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Polarimetric survey of main-belt asteroids⋆,⋆⋆

VI. New results from the second epoch of the CASLEO survey

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ABSTRACT

Aims. We present the 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 and to estimate the diversity in the polarimetric properties of asteroids that belong to different taxonomic classes.

Methods. The data were obtained using the CASPOL polarimeter at the 2.15 m telescope. CASPOL is a polarimeter based on a CCD detector and a Savart plate. The survey began in 1995 and data on a large sample of asteroids were obtained until 2012. A second period began in 2013 using a polarimeter with a more sensitive detector in order to study small asteroids, families, and special taxonomic groups.

Results. We present and analyze the unpublished results for 128 asteroids of different taxonomic types, 55 of them observed for the first time. The observational data allowed us to find probable new cases of Barbarian objects but also two *D*-type objects, (565) Marbachia and (1481) Tubingia, that seem to have phase-polarization curves with a large inversion angle. The data obtained combined with data from the literature enabled us to find phase-polarization curves for 121 objects of different taxonomic types and to study the relations between several polarimetric and physical parameters. Using an approximation for the phase-polarization curve we found the index of refraction of the surface material and the scatter separation distance for all the objects with known polarimetric parameters. We also found that the inversion angle is a function of the index of refraction of the surface, while the phase angle where the minimum of polarization is produced provides information about the distance between scatter particles or, to some extent, the porosity of the surface.

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

1. Introduction

The sunlight scattered by an asteroid surface is in a state of partial linear polarization, which is affected by the composition and roughness of the target and also depends on the illumination conditions. The variation of the degree of linear polarization as a function of the phase angle α, which is the angle between the directions to the Sun and to the observer as seen from the object, produces the so-called phase-polarization curve, which is described by some polarimetric parameters that provide information about the properties of the surface (Dollfus et al. 1989; Muinonen et al. 2002a; Kaasalainen et al. 2003).

Usually, the polarimetric observations of atmosphereless bodies 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 (which is the plane containing the Sun, the observer, and the object), respectively. The advantage of using P_r is that it gives simultaneously information on the measured degree of linear polarization and on the orientation of the polarization plane. As a general rule, for $\alpha \lesssim 19{-}20°$ the phase-polarization curves of the asteroids display the so-called branch of negative polarization, where the plane of linear polarization is found to be oriented parallel to the scattering plane. The existence of a branch of negative polarization is generally explained in terms of the occurrence of coherent backscattering phenomena (Muinonen et al. 2002a, 2007; Tyynelä et al. 2007). The value of polarization corresponding to the deepest point of the negative branch is called $P_{\rm min}$, which is generally found at a phase angle in the range $6° \lesssim \alpha_{\rm min} \lesssim 12°$. Beyond an inversion angle of $\alpha_0 \approx 19{-}20°$, the polarization plane becomes perpendicular to the scattering plane, the polarization becomes positive, and it increases linearly for larger phase angles with a slope h.

To obtain good-quality phase-polarization curves of asteroids is challenging because they must be observed at several phase angles, and this coverage requires the availability of observing time and it is affected by factors including object faintness and weather problems. As a consequence, the database of asteroid polarimetric measurements was quite small until about 1990 and very few objects had their polarimetric parameters well determined. Since 1995 we have made an extensive effort to conduct polarimetric observations at Complejo Astronómico El Leoncito (CASLEO), Argentina, with the main objective of increasing the available polarimetric database of main-belt asteroids. At the same time, we have also developed several observing

⋆ 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.

⋆⋆ Tables 1 and 2 are 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/607/A103 programs focused on more specific objectives, including an extensive polarimetric survey of taxonomic classes and asteroid groups that began in 2003. The first epoch of this survey ended in 2012 and a second epoch started in 2013 using new and more sensitive equipment. This survey provided a large number of polarimetric measurements of main-belt asteroids, including objects not observed before, and has the advantage of being an homogeneous dataset observed and reduced always following the same procedures.

