

# The Constituent Minerals in Calcium–Aluminum Inclusions: Spectral Reflectance Properties and Implications for CO Carbonaceous Chondrites and Asteroids

EDWARD A. CLOUTIS

4 Huntstrom Road Northeast, Calgary, Alberta, Canada T2K 5W3

AND

MICHAEL J. GAFFEY

Department of Earth and Environmental Sciences, Rensselaer Polytechnic Institute, Troy, New York 12180-3590

Received April 30, 1993; revised July 7, 1993

---

The reflectance spectra of the major constituent minerals of calcium aluminum inclusions (CAIs) have been measured to determine which minerals contribute to CAI reflectance spectra. Spinel appears to be the most significant phase because of its widespread presence in different classes of inclusions and chondrules and its higher ferrous iron content compared to other inclusion phases. Spectra of CAI phases such as perovskite and grossular are nearly featureless spectrally, while melilite, fassaite, and plagioclase feldspar are more weakly featured than spinel. Measured reflectance spectra of CAIs indicate a widespread and generally intense absorption feature in the 2- $\mu\text{m}$  region attributable to minerals containing ferrous iron in tetrahedrally coordinated sites, primarily spinel. CO carbonaceous chondrite reflectance spectra exhibit the clearest spectral evidence for CAI absorption features, suggesting that asteroids with CO type surface mineralogies (or  $\sim 10\%$  CAIs on their surfaces) may be spectrally detectable if the CAIs are optically isolated from the dark matrix. Telescopic reflectance spectra of the K class asteroid 221 Eos show no clear evidence for CAI absorption features. Telescopic reflectance spectra of the anomalous S class asteroids 387 Aquitania and 980 Anacostia can be interpreted as indicating the presence of a chondritic assemblage enriched in minerals which constitute CAIs, such as spinel, or as achondritic chromite-rich assemblages similar to some unique meteorites. © 1993 Academic Press, Inc.

---

## INTRODUCTION

Calcium–aluminum-rich inclusions (CAIs) are irregularly shaped aggregates of relative light-colored materials embedded in darker-colored chondritic material (e.g., Dominik *et al.* 1978). They are composed predominantly of refractory phases widely believed to have formed under

high-temperature conditions in the early history of the Solar System (e.g., Larimer and Anders 1970, Grossman 1980). Given their importance in unravelling early nebular processes and their presence in the reflectance spectra of some anomalous S class asteroids (Burbine *et al.* 1992) and carbonaceous chondrites (Rajan and Gaffey 1984), the spectral reflectance properties of their constituent minerals have been measured in order to determine: (a) which minerals contribute to CAI spectra, (b) whether different classes of CAIs may be spectrally distinguishable, (c) whether CAI spectra features can be detected in meteorite spectra, and (d) which minerals may be contributing to the CAI spectral features seen in asteroid spectra.

Clark *et al.* (1970) first described three distinct types of CAIs. Since that time various subgroups have been identified and a number of classification schemes have been proposed to bring some order to their study (e.g., Grossman 1975, Mason and Martin 1977, McSween 1977c, Wark and Lovering 1982, MacPherson and Grossman 1984, Wark 1987). The classification scheme of Grossman (1975) has been adopted for use in this paper.

Comprehensive studies of CAIs have revealed that their compositions and abundances vary from meteorite to meteorite and are most abundant in the least metamorphosed carbonaceous chondrites (e.g., McSween 1979, Cohen *et al.* 1983). They also appear to be widespread, though scarce, in types 3 and 4 ordinary chondrites (Bischoff and Keil 1983, 1984, Bischoff *et al.* 1989).

Grossman (1975) initially divided CAIs into two broad groups: type A CAIs containing 80–85% melilite, 15–20% spinel, 1–2% perovskite and rare plagioclase, hibonite,

wollastonite, and grossularite, while type B CAIs contain 35–60% Ti-rich fassaite (an aluminous pyroxene), 15–30% spinel, 2–25% anorthite, and 5–20% melilite. Other groups have been identified since that time including type C CAIs containing 30–60% anorthite and <30% fassaite, melilite and spinel (Beckett and Grossman 1988), plagioclase–olivine inclusions (POIs) containing plagioclase, olivine, pyroxene, and spinel (Sheng *et al.* 1991) and ameboid olivine inclusions (McSween 1977a,c, 1979). A number of additional minerals have been found in CAIs, including andradite (Fuchs 1971), calcite (Armstrong *et al.* 1982, MacPherson *et al.* 1983, El Goresy *et al.* 1984), corundum (Bar-Matthews *et al.* 1982, MacPherson *et al.* 1983, Hinton *et al.* 1988), diopside (Armstrong *et al.* 1982, Beckett and Grossman 1988), hercynite (Fahey *et al.* 1986), nepheline (El Goresy *et al.* 1984, McGuire and Hashimoto 1989), olivine (Dominik *et al.* 1978, Clayton *et al.* 1984, Bischoff *et al.* 1989), rhönite (Allen *et al.* 1978), sodalite (El Goresy *et al.* 1984; McGuire and Hashimoto 1989), and wollastonite (Fuchs 1971).

The abundances of inclusions, including but not restricted to CAIs, in carbonaceous chondrites ranges from 0.9 to 17.6% (McSween 1977a,b, 1979, Cohen *et al.* 1983) and are highest in petrologic types 3 and 4. The CO and CV chondrites contain the highest average abundances of inclusions (9.3 and 13.1%, respectively). Consequently, these two meteorite groups are expected to exhibit the clearest evidence for spectral features associated with the inclusions.

#### EXPERIMENTAL PROCEDURE

The quantities of mineral separates required for spectral reflectance measurements (~1 g) and the difficulties inherent in obtaining these quantities of chemically homogeneous mineral separates from meteorites necessitated the use of terrestrial samples for spectral characterization. The minerals used include grossular garnet from Los Lamentos, Mexico (GAR101), hercynite from Cochise County, Arizona, hibonite from Ft. Dauphine, Madagascar (HIB101), melilites from Riverside County, California (MEL101) and Tuscany, Italy (MEL103), perovskite from San Benito County, California (PER101), plagioclase feldspar (bytownite) from Stillwater, Montana (PLG108), aluminous clinopyroxenes (fassaite) from Tuscany, Italy (PYX131) and Vesuvio, Italy (PYX151), and spinel from Madras Province, India (SPI101). The samples have been characterized at the University of Calgary microprobe facility and are an average of 4- to 8-point analyses and area scans (Table I). The data were reduced using Bence–Albee  $\alpha$  and  $\beta$  correction factors. Ferrous iron contents were determined by wet chemical methods where sufficient sample was available, and ferric iron as the difference between total and ferrous iron.

Powders of the various minerals were obtained by crushing the samples in an alumina mortar and pestle. Purified fractions were obtained through a combination of magnetic separation and hand picking. The powders were wet sieved with acetone to obtain well sorted size ranges (<45  $\mu\text{m}$  and 45–90  $\mu\text{m}$ ). The minerals were also characterized by X-ray diffraction.

Bidirectional reflectance spectra were acquired at the Reflectance Experiment Laboratory (RELAB) spectrometer facility at Brown University (Providence, RI; Pieters 1983) at 5 nm resolution with an incidence angle of 0° and emission angle of 15° with the exception of PLG108 ( $i = 30^\circ$ ,  $e = 0^\circ$ ). All spectra were measured relative to halon, a near-perfect diffuse reflector in the range 0.3–2.6  $\mu\text{m}$  (Weidner and Hsia 1981). The spectra were corrected for minor irregularities in halon's absolute reflectance in the 2- $\mu\text{m}$  region, as well as for dark current offsets. Band depths ( $D_b$ ) were calculated using Eq. (32) of Clark and Roush (1984). The band depths of long-wavelength bands (> ~1.5  $\mu\text{m}$ ) were measured relative to the local reflectance maximum invariably present near 1.5  $\mu\text{m}$  because the long-wavelength wing of these absorption bands is normally incomplete, complicating the construction of a straight-line continuum. The terms red slope and blue slope are used throughout the ensuing discussion. Red slope refers to an *overall increase* in reflectance toward longer wavelengths. Blue slope refers to an *overall decrease* in reflectance toward longer wavelengths.

#### SPECTRA OF CAI CONSTITUENTS

Of the various minerals present in CAIs, the reflectance spectra of melilite, spinel–hercynite, perovskite, fassaite, anorthitic plagioclase, hibonite, and grossularite have been measured for this study. The reflectance spectra of other CAI phases such as calcite, corundum, wollastonite, olivine, diopside, sodalite, and nepheline have been measured by other investigators (Hunt and Salisbury 1970, Hunt *et al.* 1971, 1973, Adams 1974, Gaffey 1986, King and Ridley 1987). The minerals which are most abundant in CAIs (melilite, spinel–hercynite, fassaite, perovskite, anorthite) are expected to be the most spectrally significant as well.

