Ridge Formation and Despinning of Iapetus via an Impact-Generated Satellite

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We present a scenario that both builds the equatorial ridge and despins 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 despinning Iapetus [1].

Evaluation of this scenarios requires several steps starting with the assumption that a sub-satellite forms around Iapetus from an impact-generated disk of debris. We f rst f nd the maximum semi-major axis a sub-satellite could have before being stripped by Iapetus. We then use this maximum separation in tidal evolution integrations to estimate a mass range for sub-satellites that can expedite the de-spinning of Iapetus. Finally we address the possible re-impact of a sub-satellite after it has been stripped from orbit around Iapetus.

Stripping of Satellites by Saturn

The distance at which a satellite of Iapetus becomes unstable is important for calculating tidal evolution timescales since these timescales depend strongly on semimajor axis (as the -13/2 power). Therefore we performed a series of numerical simulations using the swift_WHM integrator (Levison & Duncan 1994; which is based on Wisdom & Holman 1991) to integrate 500 test particles which were initially on orbits about Iapetus. The lifetime of particles dropped precipitously beyond a = 0.4 $R_{\rm H}$ (21 $R_{\rm I}$). Thus for the following tidal evolution calculations a sub-satellite that evolves to 21 $R_{\rm I}$ is considered to be stripped from Iapetus by Saturn.

Tidal evolution of Iapetus due to Saturn's tides

The despinning of Iapetus by Saturn has long been considered problematic, because for nominal Q/k_2 ($\sim 10^5$), Iapetus should not have despun within the age of the solar system [4]. Using these classical formulations the despinning from 16 h to a rate synchronous with the orbital period, 79.3 days, takes 1.7×10^5 (Q/k_2) years for a density ρ = 1 g cm^{-3}. Thus, despinning in the age of the solar system requires Q/k_2 $< 2.5\times10^4$, well below the nominal value and thus problematic.

However, Q/k_2 is dependent on the tidal frequency, $(\Omega - n)$, and depends on a material's or body's response to tidal stresses. Thus, we re-evaluate the de-spinning of Iapetus due to Saturn's tides by integrating the tidal evolution equations using the frequency-dependent values for Q/k_2, which will depend on the structure and internal viscosity of Iapetus. To calculate Q/k_2 values we use a model of Iapetus consisting of a 200-km thick lithosphere with a viscosity, η = 10^{20} Pa s, which is strong enough to support the equatorial bulge and ridge [5]. This lithosphere overlies a central region of much lower viscosity, which we varied from η = 10^{15}– 10^{18} Pa s (typical for the interior of an icy satellite warmed to 240 – 270 K by dissipation occuring during despinning [5]). The values of Q/k_2 vary over an order of magnitude for each value of η for the important range of tidal frequencies. An integration was performed using a Bulirsch-Stoer integrator incorporating the frequency dependent Q/k_2 for different internal viscosities. The time for Iapetus to reach synchronous rotation was 5.36×10^9 years with η = 10^{16} Pa s. Thus, even at a viscosity of 10^{16} Pa s, or at typically assumed constant Q/k_2 values, the despinning time for Iapetus exceeds the age of the solar system.

Tidal evolution including a sub-satellite

A sub-satellite, by way of raising a bulge, will also change the spin rate of Iapetus. In doing so, its orbit will change. If the sub-satellite has an orbit below the synchronous limit, it evolves inwards while increasing the spin rate of Iapetus; if it is beyond the synchronous limit, it evolves outwards while decreasing the spin rate of Iapetus. At the same time, the tidal interaction with Saturn slowly decreases the rotation rate of Iapetus, and thus the synchronous limit slowly grows larger, possibly catching and overtaking a slowly evolving sub-satellite. Thus to study the combined system of Saturn, Iapetus and a sub-satellite, we included in the integrator the tidal equations for Saturn-Iapetus and Iapetus-satellite with the frequency dependent (Q/k_2) values. We studied systems with η ranging from 10^{15} to 10^{18} Pa s, and mass ratios, $q \equiv m_{\rm ss}/m_{\rm I}$, between 0.0001 and 0.04. The fate of the system, in regards to the escape or re-impact of the sub-satellite and the despinning time of Iapetus, are separated into three distinct classes of outcomes based on the mass ratio between the sub-satellite and Iapetus.

Synchronous lock and re-impact: Above the mass ratio $q > 0.021$, a sub-satellite gets stuck in a syncrhonous state ($\Omega_{\rm Iap} = n$), stopping its outward evolution, and thus never stripped by Saturn. After reaching a synchronous state Saturn continues to slow the spin rate of Iapetus, the synchronous limit moves beyond the sub-

satellite, which then begins to tidally evolve inwards. The sub-satellite is doomed to evolve inwards and hit Iapetus. The despinning of Iapetus (after re-impact) fin ishes later than it would have by Saturn tides alone.

