

Astronomy Education Review

Volume 4, Mar 2005 - Oct 2005

Issue 1

Simulating Formation of Rifts on Saturn's and Uranus's Satellites versus Scarps on Mercury

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Received: 11/25/04, Revised: 03/02/05, Posted: 04/11/05

The Astronomy Education Review, Issue 1, Volume 4:73-82, 2005

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Abstract

The formation of scarps or "wrinkles" on Mercury is typically explained as being due to the shrinkage of an interior covered by a crust of stony material that does not shrink. A simple classroom simulation of Mercury is to inflate a small spherical balloon and put belts of frosted plastic tape around it at several angles. Putting the balloon in a cooler causes the air in the balloon to shrink like Mercury's interior. The tape, unable to shrink with the balloon, creates scarps. Conversely, many of the medium-sized satellites of Saturn and Uranus show rifts extending for long distances over their outer crusts, which we hypothesize to be due to an expanding "ice"-rich interior. We describe a classroom simulation of the interior expansion's effect on a nonexpanding rigid crust using eggs. The shell represents the cooled solidified surface, while the white represents the water-rich semifluid interior. The eggs are put into a plastic bag and then put into a freezer. Upon freezing, the water in the interior expands. Some of the resulting crack patterns look remarkably like those on the medium satellites of Saturn or Uranus. The interior "lava" occasionally is extruded. One example was long and straight, extending almost halfway around the egg. It resembled the recently discovered rift and ridge extending across one side of the satellite Iapetus. Inspired by this resemblance, we think that the crusts of Iapetus and other satellites with similar features have a global crustal structure weaker to tension 90° to the global lines. For an equatorial rift, assume that a satellite's solid crust formed in an elongated shape continuously pointed at Saturn as the satellite rotates synchronously with its orbital motion. If the synchronism is disturbed, equatorial fractures may form because the crust there is flexed from "high" and "low" tides as the satellite turns relative to the planet. This does not happen at the poles. Then, if the interior expands, one of the fractures could open as a rift along the equator.

1. SIMULATING SCARP (WRINKLE) FORMATION ON MERCURY

In my introductory astronomy and more advanced Solar System astronomy courses at the University of Alabama in Tuscaloosa, I have developed two quick and easy simulations of surface feature formation processes on Mercury, and medium-sized satellites of Saturn and Uranus.

The formation of scarps (or wrinkles) on Mercury is typically discussed as a result of the shrinkage of an interior covered by a crust of stony material that solidifies and does not shrink. The core shrinks on cooling. The crust, having already cooled and solidified, cannot shrink, and consequently forms scarps under the action of gravity with no support from below. The observations, and later, the models, give a decrease of about 2 km in the 2500-km radius of Mercury (Solomon 1976; Strom, Trask, & Guest 1975). Because of the high mean density of Mercury, it is thought that its interior contains a high fraction of iron. In elementary texts, it is often stated that cooling of the iron core and consequent shrinkage create the scarps, but this could be an oversimplification. The shrinkage may also be due to simple cooling of the mantle (S. K. Croft, personal communication, 2005), or even slowing of Mercury's rotation (Beatty, Collins-Petersen, & Chaikin 1999). The future Messenger probe to Mercury may clarify the mechanism.

To simulate the cooling of Mercury's core, thoughts occurred to me of heating an iron ball with a blow torch, then painting it before it cooled. However, visions of accidentally burning down our building prompted a search for an alternative. The simple, safe one I settled on was to inflate a small spherical balloon and put belts of frosted plastic tape around it at several angles relative to one another. Putting the balloon in a picnic cooler with ice or in a refrigerator for a while causes the air in the balloon to shrink like Mercury's interior. The tape, unable to shrink and pulled inward by the rubber of the balloon, creates nice wrinkles or scarps. Of course, the interior of Mercury is not gas, but the interior shrinkage plus a nonshrinking exterior seem to constitute the basic process that creates the scarps.

One interesting sidelight is that this was once proposed as the origin of mountain ranges on the Earth, a pre-plate tectonics idea. Of course, we now know that the interior of the Earth is far more complex than this, with convectionlike processes driving plate tectonics.

2. SIMULATING RIFT FORMATION ON MEDIUM-SIZED JOVIAN SATELLITES

It is interesting to contrast Mercury, a small terrestrial planet, with the medium-sized satellites of Saturn and Uranus, many of which show rifts (not wrinkles) that extend for long distances over their disks. Why do they have rifts and not wrinkles? The reverse of the process thought to have occurred with Mercury may be the case. An expanding interior plus a nonexpanding crust may be the case with these satellites. If the interior expands as it cools and solidifies, the expansion forces are large, and the already solid crust has no choice but to literally crack up with long, open seams from which some sort of semifluid but cold interior "lava" may be extruded. The Voyager photos of these satellites show many of these rifts in a variety of patterns on the old, heavily cratered surfaces.

