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**Energy Production and the Potential for Life on Outer Solar System Satellites**

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**Abstract**
Scientists searching for extraterrestrial life forms have recently begun to focus their attention on a group of icy bodies in the outer solar system. These satellites, particularly Europa, Enceladus, Titan and Triton, are thought to contain both organic molecules and liquid water, and, unlike the organic-rich comets and meteorites of the inner solar system, may also have suitable energy sources for simple organic chemistry to proceed. Key energy sources on the icy satellites include radioactive heating and tidal energy production driven by the interaction of the satellites with the gravitational fields of nearby bodies. Although the amount of energy generated by each of these processes is as yet unknown, modelling exercises have suggested that either may be sufficient to melt substantial parts of the satellites' interiors and provide a sub-surface ocean suitable for extraterrestrial life to develop. Understanding energy sources on icy satellites, therefore, is important for astrobiology, as well as potentially contributing to our understanding of the geomorphology and surface evolution of those bodies. This article investigates the key energy sources on the active satellites of the outer solar system, and assesses their potential for supporting life.

**Introduction**
The giant planets and their satellites have been described as "small-scale analogs of the solar system itself" (Brown and Cruikshank 1997), with "a greater range of geologic processes on display than almost anyone would have dared hope for" (Rothery 1992). For geomorphologists, these satellites offer unique opportunities to study landscape processes like volcanism and tectonics, with ice behaving much like terrestrial silicate rock on several of the icy worlds (Murchie 1990 and see figures 1 and 2), and Io, the most internally active body in the solar system (Kawakami and Mizutani 1987), demonstrating extensive silicate volcanism (Peale 2003). On the icy satellites, this activity (which includes melting of ice masses, eruption at the surface, flows and various other volcanic and tectonic processes) is called *cryovolcanism*. The icy satellites, however, have perhaps attracted most attention from astrobiologists, who identify worlds potentially capable of harbouring life by looking for liquid water, biogenic elements and energy sources (Jakosky 1998). The icy satellites are known to possess water (largely in the form of ice, but with the potential - given their tectonic activity - for liquid reservoirs, ESA Report 1999), and some, like Europa, may have significant reservoirs of

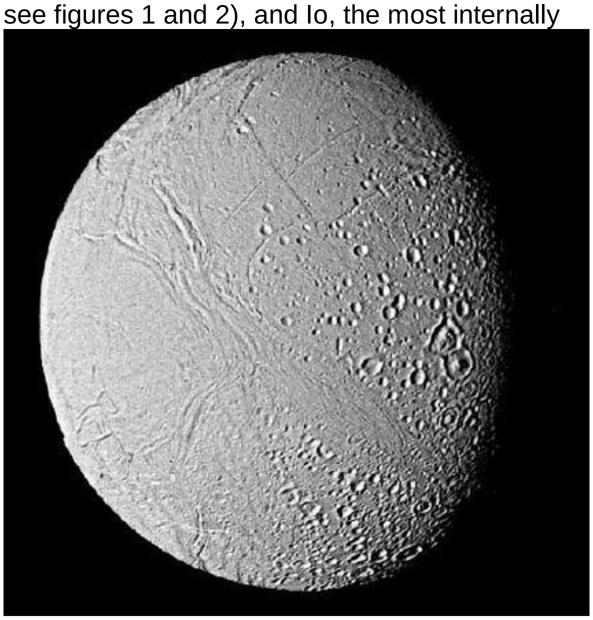

***Figure 1: A high resolution picture of the surface of Enceladus showing newly re-surfaced areas with very few craters as evidence of cryovolcanic activity. Taken from Peale 2003, his figure 9.***

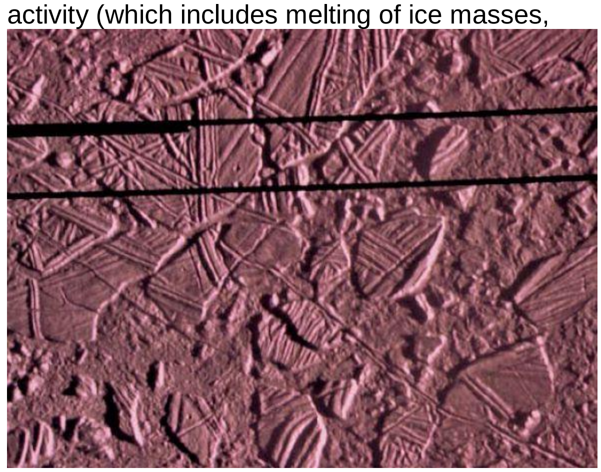

***Figure 2: An image of Europa's surface showing the linear markings where ice floes have been broken apart due to surface activity and movement. Taken from the ESA Report 1999, their figure I.5.1.1/1.***

