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ASTROBIOLOGY

Habitability of Enceladus: Planetary Conditions for Life

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Abstract The prolific activity and presence of a plume on Saturn's tiny moon Enceladus offers us a unique opportunity to sample the interior composition of an icy satellite, and to look for interesting chemistry and possible signs of life. Based on studies of the potential habitability of Jupiter's moon Europa, icy satellite oceans can be habitable if they are chemically mixed with the overlying ice shell on Myr time scales. We hypothesize that Enceladus' plume, tectonic processes, and possible liquid water ocean may create a complete and sustainable geochemical cycle that may allow it to support life. We discuss evidence for surface/ocean material exchange on Enceladus based on the amounts of silicate dust material present in the Enceladus' plume particles. Microphysical cloud modeling of Enceladus' plume shows that the particles originate from a region of Enceladus' near surface where the temperature exceeds 190 K. This could be consistent with a shear-heating origin of Enceladus' tiger stripes, which would indicate extremely high temperatures (~250–273 K) in the subsurface shear fault zone, leading to the generation of subsurface liquid water, chemical equilibration between surface and subsurface ices, and crustal recycling on a time scale of 1 to 5 Myr. Alternatively, if the tiger stripes form in a mid-ocean-ridge-type mechanism, a half-spreading rate of 1 m/year is consistent with the observed regional heat flux of 250 mW m^{-2} and recycling of south polar terrain crust on a 1 to 5 Myr time scale as well.

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Background and Introduction

The recent discovery of water vapor plumes ejected from the south pole of Saturn's satellite, Enceladus, by the *Cassini* spacecraft presents a unique window of opportunity for the geochemical characterization of an icy satellite and possibly the detection of extant life in our solar system. The plume of water ice and other materials erupting to a height of >80 km from the surface of the moon spatially associated with a massive thermal anomaly radiating 3–7 GW at temperatures of order 70 K to 150 K (Spencer et al. 2006) provides strong evidence that Enceladus' interior may be warm and that its surface is presently tectonically active. The presence of such large amounts of heat and geological activity raises the question of whether Enceladus' interior may have conditions favorable for life.

Existing studies of the habitability of icy satellites are mostly focused on Jupiter's satellite Europa, where the likely presence of a liquid water ocean beneath its surface (Kivelson et al. 2000), widespread endogenic resurfacing (Greeley et al. 2004), and continual chemical processing of its surface ice by the radiation and particles supplied by the Jovian magnetosphere (Chyba and Phillips 2002) may provide a source of energy and liquid water to sustain life. Studies of the habitability of the icy Galilean satellites conclude, however, that it is extremely difficult to start or to sustain life in these bodies. The tendency for icy satellite oceans to be physically and chemically separated from heat, light, and non-water ice materials, and thus, to chemically equilibrate imposes severe constraints on viability of chemoautolithotrophic life in their oceans. The subsurface oceans of the icy Galilean satellites Europa, Ganymede, and Callisto cannot receive sunlight to drive photosynthesis because they lie beneath ice I shells a few tens to hundreds of kilometers thick. Because the ocean is essentially geochemically isolated from the irradiated surface ices, it is possible that over time, redox gradients that may drive life in the ice-covered oceans of these bodies may have been annihilated by chemical equilibration (Gaidos et al. 1999). It has also been suggested that microbial communities could be sustained in Europa's ocean via chemical reactions that would not rely upon the circulation of its ice shell (i.e. at hydrothermal vents on the surface of Europa's rocky core), but the chemical energy available to organisms using these reactions is relatively small (Jakosky and Shock 1998; McCollom 1999; Zolotov and Shock 2004). Chyba and Hand (2001) suggest that the decay of ^{40}K can create oxidants and heat within ice I shells and oceans in icy satellites, which may provide a small nutrient source for life in the ocean and/or ice shell. The largest nutrient source available for life on Europa is the chemically processed irradiated surface ice (Chyba and Phillips 2002). However, for this to be of use to life would require the existence of a geophysical process that mixes the top ~1 m of Europa's crust into the depths of the ocean.

Life in Europa's subsurface ocean would not only be difficult to create and/or sustain: it would also be extremely difficult to detect. The top ~1 m of Europa's ice is heavily processed by radiation and particle bombardment from the Jovian magnetosphere, and therefore, is probably not representative of the composition of its interior. Although it is possible that geophysical processes such as solid-state convection may permit materials from Europa's ocean to reach its surface (Barr and Pappalardo 2003), any landed spacecraft would have to drill beneath meters of ice before reaching pristine ice in which possible microbes would be preserved. Therefore, in order to avoid chemical stagnancy and provide sufficient nutrients to sustain life over long time scales, *and* to be able to detect life, if it exists, a global geochemical cycle that operates over biologically interesting time scales must exist on Europa to permit mixing of materials between its surface and ocean.

The prolific activity and presence of a plume on Enceladus offers us a unique opportunity to sample the interior composition of an icy satellite, and to look for interesting chemistry and possible signs of life with minimal risk of forward-contamination. Enceladus' prolific cryovolcanic activity suggests that there is ample heat available to drive chemistry in its interior. The 3–7 GW of power output from its south polar terrain (Spencer et al. 2006) is a factor of ~10 larger than the expected amount of heat due to radiogenic heating in its interior. Tidal heating is a likely suspect for driving Enceladus' geological activity. However, it is not clear whether this tidal dissipation is concentrated within its icy shell or rocky interior. Nevertheless, we consider it likely that the large amounts of heat deposited within Enceladus by tides has caused it to differentiate (though perhaps incompletely) into a rocky core and a more icy outer shell. If this has occurred, the rocky core will be about 150 km in radius, leaving an outer shell of H_2O (whether it be liquid or solid is unknown at present) about 100 km thick (Barr and McKinnon 2007). For the purposes of our discussion here, we will assume that Enceladus does have a layer of liquid water under its ice shell, which would be in direct physical contact with its rocky core, similar to Europa's interior structure. This layer need not be extremely thick, but the presence of a *liquid* medium in direct contact with the rocky core significantly enhances the rates of biologically interesting chemical reactions. At the very least, the internal environment of Enceladus is inferred to contain liquid water and be favorable for aqueous, catalytic chemistry that will permit the synthesis of many complex organic compounds (Matson et al. 2007).

