Proc. NIPR Symp. Antarct. Meteorites, 7, 230–243, 1994

POSSIBLE THERMAL METAMORPHISM ON THE C, G, B, AND F ASTEROIDS DETECTED FROM THEIR REFLECTANCE SPECTRA IN COMPARISON WITH CARBONACEOUS CHONDRITES

Takahiro HIROI[1], Carlé M. PIETERS[2], Michael E. ZOLENSKY[3] and Michael E. LIPSCHUTZ[4]

[1]*SN3, NASA Johnson Space Center, Houston, TX 77058, U.S.A.*
[2]*Department of Geological Sciences, Brown University, Providence, RI 02912, U.S.A.*
[3]*SN2, NASA Johnson Space Center, Houston, TX 77058, U.S.A.*
[4]*Department of Chemistry, Purdue University, West Lafayette, IN 47907, U.S.A.*

Abstract: Reflectance spectra (0.3–2.6 μm) of the C, G, B, and F asteroids and carbonaceous chondrites are compared in detail. Mixing calculations of 13 carbonaceous chondrite powders including three unusual CI/CM meteorites are done to characterize reflectance spectra of the 23 C, G, B, and F asteroids. Similar calculations are done with Murchison (CM2) samples heated at 400–1000°C. Both of two sets of calculations show that the C, G, B, and F asteroids may contain a significant amount of thermally metamorphosed materials. Comparison of ultraviolet absorption strengths between 160 C, G, B, and F asteroids and 21 carbonaceous chondrite powders suggests that surface minerals of most of those asteroids are thermally metamorphosed at temperatures around 600–1000°C.

1. Introduction

A large number of dark asteroids whose reflectance spectra (0.3–1.1 μm) are relatively flat, used to be classified as the C asteroids as a whole, and their similarity to carbonaceous chondrites were pointed out (JOHNSON and FANALE, 1973). The C asteroids were later subdivided into four classes: C, G, B, and F (THOLEN, 1984). The evidence of aqueous alteration similar to those in CM2 chondrites have been detected on some of those asteroids (VILAS and GAFFEY, 1989), and the possible thermal metamorphism on the G, B, and F asteroids have been pointed out (THOLEN, 1984; BELL *et al.*, 1989). In spite of the above similarities between the C, G, B, and F asteroids and carbonaceous chondrites, not many studies have been done to compare those reflectance spectra in the wide wavelength range (0.3–2.6 μm) that contains significant mineralogical information (GAFFEY, 1976).

Recently, HIROI *et al.* (1993) measured reflectance spectra of carbonaceous chondrites including thermally metamorphosed ones: B-7904, Y-86720, Y-82162, and heated Murchison samples (MATZA and LIPSCHUTZ, 1977) with such a wide wavelength range, and pointed out evidence of thermal metamorphism on the C, G, B, and F asteroids. In this paper, a larger number of wide-range reflectance spectra of those asteroids are characterized in terms of carbonaceous chondrites using a reflectance mixing model.

2. Experimental Methods

Carbonaceous chondrites Orgueil and Ivuna (CI1), ALH 83100, Nogoya, Bells, ALH 84029, Murray, Murchison, Mighei, Cold Bokkeveld, LEW-90500, and ALHA 81002 (CM2), Renazzo (CR2), Vigarano, Allende, and ALH 84028 (CV3), Y-693 and ALH 85002 (CK4), and B-7904, Y-86720, and Y-82162 (Unusual CI/CM) were ground with a mortar and pestle into powders of <100 or $<125\,\mu$m in grain size. Chips and bulk powder samples of Murchison were heated in a low-pressure (initially 10^{-5} atm) hydrogen atmosphere for 1 week at 400, 500, 600, 700, 800, 900, and 1000°C (MATZA and LIPSCHUTZ, 1977). Polished thin sections were prepared from Murchison chips, and the composition of olivine and orthopyroxene grains in their matrix and chondrules were analyzed by a Cameca CAMEBAX electron microprobe. Natural mineral standards and appropriate reduction programs were employed. Further characterization of each bulk sample was made using a JEOL 2000FX STEM with a LINK EXL energy dispersive spectrometer. Each Murchison powder was sieved into grain-size fractions <63 and 63–125 μm. Laboratory bidirectional reflectance spectra (0.3–2.6 μm) of the above powder samples were measured at the viewing geometry of 30° incidence and 0° emergence angles.

3. Experimental Results

3.1. Reflectance spectra

Laboratory reflectance spectra of carbonaceous chondrite powders are shown in Fig. 1 with their subtypes. CI1 meteorites show the characteristic absorption bands at about 0.47 and 1.95 μm in wavelength. Many of CM2 meteorites show weak absorption bands at 0.7, 0.9, and 1.1 μm due to phyllosilicates. CV3 and CK4 meteorites have a composite absorption band around 1.1 μm due to olivine. A significant difference of the unusual CI/CM meteorites from the others is that they show much weaker UV absorption. The reflectance values in Fig. 1 are scaled to 1.0 at 0.55 μm in wavelength. The scaled reflectances at 0.3 μm are higher than 0.5 for the unusual CI/CM meteorites whereas those of the others are lower than 0.5.

Reflectance spectra of Murchison samples are shown in Fig. 2. The UV absorption strength doesn't depend on grain sizes and becomes weaker after heating. The overall spectral profile highly depends on grain sizes for the samples heated at temperatures below 800°C.

3.2. Mineralogy

Detailed mineralogical and compositional descriptions of carbonaceous chon-

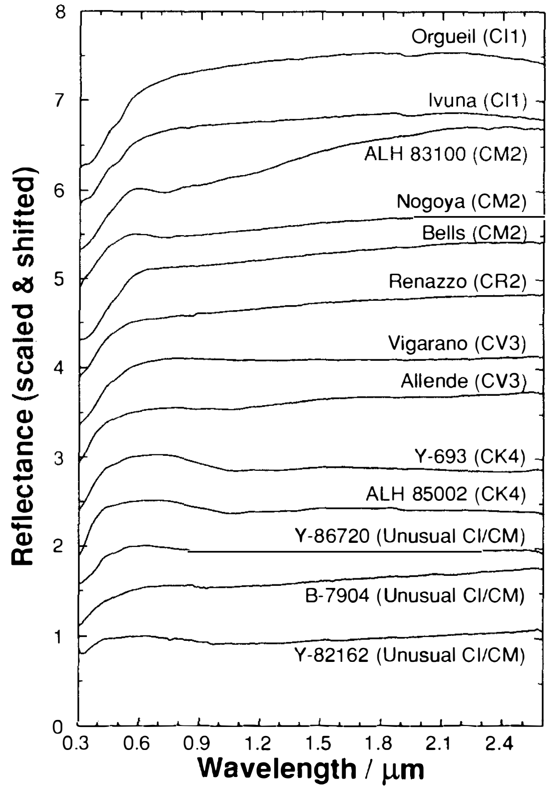

Fig. 1. Laboratory reflectance spectra of carbonaceous chondrite powders (<100 or <125 μm) measured at 30° incidence and 0° emergence angles. Reflectances are scaled to 1.0 at wavelength 0.55 μm and shifted by 0.5 from one another. Subclassifications are given in parentheses.

