GEOCHEMISTRY, THERMAL EVOLUTION, AND CRYOVOLCANISM ON CERES WITH A MUDDY ICE MANTLE.

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Introduction: Interpretation of data acquired at Ceres by the *Dawn* spacecraft demands a model for the evolution of Ceres' structure and composition to date. In a recent paper [1], we presented such a model, consistent with pre-*Dawn* observations and preliminary data returned by *Dawn*. Here, we describe this model, compare its physico-chemical outcomes to reported observations, and outline possible tests by ongoing *Dawn* measurements.

Internal structure: Constraints on Ceres' density and structure come from its mass of 9.4×10^{20} kg [2], size, shape (assuming Ceres is hydrostatic) of $\approx 482 \times 480 \times 446$ km [3], and gravity measurements [3,4]. These suggest a bulk density near 2150 kg m^{-3}, with a central density concentration [3]. Following [5,6], we assume that Ceres accreted ice and both μm- and mm-sized rock particles (mostly silicates and organics), and that micron-sized fines stayed suspended in liquid during differentiation, yielding a core of chondrules and a mantle of mixed ice and fines ("mud"). This assumption reconciles apparently conflicting observations of Ceres' near-surface composition: on one hand, it appears icy, exhibiting little large-scale topography [2]; pit craters suggestive of volatile basement material [7]; a low simple-to-complex crater transition diameter [7]; flows, domes, and evidence for glacial mass wasting [8]; and production of water vapor [9]. It also lacks a collisional family, possibly because icy mantle fragments sublimate after ejection [10]. On the other hand, Ceres' surface is dark and uniform, with mean geometric albedo < 0.1 [11,12] and spectra consistent with hydrated minerals whose unique composition suggest an (in part) endogenic origin [13-15]. Moreover, Ceres' small-scale topography requires a material stronger than ice [16].

Many two-layer structures can be matched to the above observables by adjusting the bulk rock density (which sets the bulk ice:rock ratio) and fraction of rock in fines. Here, we choose a rock density $\rho_c = 2900$ kg m^{-3}, that of grains in CM chondrites [1]. Assuming hydrostaticity, the wide range of reported shapes [2,3,17] can be matched by interiors with a rocky core size up to 360 km. We explore end members with 75% of the rock in chondrules and 25% in fines, yielding a 360-km core and a mantle comprising 74 vol% ice and 26 vol% fines; and with 1% of the rock in chondrules and 99% in fines (85-km core with a mantle comprising 62 vol% fines).

Early hydration and differentiation: Our 1-D numerical simulations of thermal evolution [1] suggest that following accretion, radionuclide decay heating melts ice in the central layers. Melting can occur quickly throughout the interior if Ceres accretes abundant short-lived radionuclides such as ^{26}Al (accretion within 4 Myr after Ca-Al-rich inclusions), or within tens of Myr and only at depth otherwise. In the first case, we assume that chondrules and fines are quickly hydrated and emplaced on the surface, overturned by impacts. In the second case, we calculate analytically that in muddy liquid of density ρ_l and viscosity η, chondrules of radius D fall distances ΔR by Stokes flow on decadal timescales:

$$t_{\text{settle}} \approx 50 \left(\frac{\rho_c - \rho_l}{800\ \text{kg m}^{-3}}\right)^{-1} \left(\frac{\eta}{0.18\ \text{Pa s}}\right) \left(\frac{\Delta R}{100\ \text{km}}\right) \left(\frac{D}{1\ \text{mm}}\right)^{-2} \text{yr} \quad (1)$$

This leads to a gravitationally unstable undifferentiated mantle atop a chondrule-free ocean, which overturns by Rayleigh-Taylor instabilities within 50 Myr at 170 K [18]. In either case, ice sublimates from the surface, leaving a lag deposit of hydrated, μm-sized fines within Ceres' first few tens of Myr. Crater counts to derive surface ages can test these model predictions. Surface particle size may be determined by fits to reflectance spectra.

