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Polarimetric survey of main-belt asteroids⋆,⋆⋆

III. Results for 33 X-type objects

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ABSTRACT

Aims. We present results of a polarimetric survey of main-belt asteroids at Complejo Astronómico El Leoncito (Casleo), San Juan, Argentina. The aims of this survey are to increase the database of asteroid polarimetry, to estimate diversity in polarimetric properties of asteroids that belong to different taxonomic classes, and to search for objects that exhibit anomalous polarimetric properties.

Methods. The data were obtained with the Torino and CASPROF polarimeters at the 2.15 m telescope. The Torino polarimeter is an instrument that allows the simultaneous measurement of polarization in five different bands, and the CASPROF polarimeter is a two-hole aperture polarimeter with rapid modulation.

Results. The survey began in 2003, and up to 2009 data of a sample of more than 170 asteroids were obtained. In this paper the results for 33 X-type objects are presented, several of them are being polarimetrically observed for the first time. Using these data we found polarization curves and polarimetric parameters for different groups among this taxonomic class and that there are objects with very different albedo in the sub-classes of the X taxonomic complex.

Key words. minor planets, asteroids: general – techniques: polarimetric

1. Introduction

The radiation that we receive from any asteroid at visible wavelengths consists of partial elliptical polarized light produced by the scattering of the sunlight on the solid surface of the body. For all the asteroids measured so far the linear polarization is more significant than the circular and the state of linear polarization varies owing to a complex interplay of surface properties. In general, the linear polarization is found with its azimuth either normal or parallel to the scattering plane, which in the solar system is the plane containing the asteroid, the Sun, and the Earth at the epoch of observation.

Usually, the results of observations are expressed using the parameter $P_r = (I_\perp - I_\parallel)/(I_\perp + I_\parallel)$, where $I_\perp$ and $I_\parallel$ are the intensities of the scattered light polarized along the planes perpendicular and parallel to the scattering plane, respectively. The advantage of using P_r is that it gives information on the measured degree of linear polarization and on the orientation of the polarization plane. The variation of P_r as a function of the phase angle, α, produces a polarization curve that is described by some parameters whose measured values are found to be diagnostic of the overall texture and optical properties of the surface. For phase angles $\lesssim 20°$, P_r turns out to be negative, reaching its most negative value at phase angles $\alpha_{\min} \approx 8$–$10°$. Beyond $\alpha \approx 20°$ the polarization becomes positive and increases for larger phase angles. This general behavior characterizes all asteroids observed so far with some minor differences depending on the taxonomic class (e.g. Muinonen et al. 2002b; Penttilä et al. 2005; Gil-Hutton 2007).

Polarimetry is one of several observational techniques used to obtain information about the light scattering phenomena and the rough surfaces of asteroids, but it was also used to study the albedo heterogeneity of asteroid surfaces (Masiero 2010), near-Earth asteroids (Belskaya et al. 2009), active main-belt asteroids (Bagnulo et al. 2010), trans-Neptunian objects (Bagnulo et al. 2008), and targets of space missions (Belskaya et al. 2010). Although polarimetry provides useful information about the physical properties of the asteroid surface, polarimetric observations of these objects are not easy to obtain due to the coverage in phase angle needed, object faintness, and the limited access to suitable polarimetric devices. As a consequence, the database of asteroid polarimetric mesasurements is not large and very few objects have polarization curves that are well determined.

With the objective of increasing the polarimetric database and reaching a better knowledge of the surface properties of these objects, we began an extensive polarimetric survey in 2003 at the Complejo Astronómico El Leoncito (CASLEO) to obtain polarimetric measurements of main-belt asteroids. In earlier papers (Gil-Hutton & Cañada-Assandri 2011, 2012) we showed the first results of that survey where polarimetric measurements of 57 S-, L-, and K-type objects, and 58 B- and C-type objects were reported. In this paper we present the results for X-type

⋆ Based on observations carried out at the Complejo Astronómico El Leoncito, operated under agreement between the Consejo Nacional de Investigaciones Científicas y Técnicas de la República Argentina and the National Universities of La Plata, Córdoba, and San Juan.

