

SPECTRAL REFLECTANCE (0.25–2.5 μm) OF OLIVINE AND PYROXENE FROM AN ORDINARY CHONDRITE

Masamichi MIYAMOTO, Mikio KINOSHITA and Yukio TAKANO

*Department of Pure and Applied Sciences, College of General Education,
University of Tokyo, 8-1, Komaba 3-chome, Meguro-ku, Tokyo 153*

Abstract: We measured the diffuse reflectance spectra (0.25–2.5 μm) of olivine and pyroxene from the ALH-769 ordinary chondrite (L6). We examined the systematic variations of the spectral reflectances of olivine-pyroxene mixtures. We also measured the spectral reflectances for olivine and pyroxene from the olivine sand in Hanauma Bay, Hawaii for comparison. The absolute calibration of the relationship between pyroxene chemistry and absorption band position determined by ADAMS (J. Geophys. Res., 79, 4829, 1974) is not accurate. The spectral feature of the pyroxene around 1.25 μm is sensitive to the existence of the small amount of olivine. This observation does not, however, hold true of the results for the Hawaii clinopyroxene-olivine mixtures. The apparent peak near 0.6 μm of the olivine is depressed by the existence of the Hawaii clinopyroxene. The absorption band depth around 2 μm is sensitive to the amount of pyroxene. With quantities of pyroxene less than 30%, the wavelength position of the olivine absorption band near 1.05 μm shifts drastically. This shift seems to be available for detecting the existence of the small amount of pyroxene in conjunction with the spectral feature around 2 μm . It is hoped to examine the systematic variations of the spectral reflectances of two-component mixtures by using the coexisting pair of the minerals which are separated from meteorites (or rocks).

1. Introduction

Many spectral reflectances for a wide variety of rocks or mineral assemblages have been measured in the laboratory to understand the spectral changes with compositional variations (e.g. BURNS, 1970; HUNT and SALISBURY, 1970; NASH and CONEL, 1974; ADAMS and FILICE, 1967; ADAMS, 1974; SINGER, 1981; PIETERS, 1974, 1983). For example, ADAMS (1974) has shown that the wavelengths of the bands centered near 1 μm and 2 μm vary as functions of pyroxene composition, making possible mineralogical and chemical deductions based on spectral reflectance curves. SINGER (1981) has measured the near-infrared spectral reflectances (0.65–2.5 μm) for systematic variations in weight percent of two-component mixtures of ferromagnesian and iron oxide minerals, and has examined spectral properties of the minerals in an intimate mixture. He has shown that there is a nonlinear change in the locations of the band minima near 1 μm for olivine-orthopyroxene mixtures. These laboratory measurements have assisted in interpreting the spectral reflectance curves of asteroids and other solar system objects and in estimating the chemical composition and relative amount of surface minerals, although the diffuse spectral reflectance depends on many complicated factors (e.g. ADAMS and FILICE, 1967).

Mineral components of asteroidal surface materials have been interpreted on the basis of the comparisons between the spectral reflectances of asteroids and those of meteorites (*e.g.* CHAPMAN, 1976; GAFFEY, 1976; GAFFEY and MCCORD, 1977, 1978). Thus, spectral features of meteorites are important for interpreting the spectral reflectances of solar system objects (*e.g.* GAFFEY, 1976; MCFADDEN *et al.*, 1982). Fewer studies have been, however, performed to measure the spectral reflectances of constituent minerals of meteorites and to investigate the spectral changes of mineral mixtures by using the mineral components which are contained in the meteorite. Because spectral reflectances are sensitive to the presence of small amounts of transition elements (*e.g.* Cr in pyroxene; *e.g.* BURNS, 1970) in minerals, it is necessary to measure the spectral reflectances of the minerals which are actually contained in the meteorites.

We tried to separate the constituent minerals from a meteorite and to measure their diffuse reflectance spectra in the wavelength region of 0.25–2.5 μm .

2. Experimental

Spectral reflectance measurements were made with a Beckman UV 5240 spectrophotometer with an integrating sphere. Halon, manufactured by Allied Chemical Corporation (VENABLE *et al.*, 1976) was used as a standard. The incident beam is perpendicular to the surfaces of both the sample and standard. Details of the instrumentation are described in MIYAMOTO *et al.* (1981). The procedures of the collection and process of spectral data are the same as those in MIYAMOTO *et al.* (1982).

The ALH-769 meteorite, an L6 ordinary chondrite (YANAI, 1979) was supplied by the National Institute of Polar Research. The meteorite sample was crushed with a clean agate mortar and pestle. The powdered sample was sieved with teflon sieves to obtain the size fraction 74–37 μm . The 74–37 μm sample was separated into main minerals, olivine, pyroxene and plagioclase, by means of an isodynamic magnetic separator (S. G. Frantz Co., Inc., L-1). Subsequently, the pyroxene fraction was purified from minor amounts of chromite and troilite grains with Clerici's solution.

The olivine sand from Hanauma Bay, Oahu Island, Hawaii was used for comparison. The sample consists of olivine and a small amount of pyroxene grains. The sample was crushed and sieved in the same manner as the meteorite sample. The 74–37 μm size fraction was separated with the isodynamic magnetic separator, and the olivine sample and the pyroxene sample were prepared.

The olivine crystal from San Carlos, Arizona was also used for comparison. The sample was crushed and sieved to obtain the 74–46 μm size fraction.

