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ASTEROID COMPOSITIONS: SOME EVIDENCE FROM POLARIMETRY

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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. In recent times there has been a revival in the field of asteroid polarimetry, on the theoretical side, in relation to experimental simulations, and due to the activity of some teams who are engaged in extensive observational campaigns. Some new discoveries of objects exhibiting unprecedented polarimetric properties have been done. The above subjects are briefly reviewed.

1. Introduction

The visible light that we receive from the asteroids and other atmosphereless bodies of our solar system is in a state of partial linear polarization, as a consequence of the fact that it consists of solar radiation scattered by the solid surfaces of the objects. The polarization properties of sunlight scattered by atmosphereless solar system bodies have been investigated since a long time, because in principle they can be a source of information about the physical properties of the materials present on the surfaces of these bodies. The first pioneering investigations in this field were carried out by Lyot,[1] and were later continued by Dollfus *et al.* at the Paris-Meudon Observatory, and subsequently by other researchers in different countries. The historical background of asteroid polarimetry was briefly summarized in a classical chapter of the Asteroids II book.[2]

The observations allow the observers to directly measure the degree of polarization of light coming from an asteroid. The state of polarization of a light beam is described by the Stokes parameters Q and U (giving the degree of linear polarization), V (related to circular polarization), and I (the total intensity of the received light). In asteroid polarimetry, the V parameter is usually negligible, and the light is in a state of partial linear polarization described by the Stokes parameters Q and U. The observations show that the plane of linear polarization is generally either parallel or perpendicular to the scattering plane, which is defined as the plane containing the asteroid, the Sun and the observer at the epoch of observation. This fact is a consequence of the sunlight scattering process across the surface of the body (see also below).

The parameter that is usually adopted to describe the polarimetric behavior of asteroids is $P_r = P\cos(2\theta)$, where P is the degree of linear polarization, given in module by $\sqrt{Q^2 + U^2}$, and θ is the angle between the measured direction of the plane of partial linear polarization (defined by the observed position angle, given by $\arctan(U/Q)$ and the normal to the scattering plane. When the P_r parameter is measured in different conditions of illumination, described by the phase angle (the angle between the directions to the Sun and to the Earth as seen from the asteroid) a well defined relation between P_r and the phase angle is usually found. The typical situation is shown in Fig. 1, for the case of asteroid (1) Ceres.

As can be seen, the relation is characterized by the presence of a range of phase angles, between 0 and about 20°, in which P_r is negative (the so-called branch of negative polarization). At larger phase angles, P_r

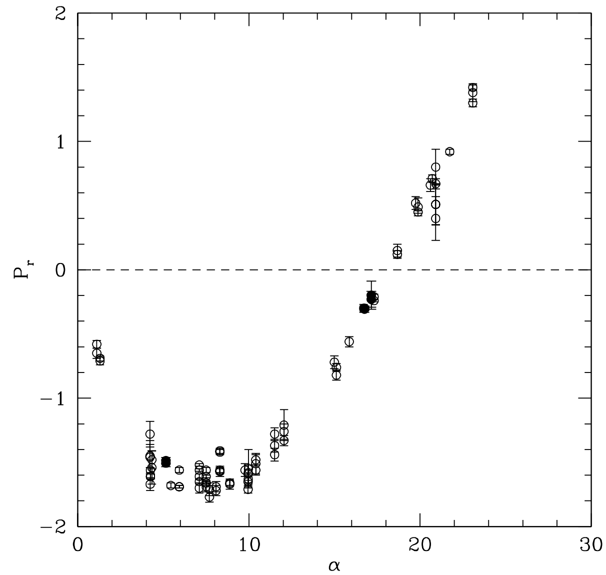

Fig. 1. A typical example of a P_r–phase curve, corresponding to the asteroid (1) Ceres. Data taken from the PDS archive (open circles) and from more recent observations carried out at the CASLEO observatory (filled circles). The phase angle, in degrees, is indicated by the α symbol.

