On a ring origin of the equatorial ridge of Iapetus

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[1] Most recent Cassini observations by the Imaging Science Subsystem (ISS) showed that the third largest Saturnian satellite, Iapetus, has a curious ridge system exactly aligned with its equator [Porco et al., 2005]. Because Iapetus has a large Hill sphere for the trapping of circum-satellitary material, a ring system might have been present during its formation. A scenario is proposed to describe how the equatorial ridge system could have been produced by the collisional accretion of a ring remnant subsequent to the formation of the proto-Iapetus.
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1. Introduction

[2] Following the successful SOI (Saturn Orbit Insertion) on July 1, 2004, the Cassini Orbiter has started its exciting scientific mission in the Saturnian system. In the first two years of the satellite tour, many interesting new results have been obtained by the instruments onboard the spacecraft. As expected, some of the preliminary results have already led to new understanding of the physical properties of the icy satellites [*Porco et al.*, 2005]. Being one of the most unusual objects in the solar system because of the dichotomy of its surface brightness distribution [*Morrison et al.*, 1984], Iapetus is very much the focus of attention [*Porco et al.*, 2005; *Buratti et al.*, 2005; *Neukum et al.*, 2005; *Spencer et al.*, 2005; *Denk et al.*, 2005a; *Cruikshank et al.*, 2005; *Giese et al.*, 2005]. Among the deluge of new data, the December 2004 images from the Imaging Science Subsystem (ISS) showing the existence of a near-equatorial ridge system must be the most curious of all. This ridge formation exists very near to the equator of Iapetus and extends more than 110° in longitude or 1300 km [*Porco et al.*, 2005]. Parts of this ridge rise above the surrounding plains by as much as 20 km and are found to be broken into segments in places. It is important to mention that from the Voyager observations *Denk et al.* [2000] found mountains on the anti-Saturn side near the equator at longitudes 180°W to 220°W possibly rising 25-km high above the surrounding terrain which is covered by dark material. In hindsight, these "Voyager" mountains may well be a continuation of the ridge system discovered by Cassini [*Denk et al.*, 2005b].

[3] The coverage of impact craters on the ridge looks similar to the neighboring regions and the global distribution. Because the crater count statistics from the Cassini observations have shown that the surface of Iapetus is quite old with an estimated age of about 4.4–4.5 Gyr [*Porco et al.*, 2005; *Neukum et al.*, 2005], the ridge system must therefore be just as old by implication.

[4] Because of its alignment with Iapetus' equator, *Porco et al.* [2005] suggested the ridge system to be the result of the tectonic stress caused by despinning of the proto-Iapetus from a rotational period of a few hours to the synchronous rotation period of 79 days. This theory makes use of the study by *Melosh* [1977] of the global fracture patterns on Mercury which might have been caused by the tidal despinning stress. This dynamical process should have been quick on Iapetus because – as mentioned before - the ridge system is probably not much younger than Iapetus itself.

[5] *Castillo et al.* [2005a] carried out thermal evolution model calculations and found that shaping of Iapetus in the observed ellipsoidal configuration via hydrostatic equilibrium would require a warm and partially melted interior when the satellite was still in fast rotation. This condition might be met if heating by the radiogenic decay of ^{26}Al as evidenced by the ^{26}Mg excesses in the Ca-Al inclusions of the Allende meteorite [*Wasserburg and Papanastassiou*, 1982] was effective. As shown before by *Prialnik and Bar-Nun* [1990], heating and significant melting of small icy satellites by the decay of ^{26}Al could be important for icy objects with radii up to 1000 km even with ^{26}Al relative abundance 10 times smaller than that of the CAI inclusion. A possible scenario is therefore for the proto-Iapetus to have its configuration to be frozen in the fast rotating mode in its subsequent despinning. In this way, the ellipsoidal shape of 747 × 744 × 713 km [*Porco et al.*, 2005] from hydrostatic equilibrium would be frozen-in and the equatorial ridge system would be created as a result of the tectonic process in later time [*Castillo et al.*, 2005a]. But what is the time scale of the tidal despinning? It should in principle be not much more than 100–300 Myr as judged from the preliminary imaging results of the crater count statistics around the equatorial ridge system [*Porco et al.*, 2005; *Neukum et al.*, 2005]. Is this consistent with theoretical expectations?

