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Elastic thickness and heat flux estimates for the uranian satellite Ariel

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ABSTRACT

The surface of Ariel, an icy satellite orbiting Uranus, shows extensional tectonic features suggesting an episode of endogenic heating in the satellite's past. Using topography derived from stereo-photoclinometry, we identified flexural uplift at a rift zone suggesting elastic thickness values in the range 3.8–4.4 km. We estimate the temperature at the base of the lithosphere to be in the range 99–146 K, depending on the strain rate assumed, with corresponding heat fluxes of 28–92 mW/m^2. Neither tidal heating, assuming Ariel's current eccentricity, nor radiogenic heat production from the silicate core are enough to cause the inferred heat fluxes. None of three proposed ancient mean-motion resonances produce equilibrium tidal heating values in excess of 4.3 mW/m^2. Thus, the origin of the inferred high heat fluxes is currently mysterious.

1. Introduction

There are five classical satellites in the uranian system: Miranda, Ariel, Umbriel, Titania, and Oberon. Like those of the saturnian system, their bulk densities vary irregularly with distance from the planet. Ariel is the 4th largest with a radius of 579 km and a fairly high bulk density of 1660 kg/m^3 (Peale, 1999), implying a mixed composition of silicate rock and ice. The internal structure of Ariel is uncertain, but it is plausible that heat fluxes were once high enough to allow differentiation after accretion, based on the observed icy surface and deformation present (Hussmann et al., 2006). Its internal structure may therefore consist of a rocky core surrounded by a layer of ice. Assuming a core density of 3500 kg/m^3 and an ice density of 930 kg/m^3, Ariel's core would be 380 km in radius.

Voyager 2 was the first and only spacecraft to image Ariel's surface, providing observational evidence of resurfacing. Most of the images taken are of the southern hemisphere and of the side facing Uranus in its synchronous orbit; only 35% of Ariel was viewed in total (Plescia and Boyce, 1987). Ariel has been divided into three terrains (cratered, ridges and plains), all of which can be seen in Fig. 1a. Cratered terrain makes up the largest portion; it is found between the younger cross-cutting grabens and is associated with albedo variations, possibly from ejecta debris (Plescia and Boyce, 1987). Unlike Oberon and Umbriel, Ariel has few very large craters in the visible region. One of the larger complex craters, Yangoor, is about 80 km in diameter D with part of the crater covered by younger terrain (Miller, 1998). Crater density studies suggest that none of the observed surfaces are as old as Umbriel or Oberon, whose surfaces date back to the heavy bombardment. Crater densities on these two satellites are about 1800 per 10^6 km^2 ($D \geqslant 30$ km) (Plescia and Boyce, 1987). However, crater frequencies found on Ariel are significantly lower, about 32 per 10^6 km^2 ($D \geqslant 30$ km) (Plescia and Boyce, 1987), strongly suggesting that Ariel has undergone significant resurfacing. Schenk and McKinnon (1988) identified several craters that are anomalously shallow, about 50–70% of the depth of more recent craters. These characteristics are indicative of viscous relaxation of the icy crust and suggest high heat fluxes, which is consistent with the observed resurfacing.

The smooth areas with few craters are termed plains and are associated with apparently extruded material found on the floor of grabens. The flooded valley floors are convex, suggesting they formed from material with high viscosity (Schenk, 1989). It is thought that vertical mobilization of warmer solid-state material may have resulted in the inferred extrusion and would require high heat fluxes (Schenk, 1989). However, we note that early interpretations of cryovolcanism on jovian and saturnian satellites based on low-resolution images have generally not been supported by later, higher-resolution images (Johnson, 2005). Some caution is therefore required in interpreting terrains on Ariel as cryovolcanic.

The grabens form extensive networks of parallel faulting, suggesting an episode of extensional tectonics (Plescia and Boyce, 1987). Whether or not the surface viewed by *Voyager* represents global or regional deformation is unknown. Nonetheless, the

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existence of the largest canyon, Kachina Chasmata, which extends for 500 km, suggests that extension was not simply a local phenomenon. Based on the regional deformation observed, Nyffenegger et al. (1997) argued that the faulting seen on Ariel is not consistent with a global volume change from refreezing of an ocean, as the orientation of faults shifts slightly clockwise across the surface of Ariel, suggestive of tidal flexing. Significant tidal stresses could have been generated during episodes of high orbital eccentricity, consistent with the many possible resonances that Ariel may have encountered (Tittemore and Wisdom, 1989; Tittemore, 1990).

Observed ridges on Ariel are generally oriented east or northeast. The similarity of their height, width and orientation to the grabens suggest that these ridges formed via similar geological processes (Plescia and Boyce, 1987). Ariel's ridged topography is comparable to the parallel-ridged terrain seen on Ganymede. The morphology of Ganymede's parallel ridge units is suggestive of an extensional environment, where horst-and-graben style normal faulting has been suggested as the principal process shaping these ridges (Pappalardo et al., 1998). As on Ganymede, Ariel's ridge terrain and grabens both crosscut the cratered terrain indicating that they are geologically younger. Additionally, cratering densities at graben and ridged terrain are similar, suggesting both formed during the same episode of tectonic activity (Plescia and Boyce, 1987). Overall, Ariel's geology suggests a period of global resurfacing after accretion, deforming the original crust. The cratered terrain formed first, followed by graben formation triggered by an endogenic heat source, which additionally caused viscous relaxation of remaining craters and possibly warm ice to extrude from graben floors (Schenk, 1991).

