Carbonaceous chondrites as analogs for the composition and alteration of Ceres

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Abstract–The mineralogy and geochemistry of Ceres, as constrained by Dawn's instruments, are broadly consistent with a carbonaceous chondrite (CM/CI) bulk composition. Differences explainable by Ceres's more advanced alteration include the formation of Mg-rich serpentine and ammoniated clay; a greater proportion of carbonate and lesser organic matter; amounts of magnetite, sulfide, and carbon that could act as spectral darkening agents; and partial fractionation of water ice and silicates in the interior and regolith. Ceres is not spectrally unique, but is similar to a few other C-class asteroids, which may also have suffered extensive alteration. All these bodies are among the largest carbonaceous chondrite asteroids, and they orbit in the same part of the Main Belt. Thus, the degree of alteration is apparently related to the size of the body. Although the ammonia now incorporated into clay likely condensed in the outer nebula, we cannot presently determine whether Ceres itself formed in the outer solar system and migrated inward or was assembled within the Main Belt, along with other carbonaceous chondrite bodies.

INTRODUCTION

No meteorites have been identified as samples of dwarf planet Ceres. The Dawn mission's investigation of Vesta benefitted greatly from having howardite, eucrite, and diogenite meteorites for instrument calibration and for the mineralogic, geochemical, and geophysical interpretations of remote-sensing data acquired by the orbiting spacecraft (*Meteoritics & Planetary Science*, vol. 48, no. 11). Constraining Ceres's bulk composition and understanding its alteration history would be similarly enhanced if samples were available. Failing that, data interpretation would benefit from characterization of closely analogous extraterrestrial materials, if they could be confidently identified.

Carbonaceous chondrites have long been considered the closest analogs for the material at the surface of Ceres in existing meteorite collections (e.g., Gaffey 1976; Feierberg et al. 1985), although interpreted differences in mineralogy suggest that their specific alteration pathways may have differed (Rivkin et al. 2011). The more highly altered CM and CI classes of carbonaceous chondrite, especially, provide plausible analogs.

Interplanetary dust particles (IDPs) might provide another possible means of sampling Ceres. It has been suggested that ejected fragments of icy asteroids are too fragile to form a collisional family and survive transit to Earth (Rivkin et al. 2014). Vernazza et al. (2015) suggested that if there are any Ceres samples in the IDP

collection, they reside among the hydrated IDPs. Some mineralogic differences between hydrous IDPs and CM/CI chondrites occur, so we will also consider these samples as possible analogs.

Here we use data from Dawn to explore the similarities and differences between Ceres and these extraterrestrial materials. We conclude that Ceres and a few other large, spectrally similar asteroids in the Main Belt should have carbonaceous chondrite-like bulk compositions, but have been more pervasively altered than the meteorites.

ALTERATION OF CM/CI CHONDRITES AND HYDRATED IDPS

Carbonaceous chondrite parent asteroids are thought to have accreted as mixtures of rock and ice. Aqueous alteration occurred rapidly after the accretion of chondritic parent bodies, based on the ^{53}Mn-^{53}Cr ages (4–5 Myr after CAIs) of alteration minerals (Fujiya et al. 2012). The timing of alteration is consistent with decay of short-lived ^{26}Al as the heat source for melting of ice. Thermal evolution models for CM/CI asteroids (Grimm and McSween 1989; Young et al. 1999; Cohen and Coker 2000; Young 2001) show that the fusion heat of ice, the high heat capacity of water, and the ability of circulating water to enhance heat loss all contributed to thermal buffering, leading to low-temperature aqueous alteration rather than to thermal metamorphism.

The atmospheric entry speeds of hydrated IDPs suggest that they had asteroidal, rather than cometary, sources (Nier 1994). These particles experienced aqueous alteration, but likely on parent bodies different from the CM/CI asteroids (Bradley 2004).

CM Chondrites

The minerals produced during aqueous alteration of CM chondrites have been thoroughly characterized and the sequence of their formation has been worked out. Most CM chondrites are mixtures of unaltered and altered phases. The degree of alteration among them is quite variable, and scales of progressive alteration have been devised, based on the composition of phyllosilicates and other petrographic observations (Browning et al. 1996; Rubin et al. 2007), on the modal proportion of phyllosilicates (Howard et al. 2015), and on bulk abundances and isotopic compositions of volatile species (Alexander et al. 2013). The meteorites also show infrared spectral differences related to changing mineralogy (Beck et al. 2010; Takir et al. 2013), but this provides a relatively crude alteration scale, most useful for comparison with
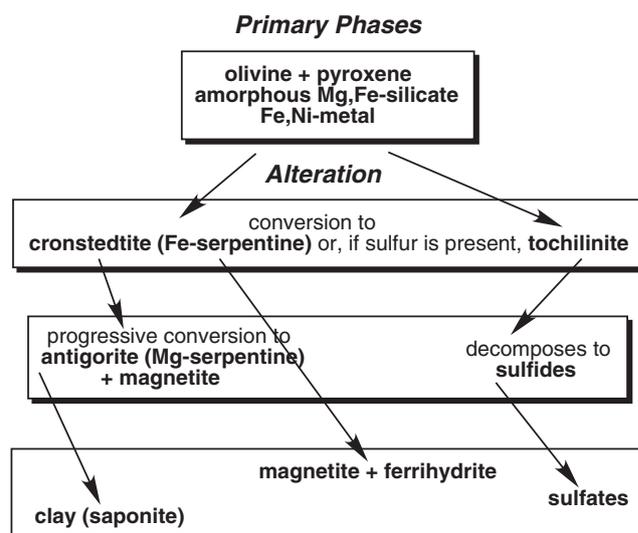

Fig. 1. Sequence of minerals formed during the progressive alteration of CM and CI chondrites. Modified from Howard et al. (2011).

asteroid spectra. A complicating factor is that most CM chondrites are breccias, and different degrees of alteration may be represented by clasts within a single meteorite.

