Available online at www.sciencedirect.com
ScienceDirect
Icarus 193 (2008) 567–571
ICARUS
www.elsevier.com/locate/icarus

Surface composition of Hilda asteroids from the analysis of the Sloan Digital Sky Survey colors

R. Gil-Hutton [a,*], A. Brunini [b]

[a] *Complejo Astronómico El Leoncito (CASLEO) and Universidad Nacional de San Juan, Casilla de Correo 467, Av. España 1512 sur, J5402DSP San Juan, Argentina*

[b] *Facultad de Ciencias Astronómicas y Geofísicas de La Plata and Instituto Astrofísico de La Plata, CONICET, Paseo del Bosque s/n, 1900 La Plata, Argentina*

Received 29 May 2007; revised 23 August 2007

Available online 19 September 2007

Abstract

In this paper we search for photometric data of asteroids in the Hilda region in the Moving Object Catalogue of the Sloan Digital Sky Survey to find the spectral characteristics of small members of this group. We found that the correlation between size and spectral slope previously suggested for Hilda asteroids is correct only for large objects ($H < 12$) but it is not supported by data obtained for the small ones. The best possibility to explain this behavior is that a space weathering process affecting the surface properties of these primitive objects is operating, modulated by a collisional resurfacing process affected by the lack of small projectiles in the population. Despite the intrinsic limitations of the few band photometry of the Sloan Digital Sky Survey, the analysis presented is based mainly in the detection of spectral slopes providing enough good indication about the taxonomic type of these asteroids and making us confident about our conclusions.

Keywords: Asteroids, composition; Asteroids, surfaces; Asteroids

1. Introduction

The Hilda asteroids group is in the 3:2 mean motion resonance with Jupiter at ∼4.0 AU and populated by low-albedo asteroids of C-, P-, and D-types (Gradie et al., 1989). Due to their large heliocentric distances, these outer belt asteroids have experienced less heating and are of more pristine composition than objects in the main belt. Jones et al. (1990) found that the P- and D-types appear to be anhydrous and Luu et al. (1994) did not find any infrared absorption bands indicative of organics, but recently Emery and Brown (2003) have been reported these bands in near-infrared spectra of several trojan D-types. However, P- and D-type asteroids may contain significant amounts of hydrosilicates without showing any detectable absorption bands if their surfaces are rich in opaque phases (Cruikshank et al., 2001). The hydration band near 3 μm has been reported only for a few inner main belt D- and P-types (Rivkin et al., 2002; Kanno et al., 2003), and Carvano et al. (2003) point out that inner belt D-type objects often have concave spectral shapes and higher albedos compared to the outer belt D-types, suggesting that they may be compositionally different. At present the general outline for the composition of these asteroids is a mixture of organics, anhydrous silicates, opaque material and ice (Bell et al., 1989; Gaffey et al., 1989; Vilas et al., 1994), but it is very difficult to define the composition of these objects since no analogous meteorites for P-type asteroids have been found on Earth and there is only one analogous meteorite for D-types: the Tagish Lake carbonaceous chondrite (Hiroi et al., 2001).

The first attempt to study outer belt asteroid composition by CCD spectroscopy was made by Vilas and Smith (1985), but further investigations on Hilda asteroids composition have been carried out by Dahlgren and Lagerkvist (1995) and Dahlgren et al. (1997). These authors found that the D-type objects comprise 34% of the numbered Hilda asteroids at that epoch, while 28% and 2% are P- and C-types, respectively. They also found that there is a spectral slope–asteroid size relation among this asteroid group, implying a size dependent surface composition

* Corresponding author. Fax: +54 264 4213693.
E-mail address: rgilhutton@casleo.gov.ar (R. Gil-Hutton).

0019-1035/$ – see front matter © 2007 Elsevier Inc. All rights reserved.
doi:10.1016/j.icarus.2007.08.026

where the P-types dominate at larger sizes. To explain this result they suggest that the main size-dependent physical process acting on these asteroids are their mutual collisions and, if D-types are more fragile than P-types, this will favor disruptive collisions among D-type precursors. In this case, a larger fraction of the smaller body population can be collisional fragments from a few shattered large D-type precursors resulting in a large fraction of small D-type asteroids, as observed.

