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Could G-class asteroids be the parent bodies of the CM chondrites?

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Abstract–I review the dynamical and compositional evidence for possibly linking CM chondrites and asteroids having G-class taxonomic designations. Three G asteroids have been identified through previous theoretical studies as being likely meteorite source bodies due to their locations near resonances. Two of these objects, 19 Fortuna and 13 Egeria, have spectral properties that are consistent with such a linkage with CM chondrites. Fortuna has a similar strength 0.7 μm absorption feature and near-infrared spectral slope to CM chondrites but a weaker ultraviolet feature. Egeria also has the characteristic 0.7 μm feature of CM chondrite spectra but does not match as well in the near-infrared. However, since the 0.7 μm feature is apparent in the spectra of approximately one-half of measured C-type asteroids, no definitive statement about any linkages can be made. Ceres is spectrally different from known meteorites in the 3 μm wavelength region and cannot be convincingly linked with any meteorite group.

INTRODUCTION

One of the most challenging aspects of planetary remote sensing is to determine asteroid surface compositions by comparing asteroid and meteorite reflectance spectra and albedos. Many minerals (*e.g.*, olivine, pyroxene, plagioclase, spinel, hydrated silicates) commonly found in meteorites have characteristic spectral absorption features that can be used to identify and, in many cases, roughly determine mineralogic compositions from reflectance spectra. Since meteorites (with the exception of SNC and lunar meteorites) are believed to be derived from asteroidal source bodies, the comparison of asteroid and meteorite spectra should allow for possible meteorite parent bodies and/or compositional analogs to be identified. Two of the most widely discussed linkages, 4 Vesta with the basaltic achondrites (Binzel and Xu, 1993) and near-Earth asteroid (NEA) 3103 Eger with the aubrites (enstatite achondrites) (Gaffey *et al.*, 1992), appear possible due to spectral similarities and plausible dynamical mechanisms for delivering fragments of these bodies to Earth. Other asteroid and meteorite links that have been suggested include the CO/CV chondrites with the K-type asteroids in the Eos family (Bell, 1988), some C-type asteroids with CI/CM chondrites that have undergone late-stage thermal metamorphism (Hiroi *et al.*, 1993), 6 Hebe and the H chondrites (Farinella *et al.*, 1993; Gaffey, 1996) and some near-Earth asteroids with ordinary chondrites (Binzel *et al.*, 1996).

Farinella *et al.* (1993) performed a dynamical study of 2355 numbered main-belt asteroids to identify the objects with the highest probability of injecting fragments into the 3:1 mean motion resonance and the ν_6 secular resonance. Both the 3:1 (Wisdom, 1983, 1985) and ν_6 (Scholl and Froeschlé, 1991) resonances, due to their ability to generate chaotic orbits, have been noted as likely source regions of Earth-approaching asteroids and, therefore, meteorites. Farinella *et al.* (1993) estimated each asteroid's relative fragment production rate (called the fragment delivery efficiency) to these resonances to determine which asteroids are theoretically supplying large numbers of fragments to the 3:1 and ν_6 resonances from cratering and breakup events. Their results showed that a significant percentage of the near-Earth asteroids and, therefore, meteorites could be generated by a small (~1%) and possibly nonrepresentative fraction of the known asteroid population that is mostly made up of large bodies located near these resonances. However, their study is highly model dependent and uses many critical parameters (*e.g.*, the width of the secular resonance, the mass *vs.* velocity distribution of the fragments) that are not well known.

Farinella *et al.* (1993) noted 28 asteroids (Table 1) that could be injecting relatively large numbers of fragments into the resonances. The asteroids are ordered according to decreasing total fragment de-

TABLE 1. Asteroids and their total fragment delivery efficiencies (E_1 plus E_2).