The alteration mineral assemblage of CM chondrites was reviewed extensively by Brearley and Jones (1998) and Brearley (2006). The formation of these minerals has been placed in the context of progressive alteration reactions (McSween 1979, 1987; Tomeoka and Buseck 1985; Zolensky et al. 1993). Most recently, our understanding of the reaction sequence has been strengthened using alteration mineral proportions that were quantified by X-ray diffraction (XRD; Howard et al. 2011). The sequence of mineral formation, with inferred reactants, in CMs is summarized in Fig. 1. Anhydrous ferromagnesian silicates first form cronstedtite (Fe-serpentine) or, if sulfur is present, tochilinite (interlayered brucite $Mg(OH)_2$ and iron sulfide $Fe_{1-x}S$). Next, cronstedtite is progressively converted to antigorite (Mg-serpentine) + magnetite, and tochilinite decomposes to form sulfides. Further alteration of any remaining cronstedtite forms more magnetite + ferrihydrite $Fe_2O_3 \cdot \frac{1}{2}H_2O$, Mg-serpentine produces saponite $Ca_{0.3}(Mg, Fe^{2+})_3(Si,Al)_4O_{10}(OH)_2 \cdot nH_2O$, and sulfides are converted to sulfates. The changing bulk chemical compositions of the phyllosilicate matrix during alteration are illustrated in Fig. 2. Comparing the arrow with mineral compositions in this figure gives a sense of the relative proportions of these phases.

This sequence involves alteration and oxidation in an open system, with the addition of water and the escape of hydrogen as H_2 and CH_4. Correlations of
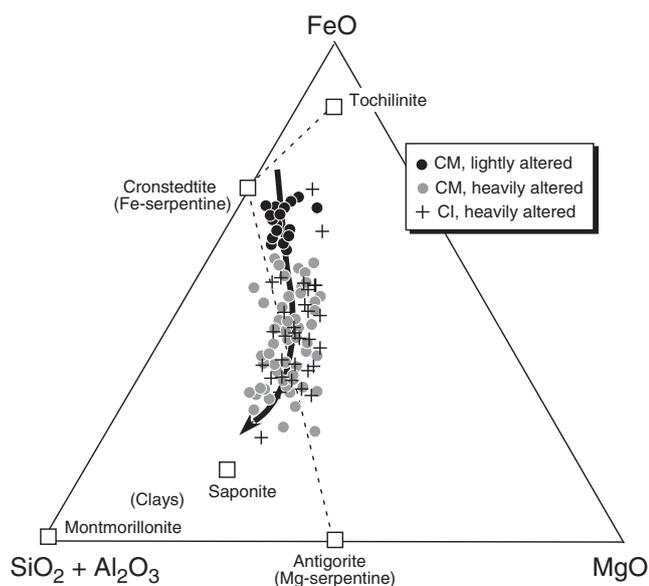
Fig 2. Progressively changing compositions of phyllosilicate matrix in CM/CI chondrites during alteration, as cronstedtite and tochilinite are replaced by antigorite and clays. Modified from Takir et al. (2013).

bulk hydrogen contents (Browning et al. 1996; Alexander et al. 2013) and hydrogen and nitrogen isotopes (Eiler and Kitchen 2004; Alexander et al. 2013) with alteration indices demonstrate the progressive loss of hydrogen and other volatiles.

Virtually all carbon in CM chondrites is contained in carbonates and organic matter. The carbonates include both calcite $CaCO_3$ and dolomite $CaMg(CO_3)_2$, although dolomite disappears in the most highly altered meteorites (De Leuw et al. 2010). The organic matter is mostly insoluble kerogen-like macromolecules, combined with lesser amounts of extractable aliphatic compounds (Sephton et al. 2000). The relative abundance of amino acids decreases with increasing degree of alteration in the meteorites, indicating that aqueous alteration has modified the organic matter in these chondrites (Glavin et al. 2010). Moreover, the proportion of insoluble organic matter (IOM) in CM chondrites decreases with progressive alteration, and carbonate abundance increases concomitantly (Alexander et al. 2015).

Differences in the degree of alteration suggest that the proportions and compositions of aqueous fluids and the temperatures of alteration were locally variable. Oxygen isotope fractionation between calcite and phyllosilicates or the water released from them indicates that CM alteration occurred at 0–80 °C (Clayton and Mayeda 1984; Baker et al. 2002). Geochemical modeling (Rosenberg et al. 2001) also supports low-temperature alteration (~25 °C) to produce the observed mineralogy.

