Tidal Dissipation in Rocky Planets with Partially Molten Mantles

Fergus Horrobin & Diana Valencia

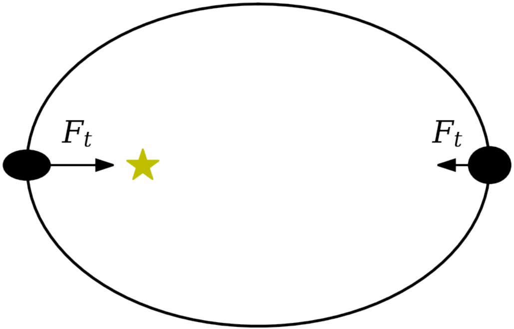
University of Toronto
David A. Dunlap Department of Astronomy and Astrophysics
Canadian Institute for Theoretical Astrophysics

Overview

1. Describe tidal dissipation using examples from solar system and exoplanets
2. Present interior model and numerical method
3. Discuss effect of melt production on dissipation
4. Present applications to Io and Trappist-1b
5. Discuss flow of melt through crust in earth-like bodies

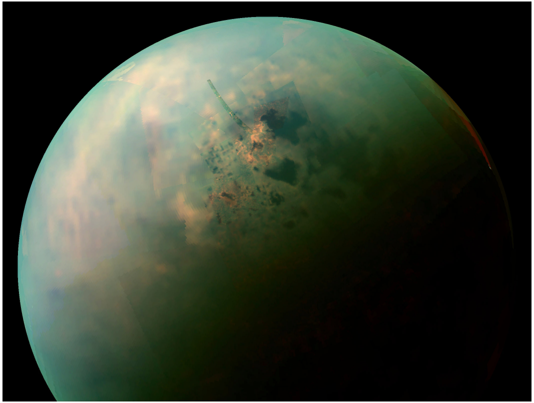
Tidal Dissipation

- Body deforms due to changes in tidal force
- Rigidity of material resists deformation
- Thermal energy dissipated from internal friction



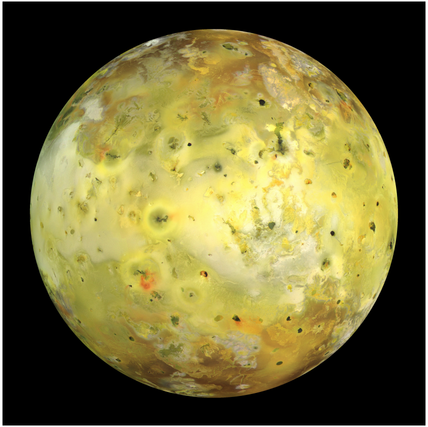
Why is Tidal Dissipation Important

Dynamics: dissipated energy is taken from orbital energy (e.g., Murray+ 2000). Can cause migration, change eccentricity. For example: Titan.



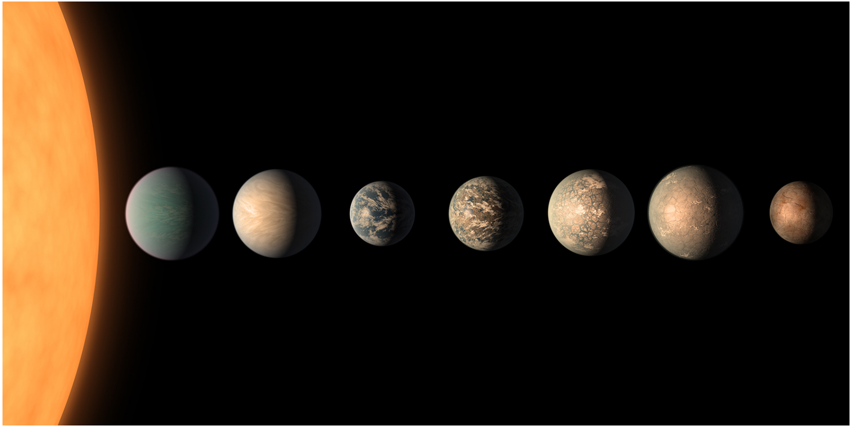
Why is Tidal Dissipation Important

Interiors: dissipation is released as thermal energy which affects convection and melt in mantle. Can increase geological activity. For example: Io



