

Watery Enceladus

John Spencer

In 1980, telescopes revealed that one of Saturn's rings is centered at the orbit of Enceladus, a medium-sized Saturnian moon. It was the first hint that Enceladus is a world like no other.

Finding liquid water is a fundamental quest of planetary science. Because H_2O is the simplest stable compound of the first and third most cosmically abundant elements, it is one of the commonest molecules in the universe. Our solar system is no exception: During its formation, temperatures in the protosolar nebula were low enough that water ice could condense in most places beyond what is now the asteroid belt. The solid worlds of the outer solar system thus tend to be rich in water ice, and the moons of the giant planets typically comprise roughly equal parts rock and ice.

From our parochial point of view as biological entities, however, H_2O is most interesting in its liquid form, which is essential for the maintenance of life on Earth. If life exists elsewhere, the best places to look for it are those with liquid water. Compared with ice and water vapor, liquid water is stable over a narrow range of temperature and pressure. So it is relatively rare in the solar system. But Jupiter's large moon Europa has been a center of attention for planetary scientists since the late 1990s, when the *Galileo* orbiter discovered evidence for a global water ocean beneath Europa's icy surface. More recently, the *Cassini* orbiter has revealed a place that not only probably hosts liquid water but also is obligingly launching fresh samples of that water into space for analysis by spacecraft instruments. That place is Enceladus—a moon of Saturn 500 km in diameter.

Knowledge prior to *Cassini*

Enceladus, discovered in 1789 by William Herschel, has intrigued astronomers since the 1980s.¹ For nearly 200 years it had been an undistinguished member of the Saturn system, one of five medium-

sized satellites circling the planet between the outer edge of the main ring system and the orbit of Saturn's giant moon Titan (see figure 1). The first hint that something exceptional was happening there came in early 1980 when scientists using Earth-based telescopes acquired new images of a faint outer ring of Saturn—the E ring—which had been discovered in the 1960s. Those images revealed that the ring's brightness peaked at the orbit of Enceladus. They also showed that unlike Saturn's other rings, the E ring scattered sunlight more efficiently at shorter wavelengths, which indicated that the ring was dominated by particles not much larger than the wavelength of light. Sputtering by charged particles in Saturn's magnetosphere would erode away such micron-sized particles on time scales of decades to hundreds of years, so something had to be replenishing the ring on comparable time scales. The peak in ring density at Enceladus pointed to that moon as the likely source.

Shortly thereafter the *Voyager 1* and *Voyager 2* spacecraft returned the first detailed images of Enceladus and the other major Saturnian moons. The surfaces of most of the moons appeared ancient, dominated by impact craters formed early in the solar system's history. But Enceladus looked very different. Much of its surface was almost crater free; instead, it was covered by tectonic fractures that evidently had formed relatively recently. The *Voyager* images also revealed that Enceladus reflects about 80% of the sunlight it intercepts and thus has the highest albedo of any known solar-system object. Ground-based spectroscopy of 1- to 2.5- μm -wavelength sunlight reflected from the surface of Enceladus and its neighboring moons showed the characteristic molecular vibration absorption bands of water ice, but the impurities that darkened the ice on the other moons appeared to be almost absent on Enceladus. Some scientists speculated that a tidal heat source inside Enceladus was generating the ob-

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Figure 1. Enceladus and the four other midsize moons of the inner Saturn system are depicted in this artist's conception, drawn to scale (though moon sizes are exaggerated for clarity). The diffuse E ring exhibits a spike in density at the orbit of Enceladus.

served tectonic activity that perhaps included geyser-like eruptions that could generate the E ring and coat the surface with clean ice.²

In the 1990s the *Hubble Space Telescope's* observation of 0.309- μm emission revealed a different kind of ring—a Saturn-circling torus of OH molecules. Like the collocated E ring, the OH torus seemed to require a continuous source of material in the vicinity of Enceladus.³

A geologically active moon

The mysteries surrounding Enceladus made it a high-priority target for the *Cassini* Saturn orbiter, a joint project of NASA and the European Space Agency. Launched in 1997 and arriving at Saturn in mid 2004, *Cassini's* originally planned four-year orbital tour of the Saturn system included four close flybys of Enceladus. The first two, in February and March 2005, revealed a disturbance in Saturn's magnetic field near Enceladus that implied a large electrically conductive obstacle to the plasma flow in Saturn's magnetosphere. Moreover, distant imaging showed evidence for a cloud of material above the south pole. Based on the magnetic results, mission scientists decided to investigate more closely and lowered the altitude of the third flyby from the planned 1000 km to 170 km.

