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A study of Cybele asteroids

II. Spectral properties of Cybele asteroids*

C.-I. Lagerkvist[1], L. Moroz[2], A. Nathues[3], A. Erikson[4], F. Lahulla[5], O. Karlsson[1], and M. Dahlgren[1]

[1] Astronomical Observatory, Box 515, 751 20 Uppsala, Sweden
e-mail: `Claes-Ingvar.Lagerkvist@astro.uu.se`
[2] DLR, Optical Information Systems, Rutherfordstrasse 2, 12489 Berlin, Germany
[3] Max-Planck-Institut für Sonnensystemforschung, Max-Planck-Strasse 2, 37191 Katlenburg-Lindau, Germany
[4] DLR, Institute of Planetary Research, Rutherfordstrasse 2, 12489 Berlin, Germany
[5] Observatorio Astronomico, Alfonso XII 3, 28014 Madrid, Spain

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Abstract. We have used the 3.5 m New Technology Telescope at ESO, La Silla, to obtain spectra of 18 asteroids belonging to the Cybele group. One additional Cybele asteroid was observed with the ESO 3.6 m telescope. From the spectra we have derived spectral slopes and taxonomy classifications. Our observations show that spectrally red D-type Cybeles tend to be smaller than more spectrally neutral P- and C-type objects from this group. Similar colour-diameter trends have previously been reported for other outer belt low albedo asteroids (Hildas and Trojans). We discuss possible reasons for this trend. In particular, the observed dominance of red objects for small diameters is consistent with a space weathering scenario, where irradiation of asteroid regoliths with solar wind plasma neutralizes their surface colours due to carbonization of originally reddish organic components. Collisional disruption of such large greyish "aged" P-type objects would produce a number of redder D-type fragments lacking mature regoliths. In addition, the observed colour-diameter trend may be due to compositional differences between D-, P- and C-type asteroids. P- and C-types may be lacking at small diameters, since their materials are less susceptible to collisional break-up than spectrally red D-type material. A simultaneous contribution of both factors (compositional differences and space weathering) to the observed trend is possible as well.

Key words. minor planets, asteroids

1. Introduction

Due to their likely pristine nature, the asteroids in the outer edge of the asteroid belt may provide a number of clues to the origin and evolution of the asteroid belt and to the formation of our planetary system. The asteroids in the outer belt, which are here defined as objects with a semi-major axis $a > 3.3$ AU, fall into three main groups. The Cybeles between 3.3–3.5 AU, the Hildas in the 3:2 resonance with Jupiter at 4.0 AU and the Trojans around the Lagrangian L_4 and L_5 points of Jupiter at 5.2 AU. Due to their large heliocentric distances, the outer belt asteroids have experienced less heating and are of a more pristine composition. They may also contain a large fraction of ice in their interiors (Bell et al. 1989).

C-type asteroids are spectrally neutral in the visible and near-infrared wavelengths with a downturn in reflectance shortward of 0.4 μm (Tholen 1989). The low albedos and relatively featureless spectral curves of C-types indicate that their surfaces are optically dominated by opaque (e.g., sulfides, magnetite) and carbonaceous phases. The distinct UV-falloff (Johnson & Fanale 1973), weak absorption bands near 0.7 μm (Vilas & Gaffey 1989) and 3 μm absorption feature detected in the spectra of many C-types (Lebofsky 1980; Jones et al. 1990; Rivkin et al. 2002) are consistent with the presence of hydrated minerals. Spectral similarity to primitive carbonaceous chondrites containing hydrated minerals (mostly hydrosilicates) suggests a genetic link between these chemically primitive meteorites and C-type asteroids (Johnson & Fanale 1973; Gaffey & McCord 1978; Feierberg et al. 1981).

D- and P-type asteroids dominate outer belt populations and appear to be compositionally different from C-types. They are characterized by low albedos and featureless reddish spectral curves in the visible and near-infrared (Tholen 1989). The low albedos, reddish colours and large heliocentric distances are consistent with the presence of complex macromolecular organic matter on the surfaces (Gradie & Veverka 1980; Cruikshank & Khare 2000). Absorption bands attributable to organic compounds have recently been detected in near-infrared spectra of several Trojan D-types

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[*] Observations were made at the European Southern Observatory (ESO) with the NTT telescope under program 56.F-0355 and the 3.6 m telescope under program 62.S-0133.

