COMETARY COLLISIONS AND THE DARK MATERIAL ON IAPETUS

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Abstract. Iapetus (S8) is unique in our solar system in that the albedo of its leading hemisphere is only 0.05 while that of the trailing side is 0.5. Several existing hypotheses are examined and found inadequate. Photometric studies of the dark side are compared to comet nuclei and class D asteroids. It is hypothesized that in the last 10^6–10^8 yrs the leading side suffered a high-velocity collision with a cometary body of mass 10^{13}–10^{15} kg and traveling at a speed of $20\ \mathrm{km\ s^{-1}}$. About 5–16% of the excavated material was ejected into space, where the vaporized ices dissipated while the dark carbonaceous/silicate material was reaccreted on the leading side. The collision, although not sufficient to break Iapetus' tidal lock, resulted in a period of oscillation of about 5 yr. Until tidal friction reasserted a lock, the oscillation gave rise to the 'longitude effect', viz., the observed fact that the dark material covers more than 220° of longitude but only 110° of latitude.

1. Introduction

Soon after G. D. Cassini discovered Iapetus (S8) in 1671, he noticed that its brightness varied markedly over a period of months. Today, we know that the leading hemisphere reflects only 5% of the light incident on its surface, while the trailing side reflects 50%, a factor of ten difference in brightness. Most of the leading side is so dark that no surface features were detected on it by the two Voyager flybys (Smith *et al.*, 1981, 1982). No other known object in the solar system has this asymmetry in its surface reflectance. Maps of Iapetus (see Burns and Matthews, 1986; pp. 908–909) indicate that the dark areas extend for almost 270° in longitude (in the equatorial regions) but through only a maximum of 110° in latitude. It should be noted, however, that the *boundary* between the light and dark regions is not sharp. This appears to be a popular misconception fostered by maps such as those found in Burns and Matthews (1986). In Squyres *et al.* (1984), for example, it is stated on p. 435 that "The 'boundary' between bright and dark material is gradual rather than sharp". (As it turns out, this is exactly what our model, which is described below, requires).

Analysis of the Voyager photometry (Squyres *et al.*, 1984) revealed that the hemispheres differ in color as well as albedo. The surface is darkest at the apex of motion, where the reflectance is 0.02–0.03, and gradually increases in brightness with increasing distance from the apex. The brightest area, however, is not the antapex but the poles, where the reflectance is 0.5–0.6.

As for the color of the two sides, both are reddish, but the dark hemisphere is much redder than the bright. Squyres *et al.* (1984) give a ratio of orange to violet reflectance of 1.45 ± 0.10 for the dark side and 1.25 ± 0.04 for the bright

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hemisphere. This differs from Phoebe (S9), which is neutral with an orange/violet ratio of 1.05.

Data collected from the two Voyager missions as well as observations from earth indicate that the bright side is composed primarily of water ice (Clark *et al.*, 1984). The dark material, however, appears to be a mixture of complex carbon compounds similar to those found in meteorites called carbonaceous chondrites plus simpler hydrocarbons (Bell *et al.*, 1985). Figure 5 in their paper shows the spectral reflectance in the visible and infrared of Iapetus. The only other objects that have the same general spectral features of this dark material are D-type asteroids and the nuclei of comets (Hartmann *et al.*, 1982; Cruikshank *et al.*, 1985; Hartmann *et al.*, 1987). Figure 1 in Hartmann *et al.* (1987) shows the comparison between the spectra of D-asteroids and comets. These same studies also show that Phoebe's spectrum most closely resembles that of C-type asteroids.

2. Origin of the Dark Material

At least four theories have been proposed for the origin of the dark material on the leading hemisphere: volcanism, deposition of dark material from Phoebe, ice erosion, and ultraviolet darkening. Unfortunately, there are serious problems with each of these models.

2.1. Volcanism

Smith *et al.* (1981) proposed that the dark material is endogenous, somehow erupting out of the interior of Iapetus and flooding the surface of the leading side by a process similar to that which formed the lunar maria. However, if the analogy were an accurate one, the flooding should have occurred on the side that always faces Saturn, where the crust would be thinner due to tidal effects, rather than on the leading hemisphere (Cruikshank *et al.*, 1983). We also agree with these authors that it would be exceedingly improbable that a volcanic episode of this magnitude, which was uncorrelated with any physical asymmetries, would be precisely aligned with the apex of motion.