##### *Melilite*

Melilite is the most abundant mineral in type A CAIs (80–85%) and is present at the few tens of percent level in type B CAIs (Grossman 1975). Melilite is more abundant in CV than in CO carbonaceous chondrite inclusions (McSween 1977a,b). CAI melilites generally contain 11–37%  $\text{Al}_2\text{O}_3$ , 1–9%  $\text{MgO}$ , 39–42%  $\text{CaO}$  and <1%  $\text{Na}_2\text{O}$ ,  $\text{FeO}$ ,  $\text{MnO}$ ,  $\text{TiO}_2$ ,  $\text{Cr}_2\text{O}_3$ ,  $\text{K}_2\text{O}$ , and  $\text{V}_2\text{O}_5$  (Cohen *et al.* 1983, MacPherson *et al.* 1983, Meeker *et al.* 1983, El Goresy *et al.* 1984, 1985, Kornacki and Wood 1985, Mac-

TABLE I  
Compositions of the Minerals Used in This Study

Wt%	GAR101	HER101	HIB101	MEL101	MEL103	PER101	PLG108	PYX131	PYX151	SPI101
SiO <sub>2</sub>	40.13	0.07	0.52	39.09	38.74	0.05	46.55	43.09	46.20	0.38
Al <sub>2</sub> O <sub>3</sub>	18.61	59.84	73.31	0.00	13.68	0.00	32.70	14.09	12.54	70.33
FeO	0.69	20.79	3.66	4.17	1.42	0.40	—	0.95	1.73	0.52
Fe <sub>2</sub> O <sub>3</sub>	3.80	ND	ND	ND	0.00	ND	0.64 <sup>a</sup>	4.25	2.30	ND
MgO	1.19	18.01	2.38	21.72	5.93	0.00	0.00	11.10	12.49	26.72
CaO	37.45	0.00	5.92	35.74	37.52	42.26	17.28	25.31	24.92	0.02
Na <sub>2</sub> O	ND	0.03	0.04	0.03	2.33	0.10	1.71	tr	0.10	ND
TiO <sub>2</sub>	0.46	0.67	3.19	0.06	0.05	55.72	0.05	0.73	0.55	0.14
Cr <sub>2</sub> O <sub>3</sub>	0.11	0.05	0.08	0.07	0.10	0.09	0.03	0.06	0.00	0.41
V <sub>2</sub> O <sub>5</sub>	0.00	0.14	0.31	ND	0.02	0.35	0.01	0.00	tr	0.13
CoO	0.00	0.04	0.00	ND	0.00	0.07	0.03	0.04	0.06	0.09
NiO	0.07	0.04	0.01	0.02	0.02	0.02	0.09	0.03	0.01	0.10
MnO	0.19	0.12	0.06	0.20	0.19	0.12	0.01	0.11	0.05	0.00
ZnO	0.00	ND	ND	ND	ND	ND	0.02	ND	0.05	1.03
Nb <sub>2</sub> O <sub>5</sub>	ND	0.00	0.00	0.00	0.00	0.04	ND	ND	ND	ND
P <sub>2</sub> O <sub>5</sub>	ND	tr	0.02	0.02	0.02	0.02	ND	ND	ND	ND
K <sub>2</sub> O	ND	0.00	0.02	ND	0.10	ND	0.02	ND	ND	ND
SrO	ND	ND	ND	ND	ND	ND	0.03	ND	ND	ND
BaO	ND	ND	ND	ND	ND	ND	0.03	ND	ND	ND
Total	102.70	99.80	89.52	101.20	100.12	99.24	99.20	99.76	101.00	99.87

Note. GAR101, grossular garnet; HER101, hercynite; HIB101, hibonite; MEL101, MEL103, melilite; PER101, perovskite; PLG108, plagioclase feldspar; PYX131, PYX151, aluminous clinopyroxene (fassaite); SPI101, spinel. ND, not determined; tr, trace (<0.01).

<sup>a</sup> All Fe reported as Fe<sub>2</sub>O<sub>3</sub>.

Pherson *et al.* 1989). Of the two terrestrial melilites which have been spectrally characterized (MEL101, MEL103), MEL101 is more Al- and Ca-poor and Mg- and Fe-rich than CAI melilites, while MEL103 is more Na- and Fe-rich than CAI melilites (Table I).

A search of the literature failed to uncover reflectance or transmittance spectra of melilites in the 0.3–2.6- $\mu$ m region. The reflectance spectra of MEL101 and MEL103 (<45- $\mu$ m grain size) are shown in Fig. 1. The spectrum of MEL103 is considered to be more representative because X-ray diffraction analysis of MEL101 indicates appreciable amounts of unseparated spinel and some layer lattice alteration products. The 1.4- $\mu$ m absorption feature in the MEL101 spectrum also indicates that some alteration has occurred. X-ray diffraction analysis of MEL103 indicates that almost no alteration product is present and that the only accessory phase present is a minor amount ( $\approx$ 5%) of fassaite.

Ferrous iron is the most abundant transition series element present in MEL103 (Table I). The absorption bands in the 1.6- to 2.0- $\mu$ m region are attributable to crystal field transitions in ferrous iron presumably located in one or more tetrahedrally coordinated sites (Deer *et al.* 1966, Rossman 1988). The intensity of the absorption feature in the 1.6–2.0- $\mu$ m region ( $\sim$ 40% band depth) is consistent with crystal field theory (Burns 1970) despite the low iron abundance of the sample (1.42% FeO). Meteoritic melilite

will probably exhibit a spectral shape similar to MEL103 but with weaker absorption features due to its lower ferrous iron content.

#### Spinel–Hercynite

Spinel (MgAl<sub>2</sub>O<sub>4</sub>) and hercynite (FeAl<sub>2</sub>O<sub>4</sub>) form a solid solution series (Deer *et al.* 1966) and thus have been grouped together here. Spinel constitutes approximately 15–20% of type A inclusions and 15–30% of type B inclusions (Grossman 1975). It is also present in POIs, type C CAIs, and types I and II chondrules in CO carbonaceous chondrites (McSween 1977a). Spinel-dominated inclusions have been found in a number of carbonaceous chondrites (Kornacki and Wood 1985, Wark 1987, Beckett and Grossman 1988). Hercynite, the iron-rich end member of spinel, is less common and in some cases may be an alteration product of previously existing hibonite (Fahey *et al.* 1986).

Spinel in CAIs generally contain 61–74% Al<sub>2</sub>O<sub>3</sub>, 12–29% MgO, <1–21% FeO, <1–5% V<sub>2</sub>O<sub>5</sub>, <1–1% Cr<sub>2</sub>O<sub>3</sub>, and <1% SiO<sub>2</sub>, TiO<sub>2</sub>, CaO, MnO, NiO, Na<sub>2</sub>O, K<sub>2</sub>O, and ZnO (Cohen *et al.* 1983, MacPherson *et al.* 1983, 1985, Meeker *et al.* 1983, El Goresy *et al.* 1984, 1985, MacPherson and Grossman 1984, Kornacki and Wood 1985, McGuire and Hashimoto 1989). The compositions of the terrestrial spinel (SPI101) and hercynite

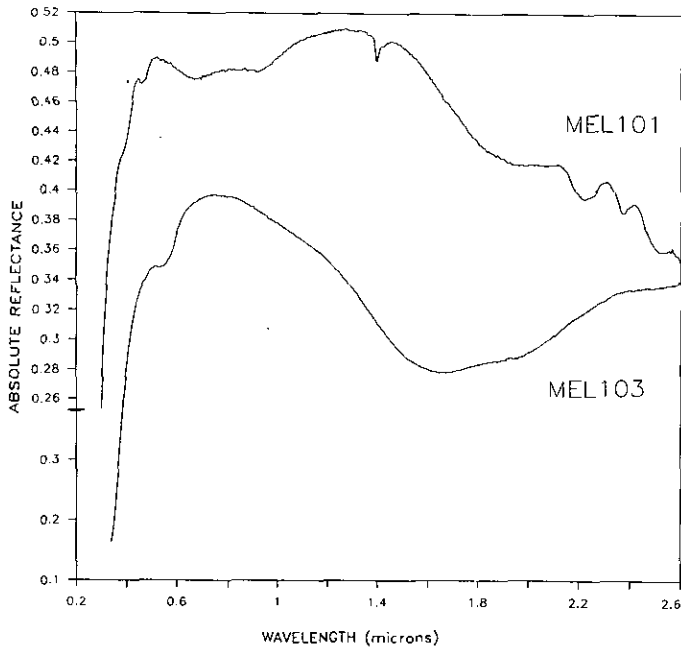


FIG. 1. Absolute reflectance spectra of melilites MEL101 and MEL103. Compositions are provided in Table I.

(HER101) are within the range measured for CAI spinels (Table I).

Previously measured spinel spectra exhibit a major absorption band centered near  $2.0 \mu\text{m}$  due to tetrahedral  $\text{Fe}^{2+}$  crystal field transitions (Adams 1975, Bell *et al.* 1975, Mao and Bell 1975, Rossman 1988). The wavelength position of the band minimum is variable and is undoubtedly related to compositional variations. Additional weaker absorption bands may appear at shorter wavelengths depending on the types and abundances of transition series elements present.

The reflectance spectra of the  $<45\text{-}\mu\text{m}$  grain size spinel (SPI101) and hercynite (HER101) are shown in Fig. 2. Both exhibit the well defined ferrous iron absorption band in the  $2\text{-}\mu\text{m}$  region. The intensity of this band in the spinel (35%  $D_b$ ) is quite high given its low iron content (0.52% FeO) but is not unexpected for tetrahedrally coordinated ferrous iron (Burns 1970). Ferrous iron transitions also account for the absorption band near  $0.58 \mu\text{m}$  (Bell *et al.* 1975).

The higher iron abundance of the hercynite results in a prominent absorption band near  $0.95 \mu\text{m}$  as well as the band in the  $2\text{-}\mu\text{m}$  region (49%  $D_b$ ). Absorption bands at shorter wavelengths are attributable to tetrahedral  $\text{Fe}^{2+}$  and  $\text{Fe}^{3+}$  (Bell *et al.* 1975). Comparison of the two spectra suggests that increasing iron content results in an increase in depth of the band near  $2 \mu\text{m}$ , a shift in its position toward shorter wavelengths, and a decrease in overall reflectance. Additional sample spectra are required to es-

tablish quantitative relationships between band position, depth, and iron content.

Meteoritic spinel should exhibit spectral properties similar to those of the terrestrial spinel and hercynite. The precise spectral shape and band depth will depend upon the ferrous iron content. Since spinel is generally more iron-rich than meteoritic melilite and is present at the tens of percent level in the major classes of inclusions as well as certain classes of chondrules (McSween 1977a,c, 1979, Beckett and Grossman 1988, Sheng *et al.* 1991) it will probably be a spectrally significant phase in CAIs.