(Emery & Brown 2003). In addition, macromolecular organic components have been found in the Tagish Lake carbonaceous chondrite which is the only known meteoritic spectral analogue for D-type asteroids (Hiroi et al. 2001).

P- and D-types beyond 2.9 AU seem to lack hydrated minerals on their surfaces (Jones et al. 1990; Vilas 1994; Emery & Brown 2003) and may contain water ice in their interiors (Bell et al. 1989). However, P- and D-type asteroids may contain significant amounts of hydrosilicates without showing any detectable absorption bands even at $3\,\mu$m if their surfaces are rich in opaque phases (e.g., Cruikshank et al. 2001). "Water of hydration" band near $3\,\mu$m has been reported only for a few inner Main-belt D- and P-types (Rivkin et al. 2002; Kanno et al. 2003). Carvano et al. (2003) point out that inner Main-belt D-type objects often have concave spectral shapes and higher albedos compared to the outer belt D-types. These observations suggest that outer belt D-types may be compositionally different from the inner Main-belt D-types.

P-type objects are less red than D-types. The nature of this difference in colour is poorly understood and may be caused by many factors including compositional and textural variations, space weathering effects and collisional evolution (Moroz et al. 1998, 2004b and references therein). The lack of detectable absorption features in the spectra of P- and D-type asteroids precludes unambiguous interpretation.

2. Observations

All spectra, except one, were obtained during the nights of March 22 and March 23 in 1996 with the 3.5 m New Technology Telescope (NTT) at the European Southern Observatory, La Silla, Chile. The weather was photometric on both nights. The multi-mode instrument EMMI was used in the red spectroscopic medium dispersion mode (red prism#1/GRAT#13) giving a dispersion of 4.37 Å pixel^{-1} (long slit#2). The detector used was a Tektronic 2048 × 2048 pixel CCD. The tracking of the telescope was adjusted to match the apparent motion of the targets. A two arcsec slit, oriented in the direction of the parallactic angle, was used. Wavelength calibration was performed with a Helium-Argon lamp. The wavelength range of the spectra are 3850–8600 Å, however, due to a possible second order overlap, only the wavelength range from 3850–7650 Å was used for the calculation of the spectral slopes. Exposure times were selected to give approximately the same signal-to-noise ratio (S/N) for all spectra of the asteroids. The peak S/N for most objects is between 55–70. Bias and flat-field frames were obtained on both nights. The nearly solar analogs HD 76 151 and HD 144 585 (Hardorp 1978) were used to achieve solar spectral calibration. Prior to the asteroid observations the spectra of these stars were crosschecked with the solar analog HD 44 594 (Hardorp 1982), which unfortunately could only be observed at rather large airmass. From this crosscheck we concluded that the spectral differences between the real solar analog HD 44 594 and both nearly solar analogs are negligible for our purposes.

The spectrum of (4014) Heizman was obtained on October 29 in 1998 with the 3.6 m ESO telescope at La Silla, equipped with the EFOSC II spectrograph. A five arcsec slit, oriented in the direction of the motion of the asteroid, and a Loral-Lesser 2048 × 2048 pixel (#40) detector were chosen. This led to a dispersive resolution of 1.34 nm pixel^{-1} and a useful wavelength range about 5500−10 000 Å, which had to be truncated longward of 7300 Å due to the low achieved S/N. Solar calibration was performed by choosing the solar analog HD 44 594.

3. Data reduction

All the acquired data were reduced using the ESO-MIDAS package. The bias and flat-field frames displayed no variation between the two nights at the NTT, thus, one median bias and flat-field frame was constructed for the observing run. The following reduction steps were performed: 1) median bias frame subtraction; 2) median spectral dome flat-field division; 3) cosmic hit elimination; 4) subtraction of the spectral sky background by using polynomial background fits; 5) transformation to a 1-dimensional spectrum; 6) wavelength calibration; 7) extinction correction using La Silla's mean extinction curve (Tüg 1977); 8) solar analog spectrum division and finally; 9) normalization at 6000 Å. The detailed spectroscopic data reduction method used is described in Dahlgren & Lagerkvist (1995) and Nathues (2000).

