STEREO IMAGING, CRATER RELAXATION, AND THERMAL HISTORIES OF RHEA AND DIONE.

C. B. Phillips[1], N. P. Hammond[1], G. Robuchon[2], F. Nimmo[2], R. Beyer[1,3], and J. Roberts[4]. [1]SETI Institute, Mountain View, CA; phillips@seti.org, [2]University of California at Santa Cruz [3]NASA Ames Research Center [4]Johns Hopkins University Applied Physics Laboratory

Introduction: We continue to use crater relaxation as a probe for subsurface temperature structure [1,2]. The growing dataset of Cassini images of Rhea and Dione, coupled with automated stereo-imaging programs, allows us to construct Digital Elevation Models (DEMs), extract crater profiles, and estimate crater relaxation. Our topographic measurements are then compared with the results of a coupled thermal evolution-viscoelastic relaxation code, allowing us to investigate the thermal histories of these satellites. So far, our numerical simulations under-predict the amount of crater relaxation we observe, suggesting that both Dione and Rhea were warmer than we initially modeled, and that Dione in particular could have had a significant subsurface liquid water ocean early in its history.

Stereo Imaging: We use overlapping image pairs drawn from the Cassini dataset available in the NASA Planetary Data System. Selected pairs are processed using ISIS software [3], tied together, and reprojected to the same viewing geometry and image resolution.

We then use stereo photogrammetry software such as Ames Stereo Pipeline [4] (ASP) and SOCET SET [5] to create DEMs. ASP is an automated stereo tool which identifies corresponding pixels and uses triangulation to calculate their vertical positions. SOCET SET performs a similar operation but allows interactive editing of the DEM.

Our stereo dataset includes 14 image pairs for Rhea and 15 image pairs for Dione, which we have used to extract profiles of 38 craters with D>50 km on Rhea, and 20 Dione craters with D>50 km. We measured 4 profiles across each crater to calculate average depth.

Crater Relaxation: Crater relaxation is defined as the change in depth since formation divided by initial depth. Estimating the initial depths of complex craters is problematic and can only done by making certain assumptions. As previously discussed in [2], we employed a method used by [6] and calculated initial crater depths by assuming that Herschel crater on Mimas is completely unrelaxed and using scaling laws to adjust for changes in gravity and crater diameter [7, 8]. Our results are shown in Figure 1.

With this technique, we have studied all available sizeable (D>50 km) craters on Rhea and Dione. We find that they fall into two categories: large craters with diameters ranging from about 150 to 500 km have generally high degrees of relaxation, ranging from 40% to as high as 75%. Mid-sized craters of around 100 km diameter have a wide range of relaxation, ranging from as low as 5% to as high as 55%. Generally, large craters on Dione are more relaxed (60-75%) than large craters on Rhea (40-60%). We then compared these measured relaxations with the results of our coupled thermal – viscoelastic relaxation model.

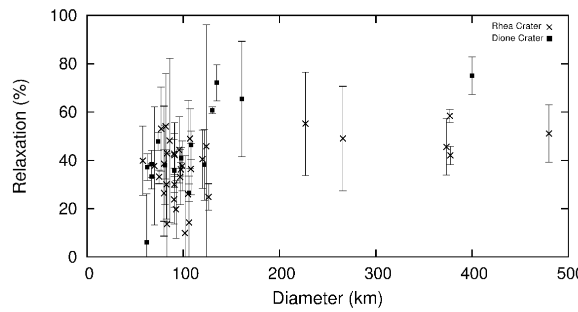

Figure 1: Relaxation percentage vs. diameter for mid- to large-sized craters on Rhea (X) and Dione (box).

Thermal-Viscoelastic Model: Our thermal model for Rhea is based on [9]. We assume Rhea is undifferentiated with a silicate density of 3510 kg m^3, an ice density of 920 kg m^3 and an 11% rock volumetric fraction of silicates [10]. The initial temperature profile is computed by assuming that 40% of the accretion energy is retained as heat [11]. We use an accretion time of 2.9 Myr and a concentration of 37.5 ppb for 26Al, based on typical elemental abundances in ordinary chondrites [12, 13]. As visible in Figure 2, Rhea forms cold, with an initial temperature profile typical for accretion (hot below the surface and cold at the center), then heats up at the onset of convection around 1-5 Myr. Convection starts with a cold plume from the hot subsurface area. The temperature peaks just below the melting point of ice. Cooling occurs from 10 Myr onward, and the lithosphere thickens from 20 to 100 km over this time.

Our model for Dione is based on [14] and assumes a differentiated body that accretes warm. For Dione we used a silicate density of 3001 kg/m^3, an ice density of 930 kg/m^3 and an average density of 1478 kg/m^3. We use an accretion time of 4 Myr and a concentration of 12.6 ppb for 26Al. We begin with a homogeneous temperature profile, and convection starts from the core-mantle boundary with a hot plume. We have a heat spike at around 10 Myr at the onset of convection which then cools off by about 100 Myr, and gradual cooling and lithospheric thickening following that.

A time-dependent viscosity structure for each satellite, calculated by our thermal evolution model, serves as input into a model of viscoelastic relaxation on a spherical shell in a 2D-axisymmetric geometry [15]. Using this approach, we investigated the expected degree of relaxation for a 100, 200, and 400 km diameter crater formed at various times on both Rhea and Dione. Figure 3 shows the expected relaxation for craters of each crater size as a function of their time of formation. Maximum relaxation is attained by craters that form very early in Rhea's or Dione's history; craters that form later have significantly less possible relaxation as the subsurface of both satellites cools.

