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The Contamination of Iapetus by Phoebe Dust

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Abstract. We examine whether the dark, orbitally-leading hemisphere of Saturn's satellite Iapetus might be coated by debris from low-albedo Phoebe, which orbits retrograde well exterior to Iapetus. Using simplified analytical models along with more complete numerical integrations, we follow the paths of various-sized particles launched gently off Phoebe following collisions with interplanetary and interstellar meteoroids. Micron grains can quickly reach Iapetus since (due to solar radiation) they trace elliptical orbits; larger grains may only hit after their more-circular orbits collapse due to Poynting-Robertson drag; few very large and very small Phoebe grains strike Iapetus. Despite some inconsistencies with observations, we conclude that Phoebe may possibly be the agent that has darkened Iapetus.

1 Introduction

Ever since its discovery by G. D. Cassini in 1671, Iapetus has confounded scientists with its dramatic hemispheric brightness asymmetry: is the satellite's albedo distribution due to external sources or is it internally generated? The mystery only deepened with Voyager images (Smith et al., 1982) which gave conflicting evidence: an exogenic mechanism was suggested by the abrupt boundary between the dark leading hemisphere and the ten-fold-brighter trailing hemisphere, and especially by the boundary's apparent connection with orbital longitude; an internal source seemed implied by dark-floored craters within the bright hemisphere.

Rather than recall all the observations and the summary of models that have been proferred to explain the dichotomy, we defer to Wilson and Sagan (1996). Buratti and Mosher (1995) argue that Voyager UVS images, showing the albedo transition to take several hundred km, favor an external cause, perhaps Phoebe-derived material as suggested by Soter (1974). However, Wilson and Sagan (1995) point out spectral differences between Phoebe and Iapetus, and show that Iapetus' spectrum can be matched by a mixture of water ice, poly-HCN and organics. Thus, the cause of the dramatic albedo differences on Iapetus is uncertain.

2 The Model and Typical Results

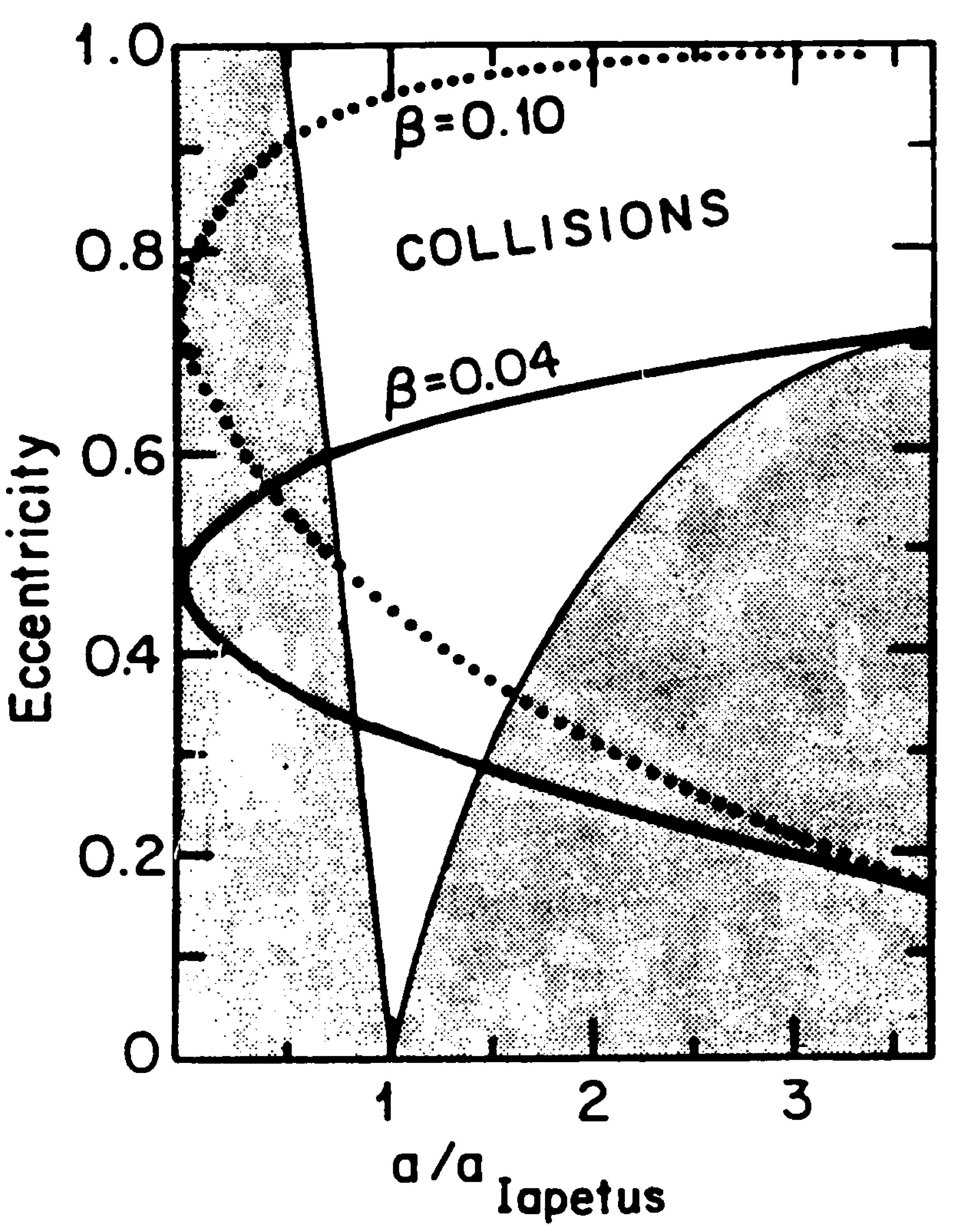
Soter's original idea is elegant – when ejecta are lost from dark and retrograde-orbiting Phoebe, they move inward (due to radiation forces) and run head-on into the leading face of neighboring Iapetus, which is thereby coated with low-albedo gunk. This scheme has never been considered in detail and now – as planning for Cassini proceeds – it is time to critically evaluate the fate of Phoebe dust.

