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Note

# Ridge formation and de-spinning of Iapetus via an impact-generated satellite

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ABSTRACT

We present a scenario for building the equatorial ridge and de-spinning Iapetus through an impact-generated disk and satellite. This impact puts debris into orbit, forming a ring inside the Roche limit and a satellite outside. This satellite rapidly pushes the ring material down to the surface of Iapetus, and then itself tidally evolves outward, thereby helping to de-spin Iapetus. This scenario can de-spin Iapetus an order of magnitude faster than when tides due to Saturn act alone, almost independently of its interior geophysical evolution. Eventually, the satellite is stripped from its orbit by Saturn. The range of satellite and impactor masses required is compatible with the estimated impact history of Iapetus.

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## 1. Introduction

The surface and shape of Iapetus (with equatorial radius, $R_I = 746$ km, and bulk density, $\bar{\rho} = 1.09\ \mathrm{g\ cm^{-3}}$) are unlike those of any other icy moon (Jacobson et al., 2006). About half of Iapetus' ancient surface is dark, and the other half is bright (see Porco et al. (2005) for discussion). This asymmetry has been explained recently as the migration of water ice due to the deposition of darker material on the leading side of the body (Spencer and Denk, 2010). Iapetus also has a ridge system near its equator, extending >110° in longitude (Porco et al., 2005), that rises to heights of ~13 km in some locations (Giese et al., 2008). The ridge itself is heavily cratered, suggesting it originated during Iapetus' early history. Finally, Iapetus' present-day overall shape is consistent with a rapid 16-h spin period rather than its present 79-day spin period (Castillo-Rogez et al., 2007; Thomas, 2010).

To some, the equatorial position of the ridge and Iapetus' odd shape suggest a causal relationship. Most current explanations invoke endogenic processes. For example, detailed models of Iapetus' early thermal evolution suggest that an early epoch of heating due to short-lived $^{26}$Al and $^{60}$Fe is required to close off primordial porosity in the object while simultaneously allowing it to rapidly de-spin, cool, and lock in a "fossil bulge" indicative of an early faster spin period (Castillo-Rogez et al., 2007; Robuchon et al., 2010). Recently, Sandwell and Schubert (2010) suggested a new and innovative mechanism for forming the bulge and ridge of Iapetus through contraction of primordial porosity and a thinned equatorial lithosphere. However, only a narrow range of parameters allows both a thick enough lithosphere on Iapetus to support the fossil bulge, while also being sufficiently dissipative to allow Iapetus to de-spin due to Saturn's influence on Solar System timescales.

In these scenarios, the ridge represents a large thrust fault arising from de-spinning. One difficulty faced by these ideas is that the stresses arising from de-spinning at the equator are perpendicular to the orientation required to create an equatorial ridge (Melosh, 1977). Other interior processes, such as a convective upwelling (Czechowski and Leliwa-Kopystyński, 2008), or convection coupled with tidal dissipation driven by the de-spinning (Roberts and Nimmo, 2009) are required to focus and reorient de-spinning stresses on the equator. These latter models have difficulty reproducing the ridge topography because thermal buoyancy stresses are insufficient to push the ridge to its observed height (see Dombard and Cheng, 2008).

Alternatively, the ridge may be exogenic. One leading hypothesis is that the ridge represents a ring system deposited onto Iapetus' surface (Ip, 2006; Dombard et al., 2010). This model has the benefit of providing a natural explanation for the mass, orientation, and continuity of the ridge, which present a challenge to endogenic models.

Here we extend this idea to include a satellite that accretes out of the ring system beyond the Roche limit. As we show below, this can significantly aid in the de-spinning of Iapetus. In particular, we hypothesize that:

