Warm icy moons

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In recent years planetary scientists have been very interested in understanding icy moons of the outer solar system. Europa (at Jupiter), Enceladus (at Saturn), and Ariel (at Uranus) provide interesting case studies of the physical processes affecting moons. It is often suggested by scientists that there could be subsurface 'oceans' in icy moons such as these, but it has proven challenging to explain how such 'oceans' could be prevented from freezing for billions of years. A young-age creation perspective in which heat is still dissipating from creation avoids many of the technical difficulties in explaining these moons.

Solar system missions to the outer planets have provided much interesting data on moons, including some that have active erupting water geysers. Europa (at Jupiter), Enceladus (at Saturn), and Ariel (at Uranus) provide interesting examples for understanding the geology of moons and how it relates to old-age assumptions. All three of these moons are in synchronous rotation (tidal lock) with their host planet, as our moon is with earth. Europa and Enceladus have both been observed with active eruptions of water mixtures significant heights above their surfaces. Eruptions such as these have motivated planetary scientists to attempt to explain the energetics of processes at work in these moons. Old age assumptions are certainly made in this research from secular scientists. However, explaining the heat from these moons and their geological activity has proved challenging to planetary scientists. Assuming a young age, rather than an old age, seems to simplify the issues.

Heat sources in moons of the outer planets include radioactive decay, tidal dissipation, and possibly certain exothermic chemical reactions. Tidal dissipation comes from the moon behaving somewhat like an elastic or plastic body as the gravitational force from its host planet varies. The eccentricity (or degree of elongation) of the orbit is an important factor in tidal dissipation, as well as the composition and internal properties of the moon. In addition, some of the moons in the outer solar system are affected by orbit resonances with other moons. Orbit resonances can cause changes in the shape of a moon's orbit, sometimes very predictably and sometimes rather chaotically. Tidal Dissipation Heating (TDH) stems from the moon's shape being altered from the gravitational pull of its host planet. The tidal effects cause kinetic energy from the orbit and spin of the two bodies to be converted to internal energy within the moon. TDH heating is very significant for Jupiter's moon, Io, for example, as it has very active volcanism. Though TDH is a very strong source of heat for Io, the tidal effects have never been shown to explain all the heat observed in infrared measurements of Io.[1] Io may be the hottest moon in the solar system, but it is not alone in creating a puzzling heat issue for scientists.

Spacecraft missions to the outer solar system have included *Voyager 1* and *2*, *Galileo* (to Jupiter), and *Cassini* (to Saturn). Other significant studies have been done from earth or using various astronomy satellites. Ultraviolet and infrared spectra have been studied significantly for some moons. Europa (at Jupiter), Enceladus (at Saturn), and Ariel (at Uranus) have all presented heat problems that expose difficulties with old-age assumptions. Europa and Enceladus have both been observed with erupting geysers and thus they are thought of as being very similar.[2,3] Both Europa and Enceladus have been conjectured to have layers or pockets of liquid water under the surface. Sometimes Europa is described as having a 'global' subsurface ocean, though not all scientists see it as that extensive. Some have suggested that a subsurface ocean could be an environment where some microorganisms could survive.

The challenging question scientists have puzzled over is: how can a subsurface water ocean still exist after billions of years? Over billions of years small bodies should lose their heat and freeze solid in the outer solar system. Yet, Europa and Enceladus have been observed erupting plumes of water. Note that the presence of a subsurface ocean in Europa and Enceladus is not the only possibility. Smaller pockets of liquid might also fit observations. But water geysers and water in the interior require a heat source that can keep liquid water present inside the moon, so this would have been essential throughout the supposed billions of years of its existence. Europa, Enceladus, and Ariel all have water ice as a significant fraction of their mass. The temperature regime of the outer solar system is such that water becomes the 'volcanic medium' for many moons, essentially, rather than molten rock. But the core or mantle of these moons could be rock. Europa is large enough that it could have an iron core, but this may not be the case for smaller moons. Gravity data obtained from orbiting spacecraft does not uniquely determine the interior structure. But it allows multiple possible models of the interior to be constructed.