The reflectance spectra of the 19 Cybele asteroids observed are presented in Figs. 1–6. More than one spectrum appear in most figures, and all except the lowest spectrum in the figures are shifted vertically for clarity. Due to incomplete removal of the atmospheric bands there are some residuals left in most of the asteroid spectra. The largest residuals are from the atmospheric O_2 A-band at 7612 Å. The spectrum of (4014) Heizman, obtained with the 3.6 m telescope, covers only the wavelength between 5600–7400 Å.

The slopes of the spectra were determined using the method introduced by Jewitt & Luu (1990), namely a linear least square fit to the spectrum between 4000–7400 Å, with unit flux at $\lambda = 6000$ Å. For (4014) Heizman we had to use the wavelength range as described above. From the obtained spectra we classified the asteroids as described by Dahlgren & Lagerkvist (1995).

4. Results

A summary of the resulting spectral slopes and other relevant data are listed in Table 1. The asteroid number and name and the derived spectral slope are listed, followed by the visual albedo from IRAS (Tedesco & Veeder 1992), the derived taxonomic type, the IRAS diameter and the absolute magnitude (H). In the last column the phase angle at the time of observation is given. For asteroids with no IRAS albedo the diameters were calculated from the absolute magnitudes given in the Ephemerides of Minor Planets for 2003. For the conversion between absolute magnitude and diameter we used the table supplied by the Minor Planet Center (`http://cfa-www.harvard.edu/iau/lists/Sizes.html`) using a mean albedo. The errors introduced by this are not of any importance for our purposes since for these small asteroids the diameter errors are at most 10 km (cf. Fig. 7).

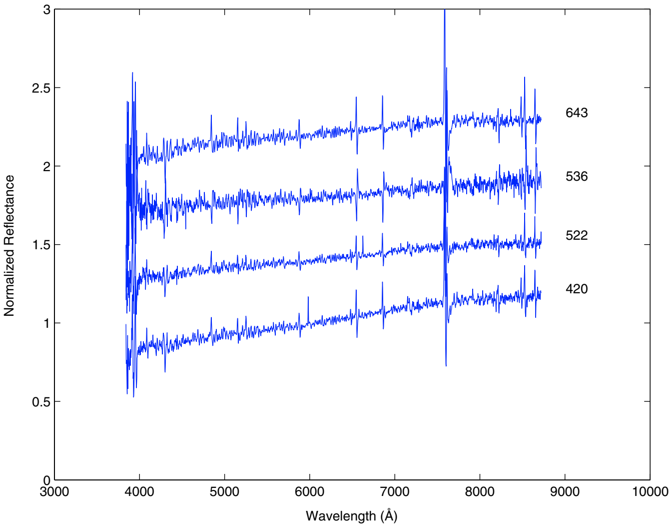

Fig. 1. Spectra for the asteroids (420) Bertholda, (522) Helga, (536) Merapi and (643) Scheherezade. The spectra have been shifted vertically for clarity.

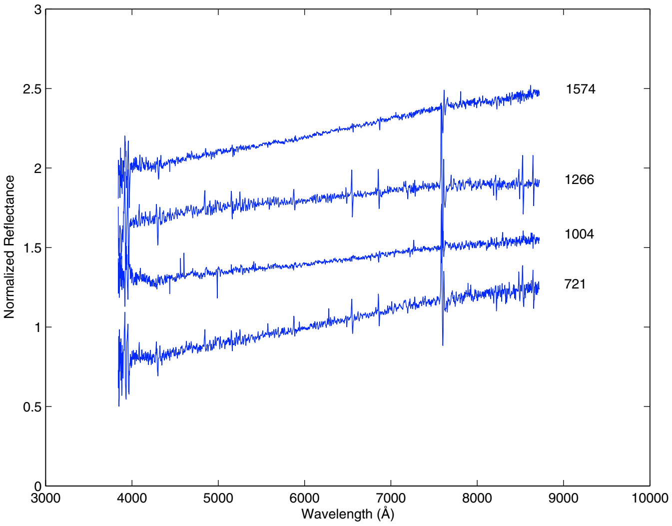

Fig. 2. Spectra for the asteroids (721) Tabora, (1004) Belopolskya, (1266) Tone and (1574) Meyer.

