lieved to be complex and largely smoothed out in time, compared to the direct detection of impacts on the moon. However, the lack of strict day to day correlations between data from Earth and moon suggest that the meteoroid stream was not homogeneous in space.

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Phyllosilicate Absorption Features in Main-Belt and Outer-Belt Asteroid Reflectance Spectra

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Absorption features having depths up to 5% are identified in high-quality, high-resolution reflectance spectra of 16 dark asteroids in the main belt and in the Cybele and Hilda groups. Analogs among the CM2 carbonaceous chondrite meteorites exist for some of these asteroids, suggesting that these absorptions are due to iron oxides in phyllosilicates formed on the asteroidal surfaces by aqueous alteration processes. Spectra of ten additional asteroids, located beyond the outer edge of the main belt, show no discernible absorption features, suggesting that aqueous alteration did not always operate at these heliocentric distances.

PRIMITIVE METEORITES OF TYPES 1 and 2 are assumed to be the result of the melting of ice and subsequent aqueous alteration of rocky materials comprising their original parent bodies (*1*). Laboratory reflectance spectra of meteorites that appear to have undergone aqueous alteration and terrestrial rock samples that are products of aqueous alteration show subtle absorption features in the visible and near-infrared spectral regions (*2*); however, telescopic reflectance spectra of asteroids labeled "primitive" have been considered featureless in the same spectral regions (*3*). In this study, we searched 26 high-quality spectra of primitive (C-, P-, D-, F-, and G-class) (*4*) asteroids for weak features in the visible and near-infrared spectral regions. The asteroid sample presented here is composed primarily of the dark asteroids located beyond the outer edge of the main asteroid belt (the outer belt). The main emphasis of the observing program from which these spectra were culled was to understand the nature of asteroids located between the main belt and Jupiter's orbit. We also observed some asteroids classed as P or D in the main belt to search for compositional differences between these objects and the outer-belt P and D asteroids (*5*).

Spectra of asteroids and Hardorp solar analog stars (*6*) were acquired during the years 1984 through 1987. All asteroid data were reduced to relative reflectance spectra scaled to 1.0 around 0.7 μm (*5*). Spectra were selected for this study on the basis of the following criteria: (i) low peak-to-peak noise within a spectrum; (ii) good observing conditions during the nights when these data were obtained; and (iii) comparison of individual spectra with maps of the telluric atmospheric absorptions that could affect spectral shape if the extinction correction insufficiently removed some atmospheric absorptions. In interpretations of the data for asteroids 1162, 1512, and 2357 we have taken account of residual telluric water vapor features in these spectra. For the rest of the asteroids included in this study, such artifacts either were not present or were not sufficiently strong to affect the interpretation (*7*). Each spectrum was treated as a continuum with discrete absorption features superimposed on it. For each object, a linear least-squares fit to the spectral data points defined a simple linear continuum, which was then divided into each individual spectrum, thus removing the sloped continuum and allowing the intercomparison of residual spectral features. The residual features for various groupings of asteroids are shown in Figs. 1 through 4 and can be compared with residual features from laboratory spectra of terrestrial phyllosilicates and carbonaceous chondrite meteorites (*8*).

These diverse features may represent the effect of some asteroidal property (real features), or they could be artifacts from the stellar calibration sources or from the observing or data-reduction procedures. The reality of the slopes and features in the asteroid spectra was tested by a number of criteria. The standard stars can be eliminated as a source of significant features because asteroid data reduced through the same standard exhibit a wide variety of spectral slopes and residual features. No one feature is present in all of the asteroid spectra calibrated with any single standard star, and similar features are seen in asteroid spectra calibrated with different standard stars. If features were not common to all objects observed during any single night and if the observational or reduction procedures provided no explanation for a feature, then we concluded that the features derived primarily from the surface mineralogy of the asteroid.