Table 1. Orbital parameters of icy moons of the outer solar system compared to earth's moon

Moon Name	Planet	Semimajor Axis Distance Ratio	Orbital Period (days)	Orbit Eccentricity	Orbit Inclination
Moon	Earth	60.3	27.3	0.055	5.15°
Europa	Jupiter	9.40	3.55	< 0.01	0.47°
Mimas	Saturn	3.075	0.94	0.020	1.53°
Enceladus	Saturn	3.95	1.37	0.0045	0.02°
Dione	Saturn	6.256	2.74	0.0022	0.02°
Ariel	Uranus	7.30	2.52	0.0034	0.31°

Table 2. Bulk size and density of selected outer solar system moons compared to earth's moon

Moon Name	Planet	Radius (km)	Density (g/cm^{-3})
Moon	Earth	1,738	3.34
Europa	Jupiter	1,569	2.97
Enceladus	Saturn	251	1.2–1.6
Ariel	Uranus	580	1.6

For many of the icy moons in the outer solar system, the crust is likely to be primarily water ice with some darker material mixed in it or covering it. Other ices may be present as well, such as (especially) methane, carbon dioxide, carbon monoxide, and some ammonia ice. The bulk density and sizes of these moons are generally well known thanks to the *Voyager*, *Galileo*, and *Cassini* missions. However, the data on Ariel is limited to mostly the *Voyager 2* mission. Table 1, above, shows orbital data for earth's moon, contrasted with that of Europa, Enceladus, and Ariel, while table 2 shows contrasting physical properties (table 2).[4] Mimas and Dione are also listed in table 1 because they interact with Enceladus. In table 1, the semimajor axis of the moon orbits are expressed as a ratio of the host planet's radius. Thus, earth's moon has a semimajor axis distance from earth that is the equivalent of about 60 earth radii.

Europa

Jupiter's moon, Europa, has a surface of ice displaying a variety of fractures (figure 1). Scientists have long suspected there could be water eruptions on Europa but there was difficulty obtaining a clear unambiguous observation of it until November and December of 2012, when the Hubble Space Telescope was used to make ultraviolet observations.[5,6] Hubble detected significant amounts of Hydrogen and Oxygen coming from the South Pole region of Europa. This is very likely from dissociated water. Observations were made at the periapse and apoapse (closest and farthest distances from Jupiter) of Europa's orbit with the expectation that the eruptions would happen in a predictable manner each orbit. However, the eruption plumes proved to be not as predictable as first thought. Io, Europa, and Ganymede are all in a three-way 1:2:4 resonance in their orbits.[1] This keeps their orbits extremely stable. Europa's orbit has a low eccentricity and the resonance does not cause much variation in the eccentricity of its orbit. A paper was published recently arguing that Europa must be precessing; this means the tilt of its spin axis would be changing periodically.[7] The paper suggests the precession of Europa's spin occasionally enhances the tidal effect.[7] This study tried to relate the location and alignment of fault structures on Europa to the timing of tidal forces and orbit variations. This is a field of investigation now referred to as 'tidal tectonics'. Tidal forces cause fault structures on the surface to alternate between being in tension and compression. This creates many criss-crossing patterns and lineaments on the surface (figure 2). In 'tidal tectonics' the goal is to determine how tidal stresses affect the surfaces and determine how they might be related to geological structures. There is some success with these methods in studying moons. The tidal stresses would make the amount of heat from tidal dissipation vary as Europa's tilt varies over the course of multiple orbits. The spin precession has been suggested as explaining why the eruptions have not been seen every time scientists have made observations.

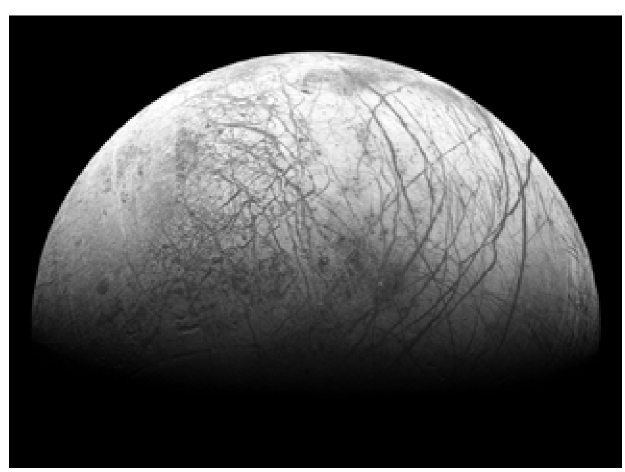

Figure 1. Europa remastered mosaic from the *Galileo* spacecraft, taken in 1995 and 1998. North on Europa is on the right. Image resolution is 1.6 km per pixel. Image has been converted to grayscale.