In this paper we report polarimetric observations obtained during the second epoch of the survey that have not yet been published and use them in combination with previously published data to find polarimetric parameters for a large number of asteroids, analyzing their relations with some physical parameters. In Sect. 2 we describe the observations, in Sect. 3 we present and discuss our results, and in Sect. 4 we sketch the conclusions.

2. Observations

Our observations were carried out during different observing runs between May 2013 and November 2016 at the 2.15 m telescope of CASLEO, using the CASPOL polarimeter. CASPOL is a polarization unit inserted in front of a CCD camera that allows high precision imaging polarimetry. It was built following the design of Magalhaes et al. (1996), and uses an achromatic halfwave retarder and a Savart plate as analyzer. The reduction and analysis of the images is done in the usual way using IRAF (Image Reduction and Analysis Facility) tasks and scripts specially designed to reduce observations made with CASPOL[1], and the polarimetric parameters and errors are obtained from a least-squares solution to the measurements made at different halfwave plate positions. All the polarimetric measurements were made using a *V*-band filter.

From the analysis of several standard stars, we found the instrumental polarization to be fairly constant and stable, always below 0.06%. Whenever 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. Each night, we observed at least 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), Gil-Hutton & Benavidez (2003), and Fossati et al. (2007).

We observed the targets consecutively several times each night with individual exposure times long enough to reach final signal-to-noise ratios $(S/N) \geq 30$. Several measurements of each object were co-added to improve the S/N, and the measurement errors were evaluated assuming a Poisson distribution. After correcting for instrumental polarization, we obtained the Stokes parameters for each filter with reduction programs specifically designed for the CASPOL polarimeter, with some modifications to optimize the reduction to the specific needs of asteroid polarimetry. This includes computations of the position angle of the scattering plane and of the polarization parameter P_r. The overall data reduction pipeline is essentially identical to that previously used in Gil-Hutton et al. (2017). As a test of the data reduction process, we analyzed the distribution of the ratio between the *U* component of linear polarization and its error and found that it is centered at zero, while all points differ from this value by less than a few σ, which supports the reliability of the polarimetric measurements.

[1] The IRAF package for the CASPOL polarimeter is available at http://www.casleo.gov.ar

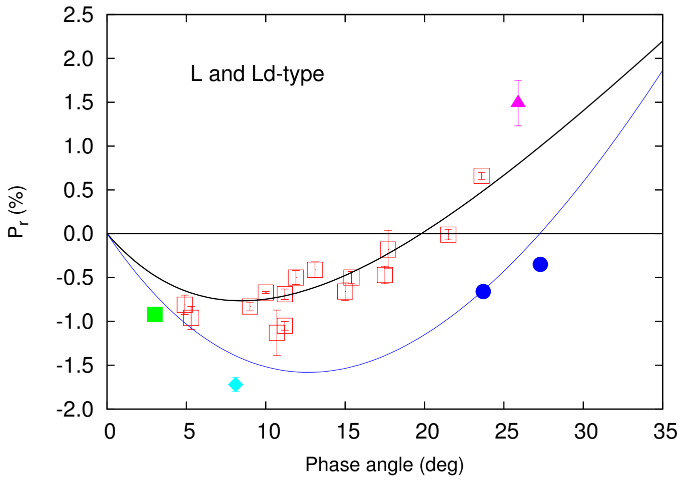

Fig. 1. Polarimetric observations of *L* and *Ld*-type main-belt asteroids. The observations of (387) Aquitania are indicated with blue circles, (980) Anacostia with a green square, (2272) Montezuma with a pink triangle, and those of (2448) Sholokhov are indicated with cyan diamonds. For comparison, the phase-polarization curves obtained by Gil-Hutton & Cañada-Assandri (2011) for *L*-type asteroids and for (234) Barbara are also shown in black and blue, respectively.