CI Chondrites

The CI chondrites are almost completely altered, with few if any relict phases surviving (King et al. 2015a). The alteration mineralogy of these meteorites was reviewed by Brearley (2006), and includes Mg-Fe serpentines interlayered with saponite (clay), carbonates, sulfates, sulfides, magnetite, and ferrihydrite. This mineralogy is similar to that of the most highly altered CM chondrites. Although minor variations in mineral compositions (Morlok et al. 2006) and XRD-determined mineral proportions (King et al. 2015a) have been noted among the CIs, similarities in mineralogy within the small CI group have so far hampered any attempt to recognize an alteration scale.

As in the CM chondrites, carbon in CIs occurs as carbonates and organic matter. The CI chondrites contain four carbonate minerals: calcite, dolomite, breunnerite $(Mg,Fe,Mn)CO_3$, and siderite $FeCO_3$ (Endress and Bischoff 1996), likely reflecting microenvironments with different fluid compositions. The organic matter in CI chondrites is also a mixture of insoluble macromolecules and other soluble compounds (Sephton et al. 2000). However, the CI complements of amino acids are dominated by γ and δ isomers (referring to the structural position of the amine), in contrast to the α and β amino acids in CM chondrites (Glavin et al. 2010), presumably related to different rates of hydrolysis during aqueous processing.

Based on oxygen isotopes in coexisting carbonate and phyllosilicate, the temperatures of alteration of CI chondrites were higher (probably 100–150 °C) and the water:rock ratios were greater than for CMs (Clayton and Mayeda 1999), as appropriate for their more advanced degree of alteration.

Hydrated IDPs

Hydrated (also called "chondritic smooth") IDPs are composed primarily of phyllosilicates and carbonates. A few of these particles are mineralogically identical to the fine-grained matrices of CM/CI chondrites, but most hydrated IDPs show some differences (Bradley 2004). Rather than being dominated by serpentine, the phyllosilicates in these IDPs are mostly poorly crystalline smectite clays. Other phases include anhydrous silicates (pyroxene and olivine), glasses, magnetite, chromite, and iron-nickel sulfides. On average, these IDPs are enriched in carbonaceous materials relative to CM/CI chondrites, with carbon abundances averaging ~13 wt% (Keller et al. 1994). Both aliphatic and polyaromatic organic compounds have been identified. The differences in mineralogy and carbon content are sufficient to regard

hydrated IDPs as having been derived from objects distinct from the CM/CI parent bodies.

COMPARISON WITH CERES SPECTRA AND COMPOSITIONAL CONSTRAINTS

Visible and Infrared Reflectance Mineralogy

Dawn's visible and infrared reflectance (VIR) spectrometer (De Sanctis et al. 2011) has provided a spectrum that constrains mineralogy. Modeling indicates the following minerals provide the best spectral match for Ceres (De Sanctis et al. 2015): Mg-serpentine (antigorite), NH_4^+-bearing clay, Mg,Ca-carbonate (dolomite), and a darkening component (possibly organic matter, magnetite, and/or sulfide). This assemblage is widespread on Ceres's surface, with only minor areal differences in the proportions of phases (Ammannito et al. 2016).

The global spectrum of Ceres (De Sanctis et al. 2015) is compared with those of CM/CI carbonaceous chondrites in Fig. 3. The chondrite spectra were obtained under vacuum conditions to allow direct comparison with asteroid spectra (Takir et al. 2015). All these spectra show a pronounced serpentine feature for structural hydroxyl at ~2.7 μm, but a spectral feature for ammoniated clay feature at 3.1 μm appears only in the Ceres spectrum. The ~4.0 μm carbonate feature in the Ceres spectrum is deeper than in the spectra of CM/CIs, and the 3.3–3.5 μm organics features are more pronounced in CM/CI spectra than in the Ceres spectrum.

Compositional anomalies occur in localized areas on Ceres. Bright regions, most prominently in Occator crater, contain deposits of natrite Na_2CO_3 (De Sanctis et al. 2016). The Na-carbonate (45–80 vol%) is mixed with Al-phyllosilicates or with other ammoniated species (carbonate or chloride). Natrite also is concentrated on the flanks of Ahuna Mons, likely a cryovolcanic dome (Ruesch et al. 2016). Exposed water ice (a few vol%) has been identified spectrally in only a few craters (Combe et al. 2016). Localized concentrations of organic matter (4–9 vol%) have been found in the northern latitudes, mostly around Ernutet crater (De Sanctis et al. 2017), although the source of these organics is as yet unclear and they might be exogenic (Pieters et al. 2017). The ~3.4 μm spectral subfeatures of organics are similar to those of the kerogen-like IOM extracted from CM/CI chondrites (Alexander et al. 2007). All these anomalous compositions are associated with relatively fresh, presumably young craters or cryovolcanic features on Ceres, and may point to differences (either vertical or horizontal) in the mineralogy of the subsurface that have been exposed by venting and/or eruption (Krohn et al. 2016).
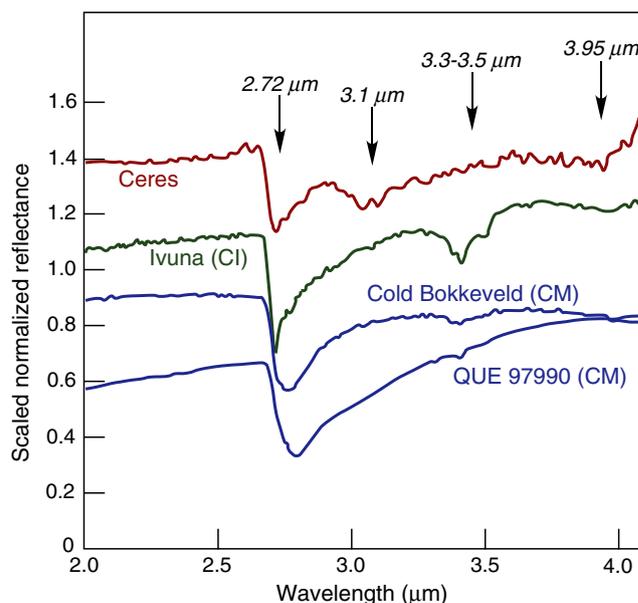

