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ScienceDirect
ICARUS
Icarus 190 (2007) 179–202
www.elsevier.com/locate/icarus

Iapetus' geophysics: Rotation rate, shape, and equatorial ridge

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Received 23 July 2006; revised 30 January 2007

Available online 28 March 2007

Abstract

Iapetus has preserved evidence that constrains the modeling of its geophysical history from the time of its accretion until now. The evidence is (a) its present 79.33-day rotation or spin rate, (b) its shape that corresponds to the equilibrium figure for a hydrostatic body rotating with a period of ∼16 h, and (c) its high, equatorial ridge, which is unique in the Solar System. This paper reports the results of an investigation into the coupling between Iapetus' thermal and orbital evolution for a wide range of conditions including the spatial distributions with time of composition, porosity, short-lived radioactive isotopes (SLRI), and temperature. The thermal model uses conductive heat transfer with temperature-dependent conductivity. Only models with a thick lithosphere and an interior viscosity in the range of about the water ice melting point can explain the observed shape. Short-lived radioactive isotopes provide the heat needed to decrease porosity in Iapetus' early history. This increases thermal conductivity and allows the development of the strong lithosphere that is required to preserve the 16-h rotational shape and the high vertical relief of the topography. Long-lived radioactive isotopes and SLRI raise internal temperatures high enough that significant tidal dissipation can start, and despin Iapetus to synchronous rotation. This occurred several hundred million years after Iapetus formed. The models also constrain the time when Iapetus formed because the successful models are critically dependent upon having just the right amount of heat added by SLRI decay in this early period. The amount of heat available from short-lived radioactivity is not a free parameter but is fixed by the time when Iapetus accreted, by the canonical concentration of ^{26}Al, and, to a lesser extent, by the concentration of ^{60}Fe. The needed amount of heat is available only if Iapetus accreted between 2.5 and 5.0 Myr after the formation of the calcium aluminum inclusions as found in meteorites. Models with these features allow us to explain Iapetus' present synchronous rotation, its fossil 16-h shape, and the context within which the equatorial ridge arose.

Keywords: Iapetus; Interiors; Geophysics; Satellites, shapes; Satellites, dynamics

1. Introduction

Iapetus is the most distant, regular satellite of Saturn. Peale (1986) noted that Iapetus' synchronous rotation period of 79.33 days is unexpected considering its large distance from Saturn (i.e., an orbit with a 3.51×10^6 km semi-major axis, or ∼60 saturnian radii, R_s). Recent measurements by Cassini of Iapetus' low density and disequilibrium shape have made this satellite's dynamical state even more anomalous.

We have revisited this anomaly using coupled thermal- and dynamical-evolutionary modeling. We used recently determined parameters for material properties and Iapetus' characteristics (see Tables 1 and 2). The most recent Iapetus data were obtained by the *Cassini* mission during the close flyby of Iapetus on December 31, 2005.

Section 2 of this paper is a discussion of the three outstanding geophysical properties of Iapetus that constrain its origin: its rotation state, its shape, and the presence of the equatorial ridge.

Section 3 describes the model and assumptions. We discuss the main constraints, which are imposed by initial composition and structure. The effects of possible compositions are tested by

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doi:10.1016/j.icarus.2007.02.018

Table 1
Iapetus' physical properties

Parameter (unit)	Value	Reference
Mean radius (km)	735.6 ± 3.0 km	Thomas et al. (2007)
Biaxial ellipsoid radii (km)	$747.4 \pm 3.1 \times 712.4 \pm 2.0$	Thomas et al. (2007)
Min–max radii (km)	35.0 ± 3.7	Thomas et al. (2007)
GM (km^3/s^2)	120.5117 ± 0.0173	Jacobson et al. (2006)
Density (kg/m^3)	1083 ± 13	Thomas et al. (2007)

Note. Gravitational constant: $G = 6.672(59 \pm 84) \times 10^{-11}\ kg^{-1}\,m^3\,s^{-2}$.

Table 2
Iapetus' dynamical properties

Parameter (unit)	Value	Reference
Semi-major axis (km)	3.5613×10^6	Yoder (1995)
Semi-major axis (R_{Saturn})	59.09	Yoder (1995)
Orbital period (days)	79.330183	Yoder (1995)
Orbital rate (rad/s)	9.1670093×10^{-7}	Yoder (1995)
Rotation period (days)	Synchronous	Yoder (1995)
Rotation rate (rad/s)	9.1670093×10^{-7}	Yoder (1995)
Eccentricity	0.0283	Yoder (1995)
Inclination (degrees)	7.52	Yoder (1995)

Note. R_{Saturn}: Saturn's radius = 60,268 km (equatorial radius).

varying the starting conditions: differing amounts of radionuclides and a range of volatile content. In terms of structure, we find that porosity is very important and its evolution must be included in the models.

