Mem. Natl Inst. Polar Res., Spec. Issue, 46, 123–130, 1987

DIFFUSE REFLECTANCE FROM 0.25 μm TO 25 μm OF THE YAMATO-691 ENSTATITE CHONDRITE

Masamichi MIYAMOTO

College of Arts and Sciences, University of Tokyo, Komaba, Meguro-ku, Tokyo 153

Abstract: We measured the diffuse reflectance from 0.25 to 25 μm of the Yamato-691 enstatite chondrite (E3) and compared it with that of an iron meteorite. The reflectance of Y-691 does not show any strong absorption bands except for the UV fall-off shorter than about 0.55 μm in the UV-visible-near infrared wavelength region. The reflectance of Y-691 in the middle infrared wavelength region shows strong absorption bands at wavelengths longer than about 9 μm mainly caused by vibrations of the Si^{4+} ion in enstatite. The reflectance of the iron meteorite (Toluca, octahedrite) does not show any strong absorption bands up to 25 μm except for the UV fall-off shorter than about 0.4 μm. The reflectance of the plate (polished) sample of Y-691 does not show the steep UV fall-off although that of the powder sample of Y-691 shows a relatively steep UV fall-off at wavelengths less than about 0.55 μm. The plate sample of Y-691 shows a weaker UV fall-off compared with that of the iron meteorite. We can distinguish enstatite chondrite-like materials from iron meteorite-like materials on the basis of spectral features around 10 μm. We may also be able to distinguish them on the basis of spectral features in the UV. We speculate that the surface composition of asteroid 16 Psyche is the enstatite chondrite-like assemblage, not the iron meteorite-like assemblage.

1. Introduction

As part of consortium studies on the Yamato-691 enstatite chondrite (E3), we measured spectral reflectances in the UV-visible-near infrared (UV-VIS-NIR) wavelength region (0.25–2.55 μm) and the middle infrared (MIR) wavelength region (2.53–25 μm). We also measured the spectral reflectances of an iron meteorite for comparison.

GAFFEY (1976) has measured spectral reflectances (0.35–2.5 μm) of nearly all types of meteorites and discussed them in terms of the composition, abundance, and distribution of the component mineral phases. He measured the spectra of four enstatite chondrites (Abee (E4), Hvittis (E6), Khairpur (E6), and Pillistfer (E6)). They are featureless with a variable reddish slope in the visible and a very slowly increasing near infrared reflectance.

SANDFORD (1984) has measured MIR transmission spectra of many meteorites and discussed them based on mineralogy of meteorites. In SANDFORD's work, the spectrum of one enstatite chondrite (Abee (E4)) is shown and is identical to that of enstatite.

The UV-VIS-NIR spectra of enstatite chondrites and iron meteorites are similar (GAFFEY, 1976), because they are featureless and have similarly reddened slopes. This causes difficulty in interpreting the mineral assemblage of the M-type asteroids (GAFFEY and McCORD, 1977, 1978). Mineral assemblages of the M-type asteroid are thought to be enstatite chondrite-like or iron meteorite-like. These meteorites do not show strong absorption bands in the UV-VIS-NIR wavelength region, because absorption bands are mainly caused by crystal field splitting energy. In the MIR region, absorption bands are mainly caused by vibrations of ions (*e.g.*, Si^{4+}). The MIR transmission spectrum of enstatite chondrite, therefore, shows many absorption bands at wavelengths longer than 9 μm (SANDFORD, 1984).

2. Samples and Experimental Techniques

2.1. *Samples*

Yamato-691 (Y-691) is classified as E3 (*e.g.*, PRINZ *et al.*, 1984) and consists mainly of enstatite and clinoenstatite (OKADA, 1975). It also contains small amounts of olivine, plagioclase (or feldspathic glass), silica, Fe-Ni metal, and troilite (PRINZ *et al.*, 1984). The sample supplied by the National Institute of Polar Research is a plate about $1.2\times0.8\times0.15$ cm in size and weighs 0.492 g (YANAI and KOJIMA, 1986).