2.2. Deposition

The second hypothesis suggests that the leading side is darkened by material ejected from the outer satellite Phoebe (Burns *et al.*, 1979). Phoebe is a small satellite (220 km diameter) in an inclined (150°) retrograde orbit. Its low velocity of escape will permit dust grains ejected by meteoroid impact to escape into retrograde orbits about Saturn. Due to the Poynting–Robertson effect, this debris slowly moves inward toward Saturn and is eventually captured by Iapetus, primarily on the leading side.

The most serious problem with this model is that the spectrum of Phoebe deviates significantly from that of the dark material on Iapetus, being neutral in the near-infrared, while that from Iapetus is reddish (Tholen and Zellner, 1983).

Secondly, since Phoebe is 3.6 times farther from Saturn than Iapetus, it should have many times fewer collisions with other objects that would produce debris than Iapetus, due to the corresponding lack of "gravitational focusing" by Saturn. Thus, the efficiency of the "Phoebe mechanism" must be questioned. Finally, since the orbital planes of these two satellites are nowhere near each other in space, this model can not account for the "longitude effect".

2.3. Ice erosion

This model envisions the dark material as being native to Iapetus – either as a minor component of the surface (Cruikshank *et al.*, 1983) or buried beneath a layer of ice (Cook and Franklin, 1970). In the first, the dark material is concentrated in the surface layers as the dominant surface material, ice, is vaporized by a hail of dust grains spiraling in from Phoebe, while in the second, the dark material is exposed when the ice layer above it is vaporized, not by dust from Phoebe, but by dust from the surrounding interplanetary medium. As with #2.2 above, the first of these models does not account for the longitude effect, and we must also question the efficiency of the suggested processes and point out the lack of pertinent experimental studies. (See Cruikshank *et al.* (1983) for additional comments).

As for the Cook/Franklin model, it requires an extremely unlikely structure for Iapetus – a dark 'carbon/silicate' mantle covered by a *very* uniform layer of frozen H_2O about a meter in thickness. This structure was 'deduced' by assuming an average density for Iapetus almost three times its presently known value.

Surprisingly, the C/F model predicted contour lines of constant erosion rate on Iapetus' surface that matched very well with the Voyager reflectance observations of over ten years later. Because of the very implausible structure this model proposes for Iapetus, we believe that the accuracy of their prediction is based on various stated and unstated assumptions in the mathematical derivations of their paper, and not on the likelihood that their hypothesis is the correct one. On p. 285, they "neglect the 12° inclination of the orbital plane of Iapetus to that of Saturn" and also "ignore the component of Iapetus' orbital motion that is perpendicular to the apex of Saturn's motion". On p. 287 they assume an "isotropic heliocentric flux" of material, which is not necessarily an appropriate distribution of interplanetary dust in Saturn's neighborhood.

2.4. Ultraviolet darkening

Squyres and Sagan (1983) argue that the dark areas contain dark organic material that is formed where UV radiation strikes CH_4-rich ice. The albedo asymmetry is then caused by a 'ballistic redistribution' of the surface material, once again because of dust from Phoebe. The hail of Phoebe dust will expose additional CH_4-rich ice on the leading hemisphere that is subsequently darkened by UV radiation. The ejecta from these collisions will lose CH_4 because the CH_4-rich ice is more volatile than other ices. This material will have a net migration to the trailing hemisphere since there are more impacts on the leading side. This CH_4-poor material that accumulates on the trailing hemisphere will not be darkened because of the lack of CH_4. This hypothesis does not explain either the longitude effect or the high albedos of the polar regions. It is also questionable whether this redistribution of material could occur rapidly enough so that the present pattern could develop before a relatively large meteoroid impact would disrupt the pattern and produce changes observable by the Voyager flybys.