[6] Note that the despinning mechanism – causing Iapetus to despin from its initially fast rotation (~10–20 hours) to the present state of synchronous rotation - is controlled by the tidal interaction between Iapetus and Saturn. According to the theory of tidal decay of satellite rotation, the despinning time scale can be expressed as [*Peale*, 1977]: $T = 2.4 \times 10^{10} \frac{P_0^4 \Delta\dot{\psi} Q}{R_S^2}$/years, where P_o is the orbital period in days, $\Delta\dot{\phi}$ is the change in the rotational angular velocity in radians/sec, R_s is the radius of the satellite in km, and finally Q is the so called specific tidal dissipation function defined as $1/Q = \varepsilon$ where ε is the phase lag of the response of the satellite to a forced periodic oscillation. With P_o = 79.33 days, R_s = 747 km, $\Delta\dot{\phi} = 1.74 \times 10^{-4}$ radian/sec (for an initial period of about 10 hours), we obtain T ~ 2.97 ×

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10^8 Q years [cf. *Peale*, 1977, Table 6.1]. The Q values of solid planetary satellites generally fall within the range of 100–1000 if their rigidity is similar to that of Earth. For Iapetus to be despun to the current state of synchronous rotation within the age of the solar system of 4.6×10^9 years it would require $Q < 10$ (for molten rock or liquid water). This is one reason why different from some other Saturnian icy satellites such as Enceladus, Tethys and Dione, Iapetus is not likely to complete the damping of its spin rotation by tidal interaction in a short time scale even with a partially melted interior. This long tidal decay time of Iapetus would hence produce a potential problem for the despinning mechanism of the ridge formation unless a new mechanism can be found [see *Castillo et al.*, 2005b].

[7] There is another interesting issue to be tackled. That is, the additional thermal heating for interior melting of Iapetus as advocated by *Castillo et al.* [2005a, 2005b] would require that Iapetus be formed in a time scale relatively shorter than or comparable to the radiogenic decay time ($\sim 7 \times 10^5$ years) of ^{26}Al. Otherwise, the released energy would not be trapped inside the satellite to produce sufficient amount of partial melting.

[8] The formation of regular satellites of the outer planets has not been studied in as much detail as that of the planetary formation. Some pioneering efforts in this direction were made by *Coradini and Magni* [1984] and *Coradini et al.* [1989] for the Jovian and Saturnian satellite systems. These authors considered the viscous evolution of an accretion disk in circumplanetary orbit [*Pringle*, 1981]. The satellite accretion disk would be composed of a thin layer of solid dust enveloped in a thicker gas disc. Protosatellites are supposed to form from collisional coagulation of planetesimals produced from the contraction and fragmentation of the thin dusk disk via the Goldreich-Ward instability. Recent work by *Canup and Ward* [2002] suggested that the Jovian and Saturnian circumplanetary disks should be relatively gas-poor to facilitate the survival of the proto-satellites against orbital migration with a relatively long satellite accretion time scale ($>10^5$ yr). Taking a different approach, *Mosqueira and Estrada* [2003] investigated the structures of extended gaseous nebulae associated with the proto-Jupiter and proto-Saturn and the corresponding satellite accretion process. These authors considered the existence of inner (and thick) disks containing Ganymede and Titan, respectively, and outer (and thin) disks containing Callisto and Iapetus, respectively. An important consequence of such a nebular dichotomy is that while the formation of the inner Jovian and Saturnian satellites should be rather speedy ($\sim 10^4$–10^5 yr), Callisto and Iapetus would have been delayed to 10^6–10^7 yr.