Unlike the Galilean satellites, Enceladus' surface ice may not be heavily processed by radiation, and so may be a meager nutrient source. Parkinson et al. (2007) introduce the notion of Saturn's E-ring as a "chemical processor" to provide additional H_2O_2. We know that water is being ejected from Enceladus in sufficient quantities to keep this ring in existence and fairly stable over time (Hansen et al. 2006). This frozen water in the ring will be exposed to energetic particles and UV irradiance over time and some of the water will be converted to H_2O_2 which can be picked up again by the moon as it sweeps through the ring while it is moving it its orbit. In this manner, the E-ring can be seen as acting as an extended "surface" providing a new oxidant source for Enceladus. In any case, there is some evidence for hydrogen peroxide on Enceladus' surface (Newman et al. 2007). Other such reactive species may also be present on the surface. If those materials can become incorporated via some process to the ice shell and ocean, this may provide a substantial energy source for life. If Enceladus has a sub-surface liquid water layer, the aqueous weathering of rocks would significantly increase the habitability of its ocean. If processes occurring deep inside its ice shell drive Enceladus' plume activity, compositional information from the plume may provide clues about its ocean chemistry. The spectral analysis of plume spectra performed by Parkinson et al. (2006) showed that many required species including CO, CO_2 and N_2 might be present. Parkinson et al. (2006) also discussed the search for signatures of these species and organics in the *Cassini* ultraviolet imaging spectrograph (UVIS) and visible infrared mapping spectrometer spectra of the plume and implications for the possible detection of life. The presence of nitrogen and carbon-based compounds in the plume and organics along the tiger stripes (Brown et al. 2006) may indicate that amino acids could be formed in Enceladus' interior. Such materials most likely are made at the interface between a subsurface liquid water ocean and Enceladus' deeper rocky core, where chemical reactions could be facilitated by clay formations arising from rock weathering by liquid water. Less likely, amino acids could be created within its ice shell due to chemical interactions between dust from micrometeorite accumulation that chemically intermingles with warm ice and small amounts of liquid water.

Here we present ideas about how Enceladus' plume, interior processes, and possible ocean processes may create a sustainable, complete geochemical cycle required for the support of life and begin to address some key issues surrounding quantification of the nutrient sources and time scales for chemical processing. To begin to understand how Enceladus' plume fits in with its other geophysical processes, we model the development of its plume particles to relate conditions at the vent to the observed conditions in the plume. We then discuss two possible methods for generating such high temperatures close to Enceladus' surface associated with geophysical processes that could allow for recycling of its surface ice to create a complete geochemical cycle. We provide an order-of-magnitude estimate for the timescale of lithospheric recycling on Enceladus based on two simple models of the formation of its tiger stripes. Finally, we discuss compelling evidence that there is surface/ocean communication on Enceladus based on the amounts of silicate dust material present in the plume particles.

A Hot Origin for Enceladus' Plume Particles

Porco et al. (2006) show that icy particles on the order of 1 μm are emanating from Enceladus' plume. We note that the water vapor jet itself cannot loft the 1 μm particles (Porco et al. 2006) and moreover, silicate nucleating particles bigger than 0.1 μm would have trouble lifting from the ice surface unless the area of the fissure was quite small (M. Combi, private communication); this may provide a possible clue as to the nature of the lofting mechanism. We use this value as our reference to guide our modeling effort using the Community Aerosol and Radiation Model for Atmospheres (Toon et al. 1988) to simulate the growth of water ice in the plume of Enceladus. In the first case, the reaction temperature is fixed at 150 K during the course of simulation. Starting with 0.1 μm sized condensation nuclei with an abundance of 10^{-3} particles cm^{-3}, we ran the model with a water vapor abundance of 3×10^{11} molecules cm^{-3} (saturation density is at 170 K). The dash-dotted line in Fig. 1 shows the result of this simulation. The "lifetime" of the particles is on the order of some tens of seconds up to about 1 min, before particles leave the plume via escape to space or falling back onto the surface (Porco et al. 2006). We see that water molecules can condense on existing particles, but only grow to 0.1 μm in less than one minute for this scenario. In order to grow 1 μm size particles in this time frame, an increase in water vapor abundance is required. Hence, we enhance the abundance of water vapor in the model sequentially to 10^{13}, 2×10^{14}, and 10^{15} molecules cm^{-3} (corresponding to the saturation densities at 190 K, 210 K, and 225 K, respectively). These results are also shown in Fig. 1, and we observe that particles can grow to the expected size much more quickly with increasing abundance. Note that in all of the cases, the coagulation process is unimportant during the time of interest. Additionally, a rough estimate of the release of latent heat that can be carried away by radiation during the formation of icy particles is only a few percent overall. Latent heat is relevant only if the (amorphous) particles are annealed to crystalline form, which won't happen on these timescales or temperatures (E. Gaidos, private communication). Hence, our modeling of the formation of 1 μm size particles is not inhibited by latent heat processes in the timeframes considered. Moreover, our models infer that the formation and growth of ice particles takes place in the regions where the temperature has to be at least 190 K. Such high temperatures strongly suggest the presence

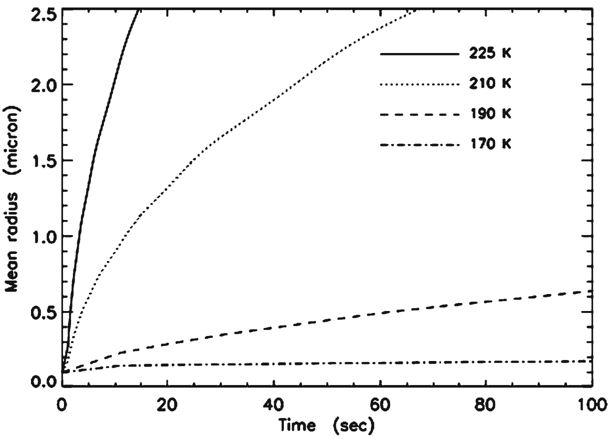


Fig. 1 The growth of water ice corresponding to conditions on Enceladus for a variety of cases are shown. We see that particles can grow much more quickly with increasing water vapor abundance. To grow ~1 μm plume particles in the time frame of tens of seconds, we need a minimal water vapor abundance of ~10^{13} molecules cm^{-3} corresponding to a minimal saturation density at ~190 K

of a currently active geodynamic or tectonic process operating beneath Enceladus' south pole. Results from Monte Carlo simulations of the water vapor plume on Enceladus (Tian et al. 2006) are not sensitive to surface temperature variations from 180 K to 140 K and hence determining vent temperatures using this method are inconclusive. However, their studies also infer that a surface density of 10^{10}–10^{11} cm^{-3} can be supplied by ice at 180 K or lower. Despite this, the higher temperatures we claim could be supported to give the velocity and number density distributions they show and are hence not precluded.