The results of Dahlgren et al. (1997) were obtained using reflectance spectra of 40 Hilda asteroids with absolute magnitude $H < 11.3$, which means diameters larger than 35 km assuming an albedo of 0.05. This sample corresponds only to the large end of the size distribution and it looks necessary to obtain spectra for smaller Hilda asteroids to confirm or not if the spectral slope–asteroid size relation exists also at smaller sizes.

It would be possible to search for data of asteroids in the Hilda region using large photometric surveys, like the Sloan Digital Sky Survey (SDSS). A sub-product of this survey is the Moving Objects Catalog (MOC), which in its third release provides five band photometry for 43424 asteroids of which 15472 have been observed twice or more (Ivezić et al., 2001; Jurić et al., 2002). In order to analyze the surface composition of asteroids and to perform taxonomic classification, multi-band photometry is not as precise as spectroscopy, but the amount of data of the SDSS-MOC significantly contrast with the only ∼2300 asteroids observed by the major spectroscopic surveys presently available: the SMASS (Xu et al., 1995; Bus and Binzel, 2002a) and the S^3OS^2 (Lazzaro et al., 2004). Moreover, while these spectroscopic surveys reached an average absolute magnitude of $H \simeq 11$, the SDSS-MOC pushed this value to $H \simeq 15$, providing taxonomic information of a huge population of very small asteroids for which spectroscopic observations can only be assessed using very large telescopes.

In this paper we search for photometric data of asteroids in the Hilda region in the SDSS-MOC to find the spectral characteristics of small members of this group. Since the spectral differences between these dark objects in the outer belt are mainly in their spectral slope, we expect to distinguish to which taxonomic class an object belongs. However, we must note that due to the intrinsic limitations of the few band photometry, this analysis provides only a good indication about the taxonomic type of an asteroid. In the following section we introduce the methodology applied to search in the database. In Section 3 we present the results, and in Section 4 we discuss them and outline the conclusions.

2. Methodology

The SDSS photometry is based on the u, g, r, i, z system of filters (Fukugita et al., 1996; Stoughton et al., 2002), with band centers at $\lambda_u \simeq 3540$ Å, $\lambda_g \simeq 4770$ Å, $\lambda_r \simeq 6230$ Å, $\lambda_i \simeq 7630$ Å, and $\lambda_z \simeq 9130$ Å, and bandwidths of $\Delta\lambda_u \sim 570$ Å, $\Delta\lambda_g \sim 1380$ Å, $\Delta\lambda_r \sim 1380$ Å, $\Delta\lambda_i \sim 1530$ Å, and $\Delta\lambda_z \sim 1350$ Å. The photometric observations are performed almost simultaneously in the five filters. Each entry in the MOC corresponds to a single observation of a moving object and provides the apparent magnitudes u, g, r, i, z with their corresponding errors. Of the 204305 entries contained in the third release of the MOC, we only considered 67637 observations that are effectively linked to know asteroids (Jurić et al., 2002). These observations correspond to 43424 unique bodies. From this sample we only select objects in the Hilda region, i.e., with semimajor axis in the range 3.85 AU $< a <$ 4.15 AU.

In order to analyze these observations, we compute the reflectance flux or albedo $F(\lambda)$ at each band center using the observed colors corrected by the solar contribution, $C_{u-r} = (u - r) - 1.77$, $C_{g-r} = (g - r) - 0.45$, $C_{r-i} = (r - i) - 0.10$, and $C_{r-z} = (r - z) - 0.14$, where the values of the solar colors were taken from Ivezić et al. (2001). The albedos at each band center, normalized to the albedo at the r band, were defined as $F_u = 10^{-0.4C_{u-r}}$, $F_g = 10^{-0.4C_{g-r}}$, $F_i = 10^{-0.4C_{r-i}}$, and $F_z = 10^{-0.4C_{r-z}}$.

