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The strange polarimetric behavior of Asteroid (234) Barbara

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Abstract

We have discovered that the Asteroid (234) Barbara exhibits very anomalous polarimetric properties. The phase–polarization curve of this asteroid is unique and is not matched by any other known atmosphereless body of our Solar System. Although a few preliminary conjectures can be made, for the moment the reasons of the peculiar polarimetric properties of this asteroid remain essentially unknown.

Keywords: Asteroids; Polarimetry

1. Introduction

The light that we receive from any asteroid at visible wavelengths consists of sunlight scattered by the solid surface of the body. As a consequence, the visible light from these objects is in a state of partial linear polarization, which varies for different illumination conditions, described by the so-called *phase angle*, namely the angle between the directions of the Earth and the Sun as seen from the asteroid. Since a long time the variations of the parameter $P_r = (I_\perp - I_{||})/(I_\perp + I_{||})$ as a function of phase has been used to describe the polarimetric behavior of asteroids. In the above definition $I_\perp$ and $I_{||}$ indicate the intensity of the incoming light having the plane of polarization perpendicular and parallel to the scattering plane, respectively (the scattering plane being the plane containing the asteroid, the Sun and the Earth at the epoch of observation).

When one plots the variation of P_r as a function of the phase angle, a well defined curve is usually obtained (see, for instance, Dollfus and Zellner, 1979; Dollfus et al., 1989). The typical behavior is shown in Fig. 1, in which the phase–polarization curves of the well-observed Asteroids (1) Ceres, (7) Iris, and (12) Victoria, belonging to different taxonomic classes, are plotted together. It can be seen that the general trend exhibited by these objects consists of the presence of a range of phase angles, approximately between 0° and 20°, for which P_r turns out to be negative, reaching a relative maximum of negative polarization at phase angles around 10°. This general behavior characterizes, with some minor differences depending on the taxonomic class, all asteroids observed so far. Beyond a phase angle of about 20°, the polarization usually changes sign, and becomes positive. The typical polarimetric behavior of asteroids belonging to different taxonomic types has been analyzed by Goidet-Devel et al. (1995).

The existence of a branch of negative polarization exhibited by atmosphereless Solar System bodies is well known, and is generally explained in terms of the occurrence of shadowing effects and, likely more important, of coherent backscattering phenomena (Muinonen et al., 2002). One major problem for modern studies of the scattering properties of asteroid surfaces is to satisfactorily explain the occurrence and the observed width of the negative polarization branch. Laboratory experiments have been since a long time a powerful tool to check the predictions of different models, and to derive important clues concerning the interpretation of the observed phase–polarization curves in terms of surface properties. A classical example is the relation found between the slope of the polarization curves at the inversion angle and the albedo of the surfaces, the so-called slope-albedo law (Dollfus and Zellner, 1979; Dollfus et al., 1989). Since the most recent light scattering models seem promisingly close to have solved the problem of reproducing the observed polarimetric properties of real asteroids (Muinonen et al., 2002), we have been surprised by the discovery of one object, (234) Barbara, exhibiting a phase–polarization curve which is absolutely unusual and has not any known analogous among other atmosphereless bodies of our Solar System for which we have available polarimetric data.

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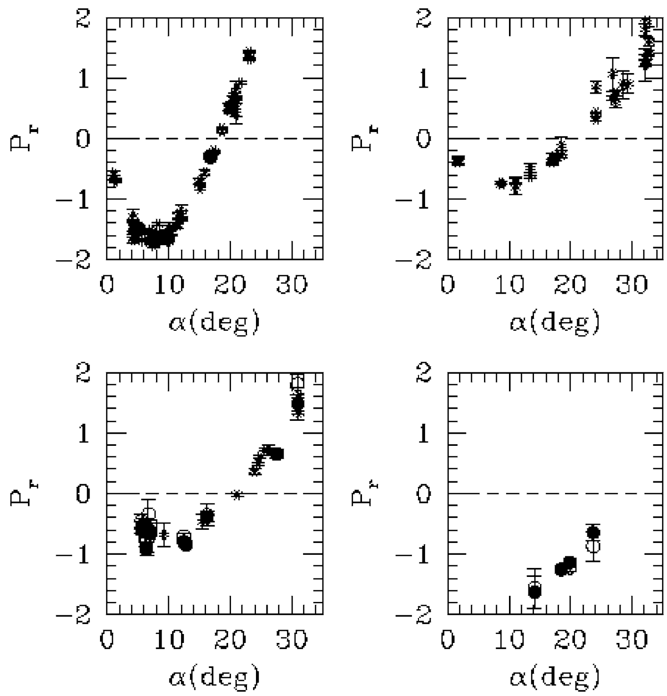

