6 Enceladus: An Active Iceball in Space

At about 6:00 PM on a Friday afternoon in January 2005, I was sitting in the waning light of my JPL office and daydreaming about my activities for the weekend. I was startled by the sudden sharp ring of the phone, which I answered promptly – all the travel audit people and administrators wanting a favor done would have left. On the other end was Trina Ray (see Figure 6.1), a crack *Cassini* science planning engineer who was in charge of leading the plans for *Cassini*'s close flybys of Titan. She was sitting in the office of Brian Paczkowski, another fabled JPL engineer who led the science planning office, and they were poring over an image of Enceladus, a small icy moon of Enceladus, that had been taken in November 2004.

"Bonnie, let me email you this image of Enceladus. We've been looking closely at an enhanced version of it. It looks like it has a plume," said Trina.

"Okay, send it over," I said.

I downloaded and looked at the image and sure enough, there appeared to be a tenuous, but well-formed, plume about the size of the crescent moon itself, which is a little over 300 miles from end to end (Figure 6.2). For comparison, our own Moon is 2,159 miles in diameter – you could fit 373 Enceladuses inside the Moon. Even though it was past 9:00 PM on the East Coast, I immediately called Paul Helfenstein of Cornell University, the Imaging Science Subsystem (ISS) representative of the group I was leading to plan all the *Cassini* targeted flybys of Enceladus and the other saturnian satellites.

"No, Bonnie, we are pretty sure that isn't a plume. We've looked at the image, and saw the 'plume,' but we think it's scattered light from the camera. But we're going to do some more tests to make sure." I didn't know it at the time, but Paul immediately called other

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FIGURE 6.1 Trina Ray of JPL.

FIGURE 6.2 An enhanced image of Enceladus obtained by the *Cassini* camera on January 16, 2005 when it was 100,000 miles from *Cassini*. A possible plume-like structure is visible off the lit crescent of the moon. NASA/JPL-Caltech. Image processing by Tom Momary.

members of the imaging team to clue them in on our discovery. There was a disagreement on the imaging team at that point. Some members were certain that they had discovered activity on the tiny moon, while another faction led by Carolyn Porco, the *Cassini* Imaging Team leader, was adamant that the features their instrument had detected were not plumes.

Trina, Brian, and other *Cassini* project personnel spoke to Project Manager Bob Mitchell about their findings, and Mitchell spoke to Porco about them. She said in an email to Mitchell that she was certain the tenuous distended feature that was seen in the November 2004 image was not an active plume from the surface of Enceladus. Porco was following the usual conservative approach of the careful scientist to explain an extraordinary scientific phenomenon by a

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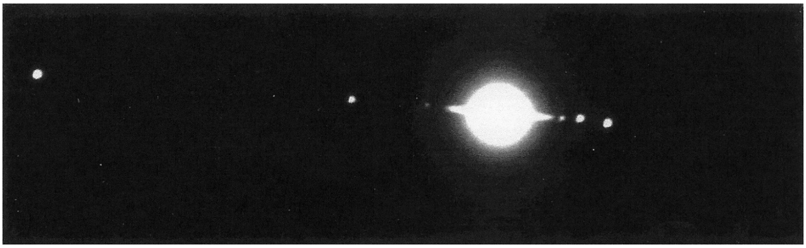

FIGURE 6.3 An image from the 60-inch telescope on Palomar Mountain during ring plane crossing in 1995. Enceladus is the bright point just to the right of the rings. From left, the other moons are Titan, Rhea, Mimas, Tethys, and Dione. This is an enhanced version of an image obtained on the same observing run as the image shown in Figure 7.1, stretched to show the inner moons.

pedestrian explanation, similar to the tack taken at the time of Linda Moribito's discovery of Io's plume 25 years earlier (see Chapter 5). But some members of Porco's team, as well as our team at JPL, had the hunch that something was there. Events would soon unfold that show again how disagreement drives scientific discovery.

