Polarimetry: From the Sun to Stars and Stellar Environments
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Polarimetry: a primary tool for the physical characterization of asteroids

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Abstract. Asteroid polarimetry has taken profit in recent years of a renewed interest triggered by exciting results from observing campaigns and theoretical studies. One of the most important applications of polarimetry to asteroid studies is the derivation of the geometric albedo and of the typical sizes of the particles forming the regolith layer covering the surface. Moreover, the serendipitous discovery of a new class of asteroids displaying unusual polarimetric properties, the so-called "Barbarians", has been followed by increasing evidence that these objects can be extremely primitive and may be interpreted as remnants of the very first generation of solid bodies accreted in the inner Solar System. In addition, some results of asteroid polarimetry are going to be interpreted, for the first time, in terms of some "ground truth" evidence, made possible by *in situ* observations of the surface of the asteroid (4) Vesta by the Dawn space probe. Finally, some preliminary evidence suggests that spectro-polarimetry is going to become a major tool for the physical characterization of the small bodies of the solar system.

Keywords. Polarization, minor planets, asteroids

1. Introduction

In spite of the advances obtained in recent years as a consequence of the improvement of available ground-based observing facilities and of the results of space missions, several important problems in asteroid science are still open. Among them, the determination of sizes and compositions by means of remote optical observations. This includes not only the need for a better and more reliable interpretation of available data for main belt asteroids, but also the need for developing techniques and facilities that would allow us to obtain a quick and reliable physical characterization of potentially hazardous objects discovered by sky surveys.

The above-mentioned tasks are challenging and share the property of requiring reliable tools to determine asteroid albedos. If we observed an asteroid (or any other atmosphereless body illuminated by the Sun) located at a distance of 1 AU from both the Sun and the observer†, and seen at zero phase angle (i.e., at perfect solar opposition)‡, the geometric albedo of the body would be defined as the ratio of its brightness to that of an idealized flat Lambertian disk with the same cross-section, seen in identical observing circumstances.

The albedo quantifies the intuitive notion of brightness or darkness of a surface illuminated by sunlight. This surface property is strictly related to its mineralogical composi-

† This definition does not correspond to any observing circumstance which might be actually possible, but it is adopted for the sake of simplicity to get rid of the dependence of the apparent brightness upon the distances from the Sun and from the observer, which is trivial and can be easily computed.

‡ The phase angle is the angle between the directions to the Sun and to the observer as seen from the observed body.

tion, since it is well known that different minerals or mineral assemblages are characterized by different albedos. On the other hand, the albedo dependence upon composition is not simple, and, more importantly, it is not always immediately predictable based on spectral reflectance data. In some cases the reflectance spectra of different asteroids observed at visible wavelengths can appear to be essentially identical, whereas albedo determinations can reveal profound composition differences among them. This is the well known case of the ambiguities among the so-called E, M, P taxonomic classes identified in the 80s (Tholen & Barucci 1989 and references therein), now included in the X complex considered in more recent analyses (Bus & Binzel 2002). This is also one of the reasons why it is not always possible to use reflectance spectra at visible wavelengths as an unambiguous diagnostic of surface composition.

The determination of the size of an asteroid often crucially relies on the determination of its albedo. If one only had photometric measurements of an object observed at visible wavelengths (as it often happens in practice), it would not be possible to distinguish between a smaller, brighter object, and a darker, bigger one without the albedo. This can be expressed through a fundamental relation which links three basic properties of an asteroid, namely its size, D (assuming a spherical shape for the sake of simplicity), its geometric albedo, p_V †, and its absolute magnitude, H (defined as the apparent magnitude in V light measured at zero phase-angle), when the object is located at 1 AU from both the Sun and the observer. This relation is:

$$\log(D) = 3.1236 - 0.2H - 0.5\log(p_V) \tag{1.1}$$

where the 3.1236 constant comes from the definition of magnitude and from the choice of working in the V magnitude.

