Icarus 307 (2018) 197–206

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Modeling an exogenic origin for the equatorial ridge on Iapetus

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ARTICLE INFO

Article history:
Received 28 July 2017
Revised 2 January 2018
Accepted 10 January 2018
Available online 11 January 2018

Keywords:
Iapetus
Impact processes
Saturn
Satellites
Surfaces

ABSTRACT

Iapetus has a ridge along the equator that extends continuously for more than 110° in longitude. Parts of the ridge rise as much as 20 km above the surrounding terrains. Most models for the formation of this enigmatic ridge are endogenic, generally requiring the formation of a fast-spinning Iapetus with an oblate shape due to the rotation speed. Many of these require specific scenarios and have constraining parameters in order to generate a ridge comparable to what is seen today. An exogenic formation mechanism has also been proposed, that the ridge represents the remains of an early ring system around Iapetus that collapsed onto the surface. Thus far, none of the models have conclusively identified the origin of the ridge. In this study, an exogenic origin for the ridge is assumed, which is derived from a collapsing disk of debris around Iapetus, without invoking any specific model for the generation of the debris disk. Here, we evaluate whether it is possible to generate a ridge of the size and shape as observed by simulating the impact of the collapsing debris using the CTH hydrocode. Pi-scaling calculations suggest that extremely oblique impact angles (1°–10°) are needed to add to ridge topography. These extreme impact angles severely reduce the cratering efficiency compared to a vertical impact, adding material rather than eroding it during crater formation. Furthermore, material is likely to be excavated at low angles, enhancing downrange accumulation. Multiple impacts from debris pieces will heighten this effect. Because infalling debris is predicted to impact at extremely low angles, both of these effects might have contributed to ridge formation on Iapetus. The extreme grazing angles of the impacts modeled here decouple much of the projectile energy from the target, and impact heating of the surface is not significant. These models suggest that a collapsing disk of debris should have been able to build topography to create a ridge around Iapetus.

1. Introduction

A wealth of information has been acquired about the icy satellites of Saturn, primarily as a result of the Cassini mission. Iapetus, the third largest satellite of Saturn, in particular, displays unusual geologic features. The moon has relatively low bulk density (Table 1), suggesting the moon is made primarily of ice with a small rock component (~10% of the mass). Iapetus is in a synchronous rotation state; however its shape is consistent with a body in hydrostatic equilibrium with a 16-h rotation period (Thomas et al., 2007; Castillo-Rogez et al., 2007; Thomas, 2010), suggesting that it may have despun from an earlier and faster rotation rate (though hypotheses exist that the bulge may also be tectonic in origin (e.g., Sandwell and Schubert, 2010; Kay and Dombard, 2011)).

Cassini observations also revealed a ridge encircling most of the equator (Porco et al., 2005), which reaches heights up to 20 km (Giese et al., 2008). The height of the ridge makes it one of the tallest topographic features in the solar system (in proportion to the size of the body); the ridge height is nearly 3% of the radius of Iapetus. It is so tall that the topography is obvious in limb profile. This ridge extends for more than 110° in longitude, roughly 1400 km, though some portions of the ridge are broken into segments (Porco et al., 2005). Earlier observations by the Voyager spacecraft revealed mountains on the anti-Saturn side of Iapetus with as much as 25-km in relief, extending from 180°W–220°W (Denk et al., 2008) which may be a continuation of this ridge.

Existing geophysical models have not previously been able to explain the formation of such extensive topography, although numerous hypotheses have been proposed. Most models of ridge formation are endogenic and related to despinning or contraction of Iapetus (Porco et al., 2005; Castillo-Rogez et al., 2007; Dombard and Cheng, 2008; Robuchon et al., 2010; Beuthe, 2010; Singer and McKinnon, 2011). In general, these models begin with a young, fast-spinning Iapetus whose rapid spin-rate led to an oblate shape for the body. If Iapetus cooled rapidly enough, this shape would

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https://doi.org/10.1016/j.icarus.2018.01.017

Table 1
Basic properties of Iapetus.

Property	Value	Units	Reference
Radius	735	km	
Bulk density	1083	kg/m^3	Jacobsen et al. (2006), Thomas et al. (2007)
Orbit distance	3.56×10^6	km	Murray and Dermott, (1999)
Orbit period	79	days	Murray and Dermott, (1999)

freeze, leaving behind an oblate body as seen today. Further processes then generated the ridge.

The majority of investigations have explored a tectonic origin for the ridge, all of which have found it challenging to generate the stresses necessary to form the ridge topography. Castillo-Rogez et al. (2007) have proposed that the ridge is the surface expression of a giant equatorial thrust fault created as the satellite despun and contracted. Although compressional surface features due to despinning are predicted at the equator for a sufficiently thick lithosphere (strike-slip faults are predicted for a thin lithosphere), the maximum compressive stress of a despun planet is along the equator. Thus, a series of north–south ridges would be predicted, and not the observed east–west ridge (Melosh, 1977; Roberts and Nimmo, 2009). Furthermore, while the compressive stresses are highest at the equator in this scenario, they will not necessarily exceed the extensional north–south stresses. Thus, despinning may promote meridional extension rather than azimuthal compression, resulting in east-west normal faults.

