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# Asteroid Polarimetry: State of the Art.

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## 1 Some historical notes

The early 70s of the XXth century were an epoch of quick progress in polarimetric studies of atmosphereless solar system bodies. Some basic results coming from new observation campaigns (especially the one initiated by T. Gehrels at the University of Arizona) and laboratory experiments were published in a number of fundamental papers. Among them, we may mention Zellner et al. (1974), Zellner and Gradie (1976b), and Zellner et al. (1977). These investigations, as well as those carried out by other authors in the same years, laid the foundation of modern asteroid polarimetry. In particular, the importance of polarimetric observations to derive information on the geometric albedo of the asteroids and to make some reliable predictions about the typical sizes of surface regolith particles was emphasized. The role played by polarimetry as a powerful tool, together with thermal radiometry and spectro-photometry, was discussed by Chapman et al. (1975). The main data sources at that time were a still limited amount of disk-integrated polarimetric measurements of asteroids, and several laboratory studies using lunar specimens and meteorite samples. The phenomenon of so-called “negative polarization” (see next Section) in a wide variety of illumination conditions was already well known and widely investigated. On the side of theoretical interpretation, it was clear that the observed polarimetric properties of asteroids and other atmosphereless solar system bodies were due to mechanisms of sunlight back-scattering, being known with excellent accuracy that the sunlight incident on planetary surfaces is not polarized. Asteroid polarimetric data were therefore seen as important constraints for physical models of light scattering phenomena.

At that time, however, a really comprehensive theory was still far from being developed. At the epoch of the first *Asteroids* book, published in 1979, the chapter on optical polarimetry of asteroids, written by A. Dollfus and B. Zellner, included a review of available data, namely a number of phase-polarization curves (see next Section) of bright asteroids, a formulation of the so-called slope-albedo “law”, and descriptions of laboratory studies. Moreover, it was pointed out that the vast majority of asteroids exhibited a noticeable uniformity in disk-integrated polarimetric properties, the only one exception being the large asteroid (4) Vesta, for which a well-defined variation of the degree of linear polarization as a function of rotation had been found by Gradie et al. (1978). Ten years later, at the epoch of publication of the Asteroids II book, a new chapter on photo-polarimetry of asteroids was assigned to Dollfus et al. This paper summarized a great deal of new laboratory activities and modeling attempts, including applications of a model based on Fresnel reflection, developed by M. Wolff (1980, 1981). On the side of observational activity, not very much had happened since the previous decade, apart from the execution of new observations of Vesta, strongly confirming the unique polarimetric behavior of this asteroid (Lupishko et al., 1988). Dollfus et al. (1989) presented also an extensive description and general interpretation of the relation that had been found between some polarimetric observable parameters and the texture of the soil of different kinds of rocky bodies, including relatively large fragments of terrestrial rocks, and very finely divided siliceous powders and lunar fines. This subject is more extensively discussed in Section 3. In the same Asteroids II book, moreover, another chapter devoted to asteroid taxonomy (Tholen and Barucci, 1989), also summarized the role of polarimetric data in the early attempts to develop an asteroid taxonomy.

Starting from the early 90s, an important step forward on the theoretical side was the realization of the important role played by the phenomenon of coherent backscattering (see chapter by Muinonen and Videen). This was a very important step forward to provide a better physical interpretation of some basic pieces of observational evidence, in the domains of both photometry and polarimetry.

Starting since the mid-90s, there has been an epoch of overall renaissance of asteroid polarimetry. This has been mainly due to the continuation of the activity of a few teams historically active in this field (mostly the Ukrainian team) and to the activity of new entries in the field, mainly in Argentina and Italy. These teams used new instruments and telescopes (described in Section 2.2), and carried out new extensive observing campaigns, which led to interesting discoveries, mostly described below, in Section 4.

Currently, the situation in asteroid polarimetry is not exempt from problems. For instance, the reason why even today the activities in the field are less intense than in the other domains like asteroid spectroscopy and thermal radiometry, is mainly due to a relative paucity of observing facilities, and to the fact that polarimetry is a more demanding technique, generally requiring several observations of the same object at different epochs. This is certainly a problem in an epoch in which the major telescopes are oversubscribed, and in the absence of instruments fully dedicated to polarimetric measurements.

# 2 Asteroid polarimetry: data and instruments.

***2.1 Asteroid polarimetric data***. So far, no *in situ* polarimetric measurements have been executed by any of the several space probes which have carried out asteroid exploration missions. As a consequence, all asteroid polarimetric data currently available are disk-integrated measurements. In particular, with very few exceptions, we deal with measurements of linear polarization. Observations aimed at measuring circular polarization have been so far extremely rare and have not provided definitive results. On the other hand, there are not very strong arguments to expect a significant degree of circular polarization in the sunlight scattered by asteroid surfaces, whereas it is natural to expect that this radiation, being the product of a scattering phenomenon, should be in a state of partial linear polarization, as is confirmed by actual observations.

Taking into account data published in the literature, in particular those included in the asteroid polarimetric catalogues available at the Planetary Data System repository[1] and in some recent papers (Gil-Hutton and Cañada-Assandri, 2011, 2012; Cañada-Assandri et al., 2012), as well as some still unpublished data obtained by two of us (AC and RGH) at the El Leoncito observatory, we find that, among all numbered asteroids, less than 350 objects have been polarimetrically observed at least once. The object for which we have the largest number of polarimetric measurements is (1) Ceres, which is now classified as a dwarf-planet. For most asteroids, no more than two or three measurements are available, insufficient to derive reliable inference about their overall polarimetric properties, and about the physical parameters which are responsible of the observed polarimetric behavior. This means that only for a very minor fraction of numbered asteroids we have at disposal today some reliable information coming from polarimetry. A lot of work remains to be done in this field, something that should be taken into account when planning the strategies for the next-generation of sky surveys from the ground and from the space.

The reason why one single polarimetric measurement of an asteroid is generally not sufficient to characterize its polarimetric behavior is that the state of polarization is not constant, but it changes as a function of

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[1] URL address: http://pds.jpl.nasa.gov/

illumination conditions. In particular, the degree of linear polarization changes when the objects are observed at different *phase angles*. The phase angle is the angle between the direction to the Sun and to the observer, as seen from the target object. Of course, a zero phase angle is reachable only in conditions of perfect solar opposition, which never happens in practice. For objects having orbits exterior to that of the Earth, like main belt asteroids, solar opposition corresponds to the epochs of maximum apparent brightness of the objects. However, an ideal solar opposition corresponding to a zero phase angle requires the asteroid to be located exactly on the line of nodes with Earth's orbit, a very rare circumstance. Due to the mutual inclinations of the Earth's and asteroid orbit, the minimum phase angle reachable in most cases tends to be of the order of one or two degrees. The maximum possible value of phase angle is dictated, again, by the orbital properties, being larger for objects which may reach shorter distances from the observer. For main belt asteroids seen by terrestrial observers, the maximum possible phase angle is of the order of 35 degrees in the most extreme cases. For much more distant bodies, like the satellites of the giant planets or the Trans-neptunian objects, the maximum attainable phase angle does not exceed a few degrees. Conversely, objects which may approach more closely the Earth, like many near-Earth objects (NEO), can be observed at phase angles which can be larger than 100 degrees in some cases.

In asteroid polarimetry, two planes of fundamental importance are recognized: the *plane of scattering* is the plane which includes the Sun, the observer and the target object. The second fundamental plane is simply the plane including the observer and the target, and perpendicular to the plane of scattering. Since the light that we receive from asteroids at visible wavelengths is sunlight scattered by their rocky surfaces, we can expect it to be in a state of partial linear polarization, with the degree of linear polarization $P$ being in principle measurable by means of a simple Polaroid device as

$$P = \frac{(I_{Max} - I_{\min})}{(I_{Max} + I_{\min})} \tag{1}$$

where $I_{max}$ and $I_{min}$ are the maximum and minimum light intensity measured by rotating the device around its optical axis. More in particular, if we limit ourselves to considerations based on elementary physics, including Fresnel reflection and Rayleigh scattering, one could expect that the $I_{max}$ value should be reached when the optical axis of the Polaroid is oriented perpendicular to the scattering plane. This, however, is not really confirmed by actual polarimetric measurements. In particular, the observations show that the plane of linear polarization is actually coincident with the scattering plane (contradicting expectations) when the objects are observed in an interval of phase angles ranging from zero up to an *inversion angle* $\alpha_0$ which is in general close to 20 degrees. At larger phase angles the plane of polarization turns by 90 degrees, and is found to be perpendicular to the scattering plane, as predicted by elementary physics. In other words, it is found that, if we call $I_{\perp}$ and $I_{//}$ the intensities of the light measured by a Polaroid when it is oriented perpendicular and parallel to the scattering plane, respectively, $I_{\perp}$ and $I_{//}$ do correspond to $I_{max}$ and $I_{min}$ in the relation (1), but the correspondence is opposite in different intervals of phase angle. As a consequence, the following parameter is always used:

$$P_r = \frac{(I_{\perp} - I_{//})}{(I_{\perp} + I_{//})} \tag{2}$$

in order to describe the state of linear polarization of the asteroids and other atmosphereless solar system objects. The absolute value of $P_r$ (generally expressed in %) gives the degree of polarization of the object, whereas its sign indicates whether $I_{\perp}$ corresponds to $I_{max}$ or to $I_{min}$. In the latter case, $P_r$ becomes negative, and this situation is generally referred to as a state of *negative polarization*. The interval of phase angles at which $P_r$ is found to be negative is named *negative branch* of polarization. Of course, this is only a convenient way to condense two pieces of information, namely the degree of linear polarization and the orientation of the linear polarization plane, into one parameter, only. On the other hand, one should never forget that negative polarization has only the above-mentioned, conventional meaning, being clear that the degree of linear polarization as a physical parameter is *per se* intrinsically a positive quantity.

*Figure 1: Phase – polarization curve for the asteroid (7) Iris.*

Figure 1 shows, as an example, the phase – polarization curve for asteroid (7) Iris. This is simply a plot of $P_r$ as a function of the phase angle. It is easy to see that the curve is characterized by a negative polarization branch extending up to a phase angle of about 22 degrees. The extreme value of negative polarization, usually referred to as $P_{min}$, is reached at a phase angle of about 10 – 12 degrees, and is about 0.7% for this asteroid. After reaching its $P_{min}$ value, $P_r$ shows a linear variation as a function of the phase angle. The slope of this linear trend, measured at the inversion angle $\alpha_0$, is indicated as *polarimetric slope h* in practically all papers of asteroid polarimetry published since the 70s or even before.

What Fig. 1 cannot show, is the fact that the increase of $P_r$ continues also at much higher values of the phase angle. This has been observed both in laboratory experiments and in observations of some near-Earth objects, which can be seen also at values of phase angle which are well above the maximum achievable for main belt asteroids. We know therefore that the increase in the degree of linear polarization continues up to a value $P_{max}$ which is reached at phase angles of the order of 100 degrees (see, *e.g*., Belskaya et al. 2009).

The morphology of the phase – polarization curve shown in Fig. 1 must be considered as fully representative of the general behavior exhibited by main belt asteroids. All known objects display a negative polarization branch, an inversion angle $\alpha_0$, a $P_{min}$ parameter, and a linear increase of $P_r$ around the inversion angle. However, the details of this general morphology vary significantly among different asteroids, in a way which can be used to establish useful relationships with some important physical parameters of the objects. All this will be discussed more in details in Section 3.

## 2.2 The telescopes and instruments used in asteroid polarimetry.

In any area of astronomy the polarization measurements are absolute and should not depend on the characteristics of the instruments used to obtain them. Possible systematic errors introduced by the instrumentation must be removed, making it critical the choice of the telescope and polarimeter to be used.