### Perovskite

Perovskite constitutes 1–2% of type A inclusions (Grossman 1975); however perovskite-rich inclusions have been found in the Allende CV3 meteorite (MacPherson and Grossman 1984). CAI perovskites generally contain 55–58%  $\text{TiO}_2$ , 37–41%  $\text{CaO}$ ,  $<1\text{--}3\%$   $\text{Al}_2\text{O}_3$ ,  $<1\text{--}2\%$   $\text{SiO}_2$ , and  $\leq 1\%$   $\text{FeO}$ ,  $\text{ZrO}_2$ ,  $\text{Nb}_2\text{O}_5$ ,  $\text{HfO}_2$ ,  $\text{V}_2\text{O}_5$ ,  $\text{Ce}_2\text{O}_3$ ,  $\text{Y}_2\text{O}_3$ , and  $\text{MgO}$  (El Goresy *et al.* 1984, Kornacki and Wood 1985). PER101 is slightly more Ca-rich than meteoritic perovskite but is otherwise compositionally similar (Table I).

The  $0.3\text{--}2.6\text{-}\mu\text{m}$  spectrum of perovskite has apparently not been previously measured. The spectrum of  $<45\text{-}\mu\text{m}$  size PER101 (Fig. 3) is relatively featureless. X-ray diffraction analysis and the small absorption features near  $1.4$  and  $1.9 \mu\text{m}$  indicate the presence of a small amount of a layer lattice alteration product. The abundance of

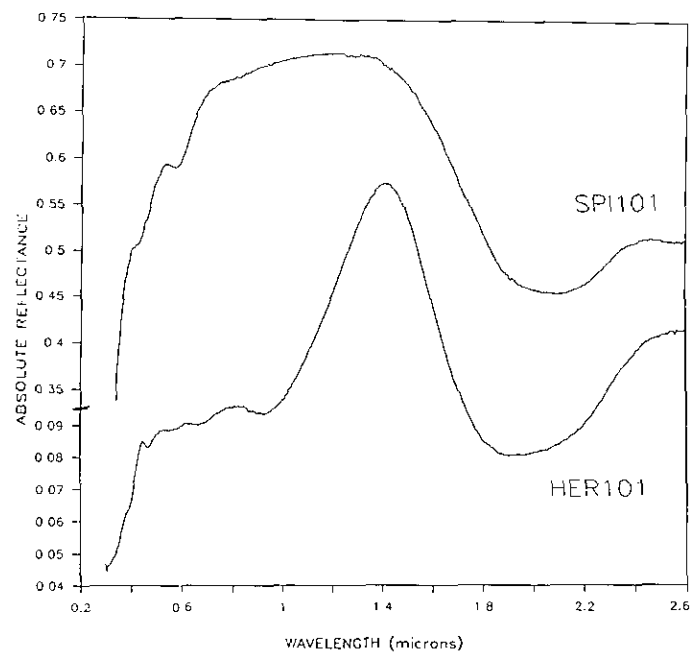


FIG. 2. Absolute reflectance spectrum of spinel (SPI101) and hercynite (HER101). Compositions are provided in Table I.

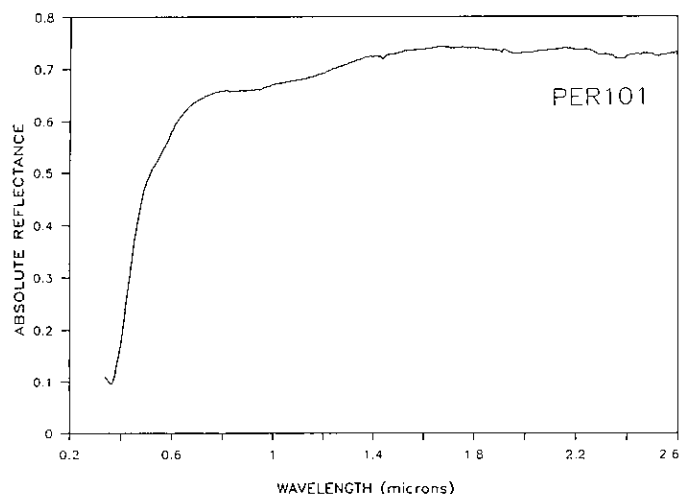


FIG. 3. Absolute reflectance spectrum of perovskite (PER101). Composition is provided in Table I.

iron, occupying 12 coordinated sites (Deer *et al.* 1966), is apparently too low to result in any appreciable absorption bands except for a weak ( $\sim 3\% D_b$ ) band or bands in the 0.9–1.1- $\mu\text{m}$  region.

#### Hibonite

Hibonite is a rare accessory mineral in types A and B CAIs (Grossman 1975). However, hibonite-rich inclusions have been found in a number of carbonaceous chondrites (Allen *et al.* 1978, Armstrong *et al.* 1982, Bar-Matthews *et al.* 1982, MacPherson *et al.* 1983, Fahey *et al.* 1986, 1988, Hinton *et al.* 1988, Mao *et al.* 1990, Ireland *et al.* 1991).

CAI hibonites generally contain 73–90%  $\text{Al}_2\text{O}_3$ , 6–10%  $\text{CaO}$ , 1–8%  $\text{TiO}_2$ , <1–4%  $\text{MgO}$ , <1–7%  $\text{FeO}$ , <1–2%  $\text{V}_2\text{O}_5$ , and <1%  $\text{SiO}_2$ ,  $\text{Cr}_2\text{O}_3$ ,  $\text{MnO}$ ,  $\text{Na}_2\text{O}$ , and  $\text{K}_2\text{O}$  (MacPherson *et al.* 1983, Burns and Burns 1984, El Goresy *et al.* 1984, MacPherson and Grossman 1984, Kornacki and Wood 1985, MacPherson *et al.* 1985, Ireland 1986, 1988, McGuire and Hashimoto 1989). The composition of the terrestrial hibonite (HIB101) is consistent with these values (Table I).

The 0.5–1.2- $\mu\text{m}$  spectra of a number of hibonites were measured by Ihinger and Stolper (1986) who determined that the intensity of the absorption band at 0.715  $\mu\text{m}$  is correlated with oxygen fugacity. The 0.3–2.6- $\mu\text{m}$  spectrum of <45- $\mu\text{m}$  size HIB101 is shown in Fig. 4. X-ray diffraction analysis indicates that the sample is nearly pure with a small amount of a layer lattice alteration product. The spectrum exhibits a number of weak absorption bands, evident as inflections, near 0.48 and 0.75  $\mu\text{m}$  and a prominent absorption band was centered near 1.85  $\mu\text{m}$ .

Titanium or iron present in one of the five possible sites (most likely in the fivefold coordinated Al(5) site) may

account for the 1.85- $\mu\text{m}$  absorption band (Burns and Burns 1984). The intensity of this band ( $\sim 20\% D_b$ ) is less than that of other CAI constituents such as spinel and melilite which contain less iron than the hibonite.

#### Grossular

Grossular garnet is a minor constituent of type A CAIs (Grossman 1975) and grossular-dominated CAIs have been documented. The grossular in CAIs contains 15–23%  $\text{Al}_2\text{O}_3$ , 33–37%  $\text{CaO}$ , 39%  $\text{SiO}_2$ , <1–12%  $\text{FeO}$ , and <1%  $\text{TiO}_2$ ,  $\text{Cr}_2\text{O}_3$ ,  $\text{V}_2\text{O}_5$ ,  $\text{MnO}$ ,  $\text{Na}_2\text{O}$ ,  $\text{NiO}$ , and  $\text{K}_2\text{O}$  (Cohn *et al.* 1983, Kornacki and Wood, 1985, McGuire and Hashimoto 1989). The composition of the terrestrial grossular garnet (GAR101) falls within this range (Table I).

Garnet spectra have been measured by a number of investigators (Clark 1957, Moore and White 1971, Slack and Chrenko 1971, Hunt *et al.* 1973, Burns 1981, Rossman 1988). While pure grossular should be spectrally featureless, the presence of ferric and ferrous iron will give rise to absorption bands near 0.8 and 1.0  $\mu\text{m}$ , respectively, as well as additional bands near 0.43 and 0.6  $\mu\text{m}$ . The GAR101 spectrum is relatively featureless with high overall reflectance (Fig. 5). The most prominent absorption band appears near 0.43  $\mu\text{m}$ , as expected. There is also evidence for a weak ( $\sim 2\% D_b$ ) band near 0.9  $\mu\text{m}$  perhaps due to the small amount of ferrous iron present (0.69%  $\text{FeO}$ ). The weak absorption features near 1.4 and 1.9  $\mu\text{m}$  may be due to substituted  $\text{OH}_4$  and/or undissociated  $\text{H}_2\text{O}$  (Hunt *et al.* 1973).

#### Fassaite

Fassaite is the most common constituent of type B inclusions (Grossman 1975), typically containing >15%

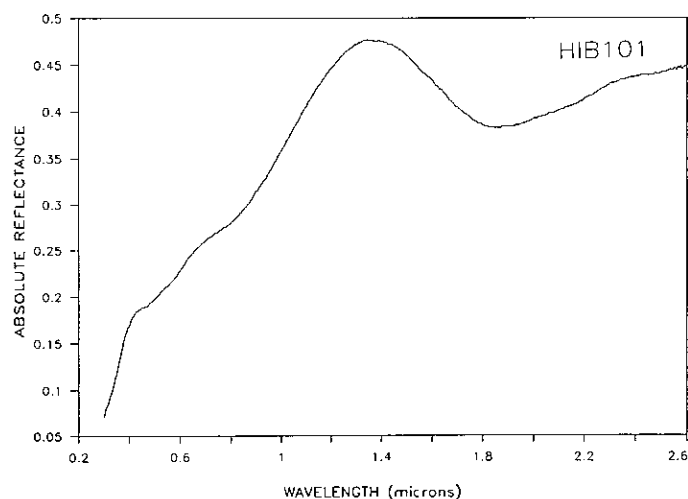


FIG. 4. Absolute reflectance spectrum of hibonite (HIB101). Composition is provided in Table I.

