Icarus 250 (2015) 32–42

Contents lists available at ScienceDirect

Icarus

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

Keeping Enceladus warm

B.J. Travis [a,b,*], G. Schubert [c]

[a] Computational Earth Sciences Group, EES-16/MS-T003, Los Alamos National Laboratory, Los Alamos, NM 87545, United States
[b] Planetary Science Institute, Tucson, AZ 85719, United States
[c] Earth, Planetary and Space Sciences Dept., University of California, Los Angeles, CA 90095, United States

ARTICLE INFO

Article history:
Received 25 February 2014
Revised 9 November 2014
Accepted 16 November 2014
Available online 22 November 2014

Keyword:
Enceladus
Interiors
Thermal histories

ABSTRACT

Despite its small size, Enceladus emits considerable heat, especially at its south pole, even long after simple thermal models predict it should be frozen. Several sources of energy have been proposed as responsible for this heating, such as tidal dissipative heating (TDH), convection and shearing in the ice shell, and exothermic chemical reactions (e.g., serpentine formation). Crater relaxation simulations suggest that episodic heating events have occurred over long stretches of Enceladus' history. Thermal history and hydrothermal simulations reported here show that a combination of steady plus episodic TDH heating could maintain at least a polar ocean to the present time. Hydrothermal circulation can play a significant role in mining Enceladus' internal heat, facilitating the persistence of an ocean even to the present by focusing internal heat to the polar regions.

1. Introduction

1.1. Anomalous energy output

Despite its small size, Enceladus emits considerable heat at its south pole, even long after simple thermal models predict that Enceladus should be frozen. The latest estimates of energy release range from 4.7 GW to 15.8 GW, depending on wavelength (Spencer et al., 2013; Howett et al., 2013). Why energy outflow is primarily at the south pole is still debated. A number of energy sources in addition to radiogenic heating have been proposed to keep Enceladus warm, including exothermic chemical reactions (e.g., serpentine formation), convection and shearing in the ice shell, and enhanced tidal dissipative heating (TDH) in the ice shell. Relevant chemical reactions require liquid water. Similarly, TDH requires the presence of a liquid layer to decouple the ice shell from the core.

Results of a numerical study are presented here that explore the relative importance of these heating mechanisms. Model simulations reveal the amount of each that is required to maintain an ocean, when acting alone, as well as in concert. A brief review of the state of knowledge regarding the possibility of liquid water in Enceladus and the various heating mechanisms sets the stage for the numerical modeling. Fig. 1 is a schematic indicating the supposed structure of Enceladus and the physical mechanisms included in our numerical modeling. Then, results of the numerical simulations are discussed and compared to a recent interpretation of observations to see which of the models could be considered realistic.

1.2. Evidence for a present-day ocean

The low density of Enceladus (~1608 kg/m^3) suggests that a considerable fraction of Enceladus' mass consists of H_2O. In a differentiated model of Enceladus (Schubert et al., 2007), the H_2O layer is on the order of 90 km thick. The ice shell that covers Enceladus may not extend down to the rocky core. There are several indicators of liquid water in Enceladus' interior. For example, Waite et al. (2009) find evidence for ammonia in Enceladus' south pole plume at about 0.8% concentration. They conclude that a liquid water reservoir exists below the ice shell. Postberg et al. (2011) find salt-rich ice particles in the plume base. They conclude that the plume must originate in a sub-ice shell body of salt water, probably containing NaCl, $NaHCO_3$, or Na_2CO_3 at 0.5–2% by mass. Chemical modeling by Zolotov (2007) finds that an ocean on Enceladus would likely contain Na salts such as $NaHCO_3$ as one of the predominant solutes. The ocean salts mixture could have a eutectic temperature as low as −35 °C, but the temperature of the present ocean may not be that cold. Sekine et al. (2013) report on experiments and geochemical simulations that imply that hydrothermal circulation in Enceladus' rocky core is consistent with the presence of silica nanoparticles (Postberg et al., 2013) in

---

* Corresponding author.
E-mail addresses: bjtravis@lanl.gov (B.J. Travis), schubert@ucla.edu (G. Schubert).

http://dx.doi.org/10.1016/j.icarus.2014.11.017
0019-1035/Published by Elsevier Inc.

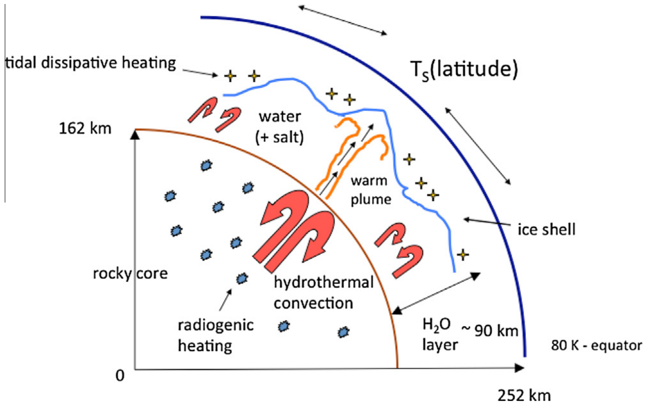

Fig. 1. Schematic showing the different regions and processes in the model.

Table 1
Radioactive elements in the model simulation at CAI formation.

