TIDAL DISSIPATION AND THE AGE OF IO

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ABSTRACT

The discovery of active volcanism on Jupiter's moon Io in 1979 has motivated significant research by the scientific community into Io's heat output. Heat radiated from Io's surface is on the order of 10^{14} Watts. In this paper, evolutionary models of Io involving tidal dissipation are reviewed and critiqued. Tidal effects between Jupiter and Io periodically distort the shape of Io (generating internal heat) and also affect its orbit. Io is also observed to be in an orbital resonance with Europa and Ganymede. Their orbital periods are in a ratio of 1:2:4. The models proposed by the planetary science community to date have various difficulties such as not allowing for a heat flow from Io that matches infrared observations, not accounting for the interior mantle parameters or the orbital parameters realistically, or not being viable over long time scales of billions of years. Io is not moving outward from Jupiter as would be expected from the tidal dissipation mechanism. Nor is there volcanism on Europa or Ganymede, though tidal dissipation also affects them. This paper shows why an age for Io of less than 10,000 years is more plausible than other treatments of the Io heat problem that have been proposed to date. It is suggested that there was more vigorous heating in Io in the past that has diminished today. This heat may have come from a special configuration of the interior of Io at creation or perhaps a more intense period of radioactive decay in the past. This study shows Io is an interesting object uniquely created by God.

INTRODUCTION

Jupiter's moon Io has been the subject of a great deal of research since about 1979. Io is one of the four "Galilean" moons, which are (in order outward from the planet) Io, Europa, Ganymede, and Callisto. Io is especially unique in the solar system because of its very active volcanic activity. In March and July of 1979 the Voyager 1 and 2 spacecrafts did flybys of Io. During this mission it was discovered that Io possessed active erupting volcanoes. At the time of the Voyager missions several volcanoes were seen erupting. Io's surface is unique in the solar system, with various hues of white, yellow, orange, red, and black material and no visible impact structures. Unlike most other moons in the solar system, Io's impacts have apparently been covered by the volcanic eruptions. Late in 1995 the Galileo spacecraft began orbiting Jupiter and collecting data on some of Jupiter's moons. Though there was concern that the spacecraft could be damaged by the intense ionizing radiation near Io, it was found that the spacecraft survived the Io environment enough to collect extensive data on the volcanic moon. Today as Galileo ends its long extended mission, there are new insights into Io from the volumes of data collected. The Hubble Space Telescope and some Earth based observatories have also collected valuable data on Io. In addition, Io and the other Galilean moons are relatively easy to observe and thus extensive observational orbital data and infrared data are available to us for this moon.

Io's nearness to Jupiter leads to very strong tidal effects. The tidal effects distort the shape of Io into a prolate spheroid and generates heat from frictional dissipation in Io's interior. The tidal effects on Io can affect Io's orbit as well as it's interior since the tides effectively transfer a small amount of Jupiter's rotational energy to Io. The tidal mechanics is further complicated by the fact that Io, Europa, and Ganymede are found to be in a three-body orbital resonance. This orbit resonance puts the orbital periods of Io, Europa, and Ganymede into a ratio of approximately 1:2:4. A more precise way to express this relationship is with an expression known as the Laplace relation, in terms of the orbital mean motion. The mean motion (n) is defined as the angle for one complete orbit (2B Radians or 360 Degrees) divided by the orbital Period (P). Thus (1) n = 360 / P. Equation 2 below expresses the Galilean orbit resonance in terms of the mean motion [16, p 892].

$$n_1 - 3n_2 + 2n_3 = 0 \qquad (2)$$

where
> n_1 = mean motion of Io (i.e. degrees per day)
> n_2 = mean motion of Europa
> n_3 = mean motion of Ganymede

As the moon nearest to Io, Europa has a significant effect on Io's orbit, and the orbit resonance with Europa tends to compete with Jupiter's tendancy to make Io drift outward from the planet. It is has been calculated that without the influence of Europa and Ganymede, the eccentricity of Io's orbit would be .00001 [16, p 892]. But the actual eccentricity of Io's orbit is .0041. Europa's eccentricity is .0101. These figures use eccentricity defined as

$$e = \sqrt{1 - \frac{b^2}{a^2}}$$

(3)

where
> a = apojove distance, equivalent to the semimajor axis
> b = perijove distance, equivalent to the semiminor axis

Though the above eccentricity of Io is small, the small variations it leads to in Io's orbit still cause signifcant tidal effects due to Jupiter. The tidal mechanics of Io and Jupiter are similar to what occurs with Earth and its Moon. Earth's Moon slowly drifts away from the Earth over time, being accelerated by the tidal bulge on the Earth produced by the Moon. This has been used by creationists to argue for a young age for the Earth and Moon [8], [21, p 67]. Planetary scientists generally believe the same process should occur for Io. However, for Io the situation is more complicated because of the influences of Europa and Ganymede. Heat due to frictional tidal dissipation in the interior is much greater in Io than in Earth's Moon. The magnitude of the change in Io's diameter due to the tides is about two orders of magnitude larger than the corresponding tides on our Moon due to the Earth [20, p 345]. This is due to Jupiter's much greater mass (318 Earth masses) and Io's nearness to the planet. Io's orbit places it about 6 Jupiter radii from the planet, whereas the Lunar orbit would be about 60 Earth radii from the planet.