Section 4 discusses the results of the modeling. We find self-consistent models, which lead to Iapetus' present-day rotation and shape. All of these successful models require formation of Iapetus early and inclusion of significant amounts of short-lived radioactive isotopes (SLRI). The main difficulty in modeling Iapetus is a shortage of heat. Without including SLRI we were not able to find realistic models that despin and still have the correct shape. Since the amount of SLRI heat needed for a particular model maps directly to formation time, one obtains the time of accretion for that model.

The models do not explicitly tell us about the formation of the equatorial ridge. However, through the prediction of decreasing surface area on Iapetus during despinning to synchronous rotation they provide a possible rationale as to why the ridge formed. Tracking surface area versus time provides some times when the ridge may have been formed.

Section 5 is a discussion of the broader implications of the models. Included are modeling techniques, convection, ridge formation, comparison with other satellites, the origin of Iapetus, and absolute chronometry and its implications.

Iapetus is a very intriguing object. Due to its circumstances, it did not have enough heat to evolve as far as other satellites. In this sense, it only partially evolved. It is this state of "suspended animation" that provides a unique opportunity for geophysical investigations.

2. The data

Three features of Iapetus' current state provide critical constraints for our models, which in turn yield information about Iapetus' past. These features are described in the next three sections.

2.1. Spin and orbit

Today, Iapetus' rotation period is 79.33 days and synchronous with its orbital period. Despinning to reach synchronicity is a result of tidal dissipation, a process that has occurred for all the regular jovian and saturnian satellites (except chaotic Hyperion). However Peale (1986) noted that Iapetus' synchronous spin was unexpected, because of its large semi-major axis ($D = 3.51 \times 10^6$ km, i.e., $\sim 60\ R_s$) and the very strong (D^{-6}) dependence of the rate of despinning on distance to the planet.

Iapetus has a mean density of $1083 \pm 13\ kg/m^3$ (Thomas et al., 2007). This means that it has a radiogenic bearing rock mass fraction of ~20%, assuming the body is not porous. Iapetus' mean density indicates that it is most likely composed of water ice and chondritic carbonaceous chondritic material (from the kronian subnebula) with an enrichment in volatiles and, possibly, light hydrocarbons (Johnson and Lunine, 2005). Its composition and current orbital state are fully consistent with formation in its present place (Ward, 1981) as part of the saturnian system. (This will be discussed further in Section 5.)

Iapetus is "dynamically frozen" (to use a phrase from McKinnon, 2002). Its eccentricity is 0.0283, which suggests little dynamical evolution. Its orbital inclination is ~7.49 degrees and its Laplace plane is inclined 14.968 degrees with respect to Saturn's equator.

2.2. Shape

Cassini images show that Iapetus is an oblate spheroid with a difference between its equatorial, a, and polar radii, c, of 35.0 ± 3.7 km (Thomas et al., 2007) (see Fig. 1). The equatorial radii a and b are the same to within 2 km, i.e., less than the uncertainty in the measurements. The residuals to limb fits over the wide range of longitudes and latitudes available, have an rms of 4.0 km (0.54% of the mean radius), and show, as does inspection of the images, that this shape is indeed an ellipsoid with superposed craterform topography. A symmetric difference of 34 km with such small residuals could not form by random cratering by large impacts. Nor is modification of a triaxial equilibrium form possible for two reasons. First, the difference of observed and predicted intermediate axes is over 26 km, a value not allowed by the measurement uncertainty. Second, to maintain an $(a - c)$ of 34.5 km with its slow rotation and observed mean density, Iapetus would have to be largely hollow with a high density, thin shell, clearly not physically plausible. The predicted $a - c$ for a homogeneous Iapetus is only ~10 m for hydrostatic equilibrium for the current spin period, as illustrated in Fig. 1. Thus, Iapetus has the largest non-hydrostatic anomaly known for a satellite larger than 1000 km in radius, with the Moon being a distant second (Garrick-Bethell et al., 2006).

If Iapetus' interior is homogeneous, the observed figure is only plausibly explained as the shape for a body in hydrostatic equilibrium with a rotation period of $\sim 16 \pm 1$ h. A differentiated