Ice in the Solar System

Louise M. Prockter

Ice exists throughout the solar system, from Mercury, the planet closest to the Sun, to the far reaches of the mysterious Oort cloud, a vast and diffuse shell of comets. Some outer solar system bodies are composed almost entirely of ice, whereas others may contain ice and rock mixtures. Ice occurs as polar caps and permafrost and may persist inside the coldest, darkest craters at the poles of otherwise rocky bodies. Ice may be ancient, present since the birth of the solar system, or young and relatively pristine; may have recently condensed from liquid; or may have migrated, molecule by molecule, from warmer areas to colder areas. I here review some of the places and forms in which this fascinating material exists in the solar system.

INTRODUCTION

Many volatiles can exist in frozen form, but the one most familiar to us is water ice. Water ice forms through a phase transition that occurs when liquid water is cooled below 273.15 K (0°C, 32°F) at standard atmospheric pressure. Ice can form at higher temperatures in pressurized environments, and water will remain a liquid or gas until 243 K at lower pressures. Water ice can take on at least 15 different crystalline forms in which the water molecules become more densely packed as pressure is increased. This results in a range of densities, from 0.92 g/cm^{-3} for the common type of ice (known as Ice I) that floats in our drinks, to up to 1.66 g/cm^{-3} for the highest-pressure phase, Ice VII. These denser phases of ice are expected at depth in icy satellites (see, e.g., the review in Ref. 1; many of the references at the end of this article contain excellent reviews of the topics covered here). For planets closest to the Sun, water ice dominates, but farther out into the solar system other types of ice are more significant.

Just as volcanoes have the power to drastically modify landscapes on the Earth, ice-rich (“cryovolcanic”) eruptions on bodies far out in the solar system have clearly played a significant role in the geology we see today, even though cryolavas have temperatures many hundreds of degrees cooler than their molten rock counterparts.[2] Cryovolcanic substances may be water based or composed of other substances such as methane and ammonia. Depending on their compositions, their densities and viscosities can range from light and runny to heavy and sluggish. A potentially important component of icy satellite volcanism may be clathrate hydrate, a crystalline phase of water ice in which other volatiles such as methane, nitrogen, CO_2, and noble gases are incorporated into cage-like structures in the water-ice lattice. Clathrate hydrates, which are well known on Earth, are found in such diverse environments as glacial ice, permafrost, and seafloor sediments. They are also thought to occur on Mars, where CO_2 clathrate hydrate may be a major constituent of the southern polar cap. Clathrates may be widespread in the outer solar system and have been proposed to exist in cometary nuclei, Titan, Triton, and the icy Saturnian and Jovian satellites. When the temperatures or pressures of clathrates exceed a critical value, the presence of the trapped volatiles may lead to explosive volcanism.

DISTRIBUTION OF ICE IN THE SOLAR SYSTEM

The distribution of rocks and ices throughout the solar system is hypothesized to depend on how they originally formed from the solar nebula (see, e.g., Refs. 1 and 3). Our Sun, like other stars, formed from a cold interstellar cloud of hydrogen (H_2) and helium (He) molecules and dust. This cloud gravitationally collapsed into a spinning disk, and eventually the central core collapsed into a rotating proto-Sun surrounded by a rotating primordial solar nebula. This nebula would have started out at ≈2000 K, and as it cooled, different elements condensed out into grains or ices, depending on their "condensation temperature." Rocks and metals were formed at temperatures above ≈1300 K, and as the nebula continued to cool to below ≈300 K, carbon grains and ices of water, carbon dioxide, nitrogen, and ammonia condensed out. The line between the areas where rocks and metals condense and where carbon and ice grains begin to condense is known as the "frost line." The exact location of the frost line is still debated, but it is thought to be around 4 AU, between the asteroid belt and the orbit of Jupiter (Earth is 1 AU from the Sun; Jupiter is 5 AU from the Sun).

Condensed grains would have stuck together when they collided and continued to coalesce as they grew large enough to gravitationally attract each other. Eventually, kilometer-sized planetesimals formed and collided with each other to form proto-planets. Closer to the Sun it is too hot for proto-planets to capture H_2 and He gases, or for ices to be stable, so in the inner solar system, small rocky bodies with few ices formed. Ices are further destroyed by the solar wind, removing the H to disperse it and other light elements radially away from the Sun. Farther out in the solar nebula, ices condensed, augmenting the masses of planetesimals that then collided to form large rock and ice cores. Jupiter and Saturn are predicted to have rock/ice cores that are 10–15 times greater than the mass of the Earth, whereas Uranus and Neptune may have rock/ice cores 1–2 times the mass of the Earth.

Some of the gas around the proto-gas giant planets formed a rotating disk of material, like a mini–solar nebula. These disks condensed out to form small rock/ice moons, with the proportion of rock and ice varying with distance as it does for the planets formed around the Sun. Jupiter's closest moon, Io, is a rocky body, while the next moon out, Europa, is mostly rock with a ≈150-km layer of water ice (and probably a liquid water ocean) at the surface. Ganymede, the third farthest moon from Jupiter, is about half ice and half rock, and the fourth and most distant large satellite, Callisto, appears to be an undifferentiated (not separated into layers) rock/ice mixture. Although most moons formed around their parent planet directly from the solar nebula, some, such as Phoebe and Triton (moons of Saturn and Neptune, respectively), were probably captured by later collisions.

Comets and other icy trans-Neptunian objects such as Pluto are probably the leftovers of solar system formation. In its outer reaches the solar nebula would have been very cold and very thin. The low temperatures would have allowed rapid accretion of ices onto rocky cores, but the scarcity of material would have kept these planetesimals small. After the planets formed, a process that may have taken about 100 million years, they were bombarded for perhaps another billion years by pieces of rock and ice remaining from the planet formation process, and any residual solar nebula gas would have been dispersed into the interstellar medium.

Theory predicts that ices make up over half of the mass of material that condensed from the solar nebula beyond the frost line. This theory is supported by observation: inner planets and asteroids tend to be small rocky bodies with few ices or volatiles present, whereas water ice has been identified spectroscopically as the dominant constituent of the majority of Jovian and Saturnian satellites, and moons farther out from the Sun appear to be small bodies of ice and rock mixtures with frozen volatiles such as methane and nitrogen.

Ice in Permanent Shadow: Mercury and the Earth's Moon

Although the inner solar system is predominantly composed of silicates and metals, there are places where the temperatures are sufficiently low that ices can exist on the surface. Perhaps the most unlikely place to find ice is on the surface of Mercury, where the sunlit surface can reach temperatures up to ≈700 K, the melting temperature of solder.

Earth-based radar imaging of Mercury has found about 20 circular areas of high radar reflectivity near the poles (Fig. 1).[4] The strength and polarization of these radar echoes—very different from the rest of Mercury's rocky surface—are similar to the radar characteristics of the south polar cap of Mars and the icy Galilean satellites, prompting researchers to suggest that Mercury's radar-reflective areas may be deposits of water ice or other volatile material.[6,7] The locations of many of these areas are coincident with craters, the largest area corresponding to the location of the crater Chao Meng-Fu.