During that July 2005 flyby, intensive scrutiny by the full complement of *Cassini's* instruments forever changed our understanding of Enceladus. The dramatic initial results from multiple instruments were published⁴ in a special issue of *Science* on 10 March 2006.

High-resolution images of the south polar region revealed four prominent parallel fractures, dubbed tiger stripes, surrounded by an intensely tectonically disrupted landscape (see figure 2). The lack of impact craters implied that the disruption had happened recently, sometime in the past few million years. Thermal emission maps revealed that

the tiger stripes were much warmer than their surroundings (see figure 3). Solar heating alone could not explain that warmth; the tiger stripes must be radiating gigawatts of internal heat.

Ultraviolet spectroscopy of a stellar occultation (that is, a star passing behind Enceladus) showed absorption of 0.1- to 0.2- μm -wavelength starlight by a cloud of water vapor above the south pole. *Cassini's* mass spectrometer recorded that the spacecraft had actually passed through the cloud; it also revealed the presence of carbon dioxide, methane, and more complex organic molecules. Clearly, ions derived from the cloud had caused the magnetic disturbance seen on the previous flybys. The spacecraft's dust detector revealed a cloud of micron-sized particles above the south pole. Dramatic images taken a few months later showed multiple particle jets emanating from the tiger stripes and combining to form a vast plume that had been glimpsed in earlier images.

The wild speculations of 20 years earlier proved to be correct: Enceladus is indeed spewing geyser-like plumes of gas and ice particles into the space around Saturn. The plumes generate the E ring and also populate a Saturn-circling torus of H_2O molecules that dissociate to produce the OH torus discovered by *Hubble*. Enceladus became the first proven geologically active ice world.

The discovery of eruptive activity on Enceladus is one of the most significant findings in planetary sciences in recent years. For one thing, Enceladus provides a test bed for understanding what icy worlds can do. Many ice-rich moons in the solar system have been shaped by processes similar to those currently occurring on Enceladus, so that moon gives us a chance to understand those processes by watching them in action.

As an example, the surface of Jupiter's much larger moon Europa is laced with mysterious double ridges with central fissures, features that are

