered from much of it,[3] making certain areas of the moon more habitable than others. This bit of important trivia will become critical as we search for in situ life there, and as we plan to explore with both robots and humans (Fig. 6.5).

Planetary geophysicists realized that Europa was subject to tidal heating similar to its sibling Io, although to a lesser degree. This meant that volcanic activity might present in two forms. First, the core of Europa might be heated enough to host seafloor volcanism, a biologically important prospect. But the effects of these volcanoes, perhaps a hundred kilometers below the surface, might not be obvious on the surface. A second type of volcanism, geysers erupting from the ice, might also be present. Investigators got to work searching for evidence of either – or both.

Our first close views of Europa from Voyager demonstrated just how different the little moon was. It lacked large impact basins completely, and a web of dark linear streaks stretched across the entire globe. These formations are called dilational bands.[4] They form as Europa's ice shell fractures and pulls apart, typically in a north-south direction, allowing liquid or slushy ice to rise from beneath. Other linear forms are thinner and may be created in different ways; some of the

---

[2] Even Io, fastest of the Galileans, falls victim to Jupiter's magnetospheric tidal wave of radiation about five times during each of its 42-h days. The moon is continually soaked in radiation, but its deadly levels rise and fall.

[3] This situation is the opposite concerning cratering; the leading hemisphere of many moons is more heavily cratered than the trailing, because it faces into the direction of travel, and of the incoming meteor debris.

[4] Initially known as "Triple Bands," these pathways take on many forms beyond their initially recognized triple-banded structure.

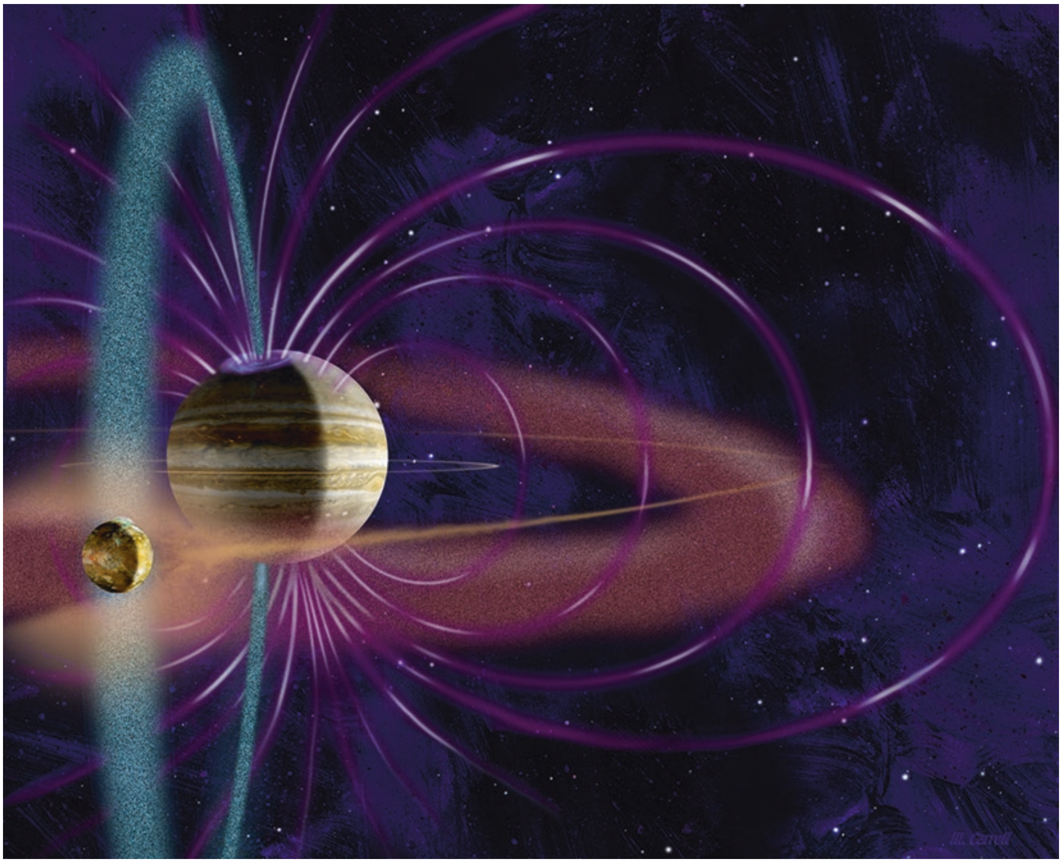


Fig. 6.5 Embedded in a sulfurous cloud, Io travels in a roughly equatorial path. The Io torus (orange) wobbles around Jupiter at an incline, locked to Jupiter's sweeping magnetosphere (purple lines). A highway of charged particles called the flux tube (blue) flows from the poles of Io to the magnetic poles of Jupiter, some 5 million amps strong. (Art by the author)

ribbed valleys run on top of others, and some stretch in a series of arcs. The general term for Europa's remarkable calligraphy of stripes is "linea."

Researchers began offering explanations immediately. Models attempted to describe conditions beneath Europa's bizarre, corrugated facade, ranging from soft ice to an ocean 100 km deep. The Galileo mission followed, imaging Europa from much closer range.

High-resolution images taken by the Galileo orbiter showed further evidence of a vast ocean on Europa. In places, the ridged surface split into sections of ice called rafts. These rafts appeared to have shifted and rotated before freezing solid again. Many of these rafts could be fit back together like a moon-sized jigsaw puzzle, clearly indicating that a once continuous surface had been broken up and shifted around. Although the plates looked like icebergs, they may not have been "floating" in seawater. Instead, they may have fractured and twisted atop a layer of warm, soft ice before settling down into their current positions.

Gravity studies and magnetospheric data confirmed a massive quantity of salt water beneath the ice, but to determine whether it was localized or global would have to wait for more data. Whatever its true internal form, Europa was clearly far more of a "water world" than Earth. Any Europan cryovolcanoes would need to be understood in light of its supposed sub-surface ocean.

Indeed, the fingerprints of leaking vapors and resurfaced landscapes lay across much of Europa's face. Something there was geologically active. But the Voyagers showed no evidence of cryovolcanic eruptions.

With the arrival of Galileo and the receipt of its higher-resolution images, further headway was made in understanding at least the possibilities for causes of the strange Europan patterns. The new revelations seemed to bolster the idea that active eruptions – or flooding onto the surface of some type – was present, at least in the recent past. Dozens of sites on the moon hint at past eruptive events involving water that has rapidly frozen in Europa's near-vacuum environment.

One of the clues leading to this conclusion lies within the highway-like dilational bands. These parallel stripes give rise to Europa's famous cracked eggshell appearance. In Voyager images, structures within many of the linea appeared as bright lines running down the center of a dark, well-defined stripe. The bands are less than 15 km across, but run over Europa's face for thousands of kilometers. The stripes are directional, with bands in the northern hemisphere tending in a northwest direction, and southern bands tending toward the southwest. This directional tendency suggests a relationship with Europa's orbital stresses. Galileo's imaging system revealed the borders of the bands to be diffuse and irregular in some areas.

One early theory for dilational band formation proposed a tidally induced fault breaking through the ice to the ocean below. In this scenario, a "cryolava" of briny water oozes up to seal the vent, while geyser-like eruptions vent from weaker locations. This style of cryovolcanism is referred to as "stress-controlled cryovolcanic eruption." The water eruptions coming out of linear fissures might be analogous to rift-magma eruptions on Hawaii, or to the fire fountains of Io's Tvashtar Catena. As the region around the fracture builds vertically, the weight of the growing ridge pulls on the surrounding ice, causing parallel fractures. These cracks, in turn, develop into more parallel ridges, duplicating the process as the band expands in girth.

The dilational bands may form in a different way. The ridges may mark boundaries of colliding ice plates. These compression ridges sink under their own weight. As the surrounding ice is pulled downward, the sunken troughs along the ridge fill with dark material. Although the details of the complex band morphology are not yet understood, it appears that the ridges bear similarity to the mid-Atlantic ridge, where seafloor spreading builds new territory beneath the Atlantic Ocean. Several shared characteristics are remarkable: fields of small hummocks scatter along parallel faults, and troughs rise to form a central axis. Terrain on either side of the medial troughs appears to be spreading symmetrically away from the center.

Along some linea, the bright ice surrounding the ridges has been painted by splotches that tint the landscape without changing its morphology. Even the central bright medians display patchy sites with halos of bright material spilling across the dark outer band. The amorphous, often radial discoloration may be the fallout from geyser-like activity. Such stained sites are called "painted terrain." Many such features exist on Europa, and most are associated with fractures or faults. The brown stains appear to be endogenic (generated from the inside), but whether they are localized events or global in nature remains to be determined. Some have well defined, flow-like, or pooled edges. Others are diffuse, fading at the boundary. Often, the dark material blankets the surrounding terrain like particulate matter rather than a flood of liquid, is reddish, and is darker than the surrounding landscape. It may be the expression of briny subsurface lakes. Radiation tints surface ices in rusty tan or greenish-gray, especially on the trailing hemisphere. Once the surface is stained, it brightens over time. Older linea are nearly the albedo of the surrounding plains on which they lie.

Just what is this dark material? The Galileo spacecraft gave scientists enough data to identify several candidate substances, including various salts, with magnesium sulfate (like Epsom salts) as the best spectral match. However, other investigators argue that Europa's spectra best matches hydrated sulfuric acid. Salts are not brown, but sulfur is. The inner Jovian environment is bathed in sulfur, thanks to Io's eruptions. Still other researchers have suggested iron compounds that presumably issue from the rocky core.

One of the best documented of the dilational bands is the majestic Rhadamanthys[5] Linea. Rhadamanthys rambles across the frozen plains like a crazed railroad track, cutting through wide brown bands, splitting hollows and domes, and tracing its scalloped gorge along 2000 km of shimmering ice. Along its borders, dark ovals and irregular blemishes emerge from within its central valley, giving the appearance of a beaded necklace. In places, the generally southeast-northwest rift doglegs more directly east-west. At these detours we find the darkest deposits, which appear to have issued from the interior. What researchers may be seeing is localized heating of the crust, which serves to sublimate and clear volatile frost. But to many experts, the chains of stained ovals look more like pyroclastic (explosive) eruptions of the darker material (Fig. 6.6).

The explosive eruptions of water that occur regularly on Saturn's Enceladus are due in major part to the flexing of the crust. If this flexing is the cause for Europa's apparent eruptions along fault lines, two specific mechanisms are under consideration: "normal" stress and "tidal walking." The first, a localized stress, would occur when Europa is under the greatest gravitational strain in its orbit around Jupiter. Near its closest passes to Jupiter, Europa's linea are under compression; they are squished together. But as the moon moves to its farthest point in its oblong path, those same fractures are in tension – they are pulled apart. This maximum stress may be the process responsible for the outgassing along faults such as Rhadamanthys. But because Europa's crust moves and bobs above its ocean, as the moon circles Jupiter the surface "walks," drifting so that some faults may shift as they crack. This classic strike-slip motion is called tidal walking. As in the first scenario, Europa makes its way around Jupiter, and its fractures compress. Later, as they pull apart again, the surface drifts ("walks"), and the two sides of the faults slide along each other. When compression occurs again, the two sections of crust come back together, but when they try to slip, they are jammed. Eruptions may occur at gaps in the stalled crust.

Using complex computer modeling, Rachel Maxwell and Francis Nimmo of the University of California, Santa Cruz, have found that the tidal walking scenario does not fit the

---

[5] In Greek mythology, Rhadamanthys was the judge presiding over Elysion, site of an idyllic afterlife.

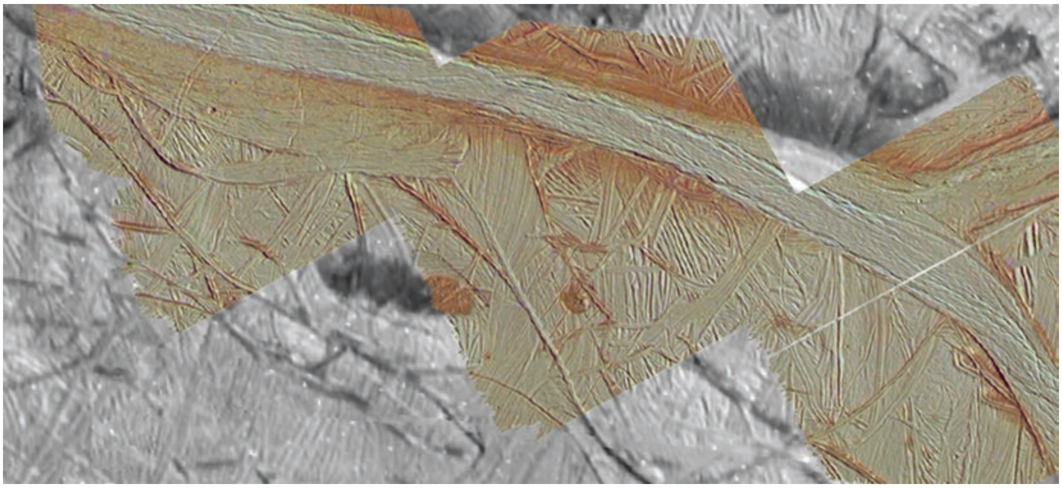


Fig. 6.6 Agenor Linea, one of the best-imaged bands by the Galileo spacecraft. (Image courtesy of NASA/JPL)

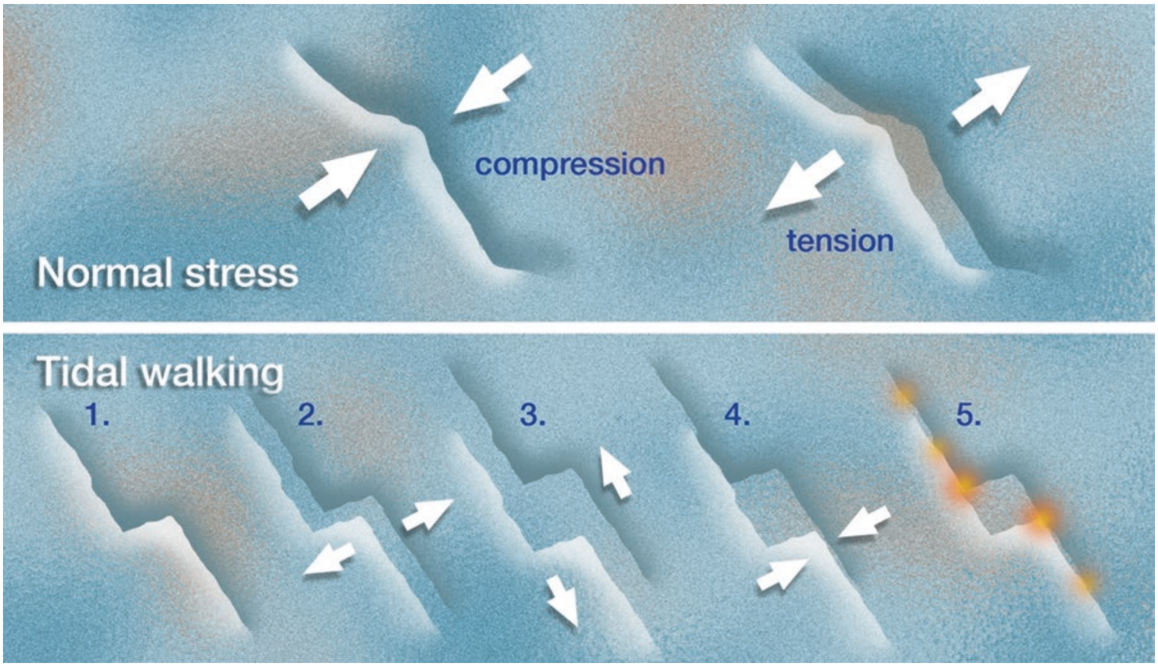


Fig. 6.7 Two ways of making linea, described in the model studied by Maxwell and Nimmo. (Diagram by the author)

observed patterns as well as does the simple localized stress concept (Fig. 6.7). A maximum stress model correlates very well with the spots seen along Rhadamanthys Linea. However, the current models can only simulate conditions in two dimensions; subsurface structure is anyone's guess. Below the faults, the ice may contain complex layering and faulting, with subduction, uplift and buried bodies of water or softer ice. In searches for fossil fuel deposits or aquifers on Earth, the surface above often masks the complexity beneath, and only 3D models can predict where to find the oil or water. Until we are able to actually map the subsurface structure of the Europan crust, our models will be necessarily incomplete. Radar must be brought to Jupiter to penetrate the surface, and this will be one goal of upcoming missions (see Chap. 11).

The elegant linea score Europa's surface in a wide range of forms and sizes, ranging from arc-shaped to "wavy" to cycloidal. They appear in different provinces on Europa, ruled by the shifting influences of the moon's out-of-round orbital pressures and by its twisting of the non-synchronous crust.

Early theories posited that the fractures occurred as water broke through from the ocean layer. Newer work suggests that linea were emplaced by forces within the solid ice crust. They cite several reasons, including the fact that many of the bands rise hundreds of meters above the surrounding plains. This suggests ductile ice rather than liquid, which would not result in a raised structure. The genesis of the hummocks also makes more sense in this scenario as well. Furthermore, there seems to be no flooding of material into adjacent ridges and valleys, which would have occurred had the linea been filled with liquid. Some linea fracture in long series of arcs.

Some of the linea appear to double, resulting in multiple parallel ridges and furrows. In some places, linea appear as segmented fractures; these form when the ice shell stretches and ruptures. These cracks cut across most other features, indicating that they are young. In some locations they also connect large outcrops of chaos terrain. Others bifurcate, splitting into a "Y" shape and continuing in two directions. A high resolution Galileo image, centered on one of these formations, reveals that a southern branch crosses the linea trending to the southwest, so it must have come later. Both pathways may have grown from individual ridges at their centers. Dark material lies within the canyon floors, which is a common feature of Europan bands. These natural lines, faults and valleys could be the result of ductile ice, but they also may hint at a great subsurface ocean, a global sea that has been confirmed using many lines of evidence.

The Europan cryovolcanism we've discussed so far is a rather gentle style compared to more active moons like Io and Enceladus. But with a massive ocean beneath its rind – or with large subsurface lakes – it is reasonable to expect similar fireworks of the watery kind on Jupiter's ocean moon. But where are they?

The southern hemisphere of Europa is bright as snow, and is likely covered in frost from active resurfacing. Saturn's Enceladus gets its blazing patina from frosts deposited by its active geysers. Could such a phenomenon have occurred on Europa in the recent past? Could it be carrying on now?

"Cryolavas" appear to have erupted or seeped onto the surface in several high resolution-imaged areas, leaving frozen pools. These smooth areas embay low-lying terrain, oozing into adjacent valleys and troughs before freezing solid. The erupted material is darker than the surrounding landscape and may be the expression of briny subsurface lakes.

In Europa's chaotic regions, where blocks of ice have fractured apart and refrozen, material appears to have risen to the surface from below, leaving darker material surrounding the ice rafts. These areas could represent sites where subsurface seas have broken through, or where volcanoes on the ocean floor have caused melt-through and collapse. But it is also possible that chaotic regions have been generated more indirectly. What concerns many planetary geologists is the distance between Europa's ocean floor and the base of its surface crust. If models are correct, solid masses of warm ice would take weeks to months to migrate from the sea floor to the surface. Additionally, chaotic regions would need to be heated for extended periods of time to explain the crustal movements observed.

To solve the distant plume problem, one model posits warm columns of ice migrating through the crust. In this scenario, a heated plume warms the ice over a long period. The heat moves through the ice much as the gooey material in a lava lamp. Rather than melting completely through the ice, the process would be gradual and relentless, softening the ice enough to free the rafts for extended periods of time. Additionally, impurities in the ice might help the process along by the lowering of the melting point. Small amounts of salt or sulfuric acid – both of which have been tentatively identified on the surface – could provide enough force to generate the domed features or chaotic regions, even through tens of kilometers of ice.

Another scenario proposes that while the ice is heated from beneath – possibly from sea floor volcanic plumes – no melt-through occurs. Instead, a rising solid mass (called a diapir) makes its way through the crust, eventually reaching the surface. These diapirs could also interact with pockets of trapped briny water. Chaotic regions need not be generated quickly, but could be the result of a long and gradual process.

The diapir model would help to explain the lenticulae, a second class of feature that may reflect seafloor volcanism. Lenticulae are dark spots or areas. They come in varied forms, including miniature chaos areas, pits, depressions, and domes. The term is Latin for "freckles" and refers to the fact that most of these features are dark. Many of these dark spots tend to be depressed beneath the surrounding plain and are stained. The ruddy ice is briny, bolstering the idea that dark materials are seeping – or erupting – onto the surface.

If Europa's ocean floor lies 100 km below the surface, as most models suggest, they are too far removed to have a direct impact on surface features. Even slow-moving diapirs might die out or fade away after such a long vertical journey. But another factor may be contributing to the chaos and other active terrains. Planetary scientist Britney Schmitt of Georgia Tech, along with other researchers, has been puzzled by the chaos terrain and other features that appear to have melted through from underneath. If Europa's crust is tens of kilometers thick, how is the ocean breaking through all that solid ice? Schmidt hit upon the idea that Europa's ice crust is impregnated with subsurface lakes. If localized bodies of water reside near the surface, they could explain some of the features on the surface. "It solves some of the problems of a thick ice crust," Schmidt says. "It lets you break up the ice in specific places without needing a ton of thermal energy, and it explains a lot of the observations like the steep-sided cliffs [surrounding the chaos regions]." A buried lake also explains why some chaos regions, like Thrace Macula, have sunk down below the adjacent terrain while supporting flotillas of iceberg-like structures on their surfaces. Blood may be thicker than water, but water is denser than ice, so it takes up less volume. The formation of a lens-shaped lake beneath the ice crust surface would cause the ice above it to sink. In the case of Thrace Macula, the chaos terrain lies some 800 m below the surrounding plains. As the lake refreezes, the surface domes, and this is exactly what is seen at Thrace, Conamara, and other chaos regions.

Schmidt's model indicates that liquid water in the chaos regions does not break through to the surface. Instead, diapirs rise from the ice/ocean boundary, and as they approach the surface, pressure on the overlying ice softens it. A subsurface lens-shaped lake appears under the surface, and the trapped lake water creates new cracks. The ice fractures into icebergs in a matrix of slushy, crushed ice. "You never have liquid water on the surface," Schmidt says. As the larger icebergs shift and move, they break up weaker ice in between. That matrix can become saturated with water, but the liquid remains sheltered from Europa's vacuum above. Over millennia to millions of years, the lake and rubble freeze solid again. This portrait of Europan plumbing echoes the magma chambers and conduits of volcanically active terrestrial worlds.

Schmidt's study demonstrates that chaos regions may exchange significant amounts of minerals between the surface – where they are manufactured in interactions with Jupiter's radiation – and underlying water bodies, including the lens lakes and even the ocean farther down. This process has major implications for life in Europa's ices and seas (see Chap. 10).

Our survey has brought us from equator to pole, and from ridged linea to chaos regions, but where are the tiger-stripe-like geysers common to Enceladus? Where are the watery versions of Io's exploding fountains? Planetary scientists have been baffled. But in 2012, a series of Hubble Space Telescope observations revealed the signature of water: a cloud of hydrogen hovering above the moon's southern hemisphere. The great water plume – if indeed that's what it was – reached some 200 km high, and investigators thought it likely that the reading showed the fingerprint of geysers. If so, those jets were erupting at an estimated 700 m/s (2400 km/h), three times the speed of a passenger airliner. Observers set to work trying to find more evidence of activity, and began searching old data from Hubble, the Voyagers, and Galileo.

For nearly 4 years, the plumes seemed to have disappeared, and some in the scientific community wondered if the readings had been spurious, a mere mirage in the data. Researchers carefully reviewed data from Galileo encounters, and could find no visible evidence of eruptions. Additionally, NASA/ESA's Cassini spacecraft, which flew by Jupiter in 2001 on its way to Saturn, also detected no plume activity. Earlier Hubble observations of Europa in October 1999 and November 2012 also did not detect any geysers. But in 2016, an observing campaign apparently detected Europa's plumes against the disk of Jupiter. In fact, Hubble actually spotted events ten times over the course of 15 months (Fig. 6.8).

Why did Galileo not detect any active plumes during its multi-year reconnaissance? The spacecraft tried on more than one occasion. Flight engineers programmed Galileo to search Europa's limb for plumes against the black backdrop of space. But in some cases its cameras missed the edge of the moon, instead imaging the landscape below. Galileo's search for plumes was severely restricted by its crippled antenna. As the Lunar and Planetary Institute's Paul Schenk put it, "The lack of evidence for plumes on Europa is due only to Galileo's inability to conduct a realistic global search at the phase angles and viewing conditions necessary to detect such plumes."

Perhaps the spacecraft did find indirect evidence, though. Researchers put Galileo's decades-old data through new computer analysis of a specific event: a brief, confined twist in a small segment of Jupiter's magnetic field that had mystified scientists ever since the close of its mission.

A new analysis using data collected much closer to one of the proposed sources represents a robust corroboration of the Hubble plume data. Melissa McGrath of the SETI institute began to study the old data, and a University of Michigan, Ann Arbor, team led by Xianzhe Jia studied a specific site McGrath mentioned as having a high density of ions above it. The site is a "hot spot" that lies 177 km north of the crater Pwyll.

During the Galileo close flyby, which took place in 1997, the orbiter skimmed past the surface of Europa at an altitude of 200 km. At the time, Galileo flight engineers had no idea that the spacecraft might be flying through a vast jet of water erupting from Europa's subsurface. But when Jia's team studied the data gathered during the flyby, magnetometer readings showed a twist in the radiation fields. Based on what they learned from the plumes on Saturn's moon Enceladus, Europa's fields showed a similar shift in the magnetic field surrounding it. The magnetic 'anomaly' was brief and localized, but it was there.

In addition to its magnetometer, Galileo carried a plasma wave spectrometer (PWS, see Chap. 3) to chart waves of plasma caused by charged particles in Jupiter's environment. That data was also consistent with an active plume.

Researchers combined data from the magnetometer and the PWS into a 3D computer model, which simulated the interactions of plasma around planets and moons. Using a scale for the possible plumes suggested by the Hubble images, the computer model matched up with the magnetic field and plasma patterns in the Galileo data, and pinpointed a region on Europa as a candidate eruptive site. Another of Galileo's instruments showed that the targeted region was warmer than the surrounding ice.

For 20 years, evidence of active volcanism on Europa has slumbered within the recordings of Galileo's data.

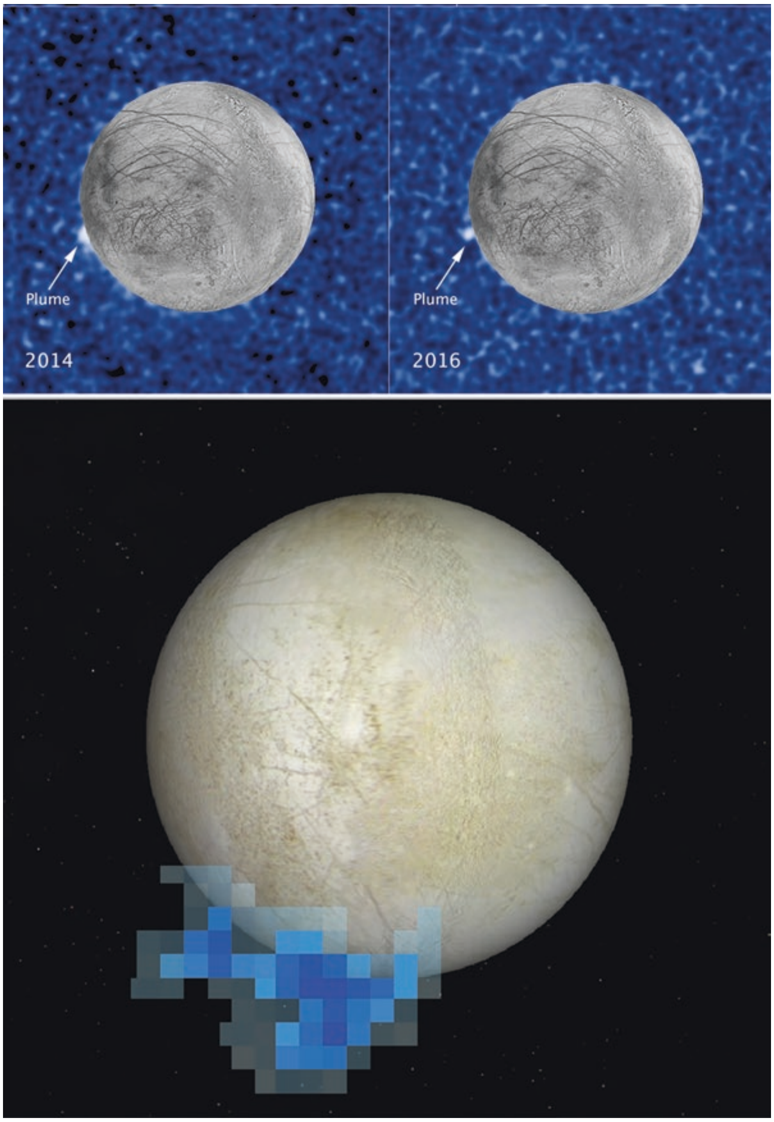


Fig. 6.8 HST images capture a plume or set of plumes erupting from Europa's surface (top). Lower: a cloud of hydrogen a few pixels across betrays the trail of water vapor, superimposed on a Galileo photo of Europa for scale and location. (Upper: Images courtesy of NASA/ESA/W. Sparks (STScI)/USGS Astrogeology Science Center; lower: NASA/ESA/L. Roth/SWRI/University of Cologne)

The magnetic field signatures were baffling, but in 1997 no one had seen the erupting jets at Enceladus. The idea was an alien one. But within the context of other moons studied since, Galileo's stream of revelations makes more sense. If, as it now appears, Hubble and Galileo have caught "cryovolcanos" in action, Europa joins a select club of volcanically active bodies in the solar system.

Cryovolcanism at Ganymede

The view from the ridge tops is spectacular: at a glance reminiscent of the Apollo Moon landing sites, the rounded canyon rims drop precipitously down into the gloom below. Dark, dusty material settles in the trenches and crater bottoms, accentuated by gleaming ice outcrops and bright rayed craters. Beyond the dark valley rises brighter terrain. It's a newer surface, ribbed by successive ridges, but still over a billion years old. The composition of Ganymede's bright terrain is almost pure water ice, suggesting cryovolcanic activity, but the areas are buckled by parallel ridges and valleys, with little to advertise past eruptions. Craters break the repeating pattern of ridges, flattening the crests into circular depressions. Some craters have been split by the moving terrain, with part of a crater carried along the linear pathway, separated from its other half. Tectonic forces have been at play here.

Circling farther away from Jupiter than Europa, Ganymede carries the distinction of being the largest moon in the Solar System. With a diameter of 5268 km, it is larger than the planet Mercury. It is also the only moon known to generate an internal magnetic field, indicating the presence of a hot convecting core containing molten iron. Ganymede also has symptoms of an induced magnetic field, suggesting a deep internal ocean of liquid briny water (Chap. 8).

The geology of Ganymede is some of the most complex among moons, displaying a marked contrast in its terrains: dark terrain, heavily cratered, forms about one-third of the surface, while the other two-thirds consist of swaths of the bright, grooved terrain. In the aftermath of the groundbreaking Voyager Jupiter encounters at the end of the 1970s, planetary scientists reached a general consensus that Ganymede was flash-frozen in its evolution. The giant moon seemed to have come to roost somewhere between the evolutionary histories of Europa and Callisto. Louise Prockter, Director of the Lunar and Planetary Institute, describes how Ganymede may have begun to become Europa-like. "The old, heavily-cratered surface began to rip apart, but then it stalled. It's kind of in limbo, halfway between Callisto and Europa." Prockter and others wonder what caused Ganymede to undergo the massive upheaval it suffered in its past. "It hit the sweet spot between Europa – where everything has been happening and there's been a lot of upheaval that may still be going on today – and Callisto, that's been quietly sitting there almost since its inception."

Ganymede's darker, ancient terrains bear striking resemblance to Callisto's surface, brutalized surfaces punctuated by bright knobs of ice sticking out of the dark regolith. Judging by the density and preservation of its craters, Ganymede's dark terrain is thought to be primordial, more ancient than 4 billion years. Galileo's instruments revealed a composition with more rocky material than the bright terrain. But geological studies of Galileo's high-resolution images confirm that the dark material is a relatively shallow layer overlaying the brighter, icy terrains. Some of the best imagery resolves objects less than 20 m across. Several show dark dust with bright donuts of ice where craters rims and knobs of bright ice rise out of the dust. These images reinforce the conclusion that the dark terrain is thin, a blanket of material layered over fresh ice.

Craters serve as windows, offering clues to what the surface is made of and what lies beneath. Craters can also reveal something about a surface's history, in how worn or preserved a crater is, how it has eroded, and how it has held its shape over time. Impacts have scarred Ganymede's face on many scales, leaving features ranging from the great impact basin of Gilgamesh spanning some 800 km across to small bowls a few meters wide. Impacts sometimes dig out dark floors or cast rays of dark material. This darkening may be caused by solar radiation tinting impurities in the ice, or it may be material left over from the impactor itself. Larger craters seem to burst across the moon's dark blue/gray surface with splashes of pristine ice. As craters age, these rays fade.

Strange central pits sink into the centers of many mid-sized and large craters. These structures may be the result of warmer ice welling up from inside after the impact, or the backsplash of the impact itself. Ganymede's larger craters have a mount inside the central pit, adding to the mystery. Central domes are fairly frequent in larger craters. Many of the central mounts resemble the end product of rising diapirs – warm masses of ice moving through the solid, surrounding ice crust. Similar forms can be seen in Earth's Arctic tundra environments.

As Ganymede's craters erode, they break into icy knobs rising from the dark regolith, similar to those we find on Callisto. Frost sometimes accumulates against shadowed slopes, especially near the poles.

The ghosts of ancient craters also haunt its surface, dim features called palimpsests. Palimpsests are a feature that Ganymede shares with its sibling Callisto. The name palimpsest actually refers to a practice of ancient writers, who penned messages on parchment. Parchment was scarce and expensive, so when a writing had served its purpose, ink could be scraped from the surface, often using milk and oat bran. The parchment would then be used again, but over time, the old writing would bleed through. This faded script tells important tales to archaeologists who study ancient writings.

The smooth profile of these sunken craters is still somewhat mysterious, but researchers have put forth two major theories. The first suggests that a bowl-shaped crater forms upon impact, and its rim eventually flows over time, relaxing into a flat feature that blends into the surrounding terrain. A second idea posits that the impact blasts through thin crust that overlays soft ice or liquid, and the impact site immediately collapses, never leaving a crater. Both possibilities describe what we see today, a bright afterimage of a more violent time.

Even 2 billion years ago, these craters were ancient. Palimpsest craters likely arose early in Ganymede's formative years, when meteors broke through the rigid ice crust, blasting out slushy material over grooves that can still just be seen near the edges of the ghost craters, valleys of the past frozen beneath the palimpsest's surface. Within the palimpsest, craters have punched through to darker material. The form of these craters suggests that they are thin disks of lighter material.

Cutting across the dark cratered provinces, the light regions scored by parallel ridges represent the most Europa-like of Ganymede's terrains. The moon's bright swaths, sometimes referred to as grooved terrain, are complex and difficult to interpret. Their origin remains uncertain. Still more baffling is the fact that the bright terrain only covers two-thirds of Ganymede's globe. It may well be the result of resurfacing by cryovolcanism and tectonism. However, even with the high spatial resolution images returned by Galileo, it is still not clear if active volcanoes have contributed to the formation of these linear strips of real estate. Arcuate depressions show up in some of the higher resolution images, and could be the sources of flows, perhaps similar to volcanic craters – calderas – on other planets. Some geologists suggest that these caldera-like features are sources of some of the bright terrain materials. But questions remain unanswered: why is the bright terrain located in swaths that crisscross the moon, and why was the entire globe not affected by the resurfacing?

The bright terrain transitions from dark ancient regions abruptly. In some places, ancient heavily cratered territory simply stops at the edge of a cliff. Beyond lie line upon line of icy precipices and drop-offs. The bright terrain tends to be lower than the dark terrain. It is probably at least 2 billion years old, so craters pepper its surface, but its crater count is far less than that in the dark terrain.

The parallel valleys of the grooved terrain bulldoze along, creating Ganymede's brightest regions. Tens of kilometers wide, these pleated avenues of ice run across the face of Ganymede for hundreds of kilometers, carving glistening paths through the dark terrain, breaking it into gigantic polygons. The ridges themselves are unlike most mountain chains on Earth, where plates shove together and force two sections of ground upward. Instead, Ganymede's valleys resemble slabs of ice that have splintered apart along fault lines and tilted over like books on a bookshelf.

Although some of Ganymede's ridges resemble the bands on Europa, their cause is probably quite different. On Europa, tidal forces have pulled apart long belts of ground. As they spread, new material wells up to fill the gaps. We can see evidence of this process in places where one pattern of ground is continued on the other side of one of these bands. But with a few rare exceptions, Ganymede has no such repetition of form. Instead, the dark terrain of Ganymede appears to have stretched as it broke apart, and was then transformed into the bright grooved lanes of parallel material. The linear grooves repeat in smaller and smaller scales, down almost to the limit of resolution. Ganymede's ice crust may have been stretched beyond its limits by the forces of gravity from Jupiter and the other Galileans, as well as by its expansion as water turned to ice. Its massive bookshelf-rises come at the hands of extensional faulting, where the crust breaks and slips as a result of expanding ground. In effect, Ganymede swelled as it froze, cracking its surface. The same extensional faulting that results from the moon's expansion could also cause graben, valleys resulting from the downward slip of the surface. Several high-resolution Galileo images captured bright ridges meandering across the surface, but the precipices have been worn down by small meteors and tempered by landslides, making them difficult to interpret. Piles of debris line the base of the cliffs in talus slopes. Some of the structures look as though they are in the process of disintegrating into lines of ice gravel and boulders. Whatever made the bright terrain did it a long time ago.

Researchers face two possibilities in terms of how Ganymede accrued its wild variety of geologic forms. The first possibility is that the bright terrain formed by ripping apart the dark terrain, exposing the bright ice that's underneath. But the second possibility, equally supported by available imaging, is that new liquid water cryolavas flood the surface, covering the dark terrain. Prockter says that, "In both cases there is extension, but in one mode the surface pulls apart like books on a shelf, and where they slide down next to each other fresh icy material is exposed, making the surface look brighter. In the second, the surface pulls apart, forming grabens (keystone-type faulting, where a block drops down between two inward-facing faults), which then get flooded with icy lavas from below creating smooth lanes of icy material." These bright bands subsequently get fractured by further deformation, or as they cool, creating the furrows in the light grooved terrain. The fractures may intersect with subsurface liquid in horizontal intrusions, or at the top of diapirs, or other pockets of liquid (Fig. 6.9).

Many investigators expected Galileo to solve the enigma of how the grooved terrain forms, but although they know extension plays a major role, how the new material gets to the surface still baffles them.

Ganymede's daytime temperatures average a mind-numbing –140°C. In polar regions, the moon's temperatures plummet even farther. Here, a thin veil of frost drapes across craters and valleys. Investigators suspect this frost is primarily water-ice, but it may be mixed with carbon dioxide ice as well. The hills and hollows of Ganymede have some deposits of ice on the shadowed sides, perhaps a few meters thick. The Galileo spacecraft took detailed images in a strip that ran along at high northern latitudes, revealing discrete ice deposits on cold-facing slopes. These deposits make up the bulk of Ganymede's polar caps.

A second factor contributes to the poles, and this one is quite alien. Polar ices build up in regions that align with the gaps in Ganymede's magnetic field lines. In these areas, Ganymede's magnetic field does not protect its surface from the inflow of Jupiter's harsh radiation. Ganymede's magnetic field actually determines its polar surface geology.

Like Europa, Ganymede has an ocean lurking beneath its frozen face. The moon's induced magnetic field confirms an interior ocean beneath the frozen crust 170 km down (see Chap. 8).

Ganymede also has something unique among the icy satellites: an intrinsic magnetic field generated by a molten core. The rocky cores of most ice worlds have cooled down enough that any radiogenic heat is too weak to sustain molten rock or metal within. It takes a molten core to generate a strong magnetic field. "This is the most important thing about Ganymede," says Louise Prockter. "It's really got no right to have its own magnetosphere that it's generated itself." Strangely, Ganymede – of all the moons – is still active enough in its interior to stave off the fierce Jovian magnetic field. That makes it a very unusual body.

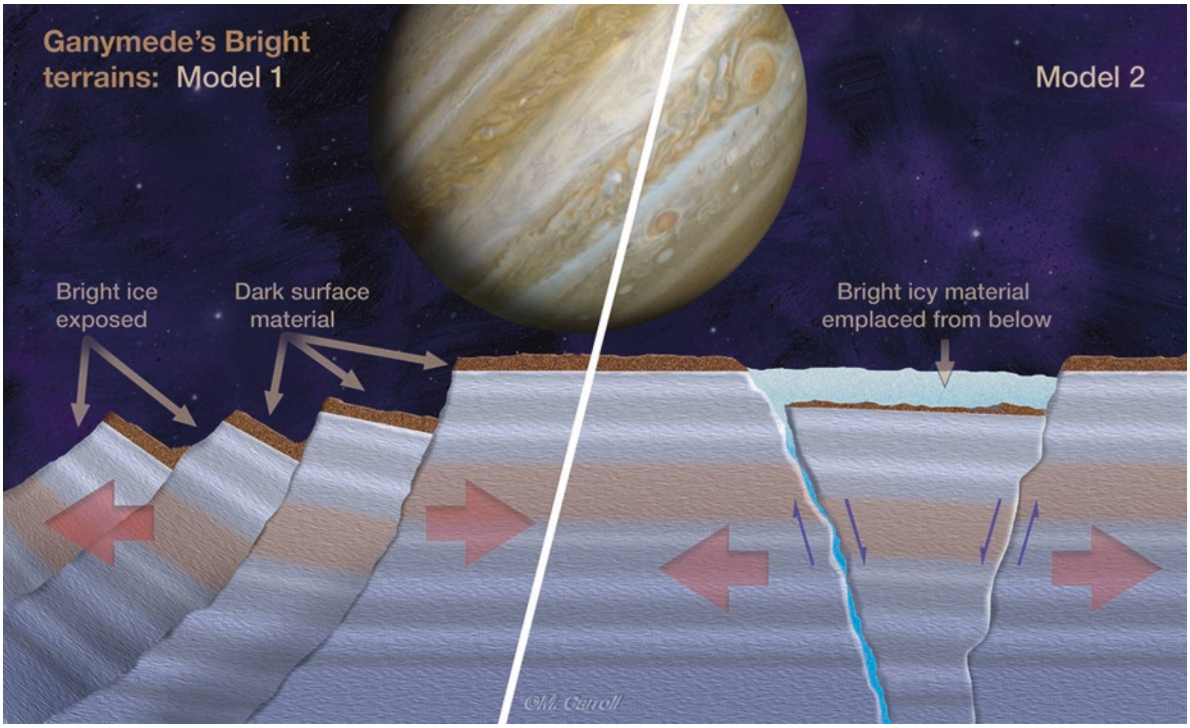


Fig. 6.9 Two theories for the generation of bright banded terrains on Ganymede. *Left*: In Model 1, fractures break the surface as the ice expands. Dark surface materials at the top surface separate, revealing a series of parallel bright ice faces below. *Right*: In Model 2, as the ice is pulled apart, some of it sinks below the surrounding landscape and becomes filled in with fresh ice in the form of thin diapirs or cryolavas from beneath. (Art by the author)

With its variety of landforms, the search has been on for evidence of volcanic sources. Vents, cones, and shield mountains are all missing from Ganymede's list. But some features have been found that seem to indicate underground activity that has broken the surface. A six-frame photographic mosaic taken by Galileo's solid state imaging system surveys an area of bright terrain crossed by the band Sippar Sulcus. The view takes in six caldera-like features, non-circular, irregular depressions rimmed by defined cliffs, many with outflow features. The sunken arenas are not believed to be impact craters, because of their steep, scalloped walls, their irregular shapes, and an absence of ejecta, which would have been thrown out in an impact. Many have nearly concentric terraces within their borders. Some even have rille-like channels nearby, forms similar to collapsed lava tubes.

Most of the caldera-like features directly abut Sippar Sulcus. In every case, the side of the caldera facing the bright band has collapsed, with material flowing into the bright pathway. It appears that either the bright band breached the calderas, or material from the calderas flowed into the band. It may be that whatever force formed the band, it cut through the crater-like features, freeing the contents inside. The larger calderas are rugged, with ridged surfaces similar to volcanic calderas on Earth containing viscous, tacky lavas. But the Sippar Sulcus band is smooth; if it is cryovolcanically related its lavas must have been thin and fluid. The band and calderas may be remnants of two types or stages of cryovolcanism.

The features at Sippar are not alone. Some forty similar formations have been identified across the Ganymede globe. All are associated with the bright terrain. The abundance of these apparent calderas shows their importance in the formation of the bright terrain, and that volcanism has somehow contributed, at least in some regions, to the nature of the bright provinces.

What cryolavas are issuing from these sources? Pure water would freeze too rapidly to leave the kind of landforms we see. Various mixtures of water and impurities have been modeled in the laboratory (for example, ammonia as a sort of natural antifreeze agent), and many demonstrate that cryovolcanic eruptions are not only possible but would result in high rates of eruption explosions and flooding. Even small amounts of gases in the mix would lead to pyroclastic (explosive) lavas covering the surrounding terrain up to 5 km from the eruptive vent. Models indicate that lavas tens of meters thick and hundreds of kilometers long are a possibility as well. These kinds of cryolavas can carve channels hundreds of meters deep. No spacecraft has glimpsed active crovolcanic plumes at Ganymede, but judging from what has been

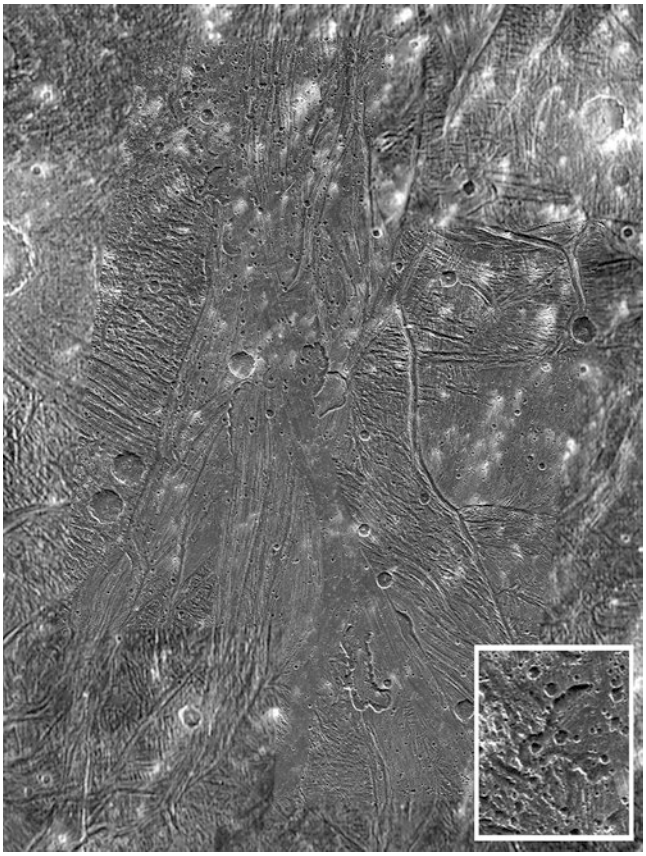


Fig. 6.10 In a “Where’s Waldo” of cryovolcanic terrain, six caldera-like features nest within the convoluted terrain of Ganymede’s Sippar Sulcus bright band region (detail of one at lower right). The six-frame mosaic was assembled from Galileo images. The features, resembling volcanic calderas, can be seen draining into the bright low-altitude band adjacent to them. (Images courtesy of NASA/JPL, LPL and Paul Schenk)

left behind, the cryovolcanoes of Ganymede may, at times, be terrifyingly violent (Fig. 6.10).

In addition to the caldera-like features, other clues hint at cryovolcanism. Some smooth plains appear to have no origin related to tectonic forces (uplift, landslides, faulting, etc.). These examples show evidence of resurfacing. One such area is a bright band that stretches for hundreds of kilometers in Nippur Sulcus. Grooved terrain on both sides of the swath is cross-cut by the smooth strip. But there are mysteries. Whatever material paved the smooth band, it did not embay the troughs in the adjacent grooves that it cut across. Some researchers have put forth the possibility that the grooved surfaces were recently resurfaced, but at finer scales than Galileo’s best images could make out. Another idea is that the region is partially flooded, leaving the highest ribs of the grooved terrain sticking out. A third theory suggests that the smooth areas have been resurfaced by cryovolcanism, but then slightly deformed in later stages afterward. But if these smooth strips are due to cryolava floods, why have the flows not entered the lowlands of the furrowed valleys next to them? Some terrestrial lava flows develop levee-like raised edges that limit flows to the outside edges. This phenomenon could have occurred with Ganymede’s cryolavas in similar fashion.

Another sign of possible cryovolcanic commotion is a sort of mirror image of the bright band flows: lake-like smooth plains that appear to flood low-lying areas, sometimes filling in bays and hollows with dark material. These regions also appear to be resurfaced by flows from within.

Hints of cryovolcanism lurk in a wide variety of places on Jupiter’s largest moon. It seems clear that cryovolcanism, while perhaps not in action currently, has sculpted Ganymede into the remarkable world we see today.