To estimate the relative errors $\Delta F/F$, we used a second-order approach $\Delta F/F = 0.9210\Delta C \times (1 + 0.4605\Delta C)$, where ΔC are the color errors computed as the root squared sum of the corresponding magnitude errors. In the case of F_r, its error was estimated as $\Delta C_r = \sqrt{2}\Delta r$. Then, we proceeded to discard what we consider as "bad" observations, i.e., those observations for which $\Delta F/F$ was larger than 10% at g, r, i, and z bands, and larger than 20% at u band. The spectral slopes were obtained as a linear fit to the albedos at g, r, i, and z bands.

3. Results

Using our selection method we ended up with a final sample of 167 observations corresponding to 122 asteroids in the Hilda region (24 objects with two observations, 4 with three, 3 with four, and 1 with five), with absolute magnitudes $H < 16$. The spectra obtained from these observations expand the database of Hilda asteroids spectral data three times and pushed four magnitudes the magnitude limit.

The taxonomic type of each object was found calculating the dissimilarities between the individual spectra and mean spectra representing the different classes. For this purpose, the dissimilarity is defined as the Euclidean distance:

$$d_i^2 = \frac{\sum_{k=1}^{n} (P_{ik} - Po_k)^2 (\sigma_{ik}^2 + \sigma_{ok}^2)^{-1}}{\sum_{k=1}^{n} (\sigma_{ik}^2 + \sigma_{ok}^2)^{-1}}, \quad (1)$$

where d_i is the distance between the ith and a mean spectrum, P and Po represents the individual channels making up the individual and mean spectrum, σ and σ_o are the errors in the channel, and the total number of channels is n. The mean spectra for each taxonomic class were obtained from Bus and Binzel (2002b). In spite that it is possible to use this method to select for each object in our sample any one of the 26 taxonomic types proposed by Bus and Binzel (2002b), it is advisable to group related taxonomic types in a broader class to circumvent the limitations of the few band photometry. Thus, the asteroids in our final sample were taxonomically classified using the dissimilarity criterion and the Bus and Binzel taxonomy, and then assigned to a broad class clustering taxonomic types with similar characteristics and with similar limits for the spectral slope than those proposed by Dahlgren and Lagerkvist

Table 1
List of candidate broad D-class Hilda asteroids

2624	11951	23186	57027	1999 VG135	2001 SA227
3202	12006	26929	63184	1999 TJ166	2001 WH44
3415	15278	36182	65821	2000 GS53	2002 KF2
3577	16843	41419	67203	2000 TJ25	2002 QG8
5368	17305	51298	68933	2000 SA75	2002 ST23
7394	17867	52068	73475	2000 XV23	2003 BZ47
8130	20628	52702	88246	2001 PR6	2003 WR81
8743	22058	54657	1999 RP104	2001 QR225	2004 CM74
9661	23174	56982			

Table 2
List of candidate broad X-class Hilda asteroids

748	52079	82043	2001 MV16	2002 BZ6	2003 SV83
3290	62145	84103	2001 QF289	2002 PK44	2003 SH202
11542	63488	85577	2001 SN18	2002 RK68	2003 SL226
12896	64739	1981 EJ21	2001 SN49	2002 RP94	2003 TF16
15626	65389	1999 TK10	2001 VF24	2002 RT181	2003 TK15
35630	68247	1999 TC71	2001 XE162	2002 TE16	2003 UT18
38684	78477	2000 DS8	2001 YD21	2003 ST50	2003 YP64
38701	78815	2000 EW5	2002 AT169	2003 SN52	2004 OF3
43818					

Table 3
List of candidate broad C-class Hilda asteroids

1345	22116	32455	77905	2001 YW79	2003 SF81
6124	22699	76810	1994 PB20	2002 RR36	2003 SJ271
13897	29574	76811	2000 YA69	2002 SY24	2003 SW310
21047					

(1995). We propose three broad classes: a broad D-class (including D-, T-, K-, L-, and Ld-types of Bus and Binzel (2002b), spectral slopes $S \geqslant 6\%/1000$ Å), a broad X-class (including X-, Xe-, Xc-, and Xk-types, $2\%/1000$ Å $\geqslant S < 6\%/1000$ Å), and a broad C-class (including C-, Cb-, Cg-, Ch-, Cgh-, and B-types, $S < 2\%/1000$ Å), with 51, 49, and 19 members, respectively (see Tables 1 to 3 and Fig. 1).