Fig. 3. Reflectance spectra of Ceres (De Sanctis et al. 2015) and CM/CI chondrites taken under vacuum (simulating space) conditions (Takir et al. 2013). See text for identification of the identified spectral features. (Color figure can be viewed at wileyonlinelibrary.com.)

Gamma Ray and Neutron Detector Geochemistry

Dawn's gamma ray and neutron detector (GRaND) instrument (Prettyman et al. 2011) measures γ-rays and neutrons to constrain the abundance of selected elements. Despite the scarcity of exposed water ice (which is not stable at the temperatures of the Main Belt) on Ceres's surface, neutron-counting data indicate significant hydrogen, interpreted as water ice, in the uppermost few decimeters of the regolith at mid-to-high latitudes (Prettyman et al. 2017). At latitudes near the equator, water occurs primarily in hydrous minerals, since stability models predict water ice there is at depths greater than GRaND can sense (Schorghofer 2016; Prettyman et al. 2017). Calculation of the H_2O abundance based on the relative volumetric (converted to wt%) proportions of minerals determined by VIR (ignoring the darkening component and normalizing other components to 100%) gives a value of ~12.5 wt%, compared to GRaND's value of 17 ± 2 wt% based on nuclear spectroscopy and stability modeling (Prettyman et al. 2017). The discrepancy between these values may reflect the presence of hydrogen in organic matter in the shallow subsurface beyond VIR's reach. In any case, the Ceres equatorial water-equivalent hydrogen (WEH) is similar to measurements of hydrogen in CI chondrites (14–19 wt% WEH, depending on the analysis technique) and the upper limits in CM chondrites (14–15 wt% WEH) (Alexander et al. 2012, 2013; Garenne et al. 2014; King et al. 2015b) (Fig. 4).
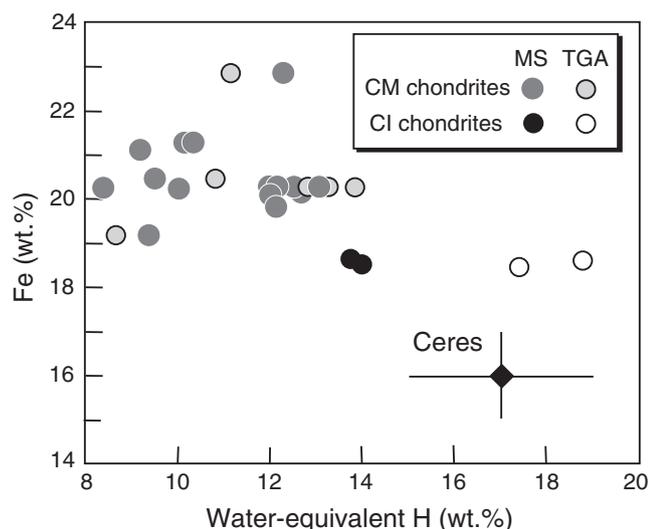
Fig. 4. Iron and water-equivalent hydrogen (WEH) measured in Ceres's equatorial regolith compared to analyses of CI and CM chondrites (Prettyman et al. 2017). WEH analyzed by different techniques—mass spectrometry (MS), Alexander et al. (2012, 2013); and thermogravimetric analysis (TGA), Garenne et al. (2014)—are shown. See Prettyman et al. (2017) for discussion of systematic uncertainties.

Other elements in the uppermost regolith at mid-to-high latitudes are presumably diluted by roughly 10 wt% ice, so we will focus on low latitudes where GRaND is sensitive to the composition of the ice-free regolith. The equatorial iron content of the regolith (Prettyman et al. 2017) is 16 ± 1 wt%, a value lower than for carbonaceous chondrites. In a plot of H versus Fe (Fig. 4), Ceres does not fall on the CI hydration line. If a spectrally neutral additive does not contain hydrogen, then removing it implies even greater hydrogen content in the ice-free material. Prettyman et al. (2017) suggested carbonaceous matter as a possible neutral component, and its removal would produce hydrogen and iron values close to the mass spectrometer measured values of CIs (Alexander et al. 2012, 2013). The measurements of iron and hydrogen jointly imply that Ceres underwent some degree of ice-rock fractionation, if the accreted materials were similar in composition to carbonaceous chondrites (Prettyman et al. 2017).