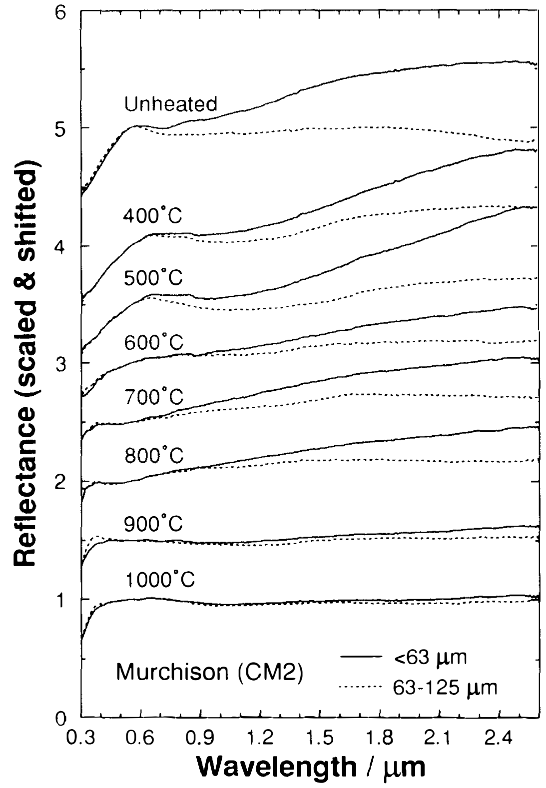

Fig. 2. Laboratory reflectance spectra of Murchison powders (<63 and 63–125 μm) unheated and heated at seven different temperatures. Reflectances are scaled to 1.0 at wavelength 0.55 μm and shifted by 0.5 or 1.0 from one another.

drites are reported by ZOLENSKY *et al.* (1993). CM2 meteorites consist, dominantly, of serpentine minerals (including cronstedtite), tochilinite, olivine (mean Fo=95), Fe-Ni sulfides, Mg-rich pyroxenes (mean En=98), and Fe-Ni metal, with the majority of the anhydrous minerals residing within matrix-supported chondrules and aggregates. Profound changes occurred to all of these minerals during the heating experiments on Murchison (see Fig. 3). At 400°C serpentine has begun to dehydrate, and transform to the "intermediate phase" described by AKAI (1990). By 600°C the intermediate phase has begun to dehydrate, and recrystallize to olivine and orthopyroxene, which are iron rich (see Fig. 4), and tochilinite has largely been converted to troilite. At 800°C Fe-Ni metal has increased in abundance, at the expense of Fe-Ni sulfides, and coarsened in grain size. At 1000°C chondrules have begun to recrystallize, and the meteorite now consists dominantly of olivine (mean Fo=80) and pyroxenes (mean En=90) with abundant scattered metal, and lessor sulfides. Similar mineralogical changes have occurred to the three unique chondrites Y-82162, Y-86720 and B-7904, although to a varied and diminished extent (ZOLENSKY *et al.*, 1993; IKEDA, 1992; AKAI, 1990; PAUL and LIPSCHUTZ, 1990).