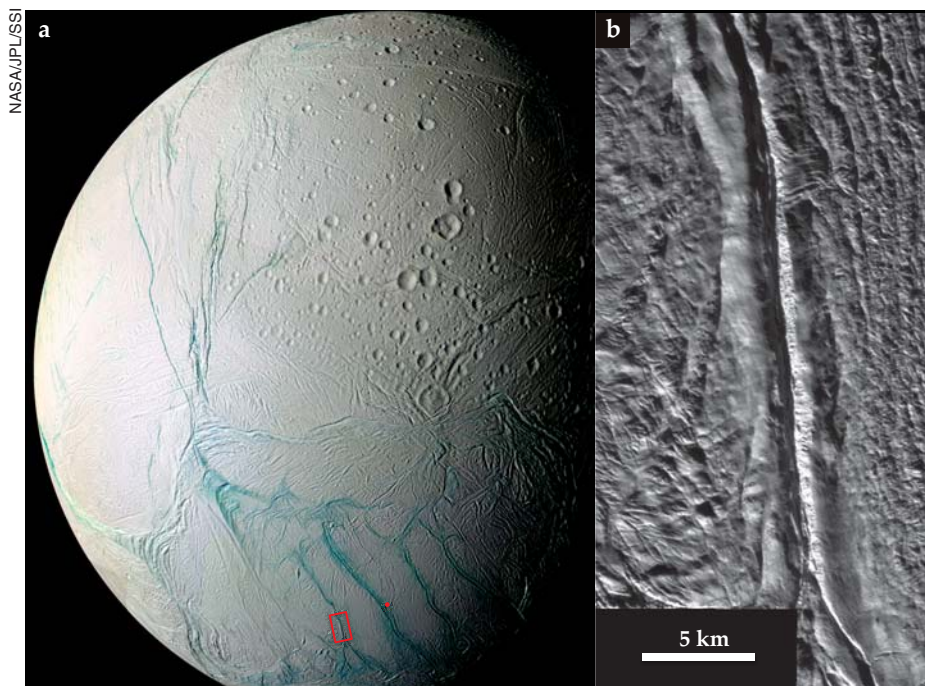


Figure 2. Tiger stripes. (a) This false-color *Cassini* mosaic of Enceladus displays a variety of landforms. The upper-right part of the 500-km-diameter disk shows some of the moon's older, cratered terrain, whereas the upper left shows tectonically disrupted terrain of intermediate age. The lower part of the disk is occupied by the young south polar terrain; the red dot indicates the south pole. The four parallel bluish fractures surrounding the south pole are the active tiger stripes, source of Enceladus's plumes. The blue color in the image arises because coarse-grained water ice absorbs the near-IR wavelength used, in part, to generate the mosaic images. The area bounded by the red rectangle is magnified in (b), a view of one of the most active parts of the tiger stripe Damascus Sulcus.

similar in many ways to the tiger stripes of Enceladus. Modeling the heat and vapor output of the Enceladan tiger stripes has allowed scientists to test models of frictional heating developed to explain the European ridges.⁵ In addition, liquid water possibly present on Enceladus, coupled with the rich chemistry hinted at by the mass-spectrometer data, could provide an environment where life might be possible if sufficient energy were available. Finally, the Enceladan plume delivers material from the active and potentially habitable zone directly, within minutes, to where it can be sampled by spacecraft instruments. That allows the detailed investigation of subsurface conditions without the inconvenience and expense of landing on the surface and drilling through the ice.

After the initial discovery of activity on Enceladus, the *Cassini* team planned a series of increasingly detailed follow-up observations. Once they determined that the risk to the spacecraft was minimal, they adjusted the trajectory of the mission's early 2008 Enceladus flyby—the last one originally scheduled—to pass much deeper through the newly discovered plume. A two-year extension to the original four-year mission, from mid 2008 to mid 2010, included seven additional close Enceladus flybys at altitudes as low as 25 km; the final seven-year extension includes 12 more.

The trajectory and spacecraft orientation during each flyby are optimized for specific science goals. Low flybys through the plume allow for direct sampling of its structure and composition. Close flybys on a range of trajectories enable a mapping of Enceladus's gravity field; more distant flybys are appropriate for surface mapping. Other flybys are designed for remote probing of the plume by stellar occultations of UV light. The data from flybys already conducted have greatly improved on the discovery observations and are helping us to

build a comprehensive picture of the moon and its activity and to understand how it operates.⁶