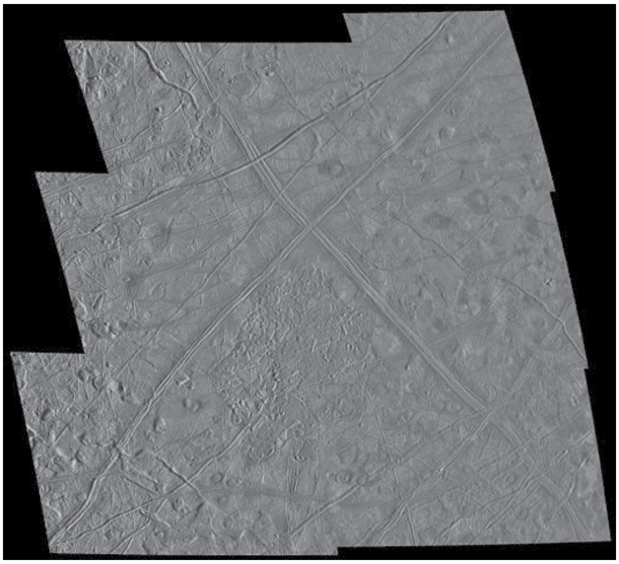

Figure 2. Close-up of Europa surface. From the *Galileo* mission to Jupiter. Image area is 300 x 300 km with north at the top.

The difficulty with this scenario is that theoretical models of the tilt precession require a greater tilt change than gravitational models of the real Europa suggest.[7] Thus tidal dissipation may not be adequate to keep a subsurface ocean liquid for over 4 Ga. One NASA webpage shows Europa's orbit inclination to be tilted 0.466° compared to the spin axis of Jupiter.[8] It is important to determine which effect is more significant in altering tidal stresses, the orbit shape or the spin tilt. The paper by Rhoden, *et al*.[7] is now suggesting Europa had a greater spin tilt in the past. This is because tidal dissipation alone is not an adequate source of heat to keep a subsurface ocean melted. The recent paper by Rhoden[7] has the following statement in the conclusion. Note that a 60° tilt, as mentioned below, would be very surprising for a moon near Jupiter. More on the spin tilt follows below.

> "We find it very unlikely that tidal stress only from eccentricity or with a constant spin pole direction would produce the observed difference in plume activity when Europa was at similar orbital positions. However, if the spin pole precessed by at least 60° between the Dec 2012 and Jan 2014 observations, we do find a more plausible set of candidate faults that are consistent with the observations."[7]

This statement should be compared with the observational evidence on the spin axis tilt of Europa. This requires a determination of the obliquity of Europa. This is the angle between a vector normal (perpendicular) to the plane of the orbit and the spin axis. This was determined by Bills in 2005 from *Galileo* spacecraft gravity measurement data.[9] Bills analyzed the spin precession and orbit inclination changes in relation to Jupiter's shape and tilt and treated the four Galilean moons of Jupiter as triaxial ellipsoids. The study also considered the possibility of periodic changes in the orbital tilt being in a resonant relationship with the spin axis depending on their relative rates. The spin precession rate for Europa was determined to be 0.191 degree/day with an uncertainty estimated as 5%.[9] The results show clearly that Europa's obliquity is much less than one degree and there is no significant orbit-spin resonance effect. The obliquity for Europa was determined to be $(9.65 \pm 0.69) \times 10^{-2}$ degrees and this angle varies very little over time. Thus the observational evidence from the *Galileo* mission appears to rule out a large (60°) change in Europa's spin axis. The tidal forces from Jupiter do cause some precession of the orbit and spin of Europa but it is clearly a very small effect. Thus, for Europa there is still a difficulty with explaining the necessary energy for the eruptions.

