

# SPECTRAL REFLECTANCE (0.25–2.5 $\mu\text{m}$ ) OF POWDERED OLIVINES AND METEORITES, AND THEIR BEARING ON SURFACE MATERIALS OF ASTEROIDS

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**Abstract:** Spectral reflectance changes with the particle size, the thickness of the sample, the species of the background materials, and effects of carbon black were examined on powdered samples of sized olivines and some meteorites in the 0.25–2.5  $\mu\text{m}$  wavelength region. The effects of the pulverization on the spectral changes are dependent mainly on very fine-grained materials (*e.g.* <46  $\mu\text{m}$ ) in the sample. These spectral changes of meteorites are as follows: 1) The albedo increases; 2) The spectra 'redden' in the range of about 1.6–2.5  $\mu\text{m}$ ; 3) The absorption band strengths in the region of about 0.5–1.5  $\mu\text{m}$  become weak and broad; 4) The reflectance near 0.4  $\mu\text{m}$  is raised; 5) The sharp drop-off less than 0.35  $\mu\text{m}$  is found.

The thickness of the sample has little effect on the reflectance spectra when the sample is more than 0.2 mm thick, while a very thin sample (<0.1 mm) reduces spectral contrast. When the background material has low reflectivity such as some meteorites, the spectral reflectance depends almost entirely on a very thin layer of the materials on the surface. A very small amount (1–2 wt%) of carbon black lowers the reflectance and depresses the details of the absorption features. Taking into consideration these results and the brecciation processes by impacts on the asteroid surface, the finer-grained C1 or C2 meteorite seems to be a better candidate for the surface material of Ceres (or Pallas) than a coarse-grained sample of this meteorite.

## 1. Introduction

In the last decade, spectral reflectance measurements of asteroids have progressed rapidly, and the spectral resolution and wavelength coverage from U.V., Visible to near-I.R. have increased. The comparison between these astronomical data and the laboratory spectral reflectance data of meteorites or various mineral assemblages

was made by GAFFEY and McCORD (1977) and others (*e.g.* CHAPMAN, 1976; GAFFEY, 1976). Their works have provided us with the possible relationship between meteorite parent-bodies and various asteroids, and have enabled us to interpret asteroidal surface materials as the mineral assemblages of meteorites.

Spectral absorption features of minerals may be interpreted on the basis of crystal-field theory or molecular orbital theory or interionic charge-transfer, and are characteristic of particular minerals. The spectral reflectance curve of the mineral mixture is ideally a function of the relative abundance of the mineral phases present. However, the relative abundance of a mineral phase does not necessarily correlate directly with its apparent band depth of an absorption spectrum (ADAMS, 1974; GAFFEY and McCORD, 1977). For example, a small amount of carbon black is efficient in lowering the albedo and suppressing other spectral features of the sample (JOHNSON and FANALE, 1973). As pointed out by ADAMS and FILICE (1967), spectral reflectance properties in the 0.4 to 2.0  $\mu\text{m}$  wavelength region depend strongly on particle grain size, particle packing, particle shape, chemical composition and illumination geometry. Thus, the spectral reflectance of mineral mixtures is a more complex problem (KING and PIETERS, 1981; MIYAMOTO *et al.*, 1981).

The presence of cratered terrain on terrestrial planets and satellites (including the small bodies such as Phobos and Deimos) confirmed by many planetary probes suggests that the brecciation (mixing) by impact is a common phenomenon on their surface. It is assumed that the surface layer of these bodies consists of the polymict breccia-like material, a complex mixture of the various mineral fragments, produced by impact processes. MIYAMOTO *et al.* (1978) suggested that the polymict breccias such as eucrite polymict breccia or howardite might be formed by the surface brecciation process on the achondrite parent-body. It is possible that the surface of small bodies such as asteroids or meteorite parent-bodies is covered with the thin layer (a regolith layer) of fine-grained materials (HARTMANN, 1978). Therefore, we tried to examine the spectral reflectance changes with the particle grain size and the thickness of the powdered samples of the mineral (olivine) or meteorites taking into consideration the condition of the surface of the planetary bodies.

## 2. Instrumentation and Sample Preparation

The spectral reflectance measurements were made with a Beckman UV 5240 UV-Visible-NIR spectrophotometer. This instrument is equipped with an integrating sphere and the  $\text{BaSO}_4$ -coated plate is used as a standard. Illumination is a deuterium lamp in the spectral range of 0.25–0.35  $\mu\text{m}$  and a tungsten lamp in the range of 0.35–2.5  $\mu\text{m}$ . Two detectors are a photomultiplier in the 0.25–0.8  $\mu\text{m}$  range and a lead sulfide (PbS) cell in the 0.8–2.5  $\mu\text{m}$  range. The incident beam is perpendicular to the surface of the sample. The spectra (0.25–2.5  $\mu\text{m}$ ) were scanned at a constant rate of 0.125 nm/s in the 0.25–0.8  $\mu\text{m}$  region and rate of 0.5 nm/s in the 0.8–2.5  $\mu\text{m}$  region.

The spectral data were recorded on a floppy-disc every 2 seconds in digital form (that is, data were recorded every 0.25 nm in the 0.25–0.8  $\mu\text{m}$  region and every 1 nm in the 0.8–2.5  $\mu\text{m}$  region), and also on a chart. The program system for a HITAC M-200H computer in order to process these spectral data with a graphic display terminal was made. Although there are slight mismatches in the spectral curves at 0.80  $\mu\text{m}$  and 0.35  $\mu\text{m}$  because of changing detectors and lamps, respectively, these differences are digitally corrected by using one of the functions of this program system. The spectral data were corrected for the Halon standard by using the spectral data of Halon measured by the  $\text{BaSO}_4$  standard.

In order to examine in detail the spectral reflectance changes with the particle grain size and the thickness of the powdered samples, the spectral reflectance measurements were made of sized olivines. Olivine crystals (San Carlo, Arizona) were crushed and ground in a clean agate mortar, and sieved to obtain seven different size fractions (590–250  $\mu\text{m}$ , 250–177  $\mu\text{m}$ , 177–149  $\mu\text{m}$ , 149–100  $\mu\text{m}$ , 100–74  $\mu\text{m}$ , 74–46  $\mu\text{m}$  and <46  $\mu\text{m}$ ). The <46  $\mu\text{m}$  powder was further ground and reduced in size by the agate mortar to produce very fine-grained olivine powder ( $\ll 46 \mu\text{m}$ ).