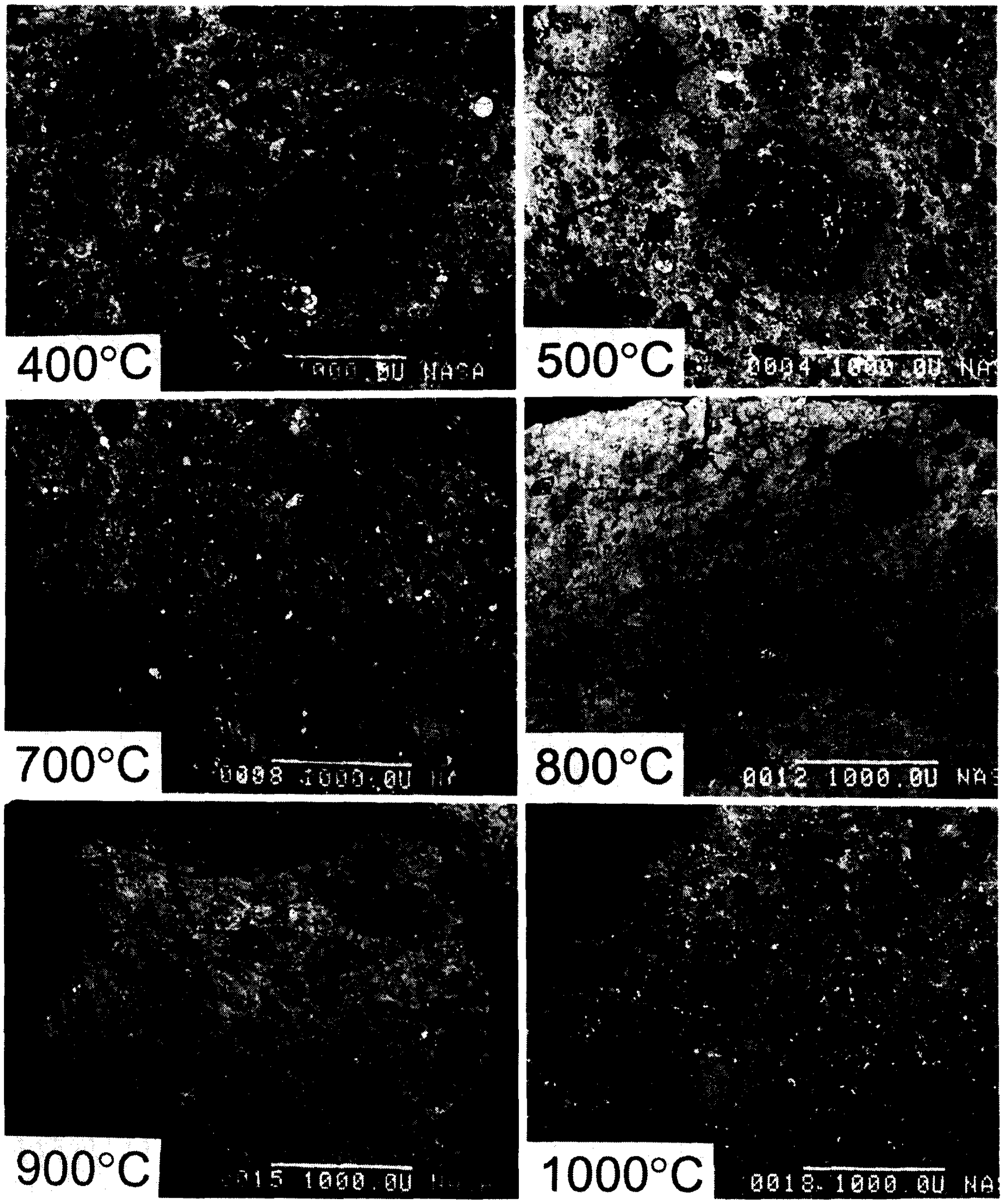

Fig. 3. Backscattered electron images of Murchison polished sections, heated to temperatures varying from 400 to 1000°C. Length of white bars is 1 mm.

4. Spectral Fittings

4.1. Method

Shown in Fig. 5 is the process of light scattering by a single opaque grain in the isograin model (HIROI and TAKEDA, 1990; HIROI and PIETERS, 1992). The isograin model consists of an infinite number of identical layers of mineral grains. Each grain is assumed to have scattering activity s that is a function of wavelength, and two constants ω_1 and ω_2 are introduced to express the distribution of scattered light. Unit incident light from the upper (or lower) layer is scattered to the upper

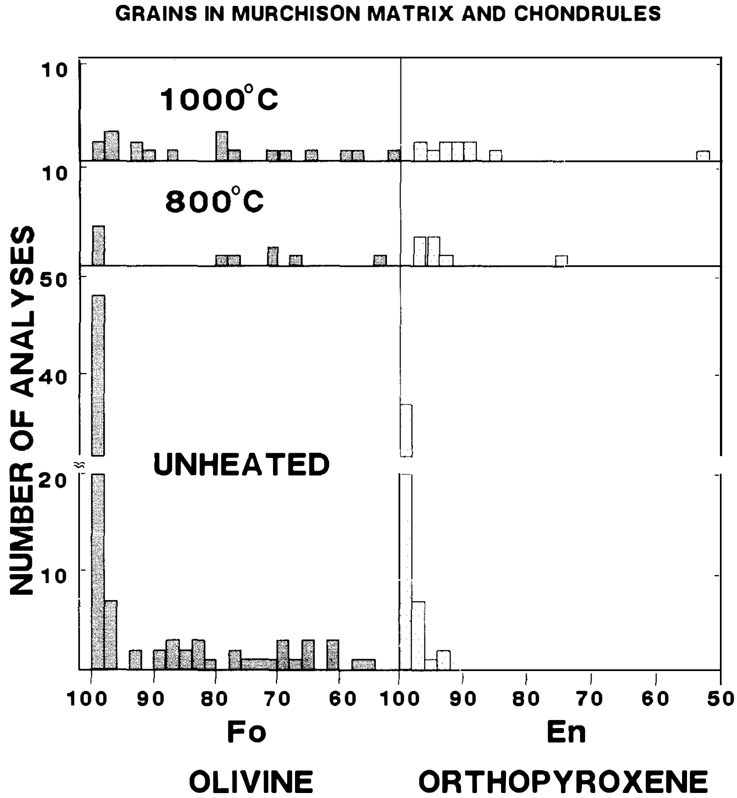

Fig. 4. A histogram of the abundances vs. Fe contents of olivine and orthopyroxene in Murchison samples analyzed by an electron microprobe.

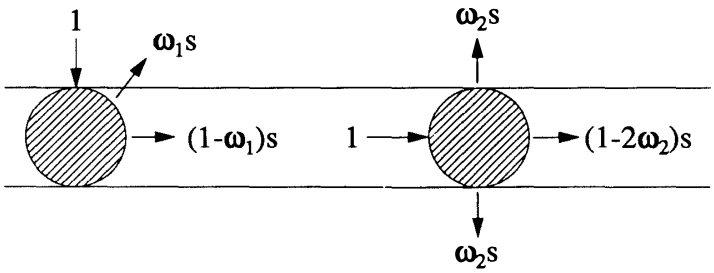

Fig. 5. Process of light scattering by an opaque grain in a layer assumed in the isograin model (HIROI and PIETERS, 1992).

(or lower) layer by $\omega_1 s$ and to within the layer by $(1-\omega_1)s$. Similarly, unit incident light from within the layer is scattered to the upper and lower layers by $\omega_2 s$ and to within the layer by $(1-2\omega_2)s$. Reflectance R_∞ of this multilayer is calculated by

$$R_\infty = R/(B+\sqrt{B^2-R^2})\ , \quad B=(1+R^2-T^2)/2\ , \qquad \text{(1a)}$$

$$R=\omega_1 s+\omega_2 sx\ , \quad T=\omega_2 sx\ , \quad x=(1-\omega_1)s/[1-(1-2\omega_2)s]\ , \qquad \text{(1b)}$$

(HIROI and PIETERS, 1992) for pure opaque mineral powders. In the case of mixtures with the different s functions and the same ω_1 and ω_2 values, the mixture s function can be calculated by

$$s=\sum_i c_i s_i\,, \quad \sum_i c_i=1\,, \tag{2}$$

where s_i and c_i indicate the s function and the volume abundance of component i.

Reflectance spectra of mixtures of carbonaceous chondrite powders are assumed to be expressed by eqs. (1a), (1b), and (2) with ω_1 and ω_2 values equal to 0.3. The average s function of each carbonaceous chondrite powder was calculated from its measured reflectance spectrum by eqs. (1a) and (1b). All the average s functions of chosen end members were combined linearly by eq. (2), and their linear combination coefficients (volume mixing ratios) were optimized to give the best fit with the target asteroid spectrum. Because the absolute reflectance values of the asteroids are unknown, visible reflectance values at 0.55 μm were optimized at the same time with the mixing ratios.

