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Despinning and shape evolution of Saturn's moon Iapetus triggered by a giant impact

Miroslav Kuchta [a,1], Gabriel Tobie [b,c], Katarina Miljković [d,e], Marie Běhounková [a], Ondřej Souček [f], Gaël Choblet [b,c], Ondřej Čadek [a,*]

[a] Charles University in Prague, Faculty of Mathematics and Physics, Department of Geophysics, V Holešovičkách 2, 180 00 Praha 8, Czech Republic
[b] Université de Nantes, Laboratoire de Planétologie et Géodynamique de Nantes, UMR 6112, F-44322 Nantes, France
[c] CNRS, Laboratoire de Planétologie et Géodynamique de Nantes, UMR 6112, F-44322 Nantes, France
[d] Institut de Physique du Globe de Paris, Université Paris Diderot, 35 rue Hélène Brion, 75205 Paris, France
[e] Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[f] Charles University in Prague, Faculty of Mathematics and Physics, Mathematical Institute, Sokolovská 83, 18675 Praha 8, Czech Republic

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A B S T R A C T

Iapetus possesses two spectacular characteristics: (i) a high equatorial ridge which is unique in the Solar System and (ii) a large flattening ($a - c = 34$ km) inconsistent with its current spin rate. These two main characteristics have probably been acquired in Iapetus' early past as a consequence of coupled interior-rotation evolution. Previous models have suggested that rapid despinning may result either from enhanced internal dissipation due to short-lived radioactive elements or from interactions with a sub-satellite resulting from a giant impact. For the ridge formation, different exogenic and endogenic hypotheses have also been proposed, but most of the proposed scenarios have not been tested numerically. In order to model simultaneously internal heat transfer, tidal despinning and shape evolution, we have developed a two-dimensional axisymmetric thermal convection code with a deformable surface boundary, coupled with a viscoelastic code for tidal dissipation. The model includes centrifugal and buoyancy forces, a composite non-linear viscous rheology as well as an Andrade rheology for the dissipative part. By considering realistic rheological properties and by exploring various grain size values, we show that, in the absence of additional external interactions, despinning of a fast rotating Iapetus is impossible even for warm initial conditions ($T > 250$ K). Alternatively, the impact of a single body with a radius of 250–350 km at a velocity of 2 km/s may be sufficient to slow down the rotation from a period of 6–10 h to more than 30 h. By combining despinning due to internal dissipation and an abrupt change of rotation due to a giant impact, we determined the parameters leading to a complete despinning and we computed the corresponding shape evolution. We show that stresses arising from shape change affect the viscosity structure by enhancing dislocation creep and can lead to the formation of a large-scale ridge at the equator as a result of rapid rotation change for initial rotation periods of 6 h.

1. Introduction

Saturn's moon Iapetus shows two spectacular characteristics: an exceptionally large flattening and a narrow equatorial ridge reaching heights up to 20 km above the surrounding terrain. The observed oblate shape of Iapetus with a polar radius of 712.1 ± 1.6 km and an equatorial radius of 745.7 ± 2.9 km (Thomas, 2010) would be consistent with a rotational period of 16 h for a homogeneous body or 15 h for a differentiated body (Castillo-Rogez et al., 2007; Thomas, 2010). Such a large ($\sim$34 km) difference between the polar and equatorial radii implies that Iapetus was rotating much faster in its early past, and then slowed down to its present-day rotation period of about 79 days, preserving its initial shape. Taking into account the large distance between Iapetus and Saturn (semi-major axis $a = 3.56 \times 10^6$ km), the despinning of Iapetus to synchronous rotation is problematic. The time for a moon to reach tidal locking is proportional to a^6 (Gladman et al., 1996). Iapetus could thus reach its present-day

* Corresponding author.
E-mail addresses: mirok@math.uio.no (M. Kuchta), gabriel.tobie@univ-nantes.fr (G. Tobie), miljkovic@ipgp.fr (K. Miljković), marie.behounkova@mff.cuni.cz (M. Běhounková), soucek@karel.troja.mff.cuni.cz (O. Souček), gael.choblet@univ-nantes.fr (G. Choblet), oc@karel.troja.mff.cuni.cz (O. Čadek).
[1] Current address: Department of Mathematics, University of Oslo, Norway.

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spin period only if the interior was efficiently dissipating the rotational energy, which required a hot interior and low viscosity (e.g. Castillo-Rogez et al., 2007) for a sufficiently long (∼1 Gyr) time. However, if this were the case, the equatorial bulge could hardly be preserved until the present time because of fast viscous relaxation.

The narrow equatorial ridge is another puzzle. It runs $\gtrsim 75\%$ of the satellite circumference, segmented in several discontinuous portions (Giese et al., 2008; Singer and McKinnon, 2011; Dombard et al., 2012; Lopez Garcia et al., 2014). Since its formation, it has been modified by cratering processes and landsliding (Singer et al., 2012), and the high crater density indicates that it is a very ancient feature (Denk et al., 2010). Its location on the top of the equatorial bulge suggests a causal link with oblate shape, however their possibly common origin is still unclear.