Some authors suggest that the ice particles in the plume form from a source of water a few meters beneath Enceladus' surface (Porco et al. 2006; Ingersoll et al. 2006). Alternatively, Kieffer et al. (2006) hypothesize that active tectonic processes in the south polar terrain of Enceladus create fractures in its lithosphere that cause degassing of clathrate ices. The explosive decompression of the clathrates would produce the observed plume. Kieffer et al. (2006) suggest that advection of gas and ice transports energy, supplied at depth as latent heat of clathrate decomposition, to shallower levels, where it reappears as latent heat of condensation of ice. From their analysis, the plume is formed from small leaks from this massive advective system. Regardless of the source of the plume particles themselves, this model still relies upon "active tectonic processes" occurring at the south pole of Enceladus, which lends additional support to our idea that its plume may provide clues to its inner workings, and to the sustainability of a global geochemical cycle.

The observed ice grain sizes on the surface of Enceladus may provide us with clues regarding the tectonic processes occurring at its surface. Once the 1 μm sized particles from Enceladus' plume land back on the surface of the moon, they must rapidly grow to 30 μm (Ingersoll et al. 2006). We use the microphysical description of sintering given by Colbeck (1998), where the new particle radius, R, is give as a function of the old radius, R_o and dihedral angle, A, viz.,

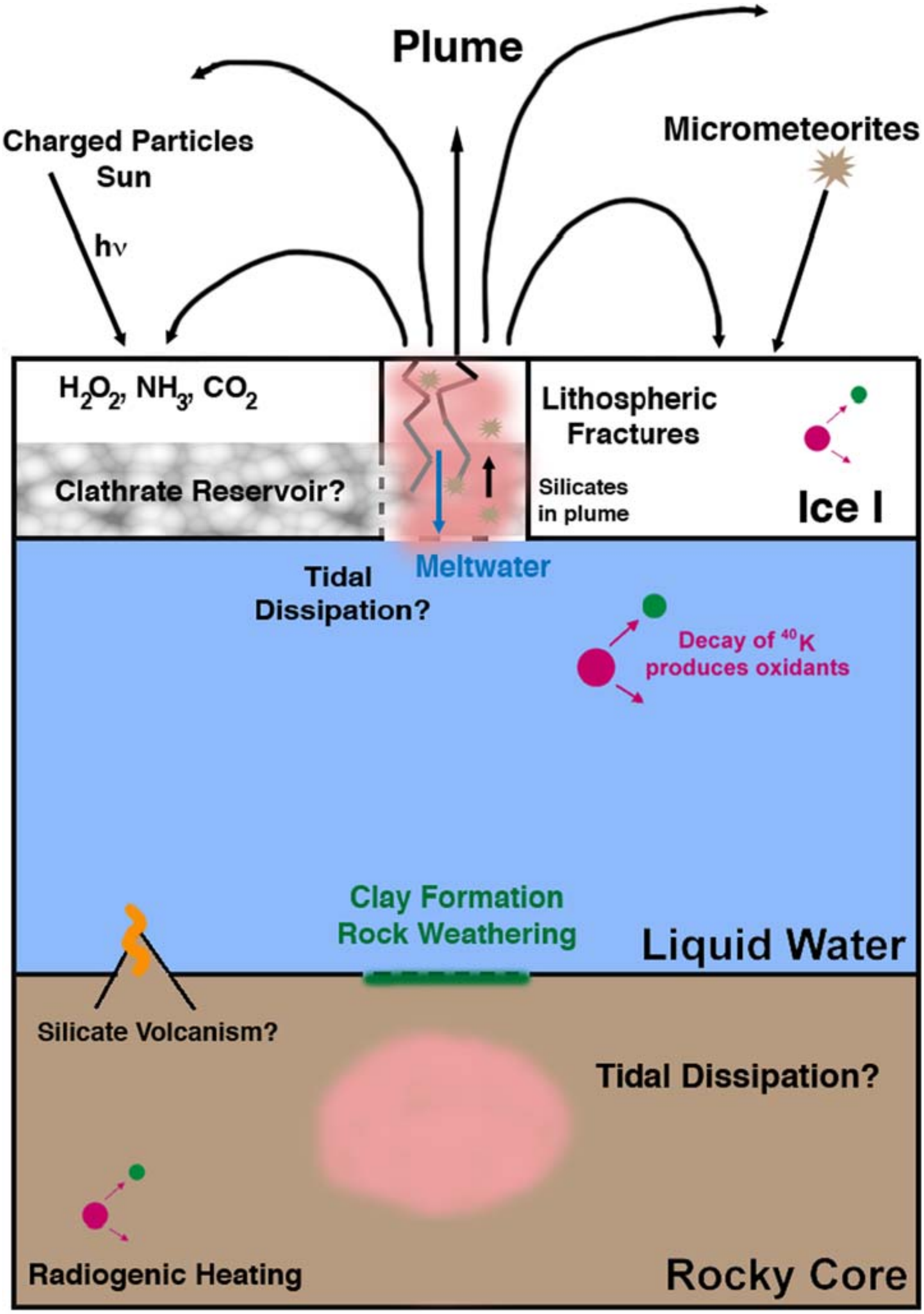
$$R^3 \sim \frac{4R_o^3}{2 + \cos(A/2)\left(2 + \sin^2(A/2)\right)}$$

The dihedral angle grows over time to ~2.5 radians when sintering is complete. Using the aforementioned Colbeck (1998) description, we find that sintering can only enhance the particle radius by a factor of ~1.1. This strongly suggests that sintering is not the controlling process for grain growth. If ice grains grew as a result of thermally-activated normal grain growth in the warm centers of the tiger stripes, grain sizes within the stripes themselves could be as large as ~30 μm after 2×10^7 years of growth at $T\sim145$ K, the estimated temperature in the center of the tiger stripes (Spencer et al. 2006). However, large grains are observed in the *flanks* of the tiger stripes, where temperatures may be as low as 70 K (Spencer et al. 2006). Therefore, the large ice grains observed on the flanks of the tiger stripes either formed in the center of the tiger stripes and moved outwards due to a mid-ocean-ridge-type spreading mechanism (which will be discussed in detail below), or that another process whose rates are significant even at low temperatures (perhaps vapor diffusion) causes the ice grains to grow rapidly.

