

RATIONALIZING THE COMPOSITION AND ALTERATION OF CERES. McSween H. Y.¹, Castillo-Rogez J.², Emery J. P.¹, De Sanctis M. C.³, and the Dawn Science Team. ¹Earth & Planetary Sciences, University of Tennessee, Knoxville, TN, mcsween@utk.edu; ²Jet Propulsion Laboratory, Pasadena, CA; ³Istituto di Astrofisica e Planetologia Spaziali, INAF, Rome, Italy.

Introduction: Ammonia, in the form of NH_4^+ -bearing clay, plus Mg-serpentine (antigorite), Mg-carbonate, and a dark component (plausibly magnetite and/or sulfide), provide the best match for the spectrum of Ceres, as measured by the VIR instrument on the Dawn spacecraft [1]. Clay (saponite, although not ammoniated) forms near the end of the progressive alteration sequence in CM/CI chondrites, and coexists with Mg-serpentine (replacing Fe-serpentine = cronstedtite), magnetite, sulfates and ferrihydrite [2], and carbonates [3]. No spectral feature of H_2O ice is present on Ceres [1], but the body's bulk density (2.16 g/cm^3) suggests an ice content of $\sim 35 \text{ wt.}\%$, some of which is water of hydration and the rest is ice [4]; we do not know the original water ice contents of CM/CI parent bodies so we cannot make a direct comparison; most present-day C-class asteroids have lower density but have high porosity [5]. The $\sim 4.0 \text{ }\mu\text{m}$ carbonate feature in Ceres spectra is deeper than in the spectra of CM/CIs, and the $\sim 3.4 \text{ }\mu\text{m}$ organics feature is more pronounced in CM/CI spectra than in Ceres [1, 6]. The proportion of a dark component in the VIR spectral model is much greater than the amount of magnetite and sulfides in CM/CI chondrites. No spectral signature of sulfates is discernable in the Ceres spectrum.

To summarize, Ceres is mineralogically similar to CM/CI carbonaceous chondrites, except for the occurrence of ammoniated clay and inferred differences in the relative proportions of carbonate, organic matter, magnetite, and sulfate. Can these differences be explained? We propose that Ceres is compositionally similar to CM/CI carbonaceous chondrites, but has been more extensively altered because of higher temperature and/or a higher water/rock ratio.

Explanation for Ammoniated Clays: Where did the ammonia in Ceres' clays come from? On thermodynamic grounds, NH_3 has been predicted to be the major nitrogen species in the nebula [7] under equilibrium conditions, and numerous models predict its condensation as dihydrate in the outer solar system. Ceres could have accreted from rocky planetesimals that formed locally and icy planetesimals that formed at $>5 \text{ AU}$ and drifted inward [8]. An alternative is that Ceres, like P- and D-type asteroids, might have migrated inward from the Kuiper belt [9]. Conversely, [10] calculated that the condensation fronts of ammonia hydrates and water ice coincided and swept inward to $\sim 2.7 \text{ AU}$ in the asteroid belt. In all of these cases, NH_3 in Ceres would have been introduced as a hydrate.

Another possibility, to be explored here, is that ammonia was accreted as part of the rocky component of Ceres, which we suggest was carbonaceous chondrite. NH_3 is commonly found in insoluble macromolecular organic matter and soluble amino acids in CM/CI chondrites [11].

Carbonaceous chondrites have been altered at temperatures ranging from $0\text{-}125^\circ\text{C}$ [12]. The ammonia-bearing organic compounds in the chondrites may have formed in parent bodies from reactions of interstellar organic precursors with accreted NH_3 -hydrate under those conditions. Experiments reveal that the ammonia in carbonaceous chondrites is released upon hydrothermal treatment at 300°C in 6 days [11], and plausibly at lower temperatures if heating periods were longer ($300^\circ\text{C}/6 \text{ days}$ is the only experimental condition explored so far). Ammonia released from organics by heating in Ceres' deep interior could have reacted with clays in a milder environment closer to the surface. In contact with liquid water, NH_3 forms NH_4^+ , which can exchange with univalent cations in clays. Thermal models for icy bodies as large as Ceres [4, 13, 14] allow for liquid water and active hydrothermal systems for as much as a 100 million years after accretion, although buried deeply in the interiors of these bodies. Early convection, as well as later excavation by large impacts, could have brought the ammoniated clays to the surface of Ceres.

Explanation for Variations in Carbonate and Organic Abundances: What about carbonates and organic matter, which account for virtually the entire carbon inventory in CM/CI chondrites [15]? The proportion of carbonate progressively increases and the proportion of organics (both insoluble macromolecules and amino acids) decreases with progressive alteration in most CM chondrites [15, 16] (Fig. 1), consistent with observed differences in the magnitude of carbonate and organic features in Ceres and CM/CI spectra. These observations further support the hypothesis that Ceres is more thermally altered than CM/CI chondrites.

