

## SPECTRAL EVIDENCE FOR A BRUCITE-CARBONATE ALTERATION ASSEMBLAGE ON CERES.

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**Introduction:** The dwarf planet Ceres is the largest object in the asteroid belt and is a primary target of NASA's Dawn mission [1]. Recent modeling has shown that Ceres is likely differentiated and consists of a thin silicate+ice crust underlain by a thicker water ice mantle [2,3]. The presence of hydrated phases on Ceres, as inferred from the 3  $\mu\text{m}$  absorption feature present in surface reflectance spectra, was discovered ~30 years ago. However, the specific hydrated phases, their origin, and links between Ceres and carbonaceous chondrites are still of considerable debate. Specifically, the presence of a narrow absorption feature at 3.06  $\mu\text{m}$  has been attributed to water ice, clays, ammoniated clays, and cronstedtite, to name a few [4-7]. In this work we show that this feature is best matched by brucite,  $\text{Mg}(\text{OH})_2$ , and that the surface of Ceres is best explained by a brucite-Mg carbonate alteration assemblage.

**Methods:** Laboratory spectra of carbonate (e.g., magnesite, dolomite), cronstedtite, brucite, and saponite powders were measured using an FTIR spectrometer (Fig. 1). The brucite spectrum is of a reagent grade powder, the ammoniated saponite is from the USGS database, the cronstedtite is from the Caltech mineral collection, and the carbonates are from the CRISM online spectral library. Brucite reacts readily with  $\text{CO}_2$  to produce magnesite, thus it is nearly impossible to obtain a pure powdered brucite sample under normal atmospheric conditions [8]. Indeed, the spectrum of our brucite sample exhibits trace amounts of magnesite as visible by the weak carbonate bands at 3.4 and 3.9  $\mu\text{m}$  (Fig. 1).

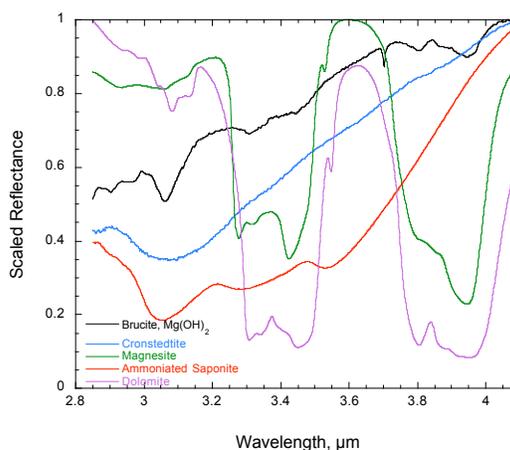
Variations in particle size between samples can strongly affect absorption strength and albedo at near-infrared (NIR) wavelengths, so the lab spectra were scaled to 1 prior to use in our NIR model. Differences in particle size have a weaker effect at longer wavelengths, thus we did not scale the lab spectra when modeling the Ceres data past 5  $\mu\text{m}$ . We performed a simple linear mixing model using the reflectance spectra of these particulate samples as inputs, also including positive and negatively sloped lines to account for continuum slopes and to adjust band strengths when modeling the NIR data. The Ceres spectrum was acquired with the SpeX instrument at NASA's Infrared Telescope Facility on Mauna Kea and is discussed in greater detail by [7]. Emissivity data from 5-13  $\mu\text{m}$  were acquired by the Kuiper Airborne Observatory [9] and were converted to reflectance using Kirchoff's Law prior to use in the model.