Instrumental polarization effects are produced in all types of telescopes, mainly in those of the reflecting type which are commonly used. Since any optical surface introduces a certain amount of instrumental polarization, the ideal combination of telescope and polarimeter must be one requiring the minimum amount of optical elements in the optical path. All the instrumental effects occurring within the instrument are then removed by means of a calibration process based on observations of standard stars of known high polarization and zero polarization. In particular, it is necessary to take into account that the degree of linear polarization to be measured in Solar System studies is usually quite small, requiring a careful minimization of instrumental effects.

During the last decades a number of teams around the world have been active in the field of asteroid polarimetry using instruments of different characteristics. Since 1983, regular polarimetric observations of asteroids have been carried out at the 1.25 m telescope of the Crimean Astrophysical Observatory (Ukraine). The telescope is equipped with a five-channel version of the double image chopping polarimeter designed by Piirola (Piirola 1973). This photopolarimeter allowed simultaneous measurements in U, B, V, R and I bands, using five separate photomultipliers. The instrument was designed to permit an automatic elimination of the polarization of the sky background, especially valuable when faint objects are observed, and/or to remove errors possibly introduced by non-negligible moonlight.

In 1994 an agreement between the Complejo Astronómico El Leoncito (CASLEO) in Argentina and the Astronomical Observatory of Torino in Italy led to install an essentially identical photopolarimeter at the 2.1-m CASLEO telescope (Scaltriti et al. 1989), and to begin an extensive observing program which is still under way these days.

The methods of observations and data processing using these instruments were described in many papers (*e.g.,* Shakhovskoy 1994, Belskaya *et al.* 1985; 1987, Scaltriti et al. 1989). Mean errors of the degree of polarization are calculated from both statistics of recorded photons and dispersion of the Stokes parameters for individual measurements during each night. The instrumental polarization is always determined by observations of non-polarized standard stars, with a typical accuracy of about 0.02%.

Few years later a new polarimeter came into service at CASLEO. This instrument was a two-hole aperture polarimeter with rapid modulation provided by a rotating achromatic half-wave retarder and a Wollaston prism beam-splitter which divide the beam to illuminate two photomultipliers operating in pulse-counting mode. With this polarimeter it was possible to observe in only one band at a time but it was very sensitive and allowed to observe faint objects up to *V* magnitudes fainter than 15.

Very recently, the old polarimeters based in photomultipliers have been replaced by a new one based on a design by Magalhaes et al. (1996). The new CASPOL polarimeter is a dual-beam imaging polarimeter with a double-calcite Savart plate which splits the incident beam in two beams with orthogonal polarizations. A half-wave plate is inserted in the optical path just before the Savart plate, to rotate the plane of polarization of the incident beam. The two beams have a separation of 0.9 mm, forming two images on the CCD detector with 10.2” between them. This instrument allows observations of much fainter asteroids with respect to the past, with a limit magnitude gain of 3 magnitudes, at least.

The availability of the Crimea and El Leoncito facilities has been very important. The results of many observing campaigns, which led to a number of important discoveries, have been published in many papers, and will be described in Section 4.

Between 2002 and 2006, a polarimetric survey of about 40 asteroids was carried out at the Astrophysical Observatory of Asiago (Italy), using a new polarimetric mode of the AFOSC detector mounted at the 1.8 m telescope. This polarimeter consists of a double Wollaston prism that splits the incoming light into four polarized beams separated by 20 arcsec (Pernechele *et al.* 2003; Desidera *et al.* 2004). The signal is recorded by a CCD camera, characterized by a much better quantum efficiency with respect to the photomultipliers used at the Crimea and CASLEO observatories described above. This Asiago polarimeter has been now moved to the NOT Observatory in La Palma (Canary islands, Spain).

An identical instrument has been very recently built at the Torino observatory, and is now attached to a new 1-meter telescope of the observatory of Nice (France), located in Calern (Pernechele et al., 2012). In spite of the relatively small size of this telescope, which is partly compensated by the quality of its CCD detector, this instrument is expected to produce soon relevant amounts of new data, having been built mainly as a facility for undergraduate and PHD students.

Among other instruments which have been used for asteroid polarimetry in recent years, we mention also the Dual-Beam Imaging polarimeter installed in the 2.2-m. Telescope of the University of Hawaii at Mauna Kea (Masiero et al. 2007), and the spectro-polarimeter HBS in use in the 0.91-m. Telescope at Dodaira Observatory in Japan (Kawabata et al. 1999).

For a long time, asteroid polarization data have been obtained using small to moderate size telescopes (up to 2 m), allowing the observers to measure only relatively bright objects with apparent magnitude not much fainter than V=15. For what concerns large telescopes, asteroid polarimetric observations have been performed using one of the 8.2-m units of the Very Large Telescope (VLT), at the Cerro Paranal ESO Observatory in Chile, in order to obtain high-accuracy polarimetric observations of faint targets. The measurements were done using the Focal reducer / low dispersion spectrograph (FORS) functioning in polarimetric mode (Appenzeller et al. 1998). This mode uses a half-wave phase retarder and a Wollaston prism as a beam splitter, with a field of view of 6.8' x 6.8'. The first application the VLT for asteroid polarimetric observations took place in 2005, having as target the main belt asteroid (2867) Steins, the target of the ESA space mission “Rosetta” (Fornasier et al. 2006). More recently, other VLT observations have been devoted to studies of the potentially hazardous near-Earth asteroids (99942) Apophis (Delbò et al. 2007) and (144898) 2004 VD17 (de Luise et al. 2007). The first application of VLT to a polarimetric survey of small main belt asteroids was carried out by Cellino et al. (2010).

As a general rule, we note that polarimetric data obtained for the same objects measured at different observing sites and using different instruments have always been found to be in very good mutual agreement, something which is *per se* encouraging, but has also some deep implications for what concerns the homogeneity of the optical properties of the material present in different regions of asteroid surfaces.

# 3 The interpretation of disk-integrated polarimetric measurements of asteroids.

The interest in studying the state of polarization of asteroids and other atmosphereless Solar System bodies is essentially twofold. From a wide theoretical perspective, this is an interesting problem of multiple back-scattering of light from solid, irregular particles having sizes larger than the wavelength of the incident light. Light scattering theories and models investigate the optical properties of different substances observed in different illumination conditions, and try to derive the dependence of such optical properties upon physical parameters including composition, size, shape, texture, and albedo. In principle, therefore, asteroid polarimetric (and photometric) measurements can be a source of very useful data to be used to feed light scattering models. On the other hand, this also means that, having at disposal accurate physical models of light scattering phenomena, in principle asteroid polarimetric data could be used to infer very useful information on some physical properties of the surface material which is hard to obtain by means of other techniques.

In practical terms, however, this is not an easy task. Many inferences about asteroid physical properties as suggested by polarimetric data have long been based mostly on a body of empirical evidence coming from laboratory experiments, not adequately supported by strong theoretical arguments. Starting since the early 90s, the situation has improved due to the discovery of the role played by the coherent backscattering effect, as mentioned in Section 1. Even today, however, we are still in a situation in which the interpretation of asteroid polarimetric data is still not univocal, nor exempt from uncertainties. On the other hand, however, also other well known disciplines in asteroid science, including for instance the interpretation of reflectance spectra in terms of surface composition, must face similar problems.

In many respects, asteroid polarimetry is a field of investigation which is still far from having been extensively exploited. What is important, in general terms, is the fact that the parameters describing the morphology of the phase – polarization curves ($\alpha_0$, $P_{min}$, $h$, as mentioned in Section 2) can be used as diagnostic of some physical properties of the surfaces. Two main relations have been used, in this respect: (1) the relation between $h$ (and also $P_{min}$) and the geometric albedo, and (2) the relation between the location of the object in the plane $P_{min}$ - $\alpha_0$ (inversion angle) and the average size of the surface regolith particles. As for the latter, a fundamental plot was included in the Dollfus *et al.* (1989) chapter in the Asteroids II book. It clearly showed that in the $P_{min}$ - $\alpha_0$ plane, samples of coarse rocks and samples of very thin particles, including fine lunar samples, both measured in the laboratory, are located in two very distinct domains which do not overlap with each other. Asteroid polarimetric data superimposed in the same plane, were found to occupy a domain which is located somewhere in between those of coarse rock samples and fine lunar powders. Dollfus et al. (1989) sketched also a famous interpretation of the above findings. According to them, the surface of a big body like our Moon is covered of a very fine regolith, produced by progressive fragmentation of surface material due to continuous macro and micro impacts over Gyrs time scales. In the case of asteroids, their polarimetric properties seem to indicate larger regolith size particles, and can be interpreted as a consequence of the fact that these bodies have a much weaker self-gravitation. The small-size end of the distribution of surface regolith particles tend to be easily ejected to infinity when receiving even tiny impulses. At the same time, the smallest and fastest fragments produced in impact events tend also to achieve speeds above the escape velocity and are preferentially lost, leaving a regolith depleted in very small particles.

It should be noted that, in the case of our Moon, polarimetric measurements were used many decades ago to infer the presence of a thick layer of fine regolith on the surface, well before the landing of the first lunar exploration missions. In this respect, polarimetry played an important role and some of its predictions based on remote observations were spectacularly confirmed by *in situ* exploration.

The most exploited relation between polarimetric and physical properties of asteroids is the one linking the polarimetric slope and the geometric albedo. This parameter, generally indicated as $p_V$, quantifies the intuitive notion of intrinsic brightness or darkness of a surface (the term albedo is derived from the Latin adjective *albus*, which means ‘’white’’). It is defined as the ratio between the actual brightness of the body seen in standard *V* light at zero phase angle to that of an idealized flat, fully reflective, diffusively scattering (Lambertian) disk with the same cross-section. The albedo is a fundamental physical parameter characterizing the surface of an object, being directly related to its composition and also to the macroscopic and microscopic roughness and texture of the soil. A well-defined relation exists between the size of an asteroid, its albedo and its absolute magnitude (the latter being defined as the apparent magnitude which would be measured in *V* light at unit distance from the asteroid and the Sun, and at zero phase angle). As a consequence, knowledge of the albedo is essential if one wants to derive the size of an asteroid knowing its absolute magnitude. In many situations, the size is derived, for instance, from accurate thermal radiometry observations. The albedo is then derived based on available estimates of the object's absolute magnitude. Such albedo estimates, unfortunately, are generally affected by large uncertainties, due to errors in the adopted absolute magnitude values. In addition to observational errors, in fact, one should also take into account that the absolute magnitude varies at different epochs, depending on the shape and on the pole orientation of the object. One should in principle adopt the correct value of absolute magnitude corresponding to the epoch of the thermal radiometry measurements, something which is never done in practice. For these reasons, the possibility offered by polarimetry to derive the albedo from polarimetric measurements alone, without need of any ancillary information, is of the highest importance in asteroid science.

It should be noted that many uncertainties affecting the interpretation of asteroid polarimetric data, and their reproducibility in the laboratories, come from the definitions of some basic parameters, including geometric albedo and absolute magnitude, which require observations to be performed at zero phase angle. The problem is that, on one hand, in the real world asteroid observations are never done in such conditions. On the other hand, even in the laboratory there are big problems in designing experimental set-ups allowing us to carry out measurements at zero phase angle. Moreover, one should also take into account that, even in ideal situations of perfect solar opposition, the width of the apparent solar disk as seen from an asteroid is not zero, so the sunlight rays incident on the object's surface are not perfectly parallel.

The task of determining the absolute magnitude is particularly difficult, because its value depends strongly on the non-linear surge observed at phase angles less than a few degrees. In particular, it is very complicated to determine a correct extrapolation of some set of brightness measurements (obtained in different illumination conditions) to zero phase angle. Due to these difficulties, it would be very important to have at disposal measurements of both brightness and linear polarization performed for a sizeable sample of real objects, covering a wide variety of illumination conditions, something which is possible in principle, but rarely achieved in practice.