Before the Voyager spacecrafts arrived at Jupiter in 1979, Peale, Cassen, and Reynolds [16] predicted that Io could have active volcanoes and that it could be "the most intensely heated terrestrial-type body in the solar system [16, p 894]." This prediction was made on the basis of an analysis of the tidal mechanics and tidal heat dissipation in Io. Though this was an excellent bit of work and the prediction was confirmed by Voyager and other observations, the heat produced by Io and radiated from its surface appears to be greater than the amount of heat generated by tidal dissipation. Of the energy transferred from Jupiter to Io via the tides, some of this energy produces internal heat in Io's interior and some of it affects the orbit, tending to cause Io to slowly drift outward from Jupiter over time. The orbit resonance with Europa and Ganymede on the other hand tends to prevent Io from drifting away from Jupiter, though it increases Io's orbital eccentricity and causes certain variations in Io's orbit. Planetary scientists today generally believe that the tidal dissipation mechanism is an adequate source of heat to drive Io's volcanism and explain Io's high surface temperatures. Io radiates a great deal of energy; the total heat power given off over its whole surface would be approximately 10^{14} Watts [23, p 17,157]. This is challenging to explain. This paper will explore this problem. Possibilities will be suggested for how observational data from Io can be explained assuming Io is young, such as less than 10,000 years. It will be proposed that either primordial heat from Creation or from an ancient radioactive decay event in the past provide the largest heat source in Io. Either of these coupled with the tidal mechanism is capable of explaining the heat output of Io, the orbital observations of Io, and allowing for a young age.

Physical characteristics of Io and interactions with Jupiter
Io's surface is dominated by various forms of sulfur and sulfur compounds, especially sulfur dioxide. At the time of the Voyager missions in 1979, the volcanic activity was thought to be limited to eruptions of sulfur compounds. There are multiple eruptions occurring on Io at any given moment. During the Voyager flybys nine eruptions were observed. Today, considering all Galileo data on Io, some suggest there may be 120 known active volcanic sites across the surface of Io. It has been estimated that Io is resurfaced at a rate of at least 1 cm per year over the whole surface. This corresponds to a volcanic volume flow rate of 10^{11} to 10^{12} m^3/yr for Io [20, p 347]. In comparison, Earth's volcanic mass flow is estimated to be less than 5×10^9 m^3/yr [20, p 347]. The average heat flux radiating off Io's surface from

this volcanic activity has been estimated at 2 ± 1 W/m^2. This is very large compared to Earth (.06 W/m^2) and our Moon (.02 W/m^2) [15, p 1664].

Only possible faint traces of water has been detected erupting from Io [18, pp 66-82]. Most moons of Jupiter and Saturn have significant quantities of water ice, making Io a striking exception. The surface of Io is also quite colorful, displaying a variety of white, yellow, orange, red, and black materials. Most of the material and these colors can be explained well as being sulfur or sulfur dioxide existing at a variety of temperatures. Table 1 below summarizes the colors exhibited by elemental Sulfur at different temperatures [4, p 144]. Generally speaking, the darker colors indicate higher temperatures.

Temperature of Sulfur (°C)	State	Color & Appearance
room temp.	solid	yellow
130	liquid	orange
160	liquid	clear, pinkish
190	liquid	red
230	liquid	black, viscous like tar
380	liquid	dark fluid
Above 380	gas	dependent on ambient pressure

Table 1 Appearance of Sulfur as a function of temperature.

The Galileo mission has led to surprising discoveries regarding the nature of volcanism on Io and the type of features on its surface. It has been found that the centers of some hot spots on Io's surface reach temperatures higher than 1800 Kelvin [11]. Such high temperatures are impossible for Sulfur or Sulfur compounds since they would vaporize long before that temperature was reached. Thus it is now generally believed that some silicate lava must be erupting from some Ionian volcanoes. The average surface temperature is in the range of 130 to 150 Kelvin. If Io had no internal heat source, its average surface temperature would be about 100 Kelvin from equilibrium with the solar radiation. There are apparently some areas where molten sulfur has been covered by a crust of other material. Io also possesses mountains that are not volcanic and has landforms that are too steep or too high to possibly be built up from Sulfur deposits. Some erupted material forms long flow channels, some spreads out over a wide area as a liquid, and some erupts Mt. St. Helens style, in which sulfur dioxide erupts to great height and is spread over a wide area. Some volcanoes on Io are quite different than those on Earth. In some cases the hot spot and center of the eruptions are in the flat plains, with the mountain nearby the hot spot. Thus there seems to be some relationship between vertical tectonics related to mountain formation and the hot spots that is not well understood. Galileo images of Io's surface reveal a variety of types of volcanic activity, indications of vertical tectonics, and a very dynamic rapidly changing surface.