3. The Scenario

We believe that the evidence strongly supports the hypothesis that the hemispheric asymmetry in brightness on Iapetus is due to an external mechanism that can be highly correlated with the direction of the satellite's orbital motion. However, to date all of the specific mechanisms postulated to occur in this manner require a large and almost continuous input of material from Phoebe and possibly other presently unknown retrograde satellites (except for the C/F model, which requires a very unusual structure for Iapetus) onto the leading hemisphere of Iapetus. This is highly unlikely when one considers the fact that the orbits of Phoebe and Iapetus do not lie anywhere near the same plane. Hence, we would question the efficiency of the "Phoebe mechanism" with regard to the amount of material required to darken the leading side of Iapetus within the last $\sim 10^8$ yr (see below). In addition, and perhaps more importantly, the longitude effect – coupled with the fact that the poles are even brighter than the antapex – requires a completely different scenario.

Therefore, we are suggesting in this paper that the dark side of Iapetus is primarily the result of a single high-speed collision with the nucleus of a comet sometime during the past 10^6–10^8 yr. As will be discussed below, the resulting impact will eject from 5–16% of the excavated material in a vapor state that, due to the shock wave, will be at high temperature and well-mixed with the dark carbonaceous material of the comet into an orbit that will permit its reaccretion in 10^5–10^6 yr. The impact is predicted to cause Iapetus to slowly oscillate back and forth along its present polar axis, thus producing the longitude effect. If the dimensions of P/Halley (roughly, a cylinder 14 km long and 7.5 km in diameter) are typical, only 5% of the comet's mass has to be ultimately recaptured in order to cover half of the surface area of Iapetus to an average depth of 1 cm. However, substantially less material than this would probably be sufficient to significantly darken the surface and obscure the water ice features in the spectrum. As Clarke *et al.* (1984) showed, the dark side's surface composition could be 95% ice (by weight) if the dark grains are submicron in size. In addition, the *original* surface material of Iapetus probably included dark carbonaceous material as a minor constituent (Cruikshank *et al.*, 1983). We will show below how this minor "contaminant" of the ice can become the major source of re-accreted material.

We will assume that the mass of the comet that struck Iapetus in our model lies in the range 10^{13}–10^{15} **kg**. Such a comet moving sunward from the Oort cloud could strike Iapetus with a wide range of velocities – from less than 1 km s^{-1} to as much as 27 km s^{-1}. *If* we postulate an almost head-on collision (This is *not* a requirement for our model; it is assumed only to test the feasibility of our hypothesis.), the most probable value of the relative collisional velocity would be about 20 km s^{-1}.

The diameters (D) of the craters formed by impacting comet nuclei can be found by the equation (Shoemaker and Wolfe, 1982)

$$D = s_g s_d c_f K_n W^{1/3.4}, \tag{1}$$

where s_g is the gravity scaling factor, s_d is the density scaling factor, c_f is the collapse factor, K_n is an empirical scaling factor based on nuclear explosions at the Nevada Test Site, and W is the kinetic energy of the comet. For Iapetus, using the parameters given in Shoemaker and Wolfe (1982), Equation (1) becomes

$$D(\text{km}) = 2.01 \times 10^{-3} M_c^{1/3.4} v_i^{2/3.4}, \tag{2}$$

where D is the crater diameter in km, M_c is the mass of the comet in kg, and v_i is the impact velocity in km s^{-1}. The values calculated for D are found in Table I. The craters range in diameter from 13.4 to 361 km.

For craters of this size, gravitational forces dominate over those of material strength and viscosity. In the gravity regime, the volume fraction f of excavated debris ejected with a velocity greater than some arbitrary value v is given (cf. Veverka *et al.*, 1986) by

$$f = C_2[v/(gD)^{1/2}]^{-b}, \tag{3}$$

where $C_2 = 0.6$ (for ice), g is the acceleration of gravity, D is the diameter of the

TABLE I

Diameters (D) of craters plus the fraction of ejecta that escapes, f_{esc}, (in [ ]) from Iapetus due to cometary collisions of velocity v_i and mass M_c