Here we hypothesize that the "active tectonic processes" that drive plume activity are also associated with recycling of Enceladus' near-surface ice (which we loosely refer to as its "lithosphere") over time. The tiger stripes of Enceladus are long linear features a few hundred meters wide, but hundreds of kilometers long; they share a vague morphological similarity to the double ridges on the surface of Europa. Europa's double ridges, which "criss-cross" its entire surface, appear to be causally linked to stresses generated within its ice shell due to nonsynchronous rotation of the ice shell and daily tidal flexing, but the method of generating their characteristic morphology—symmetrical upwarped ice cliffs ~200 m high separated by a central trough—is not well-understood. One proposed method of ridge formation suggests that double ridges form in response to frictional heating of the ice crust as fault blocks slide past each other in response to tidal flexing of the shell (Nimmo and Gaidos 2002). Friction between the moving fault blocks causes localized heating due to viscous dissipation along the fault plane, local thinning of the brittle lithosphere, and thermally-driven upwelling, which may form the uplifted ridge structure (Nimmo and Gaidos 2002). If the strike-slip velocity is large enough (on Europa, $\nu>30$ m/year), temperatures at the base of the brittle fault zone may exceed the melting temperature of ice. Melt water generated at the base of the fault zone would drain downward into the subsurface of the ice shell, resulting in net loss of near-surface lithospheric material (Barr 2004). We note that crustal material is lost in this scenario even if the ridges are created in an overall extensional tectonic environment—therefore, this process differs significantly from terrestrial crustal loss mechanisms like crustal subduction, which occurs in a compressional tectonic regime (cf. Fig. 2).

Recently, a shear-heating model has been applied to the formation of Enceladus' tiger stripes to explain the origin of the plumes and associated heat flux (Nimmo et al. 2007). While they have simplified or neglected many details of the vapor production and transport mechanisms (such as their effect on the temperature, porosity structure, and the potential for time-variable transport and release), the shear-heating hypothesis is appealing for Enceladus because it is broadly consistent with the composite infrared spectrometer (CIRS) observations of Enceladus' tiger stripes that suggest that the thermal emission at the south pole is concentrated within the centers of the stripes themselves (Spencer et al. 2006). Their Fig. 1 shows that the temperatures and temperature gradients near the strike-slip zone are significantly increased (viz., T can be as much as 220 K around the near surface brittle fault

Fig. 2 Summary of geophysical processes we hypothesize may occur within Enceladus' outer ice shell ▶ relevant to the habitability of its ocean (note, diagram is not to scale). Material from the interior of Enceladus, including ice particles, water vapor, and silicate particles are erupted from a plume on its surface. Some material is lost to space, but some material returns to its surface, creating bright deposits of H_2O_2, NH_3, and CO_2 frosts. At the base of Enceladus' ice shell, assembly of more complex amino acids and other compounds is facilitated by interactions between clays formed from weathering of the top of Enceladus' rocky core due to interaction between the silicate and liquid water. It is not known whether dissipation in the rocky portion of Enceladus contributes to its overall tidal dissipation budget, but if it did, this would provide a significant source of activity and facilitate high-temperature chemical reactions in the ocean



zone) as a result of the brittle and viscous heating when the shear velocity is 8×10^{-6} m s^{-1}, possibly allowing for liquid water to form in the shear zone. To generate the shear velocities required, it seems likely that Enceladus has a subsurface ocean, either global or possibly localized (Collins and Goodman 2007), beneath a thick ice shell. Nimmo et al. (2007) Figure 4 shows the Love number h_2 as a function of ice shell viscosity for spherically symmetric models with and without a subsurface ocean. Their model with a global subsurface ocean can reproduce the shear velocities required for reasonable assumptions of ice viscosity in a convective ice shell corresponding to temperatures in the range of 250–270 K. Nimmo et al. (2007) also propose that the CIRS signature is the result of latent heat released by local recondensation of ~90% of the vapor in cold, near-surface porous ice around the shear zone, while the remaining vapor escapes to form the observed plumes probably mainly through the brittle shear zone that is opened and closed by the periodic tidal stresses. In the Nimmo et al. (2007) model, recondensation of 1,800 kg s^{-1} vapor over a shallow subsurface zone 500 m wide and 500 km long results in a heat flow of 5 GW and an equivalent surface temperature of 137 K, consistent with the CIRS observations (Spencer et al. 2006). Heating and subsequent ice grain growth due to this recondensation is also a plausible explanation of the greater inferred grain size at the tiger stripes. All these arguments are consistent with our modeling of vapor formation by the growth of water ice in the plume of Enceladus given above.

If the tiger stripes on Enceladus form in a manner similar to Europa's double ridges, and if strike-slip velocities are sufficient to permit ice melting at the base of the brittle/ductile transition (cf. Nimmo et al. 2007; Fig. 1), the loss of material at the fault zone must be offset by inward movement of ice toward the fault zone from the adjacent ice crust (Barr 2004; Barr et al. 2002). In addition, a significant amount of Enceladus' mass is lost from its lithosphere by the direct eruption of plume particles. The total rate of mass loss at a tiger stripe is,

$$\dot{M}_{\text{total}} \sim \dot{M}_{\text{plume}} + \dot{M}_{\text{fault}} .$$

Figures 2 and 3 summarize our hypothesis about how the plume vent and tiger stripe structure might relate to the surrounding ice in Enceladus' lithosphere. If the tiger stripes

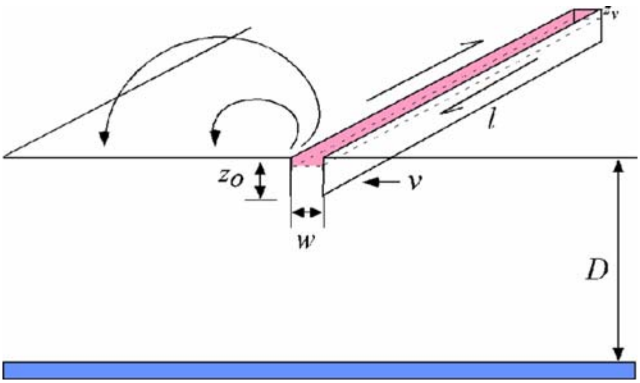


Fig. 3 Schematic of processes we hypothesize may occur at Enceladus' tiger stripes. A fracture in Enceladus' lithosphere is cyclically forced by tidal stresses resulting in melting at the base of the fault zone, in a manner similar to the proposed method of formation of Europa's double ridges (Nimmo and Gaidos 2002). The portion of the fault exposed to space, denoted by the *pink shading*, has a depth z_v, a length l and width w. Beneath Enceladus' surface, the lithospheric fracture continues to depth z_o. We envision that melt generated in the fault zone leads to net crustal loss, which can result in recycling of Enceladus' entire layer of surface ice in a time scale of ~10 to 50 Myr, or just the south polar terrain in ~1 to 5 Myr

form due to strike-slip motion of the ice shell, the source of the plume particles may represent the uppermost regions of the fault zone. Suppose that the geometry of the portion of the fault that is the source of particles is somewhat akin to a rain gutter of length l, width w, and depth z_v. The subsurface portion of the fault zone has a width w, length l, but a depth ($z_o - z_v$), where z_o is the thickness of the brittle lithosphere underneath the south pole, which is probably of order a few tens of km.

