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The fluffy core of Enceladus

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ABSTRACT

Enceladus is well known for its young south polar terrain, observed by Cassini to emit several GW of heat as well as plumes of vapor and ice. The source of this energy is believed to be tidal dissipation. However, the observed south polar heat flux cannot be sustained over the age of the Solar System. Furthermore, thermal evolution models suggest that any global subsurface ocean should freeze on a timescale of tens to hundreds of My, sharply reducing future tidal heating, unless large amounts of antifreeze are present in the ocean. Here I propose an alternative internal structure for Enceladus, in which the silicate core is fragmented, and that the tidal deformation of the core may be partially controlled by interstitial ice. I find that fragmentation of the core increases tidal dissipation by a factor of 20, consistent with the long-term dynamically sustainable level, even when the interior is completely frozen, but only if the interior starts out warm and tidal heating is strong from the beginning. If this is not the case, radioactive heating will be insufficient to prevent the interior from cooling. Although an ocean need not be present in order for the interior to experience significant tidal heating, all models that dissipate enough heat to prevent runaway cooling are also warm enough to have an ocean. Tidal dissipation in the weak core provides an additional source of heat that may prevent a global subsurface ocean from freezing.

1. Introduction

Saturn's icy Moon Enceladus is perhaps best known for its south polar terrain (Porco et al., 2006; Spencer et al., 2006). This region is extremely young, and is scored by four large fractures, named the "tiger-stripes". These lineations emit plumes of ice and vapor (Porco et al., 2006), along with a high heat flux. The Cassini Infrared Spectrometer (CIRS) has observed between 5 and 15 GW from the south polar terrain (Spencer et al., 2006; Abramov and Spencer, 2009; Howett et al., 2011, 2013). The source of this energy is believed to be tidal dissipation resulting from the eccentric orbit of Enceladus about Saturn.

Enceladus has a mean radius, $R_0 = 252$ km, and a bulk density of $\rho_0 = 1.61$ g cm^{-3} (Jacobson et al., 2006; Thomas et al., 2007) suggesting a silicate fraction of at least 50%. Observations of the shape of Enceladus and models of long-lived radioactive heating suggest that the interior is most likely differentiated (Schubert et al., 2007), although the size and density of the core are not well known. Gravity measurements from recent Cassini flybys (Iess et al., 2014) give a moment of inertia of 0.335 MR^2, which further supports a differentiated interior. The gravity field also suggests a mild deviation from hydrostatic shape (Iess et al., 2014). Although the gravity field provides some constraints, the determination of the interior structure is not unique, and the rheology of the interior is not well constrained. Classically, the interior of Enceladus is composed of a monolithic silicate core (possibly with some metal fraction), overlain by a water–ice shell 60–110 km thick (Schubert et al., 2007) (Fig. 1a). Depending on the internal temperature, the base of the ice shell may be molten, and a subsurface ocean may mechanically decouple the silicate core from the ice shell (Fig. 1b).

1.1. Maintaining a subsurface ocean

There are several reasons why a liquid water layer is suspected to exist beneath the ice shell. The high heat flux (Spencer et al., 2006; Howett et al., 2013) and plume activity in the south polar region indicate a reservoir of heat in the subsurface, and models of the plume composition (e.g., Postberg et al., 2011) require a liquid reservoir as a source of sodium and other volatiles. Mechanically, a liquid layer would also decouple the ice shell from the silicate core below. A decoupled ice shell is more easily deformed by tidal forces than if it were locked onto a more rigid core, resulting in a far greater amount of dissipated heat (Roberts and Nimmo, 2008; Tobie et al., 2008; Behounková et al., 2010) more consistent with the observed heat flux.

However, heat is lost from the interior faster than it can be produced by tidal dissipation in the ice shell (Roberts and Nimmo, 2008). Although heat loss is considerably slower if the ice shell is