Other heat sources in Europa have been considered as well. Some radioactive decay of potassium (or other isotopes) is likely in Europa and other moons, because of the presence of various silicate minerals in the interiors. But radioactive decay for these moons does not generate a great deal of heat because of the limited number of radioactive isotopes present. If there was a subsurface ocean that froze, the ice crust would be essentially coupled to the rocky mantle in such a manner that tidal dissipation would dramatically decrease and eruptions of water would likely stop. I consider the evidence for a subsurface ocean at Europa to be good because of the *Galileo* magnetic data.

Another heat source that might be considered for some moons could be ohmic dissipation due to electrical currents induced by plasma effects or magnetic phenomena within the host planet's magnetic field. Jupiter possesses an extremely strong magnetic field. Jupiter's moon, Io, experiences electrical discharges that create strong currents between Io and Jupiter and this generates some heat in Io. Jupiter's magnetic field is also capable of causing an induced current within a moon if the moon is sufficiently conductive. One of the tasks for the *Galileo* mission was to determine if Europa possessed its own permanent dipole magnetic field or if there was an induced magnetic field at Europa. This was determined to be an induced field in the *Galileo* mission to Jupiter. An induced field will vary in its orientation with Jupiter's rotation period (11.2 hours as seen from Europa[10]), whereas a permanent dipole at Europa would have a more constant orientation. The *Galileo* spacecraft was used to distinguish between the cases of whether the induced field is a) from a Europa iron core, b) from a possible liquid conductor near the surface, or c) from an ionosphere above the surface of Europa. The data from the *Galileo* magnetometer measurements made in January of 2000 point clearly to b.[10] The magnitude of the magnetic variations measured near Europa by *Galileo* covered a range of approximately 18 to 108 nT.[10] Such a weak field cannot

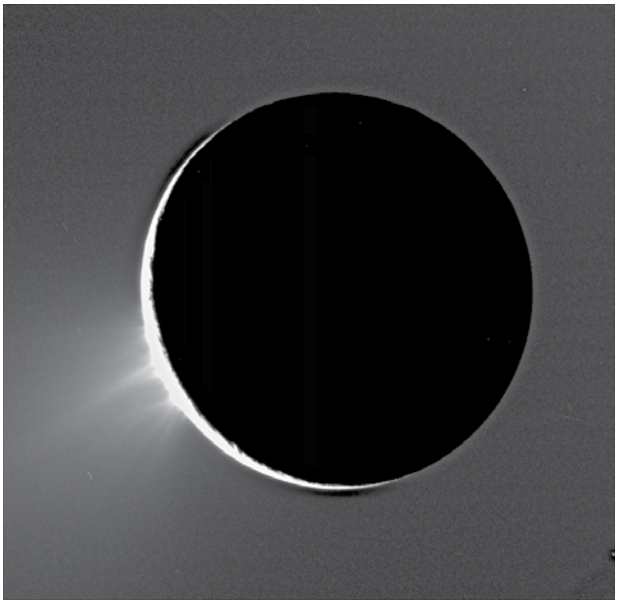

Figure 3. Fountains of Enceladus. Image is from the *Cassini–Huygens* mission to Saturn, taken November 2005.

generate strong heating, but it was unambiguously detectible by the spacecraft.

Thus, scientists want to explain how there can be liquid water or liquid mixtures present in these moons. There is also a hope of some scientists that these subsurface bodies of water could harbor bacterial life similar to life-forms near earth's hydrothermal vents on its ocean floor. At Europa there is likely liquid water erupting as well as oxygen. Spectra suggest that both water and molecular oxygen are being dissociated.[6] The surface also bears few craters and appears to be young. Most planetary scientists regard Europa as being explained by tidal dissipation heating but this does not seem to be the case. Theoretical models have sometimes been proposed that are unrealistic and do not fit observations. A simpler way to explain Europa is to view it as created with internal heat only several thousand years ago. This heat is still dissipating. Tidal dissipation is occurring and there is good evidence of liquid water under the surface, but this liquid would likely freeze if Europa were over 4 Ga old.