The spectral slopes are effected by phase reddening. Luu & Jewitt (1989) estimate the reddening coefficient to be of the order 0.2% 1000 Å^{-1} deg^{-1} for phase angles smaller than 40 degrees. The actual phase angles during our observations are small, see Table 1, and even if the phase reddening changes the derived spectral slopes somewhat the effect in Fig. 7 and the discussion is marginal.

In Fig. 7 we present the result in graphic form with the spectral slope (S') plotted versus diameter (D). In addition to our data we were able to find taxonomic classifications of 24 Cybele asteroids at The Small Bodies Node (`http://pdssbn.astro.umd.edu/`). As the spectral slope for asteroids of taxonomic type C we chose $S' = 2.0$, for P type asteroids $S' = 4.0$, for PD type asteroids $S' = 5.0$ and for D type asteroids $S' = 7.0$ (cf. Dahlgren & Lagerkvist 1995).

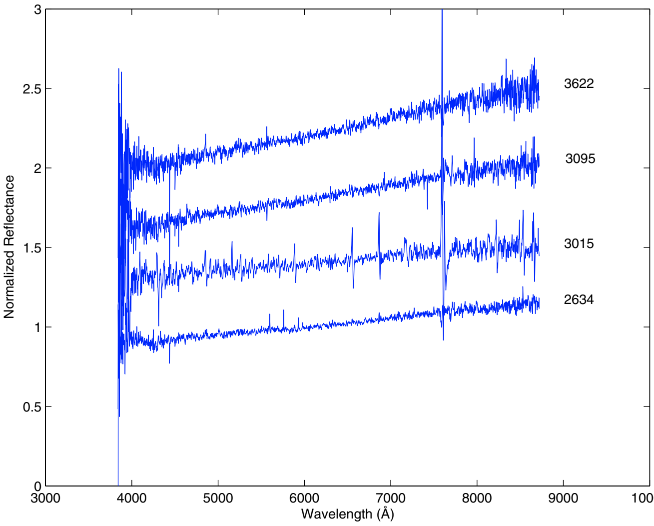

Fig. 3. Spectra for the asteroids (2634) James Bradley, (3015) Candy, (3095) Omarkhayyam and (3622) Ilinsky.

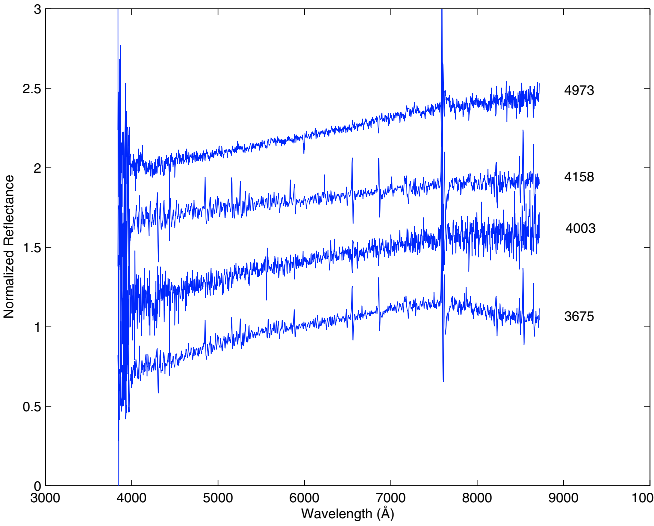

Fig. 4. Spectra for the asteroids (3675) Kemstach, (4003) Schumann, (4158) Santini and (4973) Showa.