# 4 Recent advances and most important achievements.

Recent advances on the side of theory are extensively described in other chapters of this volume, therefore in this Section we focus on the results of observations. We refer to several observing campaigns carried out to characterize the polarimetric behavior of different asteroid classes (Belskaya et al. 2003, 2005; Fornasier et al 2006b; Gil-Hutton et al. 2008, Gil-Hutton and Cañada-Assandri 2011; Cañada-Assandri et al., 2012). Other investigations were devoted to investigate the differences between asteroid albedoes derived by polarimetry and by thermal radiometry, and to measure the degree of polarization exhibited by asteroids observed at very small phase angles (Cellino et al. 1999, 2005a; Lupishko and Mohamed, 1996; Rosenbush et al. 2005, 2009). Some observing projects have also been devoted to specially selected targets, including near-Earth asteroids, members of dynamical families and targets of space missions (Lupishko et al. 1995; Kiselev et al. 1999, 2002; Cellino et al. 2006, 2010; Fornasier et al. 2006a, De Luise et al. 2007; Delbò et al. 2007; Belskaya et al. 2010). In what follows, we sketch a brief summary of a number of results and discoveries issued from the above-mentioned activities.

## 4.1 The properties of F-type asteroids

Belskaya et al. (2005) found that the asteroids belonging to the rare F taxonomic class are characterized by unusually low values of the inversion angle $\alpha_0$. The inversion angle of 14° found for the F-class asteroid (419) Aurelia, in particular, is the lowest value ever measured for an asteroid. This is an important result in many respects. The F taxonomic class was first introduced by Gradie and Tedesco (1982) and included low-albedo asteroids with a flat (that is why F) spectrum in the wavelength range of 0.3–1.1 µm. According to IRAS data discussed by Tedesco et al. (2002) the albedo of F-class asteroids ranges between 0.03 and 0.07. In terms of reflectance spectrum, they are characterized by an overall lack of absorption features. According to Gaffey et al. (1989), F-class asteroids likely include on their surfaces some organic compounds, and appear to be possibly similar to primitive CI1–CM2 meteorites. In the classical asteroid taxonomy classification by Tholen (1984) only 27 asteroids, corresponding to about 3% of all classified objects, were found to belong to the F class. Low-albedo asteroids are found to be generally more abundant at larger heliocentric distances in the main belt. Being also relatively rare, it is interesting that an anomalous clustering of F class objects was found to be located in the inner belt at about 2.44 AU close to the 3/1 mean motion resonance with Jupiter (Cellino et al., 2001). This clustering is associated with the Polana family, a swarm of objects sharing similar orbital proper elements, interpreted as having been formed by the collisional disruption of a single parent body. More in particular, the Polana family is one of the two parts of the big "Nysa–Polana clan," which was shown by Cellino et al. (2001) to consist of the overlapping of two, likely independent, families: the F-class Polana family and the S-class Mildred family. Interestingly, there seems to be no other known case of such abundance of primitive low-albedo types in the inner asteroid belt. Even more interesting, there are two near-Earth objects (3200 Phaethon and 4015 Wilson–Harrington) which were identified as comet–asteroid transition objects and were both classified as F class (Chamberlin et al., 1996). This was interpreted as a clue that F-class asteroids could have surfaces having a composition similar to that of cometary dust (Kolokolova and Jockers, 1997).

The possibility that *F*-class asteroids display properties which are similar to those of some comets is extremely exciting. In recent years, the discovery of the so-called main-belt comets, objects which have typical asteroidal orbits, but have been found to have some transient cometary activity, has clearly shown that the classical distinction between asteroids and comets is probably not so sharp as we were used to believe in the past. Interestingly, very recent polarimetric observations of two comets, 2P/Encke and 133P/Elst-Pizarro (Bagnulo et al., 2013), show that the nuclei of these two comets exhibit a polarimetric behavior characterized by low inversion angles, similar to that of *F*-class asteroids as described by Belskaya et al. (2005).

A few years ago, moreover, the near-Earth asteroid 2008TC3 was discovered and observed just a few hours before impacting the Earth. Based on the measured reflectance spectrum, this object was classified as a likely F-class (Jenniskens et al., 2009). The impact of 2008TC3 was carefully monitored. The impact site was determined, and searches in the ground led to the discovery in the Almahata Sitta site of many meteorites produced by the 2008TC3 object. Although the situation was found to be rather complicated, with many meteorites collected in the same area exhibiting rather heterogeneous mineralogical properties, it is clear that 2008TC3 was probably corresponding to a composition (polymict ureilite) having not any clear counterpart in the large variety of meteorites previously collected in many regions of the Earth. This strengthens the idea that F-class asteroids could be really interesting.

One should note that the most distinctive spectral feature of the *F* class as compared to other asteroid classes is an absence of UV absorption features. Unfortunately, more recent classifications published in recent years (Bus and Binzel, 2002, DeMeo et al., 2009) were based on asteroid reflectance spectra at visible and near-IR wavelengths, and did not cover the UV region of the reflectance spectrum. As a consequence, in modern classifications based on CCD spectra, the former *F*-class asteroids are are no longer found as a separate class, and are found to belong to the larger *C* or *B* classes. The situation is expected to improve in the next years, because the Gaia satellite, planned for launch in the autumn of this year (2013), is expected to perform a very extensive spectroscopic survey of the asteroid population including all objects having apparent magnitudes brighter than 20. In particular, the Gaia detector will cover the U and B region, so that *F*-class asteroids should be identified, again, based on their spectroscopic properties. In any case, however, through the determination of the inversion angle of polarization, polarimetry is another powerful tool to identify new *F*-class objects, or to confirm or rule out any uncertain *F* classification in presence of unclear spectroscopic behavior.

*Fig.2. Average phase – polarization curves for different asteroid taxonomic classes, characterized by moderate albedo (top) and low-albedo (bottom)*

## 4.2 Polarimetric behavior of other taxonomic classes

Although it cannot provide direct and unambiguous information on the mineralogical composition of an asteroid surface, polarimetry is a very useful tool to get an improved understanding of parameters which are intimately related to surface composition and regolith structure.

Individual fits of polarimetric data to obtain phase-polarization curves for 20 *S*-class and 4 *C*-class asteroids (Goidet-Devel et al. 1995) showed that they compare very well within the same taxonomic groups, arguing in favor of rather uniform polarimetric properties of the surfaces of asteroids belonging to the same taxonomic class. This conclusion makes it possible to study collectively the behavior of taxonomic classes using the available polarimetric database for asteroids of the same class, including those for which individual data are not sufficient to fit a full phase – polarization curve. Figure 2 shows some example of phase – polarization curves of different asteroid taxonomic classes.

Penttilä et al. (2005) using the above-mentioned results by Goidet-Devel et al. made a statistical analysis of asteroidal phase-polarization curves using clustering methods for the 14 taxonomic classes proposed by Tholen (1984). These authors classified synthetic phase-polarization curves for each class by discretizing them with a fine grid and using principal component analysis to extract the main features from the data. They found a separation in different groups which agree with the published taxonomic classifications, showing that phase-polarization curves provide similar information about surface properties as spectroscopic observations.

After some pioneering studies about the taxonomic *M*-class (Lupishko and Belskaya 1989; Belskaya et al. 1991), the improvement of the polarimetric database allowed Gil-Hutton (2007) to find a synthetic phase-polarization curve for this taxonomic type. Moreover, it was found that the phase-polarization curve of *M*-class objects displaying in their spectra the 3 μm absorption band which is diagnostic of hydration (Rivkin et al. 1995, 2000) exhibit differences with respect to those of *M*-class objects lacking this spectral feature. This is an interesting detection of a change in polarimetric properties which can be associated with the presence of possible aqueous alteration.

Recently, new and homogeneous data obtained in new observational campaigns allowed to continue with the study of taxonomic groups using polarimetry. Gil-Hutton and Cañada-Assandri (2011) obtained polarimetric measurements for 56 *S*-, *L*-, *Ld*-, and *K*-objects and found that the synthetic phase-polarization curve of these classes show clear differences between them. Gil-Hutton and Cañada-Assandri (2012) analized data obtained for 58 *B*- and *C*-type objects and found differences between several sub-groups of the *C*-class, and Cañada-Assandri et al. (2012) studied 33 *X*-type objects and obtained differences in the synthetic phase-polarization curve for objects classified as *M*- and *P*-type by Tholen (1984), as it had to be expected, because these two classes differ only in terms of albedo, whereas they have practically identical reflectance spectra at visible wavelengths .

*Figure 3: Two extreme cases of asteroid phase-polarization curve. (704) Iteramnia (top) belongs to the F taxonomic class, and is characterized by a low value of the inversion angle, around 15 degrees. As opposite, (234) Barbara (bottom), the prototype of the "Barbarian" polarimetric class, exhibits a very large inversion angle, close to 28 degrees. Note also the strongly negative polarization at phase angle around 20 degrees, where most asteroids display their inversion angle.*

### 4.3 The discovery of Barbarians

A behavior in some respects opposite to that of *F*-class asteroids was serendipitously discovered by Cellino et al. (2006). When observing the asteroid (234) Barbara at a phase angle of about 20 degrees, close to the typical inversion angle $\alpha_0$ displayed by the vast majority of objects, the above authors found, conversely, a value of $P_r$ close to -1%. This was a surprising result. Subsequent polarimetric measurements of Barbara confirmed that this asteroid exhibits an unusually wide negative polarization branch, with an inversion angle close to about 30°. Current models of the polarimetric behavior of atmosphereless bodies do not rule out, strictly speaking, the possibility to have wide negative polarization branches, but this puts some difficult constraints on the properties of the materials. In general terms, current models, including the coherent backscattering effect, tend to explain more easily fairly narrow negative branches. In terms of taxonomic classification, (234) Barbara is the largest member of an uncommon class, *Ld*, according to the extensive SMASS spectroscopic survey (Bus and Binzel, 2002). Only a dozen of objects were found by these authors to belong to this class, which appears to be a sub-class of a slightly more populous class, named *L*, characterized by a reddish spectral slope. Following the discovery of the unusual polarimetric properties of (234) Barbara, a search for other objects displaying similar properties was undertaken by different authors, and some new so-called "Barbarians" were found. The complete list includes currently four *L*-class asteroids (172, 236, 387 and 980) and one object belonging to the *K* taxonomic class (679 Pax). It should be noted that, among *L*-class asteroids, there are examples of objects which are certainly not Barbarians. Moreover, from the spectroscopic point of view, the distinction between *L*, $L_d$, and *K* objects is not always very sharp, and misclassification cannot be excluded. What is particularly interesting is the fact that the current list of recognized Barbarians includes the two asteroids (387) Aquitania and (980) Anacostia. The reason is that these two asteroids had long been found to be characterized by unusual spectral reflectance properties in the near-IR, exhibiting in particular a 2 μm feature suggesting the presence on their surfaces of the spinel mineral (Burbine et al., 1992). More recently, the same spinel feature has also been found in the reflectance spectrum of (234) Barbara (Sunshine et al., 2007).