For this study, the Antarctic meteorite samples Yamato-75258 (LL6), ALH-77230 (L4) and ALH-78115 (H6) were supplied by the National Institute of Polar Research (YANAI, 1979). The Allende meteorite was offered by courtesy of Prof. N. NAKAMURA of Kobe University. The meteorite samples were processed in the same manner as the olivine samples, and sieved to obtain two grain size fractions, <1190  $\mu\text{m}$  and very fine-grained powder ( $\ll 46 \mu\text{m}$ ).

Iron-bearing minerals in some Antarctic meteorites are suffered weathering after entering the earth's atmosphere. Although we selected the Antarctic meteorites which have been reported to have the lower grade of weathering, the samples of the meteorites were examined to remove grains with a red or orange coloration under a stereomicroscope.

Samples were placed in hollow space cut into the blackened holder and covered with the same calibrated cover glass as the  $\text{BaSO}_4$  standard. The cover glass is necessary to allow the samples to be held vertically. In order to examine the spectral changes with the thickness of the powdered samples, we made the five blackened sample holders which were respectively 2.5, 2.2, 1.6, 0.8, 0.4 and 0.2 mm in depth of the hollow space. These sample holders were blackened by an acrylic plastic paint. When the depth of the powdered sample is thinner than 0.2 mm, powdered samples were set on both sides of an adhesive tape (the powdered samples are probably less than 0.1 mm in thickness).

### 3. Results and Interpretations

#### 3.1. Particle size effect

Figure 1a shows the spectral reflectance curve of each of olivine powdered samples

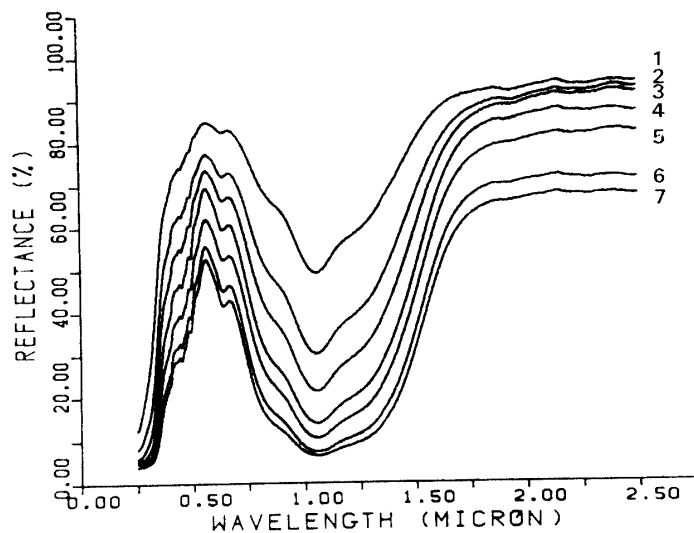


Fig. 1a. Spectral reflectance curves for the sized olivines.  
 1:  $<46\mu$ , 2:  $74-46\mu$ , 3:  $100-74\mu$ , 4:  $149-100\mu$ , 5:  $177-149\mu$ , 6:  
 $250-177\mu$ , 7:  $590-250\mu$ .

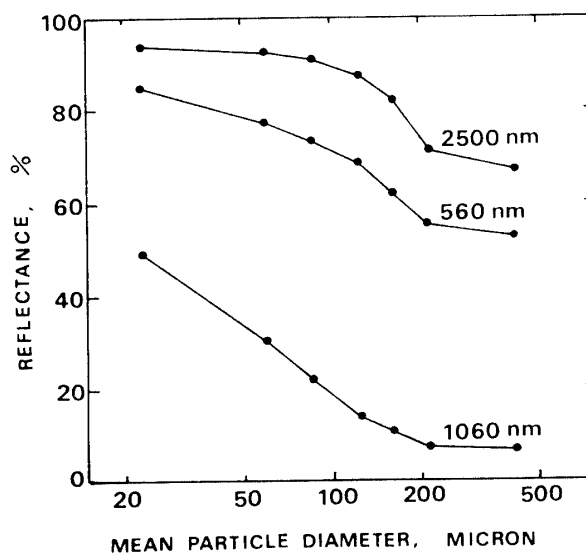


Fig. 1b. Variation of reflectance with mean particle diameter. Numbers on curves denote wavelength.

for seven different size fractions. The reflectance increases with the diminution of the particle size. Figure 1b shows the variations of the reflectance with the diminution of the particle size at three different wavelengths (2.5, 1.06 and  $0.56\mu\text{m}$ ). The reflectance sharply increases in the particle-size range of  $100-200\mu\text{m}$ . The reflectance at the wavelength of  $1.06\mu\text{m}$  increases at a relatively constant rate with decreasing particle size when the particle size is less than  $200\mu\text{m}$ . Because the powdered sample

of  $<46\ \mu$  has witnessed the remarkable spectral curve changes, the spectral reflectances of both very fine-grained sample ( $\ll 46\ \mu$ ) and  $<46\ \mu$  sample are shown in Fig. 2. The reflectance of the very fine-grained sample ( $\ll 46\ \mu$ ) is somewhat lower than that of the  $<46\ \mu$  sample in the 1.6–2.5  $\mu\text{m}$  region. These spectral changes seem to be controlled by the particle size of the material. To examine this fact in detail, Fig. 3a shows the spectral reflectance of the mixed sample consisting of 177–149  $\mu$

