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ASTROBIOLOGY

Modelling the Interior Structure of Enceladus Based on the 2014's Cassini Gravity Data

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Abstract We present a model for the internal structure of Saturn's moon Enceladus. This model allows us to estimate the physical conditions at the bottom of the satellite's potential subsurface water reservoir and to determine the radial distribution of pressure and gravity. This leads to a better understanding of the physical and chemical conditions at the water/rock boundary. This boundary is the most promising area on icy moons for astrobiological studies as it could serve as a potential habitat for extraterrestrial life similar to terrestrial microbes that inhabit rocky mounds on Earth's sea floors.

Keywords Enceladus · Icy moons · Internal structure · Subsurface water reservoir

Introduction

From the astrobiological point of view, icy moons are among the most interesting objects in the Solar System. Some of these moons could have subsurface oceans which may host extraterrestrial life. In this study we present a model for the interior structure of the icy moon Enceladus and discuss its potential habitability. Enceladus provides a unique insight into its interior through its active plumes which may originate in a potential subsurface

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sea (Postberg et al. 2009). The small mean radius of only 252.1 km (Thomas 2010) (for further parameters, see Table 1) indicates that the uncompressed density (see, e.g., Faure and Mensing 2007) of the satellite is almost equal to its bulk density, so a simplified model of Enceladus' interior is reasonable.

Previous studies of Enceladus' interior (e.g., Barr and McKinnon 2007; Hussmann et al. 2006; McKinnon 2015; Roberts 2015; Schubert et al. 2007) assumed a two-layer structure with a rocky core (core density ρ_c between 2500 and 3527.5 kg m^{-3}) and an icy outer shell (shell density $\rho_s \approx 1000$ kg m^{-3}). These estimations led to an ice shell thickness of approximately 100 km and a moment of inertia factor (MoI) of around 0.31. On the other hand, Rappaport et al. assumed a hydrated silicate core with $\rho_c \approx 2500$ kg m^{-3} which results in an ice shell thickness of just 60 km (Rappaport et al. 2007). According to the latest gravity measurements performed by the NASA spacecraft Cassini, Enceladus has a high MoI of 0.335 (Iess et al. 2014), which leads to the conclusion that this satellite is not in a fully relaxed shape, but is differentiated with a low-density core.

Model

2-Layer-Model

The MoI of Enceladus can be estimated using the Radau-Darwin approximation (see, e.g., Schubert et al. 2004):

$$MoI = \frac{C}{MR^2} = \frac{2}{3} \cdot \left\{ 1 - \frac{2}{5}\sqrt{\frac{4-k_2}{1+k_2}} \right\}, \tag{1}$$

where $k_2 = \frac{4C_{22}GM}{\omega^2 R^3} = 0.9896 \pm 0.0103$ is the fluid potential Love number. Therefore, Enceladus has a MoI of 0.3386 ± 0.0826. This is in agreement with the study by Iess et al. where the moment of inertia factor was estimated to be around 0.335 (Iess et al. 2014). Because this value is less than 0.4, it also falls under the maximum MoI for a differentiated body (de Pater and Lissauer 2010).

Enceladus' mean radius R, its mean density $\bar{\rho}$, and the calculated MoI serve as the starting points for our model. Because of the low mass of Enceladus and the resulting low radial pressure values, the density can be assumed to be constant within a certain layer. To

Table 1 Enceladus' main parameters

$R^a = 252.1 \pm 0.2$ km, (Thomas 2010)	$\bar{\rho}^b = 1\,609.79 \pm 2.99$ kg m^{-3}, (Taubner 2012)
$M^c = 1.079888 \pm 0.001653 \cdot 10^{20}$ kg, (Taubner 2012)	${C_{22}}^d = 1.5498 \pm 0.0156 \cdot 10^{-3}$, (Iess et al. 2014)
$T^e = 1.37$ days, (Jacobson 2010)	$\omega^f = \frac{2\pi}{T} = 5.30818 \cdot 10^{-5}$ s^{-1}

[a] mean radius

[b] mean density

[c] mass

[d] degree-2 gravity coefficient

[e] mean sidereal period

[f] rotation rate

Table 2 Different cases for Enceladus' interior structure (2-Layer-Model)