Ancient Activity on Saturn’s Dione and Tethys?

On both Dione and Tethys, cratered terrains have been resurfaced by some force. Nothing like these plains has been found on the other mid-sized moons, Iapetus, Rhea, or Mimas. On Tethys, a vast plain of repaved landscape stretches across 600 km of real estate on the trailing hemisphere. Here, the term “smooth” is relative; the region is heavily cratered, but it lacks any of the closely packed, large craters common to other regions. Most craters here are smaller than 50 km. What has caused this immense resurfacing?

The area is on the hemisphere directly opposite the huge crater Odysseus, and might have been disrupted by the event. But if the impact was the force that generated the resurfacing process of the area, its effects would have gradually lessened with distance from the center. This is not confirmed by the numbers of craters seen. Several researchers[6] have suggested that the plain was emplaced volcanically, with thin cryolavas that left no raised edges or flow structures. Any evidence of volcanic vents or other structures are long gone, buried beneath newer craters.

Where cryovolcanism is concerned, Dione may be a better bet. Its smooth plains spread over most of the moon’s leading hemisphere, with fewer craters than those found on the plains of Tethys. The plains are in a topographic low, which makes sense if they are the product of cryolava flooding. At the very center point of the plains lie two bizarre depressions, called Murranus and Metiscus. They are oblong, about 60 km across, and surrounded by scarps. Each is shallow, sinking below the surrounding surface by only a kilometer. The two irregular depressions are linked by a deep chasm, and several domes rise from the crater floors. All of these characteristics point to volcanism rather than impact for their formation. If they are volcanic features, they are the only ones of their kind in the entire Saturnian system.

---

[6] See, for example, Moore and Ahern (1983) and Smith et al. (1981).

Rounding out the Saturnian cryovolcanism is the behemoth moon Titan. Titan is second only to Ganymede in size, and comparable in size to the planet Mercury. Titan is such an unusual case that we will reserve discussion of its volcanoes for its own chapter (Chap. 8).

A Vesuvius Among the Moons of Uranus?

Of the five major satellites of Uranus, two exhibit evidence of cryovolcanism, with a third on the cusp. Ariel and Miranda exhibit classic features with volcanic character. Titania, larger than the others, is a more puzzling case.

Titania was the queen of the fairies in Shakespeare's *Midsummer Night's Dream*. The moons of Uranus are all named for characters in Shakespeare's plays. With her proud and coy nature, Titania is a good choice; the moon will not give up its secrets easily. Both Titania and Oberon are similar in size to Rhea, but Titania has been far more active in its past. It lacks the large impact scars seen on Oberon and Rhea, suggesting a resurfacing event in ancient times. But Titania's most remarkable feature is a series of canyons that snake across the surface. They are several kilometers deep and at least 1500 km long. The canyons mark a process of extension, where the crust has been fractured. Either the interior froze and expanded, breaking the rigid crust above it, or the outer layers cooled and shrank, cracking in the process. Although crater counts point to a primordial resurfacing epoch, no specific signs of volcanism have been seen today.

Closer in toward Uranus, the 1000-km wide Ariel has a different, more energetic story to tell. The moon is scored by dramatic flat-floored canyons whose bottom surfaces consist of cryovolcanic flows. Ariel's gorges break its moderately cratered plains into great polygons, or mesas. "Those mesas seem to be older, so the surface broke up and things dropped down and then things flowed along the floor of those rift valleys," says APL's Elizabeth Turtle, an icy moons expert. The smooth flows on the canyon floors are rounded – bowing up in the middle – with the same form as a flow of viscous lava. Sinuous troughs wander down the center of the flows, further confirming that the icy material erupted in a thicker blanket than we find on the active moons of Saturn. On the moons of Jupiter and Saturn, thin flows tend to form wide plains. On Uranus' Ariel and Miranda, and on Neptune's Triton, flows appear to be hundreds of meters thick. One possible reason may be a difference in composition. Although the ices at Jupiter and Saturn may contain mostly water and ammonia, those at Uranus and Neptune may hold large amounts of comet-like volatiles such as methanol and formaldehyde. The difference in composition would lead to a marked difference in consistency, perhaps resulting in far more viscous cryolavas at the ice giants than at the gas giants.

Turtle and other volcano experts find the large rift valleys with flows along their floors compelling. "These might indicate some kind of cryovolcanism at some point. The pictures are just not good enough to tell, but there's definitely been stuff happening there, and more than on any Saturn satellite except Enceladus."

Ariel's volcanic activity must have continued for extended periods, as it has surfaces with many different crater densities (indicating different ages). Evidence of resurfacing outside of the rift valleys may reflect fairly recent activity. Ariel's face appears to have been resurfaced sometime after the Late Heavy Bombardment era of our Solar System, a formative epoch when a rain of asteroids and comets tailed out about 3.9 billion years ago. The surface lacks many 100-km craters, confirming a geologic age younger than its battered siblings Umbriel and Oberon. The best preserved craters are small and sparser than cratered terrain of the more geologically quiet moons. Material thrown out from the craters tends to be very bright, and may be fresh ice related to material that has flowed across the surface. As with satellites of other planets, Uranian moons have impurities that darken in sunlight. If fresh ice erupts and flows across the surface, it will develop a dark crust from the solar radiation, but the light ice underneath will be preserved. The bright haloes around some of Ariel's craters may mark brighter ice excavated from just under the surface. In fact, Ariel ice is the freshest of any of the Uranian moons, being the brightest.

The heat required to trigger the kind of activity seen on Ariel is too great to come from radiogenic sources in its small core. Ariel must have been in an orbital resonance in the distant past, which would have set up tidal stresses and fired cryovolcanic eruptions and flows. Evolutionary models of the Uranian moons indicate that Ariel may have gone through several resonances strong enough to fire the hearts of cryovolcanoes (perhaps with Titania and – in particular – a 3:1 resonance with Umbriel). Ariel may well have had multiple episodes of activity throughout an early migration through the system, much as the Galileans may have migrated inward through the Jovian system. But no such relationship exists today, so Ariel's tidally driven activity must have died out some time ago.

This brings us to one of the most exotic moons in the Solar System: Miranda. Tiny Miranda weighs in with a diameter of only 470 km – $^1/_7$ that of Earth's own moon – and yet it has been the most active of all Uranian ice moons, sculpted by bizarre uplifted chevrons and oval canyons. Its smorgasbord of baffling geology reminds us of a Mimas with bits of Ganymede strewn across its surface. In fact, like Ganymede, Miranda seems to be frozen between two stages of geological evolution. Its wonders might have been missed, as many Voyager mission planners preferred to study the larger moons. Pure serendipity dictated that Voyager 2's breakneck 1989 encounter took it nearest to Miranda of all

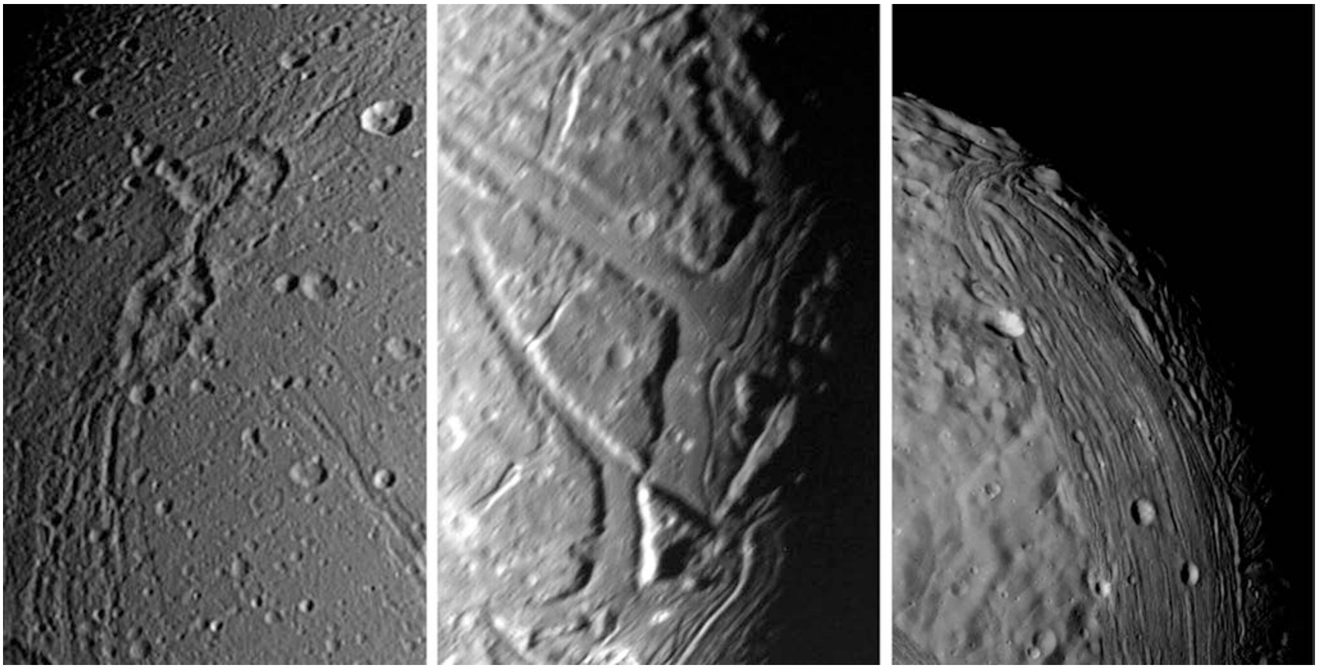


Fig. 6.11 *Left:* Three examples of possible cryoflows. The caldera-like craters Murranus and Metiscus on Saturn's Dione. *Center:* flows cut across convex canyon floors where viscous material exuded onto the surface of the Uranian moon Ariel; Miranda's tortured landscape has several features resembling cryovolcanic vents or calderas (arrow). (Images courtesy of NASA/JPL/SSI, NASA/JPL, NASA/JPL)

the Uranian satellites. The craft needed to fly near enough Uranus for a gravity assist outward to its final stop, Neptune. Miranda happened to be in the right place at the right time (Fig. 6.11).

Many of Miranda's territories remain mysterious, as less than half the satellite has been seen in detail. The hemisphere Voyager did see has been invaded in three areas by wrinkled, oblong provinces called coronae. These features are unique to the little moon. Parallel ridges scar portions of them in great chevrons, while in other zones ice flows have obliterated ancient craters. Lofty cliffs drop precipitously some tens of miles onto rolling terrain.

Like its sibling moons, Miranda has craters down to the limit of Voyager's resolution, but in many places these are wiped out by tectonic or cryovolcanic forces. One such cryovolcanic source may be visible within Elsinore Corona. At the edge of Miranda's terminator, just visible looming from the shadows, is a raised rim breached by what appears to be a flood quite similar to some types of terrestrial lava flows.

Other forces have scarred the surface. Ancient fractures slice across both the coronae and the cratered terrain, seemingly unaffected by changes in the landscape beneath them. Many are in parallel sets, implying expansion of the ices below. Faults and fractures wander in consistent ways in some regions and take surprising turns at others.

The circus-like chaotic regions known as coronae mark some of the most remarkable geologic features in the Solar System. Spreading up to 300 km across, they are comprised of concentric ridges and troughs. An early theory put forth to explain Miranda's host of features suggested that a large impact scrambled the moon as it was in the process of differentiating. The impact-jumbling theory proposed that the coronae were dense, carbon-rich portions of a primitive core that was forced to the surface, freezing in place before the material could settle back to the center of the moon. Alternatively, scientists believe that Miranda may have been shattered as many as five times during its evolution. After each shattering the moon would have reassembled from the remains of its former self with portions of the core exposed and portions of the surface buried.

However, a late impact might not have been to blame for Miranda's exotic countenance. Careful study indicates that these regions are more likely formed by uplift and faulting from extensional forces within, perhaps as the moon's ices cooled and expanded. And while some of the linear rifts appear to be faults, others resemble volcanic flows. These flows may have been a mix of water and some other material that would act as an antifreeze, perhaps liquid methane or ammonia. The coronae may have formed over plumes of rising material, diapirs heated by Miranda's core. As material spread out and impinged the surface, it would have triggered cryovolcanism, or at least floods of cryolavas. Flood deposits ooze from cracks at several sites. The parallel ridges may be thick cryolavas that have erupted along fissures. Some concentric ridges appear to have migrated from the center, covering cratered terrain at their margins. Craters on the corona regions appear fresher than those in the darker, more ancient terrains, and there are fewer of them, indicating younger age. Bright material blankets some areas, resembling the mantling that occurs on Enceladus from plume fallout. Could Miranda have had similar geyser-like jets in its past?

Within many of the coronae, ridges intersect in chevron arrangements. The most spectacular of these chevrons lies within the center of Inverness Corona. Here, a bright checkmark of ridges spanning 100 km etches the smoother ridges surrounding it. One of the major faults, Verona Rupes reaches far into the cratered terrain, rearing up some 7 km, with near-vertical slopes stretching as long as 14 km, creating one of the most spectacular scarps in the Solar System. As the great precipice vanishes into the darkness of Miranda's terminator, parts of the landscape behind it seem to be collapsing along parallel lines. The ridge top is scalloped into precarious fragments, as if ready to tumble into the abyss any moment (Fig. 6.12).

Tidal heating – the same force that keeps cropping up in our study of ice worlds – may be responsible for internal heat that led to Miranda's muddled surface. In the past, Miranda interacted gravitationally with Uranus and its nearby sibling moon Umbriel. Umbriel and the small satellite were in a resonance of 3:1. In other words, Miranda circled Uranus 3 times for every revolution made by Umbriel. Like Ariel, today Miranda is not in resonance with other moons, and carries on a quiet existence, silently circling the green ice giant. But it has left us a clue to its peculiar orbital past in the fact that its modern orbit is tilted inclined, canted compared to the plane of the others, which all orbit Uranus aligned to its equator. Miranda dips up and down at an angle of 4°. Perhaps its internal heat is long gone, leaving only shadows of that earlier, violent epoch in which Miranda migrated through the Uranian system, twisted by gravitational battles that tortured its surface and core. Today's remnants of volcanic activity are a mere shadow of the chilly fireworks accompanying the remarkable moon in the past.

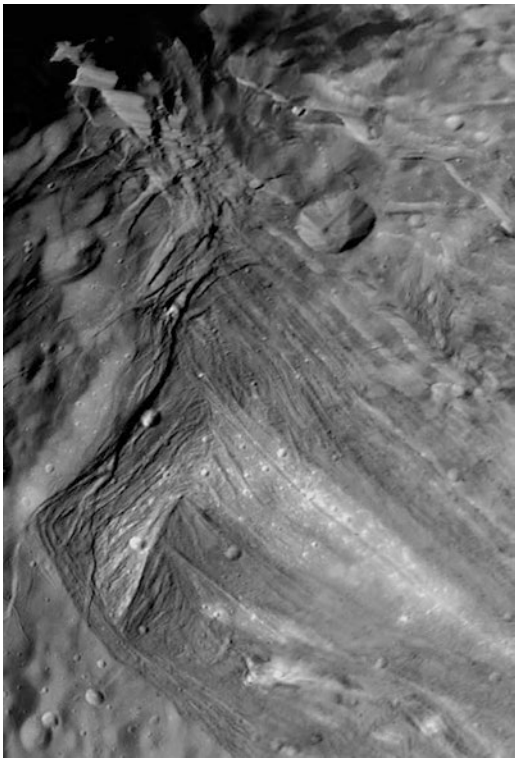


Fig. 6.12 Miranda's remarkable variety of geologic wonders parade across this mosaic taken by Voyager 2 in 1986. At the top, Verona Rupes towers some 20 km above the shattered plains, tallest cliff in the Solar System. Ancient craters have been obliterated by flows, while newer impact features bear the shape of similarly sized craters on other ice worlds such as Rhea, Phoebe, and Dione. At bottom center spreads Inverness Corona, an upwelling with a brilliant chevron and parallel rifts and ridges. The coronae bear some resemblance to forms on Ganymede, but they are unique among the worlds of our Solar System. (Image courtesy of NASA/JPL/Caltech)

Triton's Alien Volcanoes

Thanks to the spacecraft encounters from 1979 through the following three decades, we have seen volcanoes of silicate molten rock, sulfur, and water mixed with strange concoctions such as carbon dioxide, ammonia, and methane. But when Voyager 2 finally arrived at its ultimate destination, Neptune, the world was treated to a new kind of volcanism. At the outer edge of our Sun's planetary family, orbiting the azure ice giant Neptune, circles the exotic ice moon Triton.

As moons go, Triton is large, checking in as the seventh largest moon in our entire system. As we saw in Chap. 3, if Triton had formed as part of the Neptunian system, physics dictates that its orbit would take it in the opposite direction, revolving *with* the planet and any of its native moons. But it travels a retrograde, opposite path. Another odd characteristic of Triton's orbit is that it is inclined to the equator, another hint that it was imported. Perhaps more significant is the strange fact that in comparison to Jupiter, Saturn, and Uranus, Triton orbits in the same locality – relative to its parent planet – that should be inhabited by a family of major satellites. But there is only one, Proteus. What happened to all the others?

Much of Triton's surface can be explained by the violent event of its capture, and this is the explanation for a lack of mid-sized moons at Neptune. As Triton coasted into Neptune's sphere of influence, gravitational interactions with the planet and existing moons helped to capture it. But the capture required an exchange of momentum between Triton and the moons then in place. It is likely that an entire family of Neptunian moons was disrupted, tossing the satellites off into space and leaving a region devoid of the sort of mid-sized moons common to the other outer planets. One planetary scientist compared it to a cuckoo in a nest, tossing out all the other chicks.

This process was not a calm one. Triton's exotic nature stems, at least in part, from a global resurfacing triggered by its capture. When the interloper swept into the Neptune system, it may have been a heavily cratered ice/rock ball, or perhaps a vibrant world similar to Pluto. Outer planetary expert Heidi Hammel comments that Triton "is a fraternal twin to Pluto. It's a Kuiper Belt object that was captured by Neptune. You take Pluto and capture it by Neptune and melt it and turn it inside out in the process."

Capturing a moving object the size of Triton, however, is a difficult prospect. It is possible that the interloper crashed into a moon already in orbit, but this seems unlikely to many. Another way of capturing Triton is a gravitational one involving a companion. If Triton was a double "dwarf planet" – something like a more massive version of Pluto – then its capture may have occurred as part of a three-body system between Neptune, Triton, and Triton's hypothetical companion. That companion would have been ejected from the system, leaving Triton with less momentum, enabling Neptune to capture it. Triton's initial orbit probably ranged from a closest approach to Neptune of only five Neptune radii, and a far point 200 times that distance. It took Triton 100 million years to settle down into a circular orbit, but in the process, Neptune would have set up huge gravitational tides within the former Kuiper Belt object.

Any companion would have had to be similar in size to Triton itself in order to carry off enough momentum. Triton's supposed attendant would probably have been Pluto-sized (Pluto is smaller than Triton), and may well have been an active, exotic world in its own right. Where it is today, if indeed it does exist, is anyone's guess.

Gravitational forces during Triton's capture would have heated its surface to the melting point. Any rock within the satellite would have had time to settle to the center in the process of accretion. (Voyager 2 gravity mapping studies seem to bear this out.) But the ice above this rocky core would have completely melted into an ocean as Neptune's gravity forced Triton's eccentric orbit into a more circular one. Eventually, the water became an ice crust, but processes are still at work today, sculpting the moon in puzzling and outlandish ways not seen anywhere else.

Frustratingly, only a third of the moon has been imaged in moderate to high resolution (400 m/pixel). Two adjacent terrains on the visible hemisphere appear radically different in both color and form, hinting that these two distinct surface regions may have different ice compositions. Within those terrains lie landscapes unlike any other, including a remarkable zone of peculiar, dimpled flatlands called cantaloupe terrain. The distinctive territory looks like stacks of teacup saucers arranged on a table. The strange, fragmented landscape was imaged in one of the last high-resolution pictures that Voyager took.

The oblique view across the cantaloupe terrain offers some idea of what that landscape would look like if a future astronaut were on the surface. Ridges cut through in similar fashion of fractures that we've seen on Ariel or Europa, but the ridges are warped, as if a cosmic welder attacked them with a blowtorch. The ridges on Europa look very straight and pristine, as if they are from yesterday. On Triton, features appear slumped, warped, subdued, and buried in weird ways as yet not understood.

Judging by its relationship to some of the other geologic features, cantaloupe terrain may represent the most ancient of the regions on Triton. Its plates, called *cavi*, are 25–30 km across. Interconnected ridged valleys cut across the plates. The processes from which the cantaloupe terrain arose may involve as yet unknown erosional activity. But another force may be at play here, one that we have run into before: diapirs. Warm bubbles of ice moving up through the solid ice crust could weaken the surface in places, as it probably does at Europa, Ganymede, and other ice worlds. Alternatively, the territory may be the result of ices sublimating as the cavi form. In many places, low cliffs encircle the plated plains.

In other areas, cliffs stair-step down to smooth plains. Some of these plains have been flooded, apparently by cryovolcanic flows. One in particular, Ruach Planitia, appears to have frozen waves across its floor. At its center lies a collapsed pit that shares characteristics common to volcanic calderas (see below).

A vast district of salmon-colored material stretches across the southern hemisphere of Triton. At the time of encounter, Triton was approaching summer solstice in the south. The rosy material appears to be nitrogen frozen to the surface as ice. At the ice edge to the east, complex lake-like structures rest within bright haloes of material. Called maculae, or lacus (Latin for lakes), they appear to be left behind by Triton's retreating polar cap. The lacus areas span up to 100 km in diameter. They are smooth and dark, and their central regions trend toward the red so common to radiated methane in the outer Solar System. The dark shapes are edged in scalloped "shorelines," as if a waxy liquid inside them melted and collapsed the edges, eating away at them and eroding them back. The bright aureoles may be nitrogen ice, perhaps mixed with some methane, similar to the polar nitrogen ices.

In fact, Triton's surface erosion is so dynamic that most craters have been obliterated. This lack of craters underlines just how active and geologically young the surface of Triton is even now.

Triton's most remarkable features of all, though, are its active eruptions. Voyager 2 skimmed Triton's south pole on August 25, 1989, taking stereo images that showed two dark, tall plumes. The lofting material rises to an altitude of about 8 km above the surface, draping dark trails of fallout across the landscape as far as 150 km. Other images of Triton's southern polar region revealed more than 100 dark, streaky deposits, pointing preferentially northeast, away from the south polar ice cap, and roughly away from the point facing most directly into the Sun. The streaks stretch from tens to hundreds of kilometers across the surface, implying that plume activity must be fairly common. Researchers have no idea how widespread this volcanic activity is on Triton, as the northern polar regions have never been seen in detail. Triton's unique volcanism does not seem to occur at lower latitudes in the icy plains and cantaloupe terrain but is restricted to the polar cap.

Triton is incredibly cold: –235°C at the surface. This is well below the freezing point of nitrogen, the material that makes up the south polar cap. Ground-based telescopes have identified both nitrogen and methane in Triton's surface spectrum, and carbon monoxide and carbon dioxide have been found in lesser amounts. Triton's thin atmosphere consists largely of nitrogen. The atmosphere transports nitrogen ice from pole to pole every Triton year (about 165 Earth years), as the polar cap sublimates, turning into a gas and freezing again at the opposite, cooling pole. This migration of nitrogen from one pole to the other evens out global temperatures, keeping the surface temperature nearly the same everywhere. The amount of transported gases is prodigious: a meter or more of nitrogen, methane, and carbon dioxide frost may be sublimated and refrozen on the opposite pole in this seasonal dance.

Cryovolcanism on Triton is fundamentally different from active cryovolcanism on the satellites of Jupiter and Saturn. The plumes are similar to geysers, but they are caused by solar sublimation – melting directly from ice to vapor – of the nitrogen polar cap.

One model describes the plumes as the result of sunlight passing through nitrogen ice, which is very clear. The Sun's energy shifts down the spectrum toward the infrared, becoming heat in a solid ice version of the greenhouse effect. Heat builds up inside, melting the nitrogen ice and turning it into nitrogen gas. A pocket or reservoir expands beneath the ice surface. Vapor pressure builds up and finally explodes into the near-vacuum of Triton's environment.

If this model is correct, cryovolcanism on Triton is a side effect of sunlight, rather than an internally driven phenomenon. The concept of a solid-state greenhouse effect was first proposed in 1990 by Bob Brown and Randy Kirk. Since then, the same mechanism has been observed operating on the Martian polar caps, with carbon dioxide erupting through the solid CO_2 ice. The Sun penetrates the seasonal carbon dioxide ice and evaporates it. The gaseous CO_2 makes its way up through cracks in the ice and erupts as jets. These Martian geysers leave spider-like arachnoid marks on the ice. Such features would have been below Voyager's resolution, so they may exist on Triton as well.

Another theory posits that heat comes not from sunlight acting upon the ice, but rather from inside the ice itself. If the solid nitrogen ice is undergoing convection, with currents of solid ice migrating within the cap, heat is being transported to the surface and could raise the temperature enough to drive the geysers.

The dark trails left by the geysers are a bit of a mystery. They may be the trails of organic material darkened in solar radiation, much as the Sun tints dust at Phoebe and Iapetus, or darkens the older surfaces of the Uranian moons. But the trails may also mark trains of dark material carried aloft by the plumes, perhaps the "bedrock" ice of Triton beneath the polar cap.

On Triton, cryovolcanism has left its mark in other formations. Small circular or elongated cones, spanning some 7–15 km across, are capped by smooth-sided pits. Some of these breach the side of the cone. These mounds may stand alone, but some come in chains similar to terrestrial cinder cones formed in basaltic lava fields. Chains of craters may mark explosive outgassing from subsurface cryolava tubes. Paterae, smooth flattened rings of material, are rimmed by chains of merging pits very typical of volcanic paterae on other volcanic worlds. Collapsed craters typical of subsurface lava retreat can span 15 km across, with floors dropping 250 m deep.

Triton's surface is rugged. Diapirs are the likely culprit of raised faults and ridges, and cryoflows flood cratered plains. Sunken ground forms deep depressions, while in other places domes rise and crack at their crowns. Many of Triton's plains are walled by spectacular cliffs. The ice plains are probably a mix of water and ammonia, and may include methanol. Such a blend can lower the freezing point to 121°C, which could easily enable cryogenic flows to blanket the surface in floods or even fountains. The viscosity of such flows is high enough to explain the forms seen on Triton's sunken plains (Fig. 6.13).

The Southwest Research Institute's John Spencer says of Triton, "There is very little that we see on the surface that we understand. The surface is more chemically complex than any other solid surface we know of in the Solar System. It has an atmosphere, and it has seasons, and these plumes… it's just a really rich environment."

Despite the exit of Voyager and the lack of spacecraft encounters since, Triton's story continues to unfold. Since Voyager's flyby in 1989, Triton's seasons have progressed from mid-summer in the south to late southern autumn. (Uranus and Triton experienced equinox in 2007, where the Sun was directly over the equator; it continues to make its way north.) Thirty years after Voyager, observers are still learning more about the moon, but not in terms of the surface detail. Rather, Earth-based telescopes have detected dramatic changes in Triton's color. From a fairly neutral taupe, the satellite has shifted to hues of striking reddish-brown.

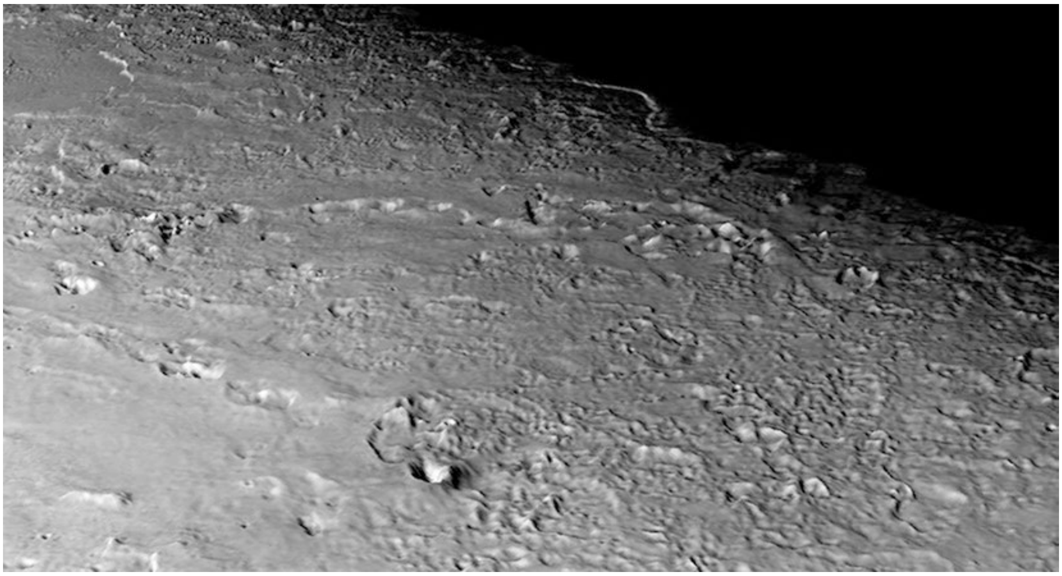


Fig. 6.13 A regional view of Triton takes in an assortment of volcanic features in a view 500 km across: smooth cryolava plains (foreground), round pits and mounds (center) and chains of collapse craters. Vertical scale has been exaggerated by 12 times for clarity. (Images courtesy of NASA/JPL/Universities Space Research Association/Lunar & Planetary Institute)

Measuring its color is difficult because of its proximity to Neptune itself, and there are several alternative explanations involving the color change actually being an artifact of the instruments, but the observations have been independently carried out by several teams.

Triton's striking color shift might be due to geyser activity at the pole infusing the thin atmosphere with reddish smog. Alternatively, it might be the result of some kind of super-plume eruption, where large areas are being resurfaced. Observers can't tell exactly where on the surface the seasonal changes are occurring, but the fact that they vary as Triton rotates suggests that they are probably not near the pole but rather equatorial. These changes may be due to gradual evaporation of frost or deposition of precipitates from Triton's "smog," rather than directly from geyser activity.

Voyager did not return direct observations of Triton's spectrum, as it carried no advanced spectrometer. But modern Earth-based observatories are doing so remotely. It is important work, because as Neptune and Triton make their way around the Sun, more and more of Triton is becoming illuminated (remember that only the south was illuminated during the Voyager 2 encounter). One of the most recent spectral studies was carried out by a team using NASA's infrared telescope facility (IRTF) on Mauna Kea, Hawaii. From 2002 to 2014, the team took 63 spectra. Their observations show changes – in both location and time – of various ices. Data shows an even distribution of water and CO_2 ice across the globe, but there is significant variation of more volatile ices across one Triton rotation (one "day" on Triton equals 5.88 Earth days). Nitrogen and carbon monoxide ices cover similar longitudes and peak in about the same hemisphere. Methane is offset from them by about 90°.

Ethane appears to be scattered globally. When Voyager imaged the southern regions in 1989, the high albedo (brightness) of Triton's only illuminated hemisphere at the time suggested nearly complete blanketing by volatile ices. Intriguingly, the recent work strongly indicates that the southern hemisphere is now stripped of volatile ices, leaving behind the "bedrock" of Triton, which is water-ice. Methane increased over the course of the observations, while the other ices remained stable. The team concludes the "the southern latitudes of Triton are currently dominated by non-volatile ices and as the sub-solar latitude migrates northwards, a larger quantity of volatile ice is coming into view."

Triton is extremely rich chemically, with brews of methane, nitrogen, carbon dioxide, carbon monoxide, and water. As the moon rotates, the chemical fingerprints change as different hemispheres come into view. The variety of texture and color on Triton's surface has no quantifiable link to the spectra that modern instruments provide. Because of telescopic resolution, the spectra are averaged together in such a way that it is difficult to tell one part of the moon from another. The spectra must then be correlated with the colors that Voyager saw, which might have changed in the last 30 years. It's a challenging process, but researchers continue to tease data from the difficult observations.

Their observations got help due to a rare stellar occultation, in 2017, in which the star UCAC4 410-143659 passed behind Triton. The European Space Agency's Gaia spacecraft helped track Triton as it passed in front of the star in the constellation Aquarius. ESA scientists were able to observe the star as it winked in and out of Triton's atmosphere, proving new data on the moon's thin atmosphere. An ESA release stated, "current analysis of the data indicates a quiet and still atmosphere." The 2017 occultation added to earlier occultation studies, which have revealed a global warming trend on Neptune's largest satellite.

Triton is a wild and bizarre world. With its sublimating atmosphere, plated and broken plains, and kilometers-high geysers, Triton fires the imagination of armchair explorers and mission designers alike. And, as we have learned from the asteroid Ceres, many of the smaller ice bodies beyond Neptune, orbiting in the Kuiper Belt, may well be visited by volcanism. One of those distant worlds might even be the former companion of Triton.

Sea Worlds

7

In the early days of planetary exploration – exploration carried out solely at the eyepiece of a telescope – astronomers searched in vain for oceans on other worlds. Clouds enshrouded Venus, although they might hide a carbonated sea. Mars was a desert world, Mercury was hotter than the boiling point of water, and the outer worlds were great spheres of gas. Earth, it seemed, was *the* water world, blessed with liquid, life-giving oceans. But with the advent of space exploration, we know better; our Solar System is awash in oceans of many kinds, and was in the past as well (Fig. 7.1).

The early days of our Solar System were wet and wild. A brutal hail of asteroids and comets brought material to the Sun, infant planets, and moons. Within these battering asteroids and comets there was plenty of water to go around. Some was incorporated into the chemistry of the rocks. Other water boiled away into space. Still more of the treasured liquid remained on the surface as lakes and seas, or as frozen deposits within craters on the shadowed sides of mountains or hiding within the depths of canyons.

For some planets and moons, so much water accumulated that it blanketed vast regions. Today, Mars bears many features indicative of a vast ancient ocean encircling the northern hemisphere, beachfront property in Elysium and Chryse. Chemical analyses point to extensive seas on primordial Venus, our other cosmic neighbor next door. But in addition to past planetary oceans, there are still seas out there, lurking within and upon the moons of the outer Solar System. Some of those planetary oceans are made up of water, but there are others as well. Sand seas undulate across the face of Saturn's Titan, just as they do on Mars and Venus. Seas of lava once flowed across the terrestrial planets and our own Moon. Quite alien oceans of liquid metallic hydrogen susurrate in the cores of the gas giants.

By the opening of the 1990s, astronomers were still unsure as to whether modern liquid water seas existed anywhere beyond Earth. At Jupiter, Europa clearly had a crust that was modified from beneath, at least by warm ice, and some proposed liquid water down there somewhere. But there was, as yet, no unequivocal proof of a subsurface ocean. Just next door, Ganymede exhibited dramatic resurfacing and was thought to have had cryovolcanism linked to an ocean some time in its past, although astronomers now estimate that tectonic forces play at least an equally important role. Voyager's glimpses of Enceladus, intriguing as they were, could not confirm the existence of an active ocean, although it was obvious that forces were sculpting the surface from the inside out. Softened craters and apparent floods of ice indicated geologically young surfaces. The most important evidence of possible liquid water within the little moon came from the fact that Enceladus orbited within the E-ring, a gossamer ring of fine dust and ice that seemed to be related to it. Voyager's flybys missed the critical eruptive sites – the tiger stripes – in the south. Saturn's behemoth moon Titan, enshrouded in its deep methane/nitrogen fog, remained an enigma, with no clear views of the surface and only scant readings of the moon's gravity and possible interior structure. That was then.

As it turns out, the planets and moons of the outer Solar System are awash with water, as ice, liquid, and vapor. The giant worlds that share a family history with their ice moons contain vast quantities of H_2O in their atmospheres, though perhaps not as much as once thought. Jupiter and Saturn have their own inventories of water. The majority of it combines with other compounds to make ammonium hydrosulfide clouds. Deeper still, where temperatures increase, clouds of pure water form. On the ice giants, Uranus and Neptune, temperatures are far too low for water vapor to form in the cloud tops. Most water has sunk to depths where it becomes a super-dense fluid that mixes with liquefied gases. Water, in some form, may account for two-thirds of the total mass of the ice giants.

Water abounds next door to each of the giant planets as well. Orbiting these outer worlds, many natural satellites have hearts of hydrated rock surrounded by thick crusts of water-ice. These deep-frozen water balls include Rhea, Dione, Tethys, Mimas, Iapetus (all at Saturn); Ariel, Umbriel, Titania, and Oberon (at Uranus); Triton (at Neptune); and the moons of Pluto with the possible exception of Charon. Other ice

M. Carroll, *Ice Worlds of the Solar System*, https://doi.org/10.1007/978-3-030-28120-5_7

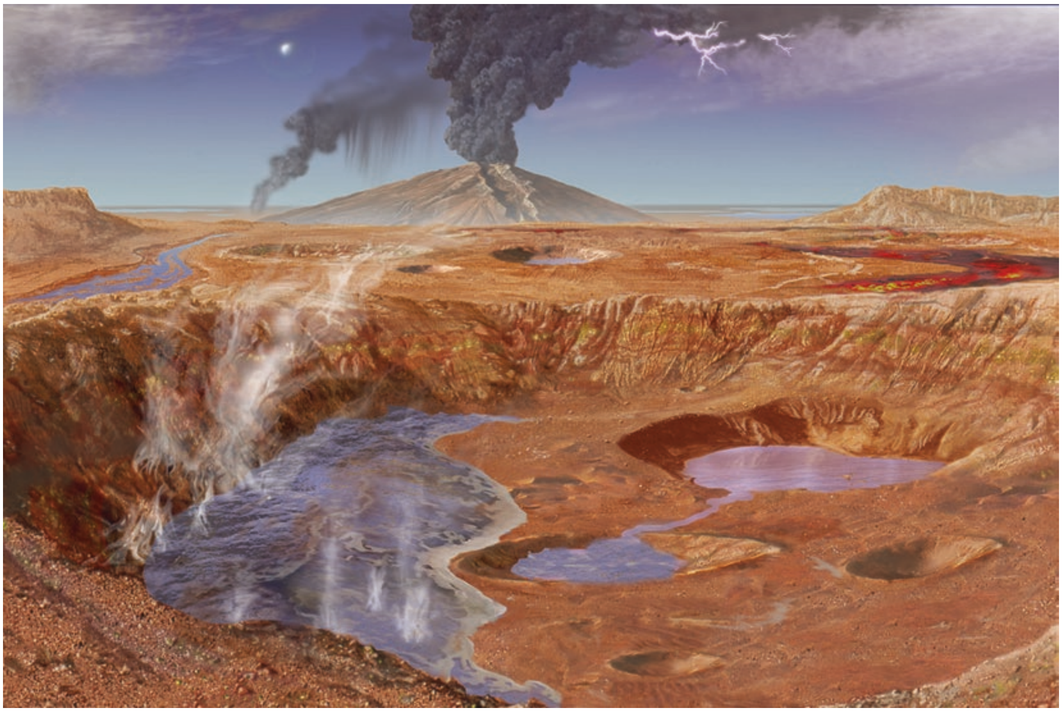


Fig. 7.1 The transient beachfront property of ancient Mars was probably a nasty brew of salts and peroxides. (Art by the author)

moons (notably Europa, Ganymede, Titan, and Enceladus) are influenced by the gravity of other moons and their home world in ways that create subsurface water oceans. Today's water oceans, vast and innumerable, gurgle and slosh under the surface, hidden beneath the ice crusts of worlds in the outer Solar System. And most of those worlds are satellites of the major planets.

It's a new paradigm, this story of maritime moons, and it changes everything.

Birth of a Global Ocean

How did all that H_2O get there in the first place? When it comes to water, our Solar System is a Dickensian tale of two planets. The Sun's family of planets formed within a disk-shaped cloud of dust and gas surrounding the Sun (the Solar System's accretion disk). This planetary nursery contained water, minerals, dust, and metals, but in the region closest to the Sun, the water was driven away or dissociated (split into hydrogen and oxygen). Farther out, the cloud was wetter. Inner worlds lost what water they had early, boiled away by our energetic young star. As we have seen, in-falling debris, mostly from the asteroids, recharged the water inventories of the terrestrials. Tiny Mercury lost much of its brew. Venus, Earth, and Mars all developed oceans to varying degrees. Only Earth's is still intact.

The outer Solar System tells a different sea shanty. The gas and ice giants cocooned themselves within their own disk-shaped clouds, miniature versions of the Sun's protoplanetary disk. As Jupiter, Saturn, Uranus, and Neptune chilled, they shrank, each leaving behind its own cooling cloud of gas, ice, and dust. And as we saw in earlier chapters, moons coalesced within these mini accretion disks. Jupiter's four major satellites, the Galileans, provide the perfect example of the result. Close in to Jupiter, Io and Europa collapsed into spheres with dense, rocky cores and, in the case of Europa, a relatively thin water/ice crust. These are Jupiter's version of the terrestrial planets. In Jupiter's outer cloud, where there was more water, Ganymede and Callisto formed as larger, less dense worlds with small stony centers[1] and deep ice crusts. We have seen how differently these conditions have played out upon the surfaces of these moons. But how much water remains as hidden oceans?

The Solar System is a far soggier place than astronomers first imagined. Icy satellites' expert William McKinnon, a veteran researcher who observed this paradigm shift, remembers, "Even though people suspected there might be oceans under Europa or even Enceladus, the data dragged us, kicking and screaming, to the conclusion that oceans are common in the icy moons."

---

[1] Callisto may not have differentiated; rather than settling to the center, its rock component is probably scattered throughout its ice.

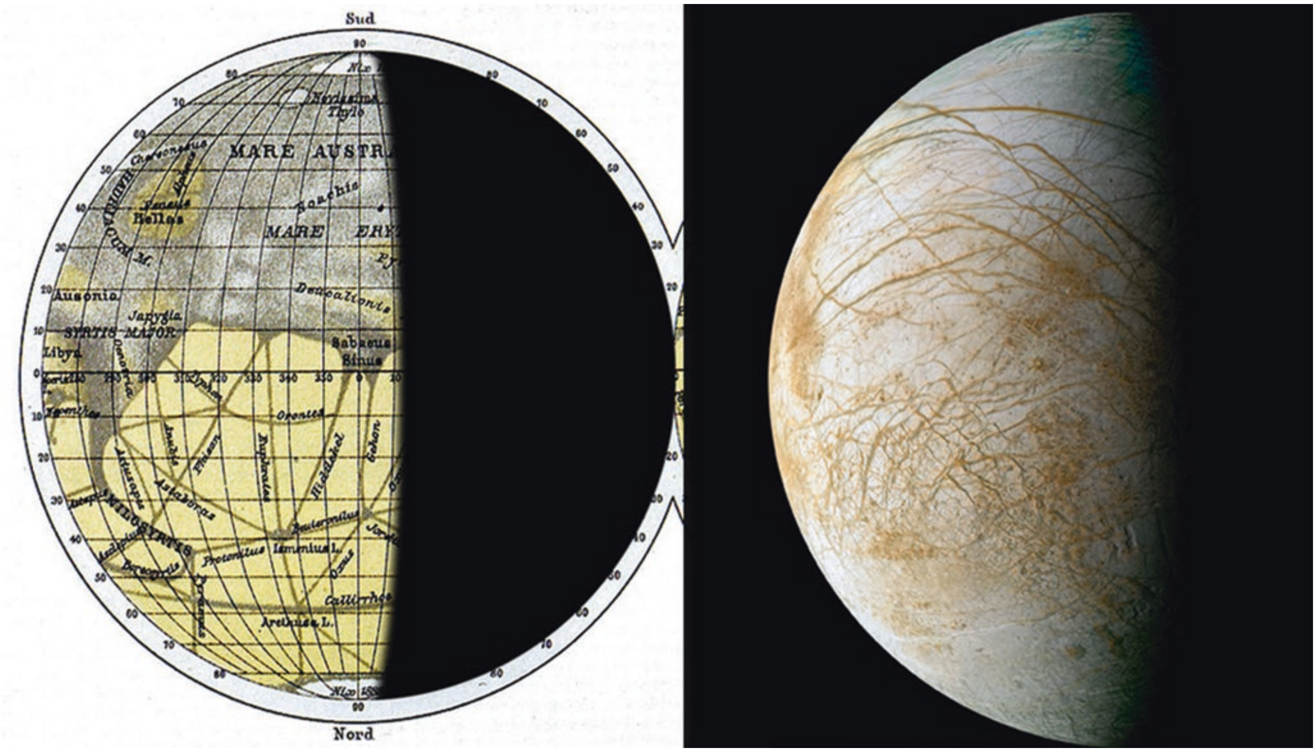


Fig. 7.2 Chart of Martian canals, mapped by Schiaparelli ca. 1888, compared to a Galileo global mosaic of Europa, ca. 1998. (*Left:* https://commons.wikimedia.org/wiki/File:Mars_Atlas_by_Giovanni_Schiaparelli_1888.jpg. *Right:* Image courtesy of NASA/JPL)

Europa: The New Mars?

Our first views of Jupiter's ice moon Europa hearkened back to the most elegant of Lowell's Victorian charts of Mars, double and triple lines, arcs, and webs stretched across the shining blue ices, linking amorphous dark centers of complex structure (Fig. 7.2).

The bellwether for extraterrestrial oceans, Jupiter's ice moon has become a favorite among many astrobiologists, a new prospect for extraterrestrial life, perhaps offering even a better chance for life than Mars. Jupiter's fourth-largest moon sparkles with a glistening surface of water ice. The graceful calligraphy etched across the surface in linear and arcuate stripes is a telltale sign of powerful tectonic forces and complex chemistry created by radiation from the Sun and from Jupiter itself.[2] Researchers offer several models to describe conditions beneath Europa's bizarre, grooved facade, ranging from soft ice over a shallow sea to an ocean 100 km deep. Whatever its true internal form, Europa is far more a "water world" than Earth ever was.

A critical hint pointing to the existence of a Europan ocean comes from its craters. The largest craters on Europa bear the traits of impacts on a surface overlaying a thin, fluid substance such as liquid water. Additional research carried out by the Lunar and Planetary Institute's Paul Schenk catalogued 28 craters larger than 4 km across. Using the data, scientists were able to estimate the thickness of the ice crust at greater than 19 km. In contrast, Callisto's ice crust is assessed at ten times that thickness. Crater totals also have a story to tell. Astronomers use crater counts to determine geological ages of planetary surfaces. A more active world with weather, volcanoes, or tectonics will erase its older craters. Europa's craters are few and far between, indicating a young geologic age – perhaps less than 50 million years. As Europa has no atmosphere to wear down its surface, this, also, adds an argument for a dynamic, watery interior. In that short amount of time (as planetary history goes), it is unlikely that an ocean would have frozen solid.

Europa has two major impact craters, Callanish and Pwyll. At 33 km across, Callanish is a multi-ringed impact site. Its pattern of concentric grabens (outside of the original impact crater itself) show that a brittle ice shell overlaid warmer, soft ice that moved toward the center, fracturing the ice around it. A second crater to the northeast, Pwyll, is the largest crater yet identified on Europa. It has a knobby, uneven rim and a complex 500-m-high central peak. Its floor is dark, and the dark material has expanded outward beyond the rim. Pwyll has a brilliant set of rays extending from it.

---

[2] Chapter 6.

Neither Pwyll nor Callanish are thought to have broken through the ice to liquid water below, but both seem to indicate that Europa's icy shell is far thinner than the ice crust of Callisto and Ganymede. Another of Europa's impact craters, Cilix, has a diameter of 19 km. Dark reddish deposits surround the crater, carpeting the surrounding ridges and hollows. The crater has terraces and scarps interior to the rim, where blocks of material have slid down toward the crater floor. Though common on terrestrial planets, terraces are rare on ice worlds.

One of the most elegant impact features on the entire globe is the multi-ringed Tyre. Its concentric ridges and a series of grabens on the outer circle are rimmed by thousands of small secondary craters, impacts from debris that blasted out during Tyre's formation. Secondaries are important, because they enable researchers to estimate the size of the original crater, which has been disguised by flowing, melting, and refreezing ices during the late stages of impact.

Tyre is considered to be a strong line of evidence for an ice crust above a liquid ocean. Ringed basins such as Tyre have only been seen on ice worlds. Multi-ring features on terrestrial (rocky) planets show different characteristics. Craters such as Tyre and Callanish form in brittle ice layers that overlay warmer, softer ice. A crust thicker than 10–20 km would not result in this radial arrangement of geologic forms.

The shape of Europa's craters offers other insights into the moon's ice crust. In the wake of the Voyager encounters, two models were favored for Europa's structure. The craters on Europa do not seem to have broken through the ice into the ocean below, demonstrating that the crust must be many kilometers thick.

Clues to Europa's ocean also come at the hands of the linea, ruler-straight lines streaking across the frozen landscape, bracketed by long ridges rising hundreds of feet into the black sky. Still other areas, called chaos regions, seem to have collapsed into a sea-like slurry, freezing in place after splintering into puzzle pieces that rotate and tip before freezing solid again. We have seen how these formations may point to cryovolcanism, but we now turn to their forms as evidence of perhaps the largest water ocean in the Solar System.

In fact, the suite of Galileo and Voyager images of Europa captured nine surface features that are consistent with an ocean beneath the ice crust. In addition to the crater forms, researchers cited the lenticulae, expanding (dilational) bands, cryovolcanic structures, chaos regions, sinuous ridges, general topography (the three dimensional lay of the land), planet-wide tectonic features like faults, and localized frost deposits on the surface. Taken separately, any of these features could be explained by soft ice above local hot-spots, but as a group, many found them convincing (Fig. 7.3).