The nature and structure of Io's interior bears heavily on the tidal dissipation process. There has been and continues to be significant debate about the nature of Io's core and mantle. Io has a bulk density of 3529.4 ± 1.3 kg/m^{-3} [1, p 711]. This value is an updated figure based on Doppler measurements of gravity effects on the Galileo spacecraft. The corresponding Galileo measurement for Europa is 2984 ± 46 kg/m^{-3}. This makes Io slightly more dense than our Moon. The fact that there are very high temperature materials erupting onto Io's surface considered with the density implies that Io is differentiated. Io could possess an interior that could include an iron core and a silicate mantle and crust, similar to the terrestrial planets and our Moon. However, a somewhat different composition would be expected due to the amount of sulfur present on the surface and the lack of water. This appears to be confirmed by Galileo data and comparative interior models done for both Io and the Moon [13]. There have been extensive studies evaluating different models of the interior of Io. The mass, density, and moment of inertia for Io are well known from the Galileo spacecraft determinations. These Galileo spacecraft measurements taken together with various interior models suggest Io has a metallic core, probably of either Iron or an Iron-Iron Sulfide (Fe-FeS) mixture. Io's radius is 1821.3 km. If the core is

the Fe-FeS type, it would be roughly half this radius in size based on Galileo measurements [13, p 210]. These spacecraft measurements cannot determine the properties of the mantle. A recent study of internal composition and structure of Io considered the Galileo gravity spacecraft data as well as geochemical and thermodynamic data and used studies of the Moon (which include seismic data) as a basis for comparison [13]. The results imply Io's bulk composition is likely similar to Mars or to type L or LL Chondrites. Though Io and Earth's Moon have very similar size and density, there seems to be significant differences in their compositions. Notable differences from Earth's Moon are higher proportions of iron oxide and lower proportions of aluminum oxide. This type of composition profile is in good agreement with Io's density and moment of inertia. The amount of topographic relief and height of Io's mountains (about 10 km) has given some clues on the thickness of Io's crust and lithosphere. Estimates of the thickness of the crust and lithosphere of Io are in the range of about 30 to 60 km [19, p 192; and 12, p 210].

The sulfur which erupts from Io's energetic volcanoes contributes to strong electrical interactions with Jupiter. A portion of the sulfur atoms ejected from Io's surface are stripped of some of their electrons. These sulfur ions may then combine into diatomic or triatomic sulfur molecules. But some of the sulfur escapes Io's gravity and causes the formation of a plasma torus that is oriented with Jupiter's magnetic equator. The torus is a large "doughnut-like" region roughly surrounding Io's orbit. This plasma torus is primarily made up of ionized sulfur and oxygen. Because the ions in the torus are carried along in orbit around Jupiter by Jupiter's magnetic field, the torus is inclined about 11E in relation to Jupiter's rotational equator. Perpendicular to the torus is what's called the Io Flux Tube (IFT). In the IFT a very powerful electrical current of five million Amperes in intensity, flows to and from Jupiter, spiraling around Jupiter's magnetic field lines [10, p 2949], [4, pp 189-197]. The ions and electrons from this current interact with Jupiter's ionosphere and produces very strong radio emissions (reaching about 1 Terawatt in power) with wavelengths in the decameter range [3, pp 228-229]. These radio emissions from Jupiter have been observed from Earth for years and are referred to as Jupiter's decametric radiation. One surprising result from the Galileo observations was that Io's ionosphere extends much farther out above Io's surface than was expected. Galileo observations of December 2001 appear to have ruled out the possibility of Io having an intrinsic magnetic field of its own. Evidence of ionized oxygen, sulfur, and sulfur dioxide were found nearly 900 km above Io. These are ions that have apparently not escaped Io's gravity, as have the ions in the torus. It was expected that the magnetosphere of Jupiter would pull away much of the material in Io's ionosphere and limit its depth.

Tidal dissipation and the heat problem
The term "tidal dissipation" refers to frictional heating in Io's interior that is a result of periodic changes in Io's shape as it orbits Jupiter. Io rotates and orbits synchronously, which means that the orbital period equals the rotation period. If Io's orbit were perfectly circular, there would be no heat generated in Io from the tidal forces because the long axis of the moon would remain in a constant orientation pointing toward Jupiter. But since Io's orbit is slightly elliptical, this causes Io's distance from Jupiter and it's orbital velocity to vary as it makes each orbit. This causes the magnitude of the tides to vary. The variation in distance produces a radial tide and the variation in Io's orbital velocity produces what is called the librational tide. It is the librational tide that is the greater of the two. Io's orbital period is 1.77 Earth days while Jupiter's rotation period is approximately 10 hours. The tidal bulges on Io do not align exactly with the direct line from Io to Jupiter. Rather they oscillate back and forth around this line. When a tidal bulge on Io (caused by Jupiter) is produced, so is a tidal bulge on Jupiter (caused by Io). Because of Jupiter's extremely rapid rotation, the tidal bulge on Jupiter is essentially ahead of the bulge on Io. The bulge on Jupiter tends to accelerate the tangential component of Io in its orbit and thus cause Io to slowly move farther from Jupiter. However, since Europa (and to a lesser degree Ganymede) are in resonance with Io, Io's orbit undergoes a forced oscillation. Io's shape therefore varies and thus Io could be described as a driven elastic oscillator.