**Results:** Although linear mixing models based on reflectance spectra do not account for complex multiple scattering effects in intimate mixtures, our results show that this simple method produces excellent fits to

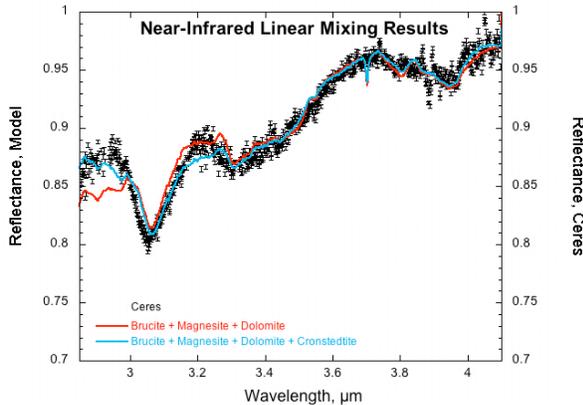
the Ceres data from 2.85 – 4.1  $\mu\text{m}$  (Fig. 2). All major spectral features can be modeled by a mixture of brucite and carbonate. Although the absorptions at ~3.4 and ~3.9-4  $\mu\text{m}$  have previously been modeled with carbonates [7], to our knowledge this is the first time the feature at 3.06  $\mu\text{m}$  has been modeled with brucite. The carbonate features are fit best by the Mg-bearing varieties (as opposed to Fe-bearing siderite), consistent with the types of carbonates found in some carbonaceous chondrites.

The presence of ammoniated saponite [6] is not required to fit the 3.06  $\mu\text{m}$  feature. Although the 3.06  $\mu\text{m}$  feature can be modeled by  $\text{NH}_4$  saponite when isolated [6], this phase does not produce a reasonable fit when brucite is excluded and the full wavelength range is modeled (Fig. 3). Therefore, all features in the Ceres spectrum can be explained by the presence of  $\text{OH}^-$ -bearing materials; there is no clear evidence for  $\text{H}_2\text{O}$ -bearing phases. However, we note that including phyllosilicates such as cronstedtite or smectites in the model improves the fit at wavelengths shorter than 3.0  $\mu\text{m}$  (Fig. 2) due to their increased reflectance in this region.

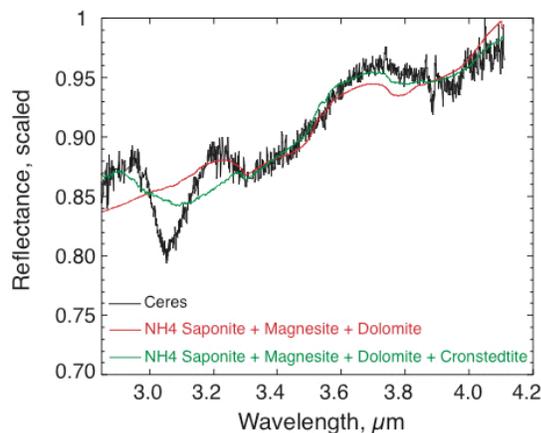
Our model results for the 5-13  $\mu\text{m}$  region are significant improvements over previous attempts [7,9], possibly because the particulate samples used in this study better approximate the particle size distribution on the surface of Ceres. Almost all major absorptions can be explained by the presence of carbonate and, to a lesser extent, cronstedtite. Pure brucite lacks strong diagnostic features at these wavelengths, but the minor amounts of carbonate in our sample produce a slight improvement in the fit when included in the model.



**Fig. 1** Laboratory spectra used as inputs for the linear mixing model. Spectra have been scaled to 1 at their maximum reflectance point over this wavelength range.



**Fig. 2** Linear mixing model results for the NIR. The feature at 3.06  $\mu\text{m}$  is best matched by the OH feature in brucite, whereas the features at  $\sim 3.4$  and  $\sim 3.9\text{-}4$   $\mu\text{m}$  are best matched by Mg-bearing carbonates.



**Fig. 3** Linear mixing model results for the NIR when brucite is *not* included in the model. Although  $\text{NH}_4$  saponite can fit the 3.06  $\mu\text{m}$  feature when isolated [6], it results in a poor fit to the Ceres spectrum when the full wavelength range is modeled.