[9] The lower limit of this time interval might indeed satisfy the constraint of the thermal budget; this will in turn lead to a very precise prediction of the formation time of the Saturnian regular satellites. On the other hand, the accretion process of Iapetus might actually take much longer time. Because the origin and evolution of the Jovian and Saturnian subnebulae are still very uncertain, this important issue must be clarified by more detailed model calculations in future. In turn, the corresponding time scales will have important implications on the formation and evolution of Iapetus as discussed above.

2. Case for a Ring Remnant

[10] Since there are a few important questions still to be addressed by the endogenous despinning effect for the production of the equatorial ridge system on Iapetus, it is important to explore whether some other possible mechanism might also be involved in producing this unique geological structure. The rapid despinning effect is interesting because it could offer a possible explanation to the location of the ridge system. Indeed, any alternative mechanism must be first able to explain why there should be large-scale mass accumulation at the equatorial region. If we turn the argument around, it would mean that the position of the equatorial ridge system holds the key to the problem. This is quite interesting because the orbit of Iapetus is unique among the Saturnian satellites in the sense that it has a rather significant inclination ($i \sim 7.5°$). Any exogenous process intrinsic to the circumplanetary system itself would have to produce a smeared pattern without the observed narrow confinement. As far as we can tell, the only other possibility is to call for the imprint of a ring system surrounding Iapetus after its formation. How would such an exogenous mechanism work?

[11] What is important for us here is that in the later stage of the satellite accretion, a circum-satellitary disk might form via mass infall similar to the accretion disks surrounding proto-Jupiter and proto-Saturn depicted in various model considerations [*Coradini et al.*, 1989; *Canup and Ward*, 2002; *Mosqueira and Estrada*, 2003]. The maximum size of such satellitary accretion disk would be determined by the radius of the corresponding Hill sphere (R_H) in the three-body problem (e.g., planet-satellite-disk particle) in which the orbital motion of the small bodies is controlled by the gravitational force of the satellite. With the Saturnian mass $M_p = 5.69 \times 10^{29}$ g, a satellite mass of $m_s = 1.88 \times 10^{24}$ g and a circumsplanetary distance of $a = 3.565 \times 10^6$ km, $R_H = (m_s/3M_p)^{1/3}\, a = 3.698 \times 10^4$ km or $R_H \sim 49$ if normalized to the equatorial radius of Iapetus of $R_I = 747$ km. It is interesting to note that the relative size of the Hill sphere of Iapetus is the largest among the planetary satellites. After Iapetus, we find Titan's Hill sphere radius $R_H \sim 20$ if normalized to Titan's radius ($R_T = 2575$ km) and similarly Callisto's $R_H \sim 14$ for $R_c = 2403$ km. The condition for the formation of a circum-satellitary ring should therefore be most favorable for Iapetus if the relative size of the Hill sphere matters. While there is no direct evidence on the existence of ring systems around any planetary satellites, the recent discovery of satellites orbiting around some of the largest Kuiper belt objects (e.g., 2003 EL61 and 2003 UB313) reported by *Brown et al.* [2006] does boost the possibility of such a scenario.

[12] As described in the classical diffusive accretion model [*Pringle*, 1981], collisional interaction among the ring particles will lead to the inward and outward radial dispersal of the ring material. If Iapetus possessed a thick atmosphere at that time, the ring particles would drift inward systematically because of gaseous drag. What kind of ring mass is required to build the ridge system? While the height of the ridge reaches as much as 20 km at some

