Publication Year	2015
Acceptance in OA	2020-05-13T15:47:21Z
Title	Asteroid Polarimetry
Authors	Belskaya, I., CELLINO, Alberto, Gil-Hutton, R., Muinonen, K., Shkuratov, Y.
Publisher's version (DOI)	10.2458/azu_uapress_9780816532131-ch008
Handle	http://hdl.handle.net/20.500.12386/24803

Asteroid Polarimetry

Irina Belskaya
Kharkiv Karazin National University, Ukraine

Alberto Cellino
INAF-Osservatorio Astrofisico di Torino, Italy

Ricardo Gil-Hutton
Complejo Astronomico El Leoncito, Argentina

Karri Muinonen
University of Helsinki, Finland &
Finnish Geospatial Research Institute, Masala, Finland

Yuriy Shkuratov
Kharkiv Karazin National University, Ukraine

Abstract

The application of the polarimetric technique to asteroid studies progressed significantly during the last decade. The most interesting results were the discovery of asteroids with peculiar polarimetric properties, new findings on wavelength dependence of polarization, and some improvements in the polarimetric method of albedo determination. We review instruments that have been and are currently used for asteroid optical polarimetry and summarize the main results of observational surveys. Recent advances in theoretical and laboratory modeling of polarization phase effects and their implications are discussed. We focus on the most important open questions and identify promising avenues for future polarimetric investigations.

1. INTRODUCTION

The application of the polarimetric technique to asteroid studies has a long history starting in 1934, when the first polarization measurements of bright asteroids were obtained by *B. Lyot* using a photographic polarimeter. Since 1954, photoelectric polarimeters have been used to measure asteroid polarization with better accuracy. Results of polarimetric observations of six asteroids were discussed by *A. Dollfus* in the first review devoted to polarimetry of asteroids (*Dollfus et al.*, 1971). In the first *Asteroids* book, the chapter on optical polarimetry included a review of polarimetric observations for about 100 asteroids and their interpretation based on laboratory studies (*Dollfus and Zellner*, 1979). All measured asteroids were found to show so-called negative polarization at small phase angles. This is better expressed using, as a fundamental parameter, the polarization degree P_r, defined in terms of the intensities of the scattered light polarized along the planes perpendicular $I_\perp$ and parallel $I_{//}$ to the scattering plane:

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

Such a definition means that the sign of the polarization degree P_r can be negative when the component $I_{//}$ with the electric vector parallel to the scattering plane predominates over the perpendicular component $I_\perp$. To achieve a detailed physical explanation of the phenomenon of negative polarization is a challenging task. *Dollfus et al.* (1989) in the *Asteroids II* book reviewed the first attempts of theoretical modeling of negative polarization, but these were later found to give unrealistic results (*Shkuratov et al.,* 1994). The chapter by Dollfus et al. (1989) also described telescopic observations of asteroids and relevant laboratory data obtained after the review published in the first *Asteroids* book (*Dollfus and Zellner*, 1979).

Muinonen et al. (2002) reviewed in the *Asteroids III* book some new theoretical and experimental findings on both photometric and polarimetric phase effects, and reported a significant progress in understanding the physical nature of negative polarization in terms of the multiple-scattering mechanism of coherent backscattering.

Detailed reviews on various aspects of the application of the polarimetric technique to study Solar System bodies can also be found in the books entitled "Polarimetric remote sensing of Solar system objects" by *Mishchenko et al.* (2010) and "Polarimetry of stars and planetary systems" (Eds. *Kolokolova et al.,* 2015). In the latter book, the chapters by *Cellino et al.* (2015a), *Muinonen et al.* (2015), and *Levasseur-Regourd et al.* (2015) summarize the role of polarimetric investigations in asteroid science, and the status of theoretical modeling and laboratory measurements, respectively.

In the present chapter, we focus on the achievements in optical polarimetry of asteroids since the *Asteroids III* book. In Section 2, we review the instruments and telescopes available for asteroid polarimetry. Section 3 summarizes the new findings obtained from recent observational surveys. A review of progress in analytical, numerical, and laboratory modeling of polarization phase effects is given in Section 4. We discuss the main applications of the polarimetric observations to study asteroid surfaces in Section 5. Finally, we outline the future prospects of the polarimetric studies.

2. TELESCOPES AND INSTRUMENTS

In the 1980s, and up to the end of the 1990s, the majority of the asteroid polarimetric observations were made using multichannel photopolarimeters of a kind originally designed by *Piirola* (1973). These instruments allowed simultaneous measurements in the UBVRI bands using five separate photomultipliers. One such instrument has been operated at the 1.25-m telescope of the Crimean Astrophysical Observatory in Ukraine since 1983. A detailed description of this instrument and a review of the obtained results are given by *Mishchenko et al.* (2010).

Another essentially identical instrument, built at the Astronomical Observatory of Torino in Italy (*Scaltriti et al.*, 1989), started operations in 1994 at the 2.1-m telescope of the Complejo Astronómico El Leoncito (CASLEO) in Argentina (*Cellino et al.,* 1999, 2005a). These two instruments, often used for joint observational programs, provided a large set of multi-band polarimetric observations of main-belt asteroids (*Belskaya et al.,* 2009a). The main limitation was a bright magnitude limit (V~13^m). Since 2000, a new double-hole aperture polarimeter with rapid modulation provided by a rotating achromatic half-wave retarder and a Wollaston prism beam-splitter started operations at CASLEO (*Gil-Hutton et al.*, 2008), and allowed the observers to reach fainter magnitudes (V~15^m). The CASLEO instruments were used for a long-term observational survey that provided polarimetric observations of more than 250 main-belt asteroids (see, e.g., *Gil-Hutton et al.*, 2014).

A new epoch in asteroid polarimetric observations has begun with new polarimeters developed around CCD detectors and the use of modern multi-mode instruments in polarimetric mode. In the period 2002-2006, a polarimetric survey of about 40 asteroids was 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 (*Fornasier et al.,* 2006a). This polarimeter allows simultaneous measurements of the polarized flux at angles 0, 45, 90, and 135 deg 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. The great advantage of the instrument is that the obtained data do not depend on atmospheric changes as in the case of multiple exposures. The Asiago polarimeter has been moved to the Nordic Optical Telescope (NOT) in La Palma (Canary Islands, Spain) in 2010 and continued to be used for asteroid polarimetry (*Fornasier et al.*, 2015). An identical instrument has been recently built at the Torino observatory, and attached to a 1-m telescope of the observatory of Nice (France), located in Calern (*Pernechele et al.*, 2012). At the same time, the old polarimeters at CASLEO based on photomultiplier tubes were recently replaced by a new dual-beam imaging polarimeter CASPOL (*Gil-Hutton et al.*, 2014) allowing to gain about 2-3 magnitudes over the previous instruments.

We can mention also some other instruments used for asteroid polarimetry during the last decade. Among them, the Dual-Beam Imaging polarimeter installed at the 2.2-m telescope of the University of Hawaii at Mauna Kea (*Masiero et al.*, 2007), and the Bologna Faint Object Spectrograph and Camera (BFOSC) in the imaging polarimetry mode at the 1.52-m Cassini telescope of the Astronomical Observatory of Bologna, Italy. Recently, polarimetry of asteroids started with the SPOL spectropolarimeter at the Steward Observatory 2.3-m and 1.54-m telescopes (*Maleszewski et al.,* 2013).

Major part of the polarimetric observations of asteroids have been obtained using telescopes up to ~2 m in diameter, allowing to measure only relatively bright objects. The first polarimetric observations using large telescopes took place in 2005 when one of the 8.2-m units of the Very Large Telescope at Cerro Paranal ESO observatory in Chile was used to study the asteroid (2867) Steins. This object, a target of the ESA space mission "Rosetta", was observed with the Focal Reducer / Low Dispersion spectrograph (FORS) in polarimetric mode (*Fornasier et al.,* 2006b). The mode uses a half-wave phase retarder and a Wollaston prism as a beam splitter (*Appenzeller et al.,* 1998, *Bagnulo et al.,* 2011). In the following years, new VLT observations were devoted to studies of the potentially hazardous near-Earth asteroids (NEAs) (*Delbò et al.,* 2007, *de Luise et al.,* 2007), to some selected main-belt asteroids (*Cellino et al.*, 2010, 2014), and Jupiter Trojans (*Belskaya et al.*, 2014). To start an observing program on spectro-polarimetry of asteroids, *Bagnulo et al.* (2015) used FORS at VLT and the ISIS instrument of the 4.2-m William Herschel Telescope (WHT) of the Isaac Newton Group of Telescopes.

In spite of the different instruments used at different observing sites, asteroid polarimetric data have always been found to be in very good mutual agreement.

A comprehensive review on various techniques and devices used in optical and near-infrared polarimetry is given by *Hough* (2005). Modern approaches to the design of astronomical polarimeters and a list of currently available polarimeters at ground-based telescopes can be found in the review by *Keller et al.* (2015).

