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Differentiation Models of Vesta and Ceres

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Abstract

Both targets of the Dawn mission – the asteroids Vesta and Ceres represent case studies for the differentiation of the protoplanets that formed in the early solar system and served as building blocks of the planets including Earth. Based on our numerical studies, we compare the process of the differentiation and the internal structure of these bodies.

1. Introduction

Vesta and Ceres, observed closely by Dawn, are both altered remnants of the planetesimals that accreted in the early solar system. Such bodies can be subdivided into rocky objects (that have chondritic bulk composition or are derivates of such bodies, such as asteroids 21 Lutetia and 4 Vesta) and icy ones having composition that contains a substantial amount of water (e.g., carbonaceous chondritic objects, the dwarf planet Ceres, and the icy satellites). Vesta and Ceres are two completely different endmembers formed during the planetesimal differentiation.

Large variation of the surface properties can be observed. For instance, Vesta has a dry, basaltic surface produced by igneous processes (indicating a differentiated structure and resurfacing by lava flows), while Ceres´ surface is characterized by water bearing minerals. There is geochemical evidence for wide-spread silicate melting and even magma oceans on Vesta as well as for ice melting and water-rock differentiation on Ceres.

According to these compositional constraints, the differentiation of these objects from an initially nearly homogeneous interior to the development of a stratified structure took entirely different paths.

2. Models

We developed numerical models to study the formation and evolution of planetesimals, asteroids and dwarf planets[1]. We investigated the influence of porosity, compaction, melting, melt migration and the redistribution of the heat sources on the thermo-chemical evolution of rocky planetesimals by further considering differentiation via porous flow and Stokes flow as well as heat transport by liquid-state convection in crystal-melt mixtures. This work provides constraints on the timing and duration of the core formation and on the formation of a silicate crust. In addition to metal-rock compositions[1,2], models for ice-silicate planetesimals were developed that include water-rock differentiation[3]. These models consider among others ice melting, water-rock differentiation, convection in a water ocean, accretional heating, and hydrothermal convection. The plausible evolution scenarios and interior structures of ice-rich planetesimals depending on their composition, formation time, and accretion duration were explored. The models described were applied to Vesta and Ceres.

3. Vesta

An unprecedented amount of data is available from the howardites, eucrites and diogenites and the Dawn mission and it is widely accepted that Vesta has a metallic core with a radius of approximately half of the asteroid's radius. Therefore, Vesta serves as a case study of melting and differentiation processes in protoplanets. While the HEDs were produced by igneous processes, they can either be products of the early partial melting or residual melts expelled by a crystallizing magma ocean. Isotopic compositions indicate differentiation within the first few Ma after CAIs, while siderophile depletions indicate core formation prior to the crystallization of eucrites and within ≈1-4 Ma after CAIs.

Model calculations show that after the accretion phase, radiogenic heating induced compaction and the associated radius decrease. Early ^{26}Al-rich silicate melt migrated towards the surface causing a strong concentration of ^{26}Al in the sub-surface. Here, the temperature increased rapidly and the melt fraction increased producing a convecting, $O(1)$ km thick "shallow" magma ocean. Above the magma ocean, partial melt percolated to the surface forming a basaltic crust. The basaltic crust and the sub-surface are the first differentiated layers. Below this layer, first the iron percolated from the upper mantle towards the center, then the rest of the mantle and the iron core formed simultaneously. However, no global magma ocean formed in the mantle. Within less than 0.3 Ma the differentiation was completed.

We favor formation of Vesta within 1 Ma after CAIs, because only then the silicate melt can reach the surface and form a crust. An important consequence is the lack of heating in the mantle, which prevents a whole-mantle magma ocean and keeps the melt fractions in the mantle below 50 %. Our results favor the early partial melt origin of the non-cumulate eucrites, while the cumulate eucrites and diogenites form from the partial melt that percolated upwards after the crystallization of the shallow magma ocean, but was not able to reach the surface. The extrusion of the basaltic melt in our calculations is due to porous flow and small-scale shallow dyking. This correlates with the presence of the crust but a lack of distinct volcanic structures on Vesta.

4. Ceres

Because no meteorites have been identified as originating from Ceres, most data comes from the observations by Dawn and from theoretical models. We modeled the compaction of a Ceres-like body that accretes as a porous aggregate, in order to test the hypothesis that Ceres' low density can be explained by a porous interior instead of the presence of ice, and whether compaction occurs due to creep or due to dehydration of hydrated minerals. The porosity change was calculated according to the thermally activated creep flow. We found that compaction of initially porous Ceres is dominated by creep and only slightly perturbed by the dehydration. In particular, dehydration alone cannot lead to compaction because creep can occur before the dehydration. Depending on the accretion timescale, timing of the compaction varies from between a few Ma and more than one Ga. Thereby, late accretion cannot prevent compaction to a porosity of <3%.

Based on the observations by Dawn and assuming a water-rich composition, we calculated water-rock differentiation models assuming 75 vol% rock and 25 vol% ice. We investigated the implications for the presence of liquids and the possibility of cryovolcanism in order to explain surface features observed by Dawn. Accretion times considered cover 1-100 Ma rel. to CAIs. Compaction of the dust pores starts with ice at ≈180-240 K and proceeds with rock minerals at temperatures of up to 730 K. Sub-surface remains too cold to close these pores. The water-rock separation proceeds by water percolation in a rock matrix. Compaction and, therefore, differentiation takes several hundred million years due to a slow temperature increase. Therefore, a water ocean starts forming within 10 Ma after CAIs, but its completion is retarded relative to the melting of ice by up to *O*(0.1 Ga). Convection keeps the ocean cold, counteracts a complete differentiation, and favors retention of a porous undifferentiated crust. Only a thin basal part of the ocean remains liquid until today, while the upper part freezes. Present-day temperatures calculated for a slow accretion (e.g., within >7 Ma) indicate that hydrated salts can be mobile at a depth of ≥5 km implying buoyancy of ice and salt-enriched crustal reservoirs.

5. Discussion

The obvious differences between Vesta and Ceres in the size, density, and composition imply different initial amount of the heat sources, values of the thermal conductivity, melting behavior, and differentiation regime. Higher temperatures are required to produce metallic and silicate melt and to differentiate Vesta completely. For Ceres, moderate temperatures of up to 600 K suffice to melt the water ice and to facilitate differentiation, while there are no indications for melting of metal and silicates in the past. The nature of the differentiation (metal-silicate for Vesta, water-rock for Ceres) necessitates, therefore, different thermal conditions (T>1300 K for Vesta, T>300-600 K for Ceres), and influences strongly the timing of differentiation (0.5 Ma after CAIs for Vesta, *O*(100 Ma) for Ceres) and the final structure (completely differentiated for Vesta vs. partially differentiated for Ceres). Finally, using the observational constraints, the models provide different resulting structures: Vesta is completely compacted and differentiated, with an iron core, a silicate mantle, and a eucritic-diogenitic crust, while Ceres is partially porous and incompletely differentiated, with a rocky core, an ice mantle, and a porous ice-rock crust. Based on the results we extract plausible formation time of 0-1 Ma after CAIs for Vesta and >4-5 Ma after CAIs for Ceres. From the accretion timescale of planetesimals, this points possibly to a formation of Ceres at a larger distance from the sun than its present orbit.

References

[1] Neumann, W., et al., EPSL, 395, 267-280, 2014. [2] Neumann, W., et al., A&A, 584, A117, 2015. [3] Neumann, W., et al., DPS 48 / EPSC 11, 506.08, 2016.