A&A 529, A86 (2011)
DOI: 10.1051/0004-6361/201015402

Astronomy & Astrophysics

Polarimetric survey of main-belt asteroids[⋆]

I. Results for fifty seven S-, L-, and K-type objects[⋆⋆]

R. Gil-Hutton[1,2] and M. Cañada-Assandri[2]

[1] Complejo Astronómico El Leoncito (CONICET), Av. España 1512 sur, J5402DSP San Juan, Argentina
e-mail: `rgilhutton@casleo.gov.ar`
[2] Universidad Nacional de San Juan, J. I. de la Roza 590 oeste, 5400 Rivadavia, San Juan, Argentina

Received 15 July 2010 / Accepted 22 February 2011

ABSTRACT

Aims. We present the first 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, similar to those shown by the asteroid (234) Barbara.

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 on a sample of more than 170 asteroids were obtained. In this paper the results of 57 S-, L-, and K-type objects are presented, most of them are being polarimetrically observed for the first time. Using these data we find phase-polarization curves and polarimetric parameters for these taxonomic classes. Furthermore, we also find two candidates, (397) Vienna and (458) Hercynia, that could have a phase-polarization curve with a large inversion angle.

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

1. Introduction

The light that we receive from any asteroid at visible wavelengths consists of partially polarized light produced by the scattering of the sunlight on the solid surface of the body. The polarization is usually found to be linear 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. In polarimetry, the results of observations are usually 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.

P_r is found to change with the angle between the incident and observation rays, usually known as the phase angle, α. A plot of P_r against α is known to produce a characteristic curve 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 $\lesssim 20^\circ$, P_r turns out to be negative, reaching a minimum of polarization, $P_{\min}$, at phase angles $\alpha_{\min} \approx 8{-}10^\circ$. This general behavior characterizes all asteroids observed so far with some minor differences (Belskaya et al. 2005) depending on the taxonomic class. Beyond $\approx 20^\circ$ of phase, the polarization changes sign at the inversion angle, α_0, and becomes positive. The existence of a branch of negative polarization exhibited by atmosphereless Solar System bodies is a well-known fact, which is generally explained in terms of the occurrence of coherent backscattering phenomena (Muinonen et al. 2002b, 2007; Tyynelä et al. 2007).

Although polarimetry provides useful information about the physical properties of the asteroid surface, polarimetric observations of these objects are not easy to obtain, because an asteroid must be followed at several phase angles to study its polarization curve, and this kind of coverage is difficult owing to object faintness, limited visibility, weather problems, etc. 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 this paper we present the first results of that survey. 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 September 2005 and November 2009 at the 2.15 m telescope of the Complejo Astronómico El Leoncito (CASLEO), San Juan, Argentina, using the Torino and CASPROF

[⋆] 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 in electronic form 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/529/A86`

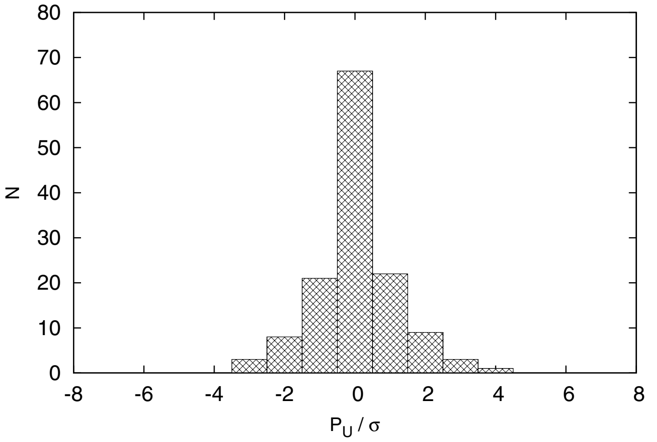

Fig. 1. Distribution of the P_U component of the polarimetric measurements normalized by the error bars.

