Melt migration through Io's convecting mantle

Graduating this year and looking for a postdoc

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Synopsis

- Io and Earth are the only planets in our solar system with currently active volcanoes.
- Io shows no signs of plate tectonics, but stagnant lid convection cannot produce Io's observed heat flux [1].
- Io's mantle is partially molten [2].
  → Advection of heat by magma is very important [3, 4].
- We investigate this by considering mantle rock passively rising between downwelling plumes (figure 2). As the rock rises, it begins to melt. The less dense magma buoyantly ascends through the solid grains.
- Our preliminary results suggest mantle temperatures of 1700K, convective velocities of 40 cm/yr, a partially molten zone in the top 600 km of Io's mantle and an average melt fraction of 15% in that partially molten zone.

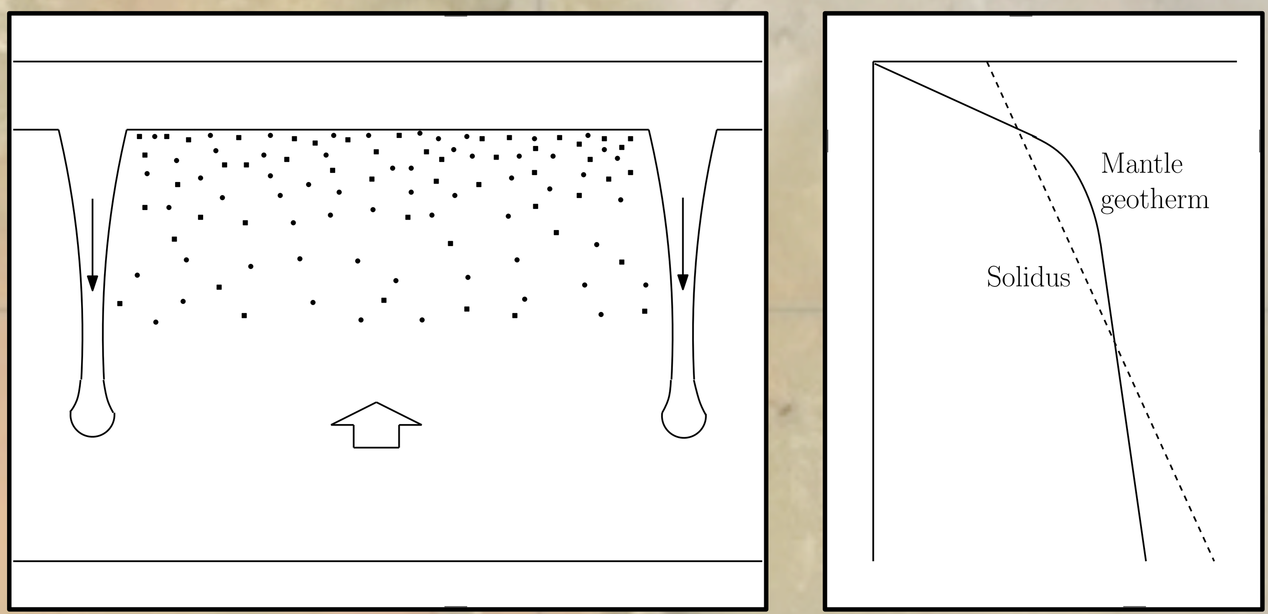

Figure 2. Cold narrow plumes sink through Io's partially molten mantle. The rest of the mantle rises and begins to melt when it reaches the solidus temperature.

Melt migration

- *High temperatures in Io's mantle cause partial melting. The lower density magma buoyantly rises through the solid grains carrying latent heat towards the surface.*
- We present a model (extended from the theory of [5]) for partial melting and melt migration in a one-dimensional column of rock rising through Io's mantle.
- The model reveals how much partial melting occurs and the positions of the boundaries between the partially molten mantle and solid mantle.
- The model conserves mass, momentum and energy, and uses Darcy's law to solve for the melt velocity.
- We also include an internal heating term in the energy equation to account for tidal dissipation.
- The upwelling velocities and the temperature at the base of the ascending mantle column are free parameters, which we specify using convective scaling laws.
- The equations are non-dimensionalized and combined into two equations which depend on the melt fraction and the difference in the solid and liquid pressure.