Enceladus had already acquired a reputation as a mysterious and intriguing object. The moon is usually swallowed up by bright light from the rings and body of Saturn, but once every 15 years or so, when the rings appear edge on to the Earth and seem to disappear, the tiny moon pops up from the black sea of space surrounding Saturn. Figure 6.3 is an enhanced version of an image I took while I was observing with my colleagues Dick French, Phil Nicholson, and Colleen McGhee at the 60-inch telescope on Palomar Mountain during such a "ring plane crossing" in 1995. The rings appear as tiny "ears" (to use Galileo's expression), but the inner satellites are bright and clear. Enceladus was discovered by William Herschel on August 28, 1789, during another Saturn ring plane crossing. Earlier that year, Herschel had finished his largest telescope, the clunky 40-foot that reigned as the most massive telescope for over 50 years. In 1795, he wrote that "having brought the telescope to the parallel of Saturn, I discovered a sixth satellite of that planet [the others were Tethys, Dione, Rhea, Titan, and Iapetus, all discovered between 1655 and

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1684 by Huygens or Cassini]; and also saw the spots upon Saturn, better than I had ever seen before, so that I may date the finishing of the 40-foot telescope from that time."[1] Three weeks later Herschel discovered the seventh moon of Saturn, Mimas, but the more agile 20-foot instrument remained Herschel's favorite. For Herschel and his assistants, the changing of the 40-foot behemoth's one-ton mirrors caused "many hair-breadth escapes from being crushed."[2]

My viewing of Enceladus in 1995 was the only time I ever saw this moon from an Earth-based telescope. (During the next ring plane crossing in 2009 I was too inundated with data from *Cassini* to work on any telescopic data.) I had been studying the moon for nearly 15 years from *Voyager* and *Cassini* images, but I had never seen the little moon in real time (well, almost real time – it takes light over an hour to reach us from Saturn's distance. But when data are gathered from spacecraft it takes about a day for a scientist to receive it because it has to be stored on the flight computer first until there are enough data to relay to one of JPL's large radio telescopes that are part of the Deep Space Network). Fourteen years later, while I was at the Royal Observatory Greenwich in London for the June 2009 *Cassini* Project Science Group meeting and doing an interview for *National Geographic*, I saw the single remaining fragment of Herschel's 40-foot instrument, lovingly posed in the Observatory gardens. Figure 6.4 is a picture I captured of this sublime moment, and Figure 6.5 shows the picture John Herschel (son of William) took of the same telescope 169 years earlier, at the dawn of photography, during the instrument's decommission. Note that the tube itself is on its side; apparently John was afraid the rotten tube would crumble and hurt his children.

When the two *Voyager* spacecraft hurtled by the moon in 1980 and 1981 to transform Enceladus from the tiny light seen in Figure 6.3 to a tangible world, they found a strange body indeed (see Figure 6.6). Part of the moon was covered with the scars of impact craters and was at first glance old looking – your typical icy satellite. But other parts of Enceladus appeared to have undergone melting and refreezing, as if the moon had been subjected to a catastrophic period of high activity.

FIGURE 6.4 A small segment of Herschel's 40-foot telescope at the Royal Observatory Greenwich.

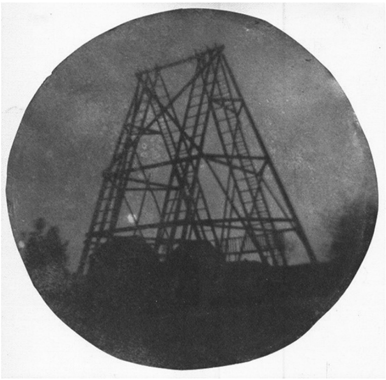

FIGURE 6.5 John Herschel's photograph of the same telescope, obtained in 1849, near the dawn of the age of photography.

These parts of the surface were smooth and crater free (see Figure 6.6). But Enceladus was unlike any other moon that showed activity: both old and young parts of the moon were very bright and reflective. In fact, they were as bright as freshly fallen snow on Earth. Other moons in the Solar System – for example Ganymede from the last chapter – have old and young areas, but in general the older areas are darker, mainly from accreting interplanetary dust – the same dust that falls on the Earth and sometimes makes it to your coffee table (although

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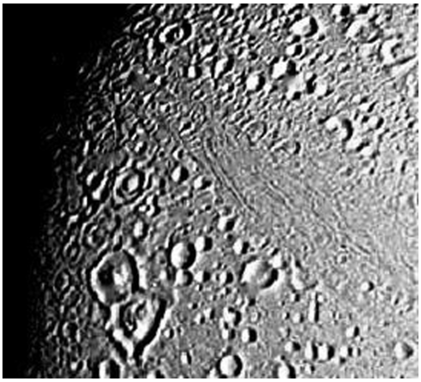

FIGURE 6.6 The best *Voyager 2* image of Enceladus, taken about 54,000 miles away on August 26, 1981. Most of the moon's terrain looks old and cratered, but there is a smooth plain in the center, suggesting some active geological process on the moon. Even more intriguing, the surface reflects nearly 100% of the sunlight falling on it, as if it were covered in freshly fallen snow. NASA/JPL-Caltech.

as mentioned in Chapter 4 *most* of the dust in your living room is from more mundane sources such as lint, cat dander, and just plain dirt). Scientists can even estimate how old a surface is by measuring how dark it is. But Enceladus was not dark *anywhere*. The young, resurfaced areas were bright, but the older cratered regions were just as bright. The moon just looked like its entire surface was covered in bright snow.