GRaND's imprecisely constrained carbon estimate lies between the abundances in CI chondrites (3.5 wt%) and dust from comet Halley (24 wt%). The equatorial average potassium concentration is 420 ± 40 μg g^{-1} (Prettyman et al. 2017), falling between the average abundances in CI (550 μg g^{-1}) and CM (370 μg g^{-1}) chondrites. Although potassium is soluble and can readily be lost or gained during aqueous processes, it is also volatile and can be fractionated by nebular processes; without knowing the bulk K content for Ceres, we cannot determine its behavior during Ceres's internal evolution.

Models of Ceres's Interior

Based on its moment of inertia factor of 0.37, Ceres is partially differentiated (Park et al. 2016), in agreement with model predictions (Castillo-Rogez and McCord 2010; Neveu and Desch 2015). Because the surface composition may not necessarily be representative of the whole, understanding the interior structure of Ceres has implications for its bulk composition.

With a bulk density (2162 ± 8 kg m^{-3}; Russell et al. 2016) between rock and ice, bulk Ceres is estimated to contain 17–27 wt% water ice (McCord et al. 2011). Heating by radioactive isotopes allowed ice to melt and be mobilized, fractionating ice from rock in the interior and promoting the aqueous alteration described above. A two-layer model for Ceres's interior (Park et al. 2016) envisions a rocky core having a density of CM/CI chondrites overlain by a 70–190 km-thick icy shell. Admittance modeling (Ermakov et al. 2017) provides an independent assessment of a 40–50 km thick icy shell. Isostacy models suggest densities for the icy shell and rocky mantle of ~1250 and ~2400 kg m^{-3}, respectively. Based on the limited viscous relaxation of craters <400 km diameter on Ceres and a simple-to-complex crater transition size that is similar to icy satellites, this icy shell is calculated to contain on the order of 70 vol% mechanically strong solids—phyllosilicates, carbonates, salts, and clathrates (Bland et al. 2016; Castillo-Rogez et al. 2017; Fu et al. 2017). The surface of Ceres may be a lag deposit of these non-icy components, remaining behind after sublimation of ice. Because of Ceres's distinctive spectrum, it is unlikely to be contaminated by significant amounts of exogenic CM/CI materials, although a spectrally neutral contaminant cannot be ruled out. Modeling by Daly and Schultz (2015) found the greatest retention of projectile material for an icy target; Dawn's GRaND and gravity data show that Ceres's crust is more rock than ice, supporting the idea of limited exogenic contamination. In mid-infrared spectra of Ceres, Vernazza et al. (2017) found evidence for ~20% anhydrous silicates that they believe to be contamination from a nearby dust band. However, that coating does not appear to carry a signature in VIR data, which Vernazza et al. (2017) ascribed to the small grain size of the anhydrous dust. Consequently, the surface mineralogy should provide an indication of the composition of Ceres's interior.

RATIONALIZING THE DIFFERENCES

Geochemical data indicate that Ceres's surface composition is broadly similar to that of CM/CI chondrites, allowing for dilution by concentrations of water ice at mid-to-high latitudes and possibly minor elemental fractionations during aqueous alteration.

Ceres's layered internal structure can also be understood as resulting from ice-rock fractionation from a carbonaceous chondrite bulk composition. We have no constraint on the original or even current ice contents of CM or CI parent bodies, so we cannot make a direct comparison with Ceres's bulk ice content. Most present-day C-class asteroids appear to have lower densities than Ceres, but also may have high porosities (Carry 2012). Estimated water/rock ratios during alteration of individual meteorite samples (0.3–0.6 for CMs, >1 for CIs; Clayton and Mayeda 1999) likely reflect local fluid flow rather than bulk ice content (Young et al. 1999), and internal pressurization may have caused these asteroids to vent some of the original fluids to space (Grimm and McSween 1989; Young 2001).

Despite the geochemical similarities, Ceres's mineralogy exhibits some characteristics that are distinct from carbonaceous chondrites. As argued below, these can be rationalized as products of more extensive aqueous alteration in Ceres.

Phyllosilicate Compositions

The serpentine on Ceres is Mg-rich, and clay, albeit ammoniated, is relatively abundant. Mg-rich serpentine and clay are characteristics that mimic those of highly altered CM (Howard et al. 2011) and CI chondrites (King et al. 2015a). Clays are also prominent in hydrated IDPs (Bradley 2004).

Ammoniated clays have not been detected in carbonaceous chondrites and, in fact, clays are relatively uncommon in the meteorites. Instead, NH_3 is a component of organic matter (both macromolecular species and amino acids) in CM/CI chondrites (Pizzarello and Williams 2012). The ammonia-bearing organic compounds may have formed from reactions of interstellar organic precursors with accreted NH_3-dihydrites under the conditions of parent-body alteration (0–125 °C; Brearley 2006). Experiments reveal that the ammonia in carbonaceous chondrites is released upon hydrothermal treatment at 300 °C in 6 days (Pizzarello and Williams 2012), and plausibly at lower temperatures if heating periods were longer (300 °C/6 days is the only experimental condition explored so far). Owing to Ceres's potential for hydrothermal circulation, thermal evolution models suggest modest temperatures (<100 °C; Travis et al. 2016), although warmer temperatures could have been reached in Ceres's core (Castillo-Rogez and McCord 2010). In contact with liquid water, NH_3 forms NH_4^+, which exchanges readily with univalent cations in clays, especially smectites, but not with serpentine (Ehlmann et al. 2017). This substitution could have occurred in a cooler environment nearer the surface (Castillo-Rogez et al. 2017).
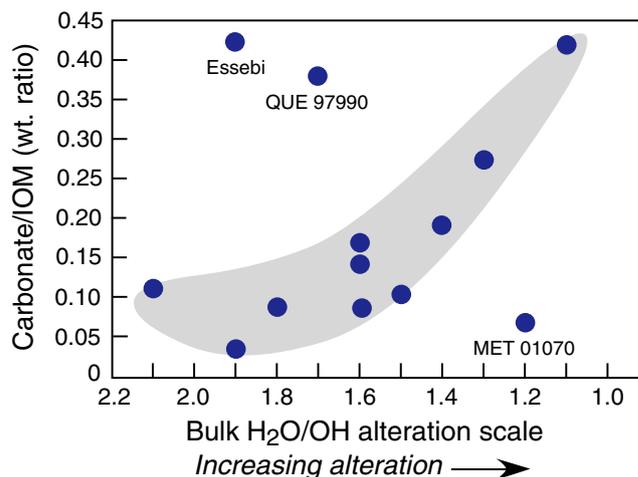