⋆⋆ Table 1 is only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/542/A11 asteroids. In Sects. 2 and 3 the observations are described and discussed, and in Sect. 4 the conclusions are presented.

2. Observations

We carried out observations during different observing runs between May 2004 and November 2009 at the 2.15 m telescope of the Complejo Astronómico El Leoncito (CASLEO), San Juan, Argentina, using the Torino and CASPROF polarimeters. A full description of the Torino photopolarimeter can be found in Piirola (1988) and Scaltriti et al. (1989). Here we recall that this instrument allows for simultaneous measurement of polarization in five bands, using separate photomultipliers and a set of dichroic filters. On the other hand, CASPROF is a two-hole aperture polarimeter with rapid modulation provided by a rotating achromatic half-wave retarder and a Wollaston prism polarizing beamsplitter. In this instrument the complementary polarized beams are detected with photomultipliers operating in pulse-counting mode, and the acquisition and guiding are accomplished with a CCD camera viewing the sky surrounding the entrance aperture. Since the received signal is, in general, exceedingly low in bands other than V and R in both instruments, only data obtained in these two bands were considered. From the analysis of several standard stars, we found the instrumental polarization fairly constant and stable, always below 0.1% for both instruments.

When it was possible, we observed the targets during runs some weeks apart to obtain measurements during the same apparition at different phase angles. Observing nights were generally assigned around the new Moon to minimize the contamination of sky polarization by moonlight when we used the CASPROF polarimeter. In all cases, we used the smallest diaphragm allowed by the observing conditions to minimize the contribution of sky background and took sky measurements frequently to test for any variation. Each night we observed a minimum of two zero-polarization standard stars and one high-polarization star to determine instrumental polarization. The standard star data were obtained from Turnshek et al. (1990) and Gil-Hutton & Benavidez (2003).

We observed the targets consecutively several times each night with individual exposure times long enough to reach final signal-to-noise (S/N) ratios ≥500 (at least 90 s and 180 s for the Torino and CASPROF polarimeters, respectively). Several measurements of each object were coadded to improve the S/N ratio and the measurement errors were evaluated assuming a Poisson distribution. After a correction for instrumental polarization, we obtained the Stokes parameters with reduction programs specially designed for each polarimeter, with some modifications to adapt the reduction to the specific needs of asteroid polarimetry, including the computation of the position angle of the scattering plane and the derivation of the polarization degree P_r. The overall data reduction pipeline is essentially identical to that already used by Cellino et al. (1999, 2006), Gil-Hutton (2007), and Gil-Hutton & Cañada-Assandri (2011). As a test of the data reduction process an histogram of the ratio between the U component of the polarization, P_U, and its error, σ, is shown in Fig. 1, where the distribution appears to be centered at zero and all points differ from this value for less than $3-4\sigma$, which supports the reliablity of the polarimetric measurements.

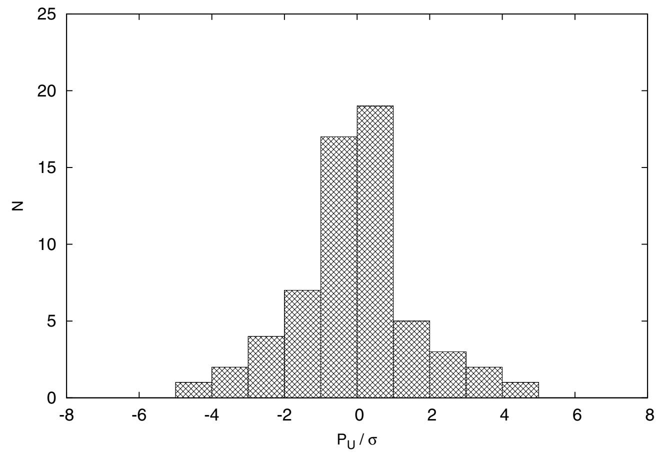

Fig. 1. Histogram of the ratio between the U component of the polarimetric measurements, P_U, and its error, σ.