Value	Element					
	^{26}Al	^{235}U	^{238}U	^{232}Th	^{40}K	^{60}Fe
Half-life, Myrs	0.72	4470	710	13,860	1265	1.5
Energy of decay, 10^{13} J/kg	1.11	1.91	1.82	1.68	0.166	0.516
Abundance, bulk mass fraction × 10^{-8}	50	2.64	0.86	5.21	66.0	0.4

Table 2
Model parameters.

Model geometry	2-D spherical (radius and latitude)
Radius, km	252
Silicate core radius, km	162
Silicate rock density, kg/m^3	3000
Thermal conductivity of rock, W/m/K	3.0
Specific heat of rock, J/kg/K	1000
Gravity, m/s^2, function of radius	0.113 (at surface)
Permeability range, darcy	0.10–1.0
Porosity of rocky core	0.10
For cases with salt:	
Initial salt concentration in mantle/core, pores and ocean, kg-salt/kg-water	0.020

Enceladus' southern polar plumes and that the rocky core interior temperature must be (or have been) at least 100–130 °C. Recently, Iess et al. (2014) concluded that an ocean extending from the south pole to about 50°S latitude below an ice shell of about 30–40 km thickness best matches interpretation of Doppler gravity data from the Cassini spacecraft. A wider latitudinal extent cannot be ruled out however. There are several mechanisms that could contribute to maintaining an ocean layer below the ice shell.

1.3. Radiogenic heating

Radiogenic heating from ^{26}Al and ^{60}Fe could warm Enceladus initially to hundreds of °C, depending on when that moon formed (Schubert et al., 2007). Even with an early formation time assumption, though, much of the energy in the core would be depleted in less than 1 Gyr, due to conduction and heat loss at the surface. An insulating layer of dust and/or snow on the surface could slow the rate of heat loss (Spencer and Nimmo, 2013), and latent heat of freezing is another large reservoir of energy that would buffer cooling, but these, along with long-term radiogenic heating, by themselves could not maintain temperatures above freezing for more than about 1.5 Gyr. Fig. 2 shows peak temperature in the core as a function of time assuming the initial abundances of radioactive elements given in Table 1. Radiogenic heating will continue to the present time, gradually decreasing. An estimate of present day core radiogenic heating is about 0.3 GW. Obviously, additional energy is needed if an ocean is present beneath the ice shell today.

1.4. Exothermic chemical reactions

Energy from exothermic reactions is another possible source of heating for Enceladus. Malamud and Prialnik (2013) (M&P) focus on serpentinization of forsterite (Mg_2SiO_4) and enstatite ($MgSiO_3$) coupled with 1-D flow in the core. Serpentinization is an exothermic reaction that releases per mole about 11 times the energy needed to melt one mole of ice. Serpentinization proceeds in the M&P model when temperature exceeds the melting point of ice, but the reaction rate is temperature dependent. The reaction proceeds relatively quickly once ice melts. M&P assume that all the rock can be involved in serpentinization, but not all of the rock will be converted, because of lack of water locally or temperature too cold locally. The core is entirely serpentinized. Serpentinization soaks up about 25% of the water through hydration, and releases heat equaling a temperature rise of about 100 °C or so. In their model, peak temperatures do not reach very high (about 150 °C), due to the late formation time they assumed for Enceladus; however, their choice of a late formation time allows the thermal impact of serpentinization to be isolated and accentuated.

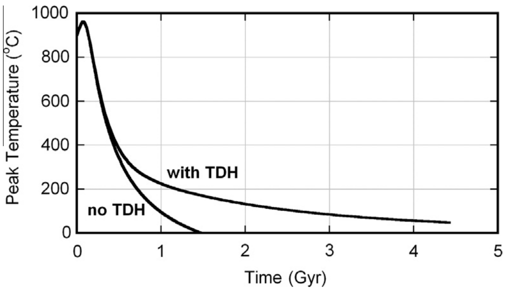

Fig. 2. Peak temperature in the core vs. time with and without TDH, from long-term simulations.

Several other models of early heating in planetesimals the size of Enceladus, or even much smaller, reach much higher peak temperatures. Peak temperature affects chemistry and mineral evolution, and can influence, at least indirectly, present day temperature. Sahijpal et al. (2007) find a peak of about 1100 K in their CM4 planetesimal model. Moskovitz and Gaidos (2011) suggest that accretion could have happened quickly; their model also reaches high core temperatures. Schubert et al. (2007) present a model of differentiation in Enceladus' early history that generates a peak temperature of over 1200 K. Time of formation is a major factor in determining peak temperature in these models but it is an uncertain quantity, with estimates ranging from less than 1 Myr to 3 Myr or more after CAI formation. Further, there are some differences between the models in terms of water/ice content and how the radiogenic elements are distributed internally. Almost all the models have relatively high early peak temperature. In M&P's case, the formation time is significantly later than in the other models, and the peak temperature is accordingly much lower. In our modeling, we assume a formation time of 1.5 Myr after CAI formation. Additional support for a warm interior comes from analysis of plume composition. Matson et al. (2007) infer, based on the presence of N_2, CO_2, CH_4, and several hydrocarbons in the southern plume, that temperatures in the interior of Enceladus could be, or at some time in the past could have been, hot (500–800 K, or even hotter), with an aqueous environment present for catalytic chemistry to occur.

Peak temperature is important for the serpentinization model of Malamud and Prialnik (2013) because serpentine will dehydrate