Only 5 of the 122 asteroids selected in our sample have been previously observed spectroscopically: (1345) Potomac, (3202) Graff, (3415) Danby, and (3577) Putilin, classified by Dahlgren et al. (1997) as P-, D-, D-, and D-type, respectively, and (1180) Rita classified by Lazzaro et al. (2004) as Xe-type. The only differences with the SDSS data are for (1345) and (1180), both asteroids with only one observation in the SDSS: the first object is included in the broad C-class due to the absorption observed in the relative albedo shortward of 6230 Å, and the second was unclassified in our broad classes due to absorption in the relative albedo shortward and longward of 6230 Å. In Fig. 2 we show the SDSS relative albedo of these two asteroids and also the SDSS relative albedo of other two objects, (39405) 1063 T-1 and 2002 SJ27, which remain as unclassified due to the same behavior as that observed for (1180).

4. Discussion

Fig. 3 shows an histogram of the spectral slopes for Hilda asteroids in our sample, where it is clearly seen two maxima which correspond to peaks formed by our broad P- and D-classes. The broad C-class appears at smaller slopes (<2%/1000 Å) but it is difficult to separate from the broad P-class. Since the number of P- and D-class objects in the Hilda region found in the SDSS are almost the same, it does not verify the correlation between size and spectral slope, or asteroid taxonomy, suggested by Dahlgren and Lagerkvist (1995) and Dahlgren et al. (1997). These authors argued that for the Hildas the D-type asteroids are significantly more numerous