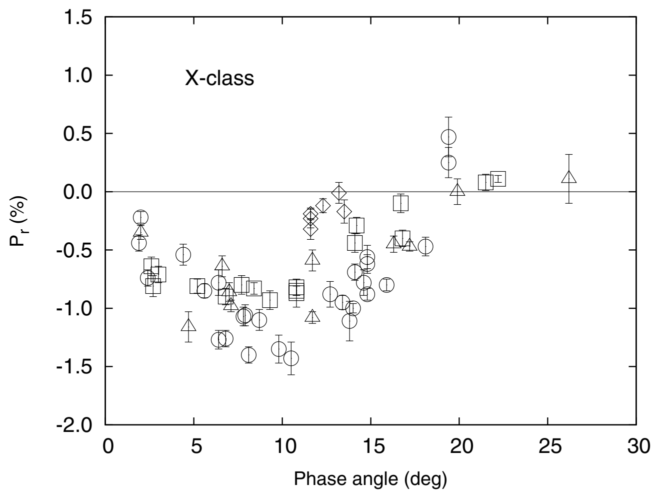

Fig. 2. Polarimetric observations of X-class main-belt asteroids. The observations indicated by squares, circles and diamonds are the observations of asteroids classified by Tholen (1989) as M-, P-, and E-type, respectively, and those by triangles are measurements of objects classified as X-type only.

3. Results

Sixty-one observations of 33 X-class asteroids have been obtained during this survey (Fig. 2). The targets were chosen to preferentially observe asteroids without any polarimetric observations or to fill gaps in their phase-polarization curve. The asteroid name, date, observing band, total integration time in seconds ($T_{\rm int}$), phase angle (α), position angle of the scattering plane ($\theta_{\odot}$), degree of linear polarization (P) and its error (σ_P), position angle in the equatorial reference frame (θ) and its error (σ_θ), P_r, and its Bus taxonomic classification (Bus 1999) taken from Bus & Binzel (2002) or Lazzaro et al. (2004), are shown in Table 1. The asteroids (276) Adelheid, (369) Aeria, (406) Erna, (420) Bertholda, (748) Simeisa, and (849) Ara do not have a Bus taxonomic type assigned but they were previously classified as M-, P- or X-type by Tholen (1989). The polarimetric observations of the objects (76) Freia, (276) Adelheid, (406) Erna, (476) Hedwig, (522) Helga, (739) Mandeville, (748) Simeisa, (838) Seraphina, and (3022) Dobermann are estimated for the first time in this work.

Since normally the polarimetric observations of asteroids obtained in the V- and R-bands agree very well with each other, the measurements made in both bands are analyzed and plotted together.

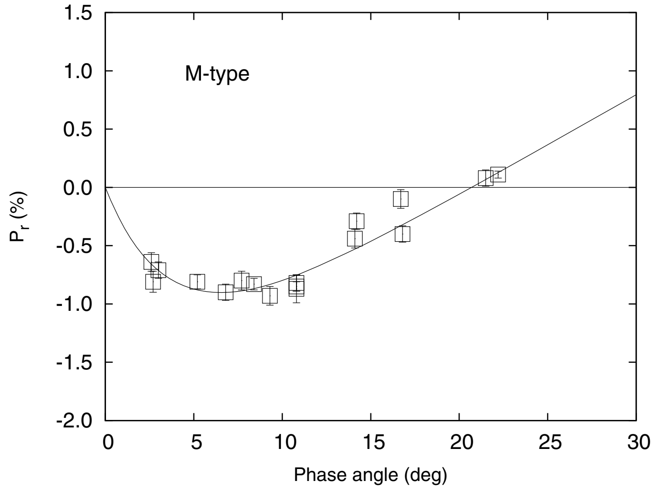

Fig. 3. Polarimetric observations of X-class main-belt asteroids classified by Tholen (1989) as M-type. The best fit found for the polarization curve is also shown.

