



Formation of brucite and cronstedtite-bearing mineral assemblages on Ceres



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ABSTRACT

Dwarf planet Ceres is the largest body in the main asteroid belt with a rocky surface and uncertain internal structure. Spectra of Ceres in near- and mid-infrared wavelengths are consistent with the occurrence of brucite, Mg-bearing carbonates, and an Fe-rich phyllosilicate cronstedtite. Spectra of 10 Hygiea and 324 Bambergia imply similar compositions. Here, we considered stabilities of these minerals to constrain their origin. Cronstedtite is most stable at the temperature of $\sim 0^\circ\text{C}$ at moderately oxidizing aqueous conditions and at high water/rock ratios. Although cronstedtite could form on planetesimals, the apparent lack of serpentine may indicate its formation by Ceres' temporary surface solutions. Brucite forms at a low activity of dissolved SiO_2 , at a low fugacity of CO_2 , and at highly alkaline pH . Brucite and cronstedtite do not form together and may not form deep in the Ceres' interior. The absence of Mg serpentine from Ceres' surface materials and the unlikely occurrence of very olivine-rich rocks do not indicate a formation of brucite through serpentinization of such rocks. Brucite could form by transient near-surface fluids which do not equilibrate with silicates. Temporary fluids could deposit Mg carbonates before, after, or together with brucite at near-surface conditions that favor CO_2 degassing. Regardless of Ceres' internal structure, internal thermal and aqueous processes may not affect cold near-surface layers. Percolation of interior fluids is not consistent with the lack of detection of low-solubility salts. However, impacts of ice-rich targets during the Late Heavy Bombardment could account for transient aqueous environments and unusual surface mineralogies of Ceres, Hygiea, and Bambergia. Brucite and Mg carbonates could have formed through hydration and carbonation of MgO evaporated from silicates. Apparently abundant carbonates may indicate an ample impact oxidation of organic matter, and the occurrence of brucite with cronstedtite may reflect turbulent and disequilibrium environments. Clay-like homogeneous surface materials on Ceres could be gravitationally sorted deposits of impact clouds.

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1. Introduction

Dwarf planet (1) Ceres is the largest and most massive body in the main asteroid belt (Table 1; McCord et al., 2011). The polar flattening determined with Hubble Space Telescope is consistent with a relaxed differentiated body with a rocky core and an icy mantle (Thomas et al., 2005; Castillo-Rogez and McCord, 2010), though such an internal structure awaits verification. Initially accreted rocks may not survive atop a water mantle because they would sink through the ice or an ocean (McCord and Sotin, 2005), and the origin of unique spectral characteristics of Ceres' rocky surface (Rivkin et al., 2011) remains to be understood in the framework of a differentiated structure. Ceres' dimensions determined with the Keck II telescope (Carry et al., 2008) do not exclude the undifferentiated or partially differentiated body without icy mantle (Zolotov, 2009). In the latter case, Ceres could consist of hydrated ice-poor

rocks with $\sim 10\%$ porosity similar to compacted CI/CM carbonaceous chondrites. Circular albedo features (Li et al., 2006; Carry et al., 2008, 2012) may be indicative of impact craters, consistent with craters on other asteroids and cratering models for Ceres (de Elía and Di Sisto, 2011). Large craters may either reflect a mantle-free internal structure or signify an impact deposition of rocks atop an icy mantle, as we discuss below. These controversies could be resolved after the determination of Ceres' gravity moments together with surface topography and morphology with Dawn in 2015 (Russell et al., 2007). Additional constraints could be gained from composition of surface materials, if formation conditions of observed minerals and chemical patterns are understood.

1.1. Observational data on surface composition

The current knowledge about Ceres' surface mineralogy is based on telescopic observations in the ultraviolet, visible, near-, and mid-infrared (IR) spectral ranges (Table 2; Rivkin et al., 2011). Ceres has the visual geometric albedo of ~ 0.09 with very minor

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Table 1
Physical characteristics of asteroids with the 3.06 μm spectral feature.

