Liquid Water Inside Ceres: The icy dwarf planet Ceres (radius \(\approx 475\) km, density \(2.1\ \text{g/cm}^3\), semi-major axis \(2.8\) AU) is the only body besides the Earth and Mars where carbonates have been observed along with brucite, another product of aqueous alteration [1]. Ceres will be visited by the Dawn spacecraft in 2015, which will offer an opportunity to constrain the origin of this large icy body. For example, it could have formed along with main-belt objects, or with Kuiper belt objects (KBOs) [2].

Models of Ceres’ thermal evolution have predicted the existence of liquid water throughout most of its history [3,4], provided that it accreted one to a few percent ammonia (NH\(_3\)) acting as antifreeze with respect to water. Ammonia has been predicted to condense within the snow line [5] and observed on a few outer Solar system bodies [6,7,8]. The eutectic point of a H\(_2\)O-NH\(_3\) mixture is around 175 K [9], much lower than that of pure water (273 K) and brines (<210 to 250 K) [10]). We have applied to Ceres thermal evolution models developed for KBOs [11] with NH\(_3 \)/H\(_2\)O=1% and confirmed the long-term preservation of a deep liquid layer in Ceres [12], whereas in absence of ammonia our models cannot maintain liquid. Observations and models both indicate that (a) aqueous alteration played a role in Ceres’ history, and (b) Ceres’ interior may have been habitable, and could still be. This brings about the need to consider geochemical processes when modeling Ceres’ evolution.

How Much Hydrothermal Activity? Shape data indicate that Ceres likely differentiated into a silicate core and a water-ice mantle [3,4,12,13]. At the core-mantle boundary, water-rock interactions can occur if a thermal gradient is high enough to initiate the circulation of fluid through hot, porous rock [14]. The core porosity and depth of fracturing determine the extent of hydrothermal activity as well as the water/rock ratio (\(W/R\)), a key geochemical parameter.

Cracks develop as the core cools and contracts. At high enough pressure \(P\) and temperature \(T\), cracks relax and seal. The balance of these two phenomena determines the depth of cracking \(z\) into the core. Previous models [14] have shown that Ceres-sized icy bodies should have a core fractured throughout \((z > R_{\text{core}} = 375\) km\), assuming a constant cooling rate \(\dot{T}\) of 1 K/yr, i.e., that typical of Earth’s mid-Ocean ridges, and using \(T\) and \(P\) profiles with depth from static geophysical models [15]. Our geophysical evolution models have predicted that Ceres’ core has been cooling much more slowly (afew 100 K/Gyr) from 2 Gyr until today (4.56 Gyr), following a decrease in radiogenic heating [4,12]. We predict lower \(\dot{T}\) because radiogenic heat is not removed as efficiently by conduction from the low thermal conductivity rocky core as it is removed at Earth’s mid-Ocean ridges through volcanism. Instead, heat builds up in the core, yielding a temperature gradient steeper than that predicted by [15].

Model Equations: Parameters and their values used in the following equations are further described in [14] and references therein. \(T\) anisotropy between square silicate grains result in a mean stress \(\bar{\sigma}\) that depends on \(\dot{T}\). The threshold temperature at which stress starts accumulating is \(T’\), defined such that \(\bar{\sigma}(T’) = 0\). An approximate analytical expression for \(T’\) is:

\[
T’ \approx \frac{Q}{R_G} \left[ \ln \left( \frac{12\Omega D_0 \delta_b E}{3^{1/2} n k_b L^3 T} \right) \right]^{-1}
\]  

where \(\Omega\) is the atomic volume, \(D_0\) and \(\delta_b\) the grain boundary diffusion coefficient and width, \(E\) Young’s modulus for all grains, \(k_b\) Boltzmann’s constant, \(2L\) the grain size, \(Q\) the activation enthalpy, \(R_G\) the gas constant, and \(n\) is an empirical fitting parameter.

Let us consider an inclusion within a matrix. If the thermal expansion coefficient of the inclusion is higher than that of the matrix, tensile stress will develop upon cooling. Microfractures occur when the tensile stress intensity \(K_I\) exceeds a critical value, \(K_{IC} = 0.6 \pm 0.3\) MPa m\(^{1/2}\) for olivine. \(K_I\) is estimated from \(T\) and \(P\):

\[
K_I = \left( \frac{2}{\pi a} \right)^{1/2} \int_0^a \sigma_{yy}(x, T, T’) \left( \frac{x}{a-x} \right)^{1/2} dx - P(a) \left( \frac{\pi a}{2} \right)^{1/2}
\]  

where a flaw of size \(a < 2L\) extends from the grain boundary \((x = 0)\) to \(x = a\). The pressure \(P\) tends to reduce the tensile stress. \(\sigma_{yy}(x, T, T’)\), whose analytical expression can be found in [14], is the normal stress along the x-axis.
In prep.


**Conclusion:** Numerical estimates suggest the upper few km of Ceres’ core are cracked. Together with an analytical estimate of a few 10 km/Gyr for hydrothermal circulation, this indicates that fluid flow through the cracked layer can happen quickly enough that the whole layer experiences hydrothermal alteration. This calls for increased fidelity models coupling physics and geochemistry that account for the feedback between the evolution of the rock composition and its physical properties (e.g. thermal conductivity, porosity). Most importantly, hydorgochemistry influences the nature and amount of antifreezes (ammonia, salts) available to preserve a deep liquid layer over the long term.

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