Flexure on Dione: Investigating subsurface structure and thermal history

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ABSTRACT

Using stereo generated topography of Dione, a moon of Saturn, we infer flexure across a prominent ridge on the leading hemisphere to estimate local elastic thickness and place constraints on Dione's thermal evolution. Assuming topography is related to the flexing of a broken elastic plate, we estimate an effective elastic thickness of 3.5 ± 1 km. This local estimate is in good agreement with global values derived from long wavelength topography. Corresponding heat fluxes of 25–60 mW/m^2 are much greater than those expected for a body heated solely from radioactive decay. It would be possible to generate our inferred heat flux values via tidal heating at close to the current orbital eccentricity of Dione, but only if a subsurface ocean were present at the time of flexural deformation.

1. Introduction

Dione is Saturn's fourth largest moon, with a radius of 561 km and a density of 1480 kg m^{-3} (Thomas, 2010). It is composed mostly of water ice and is possibly differentiated with a silicate core, although its internal structure is highly uncertain (Thomas, 2010). Like many of Saturn's moons, its surface shows evidence of tectonic resurfacing. The trailing hemisphere is covered with numerous extensional fault networks that comprise the region known as wispy terrain (Goff-Pochat and Collins, 2009; Tarlow and Collins, 2010; Wagner et al., 2009). When *Voyager* first imaged these bright linear features, it was suggested they might be geologically young (Smith et al., 1982) and were perhaps cryovolcanic deposits (Plescia, 1983; Stevenson, 1982). *Cassini* imagery later revealed that they have vertical offsets and that many dissect craters, confirming their extensional tectonic origin (Jaumann et al., 2009). Ridges are also present on the leading hemisphere that may have been a result of compression (Collins et al., 2010; Moore, 1984).

Independent of their formation mechanism, topographic features such as ridges and normal faults impose loads on the lithosphere, causing the surface to bend in response (e.g. Watts, 2001). The magnitude and wavelength of this bending is controlled by the effective elastic thickness, the portion of Dione's ice shell that behaves elastically over long timescales (Turcotte and Schu-bert, 2002). This behavior, known as flexure, has been inferred on Ganymede, Europa, Enceladus and Tethys (e.g. Billings and Kattenhorn, 2005; Giese et al., 2007, 2008; Hurford et al., 2005; Nimmo et al., 2002; Nimmo and Schenk, 2006) and has been used to calculate the elastic thickness and constrain the thermal and orbital evolution of these moons.

In this paper we describe apparent flexure from a tectonic feature on Dione and estimate the local elastic thickness. Our local estimate is consistent with global values of elastic thickness derived from long wavelength topography (Nimmo et al., 2011). We use this estimate to infer the local heat flux, helping constrain the thermal state of the ice shell when this tectonic feature formed. We find that our estimated heat flux can be generated via tidal dissipation at close to the current orbital eccentricity, but only if Dione had a subsurface ocean at the time the estimated heat flux occurred.

2. Background

Imagery from the Cassini Imaging Science Subsystem (ISS) instrument has enabled high resolution mapping of Dione, yet little work has been done to analyze Dione's complex geology utilizing this new resource. Kirchoff and Schenk (2011) classified the surface of Dione into terrain types based on crater density and morphology. Heavily cratered terrain is the oldest and most prominent, with an estimated age of 4 Gyr, using impactor flux case B from Zahnle et al. (2003). Smooth plains and wispy terrain are significantly younger, with less than half the frequency of 10 km diame-

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ter craters, suggesting approximate ages of 2 Gyr. The absolute ages of these terrains are highly uncertain, since different impactor flux models give a wide range in ages (Dones et al., 2009; Kirchoff and Schenk, 2010; Neukum et al., 2005; Plescia and Boyce, 1985). Regardless, it is clear that at least one tectonic resurfacing event occurred well after Dione's formation (Wagner et al., 2009).

Previous authors have estimated the strain across fault systems in wispy terrain by measuring the width of fault scarps on the camera plane and then correcting for the surface orientation and fault slope in order to calculate the fault throw (Goff-Pochat and Collins, 2009; Tarlow and Collins, 2010). These studies have produced local strain estimates ranging from 0.02 to 0.38. By estimating the duration of rifting, strain measurements can be used to place constraints on the strain rate, which is useful for determining the temperature at the base of the elastic layer (see below). To date, no local elastic thickness estimates have been published for Dione; however, Nimmo et al. (2011) estimated the mean global elastic thicknesses of saturnian satellites by using limb profile data. They associate a break in slope in how roughness varies as a function of wavelength with the transition from flexurally supported to isostatically supported topography, and calculate an elastic thickness of 1.5–5 km for Dione.

We estimate the local elastic thickness from flexure using a method similar to that of Giese et al. (2007), who observed uplift at the flanks of Ithaca Chasma on Tethys and interpreted this as the flexural warping of the lithosphere. Modeling the lithosphere as a broken elastic plate, they estimated the effective elastic thickness T_e to be 5–7 km. They related T_e to the yield strength envelope of the lithosphere, yielding a heat flux of 18–30 mW/m². Chen and Nimmo (2008) subsequently used these results to suggest ancient tidal heating during Tethys' passage through a 3:2 resonance with Dione. Dione and Tethys are moderately tectonically deformed icy satellites of similar size, thus these results provide a useful benchmark for comparison with our results.