	Diameter (km) ^a	Mass (kg)	Density (g/cm ³)
1 Ceres	945 \pm 23	9.44 \pm 0.06 \times 10 ²⁰ 9.35 \pm 0.14 \times 10 ^{20b}	2.13 \pm 0.15 2.11 \pm 0.35 ^c
10 Hygiea	422 \pm 26	8.63 \pm 0.52 \times 10 ¹⁹ 8.67 \pm 0.15 \times 10 ^{19d}	2.19 \pm 0.42 2.08 \pm 0.10 ^d
324 Bamberga	235 \pm 8	1.03 \pm 0.10 \times 10 ¹⁹	1.52 \pm 0.20

Notes: The data are mostly from Carry (2012).

^a The volume-equivalent diameter.

^b Kovačević (2012).

^c Based on the mass from Kovačević (2012) and the diameter from Carry (2012).

^d Baer et al. (2011).

(<6%) variations (Li et al., 2006; Carry et al., 2008, 2012). The centimeter-wave, millimeter-wave, and sub-millimeter observations indicate a low-density dry clay-like surface material with a low thermal inertia and high porosity (Webster et al., 1988; Mitchell et al., 1996; Chamberlain et al., 2009). Despite a similarity of Ceres' near-IR reflectance spectra with that of metamorphosed carbonaceous chondrites (Hiroi et al., 1995), there is no good meteoritic spectral analog for Ceres' materials (Rivkin et al., 2011). The broad absorption feature near 3 μm indicates a presence of hydrated and/or OH-bearing minerals (Lebofsky, 1978; Lebofsky et al., 1981; Feierberg et al., 1981). Ceres' near- and mid-IR spectra are

Table 2
Minerals suggested in Ceres' surface materials based on telescopic observations in the near- and mid-IR spectral ranges.

Mineral	References
Mg carbonates ^a	Rivkin et al. (2006), Milliken and Rivkin (2009) and Rivkin and Volquardsen (2010)
Brucite	Milliken and Rivkin (2009)
Cronstedtite	Rivkin et al. (2006), Milliken and Rivkin (2009)
Magnetite	Larson et al. (1979), Milliken and Rivkin (2009) and Rivkin et al. (2011)

Notes: Formulas of minerals are shown in Table 3.

^a Magnesite and/or dolomite.

Table 3
Minerals and their standard Gibbs free energies of formation, $\Delta_f G^0$ (25 $^\circ\text{C}$, 1 bar).

Mineral	Formula	Abbreviation	$\Delta_f G^0$ (kJ/mol)	Reference
Magnetite	Fe ₃ O ₄	Mt	-1012.3	HP98
Greenalite	Fe ₃ Si ₂ O ₅ (OH) ₄	Gr	-2993.0	H78
Fe–Mg serpentine	(Fe _{0.6} Mg _{0.4}) ₃ Si ₂ O ₅ (OH) ₄	Fe–Mg-sp	-3409.8	MZ
Chrysotile	Mg ₃ Si ₂ O ₅ (OH) ₄	Chr	-4030.7	HP98
Cronstedtite	Fe ²⁺ ₂ Fe ³⁺ ₂ SiO ₅ (OH) ₄	Crn	-2613.4 ^d -2618.4 ^e -2619.2 -2606.6	WJ04 V8R6 THER W10
Mg–Fe cronstedtite ^a	Fe ²⁺ _{0.4} Mg _{1.6} Fe ³⁺ ₂ SiO ₅ (OH) ₄	Mg–Fe-crn	-3170.9	MZ
Mg-cronstedtite	Mg ₂ Fe ³⁺ ₂ SiO ₅ (OH) ₄	–	-3308.7	WOL
Goethite	FeOOH	gth	-490.6	N08
Ferrihydrite	Fe(OH) ₃ ^c	fr	-711.0	N08
Amorph. SiO ₂ ^b	SiO ₂	SiO ₂ (am)	-848.9	H78
Brucite	Mg(OH) ₂	br	-834.3	HP98
Magnesite	MgCO ₃	ms	-1027.8	H78
Siderite	FeCO ₃	sid	-679.5	H78
Talc	Mg ₃ Si ₄ O ₁₀ (OH) ₂	tlc	-5516.7	HP98
Fe-talc	Fe ₃ Si ₄ O ₁₀ (OH) ₂	FeTlc	-4451.1	HP98

