

# Thermal Emission Spectroscopy of 1 Ceres: Evidence For Olivine

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**Abstract.** Thermal emission spectra of the largest asteroid, 1 Ceres, obtained from the Kuiper Airborne Observatory display features that may provide information about its surface mineralogy. The emissivity, obtained by dividing the spectra by a standard thermal model, is compared with emissivity spectra of olivines and phyllosilicates deduced via Kirchoff's law from reflectivity measurements. The spectra provide a fairly good match to fine grained olivines (0 to 5  $\mu\text{m}$  size range). The smoothness of the spectrum beyond 18  $\mu\text{m}$  is an indication of particles smaller than 50  $\mu\text{m}$ . While the abrupt rise in emissivity near 8  $\mu\text{m}$  matches many silicates, the distinct emissivity minimum centered near 12.8  $\mu\text{m}$  is consistent with iron-poor olivines, but not with phyllosilicates. It suggests the presence of opaques and does not exclude a mixture with organics and fine-grained phyllosilicates.

## 1. Introduction

Preliminary deductions about the surface composition of Ceres are summarized by Gaffey and McCord (1979) and more recently by Gaffey, Bell and Cruikshank (1989). The early deductions, based on spectral albedo and low density (Chapman 1975, Morrison 1976), suggested carbonaceous or metamorphosed carbonaceous material with a high bulk volatile content. The spectral albedo suggests an opaque phase mixed with olivine or iron-poor clay material without  $\text{Fe}^{3+}$  (Gaffey & McCord 1978). An absorption feature found at 3  $\mu\text{m}$  indicates hydrated materials (Lebofsky 1978). As the spectral coverage expanded to include most of the 0.4 to 3.6  $\mu\text{m}$  range the observed spectrum was attributed to a combination of opaques and hydrated silicates (Larson et al. 1979). Subsequent observations

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and analyses (Lebofsky et al. 1981, Feierberg et al. 1981, King et al. 1992) led to a consensus (Gaffey, Bell & Cruikshank 1989) surface composition of iron-poor phyllosilicates with magnetite and/or carbonaceous opaque phase(s) from aqueous alteration of CI/CM (meteorite) precursor material. Spectra of Ceres obtained at 12.7 km altitude aboard the Kuiper Airborne Observatory (KAO) in the 5 to 14  $\mu\text{m}$  range, were examined to determine whether asteroids could be used as thermal infrared spectral standards (Cohen et al. 1998). The same data coupled with additional spectra of Ceres from 16 to 30  $\mu\text{m}$  were presented by Witteborn et al. (1999) who noted the similarity of the Ceres emissivity beyond 8  $\mu\text{m}$  to that of small olivine grains. Significant deviations (on the order of 10 percent) of the spectral shape of Ceres from greybody behavior (see also Feierberg et al. 1983) show that mineral features must be considered in using asteroid spectra for calibration. The features, however, could be useful in determining surface composition and texture. In this paper we examine similarities between the thermal emission spectra of Ceres and minerals likely to be on its surface.

## 2. Comparison With Mineral Spectra

The plot in figure 1 is the 1 Ceres spectrum (calibrated using  $\alpha$  Boo as a standard) divided by a standard thermal model (STM).

Also shown is the emissivity spectrum deduced from reflectivity measurements by Mustard and Hays (1997) for forsteritic olivine grains < 5  $\mu\text{m}$  in diameter. The general shapes of the Ceres and the olivine curves agree in essential details, such as the maxima from 8 to 12  $\mu\text{m}$ , the minimum between 12 and 14  $\mu\text{m}$ , the broad peak near 17.5  $\mu\text{m}$ , and the slope beyond 22  $\mu\text{m}$ . Use of the 10 to 15  $\mu\text{m}$  grain reflectivities, (ibid) provides a better match to the 12 to 14  $\mu\text{m}$  dip, but not quite as good to the rest of the curve. Adjustment of the  $\beta$  term, unity in our STM, to a lower value, raises the long-wavelength side of the Ceres spectrum providing an even better match to the olivine curve. The emissivity behavior roughly matches the emission coefficients calculated by Mukai and Koike (1990) for olivine particles with a particle radius of 3  $\mu\text{m}$ . Their calculations show not only the negative slope from 23  $\mu\text{m}$  to 25  $\mu\text{m}$ , but a continued decrease past 30  $\mu\text{m}$ . The Ceres emissivity is thus similar to that of small olivine grains from 8 to 30  $\mu\text{m}$ , but olivine's emissivity is lower from 5 to 8  $\mu\text{m}$ . A mixture of olivine and a relatively emissive (black) material could thus account for the entire 5 to 30  $\mu\text{m}$  spectrum. In figure 2 we compare the Ceres emissivity (using an interpolated STM with  $\beta = 0.93$ ) with emissivities deduced via Kirchoff's law from published reflectivities (Salisbury et al. 1991, Mustard & Hays 1997) for fine-grained olivines and phyllosilicates.