Asteroid	Class	S subclass	E_1	E_2
6 Hebe	S	S(IV)	0.947	34.553
46 Hestia	P		7.158	0.054
19 Fortuna	G		3.258	0.093
335 Roberta	FP		2.683	0.085
4 Vesta	V		2.029	0.676
304 Olga	C		0.021	2.427
89 Julia	S	—	2.090	0.032
29 Amphitrite	S	S(IV)	2.091	0.000
17 Thetis	S		1.982	0.104
1 Ceres	G		1.460	0.398
13 Egeria	G		1.614	0.090
11 Parthenope	S	S(IV)	1.531	0.068
907 Rhoda	C		0.000	1.593
751 Faïna	C		1.132	0.110
631 Philippina	S		0.000	1.150
409 Aspasia	CX		0.931	0.075
449 Hamburga	C		0.879	0.000
329 Svea	C		0.764	0.100
759 Vinifera			0.007	0.849
5 Astraea	S		0.688	0.000
42 Isis	S	S(I)	0.637	0.029
405 Thia	C		0.618	0.017
344 Desiderata	C		0.589	0.021
14 Irene	S		0.596	0.000
712 Boliviana	C		0.552	0.018
134 Sophrosyne	C		0.523	0.029
7 Iris	S	S(IV)	0.515	0.000
419 Aurelia	F		0.508	0.000

Asteroid numbers, names, classes (Tholen, 1989), Gaffey *et al.* (1993) S subclasses and fragment delivery efficiencies (Farinella *et al.*, 1993) to the 3:1 (E_1) and the ν_6 (E_2) resonances for objects with E_1 or E_2 >0.5. The asteroids are ordered from highest to lowest sums of E_1 and E_2.

livery efficiencies (E_1 plus E_2). However, it is unknown if both resonances are ultimately producing Earth-crossing asteroids with comparable rates. The given fragment delivery efficiencies are useful for comparing two asteroid's relative number of fragments theoretically being supplied to each resonance. As can be seen by the values, asteroid 6 Hebe has a fragment delivery efficiency that is ~5× higher than the asteroid (46 Hestia) with the next highest efficiency and makes Hebe a likely candidate as a meteorite source body. Vesta, the proposed HED parent body, has the fifth highest theoretical total fragment delivery efficiency. Intriguingly, H chondrites, which have been proposed to be derived from 6 Hebe, have the second highest fall frequency of all meteorite classes (Table 2). The HED meteorites have the fourth highest fall frequency.

Two very interesting trends are apparent from Table 1. One is that three of the S asteroids were given S(IV) designations by Gaffey *et al.* (1993). The S(IV) asteroids have mineralogical parameters (band centers, band area ratios) derived from their spectra that are consistent with the mineralogy of ordinary chondrites. Gaffey *et al.* (1993) recognized that the S(IV) asteroids are strongly concentrated near the 3:1 resonance.

The other interesting trend is that 3 of the top 11 asteroids with the highest total fragment delivery efficiencies are G asteroids, a moderately rare type of asteroid with ~10 known members (Tholen, 1989). The G asteroids tend to have the strongest ultraviolet absorption features (Tholen, 1984), largest 0.7 μm band areas (Sawyer, 1991) and strongest 3 μm absorption features (Jones *et al.*, 1990) of all C-type (B, C, F and G) asteroids. These spectral characteristics appear to indicate that G asteroids are at the upper range of the aqueous alteration sequence in the asteroid population. This paper will discuss possible meteorite analogs for these three G asteroids and the uniqueness of such comparisons.

POSSIBLE METEORITE ANALOGS TO G ASTEROIDS

The three identified G asteroids (1 Ceres, 13 Egeria and 19 Fortuna) all have ultraviolet-visible (Chapman and Gaffey, 1979; Zellner *et al.*, 1985; Vilas and Gaffey, 1989; Sawyer, 1991; Bus, pers. comm.), high-resolution, near-infrared (Feierberg *et al.*, 1981; Bell *et al.*, 1988) and 3 μm (Lebofsky, 1980; Jones *et al.*, 1990) observations. Infrared astronomical satellite (IRAS) albedos have been measured for Ceres (0.11) and Egeria (0.08) (Tedesco, 1994). The 3 μm observations of all three asteroids (and approximately two-thirds of all C-type asteroids) indicate hydrated minerals on their surfaces with features of varying strengths (Ceres: 21 ± 1.3%; Egeria: 40 ± 15%; Fortuna: 25 ± 6%). These band depths are the relative depth from the continuum (reflectance at either 2.2 or 2.5 μm) (Jones *et al.*, 1990). (Only the high-quality 3 μm observations of Ceres are directly comparable to the carbonaceous chondrite data.) The meteorite groups whose reflectance spectra have 3 μm features of comparable strengths (approximate band depths in parentheses) are the CI (~55%), CM (~45%) and CR (~35%) chondrites (Lebofsky, 1980; Jones, 1988; Miyamoto and Zolensky, 1994). The 3 μm features of these meteorites are due to bound water in hydrated silicates.

