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Some remarks on the early evolution of Enceladus

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ABSTRACT

Thermal history of Enceladus is investigated from the beginning of accretion to formation of its core (~400 My). We consider model with solid state convection (in a solid layer) as well as liquid state convection (in molten parts of the satellite). The numerical model of convection uses full conservative finite difference method. The roles of two modes of convection are considered using the parameterized theory of convection. The following heat sources are included: short lived and long lived radioactive isotopes, accretion, serpentinization, and phase changes. Heat transfer processes are: conduction, solid state convection, and liquid state convection. It is found that core formation was completed only when liquid state convection had slowed down. Eventually, the porous core with pores filled with water was formed. Recent data concerning gravity field of Enceladus confirm low density of the core. We investigated also thermal history for different values of the following parameters: time of beginning of accretion t_{ini}, duration of accretion t_{acr}, viscosity of ice close to the melting point η_{m}, activation energy in formula for viscosity E, thermal conductivity of silicate component k_{sil}, ammonia content X_{NH3}, and energy of serpentinization c_{serp}. All these parameters are important for evolution, but not dramatic differences are found for realistic values. Moreover, the hypothesis of proto-Enceladus (stating that initially Enceladus was substantially larger) is considered and thermal history of such body is calculated. The last subject is the Mimas-Enceladus paradox. Comparison of thermal models of Mimas and Enceladus indicates that period favorable for 'excited path of evolution' was significantly shorter for Mimas than for Enceladus.

1. Introduction

Enceladus is a medium-sized satellite (MIS) of Saturn. It is the second smallest satellite of this group (the group consists of 6 satellites). All of them are ellipsoidal bodies and their radii range from 198 km (Mimas) to 764 km (Rhea). They consist of mixture of rocks and ices. The rocky component is believed to be of chondritic composition. The main component of ices is frozen H_2O but some admixture of ammonia and other volatiles is expected (e.g. Peale 2003).

Enceladus belongs to the group of 5 MIS that orbit between the A-ring and Titan. Iapetus, the 6-th MIS of Saturn, is probably of different origin and is not considered here (see e.g. Czechowski 2006, 2009).

The process of formation makes 'initial conditions' for early evolution of a given celestial body (e.g. Coradini et al. 2010). Below we list some problems found in models of MIS formation according to Charnoz et al. (2011) (citations from Charnoz et al. (2011) are in quotation marks):

a) The total averaged density of MIS "is at least 25% less than Titan's uncompressed density […]. This suggests that the material accreted into these objects was depleted in rocks, but the mechanism responsible for that situation remains to be found". The high albedo of MIS also imply "that silicates have been efficiently and systematically removed from their surfaces […]".
b) Probably some "[…] icy satellites were hit by a population of planetocentric impactors […] in addition to, or even instead of, a heliocentric one."
c) "The most puzzling properties of these satellites is perhaps their varying silicate fractions […] 26%, 57%, 6%, 50% and 33% for Mimas, Enceladus, Tethys, Dione and Rhea, respectively".
d) The fact that mass of MIS is an increasing function of distance from the planet "can be interpreted as the signature of tidal forces driving the outward migration of the satellites". According to Charnoz et al. (2011) there are indications that the dissipation factor of Saturn Ψ_p is lower than the 'traditional

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value'. Lainey et al. (2012) found the factor $\Psi_p \sim 1680$; see also Spencer and Nimo (2013) and Spencer et al. (2013).

Some of these problems could be addressed in models of evolution, e.g.:

(Ad a). The sublimation (from high temperature region) and resublimation (in cold region) of ice and/or sedimentation of ice crystals ejected in space as a result of cryo-volcanic activity could explain the high albedo.
(Ad b). Some results of Czechowski (2014) concerning the age of the surface could be interpreted as confirmation of bombardment by planetocentric impactors.
(Ad c). The high density (comparing to other MIS) of Enceladus is addressed here in hypotheses of proto-Enceladus. Note however another possibility. Mousis et al. (2009) propose that Enceladus (and Titan) formed from icy planetesimals that were partly devolatilized during their migration within the subnebula.
(Ad d) Traces of the past activity of Enceladus confirm low dissipation factor of Saturn – Czechowski (2014).

A few papers consider early thermal evolution of Enceladus. Most of them are summarized in the review papers: Matson et al. (2009); Spencer et al. (2009); Schubert et al. (2010); Spencer and Nimmo (2013). Below we discuss a few chosen positions. All of them assumes early accretion, i.e. ~4.5 Gy B.P. The late accretion discussed by Charnoz et al. (2011) should be considered in different way using different methods because the short lived radioactive elements are absent and other source of heat must be included if thermal activity is considered (mainly tidal heating). The same could be said about model of Dorofeeva and Ruskol (2010). According to them Enceladus was formed not earlier than 8–10 Myr after the formation of CAI (Calcium Aluminium-rich Inclusions in chondrites), i.e., after Al^{26} had decayed. Some results of models discussed in Schubert et al. (1986) could be applied for this case. Note that heavy cratered regions of Encleadus (and Mimas) could be significantly younger than 4.5 Gy if planetocentric impactors are considered (e.g. Charnoz et al. 2011).