We hypothesize that the mass lost over the total length of the tiger stripe is related to the mass lost from the plume through a ratio of the area of the fault zone to the area of the vent region,

$$\dot{M}_{\text{total}} \sim \dot{M}_{\text{plume}} + \dot{M}_{\text{plume}} \frac{A_{\text{fault}}}{A_{\text{vent}}}.$$

The area of the venting zone is the sum of the areas of the two sides of the sublimating zone plus the area of the base, $A_{\text{vent}}=2z_v l+wl$, where the dimensions of the zone, as estimated by Porco et al. (2006) from *Cassini* imaging science subsystem images of the tiger stripes are, z_v=500 m, l=130 km, and w=2 km. The area of the fault zone is $A_{\text{fault}}=(z_o - z_v)l$. Substituting these estimates in our expression yields a relationship between the total mass flux of material processed through the entire fault zone,

$$\dot{M}_{\text{total}} \sim \dot{M}_{\text{plume}} \left(1 + \frac{(z_o - z_v)l}{2z_v l + wl}\right) \sim \dot{M}_{\text{plume}} \left(1 + \frac{z_o}{w}\right),$$

where we can approximate the ratio between the area of the fault and area of the vent region as z_o/w because $z_o >> z_v$. Because z_o=65 w, we get

$$\dot{M}_{\text{fault}} \sim \dot{M}_{\text{plume}} \left(1 + \frac{A_{\text{fault}}}{A_{\text{vent}}}\right) = (66)\dot{M}_{\text{plume}} \sim \left(10 \text{ to } 100\,\dot{M}_{\text{plume}}\right).$$

If the mass loss from the plume is of order 100 kg s^{-1}, this gives $\dot{M}_{\text{total}} \sim 10^3 - 10^4$ kg s^{-1} and similar values for $\dot{M}_{\text{fault}}$, which is overwhelmingly dominant over $\dot{M}_{\text{plume}}$. By mass conservation, mass loss rate at the fault is related to the velocity of material moving into the fault zone (u) and the density of ice,

$$\dot{M}_{\text{fault}} \sim \rho z_o l u \cdot$$

Equating both estimates of the mass loss rate at the fault, we can obtain an estimate of

$$u \sim \frac{(10 \text{ to } 100)\dot{M}_{\text{plume}}}{\rho z_o l} \sim 1 \text{ to } 10 \text{ cm year}^{-1}$$

The south polar terrain occupies about 10% of Enceladus' total surface area, so the time scale to subsume the area of lithosphere at the south polar terrain is ~1 to 5 Myr.

It is also possible that the tiger stripes on Enceladus represent mid-ocean-rift-type spreading centers. Simple models of mid-ocean-ridge spreading behavior have been applied to the formation of ridged bands on Europa, where sub-parallel ridges and troughs have formed in response to lithospheric extension (Stempel et al. 2005). Similar to terrestrial mid-ocean-ridges, the tiger stripes on Enceladus may represent locations where warm, viscous ice rises buoyantly toward the surface of the satellite. Tidal dissipation likely plays a role in creating warm ice in the subsurface, which would rise to the surface of a rheologically-weakened lithosphere. In addition to creating tidal dissipation, the daily tidal flexing of Enceladus' lithosphere likely creates zones of weakness where the ice shell is in an extensional stress regime. Similar to the shear-heating model for the formation of the tiger stripes, a mid-ocean-rift-type mechanism may explain the observed large heat flux in the region around Enceladus' south polar terrain and the spatial association between the stripes and the large brightness temperatures observed by CIRS (Spencer et al. 2006; Stempel et al. 2005).

A simple model of the formation of terrestrial mid ocean ridges from Turcotte and Schubert (2002) relates the heat flux as a function of distance away from the mid ocean ridge to the half-spreading rate, u as

$$q(x) = k(T_1 - T_o)\left(\frac{u}{\pi\kappa x}\right)^{1/2}$$

where k=2.46 (250 K/T) W m^{-1} K^{-1} is the temperature-dependent thermal conductivity of ice, x is the distance from the spreading center, $T_1 \sim 270$ K is the temperature of the warm upwelling material, T_o is the temperature of the surface, and $\kappa = 1.47 \times 10^{-6}$ (250 K/T)^2 m^2 s^{-1} is the temperature-dependent thermal diffusivity of ice. The regional heat flux in the south polar region of Enceladus is $q_r \sim 250$ mW m^{-2} (Spencer et al. 2006), spread over an area of 75,000 km^2, the approximate area of Enceladus' surface poleward of 25° S. If we envision that this heat flux occurs due to spreading of the south polar region in a mid-ocean-ridge-type mechanism, the regional heat flux is

$$q_r = \frac{1}{21}\int_{-l}^{l} q(x)dx = 2k\,\Delta T\left(\frac{u}{\pi\kappa l}\right)^{(1/2)}$$

where $l \sim 137$ km is the half-width of a square region with an area of ~75,000 km^2. A regional heat flux of 250 mW m^{-2} gives a half-spreading rate of $u \sim 1$ m year^{-1}, which implies a time scale of ~0.1 Myr to recycle the south polar terrain, provided a mechanism for crustal burial/ loss operates at the margins of the terrain. The mass of warm ice exhumed onto the surface of Enceladus by this process, $\dot{M}_{\text{rift}}$ is related to the width of the rift zone ($w \sim 2$ km) as,

$$\dot{M}_{\text{rift}} \sim \rho w(2l)u$$

where $2l$=273 km is the length of the rift zone. A spreading rate of $u \sim 1$ m year^{-1} gives $\dot{M}_{\text{rift}} \sim 10^4$ kg s^{-1}, broadly consistent with, but at the upper range of the values obtained from the shear-heating formation mechanism described above.