Fig. 1. Phase polarization curve of (234) Barbara (bottom-right), compared with those of some well-known Main Belt asteroids: (1) Ceres (G-class) (top-left); (7) Iris (S-class) (top-right); (12) Victoria (L-class) (bottom-left). Data taken from the PDS website (asterisk symbols), and observations obtained by the authors at the CASLEO observatory (San Juan, Argentina) in V (open circles) and R (filled circles) colors (Cellino et al., 2005).

Table 1
Dynamical and physical properties of (234) Barbara

Semimajor axis (AU)	Eccentricity	Inclination (deg)	H (mag)[1]
2.38596457	0.2440731	10.53519	9.02
Rotation period (h)[2]	Size (km)[3]	Geometric albedo[3]	Taxonomic class[4,5]
26.5	44	0.23 ± 0.01	S, Ld

[1] From http://www.psi.edu/pds/archive/phot.html.
[2] From http://cfa-www.harvard.edu/iau/lists/LightcurveDat.html.
[3] See Tedesco et al. (2002).
[4] See Tedesco et al. (1989).
[5] See Bus and Binzel (2002).

2. The phase–polarization curve of (234) Barbara

Our polarization measurements for this object in V and R colors were collected at the Complejo Astronomico El Leoncito (CASLEO) in San Juan (Argentina) using the Torino photopolarimeter built in the Astronomical Observatory of Torino (for a description of the instrument, see Cellino et al., 1999, and references therein), and are shown in Fig. 1 (bottom-right). The data were collected in the framework of an observing campaign which is described in separate papers (Cellino et al., 1999; Cellino et al., 2005). In particular, the results of our observations of 234 Barbara are listed in Table 2 of the Cellino et al. (2005) paper. In addition to the V and R data, we obtained also some polarimetric measurements in U, B, and I colors, but the asteroid was fainter in these bands, then the corresponding error bars are large. For this reason, in this paper we prefer to focus on the V and R data, only, which are much more accurate. The color dependence of the phase–polarization curves are certainly interesting, for Barbara as well as for other objects observed in our campaign, but this will be the subject of a forthcoming paper, and we do not discuss this topic at this stage. Our observations cover only a limited range of phase angles, between about 14° and 24°, but they are sufficient to conclude that we deal with a very unusual behavior, since the resulting P_r values are all strongly negative, and suggest that the inversion angle for this object should occur at a phase angle no less than about 30°. Note that our measurements have been obtained in four different nights during different observing runs in May 1997, July 1997, March 2003, and June 2004, respectively (Cellino et al., 2005). Since all the measurements shown in Fig. 1 agree well with each other, with the same trend being shown in V and R colors, and have reasonably small error bars, we conclude that the observed behavior is real, and represents an unprecedented example of an asteroid exhibiting a strongly negative polarization at phases larger than 20°.

3. Discussion

What can be the explanation of such a behavior? In Table 1 we list a summary of our current knowledge of the dynamical and physical parameters which characterize this asteroid. In particular, we list the values of the osculating orbital elements semimajor axis, eccentricity and inclination, taken from the *Astdys* public website maintained at the University of Pisa at the URL address http://hamilton.dm.unipi.it/cgi-bin/astdys/astibo?orbital_elements:0;main, and the known values of the physical parameters H (absolute magnitude), rotation period, size, albedo and taxonomic class from the sources cited.