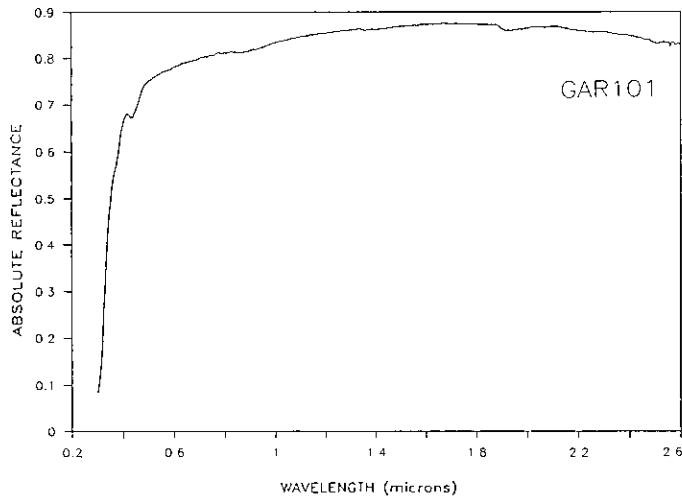


FIG. 5. Absolute reflectance spectrum of grossular garnet (GAR101). Composition is provided in Table I.

$\text{Al}_2\text{O}_3$  and  $>1.8\%$   $\text{TiO}_2$ . A number of fassaite-rich inclusions have been found in the Allende CV3 meteorite (Domink *et al.* 1978, Simon *et al.* 1991).

Fassaite in CAIs is compositionally variable, containing 1–24%  $\text{Al}_2\text{O}_3$ ,  $<1\text{--}8\%$   $\text{FeO}$ ,  $<1\text{--}18\%$   $\text{TiO}_2$ , 5–20%  $\text{MgO}$ , 21–26%  $\text{CaO}$ ,  $<1\text{--}6\%$   $\text{V}_2\text{O}_5$ , and  $<1\%$   $\text{Na}_2\text{O}$ ,  $\text{Cr}_2\text{O}_3$ ,  $\text{K}_2\text{O}$ , and  $\text{MnO}$  (Cohen *et al.* 1983, MacPherson *et al.* 1983, 1989, Meeker *et al.* 1983, El Goresy *et al.* 1984, 1985, Kornacki and Wood 1985, McGuire and Hashimoto 1989, Simon *et al.* 1991). The compositions of two terrestrial aluminum-rich clinopyroxenes (PYX131 and PYX151) fall within the range for CAI fassaites but contain slightly less Ti and Al than the values specified by Grossman (1975) for type B CAI fassaite (Table I).

The spectral properties of fassaite, both terrestrial and meteoritic, have been extensively studied. Fassaite spectra exhibit absorption bands in the visible region due to titanium and iron, a band near  $0.75\ \mu\text{m}$  due to  $\text{Fe}^{2+}\text{--Fe}^{3+}$  charge transfers, and one or two bands in the  $0.95\text{--}1.2\text{-}\mu\text{m}$  region attributable to crystal field transitions in ferrous iron located in the M1 site (Burns and Huggins 1973, Dowty and Clark 1973, Hunt *et al.* 1973, Mao and Bell 1974; Adams 1975, Bell and Mao 1976, Gaffey 1976, Mao *et al.* 1977, Burns 1981, Rossman 1988).

The reflectance spectra of PYX131 and PYX151 are shown in Fig. 6. Both the X-ray diffraction data and the reflectance spectra (in the  $2.2\text{--}2.4\text{-}\mu\text{m}$  region) indicate the presence of a small amount of a layer lattice alteration product. The PYX131 and PYX151 reflectance spectra exhibit a number of similarities: an absorption band near  $0.45\ \mu\text{m}$ , a  $\text{Fe}^{2+}\text{--Fe}^{3+}$  charge transfer band near  $0.75\ \mu\text{m}$ , an absorption band near  $0.95\ \mu\text{m}$ , a prominent inflection near  $1.15\ \mu\text{m}$  and a weak absorption band near  $2.45\ \mu\text{m}$ .

Meteoritic fassaite spectra are generally similar to the PYX131 and PYX151 spectra, displaying an absorption band near  $0.45\ \mu\text{m}$ , an absorption band near  $0.95\ \mu\text{m}$ , and a weaker band near  $2.2\ \mu\text{m}$ .

#### Plagioclase Feldspar

Plagioclase feldspar normally constitutes 2–25% of type B CAIs (Grossman 1975). Type C CAIs and POIs are more plagioclase-rich than type B CAIs (Beckett and Grossman 1988, Sheng *et al.* 1991). The plagioclase in CAIs is generally very anorthite-rich, An98–100 (MacPherson *et al.* 1983, Kornacki and Wood 1985).

Plagioclase spectra have been studied by a number of investigators (Hunt and Salisbury 1970, Nash and Conel 1974, Adams and Goullaud 1978, Crown and Pieters 1987). Plagioclase exhibits a relatively flat reflectance spectrum with a weak absorption band in the  $1.2\text{-}\mu\text{m}$  region attributable to the small amounts of iron present in the samples. The wavelength position and depth of this absorption band varies as a function of anorthite and iron contents. The reflectance spectrum of an anorthitic plagioclase (PLG108, Table I) is shown in Fig. 7. It exhibits a weak absorption band near  $1.25\ \mu\text{m}$  whose depth (18%) is much less than that of other CAI constituent phases such as spinel and melilite. Plagioclase is a weak absorber relative to other silicates such as olivine and pyroxene and is frequently difficult to identify in reflectance spectra of mineral mixtures (Crown and Pieters 1987). Plagioclase

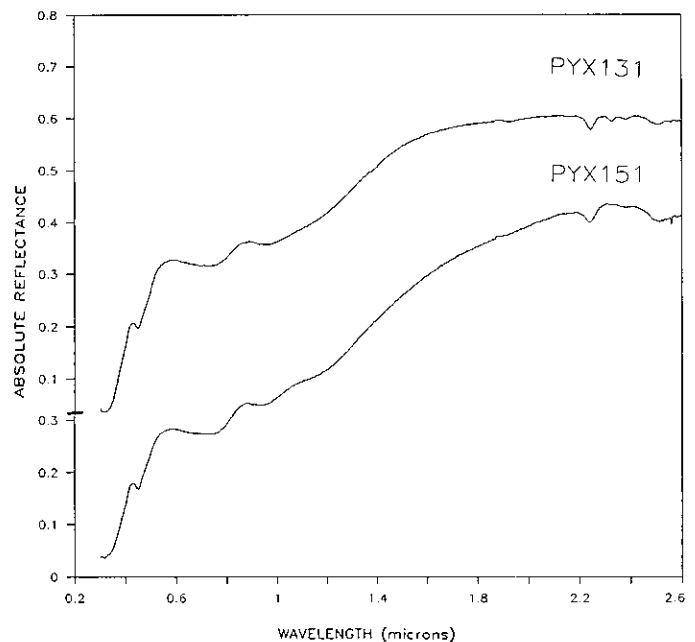


FIG. 6. Absolute reflectance spectra of two aluminous clinopyroxenes (fassaites) (PYX131 and PYX151). Compositions are provided in Table I.

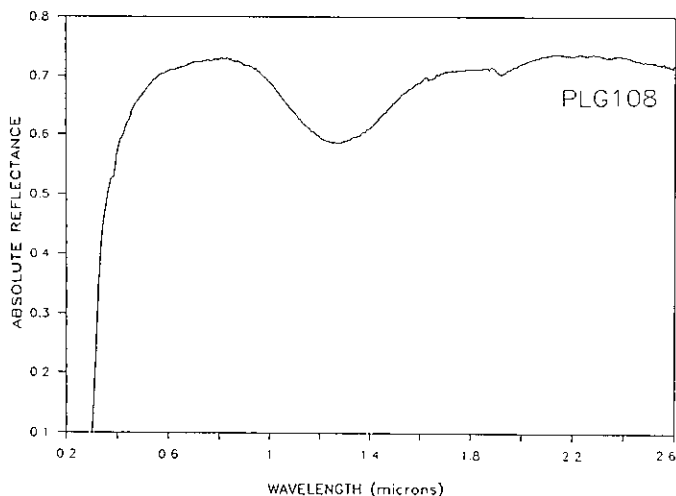


FIG. 7. Absolute reflectance spectrum of anorthitic plagioclase feldspar (PLG108). Composition is provided in Table I.

will most readily be identified in CAI spectra by the presence of an absorption band near  $1.2 \mu\text{m}$ , since this band does not significantly overlap with other CAI constituents.

#### CAI SPECTRA

The various minerals present in CAIs exhibit unique spectra whose relative abundances vary among the different classes of CAIs, suggesting that different classes of CAIs should be spectrally distinguishable. Type A inclusions are composed predominantly of melilite, spinel, and perovskite. Of these phases, perovskite will contribute little if anything to the spectrum because of its low abundance and featureless spectrum. Spinel-hercynite should dominate the lower wavelength ( $\leq 1.5 \mu\text{m}$ ) region and both spinel-hercynite and melilite will contribute to the longer wavelength interval, although the generally higher iron content of meteoritic spinel versus melilite suggests that the spinel will be more spectrally significant than its abundance would indicate.

Type B inclusions are composed predominantly of fassaite, spinel, plagioclase, and melilite. The major mineralogic difference between types A and B inclusions is the dominance of fassaite rather than melilite in the latter. Fassaite will most strongly affect the lower wavelength ( $\leq 1.5 \mu\text{m}$ ) regions and spinel and melilite will most noticeably affect the longer wavelength regions. Plagioclase, because of its low abundance and weakly featured spectrum may contribute only a minor absorption band in the  $1.2\text{-}\mu\text{m}$  region (Crown and Pieters 1987).