^a The Mg–Fe cronstedtite corresponds to the composition of a most Mg-rich phase reported in literature with Mg/(Mg + Fe) = 0.4 (Zega and Buseck, 2003).

^b Quartz is not considered because it is absent from carbonaceous chondrites.

^c The nominal formula used here.

^d The value used in calculations of equilibrium constants and phase diagrams (Table 4, Figs. 1–4).

^e The value used in calculations of chemical equilibria by the Gibbs free energy minimization method (Figs. 5–7). HP98, Holland and Powell (1998); H78, Helgeson et al. (1978); MZ, the energy was evaluated assuming ideal mixing between Mg and Fe end members; WJ04, Wolery and Jove-Colon (2004); V8R6, the LLNL database "thermo_-com_V8R6+" (1996) from the GWB site (<http://www.gwb.com>); THER, the database "thermo_dat.txt" (1986) from the GWB site; W10, Wilson (2010); WOL, evaluated by Thomas Wolery; N08, Navrotsky et al. (2008). Thermodynamic properties of aqueous species were from Shock et al. (1989, 1997).

consistent with the presence of Fe phyllosilicate cronstedtite (Rivkin et al., 2006; Milliken and Rivkin, 2009) (Tables 2 and 3). Although cronstedtite provides a better fit of mid-IR spectra than Mg-serpentine (Milliken and Rivkin, 2009), a dominance of cronstedtite among surface silicates needs confirmation. Magnetite could account for by a broad absorption at \sim 1.2 μm (Larson et al., 1979; Rivkin et al., 2011) and darken Ceres' spectra in a broad range of wavelengths (Milliken and Rivkin, 2009). However, the occurrence of magnetite is not very certain because other phases (e.g., sulfides, organic species) could be darkening agents. There are clear spectral features of Mg-bearing carbonates (Rivkin et al., 2006; Milliken and Rivkin, 2009; Rivkin and Volquardsen, 2010), which could be much more abundant than in carbonaceous chondrites (typically < 2–3 vol.%; Brearley and Jones, 1998). Although strong spectral features of suggested minerals apparently indicate their high abundances, exact volume fractions may not be evaluated from current data. The features may represent coatings rather than bulk mineral contents in surface materials. It follows that some surface minerals could be present but not seen in the reflection and emission spectra.

Ceres' spectra have no distinct signatures of many primary minerals (olivine, pyroxenes, feldspars) and Mg-rich phyllosilicates (saponite, serpentine), which are common in chondrites. Although spectral features of these minerals in the near-IR could be masked by opaque phases, mid-IR spectra are not consistent with a presence of these phases (Rivkin et al., 2006; Milliken and Rivkin, 2009). The apparent absence or deficiency of primary phases indicates through alteration of primary materials. Fe-bearing carbonates and calcite may not be abundant (Milliken and Rivkin, 2009). Sulfates are not seen, though chlorides may not be detected in visible to mid-IR spectral ranges. Although there are no clear spectral signatures of organic compounds in Ceres' spectra, absorptions of aromatic groups at 3.3–3.4 μm (Moroz et al., 1998; Rivkin et al., 2006) could be overlapped by carbonate bands (Milliken and Rivkin, 2009; Rivkin et al., 2011).

The nature of the prominent absorption feature at \sim 3.06 μm remains uncertain. The interpretation of this feature as a sign of water frost (Lebofsky et al., 1981) is not supported in subsequent

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