3. Results

During this survey we obtained 171 observations for 128 main-belt asteroids. Each asteroid's name, date, total integration time in seconds ($T_{\rm int}$), phase angle (α), position angle of the scattering plane ($\theta_\odot$), the observed polarization (P) and its error (σ_P), position angle in the equatorial reference frame (θ) and its error (σ_θ), P_r, and Bus taxonomic classification (Bus 1999) taken from Bus & Binzel (2002), Lazzaro et al. (2004), or the Planetary Data System (PDS)[2] are shown in Table 1. Of the 128 asteroids studied in this work, 55 of them were observed for the first time and are indicated using bold type in Table 1.

Figure 1 shows 20 observations of 15 *L*- and *Ld*-type asteroids, where the phase-polarization curves obtained by Gil-Hutton & Cañada-Assandri (2011) for *L*-type and for (234) Barbara are also included for comparison. Two objects that belong to this taxonomic type, (387) Aquitania and (980) Anacostia, are members of a group showing an unusual polarimetry behavior characterized by an inversion angle $\alpha_0 \simeq 30°$ (Cellino et al. 2006; Gil-Hutton et al. 2008). These objects are commonly known as Barbarians, from their prototype (234) Barbara. The observation of (980) Anacostia included in this work was made at a low phase angle ($\alpha = 3°$), but this observation is considerably more negative that the theoretical value from the phase-polarization curve for this taxonomic group. On the other hand, the observations of (387) Aquitania, at $\alpha = 23.7°$ and $27.3°$, confirm this asteroid as a member of the Barbarian group as was proposed by Masiero & Cellino (2009). The asteroid (2448) Sholokhov also shows a polarimetric measurement well below the theoretical curve at $\alpha = 8.1°$, which could indicate a polarimetric behavior of the Barbarian type. It is interesting to mention that (2272) Montezuma instead has a polarimetric measurement well above the theoretical

[2] Available at the URL http://sbn.psi.edu/pds/asteroid

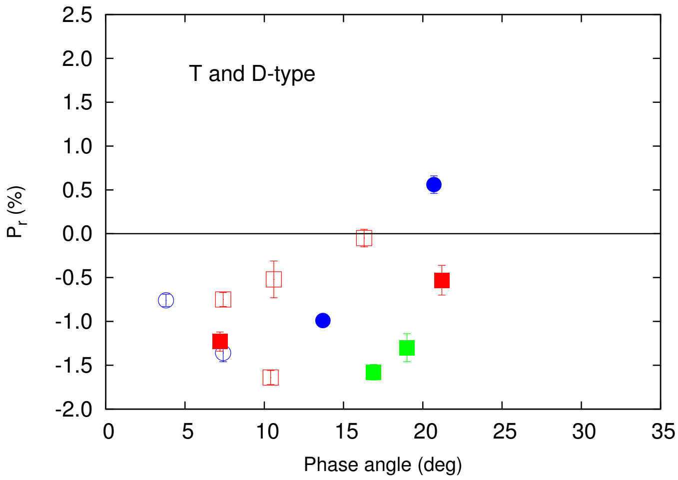

Fig. 2. Polarimetric observations of T and D-type main-belt asteroids indicated with squares and circles, respectively. The observations of (565) Marbachia are indicated with filled red squares, (773) Irmintraud with filled blue circles, and (1481) Tubingia with filled green squares.

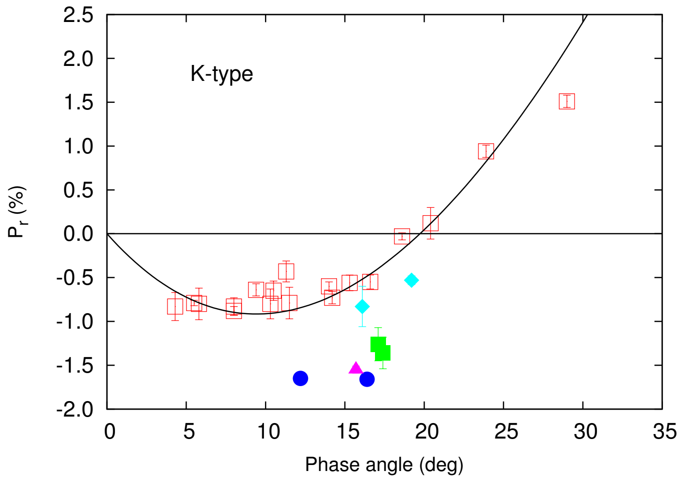

Fig. 3. Polarimetric observations of K-type main-belt asteroids. The observations are indicated by red squares, with the exception of the measurements of (397) Vienna, (460) Scania, and (599) Luisa, which are indicated with filled green squares, filled pink triangles, and filled blue circles, respectively. The phase-polarization curve for this taxonomic type found by Gil-Hutton & Cañada-Assandri (2011) is also shown.