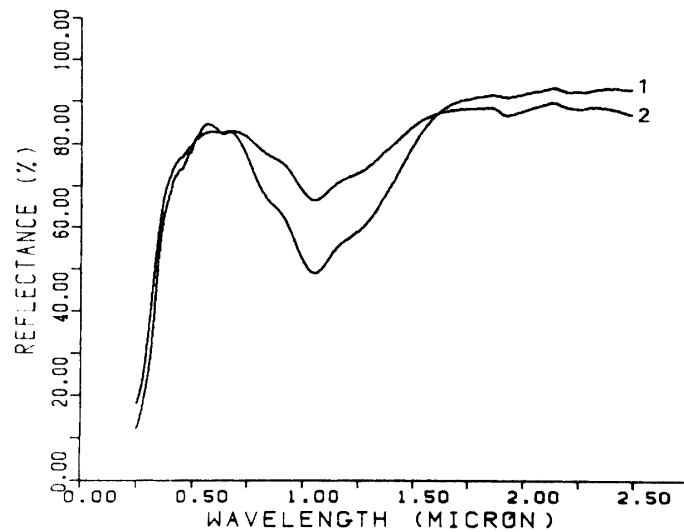


Fig. 2. Comparison between the  $<46\ \mu$  olivine and the  $\ll 46\ \mu$  sample.  
1:  $<46\ \mu$ , 2:  $\ll 46\ \mu$  (the powder into which  $<46\ \mu$  powder is further ground, but the grain size limit is not known).

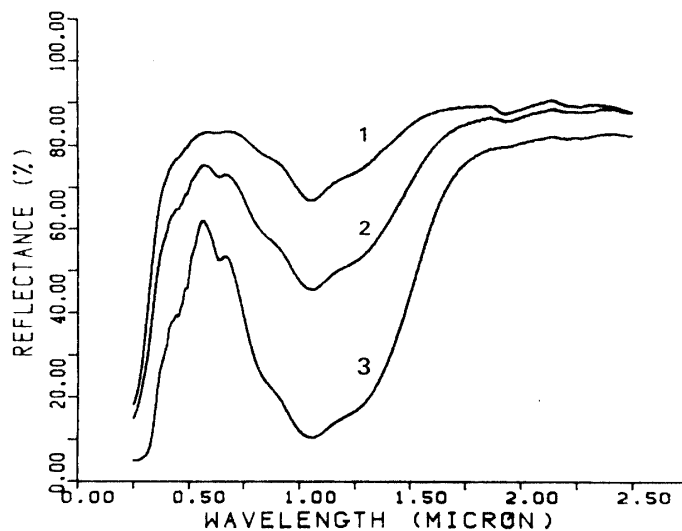


Fig. 3a. Spectral reflectance curves for the mixed sample consisting of the 177–149  $\mu$  and  $\ll 46\ \mu$  samples.  
1:  $\ll 46\ \mu$ , 2: 177–149  $\mu$  +  $\ll 46\ \mu$ , 3: 177–149  $\mu$ .

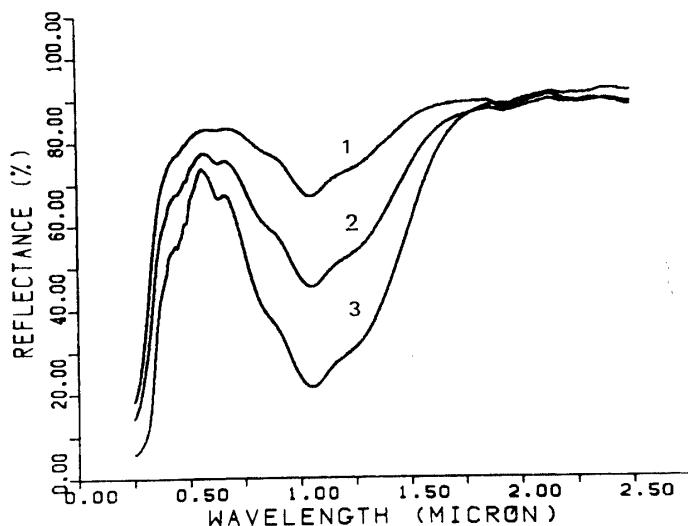


Fig. 3b. Spectral reflectance curves for the mixed sample consisting of the 100–74 $\mu$  and  $\ll 46\mu$  samples.  
1:  $\ll 46\mu$ , 2: 100–74 $\mu$  +  $\ll 46\mu$ , 3: 100–74 $\mu$ .

and  $\ll 46\mu$  sized samples which are in the volume ratio of 1:1, together with the very fine-grained sample ( $\ll 46\mu$ ) and the 177–149 $\mu$  sample. The mixed sample shows the intermediate feature of reflectance spectra between the  $\ll 46\mu$  and the 177–149 $\mu$  samples in the 0.3–1.5 $\mu$ m region. Figure 3b shows the spectral reflectance of the mixed sample consisting of 100–74 $\mu$  and  $\ll 46\mu$  sized samples which are in the volume ratio of 1:1. The reflectance curves around 0.4 $\mu$ m of these mixed samples are raised by the effect of very fine-grained materials. Very fine-grained materials contained in the sample reduce spectral contrast (Figs. 1–3).

The changes of the absorption band depth (strength) near 1 $\mu$ m with the diminution of the particle size are shown in Table 1. The absorption band depth is defined

Table 1. Variation of absorption band depth with the diminution of particle size.

Particle size ( $\mu$ m)	(1) Peak (560 nm)	(2) Absorption (1060 nm)	Band depth ((1)–(2))
590–250	52.7%	6.3%	46.4
250–177	55.7	7.3	48.4
177–149	62.0	10.4	51.6
149–100	69.3	13.9	55.4
100–74	73.4	21.5	51.9
74–46	77.3	30.3	47.0
<46	84.8	49.3	35.5
$\ll 46$	82.8	66.8	16.0

by the difference of the reflectance between the maximum peak at the wavelength of  $0.56\ \mu\text{m}$  (560 nm) and the characteristic absorption band at  $1.06\ \mu\text{m}$  (1060 nm). The absorption band depth becomes deep with the diminution of the particle size when the size fractions are larger than  $149\ \mu\text{m}$ , while the reflectance increases. Conversely, the absorption band depth becomes shallow with the diminution of the particle size when the size fractions are smaller than about  $100\ \mu\text{m}$ . This trend is pronounced in the case of the  $\ll 46\ \mu$  sample.