Enceladus

Enceladus is an interesting moon of Saturn that poses a more challenging and complex heat problem for an old-age viewpoint. Note first of all that Enceladus is much smaller than Europa, with a radius of only 251 km. This implies it cools more rapidly due to its smaller size, yet it possesses geysers that erupt with some regularity (figure 3). It is also relatively close to Saturn, which allows for a greater tidal effect. Enceladus is positioned within Saturn's E Ring. On the other hand, Saturn's tidal effects are much less than Jupiter because Saturn is considerably less dense and much less massive. Overall, the tidal effects are stronger at Enceladus than Europa. A recent paper[11] explained the issue with this opening statement:

> "Despite its small size, Enceladus emits considerable heat at its south pole, even long after simple thermal models predict that Enceladus should be frozen. The latest estimates of energy release range from 4.7 GW to 15.8 GW, depending on wavelength."[11]

Enceladus has been observed to have more regular eruptions from near its South Pole than Europa.[10] The eruption plumes consist of solid particles and vapours. The solid particles include both very small silica particles, similar to those in the E Ring, and salt particles. Gases at least sometimes present in the eruption plumes include carbon dioxide, methane, and ammonia.[11,13] Today scientists generally believe there is a kind of partial ocean or regional ocean under Enceladus's South Pole. There are also significant ridges

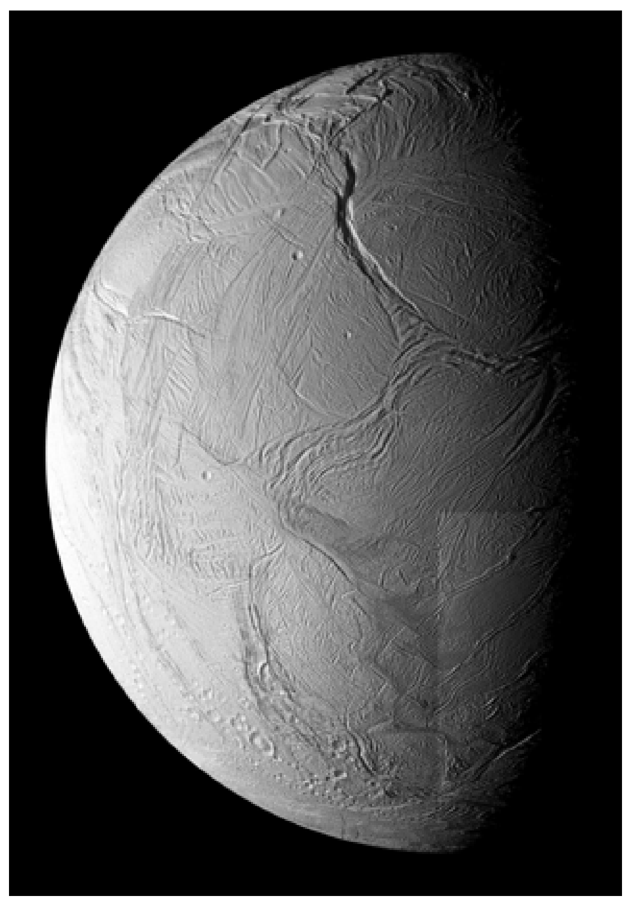

Figure 4. Enceladus with 'tiger stripes'. Photograph from the *Cassini–Huygens* mission, taken October 2008. Image has been converted to grayscale. Tiger stripes region (near the South Pole) has been brightness enhanced 40% and contrast enhanced 10% for clarity.