As with Mercury, a variety of opinions on the "expansive" hypothesis are discussed in more detail in the appendix. The reason for the expansion may lie in these small objects being very far from the Sun, and thus having formed with a large proportion of ices in their bodies. The objects may have been so warm in the past that the ices were fluid (or "molten") initially as the result of radioactive heating, but later as the result of tidal heating episodes. The parts exposed to space either quickly solidified or remained solid with

fluid beneath. Now, here on Earth, ice is different from iron or stony material in that as it solidifies from a fluid state, it expands by roughly 10% rather than contracting. We see this difference here on Earth, where ice floats on water, with about 10% sticking above the surface of the fluid--the "tip of the iceberg." In the case of these satellites, of course, one would not have simple water and water ice as on Earth. The ice may be a complex mixture with other compounds (e.g., ammonia and methane), as well as water. In any case, the existence of the rifts argues for an expansion of the interior well after the formation of a solid crust.

One way to help verify the interior expansion hypothesis is to simulate the interior's effect on a nonexpanding rigid crust and compare the morphology of the resulting features with those observed. For my class, I wanted something qualitatively realistic for the cold satellites. I used small spheroids filled with a semifluid material made mostly of water. Coating the spheroids was a small, rigid crust representing the cooled solidified satellite crust. As you may have guessed by now, these spheroids are fresh eggs, a nice classroom stand-in for a medium-sized Saturnian or Uranian satellite. Brown eggs are best, even matching the colors of some of the satellites, but white can be used if they are painted with a marker pen. This is good for the students to do.

I then put the eggs in a sealed plastic bag and put them in a freezer until the next class. As the eggs freeze, the water in the interior expands as it becomes ice. The eggs crack in a variety of patterns, some of which look remarkably like those on the medium-sized satellites of Saturn or Uranus. The interior "lava" occasionally is extruded through the cracks, hence the plastic bag to prevent a mess in the freezer and to enable the eggs to be passed around for examination.

Figure 1 shows two eggs that cracked in different patterns, and Figures 2 and 3 show photos of two medium-sized satellites of Saturn (Enceladus and Iapetus, respectively). In one case, the crack pattern is a bit complex, making a Y pattern resembling the pattern on the satellite Enceladus shown in Figure 2. The other crack is long and straight, extending almost halfway around the egg, with a larger amount of extrusion on one end versus the other. This resembles the recently discovered straight rift, with a ridge extending across one side of the satellite Iapetus (Figure 3).



Figure 1. "Simulation" crust cracks created by expanding interiors. The dark egg has a Y-shaped morphology. Compare with Enceladus in Figure 2. The green egg has a crack extending almost halfway around itself. Interior material is extruded over much of one end of the fissure. Compare with the Figure 3 black and white photograph of Iapetus.