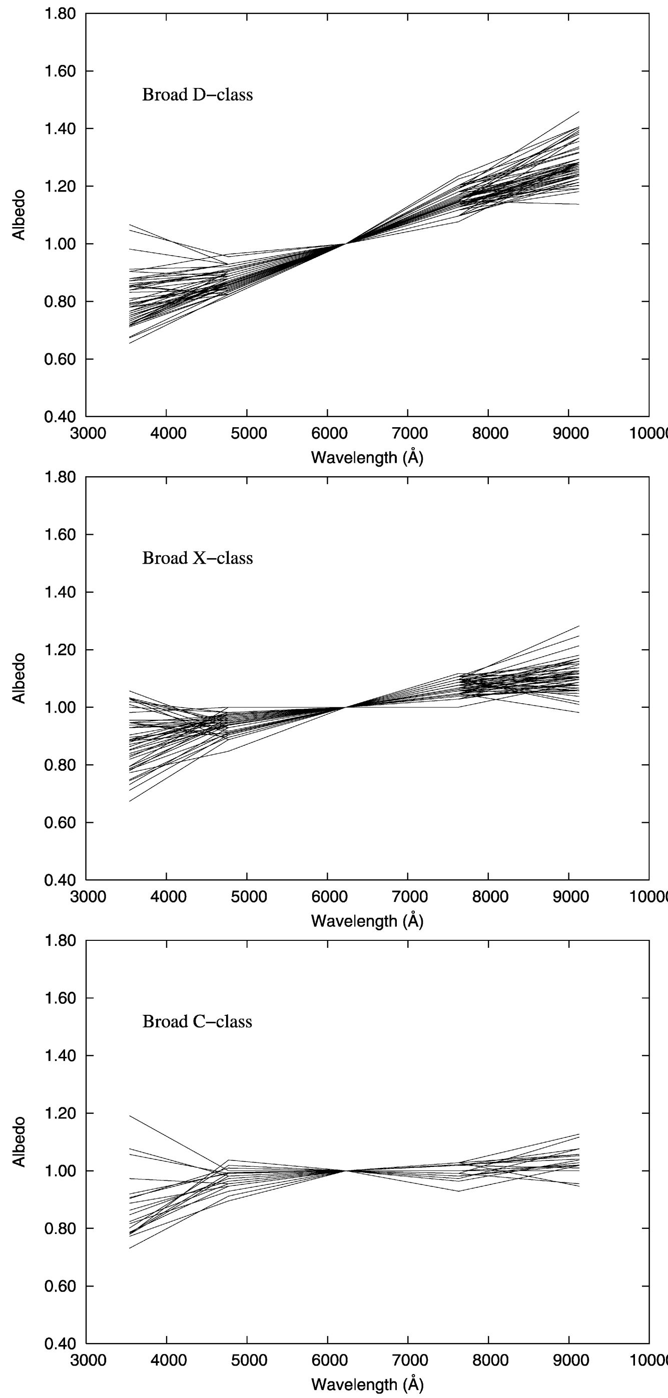

Fig. 1. SDSS relative albedos of asteroids in the broad D-, X-, and C-classes. The relative albedos are normalized to 6230 Å.

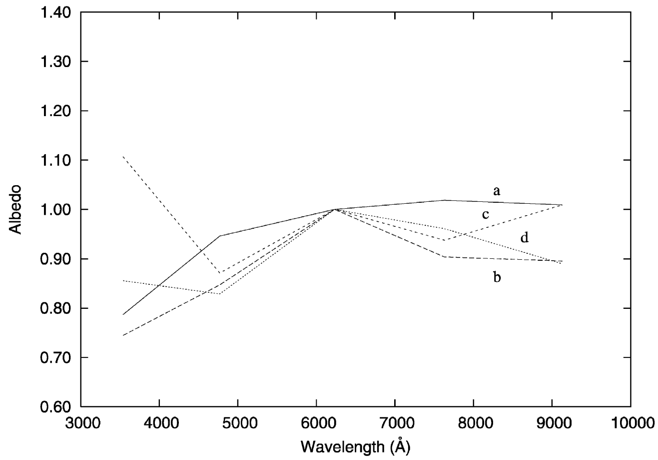

Fig. 2. SDSS relative albedos of asteroids: (a) (1345) Potomac; (b) (1180) Rita; (c) (39405) 1063 T-1; and (d) 20002 SJ27. The first one has been classified in the broad C-class when spectroscopically is a P-type (Dahlgren et al., 1997), and the other three were not included in any broad class. The relative albedos are normalized to 6230 Å.

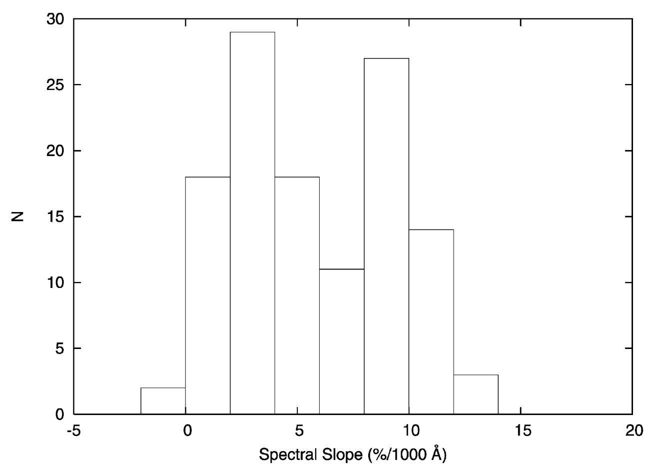

Fig. 3. Spectral slopes for Hilda asteroids in our sample. The typical slopes for the broad C-, P-, and D-classes are less than 2, between 2 and 6, and larger than 6%/1000 Å, respectively.