TABLE 2. Meteorite classes and fall frequencies (Sears and Dodd, 1988).

Meteorite Classes	Fall Frequency (%)
L Chondrites	38.3
H Chondrites	33.2
LL Chondrites	7.9
HEDs	6.3
CM Chondrites	2.2
IIIAB Irons	1.4
Aubrites	1.1

Only meteorite classes with fall frequencies above 1% are given.

Visible and near-infrared reflectance spectra of CI, CM and CR chondrites tend to be featureless except for their ultraviolet absorption features and a number of weak absorption features between 0.5 and 1 μm in CM chondrite spectra (Gaffey, 1976; Vilas and Gaffey, 1989). Simple linear combinations of the spectra of both Mg- and Fe-bearing phyllosilicates have been found to match many of the features found in carbonaceous chondrite spectra (Calvin and King, 1997). Many CM chondrites have a feature centered at ~0.7 μm. This 0.7 μm feature has been interpreted as being due to oxidized Fe in hydrated silicates (*e.g.*, antigorite, chlorite) (King, 1986; King and Clark, 1989). The ultraviolet absorption feature tends to weaken in intensity for larger particle sizes (Johnson and Fanale, 1973), increasing amounts of opaque material (Johnson and Fanale, 1973) and/or lower Fe contents in the silicates (Feierberg *et al.*, 1981). Spectra of CI, CM and CR chondrites tend to have relatively red continuum slopes for smaller particle sizes (<100 μm) and flat slopes for larger particle sizes (Johnson and Fanale, 1973). The 3 μm feature tends to decrease in intensity for increasing grain size and/or increasing amounts of nonhydrated material (Jones, 1988). The visual albedos of these carbonaceous chondrites are also very low (~0.03 to ~0.07).

1 Ceres

Of these three identified asteroids, Ceres has been the most intensively studied due to its high apparent brightness, which allows for greater signal-to-noise telescopic observations. Gaffey (1978) and Feierberg *et al.* (1981) interpreted Ceres' weaker ultraviolet ab-

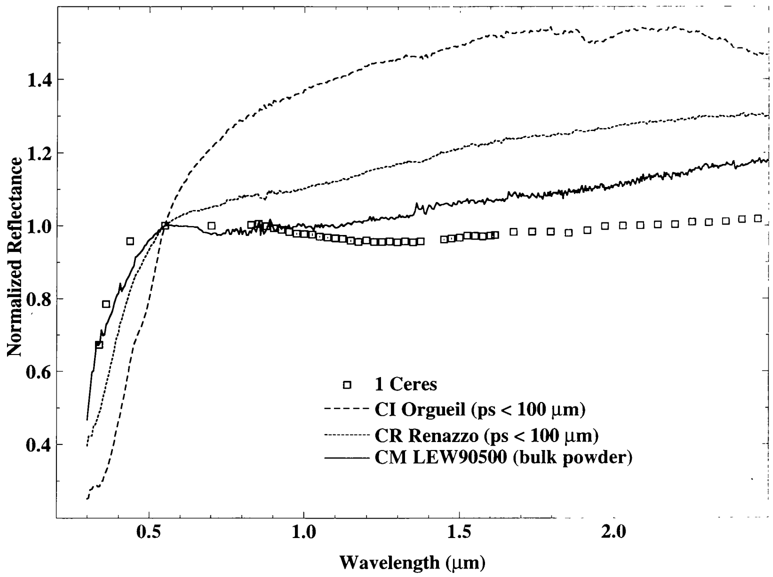

FIG. 1. Normalized reflectance *vs.* wavelength of 1 Ceres (Zellner *et al.*, 1985; Bell *et al.*, 1988) *vs.* CI chondrite Orgueil (particle size < 100 μm) (Hiroi *et al.*, 1993), CR chondrite Renazzo (particle size < 100 μm) (Hiroi *et al.*, 1993) and CM chondrite LEW 90500 (bulk powder). All spectra are normalized to unity at 0.55 μm. Error bars are $\pm 1\sigma$.