So given its proximity to the Sun, low gravity, and high surface temperatures, how might ice survive on the surface of Mercury? Since Mercury has no atmosphere,

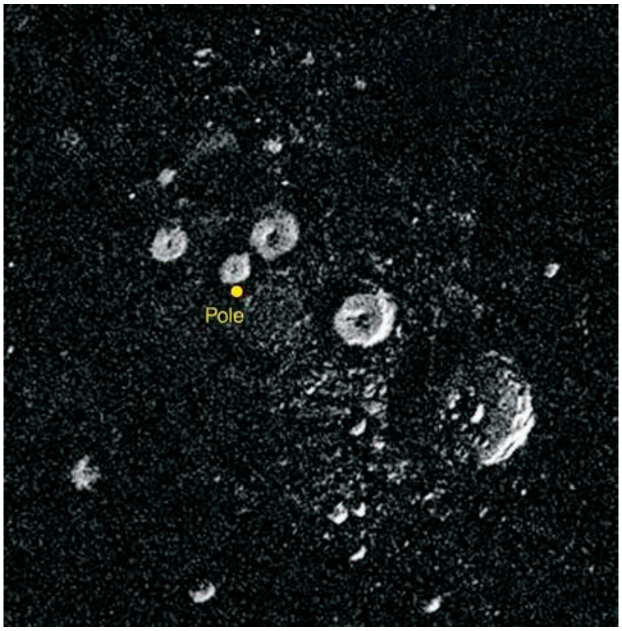

Figure 1. Arecibo radar image of Mercury's north pole in July 1999, showing bright features thought to be ice deposits within permanently shadowed crater floors. The scene measures approximately 450 km across. (Reproduced, with permission, from Ref. 5.)

water ice on the surface is directly exposed to a vacuum, leading to rapid sublimation and escape unless it is extremely cold at all times. This means that ice cannot be exposed to sunlight. The only places on Mercury where such conditions might exist are within craters near the poles. Unlike the Earth, where the 23.5° tilt of our spin axis gives us the seasons, Mercury's spin axis is barely tilted at all—only 0.1° (Fig. 2). Therefore, the strength of solar illumination on the surface does not vary, regardless of where Mercury is in its orbit. Since craters excavate material below the surface, it is highly likely that the floors of some craters are deep enough to be in permanent shadow. The existence of such permanently shadowed craters has not yet been verified, however, since the only high-resolution images obtained of Mercury to date were from the Mariner 10 spacecraft, three decades ago, which only imaged one hemisphere of the planet. Theoretical studies predict that typical craters at the poles may contain areas that never get warmer than ≈100 K, and that water ice in the polar craters could be stable over the age of the solar system (e.g., Refs. 8 and 9). If so, the ice may have originated from infalling comets and meteorites and become "cold-trapped" at the poles over billions of years. Alternatively, water vapor may have been outgassed from the interior during Mercury's early history. It has also been suggested that the polar deposits may not be water ice but rather some other material such as sulfur, which could have sublimated from minerals in surface rocks over the millennia to become trapped at the poles.

These hypotheses will be tested as part of the MESSENGER (MErcury Surface, Space ENvironment GEochemistry, and Ranging) mission. The MESSENGER spacecraft, designed and built by APL, is en route to Mercury and has just completed a flyby of the Earth during which several calibration tests were successfully carried out. The spacecraft's payload includes several instruments to investigate the polar deposits. The Gamma-Ray and Neutron Spectrometer (GRNS) will detect gamma rays and neutrons emitted by radioactive elements on Mercury's surface or by surface elements that have been stimulated by cosmic rays. It will be used to map the relative abundances of different elements and will help to determine if hydrogen exists in any polar deposits, which would suggest that the deposits contain water ice. If the deposits are sulfur, the X-Ray Spectrometer (XRS) and

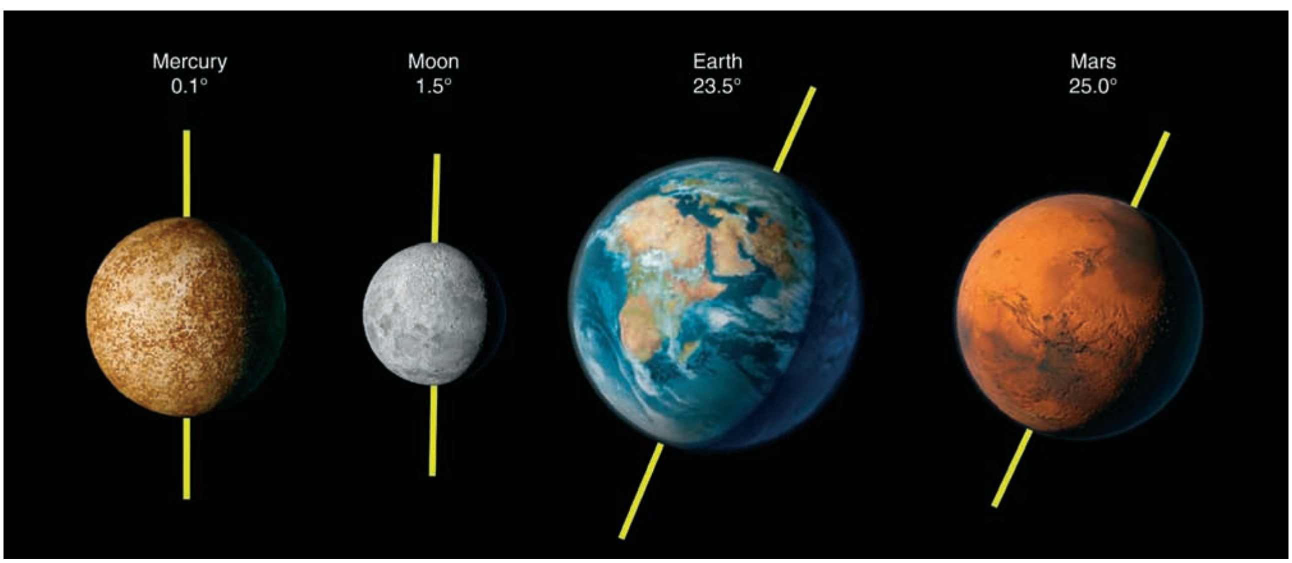

Figure 2. Spin axes. Mercury and the Earth's Moon both have almost vertical spin axes, allowing some craters at their poles to remain permanently shadowed. In contrast, the Earth and Mars have significant tilts to their axes, allowing variations in solar illumination throughout their years (resulting in seasons), and making it much less likely that permanently shadowed regions exist.

the Energetic Particle and Plasma Spectrometer (EPPS) could detect them. Gamma rays and high-energy X-rays from the Sun striking Mercury cause surface elements to emit low-energy X-rays. The XRS will detect these emitted X-rays to measure the abundances of various elements in the materials of Mercury's crust. The EPPS will measure the composition, distribution, and energy of charged particles (electrons and various ions) in Mercury's magnetosphere. Both the XRS and EPPS would detect sulfur in tenuous vapor over the polar deposits. Another instrument, the Mercury Atmospheric and Surface Composition Spectrometer (MASCS), is sensitive to light from the IR to the UV and will measure the abundances of atmospheric gases. Finally, the Mercury Dual Imaging System (MDIS) will map out the locations of craters near the pole on the hitherto unimaged hemisphere. Understanding the composition of Mercury's polar deposits will clarify the inventory of volatile materials in the inner solar system.

Mercury is not the only body likely to have permanently shadowed areas at its poles. The Earth's Moon also has a spin axis with a very small tilt—only 1.5° (Fig. 2)—and numerous craters that may be cold enough to contain ice. Data from the Clementine and Lunar Prospector missions (e.g., Refs. 9 and 10) showed that ice might exist in permanently shadowed craters at the lunar poles (Fig. 3), possibly well mixed into the lunar soil in very small concentrations. The Moon's south pole contains the 2500-km-dia. Aitken Basin, which is as much as 12 km deep, so any craters within the basin could easily be in permanent night. Data from the Neutron Spectrometer on Lunar Prospector[11] alternatively suggested that nearly pure water-ice deposits might be buried within 0.5 m of the surface, possibly extending up to 1850 km^2 in extent at each pole, although there are significant uncertainties in these numbers. As with Mercury, it is likely that the ice on the Moon came from impactors such as comets and meteorites and migrated to the poles to become cold-trapped in the shadowed areas. If ice is present at the lunar poles, this would be highly beneficial to future manned exploration as it could be used as a source of water, oxygen, and hydrogen for rocket fuel.

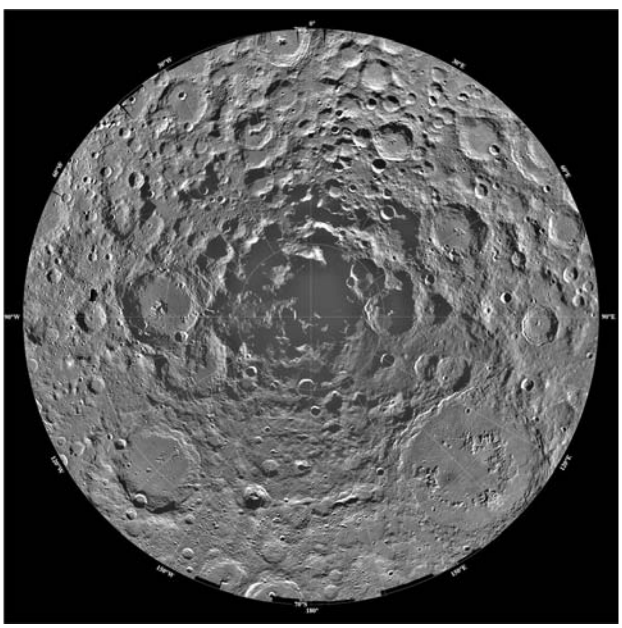

Figure 3. Mosaic composed of 1500 Clementine images of the south polar region of our Moon. A significant portion of the area near the pole may be in permanent shadow and sufficiently cold to trap water in the form of ice. (Image courtesy of NRL.)