Case	ρ_s[a] [kg m^{-3}]	R$_c$[b] [km]	d$_{ice}$[c] [km]	ρ_c[d] [kg m^{-3}]
C_{min}	917	198.8	53.3	2327.1
C_{mean}	1000	190.4	61.7	2412.7
C_{max}	1080	179.3	76.3	2550.8

[a] mean shell density

[b] core radius

[c] thickness of the ice shell

[d] mean core density

calculate the core mean density ρ_c and core radius R_c, we use a 2-layer-model (see, e.g., Hussmann et al. 2006):

$$\rho_c = \left(\frac{(\bar{\rho} - \rho_s)^{5/3})}{\frac{5}{2}\bar{\rho} \cdot MoI - \rho_s} \right)^{3/2} + \rho_s \ , \tag{2}$$

$$R_c = R \cdot \sqrt[3]{\frac{\bar{\rho} - \rho_s}{\rho_c - \rho_s}} \ . \tag{3}$$

We varied the composition, and therefore the density ρ_s of the overlying water/ice shell between 917 kg m^{-3} (pure ice I) and 1 080 kg m^{-3} (water with some other constituents such as NH$_3$ and tholins (Hendrix et al. 2010)). To illustrate our results we selected three different cases (C_{min}, C_{mean}, and C_{max}; see Table 2).

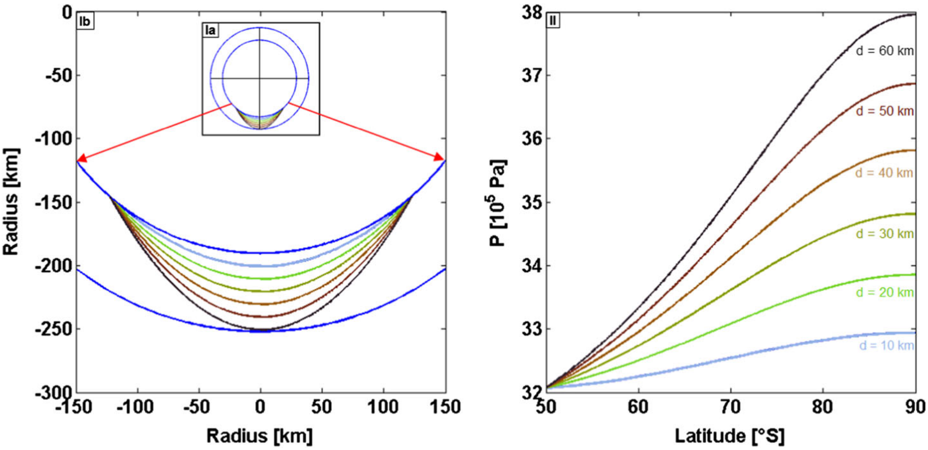

Fig. 1 Ia: Position of the local southern subsurface sea; Ib: magnified representation of the relevant area in Ia; the *coloured lines* give different potential depths of the local sea; II: pressure at the core/mantle-boundary for case C_{mean} for various water depths between 10 and 60 km

Table 3 Pressure at the water-rock boundary for different water depths for the three cases C_{min}, C_{mean}, and C_{max}

Case	p_{min}[a] [10^5Pa]	p_{max}[b] [10^5Pa]
C_{min}	28	33
C_{mean}	32	38
C_{max}	38	45

[a] minimum pressure

[b] maximum pressure

Local Southern Subsurface Sea

According to previous studies, either a local subsurface water reservoir beneath the South Polar Terrain (SPT) of Enceladus (e.g., Iess et al. 2014) or a global ocean with a thinned out ice shell at the southern region (Thomas et al. 2015) seems likely. Therefore, the second aim of our model is to estimate the pressure at the water/rock-boundary of this potential aquifer beneath Encealdus' southern region. We assume the sea or the depletion, respectively, to have the shape of a rotational paraboloid. For each of the cases C_{min}, C_{mean}, and C_{max} (Table 2) we calculated the pressure at the water/rock boundary depending on the longitude and the maximum depth of the subsurface aquifer. As seen in Fig. 1 for C_{mean} and in Table 3 for all three cases, the pressure value at the sea floor of the potential subsurface water reservoir lies between 28 and 45 bar.

Radial Pressure Gradient

We also calculated the radial distributions of pressure ($dp = \rho \cdot g(r)dr$) and gravitational acceleration ($g(r) = \frac{GM(r)}{r^2}$) for case C_{mean} with a subsurface water aquifer 10 km thick (see Fig. 2). Under these assumptions we obtained a pressure at the core/water-boundary of $32.9 \cdot 10^5$Pa and a gravitational acceleration of $0.128\ \mathrm{ms}^{-2}$.