I often wonder what it would be like to just walk the surface of this sparkling winter wonderland, or to ski on it. And to planetary scientists, bright signals fresh and new, something that could only be produced by an active geologic process. Moreover, this process would have to propel material above the surface and subsequently cause it to "rain" down upon the entire icy world. A geyser or a volcano with a large plume seemed to be the only thing that could possibly explain the appearance of Enceladus. But after all the ridicule Al Cook and his team had received over their claim of an active geyser on Europa, putting a plume on Enceladus was a hard sell.

Kevin Pang was the first planetary scientist to claim that Enceladus was erupting ice volcanoes. My colleague Anne Verbiscer of the University of Virginia made a very definitive claim for geysers on Enceladus, and reiterated an idea from an earlier paper I wrote with Joel Mosher and Torrence Johnson that bright ice particles from geysers were being launched into space and coating the other moons of

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Saturn ("Cosmic graffiti artist caught in the act," as her *Nature* paper stated).

Another mysterious aspect of Enceladus is that it is bathed in the tenuous, bloated E-ring of Saturn. This ring is even thinner than air on the surface of the Earth. We are all familiar with the bright, charismatic main ring system of Saturn. It is one of those breathtaking sights you remember the first time you see it through a telescope, or when you view the spectacular images sent back by the two *Voyager* spacecraft of fine ringlets, seemingly etched on the sky by the stylus of a giant cosmic record player. It is what makes Saturn famous. As the *New Yorker* stated so succinctly in a poem years ago: "Why study Saturn? Because of the rings!" But the E-ring is so faint it wasn't even discovered until 1980, when Bill Baum and his colleagues at Lowell Observatory placed a super-sensitive new-fangled – then, at least – charge-coupled device (CCD) being developed as a training camera for the *Hubble Space Telescope* Science Team on a 60-inch telescope owned by the US Naval Observatory. This telescope was not among the largest in the world at all. It was the new sensitive detection powers of the CCD that led to the detection of the E-ring, illustrating that the introduction of a new technology often leads immediately to new discoveries. Now that technology is part of every cell phone camera. Baum and his colleagues realized that the ring was of recent origin – otherwise it would have flattened out into a much thinner ring. Later scientists noticed that the densest part of the E-ring is at the orbit of Enceladus, as if the moon were the source of the ring.

Was the E-ring named after Enceladus? No. Scientists weren't aware of any connection between Enceladus and the E-ring when it was first discovered: Saturn's main rings are named sequentially after the letters of the alphabet: A, B, C, D, and so on. E just happened to be the next letter in line. But as we shall see, it was a fitting designation.

There had also been nagging observations of Enceladus by generations of astronomers who hinted at its weirdness. Percival Lowell makes another appearance in 1913, when he and Lowell Observatory observer E. C. Slipher reported that one side of Enceladus was about

30% brighter than the other. Then in 1972 to 1973, Otto Franz and Robert Millis, also of Lowell Observatory, observed a similar brightening on the same side. Moreover, these brightenings both occurred when the south pole of Enceladus was visible from Earth. I remember sitting for hours in my graduate student's office perplexed by the observations of Otto Franz and Bob Millis. Their observations did not agree with what I was seeing in the *Voyager* data – a uniformly bright world – but I knew that Franz and Millis were very careful, reliable observers, so it was extremely unlikely that their data were bad. It is often these nagging little details – things that just don't quite fit together – that mean a discovery is on its way.

After the reconnaissance mission of the two *Voyagers*, which visited all four of the giant gaseous outer planets, Jupiter, Saturn, Uranus, and Neptune, NASA embarked on a program of sending individual spacecraft for closer scrutiny of each one. *Galileo* studied Jupiter and its moons for nearly eight years, starting in 1995. The *Cassini* spacecraft was built to launch in 1995 for a four-year study of Saturn, its moons, and rings, to start in 2002 (the mission was extended for three additional periods: it is now scheduled to end in 2017). Named after Giovanni Domenico Cassini (1625–1712), the Italian astronomer and astrologer (yes, the two disciplines were not yet separate) who was the first director of the Paris Observatory, the program was originally to be part of a two-for-one program. *Cassini* was going to Saturn, but a second spacecraft, the *Comet Rendezvous Asteroid Flyby (CRAF)* was to greet comet Kopff for a three-year tour and the bonus of a flyby of an asteroid on the way. *CRAF* was the first mission to be developed, but when budgetary competition between the two missions developed, *CRAF* was canceled and all its funds were redirected to *Cassini*. I took the cancellation of *CRAF* pretty hard, because early in my career I had been selected by NASA Headquarters to serve on its elite Imaging Team: all that work for nothing. But I was having a lot of fun on *Cassini*, which was delayed for two years after further budgetary and technical problems. This Cadillac among spacecraft has 12 instruments, including four cameras to detect