With the January 2004 release of the President's Vision for Space Exploration,[12] manned exploration of the Moon became a priority for NASA. The agency has selected the institutions that will lead our return to the Moon by robotic lander and rover. APL is the major science contributor to both efforts, and several researchers and engineers here at the Laboratory are working to develop the scientific objectives, instruments, and missions that will help achieve this goal.

Polar Caps and Permafrost on Mars

Some of the best-studied ice features in the solar system are at the Martian poles, both of which have ice caps (e.g., Ref. 3). Because water and carbon dioxide are present at the poles, and both have freezing points that are within the range of seasonal, or even daily, temperature extremes, they can change phases over very short time periods. Each pole has a permanent year-round cap as well as a seasonal cap that appears in the Martian winter and disappears in the summer (Fig. 2). The permanent northern polar cap, composed primarily of water ice, is larger than Texas and ≈1 km thick. The southern cap is one-tenth the size of its northern counterpart and is mostly carbon dioxide ice with some water ice. It is not clear why the permanent caps differ so much in size, although in part, the southern seasonal cap is larger than the north's because winter in this hemisphere occurs when Mars is in the farthest part of its orbit from the Sun, and hence is at its coldest. Both poles show alternating bands of color, known as layered terrain, which likely contain different amounts of dust and ice. Each band was probably laid down during a different climate extreme, similar to tree rings, and studying these patterns can help researchers to untangle the history of past climate change on Mars.

Glaciers have played a major part in sculpting landforms on the Earth (Fig. 4; see, e.g., Ref. 13), and recent images from Mars suggest that glaciers may once have played a role in sculpting the Martian landscape, perhaps within the last few tens of millions of years. The Martian polar caps may be similar to glaciers that are frozen to their rock bed (where these occur on Earth, they are termed "polar" glaciers) because the temperature at the base of the ice is too low to allow any pressure melting. Therefore, any deformation must occur within the ice or the rock to which the glacier is

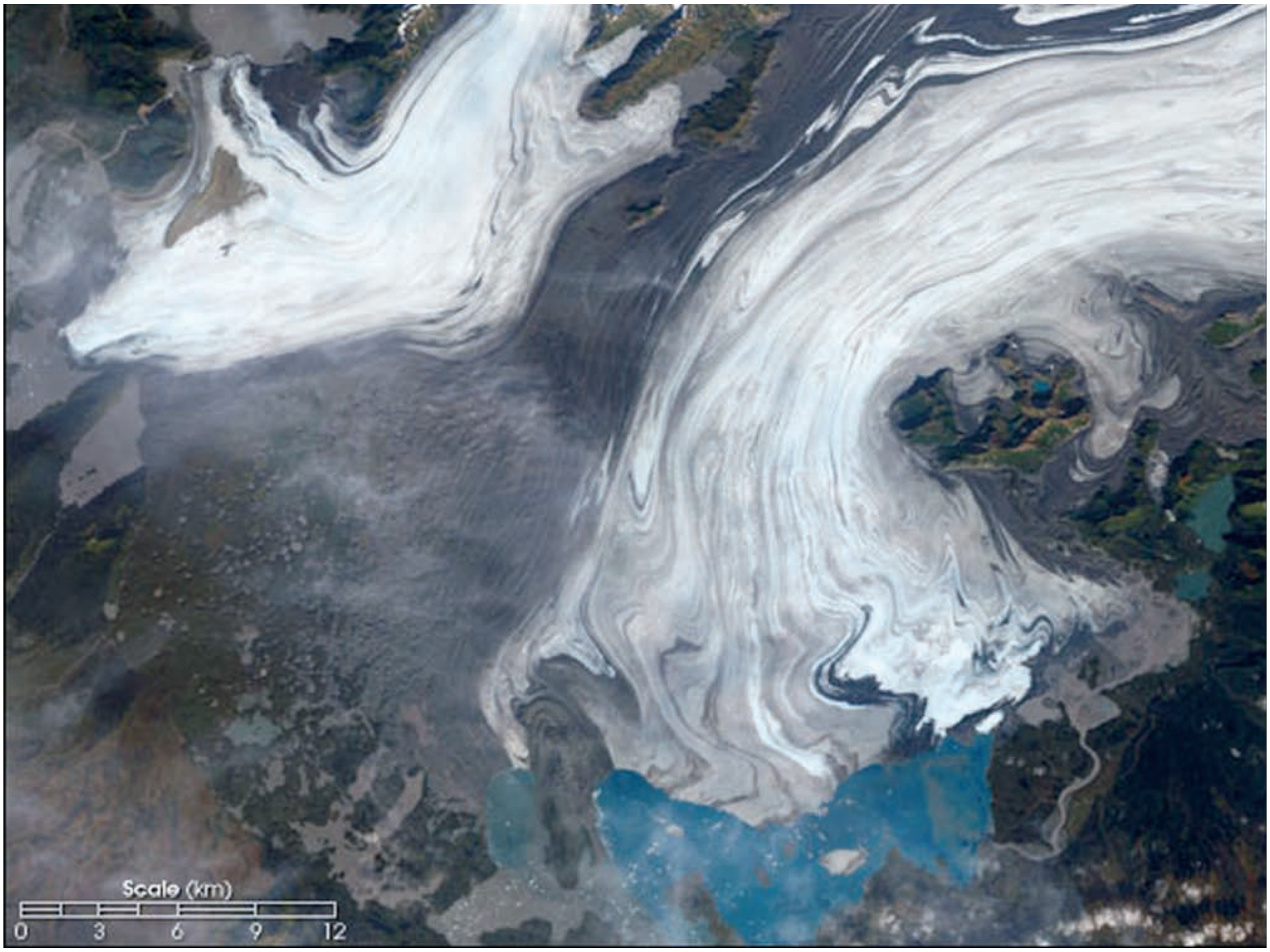

Figure 4. True color image of the Bering Glacier in Alaska, acquired on 29 September 2002 by the Enhanced Thematic Mapper plus (ETM+) instrument aboard the U.S. Geological Survey/NASA Landsat-7 satellite. The glacier has thinned by several hundred meters over the last century because of warmer temperatures and changes in precipitation. Glaciers like this may once have existed on Mars.

attached and would be expected to happen very slowly. Recent images from Mars show features that are interpreted as the result of polar glacial deformation, and these can yield clues as to how the caps have expanded and retreated over time and how they have sculpted the surface along the way.

Some of the most unusual landforms observed on Mars to date appear to be the result of sublimation of carbon dioxide frost from the southern polar cap (Fig. 5). Such features may form in a manner similar to those formed by melting ground ice on some parts of the Earth during the warmer months. Terrestrial ground ice, or permafrost, is found in polar regions where water is permanently frozen to a depth ranging from a meter to several hundred meters below the surface. Permafrost exists in pore spaces between rock and soil particles, and its contraction, expansion, thawing, and refreezing resulting from seasonal thermal changes can produce numerous different landforms as well as damage to buildings as the result of "frost heave" (Fig. 6). The average temperature at the surface of Mars is currently ≈218 K, but, depending on the season and Mars' position in its orbit, the temperature can drop by many tens of degrees K at the winter pole and rise by a similar amount on the dayside during summer. Under current conditions, the Martian ground is permanently frozen down to depths of 1 km or more. This means that liquid water cannot long exist anywhere on the surface. Despite the cold temperature, because the atmospheric pressure is less than 1% of that at sea level on Earth, even ice is predicted to be unstable near the surface within about 30° latitude of the equator. Closer to the poles, ice could exist within 1 m of the surface during local winter, but would again sublimate during the summer.