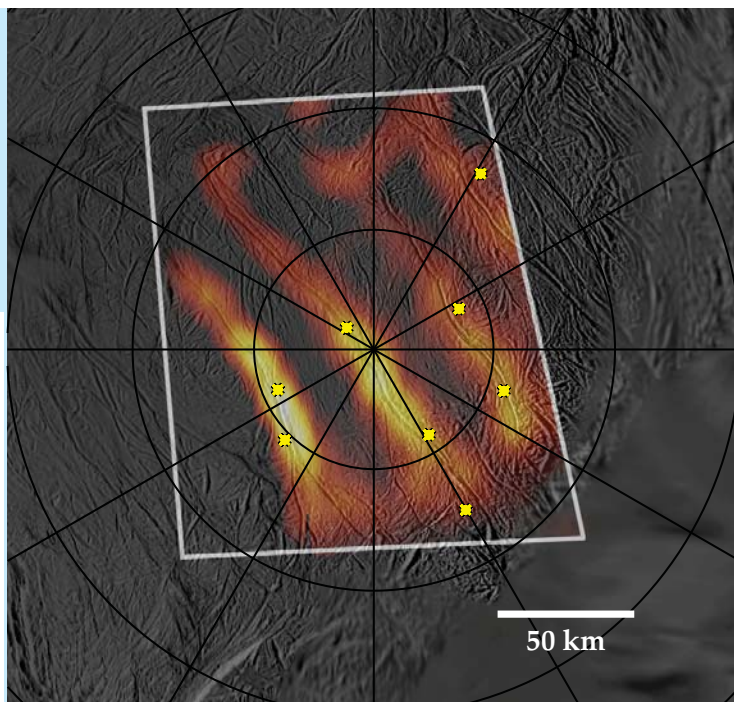
Tidal power

The current rate of heat loss through the active south polar region can be investigated with *Cassini*'s IR radiometer; the idea is to measure the observed total thermal emission and subtract the emission expected from reradiation of absorbed sunlight alone. The best estimate⁷ of the heat-loss rate is 16 GW, a surprisingly large number that defies easy explanation.

Enceladus is too small to be significantly heated by the decay of radioactive isotopes in its interior, a mechanism that generates much of the volcanic and tectonic activity on Earth. The moon's mass, measured precisely by its gravitational influence on *Cassini*'s trajectory, implies a density 1.7 times that of water ice but only about 45–65% that of plausible rocky components. The inferred bulk composition by mass is roughly 45% ice and 55% rock. The rock fraction inevitably includes radioactive isotopes, but if their composition is typical of what is found in the solar system, they would produce a mere 0.3 GW—much less than the observed radiated power.

Instead, the heat engine driving Enceladus's activity is almost certainly tidal. During the moon's eccentric orbit around Saturn, the distance separating the two varies by about 1%. Heating results from dissipation produced by the rhythmic deformation of Enceladus as the magnitude and direction of Saturn's tidal forces continually change. (For a discussion of similar processes in the Jovian system, see *PHYSICS TODAY*, August 2009, page 11.) The eccentricity, which would otherwise be damped out by the dissipation, is maintained by perturbations from the larger moon Dione, which is in a 2:1 orbital-period resonance with Enceladus. The resulting tidal heating rate depends on both the amplitude of

Figure 3. The most intense thermal emission near the south pole of Enceladus appears here as bright regions. The colored thermal map bounded by the white quadrilateral is made from *Cassini* observations of radiation at wavelengths of 9- to 16- μm and has a resolution of about 10 km. It is superimposed on a higher-resolution mosaic of the tiger stripes. The black circles on the mosaic are separated by 10 degrees of latitude. The yellow stars mark the locations of the strongest ice particle jets seen in *Cassini* images, as reported in ref. 10.



NASA/JPL/USFCS/SMI/SSI

the tidal deformation, determined by the rigidity of the satellite, and the effective viscosity of the deforming regions. Neither of those qualities can be observed, but they can be estimated with the help of models of Enceladus's interior structure.

Indeed, it is possible to construct interior models that dissipate more than 16 GW from eccentricity tides. But other constraints are more difficult to satisfy. Dissipation within Saturn leads to tidal torques that drive the moons away from the planet, just as dissipation of tides raised on Earth by our moon drives our moon outward. For that reason, the locations of Saturn's moons can be used to bound dissipation rates inside the planet. The constraint on Saturn, in turn, limits the steady-state dissipation rate within Enceladus.⁸ That's because the dissipation in Saturn, which increases both Enceladus's orbital eccentricity (via the Dione resonance) and its mean distance from Saturn, must be balanced against dissipation in Enceladus, which decreases the eccentricity and mean distance. The maximum steady-state dissipation rate is only 1.1 GW, less than 10% of the observed heat-loss rate.

The order-of-magnitude mismatch makes it unlikely that Enceladus has been radiating heat at its current high rate throughout its history. Perhaps the orbit and rate of tidal heating are relatively stable and Enceladus releases the heat episodically. Perhaps the moon is manifesting a coupled oscillation of dissipation rate and orbital eccentricity. In either case, we are lucky to have arrived at Enceladus during what appears to be an unusually active period.