And there were still other indications. Aside from visual clues, Europa provides more proof in the form of the energetic fields surrounding it. On Earth, our planet generates two types of magnetic fields. The first, and strongest, emanates from deep within the core, where molten metal meets rock. As Earth spins, its liquid metallic outer core sloshes around. That turbulence sets up strong magnetic fields that

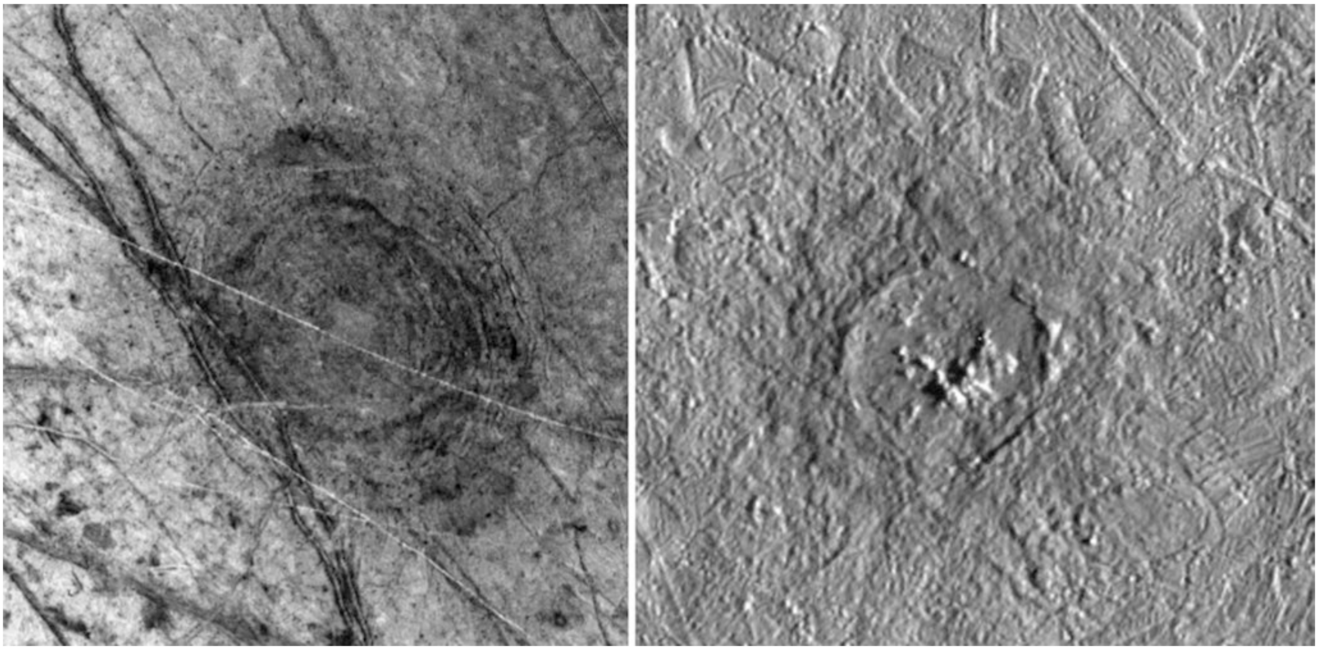


Fig. 7.3 Cosmic doilies: The craters Tyre (left) and Pwyll are remnants of impacts that may have broken through Europa's ice crust to a liquid subsurface. (Images courtesy of NASA/JPL/Caltech)

spread out into a bubble of energy fields above Earth. This magnetosphere protects the surface of Earth from some of the Sun’s deadly radiation. But a second magnetic field issues from our home planet, and it comes not from the core but from the oceans. The saltwater in our seas generates its own magnetic field with its own signature, separate and quite different from the one generated by the metallic core.

Europa generates a magnetic field strangely similar to the one we see coming from our own oceans, a field consistent with interior liquid saltwater. It’s just the kind of energy pattern that would be produced by electrically conducting liquid within Europa’s upper ice region. Unlike Earth’s oceanic magnetic field, Europa's field is induced – it is created in response to Jupiter's prodigious storm of energy. Jupiter's spin swings its mighty radiation field around with it, overtaking and sweeping across Europa. Under these harsh conditions, any conducting material swept by this field will create (or induce) a magnetic field, fending off – or at least shifting – the external magnetic field from Jupiter. This induced field leads researchers to the conclusion that a near-surface conducting layer, such as an ocean with dissolved salts, is the culprit.

Earth’s magnetic “north pole” is at the top of our planet, but Europa’s magnetic “north pole” moves along its equator in sync with the energy flowing from Jupiter. From Europa's perspective, Jupiter appears to rotate once every eleven hours. The induced magnetic field from within the moon cycles to compensate for the changing Jovian magnetic field, which sweeps by twice each "day." A compass held by an astronaut on Europa would completely reverse direction every five and one half hours – not very helpful for navigating!

However, for such an internal magnetic field, just how salty would a cosmic Mediterranean need to be? The answer is not an easy one. Models must include a variety of variables, such as ocean depth, ice thickness, and amount of salt and other impurities. It is clear that the alien sea must be fairly salty, and perhaps is even akin to the dense waters of the Dead Sea. Some estimates even project that Europa’s waters are similar to battery acid.

As we saw in Chap. 6, Europa’s surface is battered by Jupiter’s radiation, which sweeps across its trailing hemisphere each Jovian day. Jupiter’s magnetosphere strips away a ton of Io’s volcanic gas and sulfurous dust every day, carrying them around the planet in the Io torus. Some of it drifts out onto Europa. One model suggests that the elements come more directly from Io. Sodium-enriched gases vent into space, eventually crashing into Europa. They penetrate only into the upper few millimeters of ice, getting trapped in fluffy, low-density material on the surface. But Jupiter’s constant particle barrage erodes the surface, exposing the sodium, breaking it apart and releasing it back into space.

Still, some of the sulfur on the moon’s face seems to be associated with surface features, indicating that it is endogenic, or Europa-generated. Sulfur, sodium, and potassium all have been detected in Europa’s surroundings, and they all may be coming from surface salts that have made their way up from the briny seas below. The Galileo orbiter was equipped to detect certain materials on the surface; however, its later mission – which focused more on Europa – was crippled by Jovian radiation. Jupiter’s mighty energy fields partially blinded its instruments. Many of the substances Galileo searched for were also coated in water-ice, making detection difficult or impossible. Since its mission, Earth-based telescopes and laboratory tests have offered insights into Europa’s mystery reddish regions across the ice and within its dark linea bands. Hydrated (water-bearing) salts, magnesium sulfates and sulfuric acid all have spectra resembling Galileo’s results. Further telescopic research has implied the presence of chlorine associated with the magnesium sulfate.

Finding Europa’s Ocean

Throughout the outer Solar System, we have seen the power of tidal heating and its effect on cryovolcanism. At the time that the Voyagers first imaged the Galilean satellites, most planetary scientists expected Europa and its siblings to be balls of ice, frozen solid in the eons after their formation, their primordial fires long gone as radiogenic sources died out. The mighty power of tidal heating was only a theory, a footnote on the pages of our infant planetary sciences concerning moons of the outer Solar System. The Voyagers and later craft put a lie to that idea, displaying a wide spectrum of landscapes all sculpted by the hand of tidal friction. Along with Io, Europa was a spectacular example.

Europa travels halfway around Jupiter each time that Io completes an orbit, and twice for each of Ganymede’s circuits. Tidal heating is generated as a result of the moons’ gravitational tugging, heating up Europa’s interior, though to a much lesser extent than Io’s. The gravitational forces trigger volcanism, but they also enable the interior of the moons to remain supple and warm. Beneath Europa’s crust lies an ocean cut off from the outside world. Although submerged in eternal darkness, this stygian environment has one advantage for any Europan biology: it is sheltered from Jupiter’s fierce radiation. The ice crust provides a barrier to the deadly rain of energy bombarding Europa.

At first, Europa’s ocean was thought to be a localized affair, existing as large subsurface lakes or shallow seas. But further studies have proven that an immense global ocean runs from pole to pole under the ice. Tracking of surface features demonstrates that Europa’s crust is “decoupled,” or free-floating, separate from its stony heart. Gravity data from the closest flybys of the Galileo spacecraft fits a rocky interior capped by an outer layer of water 100–200 km deep, much of it liquid.

Europa's rusty stripes have provided an important clue to the crust/ocean interface. This clue comes in the form of unique "cycloidal ridges." The strange arcs congregate in two dense clusters that are far north and south of the equator and are offset in opposite directions. Over a hundred have been charted, their locations and relationships carefully analyzed. The bizarre arc-shaped tracks are laid down in a specific pattern, with northern ones trending in offsets that move laterally left. The ones in the southern hemisphere shift to the right. Their direction and form reveal that compressional forces are cracking the surface. As Jupiter pulls on the crust of Europa, a crack forms perpendicular to that pull. Europa's orbit is not perfectly circular, so the stress from Jupiter varies. (On the surface of Europa, Jupiter would seem to drift slightly from one side to another in the sky as Europa's distance from it changed.) As its stresses change direction, the crack continues to lengthen in a great curve, the force of Jupiter's gravity moving slightly from one direction to another. Finally, the stress dies down and the crack stops expanding. But when Europa returns to the same spot in its orbit, the crack begins to expand again. This time, it starts out slightly bent, because the orientation of Jupiter's tidal stress has shifted since the last time the crack was active.

Those cycloidal fractures lie in patterns indicating that the ice crust rotates at different speeds than Europa's core. Their cusps, the points at which each crack changes direction into a new arc, are spaced between 75 and 150 km apart. But Jupiter's gravitational forces cannot account completely for the forms on Europa's surface. The crust must be able to flex and drift in order to form the cracks, and that drifting means that the rate at which Europa's crust turns is not the same as the rate the moon's center is turning. It is nonsynchronous (Fig. 7.4).

The crust's nonsynchronous rotation is best explained by a free-floating crust atop an ocean, a crust not locked to the rocky ocean floor. Jupiter's formidable gravity sets up tidal stresses, causing tides within the liquid sea. Those tides cause the water to rise and fall by some 30 m each Europan day. It is these undulations, in conjunction with Jupiter's gravitational tug, that crack Europa's face like an eggshell.

Europa's massive ocean – perhaps the largest water ocean in the Solar System – surges against the moon's frozen outer shell, which forms a protective barrier against the vacuum of space. But just how thick Europa's ice husk is has inspired lively debate within the scientific community. One model posits a thin crust covering a 120-km-deep ocean. In this scenario, plumes of heated water from seafloor volcanoes impinge on the thin surface ice, breaking through to create the domes, bands, and chaos regions. A second model recommends a thick ice crust. Diapirs (solid masses) of warm ice migrate up through the crust like blobs in a lava lamp, trigger-

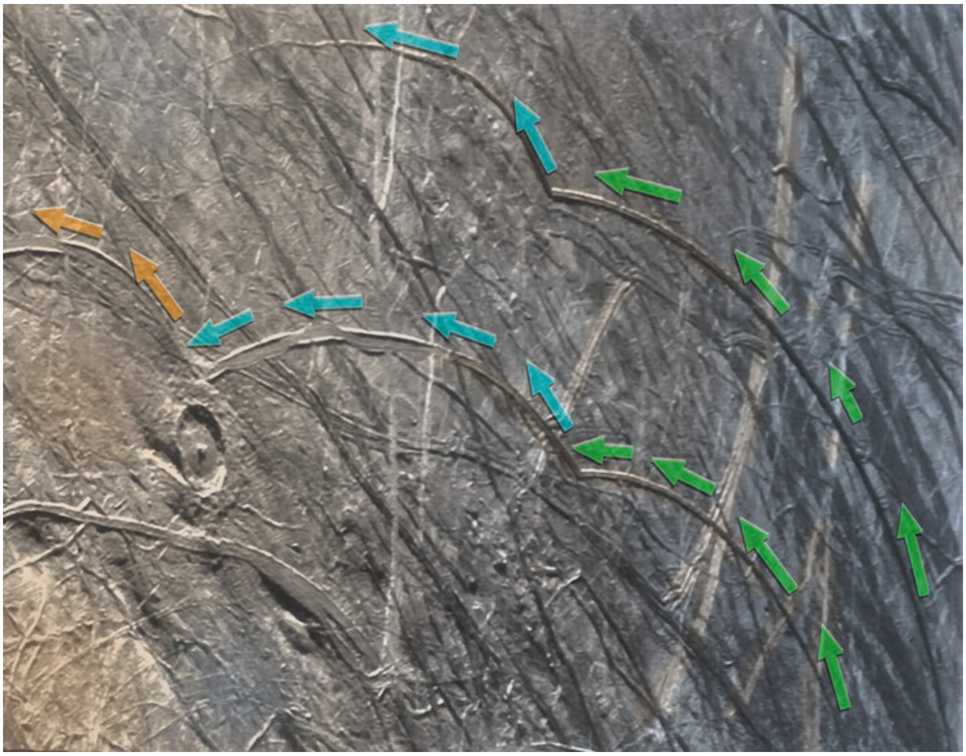


Fig. 7.4 The direction and form of cycloidal ridges reveal that compressional forces are cracking the decoupled ice crust. (Image courtesy of NASA/JPL; diagram by the author)

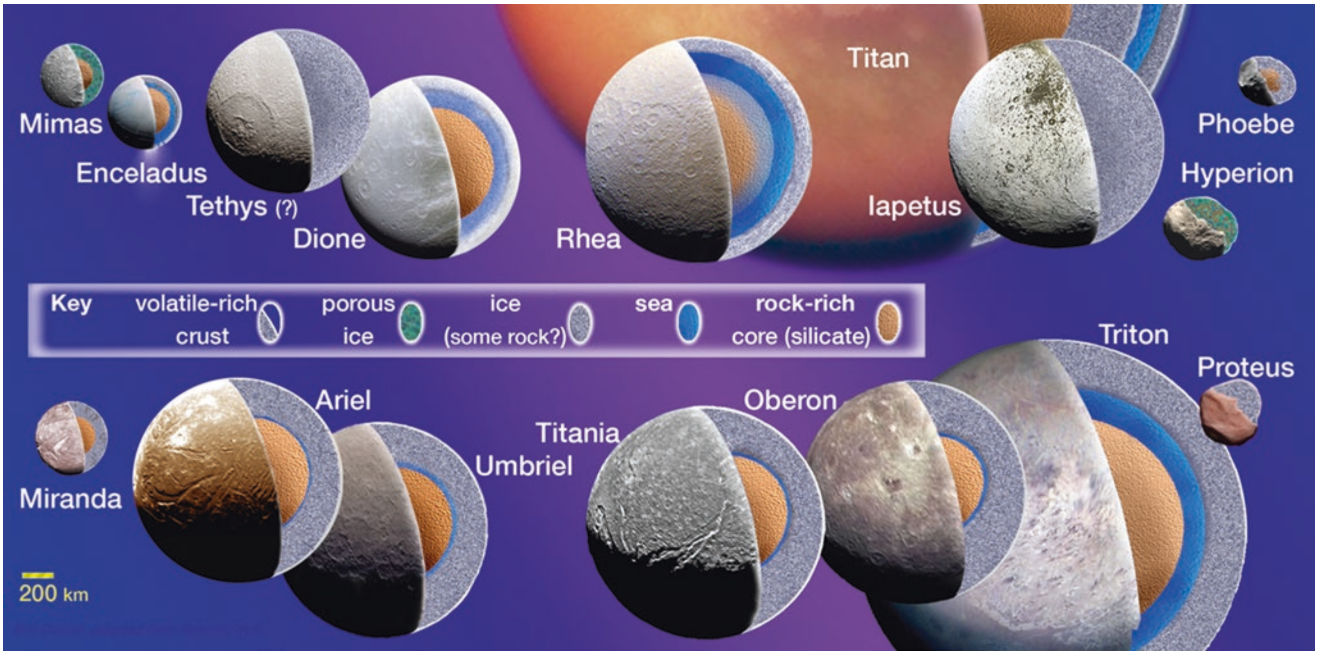


Fig. 7.5 Non-Galilean moons with confirmed (Titan, Enceladus) and possible oceans. Across the top spread the moons of Saturn. Below are the mid-sized moons of Uranus, along with Neptune's Triton. Much uncertainty exists about the details of the interiors; some of these moons may not have liquid mantles in any form. For example, note that estimates for Rhea's rock core vary between 600 and 760 km, Phoebe may have an amorphous loosely packed core, and Dione may have an ocean as deep as 95 km, but it may not have one at all! (Art by the author; Saturn data courtesy Schenk, et al. *Enceladus and the Icy Moons of Saturn*, University of Arizona Press/LPI)

ing the features we see across Europa's glistening face today. Rather than melting completely through the ice, the process would be gradual. Impurities in the ice might help the process along by lowering the melting point. Small amounts of salt or sulfuric acid – both of which have been tentatively identified by Galileo – could provide enough "antifreeze" to generate the domes and chaos, even through tens of kilometers of ice. Chaos regions in this scenario might also occur over subsurface lakes. The majority view today is that the features identified above, including craters and ridges, tend to support a thicker crust.

Still, with the formidable force of ocean tides against ice, it makes sense that the water beneath Europa's furrowed territories would sometimes escape as geysers. We have seen in Chap. 6 that halos of dark material surround possible vents, draping salts across the surface, following fracture lines. Necklaces of bright patches align with nearby rifts, adding to the evidence list of possible eruptions. Now that the Hubble Space Telescope has apparently spotted events ten times over the course of fifteen months, we have confirmed that Europa has cryovolcanoes spouting geysers of cryolava – water – through the ice crust. These sporadic plumes give us a window into the great hidden seas of Europa.

Just next door to shining Europa orbits the largest moon in the Solar System, Ganymede. Ganymede, too, has a hidden sea, but it is quite different in nature. Titan has a similar interior arrangement, so we will examine them together, along with the strange case of Callisto. First, we come to a sea similar, in many ways, to that found within Europa, and that sea is on Saturn's overachiever moon, Enceladus (Fig. 7.5).

Intriguing Enceladus

Saturn's tiny moon Enceladus is an extraordinary world by any measure. Its powdery ice surface is, in places, a tormented disarray of twisted ridges and cleft plains nearly devoid of craters. The entire moon is dusted with a fresh snow of fallout from some of the most dramatic eruptions in the Solar System. Over one hundred active geysers rise some 400 km above the south pole, driven by tidal forces similar to those that fuel the fireworks at Europa and Io. Temperatures within its gauzy plumes measure as high as 93°C (some 200 degrees warmer than the surrounding environment). This temperature is consistent with a mix of water and ammonia, which would serve as antifreeze.

Even before we had detailed images of Enceladus, observers could tell there was something strange about the moon. Enceladus orbited Saturn within the diffuse E-ring, a great donut of fog encircling the planet outside of its primary ring system. Some early observers suggested that the ring was actually coming from the tiny moon, and that it was made up of water-ice, but no known phenomenon could account for water coming from a moon that was considered inert and geologically quiet. One concept put forth envisioned an impact of a large asteroid, resulting in a debris cloud that made its way around Saturn. But if that were the case, why did we not see remnants of similar clouds associated with any of the other moons? The visitation of the Saturn system by the Voyagers gave us the answers (see Chap. 3).

Although Pioneer had visited in 1975, it passed Enceladus at a distant quarter of a million kilometers, and its rudimentary imaging system could not resolve detail on Enceladus. But the Voyagers, fresh from their discoveries of volcanism at Io two years before, confirmed that Enceladus was embedded within the E-ring. Voyager 1 revealed a moon that had endured global resurfacing in the recent geological past. Voyager 2 saw even more detail, and revealed the folded plains, canyons, and softened, cracked craters of the unique little world. Surfaces – especially ones in the southern hemisphere – appeared to be coated with some sort of fluffy ice or frost. It all added up to something like volcanoes, although Voyager saw no evidence of activity.

Voyager 2 was scheduled to take even higher resolution images, and to take more Enceladus snapshots looking back toward the Sun, when disaster struck. Its scan platform, which precisely aimed all the steerable instruments, jammed in one axis. The spacecraft missed many critical images over the course of several hours during the busiest part of its mission. Later, engineers determined that lubricants had migrated from their intended location in the vacuum and weightless environment of space. The problem has been seen in other long-term missions as well, and solutions continue to evade mission designers, although some possible solutions have been suggested.

Within the hundreds of images taken by the Voyagers, one image did capture an active Enceladan plume, but it was not recognized until decades later (see Chap. 3). Any true imaging of Enceladus volcanoes and their implications for a subsurface sea would have to wait for the Cassini orbiter.

The Cassini spacecraft's revelation of actively erupting waters embodied a two-for-one discovery: cryovolcanism combined with the remarkable subsurface ocean. The plumes themselves provided first-hand information about the Enceladan Sea. Cassini was able to fly directly through the plumes, carrying out the first in situ sampling of an alien ocean. The spacecraft identified 90% water vapor, with traces of carbon dioxide, methane, acetylene, propane, carbon monoxide, molecular nitrogen, and traces of important and complex carbon-rich molecules.

Exotic goings-on are taking place in the chemistry beneath that tectonically besieged surface. In addition to all the chemical excitement, ice particles in the plumes contain sodium chloride and other salts. The plumes appear to be bringing up salty ice grains from the interior. The frozen spray may come from remnants of a long-dead ocean, but it is more likely that salt water exists near the surface of Enceladus today, occasionally spewing into the airless sky of the glittering moon.

The Voyagers had given us our first hints of off-world seas, but Southwest Research Institute scientist John Spencer says that discoveries at Enceladus were a game-changer. "The idea that the moons of the outer planets were active in recent geologic time was a huge revelation. With Cassini discovering the activity on Enceladus, it really changed so much of what we knew there, but we were already open to that possibility, because of what Voyager had shown us of the activity on Io…. [I]t was amazing and fabulous and made sense of so many things that were quite puzzling up to that point, but it wasn't completely out of left field. We knew that such things were possible." Spacecraft have revealed patterns among the ice worlds, Spencer says. And Enceladus was the prime example. "Here you have a world that combined these very old regions where not a lot had happened for a billion years with these very new regions where things were happening last week."

Before the spacecraft imaged the plumes, Cassini detected oxygen atoms flooding the entire environment around Saturn. These were quite mysterious, but when the plumes were found, it became obvious that solar radiation was breaking down water molecules into hydrogen and oxygen. Ensuing encounters charted over 90 geyser-like jets. From 2010 to 2012, a trio of encounters mapped the moon's gravity, providing insights into the interior structure of the moon.

Surface imaging had revealed a depression across the south pole, and this area was expected to have weaker gravity than other regions. But the opposite was the case. Stronger gravity at the south pole indicated that there was more mass beneath the surface, not less, centered around the southern polar provinces where the cryovolcanoes were erupting. Liquid water – denser than the ice crust – could explain the readings if a deep ocean were present there. Modelers estimated that Enceladus hid a localized ocean beneath the southern surface, under 30–40 km of solid ice, and perhaps 8–10 km in depth. The sea probably extended to the rock/ice interface, meaning that the ocean floor was made of mineral-rich rocky material, a significant finding in the search for life.

Subsequent measurements discovered tiny particles of silica in the plume material, confirming that the geyser-like jets were in contact – at least indirectly – with a rocky ocean floor. Hot liquid conditions lead to this type of silica particles, which implies that hydrothermal eruptions were taking place on the seafloor. Here, astronomers had evidence of a geologically active rocky seafloor with hydrothermal volcanic vents spewing materials into a briny ocean, just as happens on Earth at sites like the Juan de Fuca ridge in the Pacific, or on the seafloor of the mid-Atlantic rift zone in the Atlantic Ocean.

Further maritime revelations were to come. Within those plumes lay an extra portion of hydrogen. If verified, this finding would bolster the idea that volcanoes were erupting on the ocean floor. But Cassini team members were cautious, not only because of the capricious nature of alien worlds, but also because of a quirk within Cassini's instrumentation. Its ion and neutral mass spectrometer, the equipment capable of sensing elements such as hydrogen, was constructed with titanium baffles. As particles from the plumes impinged upon the wall material, it was possible that the interaction would release hydrogen. Because of this, flight engineers worked to reconfigure the spacecraft as it sampled the plumes, protecting the titanium walls from direct impact of plume particles. Once successful, investigators gained confidence that the hydrogen they were seeing was a real component of the plumes and that hydrogen was likely being generated at the seafloor.

The vents on Enceladus's ocean floor are likely alkaline hydrothermal vents much like the "low temperature" eruptive sites in Earth's oceans. They differ from the "black smokers" seen along the Atlantic mid-ocean ridge. They are not powered by conventional volcanic plumes but rather are heated by chemical reactions between the saltwater and rocks. The process is called serpentinization. On Earth, these cool vents build fanciful towers and blades of rock, and their plumes contribute to rich undersea colonies of microbes and larger creatures.

A careful study of the locations of Enceladan surface features – especially craters – showed something remarkable. The surface of Enceladus was not turning at the same rate as the moon's core. The crust of Enceladus was decoupled, a mere shell floating on a globe-enveloping ocean. Studies limit the ice crust to a thickness of 35 km near the equator, thinning to less than 5 km at the south pole.

Our research has left us with an image of a remarkable ice world with all the right combinations for life. Plume ice particles are streaming from an interior ocean. That ocean is briny, like terrestrial seas. Active hydrothermal vents on the ocean floor are infusing the water with minerals. Organic matter, along with sulfur and nitrogen, drifts in this alien sea, accessible to any living thing present. Chemicals that pour from such hydrothermal environments on Earth contribute to life in our oceans, sustaining metabolic activity far from the Sun's energy.

All of these items form a checklist for life (see Chap. 10), but they add to a mystery – where is all of the Enceladan energy coming from? Many models and simulations show that tidal friction (from the gravitational pull of Saturn and its other moons) and radiogenic heating (from radioactive material in the rocky core) cannot account for the seas of Saturn's glistening moon. The little world should be frozen solid, as its neighbor Mimas is.

Analysts have been pondering the riddle, and in 2017 theorists presented two theories to explain the energy, the plumes, and the ocean. Researchers at the University of Nantes (France) advocated a scenario based on a porous core for Enceladus. They suggested that if the center of the moon consists of unconsolidated, pliable rock, cold sea water could be seeping in, and tidal friction would rub the rocks against the water, warming it. The simulation showed that water welling up from within the core could cause hotspots on the seafloor that unleash up to 5 gigawatts of energy.[3] The heated water would then rise back up, triggering the cryovolcanism. The authors claim that this process could generate enough energy to sustain an active plume for a billion years. Another intriguing result of the model is that the strongest effects would be felt at the poles. Over an extended period of time, the crust of Enceladus which probably averages between 20 and 25 km thick – would thin out to just a few kilometers at the poles.

Another idea concerns to a potential powerful impact by a large asteroid or comet. Studies by the Southwest Research Institute and Johns Hopkins University show that an impact 100 million years in the past could account for the heat output and deep fissures seen at the south pole provinces. An impact strong enough to break through the 20-km-thick crust (estimated to exist at the time) would deposit enough energy to result in the observed surface features today. The impact could have occurred anywhere on the globe south of the equator, but the impact site would have shifted to the south pole.

Such an event could have had dramatic consequences even beyond Enceladus. Saturn's rings are now estimated to be about 100 million years old, perhaps created by the destruction of a small ice moon. If true, the two events may be connected.

Research leads us to other theories as to why there is still an ocean on Enceladus at all, and why nearby moons see little or no effect. One new theory has to do with the exchange of rotational and gravitational energy between Saturn and its moons. Although mighty Saturn's gravity has an obvious effect on nearby moons (and on its rings), all of the affected objects have an influence on Saturn as well. There is an energy balance, a sort of exchange that occurs between planet and moon, where Saturn exerts force on a moon, but that moon "sloshes" on the inside, which also dissipates a little energy from within Saturn itself. In other words, each moon triggers tidal oscillations within Saturn, which then pushes the moon outwards and increases its eccentricity. A recent theory suggests that each moon generates these subtle disruptions within Saturn differently, so Enceladus is getting a lot of energy out of Saturn, whereas Mimas – which

---

[3] Nevada's Hoover Dam generates about two gigawatts.

is even closer to Saturn – might be getting significantly less. There are different gravitational resonances for each moon, and these will determine the extent of this gravitational energy "trade." The theory could explain why Dione's surface is more transformed than nearby Rhea, for example, and why near-twins Mimas and Enceladus are so dramatically different.

The orbit of Enceladus is quite eccentric today, and its eccentricity is sufficient to produce enough heat to sustain a liquid ocean. Although that ocean may have been initially created under very different circumstances and warmer conditions, it survives into the modern era because of other forces, and an exchange of gravitational influence between the little moon and Saturn might be at least one of those forces at work today.

The combined efforts of ground observations, laboratory studies, and spacecraft encounters have provided us with a broad outline of the Enceladan deep, a picture of an alien submarine realm. What is it like beneath the ice crust?

Voyage to the Bottom of the Sea

Although there are still many unknowns about specific details and dimensions, we can imagine future ventures beneath the ice. We first set up a pressure dome to keep any seawater from exploding into the vacuum of space. Once it is erected and pressurized, we drill down through the thinnest part of the crust, a daunting several kilometers of icy tunnel. Finally, our pathway is secure, and we lower our submarine. It slides through our tunnel of ice and hits the ocean just a thousand feet down. But the liquid here has risen to the level of the geysers outside – far above the actual level of the sea – where it turns to vapor; we still have kilometers to go before we enter open water. Through the ice we hear the explosive escape of water vapor through the famous water jets only kilometers away from our entry site. Here in the south, the ocean is as deep as 50 km, but it dwindles to a shallower 20 km at the equator, where the ice crust is much thicker.

Capped by the ice crust, the water we enter is impossibly dark, as black as the deepest oceans on Earth.[4] The complete darkness only intensifies the feeling of vast emptiness. The extent of the ocean is estimated at something equivalent to the Arctic Ocean. This is remarkable, considering that the entire moon is only as far across as the country of France. And it's cold. The waters here are kept liquid by ammonia, salts, and the constant pull of nearby Saturn and sibling moons. We float in a bath rich in the chemistry of prebiology: nitrogen, salts, potassium, ammonia, hydrogen, and complex organic materials, the very stuff that makes up our own life-defining DNA.

Water pressure is lessened by the low gravity; Earth has 86 times the gravity of Enceladus. As we descend, the pressures reach 74 bars, or 74 times the air pressure on Earth at sea level. In comparison, the pressure on the seafloor of the Mariana Trench, the deepest spot in Earth's oceans, is 1086 bars.

Farther down, the relentless gloom begins to break as orange light suffuses our surroundings. Down here, there is finally light, but it is not the light of the Sun. Rather, the abyssal depths here glow with the energy of volcanic hotspots. Collections of stony towers rise from volcanic throats in a cacophony of reds, yellows, gray and green, rock tinted by minerals coming up from Enceladus' core rocks. Temperatures around us have risen from just above freezing (at the ice/water interface) to about 90° C at the seafloor.[5] Could this undersea wonderland host life of a new, alien kind, the essence of a second genesis? (Fig. 7.6)

Sites on Earth That May Have Similar Conditions to the Ocean Floor of Enceladus

Lost City is a cool hydrothermal site near the Mid-Atlantic Ridge, where serpentinization is occurring (a process suspected of taking place on Enceladus' seafloor). The Cedars is a site on dry land in northern California where carbonate springs flow over serpentine rocks. Ikka Fjord is a Greenland site where carbonate-rich spring water meets the ocean. Lake Vida is an ice-covered salt lake in eastern Antarctica's Dry Valley region. Comparing these generalized numbers provides insight into what environments on Earth might bear some resemblance to the Enceladan Sea. Two versions of Enceladus seawater were simulated in this study, one with a pH – or alkalinity – of 9 and the other with a pH of 11. The table has been simplified from original work by Glein et al.

Site	Temp (°C)	pH	Sulfates	Sodium	Potassium
Enceladus (pH9)	0	9	Not found	130	1.3
Enceladus (pH11)	0	11	Not found	154	1.54
Lost City	90	10.6	3.31	511	10.8
The Cedars	17.2	11.5	0.001	0.94	0.1
Ikka Fjord	4	10.5	2.74	175	1.66
Lake Vida	0.4	6.2	62.9	2090	89.2

---

[4] Unless, of course, there are bioluminescent creatures swimming around…

[5] Volcanic sources on the ocean floor have been inferred from the silica detected in the plumes.

Fig. 7.6 Submarine volcano on the Pacific Ocean's Juan de Fuca ridge, made of anhydrite and sulfides. (Image courtesy of NOAA; http://ocean-explorer.noaa.gov/explorations/02fire/logs/jul29/media/anhydriteblow.html)

Ganymede's Cloistered Seas

While the oceans of Europa and Enceladus meet with a rocky, mineral-rich seafloor, oceans of a different arrangement are sequestered within the ice crusts of other moons. The first to be identified was a strange sea within the largest moon of our Solar System, Ganymede.

As moons go, Jupiter's Ganymede is the big kid on the block. Measuring 5268 km across, its diameter bests that of the planet Mercury by nearly 400 km. And with an intrinsic magnetic field (hinting at a core of molten iron) and differentiated interior, Ganymede is a planet in its own right. Using Hubble data, scientists at the University of Cologne have also found evidence of an induced magnetic field similar to Europa's, suggesting a deep internal ocean of briny water. But while Europa's ocean rests upon a floor of rock, where minerals and perhaps volcanoes add life-supporting materials to the mix, this is not the case for Ganymede. The moon's induced magnetic field heralds an interior ocean beneath the frozen crust, but it is probably sandwiched between ice layers above and below, sloshing some 170 km beneath the surface.

First hints intimating a Ganymede sea came from surface images (Chap. 6). The ubiquity of Ganymede's grooves implies that the entire moon expanded during its adolescent years. Grooved terrain tells of fierce internal forces, perhaps the imprint of heating and separation of interior components that caused expansion. The grooved terrain seen today is the frozen vestige of a violent past.

Proof of a buried sea could come from an induced magnetic field like the one seen at Europa. Between 1996 and 2000, Galileo made six targeted flybys of Ganymede, with multiple instruments scrutinizing the moon's magnetosphere. Its instrument suite included the plasma subsystem, or PLS, which measured the density, temperature, and direction of the plasma (electrically charged gases), along with magnetometers to sense changes in the surrounding energy fields. But the orbiter culled only circumstantial evidence for an induced magnetosphere. It was able to confirm a different kind of magnetic field: a strong, internally induced magnetosphere coming from the moon's core. Its magnetosphere issues from the churning of a partially molten iron core. Its strength is only about 1 percent of Earth's magnetic field, but it is strong enough for Ganymede to carve out its own energy "bubble" within Jupiter's much larger magnetosphere. This makes Ganymede unique among the Solar System's moons. It is the only moon known to have an internally generated magnetic field. Galileo's gravity measurements corroborate this narrative, signaling that much of Ganymede's mass is concentrated in a central metallic core.

Ganymede's magnetosphere points to a tumultuous history. Intense heating once melted the moon's icy interior. During the process of differentiation, the moon's ice matrix released heavier rock and metal, which sank down to form a stony mantle, while water and slurry floated upward, congealing 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 reveals that the iron core has not yet completely cooled off from its formative epoch.

Ganymede's intense heating must have taken place relatively late in Solar System history, ending only a billion years ago, judging from the residue heat that keeps the iron core molten today. This leftover heat could also trigger melting within Ganymede's interior rocky mantle. Perhaps conventional volcanoes erupt onto the surface of the rocky central region, melting some of the ice mantle against it. These eruptions would melt out huge spheres of liquid water, leaving globe-shaped ice caves some 900 km below Ganymede's visible ice surface.

What causes and maintains this heating? Gravity mapping by Galileo indicates that heat from Ganymede's strongly differentiated interior induced wide-scale geological activity on Ganymede. Tidal heating may explain the geologically active landscapes of Ganymede, and the lack of them on nearby Callisto. Jupiter sets up 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. For every Ganymede orbit around Jupiter, Europa circles twice, and Io orbits four times. This linked orbital cotillion of the three inner Galileans keeps their orbits from becoming circular; they are constantly pushed and pulled as they drift closer and then farther from Jupiter during each orbit. As we have seen on Io, Europa, Enceladus, and other moons, this flexing creates heat.

Ganymede does not receive significant tidal heating today, but there is evidence that it has not always been so quiet. The orbits of the Galilean satellites may have evolved over time, such that past tidal heating triggered Ganymede's intense heating and differentiation for a time. Silent Callisto sits out of the orbital rave, so it has never endured significant tidal heating. But the orbital taffy pull of the other Galileans, Io and Europa, has driven Ganymede and Callisto onto distinct evolutionary paths, scoring Ganymede's face with those remarkable bands and troughs while leaving Callisto's face to billions of years of unmasked battering by asteroids and comets.

What of a hidden ocean? Ganymede does, in fact, have an induced magnetic field just like Europa does. Its presence was divulged not through spacecraft encounters but rather by Hubble Space Telescope observations. Back in the late 1990s, Galileo detected spectacular aurorae over the poles of Ganymede, the first such phenomena seen outside of Earth and Io. Decades later, in 2015, Hubble was able to map the movement of Ganymede's auroral displays as they interacted with Jupiter's magnetosphere. Computer models can predict where the aurorae should be given certain structures in the interior of the moon. When researchers applied these models to the observations, the ones using a solid ice crust didn't work. The only models that lined up with the observed locations of the aurora were the ones that used a deep, saltwater ocean beneath an ice crust. As we saw at Europa, an interior saltwater sea interacts with the magnetosphere in a characteristic way, essentially setting up a second magnetic field induced by the exterior one (Fig. 7.7).

Hubble's long-term map of alien aurorae results in a similar picture to the one we have of Europa and Enceladus: a globe-encircling ocean. Initial theories described an ocean at least 100 km deep, with more water than the combined oceans of Earth. Above it lies a 150-km thick ice crust. Ganymede's depths likely contain salts, magnesium sulfates, and possibly sodium sulfate. A saltwater ocean is the only thing that can explain the observed induced magnetosphere. But unlike the seas of Enceladus and Europa, Ganymede's is nestled within the ice mantle, with many kilometers of ice both above and below it, cutting it off from the surface and also from the minerals in the rocky core. The ice of Ganymede's bottom layer – forming a "seafloor" of frozen water at the base of its ocean – is ice in a different phase, called Ice IV (see Chap. 1). This ice is subjected to higher pressures than the upper layers. It seems that the ice below cuts the ocean off from life-giving nutrients of the rocky core, but diapirs moving through the solid ice above the rock may bring material up into the ocean. (For the possibilities of life in this strange sea, see Chap. 10.)

New work suggests that Ganymede's ocean may not be so simple. In fact, the massive moon may have a series of oceans nested between layers of ice. A 2013 study by researchers at the Jet Propulsion Laboratory put forth the "club sandwich" model of Ganymede's interior. The study took into account more variables, such as salinity of the layers of water and ice and the complexities of heat transfer in differing ices. The new model shows a Russian doll arrangement, with alternating layers of ice shells and thin global seas. The individual ice layers would have different phases, depending on pressure and temperature. The deepest water in the nested seas would be the most salty.

In the new scenario, the surface of Ganymede consists of Ice I. It covers a thin layer of liquid brine, which in turn covers another ice layer, this one made of Ice III. The Ice III

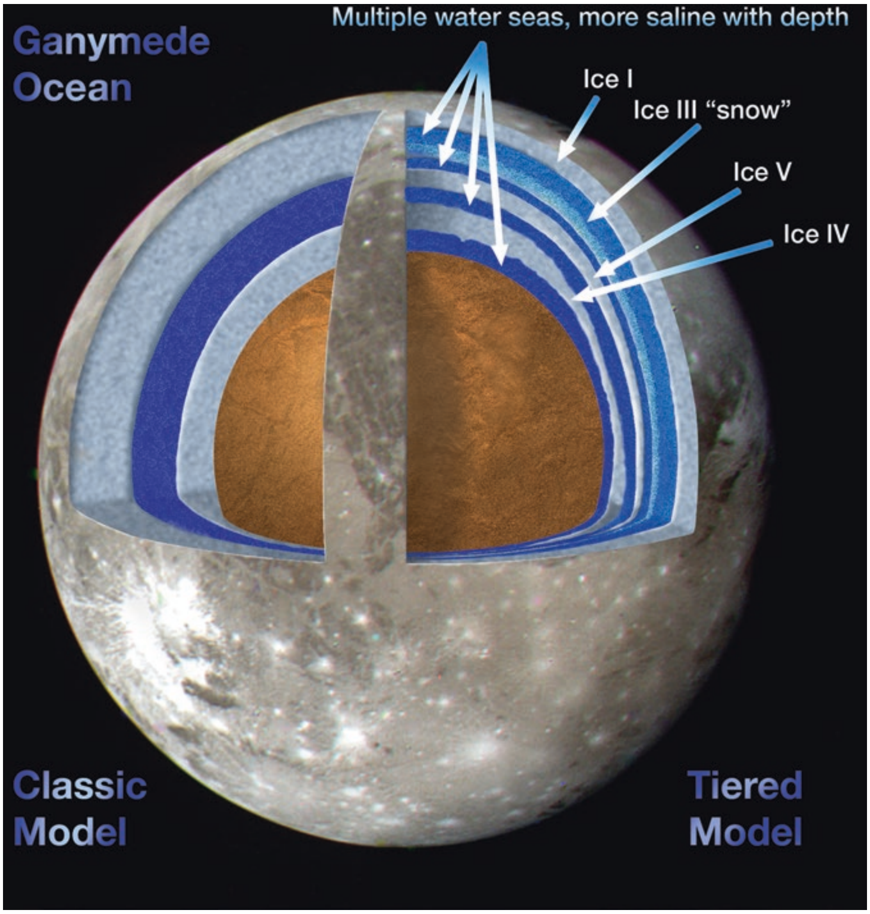


Fig. 7.7 Two models of Ganymede's global ocean. (Art by the author)

layer condenses, forming "snow" within the water. Because of the internal pressures at that level and the qualities of ice, this snow would actually move upward from below, a sort of reverse blizzard. Below these regions lies another layer of ice in the Ice V form, followed by a deeper ocean and another layer of ice in the Ice VI phase. Finally, a liquid ocean, deeper and saltier than the others, rests against a rocky seafloor, the outer edge of Ganymede's core. This deepest sea, warmed by pressure and infused with chemicals and minerals from the core, may be a site for alien biology. If life flourishes in that remote deep-freeze ocean, it must lead an existence in an environment far different from anything we have experienced, a truly alien submarine universe (Fig. 7.8).

Titan's Nautical Narrative

A similar trapped ocean may be sandwiched within the ice beneath the eerie landscape of Saturn's largest moon, Titan. As the moon rotates in its orbit around the ringed giant, its spin rate changes, indicating the presence of a large, perhaps globe-encircling ocean. If Titan's crust were solid ice, Saturn's gravity should raise tides of about one meter each Titan day. But the crust actually bends upward by about ten times that extent, showing a flexibility that can be explained by a hidden ocean. Titan's low density evidences a composition of water and rock. Its water-ice makes up the surface crust, but an ocean up to 300 km deep may persist beneath that crust. Its dark waters may be seeded with ammonia and complex organics.

Titan sustains another kind of ocean on its surface, and this may be the strangest sea of all. Beneath the moon's opaque nitrogen-methane sheath of smog lie truly alien seas consisting of methane and ethane. Titan is the only world besides our own with an active cycle involving rain fed by evaporation from surface lakes and rivers. Its river valleys drain into liquid-filled basins. Because of their size, the largest are referred to as *maria,* Latin for "seas." Titan's lakes and seas vary greatly in size, from the limits of Cassini's resolution up to about 400,000 km^2 for Kraken Mare. For comparison, North American's Lake Superior is 82,000 km^2 in extent, and Europe/Asia's Black Sea is 436,400 km^2.

The seas of Titan are complex, and we will explore them in detail in the next chapter.

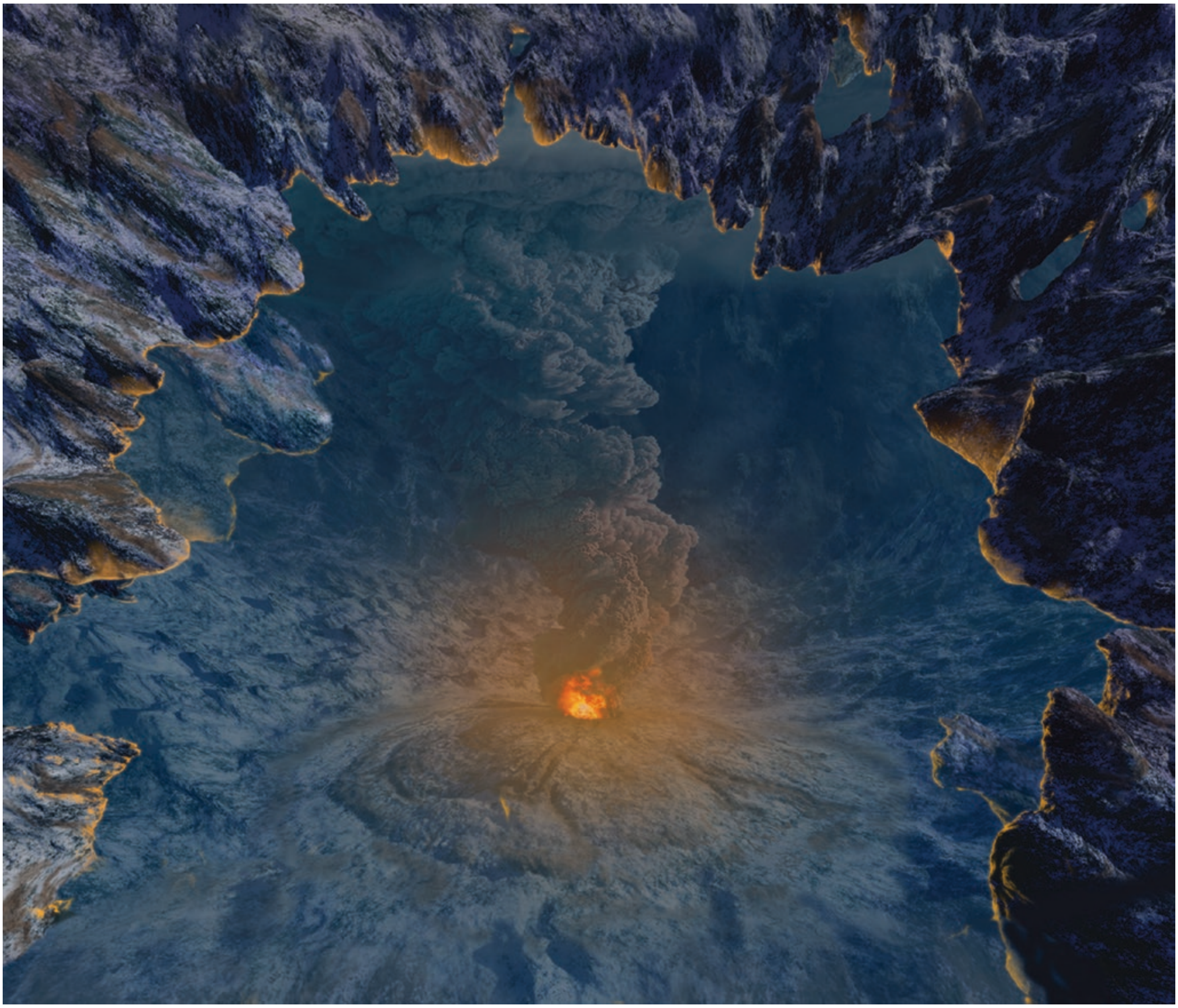


Fig. 7.8 No matter the structure of Ganymede's ocean above, another kind of localized ocean may exist where the rocky core meets the ice crust. Here, tidal heating may lead to conventional silicate volcanism. Any erupting volcano would melt a spherical ocean around it within the surrounding solid ice crust. (Art by the author)

The Surprising Case of Callisto

Jupiter's second largest moon seems to be an undifferentiated disarray of rock and ice, and in our cosmic ocean patterns, it seems a lousy candidate for an underground ocean. The huge moon lacks the exciting geologic activity of its sibling Ganymede, orbiting just next door. Callisto has no sign of grooved terrain, none of Ganymede's bright highways of ridged plains, no dramatic uplift or fractures. Only a handful of fractures break the dark, cratered terrain.

Some of Callisto's larger impact basins and palimpsests indicate that the ice here was once warmer and softer, allowing features to flow and slump after they formed. But whatever mobile ice was hiddn beneath the surface seems to have been at substantial depth. Initial post-Galileo mission models projected an interior of comingled rock and ice from surface to core. But the Galileo spacecraft's repeated flybys began to reveal a familiar tale. Something within Callisto – that battered and apparently dead world – was bending and shaping the magnetosphere of Jupiter. The interference set up by the moon is commensurate with flowing saltwater. The model that fits the variations in Jupiter's energy fields best is a model of a global ocean. The silent Callisto, too, is an ocean world.