phase-polarization curve, which could be the same as the case reported by Gil-Hutton et al. (2014) for (269) Justitia, which is classified as a Ld-type but shows a fairly small inversion angle $\alpha_0 \simeq 15°$, which seems a common property among asteroids previously classified by Tholen (1989) as F-type (Belskaya et al. 2005).

The T- and D-types of Bus are related to the Ld-type since their spectra are similar, with moderate to steep ultraviolet slopes shortward of 0.75 μm, but longward of this wavelength the slope becomes less steep or flat (Bus & Binzel 2002), so it is possible to expect similar polarimetric behavior. Figure 2 shows the observations obtained for three T-types and six D-types objects (four and eight observations, respectively), and it seems that the D-types show a bimodality in their polarimetric behavior where two asteroids, (565) Marbachia and (1481) Tubingia, seem to have phase-polarization curves with large inversion angles. Recently, Gil-Hutton et al. (2017) reported that this polarimetric behavior is also observed for (2579) Spartacus, a V-type object, so if this bimodality is confirmed in the future for D-types, it would indicate that the Barbarian group of asteroids is present in different taxonomic classes and is not an exclusivity of L-, Ld-, and K-types.

Twenty-five observations of 17 K-type asteroids are shown in Fig. 3, where the phase-polarization curve obtained by Gil-Hutton & Cañada-Assandri (2011) for this taxonomic type is also included for comparison. Until now, only three objects classified as K-type showed polarimetric behavior typical of the Barbarian group ((402) Chloe and (679) Pax, Gil-Hutton et al. 2014, 2008; (599) Luisa, Bagnulo et al. 2015), but we find that the asteroids (397) Vienna and (460) Scania are also Barbarians.

In Fig. 4, 29 observations of 15 B-type asteroids are presented. As shown by Gil-Hutton & Cañada-Assandri (2012) and Gil-Hutton et al. (2014), in any plot of the observations of B-type objects a dispersion always appears in the whole phase angle range and it seems that these objects do not follow a single phase-polarization curve. The reason is probably that the asteroids classified by Bus & Binzel (2002) as members of this taxonomic class include objects that belong to the old F-class, originally proposed by Gradie & Tedesco (1982) and included in the Tholen taxonomy, due to its flat spectrum and low albedo; but several F-class objects have phase-polarization

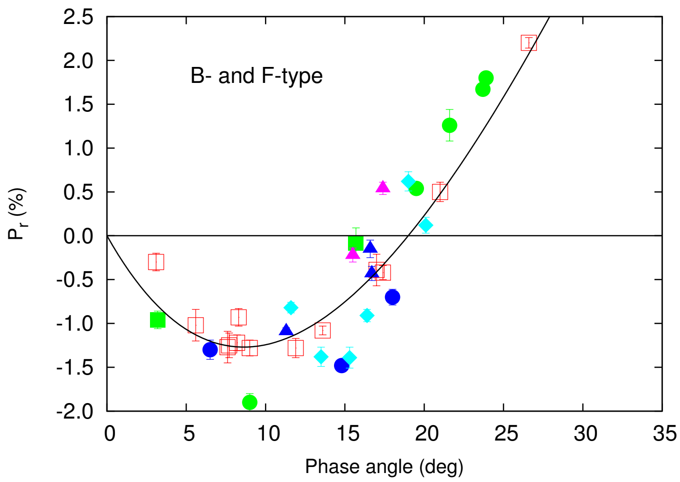

Fig. 4. Polarimetric observations of B- and F-type main-belt asteroids. The observations of (142) Polana are indicated with green squares, (213) Lilaea with green circles, (372) Palma with blue circles, (762) Pulcova with blue triangles, (877) Walkure with pink triangles, and those of (62) Erato, (314) Rosalia, (426) Hippo, (635) Vundtia, (981) Martina, and (1021) Flammario with cyan diamonds. For comparison, the phase-polarization curve for the B taxonomic type found by Gil-Hutton & Cañada-Assandri (2012) is also shown.