Fig. 5. Increase in the wt ratio of carbonate to insoluble organic matter (IOM) with degree of alteration (bulk H_2O/OH) in CM chondrites. Data are from Alexander et al. (2013, 2015). Labeled outliers are thought to be due to anomalous carbonate abundances. (Color figure can be viewed at wileyonlinelibrary.com.)

Forms of Carbon

With progressive alteration in most CM chondrites, the proportion of carbonate increases and the proportions of organic compounds (both insoluble macromolecules and amino acids) decrease (Alexander et al. 2013, 2015). This is illustrated in Fig. 5, where the alteration scale is bulk H_2O/OH (Alexander et al. 2013). The outliers are due to anomalous carbonate abundances. This trend in chondrites is thought to reflect the oxidation and conversion of organic matter to carbonates, and further supports advanced alteration on Ceres.

The alteration trend is consistent with observed differences in the magnitude of carbonate and organic features in Ceres and CM/CI spectra, which suggest that carbonate is more abundant and organics are less abundant on Ceres. An uncertainty is the possible decay of organic signals as a consequence of space weathering. In any case, the comparison of Ceres and CM/CI spectra further supports pervasive alteration in Ceres. Locally prominent sodium carbonate on Ceres is not observed in CM/CIs. NaCl, CO_2, and NH_3 in aqueous solution can promote the precipitation of sodium carbonate, suggesting that the compositions of at least late-stage fluids in Ceres may have differed from those in carbonaceous chondrite parent bodies (Castillo-Rogez et al. 2017).

Iron Mineralogy

Much of the iron in CM/CI chondrites is present in phyllosilicates, which become progressively more Mg-rich

as alteration proceeds. The iron liberated by serpentine and tochilinite alteration is mostly incorporated into magnetite and sulfides (Fig. 1). CM chondrites have 0.6–5.2 wt% magnetite and 0.6–3.9 wt% sulfides (Howard et al. 2011), the larger amounts corresponding to the more altered meteorites. The more extensively altered CI chondrites have 6–10 wt% magnetite and 4–7 wt% sulfides (King et al. 2015a). In contrast to CM/CIs that 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 (McKinnon and Zolensky 2003; Castillo-Rogez et al. 2017).

The volumetric proportion of the darkening agent in the modeled VIR spectrum of Ceres is very high, ~80%. However, the VISNIR spectra of the various components do not add linearly, so the proportion of the dark component in the VIR deconvolution may be overestimated. Magnetite and sulfides would both serve as effective darkening agents for Ceres. However, GRaND's measured iron abundance implies an upper limit on magnetite content in the regolith of ~6 wt%, much lower than the spectrally modeled darkening agent. Alternatively, Clark (1983) found that an admixture of 5 wt% carbon black diminished the reflectance of a montmorillonite spectrum from 50% to 10%, so devolatilized organic matter could also play a significant role (Hendrix et al. 2016).

IMPLICATIONS FOR CERES ORIGIN AND EVOLUTION

Is Ceres a Carbonaceous Chondrite Asteroid?

The linkages described here between Ceres and carbonaceous chondrites suggest that Ceres's bulk elemental composition is likely to be CM/CI-like. The most altered carbonaceous chondrites are a better match for Ceres than are hydrated IDPs (Vernazza et al. 2015), because the latter contain clays without serpentine, unlike Ceres. The carbonaceous chondrites experienced nearly isochemical alteration, attributed to low porosity and high rock:water ratios. However, Ceres has been subjected to more extensive aqueous alteration than the CM/CI chondrites, likely due to more efficient hydrothermal circulation, as suggested by the observed partial differentiation of ice and rock. Because we do not know the original water contents of carbonaceous chondrite parent bodies, we cannot speculate as to whether Ceres may have accreted with more water ice.

Although a connection with CM/CIs seems strong, Ceres does not appear to be a parent body for known carbonaceous chondrites. It has no asteroid family that would be a plausible source for meteorites, nor does its orbit reside near a resonance that could perturb them into Earth-crossing orbits (Rivkin et al. 2011). Moreover, any materials ejected from Ceres's surface might be too fragile to survive a journey to Earth (Rivkin et al. 2014; Vernazza et al. 2015).