Previous models have suggested that rapid despinning may result either from enhanced internal dissipation due to short-lived radioactive elements (Castillo-Rogez et al., 2007, 2011; Robuchon et al., 2010) or from interactions with a sub-satellite resulting from a giant impact (Levison et al., 2011; Dombard et al., 2012). For the ridge formation, proposed models can also be divided in two main groups: endogenic and exogenic. In the endogenic hypothesis, the ridge formation has been suggested to be related to a shape change associated either with despinning (Porco et al., 2005; Castillo-Rogez et al., 2007; Robuchon et al., 2010) or contraction caused by compaction of initially porous material due to warming (Sandwell and Schubert, 2010). The location at the equator may be attributed to a thinner lithosphere or weakening at the equator (e.g. Beuthe, 2010). However, the origin of such lithosphere thinning or weakening does not seem consistent with the long term support of the ridge and the absence of flexural signals (Giese et al., 2008; Dombard et al., 2012). In the exogenic hypothesis, the ridge formation is commonly attributed to the fall of a debris ring, either of primordial origin (Ip, 2006) or resulting from the disruption of a subsatellite formed by giant impact (Levison et al., 2011; Dombard et al., 2012). While this hypothesis naturally explains the equatorial location of the ridge, it is still unclear if the debris rain can explain the observed morphology of the ridge.

A critical aspect that has not yet been modeled in detail in previous studies is the coupled evolution of the shape and viscosity structure of the despinning body. In Robuchon et al. (2010), the change of shape was computed from the viscosity profile controlled by thermal diffusion and convection. However, the possible feedback of shape evolution on the viscosity structure was not considered. In both hypotheses, endogenic or exogenic, the change of shape during the satellite slowdown (whatever the despinning process) is expected to have a strong effect on the litospheric stress and the rheological structure of the interior. In order to re-evaluate the despinning hypothesis and its consequence for the shape evolution and the ridge formation and preservation, we have developed a new numerical tool that allows the simulation of thermo-mechanical processes in a rotating self-gravitating body with free surface and realistic composite rheology of ice.

Numerical models of thermal convection in planets and moons (e.g. Tackley, 2010; Choblet et al., 2007; Šrámek and Zhong, 2010; Běhounková et al., 2010) usually neglect the centrifugal force due to the body spin and assume that the body is spherical. For the majority of the solid bodies in the Solar System, dynamical flattening and topography induced by thermal convection are small in comparison with the body radius. The surface of the body can thus be approximated by a fixed spherical boundary and formally described by a free-slip or no-slip boundary condition. The present-day shape of Iapetus indicates that such assumptions are not valid for this moon, at least during the early stage of its evolution when it was rotating much faster than today. The non-spherical shape of the moon could have a pronounced impact on its thermal evolution. The latitudinally varying centrifugal force due to fast rotation as well as the highly flattened shape may have affected the onset of convection and its style. For a fast rotating object, the gravity force (gravitational + centrifugal force) cannot be represented by a radial vector, and the gravitational effect of a generally non-spherical body must be evaluated to obtain a correct distribution of body forces. Another effect that should be taken into account for determining correctly the viscosity structure is the strain-rate weakening due to non-linear (dislocation) viscous creep. This effect could potentially have a strong impact on the rheological structure of Iapetus' lithosphere during the despinning stage and therefore may have influenced the final shape of the moon and the formation of the equatorial ridge. All these effects are included in our new numerical code, which makes it a suitable tool for investigating the early Iapetus' evolution.

We consider two possible evolution scenarios. The first one implies only tidal deceleration due to internal friction similar as in Castillo-Rogez et al. (2007) and Robuchon et al. (2010). Following Castillo-Rogez et al. (2011), we use an Andrade rheology to describe the viscoelastic response and the associated dissipation. This rheology is much better adapted to describe the viscoelastic response of water ice on a wide range of temperature and frequency than the Maxwell or Burgers rheology, which were used previously in Castillo-Rogez et al. (2007) and Robuchon et al. (2010). However, for realistic viscoelastic rheology, thought to be representative of Iapetus' materials, as we will show by exploring systematically a wide range of initial conditions and rheological parameters, despinning of a fast rotating Iapetus is impossible in the absence of additional external interactions. In a second scenario, we consider the effect of a giant impact that partially despins Iapetus and compute the shape evolution due to the abrupt change of spin as well as the long-term evolution. By using analytical estimates and 3D impact simulations, we quantify the size of the impactor needed to trigger the despinning process and we determine what values of initial rotation can explain both the shape and the formation of an equatorial ridge.

The structure of the paper is as follows. In Section 2, we describe the method used to simulate the thermal, shape (2.1) and spin (2.2) history of the moon and we present results illustrating despinning of Iapetus due to tidal friction (2.3). We demonstrate that for physically admissible initial temperature and realistic constitutive laws, Iapetus could be tidally locked only if its initial spin period were longer than ∼30 h which contradicts the observed flattening. Motivated by this finding, we investigate in Section 3 the possibility of despinning due to a giant impact (3.1) and the consequences of such an event for Iapetus' shape evolution (3.2). The results of our numerical simulations are confronted with available data and summarized in Section 4.

2. Simulation of heat transfer and internal dynamics

2.1. Numerical model of Iapetus' thermal evolution

To simulate the thermal–mechanical evolution of an icy moon with a freely deformable irregular outer boundary we use the modeling strategy described e.g. by Harlow and Welch (1965), Gerya and Yuen (2007) and others, where instead of considering a Lagrangian mesh deforming together with the free surface, the free surface is included as an internal interface within an Eulerian mesh. This interface corresponds to the real surface of the body and separates the domain with realistic material properties from external "sticky air" (Fig. 1), an artificial low density and low viscosity material that does not restrain the real body from deforming (for recent applications of the sticky-air method, see, e.g., Tkalcec et al., 2013; Crameri and Tackley, 2014; Golabek et al., 2014).