After physical mixing in a phial, the sample was placed in a hollow space cut into the holder blackened with an acrylic plastic paint for the spectral reflectance measurement. The sample was gently tapped to produce a level surface and was covered with the same calibrated cover glass as the standard.

A few hundreds of crystal grains from each sample were embedded in araldite and polished for chemical analyses. The amounts of impurities in the olivine samples or pyroxene samples were examined by scanning the surface of the crystal grains with a JEOL JXA-5 electron microprobe. Quantitative chemical analyses of the grains were made with a JEOL JXA-733 electron-probe X-ray microanalyzer (OTSUKI, 1983).

We determined the wavelength position of the absorption band center by using the first derivative of the spectral reflectance curve by the numerical calculation. We regard the position of the band center as the wavelength where the first derivative is zero, assuming that the band minimum is the band center.

3. Results and Interpretations

Tables 1 and 2 show the results of chemical analyses of the samples used for the spectral reflectance measurements. The chemical composition was measured for every grain contained in the sample. The chemical composition of the grains contained in each sample seems to be fairly uniform.

Table 1. Olivine compositions (wt %) used in this study.

	ALH-769		Hawaii		San Carlos	
	Mean (N=28)	Range	Mean (N=10)	Range	Mean (N=10)	Range
SiO ₂	38.1	37.8 – 38.5	39.4	39.1 – 39.7	40.0	39.6 – 40.4
Al ₂ O ₃	0.01	0.00 – 0.03	0.04	0.03 – 0.05	0.02	0.00 – 0.04
TiO ₂	0.01	0.00 – 0.04	0.01	0.00 – 0.04	0.00	0.00 – 0.01
FeO	22.0	21.4 – 22.6	16.1	14.4 – 17.5	9.39	8.03 – 10.9
MnO	0.47	0.42 – 0.53	0.24	0.18 – 0.31	0.14	0.09 – 0.19
MgO	38.3	37.7 – 38.9	43.8	42.8 – 45.4	49.6	48.1 – 51.1
CaO	0.02	0.00 – 0.07	0.34	0.25 – 0.41	0.09	0.08 – 0.11
Na ₂ O	0.00	0.00 – 0.01	0.01	0.00 – 0.03	0.00	0.00 – 0.01
K ₂ O	0.01	0.00 – 0.02	0.01	0.00 – 0.02	0.00	0.00 – 0.01
NiO	0.01	0.00 – 0.06	0.22	0.15 – 0.31	0.37	0.31 – 0.44
Cr ₂ O ₃	0.02	0.00 – 0.15	0.03	0.00 – 0.06	0.02	0.00 – 0.06
V ₂ O ₃	0.01	0.00 – 0.02	0.00	0.00 – 0.02	0.01	0.00 – 0.03
Total	99.1	98.5 – 99.8	100.1	99.3 – 101.1	99.7	98.8 – 100.6
Si	1.001	0.994– 1.007	0.995	0.987– 1.003	0.986	0.979– 0.992
Al	0.000	0.000– 0.001	0.001	0.001– 0.002	0.001	0.000– 0.001
Ti	0.000	0.000– 0.001	0.000	0.000– 0.001	0.000	0.000– 0.000
Fe	0.484	0.470– 0.497	0.340	0.301– 0.370	0.193	0.166– 0.227
Mn	0.011	0.009– 0.012	0.005	0.004– 0.007	0.003	0.002– 0.004
Mg	1.501	1.484– 1.514	1.648	1.618– 1.693	1.821	1.775– 1.859
Ca	0.001	0.000– 0.002	0.009	0.007– 0.011	0.002	0.002– 0.003
Na	0.000	0.000– 0.001	0.000	0.000– 0.001	0.000	0.000– 0.000
K	0.000	0.000– 0.001	0.000	0.000– 0.001	0.000	0.000– 0.000
Ni	0.000	0.000– 0.001	0.005	0.003– 0.006	0.007	0.006– 0.009
Cr	0.000	0.000– 0.003	0.000	0.000– 0.001	0.000	0.000– 0.001
V	0.000	0.000– 0.001	0.000	0.000– 0.000	0.000	0.000– 0.001
Total*	2.998	2.992– 3.005	3.004	2.996– 3.011	3.014	3.007– 3.021
Mg**	75.6	74.9 – 76.2	82.9	81.4 – 84.9	90.4	88.7 – 91.7
Fe	24.4	23.8 – 25.1	17.1	15.1 – 18.6	9.6	8.3 – 11.3

* Cations per 4 oxygens. ** Atomic %.

Although we separated plagioclase grains from the ALH-769 sample, we could not measure the spectral reflectance because of the small amount of the plagioclase grains separated. We were not able to separate Ca-rich clinopyroxene (augite) from

Table 2. Pyroxene compositions (wt %) used in this study.