An initial chemical analysis of the Orgueil CI chondrite, performed in 1864 soon after its fall and recovery, indicated small amounts of astringent ammonia salts (Gounelle and Zolensky 2014) that have now apparently been lost to the terrestrial atmosphere. This intriguing fact prompted us to consider the possibility that Ceres might be the CI chondrite parent body. Gounelle et al. (2006) used descriptions of the Orgueil fall to constrain its entry velocity and orbit, concluding that aphelion was beyond Jupiter's orbit and therefore that the meteorite was possibly derived from a comet. This calculation, however, assumes that Orgueil was not produced by a cascade of collisions that might have altered its original orbit. That aside, there remain the other differences in mineralogy between Ceres and CI chondrites already described. Without other supporting evidence, we surmise that the meteorite bears no direct relationship with Ceres.

Is Ceres Unique?

Ceres is, by far, the largest asteroid (allowing it be classified as a dwarf planet), and its spectrum is unusual. However, it is not spectrally unique. Several other asteroids—10 Hygiea and 704 Interamnia—have very similar spectra (Takir and Emery 2012; Rivkin et al. 2014) and are also among the largest bodies (with mean diameters of 444 km and 307 km, respectively) in the Main Belt. If we interpret spectral similarity to Ceres as an indication of similar advanced degrees of alteration, we can infer that the thermal history and alteration intensity of carbonaceous chondrite asteroids are related to size, as previously noted for smaller chondritic asteroids (Fornasier et al. 2014) and suggested for larger bodies (Young et al. 2003; Bland et al. 2013). Admittedly, the available signal-to-noise for spectra of small bodies may not conclusively rule out that some of them may have spectra similar to Ceres. However, 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. More extensive alteration is favored on large bodies because the effective water:rock ratios are greater due to hydrothermal convection, and they are less likely to lose fluids through episodic fracturing and venting (Young 2001). Low thermal conductivity in the outer shell promoted by clathrate hydrates and redistribution of ^{40}K during
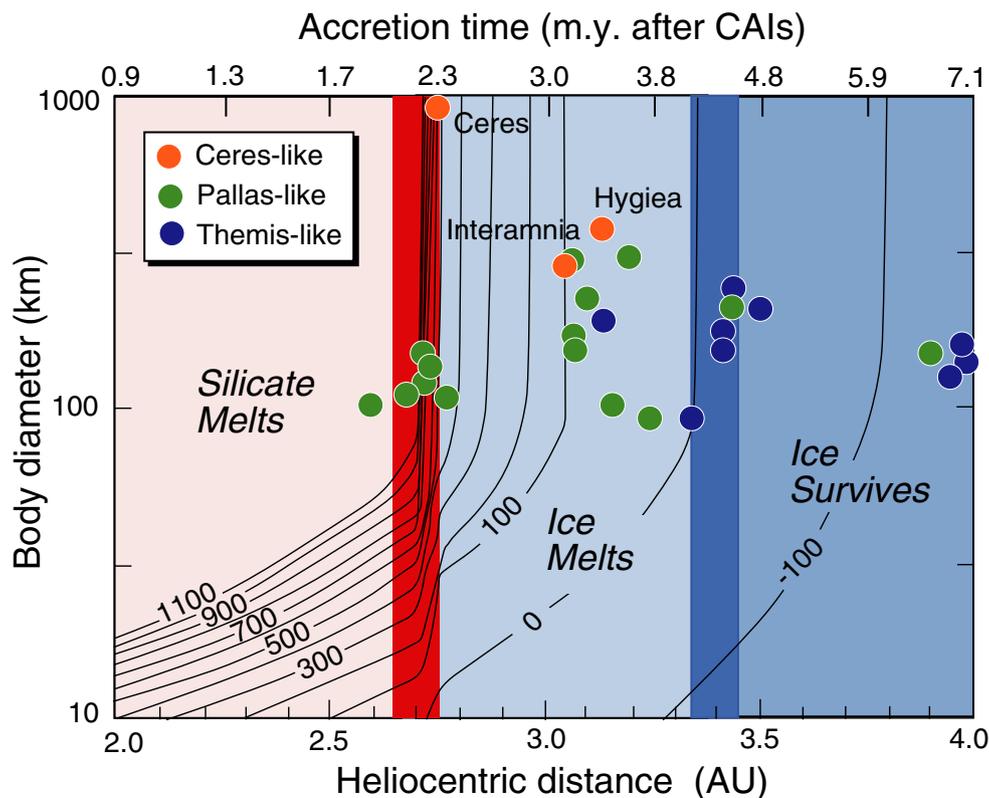
Fig. 6. Modeled thermal histories of asteroids of varying sizes, based on [26]Al heating and assuming that accretion time (top) varied systematically with heliocentric distance (Grimm and McSween 1993). Peak temperatures (°C) are indicated by contours that divide the asteroid belt into regions where silicates melt or are metamorphosed, ice melts and drives aqueous alteration, and ice survives. Ceres and two spectrally similar asteroids (Hygiea and Interamnia) are the largest C-type asteroids. Asteroids with Pallas-like spectra are altered CM/CI-like bodies, and those with Themis-like spectra are currently ice-bearing. Modified from Takir and Emery (2012). (Color figure can be viewed at wileyonlinelibrary.com.)

alteration may account for temperatures warm enough to allow a subsurface brine reservoir at present that could periodically be tapped by impacts or erupt (Castillo-Rogez et al. 2017).