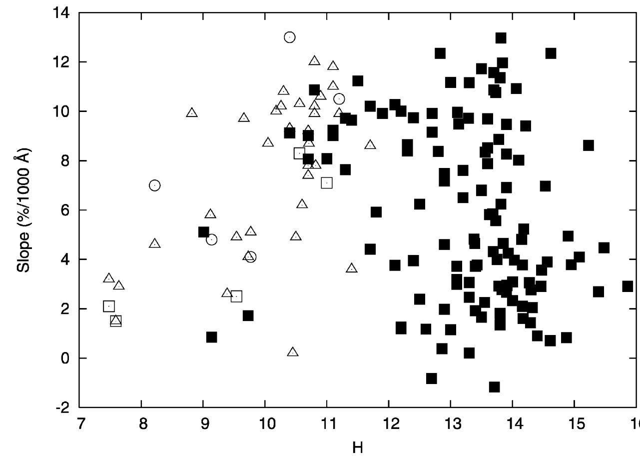

Fig. 4. Spectral slopes in function of the absolute magnitude for Hilda asteroids. Data from the SMASS survey (Bus and Binzel, 2002a) are indicated with squares, from the S^3OS^2 survey (Lazzaro et al., 2004) with circles, from other campaigns (Dahlgren and Lagerkvist, 1995; Dahlgren et al., 1997; Fitzsimmons et al., 1994) with triangles, and the sample obtained from the SDSS with filled squares.

at smaller diameters than P-types, while this taxonomic type dominates at larger sizes. In Fig. 4 we show a plot of the spectral slope in function of the absolute magnitude for Hilda asteroids, including spectroscopic results taken from the literature. Assuming that the albedo for these objects is constant, the abscissa in the plot is a direct measurement of their sizes. The correlation with spectral slope claimed by Dahlgren and Lagerkvist and Dahlgren et al. is observed only for large objects with $H < 11.5$–12. The small objects with $H > 12$, which are objects of the SDSS sample, are not concentrated at any preferential spectral slope and are equally distributed among D- and P-classes. This result present strong evidence against the preferred scenario of Dahlgren et al. (1997), where they suggest that D-type objects are more fragile than P-types, favoring disruptive collisions of precursors of the first type and resulting in a larger fraction of the smaller body population being collisional fragments from a few large D-type precursors.

Since the spectral slope–size correlation still appears as valid if we take into account the objects with $H < 12$, it is necessary to explain how this spectral slope distribution is produced taking into account the fact that there is not asteroids with spectral slopes typical of P-type objects in the absolute magnitude range of $10 < H < 12$. To explain this peculiarity of the spectral slope distribution we propose that it could be the result of a combination of the space weathering and resurfacing due to a collisional process modified by a truncation of the population size distribution. Recent results by Moroz et al. (2003, 2004) demonstrate that irradiation of dark red hydrocarbon material with low energy ions 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, a bombardment of their surfaces with low energy particles would form a thin carbonized surface layer with a more neutral slope forming what we call a P-type surface. Collisional disruption or significant collisional resurfacing would expose unweathered material resulting in a population showing spectra with different slopes simulating or resulting in a combination of taxonomic types.

On the other hand, Hilda asteroids are objects orbiting inside a narrow stable zone with $\Delta a = 0.1$ AU in the 3:2 mean motion resonance with Jupiter (Nesvorný and Ferraz-Melo, 1997; Ferraz-Mello et al., 1998), if a fragment produced by a collision reaches a relative velocity enough as to escape from the resonance it can move into the unstable regions around the stable zone and escapes shortly after (Gil-Hutton and Brunini, 2000). Due to their high ejection velocities, the smaller collisional fragments escape from the Hildas region more easily, producing a loss of small projectiles and inducing a wavy size distribution, characterized by a shortage or excess of objects in some size ranges as a consequence of the abundance or lack of projectiles that can disrupt targets of such size (Campo Bagatin et al., 1994). This peculiar size distribution affects the collisional evolution of the population and, combining its effects with the space weathering, could produce a distribution of spectral slopes which is highly dependent of the object size: the larger bodies, which did not experience catastrophic disruption or significant collisional resurfacing due to a shortage of projectiles, have more neutral colors, since their surfaces have been exposed to ion flux for longer times, may be covered with a thick layer of relative mature regolith, and their surfaces attained a saturation level of space weathering. On the other hand, the observed smaller objects could be fragments of larger asteroids recently disrupted by catastrophic collisions and show fresh and more red surfaces, or have more neutral colors due to the combination of the effect produced by the ion bombardment and lack of small projectiles in the population to disrupt or resurface it, producing a color diversity in the observable small end of the size distribution. In the intermediate size range, asteroids with absolute magnitude in the range $10 < H < 12$, the objects have the correct size to be under a collisional resurfacing process which continuously modify their surfaces exposing fresh and more red material from the interior of the asteroid.