As shown in Table 1, (234) Barbara is a quite typical Main Belt asteroid belonging to the inner region of the belt. For a long time it has been taxonomically classified as a member of the big S taxonomic class (Tedesco et al., 1989; Tholen, 1989). This taxonomic class corresponds to the most abundant class of asteroids orbiting in this region (Gradie and Tedesco, 1982; Mothé-Diniz et al., 2003). Barbara has a "normal" size and a radiometrically-derived albedo corresponding to the typical values found for objects belonging to the S taxonomic class. More recently, however, Bus and Binzel (2002) have pointed out that a number of objects previously classified as S-type can be assigned to a separate class, characterized by a reddish spectral slope, followed at longer wavelengths by a flat trend. They named L this new taxonomic class. It is fairly rare, with a large fraction of its members belonging to a dynamical family (named Henan from its lowest-numbered member), originated by the break-up of a single parent body. (234) Barbara, however, is not a member of Henan, nor of any other known family. According to Bus and Binzel (2002), from the point of view of taxonomy it belongs to a further subset of the L taxonomic class, characterized by a particularly reddish trend of the reflectance spectrum. The objects known to belong to this subclass, named *Ld*, are only a dozen, and (234) Barbara is the largest of them. No polarimetric data are available for the other known *Ld* asteroids, then we do not know whether the observed polarimetric behavior of Barbara might be typical of this class. We can only say that the larger L taxonomic class seems not characterized by any particular polarimetric property, as shown by the phase–polarization curve of Asteroid (12) Victoria, shown in the bottom-left quarter of Fig. 1.

Apart from its taxonomic classification, the only one other parameter of (234) Barbara which does not correspond to a totally usual behavior is the relatively long spin period of more than 26 h, about three times longer than the average values which characterize Main Belt asteroids. A long spin period, however, is not per se a reason to expect that the polarimetric behavior should be in any way anomalous, since there is not any relation a priori between the spin state of an object and the properties of its surface which determine the polarization of the scattered sunlight.

Although there are not many long-period asteroids which have been polarimetrically observed so far, a few examples like (10) Hygiea (27.6 h), (288) Glauke (1200 h), and (550) Senta (20.6 h) (the quoted values have been taken from the public database available at the URL address http://cfawww.harvard.edu/iau/lists/LightcurveDat.html) do not exhibit any peculiar behavior in their phase–polarization curves. In principle, it is not easy to imagine any likely physical mechanism which might produce a polarimetric behavior like that exhibited by Barbara.

We incidentally note that a slow rotation period could be diagnostic of a binary system. However, this is only a purely speculative idea. Even if it is true that there are not binary systems exhibiting fast rotation periods, a slow rotation is not per se necessarily diagnostic of the presence of a companion. In any case, it is not straightforward to explain why and how a binary asteroid should exhibit an anomalous polarimetric behavior. There is not, again, any reason to conclude that this might be true, and a few polarimetric data that are available in the case of the binary Asteroid (22) Kalliope (see http://www.psi.edu/pds/archive/apd.html) do not suggest the presence of any peculiar trend. Also 4179 Toutatis, whose radar-derived shape suggests that this near-Earth asteroid might be a contact binary, does not exhibit any peculiar polarimetric behavior (Lupishko et al., 1995).

It seems more likely that the anomalous polarization of scattered sunlight from this asteroid might be diagnostic of some unusual property of its surface. In this respect, a very speculative possibility might be related to the possible presence of very large impact craters on the surface, causing it to have extensive, large scale concavities, visible under a large variety of observing circumstances. The idea is that the presence of extensive concavities might modify the general illumination conditions of the surface with respect to the case of more usual, convex bodies. This might have some possible consequences on the resulting state of polarization of disk-integrated scattered sunlight. In principle, we do not expect that this effect should produce very strong changes of the resulting phase–polarization curve, but on the other hand this possibility has not been extensively studied so far. In this respect, polarimetric observations of asteroids which are known to exhibit extensive, large-scale surface concavities due to the presence of very large impact craters might be useful. The only one well-known example, however, is given by (253) Mathilde, observed in the past from a close distance by the NEAR probe. Unfortunately, we have not at disposal sufficiently good polarimetric observations of Mathilde. We have a few sparse unpublished observations obtained in 1995–1997, but unfortunately the target was quite faint and the quality of the obtained measurements is generally bad and does not allow us to draw any conclusion.