curves that are characterized by a comparatively low value of the inversion angle (Belskaya et al. 2005). Therefore, we also include in Fig. 4 nine observations of five asteroids classified as F-class by Tholen (1989) but included in other taxonomic types by Lazzaro et al.: (426) Hippo (X-type), (530) Turandot (C-type), (762) Pulcova (Cb-type), (778) Theobalda (C-type), and (877) Walkure (without a Bus taxonomy classification). The group of objects formed by (142) Polana, (213) Lilaea, (877) Walkure, and (1021) Flammario, all of them belonging to the old F-class, have observations indicating a low value of inversion angle, and the single observation of (314) Rosalia also indicates a similar polarimetric behavior even though it was not classified using the taxonomy of Tholen. On the other hand, the asteroids (62) Erato, (372) Palma, (635) Vundtia, and (981) Martina have measurements well below the theoretical phase-polarization curve for this taxonomic class, so it would seem to have a polarimetric behavior that corresponds more to a *C*-type than to a *B*-type. The apparent discrepancies might be indicative of some heterogeneity in the polarimetric properties within this particular taxonomic type, or alternatively, there might be some misclassification of the objects as could be the case for (635) Vundtia and (981) Martina, which were classified as C- and CFU-type by Tholen (1984).

If we analyze all the asteroid polarimetric data available today, including the data in the Asteroid Polarimetric Database (APD; Lupishko 2014) and that from papers not included in the APD (Cellino et al. 2005; Masiero et al. 2007; Rosenbush et al. 2009; Masiero 2010; Cellino et al. 2014; Zaitsev et al. 2014; Gil-Hutton et al. 2014; Bagnulo et al. 2016; Belskaya et al. 2017; Devogèle et al. 2017; Gil-Hutton et al. 2017, and the present paper), the total number of polarimetric measurements available in *V*- or *R*-band is 3028 for 515 asteroids, of which it is possible to obtain polarimetric parameters of good quality for 121 objects considering only measurements with $\sigma < 0.25\%$[3]. The polarimetric parameters were obtained by fitting the observations to a phase-polarization curve using the function proposed by Kaasalainen et al. (2003) and Muinonen et al. (2009):

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

where A_0, A_1, and A_2 are constant coefficients. The curve was then used to find $\alpha_{\rm min}$, α_0, $P_{\rm min}$, and h. The same procedure has been used recently to obtain phase-polarization curves for main-belt asteroids and to find a better calibration of the empirical relation between the albedo and $P_{\rm min}$ or h (Cellino et al. 2015), to make an updated analysis of the distributions of different polarimetric parameters and to study their mutual relations (Cellino et al. 2016), and to refine the asteroid taxonomy considering the polarimetric properties (Belskaya et al. 2017). In this work we will search for a relation between some polarimetric parameters and physical properties of the surface using for the phase-polarization curve the approximation proposed by Muinonen et al. (2002b), which is based on the fact that the coherent backscattering mechanism has been shown to be the dominant cause of the observed polarization of asteroids (Muinonen et al. 2002a). Thus, the phase-polarization curve can be written as:

$$P_r(\alpha) \sim \frac{\alpha^2}{2n} - \left(\frac{n-1}{n+1}\right)^2 \frac{(kd\alpha)^2}{2\left[1 + (kd\alpha)^2\right]}, \quad (2)$$

where the phase angle is in radians, n is the index of refraction, k is the wave number, and d is the scatter separation distance assuming a single spacing for all the particles to keep the equation as simple as possible. Using this equation it is possible to find expressions for $\alpha_{\rm min}$ and α_0 (Muinonen et al. 2002a):

$$\alpha_{\rm min} = \frac{1}{kd}\sqrt{kd\sqrt{n}\left(\frac{n-1}{n+1}\right) - 1}, \quad (3)$$

$$\alpha_0 = \sqrt{n\left(\frac{n-1}{n+1}\right)^2 - \frac{1}{(kd)^2}}. \quad (4)$$

