Io's Heat Flux and Implications for the Distribution of Tidal Heating in its Interior

Walter S. Kiefer, Lunar and Planetary Institute/USRA, 3600 Bay Area Blvd., Houston TX 77058, kiefer@lpi.usra.edu

Introduction

Io's prodigious volcanic output is driven by tidal heating. Two fundamentally different distributions of tidal heating as a function of depth within Io have been proposed, which produce very different spatial patterns of the surface heat flux [1]. Deep tidal heating has surface heat flux maxima at the poles and a minimum at the equator, whereas shallow tidal heating in a low viscosity asthenosphere has surface heat flux maxima near the equator and goes to 0 at the poles. Based on a Voyager-era stereo topography model for Io [2], it was concluded that about 1/3 of Io's tidal heating was generated in the deep interior and about 2/3 in the asthenosphere [3]. This ratio remains widely cited in the literature today. However, a far more detailed topography model for Io based on Galileo stereo imaging and limb profiles [4] is not consistent with the earlier Voyager-era topography map. This calls into question how well we actually know how tidal heating is distributed with depth inside Io.

Heat Flux Observations

An alternative approach to constraining tidal heating inside Io is to use recent compilations of Io's heat flux. The Galileo spacecraft measured heat flux as a function of location on Io using both the Near Infrared Mapping Spectrometer (NIMS, [5, 6]) and the Photopolarimeter Radiometer (PPR, [7]) during the period 1996-2003. Spatially resolved observations from terrestrial telescopes extend this time frame to include 2001-2016 [8, 9]. These data sets do not show a completely consistent spatial pattern in the inferred heat flux. In NIMS data, the heat flux distribution is relatively flat between ±60° latitude and drops off at higher latitudes [5]. In PPR data, the peak heat flux is at 60° North, with a slightly smaller peak at 30° South [7]. Ground-based telescopic data, which covers a different time period than the Galileo mission, shows peak thermal emission at equatorial and mid-latitudes (40° S to 30° N), but the most powerful volcanic outburst events have a greater concentration at high latitudes [9].

A limiting factor in these observations is that the heat flux at high latitudes on Io is poorly observed both by Galileo, which orbited in Jupiter's equatorial plane, and by ground-based telescopes. However, PPR data suggests that both poles are hotter than would be expected due to the latitudinal dependence of incident sunlight [10], and this is possibly due to elevated polar heat flux from the interior [11]. The Juno spacecraft is now in a polar orbit around Jupiter and can occasionally image Io's poles with its Jovian Infrared Auroral Mapper (JIRAM) thermal infrared imager [12]. Such observations may ultimately help to better constrain the polar heat flux on Io.

Convection Models

To better understand the expected spatial distribution of heat flux out of Io's interior, the tidal heating models of [1] have been used as an input forcing function for a finite element mantle convection model [13]. To ensure that the models are spatially well-resolved, initial modeling is being done in spherical axisymmetric geometry using a zonally averaged version of the tidal heating. Simulations include models with 100% deep heating and with 100% shallow (asthenosphere) heating, along with linear mixtures of the two models with 25%, 50% and 75% shallow heating. The results shown in this abstract are based on an internal heating Rayleigh number (Ra) of 10^8 and are performed on a grid with a spatial resolution of ~8 km on a side. Models with higher Ra and finer grid spacing, corresponding to more vigorous convection, are in development for presentation at the conference.

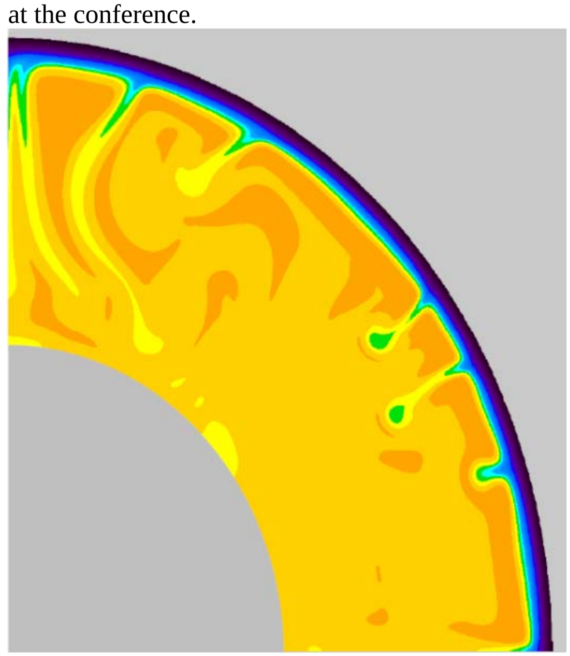

Figure 1: A representative time step of a model with 50% shallow heating and 50% deep tidal heating. Colors represent temperature. Dark blue is cold and orange is hot.