Impact velocity (km s^{-1})	Mass of the comet, M_c (kg)		
	10^{13} D (km), [f_{esc}]	10^{14} D (km), [f_{esc}]	10^{15} D (km), [f_{esc}]
v_i = 1	13.4, [1.11E-2]	26.4, [1.98E-2]	52, [3.52E-2]
5	34.6, [2.49E-2]	68.1, [4.43E-2]	134, [7.88E-2]
10	52.0, [3.52E-2]	102.0, [6.25E-2]	201, [1.11E-1]
15	66.0, [4.32E-2]	130.0, [7.68E-2]	256, [1.37E-1]
20	78.2, [4.99E-2]	154.0, [8.87E-2]	303, [1.58E-1]
25	89.2, [5.58E-2]	176.0, [9.93E-2]	345, [1.76E-1]
27	93.3, [5.79E-2]	184.0, [1.03E-1]	361, [1.83E-1]

crater, and $b = 1.7$. To obtain the fraction f_{esc} of ejecta that escapes from the satellite, set v equal to the escape velocity in Equation (3). Since $v_{esc} = (gD_I)^{1/2}$, where D_I is the diameter of Iapetus (1440 km), we have

$$f_{esc} = 0.6[D/D_I]^{0.85}. \tag{4}$$

The values calculated for f_{esc} are also found in Table I in the brackets following the crater diameters. Thus, f_{esc} ranges from only 1.1% to 18.3%. If $v_i = 20\ \mathrm{km\ s^{-1}}$, $5\% < f_{esc} < 16\%$, depending on the mass of the comet nucleus.

Upon impact at this velocity, much of the icy material at the collision site ($\gtrsim$20% by volume; McKinnon, 1981; Chapman and McKinnon, 1986) and probably all of the ice in the comet nucleus will be vaporized. It is postulated that most of the material ejected from Iapetus with speeds exceeding its escape velocity will be in this state, i.e., a mixture composed of "ice" molecules plus small dark grains. It is to be expected that there will also be ice *grains* in addition to *molecules* of the vaporized ices. However, the dark grains can come to dominate the spectrum even if they are outnumbered ten to one by the ices (Clark *et al.*, 1984). The majority of the excavated material will be moving slower than this and, hence, will be distributed over a wide area on the surface of Iapetus' leading hemisphere as part of the ejecta curtain. Since most of this material will be ice particles of all sizes, the impact site will initially be of high reflectance. The brightness asymmetry will not yet have been formed.

In the 5–16% of the excavated material that initially escapes from the satellite, it is important to distinguish between two different velocity fields. First, there is the velocity of the "field of flow" of the material escaping Iapetus due to the shock wave induced by the impact. Second, there is a thermal velocity imparted to the molecules and grains by the shock front. Since even small grains may have masses 10^{12} times that of a water molecule, they will have thermal velocities 10^6 times *smaller* than those of the molecules. Thus, in the critical minutes after the impact, the motions of the molecules become highly random with respect to the field of flow while the grain motions do not. As a result, the water molecules ultimately form a diffuse cloud around Saturn (some may even escape Saturn's gravity altogether), thus requiring well over 10^9 yr to be reaccreted by Iapetus (cf. Equation (22b), Burns *et al.*, 1984), even if the perturbations by the other satellites are ignored.

The net result of the high-velocity impact, therefore, is that although the dust component is initially small, it is selectively left in an orbit around Saturn as the hot gases from the vaporized ices thermally dissipate. This has been indirectly confirmed by several supercomputer simulations that explored the possibility that the Moon's origin is intimately linked with an impact of a Mars-sized body on the proto-Earth. (See Section VII, "Theories and Processes of Origin 3: Lunar Formation Triggered by Large Impact" (Hartmann *et al.*, 1986), especially those by Cameron (1986), Hartmann (1986), and Melosh and Sonett (1986)). Such studies account for the Moon's depletion of volatile materials with respect to the composition of the Earth.

Over this long of a period of time, the present light/dark asymmetry will be significantly altered. However, the solid grains will remain in orbits dictated by the original field of flow. With the correct choice of impact parameters (This is outside of the scope of this article; a full-scale supercomputer simulation is being planned), it is possible that enough of the dark material will remain in or near Iapetus' orbital plane so that it can be reaccreted in a reasonably short period of time (i.e., $\lesssim 10^6$ yr). 'Jetting', which may have played an important role in the formation of our own moon (Melosh and Sonett, 1986), may have also occurred here if the impact was an oblique one.

Although it is highly unlikely that the impact point of the comet will be exactly at the apex of motion, it is significantly more probable that the collision will occur on the leading rather than on the trailing side. The ratio of the cratering rate at the apex to the cratering rate at the antapex, δ, can be calculated from the equations developed in Shoemaker and Wolfe (1982), who modified for planetary satellites the theory constructed earlier for cratering on planets by Öpik (1951). For long-period comets where $e \lesssim 1$, $\delta \simeq 3$. [For impacting bodies in orbits more similar to Saturn's (viz., short-period comets), δ may be significantly larger. Of course, this would mean lower collisional velocities, while our scenario requires a high-velocity impact.]