The estimates of the spreading velocity for the mid-ocean-ridge-type rifting mechanism gives a spreading rate a factor of ~10 larger than the values obtained assuming the tiger stripes form as a result of shear heating in the ice shell. In addition, each model provides different predictions about whether the tiger stripes are sites of crustal creation (due to warm upwelling of ice in the mid ocean ridge model) or crustal loss (due to creation of melt at the base of a fault zone in the shear heating model). The lithospheric recycling mechanisms we have described here are necessarily speculative given the preliminary nature of the *Cassini* data and the wealth of unanswered questions about Enceladus' interior processes. However, these provide us with at least some order of magnitude constraints on the time scale over which surface material on Enceladus may chemically mix with its deeper interior.

Silicates: Endogenic or Exogenic?

In the previous section, we discuss the nucleation and microphysics of particle growth in the plume. The natural question arises: what is the source of the silicate particles for the nucleation process? While the surface is being bombarded by micrometeoroids, it is possible that silicate material required for nucleation of the icy particles in the plume could come from the interior of the moon. *Cassini*'s Cosmic Dust Analyzer (CDA) estimates the influx of dust to Enceladus to be ~0.2 kg s^{-1}. Both Porco et al. (2006) and Hansen et al. (2006) estimate material from the plume to be escaping at a rate of ~150 kg s^{-1}. If the silicates are <1% by weight of the plume material, then such a small amount of silicates could presumably be entrained within the ice crust of Enceladus even if the moon is fully differentiated (private communication, R. Pappalardo). However, taking the amount of dust in the plume to be ~1–2% (Kempf, private communication) we obtain ~0.15 kg s^{-1} escaping dust at the 1% level. Assuming the micrometeoroid flux of Moses et al. (2000) of ~10^{-16} g/cm^2s, moon radius, R, of 250 km, and an area of $\pi R^2 = 2 \times 10^{15}$ cm^2, giving a total influx of dust of ~0.2 g/s. This flux is far less than that obtained by *Cassini*'s CDA observation, which shows that the total influx of dust from exogenic sources is insufficient and clearly there must be material coming from under the ice mantle of Enceladus as well: the vast majority of silicate material in the plume is from this endogenic source. This provides compelling evidence that material in Enceladus' plume is coming from its deep interior. If material from the deep interior of Enceladus can be erupted in its plume, it is possible that the plume materials may hold clues about its ocean chemistry and possibly, extant life.

To date there has been essentially no evidence for salt ions in the plume. This is hard to rectify with a liquid water reservoir in the subsurface as it is reasonable to expect the plume to have ionized salts such as sodium (atomic mass 23) present that have not yet been observed thus far. Lack of detectable sodium either means there is no sodium in the upper icy lithosphere of Enceladus or that the sodium is in a form not easily detectable by an observation that requires it to be in the form of an atomic vapor. Unlike Europa, sodium does not appear in the form of a salt (Na_2SO_4 hydrated with H_2O) on the surface, so there is no surface source to form the atomic salt ion vapor via sputtering effects of energetic particles from Saturn's magnetosphere (LeBlanc et al. 2002). There is also a likely difference in the magnetospheric particle precipitation from that of Saturn that makes sputtering much less effective than at Europa. We cannot resolve this in this paper, but future flybys using the *Cassini* ion and neutral mass spectrometer (INMS) may be able to ameliorate this outstanding problem and their presence ultimately confirmed. However, there are processes that may also aid in eluding their detection. Riming, where water lacquers the nucleating silicate particles that may contain salt from the interior, would render direct detection from the silicate dust cores difficult. Additionally, since Enceladus has very pure water ice (at least in the upper part of the icy lithosphere), the water involved the riming process would lack sodium or other salts and further contribute to a difficult detection. A future detection of sodium in the plume of Enceladus might confirm a source from the deep interior of the moon. As has been done in the past (Schneider et al. 2007), it is not appropriate to compare Na (which is involatile) with H_2O (which is volatile). Na atoms are usually not free and must be released from its solid parent molecule by sputtering; H_2O can evaporate from ice readily. Thus a more appropriate comparison is between Na and OH, as both could be sputtered products of the sputtering process.

Origin of Nitrogen

The combined observations of Enceladus by the *Cassini* CAPS, INMS and UVIS instruments detected a water vapor plume in which were present molecular nitrogen (N_2), carbon dioxide (CO_2), methane (CH_4), propane (C_3H_8), 30 acetylene (C_2H_2), and several other species, together with all of the decomposition products of water (Matson et al. 2007). Propane and acetylene can be formed by photolysis of methane on the surface of the ice mantel (Allamandola et al. 1988). However, the presence of propane and acetylene may also be a possible indication of high temperatures inside the moon (500–800 K; Matson et al. 2007). The presence of N_2 in the plume could then possibly indicate thermal decomposition of ammonia earlier in the Enceladus' history, but there are ongoing competing processes contributing to the destruction of ammonia. Loeffler et al. (2006) show that energetic ions impacting the surface will destroy any ammonia present, since the resurfacing rate isn't enough to shield them from destruction. Also, there are radiogenic sources as well. There could have been NH_3 in abundance in the early history of Enceladus, but recycling of the ice mantle would "scrub" the ammonia out leaving predominantly N_2 (over one billion years, at a recycling rate of 1–200 million years, obtains 5–1,000 cycles). Cycling also results in an estimated Enceladus mass loss of ~20% (Kargel 2006). The N_2 (along with H_2O_2) would be delivered by crustal recycling over time down to the clay/rock/ice/water interface. Current estimates (Hansen et al. 2006; Waite et al. 2006; Parkinson et al. 2006) put N_2 in the plume at about 4%. Primordial values of $N_2/NH_3=3$ in the Saturnian system (Mousis et al. 2002). Four percent NH_3 by mass can be delivered to the protosaturnian disk by NH_3 clathrated planetesimals from the cold outer regions of the disk (Rs >80). Assuming the ice mantle of Enceladus had a similar value at formation, a coarse estimate would suggest an ~67% depletion of N_2 over four billion years due to the hydrological cycle of the moon. What about the northern region? Perhaps there are ammonia reservoirs deep in the ice. However, if the ice crust "moves around" at all, this may provide additional sources of ammonia, and hence, N_2. Additionally, the Cassini spacecraft has observed acetylene and propane, which presumably formed from methane by high temperature processes. Such high temperatures have been proposed by Matson et al. (2007) but it is not at all clear at this point that this is indeed the case.

The processes governing the geochemical cycle apply to all species, with methane being a lot more stable than ammonia. Therefore some methane may survive, where ammonia seems not to have done so, which is consistent with the *Cassini* observations, viz., H_2O ~91%, N_2 ~4%, CO_2 ~3%, CH_4 ~1.6%, ammonia <0.5% (cf. Hansen et al. 2006; Waite et al. 2006; Parkinson et al. 2006).