The strongest of the residual features (Fig. 2) has a maximum absorption intensity of approximately 5%. Most are considerably weaker. Features with intensities below 1% have generally been discounted, without future prejudice, in this study. Thus, a significant subset of these dark asteroids are featureless by this criterion, even though there are variations in their spectra that subsequent study may prove to be real. Asteroid 1 Ceres is the exception to this general rule. This spectrum is a composite of 31 spectra of Ceres obtained at an air mass of 1.00,

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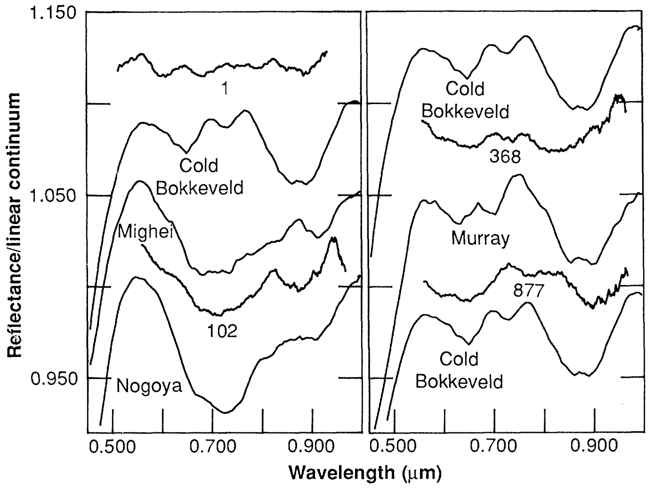

Fig. 1. Residual spectra of main-belt asteroids 1, 102, 368, and 877 compared to residual spectra of the CM2 carbonaceous chondrites Cold Bokkeveld, Murray, Nogoya, and Mighei. (In Figs. 1 through 4, spectra are linearly offset by reflectance increments of 0.05 for the purpose of display.)

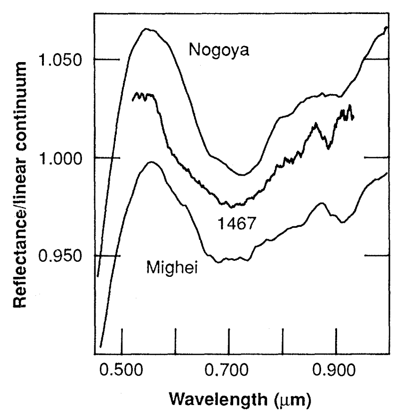

Fig. 2. Residual spectra of Cybele asteroid 1467 Mashona compared to those of CM2 carbonaceous chondrites Nogoya and Mighei.

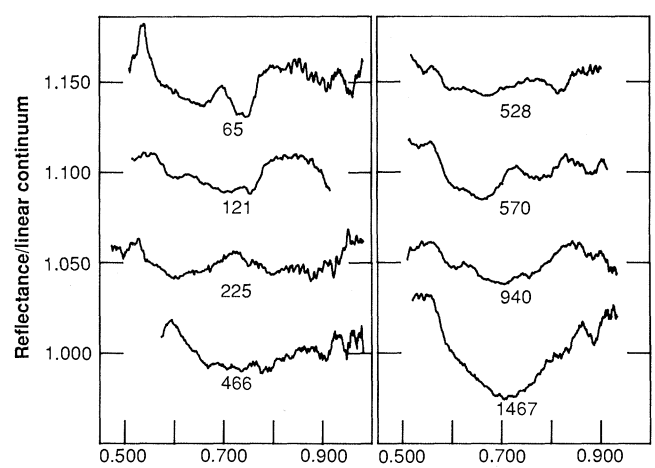

Fig. 3. Residual spectra of featured Cybele asteroids 65, 121, 225, 466, 528, 570, 940, and 1467.

each having a signal-to-noise ratio greater than 100:1. The weak features in this spectrum (Fig. 1) are most probably real and deserve additional study.

The CI1 and CM2 meteorites exhibit a suite of spectral features that are generally similar to those seen in these dark asteroids. The asteroid features are generally one-half to one-third as strong as those seen in the meteorites, with a few important exceptions discussed below. Although all of these features appear to be relatively weak, they must represent intense absorptions to be present in spectra of objects having such low albedos (amount of visible light reflected by the surface material) and therefore certainly arise from strongly featured mineral species. Only a relatively limited suite of viable candidate species meet these criteria. The strongest asteroidal features, seen in main-belt asteroid 102 Miriam (Fig. 1) and Cybele asteroid 1467 Mashona (Fig. 2), are very similar, both in shape and in intensity, to those in the spectra of CM2 (carbonaceous) chondrites Murchison, Mighei, and Nogoya. The features in 102 Miriam and 1467 Mashona as well as those in the meteorites are consistent with the absorption features in iron-bearing serpentines (antigorite) and chlorites (*2*). The features in 877 Walkure (Fig. 1) could represent absorptions by phyllosilicate phases perhaps in combination with iron oxides such as goethite (*9*).