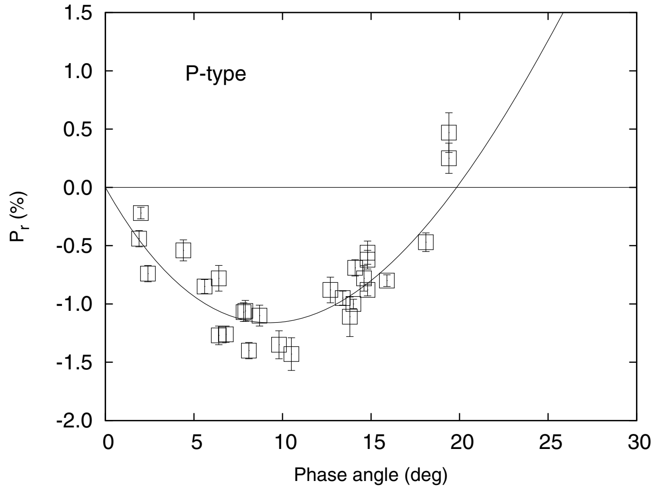

Fig. 4. Polarimetric observations of X-class main-belt asteroids classified by Tholen (1989) as P-type. The best fit found for the polarization curve is also shown.

The observations for these objects in Fig. 2 show high dispersion in the entire phase angle range. This dispersion is explained considering that the X-class of Bus includes objects classified as E-, M-, and P-type in the Tholen taxonomy (Tholen 1989). These taxonomic types were originally described as being spectrally degenerate because the asteroids belonging to them do not show mineral absorption features in their visible and near-infrared reflectance spectra and they could be subdivided into E-, M-, and P-types based only on albedo. Since the shape of the polarization curve is related to the albedo (see for instance Dollfus et al. 1989), the observations of these objects follow different curves depending on their taxonomic type, and if their observations were plotted together, the resulting graph looks dispersed.

Therefore, we divided the observations obtained in this survey according to Tholen's taxonomic types, making different plots for M-types (Fig. 3), which include the asteroids (16) Psyche, (22) Kalliope, (55) Pandora, (69) Hesperia, (77) Frigga, (132) Aethra, (161) Athor, (338) Budrosa, (369) Aeria, (558) Carmen, and (849) Ara, and P-types (Fig. 4), which include the objects (46) Hestia, (56) Melete, (65) Cybele, (76) Freia, (87) Sylvia, (140) Siwa, (153) Hilda, (406) Ena, (420) Bertholda, (476) Hedwig, (748) Simeisa, and (838) Seraphina. The observations obtained for the E-types, (44) Nysa and (64) Angelina, are so few and concentrated in a small range of phase angle that they are not useful to find a polarization curve for this taxonomic type. These observations agree throughout very well with the polarization curve obtained by Rosenbush et al. (2009) for E-type objects.

It is possible to obtain mean polarimetric parameters for these taxonomic types by fitting the observations of the objects belonging to the same taxonomic type to a polarization curve using the function proposed by Piironen et al. (2000), Kaasalainen et al. (2001a), Kaasalainen et al. (2001b), and Muinonen et al. (2002a):

$$P_r(\alpha) = A_0 \left[\exp\left(-\frac{\alpha}{A_1}\right) - 1 \right] + A_2\alpha, \quad (1)$$

where A_0, A_1, and A_2 are constant coefficients. For the M-type objects we found a minimum of the phase-polarization curve of $|P_{\min}| = 0.90 \pm 0.13\%$ at $\alpha_{\min} = 6.5 \pm 0.5°$, a slope of the linear region of the phase-polarization curve of $h = 0.094 \pm 0.006\%/°$, and an inversion angle of $\alpha_0 = 20.7 \pm 0.5°$. These results agree very well with those obtained by Gil-Hutton (2007) for this taxonomic type.