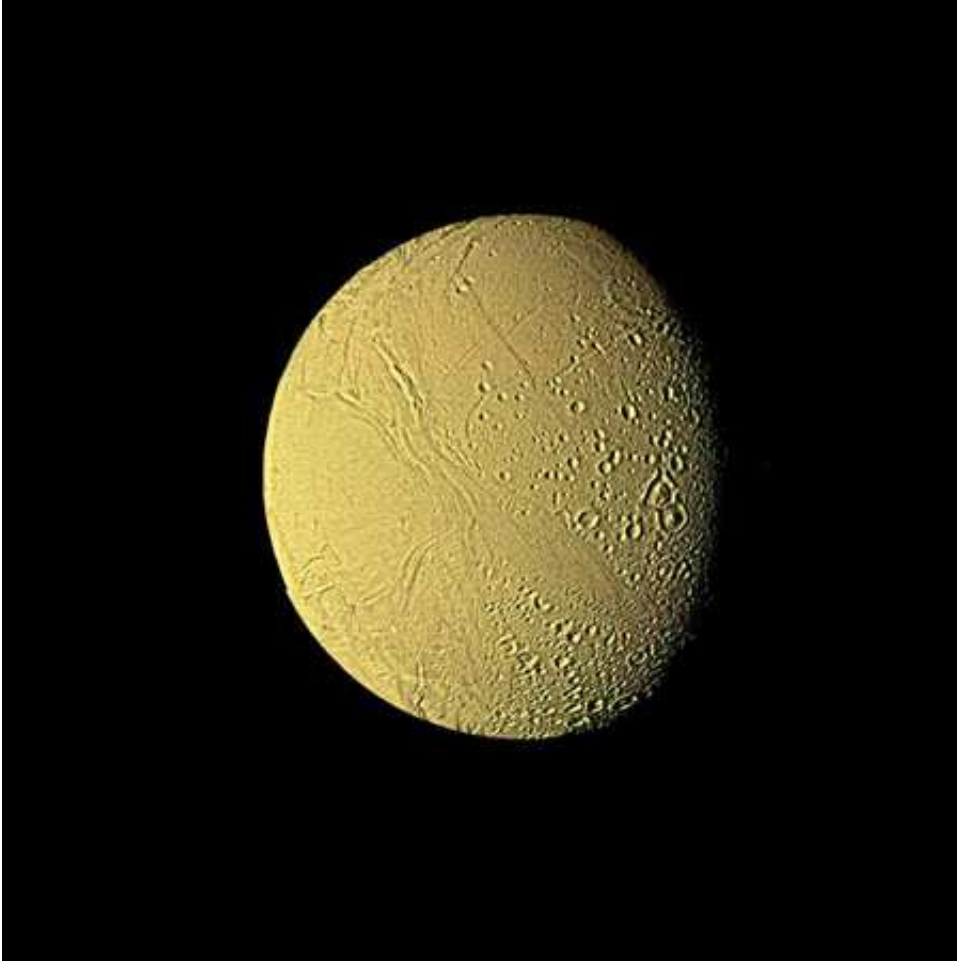


Figure 2. Enceladus: A Saturn satellite with somewhat complex Y fissures. Compare with dark-colored egg in Figure 1. Courtesy NASA/JPL-Caltech.

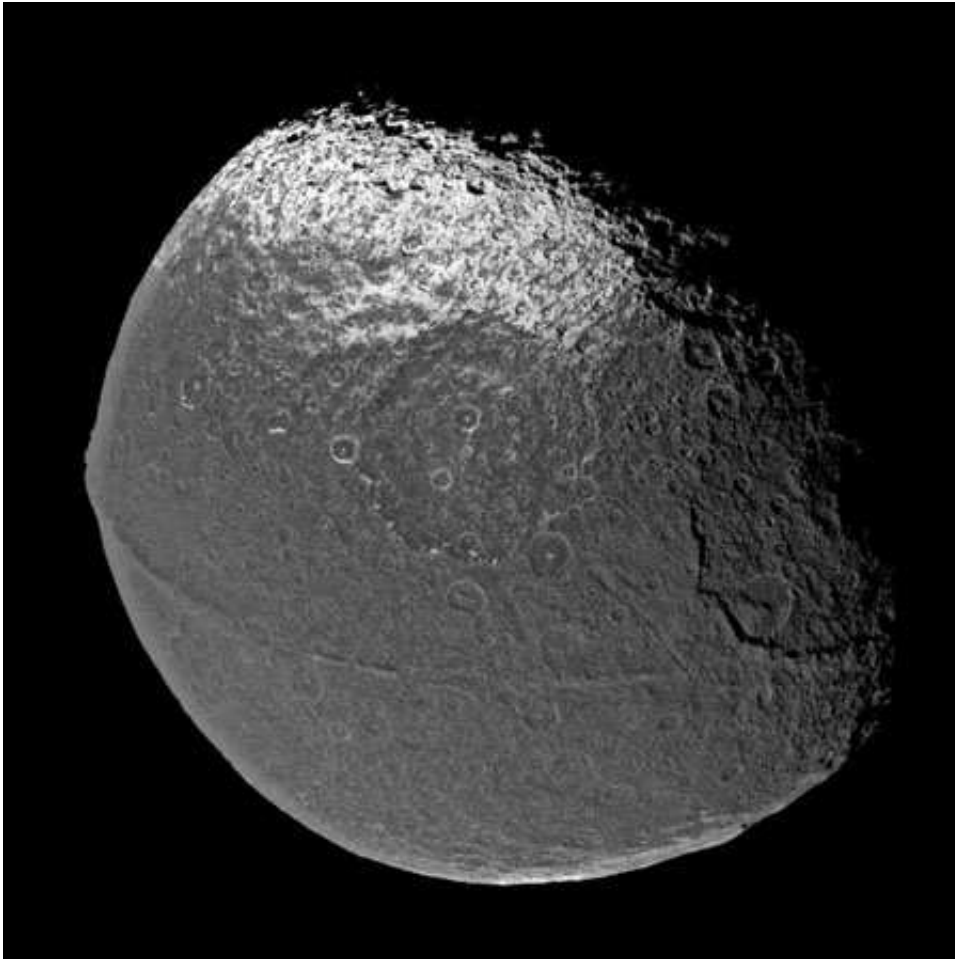


Figure 3. Iapetus black and white photo. Note the rift extending almost halfway around the satellite. Also note the "wall" of possibly extruded material. Compare with green egg "simulation" morphology in Figure 1. Courtesy of NASA/JPL-Caltech.