The Mustard and Hays data are the only ones that come close to matching the steep decline of the Ceres emissivity beyond 18  $\mu\text{m}$ . A preliminary report on the Ceres thermal emission spectrum obtained using the Infrared Space Observatory, ISO, (Mueller et al. 1998) also shows that the emissivity decreases towards longer wavelengths. The ISO group attributes this decrease to scattering processes within the surface regolith. A thermophysical model that accounts for scattering processes in the regolith is applied to Ceres and other asteroids by Mueller and Lagerros (1998). Their emissivity result for Ceres decreases be-

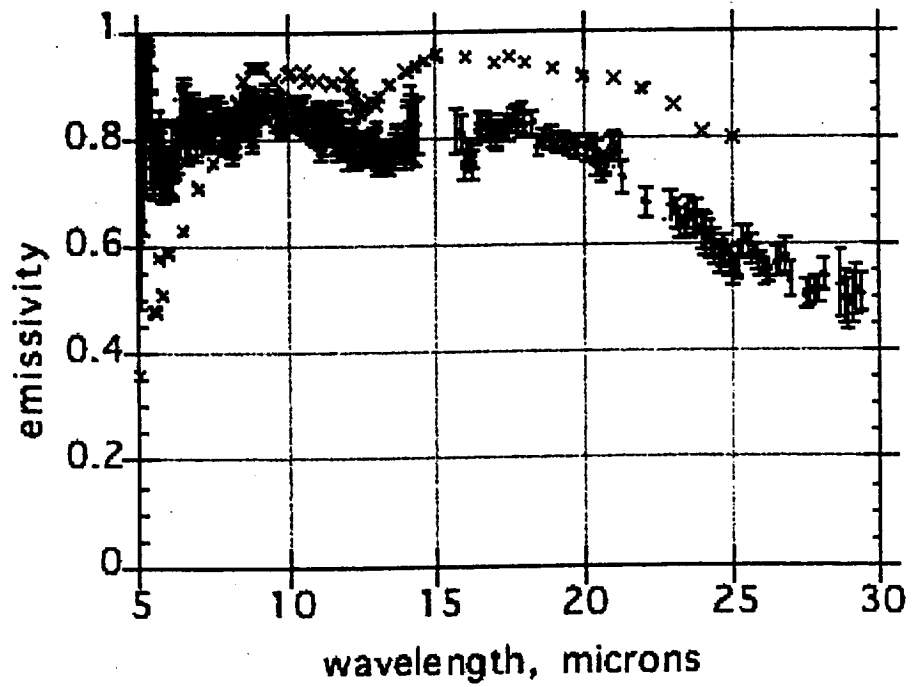


Figure 1. Ceres Emissivity vs Wavelength: Measured Ceres emissivity values (points with error bars) are compared with those measured for small olivine grains by Mustard and Hays (1997) denoted by Xs. The gap in Ceres data near 15  $\mu\text{m}$  is caused by terrestrial carbon dioxide.