	ALH-769 (opx)		ALH-769 (cpx)		Hawaii (cpx)	
	Mean (N=12)	Range	Mean (N=5)	Range	Mean (N=7)	Range
SiO ₂	55.7	55.1 – 56.7	54.1	53.5 – 54.6	49.7	48.8 – 50.9
Al ₂ O ₃	0.16	0.14 – 0.23	0.54	0.51 – 0.57	4.96	3.63 – 6.19
TiO ₂	0.18	0.15 – 0.21	0.47	0.43 – 0.54	1.27	0.86 – 1.61
FeO	13.3	12.9 – 13.6	4.55	4.23 – 4.73	6.00	5.67 – 6.72
MnO	0.49	0.42 – 0.53	0.23	0.19 – 0.26	0.08	0.05 – 0.12
MgO	28.8	28.5 – 29.5	16.4	16.3 – 16.6	14.5	13.9 – 15.1
CaO	0.70	0.53 – 0.86	21.6	21.3 – 22.1	22.3	21.6 – 22.8
Na ₂ O	0.01	0.00 – 0.03	0.50	0.43 – 0.58	0.43	0.35 – 0.53
K ₂ O	0.01	0.00 – 0.03	0.00	0.00 – 0.00	0.01	0.00 – 0.01
NiO	0.03	0.03 – 0.11	0.00	0.00 – 0.00	0.03	0.00 – 0.07
Cr ₂ O ₃	0.09	0.07 – 0.14	0.87	0.74 – 0.93	0.54	0.23 – 0.74
V ₂ O ₃	0.01	0.00 – 0.03	0.05	0.02 – 0.07	0.00	0.00 – 0.02
Total	99.5	98.6 – 101.3	99.3	98.7 – 99.9	99.7	99.4 – 100.2
Si	1.996	1.991– 2.009	1.990	1.983– 1.995	1.844	1.811– 1.888
Al	0.007	0.006– 0.010	0.023	0.022– 0.025	0.216	0.158– 0.271
Ti	0.005	0.004– 0.006	0.013	0.012– 0.015	0.036	0.024– 0.045
Fe	0.399	0.386– 0.410	0.140	0.131– 0.146	0.186	0.176– 0.209
Mn	0.015	0.013– 0.016	0.007	0.006– 0.008	0.003	0.002– 0.004
Mg	1.541	1.523– 1.561	0.901	0.893– 0.907	0.800	0.773– 0.835
Ca	0.027	0.021– 0.033	0.853	0.838– 0.869	0.888	0.862– 0.906
Na	0.001	0.000– 0.002	0.036	0.031– 0.042	0.031	0.025– 0.038
K	0.000	0.000– 0.001	0.000	0.000– 0.000	0.000	0.000– 0.001
Ni	0.001	0.000– 0.003	0.000	0.000– 0.000	0.001	0.000– 0.002
Cr	0.003	0.002– 0.004	0.025	0.021– 0.027	0.016	0.007– 0.022
V	0.000	0.000– 0.001	0.002	0.001– 0.002	0.000	0.000– 0.001
Total*	3.995	3.980– 4.000	3.990	3.986– 3.994	4.020	4.014– 4.031
Ca**	1.4	1.1 – 1.7	45.0	44.3 – 45.7	7.4	46.3 – 48.2
Mg	78.4	77.9 – 78.9	47.6	47.3 – 48.0	42.7	41.4 – 44.2
Fe	20.3	19.9 – 20.7	7.4	6.9 – 7.8	9.9	9.4 – 11.1

* Cations per 6 oxygens. ** Atomic %.

low-Ca pyroxene (orthopyroxene) contained in the ALH-769 meteorite. The olivine sample separated from the ALH-769 meteorite proved to contain about two volume percent of pyroxene, as a result of examining the surfaces of the grains of the olivine sample with an electron microprobe. This is because pyroxene grains often exist as inclusions in olivine grains or coexist with olivine.

The olivine sand from Hawaii was almost entirely separated into olivines and pyroxenes.

Figure 1 shows the spectral reflectance curves of olivine and pyroxene separated from the ALH-769 ordinary chondrite (L6) in comparison with that of the 74–46 μm sample of ALH-769. These results show fairly good separation of the olivine grains and the pyroxene grains from the sample of ALH-769.

Figure 2 shows the comparison of spectral reflectance curves for the olivines from the ALH-769 meteorite, Hawaii olivine sand and San Carlos. The reflectivity of the olivine from San Carlos is the highest of the three olivines. The positions of the band

Fig. 1. Spectral reflectance curves for (1) the olivine of 74–37 μm in grain size, (3) the pyroxene of 74–37 μm in grain size, separated from the ALH-769 ordinary chondrite (L6), and for (2) the 74–46 μm sample of ALH-769.

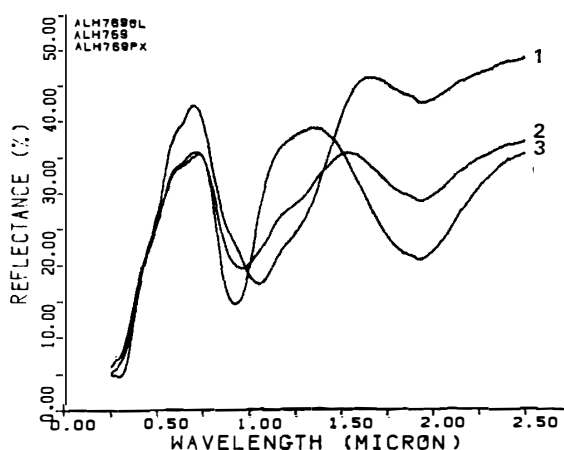
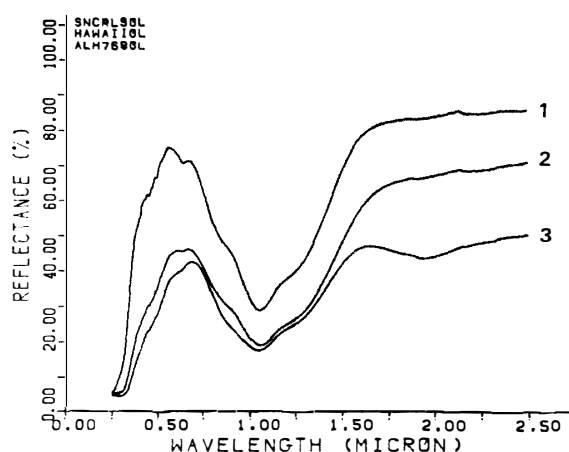