As seen in the figure there is a trend for small asteroids to have larger spectral slopes. This was also found by Dahlgren et al. (1997) in their investigation of Hilda asteroids. For the asteroids in Fig. 7 with diameters smaller than 70 km we find $S' = 8.1 \pm 2.5$. For bodies larger than 70 km the corresponding values are $S' = 4.3 \pm 2.0$. For the Hilda asteroids in Dahlgren et al. (1997) the corresponding numbers are $S' = 8.6 \pm 3.2$ and $S' = 4.5 \pm 2.3$, respectively. The two groups of outer belt asteroid thus show the same behaviour concerning the reflectance properties of small and large asteroids.

5. Discussion

Thus, the red D-type Cybele asteroids tend to have small diameters, while larger objects are more spectrally neutral and less diverse in colour (P- and C-types).

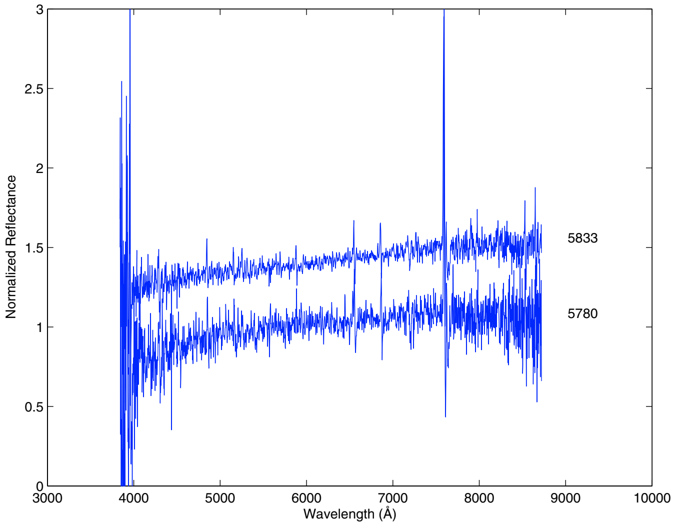

Fig. 5. Spectra for the asteroids (5780) Lafontaine and (5833) Peterson.

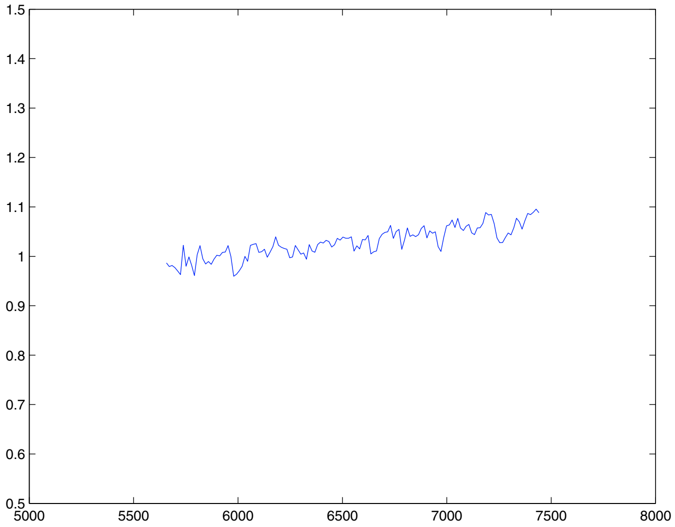

Fig. 6. Spectrum of the asteroid (4014) Heizman.

Similar trends have previously been reported for Trojans and Hildas. Jewitt & Luu (1990) have found a positive correlation between spectral slope and apparent magnitude for a sample of 32 Trojan asteroids. Jewitt & Luu (1990) argue against the possibility of a magnitude-dependent error and suggest that their observations imply a colour-diameter trend. The majority of classified Trojans belong to the D-type. If the trend is real, then the reddest D-type Trojans are dominant at small diameters, while fewer red D-types as well as a few P- and C-types are larger. Fitzsimmons et al. (1994) confirmed the trend suggested by Jewitt & Luu (1990). More convincing evidence for the colour-diameter correlation exists for Hilda asteroids. The redder D-type Hildas are significantly more numerous at smaller diameters, while the less red-sloped P-types are usually larger (Dahlgren et al. 1997). In addition, some observations suggest that the small red Hildas have more elongated shapes and are more collisionally evolved than larger and more spectrally neutral P-type Hildas (Dahlgren et al. 1999).