3. NEW FINDINGS FROM OBSERVATIONS

During the last decade, polarimetric observations of asteroids have become more frequent. Several observing campaigns have been carried out to characterize the polarimetric behavior of asteroids of different composition types (*Belskaya et al*., 2003, 2005; *Fornasier et al.,* 2006a; *Gil-Hutton*, 2007, *Gil-Hutton et al.,* 2008, 2014; *Gil-Hutton and Cañada-Assandri*, 2011; *Cañada-Assandri et al.*, 2012). Many observing projects have been devoted to the study of specifically selected targets, including near-Earth asteroids (*Kiselev* et al., 2002; *De Luise et al.*, 2007; *Delbò et al.,* 2007; *Belskaya et al.*, 2009b; *Masiero*, 2010), members of dynamical families (*Cellino et al.,* 2010), Trojans (*Belskaya et al.,* 2014), targets of space missions (*Cellino et al.*, 2005b; *Fornasier et al.*, 2006b; *Belskaya et al.,* 2010; *Hadamcik et al.*, 2011), and several individual objects (*Antonyuk and Kiselev*, 2012; *Bagnulo et al.*, 2010; *Cellino et al.,* 2006; *Masiero and Cellino*, 2009). Observations in order to investigate polarimetric behavior at very small phase angles were carried out by *Belskaya et al.* (2003), *Rosenbush et al.* (2005, 2009), and *Cellino et al.* (2005a). The latter paper aimed at providing an independent estimate of the albedos of small asteroids previously observed at thermal IR wavelengths by the IRAS satellite. The wavelength dependence of asteroid polarization has been the subject of papers published by *Belskaya et al.* (2009a), *Gil-Hutton et al.* (2014), and *Bagnulo et al.* (2015).

The number of asteroids for which polarimetric measurements are available reaches now ~350, almost three times larger than the number in the *Asteroids* book (*Dollfus and Zellner*, 1979). However, the number of asteroids with well-defined polarization phase curves did not increase substantially. For most asteroids, we have at disposal measurements obtained at only few phase angles, which is not enough for an accurate determination of the main polarimetric parameters. There are, however, asteroids for which we have polarimetric observations obtained during several oppositions, with a good phase-angle coverage. For example, a detailed polarization phase curve measured for the asteroid (21)

Lutetia, a target of the Rosetta mission, is shown in Fig.1. The data were obtained during 10 apparitions in 1973-2011 by different authors (*Zellner and Gradie*, 1976; *Belskaya et al.,* 2010, and references therein; *Gil-Hutton et al.,* 2014). The scatter of the data for this asteroid may be a consequence of its surface heterogeneity (*Belskaya et al.,* 2010).

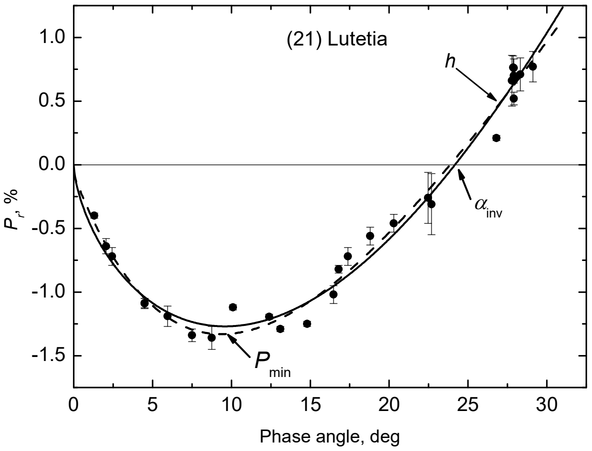

Fig.1. Polarization phase-angle dependence of asteroid (21) Lutetia measured in 1973-2011 in the V-band (see text for references). The main polarimetric parameters P_{min}, α_{inv}, and the polarimetric slope *h* are indicated by arrows. The solid line shows the trigonometric fit and the dashed line corresponds to the linear-exponential fit (see text).

The behaviour of the polarization phase curve is characterized by several parameters: the extreme value of the negative polarization branch P_{min}, which occurred at the phase angle α_{min}; the inversion angle α_{inv} at which the polarization degree changes its sign; and the polarimetric slope of the ascending branch *h* (Fig.1). These parameters are typically derived by using the so-called trigonometric fit (*Lumme and Muinonen*, 1993) or the linear–exponential function (*Kaasalainen et al.*, 2003; *Muinonen et al.*, 2009). The trigonometric fit, using four free parameters (two of them can be fixed), gives physically reasonable behaviour of the polarization-phase dependence in a wide range of phase angles up to the polarization maximum P_{max} at α_{max}~100° (see *Penttilä et al.,* 2005). The four-parameter linear-exponential function fits well the phase curve up to α~30° and can be used for a joint fit of polarimetric and photometric phase curves (see *Muinonen et al.,* 2009). For a well-sampled phase curve, both fits give almost identical results (Fig.1).

The polarimetric observations available are collected in the Asteroid Polarimetric Database (APD) at the Small Bodies Node of the Planetary Data System. The database has been compiled by *Lupishko and Vasiliev* (1997) and is annually updated (*Lupishko*, 2014). There are also other databases which include polarimetric data obtained in the specific papers (e.g., *Belskaya et al.*, 2009ab; *Cellino et al.*, 2006; *Gil-Hutton et al.*, 2008). Below, we have summarized the most interesting recent findings on the polarimetric properties of asteroids.

3.1 Asteroids with small inversion angles

In the first polarimetric survey of asteroids (*Zellner and Gradie*, 1976), the asteroid (704) Interamnia was found to have an unusually small inversion angle of about 16°. This was interpreted as either an indication of bare rock on the surface, or as being due to some peculiar surface composition unknown at that time (*Dollfus and Zellner*, 1979). *Belskaya et al.* (2005) measured an even smaller inversion angle of about 14° for the asteroid (419) Aurelia. Both of these asteroids had been previously classified by *Tholen* (1989) as belonging to the rare *F* taxonomic class. In order to assess whether a small inversion angle could be a characteristic feature of F-class asteroids, observations of these asteroids were continued (*Belskaya et al.*, 2005; *Fornasier et al.*, 2006a; *Gil-Hutton et al.*, 2012, 2014). As a result, four more F-type asteroids, (213) Lilaea, (302) Clarissa, (325) Roberta, and (1021) Flammario, were found to have small inversion angles. The polarization phase curve of the abovementioned asteroids is shown in Fig.2. Their inversion angles do not exceed 17°.

Up to now, all known cases of asteroids exhibiting small inversion angles concern the *F*-class. The most distinctive spectral feature of these asteroids, as compared to the other taxonomic classes, is the absence of UV absorption features at short wavelengths. More recent taxonomic classifications (*Bus and Binzel,* 2002; *DeMeo et al.*, 2009) use reflectance spectra covering only the visible and near-IR wavelengths and they can no longer identify a separate *F*-class. Asteroids previously classified as *F* belong today mostly to the larger *B* or C classes. *Gil-Hutton and Cañada-*

Assandri (2012) analyzed data obtained for 58 *B*- and *C*-type objects and found an indication of smaller inversion angles for several objects previously classified as *F*-type.

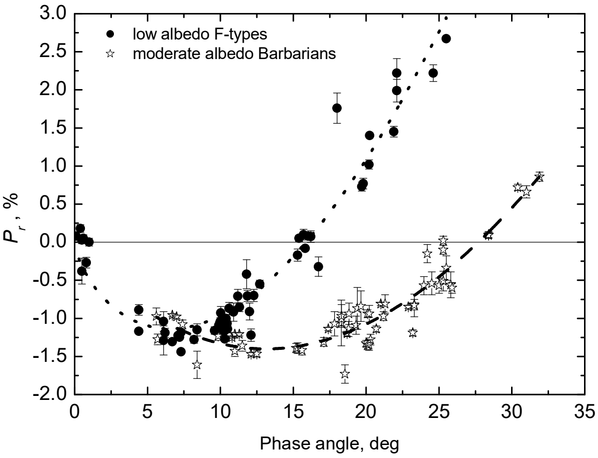

Fig.2. Extreme cases of asteroid polarization phase curves (see text for references). Data for the low-albedo *F*-type asteroids are shown by black circles. Polarization measurements of the moderate-albedo Barbarians are shown by asterisks. The dash and dotted lines display the fits using the trigonometric function (*Lumme and Muinonen*, 1993).

Unlike other very dark primitive asteroids, *F*-class objects are relatively abundant in the inner asteroid belt, a large fraction of them being associated with the Polana family (*Cellino et al.*, 2001; *Milani et al.*, 2014). At the same time, they may be also related to extinct cometary nuclei (*Kolokolova and Jockers*, 1997). Polarimetric observations of two cometary nuclei, 2P/Encke (*Boehnhardt et al.*, 2008) and 133P/Elst-Pizarro (*Bagnulo et al.,* 2010), also suggest a small inversion angle similar to the F-type asteroids.

Belskaya et al. (2005) proposed a possible interpretation of the particular polarimetric properties of the asteroid (419) Aurelia and the other *F*-class asteroids. It was shown that an optical homogeneity of asteroid regolith microstructure at scales of the order of visible light wavelengths may be responsible for relatively small values of the depth of the negative polarization branch and of the inversion angle (*Belskaya et al.*, 2005). One of the feasible mechanisms can be the existence of carbon deposits on the regolith particles of *F*-class asteroids, making them optically more homogeneous than other classes of low albedo asteroids. This assumption is in agreement with the almost flat spectra characterizing the *F*-class.

Polarimetric observations can therefore be crucial in the identification of new *F* objects among asteroids recently classified as *B*-class, and possibly to strengthen the preliminary indications of analogies with the polarimetric behaviour of comets.