In many harmonic oscillator problems as well as circuit theory a quantity known as the Quality Factor (Q) is employed to express energy conversion or energy storage efficiency in periodic processes. In tidal mechanics the Q is referred to as the tidal dissipation factor. It is a dimensionless ratio, in this case measuring the strain energy per cycle divided by the total energy dissipated per tidal flexing cycle [24, p 767]. Energy is lost from Jupiter's rotation and absorbed by Io's orbit and interior. A larger Q value indicates the energy transferred from Jupiter via the tides is more efficiently converted into heat and mechanical flexing in Io. A smaller value for Q would imply that Io's orbit would be affected more by the tides, causing Io (and Europa and Ganymede) to move outward away from Jupiter. Most researchers on the Io tidal issue use a value of 100 as an estimated value for Q, though lower values have been suggested [5, p 99], [16, p 893], [19, pp 194-195]. For Earth's Moon, Q has been estimated as 23. The

Q for Mars is suggested to be between 50 and 150. (Note that Io's bulk composition is more similar to Mars than to the Moon.) The tidal dissipation factor Q is an important parameter in the discussion of models of Io's interior. The Q value is an indicator of the relation between the heat produced in Io by the tidal dissipation process and the effect of the tides on Io's orbit. A loose way of understanding it would be to think of it as a measure of how efficiently energy is converted from orbital energy to heat energy in Io's interior. It can be useful in evaluating the various models to be discussed below.

Can the observations of the heat radiating from Io as well as the orbital observations be explained in a framework that assumes Io is less than 10,000 years in age? Is tidal dissipation the most significant heat source in Io? In order to address these questions we must first look at the observational evidence on how much heat is radiated from Io. A number of infrared measurements have been made of Io. Some have been done from Earth in eclipse observations and other special Earth-based telescopic techniques. In 1979 and shortly after, what was available was data from the IRIS experiment (Infrared Imaging Spectrometer) on the Voyager spacecraft plus some eclipse data from Earth. In 1982 Pearl and Sinton [17, pp 724-755] indicated the total radiated power given off of Io was $(6 \forall 2) \times 10^{13}$ Watts. Other similar values were published in the time period of 1979 through 1982. Also during this period, some authors reexamined data from Earth infrared observations done prior to the Voyager mission. The Voyager IRIS measurements and Earth eclipse observations, have a limitation that they only measure part of the surface of Io. Probably the most definitive values today come from a team of researchers from the Jet Propulsion Laboratory and the California Institute of Technology. This team used the Infrared Telescope Facility on Mauna Kea, Hawaii from 1983 to 1993 [23]. These measurements covered the range of longitudes of Io, so the entire surface except for a region around the poles was studied. This study also included one eclipse observation and two of Io's occasional unusually intense outbursts. This study also showed that the total power radiated from the low temperature sources was significantly more than the heat radiated from the high temperature sources. This is because the high temperature emissions are of short duration and are over limited areas of the surface. The average over the ten years of observations for the total power radiated over the surface of Io was 10.5×10^{13} Watts. This value (10^{14} W) is what theoretical models of the tidal dissipation need to be tested against.

If tidal dissipation is the largest source of heat in Io, then do we have observational evidence of Io moving farther from Jupiter? Most planetary scientists researching the Io tidal problem seem to assume that Io's orbit must slowly expand as a result of the tidal mechanism. But from observations of Io, any change in Io's orbit seems to be too small to measure. This is shown by results published by Lieske [14, pp 146-158]. This study examined a large amount of data, including 16,000 eclipse observations from 1652 to 1983. Their published value, for the rate of change of the mean motion of Io, is $(-.74 \forall .87) \times 10^{-11}$ yr^{-1}. They suggest that Io is slowly evolving out from Jupiter and out of resonance with time. But, when the uncertainty is greater than the measured change how can this be the proper conclusion? I will take the view that this result indicates Io's orbit is stable and exhibits no secular change. If tidal dissipation is the largest heat source it seems we should be able to measure some long-term change in Io's orbit. Lieske [14, p 146] comments to this effect: "The modern infra-red measurements of the energy emitted by Io . . . if interpreted as being due to interactions of Io with Jupiter . . . large secular changes in the mean motion of the satellite ought to be observable." If the orbit is not changing due to the tidal mechanism, this could at least allow for the possibility that there could be another even greater heat source in Io not related to the tidal mechanism.

A number of planetary scientists have commented to the effect that the heat produced by tidal dissipation is less than the amount radiated from Io's surface from observations. Cassen, Peale, and Reynolds, in 1982 published [5, p 102] that the heat produced by tidal dissipation had an upper limit of 3.3×10^{13} Watts (W). Later in the same article the authors state, "However, the upper bound on Io's dissipation . . . is also exceeded by a factor of two. This is a serious discrepancy whose resolution requires further study." Pearl and Sinton further comment in a different article in the same volume [5, p 753]:

> The observed high value of the heat flux can be obtained by adjusting the tidal energy dissipation factor (Q) of Io, but the required dissipation is untenable if the current eccentricity of Io's orbit is an equilibrium value determined by a balance of the effects of dissipation in Jupiter and Io . . . . As Cassen et. al. . . . point out, the satellites would have been pushed farther from Jupiter in 4.6×10^9 yr than their present distances. Hence the solution of one enigma, the old 10 to 20 :m discrepancies, has led to yet another enigma: apparent incompatibility with the present orbital configuration. . . . Complete elucidation of the heat source remains a significant outstanding problem resulting from the discovery of active volcanism on Io.

In 1990, two other researchers make comments essentially in agreement with the above [9, pp 59-60]: "We conclude that there is a problem with the current orbital distances of the Galilean satellites and the hypothesis of an approximate thermal-orbital equilibrium." These authors also consider a model by Greenberg et. al. that suggests the thermal and orbital parameters of Io are oscillating and thus we have just happened to catch Io at a peak in dissipation. But this is untenable because the heat flow cannot vary on a time scale that matches variations in the orbital parameters. So this model does not really treat the relation between the heat dissipation and the orbital effects in a realistic fashion.