The spinel ($MgAl_2O_4$) is a mineral which is present in the so-called CAI (Calcium-Aluminum inclusions), highly refractory compounds which have been found in some primitive meteorites, and are thought to be among the oldest materials in our Solar System. According to some authors, CAIs could even have been solidified in an epoch preceding the collapse of the solar nebula (Ross Taylor, 1992). If this is true, the surfaces of Barbarians could include large abundances of such extremely old material. According to some recent analyses, a dynamical family of asteroids, whose lowest-numbered member is (729) Watsonia, includes a few of the currently known Barbarians (Novakovic et al., 2011). Dynamical families being swarms of fragments issued from the disruption of a common parent body, investigations are under way in order to verify whether other members of the Watsonia family share the same polarimetric behavior of Barbarians. If this will be proven, we will have a strong indication that the Barbarian phenomenon is due to peculiar mineralogical composition of the objects, with the likely presence of a mixture of low-albedo material and high-albedo CAI including spinel. If this is the case, new problems will have to be faced, in particular due to the need of explaining the apparent paucity of spinel-bearing objects, and the fact that most of them would share a common origin from the disruption of one single body. In any case, however, polarimetry is and will be a very practical tool for discovering other examples of Barbarians in different regions of the asteroid main belt. In fact, one single polarimetric measurement at a phase angle around 20 degrees can be sufficient to identify reliably the members of the Barbarian class, which at these phase angles exhibit $P_r$ about -1%.

## 4.4 Wavelength dependence

The first measurements of linear polarization in UBV bands revealed an increase of positive polarization toward shorter wavelength for S-type asteroids (Zellner and Gradie 1976b). Conversely, detailed observations at large phase angles of the S-type near-Earth asteroids 433 Eros (Zellner and Gradie 1976a), 1620 Geographos (Vasilyev et al. 1996), 1685 Toro (Kiselev et al. 1990), 4179 Toutatis (Lupishko et al. 1995; Mukai et al. 1997; Ishiguro et al. 1997) and 25143 Itokawa (Cellino et al. 2005a) shown a decrease of both polarization degree and polarimetric slope $h$ with increasing wavelength.

The spectral dependence of the negative branch of polarization in the wavelength range 0.37–0.83 microns was studied by Belskaya et al. (1987) for a set of 5 asteroids of different taxonomic classes. It was found that the negative branch becomes deeper for increasing wavelength in the case of four of these objects, whereas an opposite trend was displayed by the only one low-albedo asteroid in this limited sample. Later, Lupishko (1998) confirmed the existence of a different behavior for low and moderate albedo asteroids using a set of new UBVRI observations (unpublished data are available in the Asteroid Polarimetric Database by Lupishko 2006). A large set of UBVRI polarimetric observations of main belt asteroids was later obtained by Cellino et al. (1999, 2005b). In total, polarimetric observations in the UBVRI bands have been obtained so far for a few tens of asteroids.

An analysis of the wavelength dependence of linear polarization for main belt asteroids belonging to different taxonomic classes shows that most asteroids display a linear wavelength dependence of the degree of linear polarization (Belskaya et al. 2009a). The variation of $P_r$ typically does not exceed 0.2% in the covered spectral range (0.37–0.83 μm) and tends to increase for increasing phase angle. More in details, asteroids belonging to the *S* and *M* classes are found to exhibit a deeper negative branch and weaker positive polarization for increasing wavelength. This means that these objects are more strongly polarized at longer wavelengths at small phase angles, below the inversion angle, whereas they tend to be less polarized at longer wavelengths when seen at large phase angles, beyond the inversion angle. Low albedo asteroids show larger dispersion of spectral slopes, but the overall trend is just the opposite with respect to *S* and *M*-class objects. They exhibit in fact a shallower negative branch and a larger positive polarization for increasing wavelength. Although rather large uncertainties affect the data of individual objects, the difference in the overall behavior of the total sample, with evidence of an opposite wavelength dependence of polarization distinguishing moderate and low-albedo asteroids, is statistically meaningful. A few exceptions from this general trend were found. Among moderate-albedo asteroids, a discrepant object is asteroid 234 Barbara, the prototype of the “Barbarian” polarimetric behavior (see Section 4.3). The observed variety in the wavelength dependence of asteroid polarization seems to be mainly attributed to surface composition. The study of the wavelength dependence of the asteroid state of polarization is certainly still in its infancy, and might take profit in the future by more detailed spectro-polarimetric measurements which can be carried out at some large telescopes. This appears to be a potentially important field of investigation, being possibly able to provide important constraints and new data to feed the modern theoretical models of light scattering phenomena.

## 4.5 Polarimetric properties of NEAs

Near-Earth asteroids (NEAs) are special targets, because they can experience close encounters with the Earth, and therefore can be observed at large phase angles. Polarimetric observations at phase angles higher than 90° have been obtained so far only for three NEAs: (1685) Toro (Kiselev et al. 1990), (4179) Toutatis (Ishiguro et al. 1997), and (23187) 2000 $PN_9$ (Belskaya et al. 2009b). All these asteroids belong to the *S* taxonomic class and have rather similar polarization properties with $P_{max}$=7.7-8.5% and $\alpha_{max}$=103-110°.

Another *S*-class NEA, (25143) Itokawa, was observed in UBVRI colors in an interval of phase angles between 40 and 80 degrees by Cellino et al. (2005b). Two high-albedo, *E*-class asteroids (33342) 1998 WT24 and (144898) 2004 VD17, were observed up to a phase angle of about 80°. The measured degree of linear polarization was found to be rather low: 1.7% for (33342) 1998 WT24 (Kiselev et al. 2002) and 2.3% for (144898) 2004 VD17 (De Luise et al., 2007). Only one low albedo asteroid, (2100) Ra-Shalom has been measured so far at a phase angle of about 60° (Kiselev et al. 1999). Available data obtained so far for NEAs, although still quantitatively limited, show that the difference in polarimetric slopes among objects of different albedo are such that even one single polarimetric measurement at phase angles $\alpha$ around 50-60° is sufficient to distinguish between low-, moderate- and high-albedo surfaces.

## 4.6 Applications to space-weathering phenomena

A long-debated problem in planetary science has been the origin of ordinary chondrites from abundant asteroid sources in the main belt. After many years of debate, there is now a general agreement on the conclusion that effects of so-called *space weathering* tend to modify the surface properties of asteroids due to the effect of irradiation by the solar wind, and to impacts with micro meteoroids (Chapman, 1996). According to currently established ideas, the effect of space weathering is twofold: it provokes an overall reddening of the reflectance spectrum, and an overall decrease of the depth of the silicate absorption band at wavelengths around 1 μm. At the same time, space weathering is also supposed to alter the albedo, producing a darkening of the surface. According to spectroscopic studies, both in the laboratory and from direct asteroid observations, it turns out that the effect of space weathering acts over short timescales. In particular, it has been found that asteroids belonging to the populous *S* taxonomic class tend to modify their surface properties over timescales as short as a few Myrs (Vernazza et al., 2009).

In order to test independently this hypothesis by investigating possible space-weathering driven changes of the albedo, polarimetry is an ideal tool. In particular, Cellino et al. (2010) observed two samples of small *S*-class asteroids belonging to the Koronis and Karin dynamical families. The Koronis family is one of the most populous swarms of ejecta from a common parent body currently identified in the asteroid main belt. Its members share a low value of orbital inclination, while the semi-major axis is between 2.8 and 3.0 AU. (243) Ida, the first binary asteroid discovered by the Galileo space probe, is a member of the Koronis family. Based on the observed impact record on Ida's surface, it has been estimated that the Koronis family is older than 1 Gyr. The Karin family is a smaller grouping which has been identified within the Koronis family. It is believed to represent the outcome of a second-generation collisional event which destroyed an original member of the Koronis family about 6 Myr ago (add references….). Therefore, by observing a sample of similar-size members of the Koronis and Karin families, one can take a snapshot of two very different stages of evolution of bodies essentially made of the same material. Cellino et al. (2010) carried out polarimetric observations of a sample of Koronis and Karin members using the ESO VLT. In the case space weathering mechanism acts over long time scales and progressively changes the albedo, one should expect to detect a systematic difference between the polarimetric slopes of Koronis and Karin members. The result of this investigation was negative. No statistically significant difference between the polarimetric properties of Karin and Koronis members was clearly identified. This can be interpreted as a clue that space weathering acts over very short timescales, and its effect "saturates" already after only a few Myr. Such a result is in agreement with similar findings based on spectroscopic observations, and shows that polarimetry can be a useful tool also for studying space weathering processes.

## 4.7 Comparisons with thermal radiometry results for asteroid albedoes

Since the 80s, with the launch of the successful IRAS satellite, thermal radiometry has been used as the most efficient tool to derive asteroid sizes and albedoes. On the other hand, while the determination of asteroid sizes by means of thermal radiometry is inherently accurate (the intensity of the thermal flux being primarily dependent on the size, and only weakly upon albedo) the situation has never been completely satisfactory for what concerns the albedo. We have already mentioned the problem posed by the need of using a correct value of the absolute magnitude to derive the albedo from thermal IR data. For what concerns IRAS data, an apparent problem was that the distribution of asteroid albedoes turned out to be different by considering asteroids larger or smaller than 50 km. In particular, larger asteroids observed by IRAS exhibited an overall bimodal distribution of albedo, which may be interpreted as being due to the prominence of two main asteroid classes, the moderate-albedo *S* class and the low-albedo *C* class, which dominate the asteroid inventory in the inner and outer belt, respectively. The same bimodality, however, turned out to be much less evident when considering asteroids smaller than 50 km. This was the reason why an observing campaign was started at CASLEO in the mid-90s, in order to obtain independent albedo determinations for small asteroids observed by IRAS. In particular, the goal was to check whether the distribution of asteroid albedoes is really size-dependent, or the IRAS results were affected by errors preferentially affecting smaller, fainter objects, closer to the detection limit of the detectors.

The results of the CASLEO campaign have never reached a final conclusion, due to a number of problems: first, it turned out that small and dark main belt asteroids were mostly too faint for their degree of linear polarization to be reliably measured with the detectors available at that time (Cellino et al., 2005a). The results of this observing campaign were therefore mostly limited to the moderate-to-high albedo subsample of potential targets. Second, this investigation immediately faced one of the fundamental problems in asteroid polarimetry, namely the lack of a robust calibration of the polarization – albedo relation. This problem is extensively discussed in Section 5.1. In spite of all difficulties, however, the results indicated a systematic overestimation of the IRAS-derived albedoes of small asteroids belonging mostly to the *S* class and other moderate-albedo classes. A systematic difference of albedo derived from thermal radiometry and by polarimetry was found to be of the order of 0.05, IRAS albedoes being higher. As noted by Cellino et al. (2005) the sample of polarimetrically observed targets was both too small and exceedingly biased in favor of moderate and high-albedo objects to draw any reliable conclusion about the bimodality of the albedo distribution. In fact, the most recent and much more extensive thermal radiometry survey carried out by the WISE satellite, which measured the thermal flux of more than 100,000 asteroids, has not evidenced any important difference between the albedo distribution of larger and smaller objects, although the smallest asteroids observed are near-Earth objects, for which there is an overall dominance of objects belonging to the moderate-albedo *S* class.

In spite of the above mentioned problems the CASLEO polarimetric survey of asteroids smaller than 50 km led to important results and some serendipitous discovery, like that of the existence of the totally new class of Barbarian asteroids (Section 4.2), a confirmation of the existence of some weak, but not negligible difference between the degree of polarization of asteroids in V and R colors, and the lack of any evidence of the existence of a possible “polarimetric opposition effect”, some kind of enhancement of the degree of polarization close to zero phase angle, as hypothesized by some authors (Rosenbush et al. 2005, 2009).

Today, in the new era of WISE-determined asteroid albedoes, the use of polarimetry can again be useful to investigate the reliability of these new thermal IR-based data base. Masiero et al. (2012) have analyzed the subsample of WISE-observed asteroids for which polarimetric observations are available, and have suggested a new relation between albedo and polarimetric properties. Given the non negligible uncertainty of WISE albedoes, however, we believe that some more detailed investigation is needed before drawing definitive conclusions, as explained in Section 5.1.