3. GLOBAL STRUCTURE IN THE CRUST OF SATELLITES WITH RIFTS

Remarking on the long major rifts in Tethys, one of Saturn's moons, and Uranus's moon Titania, Hartmann (1999) said, "Why the tectonic forces produce one major rift instead of a network of smaller fractures is unknown" (228). This was written before the discovery of the even more extreme case of the long, straight feature on Iapetus. Inspired by the similar feature in our egg simulation of Iapetus, we think that crusts of this and other satellites with similar features have a global structure that is weaker to tension 90° to the global lines. Remarkably, this seems to be the case for eggshells to produce the straight crack in Figure 1. In a more obvious example, this is the case for common Xerox machine paper. If one pulls at the short edge so as to tear the paper apart along the long dimension of the sheet, it will part in a nice straight line. However, an attempt to do this at the long side will result in an irregular curving tear.

The mechanism that creates these global features in the satellites is unknown. It may lie in the crystallization of the crust from liquid, or it may lie in having a few global tidal stress fractures in a moderate-sized satellite. We can surmise that an equatorial fracture might form in the following manner. Assume that a satellite's solid crust formed in an elongated shape continuously pointed at Saturn as the satellite rotated synchronously with its orbital period. If the synchronism was disturbed, equatorial fractures would form because the crust there was flexed from "high" and "low" tides as the satellite turned relative to the planet. An everyday example of this is the breaking of a coat hanger wire by repeatedly bending and straightening it. These fractures will be parallel and near the satellite's equator. The varying flexure would not happen at the poles. If the interior expands, one of the fractures could open as a rift along the equator, relieving the tension stress on the others so that one long equatorial rift is produced.

4. SIDELIGHTS ON THE SATELLITE SIMULATION

You can present more advanced students with a mathematical problem. They can look up the exact fraction that the volume of water expands as it freezes (≈ 0.1). The fractional change f in the volume of the egg is

$$d((4/3)\pi r^3)/((4/3)\pi r^3) = 3dr/r \leq f$$

Note that the \leq sign is used because extrusion may reduce the rift width. The rift width divided by the radius represents a fractional change in the circumference of the egg:

$$d(2\pi r)/(2\pi r) \leq dr/r$$

Solving the volume change equation for the change in the circumference (and radius) for freezing water, $dr/r \leq f/3 \approx 0.03$. Measuring the maximum width of the simple rift on the green egg and dividing by the radius, we see the expected result:

$$dr/r \approx 0.02$$

If you show the frozen eggs to the students at the start of class and then conduct your lecture or other class activities for about an hour, you may then be able to present the students with a puzzle. Depending on whether extrusion occurred, the cracks in the eggs may vanish as their interiors melt. The reason is that as the ice melts, it reshinks. In contrast to the satellites, the eggs have an elastic membrane inside the shell. If it remains intact after the expansion, the membrane may pull the edges together again as the interior water remelts. The strength of the membrane is weak compared with the force of the water as it freezes, so it does not affect the initial freezing expansion. In a satellite like Enceladus, repeated episodes and outflows could widen the rift.

5. CONCLUSIONS

We see that the morphology of the features created by an expanding interior on a nonexpanding crust in simulations can be quite similar to the features seen on the medium-sized satellites of Saturn (e.g., Enceladus, Iapetus, and Tethys) and Uranus (Titania and Ariel). Inspired by the similar feature in our egg simulation of Iapetus, we think that the crusts of Iapetus and the other satellites with similar features have a global structure that is weaker to tension 90° to some global lines. For an equatorial rift, assume that a satellite's solid crust formed in an elongated shape continuously pointed at Saturn as the satellite rotates

synchronously with its orbital motion. If the synchronism is disturbed, equatorial fractures form as a result of the crust being flexed because of "high" and "low" tides as the satellite turns relative to the planet (this does not happen at the poles). Then, if the interior expands, one of the fractures could open as a rift along the equator. A simple balloon simulation of contraction of a cooling shrinking interior works for the planet Mercury.

