Tidal Dissipation and the Interior Structure of Io: Magma Mush or Magma Ocean?

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Introduction: Io's prodigious active volcanism is maintained by tidal dissipation within its partially molten interior. There are two fundamentally different models for tidal dissipation inside Io. In the most widely used model, Io is modeled as a solid visco-elastic body, using either a Maxwell [1, 2] or the more complex Andrade [3] rheology law. In such models, Io is effectively a magma mush, in which a small amount of partial melt is present in a mostly solid matrix. Alternatively, Io has also been modeled as having a true magma ocean, in which an interior layer has sufficient partial melt that the solid structure has disaggregated and thus behaves as a true fluid [4]. This abstract considers issues associated with these two different models.

Magma Mush Model

Tidal dissipation models for Io were first developed during the Voyager era [1, 2] and were tested by comparing topography predictions [5] with a stereo topography model [6]. The conclusion of that study [5] was that tidal dissipation inside Io was generated 2/3 in a shallow, low viscosity asthenosphere and 1/3 in the deep mantle [5]. A key problem with this model is that a much more detailed topography model for Io generated using Galileo stereo data for 75% of Io controlled with Galileo limb profiles [7] is inconsistent with the earlier Voyager-era topography model [6]. This calls into question the conclusion that Io has 2/3 of its tidal heating generated in the asthenosphere.

In order to make new progress on understanding the distribution of tidal heating in Io's interior, I have been modeling a broader range of tidal heating models, ranging from completely heated in the deep interior to completely heated in the asthenosphere. These tidal heating models are used as a forcing function for finite element models of mantle convection, which transports heat from the mantle to the near-surface. In order to have highly resolved simulations at the extremely vigorous convection (high Rayleigh number) conditions that occur on Io, current models are two-dimensional (spherically axisymmetric, [8]). The convection model results are being compared with Galileo spacecraft measurements of heat flux as a function of location using the Near Infrared Mapping Spectrometer (NIMS) between 1996 and 2003 [9, 10]. The heat flux at the poles was poorly measured by Galileo, but hotter than expected polar temperatures may indicate elevated polar heat flux from the interior [11].

Results in Figure 1 were averaged over an extended time interval to minimize the effects of small-scale boundary layer instabilities on the surface heat flux patterns. A model with 75% shallow heating (red line) produces a sharp drop in heat flux from equator to pole, inconsistent with the relatively flat profile observed by Galileo (purple line). A model with 50% shallow heating and 50% deep heating is relatively flat with latitude (black line), consistent with observations.

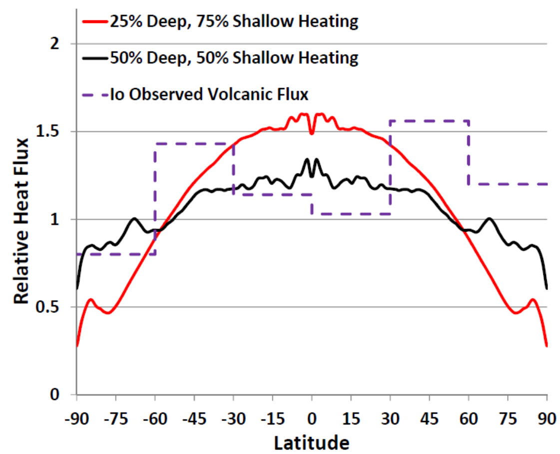

Figure 1: *Numerical model predictions of the surface heat flux on Io as a function of latitude.*

There are two potential problems with this model. First, it assumes that the actual tidal dissipation pattern can be derived as a simple average of models for pure deep heating and pure asthenosphere heating. The two models have very different viscosity structures, making it unlikely that averaging end member cases is an appropriate way to obtain intermediate models. To solve this, new models are in development in which both the depth of the asthenosphere/mantle transition and the asthenosphere/deep mantle viscosity ratio can be independently varied. This will put the inferred distribution of tidal heating on a firmer physical basis. Second, it has long been recognized that Io's volcanism is shifted in longitude by about 30-60° relative to the expected symmetry pattern for the magma mush tidal dissipation model [5, 12, 13].

Magma Ocean Model

The spatial mismatch between the location of heat flux maximum in the solid-state (magma mush) model and the observed locations of volcanism on Io was a major motivation for the development of a tidal dissipation that treats Io as a true fluid (magma ocean) [4]. Such a model can provide a better match to the current longitudinal distribution of volcanism on Io. This is certainly a point in favor of this model, although it is worth noting that alternative solutions to this problem exist. For example, the surface and interior of Io may rotate non-synchronously [13].

Before the fluid magma ocean model becomes widely accepted by the planetary science community, it is worth first assessing the physical conditions under which such a magma ocean can exist. The distinction between the solid and liquid tidal dissipation models has to do with which terms are retained in the equation of motion (Newton's Second Law of Motion). This can be assessed by non-dimensionalizing the governing equations [e.g., 14, 15]. The key parameter is the Prandtl number, $Pr=\eta/(\rho\kappa)$, where η is the viscosity, κ is the thermal diffusivity, and ρ is the density. At high Pr, inertial terms such as accelerations are unimportant, and the force balance occurs between buoyancy forces, pressure gradients, and shear stresses. Conversely, at low Pr, inertial forces become important in the force balance.

For plausible reference values of ρ=3000 kg m^{-3} and $\kappa=10^{-6}$ m^2 sec^{-1}, $Pr=3\cdot10^{12}$ ($\eta/10^{10}$ Pa-s). Viscosity is a strong function of melt fraction, which is key to assessing the behavior of the system. At low melt fraction, viscosity is a weak function of melt fraction, but once a rheologically critical melt fraction is exceeded, viscosity decreases rapidly with increasing melt fraction [16]. For peridotite, the rheologically critical melt fraction is between 25 and 30%, with a viscosity of ~10^8 Pa-s at melt fraction ϕ=0.3 and 10^7 Pa-s at ϕ=0.4 [17]. This corresponds to $Pr=3\cdot10^{10}$ and $3\cdot10^9$ respectively; at these viscosities, the system is still in the high Pr limit and the solid dissipation model applies. Extrapolating the data of [17] to higher melt fraction, it may be necessary for ϕ to exceed 0.5 to 0.6 in order to get Pr below 10^4.

The problem with such high melt fractions and low viscosities is that tidal heating in the solid state model crashes to very low values once the rheologically critical melt fraction is exceeded [18], which would make it difficult to ever heat Io sufficiently to get $\phi \sim 0.5 – 0.6$ and thus to initiate tidal dissipation in a true magma ocean. Magma transport from the underlying mantle [19] could be an additional mechanism for helping to form a liquid layer. In addition to transport from the partially molten mantle into a liquid magma layer, one must also consider loss processes, including magma transport to the crust and conductive cooling to the material both below and above the liquid layer. Additional analysis of these processes is needed, but the full set of physics is extremely complex.

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