The results for the P-type objects are $|P_{\min}| = 1.16 \pm 0.26\%$ at $\alpha_{\min} = 9.3 \pm 1.0°$, $h = 0.206 \pm 0.017\%/°$, and $\alpha_0 = 19.8 \pm 1.0°$, which agree within error bars with those found by Goidet-Devel et al. (1995). In this case, the fit is not as good as the M-types because of a higher dispersion of the data. This could be a consequence of asteroids misclassified as P-types that were included in this group, or objects with a surface that varies because rotation produces different polarimetric properties for different rotational phases. For example, the asteroid (65) Cybele was classified as P-type by Tholen (1989), Xc-type by Bus & Binzel (2002), and C-type by Lazzaro et al. (2004). Moreover, the only one observation obtained by us for this object fits to the polarization curve for C-type asteroids found by Gil-Hutton & Cañada-Assandri (2012) very well.

The E-, M-, and P-types of Tholen have similar spectroscopic properties but different albedo, therefore it is natural to use these types to classify the objects in groups and to obtain their mean polarimetric properties because of the relation between polarization and albedo. If we assume that it is not correct to analyze the data using these old taxonomic types and decide to use exclusively the classification of Bus & Binzel to group together asteroids within the same taxonomic class, the situation becomes more complex. These authors subdivided the X-class into four sub-classes (X, Xe, Xk, and Xc) but we have members of these sub-classes mixed in the E-, M-, and P-type groups (see Table 1). For example, our M-type group has four X-, two Xe-, two Xk-, one Xc-type, and two objects classified only in the Tholen taxonomy. On the other hand, the P-type group has five X-, one Xk-, three Xc-type, and three objects not classified in the taxonomy of Bus & Binzel. Finally, in the E-type group there are one Xe- and one Xc-type. Then, if we try to find a polarization curve for any of these sub-classes, we will have a dataset consisting of observations of objects with high, moderate and low albedo, producing a poor fit to find the polarization parameters for that sub-class. For example, Fig. 5 shows the scatter for the observations of asteroids observed in this survey that are classified as Xc-type in the Bus & Binzel taxonomy. These results could means that in the X-complex of Bus & Binzel there are asteroids classified in the same taxonomic subclass that have different polarimetric properties and produce a

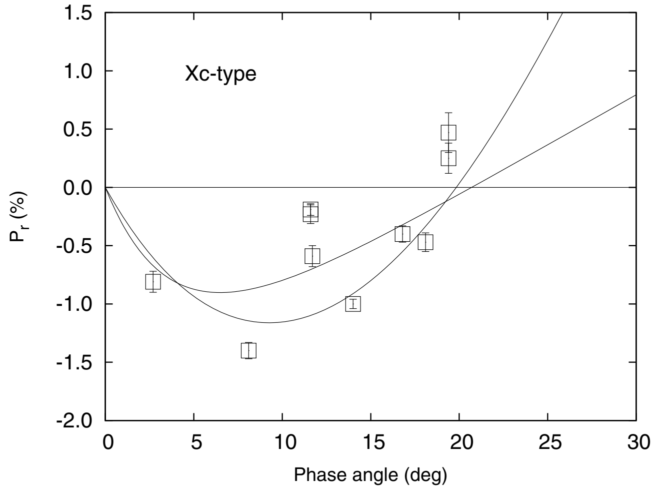

Fig. 5. Polarimetric observations of main-belt asteroids classified by Bus & Binzel (2002) as Xc-type with the polarimetric curves found for M- and P-type objects.