3.2. Asteroids with large inversion angles

Polarimetric observations of the moderate-albedo asteroid (234) Barbara unexpectedly revealed considerable negative polarization $P_r \sim -1.2\%$ at phase angles $\alpha \geq 20^\circ$ (*Cellino et al.*, 2006). This result was surprising, because all other asteroids previously observed have zero or positive polarization at such large phase angles, which are close to the typical inversion angle of “normal” asteroids. Further observations of (234) Barbara confirmed a wide branch of negative polarization with an inversion angle $\alpha_{\rm inv} \sim 28^\circ$ (*Cellino et al.*, 2007; *Gil-Hutton et al.*, 2008; *Masiero et al.*, 2009). Apart from the large inversion angle, the polarization phase curve of asteroid (234) Barbara is characterized by a fairly deep branch of negative polarization (see Fig.2). *Cellino et al.* (2006) suggested that such atypical polarimetric behavior for a moderate-albedo surface might be due to some unusual surface properties related to the rare *Ld* taxonomic classification of (234) Barbara (*Bus and Binzel*, 2002). Asteroids of the *Ld* class are characterized by a particularly reddish reflectance spectrum (*Bus and Binzel*, 2002), and had not been observed previously in polarimetry. *Gil-Hutton et al.* (2008) later found four more asteroids displaying the same Barbara-like polarimetric behavior. They are the *L*-class asteroids (172) Baucis, (236) Honoria, (980) Anacostia, and the *K*-class asteroid (679) Pax. It was then also noticed that at least two asteroids with particular polarimetric behaviour, Barbara and Anacostia, had in their spectra strong spinel features (*Sunshine et al.*, 2007). According to *Burbine et al.* (1992), the asteroids (980) Anacostia and (387) Aquitania, which have quite similar orbits, share the property of being spinel-rich, suggesting that they could be fragments of the breakup of a spinel-rich parent body with affinities to carbonaceous CO3/CV3 chondrites. Subsequent observations of (387)

Aquitania also revealed a Barbara-like polarimetric behavior, confirming the existence of a relation between the unusual mineralogical and polarimetric properties of these asteroids (*Masiero and Cellino*, 2009). *Gil-Hutton et al.* (2014) later found two more “Barbarians”, the *K*-type asteroid (402) Chloe and the *L*-type (729) Watsonia.

Among eight asteroids with large inversion angles, which were known at the beginning of 2014, at least two were members of the Watsonia family identified by *Novaković et al.* (2011). This fact raised the question on polarimetric properties of other Watsonia family members. *Cellino et al.* (2014) carried out observations of a sample of nine objects belonging to the Watsonia family and found that 7 of them are characterized by polarization curves with large inversion angles. These authors concluded that the Watsonia family is a repository of Barbarians. This strengthens the hypothesis that the peculiar mineralogical composition of these objects should be responsible for their unusual polarization properties.

A common characteristic of the Barbarians is their classification to *L*, *Ld*, or *K*-types according to taxonomic classifications based on visible wavelength data (*Bus and Binzel*, 2002). On the other hand, not all the asteroids belonging to these taxonomic classes show large inversion angles (e.g., *Gil-Hutton et al.*, 2014). Some misclassification due to similar spectroscopic properties in the visible may be present. This is confirmed by the fact that, if one looks at the more recent taxonomic classification by *DeMeo et al.* (2009), which is based on data including also the near-IR, all Barbarians currently known for which a *DeMeo* classification is available, belong to the same class (*L*).

A possible interpretation of the peculiar polarimetric properties of Barbarians is related to the presence of spinel in Ca-Al rich inclusions (CAI) at their surfaces. Spinel is characterized by an unusually high refractive index, which might be related to the unusual polarimetric behavior of these objects (*Sunshine et al.*, 2007; *Gil-Hutton et al.,* 2008; *Masiero et al.*, 2009).

The search for new asteroids with large inversion angles continues. They can be easily identified by polarimetric observations at phase angles around 20°.

3.3. Polarization behavior at small phase angles

The interest to obtain polarimetric observations at small phase angles is related to the understanding of the coherent-backscattering mechanism. This contributes to photometric and polarimetric phase dependences producing sharp features near opposition (see *Muinonen et al.*, 2002 for a review). The first pieces of evidence for the existence of polarization opposition peaks were found for high-albedo Galilean satellites of Jupiter by *Rosenbush et al.* (1997). After this discovery, extensive observations of the high-albedo asteroids were made to search for a possible polarization opposition surge. *Rosenbush et al.* (2005) presented UBVRI polarimetric observations of the E-type asteroid (64) Angelina made in three apparitions with detailed coverage of small phase angles up to 0.4°. These authors claimed the discovery of a sharp peak of negative polarization superimposed on the regular branch. The peak has an amplitude ~0.4% centered at a phase angle α~1.8° (*Rosenbush et al.*, 2005). The authors found that the amplitude and position of the polarization peak was slightly different before and after opposition and at different apparitions. New observations by *Zaitsev et al.* (2014) revealed a secondary minimum at α~1.5°. They underlined that further polarimetric observations of Angelina at α~3-5° are needed to reach a final conclusion on the shape of the phase dependence near opposition. *Rosenbush et al.* (2009) carried out observations of another high-albedo asteroid, (44) Nysa, at very small phase angles down to 0.4 deg. A polarization opposition effect with an amplitude of ~0.3% centered at α~0.8° was found. *Rosenbush et al.* (2009) put together all polarimetric measurements for the E-type asteroids and concluded that a sharp secondary minimum is present at α~1°.

Polarimetric measurements of the *V*-type asteroid (4) Vesta (*Mishchenko et al.*, 2010) and the *S*-type asteroid (20) Massalia (*Belskaya et al.*, 2003) did not reveal any sharp features at small phase angles.

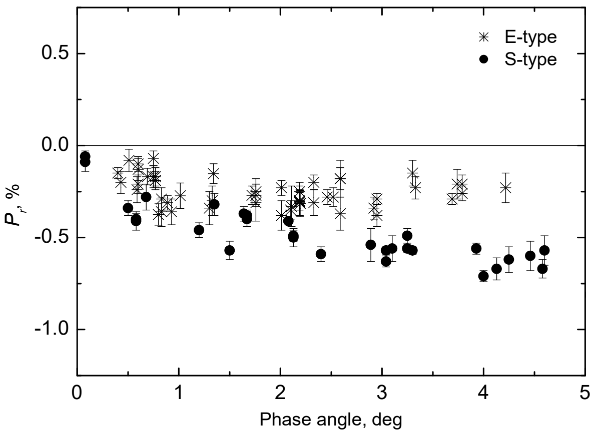

Fig.3. Polarization dependence at small phase angles for the high-albedo E-type (*Zellner and Gradie*, 1976; *Rosenbush et al.*, 2005, 2009; *Zaitsev et al.*, 2014) and the moderate albedo S-type asteroids (*Zellner and Gradie*, 1976; *Belskaya et al.*, 2003; *Fornasier et al.*, 2006a; *Gil-Hutton et al.*, 2014).

We compare the polarization behavior at small phase angles for high- and moderate-albedo asteroids in Fig.3. We plotted together all available measurements in the V and R bands having an accuracy of $\sigma_P < 0.1\%$. The moderate-albedo asteroids show a deeper negative branch down to very small phase angles. To confirm the existence of a secondary peak of negative polarization for high-albedo asteroids, more detailed and accurate measurements at α~1-2° seem to be required.

Among low-albedo asteroids, detailed observations at small phase angles were obtained for the *F*-type asteroid (1021) Flammario (*Fornasier et al.*, 2006a). The VRI observations at the phase-angle range of 0.1-1° show zero or slightly positive polarization in all filters, both before and after opposition. *Fornasier et al.* (2006a) suggested a possible explanation related to the effect of surface anisotropy. Further observations of this asteroid are needed to conclude whether or not the measured peculiarity is real.

3.4. Spectral dependence of polarization parameters

The first pioneering studies of the spectral dependence of linear polarization for the asteroids were based on broad-band multi-color measurements. *Belskaya et al.* (2009a) analyzed the observations available in UBVRI colors for 52 main-belt asteroids. Within the accuracy of the measurements, the dependence of the degree of linear polarization upon wavelength in the spectral range of 0.37–0.83 μm was generally found to be rather weak and well described by a linear trend. It was also shown that moderate and low-albedo asteroids exhibit opposite trends. This behavior, previously found for several C and S-type asteroids (*Belskaya et al.*, 1987; *Lupishko and Kiselev*, 1995) was confirmed with better statistics.

More recently, *Bagnulo et al.* (2015) have published the first example of full-fledged spectro-polarimetric measurements of asteroids for a sample of 12 asteroids. The obtained results are in agreement with the *Belskaya et al.* (2009a) findings. Polarization data covering the spectral range of 0.39-0.93 μm have a positive linear slope as a function of wavelength in the case of low-albedo asteroids, whereas moderate-albedo asteroids show a negative linear slope. We note that the values of polarization degree were considered with their signs, i.e., a *negative* spectro-polarimetric slope means, for increasing wavelength, *more* polarization in the red in the negative branch and *less* polarization in the red in the positive branch. Conversely, if one considers the spectral behavior of the absolute value of P_r, the sign of the spectral gradients $|\Delta P_\mathrm{r}|/\Delta\lambda$ for the negative and positive branches is found to have opposite values. The latter approach had been previously adopted by *Lupishko and Kiselev* (1995) who discussed the inversion of the polarization spectral dependence for the S-class asteroids. Differences in the definition of the spectro-polarimetric slopes, however, do not influence the interesting conclusion about the occurrence of opposite spectro-polarimetric behavior for moderate and low-albedo asteroids. For increasing wavelength, the negative branch of moderate-albedo asteroids becomes deeper, whereas the positive polarization becomes shallower. Low-albedo asteroids exhibit exactly an opposite behavior (*Belskaya et al.*, 2009a; *Bagnulo et al.*, 2015).

Several exceptions exist, however. Two moderate-albedo asteroids with large inversion angles, (234) Barbara and (599) Luisa, showed a shallower negative branch for increasing wavelength, while another Barbarian, (236) Honoria, has an opposite trend, typical for moderate-albedo asteroids (*Belskaya et al.,* 2009a; *Bagnulo et al.,* 2015). Among low-albedo asteroids, (87) Sylvia and (386) Siegena were mentioned as having atypical wavelength behaviour (*Belskaya et al.*, 2009a). New and more accurate polarimetric measurements of these objects are needed to clarify the situation.