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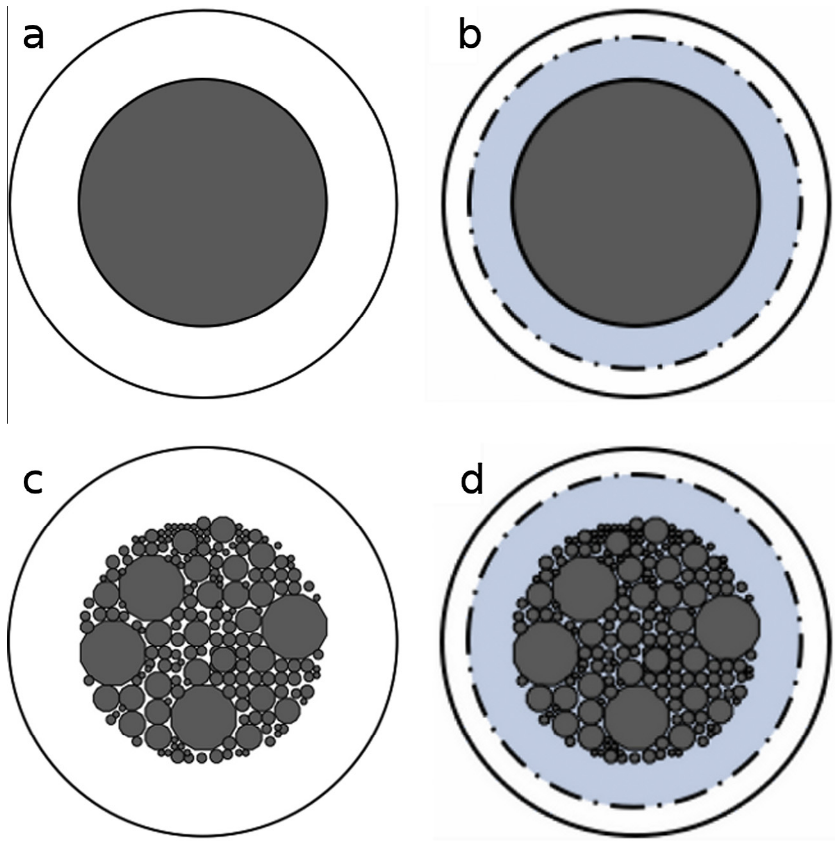

Fig. 1. Model interiors of Enceladus. a, Monolithic, rocky core overlain by an ice shell. b, a liquid subsurface ocean may exist beneath the ice shell. c, an unconsolidated "rubble–pile", rocky core overlain by an ice shell. Pore space in the core is filled with ice. d, rubble–pile core with pore space filled by water. Core fragments are not necessarily regular as seen here.

not convecting, this conclusion holds even for a purely conductive shell. A pure water ocean freezes on a timescale of tens of My. If this were to happen, the ice shell would become mechanically coupled to the much more rigid silicate core (although an organic-rich brine at the base of the ice shell expelled as the ocean froze could provide some lubrication (Zolotov, 2007; Zolotov et al., 2011)). A rigid core would severely restrict movement of the ice shell, sharply reducing dissipation in the ice as well, and inhibiting subsequent melting.

Other heat sources, such as radioactive decay and tidal dissipation in a solid silicate core are much smaller than dissipation in the ice and do not significantly contribute to the energy budget (Roberts and Nimmo, 2008). Obliquity tides have been suggested as an additional energy source in icy satellites (Tyler, 2009, 2011), but this mechanism is unlikely to work on Enceladus, as the obliquity is near zero (Chen and Nimmo, 2011; Matsuyama, 2014).

A number of mechanisms have been proposed to inhibit the freezing of the ocean and to explain the ongoing activity. One is that the liquid is not globally distributed, but is concentrated in a sea near the south pole (Collins and Goodman, 2007). In such a case, only enough heat must be dissipated in the ice shell to keep a pocket of water molten, rather than a global layer. Such a sea is consistent with (but not required by) gravity measurements (Iess et al., 2014). Although this avoids the thermal problems of sustaining a global ocean (Roberts and Nimmo, 2008; Tobie et al., 2008), it places restrictions on the size of the polar sea (Tobie et al., 2008; Behounková et al., 2010). The sea must be large enough (extending >60° from the pole) that the ice above it is free to flex and dissipate energy. However, if the sea is too large, the tidal heat must be distributed over a broad area and the solution approximates the global ocean scenario.

A second mechanism to inhibit freezing of the ocean is to consider compositions other than pure water (McKinnon and Barr, 2008, 2013). Salts, hydrocarbons, and ammonia have been detected in the plumes (Postberg et al., 2009, 2011; Waite et al., 2009), and thus are thought to be present in some concentration in a subsurface ocean. These compounds all serve to depress the melting point of the liquid solution. Ammonia is a particularly effective antifreeze agent; a eutectic NH_3–H_2O composition (32 wt% NH_3) freezes at −100 °C (Haynes et al., 2014). Although the composition of any actual subsurface ocean is not known, it cannot contain this much ammonia. As the concentration of NH_3 in the ocean increases, the density drops. At concentrations above ∼15 wt% NH_3, ice I is not buoyant (Haynes et al., 2014). In this scenario, the overlying ice shell would founder and sink, exposing the ocean to space. The entire ocean would eventually freeze. The maximum physically realistic concentration of NH_3 in the ocean of Enceladus is ∼15%, corresponding to a freezing point of no lower than −30 °C.

1.2. Softening the core

Here I describe a third mechanism for enabling tidal dissipation in the interior of Enceladus in the absence of an ocean. The main function of the ocean in the above scenarios is to mechanically decouple the ice shell from the core, allowing the less rigid ice layer to deform. This decoupling would be less critical if the core were not so rigid. Classically (e.g., Schubert et al., 2007) the core of Enceladus (and of icy satellites in general) has been considered to be a solid layer of silicate rock, perhaps with an iron inner core; analogous to the structure of terrestrial planets. Silicate rock has a shear modulus of order 100 GPa, and a viscosity in excess of 10^{20} Pa s; much stiffer than the ice layer. This corresponds to a