Cracking in Ceres’ core as an opportunity for late hydrothermal activity

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1. Liquid water inside Ceres!

Ceres (radius ≈ 975 km, density 2.1 g cm⁻³, semi-major axis 2.8 AU) bears questions about how its interior is structured (Fig. 1). Its density suggests it is made of ice and rock. Models (e.g., viscosity of Ceres’ surface temperature, 165 to 200 K. Observations and models both indicate that water-rock interactions, likely hydrothermal, shaped Ceres’ evolution.

2. How much hydrothermal activity?

Fig. 2 shows the evolution of the temperature inside Ceres, modeled using the code of Desch et al. (2009) [3]. Heating by radioactive decay melts ice and drives differentiation, providing an early opportunity for hydrothermal activity.

3. Modeling crack formation

Ceres’ radius, distance, density

Thermal evolution model 1-D

(Desc et al. 2009)

\[
\begin{align*}
\frac{dT}{dt} & = \frac{d}{dr}(k \cdot \frac{dT}{dr}) + \sum_{i} \frac{dQ_{i}}{dt} \\
E & \rightarrow T
\end{align*}
\]

Using an equation of state for either rock or water-ammonia, using heat capacities and latent heats

Cooling rate \( \frac{dT}{dt} \) at (r)

From T(r), tracks composition and pressure P

When rock cools in Ceres’ core, mineral grains shrink. By how much it depends on their thermal expansion α.

Stresses occur between grains of different α, increasing with cooling rate and Δα.

\[
\sigma_{yy}(r) \approx \frac{E \Delta \alpha}{2(1-\nu)} \left( T^{*} - T \right)
\]

σyy(r) is the stress, E is Young’s modulus, ν is Poisson’s ratio, r is location, Δα is difference in thermal expansion.

4. Results: depth of hydrothermal layer

A high cooling rate comparable to that at Earth’s mid-ocean ridges (10 Kyr) yields a core cracked down to 30-40 km, 15% of the core radius, r = 350 km.

Here, the cooling rate is fixed arbitrarily, so the depth of cracking over time is determined by the temperature T. σyy(r) is highest (and z is smallest) between 1 and 2 Gyr (see Fig. 2)

Stress vs. depth after 1 Gyr

Some plots for a much lowered cooling rate. 1 K per billion year. Less cooling leads to less cracking: z = 5-10 km.

z is still smallest between 1 and 2 Gyr.

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Now using a realistic cooling rate, calculated from the thermal model output. No cracks develop until the core starts cooling between 1 and 2 Gyr, by a few 100 K per billion years. The present depth of cracking is z = 5-10 km.

The water/rock ratio, a key geothermal input, is calculated as the ratio (total mass of liquid / total mass of cracked rock). It decreases over time, because cooling leads to liquid freezing and crack formation.

Take-home message:

1. Water-rock interactions likely played a major role in Ceres’ evolution.
2. We have introduced the first time-dependent core cracking model for an icy body. We found that late hydrothermal circulation should have been superficial.
3. This provides context for measurements by Dawn at Ceres in 2015.