biogenic elements (Pierazzo and Chyba 2002). All that remains is to identify an energy source capable of driving organic chemistry. On Earth, the amount of energy produced by any given energy source is measured in terawatts (abbreviated to TW, with one terawatt equal to $10^{12}$ watts), but on the outer solar system satellites the total energy production is probably much less, and exact figures remain unknown.

Ilya Prigogine (1978) observed that biological systems are open and dissipative in thermodynamic terms; energy is continually released by irreversible processes like the burning of solar fuel. These irreversible processes create local reversals of the second law of thermodynamics that make life possible. On the icy satellites, although solar radiation is weak, other energy sources which might drive biological systems include radioactive decay, tidal heating, chemical reactions in liquid reservoirs and the release of residual energy from the satellites' formation. This article will evaluate these energy sources and their contributions to energy production on those of the larger outer solar system satellites that are currently active. These bodies include Io (which has no liquid water and hence probably cannot support life irrespective of energy availability, McEwan 2002), Enceladus, Europa and Triton (Rothery 1992), and the newly investigated Titan, which seems to have some active cryovolcanism (Sotin and Tobie 2008, Kerr 2005).

***Radioactive Energy***

Radioactive energy is relatively well understood, as it contributes substantially to the energy budget on Earth, producing 19TW (Araki et al. 2005) out of a total heat flux for our planet estimated at 31TW ± 1TW (Hofmeister and Criss 2005). Some 84% of this terrestrial radioactive energy comes from the decay of just two isotopes, $^{238}U$ and $^{232}Th$ (Araki et al. 2005), and early thermal models of the outer solar system satellites assumed that long-lived radioisotopes like these two, $^{235}U$ and $^{40}K$ were the main drivers of heat production, geomorphologic processes and thermal and chemical evolution on these worlds (e.g. Lewis 1971, Mueller and McKinnon 1988 and Consolmagno and Lewis 1978). Tidal energy, the other major source of energy on these outer solar system worlds, was only introduced into models more recently (e.g. Sotin and Tobie 2004). Nonetheless, some models incorporating only radioactive heat generation have predicted that internal liquid water oceans could be created and maintained in icy bodies of larger radius even in the absence of other heat sources (Spohn and Schubert 2003), suggesting radioisotopes still have an important role to play.

Radioactive energy is produced when an unstable atom decays, emitting a smaller particle. Identifying the unstable atoms present in the outer solar system satellites is difficult; often, researchers simply assume a certain composition for the rocky components of these worlds. Most assume this rock is chondritic in composition – with a similar elemental makeup to the Sun, such as might occur if the satellites were simply accretions of material from the formation of the solar system (Consolmagno and Lewis 1978). Which specific type of chondrite – as there are several possibilities – is not always specified, but a revised estimate of an "average" composition for chondritic rocks suggests they will contain 7.4 parts per billion (ppb) of uranium, 29 ppb thorium and 550 parts per million potassium (McDonough and Sun 1995). This estimate enables chemists to calculate the abundances of long-lived radioisotopes in the satellites using their masses, and hence to work out the rate of energy production from these isotopes. $^{238}U$ and $^{232}Th$, the most abundant long-lived radioisotopes in the solar system, both decay via complex chains of α and β decay (respectively the emission of a helium nucleus or "alpha particle" and an electron and antineutrino) into $^{206}Pb$ and $^{208}Pb$ (Araki et al. 2005). The half lives of these two isotopes – $4.468 \times 10^{9}$ years and $1.405 \times 10^{10}$ years respectively (data from the WWW table of Radioactive Elements, Ekstrom and Firestone) – and of the less abundant $^{235}U$ and $^{40}K$ are all sufficiently long for energy to be produced today at a measurable rate.