Where does the tidal dissipation occur in Enceladus? Indirect evidence implies that the moon is differentiated, as illustrated in figure 4, with a denser silicate core and an outer water and ice shell. One piece of evidence is the high heat flow, which probably implies that the ice fraction is soft and has episodically been at least partially molten; the melting facilitates separation of the denser silicate from the ice. The silicate core is likely too rigid for significant dissipation. On the other hand, any liquid water is probably insufficiently viscous, so heat generation is probably concentrated in the ice shell. The south polar activity implies that the region has relatively high subsurface temperatures and thus relatively low ice-shell rigidity, so tidal deformation and heating will be focused there. The local concentration of the heating may thus be self-maintaining, though it's unclear how activity became focused in one small region of Enceladus to begin with.

Surface and plume

Enceladus's icy surface bears the scars of a long history of geological activity. Its oldest parts, judging by the number of superposed impact craters, are several billion years old. But even those regions have been modified, as evidenced by their craters, which are flatter than those on other Saturn satellites. One cause of the flatness is viscous collapse, which implies high subsurface temperatures and therefore low ice viscosity at some time since the craters formed. Another cause, apparently, is burial by a snow-like blanket of fine material, probably from ancient plume eruptions. Elsewhere, the ancient cratered landscape has been destroyed by intense and diverse tectonic fracturing that, according

Enceladus in brief

Mean distance from Saturn	238 000 km
Orbital and rotational period	1.37 days
Mean radius	252 km
Bulk density	$1.61 \times 10^3 \text{ kg/m}^3$
Interior composition by mass	50–60% silicate, 40–50% water ice
Radiated endogenic power ⁷	16 GW
Surface composition	Fine-grained water ice, trace CO_2 , possible NH_3 , H_2O_2
Plume gas composition by volume*	90% H_2O , 5% CO_2 , 0.9% CH_4 , 0.8% NH_3 , 0.3% H_2CO , 0.3% C_2H_2 , many other hydrocarbons, 0.2% H_2S , 0.03% ^{40}Ar
Plume particle composition by mass ¹⁶	99% H_2O , 1% NaCl , 0.3% NaHCO_3 or Na_2CO_3 , 0.01% KCl
Plume mass-loss rate ¹³	200 kg/s

*Determined from mass spectroscopy during the October 2008 flyby.¹¹ Other flybys give results that differ in detail.

to crater counts, extends back at least several hundred million years. The heat engine currently powering south polar activity must have been in operation, at least intermittently, for a very long time.

The youngest terrains on Enceladus, the ongoing plume activity depicted in figure 5, and the thermal activity are all centered almost perfectly on the south pole. That alignment is probably not coincidental. All the activity might have, for example, created a subsurface region of anomalously low density that has caused Enceladus to change its orientation and align its rotation axis in the most stable direction—that is, along the axis of maximum moment of inertia.⁹ Southward of a bounding belt of rugged ridges at a latitude of about 50° south, impact craters are almost totally absent; evidently, the entire south polar surface has been reworked within the past million years. In the center of the south polar terrain are the four parallel tiger-stripe fractures, each about 130 km long. As seen in figure 2b, each comprises a warm central trough about 0.5 km deep, source of the plume jets,¹⁰ enclosed by raised ramparts on either side that are separated by about 2 km.

The many individual particle and gas jets that emerge from the tiger stripes merge at altitude to produce a single plume that extends several thousand kilometers before it loses its identity and merges with the E ring. The plume has two observable components: micron-sized ice grains visible in reflected light and analyzed in situ by *Cassini*'s dust detector and plasma instruments, and gas that can be detected by UV spectrometry of stellar occulta-

tions, in situ by the *Cassini* mass spectrometer and, when ionized, by *Cassini*'s plasma instruments and magnetometer. The gas component is mostly water vapor, seasoned with a rich mixture of minor species.¹¹ Most of the particles are roughly 99% water ice and 1% salt.¹² The table on page 41, a summary of key Enceladus data, breaks down the plume's gas and particle content.

