Solving the mystery of Iapetus

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Since the discovery of Iapetus by G. D. Cassini, in 1672, it has been known that the leading hemisphere of this Saturnian satellite is one order of magnitude darker than the trailing hemisphere. Since the Cassini spacecraft entered the Saturnian orbit, several high-quality images of the dark hemisphere of Iapetus have been obtained, in particular during the Dec 31 2004 flyby of this satellite. These images revealed the presence of a large equatorial ridge in the dark hemisphere of Iapetus. We propose that this ridge and the dark coating of the hemisphere on which it lies are intimately interlinked and are the result of a collision with the edge of a primordial Saturnian ring, ultimately caused by a sudden change in the orbit of Iapetus. The model naturally explains all of the unique features of this satellite; it is probably the solution to one of the oldest mysteries in solar system astronomy.

1. Introduction

Recently, the dark hemisphere of Iapetus has been imaged in detail by the Cassini spacecraft. One of the main scientific goals of this flyby was to gather information pertinent to the solution of the hemispheric dichotomy. Instead, to everyone’s surprise, an extraordinary ridge was found. This feature is notorious in many ways: it follows, without deviation, a great circle along the surface of Iapetus, and this great circle happens to be exactly aligned with the equator. Its height is remarkable, more than 20 km in some points. This feature has no known counterparts in the solar system. The fact that the dark region of Iapetus (aptly named Cassini Regio) has a perfect bilateral (North-South) symmetry relative to the equatorial ridge suggests very strongly that the two features are intimately linked (Porco et al. 2005).

2. The hypothesis.

We believe that the newly discovered ridge is the key to understanding Cassini Regio. We suggest that both have a common origin, and that this is a collision with a primordial ring of Saturn. In this scenario, the ridge should, as observed, be saturated with craters, many of these would have been produced by collisions of the ring particles with the surface of Iapetus.

A collision with a ring is fundamentally different than a collision with a single object, or even a string of objects caused by tidal disruption, like Comet Shoemaker-Levy 9. In that case, we have several relatively large objects along a single line; when these impact the surface, they produce a crater chain. In a crater, the ejecta expands radially...
from the center, which to some extent prevents accumulation of material in the impact region (since the area where the ejecta accumulates is of the order $r^2$, where $r$ is the radius of the ejecta blanket). In the case of a collision with a ring, we have much smaller craters (because of the much smaller size of the ring particles) and the emergence of new collective effects: when millions of craters are being produced every second along a line, the pattern generated by the debris will have bilateral symmetry relative to that line. Therefore, the area where the ejecta accumulates increases much more slowly (with $r$), leading to a much larger accumulation of ejecta per unit surface closer to the impact line.

Another major difference is the sustained, and much larger, flux of matter. Let us suppose a ring with a surface mass density of 1000 kg m$^{-2}$ (equivalent to a width of 100 meters and an average spatial density one hundredth that of water). Let us also imagine that an object in an equatorial orbit flies for about 10000 seconds at a speed $v$ of 2.5 km/s through such a feature. The volume of material accumulated per meter along the equator would be of the order of $2.5 \times 10^7$ m$^3$. This is equivalent to a ridge of 5 km height and total width at the base of 10 km (assuming a nearly triangular section).

This multitude of collisions will lead necessarily to the sublimation of at least some of the volatile components of these ring particles. The conversion of a small percentage of the collisional energy to thermal energy would be enough to totally sublimate some of the ices commonly found at 10 a.u. from the Sun, like CO$_2$. The sublimation of such volatiles not only act as a powerful coolant of the whole process, but it would also produce a transient atmosphere at the location of the impacts, with a pressure decreasing symmetrically with distance from the impact zone. The thin but fast winds resulting from this pressure gradient could have carried large amounts of the refractory ring particle “dust” away from the area where the ring material is being deposited; a similar phenomenon is observed on comets; where ice sublimation (due in that case to solar irradiation) carries dust into space, producing the cometary dust tails. However, Iapetus has a gravitational field that is much larger than the common comet, therefore much of this dust does not escape into space, being instead deposited around the impact zone. In our hypothesis, this is the dark coating of the region known today as Cassini Regio.