[3] These data are available on the web page of the Grupo de Ciencias Planetarias at the URL http://gcpsj.sdf-eu.org/catalogo.html

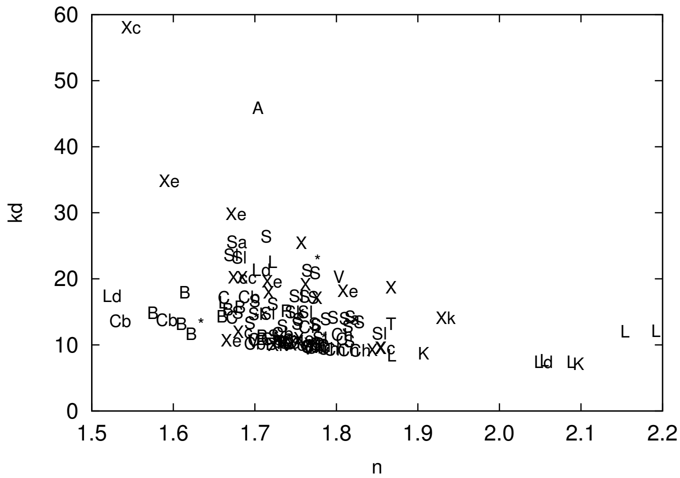

Fig. 5. Relation between n and kd for 121 main-belt asteroids. The objects without taxonomic type in the Bus taxonomy are indicated with stars.

If $\alpha_{\rm min}$ and α_0 are known, from Eq. (4) it is possible to obtain an expression for kd as a function of α_0 and n, and from Eq. (3) another expression (in this case a quadratic one) for kd as a function of $\alpha_{\rm min}$ and n. Then, replacing the first equation into the second one we finally obtain a non-linear expression to solve for n, and after a back substitution also for kd, for all the asteroids with known phase-polarization curves. Table 2 lists for the 121 main-belt asteroids with phase-polarization curves the values of $\alpha_{\rm min}$ and its error, $P_{\rm min}$ and its error, α_0 and its error, h and its error, n, kd, and the Bus taxonomic classification, and Fig. 5 shows how the objects of different taxonomic types are distributed in the n-kd plane. In that figure it is possible to observe a concentration of several taxonomic types with n in the range 1.67−1.85, where the *C*-class objects preferentially occupy the area with $kd \sim 10$, the *S*-class are in the region with $kd > 12$, and the *X*-class asteroids are mixed with *C*- and *S*-class. On the other hand, the objects with $n > 1.9$ are members of the Barbarians group, and the *B*- and *Cb*-types with $n < 1.65$ are objects with a low value of the inversion angle. The *Ld*-type object with $n = 1.525$ and $kd = 17.4$ is the asteroid (269) Justitia, which we mentioned previously because it shows a phase-polarization curve very different to the one that objects of this taxonomic type usually show because it has a low value of the inversion angle and, perhaps, this behavior could indicate a misclassification. The mean values of n and kd with their errors for all the taxonomic types with at least one object with a known phase-polarization curve are listed in Table 3, where the six members of the Barbarian group included in Table 2 are indicated as *Bar*-type.