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sorption feature (Fig. 1) compared to CI or CM chondrites as showing that Ceres' surface assemblage was more Fe-poor than studied meteorite samples. The bulk powder spectrum of CM chondrite LEW 90500 matches Ceres' ultraviolet feature; however, LEW 90500 is redder in the near-infrared. Also, Ceres' IRAS albedo (0.11) is inconsistent with the low visual albedo (0.03) of LEW 90500.

Figure 2 presents charge-coupled device (CCD) observations of Ceres by Vilas and McFadden (1992) (~0.5 to ~0.9 μm) and Bus (pers. comm.) (~0.4 to ~0.9 μm) and eight-color asteroid survey (ECAS) data from Zellner *et al.* (1985). The Bus spectrum is slightly redder than the Vilas and McFadden spectrum with the ECAS data falling intermediate between the two spectra. The cause of the slope differences between these three data sets is unknown but are within the range of spectral differences seen between ECAS and small main-belt asteroid spectroscopic survey (SMASS) observations (Xu *et al.*, 1995) of some objects. The CCD spectra show that Ceres does not have an absorption feature centered at 0.7 μm (Fig. 2) that is characteristic of many CM chondrite spectra. Other weaker apparent features (*e.g.*, 0.60, 0.67 μm) have been identified in Ceres' spectrum by Vilas and McFadden (1992). The 0.60 μm feature does appear to be present in the Bus (pers. comm.) spectrum, but the 0.67 μm feature is not readily apparent.

Hiroi *et al.* (1993, 1996) found that the reflectance spectra of three unusual CI/CM chondrites that appear to have undergone late-stage thermal metamorphism have ultraviolet features and near-infrared spectral slopes that match the relatively weak features of Ceres and other C-type asteroids. Ceres matches best with unusual CM chondrite Y-86720 (particle size < 63 μm) (visual albedo of 0.06) (Fig. 3) with both objects having ultraviolet features with similar strengths and similar spectral slopes. However, the 3 μm absorption features do not match. Ceres' 3 μm spectrum is unlike that of any known carbonaceous chondrite (Jones, 1988; Hiroi *et al.*, 1996; Sato *et al.*, 1997). A narrow absorption feature at 3.07 μm, which was originally interpreted as H_2O frost (Lebofsky *et al.*, 1981), has been interpreted by King *et al.* (1992) as indicating an ammonium-bearing mineral species, most likely ammoniated saponite (a smectite), on the surface. Saponite has been found in CI, CR and CV chondrites (Buseck and Hua, 1993), but has only been identified in one unusual CM chondrite (Bells) (Brearley, 1995).

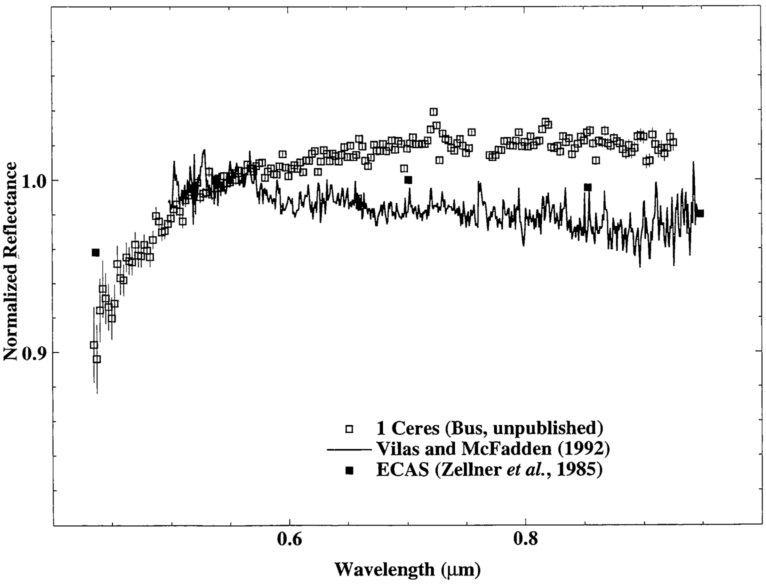

FIG. 2. Normalized reflectance *vs.* wavelength of CCD spectra of 1 Ceres from Vilas and McFadden (1992) and Bus (pers. comm.) and ECAS data from Zellner *et al.* (1985). All spectra are normalized to unity at 0.55 μm. Error bars are ±1σ.