The observing technique which has historically produced most of the available data on asteroid sizes and albedos is the so-called thermal radiometry. The idea is to measure, at the same time, both the flux of sunlight scattered by an asteroid's surface at visible wavelengths and the thermal emission of the object at mid-IR wavelengths. In principle both fluxes depend on the object's size and albedo, so a solution can be found for these two physical parameters from the measurement of the two fluxes. Unfortunately, as discussed in a number of papers (for instance, Cellino *et al.* 2012), thermal radiometry measurements in V and in the thermal IR wavelengths are never done simultaneously; The V magnitude is nearly always inferred from observations taken at a very different epoch than the thermal IR measurements (normally obtained from space-based facilities), so the two measurements correspond to different observing circumstances. Moreover, the thermal-IR flux of asteroids depends mostly on the size, and only weakly on the albedo. The bottomline is that sizes obtained by means of thermal radiometry are generally fairly accurate, but typical errors for the albedos are often above 30%. Such a large uncertainty limits very much the use of the albedo as a diagnostic tool for the composition.

It should also be noted that, from the point of view of the activities of mitigation of the impact risk posed by extraterrestrial bodies, thermal IR observations are mostly (if not exclusively) carried out from space, due to the problems posed by the atmospheric extinction at these wavelengths. This means that the availability of observing facilities is mostly limited to the operational lifetimes of satellites, which cannot ensure a continuous coverage, whereas for the purposes of a prompt physical characterization of potentially hazardous objects it is necessary to be able to react to possible discoveries at any time.

Fortunately, polarimetry offers a convenient method for the determination of asteroid

† here, the V sub-fix means that it is supposed that the observations are done in the standard Johnson V band

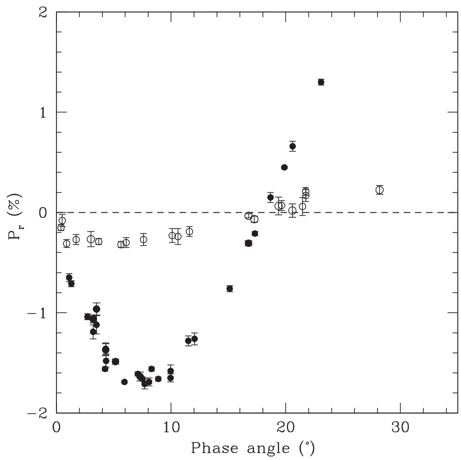

Figure 1. Phase polarization curve of (1) Ceres (full symbols) and (44) Nysa (open symbols), based on all data available in the literature for these two objects.

albedos, and one which can be applied to many objects, both using regular telescope time or, whenever needed and justified, by Target-of-Opportunity procedures. The albedo can be derived by exploiting (still mostly empirical) formulas that relate it to parameters describing the variation of the linear polarization as a function of the phase angle.

2. Asteroid Polarimetry: Basic Notions

Being the result of a phenomenon of scattering from the surface, the light that we receive at visibile wavelengths from asteroids and other atmosphereless solar system bodies, is in a state of partial linear polarization. The fraction of linear polarization depends on the phase-angle at which the observations are carried out. Note that the plane of linear polarization is always found to be, within observational uncertainty, either normal or parallel to the scattering plane (the plane containing the Sun, the object and the observer). A plane of polarization always normal to the scattering plane would be expected based on simple physical considerations (Fresnel laws), but the linear polarization measured by actual observations is found to be oriented parallel to the scattering plane over a wide range of possible phase angles. The fundamental parameter normally used in asteroid polarimetry is therefore P_r, defined as the degree of linear polarization, which is negative when the polarization plane is parallel to the scattering plane. Negative values of P_r are normally referred to as *negative polarization*. When plotting P_r against the phase angle, we obtain the so-called *phase-polarization curves* of asteroids, which are an essential piece of information in asteroid polarimetry. Figure 1 shows two typical phase-polarization curves, one of the low-albedo object (1) Ceres, belonging to the C taxonomic complex, and one of the high-albedo asteroid (44) Nysa. Note that both curves can be nicely fit using the following three-parameter function:

$$P_r(\alpha) = A\,(e^{-\alpha/B} - 1) + C \cdot \alpha \tag{2.1}$$

where α is the phase angle and A, B and C are three parameters whose values can be determined by means of least-squares fitting procedures. Although both curves shown in Figure 1 can be represented using the function given by Eq. (2.1), the values of the function parameters vary significantly from one case to another, leading to big differences in both the depth of the negative polarization branch (the so-called $P_{\rm min}$ parameter),

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and the slope (normally referred to as h) of the linear change of polarization close to the inversion angle.