Like most of the satellites of Saturn, Iapetus is presently in synchronous lock and has a rotational kinetic energy of 1.7×10^{20} J. Since the kinetic energies of the comet nuclei in Table I range from 5×10^{18} J to 3.6×10^{23} J, it is important to determine how much energy is required to break the tidal lock. In what follows we will assume that the shape of Iapetus can be approximated by an ellipsoid whose c-axis is the rotational or polar axis, the a-axis is oriented toward Saturn (the axis of the minimum moment of inertia), and the b-axis is perpendicular to the other two. The corresponding moments of inertia of Iapetus will be denoted by C, A, and B, respectively, and c, a, and b will represent the principal radii.

The potential energy of Iapetus can be approximated by MacCullagh's formula (Stacy, 1977)

$$U \cong -GM_sM_I/r - G[A+B+C-3I]/(2r^3)\,, \tag{5}$$

where M_s is the mass of Saturn, M_I is the mass of Iapetus, r is the distance between Iapetus and Saturn, and I is the moment of inertia about some arbitrary OP-axis. I may be written as

$$I = Al^2 + Bm^2 + Cn^2\,, \tag{6}$$

where l, m, n are the direction cosines of OP with respect to the x, y, z-axes. If the x-axis is taken from Iapetus toward Saturn and the z-axis as the polar (c-) axis of Iapetus, then

$$I = A\cos^2\theta + B\sin^2\theta\,, \tag{7}$$

where θ is the angle Iapetus has rotated (due to the collision) about its c-axis. Then, we have

$$U \cong -GM_sM_I/r - GM_s[A(1-3\cos^2\theta) + B(1-3\sin^2\theta) + C]/(2r^3)\,. \tag{8}$$

The restoring torque, **N**, on Iapetus can be found by taking the negative of the partial derivative of U with respect to θ:

$$N = -1.5\,GM_s(B-A)r^{-3}\sin 2\theta = -k\sin 2\theta\,, \tag{9}$$

where

$$\begin{aligned} k &= 1.5\,GM_s(B-A)r^{-3} \\ &\cong 0.6\,GM_sM_IR_Ir^{-3}\,\Delta R\,. \end{aligned} \tag{10}$$

In Equation (10), R_I is the radius of Iapetus and $\Delta R = a - b$. To find the energy required to break the tidal lock (ΔE), we merely integrate Equation (9) from $\theta = 0°$ to $90°$. If $\Delta R = 500$ m, $\Delta E = 3.5 \times 10^{17}$ J. This is close to the value of 2.9×10^{17} J obtained by Chapman and McKinnon (1986) by means of a slightly different method.

Whether or not the tidal lock is broken depends on the momentum vector of the incoming body and the point of impact on Iapetus. If angular momentum can be assumed to be conserved for this collision, the kinetic energy required for the projectile in representative cases is of the order 10^{23} J (Chapman and McKinnon, 1986). Thus, nearly head-on collisions with bodies of the mass and speed parameters found in Table I will not break the lock but will cause Iapetus to oscillate slowly back and forth about its polar axis.

The differential equation of motion is

$$\ddot{\theta} + K\sin 2\theta = 0\,, \tag{11}$$

where

$$K = k/C\,. \tag{12}$$

The period of oscillation (T) of Iapetus through the angular amplitude θ_0 is then

$$T = (8/K)^{1/2}\int_0^{\theta_0}[\sin^2\theta_0 - \sin^2\theta]^{-1/2}\,\mathrm{d}\theta\,. \tag{13}$$

The results of the numerical integration of Equation (13) are found in Table II. Note that the period is inversely proportional to $(a-b)^{1/2}$. Thus, if $(a-b) =$ 2000 m instead of 500 m, then the periods in Table II are decreased by a factor of 2. Plausible limits then give the period of oscillation of 2–6 yr. This relatively long period is due to the extremely weak restoring torque on Iapetus from Saturn. Other torques are negligible in this case.