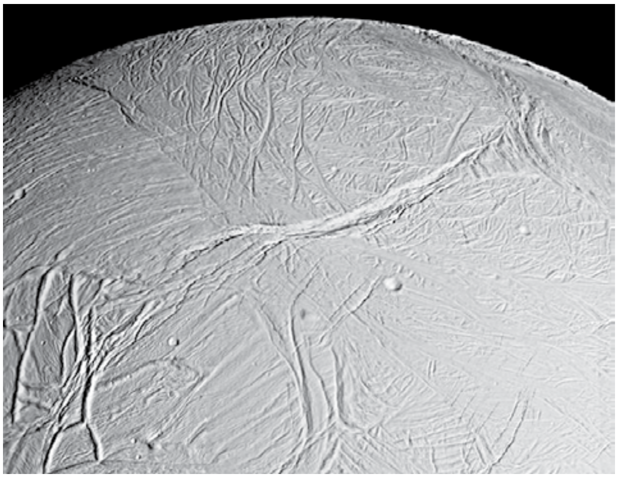

Figure 5. Enceladus's surface canyons. Mosaic visible light image from the *Cassini–Huygens* mission, taken February 2005. The view is approximately 300 km in width.

and fault structures on Enceladus's surface that have been called 'tiger stripes' (figure 4). These 'tiger stripes' are the location of eruptions of liquid.[10] Enceladus's surface is one of the brightest among all the moons of the solar system. It also possesses large linear canyons (figure 5). Enceladus's eruptions are more regular and longer-lived than those of Europa. Thus the challenge is: how can there be large amounts of liquid water in an icy moon allegedly billions of years old?

Heat sources considered for Enceladus include radiogenic heat, exothermic chemical reactions from serpentinization, constant TDH, episodic TDH cycles, and coupled constant plus episodic TDH. (Enceladus did cause some minor variations in Saturn's magnetic field but these were not significant for generating heat from induced currents.) Radiogenic heat is estimated to be only approximately 0.3 GW, presently.[11] Serpentinization has been proposed as a possible process for the formation of Enceladus's core. Serpentinization happens in earth's oceanic crust. It includes chemical reactions involving absorbing water in which magnesium silicates can change form. Serpentinization can also be accompanied by an increase in volume. It is believed that shortly after Enceladus's formation serpentinization could have generated significant heat, but it would not have been long-lived. Note that small quantities of ammonia have been observed in the Enceladus eruption plumes. But in order to make the serpentine reactions a strong heat source, some have suggested that the ice on Enceladus could be composed of as much as 30% ammonia ice mixed with water ice. However, one estimate suggests serpentinzation of Enceladus's *entire* core would generate heat that would completely dissipate in only about 40 Ma.[11] The best heat source proposed seems to be the coupling of constant tidal heating and periodic episodic tidal heating. This can generate an upper limit of about 1.5 GW,[14] but this is much less than the observed heat levels quoted above. The recent paper by Shoji *et al.* said, "Enceladus shows strong evidence that the magnitude of heating is not in steady state."[14] Saying it is not 'in steady state' implies the heat is not enough to sustain liquid water indefinitely.

The argument for episodic increases in tidal dissipation comes from unique orbital resonance phenomena that affect Enceladus. Enceladus is affected by multiple orbit resonances with its neighboring moons, the most significant of which is with the Saturn moon, Dione. There are at least three resonances between the moons Mimas and Enceladus and there is also a resonance between Mimas and Dione. When multiple resonances exist between multiple moons such as this, it is possible, over long periods of time, for one moon (in this case, Enceladus) to transition from one resonance to another, in effect. The resonance that is most important in affecting Enceladus's orbit can change over time. As Enceladus transitions from one resonance to another, the eccentricity of the orbit may increase for a period of time, thus leading to more tidal heating. The greater tidal heating also has a damping effect on the eccentricity change; thus a kind of equilibrium is reached. A study of the long-term behaviour of Enceladus under multiple orbit resonances shows that Enceladus would eventually reach a kind of steady state.[15] This resonance study shows that for approximately 1.3 Ga, Enceladus could undergo orbit oscillations but it moves through the lesser resonances and comes to a more stable orbit in the Dione–Enceladus resonance. These orbit oscillations only change Enceladus's eccentricity by 0.022 at most. Once the more stable state (under the Enceladus–Dione 1:2 resonance) is reached, the changes in its orbit are less and it oscillates stably between two eccentricity limits (varying by about 0.013).[15] This implies the coupled scenario above, assuming steady plus episodic tidal dissipation,[14] is not tenable over multi-billion-year timeframes. Secular science always assumes an old age for the solar system, but this assumption can be an obstacle to good science. Whether there is a 'partial ocean' under Enceladus' surface or not, it is more plausible that there could still be 'warm' liquid water present if Enceladus were only several thousand years old. Enceladus would be a promising topic for further research by creationists.

