Tidal Control of Geyser-like Eruptions on Enceladus.

T. A. Hurford[1], P. Helfenstein[2], G.V. Hoppa[3], R. Greenberg[4] and B. G. Bills[1,5], [1]Planetary Geodynamics Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA. [2]CRSR, Cornell University, Ithaca, NY 14853, USA. [3]Raytheon, Woburn, MA 01801, USA. [4]Department of Planetary Science, University of Arizona, Tucson, AZ 85721, USA. [5]Institute for Geophysics and Planetary Physics, Scripps Institution of Oceanography, La Jolla, CA 92093, USA.

Introduction: Enceladus is a small (radius ~250 km) moon that Saturn every 1.37 days at an average distance of about 238,000 km, between Mimas and Tethys. Due to its proximity to Saturn, tidal dissipation should have quickly circularized the orbit. However, a 2:1 mean motion resonance with Dione, which orbits just beyond Tethys, and is ~15 times more massive than Enceladus, excites the orbital eccentricity, maintaining its value at the currently observed 0.0047.

In 2005, Cassini's Imaging Science Subsystem (ISS) clear-filter Narrow Angle Camera (NAC) detected plumes near Enceladus' South Pole in three high-phase (rear illumination) images [1]. After the earlier detections on 16 January and 17 February, tests were undertaken to verify that the plumes were not artifacts of stray light or internal scattering in the camera system. Images were taken on 27 November as the spacecraft was incrementally rotated about the NAC's optical axis. This test confirmed the validity of the previous plume detections. Moreover, with the relatively high resolution of this third observation (~0.9 km/pixel), individual jets within the plume can be resolved. Also, a fainter diffuse component of the plume can be seen extending out to at least 435 km from Enceladus' surface [1].

Altough, the observed plumes have not been directly correlated with specific locations on Enceladus' surface, simple triangulation of the plumes places their sources near the South Pole where the terrain is dominated by a series of youthful-looking parallel rifts called, "tiger stripes" (Fig. 1) [1]. Moreover, the Composite Infrared Spectrometer (CIRS) has shown that the "tiger stripe" features are significantly warmer than the surrounding terrain [2] and are thus considered likely sources of the plumes [1,2].

The tiger stripe features are typically about 130 km in length, 2 km wide, with a trough 500 m deep, and are flanked on each side by 100 m tall ridges [1]. One of these features is composed of arcuate segments that are in planform similar to the cycloidal ridges on Europa, suggesting that tidal stresses may have influenced its formation [3].

Tides and Plumes on Enceladus: Saturn creates a substantial tide-raising potential throughout Enceladus, distorting the body. The exact size of the tide raised at the surface is dependent on the physical properties of Enceladus' interior structure. However, even if Enceladus' bulk properties tend to resist deformation, its low surface gravity would still result in a sizable tide. A conservative estimate of the height of the primary tide is 500 m.

Enceladus' finite eccentricity causes daily oscillations in the magnitude and location of the tidal bulge, producing patterns of stresses on its surface similar to those studied on Europa [4,5,6]. The state of stress at each point on the surface cyclically changes as the tidal shape of the body changes. Over Enceladus' orbital period, horizontal stresses resolved across the tiger stripes alternate from compressive to tensile, perhaps allowing the faults to open at some point in the orbit, and expose a subsurface volatile reservoir of liquid water or clathrate [7], creating a geyser-like eruption. Then, within a few hours, once again the stress becomes compressive, forcing cracks to close, ending any possibility of an eruption until the next cycle. To test the hypothesis that observed eruption plumes come from these cracks, we have analyzed the stresses along each tiger stripe rift to check whether any of the features were under tension during the observations.

The three hour-long observing sequences (January, February, and November) showed plume activity at different locations in Enceladus' orbit. During the January observation, Enceladus was about an eighth of an orbit past apocenter. 57% of the total tiger stripe length was in tension during the hour-long imaging sequence (Fig. 2a). An additional 13% (between 225^o and 45^o longitude) began under tension and switched to compression over the hour. During this part of the orbit, the rifts were in the process of closing as the stresses become compressive.

At the start of the February (Fig. 2b) observations, taken at about at an eighth of an orbit before pericenter, only 10% of the tiger stripes remained in tension and 4% switched to compression over the next hour. One would expect that the plumes in the February detection might be smaller than the plumes in January, but the different viewing geometries make direct comparisons between the observations difficult since particles in the plumes are strongly forward-scattering and the intensity of scattered light from the plumes dramatically changes with increasing phase angle.