Satellite is stripped: For $0.006 < q < 0.021$, the sub-satellite evolves to 21 $R_{\rm I}$ and is stripped by Saturn. During its evolution the sub-satellite de-spins Iapetus enough that Saturnian tides can finis the job after it is stripped. Independent of the viscosity, Iapetus is despun 1.5–11 times faster than it is when despun by Saturn alone. This order of magnitude difference means that Iapetus could have despun in 500 Myr, for viscosities that would otherwise require the age of the solar system.

Slow evolution of a small satellite: Below $q < 0.006$, the despinning of Iapetus due to Saturn is fast enough that the location of synchronous rotation sweeps past the sub-satellite. After this occurs, the sub-satellite is then below the synchronous limit and doomed to evolve back in towards Iapetus. In this scenario, the evolution of the sub-satellite back to the surface of Iapetus typically takes longer than it takes for Iapetus to despin.

The integrations have bracketed the possible behavior of the Saturn-Iapetus-sub-satellite system. At high and low mass ratios the sub-satellite is doomed to return to re-impact Iapetus, while for $0.006 < q < 0.021$ the sub-satellite is stripped. As Fig. 1 shows, sub-satellites with masses between $0.005 < q < 0.021$ provide a substantial time savings in the despinning of Iapetus.

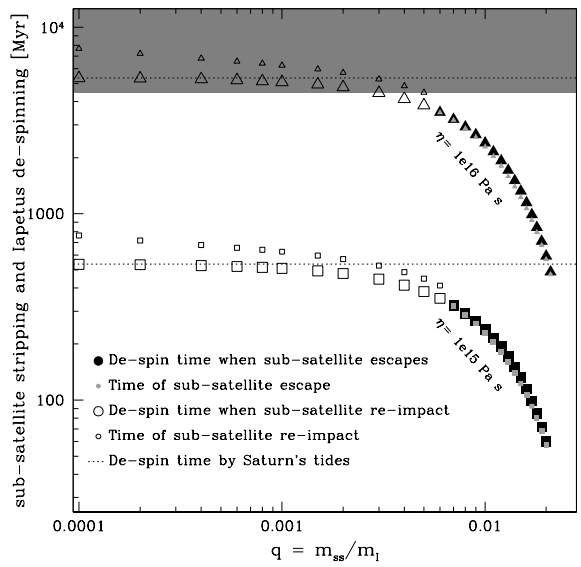

Figure 1: De-spinning timescales for viscosities, $\eta = 10^{15}$ and 10^{16} Pa s as a function of sub-satellite to Iapetus mass ratio. The dotted line shows the de-spinning time by Saturn's tides alone, open symbols show the de-spinning time when the sub-satellite re-impacts Iapetus, and closed symbols are de-spinning times when the sub-satellite is stripped by Saturn.

Ridge, ring and sub-satellite re-impact

In this scenario the equatorial ridge of Iapetus is formed from the part of the impact-generated disk inside the Roche limit (the outer parts form the sub-satellite). Estimates for the mass of the ridge vary widely, but even the highest, 4.4×10^{21} grams [6], is substantially less massive than the entire range of sub-satellite masses which provide a de-spinning timesavings (where $0.005 < q < 0.021$ is equivalent to $m_{\rm ss}$= 9.4×10^{21}–3.9×10^{22} grams). After the sub-satellite forms from the disk, it acts to push the remaining disk onto the surface of Iapetus. It is this infall of the disk, similar to the mechanism described by Ip (2006), which is responsible for the formation of the equatorial ridge shortly after the impact-generated disk is formed and the sub-satellite is accreted.

The bulk of the time-saving de-spinning scenarios involve a sub-satellite being stripped by Saturn, so we must also consider the fate of a stripped moon. The sub-satellite is typically stripped very late in the evolution, shortly before Iapetus is fully despun (see gray symbols in Fig. 1). To determine the probability of impact by a stripped sub-satellite we performed a numerical experiment consisting of the orbital evolution of massless test particles initially in orbit around Iapetus. We found that the stripped sub-satellite is likely ($\sim$88%) to hit Iapetus.

A large complex crater or basin will form if the sub-satellite were to impact Iapetus. We estimate the size of the impactors needed to produce the basins observed on Iapetus today which range from 300–800 km. At the likely speed of 0.58 km/s, the corresponding impactor radii are 64 and 193 km [7]. The tidal calculations above yielded a range of sub-satellite masses equivalent to bodies with radii of 131 and 211 km ($0.005 < q < 0.021$). Therefore, it is quite possible that one of the observed basins was caused by our hypothetical sub-satellite.

References [1] Levison et al. (2010) *Icarus*, submitted. [2] Levison & Duncan (1994) *Icarus*, 108, 18. [3] Wisdom & Holman (1991) *Astron. J.*, 102, 1528. [4] Peale (1977) *Planetary Satellites*, pp. 87–111. [5] Castillo-Rogez et al. (2007) *Icarus*, 190, 179. [6] Ip (2006) *Geophys. Res. L.*, 33, 16203. [7] Zahnle et al. (2003) *Icarus*, 163, 263.