Fig. 2. Comparison of the spectral reflectance curves for (1) the olivine of 74–46 μm in grain size from San Carlos, (2) the olivine of 74–37 μm from the Hawaii olivine sand and (3) the olivine of 74–37 μm from the ALH-769 ordinary chondrite.



minimum of Fe^{2+} crystal field absorption near 1 μm are 1.050, 1.059 and 1.050 μm for the samples of ALH-769, Hawaii and San Carlos, respectively. Because the $\text{Fe}/(\text{Mg} + \text{Fe})$ ratio of the Hawaii olivine is higher than that of San Carlos (Table 1), our results of the band minimum positions seem to be consistent with the chemical compositions (*e.g.* BURNS, 1970). Although the $\text{Fe}/(\text{Mg} + \text{Fe})$ ratio of the ALH-769 olivine is the highest among three olivines (Table 1), its band minimum position is as short as that of the San Carlos olivine. This seems to be because of the apparent shift of the band minimum position by the existence of pyroxene inclusions contained in the ALH-769 olivine grains (*e.g.* ADAMS, 1974). In fact, we can see in Fig. 1 a slight absorption band at 1.939 μm probably due to the pyroxene inclusions. Because the spectrum of the Hawaii olivine does not show the absorption near 2.2 μm , the olivine grains seem to be almost entirely separated from the pyroxene grains.

Figure 3 shows the spectral reflectance curves of the pyroxenes from ALH-769 and Hawaii. The absorption feature around 0.9 μm of the spectrum of the ALH-769 pyroxene is nearly symmetric (GAFFEY, 1976). This result shows fairly good separation and very small amounts of olivine impurities. The curve of the ALH-769 pyroxene shows two major bands centered at 0.918 and 1.924 μm , characteristic of orthopyroxene (Table 1) (*e.g.* ADAMS, 1974). The spectrum of the Hawaii pyroxene shows two prominent

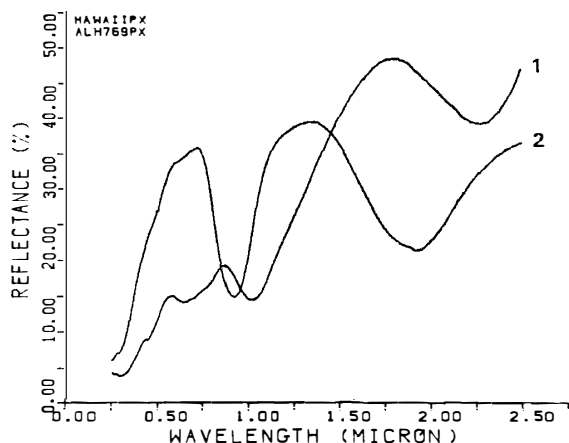


Fig. 3. Spectral reflectance curves for the pyroxene samples of 74–37 μm in grain size from (1) Hawaii and (2) ALH-769.

absorptions at 1.010 and 2.263 μm . These band positions and the curve feature of the spectrum are consistent with those of clinopyroxene (*e.g.* ADAMS, 1974). The absorption band at 0.647 μm in the spectrum of the Hawaii pyroxene is probably due to titanium or chromium in pyroxene (BURNS, 1970; MAO and BELL, 1975; STUBICAN and GRESKOVICH, 1975; BURNS *et al.*, 1976; MCFADDEN *et al.*, 1982). The clinopyroxene from Hawaii is high in TiO_2 (Table 2).

Figure 4 shows the spectral reflectance curves for systematic variations in weight percent of two-component mixtures of olivine and pyroxene from the ALH-769 ordinary chondrite at 20% intervals. With increasing pyroxene content the absorption band depth near 1.9 μm becomes deeper. The location of the band minimum, however, remains unchanged (SINGER, 1981). The shape of the spectral curve around 1.25 μm is sensitively changed by the small amount of olivine (Fig. 4a). When the amount of olivine is large (>30%) (Fig. 4), the orthopyroxene absorption band near 0.9 μm is broadened toward the long-wavelength side by the olivine absorption band near 1.25 μm ; thus, the shape of the 0.9 μm absorption band becomes asymmetric (*e.g.* ADAMS,