The results presented here show that the correlation between size and spectral slope suggested by Dahlgren and Lagerkvist (1995) and Dahlgren et al. (1997) for Hilda asteroids is correct only for large objects ($H < 12$) but it is not supported by data obtained from the SDSS-MOC for the small ones. The best possibility to explain this behavior is to suggest that a space weathering process affecting the surface properties of these primitive objects is operating, modulated by a collisional resurfacing process affected by a population with wavy size distribution. Despite the intrinsic limitations of the few band photometry of the SDSS, the analysis presented here is based mainly in the detection of spectral slopes providing enough good indication about the taxonomic type of these asteroids and making us confident about our conclusions.

Acknowledgments

The authors thank the comments and suggestions of C.-I. Lagerkvist and an anonymous reviewer. A. Brunini acknowledges the financial support of ANPCyT.

References

Bell, J.F., Davis, D.R., Hartmann, W.K., Gaffey, M.J., 1989. Asteroids: The big picture. In: Binzel, R.P., Gehrels, T., Matthews, M.S. (Eds.), Asteroids II. Univ. of Arizona Press, Tucson, pp. 921–945.

Bus, S.J., Binzel, R.P., 2002a. Phase II of the Small Main-Belt Asteroid Spectroscopic Survey. The observations. Icarus 158, 106–145.

Bus, S.J., Binzel, R.P., 2002b. Phase II of the Small Main-Belt Asteroid Spectroscopic Survey. A feature-based taxonomy. Icarus 158, 146–177.

Campo Bagatin, A., Cellino, A., Davis, D.R., Farinella, P., Paolicchi, P., 1994. Wavy size distributions for collisional systems with a small-size cutoff. Planet. Space Sci. 42, 1079–1092.

Carvano, J.M., Mothé-Diniz, T., Lazzaro, D., 2003. Search for relations among a sample of 460 asteroids with featureless spectra. Icarus 161, 356–382.

Cruikshank, D.P., Dalle Ore, C.M., Roush, T.L., Geballe, T.R., Owen, T.C., de Bergh, C., Cash, M.D., Hartmann, W.K., 2001. Constraints on the composition of trojan Asteroid 624 Hektor. Icarus 153, 348–360.

Dahlgren, M., Lagerkvist, C.-I., 1995. A study of Hilda asteroids. I. CCD spectroscopy of Hilda asteroids. Astron. Astrophys. 302, 907–914.

Dahlgren, M., Lagerkvist, C.-I., Fitzsimmons, A., Williams, I.P., Gordon, M., 1997. A study of Hilda asteroids. II. Compositional implications from optical spectroscopy. Astron. Astrophys. 323, 606–619.

Emery, J.P., Brown, M.H., 2003. Constraints on the surface composition of trojan asteroids from near-infrared (0.8–4.0 μm) spectroscopy. Icarus 164, 104–121.

Ferraz-Mello, S., Michtchenko, T.A., Nesvorný, D., Roig, F., Simula, A., 1998. The depletion of the Hecuba gap vs the long-lasting Hilda group. Planet. Space Sci. 46, 1425–1432.

Fitzsimmons, A., Dahlgren, M.-I., Lagerkvist, C., Magnusson, P., Williams, I.P., 1994. A spectroscopic survey of D-type asteroids. Astron. Astrophys. 282, 634–642.

Fukugita, M., Ichikawa, T., Gunn, J.E., Doi, M., Shimasaku, K., Schneider, D.P., 1996. The Sloan Digital Sky Survey photometric system. Astron. J. 111, 1748–1756.