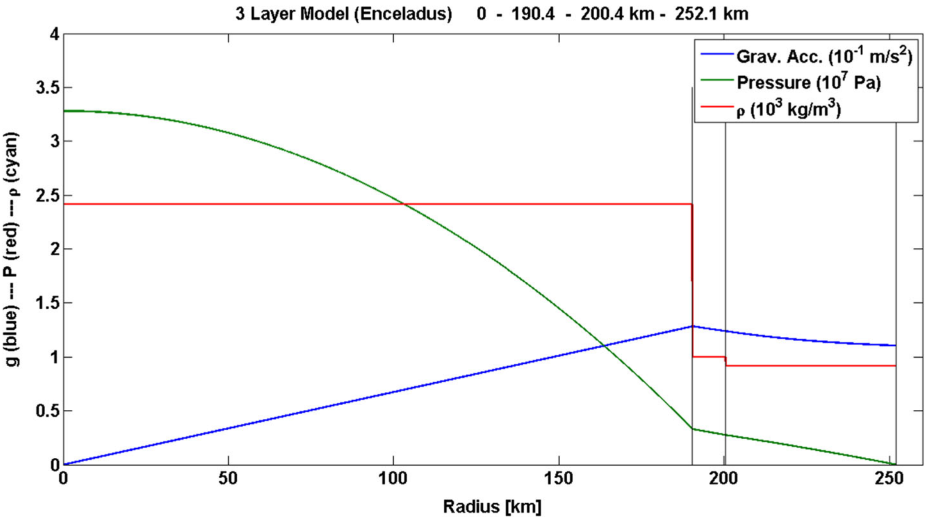

Fig. 2 Physical parameters for case C_{mean} and a 10 km thick water layer. Estimations were made for the radial gradient from the moon's core to its south pole

To validate this model we applied it to the different layers of Earth. Gravitational acceleration as well as the pressure gradient in the outer layers obtained by our model agree well with the Preliminary Reference Earth Model (PREM, Dziewonski and Anderson 1981), but the pressure values for Earth's inner core are too small. This deviation is due to the exclusion of compression or phase transition effects from our model, as these effects are negligible for small bodies like Enceladus where the uncompressed density is equal to the bulk density.

Conclusion

The most promising area on Enceladus where life may exist is at the sea floor of the potential subsurface water reservoir. Geochemical low-temperature interactions between these layers seem reasonable (see, e.g., Zolotov 2007). One of these processes may be serpentinization of ultramafic rocks which is accompanied by the production of H_2 (Schrenk et al. 2013). Furthermore, in such an environment dissolution of minerals could provide nutrients for possible lifeforms.

The organisms would have to be able to live without photosynthesis or its by-products such as oxygen. According to McKay et al., there are three known terrestrial microbial ecosystems that would fit into such a habitat (McKay et al. 2008): two are based on methanogens and the third is built on sulphur-reducing bacteria. However, the existence of sulphur-reducing bacteria is questionable because oxidized sulphur may not exist on Enceladus, which limits/excludes the process of sulphur (sulphate) reduction.

In further experimental studies, we will investigate the habitability of the subsurface water aquifer. In accordance with our model, microorganisms would have to resist a pressure of approximately 28 to 45 bar (equivalent to 2.8 to 4.5 MPa, see Table 3), which is roughly equivalent to the pressure at a depth of 290 to 460 m below sea level on Earth. Microorganisms tolerant to such pressures (and higher) are well known on Earth, e.g., the barotolerant bacteria *S. hanedai* IAM12641 (optimal growth at 0.1 MPa, (MacDonell and Colwell 1985)) or even obligate barophilic microbes such as *M. yayanosii* DB21MT-5 which was isolated from the Mariana Trench and for which no growth was detected at pressures of less than 50 MPa (Kato et al. 1998). Even multicellular organisms like deep-sea fish and worms can easily resist the pressure at this depth in the terrestrial seas, e.g., the hadal snailfish *Pseudoliparis amblystomopsis* which was even found at a depth of 8145 m in the Mariana Trench (Morelle 2014).

To conclude, pressure should not be a limiting parameter for life in Enceladus' subsurface sea.

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