Figure 1 shows the mantle temperature field for a representative time step for a model with 50% shallow and 50% deep tidal heating. The axisymmetry pole for the convection is assumed to also be the rotation pole, which is on the left side of the image, with the equatorial plane at the base of the thermal field. There is a thin, near surface thermal boundary layer. The highest temperatures occur just below this boundary layer and are due to the high rate of tidal heating in the asthenosphere. Numerous convective instabilities of the upper thermal boundary layer are present and develop into cold, sinking downwellings. However, these downwellings are not strong enough to disrupt the large scale flow (up at the equator, down at the pole), and the downwellings are eventually swept into the strong polar downwelling.

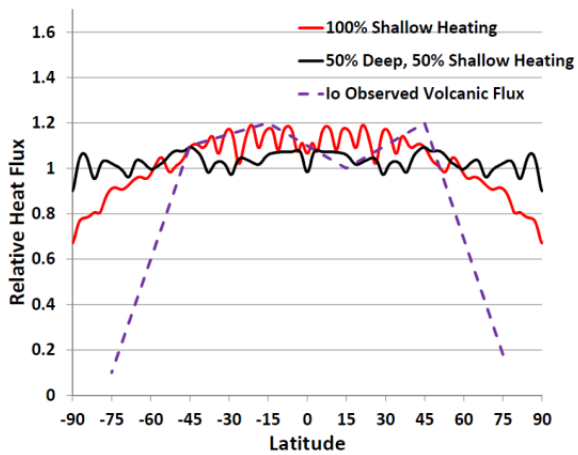

Figure 2: Comparison of the relative heat flux as a function of latitude for models with 100% shallow tidal heating (solid red line) and 50% shallow heating (solid black line) with the NIMS heat flux of [6] (dashed purple line).

The equator to pole circulation advects heat toward the poles, and as a result the mantle heat flux at the pole is larger than one would expect from the geometry of the tidal heating. The net result is that the model with 50% deep and 50% shallow tidal heating has a rather flat heat flux pattern as a function of latitude (Figure 2, black line). In contrast, the model with 100% shallow heating has a strong drop off from equator to pole (Figure 2, red line). However, the 100% shallow heating model does not have its heat flux go to 0 near the pole, as one would expect from the tidal heating geometry alone (the tidal heating does go to 0 at the pole for 100% shallow heating, [1]). This demonstrates the important role played by the large-scale convective circulation in modifying the surface heat flux amplitude [14].

The relatively flat heat flux pattern as a function of latitude observed in the Galileo NIMS data (Figure 2, purple dashed line, [6]) is a better fit to the mixed heating model than it is to the 100% shallow heating model. This favors the presence of at least some component of deep tidal heating on Io. When interpreting the results in Figure 2, recall that the near-polar heat flux is not yet observationally well constrained [6, 7] and is possibly much larger than shown in Figure 2 [11].

Based on this comparison between Galileo heat flux results and the currently completed set of mantle convection models, approximately 50-75% of Io's tidal heating is generated in a shallow asthenosphere. As an additional test of the convection models, the thermal structure of these models will also be compared with the shallow mantle temperatures inferred from Galileo magnetic field observations of Io [15].

References: [1] Segatz et al., Icarus 75, 187-206, 1988. [2] Gaskell et al., Geophys. Res. Lett. 15, 581-584, 1988. [3] Ross et al., Icarus 85, 309-325, 1990. [4] White et al., J. Geophys. Res.: Planets 119, 1276-1301, 2014. [5] Veeder et al., Icarus 219, 701-722, 2012. [6] Davies et al., Icarus 262, 67-78, 2015. [7] Rathbun et al., Astron. J. 156, article 207, 2018. [8] de Kleer and de Pater, Icarus 280, 405-414, 2016. [9] Cantrall et al., Icarus 312, 267-294, 2018. [10] Rathbun et al., Icarus 169, 127-139, 2004. [11] Veeder et al., Icarus 169, 274-270, 2004. [12] Mura et al., AGU Fall Meeting, P23E-01, 2017. [13] Kiefer and Li, Meteoritics Planet. Sci. 51, 1993-2010, 2016. [14] Tackley, J. Geophys. Res. 106, 32,971-32,981, 2001. [15] Khurana et al., Science 332, 1186-1189, 2011.