Immediately after polishing the surface of the sample by diamond lapping paste in ethyl alcohol, we measured spectral reflectances of the polished surface (plate sample) of Y-691. And then we cut jags of the sample to make a powder sample. The small fragments were crushed and ground in a clean agate mortar and sieved by a 46 μm mesh cloth to obtain the powder sample.

The iron meteorite we used is Toluca (octahedrite) about $4.5\times2.5\times0.4$ cm in size. We polished the surface of the sample in the similar manner to the Y-691 enstatite chondrite and measured spectral reflectances of the polished surface. We could not measure spectral reflectances of a powder sample of the iron meteorite because of difficulty in pulverizing the sample.

2.2. *UV-VIS-NIR measurement*

Spectral reflectance measurements were made with a Beckman UV 5240 spectrophotometer equipped with an integrating sphere. The wavelength range measured is from 0.25 to 2.55 μm. Halon was used as a standard. Incident light is perpendicular to the surface of a sample. A powder sample was placed in a hollow space 0.4 mm in depth cut into the blackened holder by an acrylic plastic paint. Details of the instrumentation and method are described in MIYAMOTO *et al.* (1981, 1982)

2.3. *MIR measurement*

Spectral reflectance measurement were made with a JASCO FT/IR-3 Fourier transform infrared spectrophotometer equipped with a diffuse reflectance attachment (DR-81). The wavelength range measured is from 3950 cm^{-1} (2.53 μm) to 400 cm^{-1} (25 μm) at a resolution of 4 cm^{-1}. Our measurements are nearly emissionless because the sample was located between the interferometer and the detector and irradiated by light modulated with the interferometer. Emitted flux from the sample to the detector is not modulated with the interferometer. Incidence angle was about 45°. A powder sample was placed in a hollow space 1.5 mm in depth. An aluminum-coated mirror was used as a standard. We passed dry air into the spectrophotometer.

3. Results and Discussion

3.1. UV-VIS-NIR spectra

Figure 1 shows the UV-VIS-NIR reflectance (0.25–2.55 μm) of the powder sample of Y-691 and plate samples of Y-691 and Toluca. The spectrum of the powder sample of Y-691 (curve 2 in Fig. 1) resembles that of E6 chondrites rather than Abee (E4) (GAFFEY, 1976). The slope of the spectrum of the powder sample of Y-691 in the NIR region and the UV fall-off are similar to those of E6. The UV fall-off of Abee is gentler than that of the powder sample of Y-691. The slope in the NIR region of Abee is steeper than that of the Y-691. This may be because Abee contains more Fe-Ni metal (about 13 vol%) than Y-691 (about 8 vol%) (PRINZ *et al.*, 1984).

Salient differences between the spectra of the powder sample and the plate sample of Y-691 (curves 1 and 2 in Fig. 1) is seen in the UV fall-off. The powder sample of Y-691 shows a relatively steep UV fall-off at wavelengths less than about 0.55 μm compared with the plate sample. It should be noted that the plate sample of Y-691 shows a weak UV fall-off compared with that of the plate sample of the iron meteorite (curves 1 and 3 in Fig. 1). For a silicate assemblage containing transition metal ions, charge transfer absorptions determine the spectral features in the UV region, that is, UV fall-off (*e.g.*, GAFFEY and MCCORD, 1977). The UV fall-off of metals is due to the effect of plasma oscillation (*e.g.*, ABELÈS, 1972). Because silicates in Y-691 contain few Fe^{2+} ions and Y-691 contains a small amount of Fe-Ni metal (about 8 vol%), the spectrum of the plate sample of Y-691 does not show a steep UV fall-off compared with that of the iron meteorite. The UV fall-off of the powder sample of Y-691 (curve 2 in Fig. 1) may be due to multiple scattering, although we need further studies to explain this. The spectral feature of the UV fall-off may enable us to distinguish enstatite-like materials from iron meteorite-like materials.