(1) Iapetus suffered a large impact that produced a debris disk similar to what is believed to have formed Earth's Moon (Canup, 2004; Ida et al., 1997; Kokubo et al., 2000). Like the proto-lunar disk, this disk straddled the Roche radius of Iapetus, and was quickly collisionally damped into a disk. As a result, a satellite accreted beyond the Roche radius, while a particulate disk remained on the inside. Also, the impact left Iapetus spinning with a period ⩽16 h, thereby causing the bulge to form.[1]
(2) Gravitational interactions between the disk and Iapetus' satellite (hereafter known as the sub-satellite) pushed the disk onto Iapetus' surface, forming the ridge. As Ip (2006) first suggested, a collisionally damped disk, similar to Saturn's rings, will produce a linear feature precisely located along the equator. Thus, it naturally explains the most puzzling properties of the ridge system. The impact velocity of the disk particles would have been only ~300 m s$^{-1}$ and mainly tangential to the surface, so it is reasonable to assume that they would not have formed craters, but instead piled up on the surface.
(3) Tidal interactions between Iapetus and the sub-satellite led to the de-spinning of Iapetus as the sub-satellite's orbit expanded. Eventually, the sub-satellite evolved far enough from Iapetus that Saturn stripped it away. Iapetus was partially de-spun and continued de-spinning under the influence of Saturn. Finally, the sub-satellite was either accreted by one of Saturn's regular satellites (most likely Iapetus itself) or was ejected to

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[1] It is important to note that the impact that we envision is in a region of parameter space that has yet to be studied. Such an investigation requires sophisticated hydrodynamic simulations and thus is beyond the scope of this paper. We leave it for future work. We emphasize, however, that the general geometry we envision has been seen in many hydrodynamic simulations of giant impacts (e.g. Canup, 2004), so we believe that our assumed initial configuration is reasonable.

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heliocentric orbit (cf. Section 5). The end-state is a de-spun Iapetus that has both a bulge and a ridge. Faster de-spinning aided by the presence of a sub-satellite likely relaxes constraints on the early thermal evolution of Iapetus determined by prior works (Castillo-Rogez et al., 2007; Robuchon et al., 2010).

Because the results of one part of our story can be required by other parts, we begin our discussion in the middle and first find, through numerical simulations, the critical distance ($a_{\rm st}$) at which a sub-satellite of Iapetus will get stripped by Saturn. Knowing this distance, we integrate the equations governing the tidal interactions between both Saturn and Iapetus, and between Iapetus and the sub-satellite, to estimate limits on the mass of the sub-satellite. We then study the fate of the sub-satellite once it was stripped away from Iapetus by Saturn. Finally, using crater scaling relations we reconcile a sub-satellite impact with the topography of Iapetus.

## 2. Satellites stripped by Saturn

The distance at which a satellite of Iapetus becomes unstable is important for calculating tidal evolution timescales. In systems containing the Sun, a planet, and a satellite, prograde satellites are not expected to be stable beyond $\sim R_{\rm H}/2$, where the Hill radius is defined as $R_{\rm H} = a(m/3M)^{1/3}$ with $a$ as the planet's semi-major axis, $m$ as its mass, and $M$ as the total system mass (Hamilton and Burns, 1991; Barnes and O'Brien, 2002; Nesvorný et al., 2003). In our case, Iapetus plays the role of the planet, and Saturn the role of the Sun. However, the tidal evolution timescale depends strongly on semi-major axis (as the $-13/2$ power, Eq. (3)) and thus the success of our model depends sensitively on the value of the critical distance, $a_{\rm st}$. Therefore, we performed a series of numerical simulations to determine $a_{\rm st}$.

This experiment used the swift_WHM integrator (Levison and Duncan, 1994; which is based on Wisdom and Holman (1991)) to integrate two sets of test particles consisting of 500 objects, each of which were initially on orbits about Iapetus with semi-major axes, $a$, that ranged from 0.1 to 0.8 $R_{\rm H}$. The particles in the first set were initially on circular orbits in the plane of Iapetus's equator. Particles in the second set had initial eccentricities, $e$, of 0.1, and inclinations, $i$, that were uniformly distributed in $\cos(i)$ between $i = 0°$ and $i = 15°$. Saturn is by far the strongest perturber to the Iapetus-centered Kepler orbits and is the main source of the stripping. For completeness, we have also included the Sun and Titan. The effects of the other saturnian satellites are at least two orders of magnitude smaller than those of Titan and thus can be ignored.

The simulations were performed in an Iapetus-centered frame. The lifetime of particles dropped precipitously beyond 0.4 $R_{\rm H}$, suggesting that any sub-satellite with a larger semi-major axis would very quickly go into orbit around Saturn (Fig. 1). Thus, we adopt this limit, which is equivalent to 21 $R_{\rm I}$, in our calculations below.