becomes positive. The phase angle at which P_r changes sign is called the inversion angle. Due to obvious geometric constraints, the branch of positive polarization cannot be sampled beyond phase angles of the order of 30–35° in the case of main belt asteroids. The polarimetric behavior at much larger phase angles, however, is well documented in the case of some near-Earth asteroids, including (4179) Toutatis and (25143) Itokawa.[3,4] Around the inversion angle, the trend of variation of P_r as a function of phase is mostly linear. The slope of this linear trend is usually indicated by the symbol h, and is an important parameter, because an empirical relation is known to exist between h and the geometric albedo p_V of the surface (in V light). This relation may be written in the form $\log p_V = C_1 \log h + C_2$, and a similar relation is also found between p_V and the absolute maximum of negative polarization, usually called $P_{\min}$, which is usually reached at phase angles between 8° and 10°. The existence of these relations between the albedo and the polarimetric properties of the objects constitutes one of the best available techniques to derive asteroid albedos.[2,5,6]

2. Theory and Experiments

The interpretation of the polarimetric properties exhibited by the asteroids and other atmosphereless solar system bodies is still a challenge, although significant advances in this field have obtained in recent years.

At present, there are not exact analytical formulae fully describing the phenomena of light scattering in situations corresponding to the case of sunlight scattered by asteroid surfaces. These situations essentially consist of light scattering by close-packed random media of inhomogeneous particles having sizes larger than the light wavelength.[7] Light scattering mechanisms must be responsible not only of the observed polarimetric properties, but also of the photometric properties, including the observed phase–brightness relation. In particular, observations show that there is a mostly linear variation of brightness upon the phase angle (the objects becoming increasingly fainter for increasing phase angle), but at small phase angles a considerable non-linear increase of brightness is observed (the so-called "opposition effect").

In recent times, it has been widely accepted the idea that both the observed polarimetric and photometric properties of the asteroids can be explained in terms of two major mechanisms: coherent backscattering and shadowing. The former mechanism is based on constructive interference of scattered electromagnetic waves in presence of multiple scattering. Interested readers can find a description of this mechanism and appropriate references to previous work in the Muinonen *et al.* chapter in the Asteroids III book.[7] The shadowing mechanism is essentially due to the fact that a photon incident on a particle on the surface can always be scattered back along the same direction of incidence, whereas along other directions it can be blocked by the presence of other surface particles.[7] According to current understanding, the coherent backscattering mechanism plays a role in the generation of both the observed brightness and polarization phase relations, while shadowing should contribute mainly in determining the brightness opposition effect. In particular, the latter seems to be nicely explained as a consequence of both a lack of shadowing at zero-phase, as well as by constructive interference of light scattered from the surface.[7]

Theoretical studies are also complemented by laboratory experiments. In this respect, many authors have produced very useful measurements in the past. Based on laboratory data, it seems that both the depth of the branch of negative polarization and the value of the inversion angle strongly depend on the albedo and microscopic inhomogeneity of the investigated material samples, as well as on their packing density. A problem has been for a long time the lack of experiments at phase angles smaller than 1°, that are very important from the theoretical point of view. The reason is that for this purpose special instruments are needed, with small angle apertures of both the light source and the receiver. Another problem is that laboratory measurements at extremely small phase angles require a very high accuracy, because the polarization degree is typically close to zero at these angles. Some attempts at improving the situation in this respect have been done only in recent years.[8] We note that laboratory experiments including polarimetric and albedo measurements at or very close to zero phase angle are very important also from the perspective of complementing available astronomical observations with laboratory data obtained in similar illumination conditions. In particular, the definition of the geometric albedo of the asteroids is based on their reflectivity at zero phase angle, thus any rigorous attempt of deriving in the future a better calibrations of the polarimetric slope–albedo relation (see above) cannot include laboratory experiments if they are not made very close to zero phase angle. The reason is that the measured luminosity at zero phase can be strongly affected by the non-linear brightness opposition surge.

To summarize the current situation, it can be said that we have today a better understanding of the most subtle physical effects involved in the generation of the photometric and polarimetric properties of the radiation we receive from the asteroids. In particular, the role of the coherent backscattering mechanism is now fully appreciated. There are still some problems in creating models able to reproduce at the same time and in details both the magnitude–phase relation and the polarimetric properties observed for the asteroids. In particular, the wide extension of the negative polarization branch in a range of phase angles of about 20° is still a challenging feature, although wide negative polarization branches are observed in some laboratory experiments, or can be numerically modeled assuming single-particle scattering. On the other hand, it seems likely that further advances in the modeling side are still possible, and the subject is currently being actively investigated by different teams.[9]

3. The Role of Polarimetry in Asteroid Taxonomy

Since many decades it has been realized that asteroids differ in terms of color and albedo. This led to the development of taxonomic classes based on these properties. The general idea, especially at the beginning, was that the differences in reflectance properties among different objects could be directly related to differences in mineralogic compositions. For this reason, some of the first taxonomic classes identified in the first pioneering works were called using symbols that were strictly related to a mineralogic interpretation (i.e., S for "silicates", M for "metals", etc.).