Note that the study of the spectral dependence of positive polarization for low albedo asteroids is still based on a small amount of data. What seems reasonably certain is that the polarization spectra of Ceres and Pallas measured at α~22-23° are characterized by a similar increase of polarization degree with wavelength (*Bagnulo et al.,* 2015).

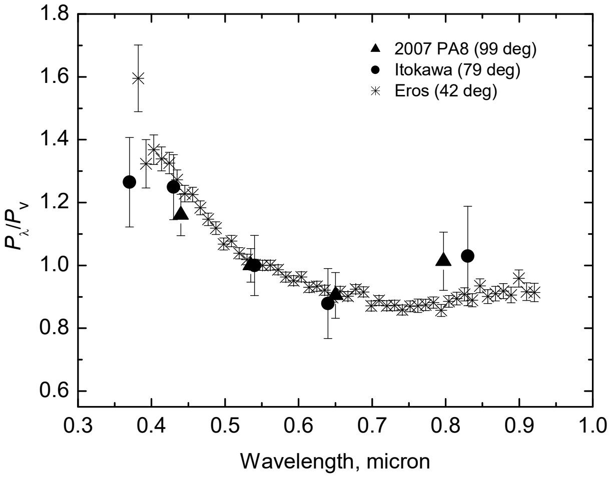

Fig.4. Wavelength dependence of moderate-albedo NEAs (433) Eros (*Bagnulo et al.*, 2015), (25143) Itokawa (*Cellino et al.*, 2005b), and (214869) 2007 PA$_8$ (*Fornasier et al.*, 2015). The phase angle at which the dependence was measured is shown in the parentheses.

As for moderate-albedo asteroids, some spectral gradients of positive polarization have been reliably measured so far for several NEAs. The BVRI polarimetry of the *Q*-type NEA 214869 (2007 PA$_8$) close to $P_{\max}$ shows a non-linear wavelength dependence of polarization (*Fornasier et al.,* 2015) which is similar to that of other moderate-albedo asteroids measured at large phase angles (Fig.4). A similar non-linear polarization spectrum was measured for the S-type asteroid Eros at a phase angle of 42° (*Bagnulo et al.*, 2015). The spectro-polarimetric behaviour of these S or Q-type NEAs shows an inverse correlation with the reflectance spectra in accordance with the Umov effect (*Umov*, 1905). A decrease of reflectance due to the 1-μm absorption feature results in an increase of polarization degree at λ>0.8 μm.

For the negative branch, the correlation between the spectro-polarimetric spectrum and the spectral reflectance is more complex. *Bagnulo et al.* (2015) have shown that some asteroids with similar reflectance spectra exhibit totally different polarization spectra. As a rule, the negative polarization of *S*-type asteroids becomes stronger at longer wavelengths for increasing albedo, i.e., a higher albedo corresponds to a deeper $|P_{\min}|$. This contradicts the well-known inverse correlation of $|P_{\min}|$ and albedo used for asteroid albedo estimations. Low-albedo asteroids tend to follow the more usual inverse correlation of $|P_{\min}|$ and albedo.

More in general, it seems that asteroid spectro-polarimetry promises to be a very important tool for the physical characterization of asteroids. The reason is that one single spectro-polarimetric measurement is able to provide, at the same time, the information usually included separately in spectroscopic and polarimetric data, complemented with the dependence of polarization upon wavelength, another piece of information to classify the behaviour of the asteroids.

4. ADVANCES IN THEORETICAL AND EXPERIMENTAL MODELING

4.1. Theoretical modeling

The understanding of the physical mechanisms responsible for the formation of the negative branch of polarization continues to improve. The role of the coherent-backscattering mechanism (CBM) was discussed in detail in *Asteroids III* by *Muinonen et al.* (2002). The CBM contributes both to the photometric and polarimetric phase dependences producing sharp features near opposition. To explain broad negative branches, the contribution of single-particle scattering becomes important (e.g., *Shkuratov et al.,* 1994, 2006; *Lumme and Rahola*, 1998). Recently, a standing-wave polarization mechanism (SWM) has been proposed for the negative linear polarization of single spherical and non-spherical particles (*Muinonen et al.*, 2011). The SWM for negative polarization relies on the generation of forward and backward propagating internal waves within the single scattering particles. Near the particle perimeter, these wave components form a standing wave that constitutes itself as an interference dial (*Muinonen et al.*, 2011). For a linearly polarized incident wave, the internal standing wave, partially linearly polarized as the incident wave, tends to be stronger in the central plane perpendicular to the incident polarization. Due to an interference effect largely resembling that of the CBM, the backward propagating wave component gives rise to negative polarization.

Several attempts were made to simulate the negative polarization of particulate surfaces. Computer modeling has been carried out by *Shkuratov et al.* (2002) and *Stankevich et al.* (2007), and applied to explain some systematic trends observed in laboratory measurements.

The successful application of the Discrete Dipole Approximation method (DDA) to the interpretation of the polarization properties of cometary dust (e.g., *Zubko et al.*, 2008, *Lasue et al.,* 2009) is also noted. In particular, an analog of the Umov effect was found for single-particle scattering (*Zubko et al.*, 2011).

Mishchenko et al. (2009) used numerically exact computer solutions of the Maxwell equations to simulate electromagnetic scattering by realistic models consisting of large numbers of randomly positioned, densely packed particles. They have shown that the negative polarization produced by the coherent backscattering effect is remarkably immune to packing-density effects. In this case, the negative polarization branch may become rather wide. The branch survives the increasing density, even if the characteristic distances between particles are of order of the wavelength.

Petrov et al. (2011) developed *Sh*-matrix methods within the *T*-matrix formalism, which allows for the derivation of analytic solutions to the light scattering by non-spherical particles. This allows for a more efficient study of scattering by irregularly shaped particles.

Quantitative agreement was documented between the computations by the radiative-transfer coherent-backscattering method (RT-CB; *Muinonen*, 2004) and the superposition *T*-matrix method (STMM) based on a direct computer solver of the Maxwell equations (*Muinonen et al.*, 2012). The RT-CB method makes use of so-called phenomenological fundamental single scatterers (*Muinonen and Videen*, 2012). An extension of the RT-CB method to a realistic particulate model for an asteroid's surface is in progress.

4.2. Laboratory experiments

Laboratory measurements devoted to the interpretation of asteroid polarimetry were rather scarce last decade (e.g., *Shkuratov et al.*, 2008). Measurements of possible meteorite analogs of the surfaces of asteroids (21) Lutetia and (2867) Steins, the targets of the Rosetta space mission, were made by *Hadamcik et al.* (2010, 2011). An average size of regolith grains smaller than 50 μm was suggested from the measurements.

The influence of particle size on the polarization phase curve was studied on particle-size separates of bright and absorbing powders (*Ovcharenko et al.*, 2006; *Shkuratov et al.*, 2008). They showed that the contributions of both the CBM and single-particle scatter are functions of particle size.

Several experiments were made to compare polarimetric properties of single particles and powdered surfaces (see *Levasseur-Regourd et al.*, 2015 for a review). *Shkuratov et al.* (2007, 2008) showed that the negative polarization strengthened and the polarization degree at large phase angles increased with surface compression. The number density of the particles was found to have a major effect on the polarization maximum (*Hadamcik et al.,* 2009).

Promising results were obtained when comparing laboratory measurements and results of numerical DDA simulations: *Zubko et al.* (2013) used experimentally measured refractive-index and size-distribution data for irregular feldspar particles to compute Mueller-matrix elements, obtaining highly consistent results.

Laboratory studies of structural analogs of asteroid regoliths remains of a great need for further progress in interpreting polarimetric measurements of asteroids.

5. POLARIMETRIC MEASUREMENTS AS A TOOL TO ASSESS SURFACE PROPERTIES

The interpretation of polarimetric observations of asteroids in terms of physical parameters is still not straightforward. The main conclusions about asteroid surface properties as derived from polarimetric measurements are mostly based on empirical relationships. Particular importance has the relation between polarimetric parameters and albedo, and the analysis of similarities and differences in the polarization behavior of various objects.

5.1. Polarimetric method of asteroid albedo determination

Polarimetry is one of the best available techniques to derive the albedo from remote observations. An advantage is that an estimate of the albedo can be derived directly from polarimetric measurements without any need of ancillary information from other sources (*Bowell and Zellner,* 1974; *Zellner and Gradie*, 1976; *Zellner et al.*, 1977). This is in contrast with other possible methods of albedo determination, primarily from thermal radiometry, for which the accuracy is limited by the uncertainties in the adopted values of the absolute magnitude. In fact, a few single measurements of polarization degree at a phase angle within 7-10 deg (near the extreme values of negative polarization) or even one single measurement at phase angles larger than 30 deg (in the positive branch of polarization) can be enough to conclude whether an asteroid has a low, moderate, or high-albedo surface. In order to determine a more precise value for the albedo (geometric albedo), the observations should cover at least 4 different phase angles to measure the polarimetric slope *h* with good accuracy. This number of observations is a minimum to reach a reliable result. This also constitutes a practical problem, due to the effort needed to observe the target in several observing runs, to allow the necessary change in the phase angle.

Another problem is the one of producing a reliable calibration of the empirical relationships "albedo – polarimetric slope" and "albedo – $P_{\min}$" used to determine the albedos of asteroids. Historically, these relations were derived from laboratory measurements of meteorites and then used to determine asteroid albedos (*Zellner and Gradie*, 1976).