Finally, during the November observation sequence, taken near apocenter (Fig. 2c), 91% of the tiger stripes experienced tension during the imaging sequence. The viewing geometry makes it difficult to determine exactly which tiger stripes are active in the image. However, large portions of the system are in tension allowing multiple discrete sources to erupt as seen in the observations.

A Cassini imaging sequence now planned for a 1.5 hour period on 24 April 2007 would take place, while Enceladus is about one fifth of an orbit past pericenter. We find that during this time 53% of the tiger stripes will be in tension. Unlike the 2005 observing times, a significant portion (12%) of the features will be in the process of opening up during the upcoming observing sequence, as the tension across them changes from compression to tension (Fig. 2d). Thus, this observational sequence could reveal an especially active phase.

Additional high-phase-angle observations of Enceladus may be possible during Cassini extended missions. Ideally, these observations should target Enceladus at multiple locations about its orbit. Observations that help quantify the amount and locations of material being erupted have the prospect of testing the extent to which eruptions are governed by tides. Based on our modeling of the stresses on Enceladus, we predict that geyser activity should be lowest when Enceladus is near pericenter and highest when Enceladus is near apocenter.

References: [1] C. C. Porco, *et al.*, *Science* **311**, 1393 (2006). [2] Spencer, J.R. et al. Cassini encounters Enceladus: Background and the discovery of a south polar hot spot. *Science* **311**, 1401-1405 (2006). [3] Hurford, T. A., Greenberg, R. & Hoppa, G. V. South Polar Cycloidal Rift on Enceladus. AAS/Division for Planetary Sciences Meeting Abstracts #18.04 (2006). [4] Melosh, H. J. Global tectonics of a despun planet. *Icarus* **31**, 221 (1977). [5] Hoppa, G., Tufts, B. R., Greenberg, R. & Geissler, P. Strike-Slip Faults on Europa: Global Shear Patterns Driven by Tidal Stress. *Icarus* **141**, 287 (1999). [6] Hurford, T. A. Tides and Tidal Stress: Applications to Europa. Ph.D. Thesis, The University of Arizona (2005). [7] Kieffer, S. *et al.*, *Science* **314**, 1764-1766, (2006). [8] Roatsch, T., et al. High Resolution Enceladus Atlas derived from Cassini-ISS images. submitted to *Planetary and Space Sciences* (2006).

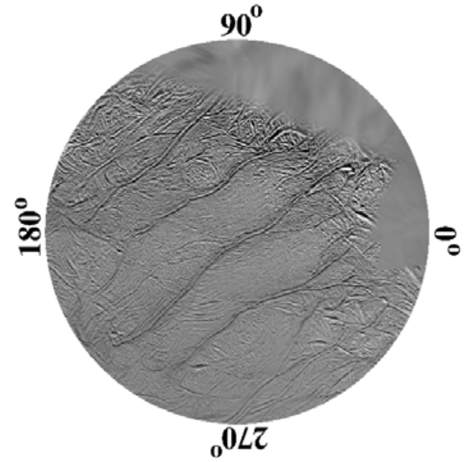

Fig. 1. The south polar region, from a high resolution atlas of Enceladus by Roatsch *et al*. [8], is shown from 65°S poleward.

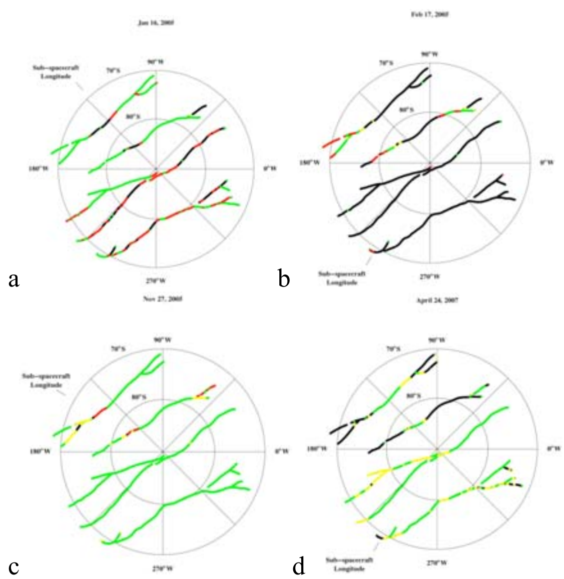

Fig. 2. The stress state across the faults is shown during each observation sequence (a-c), along with the predicted state during the planned April 2007 observation (d). Along each tiger stripe, the color indicates its stress state. Black means that portion of the feature was in compression during the entire imaging sequence while green means that it was in tension. Yellow indicates that the stress normal to the feature switched from compression to tension, opening the rift during the imaging sequence and red indicates that the stress normal to the feature switched from tension to compression, potentially closing the rift.