Although most scientists would accept that heat is still being produced by long-lived radioisotopes on the outer solar system satellites, the question of how significant this heat is to geomorphology and biology is still open to debate as the magnitude of these heat fluxes is unknown. Several recent papers have commented on the inadequacy of radioactive energy production as a full explanation for the observed geomorphology and activity on these bodies, and tidal energy is often assumed to be more important. Tackley et al. (2001), for example, in their model of Io, note that the average tidal dissipation in that body is 2.5 times the energy produced by radioactivity in the silicate portions. For Europa, however, Hussman and Spohn (2004) have estimated that radioactivity generates $2.1 \times 10^{11}$W while tidal energy fluxes are relatively smaller (an order of magnitude smaller than on Io), and on Ganymede the radioactive heat production rate is several orders of magnitude higher than the tidal one (Hussman and Spohn 2004). It is clear that radioactive heat production depends also on the age of the satellite – in the first $10^8$ years from satellite formation, radioactive heat production is similar in magnitude to the total energy production by self-compaction and differentiation, and it may remain an important hear source on medium-sized, non-tidal icy satellites (Czechowski and Leliwa-Kopystynski 2005).

***Tidal Energy***

Newton's law of universal gravitation states that every object in the Universe exerts a gravitational attraction on every other object, with the force directed along the line between their centres of mass. More recently, this has been interpreted to suggest that "every satellite or planet is distorted into a (slightly) prolate shape (i.e. exhibits a tide) by the gravitational field of another mass" (Peale 1999). Every object in the solar system is tidally deformed by every other body, but it is only those which are massive and/or near to a given body that will have any major impact (Peale 1999). In the case of the outer solar system satellites, the influence of the parent planets and neighbouring satellites may set up substantial tidal energy fluxes. These tidal forces control the orbital evolution of satellites in the early stages of formation by setting up a lag in the response of a tidally distorted body to its own rotation, resulting in a tidal buldge which is misaligned with the planet or satellite producing it (Peale 1999). This creates a torque which can transfer angular momentum from the spin of the distorted object to the orbit, with both the torque on the planet and the satellite itself contributing to the orbital evolution of the system by slowing the rotation of the satellite until it reaches a synchronous orbit (Peale 1999) and adjusting the orbit shape until it is completely circular (Peale 2003). Planetary rotation and the distance between the planet and satellite may also be affected, as has occurred in the Earth-Moon system (Williams 2000). Once these synchronously rotating orbits with zero eccentricity have been established, the rate of tidal energy production decreases dramatically, and it is only on those bodies where orbital perturbations remain active that significant tidal heating continues (Peale 1999).

Orbital perturbations are maintained by mean-motion resonances, occurring where the orbital periods of two or more adjacent satellites are in a low-integer ratio, creating a regular geometric pattern of gravitational interaction (Peale 2003). These orbits may even be the result of orbital evolution through tidal forcing (Yoder and Peale 1981), and are particularly obvious in the Galilean satellites Io, Europa and Ganymede. These satellites fulfil a Laplacian resonance (where three or more adjacent satellites are in resonance) such that Io orbits four times in the period in which Europa makes two orbits and Ganymede one (Peale 2003). This maintains orbital eccentricities of 0.0041 for Io and 0.0101 for Europa, which would quickly be dampened to zero in the absence of the Laplace resonance (Peale 2003). Saturn's Enceladus has recently been involved in a resonance with Janus with a ratio of 2:1 orbits (Lissaeuer et al. 1984), and currently resonates with Tethys and Mimas: Mimas orbits three times to Enceladus' two, and Tethys four times for every three orbits of Enceladus (Meyer and Wisdom 2007). The reason for this recent change in resonance may be the result of a range of processes which affect orbital stability, but remains uncertain (Lissauer et al. 1984).

The amount of heat produced by tidal forcing in a body depends on the gravitational force exerted on it by its primary planet (itself dependent on the distance between them) and any nearby satellites (Peale 2003). This means that significant amounts of heat are normally only produced by tidal deformation in the lowest orbiting (i.e. closest to the parent planet) of each group of resonant satellites. Where tidal heating does occur, however, it seems to be fairly important; Io, the most tidally heated of the outer solar system satellites, has a total heat flux an order of magnitude or more higher than Earth's despite its smaller size (Schubert et al. 2001 as cited in Tackley et al. 2001). Of the geologically active satellites listed in the introduction to this essay, three – Io, Europa and Enceladus – are in orbits where tidal heating may be substantial.