Figures 6 and 7 show the relation between α_0 and n, and $\alpha_{\rm min}$ and kd, respectively, indicating that there is a correlation between these parameters. These relations can be adjusted by simple functions like:

$$n = (0.0403 \pm 0.0082)\alpha_0 + (0.9438 \pm 0.1650),$$

in the first case, and:

$$kd = \frac{(558.1472 \pm 5.5233)}{\alpha_{\rm min}^{(1.67\pm0.01)}} - (1.9188 \pm 0.1926),$$

in the second one, and they show that the inversion angle is a function of the index of refraction of the surface, while the phase angle where the minimum of polarization is produced provides

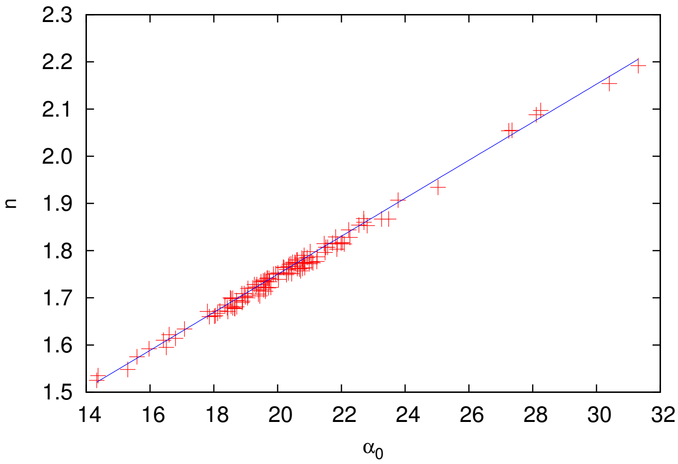

Fig. 6. Relation between α_0 and n for 121 main-belt asteroids. The best fit found is also shown in blue.

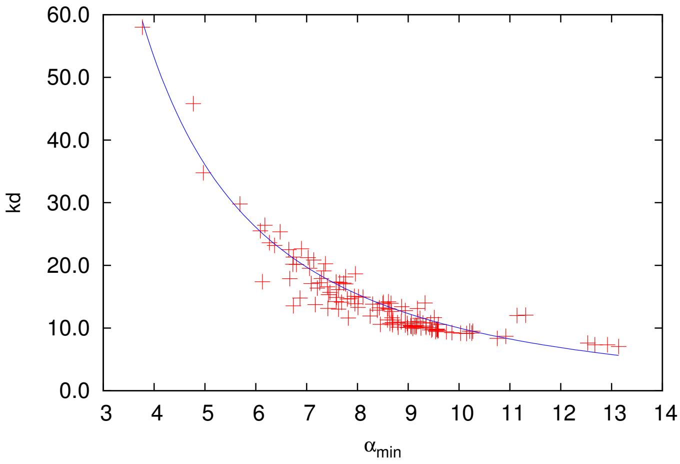

Fig. 7. Relation between $\alpha_{\rm min}$ and kd for 121 main-belt asteroids. The best fit found is also shown in blue.

Table 3. Mean values of n and kd for different taxonomic types.

Tax	N	n	σ_n	kd	σ_{kd}
A	1	1.704	0.000	45.795	0.000
B	12	1.674	0.058	12.932	2.514
C	7	1.729	0.051	11.961	2.461
Cb	6	1.662	0.073	12.871	2.356
Ch	9	1.792	0.020	10.015	1.159
K	3	1.807	0.073	9.530	0.639
L	4	1.748	0.075	14.375	5.564
Ld	2	1.616	0.092	19.361	1.960
R	1	1.739	0.000	15.066	0.000
S	23	1.758	0.041	14.794	3.774
Sa	2	1.747	0.069	19.728	5.784
Sk	2	1.727	0.022	14.811	0.165
Sl	8	1.746	0.054	15.848	4.865
T	1	1.867	0.000	13.115	0.000
V	3	1.755	0.043	13.412	4.857
X	11	1.782	0.047	14.328	5.237
Xc	7	1.707	0.087	20.104	16.037
Xe	6	1.706	0.070	20.637	8.995
Xk	2	1.831	0.103	11.974	2.023
Bar	6	2.107	0.051	8.898	2.221

Notes. The Barbarians are indicated as *Bar*-type.

information about the distance between scatter particles or, to some extent, the porosity of the surface.

