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Polarimetric survey of main-belt asteroids

II. Results for 58 B- and C-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 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 on a sample of more than 170 asteroids were obtained. In this paper the results for 58 B- and C-type objects are presented, most of them polarimetrically observed for the first time. Using these data we find phase-polarization curves and polarimetric parameters for these taxonomic classes.

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

1. Introduction

The asteroid belt is formed by small bodies of different compositions with surfaces affected by a continuous collisional process that modify their properties and structure. Polarimetry is one of several observational techniques used to obtain information about the light scattering phenomena and the rough surfaces of asteroids. The variation in the degree of polarization as a function of the angle on the asteroid formed by the directions to the Sun and the observer, the phase-polarization curve, should provide useful information about the physical properties of the asteroidal surface and also allows a whole taxonomic class to be characterized polarimetrically, since objects of the same type show similar surface and polarimetric properties (Muinonen et al. 2002b; Penttilä et al. 2005; Gil-Hutton 2007).

Apart from the theoretical information about the scattering of light and the characterization of asteroid surfaces, the polarimetric observations of asteroids are also important for showing the relation between certain polarimetric parameters and the geometric albedo of the object (see, e.g., Zellner & Gradie 1976; Zellner 1979) and for studying the albedo heterogeneity of asteroid surfaces (Masiero 2010), near-Earth asteroids (Belskaya et al. 2009), active main-belt asteroids (Bagnulo et al. 2010), transneptunian objects (Bagnulo et al. 2008), and targets of space missions (Belskaya et al. 2010).

With the objective of increasing the polarimetric database and reaching much 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 an earlier paper (Gil-Hutton & Cañada-Assandri 2011), we showed the first results of that survey where 136 polarimetric measurements of 57 S-, L-, and K-type objects were reported. In this paper we present the results for B- and C-type 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 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

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⋆⋆ Tables 1 and 2 are available in electronic form at 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/539/A115

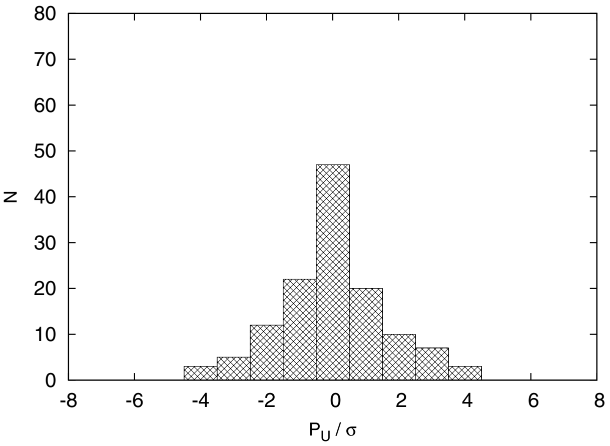

Fig. 1. Histogram of the ratio between the U component of the polarimetric measurements, P_U, and its error, σ.

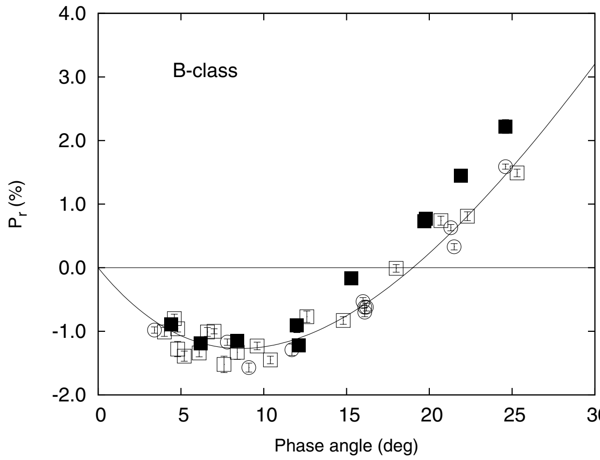

Fig. 2. Polarimetric observations of B-class main-belt asteroids. The observations indicated by circles are the observations of B-class asteroids, those by squares are measurements of objects classified also as F-type, and those by filled squares F-type objects with phase-polarization curves with small inversion angle. The best fit found for the phase-polarization curve are also shown.

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 ratios $(S/N) \geq 500$ (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, and the measurement errors were evaluated assuming a Poisson distribution. After a correction for instrumental polarization, we obtained the Stokes parameters with reduction programs specifically designed for each polarimeter, with some modifications to adapt the reduction to the specific needs of asteroid polarimetry, including computing of the position angle of the scattering plane and deriving of the polarization degree $P_r = (I_\perp - I_\parallel)/(I_\perp + I_\parallel)$, 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 overall data reduction pipeline is essentially identical to the one already used in Cellino et al. (1999, 2006), Gil-Hutton (2007), and Gil-Hutton & Cañada-Assandri (2011). As a test of the data reduction process, a 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 3–4σ, supporting the reliablity of the polarimetric measurements.