When interplanetary or interstellar meteoroids strike Phoebe, copious amounts of debris should be generated. Because the escape speed off Phoebe is much less than local orbital speed, any escaped ejecta will begin along paths that lie near the satellite's. The mechanism will only work for particles of certain sizes: immediate access is available for micron-sized grains whose orbital eccentricities will be rapidly pumped up by solar radiation pressure.When particles are tens of microns to hundreds of microns in radius, their orbits will gradually collapse, due to Poynting-Robertson drag and mass-loading, until they cross the inner satellite's. Iapetus will not be accessible to particles from Phoebe that are much larger (orbital evolution takes too long) or much smaller (on their initial orbit these collide into Saturn or escape from the system) than the sizes mentioned. After discussing these histories, we present the collision probabilities and the longitudinal distribution of impacts for grains moving on orbits of given eccentricity.

Solar radiation pressure, as measured by the coefficient β(the ratio of solar radiation force to solar gravity, which for spherical grains (of radius s and density ρ) that obey geometric optics equals $5.7 \times 10^{-5}/\rho s$, using cgs units), will cause the orbital eccentricity e of a grain to vary during one Saturn orbital period about the Sun (Burns et al. 1979). Figure 1 shows the regions of (a,e) space that will be reached by two particles ($\beta = 0.04, 0.10$) that leave Phoebe with no relative speed when its pericenter lies between Saturn and the Sun. Let us consider the $\beta = 0.04$ grain ($s = 15\ \mu m$): shortly after injection, its eccentricity oscillates between Phoebe's e of 0.16 all the way to 0.70 where the particle can strike Iapetus. As this particle's orbit collapses by P-R drag (i.e., a moves to the left in the plot), the amplitude of the e oscillation shrinks but Iapetus remains accessible during some fraction of the particle's e-cycle until the grain's path is well within Iapetus' orbit. More strongly affected particles (e.g., $\beta = 0.10$) have greater opportunities but also face greater risks, for once the particle achieves $e = 0.9$ it reaches Titan's realm and, for higher-e orbits, penetrates the main rings and the planet.