***Other Energy Sources***

Although the activity of some outer solar system satellites is well explained by tidal and radioactive heat production, these energy sources are insufficient for others. The question of Io's energy production is near-solved, with tidal heating and radioactive decay known to be sufficient to drive the observed silicate volcanism (Peale et al. 1979). Enceladus is too small for radioactive decay (which occurs only in bodies with substantial rocky components) to be significant and is thought to be almost exclusively tidally heated, with the higher than expected heat flows from that satellite most likely the result of orbital instability (Meyer and Wisdom 2007). The other three currently active satellites (Europa, Triton and Titan), however, are still under debate, and the additional energy sources proposed to explain discrepancies between the estimated heat fluxes from radioactivity and tidal heating and the observed heat budgets of those satellites will be considered here. These proposed energy sources include the presence of residual heat from accretion, chemical energy from organic reactions, and solar radiation trapping effects. The effects of residual energy may be widespread, but the other energy sources are all thought to be localised, and occur as a result of the specific conditions individual satellites.

When planetesimals collide during solar system accretion, some of the total kinetic energy is stored as potential and heat energy in the resulting fragments, and this is thought to be responsible for the initial melting of the terrestrial planets, including Mars (Solomon et al. 2005). Although collisions may have originally caused the formation of liquid water oceans on some of the large icy satellites (Kossacki and Leliwa-Kopystynski 1993), without other energy sources these oceans would be unlikely to have lasted until the present day as impacts have been rare since the end of the late heavy bombardment 3.5 million years ago. Oceans once melted by accretion might remain liquid or re-melt due to changes in ice porosity as a result of impact heating (Kossacki and Leliwa-Kopystynski 1993) and some larger satellites might retain a little residual heat from the differentiation of their interiors, but overall we can probably eliminate residual energy as a major source of energy on the outer solar system satellites today, as it is unlikely to provide much heating. Instead, the three satellites whose energy production is debated must be considered in terms of their individual properties.

Europa has recently been found to have a total (radiogenic and tidal) energy flux three orders of magnitude smaller than those supporting ecosystems on Earth – for life to exist there, new energy sources must be found (Gaidos et al. 1999). Nonetheless, much recent astrobiological research has focused on Europa because it is believed to possess a subsurface liquid water ocean (Schulze-Makuch and Irwin 2001) and may be one of the prime sites for the emergence of life in the outer solar system (Raulin 2005). Recent review papers, however, note that “estimates of available free energy have not been encouraging for supporting life” (Chyba 2000). As part of this debate, several new energy sources have been proposed to make up the energy “deficit” on Europa and re-open consideration of its potential for life. These include disequilibrium chemistry in the ocean’s ice/water cover, possibly driven by charged particles from Jupiter’s magnetosphere (Chyba 2000), electrical energy from the motion of Europa through Jupiter’s magnetic field (Reynolds et al. 1983) and kinetic energy from convection and tidal cells in the subsurface ocean (Schulze-Makuch and Irwin 2001). None have so far been confirmed.

Neptune’s moon Triton was found by the Voyager missions to support geyser-like plumes at its surface, although these occur only in areas lit by sunlight (Duxbury and Brown 1997). Several authors have therefore proposed that solar radiation is important to Triton’s activity. Grundy and Stansberry (2000), for example, propose a solid-state greenhouse effect might be responsible on the grounds that nitrogen ice, the dominant surface material, is more absorbent in thermal infrared than visible wavelengths. This means absorption, on average, occurs at greater vertical depths in nitrogen ice than thermal emission, driving sublimation at depth and condensation near the surface and possibly driving the production of cryovolcanic “magmas” and internal or surface oceans (Grundy and Stansberry 2000). Other authors favour different theories, suggesting that radiogenic heating is responsible (with the occurrence of geysers on sunward plains being coincidental or the result of radiative bias) or that convective heat transfer mechanisms allow traditional energy sources to have a greater impact on Triton (Duxbury and Brown 1997). This emphasises that anomalous geological activity need not be the result of a “new” heat source. Titan, which has a surface temperature of -179$^{o}$C (Kerr 2005), was thought until recently to be inactive. Recent Cassini-Huygens images of Titan, however, suggest otherwise, with the discovery of several large, non-cratered ice flows suggestive of cryovolcanism (Sotin and Tobie 2008). Explanations of these effects have focused on the presence of compounds like methane clathrate and ammonia in the icy layers which lower the melting point of the ice and novel mechanisms like plume structures to transport molten material to the surface (Fortes et al. 2007).