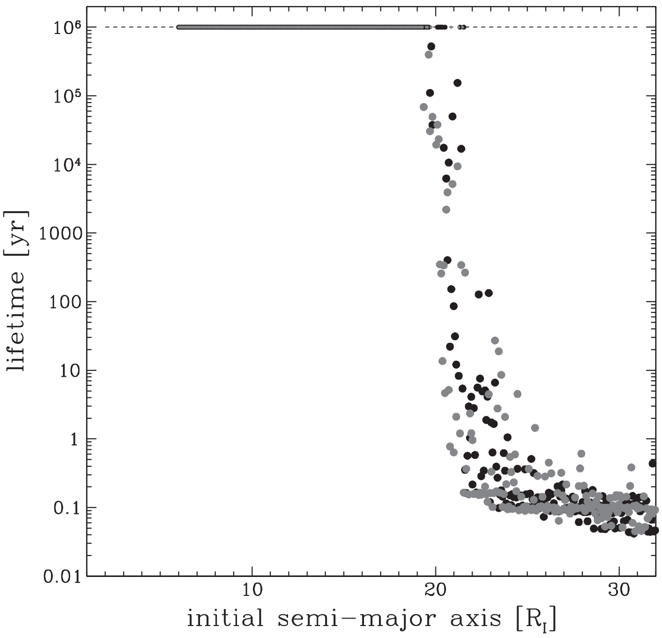

**Fig. 1.** The lifetime of each test particle is plotted as a function of their initial semimajor axis for two different initial eccentricities (black) 0.1 and (gray) 0.0. The simulations lasted for 1 Myr, which is shown as a horizontal line. Symbols for particles which survive for 1 Myr are smaller than those of particles with shorter lifetimes. The lifetime drops precipitously at $a = 21\ R_{\rm I} = 0.44\ R_{\rm H}$.

## 3. Tidal evolution of Iapetus

The de-spinning of Iapetus by Saturn has long been considered problematic, because for nominal $Q/|k_2|$ ($\sim 10^5$), Iapetus should not have de-spun over the age of the Solar System (Peale, 1977). Starting with the assumption of constant $Q/|k_2|$, and using the standard de-spinning timescale (Murray and Dermott, 1999, Eq. (4.163)),

$$\dot{\Omega}_{\rm I} = -\mathrm{sign}(\Omega_{\rm I} - n)\frac{3|k_2|}{2\alpha Q}\frac{m_h^2}{m_{\rm I}(m_h + m_{\rm I})}\left(\frac{R_{\rm I}}{a}\right)^3 n^2 \tag{1}$$

where $\alpha \leqslant 2/5$ is the moment of inertia constant of Iapetus, $m_{\rm I}$ is its mass, $\Omega_{\rm I}$ is its spin frequency, $|k_2|$ is the magnitude of the $k_2$ Love number, $Q$ the tidal dissipation factor, $m_{\rm h}$ is the mass of Saturn, and $a$ and $n$ are the semi-major axis and mean motion of Iapetus. The $|k_2|$ and $Q$ values used throughout are for Iapetus only. For the tidal interaction between Iapetus and Saturn, $\Omega_{\rm I} > n$, so the effect is always to decrease the spin of Iapetus.

For these simple assumptions, the de-spinning from 16 h to a rate synchronous with the orbital period, 79.3 days, takes $3.6 \times 10^5 (Q/|k_2|)$ years, nominally 36 Gyr, for a density $\rho = 1\ {\rm g\ cm^{-3}}$. Using detailed geophysical models, Castillo-Rogez et al. (2007) and Robuchon et al. (2010) showed Saturn can de-spin Iapetus on Solar System timescales, although only for a narrow range of thermal histories. Our goal here is to investigate how the addition of the sub-satellite affects the de-spinning times.