The ocean hiding beneath that tawny cratered surface is 170 km down, and has a depth of at least 10 km. Because Callisto orbits outside of the tidal circus going on with its

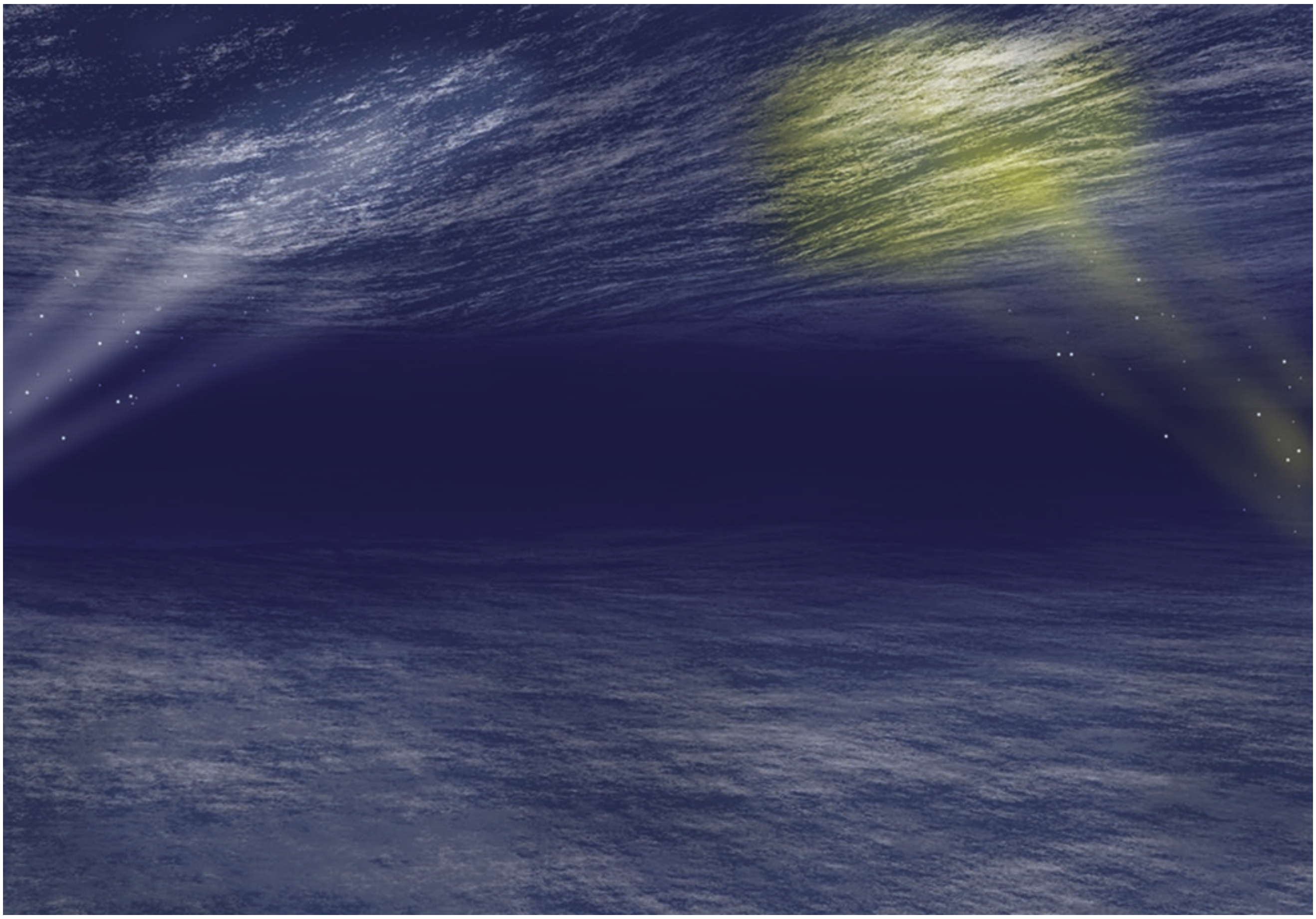


Fig. 7.9 The lights from a future probe illuminate the gloomy world of Callisto's ocean, a dismal place with floor and ceiling of solid ice. (Art by the author)

sibling Galilean satellites, the ocean must be kept liquid by the natural "antifreeze" we have seen elsewhere – ammonia, salts, and other materials. At the base of Callisto's ocean, pressure builds to the point where the water freezes into ice of an exotic nature, in this case probably Ice V. This sea ice layer may be more than 100 km deep, but still more layers of exotic ices stack up underneath it, all mixed with rock. Eventually, ice gives way to a mix of rock and metal in an amorphous core region. Scientists still face quite a few uncertainties about details of Callisto's interior, but the overall picture is generally established. Callisto's dark ocean must be a sorry place, a sterile abyss encased in dense ice above and below, set apart and cut off from life-giving energy and nutrients since its birth billions of years ago (Fig. 7.9).

Dione's Dead Sea

Among the moons of Saturn, Dione is distinctive. Wide swaths of its surface are smooth and appear younger than the other moons. Dione's craters have a distinctive shape, as if there has been enough heating to flatten them out. Dione is next to Enceladus in terms of activity, far below it but more alive that Tethys, Rhea, or Iapetus.

If liquid seas do exist beneath Dione's crust, the moon would join Europa, Ganymede, Callisto, Enceladus, and Titan as a host to an alien ocean of water, increasing its importance for future spacecraft missions. The stakes are high, and the studies continue. Recently, researchers at the Royal Observatory of Belgium analyzed gravity data from Cassini's five close Dione encounters. Their results fit with a pattern that is emerging for ocean worlds. Dione's gravity fits if its structure includes an ice crust floating on a global ocean some 100 km below. In this case, the ocean would be fairly shallow, tens of kilometers deep, and would rest on the rocky core. This makes Dione's layout quite similar to that of Enceladus or Europa, but with a thicker, more rigid crust.

The moon seems quiescent today, but its face betrays a more exciting geologic history. We have seen the possibility of active cryovolcanism in Dione's past (Chap. 6). Dione's largest impact basin, Evander, has strange features that have "relaxed," or softened. Evander might be the result of a large impact on a floating ice shell. But many smaller craters also show signs of relaxation, and with a crust as thick as Dione's is estimated to be, craters this size would be unaffected by an ocean beneath such a deep ice layer. They could, however, be affected by warm diapirs moving up through the solid ice, heated by seawater below.

Another line of evidence may point to cryovolcanic eruptions, possibly ocean-linked. Two of Cassini's instruments, its magnetometer and its radio and plasma wave instrument, sensed streams of material feeding ionized gases (plasma) into Saturn's magnetosphere. Studies indicate that the plasmas originated somewhere inside the orbits of Tethys and Dione. Researchers believe Dione, with its younger surface, is the best candidate as a source of the gas. But in all of Cassini's encounters with the moon, the spacecraft detected no traces of plumes or clouds of material. If Dione is venting gas, as Europa and Enceladus do, the venting activity may be periodic, or it may be too weak to be detected by instruments like those Cassini used.

A subsurface Dione sea is controversial in the planetary science community. Our knowledge of the moon's interior is preliminary and inconclusive. But circumstantial evidence at least leaves the possibility open.

Other Mid-Sized Marine Moons

Icy moon experts also suspect the presence of buried seas on Saturn's Rhea and several of the moons of Uranus. Rhea's interior is not well understood, and may be only partially differentiated. Some surface features (young, lightly cratered terrain, canyons, etc.) are remnants of past activity, but their drivers are unknown. An ancient subsurface ocean may be at root. Models indicate a thick ice crust, perhaps overlaying a hydrated (soggy) rock core. Estimated crust thicknesses range from 5 km (the depth of Tirawa crater) to 200 km. As for a liquid layer, the jury is still out.

As we saw in Chap. 3, the Voyager encounter of the ice giants was plagued by a balky pointing system, high encounter speeds, and low light levels. Nevertheless, the aging spacecraft was able to pull off a spectacular set of encounters. At Uranus, flyby distances depended on the location of each moon in its "bullseye" pattern of orbits from the spacecraft's point of view. Three of the moons – Titania, Ariel, and Miranda – were imaged at medium to relatively high resolution, but with limited coverage. In terms of size and orbital dynamics Titania, Oberon, and Ariel have the highest potential for past or present subsurface seas.

Water-ice and carbon dioxide are the only confirmed compounds found on the surface of Titania so far. The carbon dioxide may issue from radiation breaking down organic material. Organics may also be the cause of its reddish tint, something we see throughout the outer ice moons when they are powdered with hydrocarbons and other organic compounds. Titania's density, higher than that of Dione or Rhea, implies an even balance of rock and ice. The moon's interior may be differentiated, but this is uncertain. No tidal heating is present to help warm the interior, but judging by the patterns we have seen, if Titania is differentiated, it may have the structure needed for an ocean. It is also likely that the moon has methane or ammonia to lower the melting point of water. Interior pressures may well lead to liquid under the surface. Its rocky core, though small, may still have active radiogenic material that could further heat the ice crust into an ocean adjacent to the core. This shallow ocean would probably be no deeper than 50 km. Temperatures under Titanian sea conditions could be as low as –83°C.

Ariel is smaller than Titania and Oberon by more than a quarter. Its density is similar, with an even batch of rock and ice. Although its small size may preclude substantial leftover radiogenic heating in its core, the core size is still sizable, measuring some 720 km across. Aside from any possible radioactive core products, Ariel cashes in on the tidal heating card.

Early in the Solar System's formation, some 4 billion years ago, Ariel was probably in multiple orbital resonances with both Umbriel and Titania. This would have set up heating in all three moons, but especially in Ariel. An ocean of liquid water, laced with ammonia and methane, may well have existed at the ice/rock interface, and it may have survived – due to its impurities – to this day.

We saw in Chap. 6 that Ariel's landscape has been resurfaced by flows and trenches in what must have been extensive cryovolcanic eruptions. As we have seen, cryovolcanism and subsurface seas seem to go hand-in-hand. Remote studies from Earth are ongoing. Telescopic searches for something like Saturn's E-ring in the orbit of Ariel have, so far, been unsuccessful. Although Ariel is no longer in resonance with any of its sibling moons, primordial heat may have left it with a long-lived ocean, still active today.

Oberon is the least known of the three. Its density is similar to Titania's, so it may have a similar internal structure, with a rock/metal core spanning a diameter of roughly 950 km. Like Titania, Oberon is not subject to any significant tidal heating, but may well have ammonia and other substances to retain a liquid interior. If Oberon hides an ocean today, the moon may form part of a remarkable triumvirate of ocean worlds in orbit around Uranus.

A Sea Within Neptune's Son?

Triton is unlike any other ice world we have seen. It has no large impact craters, and yet lacks the ribbing and fractures of Europa, Ganymede, or Enceladus. Though some features may bear a faint resemblance to other ice moons, processes at Triton are clearly unique. We have visited its solid-state greenhouse-fueled cryovolcanoes and its plains of pink ice, its bizarre cantaloupe terrain, and bruise-like maculae. Can its wild landforms tell us anything about what is more than skin deep? Perhaps.

Planetologists find it instructive to compare Triton to Pluto. The ice worlds are similar in size, they have similar amounts of rock and ice, and they have similar composition, so one might expect them to look similar. But they don't. Pluto's surface seems to be much thicker and colder. But on Triton, the crust is warmer and so unable to support high mountains. Every indication is that much more heat issues from the interior of Triton than it does from within Pluto. Since Triton exhibits very few craters (only 179 were identified in Voyager images covering 40% of the moon's globe), scientists think the surface is very young. In contrast, much of the real estate on Pluto is probably 4 billion years old.

The most likely explanation is that Triton receives some tidal heating from Neptune. That's not easy to do on Triton because places like Io, Enceladus and Europa have eccentric orbits and are affected by the pull of their sibling moons. But Triton's orbit is circular and should be free of tidal heating from Neptune.

The drive behind Triton's internal furnace might have to do with the moon's orbit, which is inclined. Triton does not orbit in the same plane as the equator (the vast majority of moons do). Triton's orbit wobbles, just as a spinning top wobbles back and forth on a tabletop. This systematic wobbling is called precession. The axis of Triton has to continually change to keep up with the precession of its orbit around the planet. If an ocean exists inside, that forcing of the axis sloshes the ocean around, generating heat and resulting in the surface activity we see today. Recent research[6] indicates that if Triton's ice mantle is 300 km deep, an underground sea could remain stable, with temperatures reaching as high as –33°C if the water has salts, ammonia, or other compounds acting as antifreeze.

The same model suggests that the liquid ocean may be sandwiched between ice layers rather than resting on the rocky core. This ocean would be shallow (just a few tens of kilometers deep), with a ceiling of nitrogen and water-ice and a layer underneath consisting of ice at higher pressure (perhaps Ice III).

What are the chances, though, that Triton hides its own Davey Jones' locker? The history of the strange moon provides some hope for deep waters. As we have seen, Triton's capture by the Neptunian system took a huge toll on the moon. Its ice mantle was melted – and some of it vaporized – to the point that it created a global ocean. The process of Triton's orbital settling, in which it shifted from an elliptical path to a circular one, probably engendered enough energy to keep the ice crust and interior mantle liquid for hundreds of millions of years. Any surface record Triton may have possessed of primordial cratering or geological activity was smelted into oblivion, replaced by a resurfaced, "rebooted" crust.

The details of Triton's timeline are lost to prehistory. We cannot tell when it was captured or how long it has been in its current state. We do know that it probably took something in the neighborhood of a billion years to circularize,[7] so the event was not a recent one.

Although tidal heating within the moon is fairly subdued now, Triton also receives energy from radioactive materials within its rocky core. This heat, by itself, is not enough to keep Triton's ocean liquid for the entire course of its about4.5 billion year lifetime. But the forces from Triton's tilted orbit direct heat inward, concentrating it at the bottom of Triton's ice shell. Over time, this warming of the base of Triton's ice has created a sort of tidally heated blanket, preventing the ice shell from freezing solid all the way to the bottom. This "tidal dissipation" was even stronger when Triton's orbit was more eccentric, but lessened as the orbit became circular. This means that this tidal force was even more effective in the past, perhaps sustaining a liquid ocean even now.

Looking at its circular orbit today, analysts can trace how its orbit evolved over time, providing more insight into whether an ocean might still exist. As Triton cooled, its ice sheet expanded inward, slowly eating away at the ocean beneath. New models can calculate how the thickness of the ice crust influences that tidal heating at the ocean floor. Research shows that if the ice shell is thin, tidal heating has a stronger effect. But if the shell is thick, the crust quickly becomes rigid, and tidal heating has less of an effect. Many of Triton's variables are not well known. The size of its core and the thickness of ice are not constrained. A larger core contributes more radiogenic heating and a deeper ocean. Ocean depth may also vary across the globe, as we have seen on Enceladus. Tidal dissipation tends to concentrate the heating in the polar regions, resulting in the deepest waters there. Impurities such as salts or ammonia will also encourage the presence of liquid water. Those who study planetary chemistry estimate that the ice worlds of the outer Solar System may contain as much as 15% ammonia, an efficient antifreeze. The uncertainties make it difficult to predict whether an active ocean has survived over time.

Oceans may await us even farther out in the Solar System, at the very edge of our planetary family. Pluto's strange, tortured face exhibits hints of hidden alien seas. We will explore the possibility in Chap. 9. But first, we'll visit some seas made not of water but of something more akin to paint thinner. These organic lakes spread across the ice deserts of Saturn's illustrious moon Titan.

---

[6] For more, see by Nimmo and Pappalardo, *Ocean Worlds in the Outer Solar System* (2016).

[7] The duration of this circularization is dependent on details of Triton's interior, and those details are, as yet, unknown.

Titan

8

At the dawn of the third millennium, planet-sized Titan stood as one of the great mysteries of our Solar System. Large enough to be counted among the planets, Saturn's huge, orange moon cocooned itself in an opaque blanket of fog and mist (Fig. 8.1). Despite returning some images with resolutions better than 650 m per pixel, the best efforts of Voyagers 1 and 2 failed to gaze upon the moon's face. There were no breaks in the clouds, no clear skies. Scientists had already come to realize that surface conditions there hovered at the triple point of methane, meaning that the pressure and temperature were just right for methane to exist as a liquid, ice or vapor (Earth's environment is at the triple point of water). Was Titan graced with a global sea of liquid methane? Was it a desert, a version of Mars in cold storage? A wilderness of solid water ice? What lay beneath those frustrating clouds?

One of the Cassini mission's central tasks was the reconnaissance of the mystery world. Equipped with an advanced radar system, the Saturn orbiter could peer through the clouds in ways Voyager could not. Its radar could image the surface at high resolution (0.35–1.7 km/pixel). Additionally, Cassini's imaging science subsystem could view the surface directly through the near-infrared part of the spectrum. Rounding out its Titan-related payload, Cassini carried the Huygens probe, a European Space Agency-designed and built atmospheric probe crafted to image its voyage through Titan's haze layers and – if luck, communications, and batteries held out – right down to the surface.

Titan has turned out to be a multifaceted and compelling world, far more so than anyone had predicted. The planet-sized moon perplexed and mystified the greatest minds from the beginning of the first spacecraft encounters. Cassini/Huygens team member Ralph Lorenz remembers how our understanding of Titan and, in particular, its surprising sand dunes, "was an evolving story… that's the nature of exploration: you don't know up front what you're going to see. In fact, I had preconditioned myself into not expecting to find sand dunes on Titan at all, because we knew that Titan has methane in its atmosphere, and we knew that the methane will fall down as rain, so we expected Titan to be damp. When it's damp, you can't move sand around. We also expected to find seas, and seas trap sand. So the big-picture expectation beforehand was that we wouldn't see sand dunes. We weren't smart enough. Before Cassini arrived, we were thinking of Titan in zero-dimensional terms. 'What is the surface of Titan like?' 'It's like X.' The reality is, of course, that Titan is a wide and diverse world." Researchers were missing some key clues, information that would have hinted that Titan could manufacture desert-like conditions, despite the assumed presence of liquid methane. In particular, because Titan has a long year and a methane cycle similar to Earth's hydrological cycle, the moon goes through very strong seasonal and latitudinal effects. Those, as it turns out, conspire to circulate the atmosphere in such a way that its flow dries out the low latitudes. Much of the moisture is concentrated at the high latitudes where seas surround the north pole and sand dunes band across the equator. Says Lorenz, "That dichotomy, that profound difference in the landscape as a function of latitude is not something we were smart enough to anticipate."

A Titan Survey

Before Cassini's revelations, Titan kept its secrets well hidden beneath its orange vest. The moon's atmosphere was discovered early on, but its nature and extent were uncertain before the space age.

Gerard Kuiper, after whom the Kuiper Belt was named, discovered the presence of a methane atmosphere at Titan in 1944. But how dense that atmosphere was evaded astronomers for decades. If Titan had a fairly pure methane atmosphere, its skies would be clear, perhaps even dark, because of low pressure. In this case, the reddish color seen by observers was caused by the surface rocks. But if the air had a major component of nitrogen, which Earthbound telescopes were blind to, then the moon might be enshrouded in a deep atmosphere as opaque as that of Venus. Later studies,

M. Carroll, *Ice Worlds of the Solar System*, https://doi.org/10.1007/978-3-030-28120-5_8

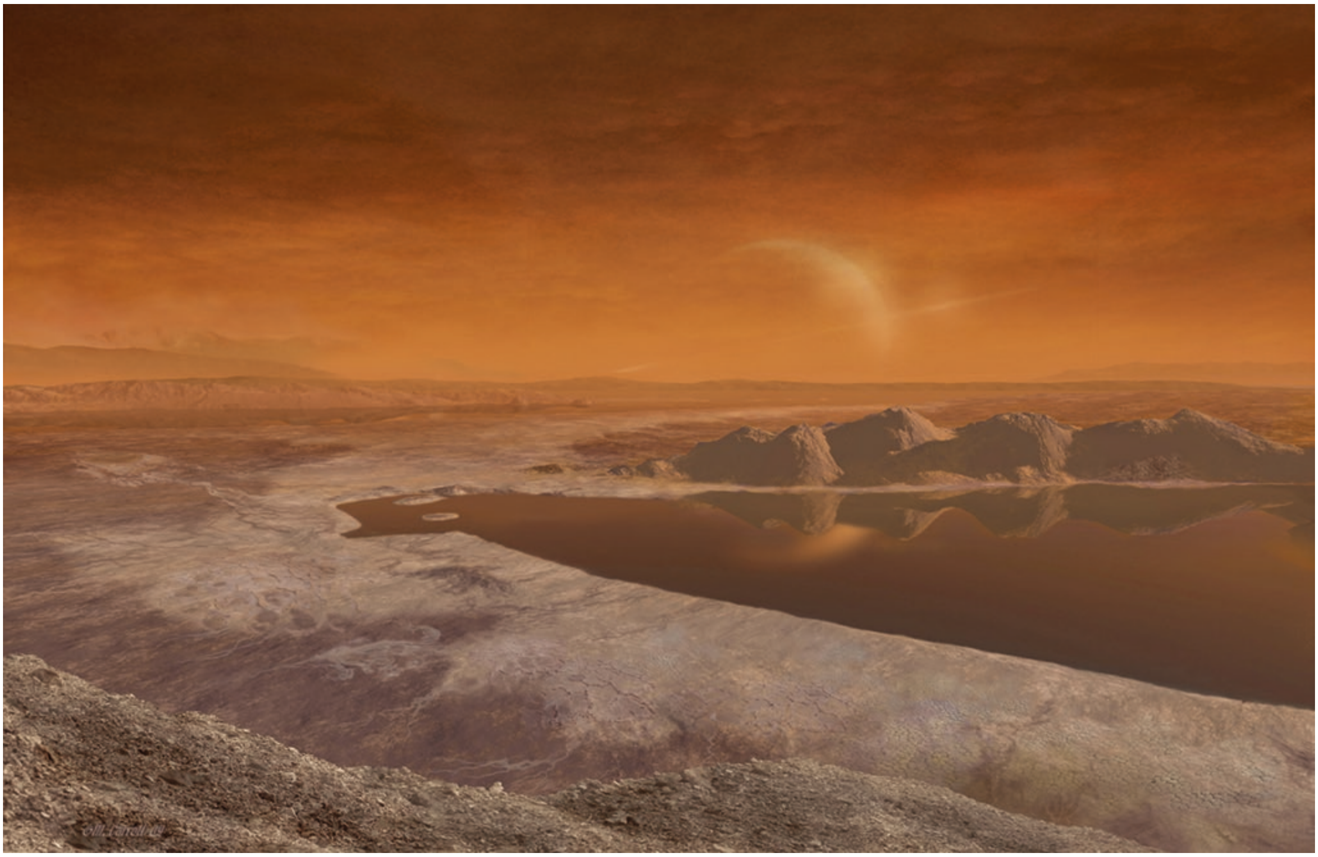


Fig. 8.1 Saturn's planet-sized moon Titan has two separate oceans, one set on the surface and one locked in the ice below. (Art by the author)

including star occultations (in which a star passes behind the object), showed that the atmosphere was substantial.

Beginning in the late 1960s, scientists knew that Titan's environment could allow for seas or oceans of liquid methane. After the Voyager flybys in the early 1980s, the idea of a global ocean was in vogue. Such a planetary ocean was formally proposed in 1983 in light of Voyager data and the fact that Titan has so much methane; something must have been restocking the atmosphere as solar radiation tore methane apart. Writing in 1992, David Rothery reported:[1] "…it has been calculated that, over time, enough ethane has been made in the upper atmosphere to have drizzled downward and formed a liquid layer about 1 km deep. Just as for Triton, hopes have been raised of finding another world with oceans."

However, continued remote sensing by Earth-based observatories continued. The Hubble Space Telescope offered an opportunity to see Titan as never before, to actually discern faint surface features. Peter Smith of the Lunar and Planetary Laboratory in Tucson, Arizona, headed up the effort. "With Titan I managed to get some Hubble Space Telescope time. I used a special filter that I could see to the surface with. There's a little window out at about 950 nanometers (light wavelength) that enables you to see down to the surface. We didn't know that ahead of time, but I wrote a proposal and said, 'I think we can see to the surface at this wavelength. I want to use this particular filter to map the surface, and at the same time we want to map clouds, too.' So the reviewers said, 'No way on Earth you're going to see to the surface, but we'll let you map the clouds.'" The HST management cut Smith's observing time in half. Hubble saw no clouds, Smith said, "but it made a beautiful map of the surface. The thinking at that time was that you couldn't see to the surface, because of the Voyager imagery. But Voyager's longest wavelength was something like 650 nm, and they just didn't have a long enough filter." In the final analysis, Hubble's data suggested that Titan was a parched desert world (Fig. 8.2).

A 1989 experiment bounced radar off Titan's surface. The signal returning to Earth was ten times the strength it would have been with even a shallow ocean. Radar experts suggested, rather, that the data indicated a dry, rough surface. Even the early Cassini orbiter data seemed to bear this out. The hoped-for Titan seas were nowhere to be seen…until 2004.

---

[1] *Satellites of the Outer Planets* by David A. Rothery (Oxford University Press, 1992).

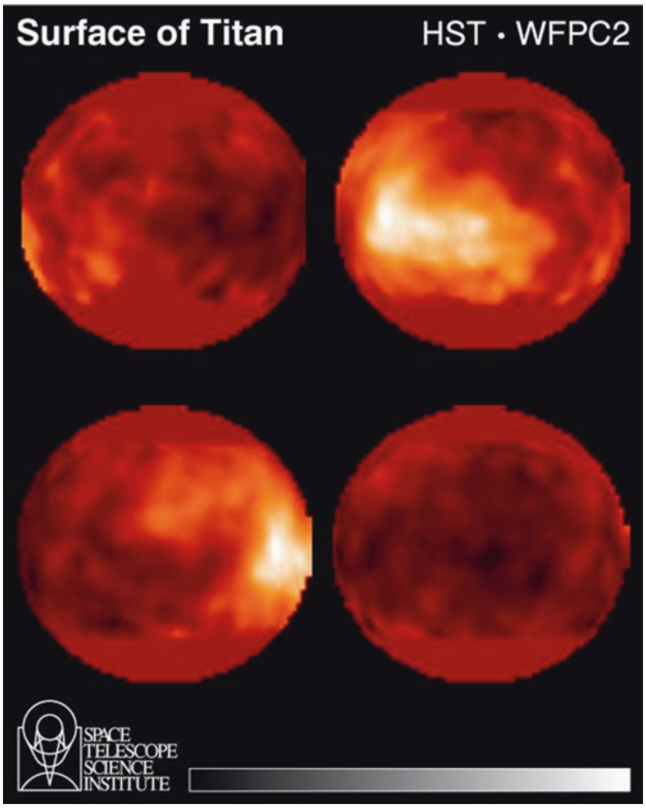


Fig. 8.2 Hubble Space Telescope near-infrared images penetrated through enough of Titan's fog to show variations on the surface. Here, we see four global views, each 90° apart. (Image courtesy of NASA/JPL/STScI)

The Voyagers revealed a moon unique among satellites in our Solar System, as the only moon to have more than a trace atmosphere. As we have seen, its gaseous envelope acts as a buffer against the cold of space, sustaining surface temperatures of up to –178°C, much warmer than adjacent Saturnian moons, whose daytime temperatures hover around –200°C. Titan's day drags on for 382 h, about equivalent to 16 Earth days. Its year – identical to Saturn's – lasts a lingering 29.7 Earth years. Titan's environment is nearly as complex as Earth's, with dynamic meteorology and an active hydrological cycle unlike anything found throughout the Solar System, with the sole exception of our own world.

Titan's landscapes echo those of our terrestrial vistas. Dendritic channels, the result of liquid erosion, score its face and carve valleys. Dark hydrocarbons, washed from the highlands, pool in low-lying areas. Aeolian (wind-driven) effects leave trails of scattered dust and sculpted forms, piling up sand into great fields of dunes. We see cloud systems and storm fronts. In short, Titan generates Earthlike processes, but they are affecting alien geology. The surface of Titan has rocks, but the rocks are thought to be water-ice. Water is available, but it's frozen 'rock solid.' And the rains of Titan are cryogenic methane, similar to the natural gas with which many of us heat our homes. Standing on the surface of this world, one could be convinced that the place was made of stone. But the ground, mountains, cliffs, and boulders of Titan are water-ice, frozen to the consistency of granite.[2]

Titan's murky blanket of nitrogen and methane has its own tale to tell. On both Earth and Titan, weather is nature's attempt to create balance between hot and cold temperatures, and high and low pressures. Heat pours (or, in Titan's case, trickles) in from the Sun, and wind carries the warm air to colder areas. Just 93 million miles from our own world, the Sun continuously pumps prodigious amounts of energy into Earth's ecosystem, along with its oceans of air and water. This makes our atmosphere a vigorous and dynamic one. Our unsettled meteorology stands in stark contrast to the slow-motion weather of remote, frigid Titan. Titan receives a scant one-hundredth the amount of sunlight that Earth does. Less heat enters the atmosphere, resulting in gentler mixing of the air. This, in turn, leads to fewer individual weather events (storms, cold fronts, etc.). An occasional storm may be all that occurs over the course of many years. Scientists liken Titan's atmospheric heating to a pot of water on a stove. When the burner is first lit, an occasional blob of water will rise from the bottom of the pan to the top, stirring a small bit of turbulence. As time goes on and the water becomes hotter, more and more of those blobs will rise through the liquid. The water in the pot can be very turbulent even before the water itself begins to boil. Titan's atmosphere may be similar to the beginning stages of our water-filled pot, where blobs of warm fluid come up only rarely. Earth's atmosphere more closely resembles the pot's liquid at the boiling stage (Fig. 8.3).

A Different Kind of Rainy Day

Long before Cassini's instruments revealed Titan's methane monsoons, they began to sense another kind of precipitation: hydrocarbons. Titan's upper atmosphere reacts with solar radiation to generate organic soot, similar to the dark red material seen throughout the ice worlds of the outer Solar System. The descending haze of fine particles, as small as a third of a micron across, is similar to the smog found hovering over Earth's major cities. This diaphanous organic powder drifts down to the surface, building up enough to fill valleys and bank into drifts. It may form a scum on the surfaces of the smaller, calmer lakes, and it seems to ring the karstic lakes in the north. This drizzle has been gradual, with a subtle but relentless precipitation over millions of years.

---

[2] For more on what the experience of human Titan exploration might be like, see *On the Shores of Titan's Farthest Sea: a scientific novel,* by Michael Carroll (Springer, 2015).

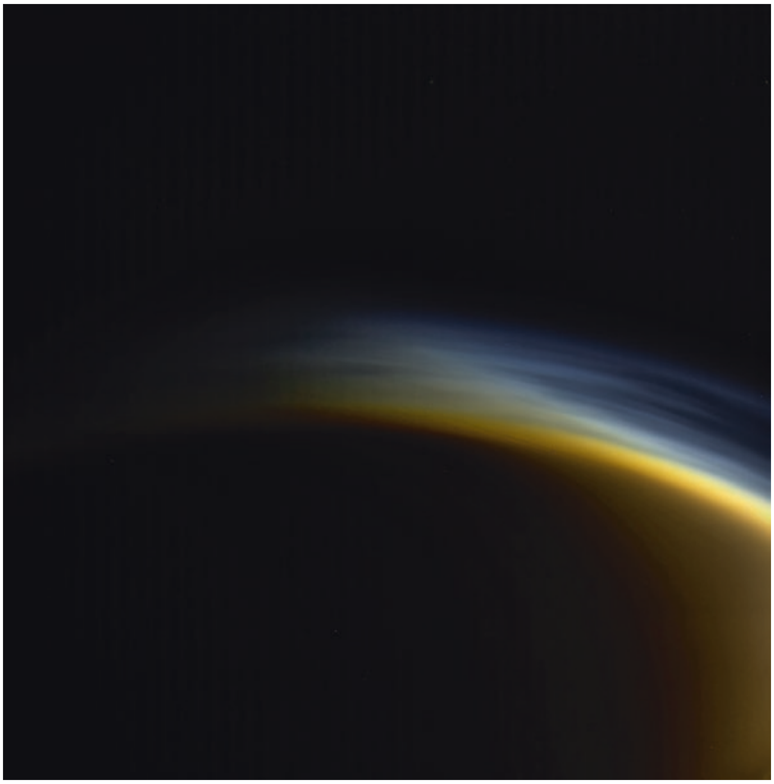


Fig. 8.3 Activity in Titan's atmosphere is sluggish compared to that on Earth. In this view, Cassini has captured the complex layers of haze that contribute photochemicals to the atmosphere, land, and seas below. (NASA/JPL/Space Science Institute)

The density of liquid methane and ethane is such that almost anything sinks in it. Under Titan's low gravity, material would sink very slowly, so any submarine cruise through Titan seas might be like a trip through Miso soup. The particles eventually settle out, but even convection currents are enough to lift the particles up. This means there are a lot of opportunities for particles to clump together in Titan's lakes before they settle, and those larger particles, once stranded on drying beaches, might become the material that builds into beaches. On Earth, sand can become sand dunes, and Titan is rich in them.

Titan's globe is split across its equator by a band of spectacular dunes. The familiar desert formations appear in a belt within about 25 or 30 degrees of the equator. The dunes lie atop an extraordinary "corridor of "bedrock (water-ice) and methane ice that straddles some 40% of Titan's surface. The icy path, discovered by a team at the University of Arizona, does not follow any surface features such as mountains or valleys, but cuts across a variety of terrain. Whatever form the ice band once took, they are in the process of being eroded by Titan's relentless rains, wind, and perhaps faulting. The frozen highway was revealed when the Arizona team collated tens of thousands of infrared images shuttered by the Cassini spacecraft's visible and infrared mapping spectrometer.

Although Cassini's first radar passes covered some of the dune fields strewn across the ice corridor, analysts did not recognize them for what they were. The dunes appeared as dark streaks, and the first ones that happened to fall into Cassini's radar path were not perfectly parallel like terrestrial dunes. They often branched in successive "Y" junctions. Investigators suspected they might be some sort of Aeolian – wind-blown – deposit, but they couldn't be sure they weren't some other kind of surface flow, perhaps related to river deposits or local landslides. Further radar passes overflew regions with nearly complete coverage of the mysterious linear features, and patterns began to come into focus. It became clear that the bright and dark lines of the radar images were slopes facing toward the radar and slopes facing away; the dark features were ridges. They were uniform, several kilometers apart, and twenty to hundreds of kilometers long. The fact that the alien forms were elevated provided the critical clue that they were depositional dunes. "The moment it finally clicked," says planetary scientist Ralph Lorenz, "was looking at a Space Shuttle picture of the Namib sand sea where, even though the sand is different and gravity is different and the air is different and all that, you see exactly the same thing: these large linear dunes two kilometers apart, a hundred or two hundred meters high, tens to hundreds of kilometers long."

The moon's midsection seems to be desiccated, nearly devoid of the methane rains that fall in other areas. Here, the dunes follow along the direction of the winds. These dunes often interact with dry river valleys, canyons, and ancient eroded impact craters. To the north and south, methane humidity increases until the lakes form.

To understand the alien nature of the moon's dunes, one must look only as far as Titan's surface makeup, says biophysicist Benton Clark. "The surface of Titan has rocks, but the rocks are water-ice. You have water available, but it's frozen 'rock solid'." If they were analogous to Earth's dunes – silica sand, which comes from crushed rock – Titan's dunes should be ice. But Titan's dunes may not be comprised of water-ice at all. They may, in fact, be composed of the organic material that falls from the sky. Cassini's visual and infrared mapping spectrometer sees all the dunes as dark. If they were water-ice, they would appear bright. Cassini's radar offers another clue. In addition to providing a visual image, radar yields insights into how the material behaves. Radar waves bounced off the surface measure a dialectric constant, data that tells scientists about the size and makeup of the material. Titan's dunes yield a dialectric constant that is not consistent with water, but instead indicates fine-grained organic material. This soot-like hydrocarbon matter precipitates out of the sky as a result of the interaction of the Sun's ultraviolet radiation and methane in Titan's atmosphere.

Observers have found it difficult to plot the direction of Titan's winds, because clouds on the moon are rare. But using Cassini's years of radar data, analysis shows that the dunes align with Titan's winds, acting as a planet-sized weather vane. Those hydrocarbon drifts reveal a surprise. Titan's winds appear to blow toward the east. This is the opposite direction to what all the atmospheric models predicted. Studying 16,000 dune sites from twenty Cassini radar passes, meteorologists were able to piece together global wind patterns.

Titan's dunes appear to be young and active, unlike many of the dunes of Mars, which have solidified in place and move very little. Titan's dynamic dunes are affected by underlying topography. They flow around obstacles such as hills and cliffs, further indicating wind direction.

Although the great dunes in the deserts of Iran rise some 40 m, those in Belet Tower are 150 m high. Instead of the silica found in terrestrial deserts, its dunes may be made up of pulverized ice or the hydrocarbon soot that rains from the sky.

Over 20 percent of Titan's surface is covered by dunes. By comparison, dunes cover about 5% of Earth's land, and roughly 1% of the Martian landscape. The shape and orientation of the dunes indicates that Titan's winds blow from west to east near the surface. Titan's sluggish air moves across the face of Titan like a planetary tidal wave. The phenomenon is called super-rotation, and only one other planet exhibits the same atmospheric movement. It, too, is a world with a solid surface and dense atmosphere like Titan, but other conditions could not be more different, because that world is Venus. The entire atmosphere of Venus circumnavigates the globe every four days.

With their hydrocarbon fallout, Titan's dunes would be flammable in the presence of oxygen. They are dunes born from the sky, not the ground. But hydrocarbon rains cannot fully explain the composition of the dunes. They are made of coarser stuff than comes from the sky. What creates it?

One theory suggests that as Saturn's orbit precesses the seasons on both Saturn and Titan lengthen in one hemisphere and shorten in the other. This change might lead to a drying out of seas in one Titan hemisphere, and a shift in methane humidity to the other. A similar phenomenon has been recorded in Earth's geological record. Vast layers of salt lie beneath the Arabian and Mediterranean Gulfs, because they were once ocean basins that became closed off, eventually drying out. In Titan's analogous process of drying out, fine hydrocarbon particles in a Titanian sea may come together as grains to make sand. The sand gets blown out and makes its way to the equator, resulting in the great sand seas that spread across the equatorial regions of the moon today (Fig. 8.4).

The dunes imaged by Cassini are similar to the largest ones seen in Earth's deserts. Although no coastal dunes have been seen near the lakes or across areas scored by river valleys, it is possible that small dunes may form in these regions, as they do on beach areas of Earth's coastlines. Many dunes may exist just below the resolution of Cassini's radar. The dune-studded equatorial region is dry enough to possess dust storms. Prodigious volumes of dust can be raised by strong wind gusts associated with the methane rainstorms. Methane storms have been observed above Titan's dune seas, increasing in strength and force around the equinox (when the Sun's equatorial heating is at its highest). In three discrete instances, Cassini's VIMS recorded brightening, localized spots that are interpreted as massive dust storms. Titan's own dust bowl merely contributes to a fuller picture of a dried planetary equator. But other areas of the bizarre world are considerably wetter.

When It Rains, It Pours

Titan's rain begins to fall from its methane clouds at an altitude of 20 km. Above that cloud layer, thinning haze drifts beneath a high altitude layer of methane ice crystals. The methane precipitation may increase closer to the poles, in the lake districts.

Titan's rains may come in intense, seasonal waves. River channels, quite familiar to Earthly eyes, spread across many of Titan's landscapes, from highlands to plains, and they typically follow forms indicating intense floods that produced them. Planetary meteorologists tell us that a steady drizzle would not explain the features we see. Titan's methane storms may be most like storms over

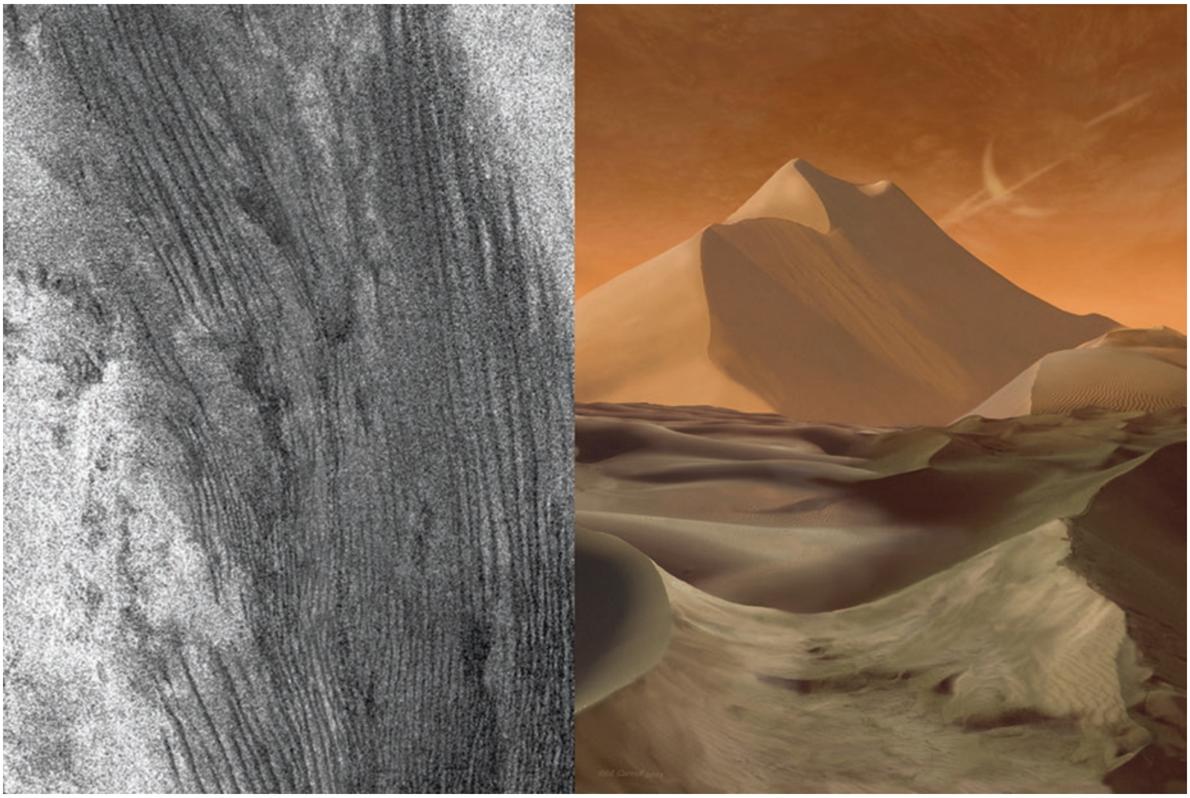


Fig. 8.4 Left: Titan's dunes resemble the dunes in terrestrial deserts like Namibia (Image courtesy of NASA/JPL/SSI). In Titan's low gravity, dunes may tower above the icy surface. (Art by the author)

terrestrial deserts that wet the ground and even carve arroyos but don't leave behind any significant buildup of standing liquid.

Despite Titan's active methane cloud systems and carved floodplains, methane rain may fall far less often on Titan than water-rain falls upon Earth. Titan is very much a desert world, where rainfall is extremely rare compared to terrestrial precipitation. Where there is rainfall, it is torrential. The question is, are those methane rainstorms seasonal, or is the precipitation a year-round phenomenon? Although the methane humidity at the equatorial Huygens site was 45%, which would be enough to trigger rainstorms on Earth, the distant Sun's heat at Titan is just too weak to drive moist air up and generate storms under current conditions. Large cloud systems would require higher humidity. The Cassini spacecraft has spied storm clouds forming over the equatorial regions and condensing cold fronts in the south, but the events have been rare. Typically, weather systems blossom rapidly to the southeast. As the storm clouds drift away, they sometimes leave in their wake a darkening of the landscape, implying a changed surface from rainfall.

Other post-rainstorm changes have been spotted on the surface. When Cassini settled into orbit around Saturn in 2004, Titan was experiencing summer in its southern hemisphere. Cassini's ISS and VIMS spotted clouds and active methane rainfall in the south. Researchers were able to model predictive climate and weather models of Titan from those and later observations. The models predicted that similar cloud systems would begin to appear farther north as summer came to the northern hemisphere. The summer solstice officially came to the north in 2017, but in the summer months leading up to it, the skies remained free of the methane monsoons.

However, a lack of clouds may not have meant a lack of precipitation. Images taken during a June 2016 flyby revealed a vast area – some 120,000 km^2 – of terrain that had suddenly begun to reflect sunlight from the surface. The increased brightness seems to indicate what researchers are calling the "wet sidewalk" effect. The shape of the region and its reflectivity suggest that the gelid summer showers covered a rough surface, perhaps blanketed by pebbles or gravel akin to what the Huygens probe saw at its landing site. Although the rains came late to the north, they did come. Modelers continue to refine their alien weather reports. Researchers estimate that the annual rainfall on Titan amounts to about 5 cm. This is the equivalent to the yearly precipitation in terrestrial desert regions such as Death Valley, California. Nevertheless, it's enough to add up, and the methane rain accumulates into lakes and seas to rival some on Earth.

Titan's Lake Districts

In 2004, the imaging science subsystem aboard the Cassini spacecraft observed Ontario Lacus, the first of a series of dark features with coastline-like shapes. It was not immediately clear whether the dark regions were filled with liquid or simply damp. Images revealed Ontario Lacus as a dark expanse near the south pole, similar in shape to Canada's Lake Ontario. Had science finally found the hoped-for oceans of another world?

Several lines of evidence supported the interpretation that the dark polar features were lakes rather than simply smooth plains. First, the features presented shapes similar to terrestrial lakes, and they seemed to have a relationship to river-like features such as channels and river deltas. Second, they exhibited low radar backscatter, implying surfaces that were very smooth. Third, Cassini found high methane humidity in the polar regions. These readings were consistent with computer predictions that used atmospheric and climate models to simulate conditions of air in regions moistened by methane. Finally, the radiometric brightness of those areas, higher by several degrees than the surrounding terrain, was consistent with the high emissivity expected for a smooth surface of liquids such as methane, ethane, butane, and other related substances.

Radiometric brightness is different from radar brightness, which shows roughness of the surface. In the case of radiometric brightness, the instrument can tell how much energy is being emitted from the surface. Warm surfaces emit more energy than cool ones, and Titan's lake-like features appeared to emit more energy – they were warmer – than the surrounding land. In following flybys, the region of Ontario Lacus was imaged in greater detail by the RADAR instrument, finally demonstrating that at least some of the dark areas such as Ontario were, in fact, filled with liquid. Decades of searching for truly alien seas had finally come to fruition (Fig. 8.5).

In the months and years to come, Cassini's radar eyes and imaging subsystem charted hundreds of small lakes, mostly contained within rounded hollows, in Titan's northern polar provinces. While dark, flat features had been seen in other regions, these were different. Their physical profiles were similar to terrestrial lakes, as was their relationship to channels, deltas, and other river-like features. They had very low radar backscatter, implying that their surfaces were very smooth. The polar regions in which they were found had high levels of methane humidity, consistent with computer predictions using atmospheric and climate models. Finally, the radiometric "brightness" – the way radar reflects off the surface – of the dark shapes was consistent with the high emissivity expected for a smooth surface of liquids such as methane, ethane, butane, and other related substances. This high reflectiveness showed that the lake areas were warmer than their surroundings.

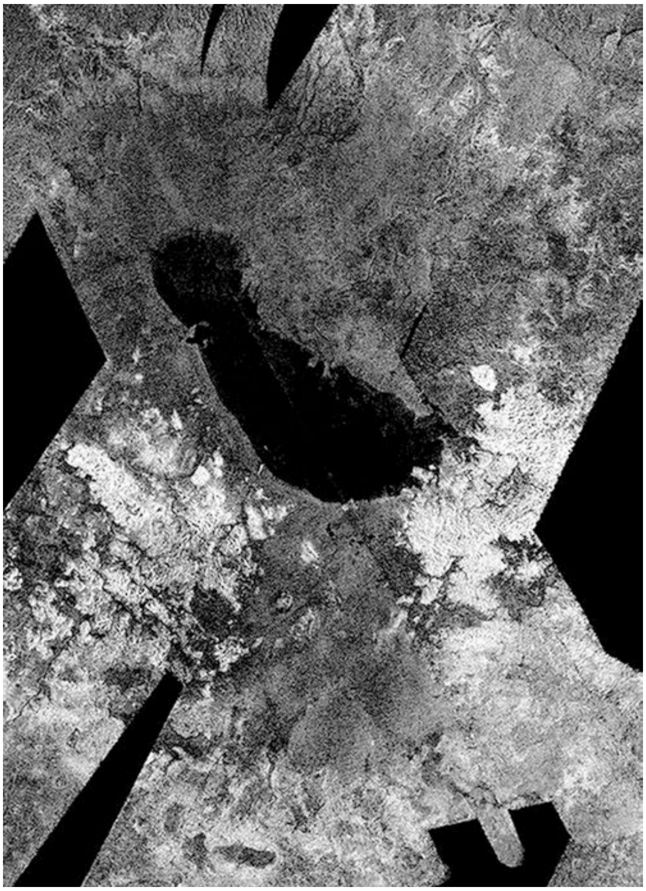


Fig. 8.5 Ontario Lacus, Titan's largest southern lake, is about 80 by 235 km across, and probably at least 10 m deep at its center (geometric black shapes at the edges are from missing data). Note the darkened outline of an ancient sea that has since retreated to Ontario's boundaries. Seas may have covered vast regions of the southern hemisphere less than 50,000 years ago. (Image courtesy of NASA/JPL/SSI)

Titan's river valleys do, in fact, drain into liquid-filled basins, some as large as the Black Sea. Because of their size, the largest methane-filled bodies are referred to as *maria,* Latin for "seas." To date only three have been classified as such. From smallest to largest, they are Punga Mare, Ligeia Mare, and the immense Kraken Mare. Titan's lakes and seas vary greatly in size, from the limits of Cassini's resolution up to about 400,000 km^2 for Kraken Mare. For comparison, the Red Sea is 438,000 km^2.

Rugged coastlines resembling the fjords of Norway or the flooded valleys of Lake Powell incise the edges of Titan's seas. A few of the largest lakes also have some rugged shores, but the smaller ones are of a character familiar to glaciologists. These ponds have mostly rounded or lozenge-shaped borders, and their margins are often quite steep. Because of their sheer rims, some researchers suggest that the lakes are the result of collapse or melting, reminiscent of the rounded lakes caused by melting ice blocks stranded by retreating glaciers in North America and Europe. Terrain dissolved by water is called karstic. On Earth, karstic regions are porous, with groundwater flowing beneath their surfaces. It may well be that on Titan, these karst lake regions drain into a web of underground methane aquifers that make their way to the coasts, eventually feeding the seas. And the shape of karst lakes on Titan echoes Earth's glaciated past. Did Titan once have methane glaciers scouring its face?