TABLE II

Period of oscillation of Iapetus; θ_0 = angular amplitude, $\Delta R = 500$ m

θ_0 (degrees)	Period (T), yr.
5	4.69
10	4.72
15	4.75
20	4.82
30	5.01
45	5.51
60	6.40
75	8.21
90	22.3

We are postulating, therefore, that as Iapetus slowly oscillates back and forth it reaccretes enough of the ejected material remaining in its orbit to cover almost 270° of longitude, producing the lowest albedo at the apex and gradually increasing with increasing distance. Of course, not all of the ejecta will be in Iapetus' orbit or even in its orbital plane. Thus, some of this material will strike Iapetus at the higher latitudes (60°–90°). However, because of the low incoming angles, it will be spread out more diffusely at the poles than elsewhere. As we will show below, probably most of this material that will ultimately be recaptured will be reaccreted in less than 10^6 yr.

In what follows, we will assume the high-velocity impact occurred on the leading hemisphere, that the orbit of Iapetus is approximately circular (actually, $e = 0.028$), and that most of the dark material ultimately recaptured remained in or near Iapetus's orbital plane. Under these conditions, it might appear that the observed light/dark asymmetry would be reversed in this scenario since material escaping from the leading side would have a higher orbital velocity and would, therefore, overtake the satellite and coat the *trailing* side. However, this would be true only if three important factors were ignored: the Poynting–Robertson effect, the effect of perturbations on the orbits of the debris particles due to the other satellites and Saturn's oblateness, and the effect of the collisionally-induced libration of Iapetus itself.

Consider a particle ejected in the direction of Iapetus' apex of motion with a velocity, v', 1.1 times that of Iapetus's orbital speed. (For other values, see Table III.) Under the above assumptions, the eccentricity of such a particle will be $e = 0.21$, and its period will be 1.424 that of Iapetus. Thus, when the particle returns to the point where it was ejected (its periapse), Iapetus will be in another part of its orbit. If it can avoid recapture for as little as 5–10 years [the time for the P–R effect to cause an "inward radial diffusion time across a volume element with the (radius) of Iapetus" (Cruikshank *et al.*, 1983, p. 99)], it may ultimately

TABLE III

Orbital decay times for particles ejected from Iapetus's apex of motion

$[v'/v_I]$[a]	$[e]$[b]	$[T]$[c]	$[g_1]$[d]	$[g_2]$[e]	g_2/g_1
1.01	0.020	1.031	0.040	0.020	0.500
1.02	0.040	1.064	0.081	0.041	0.506
1.03	0.061	1.099	0.122	0.063	0.516
1.04	0.082	1.136	0.164	0.085	0.518
1.05	0.102	1.176	0.206	0.108	0.524
1.06	0.124	1.219	0.248	0.132	0.532
1.07	0.145	1.265	0.292	0.157	0.538
1.08	0.166	1.314	0.336	0.182	0.542
1.09	0.188	1.367	0.381	0.208	0.546
1.10	0.210	1.424	0.426	0.236	0.554
1.12	0.254	1.553	0.520	0.294	0.565
1.14	0.300	1.706	0.618	0.356	0.576
1.16	0.346	1.889	0.721	0.424	0.588
1.18	0.392	2.111	0.829	0.498	0.601
1.20	0.440	2.386	0.944	0.580	0.614
1.25	0.562	3.456	1.385	0.827	0.597
$2^{1/2}$	1.000				

This table assumes that Iapetus's orbit is circular (actually, $e = 0.028$) and that $\langle de/dt \rangle$ for the ejected particles is zero.

[a] v'/v_I is the ratio of the velocity of the ejected particle to Iapetus' orbital velocity.

[b] e is the eccentricity of the particle's orbit, assumed not to change.

[c] T is the ratio of the particle's initial period to that of Iapetus.

[d] g_1 = the ratio of the time required for the particle's orbit to decay to the point where its apoapse coincides with Iapetus' semimajor axis (t_d) divided by the Poynting–Robertson exponential decay time, τ_{P-R}.

[e] g_2 = the ratio of the time for the semimajor axis of the particle to become less than the semimajor axis of Iapetus' orbit divided by the P–R exponential decay time.

g_2/g_1 = fraction of the 'collisional period' ($t_d = g_1 \tau_{P-R}$) when $v_{\text{part}} > v_{\text{Iapetus}}$ at the impact points.

be recaptured on Iapetus' leading hemisphere because of the satellite's oscillation, even though it may be moving faster than Iapetus at the points where the two orbital planes intersect.