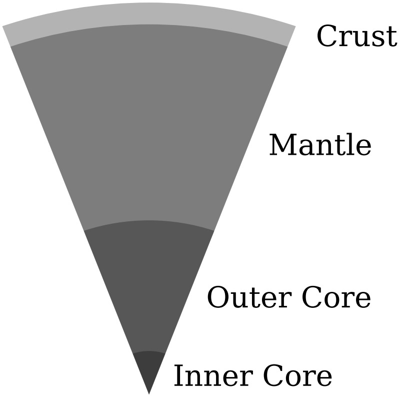
Why is Tidal Dissipation Important

Habitability: heat can transport to surface and affect surface temperatures, atmospheres (e.g., Valencia+ 2018). For example: Trappist-1



Interior Modelling and Computing Dissipation

- From values of M, R compute material model (Valencia 2007)
- Solve for continuous $\rho(r), T(r), p(r)$ in each region
- Material type, ρ, p and T specify η, G, K
- Steady state dissipation, potential averaged throughout orbit
- 3D Spherical grid: $\sim (80 \times 150 \times 75)$
- Propagator matrix method adapted from TiRADE (Roberts & Nimmo 2008)



Temperature Profile and Melt

- Iteratively alternate solving for dissipation then heat equation, melt
- Temperature profile from adiabatic potential mantle, conductive crust
- Melting curve from e.g, Gonzalez-Cataldo (2006)
- Melt transport based on Darcy's law (Moore 2001)
- Volumetric melt fraction (ϕ) directly changes the strength of the material (e.g., Mei 2002)

$$G \sim \frac{G_o}{1 + c\phi} \qquad \eta \sim \eta_o \exp\left(\alpha\phi\right)$$

- Dissipation $\implies$ melt $\implies$ dissipation (initially) increases
- Melt becomes large makes dissipation less efficient, reaches equilibrium

Io: An Example Calculation

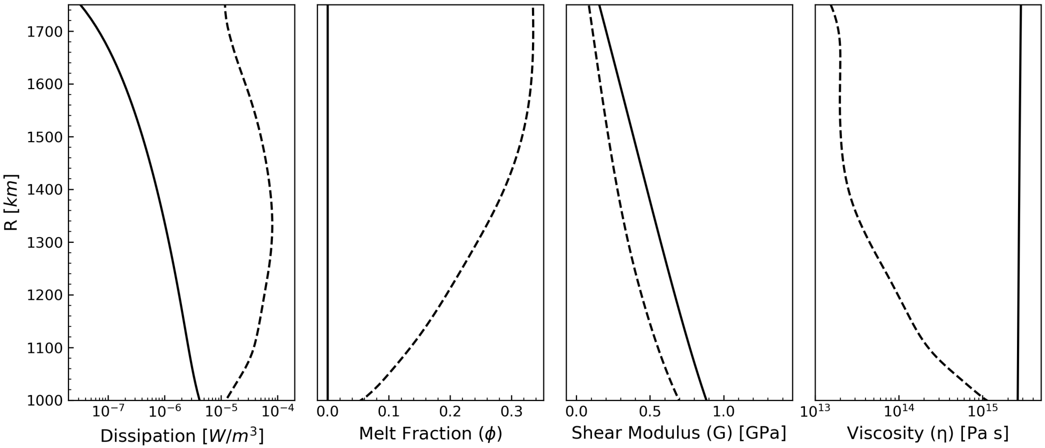


Figure: Solid line shows results without melt feedback, dashed line includes melting

Io: Comparison with Other Works and Observations

- Not novel, but good for benchmarking
- Total heat output used as one example of constraint
- $D_T \approx 9.12 \times 10^4 GW$
- Good agreement with Bierson & Nimmo (2016) ($9.82 \times 10^4 GW$)
- Other works which found similar results with different/simpler models include Moore (2003) ($\sim 2 \times 10^4 GW$), Clausen & Tilgner (2015) ($\sim 1.1 \times 10^5 GW$).
- Compatible with observed value $0.6 - 1.6 \times 10^5 GW$ (e.g., Moore et. al. 2007)