Because of its unique nature, we will henceforth refer to the equatorial ridge of Iapetus simply as “the rindge”, to mean that this feature is not a ridge in the usual sense of the term; i.e., a mountain chain caused by tectonic processes.

3. Tests.

The dark streaks observed at the edge of Cassini Regio indicate that it was a wind blowing from the equator that deposited the “dust”, as one would expect from our hypothesis. We can be certain of this because the Cassini imagery shows clearly that the dust is deposited downwind from crater rims. The same phenomenon is observed near Martian craters after dust storms. Porco et al. (2005) exclude this scenario because of the lack of an atmosphere on Iapetus, and conclude that the particles flew in ballistic trajectories from the equator, but this process can not deposit dust particles preferably downwind from crater rims. Ballistic flight might, however, have happened for larger, boulder-sized
particles nearer the rindge. A key prediction of this scenario is that the coating of “dust” should become progressively thinner away from the rindge: deposition of dust by a fluid should be proportional to its concentration in that fluid. If the deposition is significant, it will cause the dust concentration in the fluid to slowly diminish away from the equator, leading to smaller deposition per unit area with increasing latitude. This is quite apparent in the albedo and color evolution with latitude (Porco et al. 2005), such a pattern should not be observed for ballistic flight. Another, still untested prediction is that the dust particle size should be larger closer to the rindge; because fluids tend to deposit larger particles first. This has not yet been confirmed.

It has been suggested Porco et al. (2005) that the rindge could have been created away from the equator and then moved towards it by energy loss from the interior (Peale, 1977). However, the structure does not show the complex tectonic patterns produced by such migration (Perchman and Melosh, 1979). The ring collision scenario naturally produces a linear feature exactly at the equator: this is the geometric intersection of a ring plane and the surface of a moon with a (previously) equatorial orbit (more on this later). Tectonic processes are not likely to produce such a perfectly linear feature. Tectonism is unlikely on Iapetus in any case; there are no clear volcanic landforms nor is there a strong internal heat source; and the object does not seem to be differentiated.

Another key feature of the rindge is that its height varies extremely slowly with longitude. This is to be expected from a collision with a ring, but such a constant height has never been observed for any tectonic feature. If the origin of the rindge was tectonic and preceded the dark coating, then it should not necessarily be confined to Cassini Regio. If it postdated the coating, then the rindge, being built from an upwelling from the interior of Iapetus should be much brighter than the surrounding surface. The ring collision scenario predicts that the rindge should be confined to Cassini Regio (i.e. the rindge, being an accumulation of collisional debris, must necessarily be surrounded by the resulting ejecta) and have the same albedo, as observed.

4. An impact with a ring edge.

What was exactly the geometry of the collision of Iapetus with the ring? Fortunately, the imaging provides us with abundant clues. The longitudinal extent of the rindge is about 110° (Porco et al. 2005). This indicates that the Iapetus was never fully inside the ring region, otherwise the longitudinal extent of the rindge would be at least 180°. Simple considerations of orbital mechanics indicate that a collision of a satellite with a ring edge should always cause an eastwards motion of the particles relative to most of the satellite’s surface exposed to the impacts (see Figure 1).

This accounts for an important observed fact: although Cassini Regio is symmetrical relative to the rindge in the North-South direction, it is not so in the East-West direction. In particular, in a collision with a ring edge the rindge should be taller on its Western side, as the impacts there were closer to vertical and therefore more numerous per unit area (see Figure 1), and should slowly diminish in height towards the east, becoming imperceptible, as observed. These considerations should be
5. **Sudden orbital migration of Iapetus.**

The existence of the rindge suggests that the former orbit of Iapetus was equatorial, otherwise, with its present inclination, a collision with a ring would not produce a sharp rindge, but something more like a wispy dark coating of the leading hemisphere. Because rings are generally located much closer to Saturn than the present orbit of Iapetus (generally within a couple of planetary radii of the surface, where tidal effects prevent coalescence of the ring particles into larger objects, a region known as the “Roche zone”), a collision with a ring also suggests that Iapetus was once much closer to Saturn.