It should be also noted that the UV fall-off of the powder sample of Y-691 starts at about 0.55 μm, whereas that of the iron meteorite starts at about 0.4 μm and that the UV fall-off of the iron meteorite is steeper than that of Y-691 (curves 2 and 3 in Fig. 1).

The spectrum of the plate sample of Y-691 shows faint absorption band around 1 μm (curve 1 in Fig. 1). This may be due to Fe^{2+} in enstatite or olivine. Y-691 contains a relatively large abundance of olivine (7.2 vol%) (PRINZ *et al.*, 1984). The range of FeO in enstatite is 0.2–4.6 wt% and that in olivine is 0.1–4.5 wt% (PRINZ *et al.*, 1984).

The spectra of Y-691 do not show an absorption band around 0.65 μm, although Cr_2O_3 of enstatite in Y-691 is relatively high and ranges from 0.11–1.63 wt%. Olivines in Y-691 also have high Cr, with 0.1–0.8 wt% calculated as Cr_2O_3 (PRINZ *et al.*, 1984). Lunar pyroxenes have a chromium band at 0.64 μm (HAZEN *et al.*, 1978) and diogenitic pyroxenes have a chromium band between 0.60–0.62 μm (MCFADDEN *et al.*, 1982). HIROI *et al.* (1985) made crystal field calculations to assign the Cr^{3+} ion to bands around 0.6 μm in olivine, orthopyroxene, and clinopyroxene.

The 1.9 μm band in the spectra of the plate samples of Y-691 and iron meteorite is probably due to adsorbed water. The powder sample of Y-691 shows a faint absorption around 1.9 μm.

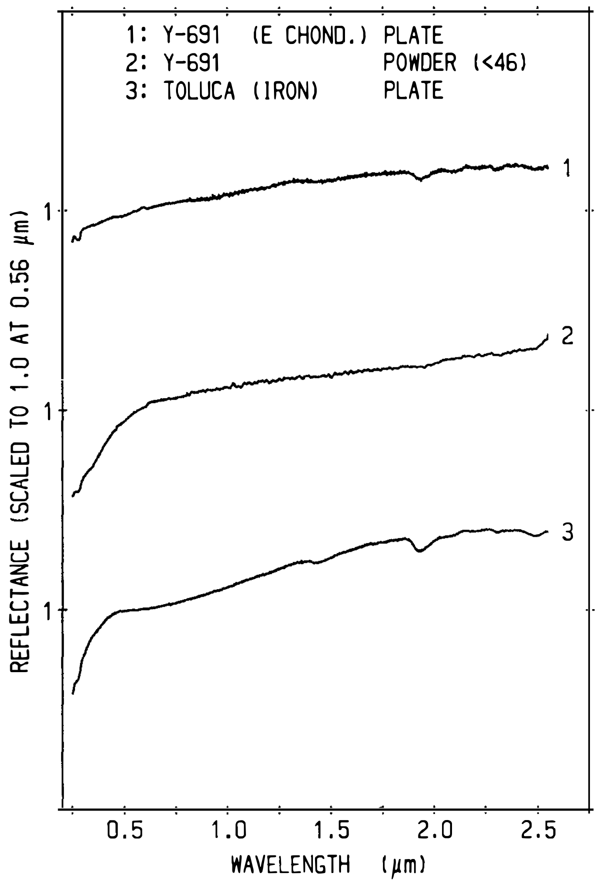

Fig. 1. Diffuse reflectance curves in the UV-visible-near infrared wavelength region (0.25 to 2.55 μm) for (1) the plate (polished) sample of the Yamato-691 enstatite chondrite, (2) the powder sample (grain size of less than 46 μm) of Y-691, and (3) the plate (polished) sample of the Toluca iron meteorite (octahedrite). The reflectances at the scaling wavelength (0.56 μm) are 8.7, 9.9, and 51.8% for the plate sample (1), the powder sample (2) of Y-691, and the plate sample of Toluca (3), respectively.