Using the data in Burns *et al.* (1979), we have calculated the time, t_d, for the orbit of the particle to decay because of the P–R effect (Assumption: $\langle de/dt \rangle = 0$; cf. Burns *et al.* (1979), p. 34; however, see below) to the point where its new apoapse coincides with Iapetus' orbit. (Values for t_d can be obtained by multiplying g_1 found in Table III by the P–R exponential decay time, τ_{P-R}, which is estimated to be in the range of $8 \times 10^4 - 3 \times 10^6$ yr (Burns *et al.*, 1979; Cruikshank *et al.*, 1983)). Thus, a time t_d after the collision, the particle will be forever out of the gravitational reach of Iapetus (assuming, of course, no "extreme" perturbations occur). For particles moving at 1.1 times that of Iapetus, t_d will be between 3.4×10^4 and 1.3×10^6 yr, depending on the optical properties of the grain material.

Our calculations show that for 55% of t_d the particle's speed will be greater than Iapetus's at the points of intersection. This can be found in the last column of Table III as the ratio of g_2 to g_1, where g_2 is the time for the particle's semimajor axis to become less than the semimajor axis of Iapetus's orbit divided again by the *P–R* time. Since the particle's velocity-squared is proportional to $[2/r - 1/a]$, where r is its instantaneous distance from Saturn and a is its semimajor axis, when $a_{\mathrm{part}} < a_{\mathrm{Iapetus}}$ *and* a collision with Iapetus occurs, then $v_{\mathrm{part}} < v_{\mathrm{Iapetus}}$.

As we showed above, some of this material can actually strike the leading hemisphere due to the libration of the satellite. However, we expect that most of the reaccretion will occur over the last 45% of t_d because the longer the elapsed time since impact, the larger will be the effects of perturbations. By a process analogous to that which produces meteor showers on the earth when it crosses the plane of an old comet, over long periods of time the dust will be spread out over a greater part of its orbit, the result being an enhanced capture rate over the latter part of t_d, a time when tidal friction has significantly dampened the magnitude of the oscillations. Thus, most of the material ends up on the leading side of Iapetus.

Although a high-velocity impact near longitude 270° *might* produce the needed effect, the time constraints make it unlikely. For example, a particle ejected from the antapex of Iapetus with 0.90 of its orbital speed will have a period of 0.77 that of Iapetus. Unless it can be recaptured in less than 10 yr, due to the *P–R* effect, its decaying orbit will put it forever out of the reach of Iapetus. However, it is obvious that much more extensive calculations would be required before any hypothesis could be considered the definitive theory for the origin of the brightness asymmetry.

The excess rotational energy imparted to Iapetus by the collision will be dissipated by tidal friction on a time scale $\lesssim 10^7$ yr (Plescia and Boyce, 1985). Since the present cratering rate for craters of diameter 10 km or greater is $0.079 \times 10^{-14}\,\mathrm{km}^{-2}\,\mathrm{yr}^{-1}$ (Smith *et al.*, 1982), tidal lock will be reestablished before another large impact occurs (time scale $\approx 1.9 \times 10^8$ yr) to both disturb the lock and possibly brighten the leading hemisphere.

There are numerous other effects that may alter the approximate results given above. For example, the classical radiation force is several orders of magnitude greater than the *PR* component. Will it therefore play a larger role in the orbital evolution of the ejected dust? To first order, it appears that it will not.

Although radiation pressure will not affect the semimajor axis of a circumplanetary orbit (Burns *et al.*, 1979; Mignard, 1984), it will produce short-term variations ($T \sim$ period of Saturn's orbit) in the eccentricity, e, some of which may increase e for a grain to beyond 1. Whether or not this occurs depends on the critical value of β, the ratio of the radiation force on the particle to the gravitational force. For dust near Iapetus, $\beta_c = 0.112$ (Burns, 1977; Burns *et al.*, 1979). For the particles considered above, $0.02 < \beta < 0.07$ (Cruikshank *et al.*, 1983). In Table III, if $e = 0.02$, then $0.18 < e_{\max} < 0.62$; if $e = 0.56$, then $0.58 <$

$e_{max} < 0.76$. Thus, these particles never escape from Saturn, and these variations in eccentricity due to radiation pressure alone will not seriously affect our above conclusions.