Gaffey, M.J., Bell, J.F., Cruikshank, D.P., 1989. Reflectance spectroscopy and asteroid surface mineralogy. In: Binzel, R.P., Gehrels, T., Matthews, M.S. (Eds.), Asteroids II. Univ. of Arizona Press, Tucson, pp. 98–127.

Gil-Hutton, R., Brunini, A., 2000. Collisional evolution of the outer asteroid belt. Icarus 145, 382–390.

Gradie, J.C., Chapman, C.R., Tedesco, E.F., 1989. Distribution of taxonomic classes and the composition structure of the asteroid belt. In: Binzel, R.P., Gehrels, T., Matthews, M.S. (Eds.), Asteroids II. Univ. of Arizona Press, Tucson, pp. 316–335.

Hiroi, T., Zolensky, M.E., Pieters, C.M., 2001. The Tagish Lake meteorite: A possible sample from a D-type asteroid. Science 293, 2234–2236.

Ivezić, Ž., and 31 colleagues, the SDSS Collaboration, 2001. Solar System objects observed in the Sloan Digital Sky Survey commissioning data. Astron. J. 122, 2749–2784.

Jones, T.D., Lebofsky, L.A., Lewis, J.S., 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.

Jurić, M., Ivezić, Ž., Lupton, R.H., Quinn, T., Tabachnik, S., Fan, X., and 10 colleagues, 2002. Comparison of positions and magnitudes of asteroids observed in the Sloan Digital Sky Survey with those predicted for known asteroids. Astron. J. 124, 1776–1787.

Kanno, A., Hiroi, T., Nakamura, R., Abe, M., Ishiguro, M., Hasegawa, S., Miyasaka, S., Sekiguchi, T., Terada, H., Igarashi, G., 2003. The first detection of water absorption on a D type asteroid. J. Geophys. Res. 30 (17), 1909.

Lazzaro, D., Angeli, C.A., Carvano, J.M., Mothé-Diniz, T., Duffard, R., Florczak, M., 2004. S^3OS^2: The visible spectroscopic survey of 820 asteroids. Icarus 172, 179–220.

Luu, J., Jewitt, D.C., Cloutis, E., 1994. Near-infrared spectroscopy of primitive Solar System objects. Icarus 109, 133–144.

Moroz, L.V., Baratta, G., Distefano, E., Strazzulla, G., Starukhina, L.V., Dotto, E., Barucci, M.A., 2003. Ion irradiation of asphaltite: Optical effects and implications for trans-neptunian objects and centaurs. Earth Moon Planets 92, 279–289.

Moroz, L.V., Baratta, G., Strazzulla, G., Starukhina, L., Dotto, E., Barucci, M.A., Arnold, G., Distefano, E., 2004. Optical alteration of complex organics induced by ion irradiation. 1. Laboratory experiments suggest unusual space weathering trend. Icarus 170, 214–228.

Nesvorný, D., Ferraz-Melo, S., 1997. On the asteroidal population of the first-order jovian resonances. Icarus 130, 247–258.

Rivkin, A.S., Howell, E.S., Vilas, F., Lebofsky, L.A., 2002. Hydrated minerals on asteroids: The astronomical record. In: Bottke Jr., W.F., Cellino, A., Paolicchi, P., Binzel, R.P. (Eds.), Asteroids III. Univ. of Arizona Press, Tucson, pp. 235–253.

Stoughton, C., Lupton, R.H., Bernardi, M., Blanton, M.R., Burles, S., Castander, F.J., and 186 colleagues, 2002. Sloan Digital Sky Survey: Early data release. Astron. J. 123, 485–548.

Vilas, F., Smith, B.A., 1985. Reflectance spectrophotometry (about 0.5–1.0 micron) of outer-belt asteroids—Implications for primitive, organic Solar System material. Icarus 64, 503–516.

Vilas, F., Jarvis, K.S., Gaffey, M.J., 1994. Iron alteration minerals in the visible and near-infrared spectra of low-albedo asteroids. Icarus 109, 274–283.

Xu, S., Binzel, R.P., Burbine, T.H., Bus, S.J., 1995. Small main-belt asteroid spectroscopic survey: Initial results. Icarus 115, 1–35.