Several attempts have been made since then to better calibrate the relationship using the albedos of asteroids available from radiometry and/or from stellar occultations (*Lupishko and Mohamed*, 1996; *Cellino et al.,* 1999, 2012; *Masiero et al.,* 2012). Most recently, *Cellino et al.* (2015b) perform a new, detailed analysis of the calibration problem of the relations between the geometric albedo and the polarization parameters of the asteroids. In all the above mentioned papers, the authors derived their own values for the constant parameters C_1 and C_2 of the commonly adopted relationship between the geometric albedo A_g and polarimetric slope *h,* namely:

TABLE 1. List of the constants C_1 and C_2 for the relationship between the geometric albedo and the polarimetric slope *h* used for asteroid albedo estimation

Source of albedo data used for calibration	C_1	C_2	Albedo			References
			h=0.04	h=0.10	h=0.30	
Meteorites	-1.00	-1.78	0.415	0.166	0.055	*Bowell and Zellner.* 1974
Meteorites	-0.92	-1.72	0.368	0.158	0.058	*Zellner et al.*, 1977
IRAS/Occultations/ Space-based	-0.983 ±0.082	-1.731 ±0.066	0.440	0.179	0.061	*Lupishko and Mohamed*, 1996
IRAS	-1.118 ±0.071	-1.779 ±0.062	0.608	0.218	0.064	*Cellino et al.*, 1999
Occultations	-0.970 ±0.071	-1.667 ±0.083	0.489	0.201	0.069	*Cellino et al.*, 2012
WISE	-1.207 ±0.067	-1.892 ±0.141	0.624	0.207	0.055	*Masiero et al.*, 2012

Occultations	-1.124 ±0.032	-1.789 ±0.025	0.606	0.216	0.063	*Cellino et al.*, 2015b

$$\log\left(A_g\right) = C_1 \log(h) + C_2 \qquad (1)$$

We have analyzed how adopting different published calibrations influences the derived values of albedo. Table 1 lists the available sets of constants C_1 and C_2 found by different authors and the references to the corresponding papers. We also give the albedos calculated from Equation 1 for three fixed values of the polarimetric slopes *h* corresponding to low, moderate and high-albedo asteroids. For low and moderate-albedo surfaces, the uncertainties in the polarimetric albedos due to different calibrations are comparable with the uncertainties caused by the errors in the measurements of the polarimetric slope *h*. A noticeable discrepancy appears in the case of high-albedo surfaces. Further investigation of the relationship of polarimetric slope and albedo for high-albedo asteroids is crucial to choose the best calibration.

The use of $P_{\min}$ for albedo determination gives less confident results. For example, in Figure 2 the polarization phase curve of the F-type objects and that of the Barbarians show similar values of $P_{\min}$ in spite of these objects having very different albedos. *Cellino et al.* (2015b) found large discrepancies between $P_{\min}$-derived albedos and those obtained from other data and recommend avoiding the use of $P_{\min}$ for the albedo estimation.

There were also some attempts to find new polarimetric parameters which better correlate with albedo. *Masiero et al.* (2012) introduced a new polarimetric quantity p^* combining *log (h)* and *log* ($P_{\min}$) in order to describe the maximum polarimetric variation when compared with the albedo and presented the albedo-p^* relation. *Cellino et al.* (2015b) proposed to use the difference in polarization degree at α=30° and α=10° as a new parameter. The comparison of albedos derived from different polarimetric parameters was generally in favour of the polarimetric slope *h,* mainly in cases when the coverage of the phase – polarization curve is not optimal. In these cases, a simple linear fit of observations around the inversion angle gives often reasonably accurate results (*Cellino et al.,* 2015b).

Last decade, many polarimetric measurements were carried out to determine albedos of particularly interesting asteroids, such as potentially hazardous near-Earth objects (*Belskaya et al.*, 2009b; *Fornasier et al.*, 2015; *Delbo et al.*, 2007; *De Luise et al.,* 2007) and targets of space missions (*Cellino et al.,* 2005b; *Fornasier et al.*. 2006b). In general, albedos derived from the polarimetric slope are consistent with the data of direct *in situ* measurements (e.g., *Fornasier et al.,* 2006b).

5.2. Regolith properties derived from polarimetry

The relationship between the two parameters characterizing the negative polarization branch $P_{\min}$ and α_{inv} has long been considered as diagnostic of the surface texture (*Dollfus et al.,* 1989). According to laboratory measurements, the bare silicate rocks and fine-grained lunar samples occupy two distinct domains in the plot $P_{\min}$ vs. α_{inv}. The pulverized rocks and meteorites with grain sizes typically between 30 and 300 μm, as well as asteroid data, lie generally in between these two domains. The general agreement of asteroid polarization phase curves with those of pulverized meteorites is considered as an indication of their similar texture.

An updated relationship between $P_{\min}$ vs. α_{inv} for asteroids is shown in Fig.5. The domains for bare rocks and lunar fines as plotted by *Dollfus et al.* (1989) are also indicated. With new data, the range of inversion angles inherent for asteroid surfaces was found to be wider than previously considered. The *F*-class asteroids with small inversion angles occupy the domain for bare rocks, while Barbarians lie behind the domain for lunar fines. Asteroid (21) Lutetia, for which the composition is still under debate (see *Barucci et al.*, 2012), belongs to the domain for lunar fines. The asteroids of the same composition class have a tendency to group in the plot of $P_{\min}$ vs. α_{inv}. This result suggests that a wide range of the inversion angles is most probably related to surface mineralogy rather than to variations of particle size of the regolith.

Penttilä et al. (2005) made a statistical analysis of the published polarimetric data of 100 asteroids in order to find relationships with

Tholen's taxonomy (*Tholen* 1984). They found groups among phase-polarization curves which agree with the published taxonomic classifications and concluded that polarimetry may provide a complementary approach for classification. Subsequent observations have confirmed that asteroids of the same taxonomic class exhibit a similar polarization phase behavior.

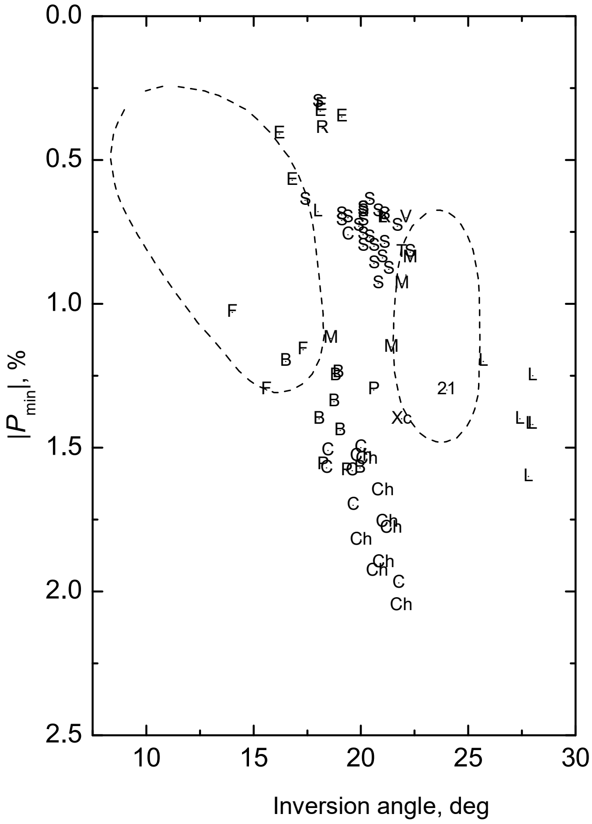

Fig.5. Relationship between $P_{\min}$ vs. α_{inv} for asteroids of different taxonomic types (shown by letters). The domains for bare rocks and lunar fines as indicated by *Dollfus et al.* (1989) are also shown.

Fornasier et al. (2006a) showed that polarimetric values obtained for 36 asteroids of different classes are typically within the range of average polarization-phase curves of a corresponding taxonomic class. Only five asteroids in the data set were outside the typical values of their classes, which may be due to either an erroneous taxonomic classification or their particular surface properties.

Gil-Hutton and Cañada-Assandri (2011) carried out polarimetric measurements for 56 *S*-, *L*-, *Ld*-, and *K*-type asteroids and found clear differences between their mean polarization phase curves. Polarimetry of 58 *B*- and *C*-type objects was presented by *Gil-Hutton and Cañada-Assandri* (2012). They found that *Ch*- and *C*-type objects show deeper negative branches than *Cb*- or *B*-types. *Cañada-Assandri et al.* (2012) observed 33 *X*-type objects and demonstrated clear differences in the average phase-polarization curve for objects classified as *M*- and *P*-type by *Tholen* (1984). A large polarimetric survey of 129 main-belt asteroids has shown that the obtained data well agree with the average polarization phase curves of the corresponding types (*Gil-Hutton et al.*, 2014).

The fact that the polarimetric properties of asteroids belonging to the same taxonomic classes are essentially identical suggests similar regolith micro-texture for them. Two extreme cases of inversion angles can be explained by optically homogeneous regolith microstructure in the case of small α_{inv} (*Belskaya et al.,* 2005) and heterogeneous regolith formed by a mixture of components with highly different optical properties in the case of large α_{inv} (*Gil-Hutton et al.,* 2008). To understand interrelations of the surface mineralogy and texture, more laboratory and numerical modelling is needed.

5.3. Application to study NEAs

Observations of NEAs give a unique possibility to investigate polarization phase dependence at large phase angles close to polarization maximum.

Recent polarimetric observations of the NEA (23187) 2000 PN$_9$ were made at the largest phase angle α=115° ever observed in asteroid polarimetry (*Belskaya et al.*, 2009b). The value of maximum polarization was estimated to be $P_{\max}$ ~7.7% at $\alpha_{\max}$~103° which is close to the previous estimations for the moderate-albedo NEAs. The *Q*-type NEA 214869 (2007 PA$_8$) showed smaller positive polarization with $P_{\max}$ ~6% at $\alpha_{\max}$~100° in the V band (*Fornasier et al.*, 2015). The polarimetric properties of the asteroid 214869 (2007 PA$_8$) are very close to those of the asteroid (25143) Itokawa (*Cellino et al.*, 2005b), suggesting possible similarity of their surface properties.