Schubert et al. (2007a, 2007b) have found that the interior of Enceladus experienced differentiation early due to melting of ice from radiogenic heating (mainly Al^{26}). At 10 to 20 My after formation, Enceladus had hot rocky core of 165 km size. However this conclusion depends on time of accretion. If Enceladus accreted 3.5 My after CAI formation, its interior would not melt, unless the initial temperature was high. If the temperature is 200 K at the time of Enceladus' formation, then differentiation occurs even for low content of Al^{26}, but it is not complete. Their model includes short-lived isotopes and phase transitions, but they do not consider heat of serpentinization and finite time of accretion.

Malamud and Prialnik (2013) in their paper compare early evolution of Mimas and Enceladus. They investigate heat and mass transport by the flow of water through a porous rocky medium. Their model includes heating by serpentinization, by short-lived and long-lived isotopes, and gravitational energy. The results confirm that Enceladus would fully differentiate as a result of heat of short-lived isotopes. In the absence of them, serpentinization in Enceladus can begin only if ammonia is present in the ice. They also suggest that serpentinization of Enceladus during its early evolution and the lack of this process in Mimas, could lead to the present difference between them. However they do not consider convection as the heat transport and finite duration of accretion.

We use parameterized theory of convection combined with the numerical finite difference model developed for investigation of Rhea (Czechowski 2012). We include heating from short- and long- lived radioactive isotopes as well as the heat of accretion, and serpentinization. The accretion is not instantaneous. Moreover, two regimes of convection are considered: liquid state convection (LSC) and solid state convection (SSC). To our best knowledge, it is the first paper that considers following processes:

(i) thermal convection during accretion of Enceladus,
(ii) thermal history of proto-Enceladus,
(iii) interaction of LSC and differentiation during core formation in MIS.

We investigate also problem of Mimas-Enceladus paradox. A few scenarios of Mimas and Enceladus evolution are considered. The aim of Section 6 of our paper is similar to the aim of Malamud and Prialnik (2013) but we consider different hypotheses and use different models and methods.

The paper is organized as follows. The heat sources and basic properties of MIS interior are described in Section 2. Section 3 treats about models of convection and numerical methods used for calculations. The differentiation and the core formation are discussed in Section 4. Section 5 discusses the roles of different parameters in thermal evolution. In the next section we consider Mimas-Enceladus paradox. Conclusions are in the last section.

2. Heat sources and properties of MIS

2.1. Meteoritic data

Data from meteorites are usually used for determination of physical parameters of non-volatile components in MIS. We present short discussion of this problem below. More detailed discussion will be in Czechowski and Losiak (2013).

For our models the most important parameters are: grain density, thermal conductivity, and energy of possible chemical reactions. The MIS and the meteorites' parent bodies are formed by accretion of small grains from the nebula. The nebula contained mainly anhydrous minerals (Scot and Krot, 2005). Only after accretion (in MIS or in parent bodies of meteorites – e.g. Cohen and Coker 2000) the minerals reacted with water and serpentines and clays are formed from anhydrous minerals like pyroxene, olivine, and plagioclase (e.g. Földvári 2011; Weisberg et al. 2006). As MIS contain more water than most of parent bodies of chondrites then more minerals in MIS are hydrated.

Consider now densities. The CI chondrites have the grain average density of 2260 ± 80 kg m^{-3} and the bulk density of 2110 kg m^3, while densities of CM are 2710 ± 110 kg m^{-3} and 2120 ± 260 kg m^3, respectively – Britt and Consolmagno (2004). The low bulk density of chondrites is a result of empty pores that probably are not very important in MIS. The porosity of CI is ~11.3% and CM: ~23.0% ± 7.5% – Britt and Consolmagno (2004). Therefore the grain density is more interesting. Britt and Consolmagno (2004) found the maximal difference between bulk and grain densities of ~600 kg m^{-3} (see also Consolmagno et al. 2013).

The hydration of minerals significantly changes their densities, e.g. the hydration of perovskite (3210–3330 kg m^{-3}) leads to the formation of chrysolite (2530 kg m^{-3}) – e.g. Földvári (2011). The proper assumption of density of non-volatiles is important in models of MIS, e.g. the size of core after possible differentiation is determined by this density. As MIS probably contain presently mainly hydrated minerals then the lower densities of non-volatiles are more realistic. Note however that we do not consider forming an iron core, so only the bulk properties of non-volatiles are considered, i.e. metallic and silicate grains are considered together (see also Section 4.5).

Thermal conductivity k of meteorites depends on the mineralogy and the internal structure of the meteorite (porosity, contact of grains, etc). Opeil et al. (2012) for 17 meteorites at 200 K