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Correspondence

THE DARKENING OF IAPETUS AND THE ORIGIN OF HYPERION

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SUMMARY

We consider the possibility that the low albedo of the leading hemisphere of Iapetus is the result of this satellite running into debris produced when the progenitor of Hyperion was destroyed by a hypervelocity impact with a comet.

1 INTRODUCTION

The origin of the dark leading hemisphere of the Saturnian satellite, Iapetus, has been the subject of debate for over 300 years. Cassini, who discovered the satellite in 1671, noted that its visual magnitude varied significantly from one side of its orbit to the other; modern measurements (Squyres *et al.* 1984) give a visual magnitude of 12·1 for the dark, leading hemisphere, and 10·3 for the bright, trailing hemisphere. These magnitudes correspond to average albedos of about 0·05 and 0·5 respectively.

Past attempts to explain this extraordinary ten-fold contrast of Cassini regio have fallen into two broad categories: endogenous and exogenous. The principal example of the former is that dark material emerged from the satellite's interior, covering the surface of one hemisphere (Smith *et al.* 1981).

However, one would expect that any such material would emerge where the crust of Iapetus was thinnest, i.e. the Saturn-facing hemisphere which is subject to the greatest tidal distortion. This is, however, orthogonal to the darkened leading hemisphere. In any case, it is difficult to understand why the material should emerge with the high degree of symmetry about the apex of motion possessed by the darkened region as found by *Voyager* imaging.

The principal example of an exogenous origin hypothesis for the darkening is that material eroded from the outer satellite, Phoebe, spirals inward under Poynting–Robertson drag to strike Iapetus on its leading hemisphere (Burns *et al.* 1979). The discovery that the spectrum of Phoebe is significantly different from that of the dark material of Iapetus (Tholen & Zellner, 1983) effectively rules out this possibility—although it remains widely quoted.

The optical properties of the dark material of Cassini regio may, however, constitute an important clue to the real origin of the darkened hemisphere. Spectrophotometric observations (Bell *et al.* 1985) show that in addition to a very low albedo, the material is very red in the visible and near infra-red, with a spectrum that is virtually identical to that of D-type asteroids and minimally active deep-space comets (Hartmann *et al.* 1987).

So, could the dark side of Iapetus be in some way connected to asteroids or comets? Given the large heliocentric distance of Iapetus, the involvement of asteroids seems somewhat unlikely. We therefore consider the exogenous-category idea that the dark material is cometary in origin.

That a comet may be involved in the darkening of Iapetus is not a new idea; Tabak & Young (1989) invoke the impact of a comet of mass 10^{13-15} kg with Iapetus. However, there are problems with having a comet interact directly with Iapetus. The symmetry of Cassini regio about the apex of motion suggests that any impact must have occurred dead-centre of the leading hemisphere, which seems improbable. In addition, one would expect the impact of a comet of the size envisaged by Tabak and Young to have left some feature within Cassini regio as the result of excavation into the underlying icy material; none appears in the *Voyager* images of Iapetus.

In view of these problems, let us turn to the possibility of an *indirect* interaction, that is, of Cassini regio being the result of violent events elsewhere in the Saturnian system.

Hyperion, the satellite next inwards towards Saturn, shows clear signs of having been involved in such events. There is now considerable *prima facie* evidence that Hyperion is not a pristine primordial object, but the impact remnant of a larger satellite—proto-Hyperion—created by collision with some hypervelocity (about 10–20 km s^{-1}) object (Farinella *et al.* 1990). The satellite is highly irregular in shape, and has a non-synchronous (indeed, chaotic) rotation.

What could have caused the break-up of Hyperion's progenitor, henceforth referred to as proto-Hyperion? Interestingly, the mean colour curve of Hyperion's surface is almost identical to that of Cassini regio—and to that of deep-space comets—and the satellite's overall albedo is considerably lower than that for the 'mainstream' Saturnian satellite. All this is suggestive of a link with cometary objects.

We therefore propose a new twist to the cometary hypothesis—that the darkening of Iapetus is the result of the satellite intercepting debris formed after a large comet hit and destroyed proto-Hyperion.

Such a scenario would at least appear to account for the spectral and photometric similarities of Hyperion, Cassini regio and deep-space comets, while avoiding the problems created by direct interaction between a comet and Iapetus.

Is such a scenario dynamically feasible? In turning to this question, we must stress that although definitive answers are desirable, a great number of imponderables is involved. A detailed supercomputer investigation would no doubt enable a whole set of different arrangements to be investigated (but even then only after a great deal of CPU time). In what follows we restrict ourselves simply to showing that the debris interception hypothesis is at least reasonably self-consistent, and does not seem to lead to results wildly at odds with what is known.