***Energy and Life***

With all these potential energy sources on the outer solar system satellites, it seems certainly plausible that some of the icy satellites could support life. Certainly, several may contain liquid water oceans (see figures 3 and 4 for the proposed internal structures of the outer solar system satellites) and organic chemicals. However, there is one more problem still to overcome – the energy must be in a form which organisms can utilise. For example, on Europa, thermal gradients in the ocean in general are so weak an organism would have to be kilometres long to exploit them (Reynolds et al. 1983), although hydrothermal activity might still exist near

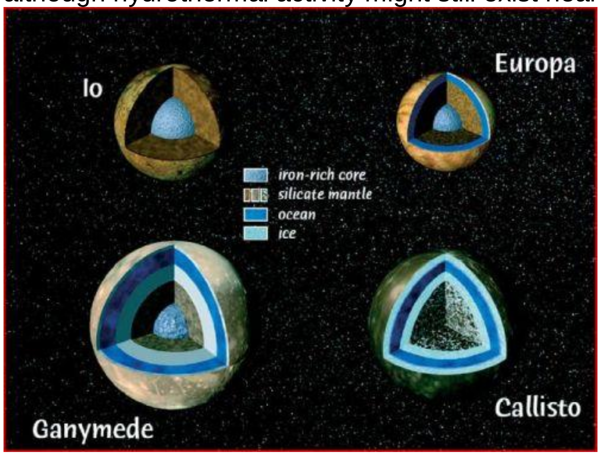


***Figure 3: Models of the internal structures of the Galilean satellites Io, Europa, Ganymede and the currently inactive Callisto. Taken from Sotin and Tobie (2004), their figure 2.***

the ocean's base and have sufficiently strong energy gradients to support life forms. In considering the availability of energy to life forms, we must work by analogy with Earth life. Most Earth organisms utilise solar energy (a very efficient, i.e. low entropy, energy source), via photosynthesis (McKay 1991), although chemical energy sources suffice and can be exploited readily (Jakosky 1998). Those organisms which utilise geothermal energy do so indirectly, gathering energy from thermodynamically-favoured oxidation-reduction reactions, driven by the chemical disequilibrium resulting from radioactive heat dissipation (Gaidos et al. 1999). The same authors note that ultimately, without some dissipative source of energy (which, as Prigogine (1978) suggested, will ultimately run down), abiotic chemical reactions will eventually act to restore chemical equilibrium. This would impose major constraints on any chemically-based life on the icy satellites (Gaidos et al. 1999), but it is possible that on worlds like Europa, geothermal, tidal, or residual heat energy could provide energy to maintain chemical disequilibrium.

Thermal energy is not directly utilised by organisms on Earth, but it has recently been suggested (Muller and Schulze-Makutch 2006) that "the ubiquity of thermal energy and thermal gradients in the Universe makes it plausible that