3.2. MIR spectra

Figure 2 shows the MIR reflectances (2.53–25 μm) of the powder and plate samples of Y-691 and the iron meteorite. The spectra of Y-691 show many absorption bands at wavelengths longer than about 9 μm mainly caused by enstatite (SANDFORD, 1984). Some absorption bands may be attributed to olivine because Y-691 contains relatively abundant olivine. JEANLOZ (1980) assigned the absorption bands shorter than 20 μm in forsterite (Mg_2SiO_4) to vibrations of the Si^{4+} ion. However, it may be too complex to assign each absorption band in Y-691 to each ion, because Y-691 shows too many absorption bands of different strength.

The spectrum of the plate sample of Y-691 is apparently different from that of the powder sample (curves 1 and 2 in Fig. 2). Some absorption bands in the spectrum of the plate sample correspond to those of the powder sample. Relatively high reflectance around 10 and 20 μm is probably caused by contribution of the specular component to reflectance, because the absorption coefficient is probably large around the wavelength positions (*e.g.*, CONEL, 1969). All specular rays are related to the absorption coefficient through Fresnel's equation (*e.g.*, VINCENT and HUNT, 1968). Therefore, spectral behavior of diffuse reflectance may be complex at the wavelength range at which the absorption coefficient is relatively large compared with the index of refraction (*e.g.*, HUNT and VINCENT, 1968). This may not be a serious problem to identify the surface materials, because the asteroidal surfaces are generally thought

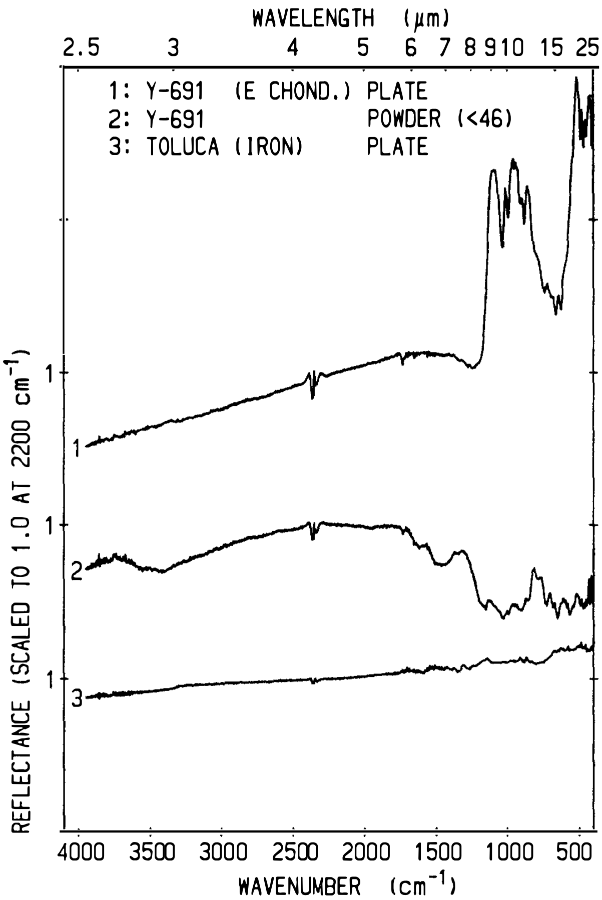

Fig. 2. Diffuse reflectance curves in the middle infrared wavelength region (2.53 to 25 μm) for (1) the plate (polished) sample of the Yamato-691 enstatite chondrite, (2) the powder sample (grain size of less than 46 μm) of Y-691, and (3) the plate (polished) sample of the Toluca iron meteorite (octahedrite).

to be covered with regolith-like materials. We need more detailed study to better understand this spectral change.