The exact blend of hydrocarbons in Titan's lakes is unknown, but it is probably a mixture of ethane and methane. Although methane rainfall is thought to be about a hundred times greater than that of ethane, methane is far more volatile than ethane. Any surface methane would evaporate more quickly. Over time, a standing body of liquid would become enriched with the more stable ethane, so ethane probably dominates the larger seas.

Ligeia Mare, which is farther north than Kraken, may be filled with more fresh methane rainfall than Kraken, as higher latitudes appear to receive more rainfall. Some researchers estimate that Ligeia Mare has up to 80% methane. But currents within the basins of Kraken Mare mix methane with the denser ethane, which might leave Kraken dominated by ethane, by as much as 60%. The variations in the two hydrocarbon seas are analogous to the salinity gradient between Earth's Black Sea and the Mediterranean.

Methane and ethane are intrinsically more transparent than is water, so visibility might be excellent along a Titan shoreline. Even using Cassini's radar, it is difficult to tell how full some of Titan's lakes are. The moon's lakes and seas are transparent to the radar instrument, but the surface of the liquid is smooth, so it acts like a mirror. The incoming radar hits it at a slight angle and reflects away, leaving a dark image. But the liquid methane also lets some of that radar pass through into its depths, like light passing into clear water. This clearness makes it challenging to tell just where the methane/ethane sea ends and the beach begins.

Within the seas of Titan, investigators observed several subsurface channels. The researchers were able to measure depth – or at least general slope – along their lengths. Because rivers flow downhill, they expected that if these were indeed drowned river valleys, the channels would get progressively darker downstream, since the spacecraft would observe them through progressively deeper liquid. This is exactly what investigators observed.

In 2009, the visual and infrared mapping spectrometer (VIMS) observed a glint of sunlight reflected off the Lake Jingpo Lacus, resolving any remaining doubt that Titan's dark areas are bodies of liquid. Cassini's VIMS also charted several instances where surface roughness within the lakes bore resemblance to wave action. In several cases, it appears that radar has captured telltale signatures of waves as well (Fig. 8.6).

Another unusual maritime formation may indicate wave-caused foam on the surface – the so-called "Magic Island." Cassini imaged the bright "island" during a flyby in July of 2013. The irregular region in Ligeia Mare was completely missing in imagery from three previous encounters. The area disappeared as abruptly and mysteriously as it had

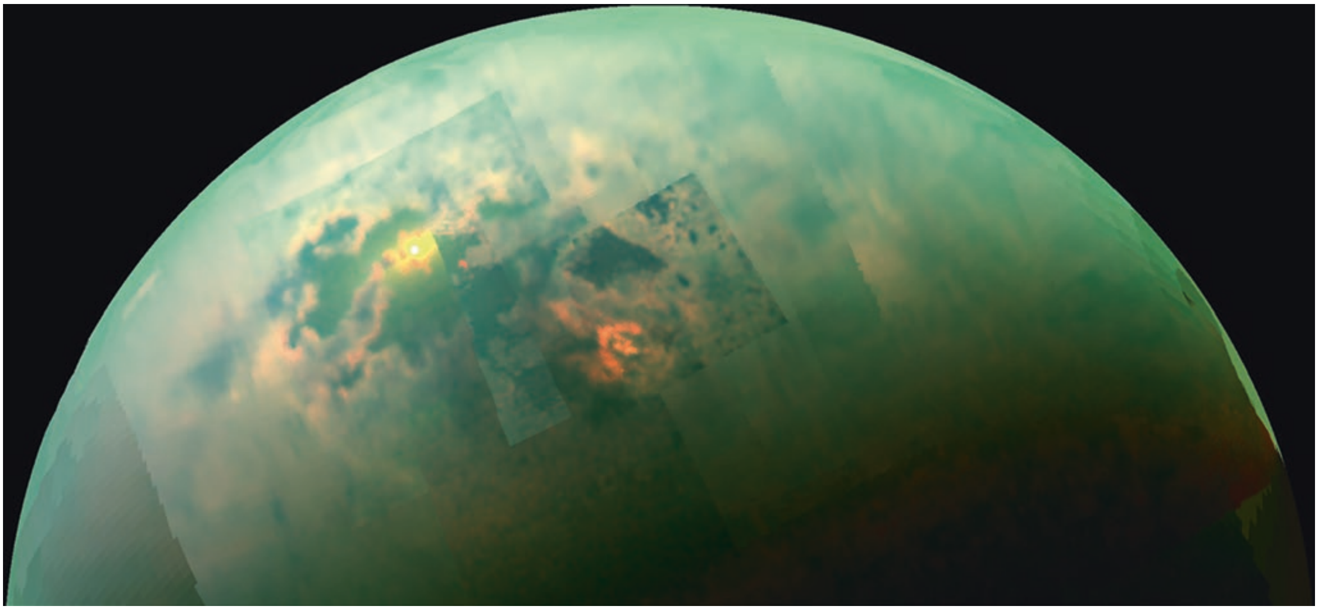


Fig. 8.6 Sunlight glimmers across the surfaces of several Titan lakes and seas in the northern polar provinces. Near-infrared VIMS Cassini image. (Image courtesy of NASA/JPL/Space Science Institute)

appeared. It was absent again on the next flyby just sixteen days later, disappearing like Houdini. The mystery feature's mercurial behavior led researchers to brand it with its name. The disappearing act may be due to the comings and goings of frothy waves. Alternatively, the brightening may be caused by gas bubbling up from the seafloor, or from icy slush floating on the surface. Methane ice is denser than methane in liquid form, so the slush would need to be a lighter related material, perhaps chains of polyacetylene or other hydrocarbons.

Adding to the portrait of Titan as a vibrant world, the lakes seem to be changing shape. The beachfront property of Titan's largest southern lake, Ontario Lacus, receded by at least 10 km over a period of 4 years. Several transient lakes in its vicinity completely vanished during the same period. Radar indicates that Ontario Lacus itself, while as vast as Lake Ontario in North America, may have an average depth of 0.4–3.2 m, with its deepest part diving to just over 7 m. Ontario Lacus may resemble terrestrial mudflats.

Although the southern lakes may be glorified ponds (albeit large ones), many of the lakes in the north are a different case. Their margins have been unchanged over a decade of observation. Clearly, they are more stable than those in the southern hemisphere. The more numerous northern lakes have steeper-sided shores, so as surface levels drop, changes may be harder to detect along the shorelines. Or, the northern pools may simply be deeper and less prone to evaporation. Whatever the cause, the lakes in the north appear to be more constant and permanent than the weather-related lakes in the south. Depths of the great Ligeia Mare may reach 170 m.

Not all of the northern lakes are static. Over the course of Cassini's years-long stay at Saturn, at least three lakes completely evaporated or drained away. Some northern lakes were known to shrink as summer waned, but these bodies completely vanished. Researchers compared radar imaging from Titan's northern winter to later radar taken the following Titan spring. During that time, the three formerly methane-filled lakes appeared to have dried up, reinforcing our view of Titan's methane cycle as a dynamic one.

Kraken Mare is the largest body of liquid known on the surface of another planet. Named after the legendary sea monster that lives off the coasts of Norway and Greenland, Kraken covers an area equivalent to Earth's own Caspian Sea. One or more channels may link Kraken to the nearby sea Ligeia Mare. Toward the northern end of the sea lies the island called Mayda Insula. Fjord-like valleys cut its rugged coastline, as they do on other coasts. The island is 100 × 170 km, covering just a bit more territory than the main island of New Caledonia.

The strange hydrocarbon seas are more backyard barbeque than swimming pool, but they may provide some intriguing compounds related to prebiotic chemistry. We will examine the exciting possibilities in Chap. 10.

Hidden Seas

Not all of Titan's seas are above ground. Work led by the University of Rome's Luciano Iess led to a remarkable conclusion. Titan likely has another ocean beneath its methane/ethane seas. The 2012 study observed Titan's shape as it circled Saturn. Titan's orbit is slightly eccentric, not quite circular. As it passes through the closest part of its orbit, Saturn's gravity pulls the spherical moon into a slightly oblate shape. At the far end of its circuit, Titan is once again a sphere. Titan's true shape is hidden by its extended atmosphere, but it could be determined by clocking Cassini as it passed by. Flight engineers carefully observed changes in the spacecraft velocity, as they do when locking down the mass of a planet or moon during a flyby (Chap. 3).

Iess' team was able to deduce Titan's gravitational influence on the spacecraft's path, which changed as Titan's shape changed. If Titan's interior were composed of solid ice and rock, Saturn's gravity would just barely shove the surface out of round, causing it to rise and fall about a meter each day. But the researchers found that Titan's surface rises and falls some 10 m during each 16-day orbit. These tides are ten times as great as they would be for a solid ice/rock globe. They could only be explained by a fluid interior layer. Titan joins the club of moons with subsurface oceans.

Another line of evidence had been put forth several years earlier. In 2008, a careful study of features on Titan's surface seemed to show that the moon's crust has wandered, shifting positions of mountains or other landmarks by as much as 30 km. But in fact, the results were an artifact of the software used to interpret the radar imaging, a technique that resulted in errors for the locations of features. Although the specifics of the 2008 study may have been off, it is clear that if Titan has a global sea, the crust is decoupled from the interior, floating on the liquid and shifting over time.

Additional clues come from Titan's orientation as it circles Saturn. Titan's axis is tilted by about 0.3 degrees. This angle – or obliquity – is too high for a solid body with its weight centered at its core. But if some of that weight were slightly above the core, in the form of liquid water nested in the solid ice crust, the obliquity would make sense. The ice shell on top may be anywhere from 150 to 200 km, while the ocean far below may range from 10 to 525 km deep. Some studies indicate that the shell may thin to a scant 10–50 km in places.

Researchers suspect that the subsurface water ocean on Titan is a witches' brew of briny water and ammonia. To fit the gravity data, the water must be dense. The water is likely high in salt content with dissolved sulfur, sodium, and potassium, elements common in the outer Solar System. This density would be at least as salty as water found in the Dead Sea or in the ponds of Badwater, Death Valley.

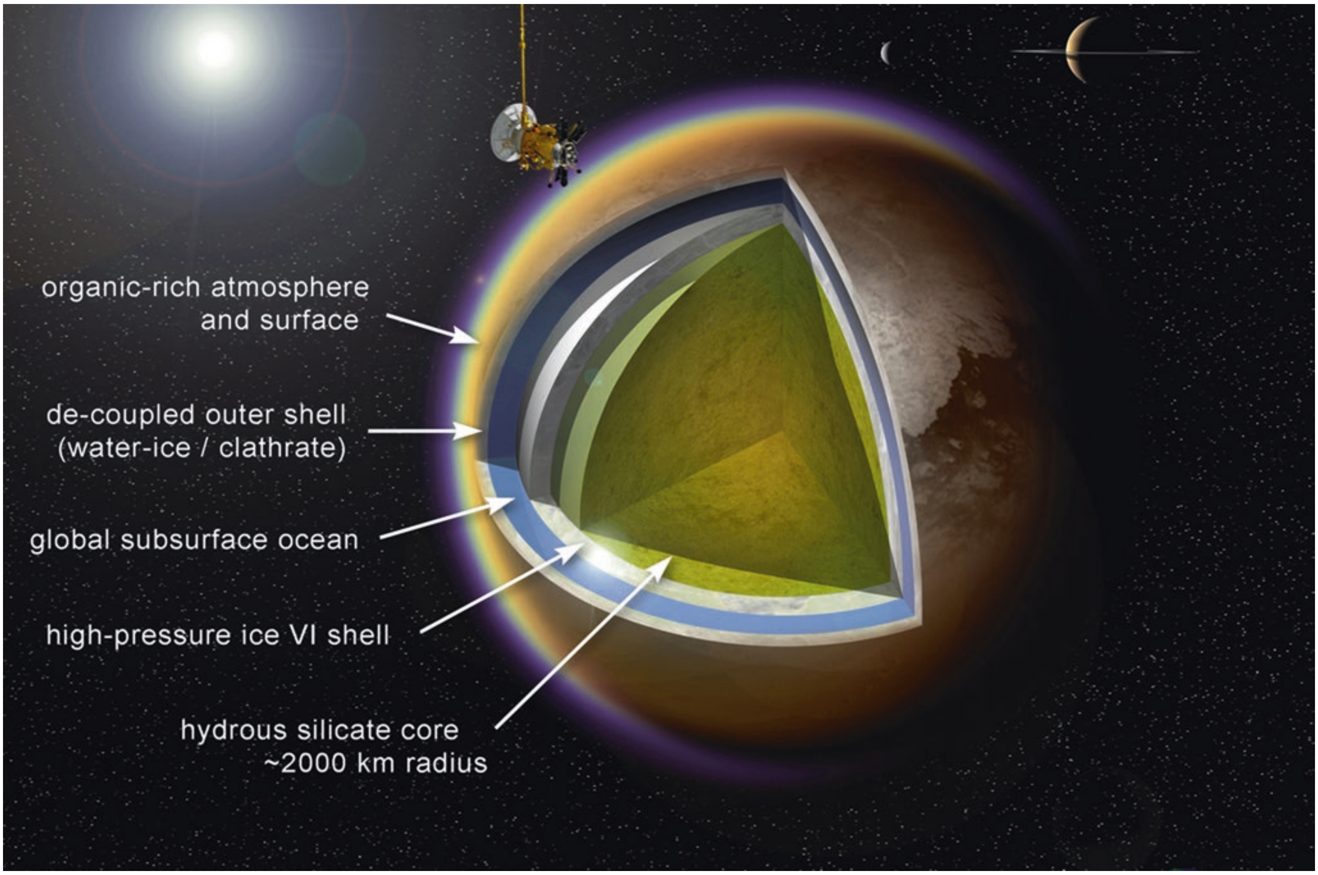


Fig. 8.7 One possible model of Titan's interior, with a hydrated rock core and a water ocean nested between shells of ice. (Art by Dominic Forte, University College, London; courtesy of NASA/JPL)

Titan's ocean, in turn, rests on another shell of ice, this one locked to the hydrated rocky core. The ice below, under great pressure, is probably in an exotic form, such as Ice VI. Titan's core is estimated to be a few thousand kilometers across (Fig. 8.7).

Cryovolcanoes in the Mist

We have seen that Titan's atmosphere, enriched with so much methane, poses a conundrum: where did all that methane come from? Larger Ganymede is essentially cloaked in a vacuum with a few oxygen molecules drifting around. And while Ganymede's higher surface temperatures make it more difficult to hang on to the kind of atmosphere that cocoons Titan, there may be other factors at play. A team of cosmochemists assert that a major portion of Titan's methane atmosphere may come from a deep-core bakery. Titan's core is large enough to retain radiogenic materials, and those materials put out heat. Deep under Titan's icy countryside, radioactive decay may split nitrogen and carbon from complex organic molecules that filter down from the atmosphere or are produced within. The nitrogen and carbon would tend to recombine into nitrogen and methane molecules, eventually making their way up into the soupy air.

Earlier analyses proposed that Titan's nitrogen came from cometary ices laced with ammonia. When sunlight splits up ammonia molecules, one resulting component is nitrogen. But the comet ice theories were carried out before the European Space Agency sent its Rosetta spacecraft to orbit Comet 67P/Churyumov-Gerasimenko. Its long-term observations revealed that the comet is a whopping 25% organic material. The comet also contains radiogenic material such as potassium, which decays into argon – an element found in abundance in Titan's air.

The significance of the findings are underscored by models of Saturn's moon formation, which suggest that comets such as 67/P were the building blocks of Saturn's icy companions. Titan's core may originally have been a dense snowball of cometary material, including organics. Cosmochemists estimate that Titan would have started out with organics in its core, where radioactive heat sautéed those materials into the abundant methane we see in Titan's atmosphere today.

Titan's interior may have pumped methane into its skies during three developmental epochs. In its formative years, as Titan accreted from the cold outer solar nebula, its rocky core formed beneath a water mantle. A water-ice crust topped the mantle, trapping a primordial ocean inside. During its first several hundred-million years, heat from the moon's formation combined with the warmth of radioactive elements in the core to melt through the crust, occasionally releasing methane.

The second release probably took place 2 billion years ago, when Titan's silicate core began to convect. This geological burst of heat again melted the ice crust, causing methane outgassing. Ammonia, salts, and methanol mixed with the water-ice would have helped to serve as a natural antifreeze, perhaps triggering widespread cryovolcanism.

As Titan calmed down after this violent epoch, a mix of methane and water-ice would have formed a lattice, called a clathrate. This clathrate crust would gradually thicken above a layer of pure ice. Convection would have begun within that outer crust itself, freeing the methane trapped within as geyser plumes or gas leaking out of the ground.

Whether the details of Titan's planetary evolution followed this path or not, many believe that methane must be escaping today, recharging the atmosphere at a fairly steady pace. The methane may drift into Titan's skies, or it may explode from the interior. If the latter occurs, it will give rise to the exciting phenomenon of cryovolcanism, something Cassini scientists watched for from the beginning.

Cassini's first radar swath covered a strip of Titan real estate nearly 8000 km long. It showed the dark-and-light terrain of smooth plains and rugged highlands, some very difficult to interpret. (After all, no one had seen Titan's surface before.) But the Cassini team also saw a circular feature sprawled across the radar strip. They named the 180-km-wide structure Ganesa, after the elephant-headed Hindu god of wisdom and art.

Researchers wondered if Ganesa were a scar from a past meteor impact, but it had no raised rim or other characteristics of an impact scar. Instead, Ganesa appeared to be something familiar to scientists who study radar images of Venus – a volcano. "We realized it wasn't an impact feature, and then we saw similarities to pancake domes on Venus," explains Rosaly Lopes, a Cassini radar team member at NASA's Jet Propulsion Laboratory in Pasadena, California.

Pancake domes are broad, flat-topped volcanic structures on Venus built by eruptions of molten rock, or magma – just like volcanism on Earth. But Titan's surface, though hard as rock, is mainly frozen water. Therefore Ganesa would not erupt molten rock, but instead a slushy "cryomagma" composed of melted water mixed with ammonia or other compounds that would serve as antifreeze.

Ganesa appeared, for all the world, to be a shield volcano. Volcanic shields consist of multiple, runny lava flows that gradually form a wide, gently sloping structure resembling an upturned shield. Hawaii's Mauna Loa is Earth's grandest shield volcano, and Ganesa looks eerily similar.

A second radar pass enabled scientists to make a stereo image of Ganesa, and the formation gave them a shock. Not only is the area *not* a dome, but it is fairly flat, with a jumble of hills on its northwestern rim. Although Ganesa does not fit the pancake dome form, it still has a central crater-like feature with flows issuing from it, so cryovolcanism is still considered likely by many.

Some cryomagma flows on Titan are massive. Roughly 2200 km distant from Ganesa lies a flow estimated to be 300 m thick. To pile up that high, the cryomagma would need to be thicker than a water-ammonia slurry. Lopes and several colleagues propose that added methanol (a type of alcohol) would thicken the flood of material enough to account for the viscosity of the flows.

Cassini may have caught a cryovolcano in action at a site called Hotei Arcus. In 2009, researchers revealed radar and infrared images of the area, whose arc of mountains give the area the nickname of "the smile of Titan." New data gave scientists a clearer view of the landscape than earlier passes, revealing flows and valleys. More significantly, the site had changed. Between October 2005 and March 2006, Hotei Arcus became brighter, and preliminary data suggested that spectrum of the bright area is becoming stronger in ammonia, a candidate for cryolava. Two close flybys on November 19 and December 5 of 2008 provided the data for detailed radar analysis of the region. Some researchers were skeptical, citing the spacecraft's different encounter angles for the differences, but studies continue.

Hotei Arcus looks suspiciously volcanic. The formation lies in a plains area ringed by rugged mountains to the south and east. It lies in western Xanadu (28 degrees south latitude and 78 degrees west longitude). Several serpentine channels, which are likely dry riverbeds, flow from the mountains onto the plains, where they fade away near the elevated flows of material. The raised flow forms have a measurable thickness of one to two hundred meters. Stereo radar imaging reveals that the channels could not have deposited the flows, which tower above the surrounding landscape.

Several other sites may display possible cryovolcanic signatures. Some features seem to have a hole in the ground like a caldera, or volcanic crater, with a thick, serpentine flow issuing from it, similar to silicate lava flows. One such site, Tui Regio, has the same unique spectra that Hotei does, and seems to be composed of similar, flow-like features. Like many formations on Titan, some flows are confusing and enigmatic. Clearly, something flowed across the surface, but the flow patterns are so diffuse that they could be thin or thick, and could be volcanic or caused by methane rain outwash.

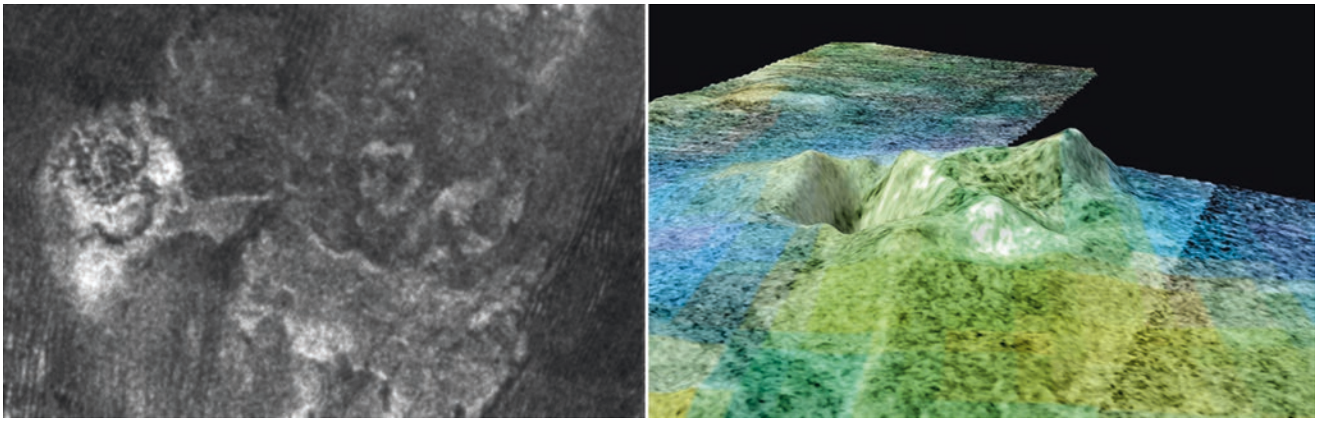


Fig. 8.8 The Doom Mons mountains of Titan. Radar imagery from above (at left) shows the twin peaks of Doom Mons and Sotra Patera, both thought to be cryovolcanic. Possible cryolavas flow to the right. Sand dunes cross the floodplain at far right. With more than one radar pass, stereo imagery can be assembled. At right, we see the formation from the side. False color from Cassini VIMS indicates variation in surface composition. Note the collapsed flank so typical of volcanic cones on terrestrial planets. Vertical dimension was multiplied by 10. (Image courtesy of NASA/JPL/SSI)

Another cryoeruptive candidate site is called Sotra Patera. Its general surroundings play host to three conical structures. The cones all tower above the surrounding plains, with summits between 1 and 1.45 km high. A 2013 paper stated that the combined features include “the deepest pit so far found on Titan (now known as Sotra Patera), flow-like features (Mohini Fluctus), and some of the highest mountains on Titan (Doom and Erebor Montes).” The adjacent massif to the west, christened Doom Mons, is one of the tallest mountains on Titan. It’s roughly conical footprint spreads 65 km in diameter. A 500–600 m deep collapse feature on its western flank leads to a circular pit at the base. The pit is another 400 m deep, the deepest pit on Titan. Other pits and craters are also associated with the structure.

The authors interpreted this region to be a cryovolcanic complex of multiple cones, craters, and flows based on several lines of evidence. The team used data from synthetic aperture radar (SAR) imaging, radiometry, and topographic data as well as compositional data from the visible and infrared mapping spectrometer (VIMS). The 2013 report suggests that Sotra Patera’s erupted cryolavas may have mixed with such ingredients as ammonium, along with like polyethelene, asphalt, paraffin, or other exotic hydrocarbon compounds. On the flanks of the collection of cones, 100-m-thick long ridges form flows of what are likely cryolavas. Although the mountains are constantly battered by winds, methane rain and snow, and hydrocarbon soot, the summits appear to be exposed water-ice.

Sotra and Doom Mons are members of a spectacular mountain chain. The mountain range extends for several hundred kilometers. Methane clouds condense on the lee of the mountains.

We saw how Titan and Venus share the atmospheric characteristic of super-rotation. They share something else: the riddle of volcanic activity. Opaque atmospheres cover both worlds. Viewing putative volcanoes with radar does not reveal whether any plumes issue from the features. When it comes to Titanian volcanism, some guesswork is required, comments JPL’s Rosaly Lopes (Fig. 8.8). “I think we came to realize that cryovolcanism is probably more common than we had expected from Voyager and Galileo results, but a landform identified from remote sensing images can sometimes be deceiving, and convincing proof can be hard to come by. In the Cassini science team, we joked that cryovolcanism on Titan is a ‘cold case.’ We will need more data in the future to tell for sure.”

More Peak Experiences

Cassini has revealed a wide menagerie of more traditional mountains, from parallel ridges to solitary raised structures to classic mountain chains. Geologists have offered four possibilities for the origin of these mountains:

1. The mountains were thrust up from below as two areas of crust pushed together in a process called compression.
2. Two sections of crust separated; one remained while the other dropped, forming a graben, or horst, ridges left along sunken terrain. This process, called extension, may be prevalent on Ganymede (see Chap. 5).
3. The mountains are remnants of blocks of material ejected from large impact craters.
4. Erosion stripped away material from a preexisting plain, leaving mesas.

Some or all of these processes may be at work. Long parallel chains trend east/west, and may be compressional. Just 200 km from the crater Sinlap lie several mountains of an entirely different nature. At first blush, these peaks appeared to be oriented radially from the crater's center, as if they were products of impact ejecta from Sinlap itself, remnants of a chain, perhaps heavily eroded by wind.

In the region called Xanadu, rugged mountains appear eroded by river action. Xanadu is a vast area of mountain peaks crammed together, transected by river valleys that look as if they have carried material fanning out across the plains.

Titan's icy summits are no Everests; they have gentle slopes with low profiles. Elevations range from 120 m to just over 1000 m. Their consistent altitudes are mystifying. Why would all the peaks be so similar in height? It may be that the mountains are all ancient and heavily eroded. Perhaps they overlie a warmer layer of ice that cannot support structures beyond a certain height. Their erosional rates may vary with impurities in the water-ice that makes up Titan's surface. Finally, their summits may be limited in altitude by the subsurface ocean, which may act to keep the ice crust too pliable to support structures any higher.

Titan Up Close and Personal, Thanks to the Huygens Probe

It was ambitious beyond the norm of space exploration. Send a planetary probe to the most distant destination ever attempted for an atmospheric mission. What made the goal doubly ambitious was that its creator, the European Space Agency, had never landed a probe on another world.[3] Further adding to the elaborate nature of the task, engineers wanted to create a lander that had a chance at surviving a landing in a variety of conditions. And the time was ripe. NASA was leaving for Saturn with a bus-sized craft that had some room to spare. Hence, the Huygens probe was born.

We saw the probe's overall mission architecture in Chap. 3. Now for the science. After a 2 ½ hour parachute descent, the coffee table-sized Huygens set down on Titan's never-before-seen frontier of ice and sand. The probe radioed its precious treasure-trove of in situ data through the Cassini orbiter passing overhead. Huygens charted Titan's complex layers of air, clouds, and mists on its way down. High altitude winds buffeted the craft, but calmed as it passed through lower altitudes.

At first, the imaging system could only see a blue sky above the brown, opaque haze. As the view began to fade into mist, surface features slowly came into focus. Blurred and mysterious at first, the images kept coming. Huygens made it down to altitudes similar to those flown by commercial airliners. Many of the landforms below were baffling, but some shapes were hauntingly Earthlike, such as branching river valleys snaking their way across great icy slopes, leading to dark lowlands. Bright ice outcrops rose from the ruddy plains as the probe continued to descend.

To one planetary exploration veteran, Huygens' aerial images "looked like the coast of Italy: streams coming down a hill into what looked like a dry lake bed and things that looked like a fault line that had shifted. Of course we know that the rain is methane and the rocks are water-ice and there are hydrocarbons all over the place, but still, the shapes of the surface looked awfully familiar."

After pausing briefly to buffer its data, Huygens began to take images and readings quickly, sending as much information back home as it could in its final airborne moments. Finally, the craft hit the surface. Engineers hoped the probe might survive impact, but what it would find was anyone's guess. Huygens was designed to land in a soft snowbank, solid ice, or a liquid methane bath, but any of these surfaces might kill it outright. As it turned out, the probe survived, bouncing once after pounding a crater into the ground 12 cm deep. Huygens skimmed across the surface for about half a meter, finally coming to rest. It continued to relay data for nearly 2 h after touchdown before contact was lost. Because of the slit-scan design of its camera system, Huygens imaged only a thin strip of Titan landscape, but that strip – and the other data coming back, told us much about Saturn's mystery moon. A diagonal smooth pathway crosses between more rocky/pebbly terrain. The dendritic channels Huygens imaged from above trended in the same direction. Surface temperature was recorded at –179°C. Humidity was at least 50%, and a drop of moisture can be seen coming and going on the camera's lens. Surface brightness was about 500 times as bright as a full moonlit night on Earth (Fig. 8.9).

Images from the now-static probe showed the soft shadow of the parachute drifting across the ground (see Fig. 2.3). Near the probe, fist-sized ice "rocks" lay partially buried in the soft sand. Huygens' instruments detected a spike in methane as the probe's warm belly heated the ground, releasing methane vapor. The stones nearby – all made of nearly pure water-ice – displayed rounded shapes, the same kinds of shapes found in river rock that has been tumbled in liquid. Huygens was witnessing an alien equivalent of a rock-filled riverbed or flood plain.

The distant ground was flat; Huygens had settled onto the dark plains between the ice highlands it had seen from its aerial views. While up there, Huygens sampled the air around itself, and it found something significant: an isotope called argon-40. Argon-40 comes from radioactive decay of potassium. Huygens' discovery shows that radiogenic heating of

---

[3] Since the Cassini mission, ESA has proven its mettle with complex encounters and surface landings on an assortment of targets.

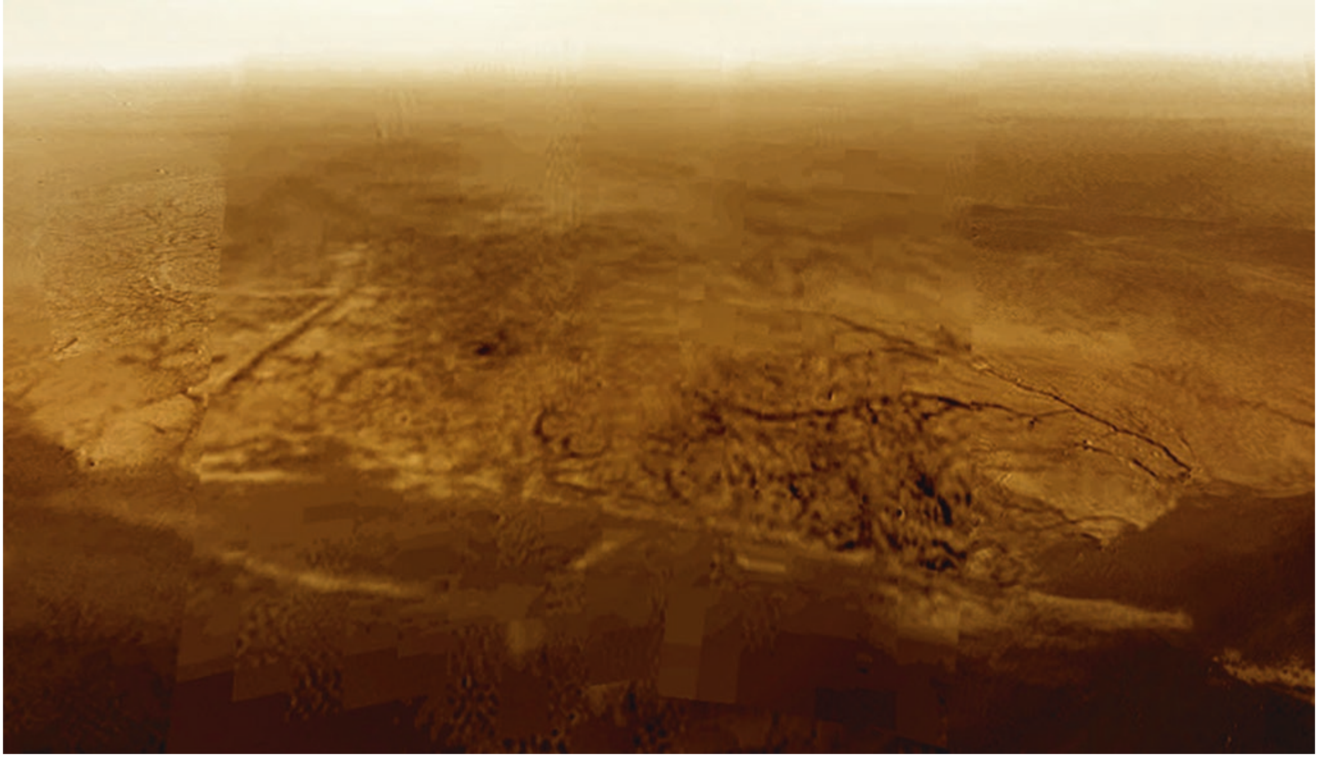


Fig. 8.9 The view from 8 km. Huygens took aerial shots on the fly during its 2 ½ hour descent to the surface of Titan. This view takes in the branching forms of methane river valleys and the dark valley floor where Huygens came to rest. (Image courtesy of ASA/JPL/ESA/University of Arizona; processing by Rene Pascal)

some kind still occurs deep within Titan. This radiogenic activity, with the release of its radiation through cryovolcanoes or other sources, means that the methane in Titan's atmosphere may be related to its geology rather than its biology. But Huygens also detected tholins in the moon's foggy layers of haze. Complex organic molecules like these building blocks of life will be critical to our understanding of life-related organic chemistry.

Huygens continued to shutter images of the same swatch of ground for at least 72 min. The probe sent 100 frames before losing contact with the orbiter. But antennae on Earth continued to hear faint signals, perhaps for as long as an hour after primary contact was broken.

We would love to know more about Titan's long-term changes – its migrating lakes, fluctuating rainstorms and shifting dunes – as the seasons come and go on this strange world. But the cogs turn slowly in the outer Solar System. By the time Cassini was commanded to enter Saturn's atmosphere at the end of its mission in 2017,[4] it had observed fewer than two full seasons of weather on the cryogenic, fog-enshrouded world. But astronomers continue to sift through its piles of data as they hone their skills at remote sensing from Earth-based platforms. Saturn's planet-moon still has tales to tell. In a sense, Titan is a window into the future of our own world, giving us a glimpse of what Earth might be like when the aging Sun becomes brighter and drives the oceans away. Earth will have vast equatorial dune seas, and whatever water is left will migrate to the poles. Perhaps in that distant future, someone will send a probe to sample the alien equatorial regions of our desert world.

---

[4] While Cassini still had some maneuvering fuel, flight engineers commanded the spacecraft to self-destruct in the atmosphere of Saturn so that it could not eventually crash into either Titan or Enceladus, where there is the possibility of extant life.

Pluto, "Ultima Thule," and the Lords of the Dark Realm

9

Beginning at about the orbit of Neptune drifts a family of objects that area relics of the most ancient times, fossils of early planetary formation preserved in a deep freeze (Fig. 9.1). The region is called the Kuiper Belt. This vast donut of material is twenty times as wide as the Asteroid Belt and two hundred times as massive. It extends from 30 AU (at about the orbit of Neptune) to 50 AU, far beyond our main family of planets. It is the place left behind, the dregs of the solar nebula that remained at the outskirts as the inner solar nebula warmed and condensed into the planets and moons we see today.

Although the asteroids consist mostly of stone and metal (see Chap. 4), members of the Kuiper Belt are comet-like, rich in ices of water, methane, ammonia, and other volatiles. Many of the comets that frequent the inner Solar System, like the famous Comet Halley, come from this region.

Before researchers knew of the Kuiper Belt, our Solar System seemed an orderly affair. Astronomers were baffled that the outer Solar System was so empty, given that the inner Solar System was so busied with asteroids and comets and planets. But the telescopes of the time simply could not detect anything that far out.

In 1988, a Canadian/MIT group, Martin Duncan, Thomas Quinn, and Scott Tremain, wrote a paper[1] speculating on the origin of the short-period comets. The authors determined that an earlier idea – that all comets come from a vast distant sphere of comets at the very fringes of the Solar System – could not be correct. Some comets did come from that far out, but others, they proposed, must come from a closer-in reservoir of icy bodies, and that region turned out to be what we now call the Kuiper Belt.

In fact, the Solar System's emptiness beyond Jupiter was an illusion caused by the limitations of the instruments. With advances in telescopes, many dozens of objects soon came to light. Astronomers used the paths of those objects to map out the structure of the Kuiper Belt.

Today, researchers see the belt as a throng of billions of rocky and icy planetoids known as Kuiper Belt objects, or KBOs. At the inner edge of the Kuiper Belt itself, many objects follow paths that are "in resonance" with Neptune. This means that for each three times that Neptune circles the Sun, a more distant object "in resonance" will orbit it exactly twice. Pluto is one of the objects in resonance with Neptune. The material in the Kuiper Belt is a treasure house of records of the early Solar System. And Pluto is the gateway to our understanding of this important cosmic neighborhood.

Pluto: The Ninth Planet?

Many astronomers speculated that a ninth planet might orbit in the darkness beyond Neptune. Percival Lowell, mathematician, diplomat, writer, and amateur astronomer, was one of the greatest champions of the idea. Observations of the orbits of Uranus and Neptune, only partially observed at the time, provided Lowell with numerical data on their pathways around the Sun. Lowell's calculations showed that something must be perturbing the two ice giants. He called that something "Planet X." It turned out, with better observing techniques, that Lowell's math and the observations of Uranus and Neptune were in error, but the search continued nevertheless.

Pluto was the first KBO to be spotted by modern astronomy, when a 23-year-old astronomer named Clyde Thombaugh spied a distant, star-like object moving across his photographic plates in 1939. His discovery, made at the Lowell Observatory in Flagstaff, Arizona, was heralded as the ninth planet of the Solar System. Pluto held that title until recently, but it was demoted because, among other reasons, it had a whole lot of company. Many other objects have been found with better telescopes. In addition, neither Pluto nor any of its fellow Kuiper Belt siblings orbit in the same stately plane as the major planets. Instead, their orbits are inclined, tilted above and below the paths of the main planets. Now, researchers see Pluto as merely one member of thousands – or even millions – and there are others that have fallen captive to the modern telescope (see below). In the early days of

---

[1] *Astrophysical Journal,* 328: L69-L73, 1988 May 15.

M. Carroll, *Ice Worlds of the Solar System*, https://doi.org/10.1007/978-3-030-28120-5_9

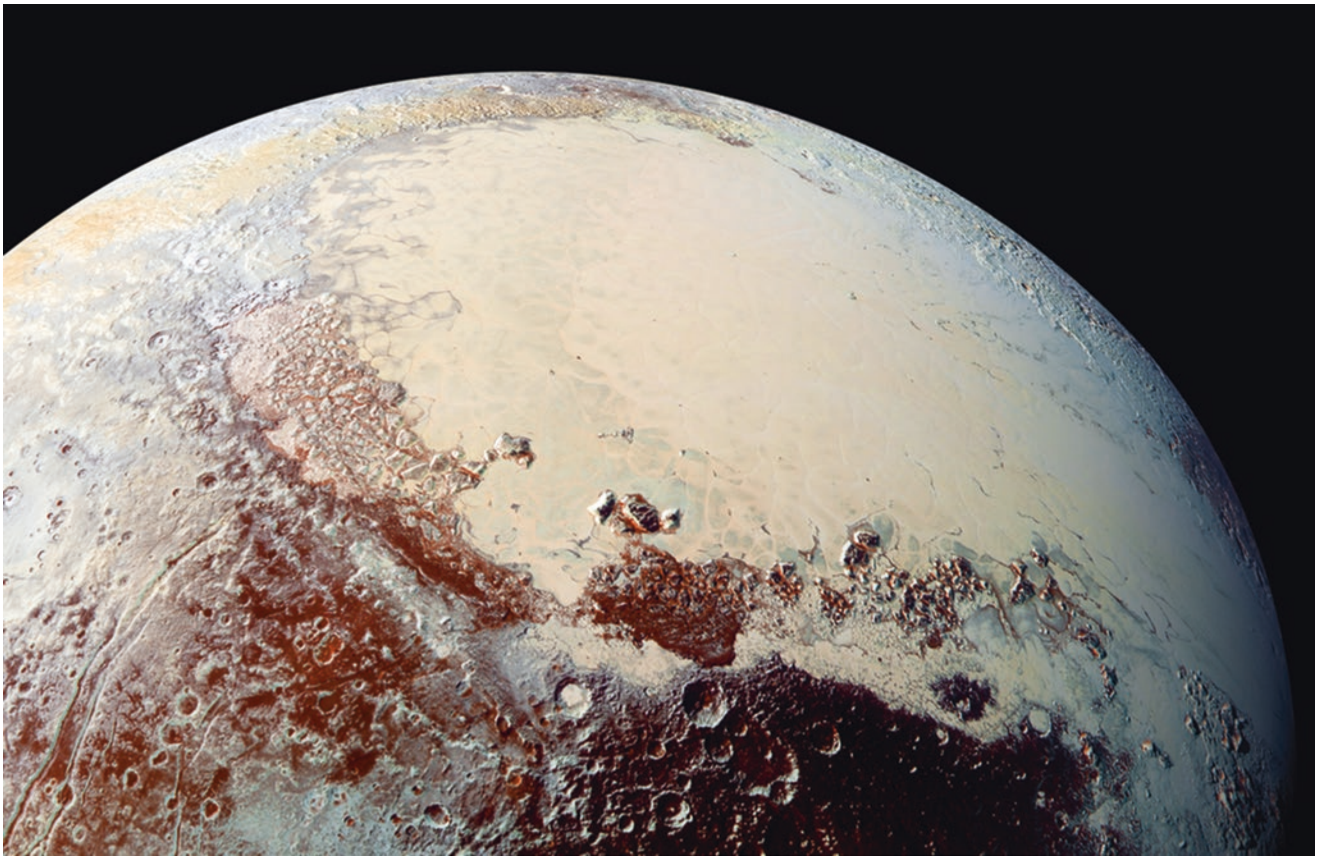


Fig. 9.1 View of Pluto's spectacular Sputnik Planitia. Of note are jagged ice mountains, the dark Cthulhu Regio at bottom, and Sputnik's celled terrain. The great glacier making up this western lobe of Pluto's "heart" consists mainly of frozen nitrogen, methane, and carbon monoxide. (Image courtesy of NASA/JHUAPL/SwRI)

study, Pluto was too far, too dark, and too small to give up many secrets.

Its orbit in the outskirts of the main planetary system provided the inspiration for the ice world's moniker.[2] Pluto was the ruler of the dark underworld and afterlife of Greek mythology. But the name had an added attraction: its first two letters were the initials of the man whose math and promotion led to the discovery of this "Planet X."

The 1966 edition of Time/Life's book *Planets* summed up our mid-twentieth-century knowledge of Pluto well: "Not much is known about Pluto. Neither its mass nor density can be stated with certainty. Its diameter is about half that of the Earth…Small, cold and dark, Pluto is the planet least likely to support life."[3]

At the time of the New Horizons encounter in 2015, Pluto had only been known and observed for 34% of its year, as the KBO takes just under 248 years to circle the Sun once. Its path extends an average of 5.9 billion km, or 39.48 AU, from the Sun in an elliptical orbit that sometimes brings it slightly closer in than Neptune. Because of its orbital resonance with Neptune, the two objects are never on a collision course. At its farthest, it wanders 49.3 AU from the Sun. And while all the major planets orbit in roughly the same plane, known as the ecliptic, Pluto's orbit is canted by some 17°. It is also far more out-of-round than the classical planets.

Pluto's axis is also unlike most of the main planets. The Pluto-Charon system is tipped over in relation to the ecliptic, so that the ice world seems to roll around the Sun. Pluto and Charon also spin in a retrograde direction. Only one other planet, Venus, does that.

Initially, it was difficult to judge the actual size of Pluto. Its intrinsic brightness was unknown, so if it was a bright object, it might have been as small as 2000 km,[4] but if it was a dark object, it could have been much larger (some early estimates ranged up to Mars-sized).

Still, astronomers could see a regular ebb and flow of Pluto's overall brightness, so they put their telescopes to

---

[2] The observatory had a naming contest; the name was suggested by 11-year-old English school girl Venetia Burney of Oxford.

[3] *Planets* by Carl Sagan, Jonathan Norton Leonard and the Editors of Life; Life Science Library, Time/Life books, ©1966.

[4] The diameter of Earth's Moon is 3474 km.

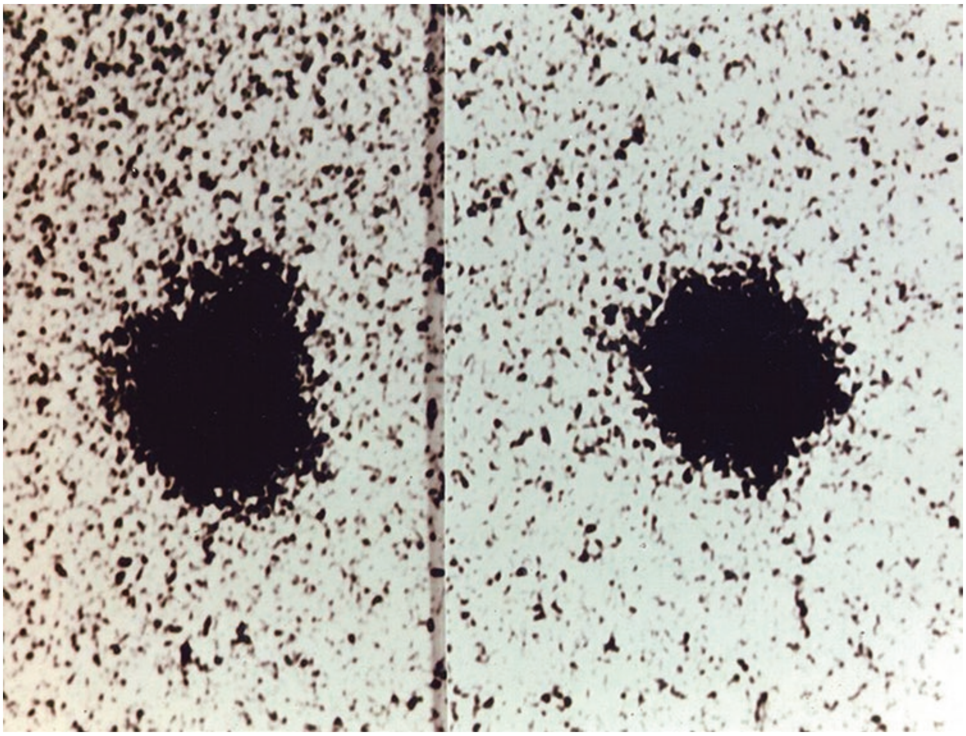


Fig. 9.2 Jame Christy's discovery photo of Charon, the blob extending from Pluto's upper right in the left-hand image. (Image courtesy of the U. S. Naval Observatory, https://commons.wikimedia.org/wiki/File:Charon_Discovery.jpg)

work, attempting to create surface maps. Although observers were able to lock down a length of day – 6 days, 9 h and 36 min – attempts at viewing surface detail were frustrated until the Hubble Space Telescope came on line. In its best views, the ice world was only a few pixels across, just enough to make rudimentary albedo maps.

Before Hubble's imaging of Pluto, astronomers were able to use spectroscopy to reveal that the surface of Pluto was covered, at least in part, by methane ice. The 1976 discovery meant that Pluto was on the bright side, which in turn meant that it was closer to the lower estimate of its size. Observers realized that Pluto must be roughly the size of Earth's Moon.

This finding was helpful, but another discovery would prove to reveal even more. In the summer of 1978, James Christy of the U. S. Naval Observatory noted that Pluto's fuzzy image was elongated, as if a huge mountain rose from one side. With further scrutiny, he realized that the irregular blobs were actually a moon in orbit around Pluto. With a moon to track, scientists could now lock down the size of Pluto with more certainty, along with its mass and the mass of its moon. With the new data in hand, Pluto weighed in at just a fifth of the mass of Earth's Moon. Its composition must have included either very porous material or a lot of low-density ice (Fig. 9.2).

The moon was named Charon, after the boatman who ferried souls across the River Styx to their afterlife in Pluto's underworld. And although it was early days, astronomers realized something else. Charon's orbital period was the same as the changing patterns on Pluto. If the two worlds had the same length of day, they were tidally locked, keeping the same face toward each other. This is in contrast to the Earth-Moon system, where our Moon turns once each orbit, keeping the same face towards Earth, but Earth turns some 29 times for each lunar cycle (giving us our month).