Explanation for Magnetite and Sulfide/Sulfate: Much of the Fe in CM/CI chondrites is present in phyllosilicates, which become progressively more Mg-rich as alteration proceeds (Fig. 2). Thus the Mg-rich serpentine in Ceres also supports extensive alteration [1]. The Fe liberated during alteration is mostly incorporated into magnetite. The proportion of the darkening agent in the modeled VIR spectrum of Ceres is $\sim 80\%$. This darkening agent is likely magnetite, although organics and sulfides could also serve this purpose. For

comparison, CM chondrites have only 0.6-5.2 wt.% magnetite and 0.6-3.9 wt.% sulfides [2]. Geochemical models for Ceres alteration based on a CM composition [14] generally yield ~35-45 wt.% magnetite, indicating that advanced alteration produces significant amounts of this dark component. In contrast to CM/CIs which contain both sulfide and sulfate, sulfur in Ceres may occur only as sulfide, because Ceres is massive enough to retain H_2 produced by serpentinization [17].

Implications of a CM/CI Composition for Ceres:

In this model, the CM/CI-like surface composition of Ceres formed by endogenic processes; extensive contamination with external meteoritic debris [18] seems unlikely, given that Ceres and bodies spectrally like it are rare in the main belt. Geochemical modeling using a CM starting composition [14] can produce the observed Ceres mineral assemblage, including ammoniated clay. Most thermal models based on a carbonaceous chondrite composition indicate a rocky core [14, 19], but complete ice-rock differentiation seems unlikely, because the formation of a lag deposit of rocky material from a pure ice shell would pose a contradiction.

Dependence on Parent Body Size: Ceres is the largest asteroid. One other large asteroid, 10 Hygiea, is spectrally similar to Ceres [20]; 324 Bamberga may also be spectrally similar but is smaller, and might represent a collisional fragment. We posit that the reason that asteroids spectrally similar to Ceres are uncommon is that only the largest ice-bearing bodies were heated sufficiently to release ammonia from organic matter and thereby incorporate it into clays. Extensive alteration is also favored on large bodies because the effective water/rock ratios are greater due to efficient hydrothermal convection, and they are less likely to lose hot fluids through episodic fracturing and venting [21]. The more pervasive alteration for Ceres, relative to carbonaceous chondrite parent bodies, is consistent with the partial differentiation of rock and ice within it, as inferred from thermal models [13, 14]. There is no evidence for such differentiation on CM/CI asteroids.

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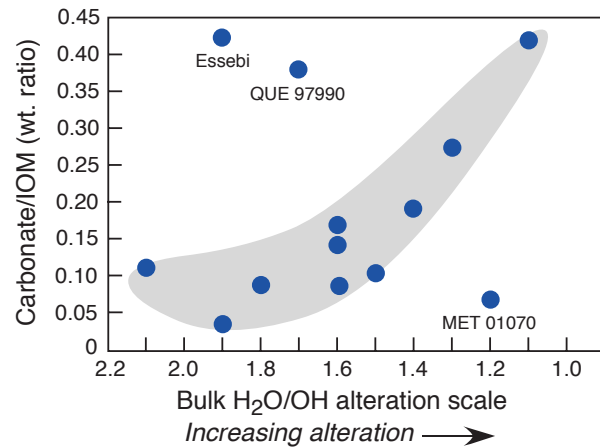


Fig. 1. Increase in carbonate and decrease in insoluble organics with progressive aqueous alteration in most CM chondrites [data from 15, 16]. Outliers are due to anomalous carbonate abundances.

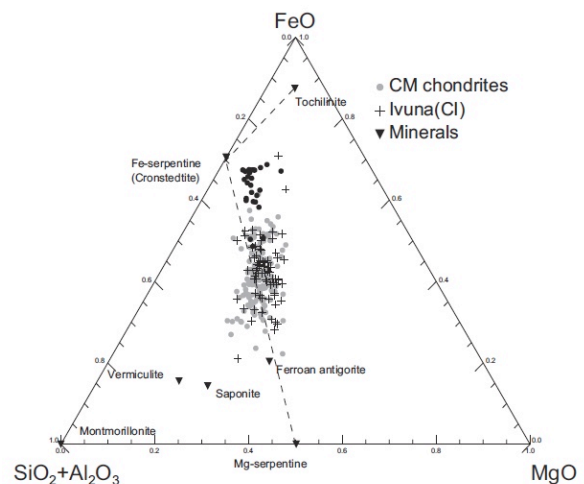


Fig. 2. Mg enrichment in serpentine during progressive alteration of CM/CI chondrites. Samples near the bottom of the figure are the most altered [6].