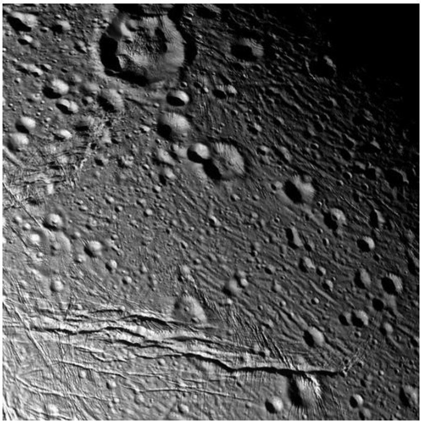

FIGURE 6.7 An image from first targeted flyby of Enceladus by *Cassini* on February 17, 2005, which approached to within 700 miles. NASA/JPL-Caltech.

signals all the way from the ultraviolet to the infrared, a radar mapper, and several instruments to detect particles and magnetic fields in the area around Saturn. The mission was executed as a joint program with the European Space Agency, with the Europeans building the sophisticated *Huygens* probe to land on Titan, the giant moon of Saturn (see Chapter 7).

Our excitement ran high as *Cassini* made its first close pass by Enceladus on February 17, 2005, approaching to within 700 miles. The spacecraft captured the illuminated face of Enceladus crossed by giant cracks and faults, and fresh, bright, snow-like deposits coating the entire moon, but there was no hint as to how this wintry landscape formed (Figure 6.7). During the next flyby, on March 9, *Cassini* swooped to within 450 miles of the surface of Enceladus, to provide more similar views of the ice world: intriguing but no smoking gun. This feat of accurately bringing the spacecraft so close to the surface of the moon while their relative velocity was about four miles per second was perfectly executed by the legendary Navigation Team at JPL. Their skills are akin to throwing a basketball from the Rose Bowl in Pasadena, California and landing it in the hoop at Madison Square Garden in New York City.

But now Enceladus was beginning to reveal some of its secrets. *Cassini*'s magnetometer detected a draping of the magnetic field of

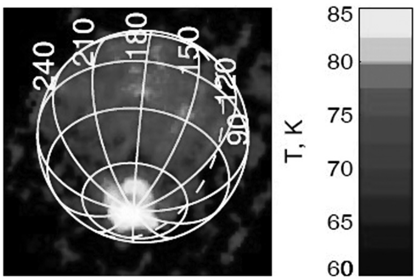

FIGURE 6.8 John Spencer's infrared image showing a large heat anomaly in the southern hemisphere of Enceladus. Courtesy John Spencer. See plate section for color version.

Saturn around the southern tip of Enceladus, as if it had met a barrier to its smooth flow. Previously the Cosmic Dust Analyzer had found evidence for a thin atmosphere. Michele Dougherty of Imperial College London, the Principal Investigator of the Magnetometer, made a pitch to the Project to lower the closest approach of the next flyby on July 14 to a breathtaking 102 miles. Most other *Cassini* scientists supported her request, and Bob Mitchell approved it, after conferring with his spacecraft safety team. One of the last holdouts continued to be Carolyn Porco, who sent an email on April 14 to John Spencer of the Southwest Research Institute, a member of the Composite Infrared Spectrometer (CIRS) Team, and several other *Cassini* scientists that stated "This sounds crazy to me . . . for the Project to tweak the tour when we're not sure that the 'thing' is real. I have encouraged my team members to act on this quickly to verify whether or not it is real. The last I heard is that it wasn't."