Ariel

Ariel is one of the 27 known moons of Uranus and is somewhat more than double the radius of Enceladus (table 2). Stereo images were taken by the *Voyager 2* spacecraft in 1986. Some other images have been taken from earth using CCD cameras. Only about 35% of Ariel's surface has been photographed. Ariel has many ridges that are believed to

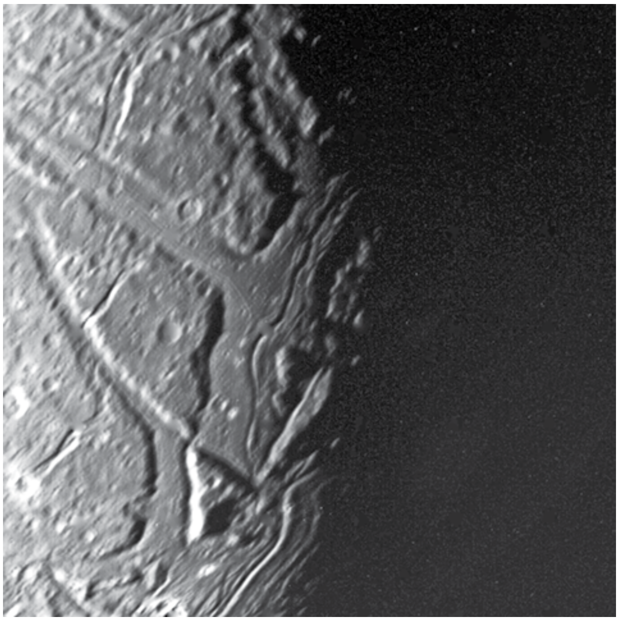

Figure 6. Ridge and valley structures on Ariel's surface. Image is from the *Voyager 2* spacecraft. Image resolution is 2.4 km per pixel.

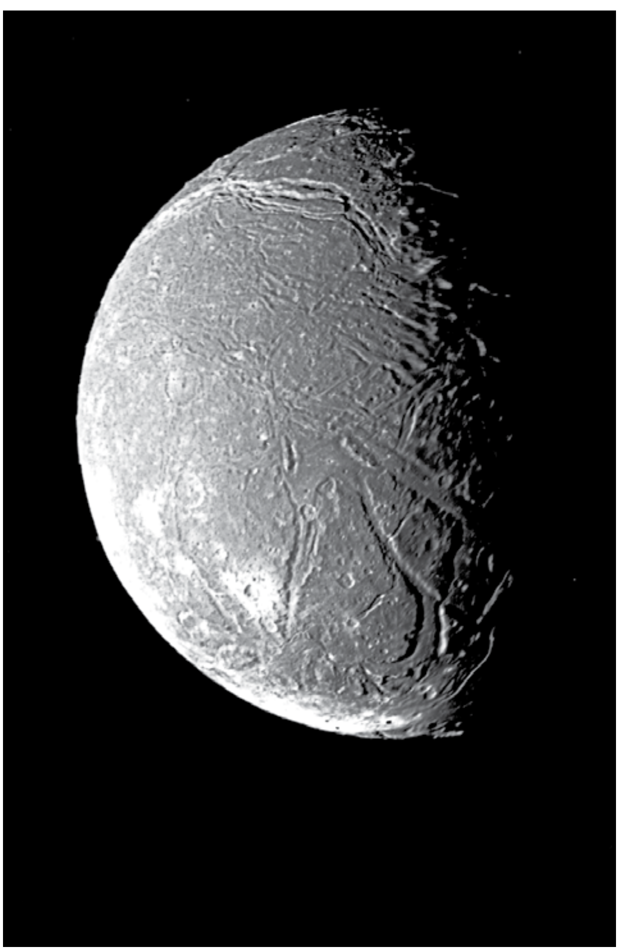

Figure 7. Ariel wide view. Taken by *Voyager 2* spacecraft, January 1986.