3. Observation

Flexural deformation is difficult to measure since its magnitude is often small relative to the topography; therefore, high resolution topographic data are required. We constructed digital elevation models (DEMs) using Ames Stereo Pipeline (Moratto et al., 2010), an automated stereo program that has been tested for accuracy against other elevation data sets for the Moon (Laura et al., 2012). For each stereo pair, camera pointing information is first adjusted with ISIS (Integrated Software for Imagers and Spectrometers) using a control network of up to 10 points. Ames Stereo Pipeline then identifies similar features in both images by using a match correlation window, typically 10 × 10 pixels in size. The parallax between features is used to determine the elevation of each pixel and a sub-pixel refinement process enables increased accuracy. For more detailed descriptions of our stereo technique see Nefian et al. (2009), Segal et al. (2010) and Phillips (2013, in preparation). As input we used overlapping Cassini ISS images with resolutions of 200–300 m/pixel, with a convergence angle of 32°. The vertical accuracy of the resulting DEM is 82 m, based on Eq. (3) from Cook et al. (1996) which accounts for the spacecraft altitudes and differences in viewing angles. For elastic thicknesses of the kind we infer, a load greater than ∼1 km in height is required to cause a detectable flexural deflection of the surface.

Our study area is Janiculum Dorsum, a 500 km long, north–south trending ridge on the leading hemisphere's heavily cratered terrain, which may be approximately 4 Gyr old (Fig. 1a). Toward the north the ridge is significantly elevated above the surrounding terrain, reducing in height irregularly toward the south. Janiculum Dorsum is distinct in morphology from ridges observed on Europa

(Collins et al., 2010; Head et al., 1999; Kattenhorn and Hurford, 2009). The ridge has a single peak and is over 30 km wide, compared to ridges on Europa, which range from 200 m to 4 km wide and most commonly appear as a set of parallel ridges (Greeley et al., 2000). However, on both Dione and Europa, parallel depressions can flank ridges. On Europa, previous authors have interpreted these depressions as flexural, which were then used to infer elastic thicknesses (Billings and Kattenhorn, 2005; Hurford et al., 2005).

4. Results

We take four profiles across the northern segment of Janiculum Dorsa where the ridge is at its maximum height. Fig. 1b shows the ridge is 1.5 km high, with a 35 km wide, 300 m deep depression on each side. We assume that this depression results from the flexing of an elastic plate, in which the distance from the load to the inferred forebulge is $\frac{3}{4}\pi\alpha$ for an unbroken plate, where α is the flexural parameter (Turcotte and Schubert, 2002). The flexural parameter is related to the elastic thickness by

$$\alpha = \left(\frac{ET_e^3}{3(1 - \nu^2)\Delta\rho g}\right)^{\frac{1}{4}}, \tag{1}$$

where g is gravity, ν is Poisson's ratio, E is Young's Modulus, T_e is elastic thickness and $\Delta\rho$ is the density contrast between the deforming and the overlying material. We use values of $E = 9 \times 10^9$ Pa from laboratory experiments (Gammon et al., 1983), $\Delta\rho = 1000$ kg m^{-3} and $g = 0.233$ m s^{-2} (Thomas et al., 2007), and $\nu = 0.3$. The observed distance to the interpreted forebulge implies $\alpha = 15$ km, which in turn yields an elastic thickness of $T_e \approx 1.5$ km. This analytic calculation assumes a line load. For a slightly more accurate estimate, we apply a trapezoidal load shown in green in Fig. 1c and calculate the resulting flexural response using the same approach as Nimmo et al. (2003). Fig. 1c shows that an elastic thickness between 1 and 3 km matches the average profile best, in agreement with the simple analytical calculation. However, if the elastic plate is broken the capacity of the elastic layer to support loads is reduced. The distance from the load to the forebulge in a broken elastic layer is $\frac{1}{2}\pi\alpha$, as opposed to $\frac{3}{4}\pi\alpha$ for an unbroken elastic layer. So to produce the same flexural response, the equivalent thickness of a broken elastic layer must be $(3/2)^{4/3}$ greater (Turcotte and Schubert, 2002). We assume a broken elastic plate and estimate an elastic thickness of 3.5 ± 1 km for Janiculum Dorsum.

5. Discussion

The elastic thickness value of 3.5 ± 1 km for Janiculum Dorsum is the first local elastic thickness estimate for Dione. We ignore membrane stresses caused by the curvature of Dione (Turcotte et al., 1981), which is appropriate given the short wavelength of this feature (Landau and Lifshitz, 1999; Melosh, 2011). The assumption that the lithosphere behaves in a perfectly elastic fashion is a simplification of more complex behavior (Damptz and Dombard, 2011), but it has been shown to be a good first order approximation of lithospheric structure (Watts, 2001; Melosh, 2011). Our local estimates of elastic thickness are consistent with the global estimate of 1.5–5 km, based on limb profile data (Nimmo et al., 2011). This agreement between two independent methods for estimating elastic thickness serves to strengthen our confidence in these values.

It is desirable to relate effective elastic thickness to heat flux at the time of load emplacement. To do so accurately requires consideration of the time-dependent elasto-visco-plastic relaxation of ice (e.g., Damptz and Dombard, 2011; Dombard and McKinnon, 2006).