Analyses of the first available spectrophotometric and polarimetric data-sets revealed that spectral reflectance properties alone were not sufficient in many cases to derive a full taxonomic classification, since it turned out that different classes existed which exhibited the same spectrophotometric properties in visible wavelengths, but were characterized by huge differences in albedo, based on their polarimetric properties.[10] The best example is given by the EMP complex, formed by three separate classes (E, M, and P), which have fairly identical spectra but largely differ in terms of albedo. In more recent years, some large systematic surveys (SMASS, SMASS2[11]) have provided spectral data for big samples of objects, from which a taxonomy has been derived. This classification is no longer based on simple color-indexes using limited numbers of filters, but on full reflectance spectra, covering wavelength ranges approximately between 0.5 and 0.9 μm. For the vast majority of these objects no polarimetric data are available, and the albedo is not known, and attempts have been made to separate different taxonomic classes based on the presence of subtle features of the reflectance spectra.[11] In particular, the E, M, and P classes correspond now to different subsets of a bigger complex called X. These subsets are distinguished on the basis of spectroscopic features that have been found to characterize objects belonging to the E, M, and P classes defined in previous, albedo-based classifications.

This does not mean, however, that polarimetrically-derived albedos and, more in general, polarimetric properties are no longer useful for taxonomy-related purposes, or for better understanding the properties of asteroid surfaces. In this respect, the albedo *per se* is a very important parameter, being strictly related to the composition and aging of the surface. It should be stressed that polarimetry must be considered as the best available technique to derive asteroid albedos. The reason is that the existence of a direct relation between the polarimetric slope (and also $P_{\min}$) and the albedo makes it possible to derive the albedo directly from the observed polarimetric parameters, without the need of knowing any other parameter. This is a big advantage with respect to other possible techniques, which cannot measure directly the albedo, but derive it more indirectly, for instance from measurements of the size, and based on nominal values of the absolute magnitude. This is the case, for instance, of thermal radiometry.

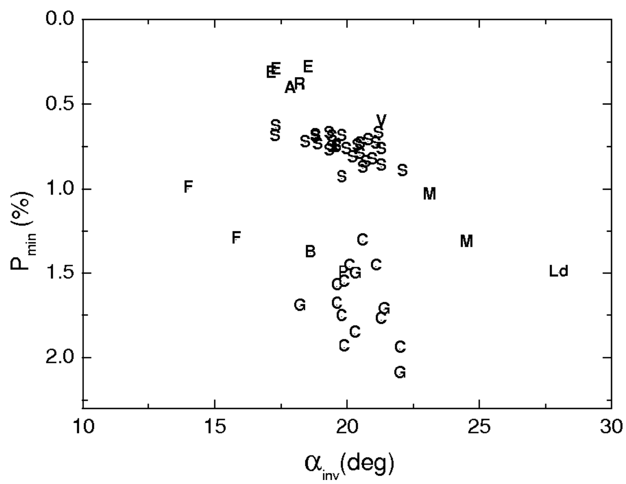

Fig. 2. $P_{\rm min}$ vs. inversion angle ($\alpha_{\rm inv}$) plot for a set of asteroids belonging to different taxonomic classes[11,13] (used as symbols in the plot). Data available in the literature.[14–17]

Moreover, polarimetry has long been found to be an important tool for taxonomic characterization purposes. As an example, Fig. 2 shows that in a plot of $P_{\rm min}$ vs. polarimetric inversion angle, not only there is a clear separation between low (F, B, C, G, D) intermediate (S, M) and high-albedo (E) objects, but also there is a fairly clear separation even among objects of similar albedo. As a matter of fact, a recent analysis[12] has convincingly shown that the availability of a good coverage of the phase–polarization curve for a sample of objects is sufficient to derive a taxonomic classification in very good agreement with that produced by spectroscopic data. In particular, a principal component analysis applied to a set of phase–polarization curves described by a polynomial or trigonometric representation has been found to produce a set of taxonomic classes that very nicely fit the classes obtained by means of purely spectroscopic data. This interesting result suggests that polarimetry and spectroscopy are nicely complementary for taxonomic purposes.