In 1987 and 1988, Pluto and Charon lined up so that they eclipsed each other with every circuit. This alignment gave astronomers even more insight into the mass and size of the system. They estimated Pluto's diameter at 2370 km, just two-thirds of Earth's Moon. They found Charon to be about half that, making Pluto and Charon a double planet system. In fact, Charon does not orbit Pluto. Instead, the two bodies orbit a point just outside of Pluto between them, like two circling ice skaters holding hands. This central point of the system is called the barycenter, the center of mass shared by both bodies.

However, to understand the geology, history, atmosphere, and interior of Pluto and its moons, scholars and the public would have to wait for a close flyby of a spacecraft. That spacecraft was New Horizons, but other space missions would provide some clues as to the nature of distant ice worlds.

The Space Age Arrives

In 1989, the decade-long mission of Voyager 2 reached a crescendo with its last planetary encounter at Neptune. Neptune had a lot to offer: a great blue globe, the second ice giant ever to be encountered. In place of an organized ring system like Jupiter, Saturn, and Uranus possessed, Neptune was encircled by strange ring arcs. It appeared to have more pronounced meteorology than Uranus, which was bland to the eyes of Voyager. But one of the most important targets of the entire Neptune encounter was not the planet itself but its icy moon Triton. (See Chap. 3 for details of the encounter.) Triton was about the same size as Pluto, and it appeared to have come from the same neighborhood: the Kuiper Belt.

With Voyager's encounter of Triton, it was tempting to see Pluto as a nitrogen-ice-covered world. If it was blanketed in nitrogen and methane ices, as Triton was, then planetary scientists could better estimate its size and mass, and perhaps even its nature.

The only way to know for sure was to observe Pluto from close range. Another mission was called for. And called for. And called for.

New Horizons at the New Pluto

New Horizons was a mission that nearly didn't happen. Many missions were proposed after the successes of Voyager, including the Pluto 350, Pluto Kuiper Express, and the Pluto and Outer System Explorer (POSSE). The New Horizons team submitted several proposals to NASA, and in 2001, one of them finally stuck. NASA selected the mission for its New Frontiers program. But in 2003, just as mission development was to get underway, the administrator of NASA zeroed out its funding. The New Horizons team lobbied, and Pluto was put on the top of the list for missions that NASA considered most important for the coming decade.[5]

New Horizons was finally selected, partly because its team members at the Southwest Research Institute and at Johns Hopkins Applied Physics Laboratory had successfully mounted the Near Earth Asteroid Rendezvous Shoemaker mission to the asteroid 433 Eros. They had a good track record.[6]

New Horizons left for Pluto on a powerful Atlas V, with a Centaur upper stage, on January 5, 2006. The probe's breakneck speed took it to a gravity assist encounter with Jupiter in February of 2007, the fastest trip to the outer Solar System on record. Equipped with far better instrumentation than any spacecraft before it, the craft studied Jupiter and its moons as a dress rehearsal for the upcoming Pluto encounter. By now, observers had found four other moons orbiting Pluto: Nix and Hydra (found in 2005), and the smaller Kerberos (2011) and Styx (2012). New Horizons would attempt images of all four small satellites and an in-depth survey of Charon as well.

Just ten days before encounter, apparent disaster befell the mission when New Horizons went into safe mode, shutting down its science systems. Alarmed controllers discovered a software flaw and fortunately were able to fix the problem before it was too late. Some science was lost, but the spacecraft would more than cover for it if it could complete its planned program of observations. New Horizons carried out its spectacular reconnaissance of Pluto and its moons, with closest approach to Pluto occurring on July 14, 2015. Twenty-two long hours of planned silence[7] led up to the spacecraft pinging Earth, confirming the completion of a successful encounter. In the course of a few frantic days, New Horizons' seven experiments carried out more than 400 observations.

Something in the Air

The planet[8] unveiled by New Horizons was spectacular beyond the expectations of many ice-world experts. Even in the most distant "far-encounter" views, it became obvious that Pluto and Charon had quite different personalities. Contrast on Pluto's surface was striking, ranging from dark reddish to bright tans and shades of gray-white. Charon was dusky, with a bluer face. But those views were just the preamble. Over the course of the encounter, New Horizons radioed back to Earth views of a geologically active world with glaciers, dune-like drifts (despite Pluto's thin air), jagged mountains, bizarre "snakeskin" terrain, ancient craters and fresh ice fields. The grand piano-sized probe also revealed a complex atmosphere, with a surprising layer-cake complexity.

Part of the rationale for mounting the New Horizons mission was that Pluto is on its way out in its elliptical orbit, heading away from the Sun's heat. Ground-based observations showed a tenuous atmosphere at Pluto, but it was expected that it would soon collapse – in similar fashion to a comet losing its coma and tail – as the planet chilled on its outward journey around the Sun. Investigators wanted to see Pluto in all its glory, before its thin atmosphere became ice locked to the surface.[9]

---

[5] Planetary Science Decadal Survey of 2003–2013.

[6] Other applicants had good track records, too, but the competition for NASA dollars is stiff.

[7] This was necessary because the spacecraft had to slew to carry out its various observations, thus pointing its primary antenna away from Earth.

[8] Although Pluto has been reclassified as a dwarf planet or ice dwarf, its complexity challenges the concept, and many in the planetary science community suggest that it should be reinstated as a traditional planet. For our purposes, we will use the term interchangeably.

[9] Pluto's last perihelion, or closest approach to the Sun, was on September 5, 1989.

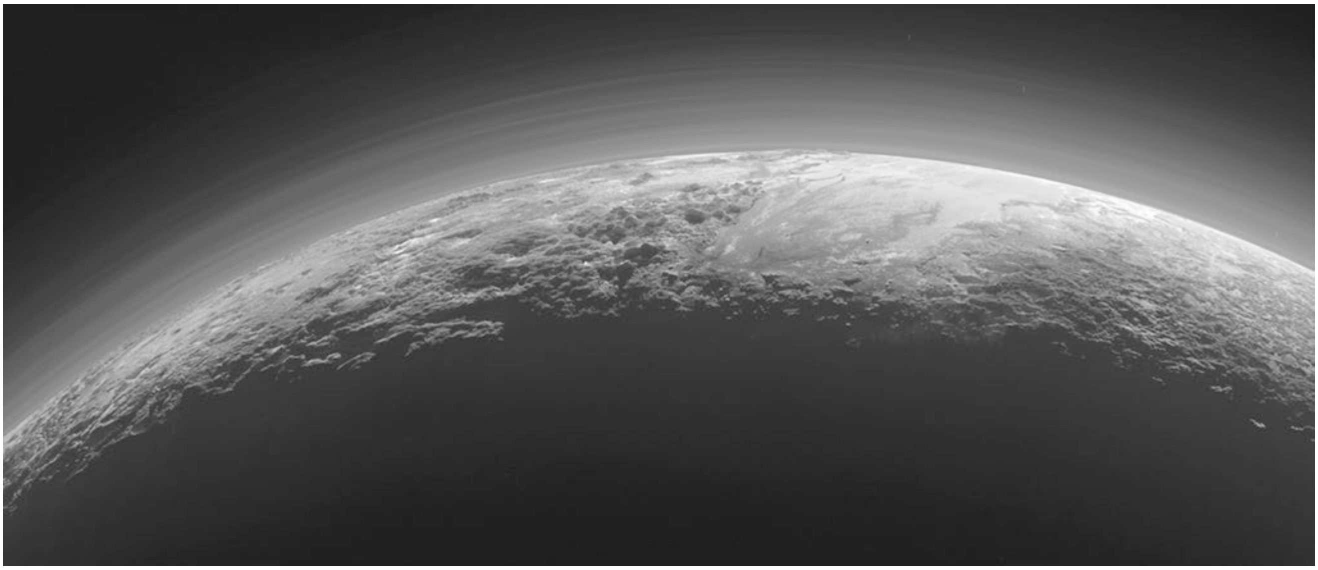


Fig. 9.3 Twilight on Pluto. Sputnik Planitia, center and right, is flanked by the 3500-m peaks of the Norgay Montes (foreground) and Hillary Montes (on the far limb). The scene covers 1250 km of Pluto real estate from one side to the other. (Image courtesy of NASA/JHUAPL/SwRI)

Instead, what New Horizons found was an atmospheric escape rate a thousand times less than estimated. Pluto's air scattered light into a lovely blue halo around the globe, with haze layers reaching altitudes of well over 200 km. In the highest resolution images taken of the atmosphere, some twenty layers can be counted, each separated by roughly 10 km of clearer air. There was yet another atmospheric surprise: the geology of the ice planet hinted that in the past, the atmospheric pressure has been tens to thousands of times higher than what it is today (perhaps three times the surface pressure found on Mars). And the latest computer models, upgraded with New Horizons data, suggest that Pluto has an atmosphere year-round (Fig. 9.3).

The gossamer atmosphere consists primarily of nitrogen, along with methane and carbon monoxide. All of these gases are in equilibrium with their ices on the surface. When Pluto is at its warmest in its elliptical orbit, more surface ice will turn directly into vapor, pumping up the pressure. As Pluto loses warmth on the far end of its track, more atmosphere will freeze to the surface as ice. Air pressure at the surface is 100,000 times less than on Earth at sea level. New Horizons measured temperatures at the surface between –210° and –230°C. But it's not that cold up above. As solar and cosmic radiation interact with Pluto's methane, a brown smog of hydrocarbons forms. These airborne tholins cause a strong greenhouse effect, so that at 30 km altitude, temperatures reach highs of –163°C before dropping again up above.

Pluto's seasons may bring exotic changes to its atmosphere. Computer modeling intimates that during Pluto's last aphelion (point farthest from the Sun) in 1865, the entire globe had accumulated prodigious quantities of volatile ices (methane, nitrogen, carbon monoxide). As the planet worked its way to equinox, the southern hemisphere tilted more and more towards the Sun. Southern ices migrated toward the colder north. By 1900, the volatiles in the southern hemisphere were essentially evaporated away, leaving only the "bedrock" water-ice. The freeing of the ice may have pumped up Pluto's air pressure significantly. At the time of the next equinox in 1987, the south was turned away from the Sun. Residual heat kept ices away for a while, but by the 2015 New Horizons encounter, ice was probably flowing across the south once again.

The wintry south pole was in deepest night during the New Horizon's encounter, but there was plenty to see to the north. A dark red band – part of which forms the "whale" of Cthulhu Macula[10] – girded the equatorial regions, where soaring mountains and rugged craters pierced through brownish organic blankets in glistening promontories. In the Tartarus Dorsa, bladed terrain sliced a snakeskin pattern through the frozen wilderness, reminiscent of the penitente ice towers and ridges found in some high deserts on Earth. To its west lay Pluto's most prominent feature: a great heart of nitrogen-ice plains and strange, celled landscapes stretching 1000 km across the face of the dwarf planet.

The Heart of Pluto

The immense nitrogen-ice glacier Sputnik Planitia stretches across a million cubic kilometers of Pluto's "heartland," on the hemisphere of Pluto facing away from Charon. It is the

---

[10] As of 2019, many features on Pluto still await formal naming.

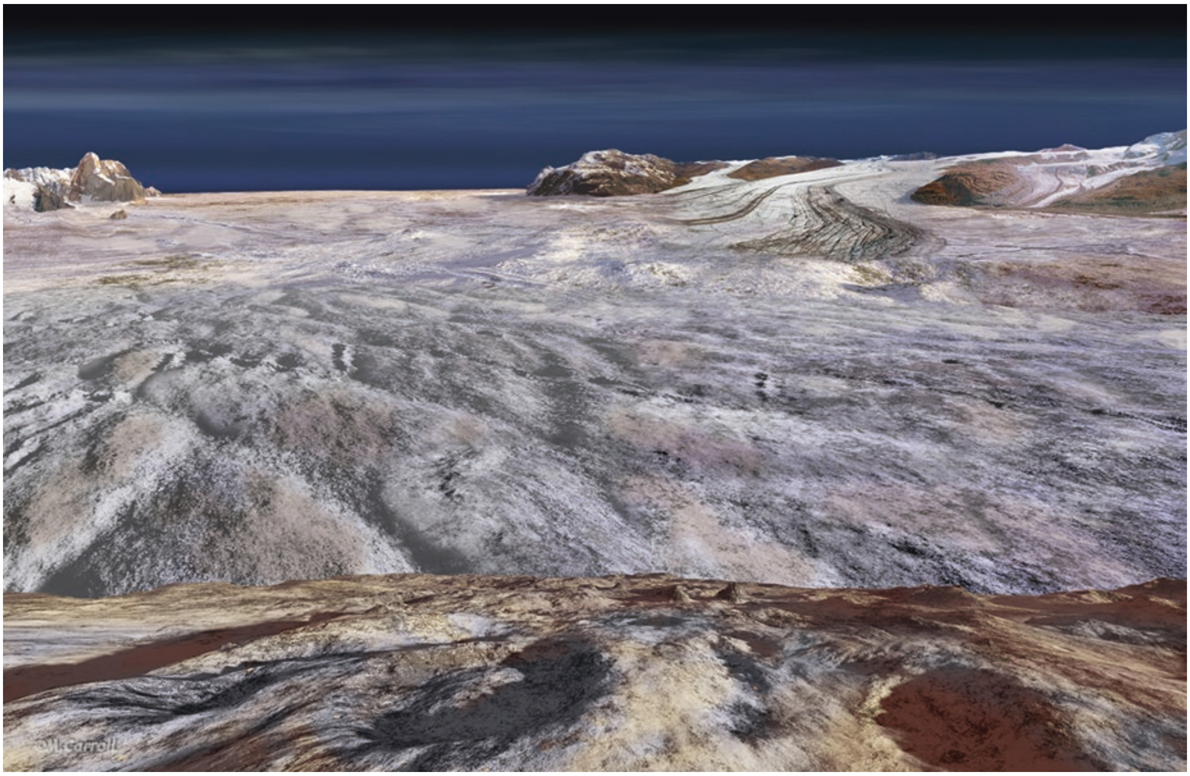


Fig. 9.4 Artist's concept of Sputnik Planitia, based on recent New Horizons data. The glacier-like flows are almost pure nitrogen-ice. (Art by the author)

largest glacier known beyond Earth.[11] Pluto has a cold heart, with surface temperatures hovering just 40°C warmer than absolute zero.

Geologically, Sputnik is new territory. It has no visible craters, and its surface appears to be fresh ice. Sputnik's plain lies 3–4 km below the level of the surrounding uplands. The processes that renew Sputnik are not well understood, but at its edges are clues about those processes. Pits cover the adjacent ice plains, scars of sublimation where the ice has vaporized directly into nitrogen gas. Some pits are rounded and similar in size and shape, about 2 km across. Many are arranged in long lines, while others have begun as hollows and then merged into long, wormlike depressions extending up to 25 km. The pits align in rows trending northeast to southwest. Slopes inside the pits are as steep as 30°. Remnants of what may be crater rims linger below the pitted surface, showing faint arcs and circles eroded away by the vaporizing ices.

The vast ice plain is smooth in places, but in other provinces it becomes humpy, with a series of cells bounded by low trenches. Superficially, the cellular terrain resembles the polygons of patterned ground found in arctic regions of Mars and Earth, where repeated freezing and thawing raises pillows of frozen earth, leaving lines of stones at the edges. At the northwest margins of Sputnik, mountains intrude into the edge of the plains. Among the outcrops, rivers of ice flow, butting up against the highlands. Their margins show them to be nitrogen glaciers with moraine-like ridges and end margins bearing striking similitude to glacial tongues. To the east, a higher, rugged jumble of terrain drains ice flows through canyons 3–8 km wide.

Sputnik Planitia forms the left lobe of Tombaugh Regio, Pluto's bright heart. The other lobe, less well defined, is infused with impurities in its ice, probably including carbon monoxide and methane, as well as smatterings of darker organics of the type found in Cthulhu Macula (Fig. 9.4).

The High Country

A disjointed mountain range rambles for several hundred kilometers along the western edge of Sputnik Planitia. The peaks are actually angular blocks of water-ice, each up to 40 km across and randomly arranged, with summits towering 5 km above the surrounding ground. At the southern end, many of the uplifts are separated by ices that have embayed their bases. At the northern end, the al-Idrisi Montes have very little space between them. The blocks appear to have

---

[11] The largest glacier on Earth, the Lambert Glacier, is 100 km wide, 400 km long, and 2500 m deep. It drains 8% of the entire Antarctic ice sheet.

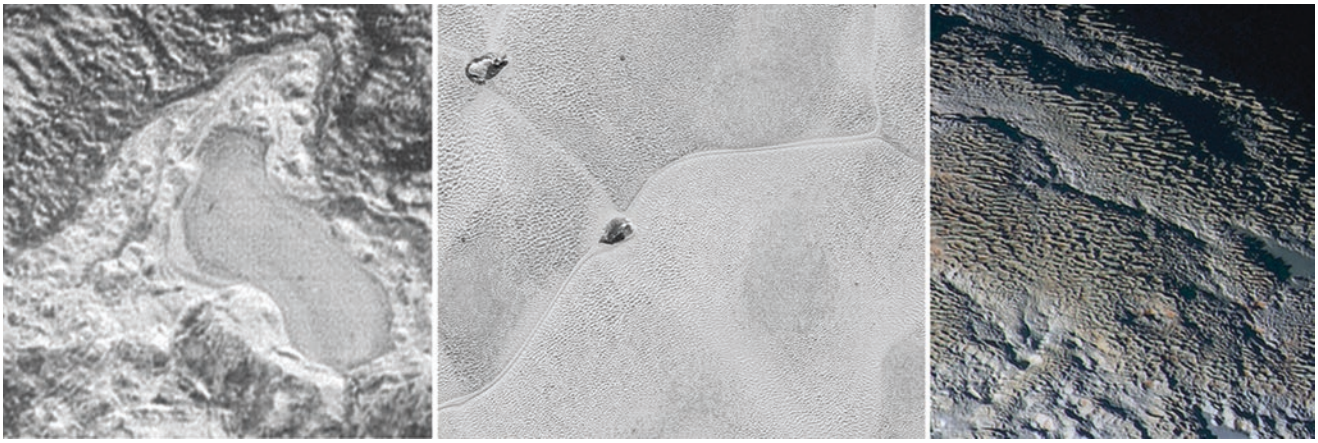


Fig. 9.5 A survey of Pluto landforms. *Left:* Lake-like formation informally named Alcyonia lacus. *Center:* Celled terrain within Sputnik Planitia. *Right:* "Snakeskin" terrain in the Tartarus Dorsa region. (Images courtesy of NASA/JHUAPL/SwRI)

come from the breakup of an earlier single surface, much like the chaos terrains of Europa. The mountains of al-Idrisi have fractured, detached from each other, where they drifted away and often rotated.

The chaotic mountain blocks, if pure water-ice, will be buoyant in nitrogen and carbon monoxide ice (but not in frozen methane). Blocks of water-ice will rise in the denser ices, in similar fashion to icebergs floating in liquid water. The smaller mountains may actually be floating within the ice, while the larger ones (2–3 km) are deep enough that their "keels" are probably resting on the water-ice bedrock. No mountains occur on the opposite side of Sputnik Planitia, and the cause for the missing highlands there is unknown (Fig. 9.5).

Cthulhu Macula and Craters of the Dark Equatorial Belt

Cthulhu is a mythological creature/deity invented by H. P. Lovecraft, described as a cross between an octopus and a dragon. To the New Horizons team who provisionally named it, the creature of dark realms seemed an appropriate image to assign to a dark, whale-shaped, ancient region along Pluto's equator. Cthulhu is heavily cratered and defines the southern edge of Tombaugh Regio from about 15° north of the equator to 20° south. It stretches nearly halfway around the entire planet.

At its eastern frontier, Cthulhu is a thin layer of dark material overlaying craters, branching valleys, scarps, and other preexisting topography beneath it. The dark material is likely hydrocarbon soot similar to that manufactured at Titan or Iapetus, perhaps complex tholins. The highest topography is also brightest, with the hydrocarbons either sloughed off or sorted by sublimation, as we saw at Iapetus. But other parts of the whale are smoother, with fewer craters. The whale "tail" in the west, not as well imaged as the terrain further east, probably comprises heavily cratered highlands similar to the head at the other end. Material from Sputnik Planitia appears to invade corridors in the eastern Cthulhu. Cthulhu's distribution of dark material is somewhat puzzling. It's one of a series of maculae – dark splotches – that encircle Pluto in a roughly equatorial band.

A wide variety of craters etch the surface of the ice world. Diameters range from 0.5 km all the way up to 250 km. An even larger impact basin may well exist beneath Sputnik Planitia, with the region's nitrogen ices filling in the basin. Parts of Pluto are heavily cratered, with several reaching to a point of near saturation. On the other end of the spectrum lie the places in Tombaugh Regio – particularly Sputnik Planitia – that appear to have no craters at all. Global patterns suggest that many of Pluto's surfaces date back nearly to the end of the Late Heavy Bombardment (see Chap. 1). At that time in our Solar System's history, the outer planets were likely being rearranged, pushing icy bodies outward into the growing Kuiper Belt. The mountainous highlands and bladed terrain are much younger.

Pluto's craters point to a great mystery that may have a bearing on the fundamental nature of the Kuiper Belt. Craters on both Pluto and Charon record collisions with Kuiper Belt objects whose diameters range from 40 to 300 m, below the resolution of most KBO telescopic observations. Recent work by a Southwest Research Institute team led by Kelsey Singer detects a "paucity of small craters less than approximately 13 km in diameter, which cannot be explained solely by geological resurfacing." The researchers assert that the cratering statistics point to a lack of KBOs smaller than 1 or 2 km in diameter. No process has been found to erase craters of a certain size, but the craters on Charon overprint the ancient features, and there are no partially "eaten" craters that would indicate missing, fully eroded craters. The abrupt absence of craters of a certain size may indicate a lack of small impactors in the Kuiper Belt, an intriguing possibility with no current explanation.

Spiders and Snakes

Among Pluto's many exotic geological formations, one stands out – a series of fractures that meet in a hub, resembling a giant spider. Most of the faults on Pluto appear to align in parallel, arranging themselves in long belts. Fractures elsewhere are likely the product of global extension. As the interior of Pluto froze, the surface expanded, cracking in the process. But the curious radial assortment of fractures at the spider may be the result of a focused source of stresses beneath that specific location. This may be the site of a diapir or other upwelling.

One of the fractures, informally named Sleipnir Fossae, stretches for more than 580 km. Sleipnir travels in a north-south direction. Another fracture extends in an east-to-west direction for about 100 km. Several of the southerly faults extend into the bladed terrain of Tartarus Dorsa, and to the northwest they incise rolling hills and mottled terrains. The fractures of the spider's "legs" reveal a deep layer of reddish deposits similar in spectrum to the organics coloring the dark regions such as Cthulhu. The formation resembles some features found elsewhere in the Solar System (see Fig. 9.6).

South of the "spider," the bladed terrain of Tartarus Dorsa rises in several swells above the nitrogen plains of Sputnik Planitia like a giant's set of cutlery. The jagged ridges of sharpened methane ice trend north/south, and may be the result of sublimation. Sunlight heats condensed methane ice directly into vapor, eroding the surface into the bizarre textures, sometimes called "snakeskin." Some blades intersect, forming a Y shape. Others merge into triangular or rectangular segments, becoming part of the plains that rise to the east.

The unique features resemble some ice sheets on Earth's high deserts, like the Atacama of the Andes, which have eroded into parallel blades of ice and snow. Called penitentes, they begin as bowl-shaped indentations a meter or more across. The walls of the depressions sublimate into towers several meters tall. The terrestrial penitentes form seasonally.

Pluto's exotic ice blades are scaled up considerably, with 500-m-deep v-shaped chasms between, spaced apart by 3000–5000 m. The chasms are steep, with slopes approaching 20°. Models suggest that the gaps between Pluto's penitentes grow downward by only a centimeter each Pluto year, or orbit, and can grow only in pressures far higher than seen by New Horizons. These facts lead to estimates of tens of millions of years for their formations, and this fits with crater

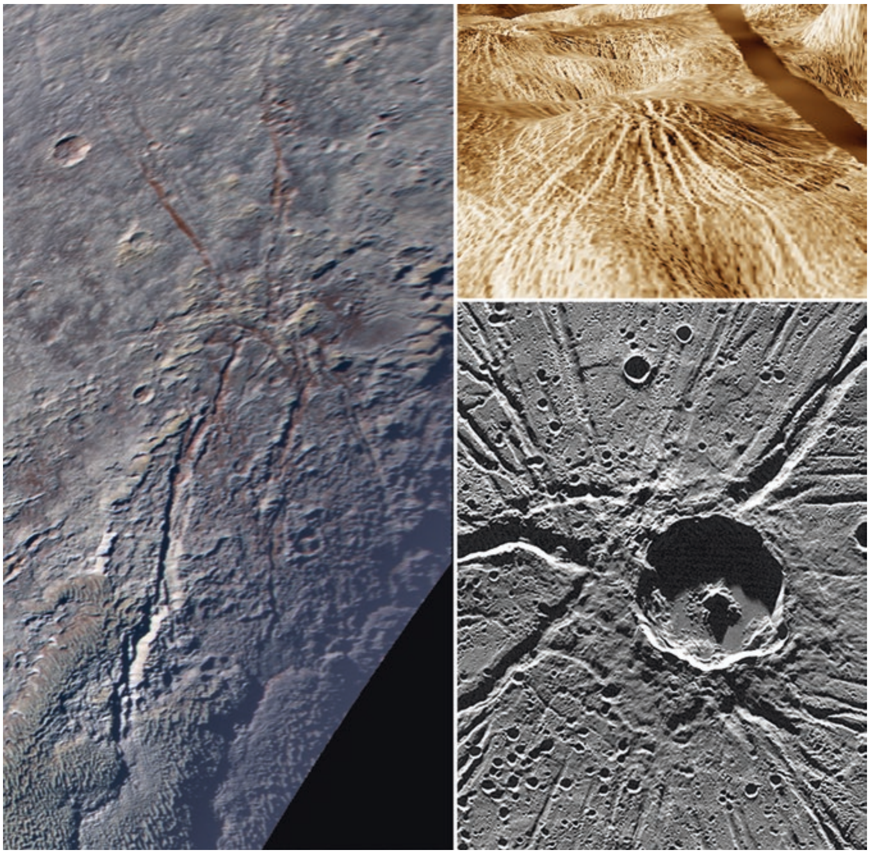


Fig. 9.6 The strange "spider" of Pluto (left) resembles features on other planets. At upper right is a "novae" formation on Venus' Yavine Corona; lower right is the crater Apollodorus on Mercury. (*Left:* Image courtesy of NASA/JHUAPL/SwRI. *Upper right:* Image courtesy of NASA/JPL/USGS. *Lower right:* Image courtesy of NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution)

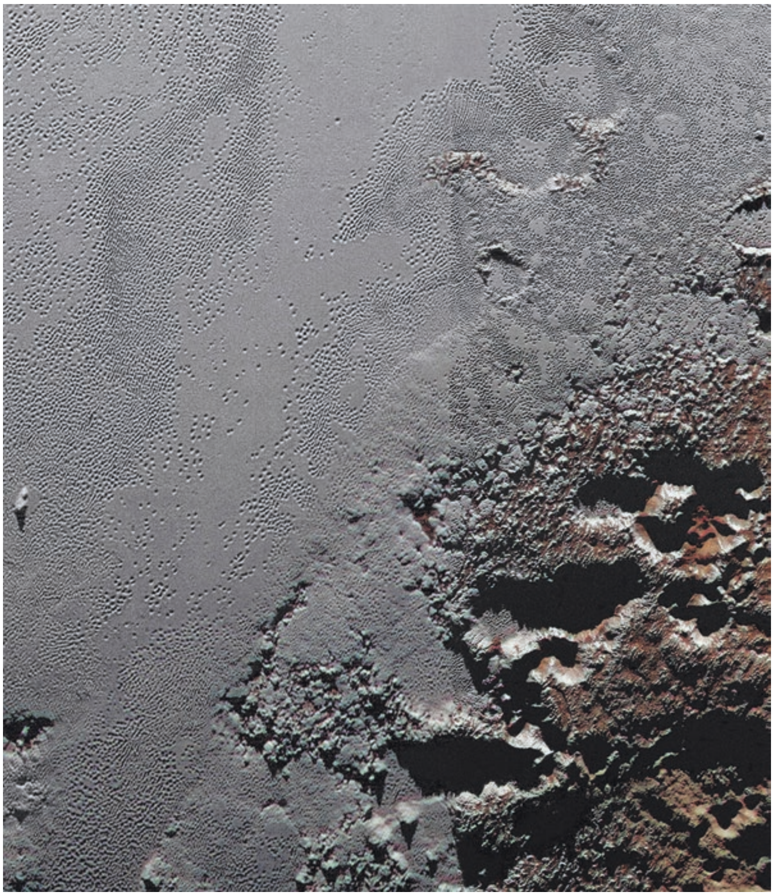


Fig. 9.7 The highlands of Krun Macula (lower right) abut pitted terrain in Sputnik Planitia. (Image courtesy of NASA/JHUAPL/SwRI)

counts of the area. This makes the bladed terrain some of the youngest geologic terrain on the planet.

Though Pluto's penitentes may have formed recently, they may be made of very ancient material. Studies indicate that the formations of Tartarus may be built from methane clathrates, a clay-like matrix. Methane clathrates are the stuff of the early solar nebula, issuing from the Solar System's formative cloud long before there were planets. If this is the case, the Tartarus blades have within them some of the oldest material in all the planets and moons of the Solar System.

The snakeskin formations may be generated more quickly if Pluto's atmospheric pressure increases. There is evidence that its atmosphere does increase periodically. A kidney-shaped frozen nitrogen lake shows evidence of liquid flow in the past. Today, the 30-km-wide feature is frozen solid, but higher air pressure and the accompanying raised temperatures could explain its erosional features and flow characteristics.

New Horizons also caught glimpses of channels that appear to have carried liquid in the past, liquid that likely could only exist under higher pressure. Pluto's wild axial tilt of 120° causes severe climate changes over time (this compares to Earth's 23° tilt). These shifts can also bring increases in air pressure as the frozen volatiles such as methane and nitrogen turn to gas and fill the atmosphere. Millions of years ago, Pluto's environment may have resembled Titan's even more, with cryogenic nitrogen raining from the skies and gathering in the lowlands as lakes and seas. The bladed terrain of Tartarus points to a time of bluer skies and stronger winds, a time when Pluto was, perhaps, just a little less alien than it is today (Fig. 9.7).

Cryovolcanoes?

An enormous mound rises from Pluto's plains in images covering the terrain south of Pluto's Sputnik Planitia region. It has been tentatively called Wright Mons, and tentatively identified as a cryovolcano. If its nature is confirmed, it will be the largest volcanic structure in the outer Solar System. The mountain spans 160 km across its base, and soars to a 4-km summit. At its top, a depression 56 km wide crowns hummocky, layered flanks. Concentric fractures around the summit crater suggest multiple eruptions and collapse.

The structure's appearance makes it a good candidate for a cryovolcano. To its south lies a second candidate, Piccard Mons. Both appear to be recent. Only one impact crater has been identified on the slopes of Wright Mons. The volcanoes

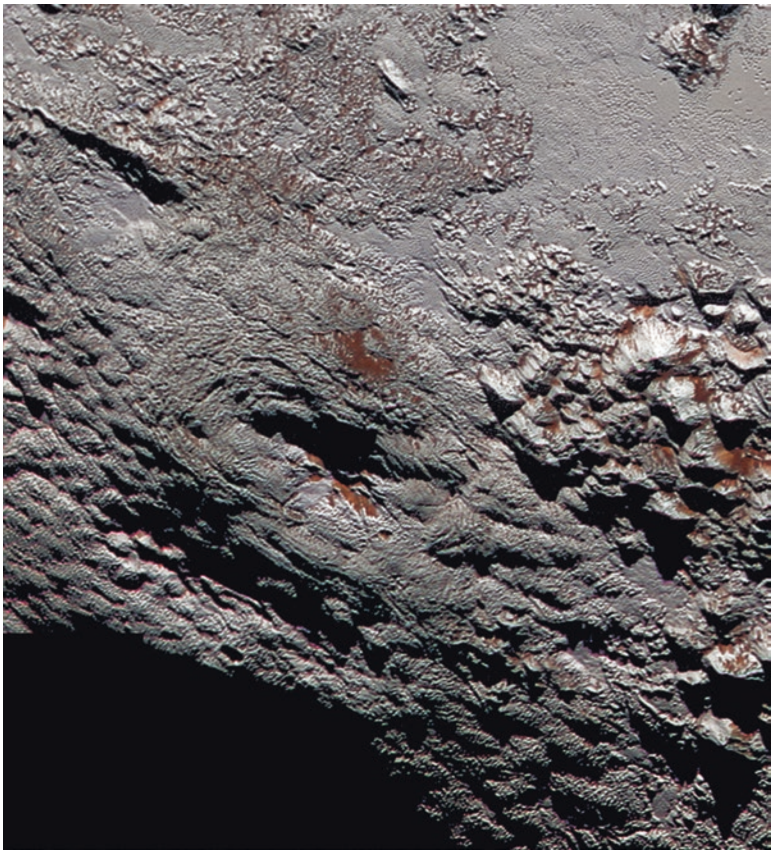


Fig. 9.8 The shield cryovolcano Wright Mons, at center of image, is seen near Pluto's terminator. (Image courtesy of NASA/JHUAPL/SwRI)

may have been active quite recently in Pluto's geologic history, and may even produce cryomagma flows today. These resemble shield volcanoes such as Mauna Loa (on Earth) and Olympus Mons (on Mars).

Although it is near some of Pluto's darkest, reddest areas, Wright Mons has limited scatterings of the presumably organic reddish material. Some of it rests within the possible caldera, while an outcrop tints the northern flanks farther down the mountain.

Piccard and Wright rest together as adjacent twin peaks. This leads scientists to wonder whether more of them exist just out of view, in the darkened territories lying beyond the terminator in New Horizons' images. The two cryovolcanoes may be members of an entire field of erupters just out of sight.

Another set of provisionally identified volcanoes lies at the northern margin of Cthulhu Macula along a canyon system called Virgil Fossae. Virgil Fossae was pulled apart by extensional forces, perhaps related to an arc of stress fractures that surround Sputnik Planitia. A 300-km-long fault along the south wall of the Virgil Fossae valley appears to be the conduit through which cryolavas erupted. Flows issued from a vent or series of vents in the western part of the main trough, freezing as they hit the surface. Nearby vents were built by fountain eruptions where pyroclastic (explosive) blankets of frozen particles blanketed terrain for 200 km on every side.

The cryoflows and the spread of particles all bear the reddish tone of hydrocarbons. A recent paper in the journal *Icarus*[12] said: "The large-scale geophysical setting of Virgil Fossae…appears to be conducive to the cryovolcanism interpretation of the structure and other characteristics of Virgil Fossae and its surroundings…" The authors go on to say that the structures could have resulted from a subsurface ocean that led to deep fracturing.

With only half of Pluto's sphere imaged to date, many more signs of cryovolcanism may lie across the face of this exotic world (Fig. 9.8).

Pluto's Seas

The Sputnik Planitia basin provides researchers with clues to a watery underworld there. Pluto and Charon face each other in their tidally locked cotillion. Sputnik's vast plain lies directly in the center of Pluto's anti-Charon-facing hemisphere. Its location tells planetary modelers that Sputnik is a positive mass anomaly, a region heavier than its surroundings. This is baffling, as the feature was likely caused by an asteroid collision that left a massive impact basin. But if

---

[12] *Recent Cryovolcanism in Virgil Fossae on Pluto*, Cruikshank et al, Icarus 330, 2019.

Pluto has a concealed ocean, its water is denser than the icy crust above. The impact would have pulled this watery interior up to the surface, creating a frozen mass that became the western lobe of Pluto's heart. Researchers estimate that this ocean may be up to 100 km deep, and it may be more salty than the Dead Sea. Other models suggest that Pluto's underworld is a sea of icy slush. "It's not yet constrained," says New Horizons' principal investigator Alan Sterns. "There's good evidence for a mass concentration below Sputnik Planitia, and the best explanation is liquid water."

Researchers suspect that any subsurface water ocean is global, maintained by the faint radioactive elements still heating the core, along with residual heat from Pluto's formation. In order for such an ocean to remain today, it must be well insulated from the cold of space. Unlike the crusts of other ocean worlds, Pluto's must be thick and rigid. Beneath the many kilometers of inflexible ice, the ocean will give us no surface clues as to its existence. Still, we can learn by some comparisons between Pluto and Triton. They are similar in size, they have similar amounts of rock and ice, and similar compositions. One might expect them to look similar, but they don't. Pluto's surface is much older; the crust seems to be much thicker and colder.

John Spencer explains, "The only way an ocean can survive on Pluto is if it's completely cut off, so it doesn't lose any heat through the crust. There's so little heat that you have to trap it in there to sustain an ocean. Once you get convection, or fracturing, or other geologic activity, that would let the heat out and the ocean would freeze." Ironically, the ocean on Pluto is evidence for *inactivity* in the crust, the opposite case for moons such as Europa and Enceladus. Pluto's deep, eternally dark sea would be a gloomy, Stygian world indeed, a place where the ferryman Charon would feel right at home (Fig. 9.9).

Charon, the Other Member of the Double Planet

Although its size is similar to the mid-sized ice moons of Saturn and Uranus, Charon is a behemoth compared to its primary planet. With its diameter about half that of Pluto's, Charon and its superior are close enough in size to qualify as a binary planet. They orbit about 1940 km apart, about the distance between Madrid and Copenhagen.

Charon's appearance is markedly different from its larger companion. It is mostly neutral gray, and unlike Pluto, most of the surface is covered in pure water-ice. Its northern pole wears a hood of deep reddish material that may link it to Pluto itself. It appears that Pluto's atmosphere extends, at least sporadically, to the surface of Charon, where the reddish, methane-processed hydrocarbons so common on Pluto also come to rest on Charon's pole, condensing as a layer over the existing landscape.

Charon has had a tortured past. A great set of canyons some 6–9 km deep cut across its face, bracketed by dramatic cliffs. The canyons cut gashes across 600 km of Charon territory, slicing through undulating plains, smooth tablelands, and cratered highlands. The ravines tell a story of global expansion, as the moon froze through and its interior ices extended the surface, splitting it like a grape peel. If the gorges were the result of tidal forces or remnants of the moon's de-spinning as it became tidally locked, computer simulations predict that their pattern would be different.

Charon's remarkable canyons are a complex of scarps, ridges, and furrows over 200 km wide in some places. Serenity Chasma is over 50 km wide and 5 km deep, while the adjacent Mandjet Chasma dives down to a 7 km depth. The chasms bear some similarity to rifts on several of the mid-sized moons, including Ariel, Enceladus, and Titania.

Charon's smooth, lightly cratered plains are consistent with volatile ices coming up from the interior, perhaps as cryofloods or eruptions. The plains make up one of two provinces on the moon, separated by a slightly tilted east/west belt of valleys and ridges. Rugged, cratered territory extends across the northern hemisphere, while to the south the terrain is smoother, with complex geological features. Some ridges and mountains reach as tall as 20 km, supported by Charon's dense water-ice and weak gravity.

In addition to its craters, the northern hemisphere is crossed by a patchwork of polygonal troughs 3–6 km deep. Another depression that appears to be independent of impact formations has irregular borders and is 10 km deep. It lies just south of the red polar hood, which the International Astronomical Union has officially called Mordor Macula. A bright ridge follows one edge of Mordor, and may be the remnant of an ancient impact basin. Across the southern edge of Mordor, a massive 6-km deep crater has blasted out a 230-km bowl called Dorothy Gale. The entire region north of the equatorial canyons appears to be roughly 4 billion years old, recording craters from the Late Heavy Bombardment.

In Charon's southern environs, a subtly grooved landscape slopes downward. The plains here may have been resurfaced by tectonic forces similar to the processes seen on other ice worlds like Ganymede and Enceladus. Deeper troughs also cut across the smooth plains, but they are quite old, sometimes interrupted by impact craters. These furrows travel roughly parallel to the chasms in the north (Fig. 9.10).

The southern flatlands may well have been resurfaced by cryovolcanism, and that activity may be present even today. Spectrum from two nearby craters shows dramatically differing levels of ammonia. The difference in craters may be due to ammonia-enriched cryolavas or vapors escaping preferentially from one crater. Alternatively, the smooth plains may have been resurfaced in an impact event that fractured the moon, leaving the chasms straddling the equator.

Fig. 9.9 Because it is a tidally locked system, Charon would appear to remain stationary in Pluto's sky, clocking through phases from crescent to full to gibbous to new, while the Sun moved across the sky, rising and setting each Pluto day (roughly 6.4 Earth days). (Art by the author)

Northeast of Charon's flatlands, visible just at the terminator in New Horizons' images, a mountain rises from the frozen plains. It is surrounded by a moat, as if the mountain's bulk has warped the ground around it.

Pluto's Smaller Attendants

New Horizons encountered Pluto's four smaller moons from a distance. Our most detailed views to date came from the encounter, with details as small as 3 km on Nix and 1.2 km on Hydra. The best measurements of Nix yield a tiny moon 54 km long and 36 km wide. Hydra is slightly smaller at 45 km long, but was imaged from a greater distance. Hydra has the same "rubber duckie" shape that comet 67P/Churyumov-Gerasimenko does. Nix has a more regular shape, with several large craters identified. The largest is distinctly redder than the rest of the surface.

Tiny Kerberos, named after the three-headed canine guard of the gates of Hell, also has two lobes, about 8 and 5 km. It circles Pluto in an orbit between Nix and Hydra. The innermost of the moons is Pluto's fifth satellite, Styx (named after

Fig. 9.10 Full disk view of Pluto's major companion; note the brownish polar hood. At top right, overhead projection of Mordor Macula, Charon's organic polar province to the north; bottom right, Charon's Kubrick Mons is a mountain surrounded by a moat. (Images courtesy of NASA/JHUAPL/SwRI)

the river separating the world of the living from the dark world of the dead). It is irregular and measures about 10 × 5 km in diameter (Fig. 9.11).

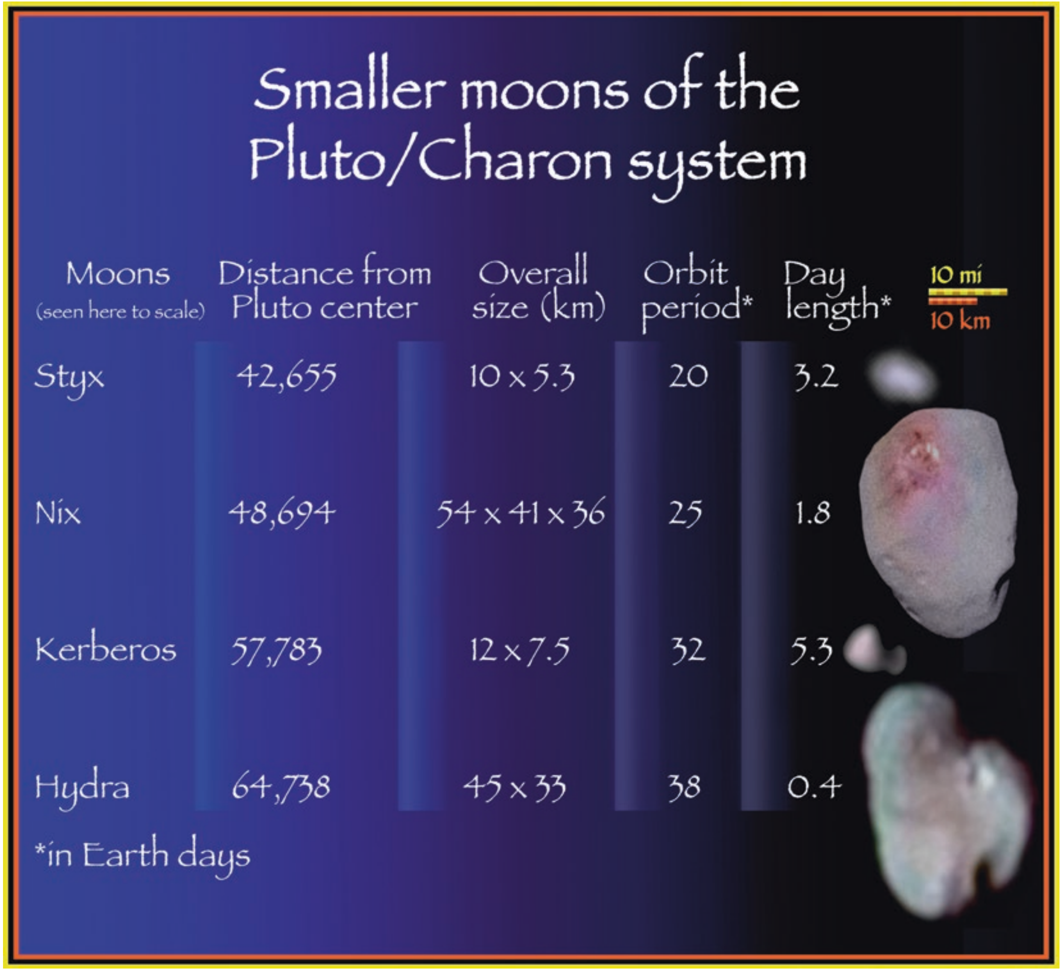
All five moons, including Charon, are thought to have formed in the Solar System's early history from a collision between Pluto and a twin-sized body. The impact tossed out a cloud of material that condensed into the moons we see today. The four smaller satellites orbit in a chaotic dance, with Hydra spinning around once each 10 h, some 89 rotations per orbit. The moon is spinning just under the speed at which it would self-destruct. Kerberos, Styx, and Nix all rotate between six and ten times per orbit. Adding to the confusion, Nix is also tilted over by 132 degrees and rotates in a retrograde motion. The other moons also have oddly aligned axes.

All five moons have surfaces dominated by water-ice, with fairly neutral colors, falling somewhere between the bright features of Pluto and the gray face of Charon. They are brighter than most Kuiper Belt objects. Nix is slightly redder than Hydra (partly due to its strikingly red major crater).

New Horizons searched for other moons and found none above the size of roughly 2 km. With the New Horizons reconnaissance of the Pluto/Charon system, we have now seen three large Kuiper Belt objects up close (counting Triton as the third). The trio has some shared characteristics, but their differences outnumber their similarities. Pluto and Triton both transport volatiles to the extent that the process changes their surfaces. Charon's surface is much calmer, devoid of many volatiles (except, perhaps, at the poles), showing a quiescent water-ice surface. Whether its volatiles sublimated away into space, or its surface has been dominated by something related to its origin or interior, is still a mystery. Pluto, Triton, and Charon provide us with a window into the wide diversity we may find among the many Kuiper Belt objects beyond Neptune.

Beyond Pluto: The Exploration of MU69, "Ultima Thule"

The term Ultima Thule comes from medieval and classical literature. To the Greek and Roman mapmakers, Ultima Thule was the farthest north notation on their charts. It may



Smaller moons of the Pluto/Charon system

Moons (seen here to scale)	Distance from Pluto center	Overall size (km)	Orbit period*	Day length*
Styx	42,655	10 × 5.3	20	3.2
Nix	48,694	54 × 41 × 36	25	1.8
Kerberos	57,783	12 × 7.5	32	5.3
Hydra	64,738	45 × 33	38	0.4

*in Earth days

Fig. 9.11 Survey of Pluto's four smaller moons, compared

have referred to Iceland or Greenland, the Shetlands, or Norway's Smola Island. In medieval literature, Ultima Thule embodied the concept of anything beyond the borders of the known world. Although it is not yet an official name for the object MU69, it is a fitting one for our discussion of the icy worlds beyond Neptune and Pluto.

MU69 orbits within the inner portion of the Kuiper Belt, a region known as the Cold Classic Belt. All of the objects in this zone are in remarkably flat, circular orbits, cruising around the Solar System in parallel to each other. To get into such flat, stable orbits, they must have had interaction with the primordial planetary nebula, and they have likely stayed in that configuration since the cloud was dispersed. Otherwise, they would have been disturbed into other, more eccentric orbits. Any kind of disturbance would increase the eccentricity of the orbit and send it out of the ecliptic.

The majority of Kuiper Belt objects are in disturbed orbits, thousands of them swept outward by Neptune. Even out where MU69 orbits, there are many objects whose orbits are tilted and eccentric, clearly out of the ecliptic. But MU69's is part of the Cold Classic Belt, in the "invariable plane" (near the ecliptic), and circular. There are a range of orbital distances among the members of the Cold Classic Belt, clusters of objects that have very similar orbits, between the orbit of Neptune out to about 43 AU. The outer fringes, at about 50 AU, begin to show more eccentric and inclined orbits.

One of the chief objectives of the New Horizons mission was to reveal processes in the outer Solar System's Kuiper Belt that might provide insight into the bigger story of planetary formation and what makes it tick. For decades, planetary dynamicists have struggled to understand the processes that ultimately led to the formation of the planets. It's a difficult problem, as most of the clues to the early Solar System formation have vanished in time, or were obliterated as craters on ancient surfaces.

One of the most frustrating issues facing those who study planetary formation is something called the meter barrier or the meter problem. When particles in the Sun's early accretion disk came together and grew, they had to eventually reach a diameter of a meter or so. But mathematical models show that meter-sized chunks of material, when orbiting more closely than 7 AU, will fall sunward and be destroyed after less than a thousand years. If the model describes reality closely, this means that any planets forming within 7 AU of the Sun must grow from a meter-sized conglomeration to stable planetoids very quickly, or they must form farther out, later migrating inwards. But dynamicists have shown that objects of a meter or more tend to collide at such high velocities that they fracture each other back into smaller pieces, preventing the development of a large planet.