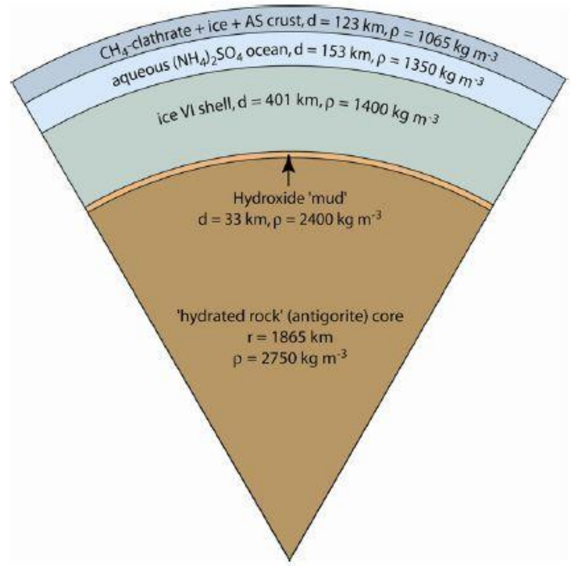


***Figure 4: A model of the internal structure of Titan taken from Fortes 2007 (his figure 5).***

somewhere organisms use it as an energy source". These authors propose that not only may early Earth organisms have utilised thermal energy (possibly in environments which are dark and nutrient poor), but such organisms may persist today on Earth and in the subsurface oceans of the icy satellites of the outer solar system. Four potential reasons that such thermal energy use has not been found on Earth are quoted; namely that use occurs but has not been observed; that thermotrophic organisms were outcompeted by phototrophs and chemotrophs; that such use never arose because phototrophy was more efficient, or that for some unknown reason use of thermal energy is biologically impossible (Muller and Schulze-Makutch 2006). The authors favour the theory that such organisms existed but were outcompeted on Earth, because of genetic and microbiological evidence, suggesting that thermotrophic life might be possible elsewhere in the solar system.

**Conclusions**

Scientists have yet to reach consensus on the contribution of various energy sources in producing the observed geomorphologies and the potential for life on the outer solar system satellites. In general, tidal heating, although not ubiquitous, may be a major source of free energy on some bodies; radioactive decay is more widespread but produces only small amounts of energy. We have yet to ascertain whether such energy sources are sufficient or suitable to sustain life, and modelling experiments produce conflicting results. Several alternative energy sources have none the less been proposed to make good any energy shortfall, including residual heating from accretion and differentiation, disequilibrium chemistry, electrical and kinetic energy and solar radiation, although most of these are specific to certain satellites. Alternatively, some authors prefer the theory that novel heat transport and trapping mechanisms are responsible for differences between calculated energy sources and observed activity levels, further complicating the calculation of energy balances. We have also not yet established whether energy on these satellites is in a form available to organisms. As of yet, no known Earth organism is capable of directly utilising thermal energy, but this does not rule out the possibility of such life. One significant unexplored area of research on the icy satellites is the question of non-typical "life-like" structures. Haken (1981) discusses life in terms of systems of external (control) and internal (order) parameters producing "states of order" which self-perpetuate and self-organise – but notes that similar ordered states arise in a number of very different structures, including in lasers and basic (inorganic) chemical systems. It is natural to speculate that self-perpetuating, self-organising systems (organisms!) could arise which are very different to those we recognise (indeed, Brasier et al. 2004 note that the European Space Agency has a stated goal of "recognising non-carbon based life"), but it is very hard to take these ideas further. This is still a very open area of research.

**References**


Araki, T. et al. (2005) Experimental Investigation of Geologically Produced Antineutrinos with KamLAND. Nature 436, 499-503.

Brasier, M.D. et al. (2004) Characterisation and Critical Testing of Potential Microfossils from the Early Earth: the Apex "Microfossil Debate" and its Lessons for Mars Sample Return. International Journal of Astrobiology 3, 139-150.

Brown, R.H. and Cruikshank, D.P. (1997) Determination of the Composition and State of Icy Surfaces in the Outer Solar System. Annual Review of Earth and Planetary Sciences 25, 243–277.

Chyba, C.F. (2000) Energy for Microbial Life on Europa. Nature 403, 381–382.

Consolmagno, G.J. and Lewis, J.S. (1978) The Evolution of Icy Satellite Interiors and Surfaces. Icarus 34, 280–293.

Czechowski, L. and Leliwa-Kopystynski, J. (2005) Convection Driven by Tidal and Radiogenic Heating in Medium Size Icy Satellites. Planetary and Space Science 53, 749–769.

Duxbury, N.S. and Brown, R.H. (1997) The Role of an Internal Heat Source for the Eruptive Plumes on Triton. Icarus 125, 83–93.

Ekstrom, L.P. and Firestone, R.B. (2004: Version 2.1) WWW Table of Radioactive Isotopes. From URL http://ie.lbl.gov/toi/index.htm, last accessed 23/04/2008.

European Science Agency (1999) Exobiology in the solar system and the search for life on Mars. Report from the ESA Exobiology Team Study 1997–1998.

Fortes, A.D. et al. (2007) Ammonium Sulphate on Triton: Possible Origin and Role in Cryovolcanism. Icarus 188, 139–153.

Gaidos, E.J. et al. (1999) Life in Ice-Covered Oceans. Science 284, 1631–1633.

Grundy, W.M. and Stansberry, J.A. (2000) Solar Gardening and the Seasonal Evolution of Nitrogen Ice on Triton and Pluto. Icarus 148, 340–346.