There are, though, additional effects that are difficult to treat in this semi-quantitative fashion. These include changes in the relative inclinations of Iapetus and the dust grains as both precess about Saturn. Neither have we included collisional effects within the gas/grain cloud of ejected material nor the gravitationally perturbing effect of Saturn's oblateness (probably negligible; cf. Mignard, 1984) as well as the proximity of Iapetus itself. It is our belief that the combination of all these effects can be treated only by a full-scale supercomputer simulation. However; we do believe that our numbers presently support our model of a single cometary collision as the reason for Iapetus's current albedo asymmetry over those hypotheses requiring large influxes of dust from Phoebe.

4. Conclusions

Of the two general hypotheses advanced to account for the dark side of Iapetus, the exogenic scenario is to be preferred over the endogenic model that suggests widespread volcanism as the source of the dark material. Until now, however, all, models based upon some form of external phenomenon – with the notable exception of the Cook and Franklin model – relied primarily on an influx of material from Phoebe. We question the efficiency of this "Phoebe mechanism" in producing the observed result on several grounds. No detailed calculations have been made concerning the amounts of debris ejected from Phoebe by meteoroid bombardment. No calculations have been made to determine what fraction of this material, if any, can reasonably be expected to be captured by Iapetus in the last 10^8 yr. Because of the completely different orbital inclinations of these two satellites, a detailed calculation is essential to lend credence to the hypothesis that relatively large amounts of material from Phoebe are presently affecting the appearance of the leading hemisphere of Iapetus.

In addition to the above, the observed longitude effect strongly suggests that most of the material captured by Iapetus was at or near its orbital plane, which coincides with its equatorial plane since Iapetus is in Cassini state 1, i.e., its spin axis is nearly normal to its orbital plane (Davies and Katayama, 1984). This would also explain the fact that the poles, with albedos ranging from 0.5–0.6 (Squyres *et al.*, 1984), are the brightest regions on the satellite.

Therefore, we are postulating that the brightness asymmetry on Iapetus is the result of a single event – a high-velocity collision with a comet of mass 10^{13}–10^{15} kg, travelling with a speed of about 20 km s^{-1}, in the last 10^6–10^8 yr. If this is true, however, the question that must be answered is 'Why Iapetus?'. Why don't any other planetary satellites have this interesting feature?

In brief, the answer may be that although Iapetus is the only satellite with this feature *now*, in the past other satellites of comparable size and mass may have exhibited a form of this brightness asymmetry. Since only collisions with a relatively narrow range of parameters can produce an effect of this nature, over long periods of time (10^8–10^9 yr) any differences in brightness would be eliminated by normal (viz., low velocity) meteoroid bombardment. The collision with the comet that made the leading hemisphere of Iapetus dark was both a relatively rare event and a recent one.

It is important to emphasize that the above scenario could only work in the outer solar system and on satellites of the comparable size and mass of Iapetus. If the satellite were much larger (e.g., Ganymede), very little of the ejecta would escape, and the vaporized ices would recondense back onto the surface, thus keeping it bright. If the satellite were much smaller than Iapetus, two things would be possible, each of which would prevent an albedo asymmetry. At one extreme, the collision could fragment the satellite. At the other, the tidal lock would be broken so that the reaccreted material would cover both hemispheres (e.g., Hyperion?).

Recently, it has been reported by Schaefer and Schaefer (1988) that Nereid, the satellite of Nepture (N2) having an eccentric orbit ($e = 0.75$) with a period of about 360 days, varies in its brightness by 1.5 mag over a period of 8–24 hr. If this observed factor of four difference in brightness is due to an albedo asymmetry rather than from the rotation of a highly irregularly shaped body, Nereid may have something in common with Iapetus, viz., a recent collision with a comet or asteroid. However, there are differences in both color and periods of rotation (Schaefer and Schaefer, 1988) – Iapetus is presently in synchronous lock while Nereid is not, as was predicted by the theoretical calculations of Peale (1977). Hopefully, Voyager 2 may help answer this question for us in August of 1989, when it passes within 4.7×10^6 km of Nereid.

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