The reflectance curve features in the  $0.3\text{--}0.8\ \mu\text{m}$  region remain unchanged with the diminution of the particle size when the size fractions are larger than  $\sim 46\ \mu\text{m}$  (Fig. 1). When the size fractions are smaller than  $\sim 46\ \mu\text{m}$ , our results (Figs. 1–3) reveal that the shape of the reflectance curve in the  $0.3\text{--}0.8\ \mu\text{m}$  region becomes broad and unpeaked, the small peaks in this region lose sharpness, and that the spectral reflectance around  $0.45\ \mu\text{m}$  is raised. Therefore, the shape of the spectral reflectance becomes relatively 'flat' in the range of  $0.3\text{--}0.8\ \mu\text{m}$ .

Because the spectral curve changes are found in the results of the very fine-grained sample ( $\ll 46\ \mu$ ) of olivine, in the case of the meteorite samples the spectral reflectances of the two different size fractions of  $<1190\ \mu$  and very fine-grained powder ( $\ll 46\ \mu$ ) were measured owing to the small amount of the samples. The sample holder which is deep enough to measure the given sample was used. Figures 4, 5 and 6 show the spectral reflectance curves of the  $<1190\ \mu$  and very fine-grained ( $\ll 46\ \mu$ ) samples of Yamato-75258 (LL6) ordinary chondrite, ALH-77230 (L4) ordinary chondrite and ALH-78115 (H6) ordinary chondrite, respectively. The comparison of the results for the  $\ll 46\ \mu$  samples of these three meteorites is shown in Fig. 7.

The effects of the pulverization of the meteorite samples on the spectral reflectance changes are similar to those of the olivine samples. They are as follows: The reflectance increases; the reflectance in the range of *ca.*  $1.6\text{--}2.5\ \mu\text{m}$  is raised with increasing wavelength ('reddening'); the reflectance near  $0.45\ \mu\text{m}$  is raised; the sharp drop-off less than about  $0.35\ \mu\text{m}$  is found; the absorption band strengths near  $1.0$  and  $1.9\ \mu\text{m}$  become weak; the peak (about  $1.5\ \mu\text{m}$ ) becomes broad and unpeaked with the diminution of the particle size. Therefore, the spectral reflectance curve loses contrast in the range of *ca.*  $0.4\text{--}1.6\ \mu\text{m}$  and there is a rise (reddening) in the range of *ca.*  $1.6\text{--}2.5\ \mu\text{m}$ . We note that the reflectance in the region of *ca.*  $0.4\text{--}0.8\ \mu\text{m}$  of the  $\ll 46\ \mu$  sample of Y-75258 is lower than that of the  $<1190\ \mu$  sample (Fig. 4). The sharp drop-off near  $0.4\text{--}0.5\ \mu\text{m}$  found in the results of ALH-77230 and ALH-78115 is due to weathering (Fig. 7) (MCFADDEN *et al.*, 1980).

### 3.2. Effects of the thickness of the powder sample

The spectral reflectance is considered to be mainly influenced by the degree of the multiple reflection among the particles contained in the sample. In order to show the spectral reflectance changes with the thickness of the powdered samples (namely, the depth of the hollow space in the sample holder), the olivine samples of  $144\text{--}100\ \mu$

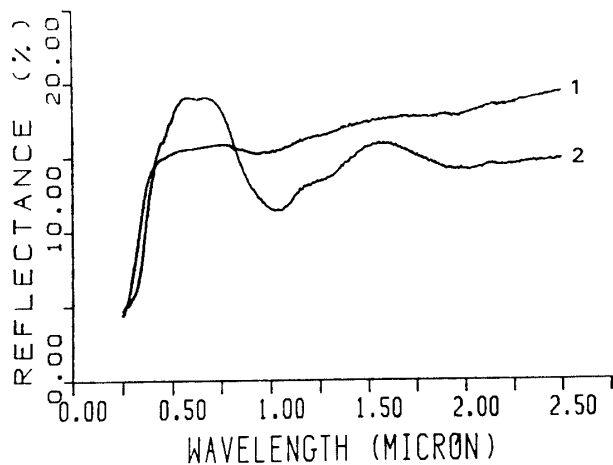


Fig. 4. Spectral reflectance curves for the  $\ll 46\mu$  and  $< 1190\mu$  samples of Yamato-75258 (LL6).  
1:  $\ll 46\mu$ , 2:  $< 1190\mu$ .

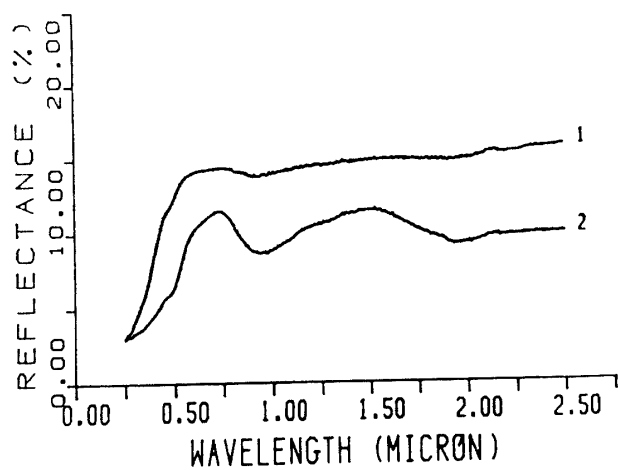


Fig. 5. Spectral reflectance curves for the  $\ll 46\mu$  and  $< 1190\mu$  samples of ALH-77230 (L4).  
1:  $\ll 46\mu$ , 2:  $< 1190\mu$ .