Two *E*-type asteroids measured at large phase angles (*Kiselev et al.*, 2002, *De Luise et al.*, 2007) provided a preliminary estimation of $P_{\max}$ ~2.3% at $\alpha_{\max}$~80° for a high-albedo object.

For low albedo asteroids, no value of $P_{\max}$ has been measured so far. The only one observation at large phase angle for (2100) Ra-Shalom gave P ~11% at $\alpha_{\max}$~60° (*Kiselev et al.*, 1999).

Large differences in the polarization degree for high, moderate, and low-albedo asteroids give a unique way to select primitive low-albedo NEAs by a single polarimetric measurement at $\alpha > 40°$. Estimations of albedo of potentially hazardous NEAs are another important application of polarimetric observations. Using instruments like the ESO 8-m VLT telescope, it is possible to obtain albedos and sizes of hazardous objects, as demonstrated by the recent observations of (99942) Apophis (*Delbò et al.*, 2007).

5. CONCLUSIONS AND FUTURE WORK

Extensive observational campaigns in the last decade considerably increased the number of asteroids with published polarimetric measurements. These campaigns led to the discovery of asteroids with peculiar polarimetric properties, characterized by narrow negative polarization branches with small inversion angles and wide negative branches with large inversion angles. Further observations have shown that these properties are related to surface mineralogy. All asteroids showing small inversion angles belong to the *F*-class asteroids, which currently are no longer identified as a separate class. Asteroids with large inversion angles, called Barbarians, seem to belong to the *L* class identified by *DeMeo et al.* (2009), using both visible and near-IR spectral data. A possible interpretation of their peculiar polarimetric properties is the presence of spinel in CAI in their surfaces. These are cases, in which even a single polarimetric measurement at a suitable phase angle can be sufficient to provide a classification, something that is not always possible based on spectroscopic data at visible wavelengths. Polarimetric measurements can be an effective tool for asteroid taxonomy.

Traditional application of polarimetry to determine asteroid albedos is especially efficient in the study near-Earth asteroids. Polarimetry has been successfully used to estimate size and albedo of potentially hazardous NEAs. Even a single polarimetric measurement at large phase angles can give a prompt assessment of an asteroid's geometric albedo.

In the following years the use of new polarimeters based on CCD detectors will extend available data to increasingly smaller objects and will allow the study of different groups which are important for the understanding of the physical evolution of the asteroid belt. Polarimetric observations of several members of asteroid families will shed some light on their surface properties and will also be used to detect interlopers (*Milani et al.*, 2014). On the other hand, the knowledge of the polarization phase curve and polarimetric parameters of different taxonomic classes not yet studied will give information about the relation between polarimetry and taxonomic classification. Finally, the analysis of larger numbers of spectro-polarimetric observations will be used as a tool to reach more robust conclusions about the relation between polarimetric parameters and mineralogy.

In the theoretical modeling of asteroid polarimetry, there are remarkable future prospects for a rigorous, numerical multiple-scattering model where the limitations of the far-field interactions in the RT-CB method will be removed. Prior to this advance, it is plausible that an approximate RT-CB method will be extended to depolarizing, nonspherical single scatterers. Such an advance will allow for the ensemble-averaged, either experimentally measured or numerically computed, scattering matrices to be fully utilized in the interpretation of asteroid polarimetry.

Great progress in polarimetric instrumentation significantly expands the opportunities for polarimetric observations of asteroids. With the improvement of interpretation models and theory, we will enter a new era of extensive application of the polarimetric technique to the study of asteroids.

Acknowledgments

Part of this work has been supported by the COST Action MP1104 "Polarization as a tool to study the Solar System and beyond", the ERC Advanced Grant No 320773 entitled "Scattering and Absorption of Electromagnetic Waves in Particulate Media" (SAEMPL), and by the Academy of Finland (contract 257966). RGH gratefully acknowledges financial support by CONICET through PIP 114-200801-00205 and PIP 114-201101-00358. We are grateful to Dmitrij Lupishko and Anny-Chantal Levasseur-Regourd for useful comments.

REFERENCES

Antonyuk K. A. and Kiselev N. N. (2012) 554 Peraga - an asteroid with unusual polarization properties? *Solar System Res.*, 46, No. 1, 54-56.

Appenzeller I., Fricke K., Furtig W., et al. (1998) Successful commissioning of FORS1 - the first optical instrument on the VLT. *The Messenger,* 94, 1-6.

Bagnulo S., Tozzi G. P., Boehnhardt H., Vincent J.-B., Muinonen K. (2010) Polarimetry and photometry of the peculiar main-belt object 7968 = 133P/Elst-Pizarro. *Astron. Astrophys.*, 514, id.A99, 13 pp.

Bagnulo S., Belskaya I. N., Boehnhardt H., Kolokolova L., Muinonen K., Sterzik M., and Tozzi G.-P. (2011) Polarimetry of small bodies of the solar system with large telescopes, *J. Quantit. Spectrosc. Radiat. Transf.,* 112, 2059-2067.

Bagnulo S., Cellino A., Sterzik M. (2015) Linear spectro-polarimetry: a new diagnostic tool for the classification and characterisation of asteroids. *MNRAS Letters*, 446, L11-L15.

Barucci M. A., Belskaya I. N., Fornasier S., et al. (2012) Overview of Lutetia's surface composition. *Planet. Space Sci.*, 66, 23-30.

Belskaya I. N., Lupishko D. F., and Shakhovskoy N. M. (1987) Negative Polarization Spectra for Five Asteroids. *Soviet Astron. Letters,* 13, 219-220.

Belskaya I. N., Shevchenko V.G., Kiselev N.N., Krugly Yu.N., Shakhovskoy N.M., Efimov Yu. S., Gaftonyuk N. M., Cellino A., and Gil-Hutton R. (2003) Opposition polarimetry and photometry of S- and E-type asteroids. *Icarus*, 166, 276-284.

Belskaya I. N., Shkuratov Y. G., Efimov Yu. S., Shakhovskoy N. M., Gil-Hutton R., Cellino A., Zubko E. S., Ovcharenko A. A., Bondarenko S. Y., Shevchenko V. G., Fornasier S., and Barbieri C. (2005) The F-type asteroids with small inversion angles of polarization. *Icarus*, 178, 213-221.

Belskaya I. N., Levasseur-Regourd A. C., Cellino A., Efimov Y. S., Shakhovskoy N. M., Hadamcik E., and Bendjoya, Ph. (2009a). Polarimetry of main belt asteroids: Wavelength dependence. *Icarus*, 199, 97-105.

Belskaya I. N., Fornasier S., and Krugly Y.N. (2009b) Polarimetry and BVRI photometry of the potentially hazardous near-Earth Asteroid (23187) 2000 PN_9. *Icarus*, 201, 167-171.

Belskaya I.N., Fornasier S., Krugly Y. N., Shevchenko V. G., Gaftonyuk N. M., Barucci, M. A., and Fulchignoni M. (2010) Puzzling asteroid 21 Lutetia: our knowledge prior to the Rosetta fly-by. *Astron. Astrophys.*, 515, A29.

Belskaya I. N., Stinson A., Bagnulo S., Christou A., and Muinonen K. (2014). Polarimetric observations of Jupiter Trojans. In: *European Planetary Science Congress 2014*, Abstract #EPSC2014-727.

Boehnhardt H., Tozzi G. P., Bagnulo S., Muinonen K., Nathues A., and Kolokolova L. 2008 Photometry and polarimetry of the nucleus of comet 2P/Encke *Astron. Astrophys*., 489, 1337-1343.

Bowell E. and Zellner B. (1974) Polarization of asteroids and satellites, In *Planets, Stars, and Nebulae Studied with Photopolarimetry* (T. Gehrels, ed.), pp.381-404. Univ. Arizona Press, Tuscon, Arizona.

Burbine T. H., Gaffey M. J., and Bell J. F. (1992) S-asteroids 387 Aquitania and 980 Anacostia - Possible fragments of the breakup of a spinel-bearing parent body with CO3/CV3 affinities. *Meteoritics*, 27, 424-434.

Bus S. J. and Binzel R. P. (2002) Phase II of the Small Main-Belt Asteroid Spectroscopic Survey. A Feature-Based Taxonomy. *Icarus*, 158, 146-177.

Cañada-Assandri M., Gil-Hutton R., and Benavidez P. (2012) Polarimetric survey of main-belt asteroids. III. Results for 33 X-type objects. *Astron. Astrophys*, 542, A11.

Cellino A., Gil Hutton R., Tedesco E. F., Di Martino M., and Brunini A. (1999) Polarimetric observations of small asteroids: preliminary results. *Icarus*, 138, 129-140.

Cellino A., Zappalà V., Doressoundiram A., Di Martino M., Bendjoya Ph., Dotto E., and Migliorini F. (2001) The puzzling case of the Nysa-Polana family. *Icarus*, 152, 225-237.

Cellino A., Gil-Hutton R., di Martino M., Bendjoya Ph., Belskaya I. N., and Tedesco E. F. (2005a) Asteroid polarimetric observations using the Torino UBVRI photopolarimeter. *Icarus,* 179, 304-324.

Cellino A., Yoshida F., Anderlucci E., Bendjoya Ph., Di Martino M., Ishiguro M., Nakamura

A.M., and Saito J. (2005b) A polarimetric study of asteroid 25143 Itokawa. *Icarus*, 179, 297-303.

Cellino A., Belskaya I. N., Bendjoya Ph., Di Martino M., Gil-Hutton R., Muinonen K., and Tedesco E. F. (2006) The strange polarimetric behavior of asteroid (234) Barbara. *Icarus*, 180, 565-567.