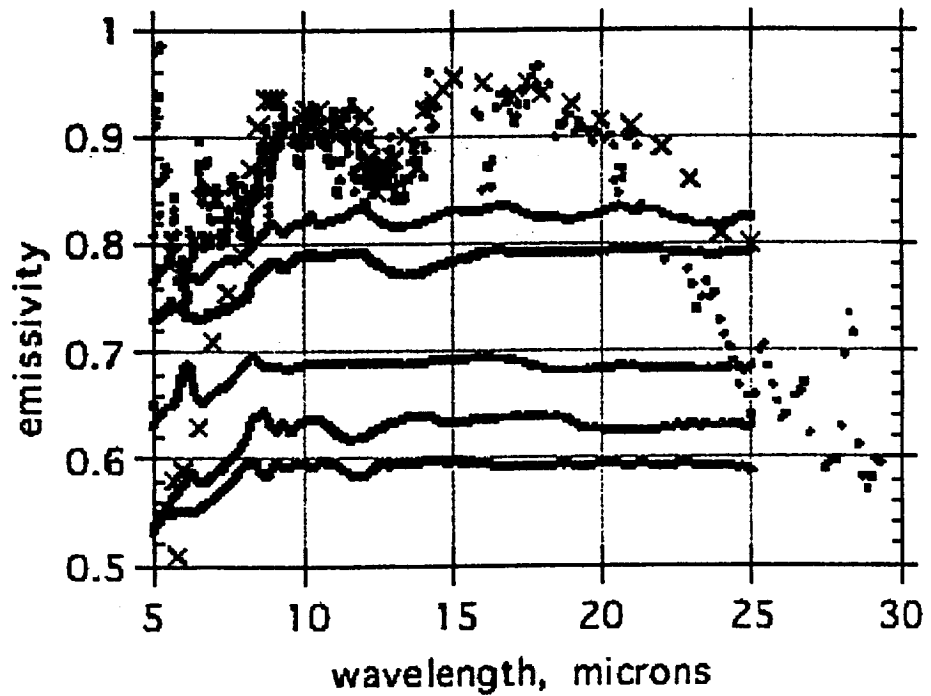


Figure 2. Spectral Emissivities: Ceres, Olivines and Phyllosilicates. The dots represent Ceres spectra divided by an STM using  $\beta = 0.93$ . (Error bars are deleted for clarity here, but are the same as in Fig. 1.) The Xs are lab spectra of 0 - 5 micron olivines as in Fig. 1. The five solid curves are determined from reflectivity data (Salisbury et al. 1991). The top solid curve is iron-poor olivine, 0 to 60  $\mu\text{m}$  sizes, displaced 0.15 downward; the 2nd solid curve is iron-poor olivine, 0 to 30  $\mu\text{m}$  sizes, displaced 0.20 downward; the 3rd solid curve is smectite, sizes less than 2  $\mu\text{m}$ , displaced 0.30 downward; the 4th solid curve is antigorite, 0 to 75  $\mu\text{m}$  sizes, displaced 0.35 downward, and the bottom solid curve is kaolinite, sizes less than 2  $\mu\text{m}$ , displaced 0.40 downward.

yond 20  $\mu\text{m}$ , though not as steeply as the Ceres emissivity spectrum presented here. Specific mineral characteristics are not included in their model. The Ceres absorption feature centered at 12.8  $\mu\text{m}$  matches the depth and location of the Mustard and Hays data, although the latter are narrower in depth. The other two olivine emissivity plots show 12.8  $\mu\text{m}$  features that are broader and shallower. We note that the Ceres absorption feature is broader towards the longer wavelengths than the 0 to 5  $\mu\text{m}$  particle emissivity spectrum. Mustard and Hays data for particles up to 20  $\mu\text{m}$  also show this behavior as do the 2 olivine plots from Salisbury et al. (1991) shown in Fig. 2. Of the phyllosilicates, smectite is relatively featureless between 10 and 15  $\mu\text{m}$ , whereas antigorite and kaolinite have their deepest features in this range centered near 11.5  $\mu\text{m}$ . Emission spectra of iron-rich olivines deduced from the Salisbury et al. collection did not match the position of the 12.8  $\mu\text{m}$  feature either and so are not shown in Fig. 2. We conclude that iron-poor olivine grains in the 0 to 50  $\mu\text{m}$  size range may be a significant component of the surface material on Ceres.

### 3. Discussion

Although no olivine features have been identified for Ceres from reflectance spectra (0.4-2.5  $\mu\text{m}$ ), such features have been detected in several small asteroids (Cloutis 1993). Furthermore even fine-grained olivine would be expected to produce observable spectral absorption near 1.1  $\mu\text{m}$  (Mustard & Hays 1997). Consequently, olivine has not been included in recent descriptions of Ceres' surface material. Being the largest of the asteroids, Ceres is a prime candidate to have undergone differentiation. Olivine is expected to be a major product of differentiation and typically forms at depth due to its relatively high density. Subsequent impacts are believed to emplace the olivine-rich material at the surface of the differentiated asteroids and perhaps spread it to others as well. The apparent absence of olivine has led to extensive discussion of an olivine or dunite deficit in the asteroid belt (Bell et al. 1989, Burbine 1994). Thus an answer to the question of why reflection spectroscopy provides no indication of olivine on Ceres, whereas the thermal observations reported here clearly suggests its presence, could have implications for the production and redistribution of differentiated material in the asteroid belt. Could the feature at 1.1  $\mu\text{m}$  be masked? Reflectance spectra probe the uppermost layers (a few mm) of a surface and spectral features are readily subdued or masked by trace amounts of opaque materials (e.g. Clark 1983). Surfaces emit energy from a variety of depths and at these wavelengths the vibrational fundamentals are so strong that they are not as readily subdued or masked by overlying materials (Christiansen & Harrison 1993). One possibility that could account for the absence of olivine absorption features in the Ceres reflection spectrum is a thin layer (say a few microns or less) of dust enriched in opaque material. Instead of a layer, there could be a mixture with fine-grained opaque material. Cloutis et al. (1990) show that even a small fraction of amorphous carbon mixed with olivine grains (especially grains smaller than 45  $\mu\text{m}$ ) is sufficient to mask the 1.1  $\mu\text{m}$  feature. In fact a mixture of olivine with some opaque material might explain the additional emissivity shortward of 8  $\mu\text{m}$  seen in the emissivity spectrum of Ceres. While small asteroids are thought to be depleted in small dust grains (Dollfus et al.

1989), Ceres is large enough to retain fine-grained dust. For example, Le Bertre and Zellner (1980) conclude that Vesta's surface has particles larger than 50  $\mu\text{m}$  coated with particles smaller than 10  $\mu\text{m}$ . These arguments coupled with the spectral feature at 12.8  $\mu\text{m}$  suggest the possibility that olivine is a significant component of the Ceres regolith. If this is true it would make the olivine deficit in the asteroid belt much less severe.

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