MELT MIGRATION THROUGH IO'S CONVECTING MANTLE. C. M. Elder[1] and A. P. Showman[1], [1]Lunar and Planetary Lab., University of Arizona, Tucson, AZ 85721, USA. cmelder@lpl.arizona.edu

Introduction: The extensive volcanism occurring on the surface of Io suggests that its interior must contain at least some partial melt. Unlike Earth, Io cannot lose its internal heat through convection alone [1]. The buoyant ascent of melt through solid mantle contributes to heat loss from Io's interior because it carries latent heat towards the surface. Understanding this form of heat loss is necessary to explain Io's high observed surface heat flux [e.g. 1, 2, 3] and is likely important for any hot planet such as Earth early in its history or tidally heated exoplanets.

In the case of Io, a global conducting layer was detected through electromagnetic induction measured by a magnetometer on the Galileo spacecraft [4]. Magnetohydrodynamic modeling showed that to match the data, the global conducting layer has to be at least 50 km thick and be at least 20% molten [4]. Any model of Io's interior should be consistent with this detection.

[5] developed a model in which all of the heat from tidal dissipation goes into melt migration and found that this would require that Io has a thick partially molten zone containing up to ~20% melt beneath a thick solid lithosphere. Previous modeling of Io's interior has included either melt migration [5] or convection [e. g. 1], but not both. We envision that the convection comprises narrow plumes descending from the base of the lithosphere through a partially molten background mantle whose net (solid + melt) mass flux is upward. Here we consider melt migration in a column of rock rising through the mantle between the downwelling plumes. This generalizes [5]'s analysis to cases with non-zero net (solid + melt) vertical mass flux in the background mantle. We self-consistently determine the melt fraction, sign and magnitude of the solid mantle vertical velocity, and extent of the partially molten zone in this rising column of rock.

Approach: [6] presents a one-dimensional model for partial melting and the buoyant ascent of magma through an ascending column of rock beneath a mid-ocean ridge on Earth. Here, we apply this approach to a one-dimensional column of rock in Io's mantle passively rising between downwelling plumes thus incorporating the effects of both mantle convection and transport of latent heat by the ascending magma. The model consists of the typical porous flow equations [e.g. 5, 7] coupled with an equation for the conservation of energy which includes latent heat consumption, heat advection and heat conduction [6]. The boundaries of the partial melt zone are treated as 'free boundaries' which must be found as part of the solution [6].

The model consists of five conservation laws: conservation of mass for the melt, conservation of mass for the solid, Darcy's law, conservation of total momentum and conservation of energy. The first four equations, equations 2.1-2.7 in [6], are described in many porous flow studies [e.g. 7, 5]. Many terrestrial porous flow studies assume the melt is already present and do not include the conservation of energy equation. Here we use the conservation of energy equation presented in [6]'s equations 2.14 and 2.15 with an additional tidal heating term which is approximated as a constant volumetric tidal heating rate in the partially molten portion of Io's mantle:

$$\begin{aligned} &mL + \rho_l c\phi\left(\frac{\partial}{\partial t} + u\cdot\nabla\right)T + \rho_s c(1-\phi)\left(\frac{\partial}{\partial t} + V\cdot\nabla\right)T \\ &-\beta T\phi\left(\frac{\partial}{\partial t} + u\cdot\nabla\right)p_l - \beta T(1-\phi)\left(\frac{\partial}{\partial t} + V\cdot\nabla\right)p_s = \\ &\nabla\cdot(\rho_s c\kappa\nabla T) + \Phi + E \end{aligned} \tag{1}$$

where m is the melt rate, L is the latent heat, ρ_l is the liquid density, c is the specific heat capacity, Φ is the melt fraction, u is the melt velocity, T is the temperature, ρ_s is the solid density, V is the matrix velocity, β is the thermal expansivity, p_l is the liquid pressure, p_s is the solid pressure, Φ, the viscous dissipation, is given by equation 2.15 in [6], E is the tidal heating rate per volume. The conservation equations for the subsolidus rock are given in [6]'s equations 2.18-2.21.

We non-dimensionalize the conservation equations in the partially molten zone in the same way as [6]. In one dimension with the same approximations used by [6], these partial melt equations can be combined into two differential equations:

$$\varepsilon\phi_t + \varepsilon W_0\phi_z + \phi N = W_0 - \delta^2 PN_{zz} + \frac{E}{Lm_0} \tag{2}$$

$$\phi N = [\phi^2(1+\delta N_z)]_z \tag{3}$$

where N is the effective pressure, the difference between the solid and the liquid pressures, W_0 is the non-dimensional upwelling velocity in the subsolidus region of the mantle and thus the upwelling velocity at the lower boundary of the partially molten region, L is the latent heat, and ε, δ, P, and m_0 are non-dimensional parameters given in [6].

[6] specifies boundary conditions at the surface, the deep mantle, and two at each interface between partially molten region and the subsolidus region. This is enough information to determine the solutions in both

the partially molten and subsolidus regions, including the locations of the interfaces between them.

We solve equations 2 and 3 numerically, integrating forward in time until the solutions reach steady state. These non-dimensional solutions for the melt fraction and effective pressure can be used to find the temperature profile, melt and matrix velocitiy profiles. We specify the net upward (solid + melt) mass flux of the column as a model input. We treat this as a free parameter, emphasizing values motivated by convective scaling laws. In the longer term, the goal is to obtain self-consistent solutions that determine the convective dynamics as a part of the overall behavior.

Goals: This approach will determine the degree of partial melting which results from a given tidal heating rate. This will allow us to estimate of the size of the partially molten region and the melt fraction profile within that region. It will also give the vertical velocity structure of the solid material in the partially molten zone. Downwelling plumes cause ascension of mantle material so the the solid and the melt may both move upwards with different velocities. However, if percolating melt transports enough mass upwards, the solid mantle will descend as melt rises through it. This model can also be applied to other bodies, such as super-Earths, which are heated to the point of becoming partially molten at which point Earth-like convection does not adequately remove heat from the interior.

Acknowledgements: This work was funded by a NASA Earth and Space Science Fellowship and a NASA PG&G grant to APS.

References: [1] Moore W. B. (2003) *J. Geophys. Res., 108, E8,* 15-1. [2] O'Reilly T.C. and Davies G. F. (1981) *GRL vol. 8 no.4,* 313-316. [3] Hussman H. and Spohn T. (2004) *Icarus, 171,* 391-410. [4] Khurana K. K. et al. (2011) *Science, 332, 6034,* 1186-1189. [5] Moore W. B. (2001) *Icarus*, *154*, 548-550. [6] Hewitt I. J. and Fowler A. C. (2008) *Proc. R. Soc. A., 464*, 2467-2491. [7] McKenzie D. (1984) *J. of Petrology*, *25, 3*, 713-765.