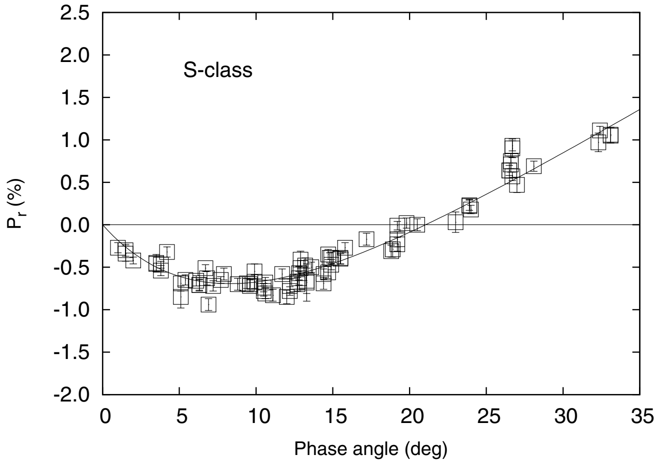

Fig. 2. Polarimetric observations of S-class main-belt asteroids. For comparison, the fit of the phase-polarization curve are also shown.

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 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 P_r parameter. The overall data reduction pipeline is essentially identical to that already used by Cellino et al. (1999, 2006) and Gil-Hutton (2007). As a test of the data reduction process a histogram of the ratio between the U component of the polarization and its error is shown in Fig. 1, where the distribution appears to be centered at zero and all points differ from this value for less than 3σ supporting the reliablity of the polarimetric measurements.

3. Results

The choice of targets was made in a way to preferentially observe asteroids without any polarimetric observations or to fill gaps in their phase-polarization curve. During this survey we obtained 136 observations of 56 S-, L-, Ld-, and K-type main-belt asteroids. The asteroid name, date, observing band, total integration time in seconds, phase angle, position angle of the scattering plane, degree of linear polarization and its error, position angle in the equatorial reference frame and its error, P_r, and its Bus taxonomic classification (Bus 1999) taken from Bus & Binzel (2002) or Lazzaro et al. (2004), are shown in Tables 1 and 2.

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

3.1. S-class asteroids

Eighty-one observations of 29 S-class asteroids have been obtained (Fig. 2). The polarimetric observations of the objects (25) Phocaea, (37) Fides, (67) Asia, (82) Alkmene, (119) Althaea, (126) Velleda, (352) Gisela, and (897) Lysistrata are the first reported for these asteroids.

Previous analyses of asteroidal phase-polarization curves showed that asteroids with similar surface properties show a similar polarimetric behavior (Penttilä et al. 2005; Goidet-Devel et al. 1995; Gil-Hutton 2007). Then, it is possible to obtain mean polarimetric parameters for any taxonomic class using all the observations for the members of that class. The observations of the S-type objects were fitted to a phase-polarization curve using a function proposed by Piironen et al. (2000); Kaasalainen et al. (2001b); Kaasalainen et al. (2001a); 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 this case the observations appear to follow a similar phase curve and we

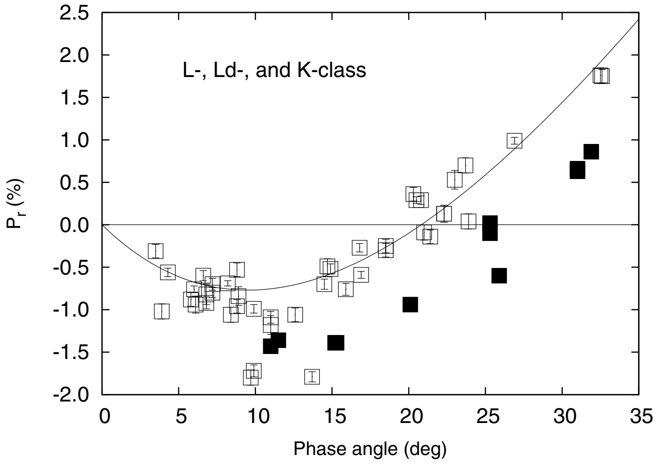

Fig. 3. Polarimetric observations of L-, Ld-, and K-type main-belt asteroids. The observations indicated with filled squares are measurements of objects with known unusual polarimetric behaviour. For comparison, the phase-polarization curve of asteroid (12) Victoria, a typical L-type object, is also shown.

found for the S-class asteroids observed in this survey a minimum of the phase-polarization curve of $|P_{\min}| = 0.69 \pm 0.04\%$ at $\alpha_{\min} = 8.3 \pm 0.2°$, a slope of the linear region of the phase-polarization curve of $h = 0.086 \pm 0.002\%/°$, and an inversion angle of $\alpha_0 = 21.0 \pm 0.5°$. This set of polarimetric parameters is different from that found by Goidet-Devel et al. (1995) for S-type objects, but these authors used the taxonomy proposed by Tholen (1989), which includes in their S-type the Bus L-, Ld- and K-types, so their result is not comparable with that found in this paper.