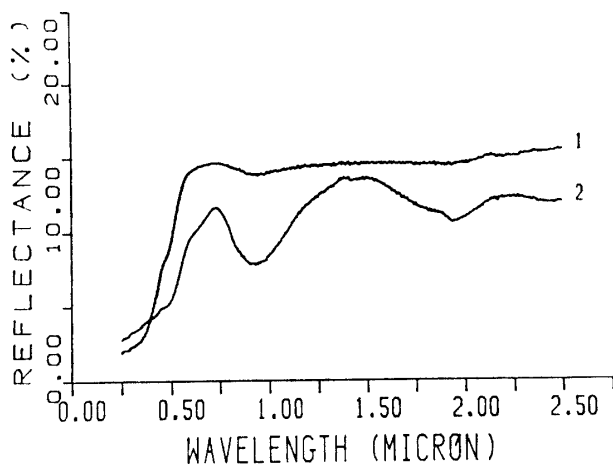


Fig. 6. Spectral reflectance curves for the  $\ll 46\mu$  and  $< 1190\mu$  samples of ALH-78115 (H6).  
1:  $\ll 46\mu$ , 2:  $< 1190\mu$ .



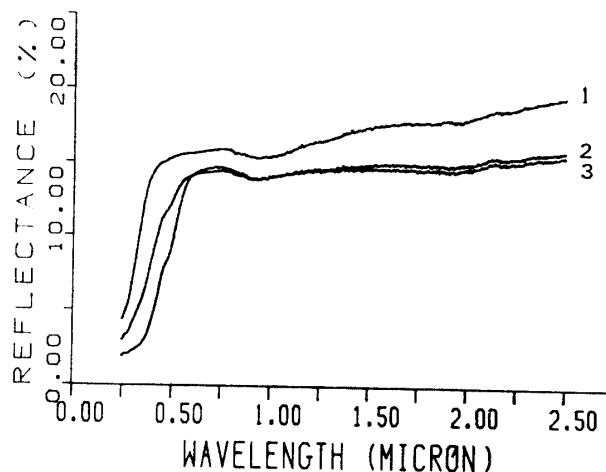


Fig. 7. Comparison of spectral reflectance curves with the  $\ll 46\mu$  meteorite samples, Yamato-75258, ALH-77230 and ALH-78115.

1: Yamato-75258, 2: ALH-77230, 3: ALH-78115.

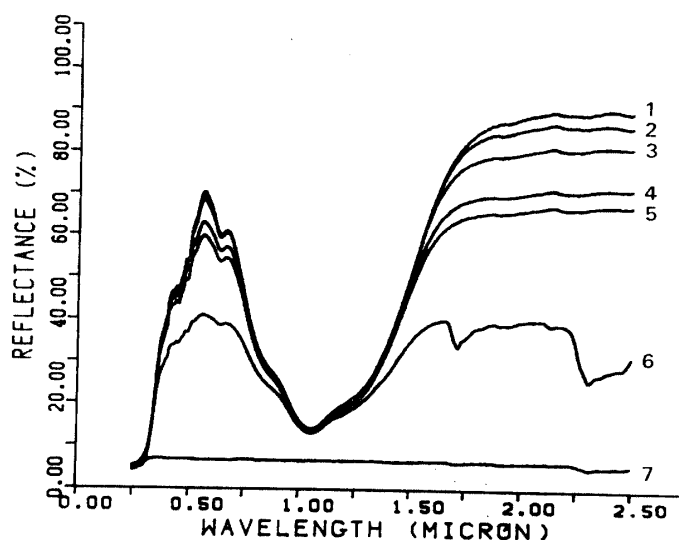


Fig. 8. Spectral reflectance curves for the  $149-100\mu$  olivine sample in different depths of holders. 1: the depth of holder is 2.2 mm, 2: 1.6 mm, 3: 0.8 mm, 4: 0.4 mm, 5: 0.2 mm, 6: the sample set on an adhesive tape, 7: an adhesive tape.

and  $\ll 46\mu$  were measured by using the sample holders of different depths (Figs. 8 and 9). The depths of the sample holders used are 0.2, 0.4, 0.8, 1.6 and 2.2 mm. The particular samples are set on both sides of an adhesive tape in order to examine only very thin sample ( $< \sim 0.1$  mm in depth).

Our results of the  $144-100\mu$  olivine sample (Fig. 8) show that the depth of the characteristic band near  $1\mu$  becomes deep with increasing depth of the holder. The reflectance taking higher value near  $0.55\mu$  and  $1.6-2.5\mu$  increases gradually with increasing holder depth. The spectral reflectance of the  $144-100\mu$  sample set on both sides of an adhesive tape makes considerable changes as shown in curve 6 in Fig. 8. The reflectance increases and a very thin sample ( $< 0.1$  mm in depth) reduces

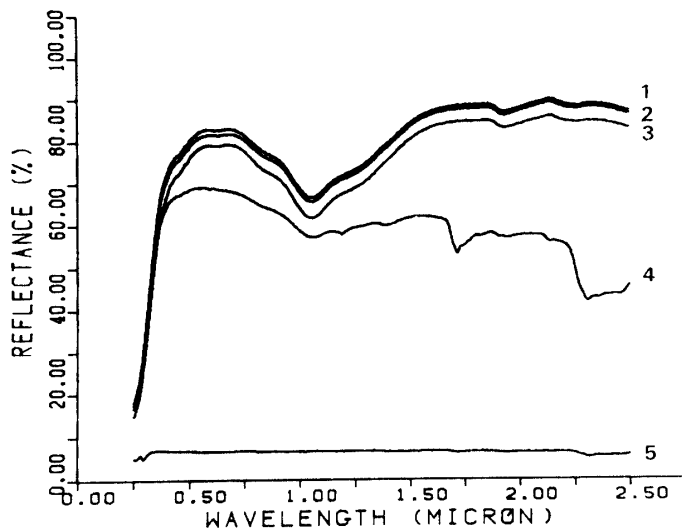


Fig. 9. Spectral reflectance curves for the  $\ll 46\mu$  olivine sample in different depths of holders. 1: the depth of holder is 0.8 mm, 2: 0.4 mm, 3: 0.2 mm, 4: the sample set on an adhesive tape, 5: an adhesive tape.

spectral contrast. Two sharp absorption bands (about 1.7 and 2.3  $\mu\text{m}$ ) are probably due to the adhesive tape. It is interesting that these absorption bands become sharp in curve 6 in Fig. 8, although these are seen only vaguely in curve 7.