Telescopic reflectance spectra of 23 C, G, B, and F asteroids from the 24-color survey (CHAPMAN and GAFFEY, 1979), the 8-color survey (ZELLNER *et al.*, 1985), and the 52-color survey (BELL *et al.*, 1988) are combined to cover the wide wavelength range 0.3–2.6 μm (Fig. 6). Classifications are based on THOLEN (1989). Those asteroid spectra were fit with laboratory reflectance spectra of two sets of end members: (1) 13 carbonaceous chondrite powders (< 100 or < 125 μm) including

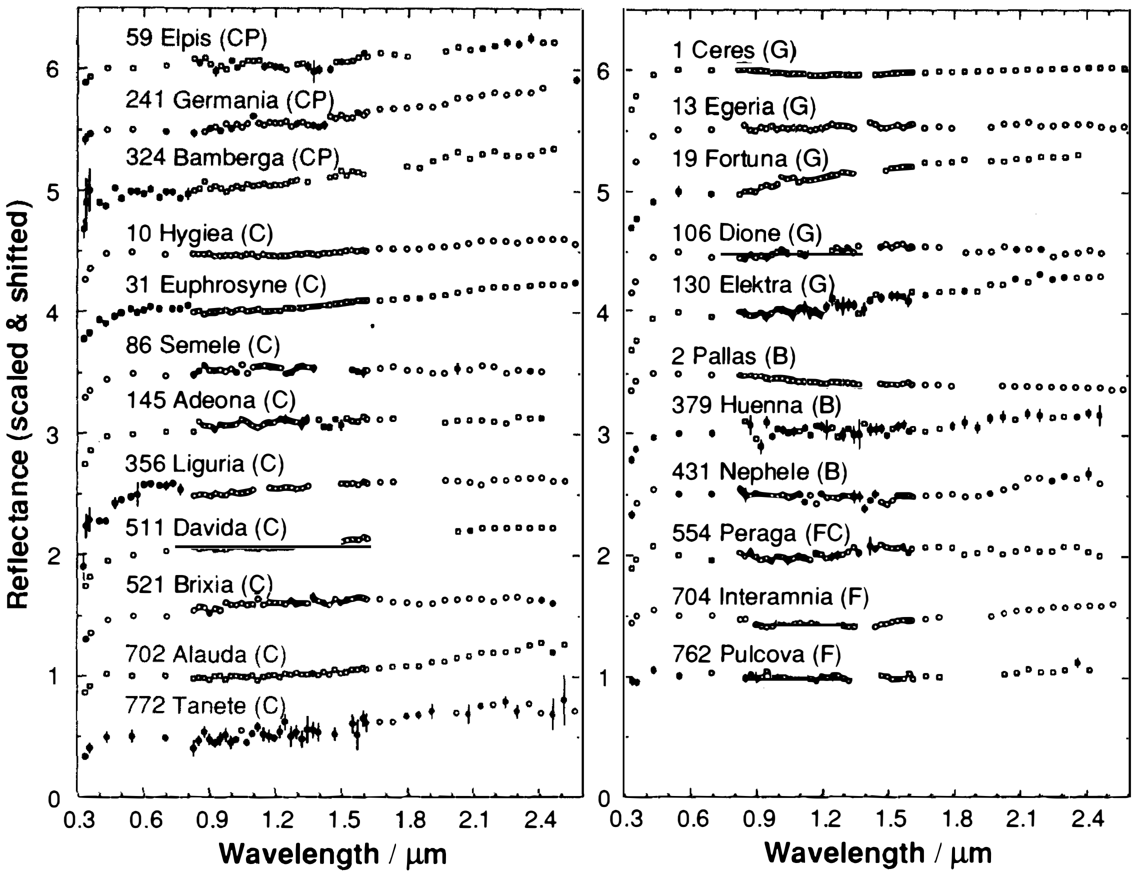

Fig. 6. Telescopic reflectance spectra of the 23 C, G, B, and F asteroids (CHAPMAN and GAFFEY, 1979; ZELLNER et al., 1985; BELL et al., 1988). Reflectances are scaled to 1.0 at wavelength 0.55 µm and shifted by 0.5 from one another.

Table 1. Results of spectral fittings of the C, G, B, and F asteroids with carbonaceous chondrites.

No.	Reflectance %			Mixing ratio (vol%)												
	RMSD	Fit 0.55 μm	IRAS albedo†	Orgueil	Ivuna	ALH 83100	Bells	Nogoya	Renazzo	Vigarano	Allende	Y-693	ALH 85002	B-7904	Y-86720	Y-82162
59	3.60	3.60	4.8	0.00	0.00	1.53	0.35	0.00	0.33	0.00	0.00	0.00	0.02	13.85	0.00	83.92
241	5.44	3.60	6.2	0.24	0.00	7.62	0.11	0.37	0.00	0.01	1.55	0.41	0.04	0.00	0.00	89.64
324	5.04	4.03	5.7	0.02	0.28	18.90	0.09	0.00	0.00	0.00	0.04	0.01	0.02	0.19	0.01	80.44
10*	1.60	3.98	7.5	0.39	0.20	0.01	0.00	5.32	1.51	0.35	0.00	0.00	3.58	0.07	0.05	88.52
31*	1.50	3.95	7.0	0.05	0.05	7.60	0.09	0.00	0.06	0.00	0.00	0.00	0.00	14.62	1.17	76.37
86	4.43	4.21	4.3	0.48	1.96	0.00	0.00	0.00	0.01	0.51	0.00	0.00	0.00	0.00	30.92	66.13
145	4.07	4.34	4.4	0.58	6.41	0.02	0.00	0.00	1.98	1.11	9.97	0.04	0.18	0.00	13.91	65.82
356*	4.07	6.58	6.2	13.59	0.05	0.00	4.62	0.84	0.00	0.00	15.63	1.62	16.62	0.49	1.55	44.98
511*	1.52	4.28	5.3	0.00	0.01	1.40	0.13	2.33	0.69	0.00	0.00	0.01	0.01	51.77	0.01	43.64
521	4.25	3.78	3.6	8.08	1.83	0.00	0.41	0.49	0.12	0.00	1.80	0.00	0.00	0.00	4.37	82.90
702	3.27	3.57	5.6	0.00	0.04	4.91	0.51	0.01	0.11	0.04	0.00	0.00	0.00	0.00	0.01	94.37
772	4.74	3.73	5.5	0.07	0.12	9.70	0.13	0.00	0.00	0.00	0.00	0.00	0.14	0.00	0.38	89.47
1*	1.62	5.74	10	0.02	0.00	0.00	0.03	0.00	0.45	2.10	0.00	0.00	12.25	0.00	37.26	47.89
13*	2.60	5.90	9.9	3.39	12.78	0.00	0.00	4.50	0.05	0.00	1.46	0.00	16.49	0.00	19.91	41.42
19	3.11	4.32		0.87	0.18	14.90	0.81	18.02	0.18	0.00	0.00	0.05	0.51	14.04	0.43	50.00
106	3.53	6.29	8.3	0.59	0.00	0.00	0.00	14.91	1.56	1.08	9.15	0.00	17.55	0.00	14.64	40.52
130*	3.54	4.69	8.9	0.23	0.00	15.83	0.15	0.53	0.01	0.33	0.57	0.18	0.30	25.14	6.74	50.00
2	8.01	5.21	14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	13.00	0.00	8.49	78.51
379*	3.57	3.93	4.5	0.04	0.05	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	36.25	0.42	69.23
431*	3.55	3.49	4.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00
554	4.66	3.56	5.1	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.46	0.00	0.00	98.53
704	4.71	3.58	6.4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00
762*	3.91	3.45	3.2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00