What seems to be the most “natural” explanation of the anomalous polarization of scattered sunlight from 234 Barbara, is that this is due to some unusual property of the microstructure of its surface, including the average regolith particle size and/or the presence of anomalous slopes in the surface layers. Several year ago the possibility to have large values of the inversion angle had been theoretically investigated in the framework of the Wolff model, based on Fresnel diffraction (Dollfus et al., 1989). More recent laboratory and theoretical modeling indicate that the negative polarization strongly increases in some particular cases, like surfaces composed of very regularly-shaped particles (spheres, crystals) or surfaces having considerable microscopic optical inhomogeneity (Shkuratov et al., 1994). The possible existence of some anomalous regolith particle properties might also be related to the unusual taxonomic classification of this asteroid, since the regolith properties may influence the behavior of the reflectance spectrum. For this reason, polarimetric observations of other *Ld*-type asteroids would be certainly very important. So far, however, the polarimetric behavior of (234) Barbara is not matched by any other known Solar System object, then in the case that its regolith has really some peculiar properties, these properties should be fairly rare.

We note also that a best-fit weighted linear fit of our polarimetric data of 234 Barbara in V color gives a polarimetric slope of 0.070 ± 0.005 (with a correlation of 0.987). Using the polarimetric slope versus albedo relationship with the set of coefficients already adopted by Cellino et al. (1999, 2005), we find a polarimetrically-derived albedo of 0.325 for this asteroid. This is quite larger than the IRAS albedo of 0.23 (Tedesco et al., 2002). In particular, the derived polarimetric albedo would be fairly large for an *S*-type object, the previous taxonomic classification of Barbara, whereas we basically do not know whether this may be a more reasonable value for the new *Ld* taxonomic class. It seems, however, that the slope–albedo relationship might give an exaggeratedly high albedo value for this object, and this, again, might be interpreted as an evidence of anomalous regolith properties.

Summarizing, we have discovered that, from the point of view of the polarimetric behavior, (234) Barbara belongs to a new, previously unknown class of asteroids. The observed properties of the phase–polarization curve of this object cannot be reliably interpreted at this stage. New observations of this asteroid are needed, as well as a more extensive survey of polarimetric observations of other objects belonging to the *L* and *Ld* taxonomic classes, in order to possibly find other cases like this. Since there are so many asteroids, it is extremely unlikely that a single object like (234) Barbara is in some respect unique. Being able to explain the observed polarimetric properties of this object will likely produce a significant progress in our understanding of the mechanisms of light scattering from asteroid surfaces, and on the physical properties of asteroid regoliths.

This should not be considered as an exercise of purely theoretical, and limited, interest. An insufficient knowledge of the light scattering properties of asteroid surfaces, for instance, will be the primary limitation for the full exploitation of the asteroid data that will be collected during the next decade by the GAIA space mission of the European Space Agency. In particular, this problem will constrain the limiting accuracy achievable in the direct measurement of asteroid sizes, and the determination of the displacement of the photocenter of GAIA asteroid images as a function of varying illumination conditions. In turn, this will affect the accuracy of the final determinations of asteroid orbital elements and physical properties that will be derived from GAIA data. For interested readers, the role of light scattering in the determination of the actual signals that will be produced by the asteroids in the GAIA focal plane has been extensively discussed in a number of meeting of the GAIA Solar System Working Group. See the web page of the GAIA SSWG at the address http://www.obs-nice.fr/tanga/SSWG/.

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