3. Results

The choice of targets was made in such a way as to preferentially observe asteroids without any polarimetric observations or to fill gaps in their phase-polarization curve. During this survey we obtained 129 observations of 58 B- and C-type main-belt asteroids. The asteroid name, date, observing band, total integration time in seconds ($T_{\rm int}$), phase angle (α), position angle of the scattering plane ($\theta_{\rm odot}$), degree of linear polarization (P) and its error (σ_P), position angle in the equatorial reference frame (θ) and its error ($\sigma_{\rm theta}$), P_r, and its Bus taxonomic classification (Bus 1999) taken from Bus & Binzel (2002) or Lazzaro et al. (2004) are all shown in Tables 1 and 2.

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

3.1. B-type asteroids

Forty two observations of 19 B-class asteroids have been obtained (Fig. 2). The polarimetric observations of the objects (62) Erato, (335) Roberta, (357) Ninina, (372) Palma, (400) Ducrosa, (404) Arsinoe, (431) Nephele, (635) Vundtia, (690) Wratislavia, (702) Alauda, and (1035) Amata are the first reported in the literature for these asteroids.

The observations for B-class objects show a dispersion in the whole phase angle range, and it seems that these objects do not follow a single phase-polarization curve. Figure 2 shows at least two groups of observations that seem to follow phase-polarization curves with different inversion angles. The reason for this behavior could be that the B-class of Bus include several objects classified as F-types in the Tholen taxonomy (Tholen 1989) due to its flat spectrum and low albedo, but some F-type objects have phase-polarization curves characterized by smaller inversion angles than do other asteroid types (Belskaya et al. 2005). This peculiar behavior could introduce some scatter in a phase-polarization plot, so it is important to identify the objects with an F-type classification and small inversion angle.

The observed asteroids included in the B-class and also classified as F-type are (85) Io, (88) Thisbe, (213) Lilaea, (335) Roberta, (372) Palma, (690) Wratislavia, (704) Interamnia, and (1021) Flammario, and those with observations suggesting a phase-polarization curve with a small inversion angle are (213) Lilaea, (335) Roberta, (704) Interamnia, and (1021) Flammario. The observation of (704) Interamnia agrees

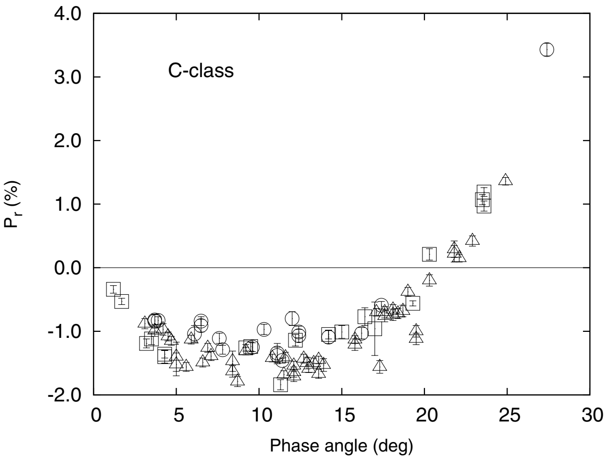

Fig. 3. Polarimetric observations of C-class main-belt asteroids. The observations indicated by circles, triangles, and squares are measurements of Cb-, Ch-, and C-type objects, respectively.

very well with the data published by Belskaya et al. (2005) with an inversion angle of 15.8°, and the measurements of (1021) Flammario also agree with the observations reported by Fornasier et al. (2006) suggesting an inversion angle of ≈17°.

Since previous analyses of asteroidal phase-polarization curves have shown that asteroids with similar surface properties have a similar polarimetric behavior (Muinonen et al. 2002b; Penttilä et al. 2005; Gil-Hutton 2007), it is possible to obtain mean polarimetric parameters for any taxonomic class using all the observations for its members. Then, the observations of the objects belonging to the same taxonomic type can be fitted to a phase-polarization curve using a function proposed by Piironen et al. (2000), Kaasalainen et al. (2001a), Kaasalainen et al. (2001b), and Muinonen et al. (2002a):

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

where A_0, A_1, and A_2 are constant coefficients. In the case of the B-class objects, excluding the observations of asteroids suggesting a small inversion angle of their phase-polarization curve, we found a minimum of the phase-polarization curve of $|P_{\rm min}| = 1.27 \pm 0.20\%$ at $\alpha_{\rm min} = 8.6 \pm 1.2°$, a slope of the linear region of the phase-polarization curve of $h = 0.222 \pm 0.024\%/°$, and an inversion angle of $\alpha_0 = 19.0 \pm 1.0°$.

