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Constraints against a porous CI chondritic Ceres

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Abstract

Ceres is the largest body in the asteroid belt having the radius of ≈ 470 km. Observations and modelling suggest severe aqueous alteration of the surface, and an icy mantle overlying a rocky core. This would place Ceres in between the rocky bodies of the inner Solar system and the icy satellites. However, alternatives including an undifferentiated porous interior and also an origin in the outer Solar system have been proposed recently. We investigate the possibility whether Ceres' low density can be explained with a porous interior, rather than with the presence of ice, by the means of a numerical model.

1. Introduction

Considered as a protoplanet along with Pallas and Vesta[1,2], Ceres can be seen as one of the remaining examples of the intermediate stages of planetary accretion, which additionally is substantially different from most asteroids. Its low bulk density (2077±36 kg m^{-3}, see [3]) suggests a global ice mass fraction of ≈ 30 % if the average porosity is negligible. Thermal models by [4] showed that Ceres has likely differentiated into a rocky core, an icy mantle and possibly a shallow still liquid layer above the core. Recent interior modelling by [5] has emphasized that warm surface temperature promotes the presence of a deep ocean in today's Ceres, provided sufficient fraction of ammonium and salts. Thereby, both studies assume an ice-silicate composition. Alternatively, Ceres could be made up of hydrated silicates (oxidised carbonaceous chondritic material) or be a homogeneous mixture of the CI chondritic material with significant porosity, without having a differentiated structure, as suggested by [6]. The observations by [3] and [7] of Ceres' shape are consistent with differentiation, but also allow for the structure suggested by [6]. Compaction of Ceres made up of hydrated silicates is estimated by [6] based on the compaction of sandstones at pressures ≥ 150 MPa, disregarding thereby the material specifications, such as the lower creep activation energy of hydrated silicates and the much higher effective pressure due to the porosity[8].

2. Model

For the investigation of the possibility of Ceres being porous we adopted the numerical model from [8] which computes the thermal and structural evolution of planetesimals, including compaction of the initially porous primordial material. If Ceres formed during the first few million years, its thermal evolution would be dominated by the decay of the short-lived nuclides ^{26}Al, ^{60}Fe and possibly ^{53}Mn, and complete compaction would be certain. For later formation times additional heating is necessary, which can be provided for a body of Ceres' size by the long-lived nuclides ^{40}K, ^{232}Th, ^{235}U and ^{238}U. The model by [8] has been extended with the radiogenic heating by the long-lived nuclides. Assuming an initial porosity of 50 % and the intrinsic geometry which is described by the simple cubic packing of spherical grains, the model computes porosity loss as a temperature and pressure dependent process:

$$\frac{\partial \log(1-\phi)}{\partial t} = Bb^{-3}\sigma_1^n e^{-E/RT},$$

with porosity ϕ, time t, a constant $B \approx 4.0\times10^{-5}$, initial grain size b, effective stress σ_1, constant $n \approx 3/2$, activation energy E, gas constant R and temperature T. In this preliminary study we use ordinary chondritic composition and the activation energy of E=85 kcal mol^{-1} derived for olivine. Thus, the final average porosity we compute in our models should be seen as an upper bound on the porosity of Ceres.

3. Results

Fig. 1 shows the porosity as function of the relative radius in a Ceres-like body that forms at different times relative to the formation of calcium-aluminium-rich inclusions. Formation time t_0 of 10, 20, 30, 40 and 50 Ma have been considered. Even for t_0 = 50 Ma, the porosity is reduced to zero except in an outer shell with the thickness of 63 km. This outer layer retains its primordial state (in particular its initial porosity). The loss of porosity is mainly due to the heating by the long-lived nuclides. The final average porosities for the upper values of t_0 are 14.63, 15.73, 16.02, 16.42 and 16.54 %, respectively. These values are somewhat predetermined by the choice of the initial porosity. Smaller initial porosity of 40 % leads to the final average porosity of 13.85 % for t_0 = 50 Ma. If Ceres formed at 10 Ma after the CAIs, some small amount of iron melt is produced, whereas in the late-forming cases the solidus temperature of the iron phase is not reached. Thus, in those simulations where a substantial part of Ceres is porous, no differentiation can be expected at all. On the other hand, formation within the first few million years after the CAIs would result in the formation of an iron core and a silicate mantle, but the compaction would be almost complete.

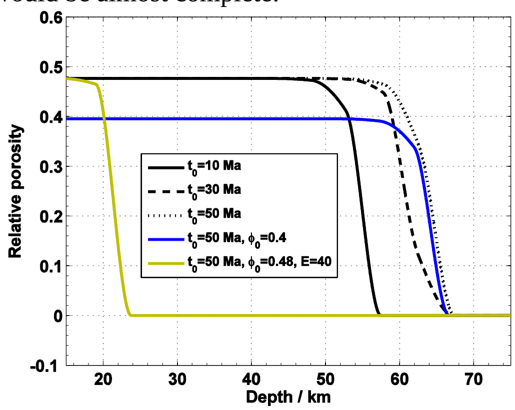

Figure 1: Porosity against depth for varying t_0.

4. Summary and Conclusions

We performed sample runs for a Ceres-sized body using an ordinary chondritic composition, corresponding abundances of the radiogenic heat sources and a rather high activation energy for the creep onset (E=85 kcal mol^{-1}) which corresponds to olivine. Thus we overestimated slightly the amount of radiogenic heating and by doing so overestimated also the extent of compaction. However, the activation energy adopted here is too high. Presence of hydrated silicates in the CI chondrites (approximately 17-22 wt.% of the composition is water) indicates an activation energy which is at least twice as small as the value used. Consequently, the compaction will proceed at considerably lower temperatures than in our sample runs and will be much more efficient (see the line corresponding to E=40 kcal mol^{-1} in Fig. 1; here the final porosity is 6.7 %). This means, that in fact the final porosity is overestimated in the presented calculations. From this consideration we conclude that it is rather unlikely that the low density of Ceres can be explained by a partially porous structure. This body is most probably ice-rich and may have a rocky core and an ice mantle. In the future we envision a more systematic study of the compaction of Ceres similar to asteroid Lutetia[10] in order to rule out completely the possibility that Ceres is undifferentiated and porous.

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