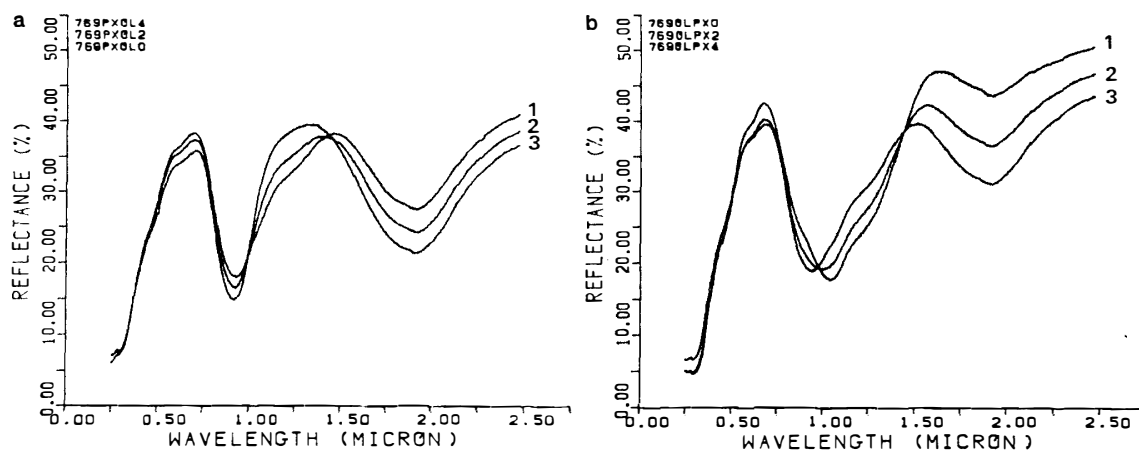


Fig. 4. Spectral reflectance curves of weight percentage mixtures (74–37 μm in grain size) of olivine and orthopyroxene from the ALH-769 ordinary chondrite (L6).

- (a) 1: olivine 40% + pyroxene 60%, 2: olivine 20% + pyroxene 80%, 3: pyroxene 100%.
 (b) 1: olivine 100%, 2: olivine 80% + pyroxene 20%, 3: olivine 60% + pyroxene 40%.

1974; GAFFEY, 1976). The UV drop-off feature below 0.5 μm remains unchanged.

Figure 5 shows the spectral reflectance curves for systematic variations of olivine-pyroxene mixtures from Hawaii. The absorption band of the clinopyroxene near 2.2 μm becomes stronger with increasing amount of the pyroxene (Fig. 5b). The location of the band remains unchanged. This result is similar to that obtained by the mixture of the ALH-769 meteorite. The shape of the spectral curve of the pyroxene around 1.25 μm is not sensitive to the small amount of olivine, in the case of the clinopyroxene such as the one used in this study (Fig. 5a). This result differs from that of the ALH-769 orthopyroxene (Fig. 4a). The peak around 0.6 μm of the olivine is very much depressed by the small amount of clinopyroxene (Fig. 5b).

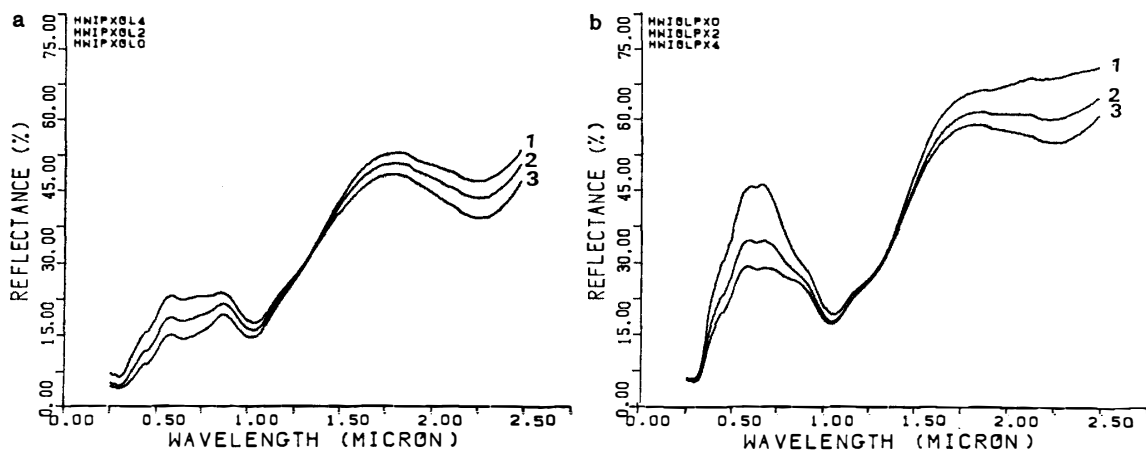


Fig. 5. Spectral reflectance curves of weight percentage mixtures (74–37 μm in grain size) of olivine and clinopyroxene from the Hawaii olivine sand.

- (a) 1: olivine 40% + pyroxene 60%, 2: olivine 20% + pyroxene 80%, 3: pyroxene 100%.
 (b) 1: olivine 100%, 2: olivine 80% + pyroxene 20%, 3: olivine 60% + pyroxene 40%.

Figure 6 shows the variations of wavelength position of the reflectance minimum near 1 μm for pyroxene-olivine mixtures. In the case of the ALH-769 orthopyroxene, with quantities of olivine up to 60% the position of the reflectance minimum gradually shifts toward long-wavelength with increasing amount of olivine. With quantities of olivine more than 70%, the position drastically shifts. As with the Hawaii clinopyroxene, the position of the band minimum gradually shifts with the increase of the amount of olivine. The amount of shift in wavelength is, however, small (SINGER, 1981).