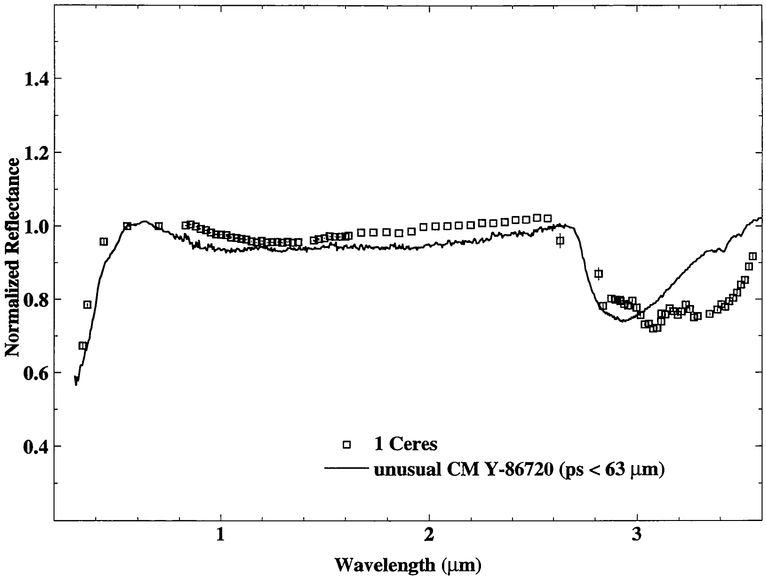

FIG. 3. Normalized reflectance *vs.* wavelength of 1 Ceres (Zellner *et al.*, 1985; Bell *et al.*, 1988; Jones *et al.*, 1990) *vs.* unusual CM chondrite Y-86720 (particle size < 63 μm) (Hiroi *et al.*, 1993). The 3 μm spectrum of Ceres is the average of multiple observations of Jones *et al.* (1990) (Hiroi *et al.*, 1996). All spectra are normalized to unity at 0.55 μm. Error bars are ±1σ.

Ceres' spectrum from 0.3 to 3.5 μm is not consistent with any known meteorite type. Either our meteorite collection contains no fragments of Ceres and/or some process is altering the spectrum of Ceres' surface. One model (Gaffey, 1978; Feierberg *et al.*, 1981) for producing both Ceres' suppressed spectral features and relatively high albedo compared to carbonaceous chondrites is by extensively aqueously altering Fe-bearing phyllosilicates on the surface. Iron would be leached from the phyllosilicates and would precipitate into relatively coarse-grained magnetite, which should decrease the intensity of the phyllosilicate absorption features and also raise the albedo. CM material with a relatively large particle size would have an ultraviolet and 0.7 μm feature with reduced strengths and a flatter spectral slope. But since the visual albedo would also be lowered (Johnson and Fanale, 1973), this is not a plausible mechanism for producing both Ceres' spectral features and its relatively high albedo.

19 Fortuna and 13 Egeria

Both Fortuna and Egeria have ultraviolet absorption features of similar strengths compared with Ceres. The visible and near-infrared spectrum of Fortuna (Fig. 4) matches very well the spectra of CM chondrite Murchison (bulk powder) (Gaffey, 1976) and LEW 90500 (particle size < 100 μm) (Hiroi *et al.*, 1993); however, the ultraviolet absorption feature is slightly weaker in Fortuna's spectrum. Bur-