New Horizons team scientist John Spencer explains the problem: "The key to forming planets is you have to bring things together and then make them stick. That's been hard to explain, because once these things get to a certain size, they tend to smash together and not stay." But researchers are exploring several scenarios that might explain the meter problem. Some have invoked interactions with clouds of pebbles or with gas, either of which would slow down colliding objects to a speed where they would survive such a contact.

And if objects somehow did accrete – as they must have – cobbling themselves into larger assemblages, astronomers would expect to see some large bodies affixed to each other. Several asteroids appear to be contact binaries, two bodies touching each other and gravitationally linked, but these have not yet been confirmed. Scientists hoped that the New Horizons encounter of MU 69, the first small Kuiper Belt object ever studied, might provide insights into the meter problem, and might even reveal a contact binary. Some projected that speeds in the Kuiper Belt during the Solar System's formative epoch would have been substantially slower, so that objects there might record the gradual encounter that, up to the time of encounter, were only theory. And as MU69 grew in the cameras of New Horizons, it became evident that the object was not a sphere or even an egg shape; it appeared to be two spheres affixed to each other.

The encounter of MU69 was a difficult one. New Horizons is the fastest-moving artificial object. The flyby was to occur much closer than the Pluto encounter, at 3500 km, but encounter speed at the Kuiper Belt object was 14 km/s, faster than at Pluto. And Ultima Thule was a small target; its relative location in the sky could only be estimated. MU69 was only discovered recently, found by the Hubble Space Telescope in 2014;[13] its exact location could not be discerned at its distance from Earth. The ancient shard is also dark, making it difficult for the navigation sensors to track.

The New Horizons team triumphed over the challenges, and the spacecraft returned its data at a trickle over the next twenty months. The encounter was the most distant ever attempted, at some 6.4 billion km from Earth. The revelations astounded researchers and public alike.

The scientists got what they came for. Ultima Thule turned out to be an incredibly ancient object, reddish in color and lobate in form, just as dynamicists had hoped. The earliest images that resolved the shape of the object MU69 revealed that it had, in fact, some kind of binary form. As images became clearer, its shape seemed to take on that of a snowman, confirming that the ancient object was probably a relic of the primordial Solar System, a record of history at the time when objects were coming together to form planets. Many investigators were surprised that the two lobes were so pristine, essentially unchanged and appearing as they would have 4.5 billion years ago. Some experts assumed the two bodies making up MU69 were fragments of something larger, much as the asteroids are. But no asteroid looks anything like this. The object is a collection of rubble, apparently drifted together gently into its bizarre form, many pieces making the whole. Mary Shelley would have loved Ultima Thule (Fig. 9.12).

New Horizons team members initially thought MU69 was shaped like a two-tiered snowman, but later imagery showed it to be shaped more like two hockey pucks – one slightly larger than the other – arranged as if touching each other on the flat surface of a rink. Its overall length consists of one segment 19 km across and another 14 km across. The two lobes have been nicknamed "Ultima" and "Thule." MU69 rotates once each 15.9 h.

One region may represent a single object that split but did not separate; its fractures may have appeared after formation. Ultima Thule is very red, and that red is probably related to the hydrocarbon theme of the outer Solar System (Fig. 9.13). Laboratory-baked tholins are quite similar in color. The little world's primordial ice surface of methane and nitrogen, bombarded by cosmic rays and solar radiation from the faint, distant Sun, would gain the same kind of patina. But its color poses a puzzle, says SwRI's John Spencer. "MU69 is smaller than just about all the others we know about, but it's the same color as the bigger ones. We see what looks like methanol, and we see it on Pluto as well. The big dark region, Cthulhu, is quite similar in spectrum. We also see hints of water-ice. We think a lot of the dark stuff on Pluto is raining out of the sky. The mystery on Pluto is why some regions are as bright as they are. There should be this continual dark rain coming out of the atmosphere. On Ultima Thule, there's no atmosphere. But it's got the same ingredients of water-ice and methane and some more exotic ices."

---

[13] The first researcher to set eyes upon the distant object was minor planet hunter Marc Buie of the Southwest Research Institute in Boulder, Colorado.

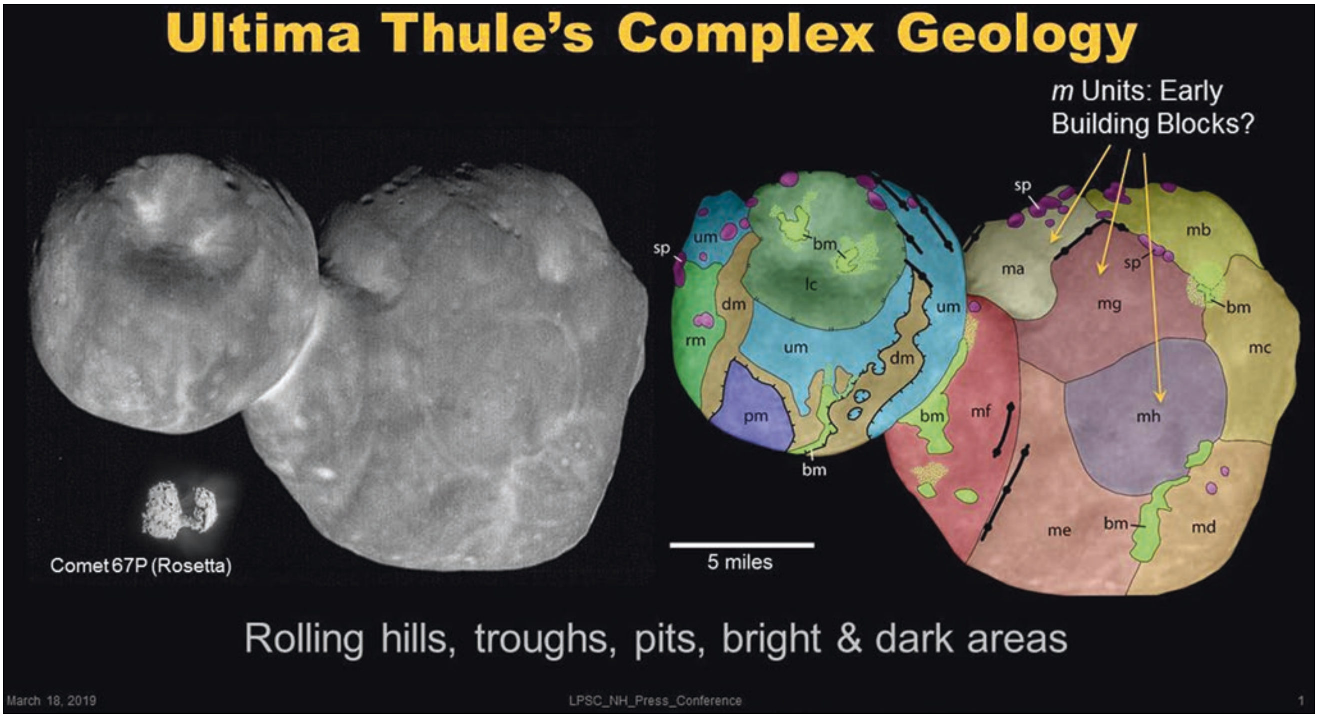


Fig. 9.12 Preliminary geological map of Ultima Thule, with different colors indicating different "building blocks" that drifted together to form the two-lobed structure. (Image courtesy of NASA/JHUAPL, SwRI, ESA)

The New Horizons team knew that many asteroids have their own satellites. The asteroid Ida, imaged by the Galileo spacecraft, has a tiny moon called Dactyl. And while Ida is larger than MU69, many near-Earth asteroids spanning only a few miles also have satellites. Additionally, the asteroid Chariklo is encircled by a tenuous ring system. Would Ultima Thule have one, too? "We didn't know what to expect," Spencer says, "so we did everything we could possibly think of. We threw everything at it." The spacecraft was commanded to search not only for moons but for rings and atmosphere. Those searches turned up nothing, but even a lack of discovery is informative.

With its strange shape and mix of rubble, MU69 should be able to provide insights into the meter barrier and other processes of the Solar System's primordial prehistory. Here, finally, was physical proof of some theories of the earliest stages of planetary formation. As a case of two objects that have stuck together, Ultima Thule is a fossil of that mysterious planet-forming process. The objects must have come together in some kind of environment where they could lose energy. They obviously collided very gently, and their orientation tells us that they kind of flopped into place. They were orbiting around each other in a stable configuration. The flat axis is aligned, and the polar axis is parallel. Current scenarios describe the two lobes as tidally locked – even within their microgravity environment – gradually spiraling in and attaching to each other.

Two objects sitting alone in space would continue to circle each other; nothing in the weightless vacuum of space would cause them to spiral in. But Ultima Thule may be a living example of a world created when its many parts – slowed down by primordial gas or smaller particles – came together in a slow motion dance lasting thousands, or even millions, of years.

Worlds of Ice Beyond Ultima Thule

Using the IAU's definition for a dwarf planet (see Chap. 1), several other members of this class have yet to be visited in these pages.

Eris

Eris is nearly a twin in size to Pluto, but it is about one quarter more massive. It is the largest world not yet encountered by spacecraft. The distant world spans a diameter of about 2326 km (compared to Pluto's 2372 km). Its size was determined by stellar occultation from ground-based observatories. Spectroscopic readings have revealed methane ice on its surface. Eris is the brightest object in the Solar System except for Enceladus. This may be due to its highly elliptical orbit, which alternately warms and chills the surface. Eris'

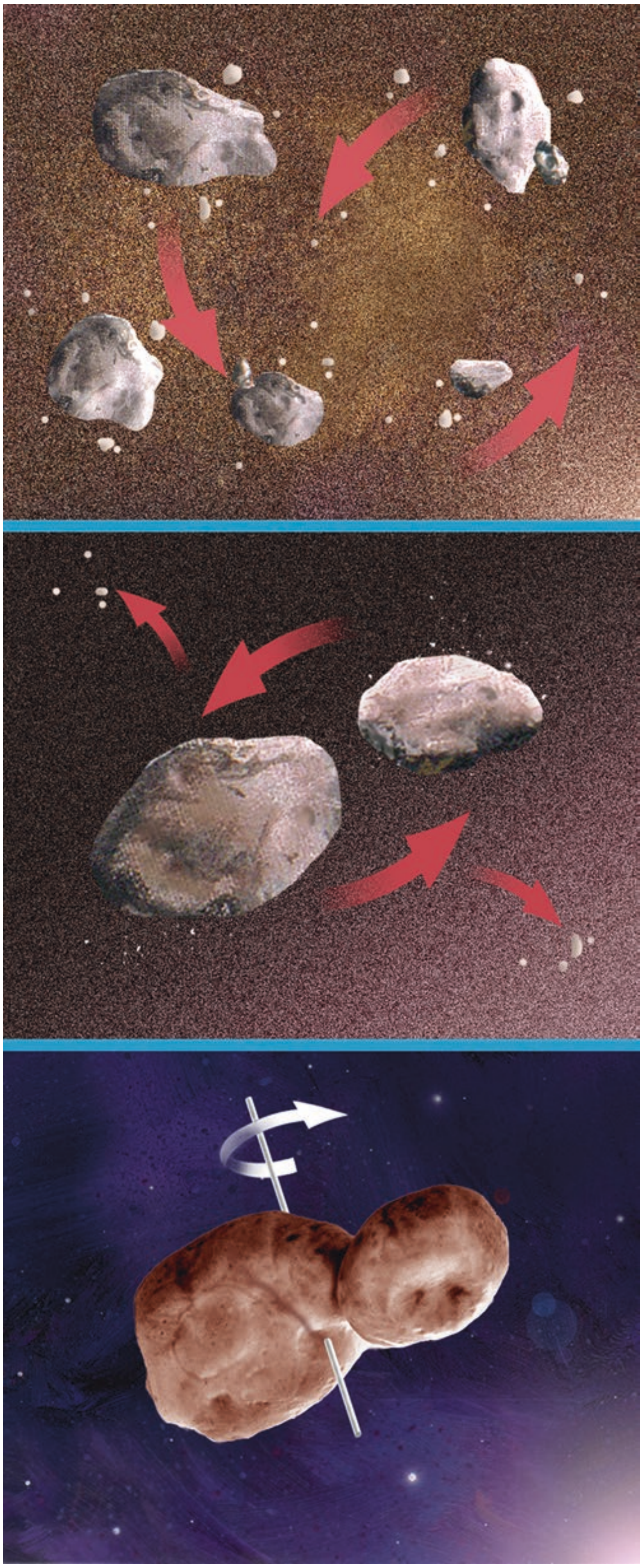


Fig. 9.13 Ultima Thule probably began as a fine cloud of spiraling debris. A small cloud of icy bodies begins to coalesce (*top*); two larger, fairly solid bodies remain, Ultima and Thule (*center*) while smaller fragments are flung away. Ultima and Thule spiral in until they make contact, forming the two-lobed object we see today. (Art by author, based on JHUAPL/NASA diagram)

path carries it as far as 97.7 AU and as close to the Sun as 38 AU (compared with Neptune's 30 AU). Its year lasts for 558 Earth years. The last time it reached the closest point to the Sun in its orbit, Thomas Savery patented the first steam engine and Russia's Peter the Great[14] was in power (in 1698). By the time Eris made it out to its farthest point, Israeli Prime Minister Menachem Begin met Egypt's Anwar Sadat, the movie *Saturday Night Fever* premiered, and Brazilian soccer hero Pele played his last game (1977). Eris' next perihelion will occur in about the year 2257.

Because of its elliptical orbit, surface temperatures range from –243° to −217°C. Its brightness may also be caused by some kind of cryovolcanism. Eris has a moon of its own, an approximately 700-km companion called Dysnomia. The little moon is 500 times as dim as Eris itself, so it must have a substantially different surface, perhaps covered by dark tholins. It orbits Eris every fifteen Earth days. It is likely that the two are tidally locked, meaning that a day on Eris is about that long as well.

Haumea

The 2000 km-long Haumea is distinctly egg-shaped with two known moons. A recent occultation (2017) provided estimates that Haumea is as long, in its longest axis, as Pluto's diameter, and half as thick at its poles. Its surface is covered in crystalline water-ice, making it one of the brightest Kuiper Belt objects known. It weighs in with a mass just one-third that of Pluto, and orbits the Sun every 284 Earth years, ranging as close as 35 AU. The ice dwarf may be in a weak orbital resonance with Neptune, but its orbit is not well-enough known to confirm this relationship yet. It spins around at a whopping 3.9 h for each rotation, making it the fastest spinning body larger than 100 km in diameter. Its rapid spin is thought to be the result of a collision that also gave birth to its two moons, Hi'iaka and Namaka. Namaka is the closest in, orbiting once every 18 days. Hi'iaka is ten times its mass with a diameter of 310 km and an orbital period of 49 days. Haumea may also have a ring system, the first discovered for a Kuiper Belt object. The ring was detected in 2017 during an occultation.

Makemake

Makemake is about two-thirds the size of Pluto, measuring 1400 km across. Its orbit lies between those of Pluto and Eris, ranging from 38 to 53 AU. It is the second-brightest of the Kuiper Belt objects yet seen, with frozen nitrogen and ethane detected on the surface. Due to its reddish color,

---

[14] In 1698, Tsar Peter imposed a tax on beards.

Fig. 9.14 Dwarf planets compared to Earth's Moon, to approximate scale. Clockwise from upper right: Makemake, Eris, Haumea, Pluto, Ceres. Note that the only dwarf planets we have so far imaged in detail are Pluto and Ceres. (Art by the author)

methane is also assumed to be in the mix. A tiny moon some 160 km in diameter orbits at an unknown period. When discovered, the moon was about 21,000 km from Makemake.

Sedna

Sedna, discovered in 2004, is not yet officially considered a dwarf planet, but its substantial size makes it worth at least a mention here. It lies so far out that it takes 115 centuries to circle the Sun. Its elliptical orbit ranges from 13 billion to 135 billion km from the Sun and is fairly typical of the odd orbits of Kuiper Belt members. Sedna's diameter is estimated at 995 km. It is one of the reddest objects in the Solar System, a color probably caused by complex hydrocarbons of the type seen on other ice bodies. Methane has been detected on its surface, bolstering this reasoning.

Sedna's far point from the Sun, at 76 AU, tells us something about its history. The dwarf world is not far enough to be influenced by passing stars, as the long-period comets of the Oort Cloud are. Instead, Sedna may have formed early in the Sun's life, when our own star may have been part of an open cluster of nearby stars. Some computer models indicate that multiple close passes by young stars in such a cluster would tend to toss objects into the kind of orbit followed by Sedna today. But Sedna may be tugged upon by a large, undiscovered planet. Some simulations duplicate Sedna's path by incorporating a Neptune-sized planet out at 2000 AU, a Jupiter-mass world at a distant 5000 AU, or even an Earth-mass planet at about 1000 AU. Astronomers estimate that another 40–120 objects of Sedna's size orbit in roughly the same region, just waiting to be discovered (Fig. 9.14).

There may be thousands of planet-sized objects lurking out in the Kuiper Belt. Current estimates put the number of objects larger than 100 km across at 100,000, with up to 10 billion larger than 2 km in diameter. For each asteroid in the main belt, there may be a thousand in the Kuiper Belt. And our solar neighborhood doesn't end there. Beyond the Kuiper Belt, a vast shell of comets entombs our Solar System. Most are long-period comets, inert and invisible until something perturbs them into an orbit bringing them nearer the Sun, where they blossom with a spectacular tail, never to be seen again in their long, looping orbits. Planet-sized ice worlds may also skulk in the outer darkness, yet to be discovered by generations to come. But for the more familiar ice worlds closer to home, we still have questions. What are they like? Can they support life? Can we mount missions to them in the near future?

Potential Life Under the Ice: Planetary Porpoises and Cosmic Calamari

10

The Solar System – and in fact, the entire universe – appears to be littered with the building blocks of life. The six main components that form amino acids, tholins, and many other life-related compounds are simmering in the hearts of nebulae and the regolith of asteroids and comets. Those elemental substances that inform and energize life-giving operations include carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur (see Chap. 6). The four main types of organic molecules (carbohydrates, proteins, lipids and nucleic acid) are all constructed from these six items, making up the acronym CHNOPS. The materials of life fall upon our planet on a regular basis, coming in on meteors and comets. They linger in lakes on Titan and simmer in subsurface seas across the outer planetary realm and into the Kuiper Belt, and even beyond (Fig. 10.1).

As we will see, it is a challenging prospect to come up with another molecule that complex life might be based upon. In a sense, this is good news. It suggests, at least, that as we search for life among the icy planets and moons of our Solar System, we need to be looking for something that will be familiar, at least chemically and perhaps even structurally.

And so the search is on. We want to look for a few nice jellyfish or squid under the ice of Europa, or microbes within the water jets of Enceladus. We want to carry out searches for living systems in the clouds of the gas giants and the hidden seas of the outer moons. But how do we define life? And if we come up with a universal definition, how can we mount such a search?

The difficulty of such an endeavor was beautifully displayed by two missions to Mars, the Viking I and II landers. The Vikings came on the heels of Mariner 9, which had resurrected hopes that Mars's environment was, at one time, more Earthlike. In the 1960s, three Mariner flybys revealed terrain more reminiscent of the Moon than Earth.[1] The science community began to think of Mars as a dead world. But Mariner 9's global survey of the Red Planet revealed canyons, volcanoes, floodplains, and entire networks of dendritic river valleys pointing to flat plains. True, the Mars of today held onto a brutally thin atmosphere of CO_2, roughly at the air pressure equal to Earth's at an altitude of 33,000 m. But it was clear that Mars once had flowing water and perhaps seas and oceans. Added to that, Mars's axis tipped over long periods of time, changing seasons and bringing a global shift in climate. Could life have held on during these dramatic climate changes, just waiting for things to warm up again? The news was good for astrobiologists, and the Viking project became focused on the active search for microbial life, perhaps life that was dormant and needed a nudge. Viking was the first spacecraft to attempt such an in-depth search for alien biology.

The First Searches for Life

Viking's assignment seemed a "mission impossible." No lander had touched down on the surface, and no orbiter had carried spectrometers capable to charting surface composition, so conditions of the soil were completely unknown. If the soil was sandy or fine powder, sampling would be easy. But what if it was more like the platy stone seen in volcanic regions? A second concern had to do with other landing attempts. The Soviet Union had recently mounted the Mars 3 landing mission. Their beachball-sized lander survived entry and landing but disappeared after 23 s on the surface. Did it sink in all that dust that seasonally blanketed Mars? Quicksand was a real concern.[2]

The logistics of carrying out a landing were left to the engineers, while the biology had its own issues, the same issues that face astrobiologists today. Where to start? Biologists would have loved to carry along a microscope to search for active microbial life, but making something like that small

---

[1] Ironically, all three spacecraft (Mariner 4, 6, and 7) took their most detailed imagery over the most ancient of Martian terrain.

[2] Because of this concern, Viking 1's first image was of its footpad, to make sure it was on solid ground.

M. Carroll, *Ice Worlds of the Solar System*, https://doi.org/10.1007/978-3-030-28120-5_10

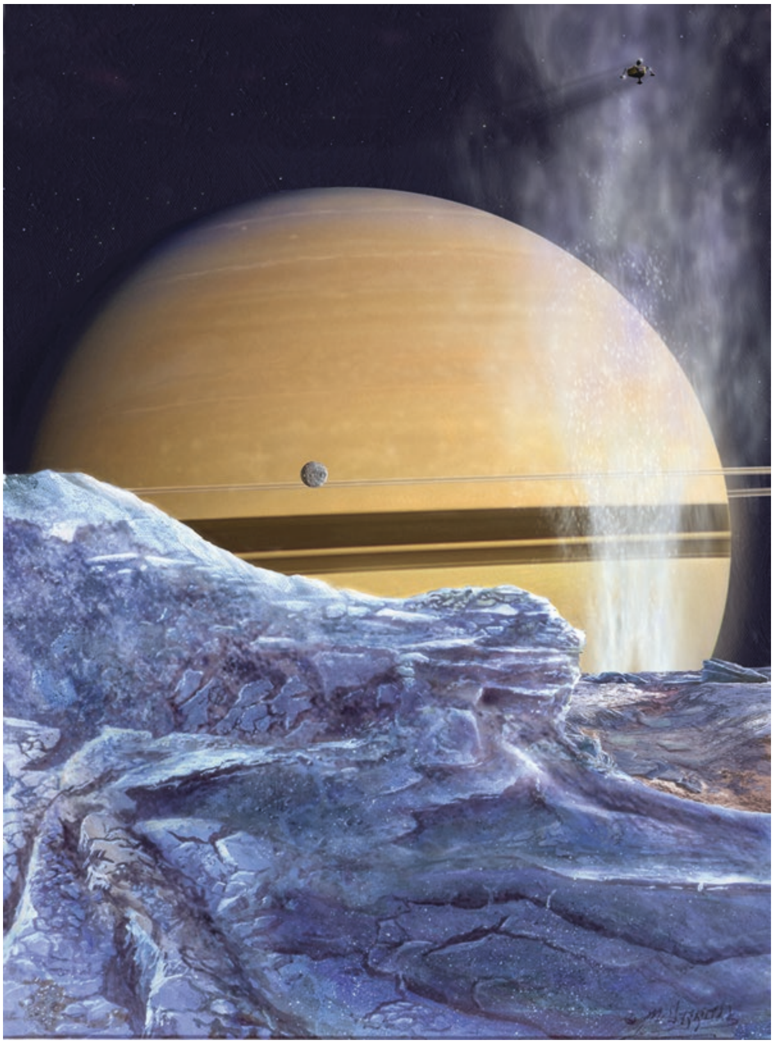


Fig. 10.1 A lander flies through plume material on final approach to the surface of Enceladus. (Art by the author)

enough to fit aboard Viking was beyond the technology of the time. Instead, biologists would look for chemical changes in the soil and atmosphere that the robot sampled.

Terrestrial microbes use an assortment of processes that change their environment. These utilize nitrogen, they reduce sulfur and sulfates, and they oxidize iron. They all have one thing in common. They change the balance of chemicals or gases around them. And all life on Earth shares another commonality. It is carbon based. This shopping list for biology would provide a foundation for the Viking tests. Assumptions had to be made, and those assumptions led to four lines of inquiry: (1) Is there anything in the dirt that exchanges gases or changes the balance of gases in the atmosphere? (2) Does the soil – and what is in it – release carbon? (3) Do those same elements in the dirt incorporate carbon from the air around it? And finally: (4) Does Martian dirt contain carbon-based compounds like those that would indicate the presence of life?

Viking would throw a suite of questions at the Martian environment. Any one positive answer would not make the case for life in itself, but a combination of positives would, it seemed, confirm or at least suggest its existence.

To answer the questions, the biology team chose four experiments, each crafted to be a miniature laboratory aboard the lander. The first was called the gas exchange experiment (GEX). For the GEX, Viking's 3 m-long arm[3] would bring a sample of Martian soil into a small tube. There it was baked, with its gases constantly monitored. Viking carried an "organic soup" of nutrients in water that it would spray onto the sample periodically, in hopes of increasing any bacterial activity. This was the nudge that some called for, a breath of the old, wetter Mars that could jolt hibernating microbes into activity again. Gases were monitored by the lander's Gas chromatograph/mass spectrometer (GCMS), which could record levels of oxygen, carbon dioxide, methane, and other gases.

---

[3] The Viking arm's clever design consisted of two sheets of aluminum that were pinched together. The boom could be wound up into a roll for stowage, or extended out, making a tube shape as it extended from within the lander.

The addition of organic soup was a controversial one, and only used on two of the four experiments. Some designers feared that the soup would result in false positives, as certain inorganic compounds might react with the water or its contents. At the same time, the GCMS would search directly for organics in the soil. The two combined results should clear up any ambiguity between organic and inorganic reactions.

Another experiment, called the labeled release (LR), was crafted to sense signs of organic activity in the Martian soil when the liquid soup, which also contained radioactive carbon-14, misted the sample. The experiment was based on the supposition that any microbes within the soil would metabolize the soup and "breathe out" the radioactive carbon. The air in the chamber was simply examined with a Geiger counter to detect any increase in radiation from the carbon-14-saturated material.

The pyrolitic release (PR) experiment rounded out the quartet of biology-sensitive instruments. PR's goal was to detect microbial activity without water or nutrients. If life existed on or near the surface, it would already be processing carbon. The experiment seeded the air in the chamber with carbon-14 laced carbon dioxide and carbon monoxide. The sample would be allowed to sit for 5 days under a Sun lamp. Then, the air would be pumped out, replaced by neutral helium, and the sample would be heated slightly. About 120 h later, the soil would be sterilized at high temperatures. Those high temperatures (625°C) would break up any organic material, releasing carbon 14 if it had been incorporated into the soil.

The experiments began in earnest just a few weeks after landing (Viking's primary mission was set at a hopeful 90 days, ambitious in light of the last Soviet lander mission lasting 23 s). Results were baffling from the outset. The GEX instrument immediately detected a spike in oxygen and carbon dioxide as soon as the nutrient soup hit the soil sample. The Viking 1 site sensed four times as much oxygen as the Viking 2 site. The steep increase in both oxygen and CO_2 seemed too abrupt for a biological reaction. More troubling for the life search was that after 50 h, the nutrient soup's effects plateaued. Martian bacteria may have stopped feeding, but it was more likely that the results came at the hands of a chemical reaction. Explanations were swift in coming: the reactions were similar to those one would experience in the presence of hydrogen peroxide and other compounds that react with water and release oxygen. The explanation was only a partial one, and data from the other results was still coming.

The pyrolitic release experiment also returned bewildering numbers. After the radioactively tagged gases were introduced and simmered for a time, and after the soil was baked, a slight increase in carbon-14 was seen. Something in Martian dirt had internalized the tagged air. If the soil sample had an extremely small population of microbial inhabitants – 1/1,000,000 as many microbes as found in a common flower bed – then the experiment might return results as it did. Whatever was going on, the PR did, at least, show that the soil was taking up the gases around it. Results from the PR also seemed to indicate a non-living, chemical explanation.

Then came the labeled release findings. When the organic soup was introduced into the soil, radiation levels in the air increased definitively at both landing sites. The LR's principal investigator, Gil Levin, called the returns "startling." It was time for a double check. To rule out the possibility that the experiment's results were trending positive because of the soil's interaction with ultraviolet radiation on the surface, the landers sampled sheltered soil from underneath rocks. Those results were also positive. Levin's team set up several control experiments. When soil was blasted by 160°C heat, it was rendered inert. But when a new sample was warmed to 50°C, there was still limited activity. Finally, a sample taken aboard before solar conjunction was stored in the lander in the dark for nearly 2 months before testing. This sample returned a negative result. Something in the Martian soil was certainly mimicking life operations. The LR team asserted that the LR experiment had discovered evidence of Martian biology.

Some other researchers were skeptical and proposed non-biological scenarios, such as peroxides, for the results. The nail in the coffin of Mars life seemed to come from the GCMS, which could find no organic material. In fact, the Martian soil was so devoid of organics as to be sterile, according to the readings. Viking, it seemed, had murdered the dream of Martian life.

However, new insights came to light with the arrival of the Phoenix lander near the north pole of Mars. Phoenix detected perchlorates in the Mars surface and below as it dug down on its ice-analyzing mission. Some researchers still held out hope for Martian life, pointing out that the perchlorates, when heated by Viking's ovens, could destroy any in situ organic material. In fact, they said, the presence of perchlorates would have yielded exactly the GCMS results returned, even if organics fortified the soil. The perchlorates would also generate chloromethane and dichloromethane, two other compounds found by the Viking landers. Scientists in the Martian optimist camp also assert that no oxidants would actually yield the same profiles found by the Viking biology analysis, especially those of the LR.

In a 2012 study, computer analysis showed that the LR results were clustered in the same biogenic groupings as the control experiments, while the other data rested with non-biological frameworks.

After decades of research and debate, the jury is still out on the Viking results. Even with new, improved instrumentation and advanced missions such as the Curiosity Rover (which has detected organics on the surface of Mars) the Viking biology suite's treasure-trove of information remains a puzzle (Fig. 10.2).

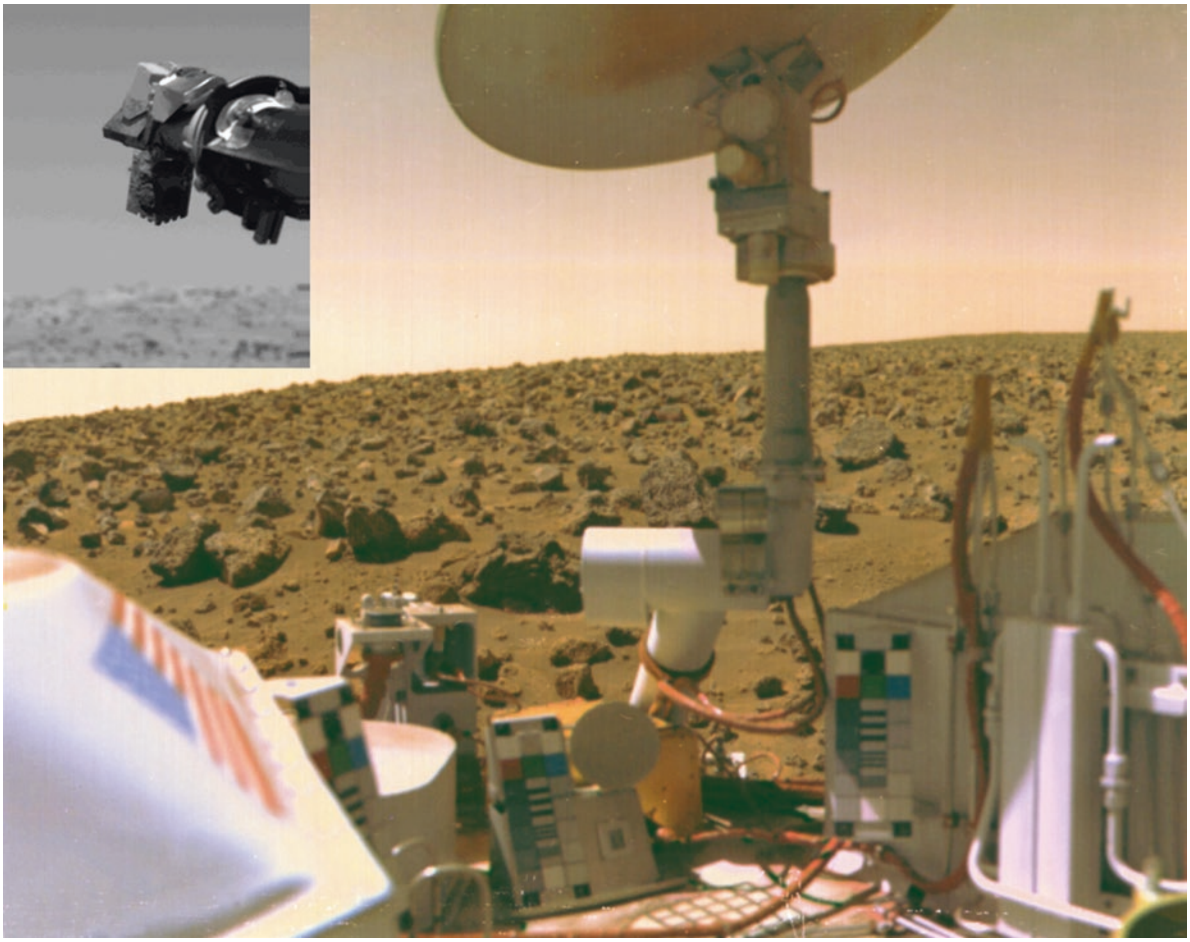


Fig. 10.2 The twin Viking Mars landers were the first spacecraft to carry a suite of experiments specifically designed to detect life. Here, we see the vent tubes leading from Viking 2's biology experiments. Inset: The collector head used to dig soil samples. (Images courtesy of NASA/JPL)

Europa: Our Next Life Search?

Today, we are faced with new worlds of ice and water, with organic material galore, in the outer Solar System. Life detection takes on new challenges, and new strategies will be required of us. Our early targets will undoubtedly be ocean worlds close to home: Europa and Enceladus.

With an ocean 100 km deep, and with energy streaming in from Jupiter's magnetosphere and tidal heating, Europa seems the ideal place for life. Its surface ice is tumbled and torn by faults and uplift. Darkened fractures mark areas where salts and other compounds have migrated from below and been irradiated into complex organics. Those organics make their way back down into the ocean, a salty brine that may closely resemble Earth's saltiest oceans.

Europa's core, inpacted by the same forces that cause nearby Io's violent volcanism, probably has enough tidal energy to trigger submarine volcanoes. On Earth, hyperthermophylic bacteria gather around seafloor vents along the mid-ocean volcanic ridges and other seamounts, living in blistering temperatures, with their chain of organisms not related to the Sun-linked biome of Earth, but rather of chemistry that comes from the rocky interior. In the case of Europa, nutrients may be welling up from beneath, as well as raining down from above. It seems reasonable, then, that Europa's seas might host similar biomes.

Georgia Tech's Britney Schmidt has been studying icy environments in conjunction with the icy moons. Europa, she says, is a good site to look for alien biomes. "At Europa, we think there are these ingredients for life – water, chemical energy, the things that we think we need…the ice shell is overturning actively. All of this material is raining down on the outside of Europa, and it's going to be sitting on that brittle ice." As the ice overturns, it gets pulled down into subsurface lakes that reside within the ice crust. When the lakes re-freeze, Schmidt says, "that ice is now much deeper in the ice shell. It's heavier than the ice around it. That oxidant-rich ice can now be pulled down into the ocean. It's basically like a highway, bringing food for the ocean down through the ice shell."

Europan life may not be based on the DNA we can recognize, but some theories of biogenesis posit that the DNA structure, or something similar to it, is universal to life. Still, if microbes do swim the seas of Europa, they may be difficult to recognize. Researchers will be looking for "handedness," the direction in which a structure like DNA tends to spiral. DNA is built like the rungs of a ladder between outer lines. Imagine taking the ends of the DNA ladder and twisting them. This twisting movement creates the double helix form so familiar to biologists. Terrestrial DNA is almost exclusively right-handed, or right twisting. There are extremely rare forms of left-handed DNA known as Z-DNA. But if left-handed DNA comes up in samples, it is likely from an alien source.

Another test for active biology is to determine if any organic structures have chirality. A chiral pattern is one that is discernible from its mirror image. If the pattern has the same "outline" but cannot be flipped to exactly imitate its mate, it has chirality. A common example from nature is the human hand. If the right hand is flipped so that it is a mirror image, it does not match the left hand. Chirality is found in biological structures.

In addition to right- and left-handed DNA, astrobiologists will chase down complex microstructures, and hunt for chemistries associated with known biological systems. Any chemical imbalance will be subject to scrutiny. The free oxygen in Earth's atmosphere will be sequestered in its rocks, combined with other elements, or largely lost to space. But it is life on Earth that pumps up the oxygen in the air. Atmospheric oxygen is a biological marker, present because of the operation of life. Another marker is methane, a gas that does not last long in a planetary atmosphere. Methane combines with other gases or drifts away into space unless recharged by either biological processes or volcanism.

Europa's standing as a possible abode for life skyrocketed with the discovery of Earth's extremophiles, microbes that thrive in extreme terrestrial environments. Hypersaline lakes such as the Great Salt Lake play host to halophillic archaea, microbes able to tolerate high concentrations of salt. These extremophiles survive the briny environment by actively pumping the salt out of their cells. They survive not by adapting to their extreme environment but by protecting themselves from it. Halophiles would be perfectly at home in the salty realm of a Europan sea.

Microbes adapted to extremely hot environments are called hyperthermophilles. These specialized life forms thrive in hot springs that flow from volcanic regions. Hyperthermophilles develop specialized types of enzymes (catalysts that enhance chemical reactions) that remain stable at high temperature.

In the depths of Earth's oceans we find another example of extreme environments: hot, high pressure water from the deep sea vents. At these vents, hot water surges from the subsurface into the ocean water. The erupting water is rich in chemicals that can sustain life. The temperature of the hottest vents is far higher than the temperature at which water usually boils (100°C), but because of the environment's high pressure, the water remains liquid and stable. Even in this extreme environment, these vents support diverse ecosystems. At some mid-ocean ridges 3–4 km beneath Earth's ocean surface, bacteria form the basis of a deep-sea food chain of creatures such as giant tubeworms, deep-sea crabs, shrimp-like crustaceans, and mussels. The colonies of hydrothermal vent organisms are governed by deep-ocean current patterns, and by topographic features such as deep fracture zones or changes in depth. One deep-sea biome stretches across more than 30 degrees of latitude along the East Pacific Rise.

These surreal ecosystems are completely cut off from the Sun's energy, nurtured by the chemical plumes of seafloor volcanoes. As such, they may be a fine example of what biomes might be possible in the gloomy depths of Jupiter's ocean moon (Fig. 10.3).

There are some complicating factors for Europan seafloor life, not the least of which is pressure. The ocean floor of Europa suffers five times the pressure found at the mid-ocean ridges on Earth. The high pressures change the nature of biology-related chemical reactions. One of the most important, methanogenesis, is the biotic fabrication of methane. On Earth, methanogenic microbes convert carbon to methane, releasing energy. Organisms feed on this energy. But pressures on Europa make the carbon in carbon dioxide harder to access. Life may have come up with alternatives, like metabolizing iron rather than carbon, and more laboratory research is being carried out to investigate the possibilities.

A further complicating factor in our search for Europan life is the vastness of Europa's seas. It's a lot of space to cover, and within Earth's oceans, vast stretches are nearly devoid of miroorganisms. (This nearly sterile region is called the pelagic.). But biota of the microscopic kind tend to congregate in certain places (within plumes and along the surfaces of bubbles, for example). These regions can be targeted by future probes in our search for Europa's alien life.

We may not need to directly sample Europan seawater to find biomarkers. Recent studies suggest that subsurface lakes may exist closer to the surface, and these lakes may themselves contain material from the ocean far below. Subglacial lakes in Antarctica are bodies of fresh water sitting on the bed of the ice sheet. Their existence was only theorized until radar mapping of the continent was carried out. The first of

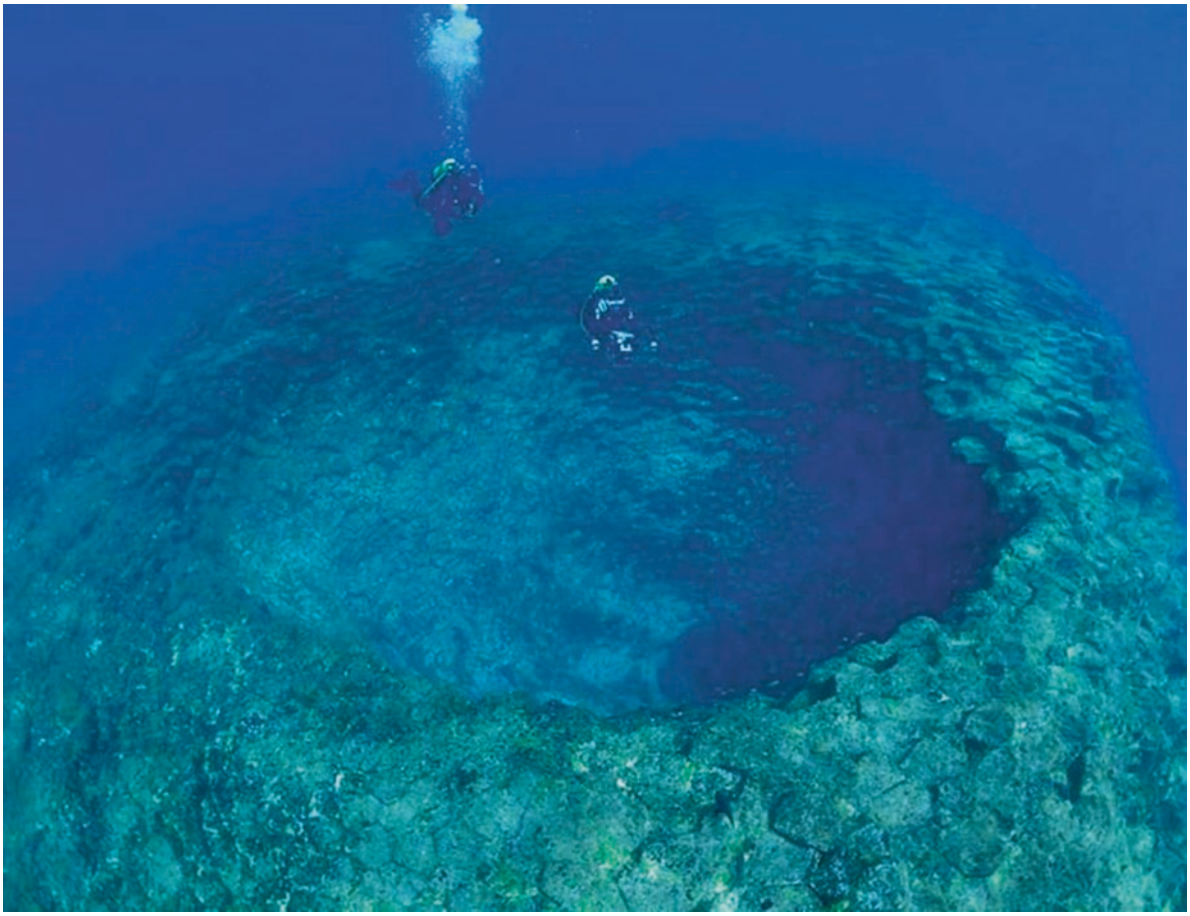


Fig. 10.3 Divers explore an undersea volcanic caldera off the coast of Madagascar. Earth's undersea volcanoes may be analogous to submarine volcanic formations on Europa's seafloor. (Photo courtesy of Michael Simire, *EnviroNews*, April 20, 2017. Used with permission.)

these lakes was discovered from data collected on one of the first long-range survey flights in 1969. Radar found an unusually flat subglacial echo beneath the Russian Sovetskaya Station in East Antarctica. It turned out to be a thick layer of water beneath the ice. In fact, 17 lakes have been located beneath the ice in eastern Antarctica alone.

In 1996, surveys confirmed that one of the largest lakes, Lake Vostok, is over 240 km long and more than 50 km wide. Between 1997 and 1999, additional remote sensing data indicated that at least some of the subglacial lakes are not isolated, but rather are connected by streams, for instance in bedrock trenches. The flow of water between subglacial lakes demonstrated that there is an active hydrological system beneath the ice. An inventory of subglacial lakes now stands at 402 lakes hiding beneath Antarctic ice.

A 2017 study showed that a plume of heat within Earth's mantle was most likely responsible for the creation of lakes and streams of water beneath Marie Byrd Land in western Antarctica. Mantle plumes are localized columns of hot magma rising by convection in the mantle, much as diapirs within ice. This scenario is similar to what is probably occurring on a regular basis within Europa's crust.

Following protocols established to prevent contamination of lake water during the sampling process, three major lakes have been tested. Water and sediment samples were taken, examined at the surface, and then sent to laboratories in the United States. Water from the subsurface Lake Whillans contained active microbes. Whillans' environment has been isolated from the atmosphere and from sunlight for at least 100,000 years. In the total darkness, thousands of meters from sunlight, these microorganisms rely on energy gained from the oxidation of chemicals or organic matter. The life forms represented a diverse mixture of bacteria and archaea. Archaea are some of the most primitive single-cell life forms on Earth. The microorganisms in Antarctic subglacial lakes are members of an ecosystem of producers and consumers.

The producers gather chemical energy and are, in turn, consumed by some of the bacteria.

Our first probes will be searching for single-celled microbes. Anything more complex requires energy sources and ecosystem infrastructure that we may not be familiar with, or capable of detecting. But one thing is certain. If there is complex life there, there will also be simple life. Initially, we may have to settle for finding a Europan paramecium. But where there are paramecia, there may be jellyfish, octopi, or whales. Complex, more advanced life forms are unlikely, given the pressures and low energy inputs to Europa's prospective ecosystem. But nature has surprised us before. It may once again at Jupiter's glistening ice world.

Another Jovian Ocean World

Of course, Europa is not the only ocean world at Jupiter. Both Ganymede and Callisto appear to have hidden seas. Callisto's ocean lies within an ice crust that is scarcely differentiated. As such, it will not have easy access to the minerals and nutrients necessary for life. But what of the other satellite, Ganymede? If the interior of Ganymede is, in fact, arranged like a Russian doll with intermingled layers of ice and water, it is indeed an alien affair. The chances of life in any of its oceans are determined by variables we are only beginning to understand. But if Ganymede is simpler on the inside, or its lower oceans are closer to active mineralogy, what might we find?

Cut off from the mineral-rich rocky core, the classic configuration of Ganymede's ocean – ten times deeper than Earth seas – seems a poor candidate for native life. But models indicate that salty water at the ice/rock interface far below may percolate upward, migrating toward the ice-locked ocean or oceans above. These diapirs, laden with nutrients from below, may eventually rise to interact with ice-locked ponds along the way.

The pressures and temperatures found in Ganymede's ice are difficult to simulate in the lab, but it may be that the ice barrier between ocean and rock is not such a barrier after all. And although they have found no roadside pubs, astrobiologists are beginning to reconsider Ganymede as a possible site of life. After all, it does have several sources of heat energy, including radiogenic heat, residual warmth from the primordial Solar System, and even tidal heating. The moon also generates its own protective magnetosphere. Spectrometers have detected organics on the surface, and these may indicate the presence of organics in the deeper layers of ice and the subsurface ocean or oceans. If the multi-layered version of Ganymede's oceans is correct, the lowest sea may well be a warm salty ocean in direct contact with the core, a good mix for life.

Microbes Within the Heart of Enceladus

At Saturn, we find two moons with oceans – and biologically interesting chemistry – of note: cryovolcanic Enceladus and methane-soaked Titan. The first, tiny Enceladus, is a world that continues to excite the astrobiology community. Along with its subsurface seas, which seem to be chemically more benign than Europa's battery-acid-like waters, the Enceladan ocean is directly accessible through its plumes. Cassini imaging team leader Carolyn Porco would choose Enceladus, with its more benevolent radiation environment, over Europa. "You don't have to bunker your spacecraft with 2 feet of lead to protect yourself. Just take a properly equipped spacecraft and test for organic molecules." Porco also points out that the drilling required on Europa is not an issue on Enceladus. "Whatever it has in its subsurface ocean is there for the asking. All you really have to do is land on the surface, look up, and stick your tongue out."

Recent work indicates that the seas of Enceladus not only benefit from direct contact with minerals in the rocky ocean floor but also that hydrothermal activity is likely occurring. Heightened hydrogen levels in the plumes point to active subsurface geyser activity like that seen on Earth's seafloor. Microbial ecosystems will find organic chemistry easier to process in the lower pressures (due to shallower waters and less gravity) of Enceladan seas. With its energetic, geyser-like activity, the surface of Enceladus may be littered with the markers of life, or even with frozen samples of life itself.

If we do discover an active biome on Enceladus, we are faced with another question. Are we witnessing a second genesis for life, or distant cousins of terrestrial life that came from a primordial common ancestor? NASA Ames astrobiologist Christopher McKay suggests that the marine environment on Enceladus is very similar to Earth, "If we find life, we're going to have to spend a lot of time asking 'Is this an independent origin of life, or is it just another offshoot of our family tree, distant cousins?'"