The absorption band around 3 μm in the powder sample of Y-691 (curve 2 in Fig. 2) is caused by OH vibrations in hydrates (hydroxyl) which were probably produced by terrestrial weathering (SALISBURY and HUNT, 1974) or adsorbed water in air.

The MIR spectrum of the iron meteorite shows no strong absorption bands (curve 3 in Fig. 2). Faint contrasts at wavelengths longer than about 10 μm are probably caused by silicate (or other minerals) inclusions in the iron meteorite. In short, although the iron meteorite does not show any strong absorption bands up to 25 μm, the Y-691 enstatite chondrite shows many absorption bands at wavelengths longer than about 9 μm. These results suggest that we can distinguish the enstatite chondrite from the iron meteorite by the reflectance around 10 μm.

The sharp absorption band at 4.26 μm is due to atmospheric CO_2. Noisy spectra around 2.6 and 6 μm are due to residual H_2O in dry air.

3.3. Speculation

FEIERBERG *et al.* (1983) measured 8–13 micrometer spectra for six main belt asteroids and suggested that the wavelength position of the emission maximum (around 10 μm) may be most useful for deriving compositional information for C and M type asteroids. These asteroids show relatively featureless reflection spectra in the UV-

VIS-NIR wavelength region. They detected silicate emission features for the C-type 19 Fortuna and the M-type 21 Lutetia. GREEN *et al.* (1985) presented 8–13 μm spectra for 12 main belt asteroids. They, however, failed to confirm the silicate emission feature for 19 Fortuna. Reobservation for 21 Lutetia by FEIERBERG also failed to confirm the emission. According to GREEN *et al.* (1985), 1 Ceres and 2 Pallas do not show significant emission/absorption features around 10 μm although they are classified into C-type asteroids and generally thought to be carbonaceous chondrite-like surfaces containing silicates.

16 Psyche appears to show the absorption around 10 μm and some contrasts in 8–13 μm (GREEN *et al.*, 1985), although the spectrum between 9 and 10 μm is not reliable because of the atmospheric ozone absorption. 16 Psyche is classified into M type by GAFFEY and MCCORD (1977) based on the UV-VIS-NIR reflectance and surface compositions of M-type asteroids are thought to be enstatite chondrite-like or iron meteorite-like. We speculate that the surface composition of 16 Psyche is the enstatite chondrite-like assemblage, if the absorption features around 10 μm are real. The UV-VIS-NIR reflectance of 16 Psyche (GAFFEY and MCCORD, 1978) shows no UV fall-off to 0.3 μm. The iron meteorite-like assemblage can be ruled out.

OSTRO *et al.* (1985), however, suggested that the highest albedo estimate for 16 Psyche is consistent with a surface having porosities typical of lunar soil and a composition nearly entirely metallic on the basis of radar observations. Infrared measurements of high enough quality of the asteroid will resolve the issue.

4. Conclusions

(1) Although the diffuse reflectance of the Y-691 enstatite chondrite does not show any strong absorption bands except for the UV fall-off shorter than about 0.55 μm in the UV-VIS-NIR wavelength region, the reflectance in the middle infrared (MIR) wavelength region shows many absorption bands at wavelengths longer than about 9 μm mainly caused by the vibrations of the Si^{4+} ion.

(2) The reflectance of the iron meteorite (Toluca, octahedrite) does not show any strong absorption bands up to 25 μm except for the UV fall-off shorter than about 0.4 μm.

(3) The reflectance of the plate sample of Y-691 does not show a steep UV fall-off although that of the powdered sample of Y-691 shows a relatively steep UV fall-off at wavelengths less than about 0.55 μm.

(4) The plate sample of Y-691 shows a weak UV fall-off compared with the plate sample of the iron meteorite.

(5) We can distinguish enstatite chondrite-like materials from iron meteorite-like materials on the basis of spectral features around 10 μm. We may also be able to distinguish them on the basis of spectral features of UV fall-off.