The CM2 and CI1 chondrites are considered to be the products of varying degrees of aqueous alteration within their parent bodies (*1*). One proposed alteration sequence starts with a primarily anhydrous parent material similar to the CV3 chondritic assemblage. Metal is altered to form iron-rich tochilinite (an Fe-Ni-S-OH mineral). Olivine alters to magnesian serpentine, and tochilinite reacts to form cronstedtite (an Fe^{3+} 1:1 layer phyllosilicate), which subsequently reacts to form iron-rich serpentine, sulfides, and magnetite.

If tochilinite is the major opaque phase in the assemblage, this alteration sequence should first produce a large decrease in albedo. If the initial assemblage had additional, strongly absorbing species such as kerogens or other organic compounds, the initial albedo would be low and only a small albedo decrease would occur. In such anhydrous parent assemblages, the absorbing material would largely overwhelm the relatively weak features of anhydrous silicates causing the spectral curve to be featureless and dominated by any spectral slope imparted by the strongly absorbing phase. The albedo should slowly increase as alteration proceeds, removing the tochilinite phase and depleting disseminated organic components. Phyllosilicate features should appear and be weakest at the initial stages of alteration both because of the competing high background absorbance (the low albedo) and because of their relatively low iron content. As alteration proceeds, the phyllosilicate features should become more pronounced as a result of the lower background absorbance (higher albedo) and their increasing iron content. Continued aqueous alteration in moderately reducing environments (as might be expected in the presence of small amounts of organic matter) should eventually leach iron from the phyllosilicates and sequester an increasingly higher proportion of this element in magnetite. If this magnetite grows to grains larger than a few tenths of a micrometer in size, it becomes much less effective either as a darkening agent or as a source of spectral features. At this stage of alteration, the albedo is substantial (perhaps 7 to 15%) and phyllosilicate features are very weak.

Four spectra of main-belt asteroids (1 Ceres, 102 Miriam, 368 Haidea, and 877 Walkure) are included in the present study (Fig. 1). Although this is a limited set, their relative spectral and albedo (*10*) differences are consistent with the alteration sequence outlined above. Asteroid 368 Haidea has the lowest albedo ($p_v \pm SE = 0.032 \pm 0.002$) and weak features and is spectrally similar to CM2 chondrite Cold Bokkeveld. Asteroid 102 Miriam has a substantially

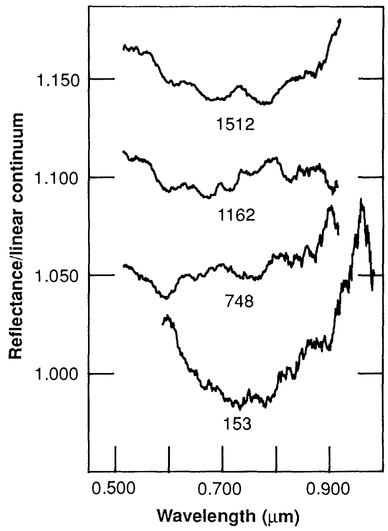

Fig. 4. Residual spectra of featured Hilda asteroids 153, 748, 1162, and 1512.

higher albedo ($p_V \pm$ SE = 0.049 ± 0.002) and the strongest features and is spectrally similar to CM2 chondrites Murchison, Nogoya, and Mighei. Asteroid 1 Ceres has a much higher albedo ($p_V \pm$ SE = 0.10 ± 0.01) and very weak features, a combination that precludes a significant iron-bearing phyllosilicate component (*11*) and that is expected under conditions of alteration different from those seen in the CM2-CI1 suite (perhaps an additional alteration stage), with no meteoritic analogs for, or samples from, Ceres yet detected in our meteorite collections. The weak features in the Ceres curve should provide clues to the identity of the major phases, presumably dominated by phyllosilicates formed under conditions of intense, low-temperature, aqueous alteration such as members of the kaolin or smectite groups. Asteroid 877 Walkure has an albedo ($p_V \pm$ SE = 0.047 ± 0.004) comparable to that of 102 Miriam and exhibits relatively strong but distinct spectral features, some similar to spectral features of CM2 chondrite Murray, which suggest an intermediate stage of alteration, perhaps somewhat less than that of 102 Miriam or perhaps along a different redox path or with different fluid:rock ratios. The data on this limited set of dark, main-belt asteroids suggest that all have been aqueously altered to some degree and that intense alteration is relatively common.