APL's Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) was recently launched onboard the Mars Reconnaissance Orbiter. One of the goals of CRISM is to detect mineral residues, such as clays and carbonates, showing that water was once present where these minerals exist. By studying the distribution and composition of these minerals on Mars, researchers can better understand the role of water in the overall volatile budget as well as its potential in enabling human exploration. Furthermore, microbial extremophiles have been

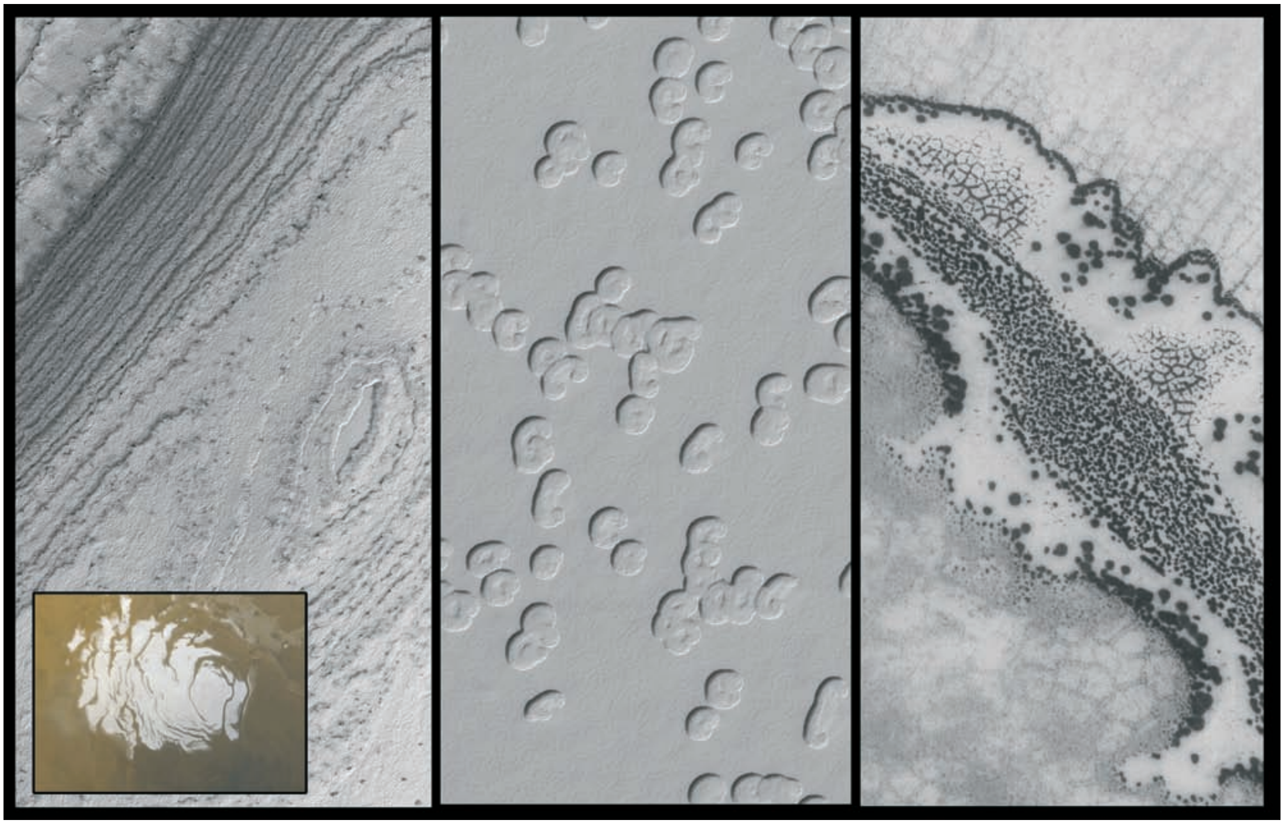

Figure 5. Images obtained by NASA's Mars Global Surveyor Mars Orbit Camera showing erosion of frozen carbon dioxide on the planet's southern polar cap (inset) during southern spring. Left: Layers of darker material, probably dust, are revealed as the ice retreats. Center: Kidney bean–shaped pits are formed by erosion. Right: A variety of patterns formed during seasonal carbon dioxide defrosting. Dark spots and dark-outlined polygons are patches of windblown or wind-eroded sand that were covered by carbon dioxide frost during the previous autumn and winter. Each image is about 3 km wide. Illumination is from the upper left. (Images courtesy of NASA/JPL/Malin Space Science Systems.)

found to exist in regions of permafrost on the Earth, so the Martian permafrost may be a good place to search for evidence of life on Mars.

Small Icy Moons

The Galileo mission recently returned a wealth of data on the Jovian moons, enabling significant new research. Three of the four large Jovian satellites—Europa, Ganymede, and Callisto—have abundant ice, but markedly different characteristics, allowing models of their formation and surface evolution to be tested and new hypotheses proposed. Callisto has a very ancient, heavily cratered surface and appears relatively unchanged since its formation. About one-third of Ganymede's surface is old and looks to be dirty water ice, whereas the remainder may have formed during some major cryovolcanic resurfacing event of cleaner ice between 1 and 3.5 billion years ago.

Figure 6. Image of permafrost on the Earth showing disruption of the overlying surface as the subsurface ice warms. (Reproduced with permission of Public Safety and Emergency Preparedness Canada.)

Of the three icy satellites, Europa is particularly intriguing, with strange surface features that have not been observed anywhere else in the solar system.[14] There are barely any impact craters on Europa, suggesting that the surface is extremely young—probably around 50 million years old, a blink of an eye in geological terms. The lack of impact craters, which cover Europa's siblings Ganymede and Callisto, implies that earlier impact craters have been wiped out by surface processes that probably include some form of exotic icy cryovolcanism. Indeed, the surface of Europa is almost completely covered with water ice and some hydrated minerals, and many surface features are colored by a reddish material that may contain organics. One of the most remarkable results from the Galileo mission is magnetic field evidence that implies the presence of a conductive layer, which is almost certainly liquid water, near Europa's surface.[15] A liquid water ocean beneath Europa's icy shell may be a place conducive to the formation of life as we understand it from our terrestrial viewpoint. Life on Earth is found wherever water is found, thus Europa is of great interest to astrobiologists, particularly those who study life in extreme environments. The presence of a liquid layer is plausible, given that Europa is tidally squeezed between its siblings Io and Ganymede, resulting in the generation of heat that may melt the interior of the ice shell.

One of the most hotly debated issues in Europa science is how far the ocean lies beneath the surface, a question that has a significant bearing on how easily the ocean can be accessed and sampled by future missions and instruments. A major thrust of my research is studying Europa's geological landforms to see what clues they provide about the thickness of the ice shell. My colleague Paul Schenk and I have been comparing the topography and geology of two huge hills or domes with an intervening dark reddish depression—Castalia Macula (Fig. 7)—to see how the area evolved.[16] We find that the depression is not filled with smooth frozen material as we had expected, but instead the dark material is actually a stain on the surface, not unlike a bathtub ring. We conclude that the depression was once filled with icy cryolavas that subsequently drained back into the interior, leaving behind the dark reddish stain. The northern dome has a remarkably steep scarp on one side that is more than 750 m high, while the depression is 350 m deep. Simple isostasy arguments based on the height of the dome and the strength of the underlying ice shell imply that the ice shell must be more than a few kilometers thick to be strong enough to support such relief. Otherwise the mountains would simply sink into the mantle.

Although their exact composition is still undetermined, the dark reddish deposits on Europa have been inferred to be sites of non-ice materials, probably hydrated minerals (see the review in Ref. 15) along with some reddish component. The reddish materials are generally associated with young features such as Castalia Macula, as well as "chaos" regions, where the surface has been disrupted. Reddish deposits have been suggested to originate from below the surface, either from Europa's putative ocean or from brine pockets lying near the surface. APL is currently developing an IR spectrometer, the Imaging Spectrometer for Icy Satellites (ISIS), to investigate the contaminants on Europa's surface. Of particular interest are materials that may be organic in origin, as these would enhance the astrobiological potential of this icy moon. If the reddish deposits do originate from the ocean, they may provide a place to sample it without resorting to drilling or melting through many kilometers of ice.