Assuming most gas escapes at the thermal speeds of 500 m/s or so inferred from observed tiger-stripe temperatures, the plume density gives a mass-loss rate of about 200 kg/s.¹³ If that rate were maintained over the age of the solar system, Enceladus would have ejected more than half its current inventory of ice. That is an implausibly large fraction and, like the high observed heat flow, argues that current activity rates are unusually high.

The majority of plume particles fall back onto Enceladus's surface, which accounts for the moon's high albedo—but enough escape to maintain the E ring. Moreover, ice particles from Enceladus coat the surfaces of the surrounding moons: Those closer to Enceladus have brighter surfaces than those farther away.¹⁴ The ice particles even extend as far as the giant moon Titan and probably provide the dominant source of oxygen in Titan's upper atmosphere. Enceladus thus exerts its influence throughout the Saturn system.

Does Enceladus contain liquid water?

A question of great interest to planetary scientists is whether liquid water exists beneath the icy surface

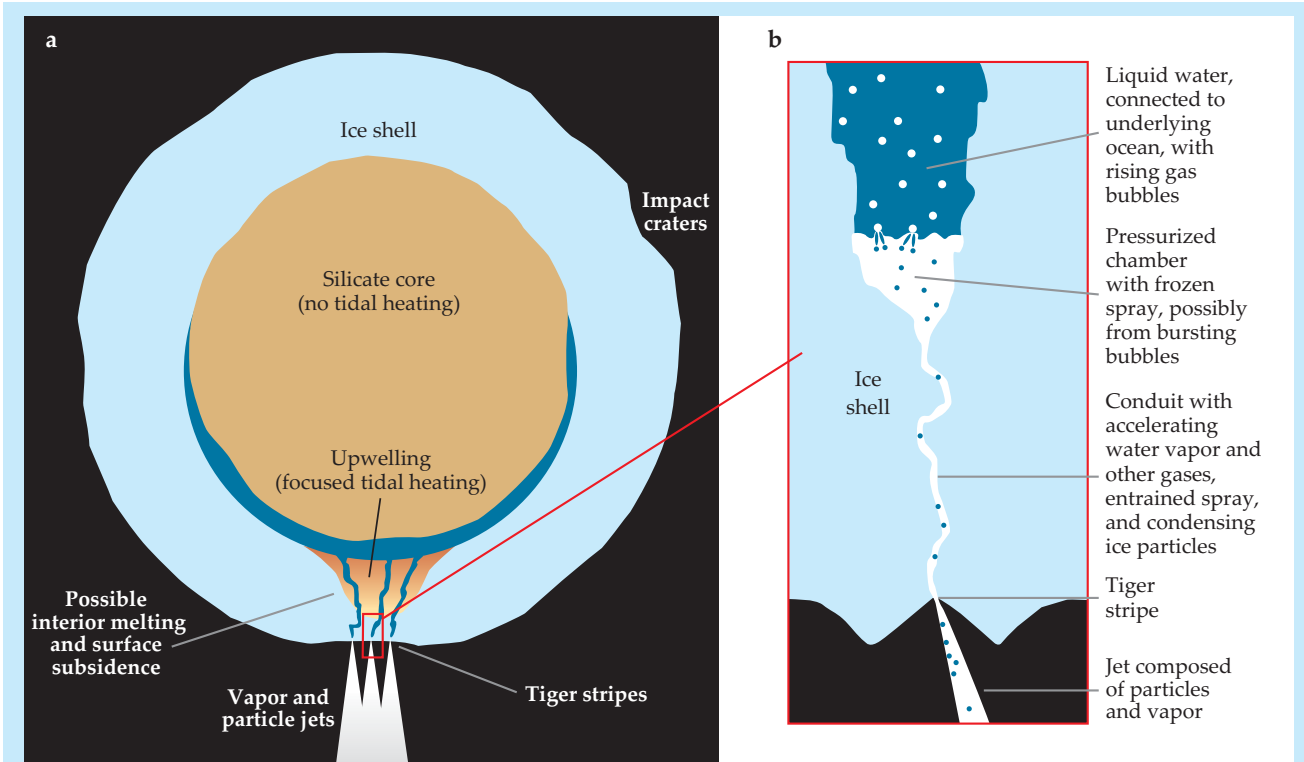


Figure 4. Enceladus in cross section. (a) In a possible structure for the interior of Enceladus, a liquid ocean separates the inner silicate core from the outer ice shell in the southern hemisphere. Enceladus's tiger stripes are near the south pole; the region around one of them, delineated by the red rectangle, is magnified (but not to scale) in **(b)**, which shows a possible path of water as it journeys from the liquid ocean, through a tiger stripe, and into space. (Panel a courtesy of Francis Nimmo.)