Type C inclusions, composed predominantly of plagioclase with lesser amounts of fassaite, melilite, and spinel, should be spectrally dominated by the fassaite below  $\sim 1.5 \mu\text{m}$  and by melilite and spinel at longer wavelengths.

The reflectance spectra of CAIs in the Allende CV3 meteorite measured by Rajan and Gaffey (1984) exhibited a number of different spectral shapes, suggesting that reflectance spectroscopy may be useful for distinguishing different classes of CAIs, if these spectral differences are related to mineralogical variations. Reflectance spectra of two CAIs are shown in Fig. 8. Curve A exhibits a number of spectra features which are inferred to be characteristic of type A inclusions: an absorption band near  $0.9 \mu\text{m}$  (attributable to spinel-hercynite or orthopyroxene), a reflectance increase from  $1.0$  to  $1.3 \mu\text{m}$ , a reflectance maximum near  $1.3 \mu\text{m}$ , and an abrupt reflectance decrease beyond  $1.3 \mu\text{m}$ . Curve B exhibits spectral features which are inferred to be characteristic of type B inclusions: an absorption band near  $1.05 \mu\text{m}$  (attributable to fassaite), a weak absorption band near  $1.2 \mu\text{m}$  (attributable to plagioclase feldspar), and a more gradual reflectance decrease longward of  $\sim 1.3 \mu\text{m}$  (attributable to a lower abundance of melilite in type B inclusions). It should be emphasized that the mineralogies of the spectrally characterized inclusions have not yet been determined and that these spectral-mineralogical relationships are tentative.

#### CARBONACEOUS CHONDRITE SPECTRA

Inclusions of all types, including CAIs, are most prevalent in CO and CV carbonaceous chondrites of petrologic types 3 and 4 (McSween 1977a,b, 1979). The reflectance spectra of many of these meteorites have previously been measured and have been reexamined in order to determine whether spectral features attributable to CAIs can be identified. The  $2.5\text{-}\mu\text{m}/1.0\text{-}\mu\text{m}$  reflectance ratio and band depths near  $2 \mu\text{m}$  have been measured for the various

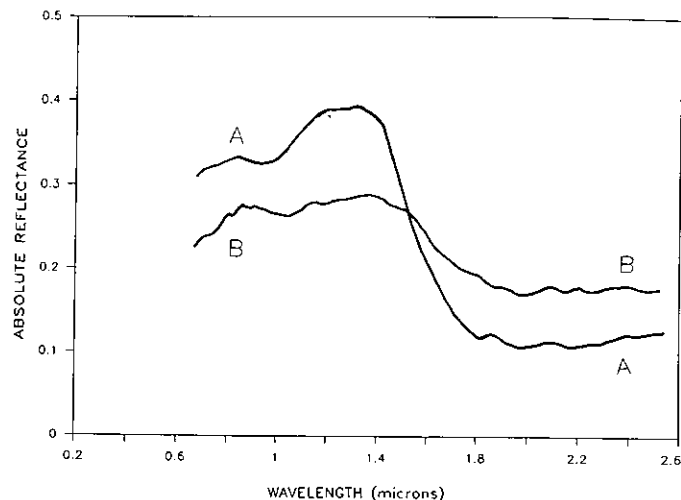


FIG. 8. Absolute reflectance spectra of two CAI inclusions from the Allende CV carbonaceous chondrite (adapted from Rajan and Gaffey 1984).

TABLE II  
Band Depths near 2  $\mu\text{m}$  and 2.5- $\mu\text{m}$ /1.0- $\mu\text{m}$  Reflectance Ratio  
of CO Carbonaceous Chondrites and Some Asteroids

	Class	Grain size ( $\mu\text{m}$ )	Band depth (%)	2.5- $\mu\text{m}$ /1.0- $\mu\text{m}$ Reflectance ratio	Source	
Carbonaceous chondrites						
Felix	CO3	Unsorted	$\leq 1$	1.36	1	
Kainsaz	CO3	Unsorted	2	1.12	2	
Karoonda	CO4	Unsorted	1	1.03	3	
			$<74$	$\leq 1$	1.35	4
			$<74$	$\leq 1$	1.08	1
			$<74$	$\sim 2$	1.21	1
Lancé	CO3	147-495	11	0.86	5	
			74-147	9	0.89	5
			$<74$	3	1.06	5
			$<74$	3	1.04	5
Ornans	CO3	Unsorted	9	1.00	2	
			147-495	13	0.79	5
			74-147	10	0.88	5
			$<74$	3	1.04	5
Warrenton	CO3	Unsorted	8-10	1.02-1.03	2	
			147-495	15	0.80	5
			74-147	14	0.87	5
			$<74$	7	1.06	5
Average	CO3	Unsorted	5	1.03	3	
Asteroids						
221 Eos			3	1.12	6	
387 Aquitania	(5/85) <sup>a</sup>		4	1.10	7	
			(5/90) <sup>a</sup>	4	1.13	7
980 Anacostia			6	1.13	7	

Note. Sources of data: (1) Salisbury *et al.* 1975; (2) Gaffey 1976; (3) Gaffey and McCord 1979; (4) Salisbury and Hunt 1974; (5) Johnson and Fanale 1973; (6) Burbine 1991; (7) Burbine *et al.* 1992.

<sup>a</sup> Date of acquisition of spectrum.

published CO carbonaceous chondrite spectra (Table II). As mentioned, spinel is expected to be the most spectrally apparent CAI mineral that exhibits an absorption feature in the 2- $\mu\text{m}$  region.

Inclusions can constitute up to 17.6 vol% of CO chondrites with CAIs often constituting a majority of the inclusions (McSween 1977a). These data suggest that CAIs can constitute up to 10% of a CO meteorite. Given that band depths in the 2- $\mu\text{m}$  region of CAIs and their constituent minerals can range up to 70%, absorption bands attributable to CAIs with depths up to 7% may be present in CO chondrite spectra if the CAI minerals are optically isolated from the dark matrix. This value represents a theoretical upper limit which would not be attained in powdered meteorite sample spectra or on asteroid surfaces. Conversely, this value could be exceeded if the band depths of the CAI minerals exceed 70% or if their abundances exceed 10%.

CO chondrites are expected to be the best candidates for detecting CAI spectral features because they contain less dark matrix material and carbon than CV chondrites (McSween 1977a,b, Gaffey and McCord 1979, McSween 1979). Given the high abundance of olivine in CO chondrites, the 1- $\mu\text{m}$  region of CO chondrite spectra may exhibit contributions from CAI phases such as spinel-her-

cynite and fassaite, as well as olivine (melilite is rare in CO chondrite CAIs; McSween 1977a). The longer wavelength regions ( $>1.5 \mu\text{m}$ ) should exhibit spectral properties attributable to the CAIs (primarily spinel) because olivine is spectrally featureless in this region (King and Ridley 1987). Pyroxene may also be expressed in the 2- $\mu\text{m}$  region of CO chondrite spectra although it is much less abundant than olivine (McSween 1977a). Reflectance spectra, of varying quality, are available for all of the non-Antarctic CO chondrites except Isna (Johnson and Fanale 1973, Gaffey 1974, Salisbury and Hunt 1974, Salisbury *et al.* 1975, Gaffey 1976, Gaffey and McCord 1979, Wagner *et al.* 1987).

The CO chondrite spectra measured by Salisbury and Hunt (1974) and Salisbury *et al.* (1975) are not available with sufficient resolution to permit detailed spectral analysis. They exhibit 2- $\mu\text{m}$  region band depths of up to 2% and 2.5- $\mu\text{m}$ /1.0- $\mu\text{m}$  reflectance ratios of up to 1.36 (Table II). The CO chondrite spectra presented by Wagner *et al.* (1987) do not extend beyond 1.8  $\mu\text{m}$  and thus omit the crucial 2.0-2.3- $\mu\text{m}$  region. However, the Warrenton (CO3) spectrum exhibits a reflectance maximum near 1.6  $\mu\text{m}$  and decreasing reflectance beyond this wavelength, suggestive of a longer wavelength absorption feature.

Johnson and Fanale (1973) measured the 0.35-2.5- $\mu\text{m}$  reflectance spectra of three grain size fractions of the Ornans, Warrenton, and Lancé CO chondrites. The finest grain size fractions ( $<74 \mu\text{m}$ ) exhibit the most resolvable absorption bands. The coarser grain size spectra are more blue sloped beyond  $\sim 0.7 \mu\text{m}$  than the finer fractions (Table II). This increasingly blue slope with increasing grain size also results in an increase in the apparent band depth of the feature near 2  $\mu\text{m}$  because of the method used to measure this parameter. The causes of the slope change with grain size variation have been discussed elsewhere (Johnson and Fanale 1973, Gaffey and McCord 1979, Moroz and Pieters 1991). All three meteorites exhibit evidence for CAI absorption features. They possess an absorption feature near 1.05  $\mu\text{m}$ , attributable to olivine which appears broadened toward longer wavelengths in the Lancé and Ornans spectra, suggestive of fassaite; however, the spectral detail is insufficient to resolve this region further. All three spectra exhibit a local reflectance maximum in the 1.5-1.6- $\mu\text{m}$  region and a broad absorption feature in the 1.9-2.4- $\mu\text{m}$  region. These features are most evident for the most metamorphosed member of the group, Warrenton. This is probably the result of recrystallization of the matrix and the accompanying reduction in its opacity (McSween 1977a). Band depths in the 2- $\mu\text{m}$  region reach 13% for the 147-495- $\mu\text{m}$  size fraction and up to 7% for the  $<74\text{-}\mu\text{m}$  size fraction (Table II). The spectra also become increasingly red sloped with decreasing grain size as measured by the 2.5- $\mu\text{m}$ /1.0- $\mu\text{m}$  reflectance ratio (Table II).