Figure 7 shows the changes of reflectance at the wavelength position of the reflectance minimum near 1 μm . The amount of the variation in reflectance is small. In the case of the ALH-769 orthopyroxene, the curve in Fig. 7 has a peak at the amount of olivine 70%. This result is probably because the two absorption bands of different wavelengths (*ca.* 0.9 μm and 1.05 μm) are superimposed. The apparent band minimum of the superimposed absorption bands seems to be high. It is interesting that the amount of olivine where the curve in Fig. 7 shows a peak corresponds to the amount of olivine where the wavelength shift begins to change drastically in Fig. 6.

Figure 8 shows the changes of the reflectance at the wavelength position of the reflectance minimum near 2 μm . With increasing amount of olivine, a linear increase

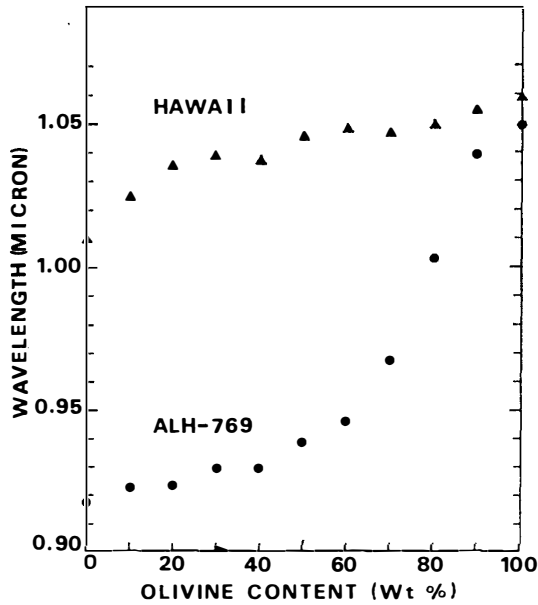


Fig. 6. Variations in wavelength position of absorption band minimum near $1 \mu\text{m}$ for pyroxene-olivine mixtures.
ALH-769: orthopyroxene + olivine.
Hawaii: clinopyroxene + olivine.

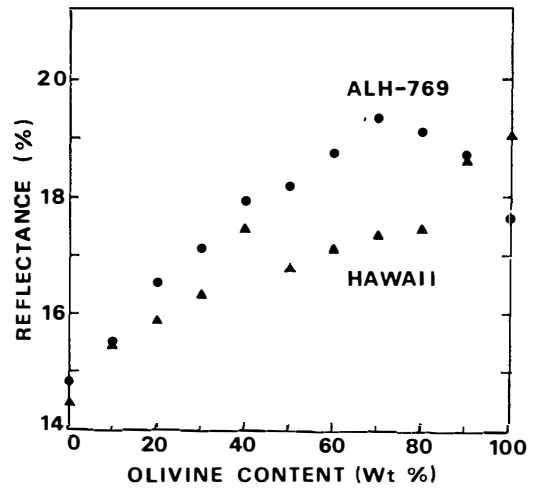


Fig. 7. Changes in reflectance at the wavelength position of reflectance minimum near $1 \mu\text{m}$ for pyroxene-olivine mixtures.
ALH-769: orthopyroxene + olivine.
Hawaii: clinopyroxene + olivine.

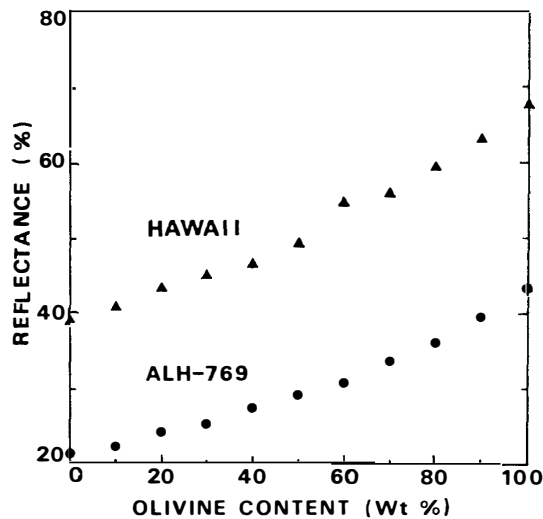


Fig. 8. Changes in reflectance at the wavelength position of reflectance minimum near $2 \mu\text{m}$ for pyroxene-olivine mixtures.
ALH-769: orthopyroxene + olivine.
Hawaii: clinopyroxene + olivine.

of the reflectance up to about 50% for olivine was observed.

4. Discussion

We intend to show, in this paper, that it is possible to measure the spectral reflectances of major constituent minerals obtained by mineral separation technique from a meteorite. It is interesting to compare the effects of olivine-pyroxene and plagioclase-pyroxene mixtures, although we were not able to measure the spectral reflectance of the

plagioclase contained in ALH-769 because of the small amount of the sample. In order to examine the systematic variations of the spectral reflectance of two-component mixtures, it is hoped to use the 'coexisting' pair of minerals. For this purpose, we need to obtain the constituent minerals of low impurity content from meteorite samples or rocks.