In this paper, we investigate the thermal history of Ariel by analyzing surface features. Topography places loads on an ice shell which can be supported either by the strength of the elastic plate or the buoyancy force due to displaced low-density material. Estimates of the elastic thickness allow calculations of local thermal gradients and, thus, heat fluxes, at the time the terrain formed (e.g. Nimmo et al., 2002), although these estimates may be affected by long-term relaxation (Damptz and Dombard, 2011). Modeling observed topographic profiles as flexural (elastically-supported) features has been applied to several other icy satellites as well. These include Europa, Tethys, Ganymede, Enceladus and Dione (Hurford et al., 2005; Billings and Kattenhorn, 2005; Giese et al., 2007, 2008; Nimmo and Pappalardo, 2004; Hammond et al., 2013).

Currently, the uranian satellites remain largely unexplored. So far, there have been no attempts to use topographic data on Ariel to estimate heat fluxes, although a study of Miranda rift flank topography from limb profiles yielded an effective elastic thickness of about 2 km (Pappalardo et al., 1997). The present-day uranian system differs from the Galilean and saturnian systems in that none of its satellites are currently in stable orbital resonances. Past papers on Ariel have investigated potential mean motion resonance configurations with the other satellites to isolate a heat source that could explain the inferred resurfacing (Dermott et al., 1988; Tittemore and Wisdom, 1989; Tittemore, 1990). However, below we conclude that neither Ariel's present eccentricity, nor radioactive heating, nor any of the previously calculated ancient resonances (2:1 with Umbriel, 5:3 with Miranda, or 4:1 with Titania) are sufficient to explain the inferred heat fluxes.

The approach that we employ below to estimate heat fluxes based on elastic thickness estimates is highly simplified compared to more sophisticated, finite-element techniques (e.g. Dombard and McKinnon, 2006). Our rationale for adopting this approach is twofold. First, fitting a simple elastic profile allows comparison with the large body of pre-existing literature on icy satellite flexure. Even though all such studies neglect the potential role of long-term relaxation of topography (Damptz and Dombard, 2011), relaxation is unlikely to change the *relative* amplitudes of

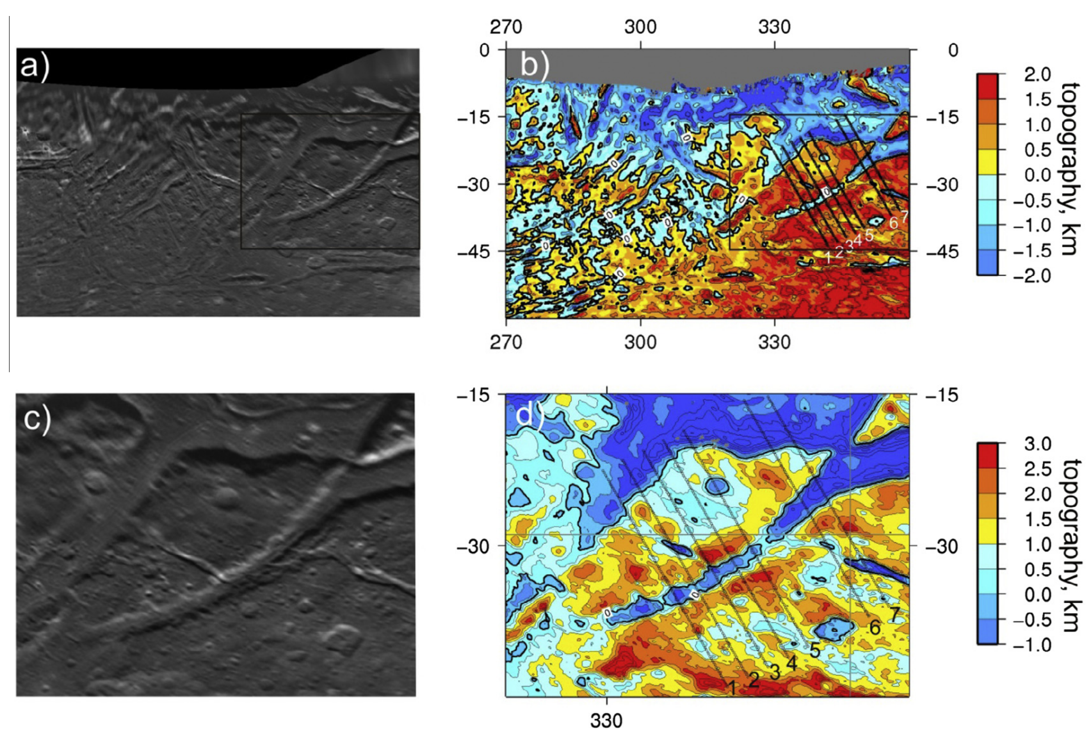

Fig. 1. (a) Image mosaic taken by *Voyager 2* of a portion of Ariel's surface illustrating the deformation of its icy exterior and young surface age. Simple cylindrical projection; 1° of latitude equals 10.1 km. The image is between 270–360°E longitude and 0–60°S latitude. Box outline denotes the zoomed-in portion shown in (c and d). (b) Simple cylindrical projection of stereo-photoclinometry-derived topography from the image shown in (a) with a contour interval of 1 km. Lines 1–7 indicate the location of the profiles extracted (see Fig. 2). (c) Zoomed-in portion of (a). (d) Zoomed-in portion of (b). Contour internal 0.5 km; note the different color scale. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)