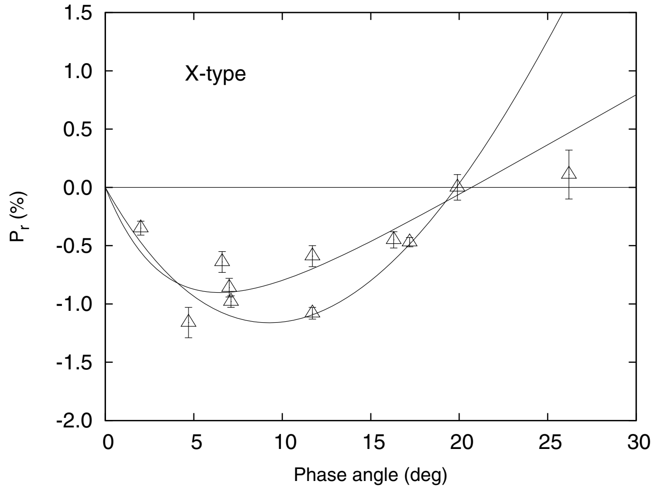

Fig. 6. Polarimetric observations of main-belt asteroids classified by Bus & Binzel (2002) as X-type with the polarimetric curves found for M- and P-type objects.

complex polarimetric behavior for that sub-class. A similar result was found by Mainzer et al. (2011) for some classes and sub-classes of the Bus & Binzel taxonomic system, in particular the X-class, using the NEOWISE data set.

Figure 6 shows the polarization curves found for M- and P-type asteroids and the observations for objects classified as X-type by Bus & Binzel (2002) that do have not been classified by Tholen (1989): (92) Undina, (184) Dejopeja, (276) Adelheid, (337) Devosa, (522) Helga, (739) Mandeville, (796) Sarita, and (3022) Dobermann. The observations obtained for (337) Devosa and (739) Mandeville agree very well with the P-type polarimetric curve, and those of (92) Undina and (276) Adelheid with the M-type polarimetric curve, which could be an indication of a possible classification of these asteroids as P- and M-types, respectively. Among these X-type objects the case of (3022) Dobermann is interesting: we have only one observation of this asteroid and it shows a polarization value of $P_r = 0.11 \pm 0.21$ at a phase angle of $\alpha = 26.2°$. This low polarization at a large phase angle could mean that the polarization curve of this object is flattened around $P_r = 0$, which is typical of E-type objects with high albedo, or that it has a peculiar polarization curve. In any case these objects deserve more atention during the next opositions.

4. Conclusions

Using the FOTOR and CASPROF polarimeters at Complejo Astronómico El Leoncito we obtained 61 polarimetric measurements for 33 X-type main-belt asteroids, nine of them are polarimetrically observed for the first time.

The data obtained in this survey led us to find polarimetric parameters for the observed sample of M- and P-type objects. The poor fit and high dispersion of the data for the P-type objects could be a consequence of asteroids misclassified as P-types that were included in this group, objects with a surface that varies because rotation produces different polarimetric properties for different rotational phases or the taxonomic P-class contain a range of compositions that can be distinguished polarimetrically but not spectrally or by albedo alone.

If the observational data are grouped using exclusively the taxonomic classification of Bus & Binzel for the X-class and its sub-classes, it is very difficult to find a good mean polarization curve because objects with very different albedo are included in each sub-class. These results could mean that the objects included in the sub-classes of the X-complex can by grouped using their similar spectroscopic characteristics, but simultaneously they also show different polarimetric properties and produce a complex polarimetric behavior for that sub-class. It is important to mention that this is the first case in the literature where it is not possible to find mean polarimetric parameters and a mean polarimetric curve for a Bus & Binzel taxonomic class or sub-class.

Finally, the observations of the asteroids (337) Devosa and (739) Mandeville follow a polarization curve corresponding to a P-type object, those of the asteroids (92) Undina and (276) Adelheid that of a M-type, and the single measurement obtained for (3022) Dobermann indicate that this object follows a polarization curve typical of an E-type or it has a peculiar shape. In any case these are interesting objects to observe in the future.