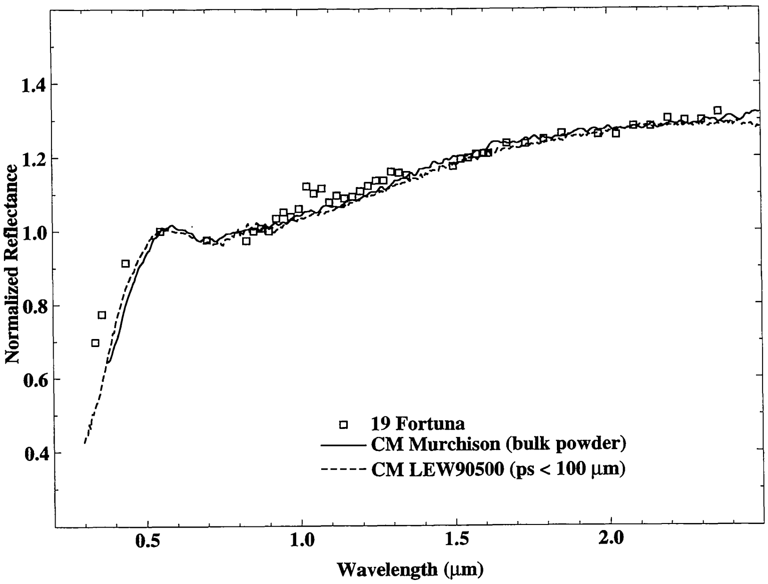

FIG. 4. Normalized reflectance *vs.* wavelength of 19 Fortuna (Zellner *et al.*, 1985; Bell *et al.*, 1988) *vs.* CM chondrite Murchison (bulk powder) (Gaffey, 1976) and CM chondrite LEW 90500 (particle size < 100 μm) (Hiroi *et al.*, 1993). All spectra are normalized to unity at 0.55 μm.

bine (1991) has noted that 19 Fortuna and the bulk powder spectrum of Murchison have one of the best spectral matches between asteroids with 52-color data (Bell *et al.*, 1988) and meteorites from Gaffey (1976). Egeria's ultraviolet absorption feature matches very well the spectrum of a bulk powder of LEW 90500 (Fig. 5); however, the bulk powder spectrum of LEW 90500 is slightly redder than Egeria in the near-infrared.

Fortuna has an absorption feature centered around 0.7 μm that is similar in shape and strength to those found in many CM chondrites. A CCD spectrum of Fortuna (Fig. 6) *vs.* spectra of Murchison (bulk powder) and LEW 90500 (particle size < 100 μm) shows the fine-grained LEW 90500 to be the best match. A CCD spectrum of Egeria (Fig. 7) matches better with the spectrum of the finer-grained LEW 90500 than with the spectrum of the bulk powder of LEW 90500. The band center (where a linear continuum has been removed) of the 0.7 μm feature in LEW 90500 (particle size < 100 μm) is at a slightly longer wavelength (~0.72 μm) than the band centers for Egeria (~0.67 μm) and Fortuna (~0.67 μm).

The difficulty in matching the spectral slope and the characteristics of the 0.7 μm absorption feature between Egeria and LEW 90500 probably implies a compositional difference between their phyllosilicates. Particle size differences do not appear to be a likely cause since increasing the particle size of the measured LEW 90500 sample to decrease the spectral slope would tend to decrease the strength of the 0.7 μm feature and make the feature look less like Egeria's feature. However, the presence of the 0.7 μm feature does imply a CM-like composition for Egeria. The wavelength difference between the band centers of Fortuna and LEW 90500 also implies a compositional difference in their phyllosilicate compositions.

CONCLUSIONS

How significant are the matches between Egeria and Fortuna and the CM chondrites? The main reason 4 Vesta has been linked with the basaltic achondrites (Binzel and Xu, 1993) is that Vesta has such an unusual spectrum that only it and small asteroids in its general neighborhood match the HED meteorites. Fortuna and Egeria are both very good spectral matches with CM chondrites. Fortuna has a similar 0.7 μm feature and spectral slope with CM chondrites Murchison (bulk powder) and LEW 90500 (particle size < 100 μm). However, these meteorites do have slightly stronger ultraviolet features than Fortuna. Egeria matches pretty well with the bulk powder spectrum of LEW 90500, but their 0.7 μm features do not match very well. Also, the band center of the 0.7 μm feature in the finer-grained LEW 90500's spectrum is at a slightly higher wavelength than Fortuna's and Egeria's minima. The presence of the 0.7 μm feature implies a CM composition for these asteroids, but the difference in wavelength positions of the centers implies that LEW 90500 is not a perfect spectral match for these objects. Ceres is spectrally different from known meteorites in the 3 μm wavelength region and cannot be convincingly linked with any meteorite group.