A few days after the July 2005 flyby, Spencer sent a few *Cassini* scientists a wondrous and historic image of Enceladus (Figure 6.8). We have all seen those infrared images of tigers burning bright in the forests of the night, or of lost people appearing in the cameras of heat-seeking helicopters. Well, Spencer showed us an infrared image of the south pole of Enceladus – the part of the moon that should have been the coldest, and devoid of a significant infrared signal. It was a blaze of heat! He had discovered the "smoking gun" that we were all seeking. The first view of the Pacific Ocean by Lewis and Clark, the first view of Half Dome by John Muir, the first view of Monument Valley

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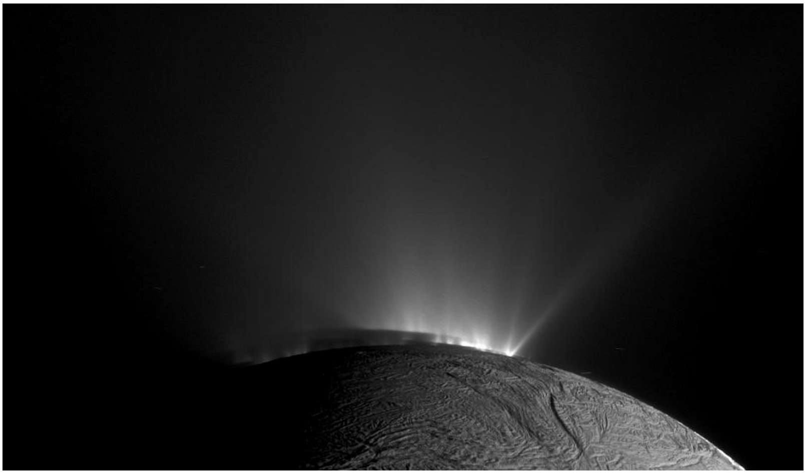

FIGURE 6.9 An image of the plume obtained on November 30, 2010 seemingly composed of smaller jets. JPL PIA 17184.

by Everett Ruess, and your own first view of the Grand Canyon – the thoughts and feelings evoked by these sightings were ours as we viewed that image. *Voyager 2* had never seen the South Pole of Enceladus because of a technical glitch: the scan platform that moved the camera and could have pointed to the South Pole had become stuck. Finally, in November 2005, Porco and her team, who now fully accepted the idea of geysers on Enceladus, used the *Cassini* camera to shoot a picture of a glorious crown of plumes perched on the globe of the moon. Even better images were soon gathered such as the one in Figure 6.9.

The area of the greatest heat was the location of one the oddest terrains on any planet or moon – a crater-free area filled with tiny grooves and four bigger cracks about 300 m (984 ft) deep called "tiger stripes" (Figure 6.10). In the whimsical way that the International Astronomical Union names features on the planets, the four tiger stripes are eponyms of cities in the Middle East: Cairo, Baghdad, Damascus, and Alexandria. Boulders and large rocks surround the tiger stripes, as if they were ejected during particularly violent eruptions (Figure 6.11). A bluish hue surrounds the stripes, perhaps

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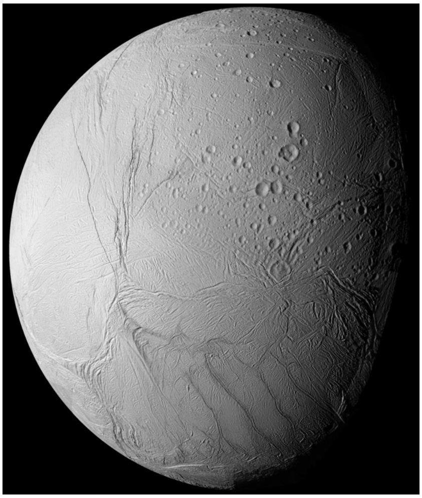

FIGURE 6.10 The tiger stripes in the south pole of Enceladus are named after cities in the Middle East: (left to right) Damascus, Baghdad, Cairo, and Alexandria. NASA/JPL-Caltech. See plate section for color version.

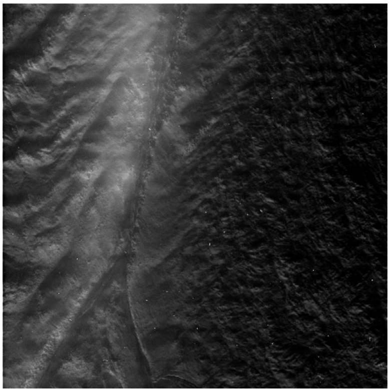

FIGURE 6.11 The flyby of August 13, 2010 showing the tiger stripe Damascus caught between day and night. Icy particles appear to be arising from the surface openings. NASA/JPL-Caltech.

because the particles that stay near the vents are heavier and bigger. One image taken at dusk shows what appear to be icy particles rising from a vent (Figure 6.12). Molecules containing the building blocks of life – hydrogen, carbon, oxygen, and nitrogen – were discovered in the plumes by *Cassini*'s particle detectors and on the surface by the Visual Infrared Mapping Spectrometer (VIMS). These molecules are often called "prebiotic" or "organic," because they are necessary for life to arise and to be sustained.