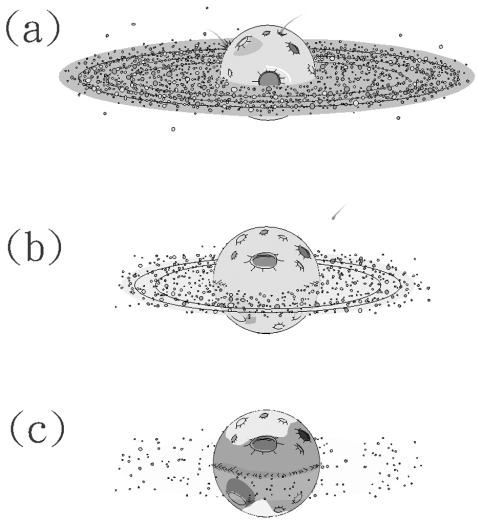

Figure 1. An illustration of the three stages of the ring system of Iapetus: (a) co-accretional growth of both Iapetus and its ring system filling up a broad region of the Hill's sphere; (b) accretion of the ring objects in orbital decay by the proto-Iapetus; (c) final disruption and destructive erosion of the ring system stored within the Roche limit. The figures are not to scale since the radius of the Hill's sphere of Iapetus should be nearly 49 times the radius of Iapetus itself.

locations [*Denk et al.*, 2000; *Porco et al.*, 2005], there are also peaks only a few km high or less [*Denk et al.*, 2005b]. Just for the sake of estimate, the maximum ring mass can be computed to be $\Delta m = 2\pi R_I \Delta w\ \Delta h\ \rho \sim 4.4 \times 10^{21}$ g for $^{\Delta}w \sim 50$ km, $^{\Delta}h \sim 20$ km and $\rho \sim 1$ g cm^{-3} for water ice composition. This mass is equivalent to an object of 74 km-radius with a mass of 0.1% of that of Iapetus. A better inventory would require more complete information on the height distribution of the ridge system around Iapetus. The important thing here is that the impact site of the ring particles must be defined by the intersection of the ring plane and the satellite surface which is the equator. A possible consequence of the surface impact is simply that regions with prior ring mass injection would tend to intercept more material – at grazing angle - because of their greater heights. This effect might help to partially explain the non-uniform height distribution of the ridge system as mentioned above. On the other hand, local geological process plus cratering events could also contribute to the disruption of the equatorial ridge (T. Denk, private communication, 2005).

[13] The Keplerian speed of the ring particles close to Iapetus surface is $V_k = (Gm_s/R_s)^{1/2} = 0.4$ km s^{-1} and the corresponding surface impact speed is $V_i \sim 0.3$ km s^{-1} for Iapetus rotating at a period $\sim$ 10 hours. It is therefore possible that no conspicuous craters would have been produced by such low-speed collisions - if the projectiles are of small sizes as would be expected from tidal breakup process. Note that for this exogenous model to work, the surface of Iapetus should have been solidified so that the imprint of the implanted ring mass could be maintained. Figure 1 illustrates the hypothetical time evolution of the Iapetus-ring system. The first stage is characterized by the global collisional impacts of circum-planetary planetesimals on Iapetus and the putative ring system. The presence of a thick accretion disk would enhance the capture efficiency of the orbiting planetesimals. Because of the deposit of a large amount of impact energy, the satellite surface must be molten or partially molten in this early phase. In the second stage, the formation of the proto-Iapetus is nearly completed and the ring particles continue to land at the equatorial region because of orbital decay effect driven by intra-particle collisions and gas drag. The surface landing mechanism might be assisted by the formation of a boundary layer between the satellite surface and the inner edge of the ring system. The viscous heating in slowing down the ring particles would lead to the pulverization and even partial liquification of the infalling material. The bulk of the ridge system might then be built up bit by bit as a sort of sandpile but in a grand scale It is required that the surface of Iapetus should be solidified already at this stage. Otherwise, no trace of the ring remnant would be able to remain. In the final phase, the residual ring system would gradually disappear because of destructive bombardment and erosion by the interplanetary stray bodies.

