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The Tidal Evolution of Rocky and Icy Worlds Subjected to Advanced Rheological Models

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Abstract

Recent laboratory experiments have shown that traditionally-used rheological laws fall short in fully describing mechanical attenuation in both rocks and ices. Advanced rheologies have been developed to better match modern results, but they have not yet been widely explored in the planetary context of tidal attenuation and dissipation. In this work, we present the tidal and thermal evolution of rocky and icy worlds subjected to the Andrade [1] and Sundberg-Cooper [2] rheologies. We have found that these models lead to greater tidal dissipation, by one to two orders of magnitude, at cooler temperatures and higher forcing frequencies. This increased dissipation allows for a greater number of thermal steady-states between heat production and extraction. This may cause one world to experience more rapid orbit and spin changes while another sees stable, moderate dissipation over long time periods. We showcase a selection of scenarios where the choice of rheology can have major ramifications in both thermal and orbital outcomes.

1. Background

Tides are one mechanism which extracts angular energy from the spin and orbits of planets and moons and deposits it into their interiors in the form of frictional heat. This heat is generated by the movement of planetary material as it attempts to align itself to the tidal forces generated by a nearby gravitational host. If the planet (with radius R_s) is experiencing a dynamic orbit (such as one that has nonzero inclination, I, and/or eccentricity, e) and/or if the object's spin-rate is not equal to its mean orbital frequency n, then the material will be in a constant state of tidal realignment and will continue to dissipate heat into the planet. The magnitude of this heating, $\dot{E}$, is often recorded as,

$$\dot{E} = K\left\{\omega, \eta, \mu\right\} \times \frac{3}{2}\frac{R_s^5 n^5}{G}\left(7e^2 + I^2\right). \qquad (1)$$

Where G is Newton's gravitational constant. This formula is applicable to a spin-synchronous world orbiting a much more massive host with a small eccentricity and inclination.

2. Advanced Rheologies

The coefficient K in Eq. 1 is an estimate of how efficiently the planet is able to dissipate tidal energy. It is dependent upon material properties, primarily viscosity (η) and rigidity (μ), as well as the forcing frequency (ω). However, the functional form can vary dramatically depending upon the rheology of the material [3]. In Fig. 1, we show tidal heating versus temperature in a rocky world similar in size and composition to Jupiter's moon Io. The Andrade and Sundberg-Cooper model show one to two orders of magnitude higher dissipation at lower temperatures (800–1500 K). A similar trend is seen in the frequency domain where these models can produce significantly more dissipation at higher frequencies.

3. Methods

We model tidal heat deposited into a viscoelastic planetary mantle layer, which subsequently loses heat via a parameterized boundary layer convection model. At each time step, temperature is used to estimate the viscosity and rigidity of the dissipating layer. These, along with forcing frequency, are the primary inputs to the rheology model which is used to find the K in Eq. 1 at the next time step. For duel-body dissipation we use a modified form the of the orbital evolution equations presented in [4]. However, unlike that work, we allow for dissipation to occur within both bodies simultaneously. We also simulate the evolution of the mean motion resonance between the Galilean moons following the methods of Hußmann & Spohn [5].

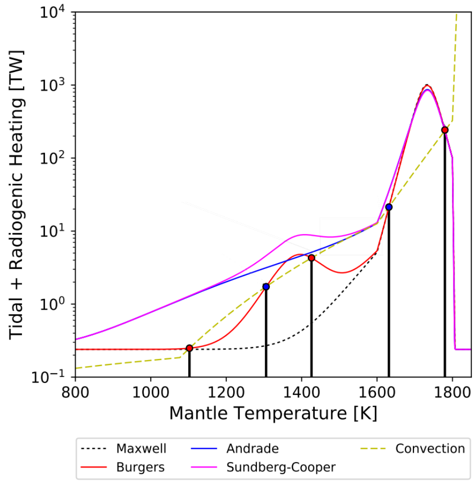

Figure 1: Two advanced rheologies, Andrade, and Sundberg-Cooper, are shown alongside two traditionally used rheological models: Maxwell and Burgers. The cooling efficiency, via convection, is shown as the yellow dashed line. Locations where this line overlaps a rheology indicates a region of thermal steady-state [3]. Steady-state points between convective heat loss, and heat production via the Burgers rheology, are shown. Note the wide separation between the curve for the Maxwell rheology, and those of the Andrade and Sundberg-Cooper rheologies, below 1600 K.

4. Applications and Results

We present the influence that advanced rheologies have on the thermal and orbital evolution for two types of systems: (1) The Laplace Resonance (and other mean motion resonances)—We have found that the Andrade and Sundberg-Cooper models exhibit *tidal resilience*, or the ability to maintain high dissipation in the face of orbital and/or thermal perturbations. This loosens the constraints on the formation of the Laplace resonance between the innermost Galilean moons and suggests that similar resonances are more likely to be stable, from a tidal perspective, for long time periods. (2) Dual-body dissipation in non-synchronously rotating, binary Trans-Neptunian Objects—It has been suggested [6] that these mini systems, such as Pluto-Charon or Eris-Dysnomia, may form from grazing or near-grazing collision/capture events. Immediately following such a formation, both objects would typically exhibit high spin-rates and eccentricities. We have found that, for a modest duration after such a system's formation, these energetic states can cause significant tidal heating, to the point of creating large regions of sub-surface water oceans.

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