The energy production from the activity on Enceladus is enormous. Recent work by John Spencer and Carly Howett, also at

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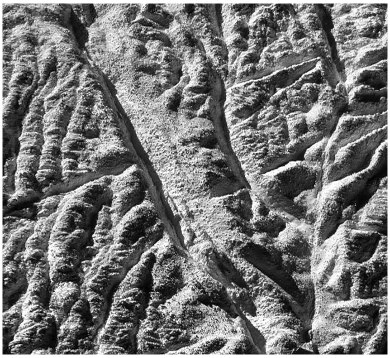

FIGURE 6.12 The flyby of November 21, 2009 showing boulders and the tiger stripes close up. The image is about seven miles on each side. NASA/JPL-Caltech.

Southwest Research Institute, suggests the heat output is about 5 GW – 5 followed by 9 zeros, in watts, the scientific unit for power. This is enough power to heat 4 million ovens running at 350°F. Another way of understanding this energy: Enceladus provides enough constant energy to power a city the size of Philadelphia.

Why is this tiny world the only icy moon that has a boiling cauldron? We don't know yet. We are still at the stage of gathering all the data we can and producing models that make sense. But most models of Enceladus's activity center on two main sources of energy: radioactivity and tidal effects. Of the icy moons of Saturn, Enceladus has the largest fraction of rocky material in its core (except for Phoebe, which was probably captured as it wandered in from the outer reaches of the Solar System). Radioactive elements such as uranium and thorium tend to be chemically bound with rocks, so the more rock a moon has, the more heat from radioactive elements it will produce. Such radioactive decay is the source of most internal heat on the Earth, and the driver of terrestrial geologic processes. But for Enceladus, there isn't enough radioactive heat to drive the plumes. Tidal energy from Saturn must add some heat. Enceladus is also in a special dynamical relationship with Dione: Enceladus orbits twice for each time Dione orbits. This orbital mean motion resonance causes an extra "tug" by Dione each time they are near each other in their orbits. The tug isn't as great as that acting on volcanically active Io by Europa and Ganymede (Chapter 5), and most scientists don't believe the tidal

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forces are sufficient to explain the vast amount of heat emanating from the south pole of Enceladus. Francis Nimmo of the University of California at Santa Cruz suggested that frictional heating from the motion of faults below the tiger stripes may provide additional heat. Perhaps the activity is cyclic, where heating, cracking, cooling, and closing of the vents occurs in spurts over tens of millions of years. If this idea is correct, we are just lucky enough to see Enceladus in one of its active periods. "Fossilized" tiger stripes near the equatorial regions of Enceladus speak of past episodes of activity on the moon.

An important point that was unresolved until 2014 is whether liquid water is powering the jets. Almost from the time we discovered the plume on Enceladus, most scientists believed a liquid ocean underneath the surface of Enceladus provided the material for the plume, and that as the water is expelled under high pressure it is rapidly quenched into small spherical particles. This transition from liquid to solid produces the heat seen at the surface. Susan Kieffer of the University of Illinois presented a counter-theory that the activity is powered by chemical reactions in ammonia that is chemically combined with water ("clathrates" in the chemist's lingo). One piece of evidence strongly implies Enceladus has a liquid ocean: the particles in the plume are frozen salt water. On the Earth, salt water in the oceans is formed by the endless cycle of rain dissolving, washing out, and transporting minerals such as salt to the Earth's seas. On Enceladus, the only way to get salt into the plume particles would be for a submerged ocean to dissolve it out from a rocky mantle in contact with liquid water. Finally, Candice Hansen of the Planetary Sciences Institute and the Ultraviolet Imaging Spectrometer team showed that particles in the plume are supersonic, which strongly suggests they are being vented as liquid jets.

Even more proof arrived for an ocean under the surface of Enceladus that was powering the jets. My colleague Jay Goguen performed a very clever experiment with VIMS during a flyby on April 14, 2012 when *Cassini* approached to within 50 miles of the surface. He designed an observation to put the instrument in "point" mode

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and to drag the detector across the face of the tiger stripes. Goguen and his team (which included me) were able to show that the emitting regions for the plumes were hot and small – about 200 kelvin (–100°F or –73°C), still cold by terrestrial standards, but 250°F (121°C) warmer than it should be – and only about 30 feet in size. Then another VIMS Team member, Matt Hedman of the University of Idaho, showed that the plume was more intense when Enceladus was further from Saturn, when tidal forces were smaller and the cracks at the tiger stripes would open up to let vapor escape. The Radio Science Team analyzed how the tiny moon pulled the spacecraft during its approaches, and the best conclusion was that there was a liquid ocean lying beneath the tiger stripes that extended about halfway up to the equator. Finally, Peter Thomas of Cornell University and his colleagues analyzed wobbles in the orbit of Enceladus and concluded that the ocean had to be global, similar to Europa's alien sea.