4. Recent Observational Results

From the point of view of observations, for a long time and until some years ago, activity in the field of asteroid polarimetry has not been very intense. There are several reasons for that, including (1) a scarce availability of suitable instruments, (2) the fact that asteroid polarimetry is intrinsically more time-consuming than other observing techniques, (3) the relative rarity of experts in the field, which is also a consequence of the somewhat particular characteristics of polarimetry, being often considered as a fairly obscure technique whose results seem mostly based on empirical and not-too-well understood laws. The items (1) and (2) in the above list are straightforward: since a polarimetric measurement implies the need of splitting the incident light beam into an ordinary and an extraordinary ray, in order to derive the Stokes parameters, fairly large telescopes are needed for the observations of faint targets. Moreover, asteroid polarimetry is intrinsically time-consuming due to the need of observing each object over fairly long intervals of time, to obtain a sufficient sampling of the phase–polarization curve. In other words, asteroid polarimetry is not for those who want to have one publication per one night of observations.

In spite of the above difficulties, in recent years there has been a significant increase of activities in the field. A significant role has been played by the availability of the Torino photopolarimeter, which equips the 2.15 m telescope of the El Leoncito observatory (Argentina). This instrument has produced in recent years a significant amount of data,[6,15] nicely complementing the observing activities of other teams, mainly in Ukraine, who have been working in this field since a long time.

The most recent observing campaigns carried out by different authors had a variety of purposes. These include a systematic check of the albedo values derived by thermal radiometry observations of small main belt asteroids, an analysis of the polarimetric behavior of different objects observed at very small phase angles, an exploration of the properties of the branch of positive polarization which, in the case of near-Earth objects, is accessible up to very large values of phase angle, and, more pertinent to the subject of the present paper, comparative analyses of the polarimetric properties of objects belonging to different taxonomic classes.

In this respect, at least a couple of interesting results have been obtained recently, namely an extensive characterization of the polarimetric properties of F-type asteroids, and the discovery of the unusual polarimetric properties of (234) Barbara, a rare Ld-type object.

The above-mentioned examples deal with phase–polarization curves characterized by extreme and opposite properties. In the case of the F-type asteroids, the most striking polarimetric property, as shown also in Fig. 2, is the very low value of the inversion angle.[16] The F taxonomic class includes objects characterized by low-albedo, and linear, featureless reflectance spectrum. F-type asteroids are believed to be primitive, representing a subclass of the big C complex, from which they can be separated based on their spectral behavior at short wavelengths. Since this part of the spectrum was not included in the spectroscopic data used in the most recent SMASS2 taxonomic classification,[11] the F class is not included among the classes identified in this survey. On the other hand, polarimetry indicates that the F-type asteroids certainly represent a separate class, exhibiting well defined and unique polarimetric properties. As mentioned above, F-type asteroids have been found to be characterized by unusually small values of the inversion angle. In the vast majority of the cases, for asteroids the P_r parameter changes sign at phase angles around 20°. In the case of F-type objects, however, the inversion takes place at much lower phase angles. In particular, 419 Aurelia exhibits an inversion angle at 14°, the smallest value ever observed for asteroids. Also the depth of its negative branch seems unusually low, for a low-albedo objects. Small inversion angles, but more usual negative branches, are also exhibited by other objects of the F class.[16] The interpretation of these properties is not straightforward, but laboratory experiments and numerical simulations suggest that these might be explained by assuming that the surface regolith consists of particles characterized by very high optical homogeneity down to scales of the order of visible light wavelengths.

The case of (234) Barbara is just the opposite. As shown in Fig. 3, in this case we deal with an object exhibiting a very high value of the inversion angle. The first measurements published for this object suggested a possible value of about 30°,[18] but more recent, and still unpublished V and R data (shown in Fig. 3) show that P_r seems to tend more rapidly to zero between 24 and 26°, and the inversion might take place at a phase angle around 28°. This behavior challenges theoretical interpretation. According to current knowledge, a large inversion angle may be expected for a regolith layer consisting of very regularly shaped particles (like spheres or crystals) and/or large optical inhomogeneity. As quoted in Sec. 2, a large value of the inversion angle is just one of the most challenging features to be reproduced by current theoretical models. In this respect, (234) Barbara is very interesting, since it exhibits the largest value of the inversion angle known today for any atmosphereless solar system body, and is possibly the prototype of a previously unknown class of asteroids, from the point of view of polarimetric properties.