2 ESTIMATED PARAMETERS OF THE DARK MATERIAL

Central to any discussion of the origin of the darkening is an estimate of the thickness, and thus mass, of the material responsible.

The *Voyager* images of the region failed to find a single crater, even where many individual pictures were summed to boost the signal to noise ratio (Smith *et al.* 1982). This lack of cratering is in contrast to the trailing hemisphere, which is well covered by craters typically 50 km in diameter.

These observations could be interpreted as showing that the dark material has been very recently deposited, and is thus still awaiting disruption by impacts. Alternatively, the absence of obvious features may mean that the dark material is thick enough to have absorbed impacts subsequent to its deposition.

On the present assumption that the destruction of proto-Hyperion is tied to the creation of the darkened hemisphere of Iapetus, we can use *Voyager* imaging data of Hyperion to discriminate between these two possibilities, and give an estimate of the thickness of the dark material.

The face of Hyperion is significantly less heavily cratered than 'normal' Saturnian satellites (Thomas and Veverka 1985), as one would expect if Hyperion was formed by an event which took place after the epoch of primordial impacts in the early solar system. However, the existence of some cratering (including one impact feature 120 km across) suggests that the destruction of proto-Hyperion is not a very recent event. Thus it seems unlikely that the absence of obvious impact features in Cassini regio is due to absence of suitable impact events.

We therefore conclude that the appearance of Cassini regio is the result of its being relatively thick. To estimate this thickness we note that crater sizes on Hyperion are typically around 10 km diameter, implying on the current hypothesis that objects capable of creating such craters have been present in the Saturnian system since the creation of Cassini regio.

Thus the thickness of the material of Cassini regio must be at least as great as the depth of craters formed by such objects striking Iapetus, or else one might expect to see bright, excavated icy material showing through on *Voyager* images. Correcting for the difference in gravity field, a crater of diameter D on Hyperion will be of diameter 0·8 D on Iapetus. Using the depth to diameter relationship for craters from detailed *Voyager* imaging of Rhea, whose gravity field is essentially identical to Iapetus (Strom *et al.* 1990), we find that an impactor creating a 10 km-diameter crater on Hyperion will penetrate Cassini regio down to a depth of 1000 metres. It appears, therefore, that the dark material on Iapetus is at least this thick.

This, in turn, enables a rough estimate of the mass of the dark material to be obtained. Cassini regio has an area of about $3 \cdot 10^{12}$ m^2. If the material is predominantly dust, a mass density of about 1000 kg m^{-3} seems reasonable, giving a total mass of dark material of about $3 \cdot 10^{18}$ kg.

Whether or not this material is mostly from the impacting comet or from proto-Hyperion is hard to assess. Spectral data do not help—the colour map of Cassini regio is, as noted earlier, similar to that of both Hyperion and of deep-space comets. The very low albedo of Cassini regio—much lower than anything else in the Saturnian system, including present-day Hyperion—

might suggest a predominance of cometary material. However, impact heating of proto-Hyperion debris may have greatly reduced its final albedo.

One might expect that, since proto-Hyperion was almost certainly somewhat bigger than the comet that destroyed it, most of the material now in Cassini regio derived from it. However, if the impact was oblique, and only shattered proto-Hyperion into low-velocity fragments—a possibility we consider in more detail below—this would not be the case.

Given such imponderables, we consider two possible impact scenarios, to see if they are at least self-consistent and lead to reasonable answers.

3 ESTIMATES OF THE IMPACT SCENARIO

The first scenario has the impact being sufficiently violent to destroy completely both the comet and proto-Hyperion, overcoming the latter's gravitational binding energy and dispersing the debris out into the Saturnian system.

In this case, we can arrive at an approximate lower limit for the *combined* mass of proto-Hyperion and the comet by estimating the maximum proportion of this mass that could have been intercepted by Iapetus. If all the material is swept up by Iapetus in a single pass, this proportion is approximately given by the ratio of the gravitational capture volume swept out by Iapetus to the total volume of the debris generated.

The debris will be anisotropically ejected into a roughly cone-shaped region whose axis lies along the initial velocity vector of the impactor, and whose apex angle can be taken as being about 40 degrees (Melosh & Sonett 1986).

If the comet struck proto-Hyperion while crossing the Saturnian system, the axis of this cone will be roughly orthogonal to the line joining the centres of Saturn and proto-Hyperion. For our purposes, the cone extends from proto-Hyperion out only as far as the orbit of Iapetus. The volume of such a cone is about 10^{28} m^3.