In addition to the main-belt asteroids, fourteen Cybele, four Hilda, and four Trojan asteroids were included in this study. Ten of these asteroids (Cybele asteroids 76, 87, 566, 643, 733, and 1167 and Trojan asteroids 884, 1172, 2357, and 2674) have spectra with no absorption features that passed our acceptance criteria, implying that these asteroids have not undergone any aqueous alteration. Of these ten objects, 733 Mocia has the highest albedo ($p_V \pm$ SE = 0.049 ± 0.009); the other nine have albedos in the range of 0.029 to 0.042. All of the measured D-class asteroids beyond the main belt are included in this featureless group. This is in agreement with recent water of hydration absorption results at 3.0 μm and the proposed models for solar system evolution (*12*).

The remaining eight Cybele asteroids (Fig. 3) and the Hilda asteroids (Fig. 4) show a diversity of spectral features, the nature of which is not yet completely understood. Although some meteoritic analogs are evident, the diversity suggests that many of these assemblages are not represented in our meteorite collections. The CM2 specimens Nogoya, Mighei, and Murchison provide very good matches both in absorption band position and in intensity to the spectrum of Cybele asteroid 1467 Mashona. The band position and intensity are indicative of a serpentine-type phyllosilicate having a well-ordered crystal structure. Asteroids 466 Tisiphone, 528 Rezia, and 940 Kordula (Cybele group objects, Fig. 3) and 153 Hilda and 1512 Oulu (Hilda group objects, Fig. 4) show a somewhat similar spectral pattern, although weaker and less well defined. These may represent assemblages that have undergone less but still substantial aqueous alteration, but the significance of the differences is unclear. Asteroids 225 Henrietta and 570 Kythera (Fig. 3) have features that are not well matched by any single phyllosilicate or iron oxide for which spectra are currently available although they are similar to components seen in spectra.

It appears that the processes that produced the most aqueous alteration among the CM2 assemblages were active to approximately the same extent on objects such as 1467 Mashona and 102 Miriam, and to a lesser extent on other objects in the main-belt, Cybele, and Hilda groups. Features in asteroids such as 368 Haidea are similar in band position to but less intense than those present in the Cold Bokkeveld and Murray spectra. The intensity difference may reflect a real mineralogical difference or a regolith process (coarse particle size versus fine). The featureless or nearly featureless spectra imply either a significant depletion of iron from the phyllosilicates (producing weak features that are easily masked by the dark phases) or the presence of an anhydrous silicate assemblage with the correspondingly weak features. It seems unlikely that a higher abundance of the dark absorbing phases, such as organics, can be the sole explanation for the absence of spectral features because that would imply substantially lower albedos than measured for these objects.

The pattern of features and the inferred postaccretionary aqueous alteration of their parent planetesimals is consistent with several recent models and observations that point to a selective heating mechanism that has a steep decline in efficiency with increasing heliocentric distance (*13*). In the Trojan asteroids, temperatures in the planetesimal interiors did not rise above the water-ice solidus (if it is assumed that ice was the primary water source for the aqueous alteration). In the main belt, most or all bodies exceeded this temperature. In the Cybele asteroids [mean semimajor axis a = 3.4 astronomical units (AU)] and the Hilda asteroids (a = 4.0 AU), somewhat more than half of the bodies exceeded this temperature to produce aqueous alteration.

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8. The removal of a sloped continuum has a distorting effect on the residual features. In general, this procedure will tend to weaken the low albedo edge (generally the shorter wavelength side) of the feature relative to its actual absorbance. The magnitude of this effect correlates directly, but not linearly, with spectral slope and inversely with albedo. The net effect for steeply sloped spectra (the slope indicating that an absorbing agent is operating more effectively at lower wavelengths) is to shift the effective centers of features toward longer wavelengths and to underrepresent the short-wavelength components in compound absorption bands. These effects have been considered in a qualitative fashion in the present discussion.
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