One of the most interesting facts concerning (234) Barbara is that it has been found to belong to a fairly rare taxonomic class that has been introduced only recently based on spectroscopic data collected by

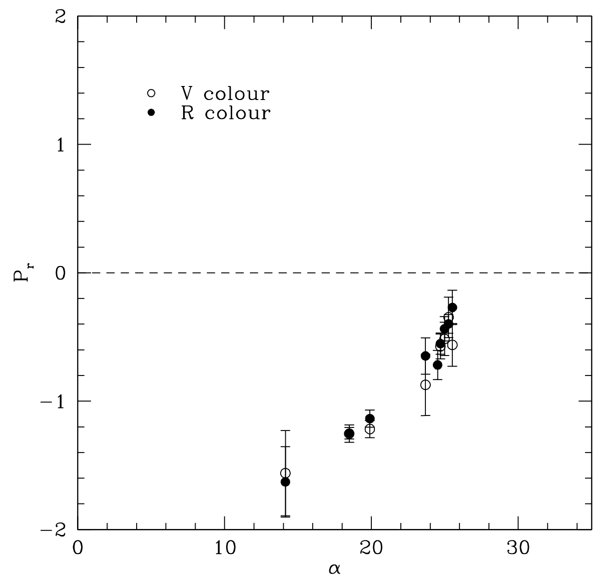

Fig. 3. The phase–polarization curve of (234) Barbara, from observations in V and R colors by some of the authors of the present article. The data include some unpublished data obtained recently at the El Leoncito observatory. The phase angle, α, is given in degrees.

the SMASS2 survey.[11] The objects now classified as *Ld* are a subclass of a larger class called *L*. Both *L* and *Ld* asteroids were previously classified as *S*, the dominant taxonomic class in the inner part of the asteroid main belt. Is the unusual taxonomic classification of (234) Barbara directly related to its peculiar polarimetric behavior? We have not yet answered this question, due to a lack of polarimetric data on other *Ld*-type objects. On the other hand, it is known that a few asteroids belonging to the wider *L* class for which observations are available exhibit "normal" polarimetric properties, as in the case of (12) Victoria. It is clear that new observations of both *L* and *Ld*-type asteroids are needed.

What seems also clear at this stage is that polarimetric properties can be a powerful tool for investigating some properties of the surface regolith particles at a microscopic scale, nicely complementing the information that can be obtained by means of other techniques like spectroscopy. Of course, a strong effort on the modeling and theoretical side, as well as in the field of laboratory experiments, is still needed to increase the diagnostic power of polarimetric data. The wealth of new results obtained in recent years seems to indicate that the field of research in asteroid polarimetry is currently experiencing a new era of rapid development.

5. Future Developments

Apart from the perspectives in the field of theory and laboratory experiments, we want to focus here on some perspectives concerning future observational activities. Future observations will be devoted to a continuation of current efforts, but will probably be aimed also at exploring new fields of research, including an extensive analysis of the wavelength dependence of asteroid polarimetric properties. Another field in rapid development seems to be the study of near-Earth objects. These objects are interesting in many respects. First, they allow the observers to study the polarimetric properties at much larger phase angles, where available data are still scarce. Moreover, NEOs are important also from the point of view of the collision hazard. In this respect, a big effort is being produced by many teams to discover the most dangerous objects. A lot of work must be done, however, on the side of the study of the physical properties of these objects. In this respect, polarimetry can play an invaluable role as a powerful tool to derive the surface albedo, and consequently the sizes of the objects. Using instruments like the ESO VLT 8-m telescope, it is possible to efficiently obtain albedos and sizes of dangerous objects, as demonstrated by some recent observations of (99942) Apophis.[19]