It is possible to use these polarimetric parameters to find the mean polarimetric albedo p by applying two empirical relations linking it with h or $P_{\rm min}$. These relations are expressed by means of very simple mathematical forms:

$$\log p(h) = C_1 \log h + C_2, \tag{2}$$

$$\log p(P_{\rm min}) = C_3 \log P_{\rm min} + C_4, \tag{3}$$

where C_1, C_2, C_3, and C_4 are constants. In this paper we use the set of constants proposed by Cellino et al. (1999), namely: $C_1 = -1.118 \pm 0.071, C_2 = -1.779 \pm 0.062, C_3 = -1.357 \pm 0.140$, and $C_4 = -0.858 \pm 0.030$. Using these empirical relations with the polarimetric parameters found previously, we obtain $p(h) = 0.09 \pm 0.02$ and $p(P_{\rm min}) = 0.10 \pm 0.04$ for the objects of the B-class.

3.2. C-, Cb-, and Ch-type asteroids

Eighty-seven observations of 39 C-, Cb-, and Ch-type asteroids were obtained in this survey (Fig. 3). The polarimetric observations of the asteroids (34) Circe, (49) Pales, (50) Virginia, (78) Diana, (90) Antiope, (98) Ianthe, (104) Klymene, (106) Dione, (130) Elektra, (160) Una, (185) Eunike, (195) EuryKleia, (210) Isabella, (253) Mathilde, (284) Amalia, (481) Emita, (694) Ekard, and (1235) Schorria are the first reported in the literature for these objects.

The observations for these objects also show high dispersion in a phase angle-polarimetry, so it is not easy to fit a single phase-polarization curve to these measurements. This dispersion is a consequence of including polarimetric observations of

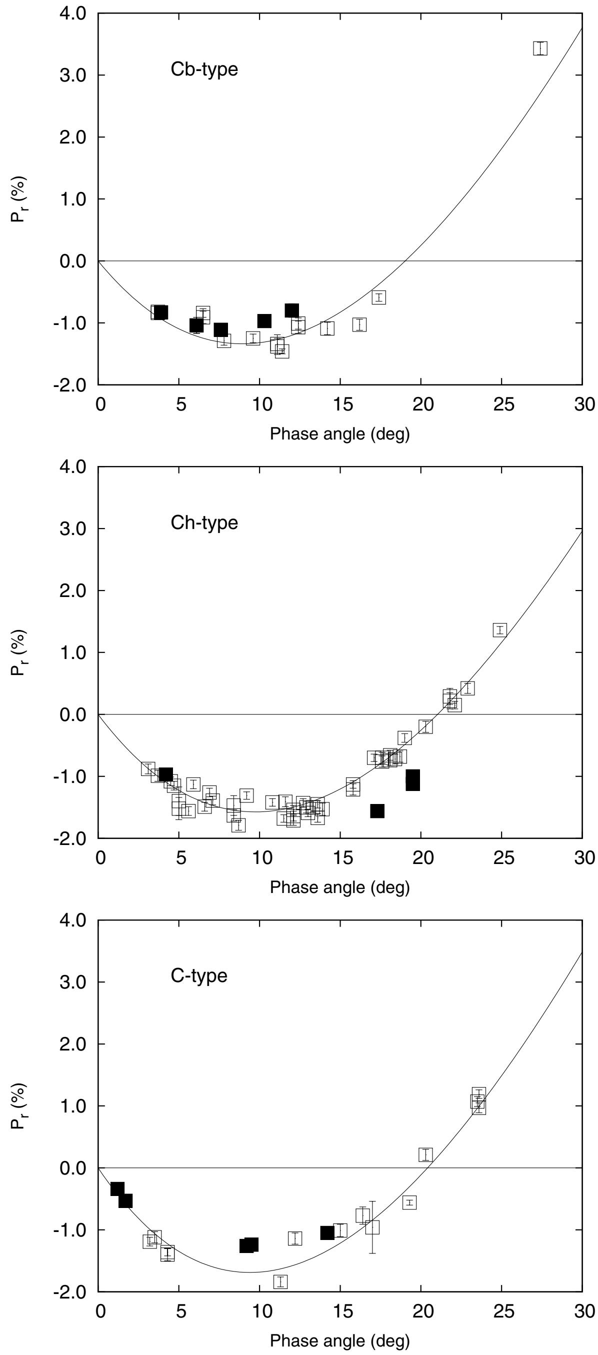

Fig. 4. Polarimetric observations of Cb-, Ch-, and C-type main-belt asteroids with the best fit of the phase-polarization curve for each type. The observations indicated by filled squares are measurements of Cb-type object (210) Isabella, Ch-type object (48) Doris, and C-type object (52) Europa. The observations of (210) Isabella, (48) Doris, and (52) Europa were not considered to obtain the fits.

objects belonging to different taxonomic subtypes of the C-class in the plot. Thus, we divide the observations into three groups (see Fig. 4): one with all the observations obtained in this survey for Cb-type objects, another one for Ch-type objects, and a last one, which we called C-type, with all the remaining observations that are not Cb- or Ch-type objects.