† TEDESCO (1989). * The 10 best-fit asteroids.

three thermally metamorphosed ones in Fig. 1, and (2) Murchison powders (<63 μm) unheated and heated at 7 different temperatures in Fig. 2.

4.2. Results

Results of the spectral fittings of the C, G, B, and F asteroids with carbonaceous chondrites are listed in Table 1. The Root Mean Square Deviations (RMSD) of calculated reflectances from the observed ones, the optimized visible reflectance at 0.55 μm, the IRAS albedos (TEDESCO, 1989), and the mixing ratios of carbonaceous chondrite powders are listed. Based on the RMSD values and the matches of the absorption band features between calculated and observed asteroid reflectance spectra, the 10 best-fit asteroids are chosen. Those 10 best spectral fits are shown in Fig. 7, and their mixing ratios of meteorites are plotted in Fig. 8. Three naturally heated CI/CM meteorites are very compatible with all the best-fit asteroids because of their weak UV absorptions similar to the C, G, B, and F asteroids (see Figs. 1 and 6). Relatively speaking, B-7904 is C-like, Y-86720 is G-like, and Y-82162 is B- or F-like in terms of their reflectance spectra.

Results of the spectral fittings of the C, G, B, and F asteroids with unheated and heated Murchison samples are listed in Table 2. The 10 best-fit asteroids are chosen in the same way as in Table 1, and their spectral fits are shown in Fig. 9, and

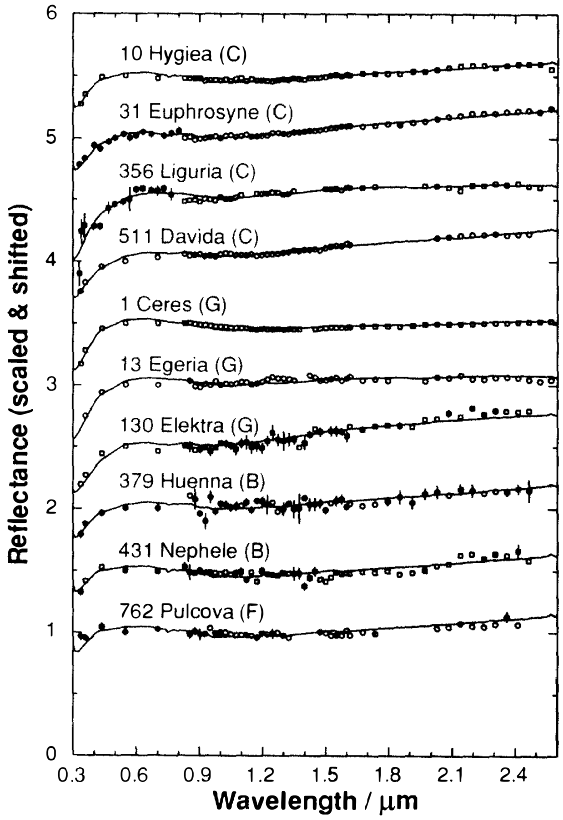

Fig. 7. The 10 best fits between the 23 asteroid reflectance spectra in Fig. 6 and the computational mixtures of the 13 carbonaceous chondrite spectra in Fig. 1.

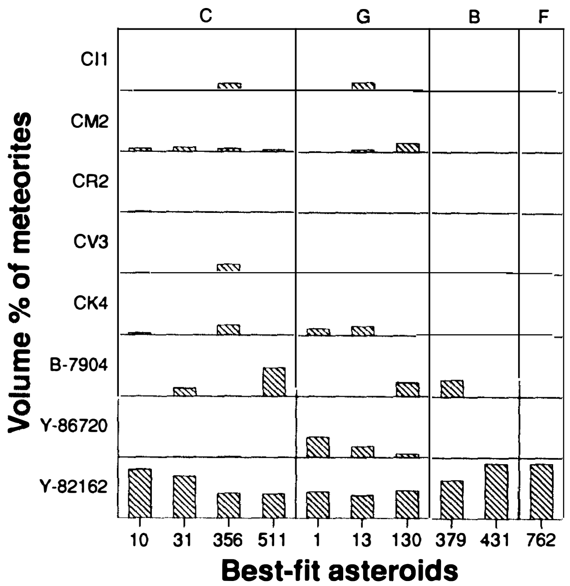

Fig. 8. Volume abundances of carbonaceous chondrites on the 10 best-fit C, G, B, and F asteroids obtained from spectral fits in Fig. 7.

Table 2. Results of spectral fittings of the C, G, B, and F asteroids with heated Murchison samples.

