

SPECTROSCOPIC PROPERTIES OF MARTIAN METEORITE ALH84001 AND IDENTIFICATION OF MINERALS AND ORGANIC SPECIES. J. L. Bishop¹, C. M. Pieters² and T. Hiroi²,
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Chemical and mineralogical analyses of the Martian meteorite ALH84001 have shown that it contains primarily orthopyroxene, which differentiates it from other Martian meteorites [1,2]. The secondary components augite, apatite, carbonate, chromite, clinopyroxene, iron oxides, maskelynite, olivine and pyrite have been identified as well [1,2,3,4]. Small quantities of organic material in the vicinity of carbonates and iron oxides have also been found in this meteorite [4]. Initial spectral analyses of ALH84001 focused on the dominant NIR absorptions near 1 and 2 μm , that are characteristic of pyroxene, and orthopyroxene (opx) in particular [5]. The mid-IR spectral features observed near 9.1, 11.4 and 20 μm are characteristic of the opx mineral hypersthene [5]. More detailed spectroscopic analyses of multiple chip surfaces and a particulate sample of ALH84001 are presented here. The IR spectra of the chip and powder samples exhibit features characteristic of several minerals. The 5-25 μm spectra of ALH84001 are especially difficult to interpret because of multiple mineral components and particle size variations.

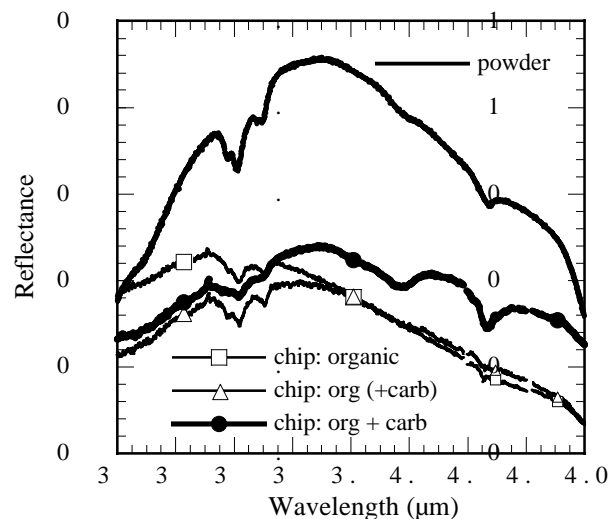
Methods. Reflectance spectra were measured of one small chip (~3X5X10 mm) of meteorite ALH84001. This chip was measured at 7 locations across the surface using a biconical FTIR spectrometer (beam ~1 mm dia) and at two locations from 0.3-2.5 μm using the bi-directional RELAB spectrometer (beam 3-4 mm dia). The chip was then ground to <125 μm particle size and remeasured. Multiple FTIR spectra at 1 cm^{-1} resolution were obtained of this powder sample. Visible-infrared spectra from our library and from Salisbury and colleagues [6] have been used for mineral identification in this study.

Results: 0.3-2.5 μm region. Two broad diagnostic bands are observed in this region near 0.93 and 2.0 μm and are characteristic of orthopyroxene with 30-60 %Fe/(Ca+Mg+Fe) and 0-30 %Ca/(Ca+Mg+Fe) based on the results of Cloutis and Gaffey [7]. However, the presence of additional iron-bearing components is possible as well. Clinopyroxene [1], olivine [3], and iron oxides [4] have been identified in ALH84001 and if present would be contributing to the 1 and/or 2 μm bands.

Results: 2.5-5 μm region. Bound Water. The strongest spectral feature in this region is a broad, bound water band near 3 μm . Plausible minerals exhibiting similar band position and shape include pyrite and goethite (most pyroxenes exhibit a sharper band at shorter wavelengths). **Organics.** Weak features in the range 3.3-3.5 μm are assigned to superimposed features of organic material and carbonate, likely siderite, and are shown here in Fig. 1 (note: powder spectrum offset by -0.12; CO₂ atmosphere removed from chip spectra in the range 4.2-4.4 μm). Although it is difficult to prove that the 3.3-3.5 μm features are not due to lab contamination, spectral measurement of numerous meteorite and lunar samples have been made in

our laboratory and several show no features here. The recent evidence of organics and carbonates in ALH84001 [4], leads us to believe that some of these features near 3.3-3.5 μm may be due to inherent components of the meteorite. Spectral variation across the surface of the chip near 3.3-3.4 μm , where organic and carbonate features overlap, especially suggests that these features are due to heterogeneous components in the meteorite and not due to contamination. **Carbonates.** The powder spectra and some of the chip spectra exhibit a weak band near 3.97 μm , characteristic of calcite, magnesite and siderite [8]. This feature, although weak, is the most readily identifiable carbonate band because there are few bands from other components in this region. The chip spectra shown in Fig. 1 were selected to illustrate variation in the carbonate features near 3.35 and 4.0 μm . **Other.** A very distinctive weak band occurs near 4.27 μm . As CO₂ atmospheric bands frequently occur in FTIR spectra from 4.2-4.3 μm , great care was taken to assure that this a real and repeatable feature in the sample. The origin of this 4.27 μm is as yet unresolved, but it is characteristic of some phosphate, sulfate and carbonate minerals, as well as some less common N- or P- containing compounds; it may be due to a combination of apatite and carbonate or it may be due to a more interesting species. This feature has also been observed in a few other meteorites (CK4, CK5) and in a clinopyroxene volcanic nodule.