# 5 Some open problems

One of the fundamental problems of modern asteroid polarimetry is the still unsatisfactory quantification of the relation between the geometric albedo and the properties of phase – polarization curves. The relation which has been classically adopted in the literature is the following:

$$\log(p_V) = C_1 \log(h) + C_2 \qquad (1)$$

In the above relation, $p_V$ is the geometric albedo and $h$ is the phase–polarization slope described in Section 2. $C_1$ and $C_2$ are two calibration coefficients whose values must be determined from observations. Another relation having an identical form, but linking $p_V$ with another polarimetric parameter, $P_{min}$, has also been used in the past by some authors, but it is no longer used because this relation between albedo and $P_{min}$ seems to be weaker.

The problem is that the above calibration coefficients have not been so far sufficiently constrained. The consequence is that the uncertainty in the computation of the albedo from asteroid polarimetric observations is today generally dominated by the uncertainty on the values of $C_1$ and $C_2$, rather than by the errors in the measurement of the polarization slopes (Delbò et al., 2007).

In order to obtain a satisfactory calibration of the slope–albedo relation, through the determination of accurate values for the $C_1$ and $C_2$, it is necessary to have at disposal a sample of objects for which both the albedo and the polarization properties are known with good accuracy. Unfortunately, the accurate measurement of the albedo for small Solar System bodies is not trivial.

In principle one could think that the best way to determine $C_1$ and $C_2$ in Eq. (1) should be to do this by means of laboratory experiments. The situation, however, is more complicated in practice. Even using in the experiments samples of extraterrestrial material taken from meteorites, we have not at disposal any detailed information on the structures and textures of the regolith layers covering the surfaces of the original meteoroids, and these are parameters which play a key role in scattering phenomena. Moreover, the measurement of geometric albedo in the laboratory requires necessarily some photometric measurements to be done in illumination conditions corresponding to zero phase angle observations, something which is not so easy to do in practical experiments. Because the brightness varies non-linearly with the phase angle when this is close to zero, this introduces further uncertainty.

For the above reasons, an easier calibration procedure seems to be based on observations of selected samples of real asteroids for which the albedo is thought to be well known. We have already discussed that albedoes derived from thermal radiometry are not expected to be sufficiently accurate for calibration purposes. What has been done in recent years is to use a list of asteroid albedoes published by Shevchenko and Tedesco (2006). This is a list of 57 asteroids whose albedoes are expected to be quite accurate, because they were derived from supposedly good knowledge of the absolute magnitude, coupled with extremely accurate determinations of the size, derived directly from observations of stellar occultation events, or even by direct in situ exploration.

For 18 of these asteroids, the estimated accuracy in the size seems to be better than 5%, a factor of two better than the usual accuracy of size determinations done using thermal radiometry. Being known the size and absolute magnitude of an object, its albedo $p_V$ can be computed from the relation which links together these three parameters, namely

$$\log(D) = 3.1236 - 0.2\, H - 0.5 \log(p_V)$$

where D is the equivalent diameter of the object.

In this computation, the major source of uncertainty is the adopted value of the absolute magnitude $H$, which, as we have already mentioned, is not strictly speaking a constant parameter, but it changes at different epochs and is difficult to determine.

The most recent determination of the calibration coefficients $C_1$ and $C_2$ in Equation (1) has been published by Cellino et al. (2012), who derived the polarimetric slopes of 25 targets belonging to the Shevchenko and Tedesco (2006) list and found the following values:

$C_1 = -0.97 \pm 0.07$

$C_2 = -1.68 \pm 0.08$

The uncertainty in the above values, however, is still exceedingly high, and a campaign of further observations of a larger number of targets is currently under way at CASLEO.

The results obtained so far, however, suggest that it is possible that the traditional form of the slope – albedo relation (1) might be not necessarily the best choice. Attempts are under way to explore the possibility that the relation between albedo and polarimetric properties might be better described in a form taking into account not only one single polarimetric parameter like $h$, but a more detailed description of the morphology of the phase – polarization curves. In this respect, we show in Figure 4 a fit of the phase – polarization curve of asteroid (85) Io, obtained using the following linear-exponential relation, adopted in the past by several authors:

$$P_r = A(e^{\alpha / B} - 1) + C \cdot \alpha$$

In the above relation $\alpha$ is the phase angle expressed in degrees, and $A,B,C$ are coefficients to be determined by a best-fit procedure. Note that the above mathematical formulation ensures that $P_r$ is null at zero phase angle, and that at large phase angles the dominant term is the linear increase with slope $C$. The above relation has been used, for instance, to fit the phase – polarization curves of different taxonomic classes shown in Fig.2. From the plot shown in Fig.4, we can see that the fit looks very reasonable even in individual cases, like the one of asteroid (85) Io, in which the data are fairly sparse and some of them are affected by significant error bars. Work is in progress to investigate whether some relation of the albedo with some combination of the $A,B,C$ parameters could be found to produce smaller residuals with respect to the classical relation (1) adopted so far.

*Figure 4: A fit of the phase-polarization curve of asteroid (85) Io using the linear-exponential relation described in the text.*

In this respect, we note that Masiero et al. (2012) using available polarimetric data for the sample of asteroids whose albedo has been derived from WISE thermal radiometry data, found that a stricter relation between albedo and polarization can be found by using a new polarimetric parameter, which they called $p_*$, defined as:

$$p_* = (0.79 \pm 0.02) \log h + (0.61 \pm 0.03) \log \mathrm{P_{min}}$$

in particular, the above authors find that the best-fit relation between the albedo and $p_*$ is given by:

$$\log pV = (-1.58 \pm 0.09) + (-1.04 \pm 0.04)\, p_*$$

Investigations are currently under way to check whether this kind of relation can be supported also by using as calibration objects the smaller but supposedly more accurate list of asteroid albedoes published by Shevchenko and Tedesco (2006).

One of the reasons why it is so interesting and important to obtain accurate albedo values from polarimetric observations, is the need of checking whether extremely low values of albedo, down to 0.02, really exist as suggested by thermal radiometry results, or not. Such extremely low values of the albedo put some hard constraints for interpretation in terms of mineral composition, and are related to questions including the formation of the most primitive solid bodies in our Solar System, the composition of the proto-solar nebula and proto-planetary disk*, etc*. For this reason, it is important to have the possibility to derive accurate asteroid albedoes from polarimetric observations. A problem is that the classical slope- albedo relation (1) tends to saturate for very low values of the albedo. In any case, so far, extremely steep polarization slopes, possibly corresponding to very low albedo values have never been derived from polarimetric observations. Of course, in the case that the classical relation (1) must be replaced by some other kind of relation, it will be interesting to see whether albedo values lower than, say, 0.04 are made possible by an updated polarimetric approach.

Another intriguing open question in asteroid polarimetry is the possible existence of sharp peak of negative polarization at small phase angles. Rosenbush *et al.* (2005, 2009) reported on the detection of a negative polarization peak of about -0.3-0.4% centered at a phase angle of 0.8-1.8 deg and superimposed on the regular negative branch for the high-albedo, E-class asteroids (64) Angelina and (44) Nysa. On the other hand, Cellino et al. (2005a) carried out observations of several asteroids belonging to a variety of taxonomic classes, but not including the *E* class, and found no clear evidence of any polarization peak. If really present, this kind of "polarimetric opposition effect", limited to high-albedo asteroids, must be theoretically explained. However, published observational data supporting the existence of this polarization peak are rather noisy; therefore doubts remain concerning the real existence of this effect. Further accurate polarimetric measurements of *E*-class asteroids are needed to draw definitive conclusions.

## 6 A discussion of the role of polarimetry in asteroid science

What is the role of polarimetry in modern asteroid science? According to what we have seen in previous Sections, we can say that polarimetry is an important tool which has been so far under-exploited. This is a consequence of the peculiar requirements of this technique. In particular, the need of sampling satisfactorily the phase – polarization curves of the objects, is a task requiring a strong observational investment. The reward, on the other hand, is important. Polarimetric measurements allow observers to obtain information on physical parameters which are very hard to obtain by means of other techniques. In particular, the state of polarization depends on properties of the surface for which most observing techniques are only weakly, or simply not, sensitive. This includes surface texture and geometric albedo, the latter being, in turn, related to composition. In this respect, polarimetry and reflectance spectroscopy are nicely complementary: at visible wavelengths, spectroscopy is not able to distinguish between some classes of objects which have similar, reddish spectra, but differ very much in terms of albedo. For his reason, in the past some taxonomic classifications took into account not only reflectance spectra, but also some polarimetric parameters (Chapman et al., 1975). The use of polarimetric data to complement spectroscopic evidence for the purposes of asteroid taxonomy has been abandoned since many years mainly as a consequence of the exceedingly slow progress of the polarimetric database. Starting since the epoch of the successful IRAS satellite mission, the determination of asteroid albedoes has been mostly carried out based on thermal radiometry data. The most recent catalog of asteroid sizes and albedoes derived from thermal IR observations has been produced by the WISE satellite (Masiero et al. 2011), and includes a number of the order of 100,000 asteroids. In this situation, one might wonder whether there is really any need to still use in the future polarimetry for the purposes of asteroid albedo determination. It is clear, for instance, that to produce polarimetrically-derived asteroid albedoes for a sample of 100,000 objects one would need a huge amount of telescope time and dedicated instruments which simply do not exist.

However, this does not mean that the input coming from polarimetric data is no longer relevant for asteroid science. There are different reasons for that. First, although polarimetry cannot compete with thermal radiometry in terms of quantity, it certainly can in terms of quality. In fact, polarimetry is in principle the best available technique to derive the albedo. Opposite to all other possible techniques, in fact, polarimetry is the only one able to derive the albedo directly from its own measurements, without any need of ancillary information (size, absolute magnitude) coming from other data sources. For instance, asteroid albedoes derived by the WISE satellite have typically uncertainties of the order of 30% or larger, simply due to errors in the adopted values for the absolute magnitude, without considering any further uncertainty coming from the adopted thermal models. These absolute magnitude errors, we remind, are a consequence both of the errors in the nominal values listed in the catalogs, as well as of the fact of using one single value of absolute magnitude, which does not correspond necessarily to the value to be used for the epochs of thermal IR observations. Albedoes derived from polarimetry are not affected *a priori* by this kind of uncertainties. In all tasks for which a reliable determination of the albedo is particularly necessary, polarimetric observations become absolutely necessary. This can include also the attempt to explore some possible relations between the geometric albedo and some observable photometric parameters. As an example, in the case of the imminent launch of the Gaia mission, the availability of a large sample of very accurately derived asteroid albedoes is of the highest importance. The reason is that Gaia will observe, during five years of operational lifetime, a number of the order of 100,000 asteroids. For a large fraction of these objects an inversion of sparse photometric data will lead to determine the rotational properties and the so-called phase coefficient, namely the slope of the generally linear relation between magnitude and phase angle, as it is observed far from solar opposition. A possible relation between the phase coefficient and the albedo was proposed in the past by Belskaya and Shevchenko (2000), and in principle could be adopted to derive at least some tentative estimation of the albedo based on the photometric behavior observed by Gaia. The proposed relation, however, is still very uncertain and certainly needs to be confirmed and better calibrated by using a larger set of data, including necessarily a good sample of polarimetrically-derived albedoes. The same is true for any future attempt to find relations between the albedo and the parameters of the new ($H, G_1, G_2$) photometric system which has been recently adopted by the IAU for Solar System objects (Muinonen et al., 2010).