Since Phoebe-derived particles that strike Iapetus do so along elliptic orbits (Fig. 1), their relative velocity will have a radial component in addition to the retrograde transverse one, which is roughly twice Iapetus's circular speed or 6.5 km/sec. This means that impacts will occur over more than 180° of longitude. Fig. 2 plots the longitudinal extension around Iapetus as a function of the impacting particle's a and e. This explains the 10°-20° extension that is measured.

We have computed the probability per orbit of a collision with Iapetus of particles having given a and e as the orbits of those particles evolve inward. To first order, that probability is independent of e. Knowing typical orbital collapse times for various-sized grains (Burns et al. 1979), we can compute a particle's likelihood of surviving passage through the zone when its orbit crosses Iapetus' or any other satellite's. For example, we find that nearly 70% of 10 μm grains strike Iapetus; of those that slip past, nearly 60% hit Hyperion and all the remaining are lost to Titan. If the orbits evolve more rapidly, Iapetus and Hyperion are less successful but Titan still absorbs all that try to pass so that the inner Saturnian satellites receive little Phoebe dust. Thus, since Hyperion is chaotically tumbling (and so would not exhibit any hemispherical asymmetry) and Titan is cloud-shrouded, Iapetus alone should show brightness asymmetry. We find that, among material derived from Phoebe, a significant fraction of grains in the range of a few microns up to hundreds of microns will strike the leading face of Iapetus.



