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Refining the asteroid taxonomy by polarimetric observations

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ABSTRACT

We present new results of polarimetric observations of 15 main belt asteroids of different composition. By merging new and published data we determined polarimetric parameters characterizing individual asteroids and mean values of the same parameters characterizing different taxonomic classes. The majority of asteroids show polarimetric phase curves close to the average curve of the corresponding class. We show that using polarimetric data it is possible to refine asteroid taxonomy and derive a polarimetric classification for 283 main belt asteroids. Polarimetric observations of asteroid (21) Lutetia are found to exhibit possible variations of the position angle of the polarization plane over the surface.

1. Introduction

During the last decade polarimetric techniques have been actively applied to study asteroid surfaces. Long-term observational programs were carried out at the 2.1 m telescope of the Complejo Astronómico El Leoncito (CASLEO) in Argentina (Gil-Hutton et al., 2014), at the 1.25 m telescope of the Crimean Astrophysical Observatory in Ukraine (Belskaya et al., 2009), and at the 1.8 m telescope of the Astrophysical Observatory of Asiago in Italy (Fornasier et al., 2006). The observational surveys were mainly aimed to characterize the polarimetric behavior of asteroids of different composition (Belskaya et al., 2003 , 2005; Fornasier et al., 2006; Gil-Hutton, 2007; Gil-Hutton et al., 2008 , 2014; Gil-Hutton and Cañada-Assandri, 2011 , 2012; Cañada-Assandri et al., 2012).

The linear polarization degree P_r of sunlight scattered by asteroid's surfaces is usually defined in terms of differences between the intensities of the components of the light beam polarized along the planes perpendicular ($I_\perp$) and parallel ($I_{||}$) to the scattering plane:

$$P_r = \frac{I_\perp - I_{//}}{I_\perp + I_{//}}.$$

Using this definition, asteroids (and other atmosphereless Solar System bodies) exhibit a typical dependence $P_r(\alpha)$ of linear polarization upon the phase angle α, characterized by the presence of a negative polarization branch reaching an extreme (negative) value $P_{\min}$ at the phase angle $\alpha_{\min}$, and an ascending branch, characterized by an inversion angle $\alpha_{\rm inv}$ at which P_r changes its sign, showing a linear trend characterized by a polarimetric slope h. All these polarimetric parameters are of great interest as they characterize surface physical properties, mainly being related to the geometric albedo and texture.

The interpretation of polarimetric observations of asteroids in terms of physical characteristics of their surfaces is not straightforward. The main conclusions from asteroid polarimetry are mostly based on various empirical relationships (see Belskaya et al., 2015 for a review). It was shown that asteroid's albedo Ag can be derived directly from polarimetric measurements by using the empirical relationship

$$\log(A_g) = C_1 \log(h) + C_2,$$

where the parameters C_1 and C_2 are constants. Such kind of the empirical relationships "albedo – polarimetric slope" and "albedo – $P_{\min}$" have been successfully used to determine asteroid albedos from polarimetric data alone (Zellner and Gradie, 1976; Lupishko and Mohamed 1996; Cellino et al., 1999). Recently Cellino et al. (2015b) made a new analysis of the relationships between the ge-

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ometric albedo and polarization parameters of asteroids. They proposed new calibrations and used them to derive polarimetric albedos from re-analysis of published data (Cellino et al., 2015b , 2016).

In this paper we assess the possible role of polarimetry in refining asteroid taxonomy. In the 70s and 80s, values of geometric albedo derived from polarimetry had been used in the derivation of different taxonomic classes, in particular to distinguish between objects exhibiting similar spectro-photometric properties, but quite different albedos (see Tholen and Barucci, 1989 for a review). The insufficient growth of the polarimetric database led subsequently to exclude polarimetric data from the derivation of asteroid taxonomic classes. Later two new analyses were published by Goidet et al. (1995) and Penttilä et al. (2005). They considered polarimetric observations of about 100 asteroids and compared the average phase curves characterizing different asteroid classes. They concluded that, with respect to spectral reflectance data, polarimetry provides a fully complementary approach to asteroid classification. The polarimetric properties of asteroids of various taxonomic classes were also derived and discussed in several more recent papers (Belskaya et al., 2005; Fornasier et al., 2006; Gil-Hutton, 2007; Gil-Hutton et al., 2008 , 2014; Gil-Hutton and Cañada-Assandri, 2011 , 2012; Cañada-Assandri et al., 2012). The main conclusion is that asteroids of the same taxonomic class as derived from spectral reflectance data, tend also to show similar polarimetric properties.

Here we complement previous analyses with new polarimetric data. Section 2 presents new observations of 15 main belt asteroids and their analysis. In Section 3 we discuss polarimetric properties of main asteroid classes and define a polarimetric classification for 283 main-belt asteroids.

2. Observations and results

Polarimetric observations of 15 main belt asteroids were carried out in 2005–2012. Table 1 presents the results of our polarimetric observations. For each asteroid observation, we list the epoch and mean time of observations in UT, the adopted filter, the phase angle α, the polarization degree P_r and the position angle θ_r in the coordinate system referring to the scattering plane as defined by Zellner and Gradie (1976), together with their root-mean-square errors σ_P and σ_θ. The last column refers to the observation site where observations were carried out.