Figure 1 Reflectance Spectra of ALH 84001



Results: 5-10 μm region. This part of the spectrum contains several superimposed features, including a weak feature near 5.2 μm , a stronger band near 6.1-6.3 μm , a change of slope near 7.2 μm , from where the reflectance drops to a minimum (also called Christiansen feature) near

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8.5-8.6 μm , and finally reaches a maximum near 9 μm (reststrahlen band). The feature near 5.2 μm is found in the spectra of carbonates [8], goethite and high-Al augite. A broad band at 6.1-6.3 μm is observed in spectra of fine-grained hypersthene and enstatite. A narrower band near 6.1 μm is characteristic of calcite and some other carbonates, goethite and pyrite. Comparison of the 7 chip spectra shows that the spectra containing a narrower band near 6.1 μm also exhibit a strong slope decrease near 7.2 μm , which indicates that these features are related; they are probably due to calcite or siderite.

A strong doublet with a shoulder near 8.8 μm and peaks near 9.0 and 9.1 μm is observed in the chip spectra and a weaker, broader maximum near 9.1 μm is observed in the particulate spectrum. The reflectance minimum and maximum observed in the particulate spectrum most closely resemble these features in spectra of particulate hypersthene and augite. Apatite exhibits a strong doublet near 9.1 and 9.5 μm [9] that may also be contributing to this band in the particulate spectra and hedenbergite exhibits a maximum near 8.8 μm that is likely responsible for the shoulder observed here.

Results: 10-25 μm region. The chip and powder spectra exhibit a strong reflectance maximum near 19.5 μm characteristic of hypersthene, with a broad shoulder extending to near 21 μm . This shoulder is highly variable across the chip and may be due to chromite, goethite and/or hedenbergite. Additional strong features in the chip and powder spectra in this region can be found near 10-10.5, 11.3 and 17.8 μm and are consistent with hypersthene. A strong peak near 18.5 μm and weaker peaks near 14, 14.7, 15.6 and 22.5 μm are observed in all spectra and cannot be attributed to hypersthene. If goethite is present it would be consistent with the peaks near 17.8 and 22.5 μm . The feature near 10-10.5 μm could be partially due to olivine and calcite. A high-Mg olivine would also exhibit peaks near 18.5 and 23 μm . Augite is likely to be responsible for the weak feature near 15.6 μm and a shoulder near 16.5 μm . Pyrite could be contributing to the features near 16.5 and 22.5 μm and magnetite could be contributing to the feature near 17.8 μm . The powder spectrum exhibits an additional reflectance peak not observed in the chip spectra, near 12.5-13 μm , most likely a "transparency" feature of fine-grained hypersthene [6].

Weak features observed only in the chip spectra near 12.2-12.4 μm are likely due to carbonates in ALH84001. Siderite and magnesite exhibit features in this region [10]. These features are weak and vary with location across the sample surface. As they are not observed in the homogenized, particulate sample, these features are probably due to a mineral whose composition varies throughout the meteorite and is particle size dependent. Narrow features such as these are characteristic of carbonate minerals and spectra of carbonates in the mid-IR are highly sensitive to particle size [6].

Conclusions. The low-Ca pyroxene bulk mineralogy of this Martian rock is readily identified using visible-NIR spectroscopy. The dominant infrared features measured in several locations across the surface of our chip and subsequently of a <125 μm powder of this chip are also

consistent with the spectral features observed in hypersthene. Weaker infrared spectral features have been identified that may be due to augite, calcite and/or siderite, chromite, goethite, hedenbergite, magnetite, olivine and pyrite. Unambiguous identification of these minerals and their relative abundances is not clear at this point and requires measurement of additional pieces of ALH84001. Spectral features from 2.5-5 μm are particularly sensitive to components associated with water, organics, carbonates and an unknown (potentially important) species.

Applications to Mars. Spectral analyses of Martian meteorites provide important information about the mineralogy of Mars, as well as clues that may be useful in deconvolving remote sensing spectra containing both the fine-grained surface soil and other surface rocks. Recent analysis of emittance spectra of several Martian meteorites were successful in identifying the primary mineralogic components of these meteorites [11]. Visible-NIR spectroscopic measurements have been successfully used to identify and quantify minerals in Martian meteorites [12] and on the surface of Mars [13]. Visible-infrared measurement across the surface and of a powder of ALH84001 has enabled us to identify multiple major and minor components of this meteorite. This implies that high spatial resolution spectra of Mars will allow for detection of secondary or minor rock and soil components, as well as identification of the primary lithologies. Spectroscopic identification here of minor organic and carbonate components suggest that detection of even small amounts of these (if present) in the surface rocks or soils on Mars would also be possible using high spectral resolution near- and mid-infrared spectra.

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References. 1 Mittlefehldt D. (1994) *Meteoritics*, 29, 214. 2 McSween H. (1994) *Meteoritics*, 29, 757. 3 Harvey R. & McSween H. (1994) *Meteoritics*, 29, 472. 4 McKay D. et al. (1996) *Science*, 273, 924. 5 Bishop J. et al. (1994) *Meteoritics*, 29, 444. 6 Salisbury J. et al. (1991) *Infrared Spectra of Minerals*, Johns Hopkins Univ. Press; Salisbury J. (1993) In *Remote Geochemical Analysis: Elemental and Mineralogical Composition* (eds. Pieters and Englert) Cambridge Press. 7 Cloutis E. & Gaffey M. (1991) *JGR*, 96, 22809. 8 Calvin W. et al. (1994) *JGR*, 99, 14659. 9 Ross S. (1974) In *Infrared Spectra of Minerals* (ed. Farmer) Miner. Soc., London. 10 Sandford S. (pers. comm.). 11 Hamilton V. et al. (1997) *JGR*, submitted. 12 Sunshine J. et al. (1993) *Icarus*, 105, 79; McFadden L. (1997) in prep. 13 Mustard J. & Sunshine J. (1995) *Science*, 267, 1623.