Besides increasing the particle size, one possible way to reduce the strength of the ultraviolet feature in carbonaceous chondrite spectra is to heat the material (Hiroi *et al.*, 1993). However, the 0.7 μm feature disappears in the spectra of CM material heated to temperatures above ~400 °C. Hiroi *et al.* (1996) have speculated that the large (diameter > 60 km) C-type asteroids are the inner portions of carbonaceous objects that were heated to temperatures of ~500–600 °C and represented in our meteorite collection by the unusual CI/CM chondrites that appear to have undergone late-stage thermal metamorphism. The CI and CM chondrites may be derived then from the outer portions of these objects that have been removed by impact processes. The presence of the 0.7 μm feature in the spectra of Egeria and Fortuna would imply then that some CM material must still be present on these objects.

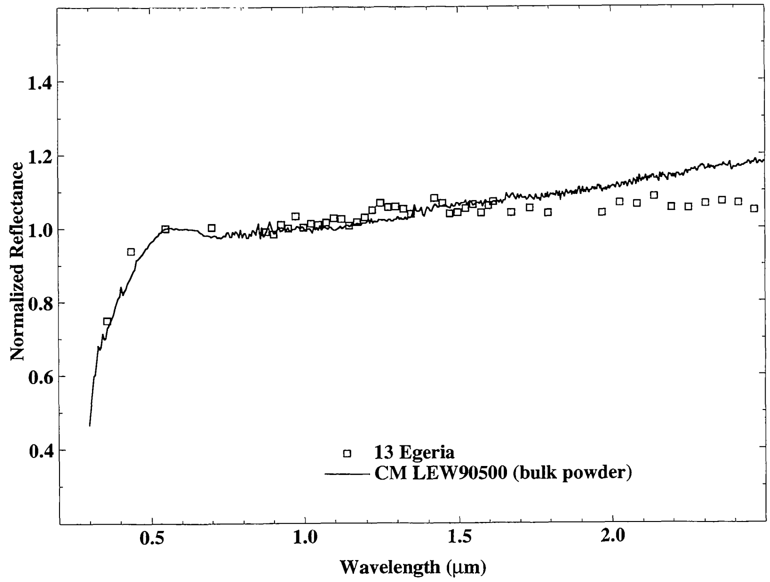

FIG. 5. Normalized reflectance *vs.* wavelength of 13 Egeria (Zellner *et al.*, 1985; Bell *et al.*, 1988) *vs.* CM chondrite LEW 90500 (bulk powder). All spectra are normalized to unity at 0.55 μm.

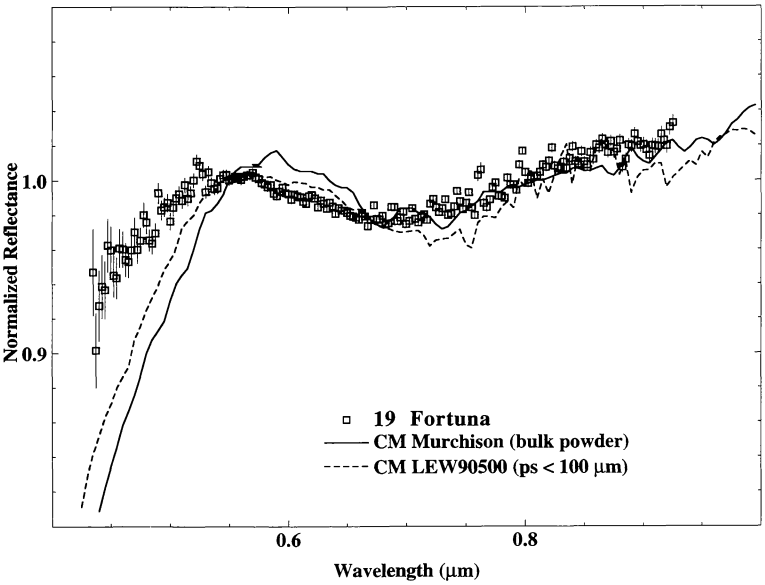

FIG. 6. Normalized reflectance *vs.* wavelength of CCD spectra of 19 Fortuna (Bus, pers. comm.) *vs.* CM chondrite Murchison (bulk powder) (Gaffey, 1976) and CM chondrite LEW 90500 (particle size < 100 μm) (Hiroi *et al.*, 1993). All spectra are normalized to unity at 0.55 μm. Error bars are $\pm 1\sigma$.