The results of the  $\ll 46\mu$  olivine samples (Fig. 9) show that the spectral reflectances increase gradually with increasing depth of the holder. The absorption feature and the details of the peaks remain unchanged. In the case of the  $\ll 46\mu$  sample set on an adhesive tape, the peaks in the Visible region become broad, and the reflectance in the NIR region decreases remarkably. The spectral reflectance becomes relatively 'flat'. We note that this diffuse spectral curve may depend on the particle packing in the sample. Further study will be necessary to verify the packing effect.

### 3.3. Effects of the background materials

In order to simulate one of the possible conditions of the surface of small planets (covered with very thin regolith layer), the  $\ll 46\mu$  olivine sample upon the 1190–144 $\mu$  olivine and the  $\ll 46\mu$  sample of Y-75258 upon the  $<1190\mu$  sample of Y-75258 were measured as shown in Figs. 10 and 11. The  $\ll 46\mu$  samples were set on both sides of an adhesive tape. Figures 10 and 11 also show that the spectral curves of the  $\ll 46\mu$  samples of the olivine and Y-75258, respectively to compare the spectral changes with the difference of the background material. These samples were set on an adhesive tape and measured upon the black plate.

In the case of the olivine powdered samples, the absorption band strength of about 1  $\mu\text{m}$  is depressed when the  $\ll 46\mu$  sample is upon the black plate. The results of Y-75258 samples show that the spectral reflectance is almost identical between the

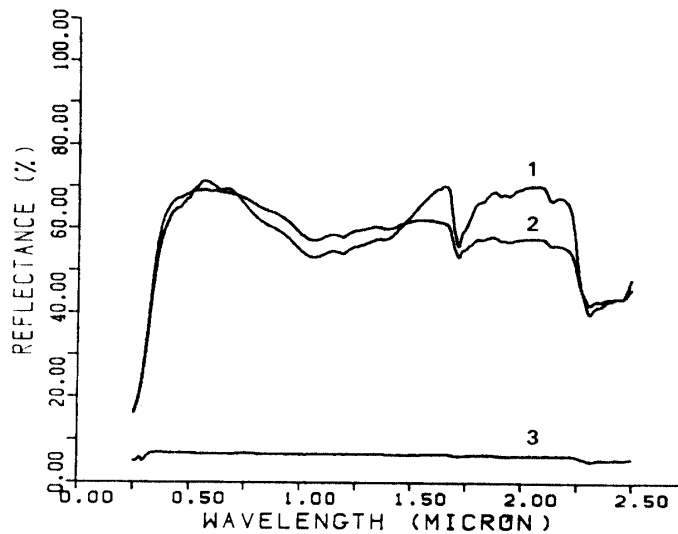


Fig. 10. Comparison of the  $\ll 46\mu$  thin olivine sample with different background materials. 1: the  $\ll 46\mu$  thin sample (set on an adhesive tape) upon the  $1190\text{--}149\mu$  olivine sample, 2: the  $\ll 46\mu$  thin olivine sample upon the black plate, 3: an adhesive tape.

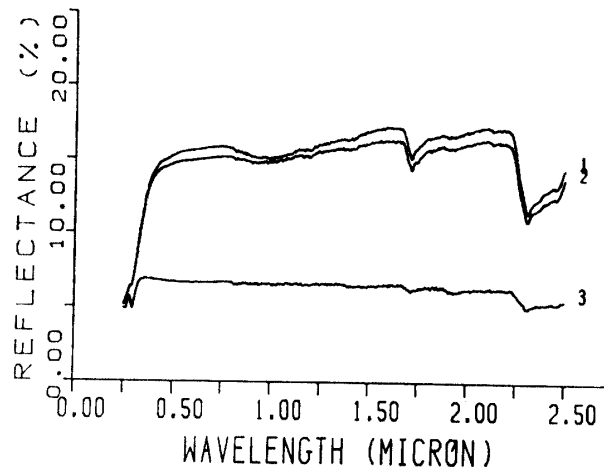


Fig. 11. Comparison of the  $\ll 46\mu$  thin sample of Yamato-75258 with different background materials. 1: the  $\ll 46\mu$  thin sample of Y-75258 (set on an adhesive tape) upon the  $<1190\mu$  Y-75258 sample, 2: the  $\ll 46\mu$  thin sample of Y-75258 upon the black plate, 3: an adhesive tape.

two cases except for the slightly high reflectance of the  $\ll 46\mu$  sample upon the  $<1190\mu$  sample. In short, it can be considered that there is little effect of the background material when the background material is the sample such as meteorite or asteroid which shows low reflectance.

#### 3.4. Effects of carbon black on the reflectance curve

Because astronomical studies have revealed that many asteroids have very low

albedos (MORRISON, 1977), we performed the spectral reflectance measurements of the meteorite samples in which carbon black (Koso Chemical Co., SOJ 2481) of various amounts was mixed. Figure 12 shows the spectral reflectance curves of the  $<590\mu$  sample of the Y-75258 meteorite containing 1 and 5 wt% carbon black, compared with those of pure carbon black and the  $<1190\mu$  sample. Only 1 wt% carbon black lowers the spectral reflectance and depresses the absorption feature remarkably (Figs. 4 and 12). Figure 13 shows the spectral reflectance curves of the  $\ll 46\mu$  samples of Y-75258 which contain 2 and 5 wt% carbon black together with the  $\ll 46\mu$  sample without carbon black. These results also show that a very small amount of carbon black lowers the reflectance. It is an interesting fact that carbon black is more effective on reflectance and absorption band strength of the  $<590\mu$  samples (Fig. 12) than on those of the  $\ll 46\mu$  samples (Fig. 13).

The spectral reflectance curve of the  $<1190\mu$  sample of the Allende meteorite is shown in Fig. 14. The spectral curves of the  $\ll 46\mu$  sample in the holders of 0.2 and 0.7 mm depths are also shown in Fig. 14. The difference between the two cases is found in reflectance. It may be due to the particle packing that the reflectance of the  $\ll 46\mu$  sample in 0.2 mm depth is higher than that in 0.7 mm depth. By the pulverization of the Allende meteorite the spectral reflectance in *ca.* 1.0–2.5  $\mu\text{m}$  region increases. Figure 15 shows the spectral reflectance curves of the  $\ll 46\mu+2$  wt% carbon black sample of the Y-75258 meteorite and the  $\ll 46\mu$  sample (in the 0.7 mm holder) of the Allende meteorite. The spectral reflectance of Y-75258+2 wt% carbon black ( $\ll 46\mu$ ) resembles that of the  $\ll 46\mu$  sample of the Allende meteorite except for the features of UV-Visible region. Figure 16 shows the spectral reflectance curves of the  $<590\mu+1$  wt% carbon black sample of Y-75258 and the  $<1190\mu$  sample of Allende.