Veeder, et. al. in their 1994 analysis of the ten years of infrared observations of Io, also point out the problem [23, p 17,159]. These authors plot several theoretical determinations for the heat flow at Io from the tidal effect. Two different values of the Q for Io are considered (50 and 100). Considering their own observed infrared heat flux (10^{14} W) and the tidal dissipation values from two other theoretical determinations, Veeder, et. al. [23] make the following comment: "These estimates all are significantly lower than the observed heat flow values determined from thermal emission. Heating by the decay of radiogenic elements and heating by electrical induction are 2 orders of magnitude smaller and plot off scale." Thus the infrared data from Veeder, et. al. implies theoretical figures for the heat generated in Io by tidal dissipation are approximately one order of magnitude less than the observed heat flux from Io's surface.

Not all planetary scientists have agreed with the assumption that tidal dissipation is the largest heat source in Io. Other heat sources have been seriously considered as well. One notable example is Kopal [12, pp 117, 119-120]. Kopal has published extensively on the tidal mechanics of the Earth-Moon system. In applying his approach to Io, Kopal argues that if tidal dissipation were so significant for Io as to drive the volcanism, the same would be found to be true for Europa, Ganymede, and Callisto. Kopal argues that second-order dynamical tides would be significant for Europa, Ganymede, and Callisto because of their higher orbital eccentricity. Though Kopal used now outdated eccentricity values, he may have a very valid point. If Kopal were correct, Ganymede would be expected to be the most active object volcanically, rather than Io. But, no volcanism has been observed on Europa, Ganymede, or Callisto. Thus Kopal argues I think correctly that the volcanism on Io must be driven by a process which does not affect the other three Galilean satellites. Kopal's arguments seem to have been ignored by other planetary scientists. Personally, I suspect Kopal has a valid point though I doubt that the tidal effects in the other Galilean moons would be as great as he suggested. Table 2 summarizes estimates of the amount of heat generated by various processes other than tidal dissipation. The radiogenic heat figures are estimates for Earth's Moon and for Chondritic meteorites, taken as approximately valid for Io as well.

Physical Heat Source	Heat Power	Power Density	Reference
Ions in plasma torus bombarding Io's surface (10^{10} ions/cm^2-sec at 300 eV)		5×10^{-3} W/m^2	[15]
Heat from current in Io Flux Tube	2×10^{12} W		[15]
Heat from variations in Jupiter's magnetic field creating transverse electric mode currents in Io		1.1×10^{-2} mW/m^2	[7]
Radiogenic heat, for Moon, (Chondrites)	6.1×10^{11} (4.5×10^{11})		[5]
ACTUAL OBSERVED VALUES	10^{14} W	2.5 W/m^2	[23]

Table 2 Estimates of heat power over entire Io surface possible from various known physical processes unrelated to tidal dissipation.

Interior models and the history of Io
Let us examine some of the various models of Io's interior and consider how realistic they are in the light of current data on Io. Then some aspects of the evolutionary histories of Io based on the various models will be summarized and related to the question of the age of Io. The structure and nature of Io's interior has great bearing on the issue of what drives the volcanoes and what generates the heat in Io. There are of course still significant limitations on the types of data that we have on Io. We have no seismic data on Io such as we have on Earth and the Moon. Some parallels can be drawn from Earth's Moon to

Io, but care must be taken in such analogies because Io's interior is undoubtedly hotter than the Moon and is of somewhat different composition. There are still many unanswered questions about Io's surface as well. For instance it is not known how thick the sulfur and sulfur dioxide materials are on Io's surface in general. There is general agreement in the planetary science community that Io's interior must contain at least some melted silicate magma. There's also agreement that there is essentially no water in Io but that there are significant amounts of Sulfur. The gravity measurements from the Galileo spacecraft point clearly to an Iron or mixed Iron and Iron Sulfide core. There continues to be debate over whether the core is solid or partially liquid and over how much melt is present in the mantle. The models of Io's interior can perhaps be placed into two broad categories based on whether they presuppose tide-orbit equilibrium. "Tide-orbit equilibrium" means that 1) any long-term change in Io's orbit is due to the effects of the tides and 2) there are no thermal effects in Io more significant than those produced by the tides. A "disequilibrium" model then would be one which rejects either or both of these presuppositions.

In 1979, when Peale, Cassen, and Reynolds published their well known paper predicting volcanism on Io, they suggested something referred to as "runaway melting" in Io [16]. In this paper, a simple equilibrium model was suggested in which Io has a liquid core, that there are large amounts of melt in the mantle, and the core increases in radius due to tidal dissipation until a limit is reached due to conduction through the outer layers. This approach only provided a heat flux of about one half the amount observed as of the time of the Voyager measurements. Others proposed similar "runaway melting" models (disequilibrium in type) but planetary scientists seem to have come to a consensus that such an approach is not plausible. The main reason is because of what would happen over long time frames. In a scenario where large volumes of the mantle are melted, there would be rapid convection and conduction of heat out through the surface. The rapid convection would transfer heat out very rapidly and then the mantle would resolidify, leaving a very hot core, a solid or nearly solid mantle, and a hot upper mantle (or asthenosphere). This process would take approximately 100 million years [19]. The implication of this is that over billions of years of time, the satellite would not still be so hot and active geologically as we see it today.