Meanwhile, Porco and her team were busy locating the position of over 100 jets seen in *Cassini* images. She confirmed that they came from small hot spots that Spencer and Goguen and their teams had mapped on the tiger stripes. Frictional heat could not be a major source of heat because the entire tiger stripe was not very hot and yet it was ejecting a great mass of water vapor. It is important to recognize that the models of Sue Kieffer on ammonia clathrates and Francis Nimmo on frictional heat were completely valid theories at the time they were presented. Conflicting theories compel scientists to gather more data and arrive at scientific truth. Without disagreement science does not progress. Nimmo in fact did some later theoretical work on the nature of the tides in the liquid ocean and its interaction with the surface of Enceladus. And later Joseph Spitale of the Planetary Science Institute presented convincing evidence that many of the jets were not real. Instead, the water was ejected as a curtain, and that many of the jets were just more dense regions of the curtain, or sections seen edge-on.

Enceladus was literally "bursting at the seams" (as JPL described in a press release), but why are the seams only at the south pole? The tiger stripes are in a basin, but why is the basin where it is? Bob Pappalardo and Francis Nimmo developed a clever idea from classical geology that a diapir, a lighter blob of material, moved up from the interior of Enceladus into the more brittle ice crust of the moon. This process is similar to the wax rising in a lava lamp. Once the material rose to leave a density deficit in the interior of the moon, the rotation axis realigned to the most stable configuration, which was to have it where the density was lowest.

One question we haven't answered yet is how variable the geysers on Enceladus are. For all of you used to sitting on that bench at Yellowstone and waiting for Old Faithful to come out at its appointed times, we haven't seen anything like that on Enceladus. So far the plumes appear to be fairly stable, over time periods of years.

Enceladus is truly a world fantastic, but in one way it is a world familiar: it has a habitable environment. When we explored Europa, we found that it almost certainly has a liquid ocean below the surface. Just as Europa does, Enceladus possesses the three main requirements for life: liquid water, food (the "prebiotic" molecules), and a source of energy. In 2015, NASA announced that there are warm jets of water erupting on the floor of the subsurface ocean: these "smokers" are ideal locations for life to form, similar to the oceanic vents around which life on Earth is believed to have arisen. There is currently no evidence that life exists on Enceladus and, if it did, it would probably be bacteria or other primitive life forms. NASA is currently studying a mission to Enceladus that would include a radar sounder to peer below the surface and to map the extent of any ocean. Seismometers on the surface would reveal the depth of the ocean and its extent in great detail. But such a mission is very expensive and there are currently no funds in NASA's budget to start this attractive mission.

It took us a long time to discover the plumes and the hot spot on Enceladus. Both *Voyager* spacecraft flew by Enceladus without discovering any of the good stuff on Enceladus, and during the first close targeted flyby by *Cassini*, the moon's active region never entered the spacecraft's field of view. Is it possible that other moons of Saturn have plumes or other types of activity waiting to be discovered? In 2007, Jim Burch of the Southwest Research Institute and his colleagues discovered that both Dione and Tethys seemed to press against the

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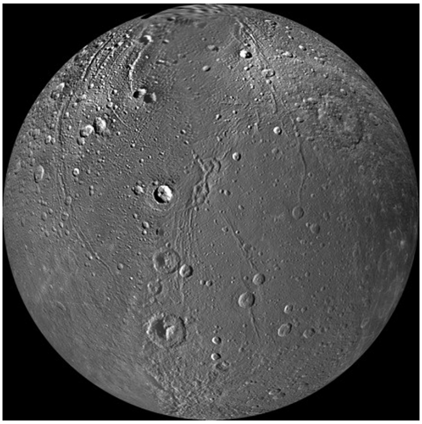

FIGURE 6.13 Dione shows possible cryovolanoes in the middle, with some cracks in the surface and global powdery deposits. NASA image processed by Paul Schenk.

magnetic field of Saturn. They attributed this interaction to streams of particles coming from the moons. Krishan Khurana of the University of California at Los Angeles and a member of the magnetometer team reported an outflow of material from Dione of about 0.6% (less than a hundredth) of the material from Enceladus. Perhaps even more intriguing, an image of the south pole of Dione shows what appear to be old, perhaps inactive, tiger stripes, and Paul Schenk of the Lunar and Planetary Institute has identified what he believes to be ice volcanoes on Dione (see Figure 6.13). These volcanoes are surrounded by what appears to be a huge plain of fine particles. Could this plain have been created by material expelled from the ice volcanoes and reaccreted back on to the surface? Roger Clark at the Planetary Sciences Institute detected a transient atmosphere around Dione in 2005 with one of the *Cassini* instruments, but he hasn't seen it since. In spite of vigorous plume searches, we haven't discovered any plumes yet from Tethys or Dione. Could the "plumes" causing the disturbances in Saturn's magnetic field just be anemic puffs outgassing from an old, almost inactive tiger stripe or a small vent? We just don't know. We will continue to look, but the question of activity on Dione may never be answered in the lifetime of the *Cassini* mission.