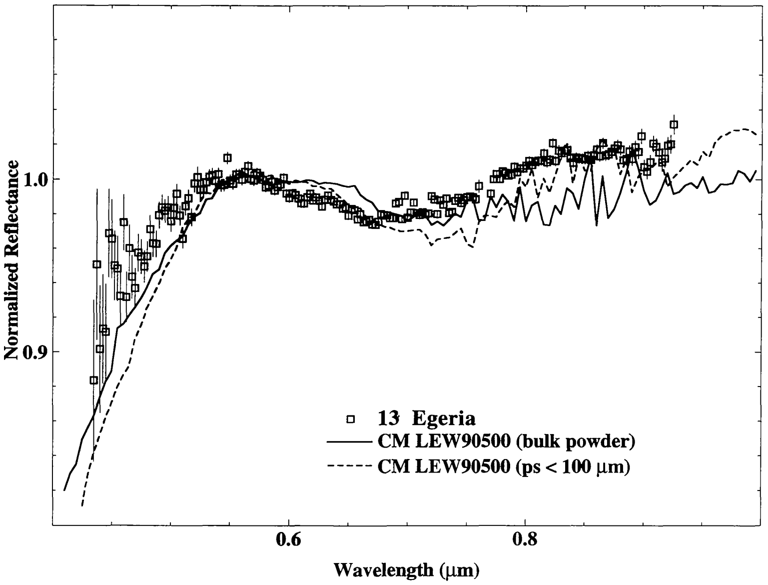

FIG. 7. Normalized reflectance *vs.* wavelength of CCD spectra of 13 Egeria (Bus, pers. comm.) *vs.* CM chondrite LEW 90500 (particle size < 100 μm, Hiroi *et al.*, 1993; bulk particle size). All spectra are normalized to unity at 0.55 μm. Error bars are $\pm 1\sigma$.

Recent theoretical work (*e.g.*, Love and Ahrens, 1996) has suggested that most asteroids are rubble piles. These are objects that have been shattered but whose gravitational attraction has kept them intact. Vilas and Sykes (1996). have proposed that if the weaker ultraviolet feature in C-type asteroid spectra compared to carbonaceous chondrites is due to heating, then the presence of the 0.7 μm feature in the same spectrum may imply a rubble pile whose surface consists of metamorphosed material from the interior and CM material from the original body's exterior.

The CM chondrites are known to contain members with varying degrees of alteration; however, compositional trends among different alteration parameters suggest that the CM chondrites experienced similar processes (*e.g.*, Browning *et al.*, 1996). The two CM chondrites (Murchison and LEW 90500), even though spectrally similar, have experienced different degrees of alteration (Hanowski and Brearley, 1997), implying different formation locations on the same parent body or in different parent bodies altogether.

Fortuna and Egeria are spectrally similar to measured CM chondrites, which implies some type of compositional similarity. But the problem with trying to link these asteroids with the CM chondrites is that these asteroids' spectral features are not unique. Observational surveys estimate approximately one-half (Barucci *et al.*, 1997) to three-quarters (Sawyer, 1991) of C-type asteroid spectra contain the 0.7 μm absorption feature. Vilas (1994) has estimated, using an algorithm to predict the presence of the 0.7 μm feature in an asteroid's spectrum from ECAS data, that this feature is found in the spectra of approximately one-half of C-type asteroids. Since this feature can be found in the spectra of a significant number of other asteroids, it is impossible to make any definitive conclusions between any proposed relationships between Fortuna and Egeria and the CM chondrites. Since these asteroids should be supplying a relatively large number of fragments into Earth-crossing orbits, it is likely that samples of these asteroids do exist in our meteorite collection. If samples of Fortuna and Egeria have been found, they have probably been classified as CM chondrites.

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