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

$$\log p(h) = C_1 \log h + C_2, \tag{2}$$
$$\log p(P_{\min}) = C_3 \log P_{\min} + C_4, \tag{3}$$

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 for the observed sample of S-class asteroids $p(h) = 0.26 \pm 0.06$ and $p(P_{\min}) = 0.23 \pm 0.03$.

3.2. L-, Ld-, and K-type asteroids

Thirty observations of 16 L- and Ld-type asteroids, and 25 observations of 11 K-type objects have been obtained in this survey (Fig. 3). The polarimetric observations of the asteroids (122) Gerda, (233) Asterope, (269) Justitia, (339) Dorothea, (397) Vienna, (402) Chloe, (458) Hercynia, (478) Tergeste, (487) Venetia, (579) Sidonia, (592)Bathseba, (616) Elly, (753) Tiflis, (908) Buda, and (1099) Figneria are the first reported for these objects.

These observations show more dispersion than that observed for the S-class objects, and it is not easy to fit a single phase-polarization curve to these measurements. Nevertheless, it is possible to divide them into two different groups: one group that follows the phase-polarization curve typical of L-type objects, and another one with large negative P_r observations (see Fig. 3). This last group is mainly composed of observations of asteroids that are known to show unusual polarimetric behavior and follow a phase-polarization curve with a large inversion angle: (172) Baucis, (234) Barbara, (236) Honoria, (387) Aquitania, (679) Pax, and (980) Anacostia (Cellino et al. 2006; Gil-Hutton et al. 2008; Masiero & Cellino 2008).

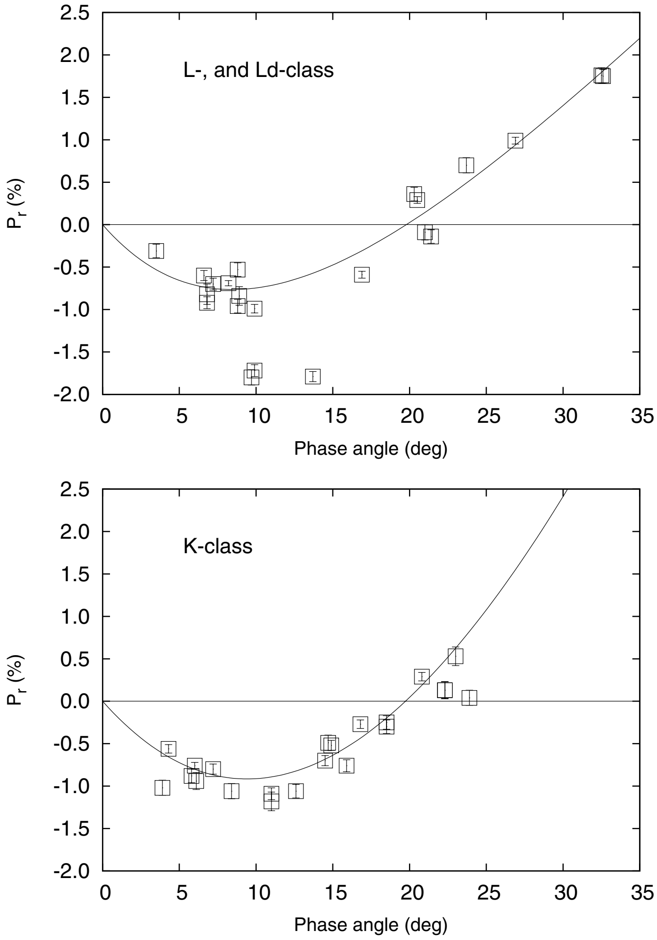

Fig. 4. Polarimetric observations of L- and K-type main-belt asteroids with the best fit of the phase-polarization curve for each group. The observations of the L-type asteroid (458) Hercynia and K-type object (397) Vienna were not considered to obtain the fit.

From these observations there are three interesting points that must be indicated. First, the observations of the L-type asteroid (458) Hercynia at phase angles $\alpha = 9.7°$, $9.9°$, and $13.7°$ are too negative and are incompatible with a typical L-type phase-polarization curve. Thus, it seems that this object also follows a phase-polarization curve with a large inversion angle like (234) Barbara.

Second, the observation of the K-type asteroid (397) Vienna at $\alpha = 3.9°$ is more negative that what can be expected, and this could be an indication that this object follows a phase-polarization curve with a deeper negative branch compared with other objects of these taxonomic types. It is important to mention that this object was observed at $\alpha = 23.9°$ with a polarization value of $P_r = 0.04 \pm 0.04\%$, which could be an indication of a phase-polarization curve with a large inversion angle.