Some general results based on polarimetric measurements are also worth to be mentioned. For instance, it is important to note that the polarimetric behavior of the asteroids observed so far seems to be essentially independent on the observational circumstances, apart from the phase angle. In other words, the surface properties of asteroids which can be derived from measuring the state of polarization of the scattered sunlight seem to be essentially independent on the region of illuminated surface visible by the observer in different circumstances. This means that the surface properties of the objects are essentially uniform, the only one well known exception being the big asteroid (4) Vesta, for which a modulation of the degree of linear polarization as a function of rotation is apparent, and diagnostic of a global non-uniformity of the surface.

Another interesting result is the fact that the polarimetric properties of asteroids belonging to the same taxonomic classes, but having very different sizes, are essentially identical. A good example is given by tiny *S*-class, near-Earth asteroids like (99942) Apophis and (25143) Itokawa, whose phase-polarization curves are apparently very similar to those of *S*-class, main belt asteroids with sizes above 100 km. This fact seems to suggest that the properties of regolith particles of large and small asteroids are very similar, in spite of the fact that one could expect that smaller bodies might be increasingly depleted in thin surface particles, due to their very weak self-gravitation. A tentative explanation of this apparent paradox has been given by Masiero et al. (2009).

We have already described several cases in which polarimetric observations can play a key role in the physical characterization of asteroids. These include the identification of *F*-class asteroids, possibly sharing important surface properties with comet nuclei. We mention again also the identification of Barbarians, whose polarimetric behavior might be due to the presence on their surfaces of high contents of the most primitive materials known in the Solar system. These are cases for which even one single polarimetric measurement carried out at a suitable phase angle can be sufficient to identify an object belonging to the above classes.

We also would like to remind the case of asteroid (21) Lutetia, one of the two asteroidal targets of the Rosetta mission. Lutetia was long considered to be a normal, thermally evolved member of the *M* taxonomic class, based on the reflectance spectrum at visible wavelengths. Polarimetric measurements carried out before the Rosetta encounter, however, showed that the phase – polarization curve of this asteroid is not typical of the *M* taxonomic class, but it is rather peculiar, with a rather high value of the inversion angle, and a negative branch and polarization slope closer to those normally exhibited by primitive, low-albedo asteroids. Rosetta images, and spectrophotometric data extending into the near-IR showed that (21) Lutetia is a heavily cratered object with a composition close to primitive meteorites, another significant example of the predictive power of polarimetric measurements (Belskaya et al., 2010).

Finally, we have already mentioned in Section 4.5 that polarimetry has potentially very important applications in the field of near-Earth asteroids. This is due to the fact that NEAs can be visible at large phase angles, and even one single polarimetric measurement at a phase angle larger than 40-50 degrees can be already sufficient to estimate whether the polarimetric slope *h* is steep or shallow, and hence the albedo. In this respect, we note that the phase angle of Earth-approaching NEAs may change very rapidly over consecutive nights, making it possible to obtain an acceptable sampling of the phase polarization curve in just a few nights, as shown in the case of (25143) Itokawa observed by Cellino et al. (2005b). We conclude therefore that polarimetry can be an excellent tool to quickly infer the albedo, and hence the overall composition and thermal history of potentially hazardous objects, which are currently the object of great observational efforts in many countries, primarily the US and the European Community, through its Space Situational Awareness program. Of course, newly discovered NEAs tend to be small and faint, and telescopes of the 8-meters class or larger are generally needed to measure the degree of polarization of these objects, apart when they may pass at small distances from the Earth, as in the above-mentioned case of Itokawa. On the other hand, however, a single polarimetric measurement is something that can be done quickly as a Target of Opportunity in service mode. We remind that physical characterization of potentially hazardous objects is a very important task, and a generally hard one. Due to the fact that, once a dangerous object is discovered, the first question which must be answered after the determination of its trajectory is how big it is, we firmly believe that any serious program of mitigation of impacts with extraterrestrial bodies should include the possibility to take advantage of the contribute offered by polarimetric measurements.

# 7 Some promising subjects of investigation for the future

Apart from the usual considerations about the need of new data, which tend to be included in the conclusive sections of so many papers in the field of Astrophysics, we would like to focus on a couple of hot topics which look important for a general advancement in the field of asteroid polarimetry.

The first subject is the need of converging soon to a new, widely accepted calibration of the relation between albedo and polarimetric properties. Due to the capability to obtain from polarimetry the best possible estimates of asteroid albedoes, it is clear that a primary objective for present activities is to produce either a better calibration of the traditional slope – albedo "law" (See Section 5) or to produce a new and better mathematical formulation of the albedo – polarization relation, possibly not limited to using only one single polarimetric parameter as the *h* slope. As mentioned before, a step in this direction has been recently proposed by Masiero et al. (2012) using albedo values derived from WISE thermal radiometry observations, but this matter deserves some deeper investigation.

A second, and fundamental, field of investigation is based on the possibility, for the first time, to obtain some kind of "ground truth", by linking the results of remote, disk-integrated polarimetric measurements of an asteroid with the details of its surface derived from accurate and extensive *in situ* measurements. This possibility is offered by the recent exploration of (4) Vesta by the DAWN space probe. Vesta is a peculiar object, being the only one for which a dependence of the degree of linear polarization upon rotation has been unambiguously obtained in the past. We have therefore for the first time the possibility to find relations between the changes of polarization over different regions of the surface. We know already that Vesta's surface is a complex one, including a couple of extremely large impact craters and an inhomogeneous surface, characterized by different composition (for instance, at different depths in the big craters) and exhibiting patches of dark material everywhere, whose origin is still a matter of debate. Some of us are already involved in a study aimed at analyzing the location of the sub-Earth point on Vesta, corresponding to the epochs of different single polarimetric measurements obtained in the past, in order to find correlations between the variation of the state of polarization and the progressive change of the surface properties in the zones visible at different instants. We hope that this analysis, which is currently beginning, will enhance our understanding of the polarimetric behavior of the asteroids and other atmosphereless Solar System bodies. Similar analyzes will then be carried out in the future for (1) Ceres, the next target of DAWN, and, hopefully for a number of other asteroids which will be explored in the future by space missions. In this way, we may hope to be able to draw from remote, disk-integrated polarimetric data some more accurate hints on the underlying properties of asteroid surfaces.

Finally, it is clear that any progress in the field of asteroid polarimetry will be highly dependent on the availability of observing time. In particular, we think that telescopes in the class of 4 meters, which are considered to be “small” with respect to the large telescopes of current and next generation, can play a key role. These instruments would permit to significantly extend the possibility to achieve high-quality polarimetric data to a large number of objects which are now beyond the limits of the telescopes routinely used so far (see Section 2.2). Larger telescopes, of the 8-meters class and above, are of course even better, but in practical terms their use will be forcedly limited to investigations focused on particular targets for which information on the polarization state is particularly important and/or urgent, but too faint to be measured using smaller telescopes. On the other hand, telescopes in the 4 meters class can produce an enormous amount of new valuable data in asteroid polarimetry, playing also a role in the activities of physical characterization of potentially hazardous objects, a very timely topic due to the important investments devoted to impact risk mitigation techniques in the US and Europe.

## References

Appenzeller, I., Fricke, K., Furtig, W., and 16 co-authors (1998) Successful commissioning of FORS1 - the first optical instrument on the VLT. *The Messenger,* **94**, 1.

Belskaya, I.N., and Shevchenko, V.G. (2000) Opposition effect of asteroids, *Icarus*, **147**, 94-105.

Belskaya, I. N., Efimov, Y. S., Lupishko, D. F., and Shakhovskoy, N. M. (1985) Five Color Polarimetry of the Asteroid 16-Psyche. *Soviet Astronomy Letters,* **11**, 116-118.

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

Belskaya, I. N., Kiselev, N. N., Lupishko, D., and Chernova, G. P. (1991) Polarimetry of CMEU asteroids. II - A peculiarity of M-type asteroids. *Kinematics Phys. Celest. Bodies,* **7**, 8-11.

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, Yu.G., Efimov, Yu.S., Shakhovskoy, N.M., Gil-Hutton, R., Cellino, A., Zubko, E.S., Ovcharenko, A.A., Bondarenko, S.Yu., 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, Yu.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.

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. Quantitative Spectroscopy & Radiative transfer,* **113**, 2552-2560.

Chamberlin, A.B., Mc Fadden, L.-A., Schulz, R., Schleicher, D.G., and Bus, S.J. (1996) 4015 Wilson Harrington, 2201 Oljato, and 3200 Phaethon: Search for CN Emission. *Icarus*, **119**, 173-181.

Chapman, C.R. (1996) S-Type Asteroids, Ordinary Chondrites, and Space Weathering: The Evidence from Galileo's Fly-bys of Gaspra and Ida. *Meteoritics & Planetary Science*, **31**, 699-725.

Chapman, C. R., Morrison, D., and Zellner, B. (1975) Surface properties of asteroids - A synthesis of polarimetry, radiometry, and spectrophotometry. *Icarus,* **25**, 104-130.

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.

Desidera, S., Giro, E., Munari, U., Efimov, Yu. S., Henden, A., Benetti, S., Tomov, T., Bianchini, A., and Pernechele, C. (2004) Polarimetric evolution of V838 Monocerotis. *Astron. Astrophys*., **414**, 591-600.

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

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

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

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

Gaffey, M.J., Bell, J.F., and Cruikshank, D.P. (1989) Reflectance spectroscopy and asteroid surface mineralogy. In *Asteroids II* (R.P. Binzel, T. Gehrels, and M. S. Matthews, Eds.), 98-127, Univ. of Arizona Press, Tucson.

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

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., 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.

Goidet-Devel, B., Renard, J. B., and Levasseur-Regourd, A. -C. (1995) Polarization of asteroids. Synthetic curves and characteristic parameters. *Planet. Space Sci*, **43**, 779-786.

Gradie, J., and Tedesco, E.F. (1982) Compositional structure of the asteroid belt. Science, 216, 1405-1407.

Gradie, J., Tedesco, E.F., and Zellner, B. (1978) Rotational Variations in the Optical Polarization and Reflection Spectrum of Vesta. *Bulletin of the American Astronomical Society*, **10**, 595.

Ishiguro, M., Nakayama, H., Kogachi, M., Mukai, T., Nakamura, R., Hirata, R., and Okazaki, A. (1997) Maximum Visible Polarization of 4179 Toutatis in the Apparition of 1996. *Pub. Astron. Soc. Japan*, **49**, L31-L34.

Jenniskens, P., Shaddad, M.H., Numan, D., and 33 co-authors (2009) The impact and recovery of asteroid 2008 $TC_3$. *Nature*, **458**, 485-488.

Kawabata, K., Okazaki, A., Akitaya, H, and 6 co-authors (1999) A New Spectropolarimeter at the Dodaira Observatory. *PASP* **111**, 898-908.

Kiselev, N. N., Lupishko, D. F., Chernova, G. P., and Shkuratov, Yu. G. (1990) Polarimetry of the asteroid 1685 Toro. *Kinematika i Fizika Nebesnykh Tel*, **6**, 77-82.

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, Yu.S., Lupisjko, 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.). 887 – 890, ESA SP-500. Noordwijk, Netherlands.

Lupishko, D. F. (1998) Bimodality in the Albedo Distribution of S-Asteroids. *Solar Sys. Res*., **32**, 233.

Lupishko, D., and Belskaya, I. N. (1989) On the surface composition of the M-type asteroids. *Icarus* **78**, 395-401.

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., Belskaya, I.N., Kvaratskheliia, O.I., Kiselev, N.N., and Morozhenko, A.V. (1988) The polarimetry of Vesta during the 1986 opposition. *Astronomicheskii Vestnik*, **22**, 142-146 (in Russian).

Lupishko, D.F., Vasilyev, S.V., Efimov, Yu.S., and Shakhovskoy, N.M. (1995) UBVRI polarimetry of asteroid (4179) Toutatis. *Icarus*, **113**, 200-205.