Although the olivine grains from the ALH-769 meteorite include a few volume percent of pyroxene impurities, it seems to be impossible to separate completely the olivine grains from the pyroxene impurities because pyroxene often exists in olivine grains as inclusions. Our separation technique, however, seems to be fairly good. The influences of the pyroxene impurities are found in (1) the weak absorption band at about 1.9 μm in curve 1 in Fig. 4b, (2) and the shorter wavelength (1.050 μm) of the absorption band of olivine than that expected from its $\text{Fe}/(\text{Mg} + \text{Fe})$. This is also shown in Fig. 6 as unexpected variation of the curve at olivine 100%. If in Fig. 6 we extrapolate the data of the amount of olivine of 60, 70, 80 and 90% to the amount of olivine 100%, we obtain wavelength position about 1.070 μm for the hypothetical reflectance minimum of pure olivine sample. This value seems to be consistent with the chemical composition (Table 1) (*e.g.* BURNS, 1970).

The reflectance minimum near 1 μm in the spectral reflectance of the ALH-769 chondrite (L6) is 0.951 μm . From Fig. 4, this value corresponds to the amount of olivine about 60%. This result seems to be consistent with the ratio of amount of olivine to that of pyroxene contained in the L chondrite.

Pyroxenes often show the exsolution texture or intergrowth texture. Our microprobe examination of the ALH-769 pyroxene grains detected the clinopyroxene phase as inclusions (about 10 μm in size). Although we were not able to separate the clinopyroxene from the orthopyroxene, we cannot find the absorption band around 2.2 μm , due to the clinopyroxene in the spectral reflectance curve of the ALH-769 pyroxene (Fig. 4a).

The major element chemistry of the pyroxene can be estimated from the wavelength position of the 0.9 μm band and from the calibration of the pyroxene composition determined by ADAMS (1974). The 0.9 μm band of the ALH-769 orthopyroxene measured in this study has a band centered at 0.918 μm . According to ADAMS's calibration, the value of 0.918 μm corresponds to the chemical composition of the pyroxene with about 50% $\text{Fe}/(\text{Mg} + \text{Fe} + \text{Ca})$ and about 6% $\text{Ca}/(\text{Mg} + \text{Fe} + \text{Ca})$. Therefore, the pyroxene calibration as determined by ADAMS (1974) does not agree well with the major element chemistry of the ALH-769 pyroxene obtained by the microprobe analyses (Table 2; $\text{Ca}_{1.4}\text{Mg}_{78.4}\text{Fe}_{20.3}$). This discrepancy may be because of the following reasons: (1) the ALH-769 pyroxene sample used in this study includes olivine impurities; (2) the ALH-769 pyroxene includes clinopyroxene impurities; and (3) the absolute calibration by ADAMS (1974) is not accurate (MCFADDEN *et al.*, 1982). As shown in Fig. 6, even if the small amount of olivine is included, the wavelength position of near 0.9 μm scarcely shifts. As seen in Fig. 3, our ALH-769 pyroxene does not include the large amount of clinopyroxene impurities because the reflectance curve of the pyroxene (curve 2 in Fig. 3) does not show the absorption band around 2.2 μm . According to Fig. 7 in SINGER (1981), the wavelength position shift of near 0.9 μm of orthopyroxene caused by clinopyroxene is small when the amount of clinopyroxene

involved is small. Therefore, reasons both (1) and (2) are excluded.

Reason (3) is the most plausible. MCFADDEN *et al.* (1982) have pointed out that the major element chemistry of the pyroxenes as determined from the position of the 0.9 μm band and the pyroxene calibration as determined by ADAMS (1974) does not agree with microprobe measurements of iron and calcium in pyroxene in the Antarctic diogenites, and that the absolute calibration by ADAMS (1974) is not accurate. The composite 0.9 μm band of Antarctic diogenite Yamato-74013 has a band center at 0.924 μm (MCFADDEN *et al.*, 1982). The microprobe measurement for the pyroxene in Yamato-74013 shows its chemical composition $\text{Ca}_{2.6}\text{Mg}_{73.6}\text{Fe}_{23.8}$. Our results for the pyroxene in the ALH-769 ordinary chondrite are band center 0.918 μm and chemical composition $\text{Ca}_{1.4}\text{Mg}_{78.4}\text{Fe}_{20.3}$. Thus, our result of the band center is consistent with that for the diogenite pyroxene by MCFADDEN *et al.* (1982). It may be, however, inappropriate to compare these two band centers because the two techniques for determining the band centers are not the same. As was pointed out by MCFADDEN *et al.* (1982), the absolute calibration of the relationship between pyroxene chemistry and absorption band position of the 0.9 and 2.0 μm bands by ADAMS (1974) should be recalibrated using laboratory measurements and for numerically analyzed bands.

In short, Fig. 4a shows that the curve feature of the pyroxene around 1.25 μm is fairly sensitive to the existence of the small amount of olivine (*e.g.* SINGER, 1981). However, this observation does not hold true of the results for the Hawaii clinopyroxene-olivine mixtures (Fig. 5a). Figures 4b and 5b show that the absorption band depths near 2 μm are sensitive to the existence of the small amount of pyroxene. As is the case with the Hawaii clinopyroxene used in this study, the apparent peak near 0.6 μm of olivine was drastically depressed by the existence of clinopyroxene (Fig. 5). The shift of wavelength position of the olivine absorption band near 1.05 μm seems to be available for detecting the existence of the small amount of pyroxene in conjunction with the spectral feature around 2 μm .