3. The Determination of Asteroid Albedos from Phase-Polarization curves

The dependence of the polarimetric slope, h, upon the albedo has been most widely exploited in asteroid polarimetry to derive the albedo of the objects. Historically, the analytical form most frequently adopted has been:

$$\log(p_V) = C_1 \log(h) + C_2 \tag{3.1}$$

where C_1 and C_2 are two parameters to be determined by least-squares techniques. One of the most difficult problems in asteroid polarimetry has always been the determination of these two parameters. In many cases (see, for instance, Delbò *et al.* 2007) the uncertainty affecting the determination of the albedo of an object is mostly due to the uncertainties in C_1 and C_2 rather than to the scatter in the polarization measurements.

The calibration of Eq. (3.1) can be done using a number of objects for which both the polarimetric slope h and the albedo are known with good accuracy. In principle, several options are possible. This includes laboratory measurements of a variety of minerals and/or meteorites, an option that was mainly used in the pioneering works of the '70s, but has been abandoned in more recent times due to several problems, the most important one being the lack of calibration objects that are representative of the surfaces of asteroids. More recently, the trend has been to use real asteroids (whose albedo has been accurately estimated) for calibration purposes. The idea is to use Eq. (1.1) and to derive the albedo for objects for which both D and H are known with very good accuracy. A list of suitable calibration asteroids has been published by Shevchenko & Tedesco (2006). The sizes of these particular objects has been derived either from accurate measurements of star occultations or from *in situ* measurements by space probes.

Cellino *et al.* (2012) publised the most recent calibration of Eq. (3.1). These authors found the following values: $C_1 = -0.970 \pm 0.071$, and $C_2 = -1.677 \pm 0.083$. Their analysis is still in progress, however, using new data collected after the publication of the Cellino *et al.* (2012) paper, Cellino *et al.* (2015) presented the results of a wider study aimed at considering some alternative forms of the polarization-albedo relation, which could give better fits to the available polarimetric data for the objects belonging to the Shevchenko & Tedesco (2006) list.

4. The Barbarians

Some years ago, Cellino *et al.* (2006) discovered that asteroid (234) Barbara displayed unusual polarimetric properties, in particular a very extended (up to about 30°) negative polarization branch (in case of most asteroids, the negative polarization branch is limited to an interval of $\sim 0 - 20°$). Later, a few other asteroids were found to exhibit the same polarimetric behaviour. Figure 2 shows the phase-polarization curves of the first six Barbarians discovered, and gives a clear idea of the anomalous behaviour of these objects. Compare with Figure 1 to see how strongly negative the polarization of the Barbarians, at the phase angle where the P_r of normal asteroids changes sign, is. According to Bus & Binzel (2002), the first discovered Barbarians belonged to a few minor taxonomic classes, including L, Ld and K. The interpretation of their polarization behaviour, as well as of their rarity, was challenging. More recently, it was discovered that asteroid (729) Watsonia is also a Barbarian. This is important, because Watsonia, a high-inclination main belt

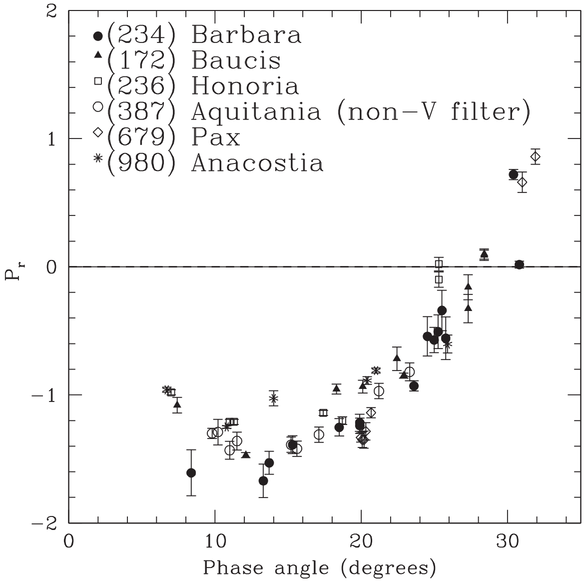

Figure 2. Phase polarization curves of (234) Barbara and other five Barbarian asteroids.

asteroid, gives its name to an associated dynamical family (Novaković *et al.* 2011). In other words, Watsonia and the other members of its family are supposed to be fragments from the collisional disruption of a common parent body. This led Cellino *et al.* (2014) to make polarimetric observations of a sample of other members of the Watsonia family. The striking results showed that the Watsonia family consists of Barbarian objects. This suggests that the Barbarian behaviour is not simply a surface property, but it must be a peculiar characteristic of the whole composition of these objects, because all of the members of a family come from the interior of the same parent body.