Magalhães, A. M., Rodriguez, C. V., Margoniner, V. E., Pereyra, A., and Heathcote, S. (1996) High Precision CCD Imaging Polarimetry. In *Polarimetry of the interstellar medium* (W.G. Roberge and D.C.B. Whittet, Eds). *Astronomical Society of the Pacific Conference Series*, **97**, 118.

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

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

Muinonen, K., Belskaya, I. N., Cellino, A., Delbò, M., Levasseur-Regourd, A.-C., Penttilä, A., and Tedesco, E. F. 2010. A three-parameter magnitude phase function for asteroids. *Icarus*, **209**, 542-555.

Mukai, T., Iwata, T., Kikuchi, S., Hirata, R., Matsumura, M., Nakamura, Y., Narusawa, S.-Y., Okazaki, A., Seki, M., and Hayashi, K. (1997) Polarimetric Observations of 4179 Toutatis in 1992/1993. *Icarus*, **127**, 452-460.

Novakovic, B., Cellino, A., and Knezevic, Z. (2011) Families among High-Inclination Asteroids. *Icarus*, **216**, 69-81.

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., Giro, E., and Fantinel, D. (2003) Device for optical linear polarization measurements with a single exposure. *Proceedings of SPIE,* **4843**, 156-163.

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,* **8446**, 84462H.

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

Rivkin, A. S., Howell, E. S., Britt, D. T., Lebofsky, L. A., Nolan, M. C., and Branston, D. D. (1995) Three-micron spectrometric survey of M-and E-class asteroids. *Icarus*, **117**, 90-100.

Rivkin, A. S., Howell, E. S., Lebofsky, L. A., Clark, B. E., and Britt, D. T. (2000) The nature of M-class asteroids from 3-micron observation. *Icarus,* **145**, 351-368.

Roberge, & D. C. B. Whittet (…) *ASP Conf. Ser*, **97**, 118.

Rosenbush, V.K., Kiselev, N.N., Shevchenko, V.G., Jockers, K., Shakhovskoy, N.M., and Efimov, Yu.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.

Ross Taylor, S. (1992) *Solar System Evolution*. Cambridge University Press, New York.

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.

Shakhovskoj, N. M. (1994) Methods for analysis of polarization observations. *Izv. Krym. Astrofiz. Obs.*, **91**, 106-123

Shevchenko, V. G. and Tedesco, E. F. (2006). Asteroid albedos deduced from stellar occultations. *Icarus,* **184**, 211-220.

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. *Bulletin of the American Astronomical Society*, **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.), 298-315, Univ. of Arizona Press, Tucson.

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

Vasil'Ev, S. V., Lupishko, D. F., Shakhovskoj, N. M., and Efimov, Yu. S. (1996) UBVRI polarimetry and photometry of the asteroid 1620 Geographos. *Kinematics Phys. Celest. Bodies*, **12**, 8-12.

Vernazza, P., Binzel, R.P., Rossi, A., Fulchignoni, M., and Birlan, M. (2009) Solar wind as the origin of rapid reddening of asteroid surfaces. *Nature*, **458**, 993-995.

Wolff, M. (1980) Theory and application of the polarization-albedo rules. *Icarus*, **44**, 780-792.

Wolff, M. 1981. Computing diffuse reflection from particulate planetary surface with a new function. *Applied Optics,* **20**, 2493-2498.

Zellner, B., and Gradie, J. (1976a) Polarization of the reflected light of asteroid 433 Eros. *Icarus,***28**, 117-123.

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

Zellner, B., Gehrels, T., and Gradie, J. (1974) Minor planets and related objects. XVI. Polarimetric diameters. *Astron. J*, **79,** 1100-1110.

Zellner, B.; Leake, M.; Lebertre, T.; Dollfus, A. 1977. Polarimetry of Meteorites and the Asteroid Albedo Scale. Lunar and Planetary Science Conference 8, 1041.

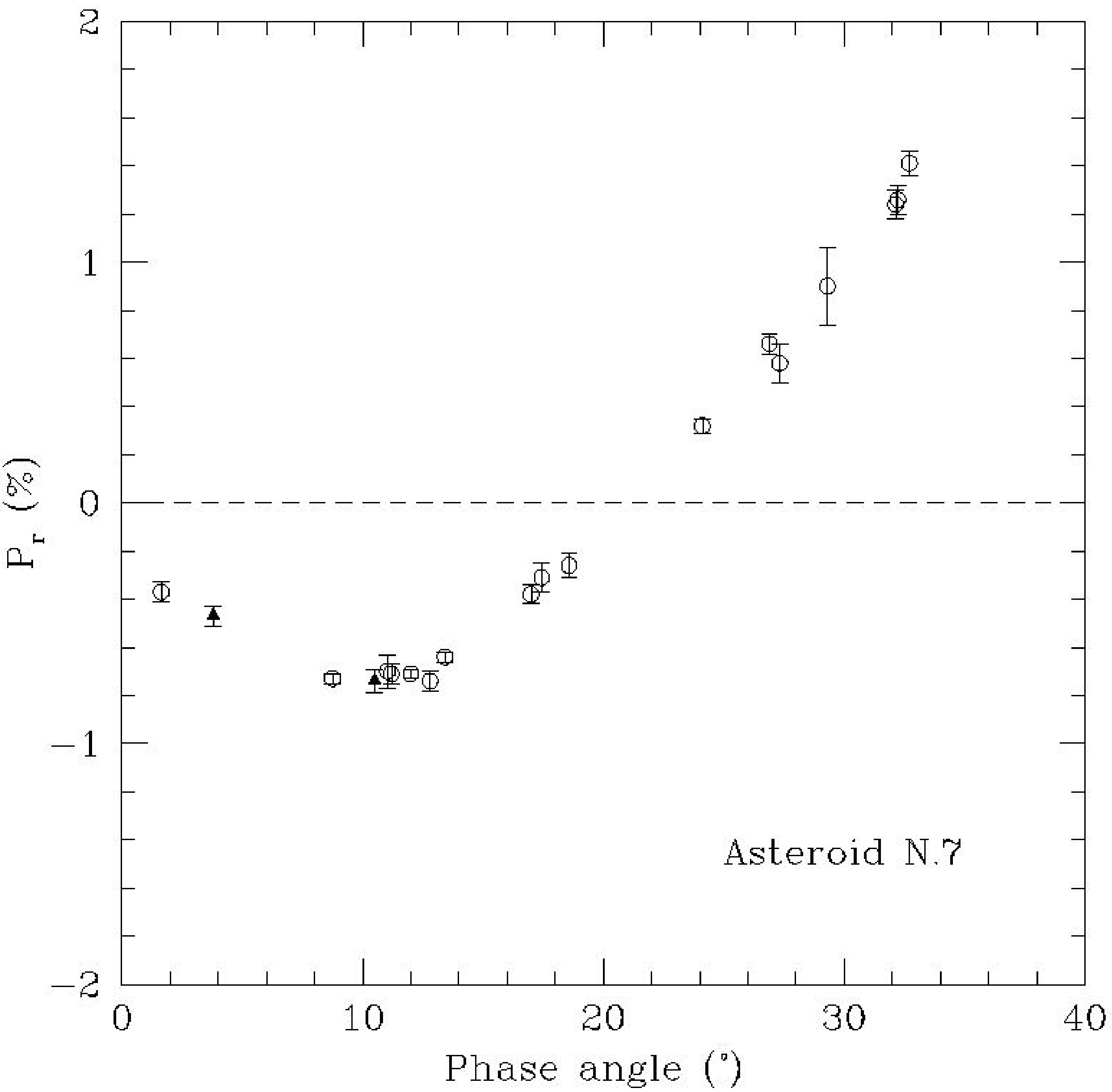

Figure 1: phase –polarization curve for asteroid (7) Iris

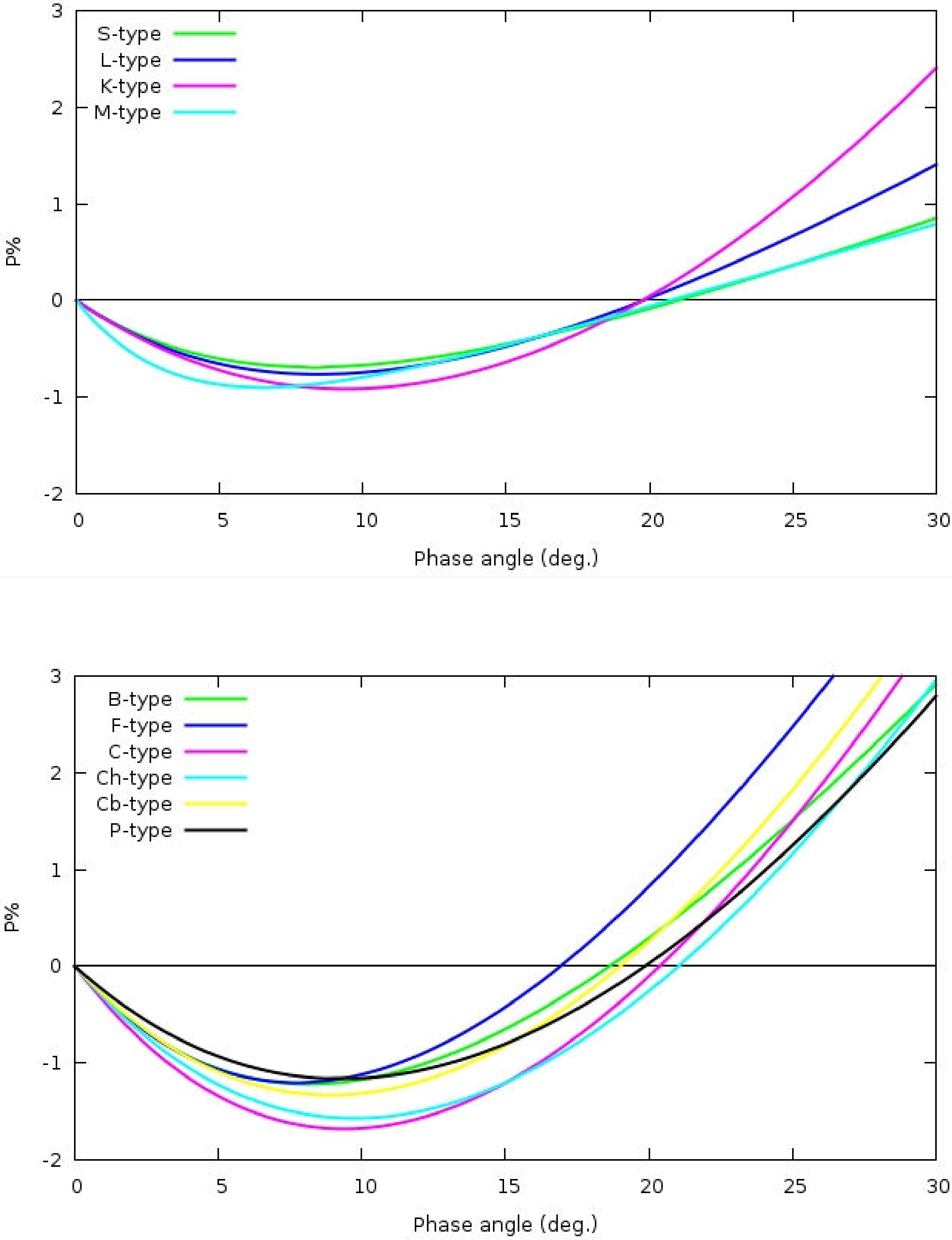

**Figure 2a, 2b: Average phase – polarization curves for different asteroid taxonomic classes, characterized by moderate albedo (top) and low-albedo (bottom)**