No.	Reflectance %			Mixing ratio (vol%)							
	RMSD	Fit 0.55 μm	IRAS albedo†	Unheated	400°C	500°C	600°C	700°C	800°C	900°C	1000°C
59*	3.23	5.27	4.8	2.86	4.44	4.27	0.00	0.21	18.75	58.36	11.10
241*	3.50	4.58	6.2	0.02	0.00	19.26	5.46	0.00	29.76	45.50	0.00
324*	3.66	4.31	5.7	0.00	0.97	28.44	0.01	20.55	17.67	32.34	0.02
10*	1.89	5.98	7.5	1.14	4.12	8.42	0.00	0.00	0.58	42.88	42.86
31*	1.32	5.27	7.0	0.00	17.03	12.53	0.00	0.04	15.74	0.01	54.65
86	4.63	5.69	4.3	0.00	1.02	0.06	2.06	22.24	0.00	33.78	40.85
145	3.95	5.68	4.4	10.19	0.67	0.00	20.40	2.37	0.00	0.00	66.37
356	5.77	6.60	6.2	27.10	3.82	0.00	0.00	0.00	0.09	8.38	60.61
511*	1.68	5.62	5.3	19.87	0.29	0.00	16.88	0.00	0.00	34.48	28.48
521	3.75	6.18	3.6	16.68	0.00	0.00	0.00	3.88	1.39	8.19	69.86
702*	2.73	5.09	5.6	0.00	8.53	10.29	7.85	3.29	0.00	55.94	14.10
772	3.97	4.88	5.5	0.00	8.60	14.49	0.00	0.00	25.62	43.64	7.65
1	5.01	5.87	10	1.58	0.13	0.00	18.56	0.00	0.00	52.43	27.31
13	4.15	5.67	9.9	2.12	0.46	0.00	21.63	3.14	12.14	0.00	60.50
19*	2.01	5.44		31.72	0.00	0.00	10.69	21.49	0.00	18.16	17.94
106	5.09	6.28	8.3	13.56	0.00	0.00	8.41	0.00	0.00	43.18	34.85
130*	2.75	5.04	8.9	14.36	14.90	15.66	10.38	0.02	0.00	28.23	16.45
2	11.20	5.98	14	0.00	7.17	0.00	0.00	28.69	0.00	40.79	23.36
379*	3.60	5.53	4.5	2.22	10.18	0.00	14.24	0.00	0.00	29.20	44.15
431	4.21	6.02	4.8	0.11	0.28	9.87	0.30	0.05	1.40	37.98	50.00
554	3.50	6.14	5.1	0.00	0.00	0.01	2.05	0.01	0.02	46.08	51.83
704	6.94	5.92	6.4	0.00	0.00	0.00	15.37	9.33	4.99	20.30	50.00
762	5.29	5.73	3.2	0.10	0.00	0.13	18.47	1.95	6.30	23.05	50.00

† TEDESCO (1989). * The 10 best-fit asteroids.

their mixing ratios of Murchison samples are plotted in Fig. 10. The CP asteroids (P-like C asteroids) have the smallest amount of 1000°C Murchison component, and the G asteroids have less high-temperature (900 and 1000°C) products than the C or B asteroids.

5. UV Absorption Strength

In order to compare more C, G, B, and F asteroids with carbonaceous chondrites, the UV absorption strengths are compared between those asteroids and carbonaceous chondrites. Reflectance values through two broad-band filters centering at wavelengths 0.337 and 0.55 μm were taken from the 8-color asteroid survey (ZELLNER *et al.*, 1985), and the corresponding values for carbonaceous chondrites were calculated from their laboratory reflectance spectra by assuming Gaussian distributions of transmittance spectra of those two filters. The 160 C, G, B, and F asteroids that have both the 8-color reflectance data and the IRAS albedo data (TEDESCO, 1989) were chosen for comparison with carbonaceous chondrites.

Shown in Fig. 11 is a plot of the scaled UV reflectances and the visible reflectances of the C, G, B, and F asteroids and carbonaceous chondrite powders.

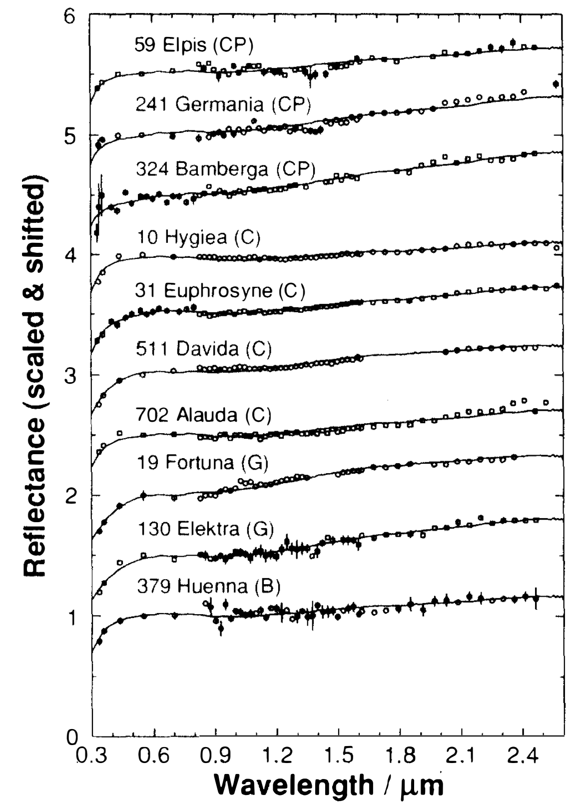

Fig. 9. The 10 best fits between the 23 asteroid reflectance spectra in Fig. 6 and the computational mixtures of reflectance spectra of the Murchison powders unheated and heated at seven different temperatures.

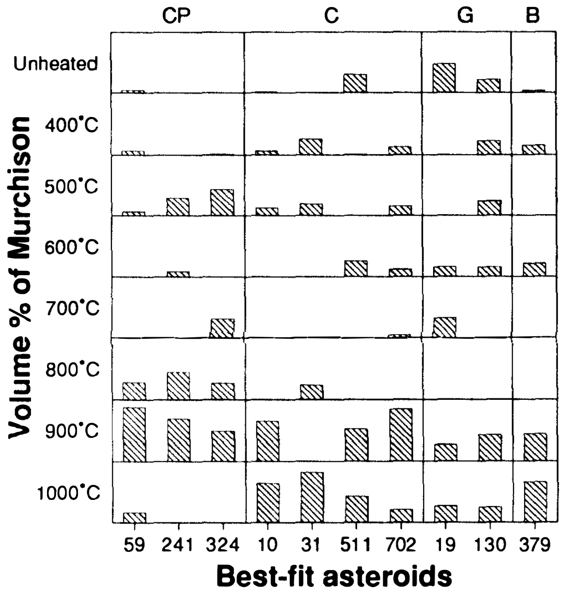

Fig. 10. Volume abundances of Murchison powders unheated and heated on the 10 best-fit C, G, B, and F asteroids.