The gravitational capture volume of Iapetus is given by its gravitational capture cross-section multiplied by the length of the satellite's path as it passes through the cone of debris.

The capture cross-section is πR_h^2, where R_h is the radius of the Hill sphere for Iapetus in the Saturnian gravitational field, i.e. $(M_i/3M_s)^{1/3}\, a_i$, where M_i is the mass of Iapetus, M_s that of Saturn and a_i the semi-major axis of Iapetus; thus $R_h = 4 \times 10^7$ m in this case. The length of Iapetus's orbit inside the cone of debris would be about $2{\cdot}5 \times 10^9$ m, giving a total gravitational capture volume for Iapetus of about 10^{25} m^3. Thus the maximum proportion of material likely to have been captured in a single pass is about 10^{-3} of the total amount involved in the collision. This leads to a figure for the initial mass involved of around $3 \times 10^{18}/10^{-3} = 3 \times 10^{21}$ kg.

Although pretty rough and ready, this value is at least not utterly unreasonable. For example, the currently largest-known comet is Chiron, an upper limit for whose diameter has recently been set at 372 km (Sykes & Walker 1991). Taking a cometary material density of 10^3 kg m^{-3}, this leads to an estimated mass for Chiron of around 10^{19} kg. Thus the above estimated total mass figure is probably a reasonable lower limit on the mass of proto-

Hyperion. It is comparable to the masses of three of Hyperion's present neighbours (including Iapetus), and comfortably (i.e. two orders of magnitude) less than the mass of the largest Saturnian satellite, Titan.

The mass figure is also consistent with the mass of satellite which a Chiron-sized object could disrupt. Assuming that a proportion ε of the kinetic energy of such an object is injected into overcoming the gravitational binding energy of proto-Hyperion, $3\,GM_H^2/5\,R_H$, the maximum mass of proto-Hyperion, M_H, which could be disrupted by a Chiron-like object is given by:

$$M_H = 8{\cdot}6{\cdot}10^5\,(\varepsilon M_c v_c^2/\rho_H^{1/3})^{0{\cdot}6}\ \text{kg}.$$

Here M_c is the mass of the impactor, v_c its velocity and ρ_H is the mean density of Hyperion's progenitor.

Taking ε as 0·1, ρ_H as 1200 kg m^{-3} and v_c as 15 km s^{-1}, we find $M_H = 10^{21}$ kg. It is, of course, possible that larger comets than Chiron have existed, raising this figure still further.

Given the uncertainties involved in the above analysis, however, it is worth considering another, somewhat dynamically simpler, possibility: that the impact event was oblique and fragmented but did not disperse proto-Hyperion. Such an event requires considerably less kinetic energy, and is thus more likely. It also implies that what we see in Cassini regio is primarily cometary material from the impactor.

There is an immediate question, however: if kinetic energy from the impact did not disperse the fragments of proto-Hyperion, what did? There is strong resonance locking between the orbit of proto-Hyperion and Titan, and it is this which is likely to prevent a fragmented proto-Hyperion from reaccumulating (Farinella *et al.* 1990).

If essentially no proto-Hyperion debris reached Iapetus, it would imply that what is now seen on Cassini regio is primarily cometary impactor material. Some support for this simpler view comes from the fact that the albedo of the region is certainly somewhat closer to that of comets than of Hyperion today.

The mass of dust would, according to this second impact scenario, constitute a lower limit on the mass of the comet responsible for destroying proto-Hyperion. For an estimated mass for the Cassini regio material of $3{\cdot}10^{18}$ kg, we arrive at an estimated lower limit for the diameter of the comet of about 180 km. This figure would have seemed unreasonably large some years ago; we now know it is considerably below the size of Chiron.

4 CONCLUSIONS

We have explored the possibility that the darkened leading hemisphere of Iapetus is the result of an impact between the progenitor of Hyperion and a large (Chiron-sized) comet. It is concluded that Cassini regio on Iapetus may have been created when Iapetus ran into the debris from the event.

Such a scenario does not seem to be contradicted by spectrophotometric data from Iapetus, Hyperion and deep-space comets (which is an improvement on some previous suggestions).

Attempts to model the dynamics of the impact are, however, beset by a large number of imponderables. We have looked at two types of impact, and these at least seem to lead to self-consistent results that do not seem too far-fetched.

Given the prospect of a single explanation for two of the most enigmatic features in the Saturnian system, the ideas put forward here may be worth exploring by supercomputer simulations.

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