(6) We speculate that the surface composition of asteroid 16 Psyche is the enstatite chondrite-like assemblage, not the iron meteorite-like assemblage on the basis of spectral features around 10 μm.

Acknowledgment

The author thanks Prof. K. YANAI and Prof. Y. IKEDA for the opportunity to participate in this consortium and for generously providing the Yamato-691 sample, Mr. T. HIROI for processing the spectral data, and Prof. H. HASEGAWA and Dr. L. A. MCFADDEN for critical reading of the manuscript.

References

ABELÈS, F. (1972): Optical properties of metals. Optical Properties of Solids, ed. by F. ABELÈS. Amsterdam, North-Holland, 93–162.

CONEL, J. E. (1969): Infrared emissivities of silicates; Experimental results and a cloudy atmosphere model of spectral emission from condensed particulate mediums. J. Geophys. Res., **74**, 1614–1634.

FEIERBERG, M. A., WITTEBORN, F. C. and LEBOFSKY, L. A. (1983): Detection of silicate emission features in the 8- to 13-μm spectra of main belt asteroids. Icarus, **56**, 393–397.

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.

GREEN, S. F., EATON, N., AITKEN, D. K., ROCHE, P. F. and MEADOWS, A. J. (1985): 8- to 13-μm spectra of asteroids. Icarus, **62**, 282–288.

HAZEN, R. M., BELL, P. M. and MAO, H. K. (1978): Effects of compositional variation on absorption spectra of lunar pyroxenes. Proc. Lunar Planet. Sci. Conf., 9th, 2919–2934.

HIROI, T., MIYAMOTO, M. and TAKANO, Y. (1985): An assignment of photon absorptions to Fe^{2+} and Cr^{3+} in pyroxenes and olivine by crystal field theory. Lunar and Planetary Science XVI. Houston, Lunar Planet. Inst., 356–357.

HUNT, G. R. and VINCENT, R. K. (1968): The behavior of spectral features in the infrared emission from particulate surfaces of various grain sizes. J. Geophys. Res., **73**, 6039–6046.

JEANLOZ, R. (1980): Infrared spectra of olivine polymorphs; α, β phase and spinel. Phys. Chem. Miner., **8**, 327–341.

MCFADDEN, L. A., GAFFEY, M. J., TAKEDA, H., JACKOWSKI, T. 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.

OKADA, A. (1975): Petrological studies of the Yamato meteorites. Part 1. Mineralogy of the Yamato meteorites. Mem. Natl Inst. Polar Res., Spec. Issue, **5**, 14–66.

OSTRO, S. J., CAMPBELL, D. B. and SHAPIRO, I. I. (1985): Mainbelt asteroids; Dual-polarization radar observations. Science, **229**, 442–446.

PRINZ, M., NEHRU, C. E., WEISBERG, M. K., DELANEY, J. S. and YANAI, K. (1984): Yamato-691, a Type 3 enstatite chondrite; Relationship with other unequilibrated enstatite chondrites (UEC's). Papers presented to the Ninth Symposium on Antarctic Meteorites, 22–24 March 1984. Tokyo, Natl Inst. Polar Res., 14–17.

SALISBURY, J. W. and HUNT, G. R. (1974): Meteorite spectra and weathering. J. Geophys. Res., **79**, 4439–4441.

SANDFORD, S. A. (1984): Infrared transmission spectra from 2.5 to 25 μm of various meteorite classes. Icarus, **60**, 115–126.

VINCENT, R. K. and HUNT, G. R. (1968): Infrared reflectance from mat surfaces. Appl. Opt., **7**, 53–59.

YANAI, K. and KOJIMA, H. (1986): Yamato-691 E3 chondrite; recovery, curation and allocation. Papers presented to the Eleventh Symposium on Antarctic Meteorites, 25–27 March 1986. Tokyo, Natl Inst. Polar Res., 87–88.

(Received September 21, 1986; Revised manuscript received December 10, 1986)