Figure 1. Volcanic plumes on Io (Image credit: NASA/JPL)

Mantle convection

- *Partial melting of the mantle affects the viscosity, the density contrast driving convection, and offers another mechanism for losing heat. We use convective scaling laws to estimate the temperature and velocity of the mantle.*
- Boundary layer stability analysis can be used to derive convective scaling laws estimating the internal mantle temperature and the root mean squared velocity of mantle material based on the internal heating rate [e.g. 6, 7].
- Partial melting increases the density contrast between the cold solid crust and the warm partially molten mantle, so the Rayleigh number depends on both the temperature contrast and the melt fraction contrast.
- We incorporate the effects of partial melt on the viscosity by multiplying the viscosity by exp(-Bϕ) as in [1].
- Energy must be conserved, so the heat generated in the mantle must be balanced by the heat conducted through the boundary layer and the melt advecting latent heat:
  $F_{tidal} = F_{cond} + F_{melt}$
- Eruption is an inherently episodic process, so we approximate F_{melt} as jF_{tidal} where j is a model parameter that can be varied.
- The velocity in the convecting region is found by equating the volume integrals of the viscous dissipation and of mechanical work done by convection per unit time [7] which is affected by partial melt.

Coupling the equations

- *The melt migration model and the convective scaling laws are coupled to determine the state of Io's mantle.*
- The melt migration and generation model depends on the mantle temperature and velocity.
- The mantle temperature and velocity depend on the melt fraction.
- We solve the equations numerically and iterate between the convective scaling laws and the melt migration equations until the system evolves to steady state.

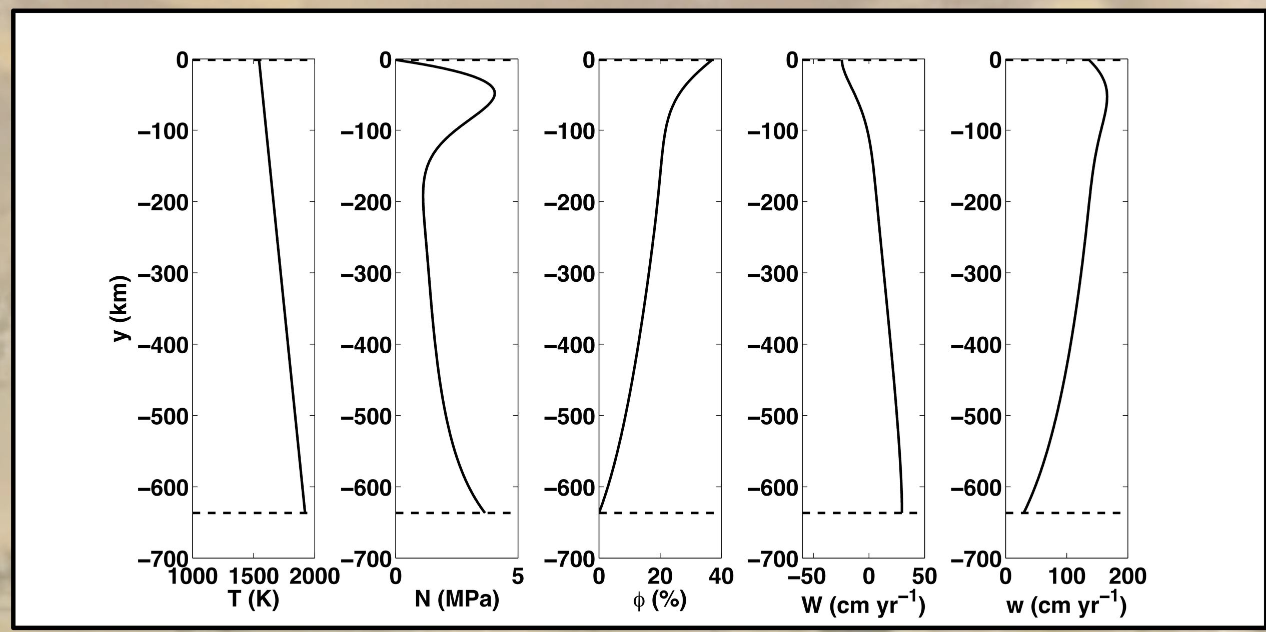

Figure 3. Radial profiles of temperature (T), solid and liquid pressure difference (N), melt fraction (φ), solid velocity (W), and melt velocity (w) in Io's mantle for a tidal heating rate of 10^{14} W and assuming 95% of this heat is lost through eruption.

Preliminary results	
Mantle temperature	1770 K
Mantle convective velocity	42 cm/yr
Average melt fraction	15%

Conclusions and future work

- Preliminary results predict a melt profile which is consistent with [2]'s observations.
- Future plans include testing a range of parameter values to determine the melt fractions, temperatures, and velocities possible in Io's mantle.

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Acknowledgments

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