Cellino A., Delbò M., Bendjoya Ph., and Tedesco E. F. (2010) Polarimetric evidence of close similarity between members of the Karin and Koronis dynamical families. *Icarus*, 209, 556-563.

Cellino A., Dell'Oro A., Bendjoya Ph., Cañada-Assandri M., and Di Martino M. (2012) A new calibration of the albedo–polarization relation for the asteroids, *J. Quantit. Spectrosc. Radiat. Transf.,* 113, 2552-2560.

Cellino A., Bagnulo S., Tanga P., Novakovic B., and Delbò M. (2014). A successful search for hidden Barbarians in the Watsonia asteroid family. *MNRAS*, 439, L75-L79.

Cellino A., Gil-Hutton R., and Belskaya I. (2015a) Polarimetry of asteroids. In: *Polarimetry of stars and planetary systems* (L. Kolokolova, A.-C. Levasseur-Regourd, J. Hough, eds.), 20 pp., Cambridge University Press, Cambridge, U.K, in press.

Cellino A., Bagnulo S., Gil-Hutton R., Tanga P., and Cañada-Assandri M. (2015b). On the calibration of the relation between geometric albedo and polarimetric properties for the asteroids. *MNRAS*, accepted.

De Luise F., Perna D., Dotto E., Fornasier S., Belskaya I.N., Boattini A., Valsecchi G., Milani A., Rossi A., Lazzarin M., Paolicchi P., and Fulchignoni M. (2007) Physical investigation of the potentially hazardous Asteroid (144898) 2004 VD17. *Icarus*, 191, 628-635.

Delbò M., Cellino A., and Tedesco E. F. (2007) Albedo and size determination of potentially hazardous asteroids: (99942) Apophis. *Icarus*, 188, 266-269.

DeMeo F. E., Binzel R. P., Slivan S. M., and Bus S. J. (2009) An extension of the Bus asteroid taxonomy into the near-infrared. *Icarus*, 202, 160-180.

Dollfus A. (1971). Physical studies of asteroids by polarization of the light. In: *Physical studies of Minor Planets* (T. Gehrels, ed.), pp. 95-116. NASA SP-267, Washington.

Dollfus A., Wolff M., Geake J.E., Lupishko D.F., and Dougherty L.M. (1989) Photo-polarimetry of asteroids. In *Asteroids II* (R.P. Binzel, T. Gehrels, M.S. Matthews, Eds.), pp. 594-616, Univ. Arizona Press, Tucson.

Dollfus A., and Zellner B. (1979) Optical polarimetry of asteroids and laboratory samples. In *Asteroids* (T. Gehrels, Ed.), pp. 170-183 Univ. Arizona Press, Tucson.

Fornasier S., Beskaya I.N., Shkuratov Yu.G., Pernechele C., Barbieri C., Giro E., and Navasardyan H. (2006a) Polarimetric survey of asteroids with the Asiago telescope. *Astron. Astrophys.*, 455, 371-377.

Fornasier S., Belskaya I.N., Fulchignoni M., Barucci M.A., and Barbieri C. (2006b) First albedo determination of 2867 Steins, target of the Rosetta mission. *Astron. Astrophys.*, 449, L9-L12.

Fornasier S., Beskaya I.N., Perna D. (2015) The potentially hazardous asteroid 2007 PA8: an unweathered L chondrite analogue surface. *Icarus*, 250, 280-286.

Gil-Hutton R. (2007) Polarimetry of M-type asteroids. *Astron. Astrophys*, 464, 1127-1132.

Gil-Hutton R., Mesa V., Cellino A., Bendjoya Ph., Peñaloza L., and Lovos F. (2008) New cases of unusual polarimetric behavior in asteroids. *Astron. Astrophys.*, 482, 309-314.

Gil-Hutton R. and Cañada-Assandri M. (2011) Polarimetric survey of main-belt asteroids. I. Results for fifty seven S-, L-, and K-type objects. *Astron. Astrophys.*, 529, A86.

Gil-Hutton R. and Cañada-Assandri M. (2012) Polarimetric survey of main-belt asteroids. II. Results for 58 B- and C-type objects. *Astron. Astrophys.*, 539, A115.

Gil-Hutton R., Cellino A., Bendjoya Ph. (2014) Polarimetric survey of main-belt asteroids. IV. New results from the first epoch of the CASLEO survey. *Astron. Astrophys.*, 569, id.A122, 6 pp.

Hadamcik E., Renard J.-B., Levasseur-Regourd A.C., and Worms J.C. (2009) Laboratory measurements of the light scattered by clouds of solid particles by imaging technique, In: *Light scattering reviews 4* (Kokhanovsky, A.A., Ed.), pp. 31-70, Springer, Berlin.

Hadamcik E., Levasseur-Regourd A.C., and Renard J.-B. (2010) Observations and laboratory simulations of asteroids by polarization measurements. In: *Electro-*

*magnetic and light scattering XII (*Muinonen K., Penttilä, A., and Lindqvist H., Eds.), pp.70-73, Univ. Helsinki, Helsinki.

Hadamcik E., Levasseur-Regourd A.C., Renard J.-B., Lasue J., and Sen A.K. (2011) Polarimetric observations and laboratory simulations of asteroidal surfaces: The case of 21 Lutetia. *J. Quantit. Spectrosc. Radiat. Transf.*, 112, 1881-1890.

Hough J. H. (2005) Polarimetry techniques at optical and infrared wavelengths, In: *ASP conf. series,* 343, 11 pages.

Kaasalainen S., Piironen J., Kaasalainen M., Harris A. W., Muinonen K., and Cellino A. (2003) Asteroid photometric and polarimetric phase curves: empirical interpretation. *Icarus*, 161, 34-46.

Keller C.U., Snik F., Harrington D.M., and Packham C. (2015). Instrumentation. In: *Polarimetry of stars and planetary systems* (L. Kolokolova, A.-C. Levasseur-Regourd, J. Hough, eds.), 25 pp., in press, Cambridge University Press, Cambridge, U.K.

Kiselev N. N, Rosenbush V. K., and Jockers K. (1999) NOTE: Polarimetry of Asteroid 2100 Ra-Shalom at Large Phase Angle. *Icarus*, 140, 464-466.

Kiselev N. N., Rosenbush V. K., Jockers K., Velichko F. P., Shakhovskoy N. M., Efimov Y. S., Lupishko D. F., and Rumyantsev V. V. (2002) Polarimetry of near-Earth asteroid 33342 (1998 WT24). Synthetic phase angle dependence of polarization for the E-type asteroids. In: *Proceedings of Asteroids, Comets, Meteors - ACM 2002* (B. Warmbein, Ed.), pp. 887 – 890, ESA SP-500. Noordwijk, Netherlands.

Kolokolova L., and Jockers K. (1997) Composition of cometary dust from polarization spectra. *Planet. Space Sci.*, 45, 1543–1550.

Lasue, J., Levasseur-Regourd, A.C., Hadamcik, E., and Alcouffe, G. (2009) Cometary dust properties retrieved from polarization observations: application to C/1995 01 Hale-Bopp and 1P/Halley. *Icarus*, 199, 129-144.

Levasseur-Regourd A.C., Renard J.-B., Shkuratov Y., and Hadamcik E. (2015) Laboratory studies. In: *Polarimetry of stars and planetary systems* (L. Kolokolova, A.-C. Levasseur-Regourd, J. Hough, eds.), 15 pp., in press, Cambridge University Press, Cambridge, U.K.

Lumme K. and Muinonen K. (1993) A two-parameter system for linear polarization of some SolarSystem objects. In *IAU Symposium 160, Asteroids, Comets, Meteors*, Abstract p. 194

Lumme K. and Rahola, J. (1998). Comparison of light scattering by stochastically rough spheres, best-fit spheroids and spheres. *J. Quantit. Spectrosc. Radiat. Transf.,* 60, 439–450.

Lupishko D.F. and Kiselev N.N. (1995) Inversion effect of spectral dependence of asteroid polarization. *BAAS*, 27, 1064.

Lupishko D.F. and Mohamed R.A. (1996) A new calibration of the polarimetric albedo scale of asteroids. *Icarus*, 119, 209-213.

Lupishko D.F. and Vasiliev S.V. (1997) Asteroid Polarimetric Database. *Kinematics and Physics of Celestial Bodies,* 13, No. 3, 17-23.

Lupishko D. F. (2014) Asteroid Polarimetric Database V8.0. *NASA Planetary Data System*, EAR-A-3-RDR-APD-POLARIMETRY-V8.0.

Maleszewski C., McMillan R. S., and Smith P.S. (2013) Contrasting Q-type Asteroid Regolith from the S-complex Through Polarimetry. In *American Astronomical Society, DPS meeting* #45, Abstract #208.14.

Masiero J., Hodapp K., Harrington D., and Lin H. S. (2007) Commissioning of the Dual-Beam Imaging Polarimeter for the University of Hawaii 88 inch Telescope. *PASP,* 119, 1126-1132.

Masiero J. and Cellino A. (2009). Polarization of Asteroid (387) Aquitania: The newest member of a class of large inversion angle asteroids. *Icarus*, 199, 333-337.

Masiero J., Hartzell C., and Scheers D.J. (2009) The effect of the dust size distribution on asteroid polarization, *Astron. J*, 138, 1557–1562.

Masiero J. (2010) Albedo heterogeneity on the surface of (1943) Anteros. *Icarus*, 207, 795-799.

Masiero J. R., Mainzer A. K., Grav T., et al. (2011) Main Belt Asteroids with WISE/NEOWISE. I. Preliminary Albedos and Diameters. *Astrophys. J.*, 741, id. 68, 20 pp.

Masiero J. R., Mainzer A. K., Gray T., Bauer J. M., Wright E. L., Mc Millan R. S., Tholen D.