Haken, H. (1981) The Science of Structure: Synergetics. Van Nostrand Reinhold Company Publishers, Wokingham, England.

Hofmeister, A.M. and Criss, R.E. (2005) Earth's Heat Flux Revised and Linked to Chemistry. Tectonophysics 395, 159–177.

Hussman, H. and Spohn, T. (2004) Thermal Orbital Evolution of Io and Europa. Icarus 171, 391–410.

Jakosky, B.M. (1998) Searching for Life in Our Solar System. Scientific American (the Magnificent Cosmos Special Edition), March 1998, 16–21.

Kawakami, S-I and Mizutani, H. (1987) Thermal History of the Jovian Satellite Io. Icarus 70, 78–98.

Kerr, R.A. (2005) Icy Volcanism has Rejuvenated Titan. Science 308, 193.

Kossacki, K.J. and Leliwa-Kopystynski, J. (1993) Medium Sized Icy Satellites: Thermal and Structural Evolution During Accretion. Planetary and Space Science 41, 729–741.

Lewis, J.S. (1971) Satellites of the Outer Planets: Their Physical and Chemical Nature. Icarus 15, 174–185.

Lissauer, J.J. et al. (1984) Ring Torque on Janus and the Melting of Enceladus. Icarus 58, 159–168.

McDonough, W.F. and Sun, S.-S. (1995) The Composition of the Earth. Chemical Geology 120, 223–253.

McEwan, A.S. (2002) Active Volcanism on Io. Science 297, 2220–2221.

McKay, C.P. (1991) Urey Prize Lecture: Planetary Evolution and the Origin of Life. Icarus 91, 93–100.

Meyer, J. and Wisdom, J. (2007) Tidal Heating in Enceladus. Icarus 188, 535–539.

Mueller, S. and McKinnon, W.B. (1988) Three-Layered Models of Ganymede and Callisto: Compositions, Structures and Aspects of Evolution. Icarus 76, 437–464.

Muller, A.W.J. and Schulze-Makutch, D. (2006) Thermal Energy and the Origin of Life. Origin of Life and Evolution of Biospheres 36, 177–189.

Murchie, S.L. (1990) The Tectonics of Icy Satellites. Advances in Space Research 10, 173–182.

Peale, S.J. et al. (1979) Melting of Io By Tidal Dissipation. Science 203, 892–894.

Peale, S.J. (1999) Origin and Evolution of the Natural Satellites. Annual Reviews of Astronomy and Astrophysics 37, 533–602.

Peale, S.J. (2003) Tidally Induced Volcanism. Celestial Mechanics and Dynamical Astronomy 87, 129–155.

Pierazzo, E. and Chyba, C.F. (2002) Cometary Delivery of Biogenic Elements to Europa. Icarus 157, 120–127.

Prigogine, I. (1978) Time, Structure and Fluctuations. Science 201, 777–785.

Raulin, F. (2005) Exo-Astrobiological Aspects of Europa and Titan: From Observations to Speculations. Space Science Reviews 116, 471–487.

Reynolds, R.T. et al. (1983) On the Habitability of Europa. Icarus 56, 246–254.

Rothery, D.A. (1992) Satellites of the Outer Planets: Worlds in their Own Right. Oxford University Press, Oxford and New York.

Schulze-Makuch, D. and Irwin, L.N. (2001) Alternative Energy Sources Could Support Life on Europa. Transactions of the American Geophysical Union 82, 150–152.

Solomon, S.C. et al. (2005) New Perspectives on Ancient Mars. Science 307, 1214–1220.

Sotin, C. and Tobie, G. (2004) Internal Structure and Dynamics of the Large Icy Satellites. Comptes Rendus Physique 5, 769–780.

Sotin, C. and Tobie, G. (2008) Titan's Hidden Ocean. Science 319, 1629–1630.

Spohn, T., Schubert, G. (2003) Oceans in the Icy Galilean Satellites of Jupiter. Icarus 161, 456–467.

Tackley, P.J. et al. (2001) Three-Dimensional Simulations of Mantle Convection in Io. Icarus 149, 79–93.

Williams, G.E. (2000) Geological Constraints on the Precambrian History of Earth's Rotation and the Moon's Orbit. Reviews of Geophysics 38, 37–59.

Yoder, C.F. and Peale, S.J. (1981) The Tides of Io. Icarus 47, 1–35.