The availability of new polarimeters in the future is needed to ensure a stable development of asteroid polarimetry. Recently, a few new instruments, including a single-color polarimeter using phototube detectors, has entered into operations at the El Leoncito observatory. Compared to the older Torino photopolarimeter, which performs simultaneous measurements in five colors (UBVRI), the new instrument has a more limited spectral capability, but this is compensated by an increased sensitivity in V light, which should allow the observers to observe fainter and darker objects. Another instrument which has been developed recently is the CCD polarimeter built at the Asiago observatory (Italy), which has started recently to produce its first data.[17]

Coupled with the recent availability of the VLT telescope for a number of asteroid polarimetry campaigns, we hope that the above-mentioned developments can be diagnostic of a real renaissance of asteroid polarimetry. We are convinced that a new burst of activity in this field can produce in the next years very important advances in several fields of modern asteroid research, including primarily the study of the properties of asteroidal surfaces.

References

1. B. Lyot, *Ann. Obs. Paris* **8(I)** (1929) 1.
2. A. Dollfus, M. Wolff, J. E. Geake, D. F. Lupishko, L. M. Dougherty, in *Asteroids II*, eds. R. P. Binzel, T. Gehrels and M. S. Matthews (University of Arizona Press, Tucson, 1989), pp. 594–616.
3. A. C. Levasseur-Regourd and E. Hadamcik, *J. Quant. Spectrosc. Radiat. Transfer* **79–80** (2003) 903.
4. A. Cellino, F. Yoshida, E. Anderlucci, Ph. Bendjoya, M. Di Martino, M. Ishiguro, A. M. Nakamura and J. Saito, *Icarus* **179** (2005) 297.
5. D. F. Lupishko and R. A. Mohamed, *Icarus* **119** (1996) 209.
6. A. Cellino, R. Gil Hutton, E. F. Tedesco, M. Di Martino and A. Brunini, *Icarus* **138** (1999) 129.
7. K. Muinonen, J. Piironen, Yu. Shkuratov, A. Ovcharenko and B. E. Clark, in *Asteroids III*, eds. W. F. Bottke, A. Cellino, P. Paolicchi and R. P. Binzel (University of Arizona Press, Tucson, 2002), pp. 123–138.
8. Yu. G. Shkuratov, A. Ovcharenko, E. Zubko, D. Stankevich, O. Miloslavskaya, K. Muinonen, J. Piironen, R. Nelson, W. Smythe, V. Rosenbush and P. Helfenstein, *Icarus* **159** (2002) 396.
9. A. C. Levasseur-Regourd, E. Hadamcik and J. Lasue, *Adv. Space Res.* **37** (2006) 161.
10. D. J. Tholen and A. Barucci, in *Asteroids II*, eds. R. P. Binzel, T. Gehrels and M. S. Matthews (University of Arizona Press, Tucson, 1989), pp. 298–315.
11. S. J. Bus and R. P. Binzel, *Icarus* **158** (2002) 146.
12. A. Penttilä, K. Lumme, E. Hadamcik and A.-C. Levasseur-Regourd, *Astron. Astrophys.* **432** (2002) 1081.
13. D. J. Tholen, in *Asteroids II*, eds. R. P. Binzel, T. Gehrels and M. S. Matthews (University of Arizona Press, Tucson, 1989), pp. 1139–1150.
14. B. Zellner and J. Gradie, *Astron. J.* **81** (1976) 262.
15. A. Cellino, R. Gil Hutton, M. Di Martino, Ph. Bendjoya, I. N. Belskaya and E. F. Tedesco, *Icarus* **179** (2005) 304.
16. I. N. Belskaya, Yu. G. Shkuratov, Yu. S. Efimov, N. M. Shakhovskoy, R. Gil Hutton, A. Cellino, E. S. Zubko, A. A. Ovcharenko, S. Yu. Bondarenko, V. G. Shevchenko, S. Fornasier and C. Barbieri, *Icarus* **178** (2005) 213.
17. S. Fornasier, I. N. Belskaya, Yu. G. Shkuratov, C. Pernechele, C. Barbieri, E. Giro and H. Navasardyan, *Astron. Astrophys.* **455** (2006) 371.
18. A. Cellino, I. N. Belskaya, Ph. Bendjoya, M. Di Martino, R. Gil Hutton, K. Muinonen and E. F. Tedesco, *Icarus* **180** (2006) 565.
19. M. Delbò, A. Cellino and E. F. Tedesco, submitted to *Icarus* (2006), in press.