## 4. Discussions

### 4.1. Spectral absorption feature

It is well known that the albedo increases by the pulverization of the sample (ADAMS and FILICE, 1967). This effect can be seen by the naked eye. On the other hand, for opaque minerals such as ilmenite, the effect is reversed (HUNT *et al.*, 1971). The extent of spectral change is dependent on the mineral assemblage in the sample. It has been known that whether the absorption feature becomes deep or not with the diminution of particle size also depends on the mineral species present (ADAMS and FILICE, 1967). It is necessary to examine the effects of the pulverization of the sample on the representative meteorite groups. We need to take notice of the weathering of the meteorites, especially Antarctic meteorites (MCFADDEN *et al.*, 1980).

It is found that very fine-grained materials ( $\ll 46\mu$ ) reduce spectral contrast, and that the reflectance in the range of about 1.6–2.5  $\mu\text{m}$  is raised (reddening) by pulverization.

Fig. 12. Spectral reflectance curves for the Yamato-75258 samples mixed with different amounts of carbon black. 1:  $<1190\mu$  Y-75258 sample, 2:  $<590\mu$  Y-75258 mixed with 1 wt% carbon black, 3:  $<590\mu$  Y-75258 mixed with 5 wt% carbon black, 4: pure carbon black.

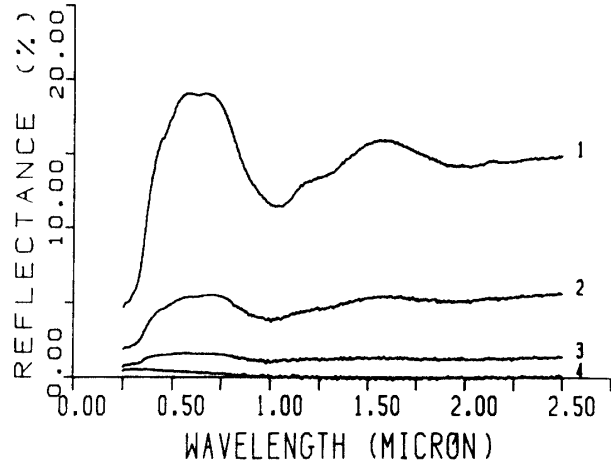


Fig. 13. Spectral reflectance curves for the  $\ll 46\mu$  samples of Yamato-75258 mixed with different amounts of carbon black. 1:  $\ll 46\mu$  Y-75258 sample, 2:  $\ll 46\mu$  Y-75258 mixed with 2 wt% carbon black, 3:  $\ll 46\mu$  Y-75258 mixed with 5 wt% carbon black.

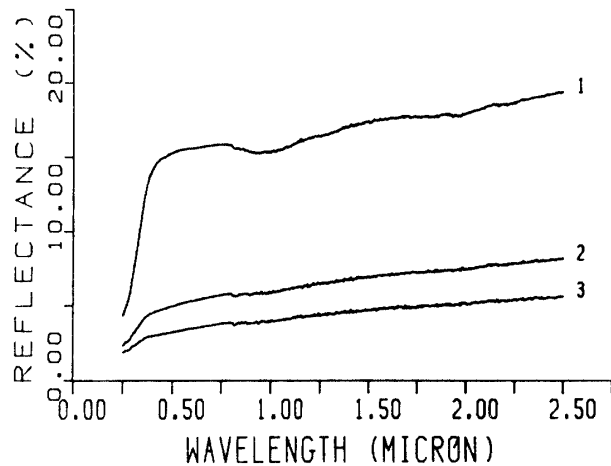
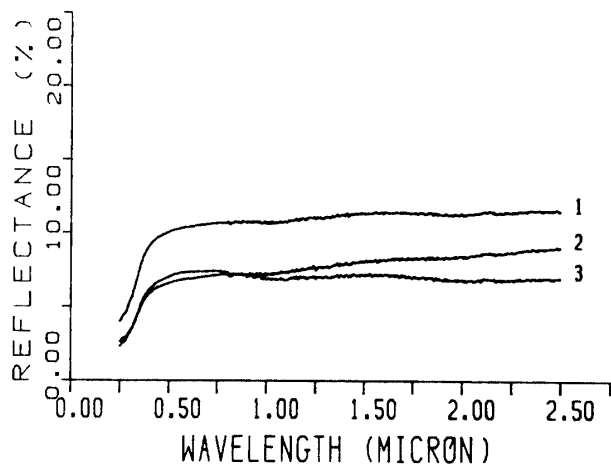


Fig. 14. Spectral reflectance curves for the Allende meteorite. 1: the  $\ll 46\mu$  sample in 0.2 mm depth holder, 2: the  $\ll 46\mu$  sample in 0.7 mm depth holder, 3:  $<1190\mu$  sample.



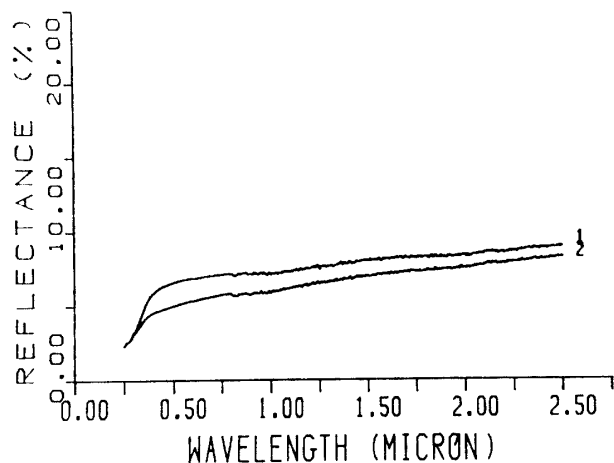


Fig. 15. Comparison between the  $\ll 46\mu$  sample of Allende and the  $\ll 46\mu$  sample of Y-75258 mixed with 2 wt% carbon black.  
1:  $\ll 46\mu$  sample of Allende, 2: the  $\ll 46\mu$  of Y-75258 mixed with 2 wt% carbon black.