The UV reflectances at wavelength 0.337 μm are scaled by those at 0.55 μm. As the measure of the visible reflectances, the IRAS albedos are plotted for the asteroids, and laboratory reflectances at wavelength 0.55 μm for carbonaceous chondrites including heated Murchison samples.

The scaled UV reflectances of the C, G, B, and F asteroids are higher than 0.6, and those of carbonaceous chondrites are lower than 0.6 except for thermally-metamorphosed ones: three unusual CI/CM meteorites and heated Murchison sampls. The IRAS albedos of those asteroids and laboratory reflectances of carbonaceous chondrites at wavelength 0.55 μm share the same range (0.025–0.15). In particular, Y-82162, B-7904, and Murchison samples heated at 600–1000°C plot in the crowded region of the C, G, B, and F asteroids.

6. Discussion

It has been known that reflectance spectra of carbonaceous chondrites can greatly change if the finest grains (< 63 μm for example) are removed (JOHNSON and FANALE, 1973). This is because the absorption bands at 0.7, 0.9, and 1.1 μm and red overall spectral profile are due to phyllosilicates that preferentially exist as

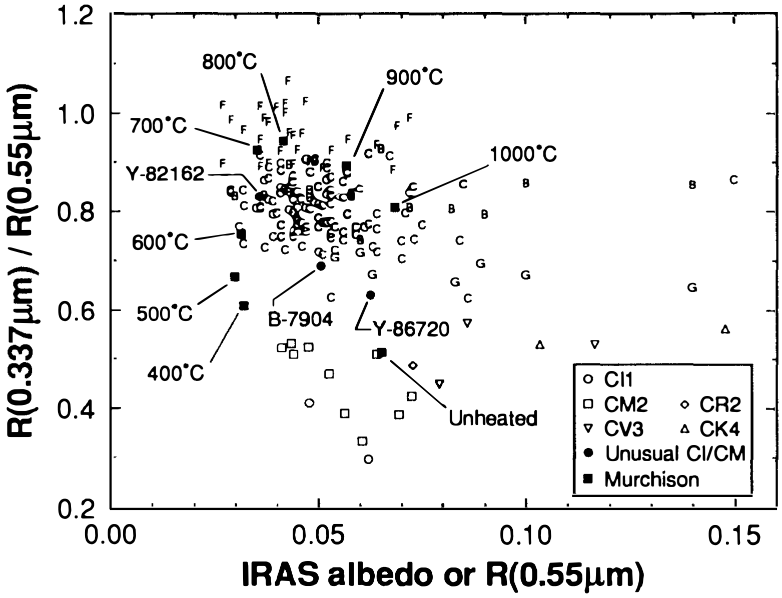

Fig. 11. *The scaled UV reflectances vs. the visible reflectances of the 160 C, G, B, and F asteroids and carbonaceous chondrites. Asteroid reflectances at wavelengths 0.337 and 0.55 µm were taken from the 8-color asteroid survey (ZELLNER et al., 1985), and the corresponding values for carbonaceous chondrites were calculated from their laboratory reflectance spectra, part of which are shown in Fig. 1. As the measure of the visible reflectances, the IRAS albedos (TEDESCO, 1989) were taken for the asteroids, and reflectances at wavelength 0.55 µm for the meteorites.*

submicron grains (ZOLENSKY *et al.*, 1993) and phyllosilicates often show those features strongly when they exist as fine grains (KING, 1986). These fine grains tend to adhere to the surfaces of larger grains, and if this happens on asteroids as well, fine grains should dominate the reflectance spectra.

There is some terrestrial weathering in meteorite samples, especially Antarctic ones. However, weathering usually causes stronger UV absorption, which is not the case with the unique carbonaceous chondrites that have weaker UV absorption.

The deviations between the observed and calculated reflectance spectra are comparable to the observational errors for the best-fit asteroids in Figs. 7 and 9. However, more detailed observations of those asteroids might reveal minor differences between those spectra. The volume abundances of carbonaceous chondrites obtained from the spectral fittings of the asteroids depend on the choice of the end members (carbonaceous chondrites). Just as three unusual CI/CM chondrites have greatly improved the spectral matches between asteroids and meteorites, discovery of a new type of meteorite might greatly change the result.

If the spectral comparisons in this work are correct, the most common carbonaceous chondrites (CI, CM, etc.) are not present on the observed C, G, B, and F asteroids. One possible reason for this discrepancy is that the parent bodies of carbonaceous chondrites were thermally zoned, with relatively unheated materials outside and heated materials inside. The outer unheated portions could have been easily removed by impact processes to produce smaller pieces (smaller C, G, B, and

F asteroids and carbonaceous chondrites), and most of the current larger observable C, G, B, and F asteroids may have been the inner heated portions of their parent bodies. However, these outer portions of the parent bodies must have been heated moderately ($>0^\circ$C) to produce the aqueous alterations found in carbonaceous chondrites. Internal heating by radioactive isotopes can form such thermal zoning (MIYAMOTO, 1991).

Infrared reflectance spectra of CI and CM chondrites usually show strong absorption bands around 3 μm due to hydrated silicates, and the unusual, naturally-heated CI/CM chondrites B-7904, Y-82182, and Y-86720 still show a weak absorption band near 2.9 μm (MIYAMOTO, 1992). Similar absorption bands were also observed for many C, G, B, and F asteroids (FEIERBERG *et al.*, 1985; JONES *et al.*, 1990). Thermal metamorphism of the unusual CI/CM chondrites and those asteroids should have been heterogeneous preserving some relatively unheated materials. It is also possible that those asteroids were originally formed of anhydrous silicates and water ice and that those silicates subsequently underwent different degrees of aqueous alteration. If the observed 3.1-μm band of 1 Ceres (JONES *et al.*, 1990) is really due to water ice, Ceres may not have undergone any extensive thermal metamorphism. However, reflectance spectrum of Ceres in Fig. 6 does not show any absorption bands around 1.5 and 2.0 μm that are typical for water ice (CLARK and ROUSH, 1984).