Czechowski and Leliwa-Kopystyński (2008) modeled convection in the ice shell of Iapetus and suggested that the ridge may have initially formed as dynamic topography reflecting the convective pattern in the interior. As Iapetus cooled, this ridge topography could have been frozen in. However, the mechanism for producing the initial equatorial upwelling pattern was not discussed. Roberts and Nimmo (2009) found that the variation in surface temperature with latitude (arising from latitude-dependent insolation) is a substantial fraction of the temperature difference across the ice shell and thus should have a significant effect on mantle dynamics. The equatorial ice is warmer than the surroundings and therefore buoyant, promoting equatorial upwellings. Such upwellings can form dynamic topography at the surface, but the modeled rise is broader and the uplift is much less than the height of the observed ridge.

Beuthe (2010) and Sandwell and Schubert (2010) investigated elastic buckling of the lithosphere of Iapetus. Beuthe (2010) found that compression of a lithosphere with variable thickness (e.g., having been locally thinned by equatorial convective upwellings (Roberts and Nimmo, 2009) results in narrow uplift resembling the observed ridge. However, formation of such a ridge by purely elastic buckling requires meridional stresses exceeding the yield strength of the ice. Sandwell and Schubert (2010) found that appropriate stresses might arise as a result of global contraction due to heating in the interior, resulting in the reduction of initial porosity. However, this model requires an additional mechanism to focus deformation along the equator. In general, the endogenic models require specific circumstances and constrained early conditions for Iapetus to account for the ridge formation.

Other studies propose an *exogenic* formation hypothesis (Ip, 2006; Levison et al., 2011; Dombard et al., 2012). The location of the ridge points to an equatorial distribution of the source material, and this suggests a circumsatellite ring system. Levison et al. (2011) proposed that an impact-generated satellite and debris disk may a plausible source for the ring material. In this scenario, ejecta from an impact on Iapetus forms a disk of debris in orbit. A “sub-satellite” of Iapetus forms outside the Roche limit, and a ring system forms inside. Tidal interactions between ring and satellite result in inward migration of the ring material, and outward migration of the satellite, where it is eventually stripped from Iapetus orbit by Saturn’s gravity. This satellite may eventually re-impact on Iapetus and may result in more rapid despinning regardless of the interior structure of Iapetus (Levison et al., 2011). Dombard et al. (2012) suggested that ridge formation is delayed due to the material being sequestered in a subsatellite until it is tidally disrupted. Such a delay may allow the ridge to form on thick, stiff lithosphere, which is will not flex (Dombard et al., 2012) and will be more easily able to support the load. This model requires that the ridge formed late (more than ~1 Gy after CAIs). Whether the ridge formed early (Ip, 2006; Levison et al., 2011) or late (Dombard et al., 2012), the infalling source material must accumulate, forming positive topography, rather than forming craters, which would destroy existing topography.

Any hypothesis for the ridge formation on Iapetus must be able to explain several observations: (1) the location of the ridge at the equator; (2) the horizontal extent and topographic relief of the ridge; (3) that similar features are not found on other solar system objects, and any successful model must be consistent with the synchronous rotation state of Iapetus. Models can be checked individually by comparing against observations. Positively identifying products on Iapetus that could result from different hypotheses, however, is challenging and it is difficult to uniquely identify *which* of the various hypotheses caused the ridge. New, high-resolution observations of the surface may be able to identify impact signatures to support an exogenic origin, but the limited observations available now cannot rule out either the endogenic or exogenic cases.

The location of the ridge suggests an equatorial distribution of the source material, possibly sourced from a circum-satellite ring system. Here, we assume an exogenic origin for the ridge, derived from a disk of debris around Iapetus (e.g., Levison et al., 2011), without invoking any specific model for the generation of the debris disk. We use hydrocode simulations to examine crater formation and topography generation by infalling debris. We evaluate whether it is possible to generate a ridge of the size and shape as observed on Iapetus today.

2. Methods

2.1. Size distribution of ejecta

Estimates for the ridge mass fall between 5×10^{17} and 5×10^{18} kg (Ip 2006; Levison et al., 2011), which is ~0.1% that of Iapetus. This mass is consistent with the excavation of a 150–350 km diameter crater on the surface of Iapetus, which could produce fragments up to ~1.5 km across (Vickery, 1986). Scaling rules can then be used to determine the appropriate ejecta size that would make up the debris disk around Iapetus. We assume a power law size frequency distribution: $N(\mathit{mass}) = k^{*}\mathit{mass}^{b}$, where N is the number of particles, *mass* is the particle mass, and b is typically −0.8 (e.g., Gault et al., 1963). Assuming the debris is made up of ice with a maximum particle size of ~1.5 km gives $k_{\mathrm{ice}} = 6.27 \times 10^9$ kg$^{-0.8}$. Fig. 1 shows the resulting predicted distribution of debris sizes. This was used to focus this study and examine the effects of impactors across the range from 1 m to 1 km in diameter.