of Enceladus. Water might occur in several places: as a global ocean between the silicate core and the ice crust, as a more local south polar sea beneath the ice shell (as depicted in figure 4), or as localized bodies of water in the ice shell itself.

A global ocean would decouple the ice shell from the core. That would allow greater tidal distortion of the shell and make it easier to generate the observed 16 GW of tidal heat.⁵ However, some of that global ocean would freeze unless sufficient heat was available away from the south pole or the ice shell was highly insulating, and it's not clear that either of those criteria are met. A localized south polar sea would be easier to maintain, given the high south polar heat flow.

Chemical evidence for an ocean of some sort comes from the salty composition of the ice grains in the plume. It is difficult to produce salty ice grains except by flash-freezing salty liquid water. The salt composition is similar to that expected for liquid water that has reached chemical equilibrium with a silicate core, so the water is probably not simply local melt produced within the ice shell.¹⁵ However, some plume gases, particularly carbon dioxide and methane, are more abundant than their solubility in water would indicate.¹¹ Rather than having their origins in an ocean, at least some plume gases may be introduced from a separate reservoir that is part of a complex plumbing system beneath the tiger stripes.

The salty ice grains provide compelling evidence that water is sufficiently close to the surface of Enceladus for particles flash-frozen from the water to actually make it to the surface. Just how close that water is, however, is open to debate. The highest measured surface temperatures near the tiger stripes are about 190 K, well below the melting temperature of water. However, the vents themselves may be less than a meter wide, too narrow for their thermal emission to be detectable by *Cassini*. If so, they might be warm enough for liquid water to exist near the surface. And, of course, temperatures inevitably increase with depth, though details depend on the efficiency of heat transport.

One early model for plume formation proposed explosive boiling of liquid water close to the surface. That mechanism could readily generate the observed high density of flash-frozen salty ice particles. However, it may be difficult to supply heat to the water surface quickly enough to prevent the rapidly boiling water from freezing. An alternative possibility is sketched in figure 4b: The water evaporates more slowly in pressurized chambers and leaks to the surface along narrow fissures to produce the plumes.¹⁶ In that scenario, the challenge is to introduce the flash-frozen ice grains into the plume flow. Perhaps they are generated by bubbles bursting as plume gases other than H₂O reach the water surface.

To life!

Has life developed in the warm, wet conditions that we suspect exist within Enceladus? A positive answer would have profound implications for the ubiquity of life throughout the cosmos and its ability to develop independently of solar or stellar en-