Figure 7. Castalia Macula (white arrow), a dark, reddish 350-m depression on Europa. The domes to the north and south (black arrows) are 900 and 750 m high, respectively. Castalia Macula may be a place where Europa's ocean has oozed onto the surface. North is up. (Image courtesy of NASA/JPL.)

If the ice above Europa's ocean is tens of kilometers thick, we might ask how the ocean could communicate with the surface. One of the properties of water ice is that it floats on liquid water, enabling us, for example, to go ice-skating on the C&O canal when it's really cold. However, this property makes it difficult to get liquid ocean water up to the surface of an ice-covered world. For liquid material from the ocean to reach the surface through the overlying ice shell, it must either be forced upward through overpressurized cracks or reduced in density such as by gas bubbles from contaminants like CO_2 or SO_2.

As noted earlier, some areas on Europa's surface, aptly called chaos regions, have undergone significant disruption, with the brittle top layer being cracked into huge ice rafts that can lie atop a finer-textured matrix, or be disaggregated thermally and/or mechanically into even smaller,

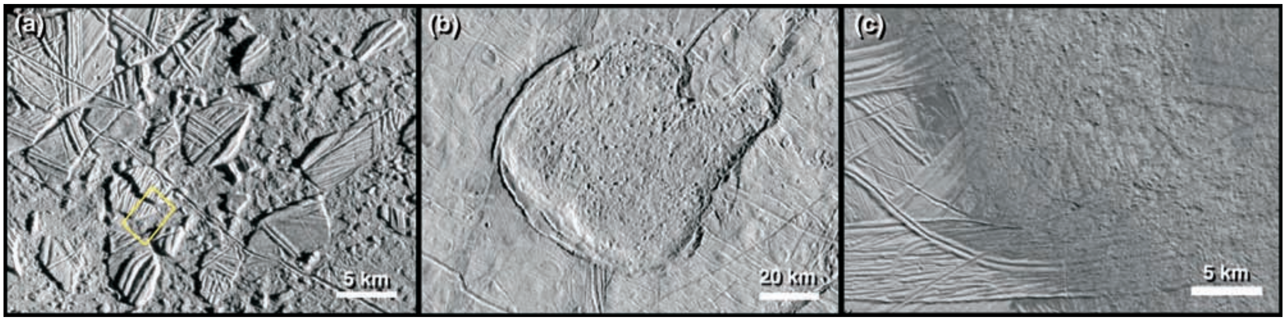

Figure 8. Chaos features on Europa, which are likely to have a cryovolcanic or cryomagmatic origin. (a) Conamara Chaos, an area in which preexisting terrain has been fractured into plates that have moved and rotated in a matrix of lower albedo material. The yellow box indicates the location of the region shown in Fig. 9 (top). (b) Murias Chaos, a different morphological type of chaos in which the preexisting terrain is barely recognizable, leading to a texture like frozen slush. This feature bulges several hundred meters above the surface. (c) The western margin of Thrace Macula, where chaos appears to have formed by *in situ* disintegration as evidenced by faint traces of preexisting ridges. Dark once-fluid material has flowed away from the chaos region to embay troughs within the surrounding terrain. (Images courtesy of NASA/JPL/APL.)

more uniform pieces (Fig. 8). Given our current understanding of the properties of ice and the energy sources available at Europa, it is difficult to conceive of how such extreme melting and eruption of liquid cryolavas could occur on these scales (Fig. 9). Most Europa researchers think that chaos terrain instead formed when a blob or "diapir" of ice became buoyant with respect to its surroundings and migrated upward to crack the surface. Although "warm ice" may sound like an oxymoron, a diapir of ice can be buoyant if it is only a degree or two warmer than its surroundings (thermal buoyancy) and can rise upward like a salt diapir on the Earth. Alternatively, the diapir could be compositionally buoyant, requiring that it have some lower melting temperature material mixed in. Whatever hypothesis is correct, there is no doubt that Europa is one of the most fascinating icy bodies we have investigated to date, and it still has many secrets to reveal.

The Cassini spacecraft is currently in orbit around Saturn and has already had a few close encounters with some of the satellites after flying through Saturn's rings and dropping the Huygens Probe into Titan. Spectra of the Saturnian satellites show that, except for Iapetus, they are composed of remarkably clean water ice.[17] Voyager images of Enceladus, which is only ≈500 km across, showed clear evidence of cryovolcanic resurfacing in recent geological times (some areas of its surface are only sparsely cratered). In addition, Enceladus has long been suspected of being responsible for the generation

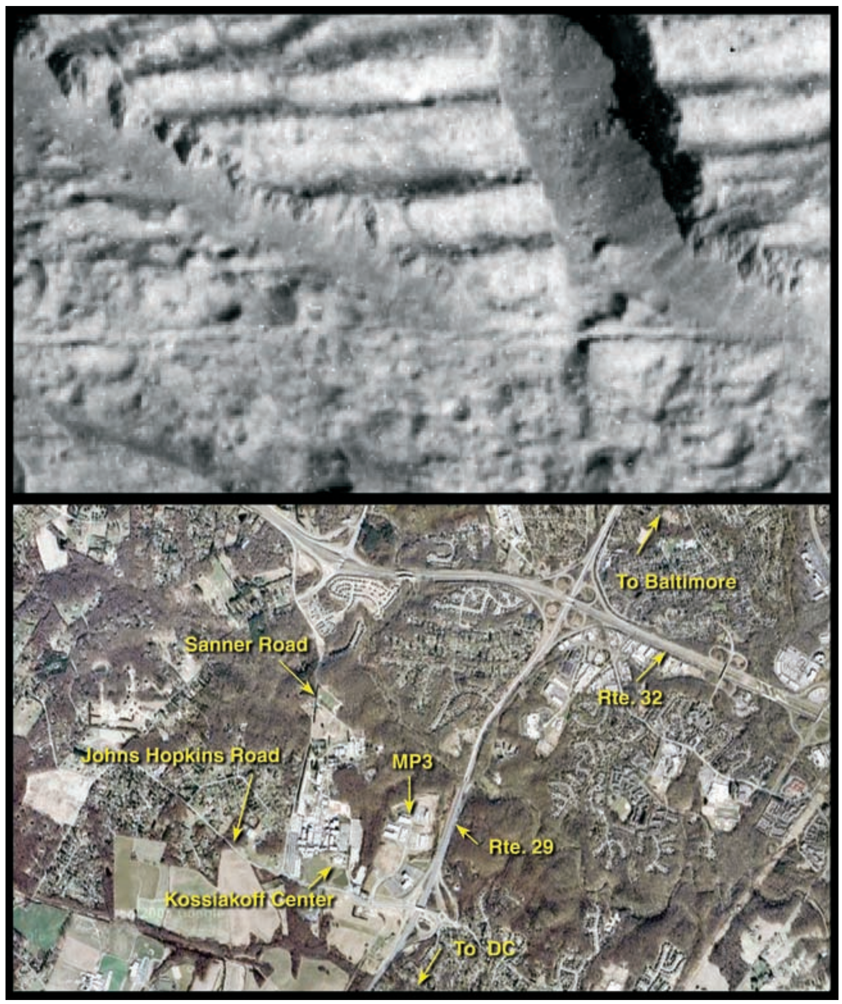

Figure 9. Top: Close-up of a piece of a chaos plate in Fig. 8a (yellow box) showing dark material at the foot of steep icy cliffs. Bottom: Satellite image of the APL campus and surrounding area at the same scale for comparison. (Chaos image courtesy of NASA/JPL; satellite image courtesy of Google Maps, http://maps.google.com/.)

of Saturn's E-ring, although how is not clear. Recent Cassini results have shown an astonishing thermal anomaly at Enceladus's south pole, which is associated with large cracks on the surface (Fig. 10).[18] Enceladus is very bright and reflects about 80% of the sunlight that reaches its surface. Even with the remaining 20%, we would expect the equator to be warmer than the poles, since the sunlight hits obliquely on the latter. However, composite IR spectrometer data show that the warm region at the south pole is about 85 K, approximately 15 K warmer than expected, and is more than 110 K in some places.[18] It is likely that evaporation of the "warm" ice in this area generates the cloud of water vapor that has been detected by several other Cassini instruments above Enceladus's south pole. Other measurements of the Enceladus environment have been made with APL's Magnetospheric Imaging Instrument (MIMI), and those results will help to clarify the processes that occur there.