Thermal evolution and present state: We simulated Ceres' thermal evolution until the present day [1], using the same code as [19,20], modified to implement the assumption that fines and ice are well mixed by forcing differentiated layers to retain a set percentage of their initial rock mass. Rocky fines have lower thermal conductivity (≈ 1 W m^{-1} K^{-1}) than ice (≈ 3 W m^{-1} K^{-1}), making the mantle insulating [19]; they also increase its viscosity by a factor $(1\text{-}\phi/0.63)^{-2} \approx 3$ or 4000 for volume fractions $\phi = 0.26$ and 0.62, respectively [21].

These simulations suggest that the present-day core-mantle boundary in the large-core case is warm enough ($\approx$250 K) to allow liquid brine pockets. For the small-core case, the muddy hydrosphere remains liquid below 110 km depth. These results are robust to various amounts of long-lived radionuclides (CO to CI chondrite abundances).

Geochemistry: The above scenarios provide ample opportunities for water-rock interaction. We investigated equilibrium fluid and rock compositions using the geochemical modeling software *PHREEQC* [22]. Initial rock minerals and abundances were chosen to match representative elemental [23] and mineralogical [24] compositions of CM chondrites to within a few percent for each element and mineral group, including all elements more abundant than 500 ppm, plus N and other elements. Two initial fluid compositions were simulated: pure water and water with 5 mol% C, 2 mol% N, 0.5 mol% S, and 520 mol ppm of Cl to approximate the volatile (C, N, S) content of comets [25] and the chlorine content of CI chondrites [23].

Water-rock interactions yield fluids rich in S ($S_5O_6^{2-}$), C (methane), and N as NH_3 or NH_4^+, with <25% of the solutes being Na and Ca. Hot fluids can be rich in H_2. The main mineralogies are magnetite and clays (saponite smectite; antigorite, cronstedtite, and greenalite serpentines; chlorites; NH_4-clays), notably in qualitative agreement with those observed by *Dawn* instruments [15]. Carbonates, which seem prominent on Ceres [14,15], are absent from our equilibrium mineral assemblages, but present in some solutions from which they could precipitate upon freezing or vaporization.

Ongoing cryovolcanism? Ceres' surface displays several peculiar, geologically young features: several bright spots, prominent in Occator crater, and domes exemplified by Ahuna Mons [26]. The bright spots have been interpreted as salt leftover from sublimated water [1,26], and Ahuna Mons as a volcanic construct [27].

Cryovolcanism is remarkably plausible in the context of our evolution models. Extant subsurface liquid is expected as a refreezing ocean in the small-core scenario, bearing solutes leached from its interaction with rock; and as brine reservoirs in the large-core scenario. As just 2% of a liquid reservoir freezes, it compresses the liquid, overpressurizing it by the ~10 MPa needed for it to ascend ~100 km [28-30]. In the large-core case, the liquid density ρ_l = 1526 kg m^{-3} and fines volume fraction $\phi = 0.26$ yield a hydrosphere volume increase of 4.1% upon freezing, equivalent to a global layer 77 m thick (20 m once the ice has sublimated away). In the small-core case, with $\rho_l = 1526$ kg m^{-3} and $\phi = 0.62$, the volume increase is 1.4%. Our simulations suggest that only the upper 110 km have refrozen so far, corresponding to a global layer 18 m thick after sublimation. Liquid is likely to effuse to the surface through preexisting fractures, such as those in the basements of craters [31]. Perhaps basement fractures formed during the Occator impact intersect the large NW-SE oriented fracture network in the Ebisu and Palo mapping quadrants, favoring ongoing effusion in this particular region of Ceres. Evidence of slow effusion might be restricted to large craters, without sufficient material erupted (<20 m equivalent global layer) to significantly erase impact morphologies at the scales observed by *Dawn*'s Framing Camera.

Because sulfates freeze only a few degrees below 0°C, leaving chlorides in the brine, chloride salts may be concentrated relative to sulfates in areas of cryovolcanic effusions. Fines of aqueously altered minerals may be erupted along with the fluids.

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