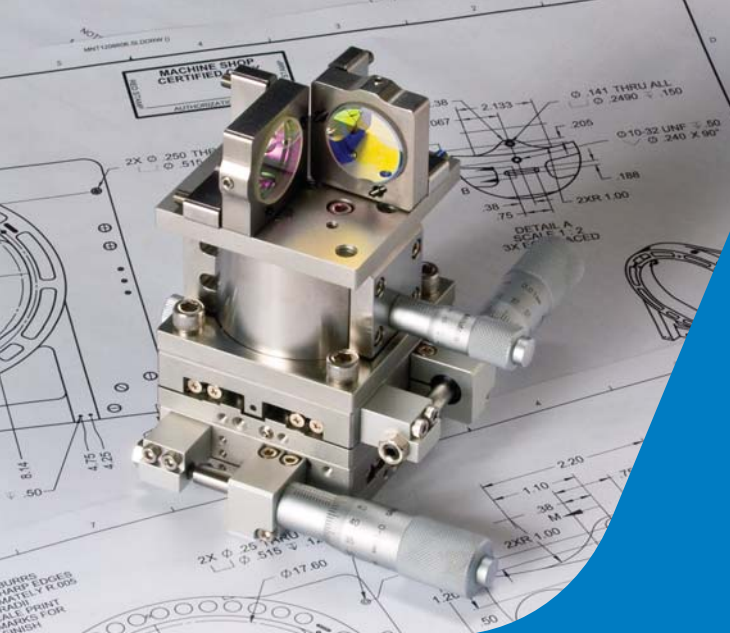


Figure 5. Multiple plume jets erupting from the four tiger-stripe fractures near Enceladus's south pole are visible in this *Cassini* image. The jets appear not only on the edge of Enceladus's disk but also where they rise up into sunlight from sources on the night side of the moon.

ergy input. Even if the answer is negative, an understanding of how close Enceladus has come to being able to support life would tell us much about the potential development of habitable environments elsewhere in the solar system and beyond.

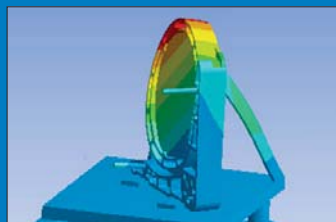
The chemistry of the Enceladan plume indicates that the elements essential to the support of terrestrial life are probably present at the plume source. But even liquid water and all the necessary chemicals don't guarantee that an environment is habitable. The environment must have sufficient chemical energy available, and we don't know if that's the case under the surface of Enceladus. Certainly, the subsurface will be devoid of sunlight, the ultimate energy source for almost all life on Earth—including the famous deep-sea hydrothermal vent communities that depend on seawater oxygen derived from near-surface photosynthesis. A few known terrestrial microorganisms, however, exploit chemical energy sources directly and are truly independent of sunlight. For instance, some microorganisms found in the Columbia River basalts live on hydrogen derived from rock–water reactions.¹⁷ Analogous ecosystems on Enceladus may be possible, powered, for instance, by oxidants produced by irradiation of surface ice by plasma in Saturn's magnetosphere or by hydrogen derived from thermal decomposition of methane. Whether suitable conditions have existed continuously on Enceladus long enough for life to develop and survive is another question—one that will remain unanswered until we better understand both how rapidly life developed on Earth and the stability of activity on Enceladus.

Magnificent as *Cassini*'s achievements have been and promise to be, much will remain to be learned after its last close flybys of Enceladus in late 2015. For instance, the spacecraft's mass spectrometer cannot measure masses above 100 atomic mass units, so it is blind to the complex organic molecules that could reveal just how far organic chemical evolution has progressed on Enceladus. *Cassini*'s best images of the active vents have a resolution of about 10 meters in the visible and hundreds of meters in the IR. That's not good enough to resolve the details



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of the vents themselves, and, moreover, *Cassini* lacks instrumentation such as an ice-penetrating radar to probe conditions beneath the vents. Nor can *Cassini* directly measure Enceladus's tidal flexing to understand the heat engine that powers the vent activity and determine the extent of any subsurface ocean.

A follow-up mission with improved instrumentation and a trajectory optimized for Enceladus science could provide definitive answers to many of our questions about that moon, in particular regarding physical and chemical conditions at the plume source and the habitability of the subsurface environment. Conceivably, such a mission could detect biological activity by spotting biochemical signatures in ejected plume materials. Several mission studies have been performed since the 2005 discovery of activity. Some involve Enceladus orbiters; others, landers; some would even fly through the plume and return samples to Earth.

The most recent studies, performed for the 2010 planetary sciences decadal survey, concluded that an Enceladus orbiter would be the most cost-effective next step and that it could be accomplished for about \$2 billion.¹⁸ Of the large missions recommended by the decadal survey, the Enceladus orbiter was the cheapest, but others ranked higher in priority: The orbiter tied for fourth place among recommended large missions to be started in the coming decade. Unfortunately, current projected NASA budgets may have insufficient funding for even the highest-priority large mission, to collect Martian rocks for later return to Earth. So we may have to wait a while before another spacecraft probes the mysteries of Enceladus. In the meantime, *Cassini*'s rich data harvest will keep planetary scientists busy for years to come.

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