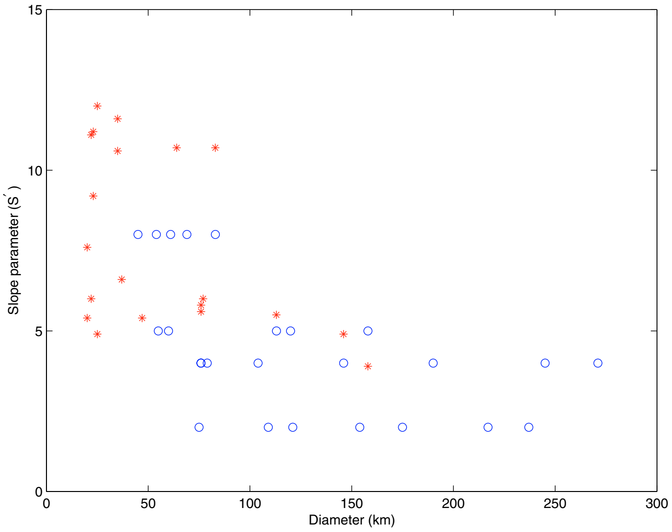

Fig. 7. Spectral slope plotted versus diameter for Cybele asteroids. Results from the present study have been marked by asterisks, values from the literature are represented by open circles.

It is possible that compositional variations exist within populations of Cybeles, Hildas and Trojans. The C-type objects most probably differ in composition from P- and D-types as mentioned above. The question arises as to whether P-type objects are compositionally different from the redder D-types dominating at smaller diameters. Although anhydrous and/or hydrated minerals might dominate by volume, the opaque and carbonaceous/organic phases optically dominate the surfaces of outer belt asteroids and Trojans in the visible and near-infrared spectral ranges (Moroz et al. 2004b). Therefore the abundances, composition and texture of the latter components are most probably responsible for the spectral slope variations (Moroz et al. 2004b). Red spectral slopes may be due to a long wavelength wing of a broad UV feature caused by absorption of polycyclic aromatic hydrocarbons with a relatively high H/C ratio (Moroz et al. 1998). If P- and D-types are compositionally diverse, then the less red colours of P-types compared to the D-types may be due to more carbonized organics on their surfaces, or due to lower abundance of red organics, or due to higher content/finer grain sizes of opaques (sulfides, elemental carbon, magnetite) neutralizing the spectral slope (Moroz et al. 1998, 2004b). In this case, the dominance of red D-types at small diameters may be either primordial, or imply that red D-types are more susceptible to collisional break-up than P- and C-types as was suggested by Jewitt & Luu (1990) and Dahlgren et al (1997). Dahlgren et al. (1997) also suggested that small red D-type Hildas have been ejected from the upper layers of large thermally metamorphosed objects whose interiors have been modified by heating. In this scenario large P-types represent the exposed heated interiors of larger precursors, although Dahlgren et al. (1997) do not discuss why mild internal heating would neutralize their originally red colours.

Particle size variations, temperature-induced effects and viewing geometry appear to be unlikely reasons for the observed dominance of red objects at small sizes as discussed by Dahlgren et al. (1997) and Moroz et al. (1998, 2004b).

Table 1. Results.

Asteroid	S' (%/1000 Å)	Albedo (%)	Tax. type	Diameter (km)	H	Phase angle (deg)
(420) Bertholda	4.9	0.042	D	146	8.31	16
(522) Helga	5.5	0.039	PD	113	9.12	11
(536) Merapi	3.9	0.045	P	158	8.08	16
(643) Scheherezade	5.6	0.045	PD	76	9.72	6
(721) Tabora	10.7	0.060	D	83	9.26	13
(1004) Belopolskya	6.0	0.035	DP	77	9.99	10
(1266) Tone	5.8	0.057	PD	76	9.41	5
(1574) Meyer	10.7	0.039	D	64	10.3	11
(2634) James Bradley	5.4	0.092	G?	47	10.2	12
(3015) Candy	4.9		X	25	11.1	4
(3095) Omarkhayyam	9.2		D	23	11.3	11
(3622) Ilinsky	11.1		D	22	11.4	10
(3675) Kemstach	12		S	25	11.1	7
(4003) Schumann	11.6		D	35	10.8	11
(4003) Schumann	10.6		D	35	10.8	11
(4014) Heizman	5.4		PD	20	11.9	3
(4158) Santini	6.0		X	22	11.4	1
(4973) Showa	11.2		D	23	11.3	14
(5780) Lafontaine	7.6		D	20	11.8	6
(5833) Peterson	6.6		X	37	10.7	13