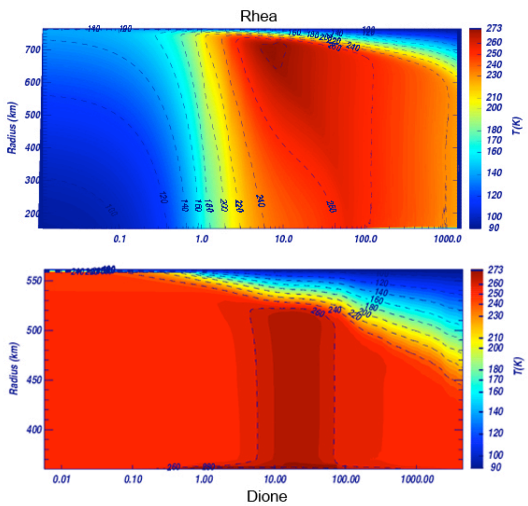

Figure 2: Temperature with depth over time for Rhea (top) and Dione (bottom). The horizontal axis is time in Myr.

Discussion: Comparison of the observed with the predicted relaxation fractions shows that the thermal model underpredicts the amount of relaxation observed for both satellites. Our observations for Rhea show 100 km craters range from 0 - 40% relaxed while our model suggests a crater of this size could only be a maximum of 10% relaxed. We observe that Rhea craters larger than 250 km are all approximately 40% relaxed but this is only consistent with our model if all these craters formed almost directly after Rhea accreted. The case for Dione is even further from our observations, which show relaxation percentages for 100 km diameter craters between 5% and 50%, while the maximum in our model is only 4%. For 200 km and 400 km diameter craters we measure relaxation percentages of 70% to 80%, while our model has a maximum of 8% to 16%. Clearly, there are systematic and significant differences between our measured relaxation percentages and those predicted by the viscoelastic relaxation model.

Our suggested solution to this problem is that our models assume that the subsurface layers of both Rhea and Dione are composed of solid ice, but that in fact Dione (and perhaps Rhea as well) possessed subsurface liquid water layers early in their geological histories. We need more heating early in the history of these satellites to explain the high relaxation percentages observed in this work, but our thermal models (Figure 1) are already very close to the melting point of ice. We need a liquid water layer to permit more relaxation. Interestingly, large craters on Dione are more relaxed than similar-sized craters on Rhea and are far more relaxed than predicted from our Dione models. Dione is also much more heavily fractured than Rhea, and flexure measurements point to a potentially thin elastic lithosphere at the time of formation of these features [16]. This evidence could suggest that Dione had a sizable subsurface liquid water ocean early in its geological history, which then froze out and resulted in the extentional tectonic features visible on its surface due to the slight volumetric increase.

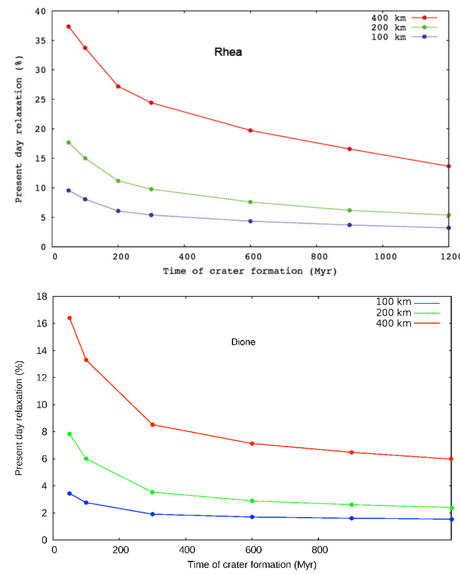

Figure 3: Modeled relaxation of a 400 km, 200 km, and 100 km diameter crater over time on Rhea (top) and Dione (bottom).

Conclusions and future work: Our current study includes most large craters on Dione and Rhea imaged by the Cassini spacecraft. We are currently working to incorporate Voyager imagery to expand our available dataset, as well as beginning our work on the other satellites of Saturn. We are also expanding our study to the Galilean satellites of Jupiter. Using the relaxation state of craters we will attempt to understand and compare the thermal histories of these moons.

References: [1] Dombard, A. J., and McKinnon W. B. (2006) JGR, 111 E01001 [2] Hammond et al. (2011) LPSC XLII, #2633 [3] Gaddis, L. et al. (1997) LPSC 28, #387 [4] Moratto, Z. M. et al. (2010) LPSC XLI, #2364 [5] Miller S.B. And Walker A.S. (1995) Z. Phot. Fern. 63(1),4-16 [6] Thomas, P.J. and S.W. Squyres (1988) JGR 93, 14919-14932 [7] Pike R. J. (1977) Impact and Explosion Cratering, Pergamon, New York [8] Gault D.E. et al. (1975) JGR, 80, 2444-2464 [9] Robuchon, G. et al. (2011) Icarus 214, 82-94 [10] Matson D. et al. (2009) in Saturn from Cassini-Huygens, Springer NY [11] Schubert, G. et al. (1981) Icarus 47, 46–59 [12] Amelin, Y. et al. (2002) Science 297, 1678–1683 [13] Castillo-Rogez, J. et al. (2007) Icarus 190, 179–202 [14] Robuchon, G. and F. Nimmo (2011) Icarus 216, 426-439 [15] Zhong S.J. et al. (2003) G.J. Int. 155, 679-695 [16] Hammond, N. P., et al. (2012) LPSC XLIII, #2374.