Some of the CO spectra measured by Gaffey (1974, 1976) exhibit absorption features near  $0.9\ \mu\text{m}$  in addition to the olivine absorption band near  $1.05\ \mu\text{m}$ . Most of the spectra also exhibit absorption features beyond  $1.5\ \mu\text{m}$ . The broadness and shallowness of these features hinders determinations of band minima, but in the clearest cases (Ornans, Warrenton) minimum reflectance appears to be in the  $2.0\text{--}2.2\text{-}\mu\text{m}$  region, well beyond the expected wavelength of  $\sim 1.9\ \mu\text{m}$  if pyroxene were the cause of this feature (Cloutis and Gaffey 1991). Neither the opaque phases nor the olivine can be invoked to explain this feature as a pyroxene absorption band shifted to longer wavelengths due to the presence of these phases (Cloutis *et al.* 1986, 1990). Band depths in the  $2\text{-}\mu\text{m}$  region range up to  $\sim 10\%$  and the spectra are not appreciably red slopes (Table II).

Gaffey and McCord (1979) presented the average of a number of CO chondrite spectra. It shows clear evidence for an olivine absorption feature near  $1.05\ \mu\text{m}$ , prominent inflections near  $0.9$  and  $1.2\ \mu\text{m}$ , a local reflectance maximum near  $1.5\ \mu\text{m}$ , and a reflectance minimum near  $2.1\ \mu\text{m}$ . Once again, the wavelength position of the  $2.1\text{-}\mu\text{m}$  minimum is not consistent with a low-calcium, low-iron-content pyroxene and the band area ratio is too high to be accounted for by pyroxene (Cloutis *et al.* 1986). These factors, including the  $1.2\text{-}\mu\text{m}$  inflection are all consistent with the spectral properties of CAI inclusions present in abundances in agreement with those measured (McSween 1977a). The weak  $2\text{-}\mu\text{m}$  region band in Karoonda ( $\sim 1\% D_b$ ) is consistent with the low abundance of CAIs in this meteorite (Kallemeyn *et al.* 1991).

A similar examination of CV meteorite spectra indicated that they are less strongly featured than CO spectra and unambiguous absorption features are harder to identify. This is probably due to the higher abundance of dark matrix and carbon in CV meteorites compared to CO meteorites (McSween 1977a,b, 1979). Consequently, a detailed examination of CV spectra was not undertaken.

The possibility exists that the longer wavelength absorption features seen in the CO carbonaceous chondrite spectra may be due to pyroxene. However, a number of lines of evidence suggest that the CAIs are a major spectral component in the longer wavelength regions. Pyroxene contents of CO chondrites are generally too low (McSween 1977a) for pyroxene to contribute significant absorption features to the spectrum, and no evidence is seen for pyroxene absorption features near  $0.9\ \mu\text{m}$  as expected for low-iron, low-calcium pyroxene (Cloutis and Gaffey 1991). In addition, olivine, which is much more abundant than pyroxene, exhibits band depths  $< 10\%$  in the  $1\text{-}\mu\text{m}$  region of CO spectra. The band  $\text{II}^*/\text{I}^*$  area ratios (Cloutis *et al.* 1986) of the CO chondrite spectra suggest pyroxene/olivine ratios exceeding 1, well above the actual value (McSween 1979). This suggests that additional

phases are contributing to the  $2\text{-}\mu\text{m}$  region absorption features. A CO chondrite type pyroxene should exhibit absorption bands near  $0.9$  and  $1.9\ \mu\text{m}$  (Cloutis and Gaffey 1991). The CO spectra all exhibit an absorption feature in the  $1.9\text{-}\mu\text{m}$  region but the absorption feature is considerably broader than expected for pyroxene and a region of low reflectance generally extends from  $\sim 1.9\ \mu\text{m}$  out to  $\sim 2.2\ \mu\text{m}$ . This is suggestive of CAI phases such as spinel, hercynite, fassaite, and melilite. Band depths in the  $2\text{-}\mu\text{m}$  region for the  $< 74\text{-}\mu\text{m}$  fractions of the CO chondrites range from 3 to 7% (Table II), in agreement with the predictions based on CAI spectral properties and their abundances in CO chondrites for CAI minerals optically isolated from dark matrix material.

The available spectral data for the CO chondrites indicates that the spectral signature of the CAIs is not completely suppressed by the presence of an olivine rich matrix and the CAI spectral features are most clearly expressed in the longer wavelength regions ( $\geq 1.5\ \mu\text{m}$ ) of CO spectra.

#### CAI/SPINEL FEATURES IN ASTEROID SPECTRA

Identification of possible asteroidal analogues for CO chondrites has been hampered by the lack of longer wavelength spectral data for most asteroids, a shortcoming which is gradually being rectified (Bell *et al.* 1988, Gaffey *et al.* 1989). Bell (1988) tentatively proposed that certain asteroids with spectral properties intermediate between S and C classes (provisionally grouped into the new K class) possess spectral affinities with CO and/or CV chondrites. The  $0.3\text{--}2.6\text{-}\mu\text{m}$  reflectance spectrum of the K class asteroid 221 Eos is similar to that of the Allende CV3 carbonaceous chondrite (Burbine 1991) and shows no good evidence for a broad absorption band in the  $2\text{-}\mu\text{m}$  region. Consequently, this asteroid appears to have more spectral affinities to CV rather than CO carbonaceous chondrites.

Broad absorption features in the  $2\text{-}\mu\text{m}$  region, attributable to CAI type minerals have been found in the reflectance spectra of the "anomalous" S asteroids 387 Aquitania and 980 Anacostia (Burbine *et al.* 1992). The spectra have been interpreted as perhaps indicating a surface assemblage similar to CV or CO carbonaceous chondrites enriched in CAIs. However, a number of other spectral properties are incompatible with a carbonaceous chondrite type surface assemblage. The presence of a spinel type mineral on their surfaces appears to be well established, however.

An alternative explanation for the surface mineralogies of these two asteroids centers on the recent description of two unique meteorites. Chromite (a member of the spinel group) is spectrally similar to spinel, exhibiting a reflectance maximum near  $1.4\ \mu\text{m}$  with reflectance de-

creasing toward longer and shorter wavelengths (Hunt and Wynn 1979, Hunt and Evarts 1981). Thus, spectrally significant amounts of chromite could also account for the presence of a broad absorption feature in the 2- $\mu\text{m}$  region.

The two recently described meteorites are a unique ureilite (LEW88774) containing "abundant" Cr-spinel (Meteorite Working Group 1993) and a unique achondrite (EET84302) containing 23 vol% chromite (Takeda *et al.* 1993). These specimens indicate that chromite is a major constituent of some achondrites. S asteroid spectra, including 387 Aquitania and 980 Anacostia, are commonly interpreted as indicating the presence of metal on their surfaces primarily due to their red-sloped spectra from 0.3 to  $\sim 1.5 \mu\text{m}$ . The presence of both metal and chromite in EET84302 could explain many of the spectral properties of these two asteroids. Thus, while a spinel type mineral is indicated by the asteroid spectral data, it is not necessarily characteristic of either a chondritic or achondritic surface assemblage. Additional studies are underway to determine the spectra properties of chromite bearing mixtures.

#### SUMMARY

Of the major minerals present in carbonaceous chondrite inclusions (melilite, fassaite, olivine, plagioclase, spinel), spinel is the most spectrally significant for a number of reasons. It is present at up to the few tens of percent level in types A, B, and C CAIs, POIs, and types I and II chondrules (Grossman 1975, McSween 1977a,c, 1979, Beckett and Grossman 1988, Sheng *et al.* 1991). It is generally more iron-rich than either melilite or plagioclase and exhibits intense ferrous iron absorption bands even when iron content is low ( $< 1\%$  FeO). The most prominent of these bands is located near 2  $\mu\text{m}$  and its depth can exceed 50%.

The significance of minerals containing ferrous iron in tetrahedral coordination (primarily spinel) is evident from the reflectance spectra of most CAIs measured by Rajan and Gaffey (1984) where absorption bands in the 2- $\mu\text{m}$  region can range up to 70% in depth.

Mineralogical and petrological considerations indicate that CAI spectral features should be most evident in CO3 carbonaceous chondrite reflectance spectra. Available CO meteorite spectra show widespread evidence for CAI absorption features in the 2- $\mu\text{m}$  region with maximum band depths for fine-grained samples ranging up to  $\sim 7\%$ . This indicates that CAI abundances on the order of 10% on asteroid surfaces should be readily detectable if the CAIs are optically isolated from the dark matrix (Cloutis *et al.* 1990).

The telescopic spectral data for the K class asteroid 221 Eos show no clear evidence for CAI spectral features. The spectral data for the anomalous S class asteroids

387 Aquitania and 980 Anacostia have been interpreted as indicating the presence of spectrally detectable amounts of spinel and/or CAIs in a presumably chondritic matrix. However, recently described achondritic meteorites suggest that these asteroids could possess a chromite-rich achondritic surface assemblage.

#### ACKNOWLEDGMENTS

We extend thanks for the support provided in the form of research grants from the Geological Society of America (to E.A.C.) and NASA Planetary Geology and Geophysics Grant NAGW 642 (to M.J.G.). Chemical analyses of the samples was made possible through the assistance of Dr. E. D. Ghent and John Machacek at the University of Calgary electron microprobe facility and Alex Stelmack and Diane Caird at the University of Alberta. Thanks also to Dr. Carle Pieters and Stephen Pratt of the NASA Reflectance Experiment Laboratory (RELAB) spectrometer facility in the Department of Geological Sciences at Brown University for their generous support in acquiring some of the reflectance spectra.