A model attempting to explain the solar system distribution of asteroids with different thermal histories (Grimm and McSween 1993) is shown in Fig. 6. The model assumes that bodies forming closer to the Sun accreted earlier and thus had more [26]Al, the putative heat source for silicate melting, thermal metamorphism, and ice melting. Although this model may be somewhat dated, in light of more recent hypotheses of orbital scrambling in the Main Belt, it is interesting that the heliocentric distributions of Pallas-like (interpreted to be similar to CM/CIs, in which ice melted; Takir and Emery 2012) and Themis-like (interpreted to still be ice-zbearing; Rivkin and Emery 2010) asteroids (Fig. 6) are generally consistent with this model (Takir et al. 2015). Ceres, Hygiea, and Interamnia are among the largest C-class bodies (Fig. 6), and they are apparently the most heavily altered.

Where Did Ceres Form?

It has been speculated that Ceres, like the P- and D-type asteroids (Levinson et al. 2009), might have accreted in the Kuiper Belt and migrated inward (McKinnon 2008), although the probability of capture of an object of Ceres's size is low (McKinnon 2012). Larger planetesimals like Ceres may have been scattered when the giant planets cleared their planetesimal reservoirs toward the end of accretion (Grazier et al. 2014). The presence of ammoniated phyllosilicates and sodium carbonate may support the hypothesis that Ceres, or at least its proto-constituents, formed in the outer solar system (De Sanctis et al. 2015, 2016). On thermodynamic grounds, ammonia has been predicted to be the major nitrogen species in the nebula (Lodders 2003), and numerous models predict its condensation as dihydrate in the outer solar system.

As an alternative, ammonia hydrates formed at >5 AU could have survived inward migration and been incorporated into Ceres (Mousis and Alibert 2005).

However, the opening of Jupiter's gap in the early solar nebula could have led to ammonia depletion in the small planetesimals considered in that model (Turner et al. 2012). Conversely, Dodson-Robinson et al. (2009) calculated that the condensation fronts of ammonia hydrates and water ice coincided and swept inward to ~2.7 AU in the asteroid belt. In that case, Ceres could have accreted from rocky and icy bodies near its present location in the Main Belt.

The linkage of Ceres with carbonaceous chondrites may further support a less distant formation location. The present orbits of Ceres and other spectrally similar asteroids reside near the locations of Pallas-like asteroids interpreted to have CM/CI-like compositions (Fig. 6). The ammonia-bearing organic compounds in CM/CI chondrites may have formed in parent bodies from reactions of interstellar organic precursors with accreted NH_3-hydrate during aqueous alteration. The chondrites also have deuterium/hydrogen (D/H) ratios consistent with formation near the snow line within the asteroid belt. Although there is no unequivocal indication that hydrated CM/CI asteroids formed near their present locations, stable isotope anomalies (D17O, e54Cr, e50Ti) in carbonaceous chondrites have been interpreted to reflect their formation in the outer solar system (Warren 2011). Krot et al. (2015) noted that meteorite observations provide no evidence supporting dynamical models that suggest they formed beyond the giant planets and were implanted into the Main Belt.

CONCLUSIONS

Constraints on the composition of dwarf planet Ceres, provided by its mineralogy and geochemistry, are consistent with CM/CI-like carbonaceous chondrites. These meteorites give insights into the alteration reactions and processes on Ceres. Differences can be rationalized as products of more advanced alteration on Ceres

1. Ammoniated clay may have formed when NH_3 was released from organic compounds during heating.
2. Mg-rich serpentine has replaced Fe-serpentine (cronstedtite) during progressive alteration.
3. The relative proportion of carbonate has increased at the expense of organic compounds.
4. Magnetite and sulfides formed during alteration may serve as a darkening agent for Ceres spectra (along with organic matter or carbon).
5. Partial differentiation of Ceres fractionated water ice and silicates in the interior, and water ice has been concentrated in the regolith at high latitudes.

Ceres is spectrally distinctive but not unique among the largest asteroids; Hygiea and Interamnia have similar spectra and likely have also suffered advanced alteration. The orbits of all these bodies lie in the same part of the Main Belt as CM/CI-like asteroids. The largest carbonaceous chondrite bodies have experienced the greatest degrees of alteration, likely because convection increases the effective water:rock ratios and larger bodies are less prone to fracturing and venting of volatiles.

Ammonia is commonly thought to have condensed as dihydrate in the outer solar nebula, leading to the idea that Ceres, or at least its proto-components, formed beyond 5 AU. Although that remains a possibility, there is no a priori reason that Ceres had to have formed at great heliocentric distance, unless other carbonaceous chondrite asteroids did as well. Its location, along with other large, spectrally similar bodies, in the central Main Belt where CM/CI-like bodies occur suggests that its properties may reflect its size, rather than its formation location. Ammonia ice that condensed in the outer solar system could have drifted inward to be incorporated into all these bodies, which then formed NH_3-bearing organics and, ultimately, NH_3-bearing clays. This scenario can be tested with experimental study of organic degradation under conditions appropriate to Ceres and carbonaceous chondrite parent bodies and with continued spectral characterization of bodies in the outer Main Belt.

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