Discussion and Conclusions

Enceladus' spectacular cryovolcanic activity, tectonic resurfacing, and the presence of a plume of water and other materials erupting from its south pole make it a compelling target for astrobiological exploration. Unlike the icy Galilean satellites, whose geological activity may have occurred millions of years ago, Enceladus is active today, and its plume provides us with an opportunity to sample its deep interior without the risk of forward-contamination by a landed spacecraft.

Here we have discussed how characterization of Enceladus thus far suggests that a global geochemical cycle exists wherein material from the surface of Enceladus is mixed into its ocean, and ocean materials are erupted into the plume. The presence of a geochemical cycle significantly enhances the habitability of Enceladus' ocean, and most importantly, our ability to detect possible life.

Modeling of the development of the plume particles at Enceladus' south pole showed that the plume particles originate from a region of Enceladus' near surface with $T > 190$ K. We have discussed the geophysical and astrobiological implications of the formation of Enceladus' tiger stripes and associated plumes due to shear-heating, which can result in extremely high temperatures (~273 K) in the subsurface, consistent with the high vent temperatures obtained in our plume modeling. If the tiger stripes form due to cyclical strike-slip motion in the lithosphere, melt generated at the base of the fault zone can drain downward into the ice shell, resulting in net crustal loss. If about five to ten tiger stripe-like features operate on Enceladus at any given time, the surface area of the south polar terrain can be "recycled" on a time scale between 1 to 5 Myr. Conversely, if the tiger stripes form in a manner similar to terrestrial mid-ocean-ridges, half-spreading rates consistent with the regional heat flux of 250 mW m^{-2} are of order 1 m $year^{-1}$, resulting in the creation of 10^4 kg s^{-1} of new crust, which must be balanced against crustal loss rates at the margins of the south polar terrain. Finally, we have presented compelling evidence that there is surface/ocean communication on Enceladus based on the amounts of silicate dust material present in the plume particles. Therefore, we conclude that the presence of Enceladus' plume and associated tectonic processes imply that tiny, active Enceladus possesses a global geochemical cycle.

A final question then arises as to whether or not this geochemical cycling could be large enough to drive either the origin of life, or, if life could somehow be transmitted there through natural or artificial processes, the maintenance of a biogeochemical cycle of some sort. As noted by Kirschvink and Weiss (2002), the two processes are quite distinct. As a fundamental rule, all biological processes are governed by the laws of Evolution through Natural Selection (Darwin 1859), which generally operates by taking an inefficient, sloppy process and perfecting it down to the thermal noise limit. As all known life is based on electrochemistry[1], we would expect that the initial environment for an origin of life would need steep chemical gradients, allowing a self-replicating system to function, albeit inefficiently. Evolution would then improve the metabolism, allowing sub-groups to exploit more subtle chemical gradients. The peroxide to methane, ammonia, or hydrogen geochemical gradients expected to be on Enceladus would certainly fulfill this requirement for initial large gradients, assuming that appropriate conditions for the synthesis of necessary organic components could be met (e.g., compounds like ribose as discussed by Ricardo et al. 2004). On the other hand, it is clear that aerobic respiration, such as that which most of the terrestrial biosphere depends upon now, would not function easily, as the process of oxidative phosphorilization shuts down if the oxygen concentration is less than that of the Pasteur point, about 0.1 of Earth's present atmospheric concentration. Better measurements of the geochemical composition of Enceladus' plume might help place constraints on these parameters.

Enceladus may have the necessary geologically active, energy-generating reactions sufficient to create a redox gradient favorable for life. The most abundant oxidant on icy

[1] By "electrochemistry", we mean utilizing one of the various electron transport chains that generate ATP and/or $NADH^+$ via the pumping of protons across membranes. The enzymes that convert that proton-motive force into ATP (f-ATPase family) were present in the last common ancestor of all living things. Hence, all life is indeed based on electrochemical potentials of the oxidation reduction reactions. The one possible exception are some photosynthetic archaea, which use a rhodopsin-like molecule that undergoes a cis/trans conformation when it adsorbs a photon, and uses the energy to pump a proton across a membrane, but even these bugs have other electron transport chains.

satellites is H_2O_2, which has been detected on Europa and Enceladus. We assume that the ratio of the H_2O_2 production rate and the H_2O sputtering rate is the same for Europa and Enceladus. This implies that the production rate of H_2O_2 at Enceladus would be of the same magnitude as that on Europa $\sim 10^{11}$ molecules cm^{-2} s^{-1}. Baragiola (private communication) suggests this value may be one or two orders of magnitude too high and we therefore use $\sim 10^9$ molecules cm^{-2} s^{-1} in order to more rigorously constrain our calculations. Following Chyba and Phillips (2002) for Europa, it is possible to estimate the total number cells that could exist in an ecosystem underneath Enceladus' ice crust in the vicinity of the plume vent. Using our estimated value for a crust turn-over time of ~ 5 Myr and assuming the conditions (such as the concentrations of H_2O_2 and HCHO, and a recycling ice thickness of 1.3 m) of Enceladus are similar to those of Europa, we estimate the microbial ecology in the region of Enceladus' plume to be $\sim 10^{19}$–10^{20} cells (for a 10^3 year biological turn-over time). The same calculation for Europa with similar values yields a total of microbe volume of $\sim 10^{21}$–10^{22} cells. Given radii of 1565 and 250 km for Europa and Enceladus, respectively, our estimated value is about the same order of magnitude per unit area for Enceladus as that for Europa.

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References

Allamandola LJ, Sandford SA, Valero GJ (1988) Photochemical and thermal evolution of interstellar/pre-cometary ice analogs. Icarus 76:225–252

Barr AC (2004) Convection in ice I with non-Newtonian rheology: application to the icy Galilean satellites, Ph.D. thesis, University of Colorado, Chapter 5

Barr AC, McKinnon WB (2007) Convection in Enceladus' ice shell: conditions for initiation. Geophys Res Lett 34:9 2006GL028799

Barr AC, Pappalardo RT (2003) Numerical simulations of non-Newtonian convection in ice: application to Europa, in Lunar and Planetary Science Conference, Abs. [CD-ROM] Lunar and Planetary Science Institute, Houston TX, abstract no. 1477

Barr AC, Nimmo F, Pappalardo RT, Gaidos E (2002) Rise of deep melt into Ganymede's ocean and implications for astrobiology, in Lunar and Planetary Institute Conference Abstracts, p. 1545