Enceladus is a very small moon compared with other solar system satellites (Fig. 10), and there is no known explanation for how such a small body might generate enough internal heat to drive active geology. One possible source is tidal heating, but given our current knowledge of this process, it would be insufficient to create the observed anomalies. Cassini is only 1 year into its 4-year nominal mission, so it is likely that much more will be learned about the processes occurring on Enceladus before the mission is over.

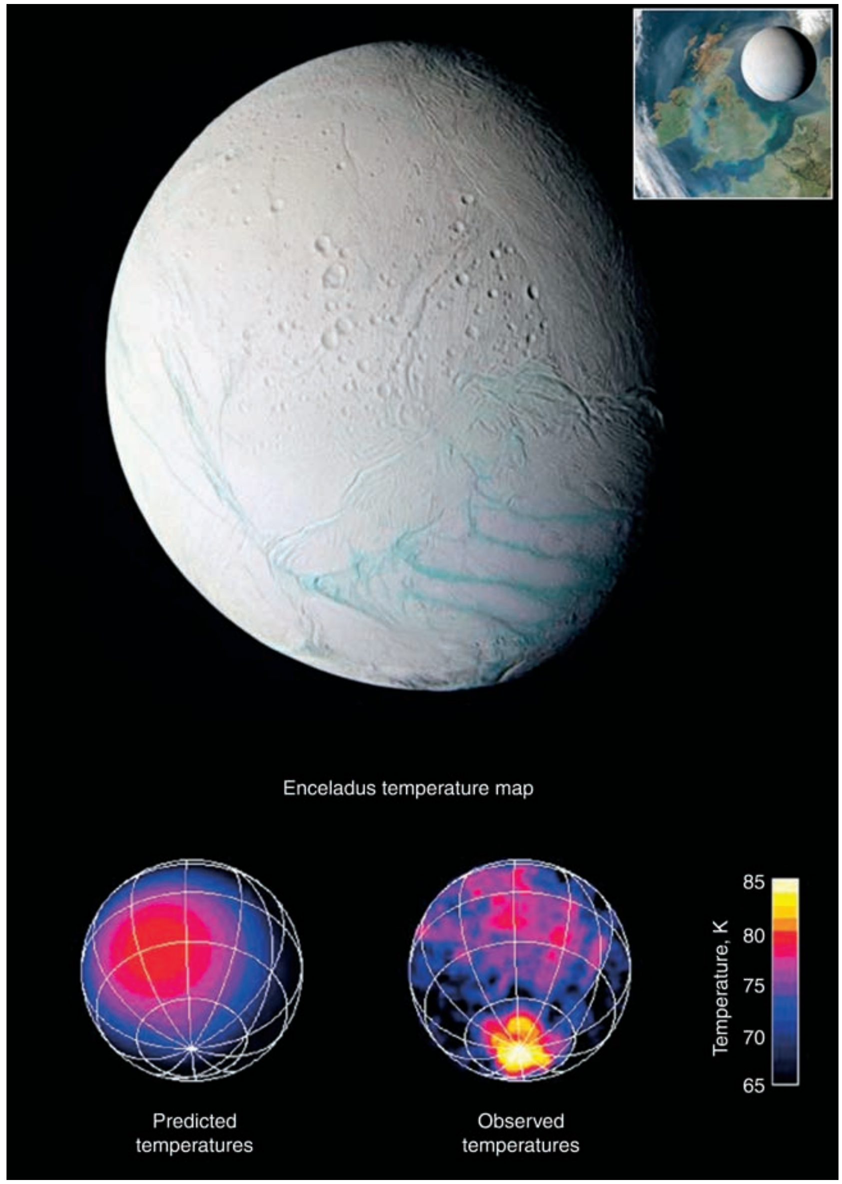

Figure 10. Top: The smooth, sparsely cratered surface of Enceladus. Enhancement of the color shows a bluish tinge to the fractures near the south pole, evidence that they contain fresh, icy material. Bottom: This temperature map from the Cassini Composite IR Spectrometer shows the predicted temperatures (left) and the actual enhanced IR (heat) radiation from the south pole (right). This thermal anomaly is probably the signature of internal heat escaping from the icy moon. The inset shows the relative size of Enceladus compared with the United Kingdom. (Image courtesy of NASA/JPL/GSFC; inset courtesy of NASA/JPL/Space Science Institute.)

The lavas responsible for the cryovolcanic flows inferred on the surface of Enceladus, as well as those thought to exist on its siblings Tethys and Dione, may have had a composition of ammonia and water. Ammonia may have been bound in the water-ice crystal lattice of the satellites as a hydrate when temperatures in Saturn's protosatellite nebula cooled to about 150 K. Ammonia acts as a highly efficient anti-freeze—it can decrease the freezing point of an aqueous solution by almost 100 K. Thus, when ammonia is present along with ice, only moderate increases in temperature are necessary for melting to occur in a satellite. As yet, however, ammonia has not been identified spectroscopically on any solar system satellite except perhaps on Pluto's moon Charon, possibly because its molecules may not survive long in a vacuum or within the harsh radiation environments present at these moons. Instruments on Cassini may be able to identify ammonia if it exists in young areas such as around fresh impacts, but this has not occurred to date.

Cassini recently investigated the surface and atmosphere of Titan, revealing a world composed of icy materials and hydrocarbons. Although the temperature at Titan's surface (≈94 K) is too low for the occurrence of liquid water, large amounts of water ice are predicted to be present within the crust and mantle on the basis of Titan's density. Recent Titan images returned by Cassini's Visible and Infrared Mapping Spectrometer (VIMS) revealed a bright, circular feature interpreted to be a cryovolcano composed of methane and water ice (Fig. 11).[18] Such a volcano may spew methane into Titan's atmosphere. Other evidence for cryovolcanic domes on Titan comes from Cassini's radar instrument, which also found evidence of lobate features interpreted to be cryovolcanic flows. Thus far, the evidence for cryovolcanism has been based on the morphology of features imaged at relatively low resolution. Their composition and detailed morphology await further analysis. Almost 40 flybys of Titan are planned over the next 3 years, so these features will be exhaustively studied to determine their origin and evolution.

Many icy moons exist beyond the orbit of Saturn, each with its own characteristics. The Uranian moons were imaged by only one spacecraft, Voyager 2, as it sped by in 1986. The major satellites imaged at a distance showed some evidence of cryovolcanic resurfacing, and a range of compositions and eruption conditions have been inferred. The only high-resolution images returned were of Miranda, which turned out to have a surprisingly complex surface (Fig. 12). Much of the satellite's surface is composed of bright, cratered terrain, but embedded within are three vast, dark, polygonal features termed "coronae." Coronae are interpreted to have formed through uplift (perhaps by buoyant ice),

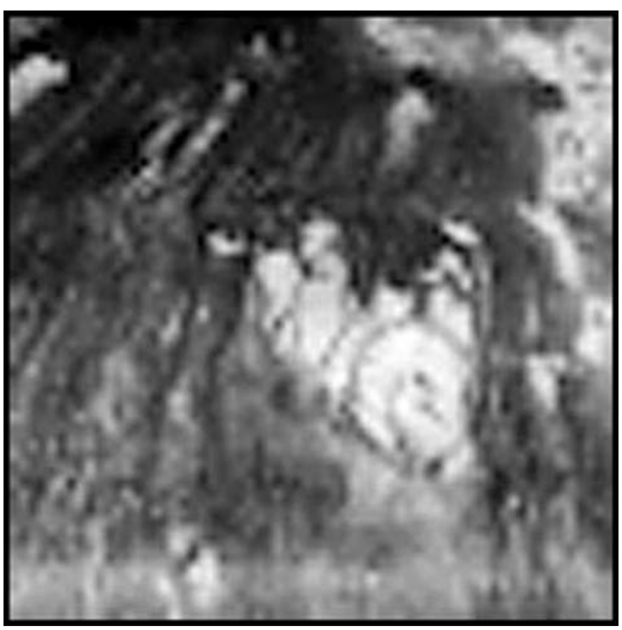

Figure 11. Titan's surface as captured by the Cassini VIMS instrument from an altitude of 1200 km, Cassini's closest approach to Titan to date. Taken at a wavelength of 2 μm, the image reveals complex landforms with sharp boundaries, including a bright, subcircular feature thought to be a cryovolcano. (Image courtesy of NASA/JPL/University of Arizona.)

