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Modeling the Interior Evolution of Water-Rich Bodies: From Dust Aggregates to Ocean Worlds

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Abstract

The properties and structures of small planetary bodies are greatly diverse. These objects can be subdivided into rocky asteroids with ordinary chondritic bulk composition and icy bodies that have a substantial amount of water (carbonaceous chondritic objects, dwarf planet (1) Ceres, icy satellites). The water is either bound in minerals, or is available as a free phase within the planetesimal. Several thermal evolution models for ice-silicate planetesimals were developed and applied to the dwarf planet Ceres (assuming both a CI/CM chondrite-like composition without free water and a water-rock composition with a free water phase), to ice-silicate planetesimals in general, and to Enceladus, the sixth-largest moon of Saturn. A review of the results of these models, the implications for planetesimals in general as well as for some prominent bodies will be presented.

1. Introduction

Small bodies are potential proxies for the building blocks of the Earth. Most of them are clustered in belts, but some of them move on distinct orbits (e.g. NEAs, comets) or are satellites (icy moons). Small bodies cover a spectrum of compositions in terms of H_2O content, ranging from dry objects (Vesta) to those that contain a high H_2O fraction in a distinct layer (Ceres, Enceladus). Both types (e.g. Vesta, Ceres) are found in the asteroid belt; bodies of the second type are also found in the outer solar system (e.g. Enceladus, Charon).

Large variation of their surface properties is observed, ranging from dry, basaltic surfaces produced by igneous processes, over primordial ones, to surfaces characterized by water bearing minerals (Ceres) or silicates that are low in iron and water (Pallas). There is geochemical evidence for silicate melting and even magma oceans (Vesta, Lutetia) on some small bodies, and for ice melting and water-rock differentiation on the others (e.g., Ceres, Enceladus). To understand the formation and evolution of the planets it is essential to know by which mechanism, how, and when this diversity emerged. The insights gained from the interior evolution models for small bodies bring planetary science closer to the understanding of the evolution of the Solar System as a whole and of the planets in particular.

Here, an overview over some recent modeling results and the implications for icy planetesimals in general as well as for some prominent bodies (e.g. Ceres, Enceladus, Charon) will be presented.

2. Model

Several numerical models for rocky and icy planetesimals and planetary embryos were developed previously[1-5] in order to study the formation and evolution of asteroids, moons and dwarf planets. The models consider processes relevant for the interior evolution of small icy objects, such as accretion, accretional heating, closure of the dust porosity, melting of ice, water-rock separation by matrix compaction, and convection (solid/liquid-state ice/ water convection and hydrothermal circulation). The investigations performed using these models provide constraints on the timing and duration of the formation of rocky core and icy mantle, as well as the present-day state of icy bodies. The scientific goal is to find likely evolution scenarios and interior structures of such objects depending on their composition, formation time, and accretion duration, and to reproduce features observed by space missions.

3. Selected Results

Specific objects of the very diverse set of icy bodies that were observed by space missions are the dwarf planet Ceres, the icy moon Enceladus and various KBOs (e.g. Charon). The water-rock separation on Ceres and the stability of the crust, as well as the hypothesized present-day porosity in Enceladus' core were investigated by calculating the thermal evolution and the differentiation of these bodies.

Calculations that assume a free H_2O fraction of ≈ 25 vol% in the initially homogeneous interior for Ceres produce a partially differentiated structure with a more dense undifferentiated ice-silicate crust atop of a less dense (possibly “muddy”) H_2O layer and a silicate core (Fig. 1). Such potentially gravitationally unstable configuration can develop further by subduction and overturn, attended by mixing of the crustal material with the H_2O layer. However, a stiff crust with a viscosity that is higher than the “critical” viscosity for the development of the Rayleigh-Taylor instabilities will not overturn and remain stable on a geological timescale.