Two tidal equilibrium models were examined by another team of scientists with the goal of 1) explaining the heat flux off of Io's surface and 2) to explore the distribution of hot volcanic regions on the surface that would be produced by the two approaches [19]. The first equilibrium model, known simply as Model A, assumes a liquid core, a mantle, and a lithosphere in Io's interior. Io's composition is assumed to be similar to a type C2-chondrite but with the exception of it being totally depleted of water. In Model A the heat generated from the tidal process is spread over the entire mantle. Model B has a similar core and lithosphere but also contains an asthenosphere layer (50 km thick) in the upper mantle. In Model B, most of the heat is dissipated in the asthenosphere, rather than the entire mantle.

These two models produce strikingly different distributions of heat flow from the surface. Model A, the mantle dissipation model, leads to maximum heat flow at the poles and minimums near the points toward and opposite Jupiter. Model B, the asthenosphere dissipation model, leads to heat flow maxima being near the equator. The actual observed distribution of hot spots and volcanoes on Io's surface was not well known until the Galileo mission in recent years. The distribution of hot spots on the surface from Galileo is not as simple as either of these models, but it suggests more of the dissipation is in the upper mantle or asthenosphere than in the lower mantle [19], [20, p 349].

In both models A and B the mantle is treated as "viscoelastic," so that it can behave as either a viscous fluid or an elastic solid depending on the temperature and other material properties. The lithosphere is assumed to be 30 Km thick in these models, with probable convection in the lithosphere as well. Unlike on Earth, where mantle convection seems to have moved crustal plates laterally across the surface, in Io, mantle convection appears to drive a separate convection in the lithosphere. Model A results gave a maximum dissipation rate of 3×10^{15} W for a Q value of 36. In Model B, dissipation rates of about the same magnitude were possible (10^{15} W), but the Q values for realistic asthenosphere thicknesses were unrealistically large. From these results [19], the mantle dissipation model (A) appears the most successful, but the distribution of the heat flow on the surface does not match the Galileo data well. In addition, the assumption of a liquid core is very questionable for both of the equilibrium models considering Galileo orbital gravity measurements [1]. Model B actually is now more consistent with all current data regarding the interior of Io, where it includes a "cool" mantle and a hot partially molten asthenosphere. However, it is very difficult to model the fluid mechanics and convection so that realistic values of all the relevant parameters can be obtained, such as viscosity, shear modulus, thermal conductivity, temperature, and Q.

The most recent study of the tidal dissipation problem for Io is published by Tilman Spohn in 1997 [19]. I will refer to this model as the Turbulent Convection Model. Spohn acknowledges that there is a gap of about one order of magnitude between the observed heat flow from infrared measurements and the heat flow theoretically determined from tidal dissipation models. Spohn assumes first of all that Io's core has at least a molten outer layer and that there is a significant amount of melt in Io's mantle. He assumes that Io formed undifferentiated and that initially Io and the other Galilean moons were in orbits different than today. The Galilean moons Io, Europa, and Ganymede then evolved into resonance by the influence of gravity over about 2.5 billion years of their early existence. Following this (about 2 billion years ago) these three satellites settled into the current resonant orbits. Thus in Spohn's approach, the orbital interactions of these moons, as well as the tidal-orbit mechanism, have been operating for about 2 billion years. Spohn assumes that the temperature of Io's core was 2300 Kelvin at the time Io entered the resonance [19, p 369]. He further assumes a radiogenic heating rate of 10^9 Watts. In Spohn's approach the orbital parameters of Io undergo a periodic variation with a period of 10^8 years [9, p 61]. Spohn relates thermal parameter variations to the orbital parameters in a manner different from other researchers (he does not use the Q parameter). Spohn's model is a disequilibrium model.

In the Turbulent Convection Model, a key to the process is the specific type of fluid motion Spohn assumes to be taking place in the mantle of Io. Spohn suggests the convection flow in the mantle is in a flow regime known as hard thermal turbulence [19, p 372] and may have significant random chaotic fluctuations. This type of convection is a very energetic type of fluid flow. It is characterized by Rayleigh numbers greater than 4×10^7, turbulent mixing of hot and colder fluids, and rapid temperature fluctuations [6, p 7]. Spohn's model also suggests that as this energetic convection takes place in Io's interior, certain mantle "hot spots" could form where molten magma would build up in the upper mantle or asthenosphere over a time scale of about 10,000 years. After this time, the magma, which had built up under Io's crust, would produce eruptions as the hot magma came in contact with more volatile sulfur compounds in Io's crust and lithosphere. This approach is based on theoretical studies of turbulent convection for Earth. Spohn applies the concept to Io [2]. Spohn suggests that in this mechanism the melting of 10^{15} m^3 of lava in Io's mantle, which is a very small proportion of the total mantle volume, would be sufficient to generate a heat flow of 10^{14} W from Io's surface. Spohn comments on this [19, p 374]:

> The time required to generate the lava is about 10^4 years accounting only for the latent heat. The hot-spots in the mantle would thus use about 10% of the tidal dissipation power and store the energy in magma for about 10^4 years. This energy can then be released at an average rate of 10^{14} W from the surface in about a century after the lava has erupted.