#### REFERENCES

- ADAMS, J. B. 1974. Visible and near-infrared spectra of pyroxenes as applied to remote sensing of solid objects in the solar system. *J. Geophys. Res.* **79**, 4829-4836.
- ADAMS, J. B. 1975. Interpretation of visible and near-infrared diffuse reflectance spectra of pyroxenes and other rock-forming minerals. In *Infrared and Raman Spectroscopy of Lunar and Terrestrial Minerals* (C. Karr, Jr., Ed.), pp. 91-116. Academic Press, New York.
- ADAMS, J. B., AND L. H. GOULLAUD 1978. Plagioclase feldspars: Visible and near-infrared diffuse reflectance spectra as applied to remote sensing. *Proc. Lunar Planet. Sci. Conf. 9th*, 2901-2909.
- ALLEN, J. M., L. GROSSMAN, A. M. DAVIS, AND I. D. HUTCHEON 1978. Mineralogy, textures and mode of formation of a hibonite-bearing Allende inclusion. *Proc. Lunar Planet. Sci. Conf. 9th*, 1209-1233.
- ARMSTRONG, J. T., G. P. MEEKER, J. C. HUNEKE, AND G. J. WASSERBURG 1982. The Blue Angel. I. The mineralogy and petrogenesis of a hibonite inclusion from the Murchison meteorite. *Geochim. Cosmochim. Acta* **46**, 575-595.
- BAR-MATTHEWS, M., I. D. HUTCHEON, G. J. MACPHERSON, AND L. GROSSMAN 1982. A corundum-rich inclusion in the Murchison carbonaceous chondrite. *Geochim. Cosmochim. Acta* **46**, 31-41.
- BECKETT, J. R., AND L. GROSSMAN 1988. The origin of type C inclusions from carbonaceous chondrites. *Earth Planet. Sci. Lett.* **89**, 1-14.
- BELL, J. F. 1988. A probable asteroidal parent body for the CV or CO chondrites. *Meteoritics* **23**, 256-257.
- BELL, P. M., AND H. K. MAO 1976. Crystal-field spectra of fassaite from the Angra dos Reis meteorite. *Yearb. Carnegie Inst. Washington* **75**, 701-705.
- BELL, P. M., H. K. MAO, AND G. R. ROSSMAN 1975. Absorption spectroscopy of ionic and molecular units in crystals and glasses. In *Infrared and Raman Spectroscopy of Lunar and Terrestrial Minerals* (C. Karr, Jr., Ed.), pp. 1-38. Academic Press, New York.
- BELL, J. F., P. D. OWENSBY, B. R. HAWKE, AND M. J. GAFFEY 1988. The 52-color asteroid survey: Final results and interpretation. *Lunar Planet. Sci. Conf. XIX*, 57-58.
- BISCHOFF, A., AND K. KEIL 1983. Ca-Al-rich chondrules and inclusions in ordinary chondrites. *Nature* **303**, 588-592.
- BISCHOFF, A., AND KEIL 1984. Al-rich objects in ordinary chondrites:

- related origin of carbonaceous and ordinary chondrites and their constituents. *Geochim. Cosmochim. Acta* **48**, 693–709.
- BISCHOFF, A., H. PALME, AND B. SPETTEL 1989. Al-rich chondrules from the Ybbsitz H4-chondrite: Evidence for formation by collision and splashing. *Earth Planet. Sci. Lett.* **93**, 170–180.
- BURBINE, T. H. 1991. *Principal Component Analysis of Asteroid and Meteorite Spectra from 0.3 to 2.5  $\mu\text{m}$* . M.Sc. thesis, University of Pittsburgh.
- BURBINE, T. H., M. J. GAFFEY, AND J. F. BELL 1992. S-asteroids 387 Aquitania and 980 Anacostia: Possible fragments of the breakup of a spinel-bearing parent body with CO3/CV3 affinities. *Meteoritics* **27**, 424–434.
- BURNS, R. G. 1970. *Mineralogical Applications of Crystal Field Theory*. Cambridge Univ. Press, New York.
- BURNS, R. G. 1981. Intervalence transitions in mixed-valence minerals of iron and titanium. *Annu. Rev. Earth Planet. Sci.* **9**, 345–383.
- BURNS, R. G., AND V. M. BURNS 1984. Crystal chemistry of meteoritic hibonites. *J. Geophys. Res.* **89**, C313–C321.
- BURNS, R. G., AND F. E. HUGGINS 1973. Visible-region absorption spectra of a  $\text{Ti}^{3+}$  fassaite from the Allende meteorite: A discussion. *Am. Mineral.* **58**, 955–961.
- CLARK, S. P., JR. 1957. Absorption spectra of some silicates in the visible and near infrared. *Am. Mineral.* **42**, 732–742.
- CLARK, R. N., AND T. L. ROUSH 1984. Reflectance spectroscopy: Quantitative analysis techniques for remote sensing applications. *J. Geophys. Res.* **89**, 6329–6340.
- CLARKE, R. S., JR., E. JAROSEWICH, B. MASON, J. NELEN, M. GOMEZ, AND J. R. HYDE 1970. The Allende meteorite shower. *Smithsonian Contrib. Earth Sci.* **5**, 1–53.
- CLAYTON, R. N., G. J. MACPHERSON, I. D. HUTCHEON, A. M. DAVIS, L. GROSSMAN, T. K. MAYEDA, C. MOLINI-VELSKO, J. M. ALLEN, AND A. EL GORESY 1984. Two forsterite-bearing FUN inclusions in the Allende meteorite. *Geochim. Cosmochim. Acta* **48**, 535–548.
- CLOUTIS, E. A., AND M. J. GAFFEY 1991. Pyroxene spectroscopy revisited: Spectral-compositional correlations and relationship to geothermometry. *J. Geophys. Res.* **96**, 22,809–22,826.
- CLOUTIS, E. A., M. J. GAFFEY, T. L. JACKOWSKI, AND K. L. REED 1986. Calibrations of phase abundance, composition, and particle size distribution for olivine-orthopyroxene mixtures from reflectance spectra. *J. Geophys. Res.* **91**, 11,641–11,653.
- CLOUTIS, E. A., M. J. GAFFEY, D. G. W. SMITH, AND R. ST J. LAMBERT 1990. Reflectance spectra of mafic silicate-opaque assemblages with applications to meteorite spectra. *Icarus* **84**, 315–333.
- COHEN, R. E., A. S., KORNACKI, AND J. A. WOOD 1983. Mineralogy and petrology of chondrules and inclusions in the Mokoia CV3 chondrite. *Geochim. Cosmochim. Acta* **47**, 1739–1757.
- CROWN, D. A., AND C. M. PIETERS 1987. Spectral properties of plagioclase and pyroxene mixtures and the interpretation of lunar soil spectra. *Icarus* **72**, 492–506.
- DEER, W. A., R. A. HOWIE, AND J. ZUSSMAN 1966. *An Introduction to the Rock-Forming Minerals*. Longman, England.
- DOMINIK, B., E. K. JESSBERGER, T. STAUDACHER, K. NAGEL, AND A. EL GORESY 1978. A new type of white inclusion in Allende: Petrography, mineral chemistry,  $^{40}\text{Ar}$ – $^{39}\text{Ar}$  ages, and genetic implications. *Proc. Lunar Planet. Sci. Conf. 9th*, 1249–1266.
- DOWTY, E., AND J. R. CLARK 1973. Crystal-structure refinement and optical properties of a  $\text{Ti}^{3+}$  fassaite from the Allende meteorite: Reply. *Am. Mineral.* **58**, 962–964.
- EL GORESY, A., H. PALME, H. YABUKI, K. NAGEL, I. HERRWERTH, AND P. RAMDOHR 1984. A calcium–aluminum-rich inclusion from the Essebi (CM2) chondrite: evidence for captured spinel–hibonite spherules and for an ultra-refractory rimming sequence. *Geochim. Cosmochim. Acta* **48**, 2283–2298.
- EL GORESY, A., J. T. ARMSTRONG, AND G. J. WASSERBURG 1985. Anatomy of an Allende coarse-grained inclusion. *Geochim. Cosmochim. Acta* **49**, 2433–2444.
- FAHEY, A., E. ZINNER, AND G. KURAT 1986. Anomalous Ca and Ti in a hercynite-hibonite inclusion from Lancé. *Meteoritics* **21**, 359–360.
- FUCHS, L. H. 1971. Occurrence of wollastonite, rhönite, and andradite in the Allende meteorite. *Am. Mineral.* **56**, 2053–2067.
- GAFFEY, M. J. 1974. *A Systematic Study of the Spectral Reflectivity Characteristics of the Meteorite Classes with Applications to the Interpretation of Asteroid Spectra for Mineralogical and Petrological Information*. Ph.D. dissertation, Massachusetts Institute of Technology.
- GAFFEY, M. J. 1976. Spectral reflectance characteristics of the meteorite classes. *J. Geophys. Res.* **81**, 905–920.
- GAFFEY, S. J. 1986. Spectral reflectance of carbonate minerals in the visible and near infrared (0.35–2.55 microns): calcite, aragonite, and dolomite. *Am. Mineral.* **71**, 151–162.
- GAFFEY, M. J., AND T. B. MCCORD 1979. Mineralogical and petrological characterizations of asteroid surface materials. In *Asteroids* (T. Gehrels, Ed.), pp. 688–723. Univ. of Arizona Press, Tucson.
- GAFFEY, M. J., J. F. BELL, AND D. P. CRUIKSHANK 1989. Reflectance spectroscopy and asteroid surface mineralogy. In *Asteroids II* (R. P. Binzel, T. Gehrels, and M. S. Matthews, Eds.), pp. 98–127. Univ. of Arizona Press, Tucson.
- GROSSMAN, L. 1975. Petrography and mineral chemistry of Ca-rich inclusions in the Allende meteorite. *Geochim. Cosmochim. Acta* **39**, 433–454.
- GROSSMAN, L. 1980. Refractory inclusions in the Allende meteorite. *Annu. Rev. Earth Planet. Sci.* **8**, 559–608.
- HINTON, R. W., A. M. DAVIS, D. E. SCATENA-WACHEL, L. GROSSMAN, AND R. L. DRAUS 1988. A chemical and isotopic study of hibonite-rich refractory inclusions in primitive meteorites. *Geochim. Cosmochim. Acta* **52**, 2573–2598.
- HUNT, G. R., AND R. C. EVARTS 1981. The use of near-infrared spectroscopy to determine the degree of serpentinization of ultramafic rocks. *Geophysics* **46**, 316–321.
- HUNT, G. R., AND J. W. SALISBURY 1970. Visible and near-infrared spectra of minerals and rocks. I. Silicate minerals. *Mod. Geol.* **1**, 283–300.
- HUNT, G. R., AND J. C. WYNN 1979. Visible and near-infrared spectra of rocks from chromium-rich areas. *Geophysics* **44**, 820–825.
- HUNT, G. R., J. W. SALISBURY, AND C. J. LENHOFF 1971. Visible and near-infrared spectra of minerals and rocks. III. Oxides and hydroxides. *Mod. Geol.* **2**, 195–205.
- HUNT, G. R., J. W. SALISBURY, AND C. J. LENHOFF 1973. Visible and near infrared spectra of minerals and rocks. VI. Additional silicates. *Mod. Geol.* **4**, 85–106.
- IHINGER, P. D., AND E. STOLPER 1986. The color of meteoritic hibonite: An indicator of oxygen fugacity. *Earth Planet. Sci. Lett.* **78**, 67–79.
- IRELAND, T. R. 1986. Correlated morphological, chemical, and isotopic systematics from Murchison (C2M) hibonites. *Lunar Planet. Sci. Conf. XVIII*, 451–452.
- IRELAND, T. R. 1988. Correlated morphological, chemical, and isotopic characteristics of hibonites from the Murchison carbonaceous chondrite. *Geochim. Cosmochim. Acta* **52**, 2827–2839.
- IRELAND, T. R., A. J. FAHEY, AND E. K. ZINNER 1991. Hibonite-bearing microspherules: A new type of refractory inclusion with large isotopic anomalies. *Geochim. Cosmochim. Acta* **55**, 367–379.