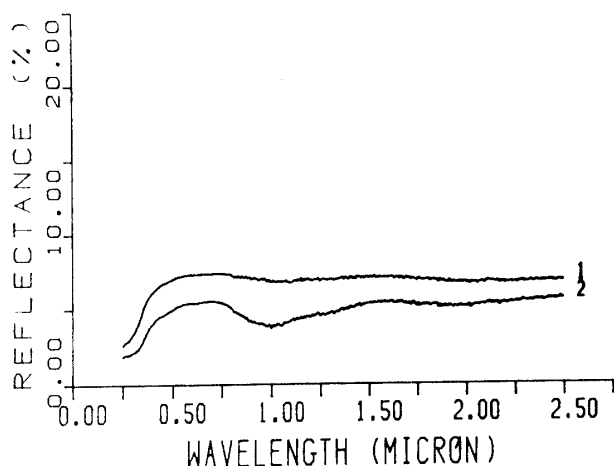


Fig. 16. Comparison between the  $< 1190\mu$  Allende sample and the  $< 590\mu$  of Y-75258 mixed with 1 wt% carbon black.  
1: the  $< 1190\mu$  Allende, 2: the  $< 590\mu$  of Y-75258 mixed with 1 wt% carbon black.

Although the thickness of the sample has little effect on the reflectance change when the sample is fine-grained and more than 0.2 mm thick, very thin samples ( $< \sim 0.1$  mm) reduce spectral contrast.

When the background material has low reflectance such as some meteorites or asteroids, the spectral reflectance feature depends almost entirely on a very thin layer of the materials on the surface. The thin layer of the surface materials of the planets (asteroid, etc.) can be determined on the basis of their reflectance spectra in the UV-Visible-NIR region.

A very small amount of carbon black lowers the reflectance and depresses the details of the absorption features. As shown in Fig. 15, the spectral reflectance of Y-75258 (LL6) ( $\ll 46\mu$ )+2 wt% carbon black resembles that of the  $\ll 46\mu$  sample of Allende, though the curvature of the drop-off near  $0.35\mu$  is different from each other.

We note that it is necessary to examine in detail the curvature of the drop-off of the reflectance near  $0.35\ \mu\text{m}$  because this wavelength region is susceptible to the particle size or the mineral assemblage in the sample or the presence of the carbon black.

#### 4.2. *Speculation about the surface composition of asteroids*

The spectral reflectances of asteroids 1 Ceres and 2 Pallas have been the subject of controversy (JOHNSON and FANALE, 1973; CHAPMAN and SALISBURY, 1973; McCORD and GAFFEY, 1974; CHAPMAN *et al.*, 1975; CHAPMAN, 1976; GAFFEY and McCORD, 1978; LARSON and VEEDER, 1979). The spectral reflectance of these asteroids reported by LARSON *et al.* (1979) or FEIERBERG *et al.* (1980) shows a relatively flat feature in the region of *ca.*  $0.5\text{--}2.5\ \mu\text{m}$ , monotonically increasing with wavelength (reddening) in the NIR region, a small broad peak at *ca.*  $0.4\text{--}0.5\ \mu\text{m}$ , a weak and broad absorption around  $1\ \mu\text{m}$ , and a sharp drop-off at wavelength less than about  $0.4\ \mu\text{m}$ . It has been considered that these reflectances resemble those of the carbonaceous chondrite materials or carbonaceous chondritic mineral assemblages. LARSON *et al.* (1979) proposed that the spectral reflectances of these asteroids are consistent with mixtures of opaques and hydrated silicates such as are found in types C1 and C2 meteorites on the basis of the broad band spectral reflectances over  $0.4$  to  $3.6\ \mu\text{m}$  combined with previous spectral measurements. A salient difference between the spectral reflectance curves of Ceres and C2 carbonaceous chondrite (Fig. 6 in LARSON *et al.*, 1979) is the position or curvature of the UV drop-off. The wavelength of this drop-off of the meteorite spectra is longer than that of Ceres.

The curve feature of the UV drop-off is influenced considerably by the pulverization of the sample. Taking into consideration the brecciation processes by impact and the regolith layer produced by them on the surface of the planets, the finer-grained C1 or C2 meteorite seems to be a better candidate for the surface material of Ceres than a coarse-grained sample of this meteorite. This is in line with the result reported by DOLLFUS and WOLFF (1981) that the surface material of the C-type asteroids appears to be finer-grained than the S-type asteroids.

On the other hand, the spectral reflectances of these asteroids (according to asteroidal spectral types (CMZ) defined by CHAPMAN *et al.* (1975), 'C' or 'U' type) seem to have some resemblance (*e.g.* the flatness or drop-off less than  $0.4\ \mu\text{m}$ , and reddening) to those of powdered samples of meteorites (including ordinary chondrites). One of the differences between the asteroids and the meteorites is that the albedo of the powdered meteorite samples is higher than that of the asteroids. The low albedo of these asteroids is a very important spectral parameter to interpret the surface material of the asteroids. A small amount of low reflectivity material (such as carbon black or magnetite) is very effective in lowering the albedo and depressing other spectral features. The spectral features depend on a small amount of low reflectivity materials instead of the host materials. We cannot exclude the possibility that the host material

is not C1 or C2 meteoritic material. It is important to determine the mineral species which have low reflectivity on the basis of the observational spectral data and mineralogical or petrological study on meteorites.

The curvature of the UV drop-off susceptible to the influence of carbon black as well as the effects of pulverization. It is necessary to examine in more detail the curvature of the drop-off near  $0.35 \mu\text{m}$  of the astronomical reflectance spectra, in order to identify exactly the surface materials of the asteroids which show 'C' or 'U' type spectral curve.

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