J., and Blain A.W. (2012) A revised asteroid polarization-albedo relationship using WISE/NEOWISE data. *Astrophys. J.,* 749, id.104, 6 pp.

Milani A., Cellino A., Knežević Z., Novaković B., Spoto F, and Paolicchi P. (2014) Asteroid families classification: Exploiting very large datasets. *Icarus,* 239, 46-73.

Mishchenko M., Dlugach J., Liu L., Rosenbush V., Kiselev N., Shkuratov Y. (2009) Direct solutions of the Maxwell equations explain opposition phenomena observed for high-albedo solar system objects. *Astrophys. J. Letters*, 705, L118-L122.

Mishchenko M.I., Rosenbush V.K., Kiselev N.N., Lupishko D.F., Tishkovets V.P., Kaydash V.G., Belskaya I.N., Efimov Y.S., Shakhovskoy N.M. (2010) *Polarimetric remote sensing of Solar System objects*. Kyiv: Akademperiodyka, 291 pp.

Muinonen K. (2004) Coherent backscattering of light by complex random media of spherical scatterers: Numerical solution. *Waves in Random Media 14(3)*, 365-388.

Muinonen K., Piironen J., Shkuratov Y.G., Ovcharenko A.A., and Clark B.E. (2002) Asteroid photometric and polarimetric phase effects. In: *Asteroids III* (W. Bottke, et al. eds.), pp.123-138, Univ. Arizona Press, Tucson.

Muinonen K., Penttilä A., Cellino A., Belskaya I.N., Delbò M., Levasseur-Regourd A.C., Tedesco E.F. (2009) Asteroid photometric and polarimetric phase curves: Joint linear-exponential modeling. *Meteoritics and Planetary Science*, 44, 1937-1946.

Muinonen K., Tyynelä J., Zubko E., Lindqvist H., Penttilä A., and Videen G. (2011). Polarization of light backscattered by small particles. *J. Quantit. Spectrosc. Radiat. Transf.* 112, 2193-2212.

Muinonen K. and Videen G. (2012) A phenomenological single scatterer for studies of complex particulate media, *J. Quant. Spectrosc. Radiat. Transf.*, 113, 2385–2390.

Muinonen K., Mishchenko M. I., Dlugach J. M., Zubko E., Penttilä A., and Videen G. (2012) Coherent backscattering numerically verified for a finite volume of spherical particles. *Astrophys. J.* 760, 118, 11 pp.

Muinonen K., Penttilä A., and Videen G. (2015) Multiple scattering of light in particulate planetary media. In: *Polarimetry of stars and planetary systems* (L. Kolokolova, A.-C. Levasseur-Regourd, J. Hough, eds.), 17 pp., in press, Cambridge University Press, Cambridge, U.K.

Novaković B., Cellino A., and Knežević Z. (2011) Families among high-inclination asteroids. *Icarus* 216, 69-81.

Oliva T. (1997). Wedged double Wollaston, a device for single shot polarimetric measurements. *Astron. Astroph*., 123, 589-592.

Ovcharenko A.A., Bondarenko S.Y., Zubko E.S., Shkuratov Y.G., Videen G., and Nelson R. (2006) Particle size effect on the opposition spike and negative polarization, *J. Quantit. Spectrosc. Radiat. Transf.,* 101, 394-403.

Penttilä A., Lumme K., Hadamcik E., and Levasseur-Regourd A.-C. (2005) Statistical analysis of asteroidal and cometary polarization phase curves. *Astron. Astrophys.,* 432, 1081-1090.

Pernechele C., Abe L., Bendjoya Ph., Cellino A., Massone G., Rivet J. P., and Tanga P. (2012) A single-shot optical linear polarimeter for asteroid studies. *Proceedings of SPIE Ground-based and Airborne Instrumentation for Astronomy IV,* 8446, id. 84462H.

Petrov D., Shkuratov Y., Videen G. (2011) An analytical approuch to electromagnetic wave scattering from particles of arbitrary shapes. *J. Quantit. Spectrosc. Radiat. Transf.*, 112 (11), 1636-1645.

Piirola V. (1973) A double image chopping polarimeter. *Astron. Astrophys*, 27, 383-388.

Rosenbush V.K., Avramchuk V.V., Rosenbush A.E., and Mishchenko M.I. (1997) Polarization properties of the Galilean satellites of Jupiter: observations and preliminary analysis. *Astrophys. J.*, 487, 402-414.

Rosenbush V.K., Kiselev N.N., Shevchenko V.G., Jockers K., Shakhovskoy N.M., and Efimov Y.F. (2005) Polarization and brightness opposition effects for the E-type Asteroid 64 Angelina. *Icarus*, 178, 222-234.

Rosenbush V.K., Shevchenko V.G., Kiselev N.N., Sergeev A.V., Shakhovsloy N.M., Velichko F.P., Kolesnikov S.V., and Karpov N.V. (2009) Polarization and brightness opposition effects for the E-type Asteroid 44 Nysa. *Icarus*, 201, 655-665.

Scaltriti F., Piirola V., Cellino A., Anderlucci E., Corcione L., Massone G., Racioppi F., and Porcu F. (1989) The UBVRI photopolarimeter of the Torino Astronomical Observatory. *Mem. Soc. Astron. It*., 60, 243-246.

Shkuratov Y. G., Muinonen K., Bowell E., et al. (1994) A critical review of theoretical models for the negative polarization of light scattered by atmosphereless solar system bodies. *Earth Moon Planets*, 65, 201–246.

Shkuratov Yu., Ovcharenko A., Zubko E., Miloslavskaya O., Nelson R., Smythe W., Muinonen K., Piironen J., Rosenbush V., Helfenstein P. (2002) The opposition effect and negative polarization of structurally simulated planetary regoliths. *Icarus,*159. 396-416.

Shkuratov Yu., Videen G., Kreslavsky M.A., Belskaya I.N., Ovcharenko A., Kaydash V.G., Omelchenko V.V., Opanasenko N., Zubko E. (2004) Scattering properties of planetary regoliths near opposition. In: *Photopolarimetry in Remote Sensing* (Videen G. et al., eds.), pp. 191-208. NATO Sci Ser. Kluwer Acad. Publ., London.

Shkuratov Y., Bondarenko S., Ovcharenko A., Videen G., Pieters C., Hiroi T., Volten H., Hovenier J., and Munos O. (2006) Comparative studies of the reflectance and degree of linear polarization of particulate surfaces and independently scattering particles. *J. Quantit. Spectrosc. Radiat. Transf.*, 100, 340-358.

Shkuratov Y., Bondarenko S., Kaydash V., Videen G., Munos O., and Volten H. (2007) Photometry and polarimetry of particulate surfaces and aerosol particles over a wide range of phase angles *J. Quantit. Spectrosc. Radiat. Transf.*, 106, 487–508.

Shkuratov Y., Ovcharenko A., Psarev V., Bondarenko S. (2008) Laboratory measurements of reflected light intensity and polarization for selected particulate surfaces. In: *Light scattering reviews 3. Light scattering and reflection* (A. A. Kokhanovsky, Ed.), pp.383-402, Praxis Publishing Ltd., Chichester, UK.

Stankevich D., Istomina L., Shkuratov Yu., Videen G. (2007) The coherent backscattering effects in a random medium as calculated using a ray tracing technique for large non-transparent spheres. *J. Quantit. Spectrosc. Radiat. Transf.*, 106, 509–519.

Sunshine J., Connolly H. C., McCoy T. J., and Bus S. J. (2007) Refractory-Rich Asteroids: Concentrations of the Most Ancient Materials in the Solar System. *BAAS*, 39, 476.

Tedesco E.F., Noah P.V., Noah M., and Price S.D. (2002) The Supplemental IRAS Minor Planet Survey. *Astron. J*., 123, 1056-1085.

Tholen D. (1984) Asteroid taxonomy from cluster analysis of photometry. Ph. D. thesis, Univ. of Arizona.

Tholen D. J., and Barucci M. A. (1989) Asteroid taxonomy. In *Asteroids II* (R. Binzel, T. Gehrels, and M. S. Matthews, Eds.), pp. 298-315, Univ. of Arizona Press, Tucson.

Umov N. (1905). Chromatische depolarisation durch Lichtzerstreuung. *Physik. Z.* 6, 674–676.

Zaitsev S.V., Kiselev N.N., Rosenbush V.K., Kolesnikov S.V., and Antonyuk, K.A. (2013) Polarimetry of the E-type asteroid 64 Angelina. *Kinematics and Physics of Celestial Bodies,* 30 (3), 155–160.

Zellner B. and Gradie J. (1976) Minor planets and related objects. XX. Polarimetric evidence for the albedos and compositions of 94 asteroids. *Astron. J*., 81, 262-280.

Zellner B., Leake M., Lebertre T., Duseaux M., and Dollfus A. (1977) The asteroid albedo scale. I. Laboratory polarimetry of meteorites. In: *Proc. Lunar Sci. Conf., 8th*, *v.1,* Houston, Tex., 1091-1110.

Zubko E., Shkuratov Y., Mishchenko M., Videen G. (2008) Light scattering in a finite multi-particle system. *J. Quantit. Spectrosc. Radiat. Transf.*, 109, 2195–2206.

Zubko E., Videen G., Shkuratov Y., Muinonen K., Yamamoto T. (2011) The Umov effect for single irregularly shaped particles with size comparable with wavelength. *Icarus,* 212, 403-415.

Zubko E., Videen G., Muinonen K., Muñoz O., Nousiainen T., Shkuratov Y., Sun W. (2013) Light scattering by feldspar particles: comparison of model agglomerate debris particles. *J. Quantit. Spectrosc. Radiat. Transf.*, 131, 175-187.