Given that detailed models of Castillo-Rogez et al. (2007) and Robuchon et al. (2010) used different methods, and that we are only interested in how the de-spinning timescale changes with the addition of a satellite, we take a simple approach of integrating a modified version of Eq. (1). Our first adjustment is to remove the assumption of constant $Q/|k_2|$. This ratio is dependent on the tidal frequency, $(\Omega - n)$, and accounts for the manner in which a material or body reacts to tidal stresses. We start with a model of Iapetus consisting of a time-invariant 200-km thick lithosphere with a Maxwell viscoelastic rheology with rigidity $\mu = 3.6 \times 10^9$ Pa and viscosity $\eta = 10^{22}$ Pa s, which is strong enough to support the equatorial bulge and ridge (Castillo-Rogez et al., 2007), overlying a mixed ice/rock mantle with a lower viscosity, representative of an interior warmed by radiogenic heating. We performed two types of simulations. In the first, the viscosity of the mantle is held constant with time and has values from $\eta = 10^{15}$ to $10^{18}$ Pa s (typical for the interior of an icy satellite at 240–270 K). In the second, we allow $\eta$ of the inner ice/rock mantle to vary according to the thermal evolution models in Castillo-Rogez et al. (2007) and Robuchon et al. (2010). In particular, we employ the LLRI model of Castillo-Rogez et al. (2007), and the 0.04 and 72 ppb $^{26}$Al cases from Robuchon et al. (2010). Love numbers are calculated for a spherically symmetric, uniform-density Iapetus using the SatStress software package (Wahr et al., 2009). We calculate the Love number $k_2$ (which is a complex number for a viscoelastic body, see Wahr et al. (2009) for discussion) and estimate $Q/|k_2| = 1/{\rm Im}(k_2)$ (Segatz et al., 1988). The values of $Q/|k_2|$ vary over an order of magnitude for each value of $\eta$ for the important range of tidal frequencies.

An integration of Eq. (1) was performed using a Bulirsch–Stoer integrator for times up to 100 Gyr, incorporating the frequency dependent $Q/|k_2|$ for different internal viscosities which, in turn, is a function of temperature. Without the sub-satellite, the time for Iapetus to reach synchronous rotation ranged between $5 \times 10^8$ (fixed $\eta = 10^{15}$ Pa s) and $2 \times 10^{12}$ years (0.04 ppb $^{26}$Al case from Robuchon et al. (2010)). We describe an investigation of the effect that a sub-satellite could have on the spin of Iapetus in the next subsection.

### 3.1. Tidal interaction with a sub-satellite

The sub-satellite raises a tidal bulge on Iapetus, causing Iapetus to de-spin and the sub-satellite's orbit to change. The change in spin rate for Iapetus due to a sub-satellite is (Murray and Dermott, 1999, Eq. (4.161)),

$$\dot{\Omega}_{\rm I} = -\mathrm{sign}(\Omega_{\rm I} - n)\frac{3|k_2|}{2\alpha Q}\frac{m_{\rm ss}^2}{m_{\rm I}(m_{\rm I} + m_{\rm ss})}\left(\frac{R_{\rm I}}{a}\right)^3 n^2 \tag{2}$$

and, the change in the satellite's orbit by (Murray and Dermott, 1999, Eq. (4.162)),

$$\dot{a} = \mathrm{sign}(\Omega_{\rm I} - n)\frac{3|k_2|}{2\alpha Q}\frac{m_{\rm ss}}{m_{\rm I}}\left(\frac{R_{\rm I}}{a}\right)^5 na. \tag{3}$$

Together, Eqs. (2) and (3) describe the interaction between the sub-satellite and Iapetus, where $m_{\rm ss}$ is the mass of the sub-satellite. The term $\mathrm{sign}(\Omega_{\rm I} - n)$ is of great importance, determining whether the satellite evolves outward while decreasing the spin of Iapetus, or inwards while increasing the spin of Iapetus. At semi-major axis $a_{\rm sync} = (G(m_{\rm I} + m_{\rm ss})/\Omega_{\rm I}^2)^{3/2}$, $\Omega_{\rm I} = n$, representing a synchronous state. If the sub-satellite has $a < a_{\rm sync}$, it evolves inwards; if $a > a_{\rm sync}$, it evolves outwards. Saturn is gradually decreasing the rotation rate of Iapetus, and thus the synchronous limit slowly grows larger, possibly catching and overtaking a slowly evolving sub-satellite. The orbital period of a sub-satellite at 21 $R_{\rm I}$, the distance at which we consider a satellite stripped by Saturn, is ~12.8 days. Thus, if Iapetus is de-spun to a period of 12.8 days before the sub-satellite reaches 21 $R_{\rm I}$, it will be caught by the expanding synchronous limit.

For the integrations of the sub-satellite's tidal evolution, the sub-satellite's mass is used as a free parameter, while the starting semi-major axis is set to 3 $R_{\rm I}$. This distance is derived from the expected origin of the sub-satellite accreting from an

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