The contracting balloon and expanding egg demonstrations are striking cooperative in-class activities that can be prepared at little expense. They demonstrate two major types of planetary and satellite surface features. Moreover, they are a great way to incite a discussion about the interiors and surface processes of these objects during which the students can make a distinction between casual assertion and a model supported by mathematics or simulations. Meanwhile, the undoubtedly complex nature of the interiors must be kept in mind, and short of actually drilling to the cores of these objects, knowledge of their interiors must be limited by uncertainties in the processes of extrapolation and modeling. The demonstrations represent the scientific strategy of first concentrating on features obvious or simple enough to begin to explain (e.g., the fissure on Iapetus rather than the black and white asymmetry over its disk).

Acknowledgments

Thanks to referee S. K. Croft for a thoughtful review that resulted in an expansion of the astronomical background and the discussion of scientific methodology in this article.

This work was partially supported by NSF Grant AST020177 to Beville State College in Fayette, Alabama.

Appendix—Background and Controversy about Features on Saturn's and Uranus's Satellites

For a popular-level discussion of Jovian satellites, I suggest *The New Solar System* (Beatty et al. 1999). Somewhat more technical books are *Moons and Planets* (Hartmann 1999) and *Physics and Chemistry of the Solar System* (Lewis 1997), which discuss some of the controversies about satellite surface features. It is important to discuss these disagreements to emphasize that science is not a monolithic, authoritarian enterprise, but instead is a continuing investigation with different levels of certainty at different stages. In my experience, an element of controversy makes a subject more interesting to students.

First, it should be noted that although rifts are a common feature on Jovian satellites, the smallest satellites show no such features, and the largest may show a chaotic multitude of shorter rifts (compared with the satellite radius). Lewis (1971a, 1971b) suggested from their densities that Jovian satellites would form rocky or muddy cores, watery mantles, and icy surface crusts. Thermal history calculations (Lewis 1997, 256; see also the review by Hartmann 1999) show that the degree of melting is strongly dependent on size/mass, with composition also being a factor. For small icy bodies, heat generated by radioactivity is conducted away on a short time scale (the radioactive half-life of the important heat-generating isotopes). However, bodies larger than about 500 km in radius might accumulate heat and form the above-mentioned stratified structure. The presence of ammonia ices would reduce the melting point. However, large bodies with a radius of 2000 km or larger may have a more complex evolution via convective motions in the interior. I have used the phrase "medium-sized moons" in the first part of this article to discuss satellites large enough to not quickly conduct any internal heat away, but not so large as to have complex convective motion or other processes dominating thermal evolution. Note that although I use the term

Jovian satellite, Jupiter itself lacks medium-sized satellites, while Saturn has a number of examples in or near the intermediate size range--Mimas, Enceladus, Tethys, Dione, Iapetus, and Rhea, ranging from 400 to 1500 km.

The simplest picture is of the medium-sized satellite forming and becoming molten inside, with a solid exterior crust. As the molten interior solidifies, it expands, creating the rifts in the solid crust. However, at the time of formation, the satellites are under intense meteoritic bombardment. Features dating from formation should show many craters, and might have been obliterated entirely. Examining the photograph of Enceladus (Figure 2) and other satellite photographs, one notes that the middles of the rifts and the apparently extruded material show few craters compared with the rest of the surface, and must have been created less than a billion years ago (Smith et al. 1982), long after the original radioactive heating had died away.

However, the prediction of orbital disturbance by an adjacent satellite and consequent tidal heating by the planet as applied to Jupiter and Io (Peale, Cassen, & Reynolds 1979) has provided a heating mechanism that can occur well after the cessation of internal radioactive heating. This prediction was verified by the Voyager space probe shortly thereafter. One would think that similar processes might occur in the Saturn system, but Peale, Cassen, & Reynolds (1980) concluded that tidal heating was not important in the Saturn system.

However, in another case, Yoder (1979) predicted that the Saturn satellite Enceladus would be perturbed by the nonadjacent satellite Dione into a more eccentric orbit, resulting in an episode of tidal friction. However, there is uncertainty about whether tidal heating would be sufficient to melt a water ice body (Dermott, Malhotra, & Murray 1988). Alternative ideas are that impacts have created fracture zones where tidal heating is maximized, and that an admixture of ammonia ice and water ice lowers the temperature required for melting from 273 K to 173 K (Smith et al. 1982; Beatty et al. 1999, page 303, photo). The amount of energy required would thus be greatly reduced. Students might find mixing ice and salt to be an interesting qualitatively similar demonstration of lowering the melting point of water by a mixture, particularly if one makes ice cream while doing it!

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