- JOHNSON, T. V., AND F. P. FANALE 1973. Optical properties of carbonaceous chondrites and their relationship to asteroids. *J. Geophys. Res.* **78**, 8507–8518.
- KALLEMEYN, G. W., A. E. RUBIN, AND J. T. WASSON 1991. The Karonda (CK) group of carbonaceous chondrites: A new group found exclusively in Australia and Antarctica. *Lunar Planet. Sci. Conf. XXII*, 675–676.
- KING, T. V. V., AND W. I. RIDLEY 1987. Relation of the spectroscopic reflectance of olivine to mineral chemistry and some remote sensing implications. *J. Geophys. Res.* **92**, 11,457–11,469.
- KORNACKI, A. S., AND J. A. WOOD 1985. Mineral chemistry and origin of spinel-rich inclusions in the Allende CV3 chondrite. *Geochim. Cosmochim. Acta* **49**, 1219–1237.
- LARIMER, J. W., AND E. ANDERS 1970. Chemical fractionations in meteorites. III. Major element fractionations in chondrites. *Geochim. Cosmochim. Acta* **34**, 367–387.
- MACPHERSON, G. J., AND L. GROSSMAN 1984. "Fluffy" Type A Ca-, Al-rich inclusions in the Allende meteorite. *Geochim. Cosmochim. Acta* **48**, 29–46.
- MACPHERSON, G. J., M. BAR-MATTHEWS, T. TANAKA, E. OLSEN, AND L. GROSSMAN 1983. Refractory inclusions in the Murchison meteorite. *Geochim. Cosmochim. Acta* **47**, 823–839.
- MACPHERSON, G. J., A. HASHIMOTO, AND L. GROSSMAN 1985. Accretionary rims on inclusions in the Allende meteorite. *Geochim. Cosmochim. Acta* **49**, 2267–2279.
- MACPHERSON, G. J., G. CROZAZ, AND L. L. LUNDBERG 1989. The evolution of a complex type B Allende inclusion: An ion microprobe trace element study. *Geochim. Cosmochim. Acta* **53**, 2413–2427.
- MAO, H. K., AND P. M. BELL 1974. Crystal-field effects of trivalent titanium in fassaite from the Pueblo de Allende meteorite. *Yearb. Carnegie Inst. Washington* **73**, 488–492.
- MAO, H. K., AND P. M. BELL 1975. Crystal-field effects in spinel: Oxidation states of iron and chromium. *Geochim. Cosmochim. Acta* **39**, 865–874.
- MAO, H. K., P. M. BELL, AND D. VIRGO 1977. Crystal-field spectra of fassaite from the Angra dos Reis meteorite. *Earth Planet. Sci. Lett.* **35**, 352–356.
- MAO, X. Y., B. J. WARD, L. GROSSMAN, AND G. J. MACPHERSON 1990. Chemical compositions of refractory inclusions from the Vigarano and Leoville carbonaceous chondrites. *Geochim. Cosmochim. Acta* **54**, 2121–2132.
- MASON, B., AND P. M. MARTIN 1977. Geochemical differences among components of the Allende meteorite. *Smithsonian Contrib. Earth Sci.* **19**, 84–95.
- MCGUIRE, A. V., AND A. HASHIMOTO 1989. Origin of zoned fine-grained inclusions in the Allende meteorite. *Geochim. Cosmochim. Acta* **53**, 1123–1133.
- MC SWEEN, H. Y., JR. 1977a. Carbonaceous chondrites of the Ormans type: A metamorphic sequence. *Geochim. Cosmochim. Acta* **41**, 477–491.
- MC SWEEN, H. Y., JR. 1977b. Petrographic variations among carbonaceous chondrites of the Vigarano type. *Geochim. Cosmochim. Acta* **41**, 1777–1790.
- MC SWEEN, H. Y., JR. 1977c. Chemical and petrographic constraints on the origin of chondrules and inclusions in carbonaceous chondrites. *Geochim. Cosmochim. Acta* **41**, 1843–1860.
- MC SWEEN, H. Y., JR. 1979. Are carbonaceous chondrites primitive or processed? A review. *Rev. Geophys. Space Phys.* **17**, 1059–1078.
- MEEKER, G. P., G. J. WASSERBURG, AND J. T. ARMSTRONG 1983. Replacement textures in CAI and implications regarding planetary metamorphism. *Geochim. Cosmochim. Acta* **47**, 707–721.
- Meteorite Working Group 1993. *Antarctic Meteorite Newsletter* (R. Score and M. Lindstrom, Eds.), Vol. 16, pp. 15, March 1993. NASA Johnson Space Center, Houston.
- MOORE, R. K., AND W. B. WHITE 1971. Intervalence electron transfer effects in the spectra of melanite garnets. *Am. Mineral.* **56**, 826–840.
- MOROZ, L. V., AND C. M. PIETERS 1991. Reflectance spectra of some fractions of Migei and Murchison CM chondrites in the range of 0.3–2.6  $\mu\text{m}$ . *Lunar Planet. Sci. Conf. XXII*, 923–924.
- NASH, D. B., AND J. E. CONEL 1974. Spectral reflectance systematics for mixtures of powdered hypersthene, labradorite and ilmenite. *J. Geophys. Res.* **79**, 1615–1621.
- PIETERS, C. M. 1983. Strength of mineral absorption features in the transmitted component of near-infrared light: First results from RELAB. *J. Geophys. Res.* **88**, 9534–9544.
- RAJAN, S., AND M. J. GAFFEY 1984. Spectral reflectance characteristics of Allende white inclusions. *Lunar Planet. Sci. Conf. XV*, 659–660.
- ROSSMAN, G. R. 1988. Optical spectroscopy. In *Reviews in Mineralogy 18. Spectroscopic Methods in Mineralogy and Geology* (F. C. Hawthorne, Ed.), pp. 207–254. Mineralogical Society of America, Washington, DC.
- SALISBURY, J. W., AND G. R. HUNT 1974. Meteorite spectra and weathering. *J. Geophys. Res.* **79**, 4439–4441.
- SALISBURY, J. W., G. R. HUNT, AND C. J. LENHOFF 1975. Visible and near-infrared spectra: X. Stony meteorites. *Mod. Geol.* **5**, 115–126.
- SHENG, Y. J., I. D. HUTCHISON, AND G. J. WASSERBURG 1991. Origin of plagioclase-olivine inclusions in carbonaceous chondrites. *Geochim. Cosmochim. Acta* **55**, 581–599.
- SIMON, S. B., L. GROSSMAN, AND A. M. DAVIS 1991. Fassaite composition trends during crystallization of Allende Type B refractory inclusions melts. *Geochim. Cosmochim. Acta* **55**, 2635–2655.
- SLACK, G. A., AND R. M. CHRENKO 1971. Optical absorption of natural garnets from 1000 to 30 000 wavenumbers. *J. Opt. Soc. Am.* **61**, 1325–1329.
- TAKEDA, H., K. SAIKA, M. OTSUKI, AND T. HIROI 1993. A new Antarctic meteorite with chromite, orthopyroxene and metal with reference to a formation model of S asteroids. *Lunar Planet. Sci. Conf. XXIV*, 1395–1396.
- WAGNER, J. K., B. W. HAPKE, AND E. N. WELLS 1987. Atlas of reflectance spectra of terrestrial, lunar, and meteoritic powders and frosts from 92 to 1800 nm. *Icarus* **69**, 14–28.
- WARK, D. A. 1987. Plagioclase-rich inclusions in carbonaceous chondrite meteorites: Liquid condensates? *Geochim. Cosmochim. Acta* **51**, 221–242.
- WARK, D. A., AND J. F. LOVERING 1982. The nature and origin of type B1 and B2 Ca–Al-rich inclusions in the Allende meteorite. *Geochim. Cosmochim. Acta* **46**, 2581–2594.
- WEIDNER, V. R., AND J. J. HSIA 1981. Reflections properties of pressed polytetrafluoroethylene powders. *J. Opt. Soc. Am.* **71**, 856–861.