The fact that the collision has occurred indicates a sudden change of its orbital parameters prior to the ring collision, in particular a large increase in the eccentricity (but not the inclination) of the orbit, otherwise the ring would have time to adjust to the gravity of Iapetus and no collisions would occur (as observed for the satellites embedded in the rings). The cause of this sudden change of orbit could be an interaction with other satellites of Saturn or even an intruding object, but the fact that the orbit of Iapetus was equatorial during the ring collision strongly favors an interaction with another satellite of Saturn. A sudden change of eccentricity would generally be associated with a sudden change of orbital period. That would make the rotation of the satellite asynchronous for some time, so the leading hemisphere at the time of the impact is not necessarily the leading hemisphere observed today; the model indicated above (see also Fig. 1) suggests that the center of the leading hemisphere at the time of the collision was closer to the western edge of the rindge, which is now nearer the anti-Saturn point.

The sudden increase of eccentricity implied by the collision with a ring is likely to lead to further orbital changes: satellites in eccentric orbits and low inclinations have much increased probability of crossing the orbits of other satellites and therefore interact gravitationally with them.

The present orbit of Iapetus is an enigma. It is the most inclined of all the regular satellites of Saturn (about 7°). This orbit is stable, i.e., Iapetus never comes close to Titan. However, this implies that no interaction with extant satellites could have made Iapetus change from an eccentric orbit with small perisaturnium to its present orbit, which has a perisaturnium more than twice as large as the aposaturnium of Titan. The transition from a previously equatorial orbit closer to Saturn to its present orbit is the major conceptual problem with the scenario discussed above. Its is likely to be a low-probability event, probably caused by an interaction with a now lost object in the general vicinity of the present orbit of Iapetus.

The low probability of such an event would have profound consequences. Many proto-satellites formed in the Saturnian system were in orbits that started, or later became, unstable. In the later stages of satellite formation, proto-satellites in such orbits either end up colliding with other proto-satellites, or are ejected from the Saturnian system by close encounters with other proto-satellites, or get tidally disrupted by close approaches to Saturn (forming a ring system). Many objects have to go through such processes to account for the formation of the large satel-
lites, in particular Titan. This scenario, a small replica of what is thought to have happened with the early solar system (Cassen and Woolum, 1999), is the “canonical” explanation for the formation of the large satellites of the giant planets (Buratti, 1999). With so many protosatellites in chaotic orbits, collisions with rings are a definite possibility for many objects. If the survival of one of them in a distant orbit like that of Iapetus is a small probability event, then the mere existence of Iapetus would imply a large number of such primordial objects. That would add support for the current understanding of planetary (and large satellite) formation.

Acknowledgments. The author would like to thank discussions and encouragement from the Arecibo Observatory staff, in particular Michael Nolan, Steve Torchinsky and Avinash Deshpande.

Notes
1. This is a potential explanation to the features observed in the leading hemispheres of Rhea and Dione.

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Figure 1. A collision with a ring edge should always produce an eastward motion of the ring particles relative to the surface of the satellite being exposed. top In one scenario, Iapetus only meets the ring at the aposaturnium of its transient orbit. In this case, the ring particles are moving faster towards the east than Iapetus, resulting in eastwards motion relative to the surface and a taller Western end of the ridgde. bottom In the alternative scenario, Iapetus touches the ring at the perisaturnium of its transient orbit, moving faster towards the East than the ring particles. Again, an eastwards motion of the particles relative to the exposed surface is observed. We believe that this is what eventually occurred, because the evidence points towards a single ring collision and Iapetus is now much further out than the outer rings of Saturn. The thick arc indicates the forming ridgde, the letter "c" indicates where the “dust” is being deposited. This is the region now known as Cassini Regio.