It is necessary to measure the spectral reflectances of the constituent minerals in the various kinds of meteorites by separating the minerals from the meteorites. These spectral reflectance data will be available for interpreting the spectral reflectances of asteroids.

Acknowledgments

We are indebted to the National Institute of Polar Research for supplying us with the Antarctic meteorite sample, to Dr. N. FUJII for the Hawaii olivine sand and the San Carlos olivine, to Dr. H. TAKEDA, Prof. N. ONUMA, Dr. O. OSHIMA, Dr. T. ISHII, and Dr. M. OTSUKI for helpful advice and discussions, and to Mr. T. HIROI for improvement of the manuscript. We thank Dr. L. A. MCFADDEN and Dr. N. FUJII for critical reading of the manuscript.

References

- ADAMS, J. B. (1974): Visible and near infrared diffuse reflectance spectra of pyroxenes as applied to remote sensing of solid objects in the solar system. *J. Geophys. Res.*, **79**, 4829–4836.
ADAMS, J. B. and FILICE, A. L. (1967): Spectral reflectance 0.4 to 2.0 microns of silicate rock powders.

- J. Geophys. Res., **72**, 5705–5715.
- BURNS, R. G. (1970): Mineralogical Applications of Crystal Field Theory. London, Cambridge Univ. Press, 255 p.
- BURNS, R. G., PARKIN, K. M., LOEFFLER, B. M., LEUNG, I. S. and ABU-EID, R. M. (1976): Further characterization of spectral features attributable to titanium on the moon. Proc. Lunar Sci. Conf. 7th, 2561–2578.
- CHAPMAN, C. R. (1976): Asteroids as meteorite parent-bodies: The astronomical perspective. Geochim. Cosmochim. Acta, **40**, 701–719.
- GAFFEY, M. J. (1976): Spectral reflectance characteristics of the meteorite classes. J. Geophys. Res., **81**, 905–920.
- GAFFEY, M. J. and MCCORD, T. B. (1977): Asteroid surface materials; Mineralogical characterizations and cosmological implications. Proc. Lunar Sci. Conf. 8th, 113–143.
- GAFFEY, M. J. and MCCORD, T. B. (1978): Asteroid surface materials; Mineralogical characterizations from reflectance spectra. Space Sci. Rev., **21**, 555–628.
- HUNT, G. R. and SALISBURY, J. W. (1970): Visible and near infrared spectra of minerals and rocks, I. Silicate minerals. Mod. Geol., **1**, 283–300.
- MAO, H. K., and BELL, P. M. (1975): Crystal-field effects in spinel; Oxidation states of iron and chromium. Geochim. Cosmochim. Acta, **39**, 865–874.
- MCFADDEN, L. A., GAFFEY, M. J., TAKEDA, H., JACKOWSKI, T. L. and REED, K. L. (1982): Reflectance spectroscopy of diogenite meteorite types from Antarctica and their relationship to asteroids. Mem. Natl Inst. Polar Res., Spec. Issue, **25**, 188–206.
- MIYAMOTO, M., MITO, A., TAKANO, Y. and FUJII, N. (1981): Spectral reflectance (0.25–2.5 μm) of powdered olivines and meteorites, and their bearing on surface materials of asteroids. Mem. Natl Inst. Polar Res., Spec. Issue, **20**, 345–361.
- MIYAMOTO, M., MITO, A. and TAKANO, Y. (1982): An attempt to reduce the effects of black material from the spectral reflectance of meteorites or asteroids. Mem. Natl Inst. Polar Res., Spec. Issue, **25**, 291–307.
- NASH, D. B. and CONEL, J. E. (1974): Spectral reflectance systematics for mixtures of powdered hypersthene, labradorite, and ilmenite. J. Geophys. Res., **79**, 1615–1621.
- OTSUKI, M. (1983): PROBE. JCL Reference manual. (unpublished manuscript), 214 p.
- PIETERS, C. M. (1974): Polarization in a mineral absorption band. Planets, Stars and Nebulae Studied with Photopolarimetry, ed. by T. GEHRELS. Tucson, Univ. of Arizona Press, 405–418.
- PIETERS, C. M. (1983): Strength of mineral absorption features in the transmitted component of near-infrared reflected light; First results from RECAP. J. Geophys. Res., **88**, 9534–9544.
- SINGER, R. B. (1981): Near-infrared spectral reflectance of mineral mixtures; Systematic combinations of pyroxenes, olivines, and iron oxides. J. Geophys. Res., **86**, 7967–7982.
- STUBICAN, V. S. and GRESKOVICH, C. (1975): Trivalent and divalent chromium ions in spinels. Geochim. Cosmochim. Acta, **39**, 875–881.
- TAKEDA, H., MIYAMOTO, M., YANAI, K. and HARAMURA, H. (1978): A preliminary mineralogical examination of the Yamato-74 achondrites. Mem. Natl Inst. Polar Res., Spec. Issue, **8**, 170–184.
- VENABLE, W. H., WEIDNER, V. R. and HSIA, J. J. (1976): Information sheet on optical properties of pressed Halon coatings, report. National Bureau of Standards, Washington, D. C.
- YANAI, K., comp. (1979): Catalog of Yamato Meteorites. 1st. ed. Tokyo, Natl Inst. Polar Res., 188 p. with 10 pls.

(Received May 26, 1983; Revised manuscript received August 13, 1983)