From these observations there are three interesting points that must be indicated. First, the dispersion of the observations for asteroids belonging to the Cb-type is due to the observations reported here for (210) Isabella, which are indicative of a small inversion angle. The other F-type objects observed in this survey are (419) Aurelia and (762) Pulcova. (419) Aurelia shows a phase-polarization curve with an inversion angle of $\approx 15°$ (Belskaya et al. 2002), but the observation reported here was made at $\alpha = 6.1°$, which is not in the phase angle range that allows defining the inversion angle of the phase-polarization curve. In the case of the asteroid (762) Pulcova, the observations by Belskaya et al. (2005) exclude a small inversion angle and the observations obtained in this survey agree with this result.

Second, the observations of (48) Doris at $\alpha = 17.3°$ and $19.5°$ are more negative than what can be expected and could indicate of a larger inversion angle or a deeper negative branch compared with objects of this taxonomic type. It is important to mention that this object was classified as CF-type by Tholen (1989), and its observations follows a phase-polarization curve similar to that of Cb-type objects.

Third, the polarimetric observations of the asteroid (52) Europa at $\alpha = 9.2°$ and $9.5°$ are more positive than what can be expected for a C-type and could indicate of a shallower negative branch than other objects of this taxonomic type.

To obtain mean polarimetric parameters for these taxonomic types, we fitted the observations to a phase-polarization curve following the same procedure as in the case of the B-type objects. The results are shown in Fig. 4 where the observations of (48) Doris, (52) Europa, and (210) Isabella were not considered to obtain the fits. The mean polarimetric parameters obtained are $|P_{\rm min}| = 1.34 \pm 0.21$ % at $\alpha_{\rm min} = 8.9 \pm 1.2°$, $h = 0.248 \pm 0.027\%/°$, and $\alpha_0 = 19.0 \pm 0.2°$ for Cb-type objects, $|P_{\rm min}| = 1.57 \pm 0.15\%$ at $\alpha_{\rm min} = 9.8 \pm 0.4°$, $h = 0.259 \pm 0.018\%/°$, and $\alpha_0 = 21.0 \pm 0.2°$ for Ch-type objects, and $|P_{\rm min}| = 1.69 \pm 0.21\%$ at $\alpha_{\rm min} = 9.4 \pm 1.1°$, $h = 0.282 \pm 0.025\%/°$, and $\alpha_0 = 20.4 \pm 0.2°$ for C-type objects. These sets of polarimetric parameters agree very well with those found by Goidet-Devel et al. (1995) for C-type objects, even though these authors used the taxonomy proposed by Tholen (1989).

Then, using these polarimetric parameters and following the same procedure used previously to find the mean polarimetric albedo of the observed sample of B-class asteroids, we obtain $p(h) = 0.08 \pm 0.02$ and $p(P_{\rm min}) = 0.09 \pm 0.04$ for the observed sample of Cb-type asteroids, $p(h) = 0.07 \pm 0.02$ and $p(P_{\rm min}) = 0.08 \pm 0.02$ for the Ch-type objects, and $p(h) = 0.07 \pm 0.01$ and $p(P_{\rm min}) = 0.07 \pm 0.02$ for the C-type objects.

4. Conclusions

Using the FOTOR and CASPROF polarimeters at CASLEO we obtained 129 polarimetric measurements for 58 main belt asteroids of B- and C- taxonomic types, 29 of them polarimetrically observed for the first time. The data obtained in this survey let us obtain polarimetric parameters for the observed sample of B-, Cb-, Ch-, and C-type objects, calculate the polarimetric albedo for these groups, and find that the observations obtained for the asteroids (48) Doris, (52) Europa, and (210) Isabella could follow phase-polarization curves that are not the expected ones for their taxonomic types.

The mean polarimetric parameters obtained for B- and Cb-types agree very well with values of $|P_{\rm min}| = 1.3\%$ at $\alpha_{\rm min} < 9°$, $h = 0.23\%/°$, $\alpha_0 = 19°$, and $p = 0.09$. On the other hand, the Ch- and C-type objects show deeper negative branches at larger phase angles and lower geometric albedos than Cb- or B-types.

It is important to mention the case of the objects classified as F-type by Tholen (1989) since there are several members of this group that are now classified in the B-class in the Bus & Binzel taxonomy, but they show polarimetric properties that are different from those of the other members of this class. This could be the consequence of a peculiar mineralogical difference between these groups since the phase-polarization curve of asteroids is independent of the size of the particles on the surface (Masiero et al. 2009).

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