Spohn's analysis of the tidal-orbit interaction and its relation to processes in Io's interior seems to be the most comprehensive to date. Spohn would not agree with a young-age creationist approach to origins or an age of the solar system of less than 10,000 years. Spohn does comment that "The long term evolution of this model remains to be studied [19, p 374]." None of the other models examined here have realistic values for all the various parameters and account for all the recent data from the Galileo mission. The runaway melting model did not have plausible long-term behavior, from an evolutionary viewpoint, to account for all the observations. Both Models A (mantle dissipation) and B (asthenosphere dissipation) above assume a liquid core for Io, which is probably not realistic considering the Galileo gravity data. A molten outer core is not ruled out by the Galileo data but an entirely liquid core would probably not agree with the Galileo data. The authors publishing the results of the Galileo gravity measurements use figures for the density of Io's core of either 5150 kg-m^{-3} for an Fe-FeS core to 8090 kg-m^{-3} for a pure Fe core [1]. These values would suggest Io's core could be nearly entirely solid. The asthenosphere model comes closer to explaining the distribution of surface heat flow for Io, but it involves unrealistic assumptions about the relationship of the tides and thermal phenomena to the orbital evolution. Spohn's analysis seems the most successful in accounting for all aspects of the problem and yet even it has potential weaknesses.

Some potential weaknesses of Spohn's analysis are the following. In Spohn's approach, the turbulent convection would have taken place in Io's interior for over two billion years. In this time, Io's interior properties would be likely to change due to the heat transferred to the surface and the amount of sulfur and silicate compounds deposited on the surface. It seems doubtful that the interior properties could support this type of convection for such a long time. Secondly, the time scale of the build up of the mantle hot spots, (or magma chambers) from Spohn's model is only 10,000 years, yet the time frame of the orbital oscillations is on the order of 100 million years. These two phenomena should be related in

some realistic way if tidal dissipation is the primary heat source in Io. Spohn also assumed a high temperature value at the beginning of the resonance period in Io's history (2300 K). This high temperature would stem from radioactive decay in Io's early history and a proposed period of greater tidal dissipation in the past as Io's orbit was evolving into resonance. Considering other studies of heat from radioactive decay, from an evolutionary viewpoint, this temperature may be unrealistic. Most other studies of Io's interior use temperatures of approximately 1500 or 1600 K.

Creation Alternatives
These difficulties suggest a possibility not considered by any planetary scientists to date. A process similar to Spohn's model could be more realistic if it operated only for a time frame of less than 10,000 years. But another heat source would be required to explain how Io's interior could have sufficient temperature and other properties to drive rapid convection. Thus I suggest there was a heat source that caused more rapid heat transfer in Io in the past than is the case today. I will refer to this as a primordial heat source. This process caused a rapid convection that could be similar to what Spohn has modeled, but convection may have slowed down today compared to what it once was. The rapid convection in the past built up hot melted regions in the asthenosphere or lithosphere of Io that continue to drive volcanism and other geological processes to this day. There are at least two possibilities for this large heat source in the past. Whatever this heat source was, it was unique to Io and thus we do not see active volcanism on the other Galilean moons. First, Io may have been created with an initial high temperature configuration in the core and/or the mantle that was ideal for driving rapid convection. In this case, the heat put into Io by the Creator in the beginning may still be dissipating today. Another possibility, in the light of the RATE research initiative sponsored by the Institute for Creation Research, would be that radiogenic heat was a major heat source in the past but heat from this has greatly diminished from what it once was. RATE, which is an acronym for Radioisotopes and the Age of the Earth, is a collaborative research project examining the possibility that radioactive decay rates were significantly higher in the past and that this can explain some observations regarding radioactive decay [22]. Such a period of more intense radioactive decay in the past may have essentially ended, reducing current radiogenic heat to a small proportion of what it once was. The tidal dissipation mechanism is a real mechanism that has probably been fairly constant from the beginning, assuming the orbits of the Galilean moons have not changed drastically.

The orbital resonance between Io and the other Galilean moons brings up additional interesting questions. What is the origin of the orbital resonance between Io, Europa, and Ganymede? A few planetary scientists have estimated the age of this resonance relationship. All these estimates assume that the Galilean moons formed by accretion from the same cloud of gas and debri that Jupiter formed from, then Io and the other moons gradually came into a resonant relationship over time, as a result of the influence of gravity, orbital variations, and the various tidal forces. Estimates of the age of the Galilean resonance have ranged from 60 million years, to 500 million years, to 2 billion years [19, pp 367-8]. I suspect that in a young solar system view (with an age of approximately 6 to 8,000 years) there would not be adequate time for Io, Europa, and Ganymede to come into resonance since creation. Thus it seems best to assume that these moons were created with their orbits in a resonant relationship. This implies the orbit of these three moons reflect intelligent design. Sometimes analysis of long-term variations in orbit parameters can give insights into whether the current orbit is significantly different than it was in the past. To me the evidence suggests Io's orbit is stable and has not significantly changed, allowing for variations that are to be expected as a result of the resonance. If there is any slow secular change in Io's orbit, the observational evidence, according to Lieske [14] suggests Io is moving out of resonance with time, not further into resonance. I would not generalize this conclusion of the resonance being a created relationship for all orbital resonances in the solar system. There are a number of cases of orbit-orbit or orbit-spin resonances in our solar system. Gravity and tidal forces can pull objects into resonant relationships. But in a young age time scale there may not be time for some of these relationships to gradually come about merely by gravity. Other orbit resonances in the solar system would have to be evaluated on a case-by-case basis as to whether they came about by divine engineering in the beginning, or by natural processes, or by catastrophic processes.

