Modelling of the thermo-chemical evolution of Ceres

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Introduction

Ceres is the largest body in the asteroid belt. It can be seen as one of the remaining examples of the intermediate stages of planetary accretion, which in addition is substantially different from most asteroids. Studies of protoplanetary objects like Ceres and Vesta provide insight into the formation of Earth and other rocky planets. One of Ceres’ remarkable properties is its low bulk density of 2077±36 kg m⁻³. For a nearly chondritic composition, this value indicates either a high average porosity, or the presence of a low density phase (water ice or hydrated silicates) differentiated from the silicates forming an icy mantle over a rocky core. However, Ceres’ shape and the moment of inertia allow for both a porous and a differentiated structure. In the first case, Ceres would be just a large version of a common asteroid. In the second case, however, this body could exhibit properties characteristic for a planet rather than an asteroid: presence of a core, mantle and crust, as well as a liquid ocean in the past and maybe still a thin basal ocean today.

Parameters

Table 1, Composition, mass and volume fractions of the constituents, and further key parameters for the modelling of compaction (mostly from [7]).

<table>
<thead>
<tr>
<th>Material</th>
<th>Mass fraction</th>
<th>Volume fraction</th>
<th>mass density</th>
<th>k</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>ice</td>
<td>0.4764</td>
<td></td>
<td></td>
<td>1.1102E23</td>
<td>1.1102E23</td>
</tr>
<tr>
<td>rock</td>
<td>0.4985</td>
<td></td>
<td></td>
<td>3.33E26</td>
<td>3.33E26</td>
</tr>
<tr>
<td>water</td>
<td>0.0076254432</td>
<td></td>
<td></td>
<td>1.1102E23</td>
<td>1.1102E23</td>
</tr>
</tbody>
</table>

Table 2: Parameter values used to simulate the radioactive heat production by the short- and long-lived isotopes.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-life (yr)</th>
<th>Total decay energy per gram initial heat production</th>
<th>Fracture fraction</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>22Na</td>
<td>998000</td>
<td>6.352E+10</td>
<td>1.23E-01</td>
<td>1.23E-01</td>
</tr>
<tr>
<td>47Ca</td>
<td>1.393E+03</td>
<td>5.09E+10</td>
<td>1.23E-01</td>
<td>1.23E-01</td>
</tr>
<tr>
<td>85Sr</td>
<td>5.05E+03</td>
<td>5.09E+10</td>
<td>1.23E-01</td>
<td>1.23E-01</td>
</tr>
<tr>
<td>40K</td>
<td>1.378E+09</td>
<td>1.610E+10</td>
<td>1.23E-01</td>
<td>1.23E-01</td>
</tr>
<tr>
<td>147Pm</td>
<td>1.393E+03</td>
<td>5.09E+10</td>
<td>1.23E-01</td>
<td>1.23E-01</td>
</tr>
<tr>
<td>99Mo</td>
<td>1.393E+03</td>
<td>5.09E+10</td>
<td>1.23E-01</td>
<td>1.23E-01</td>
</tr>
</tbody>
</table>

Conclusions

• High effective stress and low activation energies enable almost complete compaction of Ceres even for late formation times
• In all simulations the present average porosity falls far below 10% yielding a far higher average density that the measured one
• This argues against the porous structure suggested by [2]
• It is rather unlikely that the low density of Ceres can be explained by a partially porous structure
• Thus, Ceres is most probably ice-rich and may have a rocky core and an ice mantle (thus, processes associated with the presence of water need to be considered)
• A more systematic study of the compaction of Ceres similar to that of asteroid Lutetia[10] is necessary in order to exclude the possibility that Ceres is not differentiated and porous completely

Next steps

• Combined treatment of accretion, compaction and differentiation into a rocky core and a water mantle of small icy bodies
• Consideration of processes like amorphous to crystalline ice transition, ice melting, water-rock differentiation, hydrothermal convection, hydration of silicate minerals (e.g. formation of serpentinite from forsterite and H2O), water release due to dehydration, metal-silicate differentiation, etc.
• Investigation of most likely evolution scenarios and structural end-members of Ceres depending on its composition and formation time
• A better understanding of other bodies like icy asteroids and satellites
• Conclusions on the astrobiological potential and habitability of Ceres

Future Perspectives

For the investigation of the possibility of Ceres being porous we adopted the numerical model from [5] Neumann et al. (2012) which computes the thermal and structural evolution of planetesimals, including the compaction of the initially porous primordial material.

\[ \rho \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + \dot{Q}(r,t) \]

Porosity-dependent parameters, e.g.:\[ k = k_0 \left( \frac{\rho_p}{\rho_o} \right) \]

Radius change due to compaction: Effective stress

\[ \sigma = \frac{1}{3} \left( \nabla p + \nabla \cdot \mathbf{e} \right) \]

Dynamical scaling of radial variable: Temperature dependence:

\[ \eta = \frac{\rho_T}{\rho_T(r)} \]

\[ \rho_T(r) = \rho o \left( \frac{r}{r_o} \right)^{3(1-3\eta)} \]

\[ T(r,t) = T_o \left( \frac{r}{r_o} \right)^{3(1-3\eta)} \]

Results

Fig. 1. Artist’s impression of Ceres

Fig. 2. Deformation geometry of the simple cubic packing of spherical grains adopted in the present study. a) Geometry at the contact area between two grains. b) Simple cubic unit cell. c) Top view of the simple cubic unit cell. Figure from [6].

Fig. 3. Central temperature vs. time for different formation times t between 2 and 60 Ma after the CAIs. For small t, thermal evolution is dominated by the decay of 40K, 47Ca and 147Pm with rather high temperatures. For later formation times the slower temperature increase is due to the heating by 99Mo, 22Na, 238U and 226Ra. Formation prior to 4 Ma rel. to CAIs indicates silicate-metal differentiation.

Fig. 4. Temperature profiles taken at 4.5 Ga for varying t_o. Depending on t_o, the temperature of 273 K is reached in the depth of 650 km. This supports the existence of liquid water in the sub-surface and interior of the present-day Ceres.

Fig. 5. Porosity profiles taken at 4.5 Ga for varying t_o. The thickness of the porous layer is at best ~ 30 km. Late formation implies stronger insulation of the interior by a thicker porous layer. However, the final average porosity is < 0.02 in all cases.

Fig. 6. Samples of the lithostatic pressure, the effective pressure and the corresponding porosity profile. Shown are the profiles assuming t_o = 7 Ma rel. to CAIs at the time instance t = 8.15 Ma rel. to CAIs. While the porosity deviates only moderately from the initial one, the effective stress lies two orders of magnitude above the lithostatic pressure. With decreasing porosity the lines will converge.

References