Moroz et al. (2003, 2004b) suggested that a negative correlation between spectral slopes and sizes within Hilda, Cybele and Trojan populations is due to space weathering effects. Recent results of ion irradiation experiments by Moroz et al. (2003, 2004a) demonstrate that irradiation of dark red hydrocarbon material with low energy ions (such as solar wind plasma) neutralize the spectral slope in the visible and near-infrared spectral ranges. If dark red hydrocarbon material optically dominate the surface of D-type asteroids, then bombardment of their surfaces with low energy charged particles would form a thin (≈1000 Å) carbonized surface layer with a more neutral spectral slope. More penetrating ions (e.g., cosmic rays) are ineffective in neutralizing the colours of complex organics (Moroz et al. 2004a,b). Impact-induced carbonization (Korochantsev et al. 1997) and modification of the surface regolith by micrometeorite impacts (Hiroi et al. 2003) may also contribute to the neutralization of the spectral slope. Collisional disruption or significant collisional resurfacing of such a "grayish" P-type object would expose "fresh" red unweathered material. Therefore, a negative correlation between the spectral slope and size of the object is expected for a collisionally evolved population of such dark primitive objects. Smaller objects represent fragments of larger asteroids disrupted by catastrophic collisions. They are relatively red (or diverse in colour) since their surfaces are younger and their ability to accumulate regolith is diminished due to their small sizes. The larger bodies which did not experience catastrophic disruption have more neutral colours, since their surfaces have been exposed to ion flux for longer times and may be covered with a thick layer of relatively mature regolith.

The smaller objects appear to be more diverse in colour than the larger ones (Fig. 7). Since smaller asteroids have shorter collisional lifetimes, their surfaces would not have time to attain a saturation level of space weathering that would be more common on larger asteroids.

A possible difficulty with this scenario is that exposure to solar wind plasma would neutralize the colours of bare red surfaces of collisional fragments after a few thousands years as calculated by Moroz et al. (2004b). However, the authors argue that such a thin neutral layer may be easily eroded, e.g., by impacts of dust particles of various origins. For example, dust detectors onboard Ulysses and Galileo spacecraft detected intense streams of tiny dust particles with extremely high impact rates and velocities within about 1.7 AU from Jupiter (Krüger et al. 1999).

The colour-diameter trend observed within populations of outer belt asteroids is consistent with the latter scenario, however, the explanation suggested by Dahlgren et al. (1997) is possible as well.

Carvano et al. (2003) did not discuss similar colour-diameter trends in their recent analysis of a spectral dataset of 460 featureless asteroids from the Main-belt as a whole. However, as pointed out by Moroz et al. (2004b), the dataset reported by Carvano et al. (2003) also shows a lack of D-type objects at large diameters.

6. Conclusions

Our observations demonstrate that asteroids from the Cybele group, similarly to Hildas and Trojans, appear to show that spectrally red D-type objects are numerous at small diameters, while larger objects have more neutral colours. If the surfaces of outer belt asteroids are optically dominated by originally red dark organic materials, this result may imply that the spectral properties of these asteroid populations are affected by space weathering processes neutralizing their surface colours. In this case, small red D-type objects are collisional fragments of disrupted large P-type precursors covered with greyish mature regolith. Alternatively, the observed colour-diameter trend may imply that small objects in the Cybele group and other outer belt populations are compositionally different from the larger objects. In the latter case the colour-diameter trend may result from a different strength of the D-type material compared to the materials composing the larger objects (P- and C-types). Both factors may contribute to the observed trend. For example, compositional factors may be responsible for the apparent lack of small C-type objects, while space weathering effects may result in the difference in colour and size between P- and D-type outer belt asteroids.

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