be graben structures 3–4 km in depth, formed mainly by normal faults. The graben structures in some cases crosscut crater structures, implying geological activity after the impacts (figure 6). A significant characteristic of Ariel, compared to its neighbouring moons is its low crater density. Two other Uranian moons, Umbriel and Oberon, both have crater densities on their surfaces of about 1,800 per million km^2 (minimum counted diam. 30 km). But Ariel's surface crater density is only 32 per million km^2.[16] Ariel's surface is also brighter than that of the other Uranian moons. Some craters make bright icy rings (figure 7). All this suggests that Ariel has been resurfaced. Ariel is believed to have a silicate core surrounded by an icy mantle and crust.[16] The composition of Ariel's ice is uncertain, although there is spectral evidence of some carbon dioxide ice in addition to water ice.

Estimates of the heat from Ariel are based on indirect calculation from the topographic features. No eruptions have been observed on Ariel. Models generally treat it as a somewhat elastic body and consider ice properties under various stresses implied by surface structures. This approach depends on the assumption that the structures on Ariel are indeed grabens, which behave in a well-understood manner. These methods are perhaps crude but have a legitimate relationship to surface features believed to apply to when the surface features formed. Any conclusions regarding Ariel should be considered tentative at present because there is a need for better data on the moons of Uranus. Estimates give heat fluxes of 28–92 mW/m^2 at the time of formation of the surface.[16] This is a significant amount of energy from a small moon like Ariel. Planetary scientists generally assume a tectonic resurfacing event after the Late Heavy Bombardment (LHB) that did not take place on Umbriel or Oberon. Radioactive heat today is estimated to be 0.6–1.0 mW/m^2. Assuming naturalistic formation of Ariel with Uranus, scientists have estimated radioactive heat could have been as much as 5–8 mW/m^2 shortly after Ariel's formation. Radioactive heat estimates such as these assume a composition of the silicate minerals in the moon to be similar to type CI or LL Chondrite meteorites. Then the estimate referred to as for 'today' is assuming that the decay of the shorter half-life isotopes has ended (after 4.6 Ga) and that only a small proportion of the long-lived isotopes still decays.[17] Such estimates come with old-age assumptions, but even allowing the highest value estimated seems very inadequate for having an energy source sufficient for formation of the surface features.

Today Ariel is not significantly affected by any resonances and TDH would only generate from about one thousandth to one tenth of the required range, above. The possibility of a past resonance with neighbouring moon Miranda has been considered, but in the Uranus system, no resonance would be long-lasting. Also, such a resonance would affect Miranda much more than Ariel because of Miranda's smaller size. For heat in the range from 28 to 92 mW/m^2 to come from TDH, the eccentricity of Ariel's orbit would have to be greater than its observed value by a factor of approximately 10 to 100. Another scenario considers the possibility that in their formation, Ariel and another Uranian moon, Titania, entered a resonance for a period of time. But even adding radioactive decay in the early solar system to the Titania resonance, this only generates approximately 12 mW/m^2 of heat. Moreover, this resonance would not last billions of years. Thus the authors of the recent paper on Ariel sum up their conclusions this way (from the abstract), "Thus, the origin of the inferred high heat fluxes is currently mysterious."[16]

A creation perspective

Though some popular-level articles on the icy moons of the outer solar system may give the impression that scientists have answered the major questions, examining the technical literature often gives a different picture. An old age of billions of years is merely assumed in solar system research. The icy moons of the outer solar system are a promising topic for further research by young-age creationists. In a solar system only several thousand years old, there could be heat from creation that is still present today, without the necessity of appealing to various orbit changes. This heat from creation may not be from radioactive decay. Tidal resonance is a real process that affects moons in the solar system, but it is not always the most significant heat source. In a young solar system, heat from the Creation Week could still be dissipating and driving geological processes. Tidal dissipation seems insufficient to explain the heat from Europa, Enceladus, and Ariel. Tidal heating has been explored by planetary geologists because it is an ongoing process. However the tendency of moon orbits to move to a stable configuration tends to prevent orbit changes from continuing for billions of years. Thus, it seems that our solar system was created stable, and icy moons are still 'warm' from creation. This is consistent with the solar system being only thousands of years old.

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