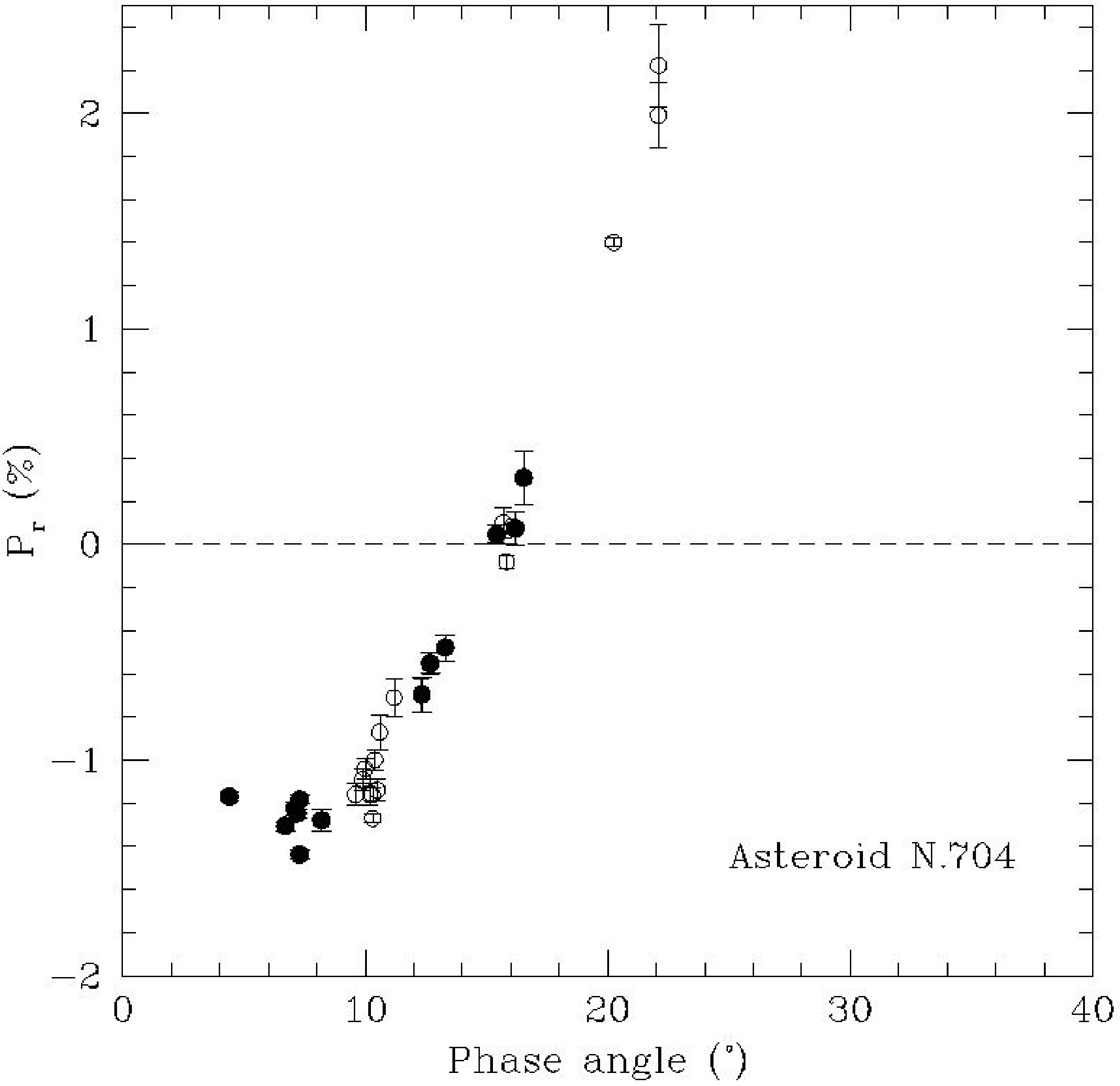

**Figure 3a**

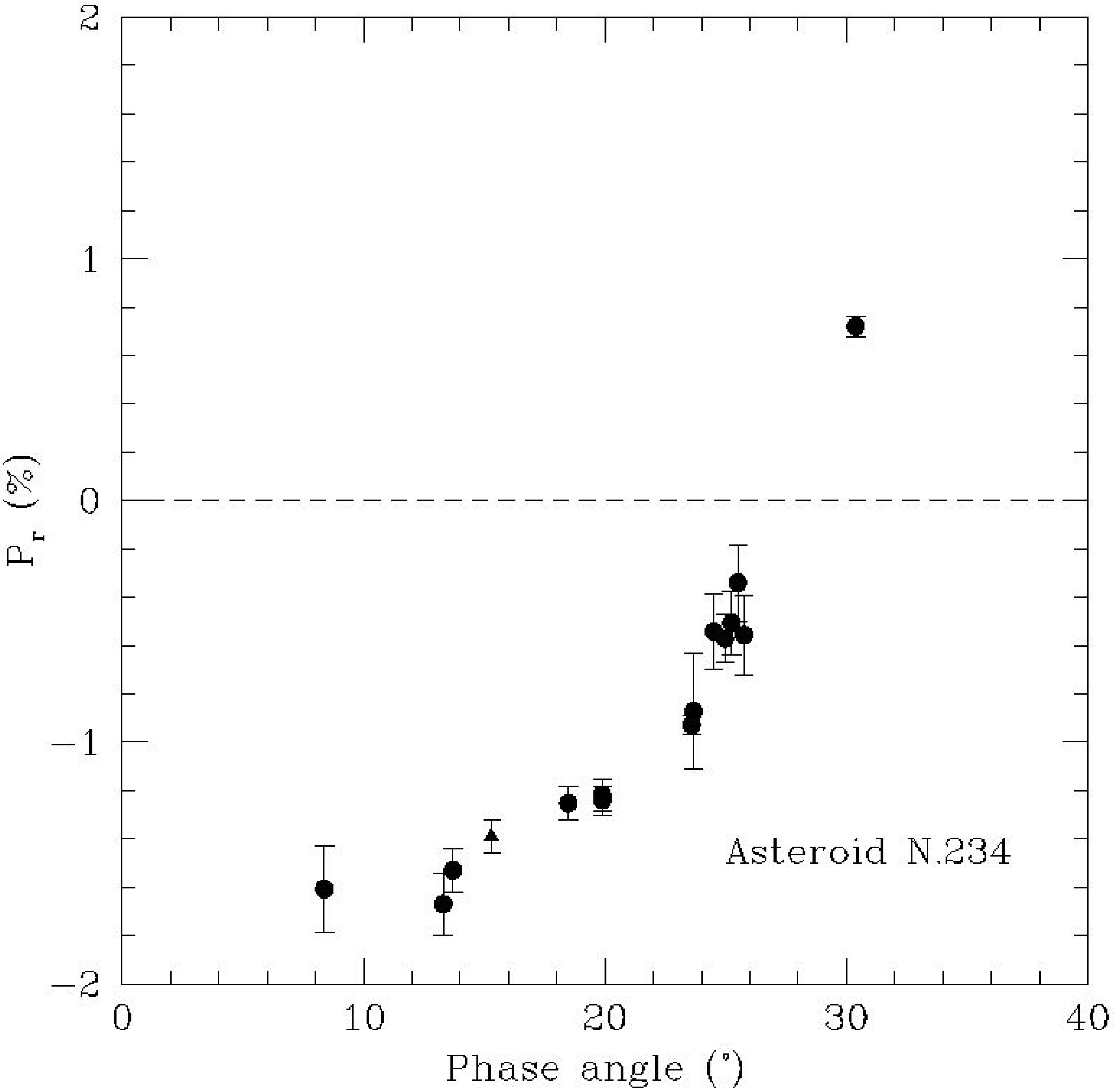

**Figure 3b**

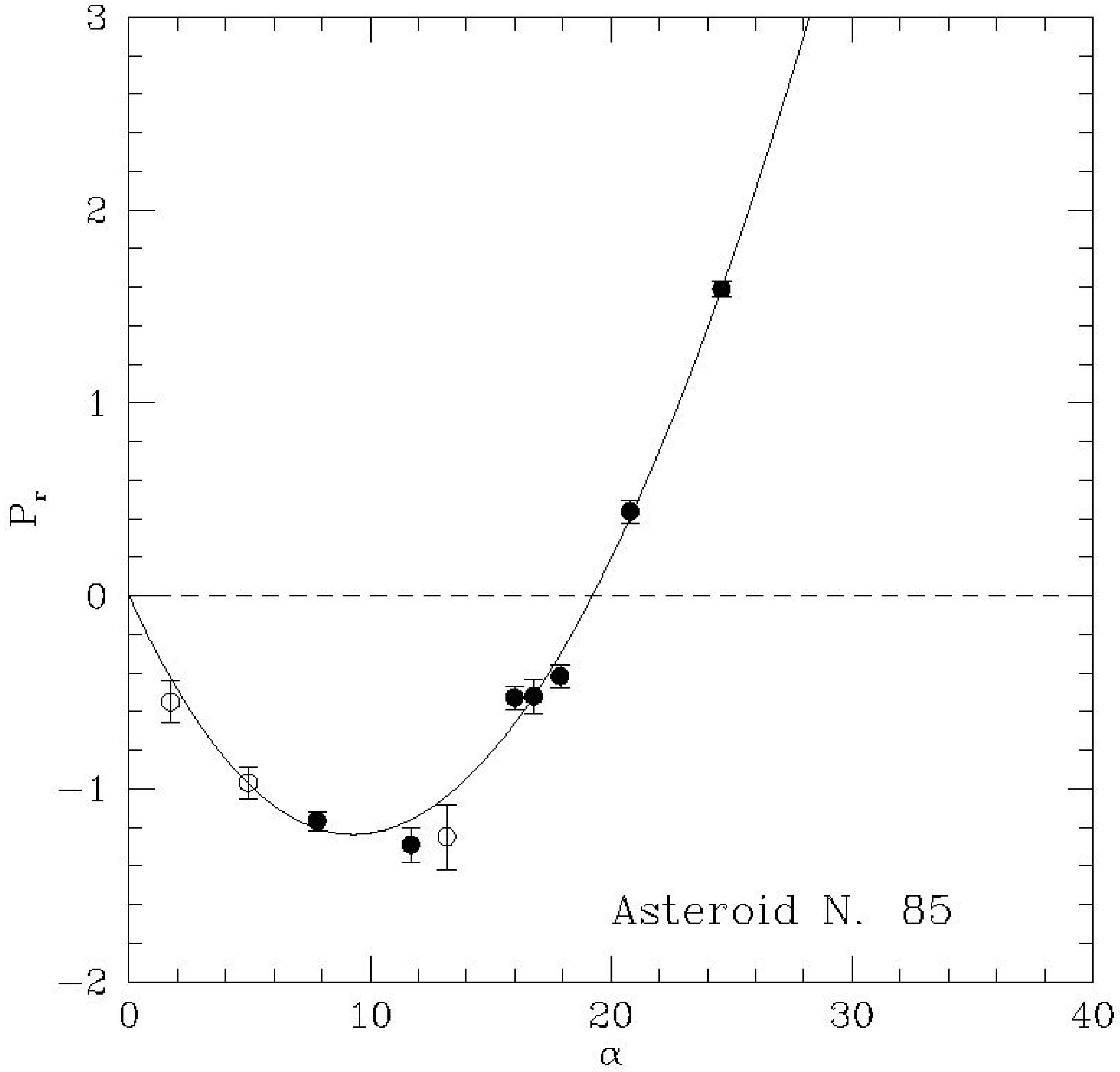

**Figure 4. A fit of the phase-polarization curve of asteroid (85) Io using the linear-exponential relation described in the text.**