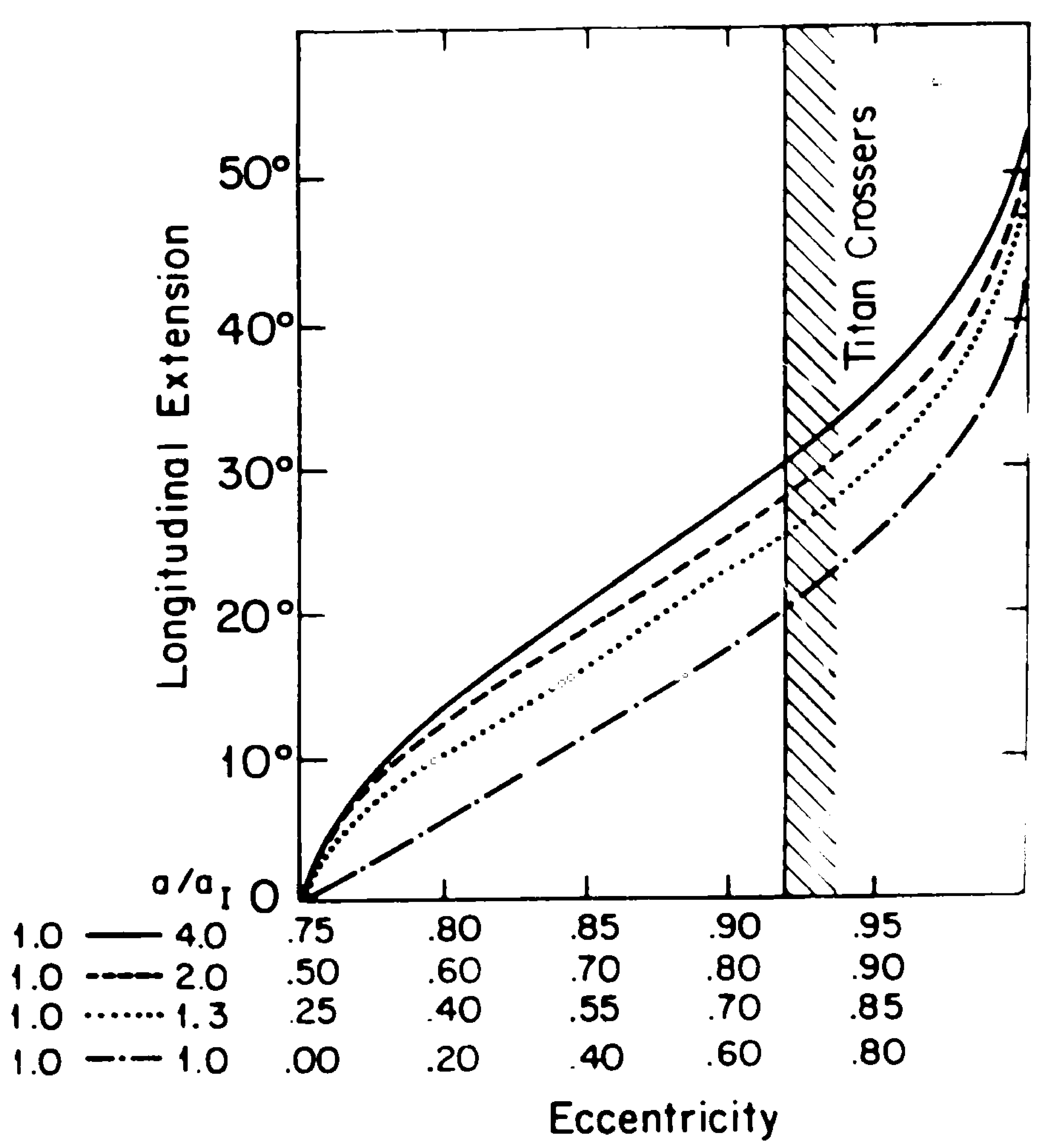


Figure 1. *The average variation of orbital eccentricities produced by radiation pressure for grains that orbit Saturn at different distances having started near Phoebe ($a = 3.64\ a_I$, $e = 0.16$). β is the radiation pressure coefficient. The stipled area corresponds to the a, e values of orbits that do not cross Iapetus'.*
Figure 2. *The longitudinal extension of the impact sites on Iapetus beyond the leading-trailing boundary, as a function of the orbital elements of the colliding grains. Orbits that cross Titan's are in the region to the right of the vertical line.*

3 Inconsistencies

Despite the appeal of this mechanism owing to its simplicity, this explanation for Iapetus' darkening fails in three regards: i) the precise areal distribution of darkening does not match Iapetus' (Squyres and Sagan 1983); and ii) the supply of material is inadequate to cause Iapetus' brightness variations. **Distribu-**

tion: As mentioned already, material from Phoebe will extend around Iapetus' equator primarily because of orbital eccentricity. Orbital inclinations similarly augment latitudinal coverage. Since orbital inclinations are relatively large, due to both Iapetus's complex orbital history and the effect of out-of-plane radiation forces, significant polar regions should be contaminated and yet these areas appear quite bright. Thus an additional mechanism is needed to retain Iapetus' polar caps; perhaps condensation of sputtered and vaporized ice, as proposed to explain Ganymede's ice-shrouded poles, is occurring. In this case the color of poles may be unique. **Supply**: The same (presumably isotropic) flux of projectiles that is excavating Phoebe's surface also bombards Iapetus. Hence, if the Iapetus' hemispherical dichotomy is to be evident, despite this uniform peppering, the retrograde stream from Phoebe must overwhelm the isotropic flux. We estimate the ratio of these fluxes to be about $2(R_P/R_I)2Y fc$, where the Rs are the satellite radii, Y is a multiplicative constant giving the impact's yield, f is the fraction of ejecta that escape Phoebe, and c is the portion of these that collide with Iapetus. Since Iapetus is so much larger than Phoebe, f is (maybe much) less than 1 and c is smaller than 1, Phoebe falls significantly short as a source despite Y's large value for hypervelocity impacts. Thus, for Soter's mechanism to succeed, the supplying area must be larger than apparent. However, Phoebe is likely to be only the largest of an unseen swarm of retrograde satellites; such companions are expected since all large particles knocked off Phoebe over the aeons will stay in the orbital neighborhood and will not be reaccreted. If the debris extends with a typical power-law distribution down to 1 cm in radius, the aggregate surface area can be many tens of times greater than Phoebe's. **Comparison to Phoebe**: Even though composition lies outside the scope of this dynamical paper, we note that the color match between Phoebe and Iapetus' dark material, while far from perfect, is fairly close (Bell et al. 1985, cf. Wilson and Sagan 1996). Surface coloration may be modified by the high-speed impact itself, which should be capable of breaking organic bonds, or by mixing with the native material. It is tantalizing that Hyperion, which according to this mechanism should be also bombarded by Phoebe dust, has a color that is close to dark Iapetus (Buratti and Mosher 1995).

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