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The tidal history of Iapetus. Spin dynamics in the light of a refined dissipation model

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Abstract

We study the tidal history of an icy moon, basing our approach on a dissipation model, which combines viscoelasticity with anelasticity, and takes into account the microphysics of attenuation. We apply this approach to Iapetus, the most remote large icy moon in the Saturnian system. Estimates of Iapetus' despinning timescales, provided by different authors, differ by several orders of magnitude. One reason for these differences is the choice of the dissipation model used for computing the spin evolution. As laboratory data on viscoelastic properties of planetary ices are sparse, many studies relied on dissipation models that turned out to be inconsistent with experiment. A pure water ice composition, generally assumed in the previous studies of the kind, yields despinning times of the order of 3.7 Gy for most initial conditions. We demonstrate that, through accounting for the complexity of the material (like second-phase impurities), one arrives at despinning times as short as 0.9 Gy. A more exact estimate will remain unavailable until we learn more about the influence of impurities on ice dissipation. By including the triaxial-shape-caused torque, we encounter a chaotic behaviour at the final stage of despinning, with the possibility of entrapment in the intermediate resonances. The duration of these entrapments turns out to be sensitive to the dissipation model. No long entrapments have been found for Iapetus described with our laboratory-based dissipation model.

1. Statement of the Problem

Behaviour of icy moons under high tidal stress, such as Europa or Enceladus (where the tidal stress is of the order of 10^5 Pa) has received much attention, since for these bodies tides are easily identified as a major driver of endogenic activity. At the same time, tidal dissipation and its impact on the internal evolution of objects subject to very low stressing still await exploration. This is why we address Iapetus, an icy moon experiencing tidal stresses of the order of 100 Pa. We construct a new dissipation model, which rests on our laboratory-based understanding of the viscoelastic properties of ice. While no attenuation measurements on icy materials have yet been obtained under conditions exactly identical to those on Iapetus, our approach is based on a large bulk of relevant experimental observations and theoretical considerations available by now. Our approach includes quantifying the friction rate as a function of the deformation mechanisms expected to act in Iapetus under the assumption of low porosity.

In our computations, we trace the time evolution of the temperature and of the excitation frequency, and thereby of the viscoelastic properties of the material. Our simulations are based on the despinning theory developed by Efroimsky and Williams (2009), combined with the geophysical model by Castillo-Rogez et al. (2007). Specifically, we amend that model with a realistic dissipation law, which relies on experimental measurements. We also consider the effect of Iapetus' triaxial shape (triaxiality) on despinning. Finally, we explore the important question of the evolution of the tidal torque on approach to a spin-orbit resonance.

2. Strategy

Our study of the despinning history of Iapetus is based on the observation that, under the stress and temperature conditions relevant to Iapetus following accretion, the most likely anelastic and viscoelastic dissipation mechanisms involve the motion and rearrangement of defects in the ice lattice (self-lattice diffusion). In this sense, Iapetus is typical, in that most of the other large icy moons, too, are subject to low tidal stressing. We employ the Andrade model, which has proven adequate to describe anelasticity in a wide variety of materials, including ices. An important improvement of this approach upon earlier studies, is that it enables us to combine the viscous and transient creep components in one model, in a self-consistent manner. We also explore the role of proton reorientation as an additional source of attenuation leading to a possible departure of the dissipation law from the Andrade model at certain temperatures.

3. The Key Results

Using the available empirical data as well as necessary extrapolations, we demonstrate that tidal dissipation in Iapetus is sufficient to achieve efficient despinning at temperatures much below the water ice melting temperature. Under these conditions, the convection in Iapetus, pointed out by Castillo-Rogez et al. (2007) and explored by Robuchon et al. (2010), is no longer a factor limiting the dissipation and despinning rate. At the same time, our study has highlighted certain difficulties inherent in this type of problems. Specifically, if we model dissipation under the assumption that Iapetus is made of a pure water ice, the resulting despinning timescales come up to about 4 Gy, a result that may be inconsistent with the available geological data. Then impurities, whose presence in the ice-dominated satellites is suspected but whose affect is generally not quantified, may have a significant impact on the attenuation mechanism. Rock impurities are expected to inhibit boundary sliding at these stress levels (Raj 1975), while low-eutectic, second-phase volatiles are likely to decrease the viscosity locally by promoting defect mobility. While the prospect of investigating these processes in future is most appealing, virtually no experimental data are available so far. This has limited our ability to narrow down our estimates for Iapetus' despinning timescale. While the obtained estimate places the despinning time within the interval from 0.9 Gy through 3.7 Gy, a more exact estimate remains unavailable until we learn more about the influence of impurities upon dissipation in ices.

By adding the triaxiality-caused torque to the tidal one, we encounter a chaotic behaviour at the final stage of despinning, a behaviour that sometimes includes long-term entrapment in the intermediate resonances. Although this phenomenon needs further investigation, our numerical runs indicate that entrapment becomes more likely when one employs unphysical dissipation models. On the other hand, when calculation of the tidal torque is based on a more realistic mechanical model, the tidal torque remains large enough even at the latest stages of despinning. So the despinning rate stays sufficiently high, thus reducing the chances of getting stuck at an intermediate resonance.

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