The relation between α_0 and n was first suggested by Masiero et al. (2009) in their study of the effects of the regolith size distribution on asteroid polarization. These authors modeled these effects and found that a variation of the refractive index results in significant changes in the location of the inversion angle and the depth of the negative polarization branch of the phase-polarization curve. This theoretical result is confirmed empirically through the relationship proposed here.

The results obtained for the index of refraction shown in Fig. 6 are in the range of values that are expected for materials in asteroid surfaces (for example, piroxene with $1.65 \leq n \leq 1.77$ and olivine with $1.63 \leq n \leq 1.88$), but there are also some high values for asteroids with phase-polarization curves typical of the Barbarian group. It is important to note that the phase-polarization curves of these asteroids could be produced by a mixture of two components with different geometric albedo (Shkuratov et al. 1994; Gil-Hutton et al. 2008) and perhaps this mixture of materials also produces a high refractive index, but in any case this must be taken with some caution since neither the material present on the surface of these objects nor the effectiveness of the process by which a mixture of materials could produce those high n values is known at present. Because asteroids that appear to have high refractive indexes are Barbarians, a good candidate would be a mineral with rich spinel inclusions in a dark matrix (see, Sunshine et al. 2008), but again this must be taken with some caution.

Taking into account that the observations used for these calculations were made in V- or R-bands, the scatter separation distance obtained in Fig. 7 is between 1 and 6 μm with a significant concentration in the range $1 \leq d \leq 2$ μm. If we assume that the spacing between the particles is of the same order as the mean particle size in the regolith, we can use the value of the phase angle where the minimum of polarization is produced as an estimation of the porosity of the surface. It is important to mention that the use of a single spacing for all the particles is a choice to simplify the calculations, since if we used a distribution for d the resulting expressions would become too complex to obtain any useful result.

4. Conclusions

Using the CASPOL polarimeter at Complejo Astronómico El Leoncito, we obtained 171 polarimetric measurements for 128 main-belt asteroids of different taxonomic types, 55 of them observed for the first time. The observational data allowed us to find a probable new case of a Barbarian object. The asteroid (2448) Sholokhov has a polarimetric behavior of this kind, but also the asteroids (565) Marbachia and (1481) Tubingia seem to have phase-polarization curves with large inversion angle although they are classified as D-types. If this polarimetric behavior is confirmed, it would indicate that the Barbarian group of asteroids is present in different taxonomic classes and is not an exclusivity of L-, Ld-, and K-types.

Instead, the L-type asteroid (2272) Montezuma was observed only once but its single polarimetric measurement is well above the theoretical phase-polarization curve for this taxonomic type indicating a small inversion angle, which could be the same as the case reported by Gil-Hutton et al. (2014) for (269) Justitia. The B-type object (877) Walkure has observations indicating a low value of inversion angle, and the single observation of (314) Rosalia also indicates similar polarimetric behavior even though it was not classified using the taxonomy of Tholen. On the other hand, the asteroids (62) Erato, (372) Palma, (635) Vundtia, and (981) Martina have measurements well below the theoretical phase-polarization curve for this taxonomic class, so these asteroids should seem to have a polarimetric behavior that would correspond more to a *C*-type than to a *B*-type asteroid, indicating perhaps in some cases a misclassification.

Taking into account all the polarimetric measurements in the literature taken in the *V*- or *R*-band, we obtain good quality phase-polarization curves and polarimetric parameters for 121 main-belt asteroids. These results are available on our web page as a catalog and they are useful to define the best targets to observe in future campaigns taking into account the phase angle coverage and the degree of completeness of their phase-polarization curves. We plan to keep this catalog up to date.

Using the approximation for the phase-polarization curve proposed by Muinonen et al. (2002b), we found the index of refraction of the surface material and the scatter separation distance for all the objects with known polarimetric parameters, obtaining their mean values and errors for all the taxonomic types with at least one object with a known phase-polarization curve and for the Barbarians. Finally, we found relations between α_0 and n, and $\alpha_{\rm min}$ and kd, showing that the inversion angle is a function of the index of refraction of the surface, while the phase angle where the minimum of polarization is produced provides information about the distance between scatter particles or, to some extent, the porosity of the surface.

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