In particular, the observations were carried out using different telescopes and instruments at four observational sites which we briefly characterized below.

Observations at the Asiago Observatory. Polarimetric observations were carried out using the polarimetric mode of the Faint Object Spectrographic Camera (AFOSC) mounted at the 1.8 m telescope of the Astrophysical Observatory of Asiago in Italy. The polarimeter allows simultaneous measurements of the polarized flux at angles 0, 45, 90, and 135° using a wedged double Wollaston prism (Oliva, 1997). These four beams are sufficient to determine the linear polarization parameters *I, Q,* and *U* with a single exposure. A polarimetric survey of asteroids at the Asiago telescope was made in 2002–2006. The results of most of the observations were published by Fornasier et al. (2006) where the description of the instrument, data acquisition and reduction was given. Here we present observations done in 2005–2006 which were not included in the above-mentioned paper. More recently, the Asiago polarimeter has been moved to the Nordic Optical Telescope (NOT) in La Palma (Canary Islands, Spain) and continued to be used for asteroid polarimetry (e.g. Fornasier et al., 2015).

Observations at the Crimean Astrophysical Observatory (CrAO). The observations were made in 2012 using the 1.25 m telescope of the Crimean Astrophysical Observatory equipped with a five-channel UBVRI photopolarimeter (Piirola, 1989). The method of observations and data processing have previously described in details (see Shakhovskoy and Efimov 1972; Belskaya et al., 1987). Here we consider observations only in the R-band which was obtained with the best accuracy.

Observations at the Complejo Astronómico El Leoncito (CASLEO). For observations we use the 2.1 m telescope equipped with a double-hole aperture polarimeter. The polarimeter has rapid modulation provided by a rotating achromatic half-wave retarder and a Wollaston prism beam-splitter. The detailed description of the polarimeter, data acquisition and data reduction can be found in Gil-Hutton et al. (2008).

Observations at the LOIANO Observatory. Polarimetric observations were carried out in 2010–2012 at the Loiano station of the Astronomical Observatory of Bologna, Italy. We used the 1.52 m Cassini telescope equipped with Bologna Faint Object Spectrograph and Camera (BFOSC). The technical specifications of the instrument are given at http://www.bo.astro.it/loiano. The imaging polarimetry mode of the BFOSC is implemented with a Wollaston prism in the filter wheels and with the relative mask in the slit wheels. The prism gave strips of the images with orthogonal polarization of dimensions 1100×80 pixels, corresponding to about $10' \times 40''$. To measure the Stokes parameters, couple of images were recorded with the BFOSC in the standard position and another couple with the BFOSC rotated by 45°. We obtained sequence of images at the four angles, i.e. 0, 45, 90, and 135°.

All obtained polarization measurements were of a good quality (see errors in Table 1). In order to control instrumental polarization we measured two polarimetric standard stars with large and small polarizations each night. Observations of the same object obtained with different instruments are well consistent, indicating that the instrumental polarization was carefully corrected. Having at our disposal these new data we are now able to better characterize the polarization-phase behavior of the observed asteroids. We summarize the estimated polarimetric parameters of the measured asteroids in Table 2. The Table also includes diameters and albedos taken from Usui et al. (2013), and composition types according to Tholen (1984) and DeMeo et al. (2009).

The individual phase curves including both new and already published data for the observed asteroids are presented in Fig. 1. The data for asteroids (21) Lutetia and (64) Angelina are shown in Figs. 2–4. The data were fit to the so-called trigonometric function proposed by Lumme and Muinonen (1993) (see Section 3 for details) .We comment the results obtained for each target below.

(21) Lutetia. It was the target of the ESA Rosetta space mission fly-by on July 10th, 2010 (Sierks et al., 2011). Belskaya et al. (2010) found indications of possible variations of linear polarization over Lutetia's surface. These authors analyzed polarimetric observations of the asteroid performed in 1973–2008 at different telescopes (Zellner and Gradie, 1976; Fornasier et al., 2006; Gil-Hutton, 2007; Belskaya et al., 1987 , 2009, 2010) and noticed a scatter in the polarization phase curve exceeding observational errors. The analysis of the deviations of the polarization degree from the fit of the phase curve has shown systematic rather than random polarization variations probably correlated with asteroid rotation. To check this assumption we have performed new polarimetric observations of (21) Lutetia in March 16–18, 2010. Observations were aimed at studying possible variations of the polarization with the asteroid rotation. Simultaneously with polarimetric measurements we obtained photometric lightcurves in order to check for possible correlations.

The measured polarization degree and position angle of the polarization versus rotational phase are shown in Fig. 2. The lightcurve measured in the *R* band during our observations is also presented. The possible variations in polarization degree are about ±0.1%, which do not exceed 2σ of our measurements. If these variations are real, they do not apparently correlate with the Lutetia's lightcurve.