[14] To estimate the time taken for the surface of Iapetus to solidify after the subside of the major episode of accretional impact, we can first compute the accretional energy stored – which is determined by the internal energy in excess of keeping the interior just melted [*Schubert et al.*, 1981], $E_a = \rho c \int_{R0}^{Rs} (T_{(R)} - T_m) 4\pi R^2\, dR$, where R_s is the satellite radius, ρ is the density, c is the specific heat, T_m = 300 K is the temperature of the melted water, R_o is the radius where $T_a = T_m$ and the accretional temperature at radius R is given to be [*Kaula*, 1968],

$$T_a(R) = \frac{hGM(R)}{cR} \quad \left[1 + R_u^2/2GM(R)\right] + T_e,$$

where u is the impact speed of the planetesimals, h is the so-called energy retention factor (i.e., h = 0 for no energy gained and unity for complete storage), G is the gravitational constant, M(R) is the mass of satellite at radius R, and T_e is the temperature of the surrounding environment. These all together yield the following expression:

$$E_a = \frac{3}{5} Mc(T_m - T_e)\left[\left(h/h_0\right) - \frac{5}{3} + \frac{2}{3}(h_0/h)^{3/2}\right]$$

where h_o is the critical value for which melting is possible (e.g., $E_a > 0$ only if $h > h_o$). Now if the energy is transported away by subsolidus convection in the outer layer, we have [*Schubert et al.*, 1981]:

$$\dot{E}_{conv} = R^2 k \Delta T \left(\frac{g\alpha\Delta T}{\nu k}\right)^{1/3},$$

where $\kappa(=10^{-2}$ cm^2 sec$^{-1})$ is the thermal diffusivity, g is the surface gravity, $\nu(=10^{14}$ cm^2 sec$^{-1})$ is the viscosity, and ΔT = 150 K. The corresponding convective time scale is given by $\tau_{con} = E_{ea}/\dot{E}_{ccon}$ or $\tau_{con} \sim 1.5 \times 10^6$ yr $[(h/h_o) - 5/3 + 2/3(h_o/h)^{3/2}]$ from a scaling of the estimate for Callisto by *Schubert et al.* [1981]. This result suggests that the surface of Iapetus could have been largely solidified during the final episode of ring infall if it lasted longer than a few million years.

3. Summary and Discussion

[15] The discovery of a circumferential ridge system along the equator by the Cassini imaging team has led to the very interesting suggestion of a rapid despinning of Iapetus from a rotation period of about 17 hours to the synchronous rotation state [*Porco et al.*, 2005; *Castillo et al.*, 2005a, 2005b]. According to this theory, the ridge system was created by the large-scale tectonic process related to the despinning process. This endogenous model sets important dynamical constraints on the time scales of the formation of Iapetus and the tidal decay of its rotation. By the same token, a few important time scales in the despinning mechanism still remain to be resolved according to current theoretical estimates. What we have suggested as a possible alternative is that the observed equatorial ridge system is the result of mass accumulation from the surface impact of a ring system. An additional important strength of this model has to do with the equatorial location of the ridge system if it is indeed related to a ring remnant. The discovery of satellites around some of the largest Kuiper belt objects might indeed be used as supporting evidence of this new idea [*Brown et al.*, 2006]. We venture to propose this scenario because it could potentially throw new light on the origin of Iapetus as well as satellite formation in general. For example, the ring formation might have been related to the inclined orbit of Iapetus (with $i = 7°$) against the local Laplacean plane which is very different from those of all other regular satellites (with $i \sim 0°$) of Saturn. Could this unique feature have originated from a heavy collision event leading to the formation of an accretion disc? We don't really know. A detailed formulation of the accretion disk formation, ring evolution and mass distribution of the hypothetical ring system is beyond the scope of the present work. Furthermore, some of the seeming weaknesses of the present ring-ridge theory such as the relation to the tidal despinning process and the formation and maintenance of the equatorial ridge system must be addresses in future. In any event, we hope that the present discussion will contribute to the current investigations of Iapetus which is one of the most enigmatic objects in the Saturnian system if not in the solar system. Further data analyses and observations by Cassini will probably give us more definite idea on the geophysical properties of its ridge system.

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