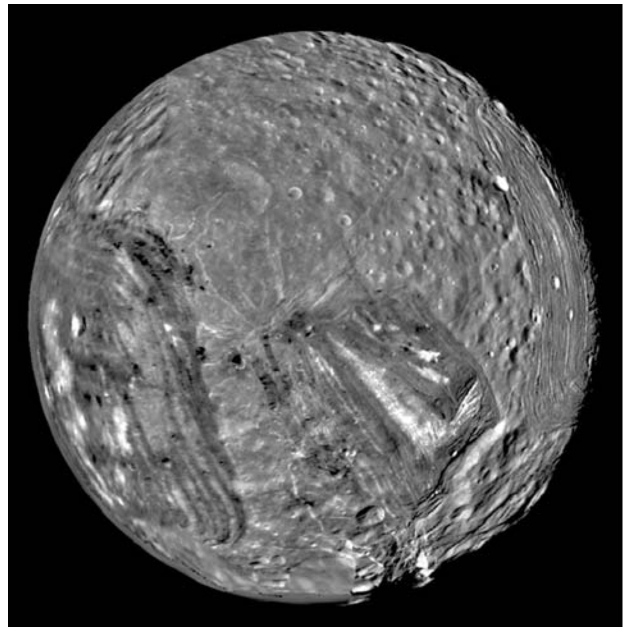

Figure 12. Miranda is only ≈480 km in diameter, yet has vast ovoidal areas of bright and dark chevrons. These may be due to tectonic activity, possibly the result of internal heating and melting of low-temperature (perhaps ammonia) ices that have impinged on the surface as diapirs. (Image courtesy of NASA/JPL.)

which may have ripped the surface apart, leading to the formation of huge fissures with the associated eruption of cryomagmas. Because of the distance of Miranda from the Sun, these icy lavas probably included materials (e.g., ammonia) that could form sluggish lavas viscous enough to form ridges or mountains. This catastrophic partial resurfacing is likely the result of the beginnings of differentiation in this tiny moon (at ≈480 km, Miranda is even smaller than Enceladus), in which different compositions of material would separate out into layers; however, it is likely that Miranda froze completely before this process could reach completion.

One of the largest and most intriguing icy moons is Neptune's Triton. At 2705 km in diameter, Triton is Neptune's only large moon and the only one to be imaged in sufficient detail to discriminate morphological features other than craters. Triton is composed of rock, water ice, organics, and volatile ices such as nitrogen and methane. Voyager 2 explored Triton in 1989, returning images of over half the surface that revealed a wealth of geological features on a surface that has few impact craters and appears remarkably young (Fig. 13). It may, like Europa, still be active today. Many landforms are interpreted to be cryovolcanic in origin, including eruptive hills, flow lobes, and depressions that resemble terrestrial volcanic calderas (see the review in Ref. 2). Relationships among different types of features hint at multiple episodes of both explosive and effusive events, and some flows have thicknesses that imply they were quite stiff and sluggish when they were erupted (imagine smooth peanut butter at room temperature). Some of the

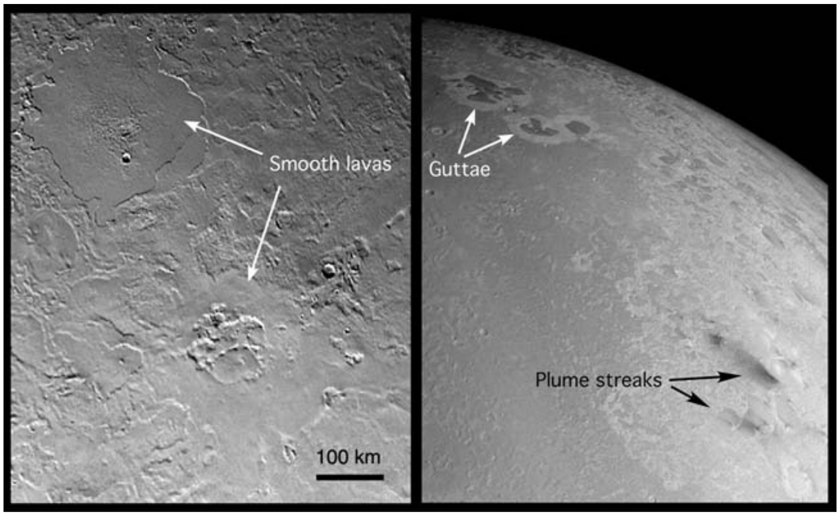

Figure 13. A wealth of probable cryovolcanic features is found even over a relatively small region of Triton. Left: This view shows smooth, frozen lavas filling shallow circular depressions. Many of Triton's features are similar to volcanic features on terrestrial planets. Right: Triton's mysterious guttae are giant lobate features, each with a dark core and bright annulus, thought to have a volcanic origin. Dark streaks from explosive plumes overlie the bright south polar cap. (Images courtesy of NASA/JPL.)

landforms look as if they were fragmented as they came out of the ground, implying that they may have been emplaced explosively.

As Voyager 2 flew by Triton, dark streaks were observed on the bright southern polar cap (Fig. 13). Although the presence of dark material is not unexpected—methane on the surface can be converted to dark organic material by radiation, for example—it was surprising that the streaks were visible at all. Triton has seasons, as do the Earth and Mars, and nitrogen, methane, and carbon dioxide frosts are boiled off ("sublimated") from one pole by heat from the Sun during summer and deposited (cold-trapped) on the opposite, winter pole. It is predicted that a meter or more of these exotic frosts would be transported from pole to pole on the cycle of 1 Triton year, equivalent to 165 Earth years. Therefore, the presence of the dark streaks on the surface implied that they were probably younger than a Triton year, i.e., they were emplaced very recently. It wasn't until shortly after the Triton encounter by Voyager, however, that the cause of this "smoking gun" was identified; stereoscopic images showed clear plumes above Triton's illuminated limb.[19] The plumes appeared as dark columns up to 8 km high and were probably composed of fine dark particles and vapor. Some of this material fell back to the surface in the form of dark streaks (Fig. 13).

One model that has been suggested as the mechanism driving the plumes is that of explosive venting of nitrogen gas pressurized by solar heating.[19] Triton has one of the lowest surface temperatures in the solar system at ≈38 K and appears to be blanketed with a thin (≥1-m) layer of transparent solid nitrogen ice. This model proposes that dark material at the base of the ice layer is warmed by sunlight, and because dark material absorbs heat more efficiently than bright material, it undergoes an increase in temperature relative to the overlying nitrogen ice. This warming melts the base of the overlying ice layer, resulting in pockets of highly pressurized nitrogen vapor that erupt explosively through vents (perhaps preexisting cracks or other weaknesses in the ice), dragging some of the dark material upward. The resulting geysers could loft material into Triton's very tenuous atmosphere, accounting for the dark streaks associated with the plumes. A temperature increase of only 2 K would be sufficient to propel the plumes above the surface to observed altitudes. An alternative driving mechanism suggests that the heat source for the geysers comes not from the Sun but from within Triton. If the subsurface ice or the solid-nitrogen polar caps were undergoing thermal convection, heat would be transported to the surface and could result in a temperature rise sufficient to drive the geysers. Although other models have also been proposed, an explosive venting model seems the most likely, regardless of the heat source.