The Barbarian puzzle includes two important pieces of evidence: *i)* the available spectroscopic data suggest that these asteroids have surfaces characterized by anomalously high abundances of refractory materials, in particular the spinel minerals, which are abundant in the Calcium-Aluminum-rich inclusions found in many meteorites. These are extremely primitive minerals, and can represent samples of the very first solid bodies condensed and accreted in the early solar system (Sunshine *et al.* 2008). *ii)* (729) Watsonia, (387) Aquitania and (980) Anacostia are located nearby in the space of orbital proper elements. Although they are currently too distant from one another to be included in a unique collisional family, their proximity suggests that they could be the few and biggest remnants of a first-generation family produced in a very early epoch. In this respect, Barbarians might represent a constraint for the most modern theories of the early evolution of our solar system. Studies to investigate these preliminary conclusions are ongoing.

5. Future work

The importance of polarimetry in asteroid science is increasing and we expect important developments in the near future. On the one hand, theoretical improvements of the models of the phenomena of light scattering are contributing to counteract the reputation of asteroid polarimetry as an empirical and mysterious science. At the same time, we are at the beginning of a new era, characterized by the generalized adoption of

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spectro-polarimetry as a very important tool for the physical characterization of atmosphereless solar system bodies. The wavelength dependence of asteroid polarization has been a virgin land for very long, with the exception of a few pioneering papers dealing with multi-band polarimetric data (Belskaya *et al.* 2009 and references therein). Only recently, a real "wedding" between Polarimetry and Spectroscopy (blessed by the use of state-of-the-art instrumentation) has been celebrated in the realm of asteroid science. Preliminary results obtained by Bagnulo *et al.* (2015) indicate that this technique, that simultaneously provides the reflectance spectrum of an object, its polarization at different wavelengths and (very important and new) the gradient of the polarization as a function of wavelength, is a very powerful tool. Data obtained so far suggest there are important differences among objects belonging to different taxonomic and albedo classes, and differences of behaviour when objects are observed at phase angles corresponding to either negative or positive polarization. This also opens new lines of investigation for theoretical studies, which are expected to promote further advancements in our understanding of light scattering phenomena from planetary surfaces, and our ability to better determine the properties of the objects based on their observed spectro-polarimetric behaviour.

Another promising line of research is offered by the detailed *in situ* exploration of asteroid (4) Vesta, to interpret available disk-integrated polarimetric data in terms of the average local properties of the surface visible from the Earth at different epochs. Vesta seems to be particularly suitable for this investigation, due to the fact that this asteroid exhibits unambiguous changes of polarization as a function of rotation. Ongoing studies will hopefully lead to finding the "ground truth" to interpret Vesta's polarimetric behaviour, and to extend it to the interpretation of other bodies.

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References

Bagnulo, S., Cellino, A., & Sterzik, M. F. 2015, *MNRAS* 446, L11

Belskaya, I. N., Levasseur-Regourd, A.-C., Cellino, A., Efimov, Y. S., Shakhovskoy, N. M., Hadamcik, E., & Bendjoya, Ph. 2009, *Icarus* 199, 97

Bus, S. J. & Binzel, R. P. 2002, *Icarus* 158, 146

Cellino, A., Bagnulo, S., Gil-Hutton, R., Tanga, P., & Cañada-Assandri, M. 2015, submitted to *MNRAS*

Cellino, A., Bagnulo, S., Tanga, P., & Novaković, B, Delbò, M. 2014, *MNRAS* 439, L75

Cellino, A. Gil-Hutton, R., Dell'Oro, A., Bendjoya, Ph., Cañada-Assandri, M., & Di Martino, M. 2012, *JQSRT* 113, 2552

Delbò, M, Cellino, A. & Tedesco, E. F. 2007, *Icarus* 188, 266

Novaković, B., Cellino, A., & Knežević, Z. 2011, *Icarus* 216, 69

Shevchenko V. G. & Tedesco, E. F. 2006, *Icarus* 184, 211

Sunshine, J. M., Connolly, H. C., McCoy, T. J., Bus, S. J., & La Croix L. M. 2008, *Science* 320, 514

Tholen, D. J. & Barucci, M. A. 1989, in: R. P. Binzel, T. Gehrels, M. S. Matthews (eds.), *Asteroids II*, p.298, University of Arizona Press, Tucson