Life on Enceladus and Earth might share a common origin in a pre-solar input of life. Comets coming into the early solar nebula might have sprinkled the whole system with viable cells, so that everything we see now is developed from that common origin. "It's an interesting story, but it's still N = 1. We have to really be sure that it's not just a deeply rooted relation to us. We can only track back the tree of life on Earth to the last common ancestor on Earth. There's a big gap between that last cellular ancestor and the origin of life. It could be that there are things going on between the origin of life and last common ancestor that are still traced back from one or that look fundamentally different. It could be that there are deeply rooted branches of our tree that look so different that they will fool us into thinking they're from a different source." It is a very challenging problem, one that we cannot solve theoretically, McKay asserts. “We have to solve it empirically by finding what the life on Enceladus is, what it looks like, and does it have some RNA/DNA/amino acids. Maybe they are our cousins that broke off before we made the transition from the RNA world to the DNA world. The family might have split before they chose their genetic molecules.”

Even chirality may not be the final test of a second, independent genesis. If the origin of life occurred somewhere else in the distant past – say within nebular gases drifting through interstellar space before the birth of our Sun – then DNA structures or chirality might have been characteristics of life that split off later on.

Finding a clear data point that proves a different origin may be impossible. Determining that a life form has come from an independent genesis may require a suite of evidence, and we may have to settle with a burden of proof rather than proof positive.

One of the stumbling blocks in the Enceladus life narrative is the age of its ocean. Although most researchers assume that Enceladus formed within the Saturn system some 4.5 billion years ago, it may have formed later, as recently as 2 billion years in the past. Crater counts may not tell an accurate story, as cratering rates probably have varied in the outer Solar System – and in the Saturn neighborhoods – in ways that are not currently understood. And even if Enceladus itself is as old as the Saturnian system, its ocean may not be. Some researchers assign an age of only 500 million years or less for the current ocean. They point to models that show a periodicity in sea formation. The oceans of Enceladus may come and go. If they do, what does this mean for the genesis of life there?

Biologists still do not understand the progression of life’s origins. Is this enough time? Could life hold on, dormant in the ice, waiting for the next ocean to form? At this point, life on Earth and elsewhere is shrouded in many such mysteries, and the study – and discovery – of life on Europa, Enceladus, or another ice world will undoubtedly put us light-years ahead in our understanding of the origin and development of living things.

Titan and Life

As we saw in Chap. 8, Titan is another member of the subsurface sea club. Its buried ocean shares the same promise and problems that Ganymede’s does. But Titan has other seas, far more exotic and less familiar to us Earthbound observers. These are its methane lakes, rivers, and oceans. In this cryogenic realm, with low energy from the Sun and sluggish chemical reactions, life seems unlikely. But recent work brings hope for the possibility of alien life on the surface seas of this planet-moon.

Cosmochemists at the Southwest Research Institute found that radiogenic materials in Titan’s rocky core may split nitrogen and carbon off from organic molecules. Once those elements are free, they recombine into nitrogen and methane, escaping into the atmosphere. The reactions could account for half the methane and all of the nitrogen in Titan’s dense atmosphere. Although organic material has been found all over Titan’s globe, organics coming from the core would feed not only the ices above but also the subsurface ocean trapped within Titan’s ice mantle. The presence of organics in a warm core increases the habitability of Titan’s underground sea.

However, it’s what is aboveground that is getting the attention of astrobiologists. Methane and hydrocarbons aren’t the only things falling from Titan’s soupy skies. Sunlight and radiation from Saturn’s radiation fields breaks up nitrogen and methane molecules in Titan’s upper atmosphere. When these fragments recombine, they create a compound called vinyl cyanide. Vinyl cyanide is important in the search for life, because it tends to assemble into membranes like those found in terrestrial living cells.[4] Thousands of tons of the stuff float high in Titan’s upper atmosphere, and another 10 billion tons may have accrued in Titan’s largest methane seas, Ligeia and Kraken Mare.

A cell membrane is certainly not a guarantee of life, but it is likely one of the prerequisites. Titan’s skies produce hundreds of compounds of organic materials, which rain down into the methane lakes, congregating into more complex combinations such as tholins, perhaps leading to the precursors of life. But some biologists point out that organisms may not even need cell membranes to carry on the functions of life. It may be that life on Earth only needs a membrane because we live in the presence of that corrosive liquid called water. Perhaps in a more benign liquid such as cold methane, they suggest, life has come up with a different approach, different chemistries, and different structures.

The main roadblock to Titan life is its cryogenic temperature, which impedes chemicals from combining. But some laboratory analysis carried out at NASA/Ames implies that Titan may be able to combine these compounds over long periods of time.

Low temperatures may actually be an advantage for Titan life, Christopher McKay asserts. “It can be both a problem and a feature. Reactions go slow. In some cases, they just don’t happen at all. But low temperatures can be good *because* everything is slow; you don’t have to work very hard; you don’t need a lot of energy. Being slow is a feature if you don’t have very much energy.”

Methane is chemically benign compared to water, which tends to break biomolecules apart. Titan does not suffer from ultraviolet radiation, something that terrestrial life must con-

---

[4] See *Astronomy Magazine*, May 2019.

stantly combat. Finally, in Titan's low temperatures, life will decompose slowly.

Some biologists are skeptical that such slow biological processes can occur. It is possible that biotic forms may have developed weaker chemical bonding than terrestrial life requires, so the chemical reactions might not be so limited, but this has not as yet been seen in nature. Additionally, biochemists have failed to find any models that they can point to as a possible genetic molecule for Titan (a molecule that could store information akin to DNA). As yet, there are no candidates for information-bearing molecules. Unlike the diverse structure of protein molecules, hydrocarbon molecules are limited in the way their physical structures interact with each other and other compounds in their environment.

Could Titan support life in ways quite different from terrestrial processes? Researchers have examined analogs to oxygen, which creatures on Earth use in processing organic material. On Titan, almost every organic compound can react to hydrogen to release energy. Hydrogen may be, to a Titan life form, what oxygen is to Earth's microbes, fish, birds, and mammals.

When it comes to finding truly alien life, some astrobiologists find Titan much more interesting than Enceladus or Europa, whose life forms – if they exist – are likely quite like those found in terrestrial seas. If a family tree of life has taken hold on Titan, it likely is fundamentally different from that of the chain of life on Earth, with an independent origin. "I'd much rather discover aliens than cousins," McKay says. "Cousins are boring; they don't know anything you don't know. At Titan, if we find life in liquid methane, living in cryogenic conditions, that right away tells us there's more than one kind of life in the universe. There's multiple life and there's diversity. There is no way we're related to orgs that live in liquid methane. I'm all for aliens; the weirder the better. On the other hand, we know what we're looking for [at sites like Enceladus and Europa]. It's really looking under the lampshade. We've got to look where we know what we're looking for, in places that might give us a clear answer, and those other harder places as well. We've got to look everywhere we can."

Triton and Pluto: Life in the Outer Fringes

As we reach the dark realms of Triton and Pluto, any liquids we became so familiar with on the other ice moons now become frozen ice. Methane and nitrogen, no longer free as air, lie across the surfaces of these worlds, where water becomes the bedrock, gases the snows and glaciers. Both Triton and Pluto may have subsurface oceans, but the ices beneath them cut them off from the rocky core because of the great pressures combined with low temperatures.

Triton's ocean may reach temperatures as high as –97°C, but this is so cold as to preclude many chemical reactions important to life. The same is true of Pluto, although with its elliptical orbit it becomes even colder. Its ocean, probably global but deepest beneath Tombaugh Regio, is projected to have such high levels of ammonia that life as we know it could not exist. But as we have seen at Titan, life may take exotic forms that are unimagined in our current biological sciences. One thing is certain. If we want to find in situ life among the icy worlds, we will have to go there.

11

Future Explorations, Robotic and Human

The outer worlds of frosted vistas and thundering cryovolcanoes continue to beckon, like distant lighthouses in the fog. We have only penetrated that fog nine times, with Pioneers 10 and 11, Voyagers 1 and 2, Galileo, Cassini, New Horizons, Juno, and Dawn.[1] As of this writing, New Horizons threads its way through the Kuiper Belt, and the Juno spacecraft continues to send reports from Jupiter. Juno marked the first solar-powered craft to operate long-term in the outer Solar System,[2] and its success paves the way for future solar-powered missions. The first two of these upcoming missions are destined for Jupiter. The Europeans are training their sites on a mission to study the Galilean satellites, with a focus on Ganymede, while NASA and its international partners want to carry out an in-depth reconnaissance of Jupiter's ocean moon Europa.

NASA's Europa Clipper and Company

Although the Galileo Jupiter mission was a triumph of creative engineering and programming over failed hardware, it is disappointing to compare the ambitions of the mission to its final results. A sense of loss permeates some of the caption material in Paul Schenk's excellent *Atlas of the Galilean Satellites:*[3] "These are our highest resolution images of Io, but context images planned for later orbits were never acquired, and the geologic context is unknown and precise location on the surface is uncertain." "These images are part of a mosaic (only half of which was returned)…" "This mosaic is the only surviving half of a planned stereo sequence." "These images were not corrupted by the I24 anomaly." "Only fragments of this five-frame mosaic were returned to Earth." Galileo fell far short of its potential. But a new spacecraft may make up for some of the deficit.

NASA's next flagship mission (also called a Large Strategic Science Mission)[4] is called the Europa Clipper. This high-profile mission, a Jupiter orbital tour, calls for some 45 flybys of Europa. Encounters will entail closest approaches of between 2700 km to a hair-raising 25 km above the tortured Europan landscape. Clipper's path is designed to keep the Jupiter orbiter outside of the most dangerous regions of Jupiter's magnetosphere for most of its flight. Its flower-petal orbits will dive down to Europa and quickly rise again, keeping total radiation to a minimum.

Jovian radiation is severe enough to wreak havoc with electronics, as became apparent during the Galileo mission beginning in the late 1990s. The radiation-hardened orbiter followed dozens of orbits around the planet, and most remained outside the orbit of Europa. But closer in, the exotic, volcanic moon Io was too tempting a target to leave alone. Additionally, the gravity of Io was sometimes needed to bend Galileo's orbit toward its next encounter. The first Io pass occurred on October 11 of 1999. As the spacecraft dove inside the more benign orbit of Europa on its way to the innermost Galilean satellite, it experienced what engineers call a safing event, in which the computer, overwhelmed by radiation, shuts down most of its critical functions until it can hear from Earth. Engineers scrambled to reboot the spacecraft, successfully "waking it up" 2 h before the Io encounter. The following November, another safing event crippled the spacecraft 4 h before a second close Io flyby. Flight engineers were able to reconnect with the craft just 3 min before its closest approach, saving most of the data.

After a February 2000 encounter in which a safing event occurred after the flyby, Galileo's closest flyby was on tap for January of 2002. Just 28 min before closest approach,

---

[1] The international craft Ulysses also looped around Jupiter on its way to the primary mission of observing the Sun's poles.

[2] All previous outer planets' craft carried plutonium for power.

[3] *Atlas of the Galilean Satellites* by Paul Schenk, Cambridge University Press, © 2010.

[4] Large Strategic Science Missions have budgets usually exceeding one billion USD, and advance multiple strategic science priorities. These missions typically require international partners to help both financially and scientifically. A new one typically flies once each decade.

M. Carroll, *Ice Worlds of the Solar System*, https://doi.org/10.1007/978-3-030-28120-5_11

the craft was blinded by radiation again, and this time, all data was lost. Cameras suffered permanent damage from the high dose of rads, and some had to be turned off completely. During its 13-year mission, entailing 37 close flybys of planets, asteroids, and moons, Galileo was exposed to four times the cumulative dose of radiation that designers built it to weather.

Europa Clipper benefits from advances in technology that will enable it to survive higher radiation levels, but the delicate equipment will still face brutal storms of radiation. The orbiter's main computer hunkers down within a "vault" that will protect it from many of the incoming particles. Scientific instruments are also radiation hardened to survive the deadly barrage.

Clipper hosts a variety of advanced instruments. These include the following.

E-THEMIS: Europa Thermal Emission Imaging System

This heat-viewing instrument will search for geologically recent regions such as resurfaced areas and areas of plume activity. It does this by charting differences in temperature.

ICEMAG: Interior Characterization of Europa Using Magnetometry

This magnetometer, the most sensitive ever flown to Jupiter, will map the magnetic fields induced by Europa as it travels through Jupiter's magnetosphere. By observing these fields, ICEMAG will reveal the ocean depth and ice shell thickness, especially when combined with the PIMS and REASON (see below).

MASPEX: Mass Spectrometer for Planetary Exploration/Europa

MASPEX is a high-resolution mass spectrometer capable of discerning a wide array of chemical compounds, even in complex mixtures.

MISE: Mapping Imaging Spectrometer for Europa

This imaging spectrometer senses a range from the near- to mid-infrared. These spectral regions reveal hydrates (water-containing materials) and bulk surface composition, organics, most radiolytic substances (chemicals created by Europa's high-radiation environment), and salts. MISE can also detect large organic molecules such as tholins. MISE can also measure thermal emissions from active regions.

PIMS: Plasma Instrument for Magnetic Sounding

PIMS measures the plasma surrounding Jupiter and its interaction with Europa's exosphere. Data from these studies will also shed light on the location and depth of Europa's subsurface ocean.

REASON: Radar for Europa Assessment and Sounding: Ocean to Near-surface

REASON is an ice-penetrating radar system that will chart Europa's crust from the surface to the ocean. REASON will be able to map features within the ice, including subsurface lakes.

SUDA: Surface Dust Mass Analyzer

SUDA will measure the composition of small solid particles ejected from Europa's surface, directly sampling the surface and potential plumes on low-altitude flybys. The instrument can pinpoint traces of organic and inorganic compounds in the ice particles above Europa's surface (Fig. 11.1).

In addition to instruments already accepted, NASA is considering how to fill 250 kg that is still available. Possibilities include cubesats that could be dispatched to fly through active plumes, or a more sophisticated second orbiter, the Biosignature Explorer for Europa (BEE). The BEE would have the capability to maneuver into active plumes, retrieve samples, and then sail on away from the severe radiation before testing the samples on board. Small landers are also under study.

If Europa does, indeed, hide a living biome within its deep waters, many researchers suspect the surest way to find it is with a lander. In situ experiments can search for biosignatures of active or past life. The United Kingdom and the Netherlands are both studying impact probes, and the University of Colorado (United States) is considering a piggyback probe called ELSA,[5] the Europa Life Science Acquisition probe. NASA/Caltech's Jet Propulsion Laboratory is in the process of carrying out one of the most advanced lander studies. Their multi-billion dollar lander would pull out all the stops, launching on a huge SLS with its own relay orbiter. Entering Jupiter's orbit in 2030, the Europa

---

[5] Not to be confused with the proposed Enceladus mission called ELSAH.

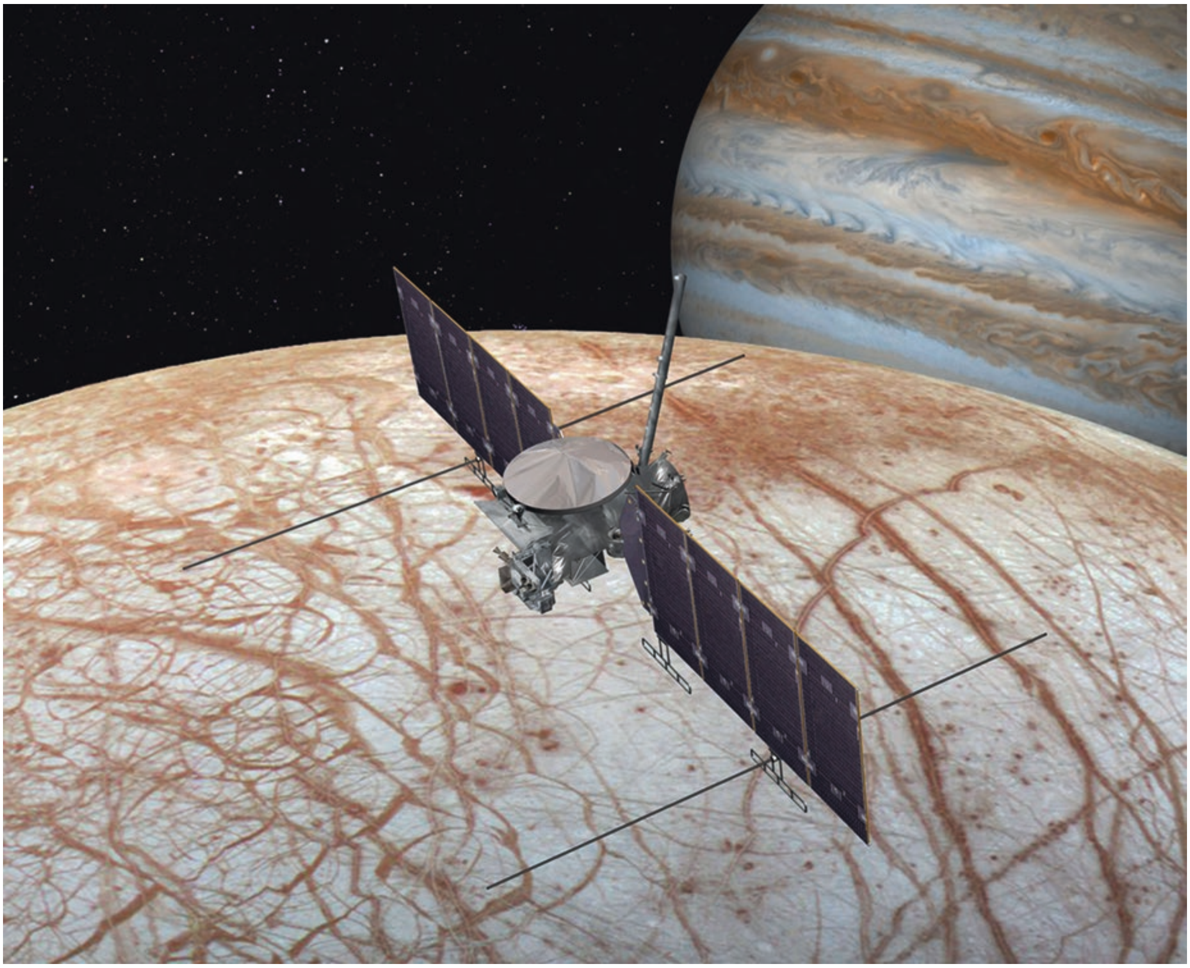


Fig. 11.1 Artist's concept of Europa Clipper in its radar imaging mode. (Image courtesy of NASA/JPL/Caltech)

lander would touch down no earlier than December of the following year. The battery-powered lander would operate on the surface for nearly three weeks, relaying communications to Earth through the mother craft in orbit above.

Engineers are studying the concept of equipping the lander with a large antenna to enable direct-to-Earth communications. This version would utilize a flat-panel antenna 80 cm across, instead of smaller antennas that would communicate with the orbiter. One sample quadrant of the larger antenna has already been successfully tested at JPL.

Designers are also hoping to reduce the cost of the lander by redirecting the focus of its science requirements. Although designers were initially given the task of equipping the lander to directly detect life, the design team has taken a new tack – looking for biosignatures of past or present life. This streamlines the science requirements for the mission goals, reducing the amount of data transmitted back to Earth. Even with this new, simplified approach, the lander's instruments might be able to detect active biology.

Engineers are also developing "terrain relative navigation" techniques that enable the lander to carry out precise landings on the rugged ice surface. Cryogenic sampling devices must also be developed to drill into Europa's rock-hard ice surface for sample collection and analysis.

Although researchers would dearly love to get their hands on surface samples, a sophisticated, large lander is probably not in the cards for the Europa Clipper mission. Initial scenarios for Europa Clipper's flight plan call for a nonstop, fast, and furious path to Jupiter, skipping any gravity assists by launching direct on a powerful booster. The only launch vehicle currently capable of such a flight is NASA's Space Launch System booster, still under development. But the SLS is behind schedule and over budget. If Clipper must use a smaller, already existing vehicle, flight times will increase by 5 years, as the craft must carry out gravity assist flybys of Earth and Venus.

In 2018, the U. S. Congress also allocated $195 million for a lander mission that would launch 2 years later, an astrobiology-specific mission. The lander would be lowered

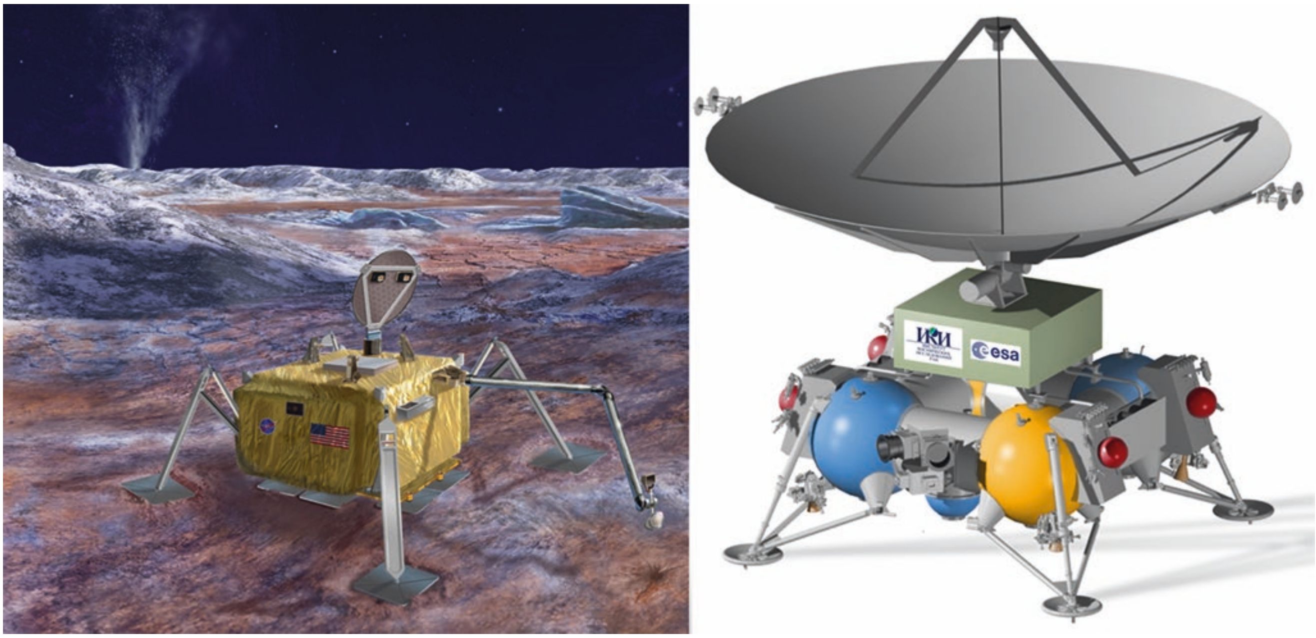


Fig. 11.2 *Left:* A NASA study of an advanced Europa lander, drilling into the surface ice. (Image courtesy of NASA/JPL/CalTech image by the author) *Right:* Russia's study of a Ganymede lander (Image courtesy of Konstantin Marchenkov, Institute of Space Research/Lavochkin)

on a "sky crane" similar to that used on the Curiosity Mars rover. Aside from a gentle touchdown, the sky crane approach shelters the surface from the rocket exhaust, protecting the pristine ice for sampling.

Engineering challenges face designers of a surface mission. A lander presents a high launch mass, so the mission either needs to utilize a huge, expensive booster, or face a years-long series of gravity assists. The high radiation levels on the Galilean moon's surface increases the weight and complexity of electronics, as instruments must be radiation hardened or protected in a vault. Delicate experiments must also survive the sterilization process at home as planetary protection requirements are stringent, and assurance must be made that any biomarkers discovered by the lander was not brought from Earth. The lander would run on batteries with a lifetime of about 20 days of surface operations. Using a drill, a Europa lander would dig into the surface, bringing to bare a suite of experiments keyed to searching for biosignatures in the ice. The craft would also chart the non-ice materials on the surface and constrain the location of liquid water beneath the lander. NASA has called for submissions of science instruments for consideration, but the lander and its booster would double the price tag, so its future is in doubt (Fig. 11.2).

U. S.-based Honeybee Robotics[6] proposes a "dangling drill," an active burrowing device suspended from a fine tether that would claw its way through the crust to the ocean below. The European Space Agency envisions a simpler penetrator that would embed itself into the ice directly from orbit at high speed without the need of a landing system. Ice forced into the front of the probe could be analyzed in a protected instrumented compartment farther back.

Once a Europa lander is eventually built, the question is where to land it. Despite rugged terrain, many ice moon experts recommend landfall in a chaos region. These broken-ice-floe areas are typically darker and redder than their surroundings, tinted by contaminants – possibly including organics – from the interior. Chaos areas may overlay sites of upwelling diapirs or subsurface lakes, all of which are in indirect contact with the deep ocean below.

Another possible landing site is the region that plays host to the Europa plumes. But those geyser-like eruptions have been coy, dodging our direct imaging in all but a few rare Hubble sightings. Their specific location and their frequency of eruption remain a mystery, so landing near a possible geyser site is considered of less certain value than landing on ice already darkened by geologic action, such as the chaos regions or areas where linea appear to have spread dark material beyond their boundaries.

ESA's JUICE

The European Space Agency plans to venture to the Galilean satellites with its ambitious JUpiter ICy moons Explorer, or JUICE. The solar-powered craft, energized by 100 m^2 of

---

[6] See "The Ice of a Different Moon" by Meghan Rosen, *Science News*, May 17, 2014, p. 20.

solar cells, will drop into Jupiter's orbit in 2029, where it will carry out a 3-year mission, culminating in an orbital survey of Ganymede. Like other large outer planet missions like Galileo (Jupiter) and Cassini (Saturn), JUICE is heavy, weighing in at over 5 tons. The massive craft will need to make use of several gravitational assists to get to Jupiter. The gravity of Earth, Venus, and Mars will slingshot the craft on a circuitous, 8-year journey to the king of planets. If the mission departs on schedule in 2022, it will loop around the Sun, coming back for a first flyby of Earth in May of 2023 and of Venus in October of the same year. Its second gravity assist at Earth will take place in September of 2024, followed by a Mars flyby in February of 2025. Arrival at Jupiter is scheduled for five long years later, in January of 2030.

ESA will contribute 940 million euros (in 2014 terms) towards the overall budget of the mission, covering the construction of the spacecraft, an Ariane 5 launch vehicle, the operations and scientific ground segment, as well as the actual running of the mission. The mission's 10 scientific instruments, including cameras, ice-penetrating radar, a laser altimeter, radio science experiments, and sensors to monitor the magnetic field, will be paid for by the individual space agencies of ESA's member states.

Italy will be a key contributor, delivering three of the experiments and contributing to a fourth instrument. Sweden and Germany will each fabricate two instruments. France and Britain will each contribute an instrument. Some 60 companies have already been chosen to fabricate components for the spacecraft.

Although JUICE will observe Jupiter's atmosphere and fierce radiation fields, the craft's main focus will be the moons of Jupiter. Io, cocooned deep inside Jupiter's deadly magnetosphere, will be studied from a distance, but JUICE will do two close flybys of Europa, affording scientists soundings of the moon's subsurface. Instruments will also scrutinize the minerals in the water-ice crust, and a series of high-resolution images will be returned. After the Europa encounters, JUICE will carry out another eighteen flybys of Ganymede and Callisto. As it did with Earth, Venus and Mars, JUICE will use the gravity of Callisto and Ganymede to keep on course for its many encounters with the Galilean moons. Callisto is perfectly placed to pump the orbit up over the poles, affording JUICE a bird's-eye view of Jupiter's complex polar structures. Each flyby of Callisto will provide rich material for scientists to digest.

Once the polar campaign is finished, JUICE will settle into its orbit around Ganymede, where it will study the Solar System's largest moon for 8 months. Mission goals include gauging the thickness of Ganymede's ice crust to see whether – and how – it transitions to liquid below. JUICE will also map the magnetic fields, whose patterns provide insights into the internal structure and any oceans present, and will characterize the moon's complex surface.

Flight engineers will then command an impact on the surface, with high-resolution imagery streaming back during the spacecraft's final moments.

The preliminary design of JUICE and its interfaces with the scientific instruments and the ground stations have now been established, enabling engineers to assemble a prototype spacecraft. ESA's industrial partners, led by Airbus, have begun preparing the spacecraft components that they will subject to various tests. These will simulate the harsh conditions of launch, as well as the extreme range of environmental conditions the spacecraft must endure as it travels toward the blistering heat of Venus and the cryogenic cold of the outer Solar System (Fig. 11.3).

The twenty-two member states of ESA have a formidable and impressive track record of working together as partners. ESA also shares a rich history of collaboration with the United States. For their Jupiter mission, another potential partner came knocking, from an unexpected place.

The Russian Proposals

Throughout the history of planetary exploration, from its inception to the end of the Cold War, Soviet robotic forays remained hidden from Western world. But later missions became more high-profile and transparent, as international partners from east and west began to combine forces in the Russian program.

The first decade of the twenty-first century saw an economic recovery in Russia, accompanied by increased interest – and funding – for planetary exploration. When the United States pulled out of joint ventures to Jupiter with ESA's twenty-two member nations, Russian engineers saw an opportunity. They reasoned that the European plan to explore the moons of Jupiter lacked one thing: a lander.

In 2011, after several years of studying various scenarios for orbiters and flyby vehicles, Russian designers began to focus on the Sokol-Laplas-P lander, a craft that would accompany the European endeavor, dropping a package onto the surface of Europa. Their mission profiles included stationary landers, penetrators, rovers, or a probe with a nuclear heating system to melt through the ice to the ocean beneath. ESA's plans, in turn, called for the use of a Russian Proton launch vehicle. (This part of the plan has been abandoned in favor of JUICE launching aboard an Ariane 5.)

By 2013, Russian engineers concluded that Jupiter's radiation was too strong at Europa to conduct a mission of more than a few hours or days. Current technology simply wasn't up to protecting the delicate electronics of a Europa lander. So the lander changed course even while it was still on paper, shifting from Europa to Ganymede. Ganymede was far enough out that radiation levels were more benign, and

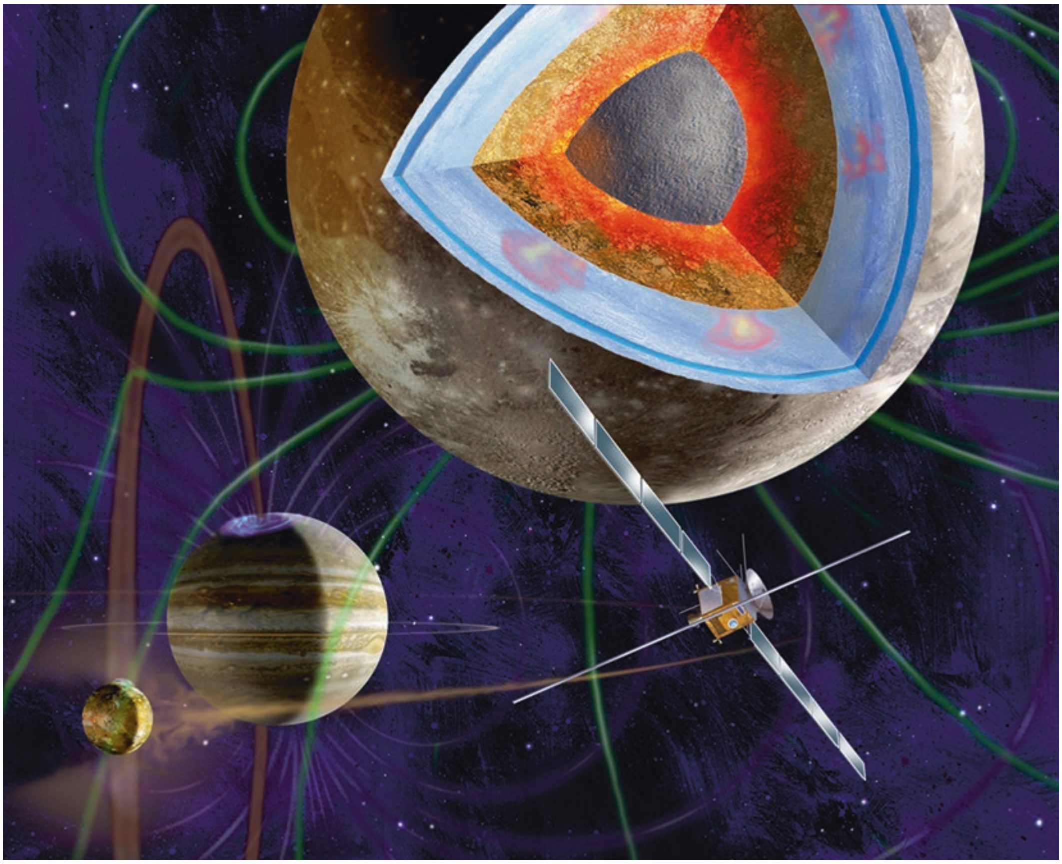


Fig. 11.3 JUICE is designed to study the environs of Jupiter and the Galilean satellites, with a focus on Ganymede, seen here at upper right. (Art by the author)

Ganymede was still an ice moon with an ocean, a fascinating world in its own right.

Roskosmos officially invested 50 million rubles ($1.5 million) to mature the project into a phase that would make the lander ready for manufacturing to begin in 2017. An original orbiter was scrapped in favor of piggybacking the lander to the JUICE orbiter. Its surface operations would continue, it was hoped, for over a decade.

With increasing financial problems in Russia's planetary program, other less ambitious craft continued to be canceled or delayed. In 2017, the Space Research Institute (IKI) announced that reduced funds required a decision between the Ganymede lander and the advanced Venera-D. With Russia's spectacular record at Venus, Venera-D was the winner; Russian exploration of the ice worlds will have to wait.

Worlds of Ice Beyond Jupiter

Future proposed missions to the outer worlds include orbiters of the ice giants, orbiters carrying multiple atmospheric probes, orbiters with landers for various moons, flyby tours of various moons (Ariel, Miranda, Triton) in similar fashion to the Galileo and Cassini missions, and follow-on flights to the Kuiper Belt. Exploring the ice worlds associated with the ice giant planets will entail some sort of orbiter or flyby bus. An ice giant orbiter is appealing, because there are many unknowns about this class of world. For example, astronomers wonder why Neptune puts out more heat than it receives (as do Jupiter and Saturn), but Uranus is cold. Their compositions are also baffling. Unlike the gas giants, Uranus and Neptune are enriched in metals. Knowing more about their specific composition will provide insights into their formation, location of accretion, and their migration through the Solar System. Ice giant ring structures are quite different from those of the gas giants, and their magnetospheres are complex and elegant. Why? These and other mysteries make missions to the ice giants – and the icy moons around them – likely in the coming years.

Even assuming the Europa Clipper mission is a success, many are turning their gaze toward Enceladus first. Several astrobiology missions have recently been proposed. Among them are: Enceladus Life Finder (ELF); EnEx Enceladus Explorer (Germany); Enceladus Life Signatures And Habitability, or ELSAH (NASA/Ames); and Explorer of Enceladus and Titan, called E2T (European Space Agency). One of the missions that has gained traction within NASA's realm is ELSAH.

The main thrust of the ELSAH mission is to directly sample the plume of Enceladus, analyzing it for evidence of biosignatures and charting just how habitable the ocean is. While not selected, ELSAH was awarded more funding for technology development. Said one ELSAH team member, “Our reviews basically said, ‘we like what you’re doing. We think it’s the best approach, but we don’t think you’ve solved the problem of Earth contamination. Go work on that, and work on it for everybody’s benefit. Do it for all life detection missions.”

We have seen that the Enceladus plume particles originate from a subsurface ocean, that the ocean contains salts, and that hydrothermal activity is likely occurring now (Chap. 6). It is also likely that water is in contact with rock. Organic material, sulfur, and nitrogen are present in forms that can be used by biology. Additionally, there are chemical energy sources similar to those on Earth that support biological activity. As Cassini did, ELSAH will fly through the plumes, but it will accumulate ice particles and then melt them for analysis.

ELSAH’s biology suite is designed to search for four key biomarkers: (1) ratios of amino acids, (2) amino acid enantiomeric excess, (3) molecular patterns of lipids, and (4) lipid distributions. Together these four measurements – along with investigations of salinity and pH in the water – will give researchers some confidence in whether the ingredients of life are present, and whether those ingredients have combined to engender active biology.

Germany’s DLR is developing key technologies for Enceladus surface exploration. The DLR proposes an ice “mole” that can autonomously bore into Enceladus’ subsurface ices. The probe has been successfully tested in several locations, including Austria’s Hintereisferner Glacier and Blood Falls, Antarctica.

Another NASA contender, the Enceladus Life Finder (ELF), would carry two mass spectrometers. The MASPEX (Mass Spectrometer for Planetary Exploration) would be crafted to sample the gases on the plumes, while the ENIJA (Enceladus Icy Jet Analyzer) would study the solid grains. Like the ELSAH mission, ELF would search for amino acids, isoprenoids (fatty acids), and life-related molecules such as methane and carbon, performing three specific tests for life.

Titan: A Truly Alien Biome

Saturn’s exotic moon of seas and organic sand is fundamentally different that other moons we have visited. Its methane-based “hydrological” cycle and bizarre environment mean that if life has arisen there, it will be unlike anything we have seen. Its unique form will dictate how we go about exploring it.

It turns out that organics on Titan react with hydrogen for energy. This fact gives us a key on which to base our exploration strategy, especially if it involves searching for life. It is informative to use Earth and its life as a comparison.

The majority of land organisms on Earth – not counting the plant kingdom – metabolize oxygen. But if our probe were to land on Earth and start measuring oxygen, it would not detect any variations, even though it was surrounded by organisms that were consuming it. The reason is that the rate of consumption is small compared to the amount of oxygen in the air. Oxygen levels would look rock steady. Whether in a house, in a forest, or by a river, our lander would see the same levels of oxygen. However, if our probe measured CO_2, it would find that the gas was highly variable. If our craft measured CO_2 in a forest in the morning, levels would be very different from that forest at night. If it landed in someone’s house, CO_2 levels would shoot up.

Carbon dioxide varies with seasons. It varies with location and time. And the reason it does is that the concentration in the atmosphere is very small, and the variation is large enough to affect it. So if life on Titan consumes hydrogen the way Earth organisms cycle oxygen and carbon dioxide, it may be that hydrogen levels will also vary once we’ve landed. Levels might vary near a shore or after a rain. Many researchers suggest that the Huygens probe landed just after a rainstorm. Had the ground been saturated with hydrogen-metabolizing life, that ground would wake up – biologically – and it would start consuming hydrogen. If our probe, equipped with a hydrogen detector, were sitting on Titan soil and the rain came, the hydrogen level would start dropping, just as CO_2 does in a desert when the rain comes and the plants and organisms wake up and start consuming it.

A recently accepted proposal, called Dragonfly, will be able to measure hydrogen levels. The probe is designed like a drone. In Titan’s light gravity and dense air, the flyer can maneuver over great distances for long periods, visiting multiple sites and sampling to its heart’s content.

Dragonfly looks for hydrogen, and it scoops up the material and does a general GCMS analysis of it. On Mars and Earth, we have a clear idea of what we should be looking for biologically. We’re looking for water-based life, so we are searching for molecules that work well in water (such as amino acids and lipids). On Titan, we have no idea about what molecules to look for. As NASA’s Chris McKay puts it, “We’d be looking for anything that sticks out and says, ‘Hey I’m an interesting pattern here, think about it.’”

Planetary Submarines

The Solar System is awash in watery oceans (see Chap. 7), and most are locked away beneath ice crusts. But they’re there, lurking under the surfaces of Ganymede, Europa, Enceladus, and perhaps other worlds such as Titan, Dione, and Pluto. These maritime sites may provide the best venues for life beyond Earth, but getting to them is the tricky part. In the case of Jupiter's ice moon Europa, its 100-km deep ocean ebbs and flows beneath kilometers of solid ice, effectively blocked from our direct access. Some engineers propose that the best way to search for life in these deep waters is to deploy a submarine. Delivering a probe to moons of the outer giants, safely down to the surface, through the ice and into the ocean is a daunting prospect.

It's just the kind of prospect that fires the visions of aerospace engineers, and some are taking the vision beyond imagination, into the practical world of exploration. Engineers have tested cryobots (super-cold robots) beneath Alaska's Matanuska glacier, under frozen sea ice and inside permanently iced-over lakes in Antarctica. One, called VALKYRIE, operates not by drilling nor by melting through the crust with heated water. Instead, a laser takes advantage of the fact that certain frequencies transmit power through liquid water and yet absorb through ice. By carefully selecting the focal length of the set of laser optics, the probe can increase or decrease its rate of descent toward the liquid ocean below. Stone Aerospace, led by William Stone, is continuing testing of its laser-excavating vehicle.

Other research groups have drawn plans for planetary subs. Sweden's Uppsala University proposes a submersible the size of two soda cans, and Georgia Institute of Technology's Icefin also follows an elongated design. Georgia Tech's Britney Schmidt brought a team to drill a hole in Antarctic's Ross Ice Shelf, where their Icefin robot entered the water and descended to the ocean floor, a flight profile identical to a baseline Europa mission. Louisiana State University is working on several projects, including the Sub-glacial Polar ice Navigation, Descent, and Lake Exploration (SPINDLE). The autonomous cryobot melts through dense ice to explore the lake below. Plans call for SPINDLE to deploy a second-stage probe, called a hovering autonomous underwater vehicle (HAUV), into the water. Another LSU probe design can travel untethered under ice and create three-dimensional maps of its underwater surroundings. The probe can obtain samples of microbes and has already done so in a 25-m-deep frozen lake in Wisconsin. Next stop for the probe's tests is a permanently ice-covered lake in Antarctica.

After flyby and orbital missions, the first surface probes to Europa will probably be stationary landers, perhaps outfitted with coring devices to sample the first few meters of ice. It's a good start, but chances of finding extant microbial life on Europa's surface, or even within the first meter or two down, are slim given the radiation environment. But if a probe can get through to the ocean, it opens up new possibilities.

Once deployed in the ocean, the robot sub would map the seafloor, chart currents and chemical streams, and look for life. A cryobot can be programmed to search for sources that may host life. Clues lie in shock layers or high gradients. For example, a plume with higher sulfur content might indicate likely hydrothermal vents, so the probe would try to follow the sulfur trail back to its source. The next step is to maneuver to that site, and use machine vision to look for changes in the background that would suggest the presence of microbial communities (such as mats or color changes). The cryobot would return high definition video.

Cosmic Yachting

Saturn's Mercury-sized moon Titan is blessed with two sets of seas, one within its ice crust and others on its surface (Chap. 7). The surface seas are a mix of methane and ethane, an exotic marine environment that calls out for exploration.

The vast lakes of methane and ethane wash across the northern hemisphere, with another huge body – Ontario Lacus – in the south. The largest of Titan's hydrocarbon oceans is Kraken Mare, followed closely by Ligeia Mare.

Some aspects of Titan's methane seas actually make them less challenging for a submarine than terrestrial oceans, because hydrocarbons are not electrically conductive. There is no need to worry about exposed connectors. There is also a possibility that radio signals can penetrate the liquid more easily than water. We know that at least one of Titan's seas is quite radio transparent, because Cassini bounced radar off the bottom of it.

However, despite its advantages, Titan presents a new set of challenges for submersible design. The liquid is very cold (–179°C), so just staying warm will draw a large part of a probe's energy and dictate its structure. Another problem is how Titan's atmosphere reacts with its methane seas. On Earth, submarines can use air to fill their tanks and regulate buoyancy. But the nitrogen that makes up the majority of Titan's atmosphere is very soluble in liquid methane, so it has less power to make the sub buoyant. If designers use nitrogen for flotation, the gas will only be effective at limited depths. The other option is to use a noble gas such as neon. This is under study now.

Another probe under consideration is something more like a dinghy, a robot that could float on the surface rather than diving. Titan boat probes could float on the methane lakes. One such mission, called the Titan Mare Explorer (TiME), would drift for weeks or months on the surface of Ligeia Mare, the second-largest of Titan's methane seas. Studies show that natural lake currents would take the probe completely around the sea to sample the environment at many sites (Fig. 11.4).

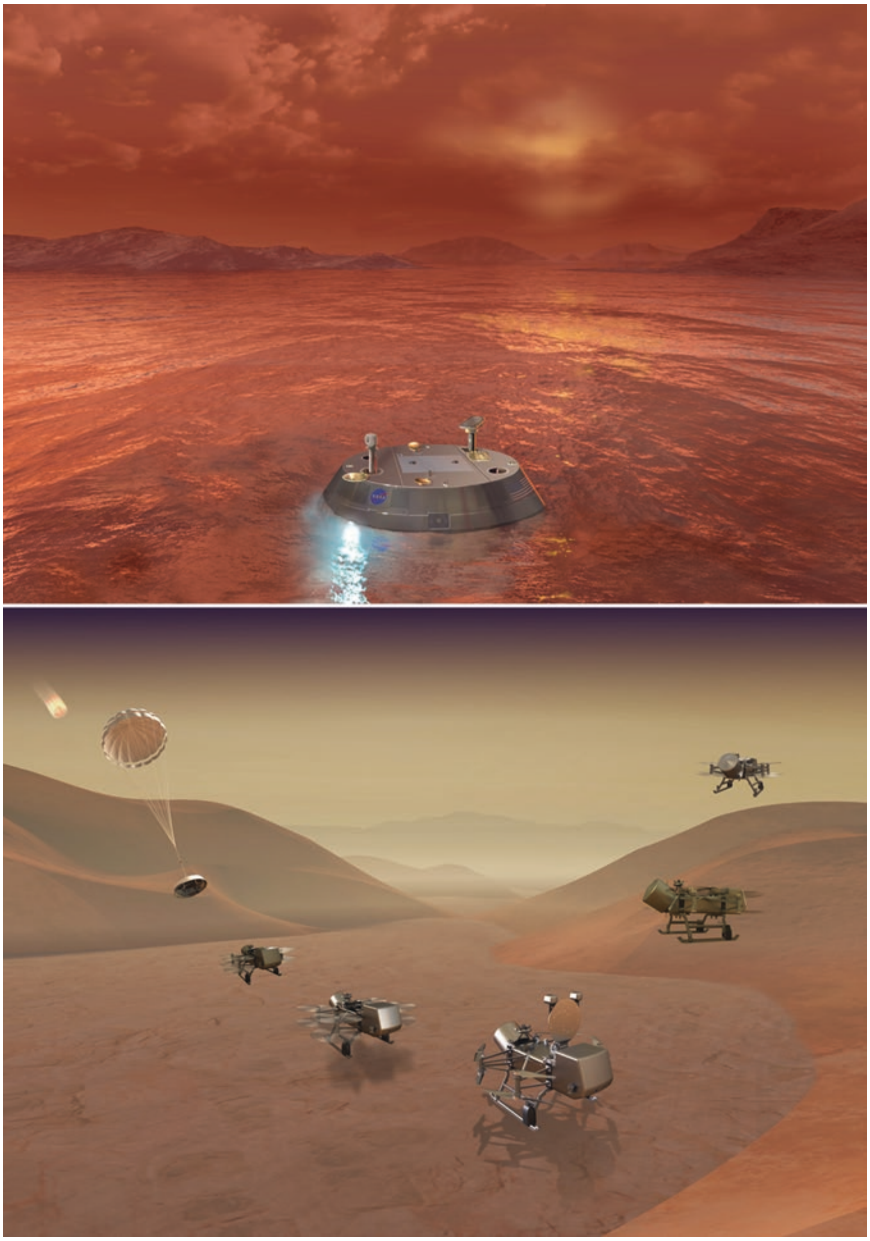


Fig. 11.4 *Top:* A Titan boat proposal called Titan Mare Explorer would study methane seas from the surface. (Art by the author) *Bottom:* The drone-like Dragonfly probe would explore Titan skies. (Image courtesy of Johns Hopkins University Applied Physics Laboratory)

Into the Future

Beyond the exploration of the ice worlds orbiting Jupiter, Saturn, and Uranus, a significant ice world lies nearly unexplored, save for a brief flyby. That world is Neptune's moon Triton. Its 2707-km diameter places it as the seventh largest ice world in our known Solar System.[7] Triton's unique cryovolcanism and its apparent genesis in the Kuiper Belt make it an important target for future exploration. Although orbiters at Neptune are a possibility, Triton orbiters or landers have also been studied. Streamlined missions could fly through the Neptune/Triton system with spacecraft far more advanced than Voyager 2, even dropping off surface probes as they passed. Many scenarios are under consideration.

For future Neptune missions, Triton can provide an important navigational tool. It is large enough for an orbiter to use its gravity as a slingshot, changing a spacecraft's orbital direction. (Even the biggest moons of Uranus are not big enough to do that.) Triton may gift future explorers with a gravitational fulcrum critical to navigate the wonders of this farthest of the giant worlds, just as Titan provided a springboard for the Cassini orbiter. Pluto, more difficult to get to, shocked researchers with its active surface and tempts

---

[7] Followed closely by Pluto at 2376 km.

us with future missions. Triton stands as its sibling in size and composition. Triton's stunning geology, spectacular cryovolcanism, and strategic position within the ice giants may make it a key player in future expeditions, both robotic and human.

Less than half a century ago, no one had seen the glistening faces of ice moons. Planetary scientists didn't dream of gossamer curtains of water vapor waving across Enceladan skies like Roman chariot banners. Few astronomers could guess that some moons were as large and complex as planets, that others had hidden oceans of greater extent than the "water world" Earth, and that one of them had alien rainstorms of methane and hydrocarbons. And no one had guessed at the exciting energies pent up inside these ice worlds, often expressed as dramatic cliffs and canyons or even exploding geysers. Today, we know these places. We have seen one of them from its surface, and we have plans for future forays into this dark realm. Across the outer Solar System, worlds of frost and fury beckon us forward, out into the dark – but far from silent – worlds far beyond our own.

Index

M. Carroll, *Ice Worlds of the Solar System*, https://doi.org/10.1007/978-3-030-28120-5