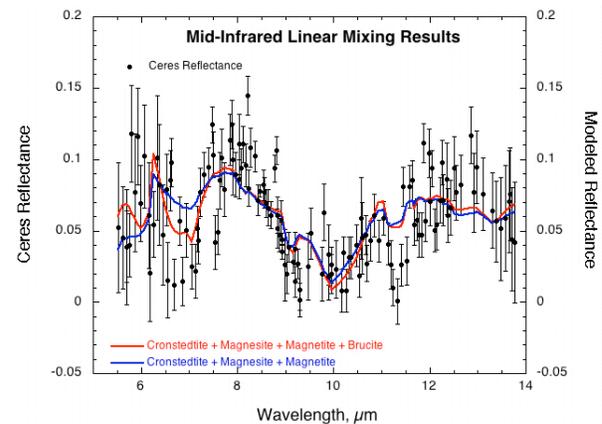
**Discussion:** Reflectance spectra of Ceres, and in particular the 3  $\mu\text{m}$  ‘hydration’ features, are consistent with the presence of brucite and Mg-carbonates, where the latter forms readily from the interaction of brucite with  $\text{CO}_2$ . Although carbonates are present in the carbonaceous chondrites, as well as brucite layers in the form of tochilinite, the alteration assemblage on the surface of Ceres appears to be distinct from what is seen in C1 and C2 chondrites. Brucite is not a significant phase in any known chondrites, although brucite and serpentine have been suggested to exist on Ceres and on chondrite parent bodies [2,10]. Brucite is a common alteration product of peridotite and its presence suggests the silicates on Ceres are likely Mg-rich. Although there is no unambiguous spectral evidence for magnetite on the surface, an Fe-bearing phase such as this is also common during the alteration of olivine and is consistent with Ceres’ low albedo.

The carbonate features in the Ceres’ spectrum are quite strong for such a dark object and are stronger than what is observed in most laboratory spectra of

carbonate-bearing meteorites. Therefore, it is likely that the surface of Ceres’ contains more carbonate than is present in known chondrites. This suggests that Ceres may have experienced more pervasive aqueous alteration than the C1 and C2 chondrites, although the full alteration assemblage must be identified to determine the oxidation state of Ceres during this alteration.

The presence of a significant water ice mantle in Ceres’ interior [2,3] implies low temperatures in the subsurface, thus the carbonates on Ceres were likely formed at temperatures similar to those for carbonates in chondrites ( $<25^\circ\text{C}$ ) [11]. The differentiated and cold nature of Ceres would make it difficult for these alteration products to form in the deep interior and be transported to the surface. However, impacts would provide enough heat to melt ice within (and possibly below) the thin silicate+ice crust. Transient liquid water could alter peridotite-like material at low temperatures to form brucite, some of which could in turn be altered to Mg-carbonates in the presence of  $\text{CO}_2$ .

**Conclusions:** Our work shows that the alteration assemblage on Ceres is significantly different from the carbonaceous chondrites and that Ceres is not represented in existing meteorite collections. One reason for this difference may be due to the larger size of Ceres compared to possible chondrite parent bodies, which has allowed Ceres to differentiate and retain an ice-rich mantle. The Dawn spacecraft will reach Ceres in 2014 and carries a payload capable of testing these hypotheses.



**Fig. 4** Linear mixing model results for the IR data. The major features can be fit by linear mixtures of particulate carbonate, cronstedtite, and a darkening agent such as magnetite. Pure brucite lacks strong absorption features in this wavelength region, but the presence of minor amounts of carbonate in the brucite sample improve the fit shortward of 8  $\mu\text{m}$ .

**References:** [1] Rayman, M. et al. (2006), *Acta Astron.*, 58, 605-616; [2] McCord, T. & C. Sotin (2005), *JGR*, 110, E05009; [3] Thomas, P. et al. (2005), *Nature*, 437, 224-226; [4] Lebofsky, L. (1978), *Mon. Not. R. Astron. Soc.* 182, 17-21; [5] Feierberg, M. (1981), *GCA*, 45, 971-981; [6] King, T. et al. (1992), *Science*, 255, 1551-1553; [7] Rivkin, A. et al. (2007), *Icarus*, 185, 563-567; [8] Mara, R. T(1954), Ph.D. Thesis, U. of Michigan; [9] Cohen, M. et al. (1998), *Astron. Jour.* 115, 1671-1679; [10] Grimm, R. & H. McSween (1989), *Icarus*, 82, 244; [11] Benedix, G. et al. (2003), *GCA*, 67, 1577-1588.