7. Conclusions

1) The unusual CI/CM meteorites B-7904, Y-86720, and Y-82162 are likely to be fragments of the observable C, G, B, and F asteroids.

2) If the parent bodies of the C, G, B, and F asteroids were made of Murchison-like material, they may have been heated at various temperatures up to 600–1000°C.

3) Most of carbonaceous chondrites that fell to the Earth may have been the outer, relatively unheated portion of their parent bodies.

Acknowledgments

We thank Dr. Jeffrey F. BELL for the 52-color asteroid reflectance spectra. We also thank Drs. M. MIYAMOTO, H. Y. MCSWEEN, Jr., M. J. GAFFEY, and F. VILAS for helpful suggestions. Antarctic meteorite samples were loaned from the National Institute of Polar Research and the Meteorite Working Group. Reflectance spectra of meteorite powders were measured at RELAB in Brown University. We thank S. F. PRATT for assistance with the measurements. RELAB is a multiuser facility operated under NASA grant NAGW-748. This research was supported in part by NASA grant NAG 9–48 to M. L. and a NASA Origins of Solar Systems Program grant to M. Z. This work was done while T. H. held a National Research Council-NASA/JSC Research Associateship.

References

Akai, J. (1990): Mineralogical evidence of heating events in Antarctic carbonaceous chondrites, Y-86720 and Y-82162. Proc. NIPR Symp. Antarct. Meteorites, **3**, 55–68.

Bell, J. F., Owemsby, P. D., Hawke, B. R. and Gaffey, M. J. (1988): The 52-color asteroid survey: Final results and interpretation. Lunar and Planetary Science XIX. Houston, Lunar Planet. Inst., 57–58.

Bell, J. F., Davis, D. R. and Gaffey, M. J. (1989): Asteroids: The big picture. Asteroids II, *ed.* by R. P. Binzel *et al.* Tucson, Univ. Arizona Press, 921–945.

Chapman, C. R. and Gaffey, M. J. (1979): Spectral reflectances of the asteroids. Asteroids, ed. by T. Gehrels. Tucson, Univ. Arizona Press, 1064–1089.

Clark, R. N. and Roush, T. L. (1984): Reflectance spectroscopy: Quantitative analysis techniques for remote sensing applications. J. Geophys. Res., **89**, 6329–6340.

Feierberg, M. A., Lebofsky, L. A. and Tholen, D. J. (1985): The nature of C-class asteroids from 3-μm spectrophotometry. Icarus, **63**, 183–191.

Gaffey, M. J. (1976): Spectral reflectance characteristics of the meteorite classes. J. Geophys. Res., **81**, 905–920.

Hiroi, T. and Pieters, C. M. (1992): Effects of grain size and shape in modeling reflectance spectra of mineral mixtures. Proc. Lunar Planet. Sci., **22**, 313–325.

Hiroi, T. and Takeda, H. (1990): A method to determine silicate abundances from reflectance spectra with applications to asteroid 29 Amphitrite associating it with primitive achondrite meteorites. Icarus, **88**, 205–227.

Hiroi, T., Pieters, C. M., Zolensky, M. E. and Lipschutz, M. E. (1993): Evidence of thermal metamorphism on the C, G, B, and F asteroids. Science, **261**, 1016–1018.

Ikeda, Y. (1992): An overview of the research consortium, "Antarctic carbonaceous chondrites with CI affinities, Yamato-86720, Yamato-82162, and Belgica-7904". Proc. NIPR Symp. Antarct. Meteorites, **5**, 49–73.

Johnson, T. V. and Fanale, F. P. (1973): Optical properties of carbonaceous chondrites and their relationship to asteroids. J. Geophys. Res., **78**, 8507–8518.

Jones, T. D., Lebofsky, L. A., Lewis, J. S. and Marley, M. S. (1990): The composition and origin of the C, P, and D asteroids: Water as a tracer of thermal evolution in the outer belt. Icarus, **88**, 172–192.

King, T. V. V. (1986): Contributions toward a quantitative understanding of reflectance spectroscopy: Phyllosilicates, olivine, and shocked materials. Ph.D. thesis, Univ. of Hawaii.

Matza, S. D. and Lipschutz, M. E. (1977): Thermal metamorphism of primitive meteorites—VI. Eleven trace elements in Murchison C2 chondrite heated at 400–1000°C. Proc. Lunar Sci. Conf., **8**, 161–176.

Miyamoto, M. (1991): Thermal metamorphism of CI and CM carbonaceous chondrites: An internal heating model. Meteoritics, **26**, 111–115.

Miyamoto, M. (1992): Infrared diffuse reflectance spectra of several thermally metamorphosed carbonaceous chondrites. Proc. NIPR Symp. Antarct. Meteorites, **5**, 155–164.

Paul, R. L. and Lipschutz, M. E. (1990): Consortium study of labile trace elements in some Antarctic carbonaceous chondrites: Antarctic and non-Antarctic meteorite comparisons. Proc. NIPR Symp. Antarct. Meteorites, **3**, 80–95.

Tedesco, E. F. (1989): Asteroid magnitudes, UBV colors, and IRAS albedos and diameters. Asteroids II, ed. by R. P. Binzel *et al.* Tucson, Univ. Arizona Press, 1090–1138.

Tholen, D. J. (1984): Asteroid taxonomy from cluster analysis of photometry. Ph.D. thesis, Univ. of Arizona.

Tholen, D. J. (1989): Asteroid taxonomic classifications. Asteroids II, ed. by R. P. Binzel *et al.* Tucson, Univ. Arizona Press, 1139–1150.

VILAS, F. and GAFFEY, M. J. (1989): Phyllosilicate absorption features in main-belt and outer-belt asteroid reflectance spectra. Science, **246**, 790–792.

ZELLNER, B., THOLEN, D. J. and TEDESCO, E. F. (1985): The eight-color asteroid survey: Results for 589 minor planets. Icarus, **61**, 355–416.

ZOLENSKY, M. E., BARRETT, R. and BROWNING, L. (1993): Mineralogy and composition of matrix and chondrule rims in carbonaceous chondrites. Geochim. Cosmochim. Acta, **57**, 3123–3148.

(Received August 11, 1993; Revised manuscript received December 15, 1993)