Trappist-1b

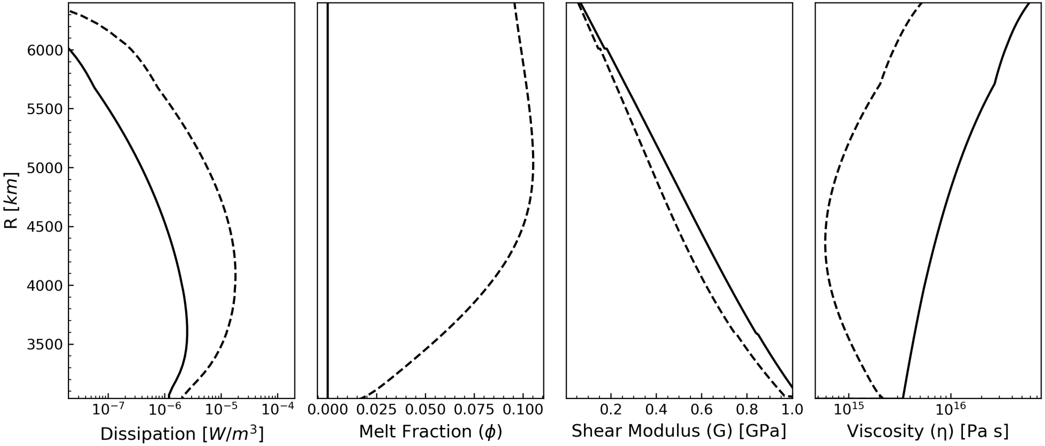


Figure: Solid line shows results without melt feedback, dashed line includes melting. Comparison see: Dobos et. al (2010).

Melt Flow Through Crust - Intrusive Melt

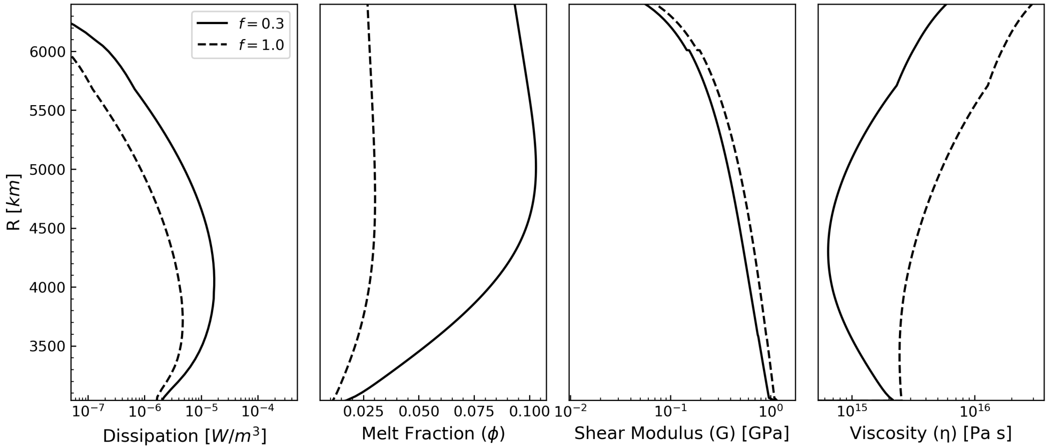


Figure: f measures efficiency of melt percolation through crust. 1.0 $\rightarrow$ Darcy flow continues through crust, 0.3 $\rightarrow$ some melt trapped by rigid crust. (e.g., Tackley 2000)

Conclusions

- Dissipation structure and amount depend on the melt fraction
- Melt fraction depends on amount and localization of dissipation
- Feedback between them occurs, treating rheology well is important
- We combine high resolution models of rheology, dissipation and mantle melt
- Still lots of constraints need to be made to create accurate model
- Discussing dissipation in an accurate way necessitates bringing geophysical knowledge into planetary astronomy