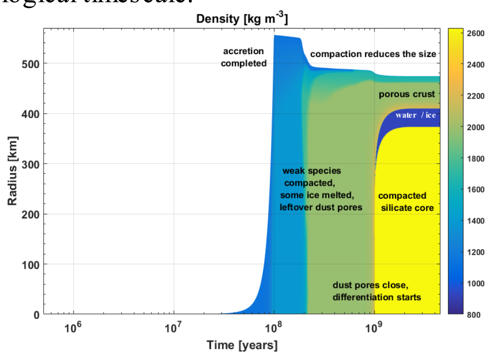

Figure 1. Evolution of the density assuming accretion of Ceres in the Kuiper belt within 100 Ma and migration into the asteroid belt after the late heavy bombardment. Due to the sluggish compaction of the rock, water separates very slowly on a time scale of several hundred Ma. The differentiation is not completed because a porous undifferentiated crust is retained. Free water is present in the ocean, while in the undifferentiated crust and in the porous outer core interaction between the liquid water and the rock results in aqueous alteration if the precursor material contained dry silicates.

The evolution of the viscosity at the base of the crust and of the critical viscosity for the stability of the crust (Fig. 2) implies that in case that Ceres retained a largely undifferentiated crust in the course of the water-rock separation in the interior, this crust could have remained stable as a separate layer until present.

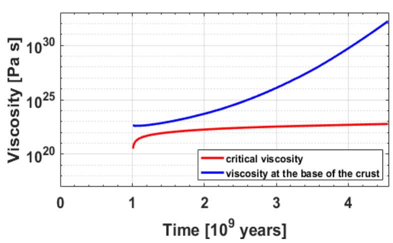

Figure 2. Crust Stability: Comparison of the viscosity at the base of the undifferentiated crust with the critical viscosity for the body from Fig. 1 indicates survival of the crust if Ceres formed late.

A much higher H_2O fraction of > 45 vol% suggested for Enceladus implies a rapid water-rock separation after the onset of ice melting. Rock particles that settle by Stokes flow in a liquid layer form a grain agglomerate with water-filled pores. Calculations of core compaction for different core compositions (dry/wet olivine, antigorite) indicate that a porous layer can be retained for a suitable choice of parameters for both dry and wet olivine rheologies. By contrast, if the core material is dominated by antigorite, the compaction is efficient and no porosity remains for any reasonable choice of parameters. Figure 3 shows porosity profiles for a core with a wet olivine rheology obtained for several successful models that produced a porous outer core layer.

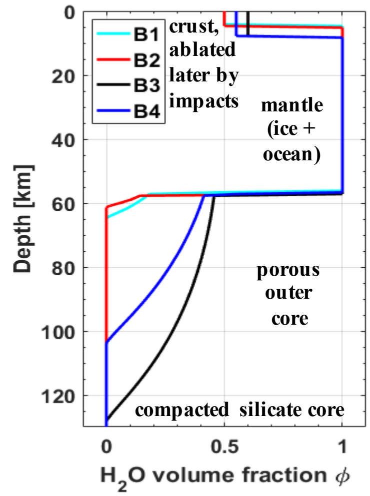

Figure 3. Final porosity profiles in the outer 130 km of Enceladus after differentiation and compaction assuming “wet” olivine rock rheology. Models **B1-B4** correspond to different values of parameters (accretion time, H_2O fraction, creep activation energy, grain size, water fugacity) and they result in a different thickness of the porous layer.

4. Summary and Conclusions

The initial amount of ice is the main criterion that determines the mechanism and the timing of the differentiation of small icy planetesimals (quasi-instantaneous or not). If the ice fraction is small and differentiation occurs slowly in the matrix compaction regime, the composition of the rock determines the timing of the differentiation and the stability of the crust. This is initially not the case for a high ice fraction. However, when a rocky core forms the structural evolution is highly dependent on the compaction rate, and, thus, on the composition of the core.

A highly viscous rock component can extend the time of the differentiation of Ceres to up to ≈ 1 Ga and ensure crust stability on this time scale. In the case of Enceladus, modeling confirms the conjecture of a porous core for an olivine-like core composition, but not for a core that is dominated by antigorite.

References

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