Speaking of lifetimes, all spacecraft eventually die, like creatures of flesh and blood. NASA does not like to fund missions forever,

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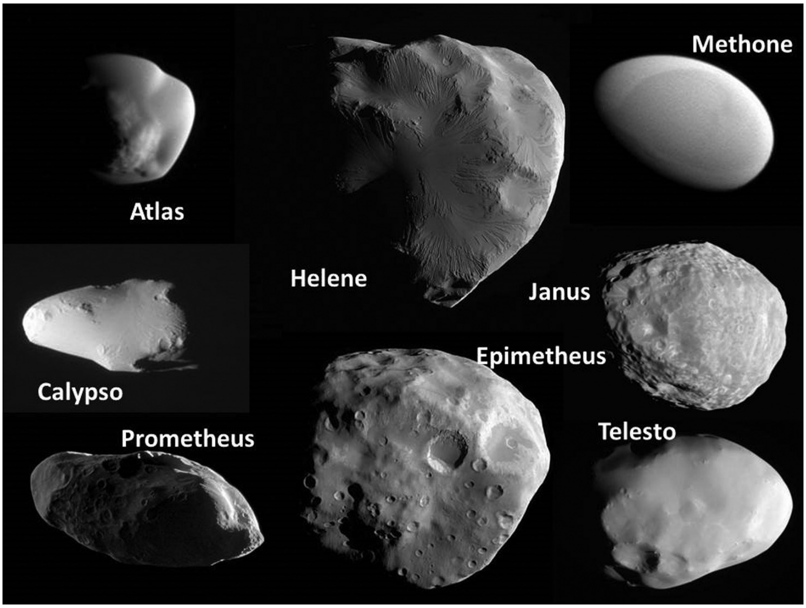

FIGURE 6.14 A montage of some of the small moons of Saturn, showing diverse surfaces ranging from ones that are heavily cratered to those that are entombed in a coat of icy particles. These particles have tumbled down almost like avalanches from the rugged crags of Helene and formed a little skirt around Atlas. The sizes of the moons are not to scale. Their mean diameters in miles are: Atlas, 19; Helene, 22; Methone, 2; Calypso, 13; Prometheus, 53; Epimetheus, 72; Janus, 110; and Telesto, 16. Figure constructed by the author, based on NASA images.

as new and better projects are waiting patiently in line to come to life. We *Cassini* scientists have decided to end our spacecraft violently, by plunging this marvel of human engineering into Saturn. At the end of the mission in late 2017, *Cassini* will orbit Saturn in an ever-tightening series of orbits, including some daring passes between the rings and the planet itself. This death spiral will offer unprecedented views of the great globe of Saturn and its rings, with a breathtaking final descent into the depths of the planet. We will swoop to within a few thousand miles of some of Saturn's strange small moons (jokingly called "Rocks" by our Science Team). Figure 6.14 shows a montage of these strange moons compiled for our NASA "Senior

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Review" in 2014 when a team led by *Cassini* Project Scientist Linda Spilker argued before NASA Headquarters that we should be allowed to explore until 2017.

In *Cassini*'s final plunge into the cloud tops of Saturn, the pressure of the planet's thick atmosphere will crush the spaceship and eventually dissolve its parts to mix with the stuff of Saturn: a fitting grave to this gallant robot. We will be taking data as long as we can. With that first touch of humanity to the farthest planet known to the ancients, Enceladus, which peeked out behind the veil of scattered light from Saturn to reveal its face, will go back into hiding, awaiting another generation of scientists to step forward and lift its veil again.

NOTES

1 Herschel, W. 1795. Description of a forty-feet reflecting telescope. *Philosophical Transactions of the Royal Society of London* 85, 347–409.

2 Herschel, C. 1879. Memoir and correspondence of Caroline Herschel. Edited by Mrs. John Herschel, quoted in *The Age of Wonder*, by Richard Holmes (Pantheon, New York) 2008, p. 191.