Modeling Triton's resurfacing rate based on the lack of impact craters suggests that it may be second only to Io and Europa in the level of geological activity in the outer solar system. The reason for this apparent activity is that Triton was probably a Kuiper Belt object that was originally in an independent orbit around the Sun with other (smaller) companions just beyond the orbit of Neptune. At some time in its early history, it was captured by Neptune's gravity, a cataclysmic event that caused widespread melting and differentiation of the new satellite along with outgassing of a massive atmosphere. Tidal heating may have sustained warm interior temperatures for upwards of a billion years, and a subsurface liquid ocean may still persist today if ammonia is present in the icy mantle. Recently, colleagues Francis Nimmo, Bob Pappalardo, and I compared some unusual double ridges on Triton with similar ridges on Europa, the only other places we have seen these features.[20] By studying the surface geology, and assuming that the ridges formed because of tidal stresses at the surfaces of both moons, we concluded that Triton may have been captured more recently than was originally thought. Unfortunately, there are no plans to return to the Neptune system anytime soon, and it will be a long time before we are able to image the hemisphere of Triton we have not yet seen.

Pluto and Beyond

To date, Pluto and its moon Charon have been imaged in only limited detail by ground-based observations and the Hubble Telescope (Fig. 14). The smallest of the planets—it has a diameter of only ≈2300 km—Pluto's surface temperature is about 40 K and is composed of a mélange of organics and ices, dominated by nitrogen but with some frozen methane and carbon monoxide.[1,3] To date, only water ice has been observed on Charon. The densities of both Pluto and Charon are about twice that of water (and much less than rock), suggesting that they are a mixture of rock and ice.

Because of its composition and highly elliptical orbit, it has been suggested that Pluto represents a remnant planetesimal that has survived from the early solar system and may be best grouped with objects of the Kuiper Belt. The similarity of bulk properties of Pluto with those of Neptune's moon Triton has led to suggestions that Triton, like Pluto, was once in independent orbit around the Sun before it was captured. However, Triton has probably undergone global melting as a result of its capture and may have a much younger surface. The APL-led New Horizons mission is scheduled to launch in 2006 and fly by the distant Pluto and Charon system in 2015. If there is sufficient fuel remaining, New Horizons will visit one or more additional Kuiper Belt objects by 2026.

We generally think of the edge of the solar system as ending somewhere around Pluto, but in fact the Sun's influence extends almost 2 light years away. Two huge reservoirs of comets exist within this space, formed from material left over from the solar nebula. These reservoirs were only recently recognized and are the source of all comets passing through the inner solar system.[3] Comets are split into two primary groups: short- and long-period comets. Short-period comets, such as Halley and Encke, orbit in less than 200 years (sometimes less than 20 years), while long-period comets like Hale-Bopp and Hyakutake have orbits ranging from 200 years to more than a million years. In addition, short-period comets have orbits inclined within 40° of the plane in which the Earth orbits, while long-period comets are isotropically distributed. These differences imply that the two groups of comets originated in different places. The orbits of the long-period comets can be traced back to their source—the Oort cloud—a vast diffuse shell of comets that has never been observed but is hypothesized to envelop our solar system and extend halfway to the nearest stars. Bodies within the Oort cloud are so weakly bound by the Sun's gravity that passing stars can perturb their orbits, causing them to fall toward the inner solar system. It is estimated that the number of comets in the Oort cloud could be in the trillions and their origin is not yet understood, but it is likely that they comprise material ejected from the outer solar system and could include some asteroids. In the farthest reaches of the Oort cloud, noontime temperatures would be as low as 33 K above absolute zero.

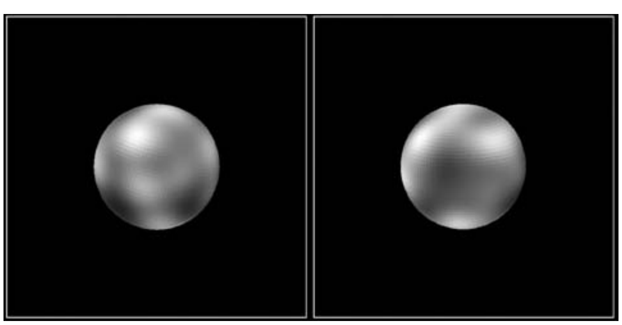

Figure 14. Hubble Space Telescope images of the two hemispheres of Pluto. The bright and dark regions on its surface may be the result of bright frost migration. (Images courtesy of A. Stern and M. Buie/NASA/ESA.)

Some short-period comets, with high inclinations and orbits of between 20 and 200 years, probably also come from the Oort cloud. The remaining short-period comets originate in the Kuiper Belt beyond Neptune's orbit. The first of these trans-Neptunian objects was directly observed in 1992, and the number of known objects has increased rapidly since then to almost 400 today. It is estimated that the Kuiper Belt may contain as many as 35,000 objects more than 100 km in diameter. One recent discovery, the Kuiper Belt object Quaoar at around 1250 km in diameter, is half the size of Pluto and slightly larger than Pluto's moon Charon.

Comets are composed of a primitive mixture of dust, gas, and ice, possibly unchanged from when they formed in the coldest regions of the solar system 4.5 billion years ago. As such, they are excellent laboratories to study the composition of the early solar nebula. Their interiors are thought to be a conglomerate of ice and dirt (the "dirty snowball" model first coined by astronomer Fred Whipple in 1950). As the comet approaches the Sun, the surface layers become warm enough that ices begin to sublimate, leaving behind a dusty crust that insulates deeper layers. Irregular areas may sublimate faster, producing "jets" of material and resulting in the irregular shape of the nucleus. When comets approach the Sun, outgassed ice and dust form a large but tenuous atmosphere called a "coma." The Sun's radiation pressure and solar wind exert a force on the coma. This creates a dust tail, which is left behind along the comet's path, and an ion (gas) tail, which always points directly away from the Sun since it is more strongly affected by the solar wind and follows magnetic field lines. Comet nuclei are generally less than 50 km across, but their tails can extend 1 AU or more. Recent probes to comets have shown that they are extremely dark, possibly because of complex organic compounds. This is consistent with sublimation of ices near the surface during outgassing, leaving heavier, tar-like organics behind.

The actual amount of ice in comets is still unknown. Investigation of comet Borelly by the NASA Deep Space 1 mission showed a dry surface with no traces of water ice, although it may have been buried or masked by the dark material on the surface. Jets were observed, however, indicating that volatiles must be present. Spectra from instruments onboard the recent Deep Impact mission also showed evidence of water on comet Tempel 1 after the spacecraft dropped its impactor onto the surface, and an interpretation of the results is still under way.

Images of the surfaces of comets show a variety of landforms that appear to be related to impact cratering, sublimation, and perhaps fracturing and landslides (Fig. 15). These look very different from the landforms we have observed to date on icy moons, and by comparing and contrasting them to other ice features, we can investigate how morphological processes vary on icy solar system bodies of different sizes and compositions.

CONCLUSION

The study of ice presents particular challenges, not only in the need for specific technologies and instruments, but also in the commitment to long-term scientific goals and exploration that may not be realized for decades. We are beginning to understand how ices contribute to the formation and evolution of planets, moons, and small bodies; however, we still have much to learn about the unique and fascinating role of ice in the solar system.

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Figure 15. Left: Nucleus of comet Wild 2 imaged by the NASA spacecraft Stardust. The nucleus is ≈5 km in diameter. Right: Nucleus of comet Tempel 1 a few minutes before the Deep Impact probe smashed into it, forming a crater. The nucleus is about 5 km in diameter and 7 km at its long dimension. Both comets show ample evidence of sublimation and venting, but Tempel exhibits some smooth areas and appears less degraded overall. (Left image courtesy of NASA/JPL-Caltech; right image courtesy of NASA/JPL-Caltech/University of Maryland.)

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THE AUTHOR

Louise M. Prockter is a member of the Senior Professional Staff at APL. She has a Ph.D. and an M.S. in planetary geology from Brown University and joined the Space Department in 1999 as a postdoctoral researcher. Dr. Prockter was an imaging team affiliate on the Galileo and NEAR missions and is currently the Deputy Instrument Scientist for the Mercury Dual Imaging System on the MESSENGER mission. Her research includes studying the surfaces of icy satellites and asteroids and investigating new mission and instrument concepts. Dr. Prockter is currently a member of the National Academy of Sciences Committee for Planetary and Lunar Exploration (COMPLEX), an editor for the scientific journal *Icarus*, and the Secretary/Treasurer of the Geological Society of America Planetary Division. Her e-mail address is louise.prockter@jhuapl.edu.

Louise M. Prockter