CONCLUSIONS
Research on the tide-orbit interaction between Jupiter and Io have been reviewed in their relation to the heat radiated from Io's surface. Planetary scientists have found it very challenging to explain the great amount of energy radiating from Io in terms of the tidal dissipation mechanism. If tidal dissipation is the primary heat source for Io, it should be possible to measure a long-term change in Io's orbit. Observational data on Io's orbit is most consistent with the view that Io's orbit is stable, except for minor variations that are a result of the orbital resonance with Europa and Ganymede. In spite of this, the

planetary science community seems to consistently believe that Io's orbit should change under the influence of tidal dissipation.

There seems no clear reason why tidal dissipation would not lead to active volcanism on Europa and Ganymede as well as Io if tidal dissipation is the largest heat source. Ganymede very likely has a metallic core very similar to Io in both composition and size; Europa also probably has a metallic core but somewhat smaller than Io's. Europa also has a more eccentric orbit than Io, which enhances the tidal effect. It seems there should be active volcanism on Europa or Ganymede if tidal dissipation were the primary heat source, though the erupting medium might be different than for Io (such as water for instance).

Tidal dissipation models have had difficulty explaining the observed heat flow from Io (10^{14} Watts) in ways that allow for realistic values of all the other parameters. The original proposal by Peale, Cassen, and Reynolds [16] could only be reconciled with the observed heat flux from Io by making unrealistic adjustments to the tidal dissipation factor, Q. This was untenable since it would mean Io would have moved outward from Jupiter farther than we observe it today. Infrared measurements published since 1979 have revised upward the Io heat flux to 10^{14} Watts. The turbulent convection model of Tilman Spohn, though a promising approach, seems unrealistic over long time scales such as two billion years, which is the alleged age of the resonance. The turbulent rapid convection and consequent mantle "hot spots" could be more realistic assuming a shorter time scale, such as less than 10,000 years. Over this time scale, assuming some conditions in Io in the past that led to greater thermal convection in the interior, magma could have accumulated in regions so as to drive the active volcanoes observed. A 10,000 year time scale allows for the melting of magma in hot spots in a manner such as suggested by Spohn, but it avoids the problems of the long-term viability of his turbulent convection and questionable relationship to Io's orbital evolution.

I would suggest, as a young-age creationist view of Io, that Io was created with some unique characteristics by the God of the Bible less than 10,000 years before present. The orbital relationship between Io, Europa, and Ganymede, given in the Laplace relation, is a divinely engineered pattern very likely designed to increase the stability of Io's orbit and counteract the tendency of the tides to cause Io to move outward from Jupiter. Either by virtue of initial high temperatures created in Io's interior or possibly by a period of intense radioactive decay in the past, large amounts of heat drove rapid convection in Io that has slowed down in the present. This rapid heating in the past built up mantle "hot spots" in Spohn's terminology, that continue to drive volcanism and other geologic processes in Io today. Thus as the "primordial" heat source of the past diminished, the tidal dissipation mechanism became the greatest current ongoing heat source in Io. The other Galilean moons are also influenced by the tidal dissipation mechanism, but they were apparently not created with the unique composition or configuration of the interior that allowed for the rapid convection in Io. Thus Io's energy comes from the summation of a primordial heat source from creation (or possibly the time of Noah's Flood) plus the tidal dissipation mechanism. The primordial source decayed or dissipated over time but the tidal dissipation would have remained approximately constant since Io's orbit appears to be relatively stable.

The possibility of significant radiogenic heating in Io in the past raises the question of what radioisotopes would be available. Though we have no direct seismic data from Io's interior or samples, theoretical interior models suggest Io's composition to be similar to type L and type LL chondrite meteorites. This would suggest that oxides of several metals would have significant proportions in Io's mantle, including silicon dioxide, magnesium oxide, iron oxide, and calcium and sodium oxides [13, p 212]. Some of these metals are found in small amounts in the Io plasma torus (Na, K, and Mg). It is believed that they were driven off the surface by sputtering erosion. In addition, some material coming from the volcanic eruption zones on Io have temperatures greater than 1800 Kelvin. This is higher than the melting point of some minerals. This and the bulk density of Io (3529.4 kg-m^{-3}) suggest Io could have many of the same radioactive isotopes present in Earth's Moon, though likely in different proportions.

Io is a unique and interesting object in our solar system. The complex interactions of the tides, processes in Io's interior, and the orbital resonance should increase our convictions of the greatness of the Creator-God. The proposal here is only a general treatment of the issues and not a quantitative treatment. Thus there is a need for more research on the Io heat problem and its age. Evidence of Io being of a young age would tend to argue for a young age for Jupiter, Europa, and Ganymede as well because of the orbital relationships of all these bodies. In a creation viewpoint, it is not a requirement that all the planets and moons have compositions or structures dictated by having formed from a common set of source materials. The high heat flow from Io points to a created uniqueness. This

suggests God's creativity and power as Creator. It is hoped that the proposal above will help explain the scientific data regarding Io in a manner consistent with a young-age time scale.

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