Third, the polarimetric observations at $\alpha = 10{-}12°$ with $P_r \sim -1.0\%$ belong to K-type objects and do not follow the typical phase-polarization curve of a L-type object indicated in Fig. 3. This result could indicate that L- and K-type objects follow different phase-polarization curves. Therefore, to test this hypothesis we made a fit of the observations of the observed L- and K-types objects to theorical phase-polarization curves, excluding in the fitting the observations of (458) Hercynia, (397) Vienna, and those that are known to have phase-polarization curves with a large inversion angle. The results are shown in Fig. 4 and the mean polarimetric parameters obtained are $|P_{\min}| = 0.77 \pm 0.05\%$ at $\alpha_{\min} = 8.5 \pm 0.1°$, $h = 0.115 \pm 0.007\%/°$, and $\alpha_0 = 19.8 \pm 0.3°$ for L- and Ld-type objects, and $|P_{\min}| = 0.92 \pm 0.14\%$ at $\alpha_{\min} = 9.4 \pm 0.7°$, $h = 0.169 \pm 0.010\%/°$, and $\alpha_0 = 19.7 \pm 0.3°$ for K-type objects.

Then, using these polarimetric parameters and following the same procedure used previously to find the mean polarimetric albedo of the observed sample of S-class asteroids, we obtain $p(h) = 0.19 \pm 0.04$ and $p(P_{\min}) = 0.20 \pm 0.02$ for the observed sample of L-type asteroids, and $p(h) = 0.12 \pm 0.02$ and $p(P_{\min}) = 0.15 \pm 0.03$ for the K-type objects.

4. Conclusions

Using the FOTOR and CASPROF polarimeters at Complejo Astronómico El Leoncito we obtained 136 polarimetric measurements for 56 main belt asteroids of S-, L-, Ld-, and K-taxonomic types, 24 of them polarimetrically observed for the first time.

The data obtained in this survey let us obtain polarimetric parameters for the observed sample of S-, L-, and K-type objects, calculate the polarimetric albedo for these groups, and find two objects, (458) Hercynia and (397) Vienna, that could have phase-polarization curves with a large inversion angle.

Acknowledgements. We thank the referee, S. Bagnulo, for his very useful review, which led to a substantial improvement of the paper. The authors acknowledge partial financial support by CICITCA, Universidad Nacional de San Juan, through a research grant. RGH gratefully acknowledges financial support by CONICET through PIP 114-200801-00205.

References

Belskaya, I. N., Shkuratov, Yu. G., Efimov, Yu. S., et al. 2005, Icarus, 178, 213
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
Gil-Hutton, R. 2007, A&A, 464, 1127
Gil-Hutton, R., & Benavidez, P. 2003, MNRAS, 345, 97
Gil-Hutton, R., Mesa, V., Cellino, A., et al. 2008, A&A, 482, 309
Goidet-Devel, B., Renard, J. B., & Levasseur-Regourd, A. C. 1995, Planet. Space Sci., 43, 779
Kaasalainen, S., Muinonen, K., & Piironen, J. 2001a, Appl. Opt., 41, 4416
Kaasalainen, M., Torppa, J., & Mulnonen, K. 2001b, Icarus, 153, 37
Lazzaro, D., Angeli, C. A., Carvano, J. M., et al. 2004, Icarus, 172, 179
Masiero, J., & Cellino, A. 2009, Icarus, 199, 333
Muinonen, K., Piironen, J., Kaasalainen, S., & Cellino, A. 2002, Mem. Soc. Astron. It., 73, 716
Muinonen, K., Piironen, J., Shkuratov, Yu. G., Ovcharenko, A., & Clark, B. E. 2002, in Asteroids III, ed. W. F. Bottke Jr., A. Cellino, P. Paolicchi, R. P. Binzel (Tucson: Univ. of Arizona Press), 123
Muinonen, K., Zubko, E., Tyynelä, J., Shkuratov, Yu. G., & Videen, G. 2007, JQSRT, 106, 360
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
Scaltriti, F., Piirola, V., Cellino, A., et al. 1989, Mem. Soc. Astron. It., 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
Tyynelä, J., Zubko, E., Videen, G., & Muinonen, K. 2007, JQSRT, 106, 520