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References

Bagnulo, S., Belskaya, I., Muinonen, K., et al. 2008, A&A, 491, L33
Bagnulo, S., Tozzi, G. P., Boehnhardt, H., Vincent, J.-B., & Muinonen, K. 2010, A&A, 514, A99
Belskaya, I., Fornasier, S., & Krugly, Yu. N. 2009, Icarus, 201, 167
Belskaya, I., Fornasier, S., Krugly, Yu. N., et al. 2010, A&A, 515, A29
Bus, S. J. 1999, Ph.D. Thesis, Massachusetts Institute of Technology, Boston
Bus, S. J., & Binzel, R. P. 2002, Icarus, 158, 146
Cellino, A., Gil-Hutton, R., Tedesco, E. F., Di Martino, M., & Brunini, A. 1999, Icarus, 138, 129
Cellino, A., Belskaya, I. N., Bendjoya, Ph., et al. 2006, Icarus, 180, 565
Dollfus, A., Wolff, M., Geake, J. E., Lupishko, D. F., & Dougherty, L. 1989, in Asteroids II, ed. R. P. Binzel, T. Gehrels, & M. S. Matthews (Tucson: Univ. of Arizona Press), 594
Gil-Hutton, R. 2007, A&A, 464, 1127
Gil-Hutton, R., & Benavidez, P. 2003, MNRAS, 345, 97
Gil-Hutton, R., & Cañada-Assandri, M. 2011, A&A, 529, A86
Gil-Hutton, R., & Cañada-Assandri, M. 2012, A&A, 539, A115
Goidet-Devel, B., Renard, J. B., & Levasseur-Regourd, A. C. 1995, Planet. Space Sci., 43, 779
Kaasalainen, M., Torppa, J., & mulnonen, K. 2001a, Icarus, 153, 37
Kaasalainen, S., Muinonen, K., & Piironen, J. 2001b, Appl. Opt., 41, 4416
Lazzaro, D., Angeli, C. A., Carvano, J. M., et al. 2004, Icarus, 172, 179

Mainzer, A., Grav, T., Masiero, J., et al. 2011, ApJ, 741, 90
Masiero, J. 2010, Icarus, 207, 795
Muinonen, K., Piironen, J., Kaasalainen, S., & Cellino, A. 2002a, Mem. Soc. Astron. Italiana, 73, 716
Muinonen, K., Piironen, J., Shkuratov, Yu. G., Ovcharenko, A., & Clark, B. E. 2002b, in Asteroids III, ed. W. F. Bottke jr., A. Cellino, P. Paolicchi, & R. P. Binzel (Tucson: Univ. of Arizona Press), 123
Penttilä, A., Lumme, K., Hadamcik, E., & Levasseur-Regourd, A.-C. 2005, A&A, 432, 1081
Piirola, V. 1988, in Polarized Radiation of Circumstellar Origin, ed. G. V. Coyne et al. (Tucson: Univ. of Arizona Press), 735
Piironen, J., Muinonen, K., Keränen, S., Karttunen, H., & Peltoniemi, J. 2000, in Advances in Global Change Research, ed. M. Verstraete, M. Menenti, & J. Peltoniemi (Dordrecht: Kluwer Academic), 4, 219
Rosenbush, V., Shevchenko, V. G., Kiselev, N. N., et al. 2009, Icarus, 201, 655
Scaltriti, F., Piirola, V., Cellino, A., et al. 1989, Mem. Soc. Astron. Italiana, 60, 243
Tholen, D. J. 1989, in Asteroids II, ed. R. P. Binzel, T. Gehrels, & M. S. Matthews (Tucson: Univ. of Arizona Press), 1139
Turnshek D. A., Bohlin, R. C., Williamson II, R. L., Lupie, O. L., & Koornneef, J. 1990, AJ, 99, 1243