Brown RH, Clark RN, Buratti BJ, Cruikshank DP, Barnes JW, Mastrapa RME, Bauer J, Newman S, Momary T, Baines KH, Bellucci G, Capaccioni F, Cerroni P, Combes M, Coradini A, Drossart P, Formisano V, Jaumann R, Langevin Y, Matson DL, McCord TB, Nelson RM, Nicholson PD, Sicardy B, Sotin C (2006) Composition and physical properties of Enceladus' surface. Science 311:1425–1428

Chyba CF, Hand K (2001) Life without photosynthesis. Science 292:2026–2027

Chyba CF, Phillips CB (2002) Europa as an abode of life. Orig Life Evol Biosph 32:47–67

Colbeck SC (1998) Sintering in a dry snow cover. J Appl Physi 84:4585

Collins GC, Goodman JC (2007) Enceladus' south polar sea. Icarus 189:72–82

Darwin C (1859) On the origin of species by means of natural selection, or the preservation of favored races in the struggle for life. Cambridge University Press, Cambridge, p 502

Gaidos EJ, Nealson KH, Kirschvink JL (1999) Life in ice-covered oceans. Science 284:1631–1633

Greeley R et al (2004) Jupiter: The planet, satellites, and Magnetosphere. Cambridge University Press, Cambridge, pp. 329–362

Hansen CJ, Esposito L, Stewart AIF, Colwell J, Hendrix A, Pryor W, Shemansky D, West R (2006) Enceladus' water vapor plume. Science 311:1422–1425

Ingersoll AI, Porco CC, West RA, Mitchell C, Turtle EP (2006) American Geophysical Union, Fall Meeting abstract # P22-B-04

Jakosky BM, Shock EL (1998) The biological potential of Mars, the early Earth, and Europa. J Geophys Res 103:19,359–19,364

Kargel J (2006) Enceladus: cosmic gymnast, volatile miniworld. Science 311:1389

Kieffer SW, Lu X, Bethke CM, Spencer JR, Marshak S, Navrotsky A (2006) A clathrate reservoir hypothesis for Enceladus' south polar plume. Science 314:1764–1766

Kirschvink JL, Weiss BP (2002) Mars, panspermia, and the origin of life: where did it all begin? Palaeontol Electronica 4(2):8–15

Kivelson MG, Khurana KK, Russell CT, Volwerk M, Walker RJ, Zimmer C (2000) Galileo magnetometer measurements: a stronger case for a subsurface ocean at Europa. Science 289:1340–1343

LeBlanc F, Johnson RE, Brown ME (2002) Europa's sodium atmosphere: an ocean source? Icarus 159:132–144 doi:10.1006/icar.2002.6934

Loeffler MJ et al (2006) Enceladus: a source of nitrogen and an explanations for the water vapor plume observed by Cassini. Astrophys J 649:L133–L136

Matson DL, Castillo JC, Lunine J, Johnson TV (2007) Enceladus' plume: compositional evidence for a hot interior. Icarus 187:569–573

McCollom TM (1999) Methanogenesis as a potential source of chemical energy for primary biomass production by autotrophic organisms in hydrothermal systems on Europa. J Geophys Res 104:30,729–30,742

Moses JI, Lellouch E, Bezard B, Gladstone GR, Feuchtgruber H, Allen M (2000) Photochemistry of Saturn's atmosphere. Icarus 145:166

Mousis O, Gautier D, Bockelee-Morvan D (2002) An evolutionary turbulent model of Saturn's subnebula: implications for the origin of the atmosphere of Titan. Icarus 156:162–175

Newman SF, Buratti BJ, Brown RH, Jaumann R, Bauer J, Momary T (2007) The search for hydrogen peroxide on Enceladus, 38th Lunar and Planetary Science Conference abstract no. 1338, 1769

Nimmo F, Gaidos E (2002) Strike-slip motion and double ridge formation on Europa. J Geophys Res 107:5021 doi:10.1029/2000JE001476

Nimmo F, Spencer JR, Pappalardo RT, Mullen ME (2007) Shear heating as the origin of the plumes and heat flux on Enceladus. Nature 447:289–291 doi:10.1038/nature05783

Parkinson CD et al (2006) Enceladus: Cassini observations and implications for the search for life (Research Note); Astronomy and Astrophysics, 463:353

Parkinson CD, Liang MC, Hartman H, Hansen CJ, Tinetti G, Meadows V, Kirschvink JL, Yung YL (2007) Astron Astrophys 463:353–357

Porco CC, Helfenstein P, Thomas PC, Ingersoll AP, Wisdom J, West R, Neukum G, Denk T, Wagner R, Roatsch T, Kieffer S, Turtle E, McEwen A, Johnson TV, Rathbun J, Veverka J, Wilson D, Perry J, Spitale J, Brahic A, Burns JA, DelGenio AD, Dones L, Murray CD, Squyres S (2006) Cassini observes the active south pole of Enceladus. Science 311:1393–1401

Ricardo A, Carrigan MA, Olcott AN, Benner SA (2004) Borate minerals stabilize ribose. Science 303: 196–196

Schneider NM, Burger MH, Johnson RE, Kargel JS, Schaller EL, Brown ME (2007) No ocean source for Enceladus' plumes, 2007, AGU Fall Meeting Abstracts, 8, 2007AGUFM.P11F.08S

Spencer JS, Pearl JC, Segura M, Flasar FM, Mamoutkine A, Romani P, Buratti BJ, Hendrix AR, Spilker LJ, Lopes RMC (2006) Cassini encounters Enceladus: background and the discovery of a south polar hot spot. Science 311:1401–1405

Stempel MM, Barr AC, Pappalardo RT (2005) Model constraints on the opening rates of bands on Europa. Icarus 177:297

Tian F et al (2006) Monte Carlo simulations of the water vapor plume on Enceladus. Icarus 188:154–161

Toon OB, Turco RP, Westphal D, Malone R, Liu MS (1988) A multidimensional model for aerosols, description of computational analogs. J Atmos Sci 45:2123–2143

Turcotte DL, Schubert G (2002) Geodynamics. Cambridge University Press, Cambridge

Waite JH, Combi MR, Ip WH, Cravens TE, McNutt RL, Kasprzak W, Yelle R, Luhmann J, Niemann H, Gell D, Magee B, Fletcher G, Lunine J, Tseng WL (2006) Cassini ion and neutral mass spectrometer: Enceladus plume composition and structure. Science 311:1419

Zolotov Yu M, Shock EL (2004) A model for low-temperature biogeochemistry of sulfur, carbon, and iron on Europa. J Geophys Res 109:E06003 doi:10.1029/2003JE002194