Mem. S.A.It. Vol. 87, 93

Memorie della

Recent advances in asteroid polarimetry

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Abstract. Asteroid polarimetry has experienced important advancements in recent years. This includes the discovery of new classes of objects, the calibration of some classical relations between geometric albedo and some polarimetric parameters, the development and calibration of new polarimetric parameters to be also used for the determination of the albedo, the first attempt to use *in situ* analyses of asteroid (4) Vesta obtained by the Dawn mission to better understand the relation between local surface properties and disk-integrated polarimetric measurements, and the first applications of spectro-polarimetry to the physical characterization of the asteroids, including the discovery of cases of violation of the Umov law.

1. Introduction

Polarimetry is a powerful tool for the physical characterization of atmosphereless solar system bodies. For a long time, this technique was not applied in a systematic way to the study of asteroids, as a consequence of some difficulty in obtaining for each object a sufficient number of polarimetric measurements taken at different epochs, in such a way as to obtain a sufficiently good determination of the variation of linear polarization in different illumination conditions. Moreover, the lack of a comprehensive physical theory of light-scattering phenomena, sufficient to provide firm explanations of the variety of polarimetric data exhibited by bodies like the asteroids, contributed for a long time to discourage many researchers, who considered the study of polarization phenomena as a kind of fairly obscure discipline.

The situation has started to change since the mid-80s and has been rapidly evolving in recent years. New dedicated teams made important efforts to increase the database of asteroid polarimetric data, and to improve our overall capability to use available measurements as a primary source of information about some important physical properties of asteroid surfaces, including the geometric albedo and some regolith properties that are hard to infer by using other observing techniques. This paper is aimed at making a summary of the current situation in asterpid polarimetry, and at presenting relevant, recent advances in this field.

2. Polarimetry as a powerful tool to derive asteroid albedos

The determination of the geometric albedo is a very important task to achieve a satisfactory characterization of asteroid surfaces. This fundamental parameter quantifies the reflectance of a planetary surface, and is strictly related to the composition and particle size distribution of the minerals forming the surface regolith, namely the most external surface layer. The determination of the albedo by means of polarimetric measurements has been long based on some classical relations, first tested in laboratory experiments several decades ago, between the geometric albedo and some parameters that describe the variation of linear polarization as a function of the phase angle (that is, the angle between the directions to the Sun and to the observer, as seen from the target body). Polarimetric data obtained at different phase angles, are collected and used to obtain the so-called phase - polarization curves, which are characterized by a common, general morphology, described traditionally by means of a small number of parameters, but with some individual differences that are known to be due to differences in geometric albedo.

In the past, several authors performed analyzes to establish quantitative relations between the albedo and some parameters describing phase - polarization curves. The situation has long been confused, because there has never been a strong convergence to a unique approach, and also because the calibration of some generally adopted relations (like the so-called slope - albedo law) has been for a long time a difficult task, limiting the practical effectiveness of polarimetric measurements to the derivation of the albedo. As a consequence, most available catalogs of asteroid albedos have been historically obtained mostly by means of other techniques, primarily thermal radiometry. These published albedo values are unfortunately affected by errors that can be often very large, so justofying an effort tyo improve the situation by a general improvement of polarimetric studies.

In a recent paper, Cellino et al. (2015) carried out a new extensive analysis of currently available polarimetric data, including a large number of new data obtained by the same authors, and proposed some updated calibrations of different relations between the albedo and some different polarimetric parameters. According to the results, several reliable relations can be successfully established, and can provide albedo determinations much more accurate than those obtained by means of thermal radiometry.

2.1. The ground truth from Vesta

The asteroid (4) Vesta, recently visited and extensively studied by the DAWN probe, is an ideal target to better understand the relation between physical properties of an asterid surface and the polarization properties determined by means of disk-integrated measurements. The reason is that Vesta is the only one asteroid for which the existence of a clear variation of linear polarization as a function of rotation has been convincingly established. After the *in situ* study of Vesta's surface by DAWN, it is now possible to perform an analysis to establish the existence of well-established relations between physical properties of the surface, like albedo, texture and composition, and the disk-integrated polarimetric signals measured from the ground at different epochs, corresponding to different rotational phases of the asteroid. This exercise has been attempted by Cellino et al. (2016), who have obtained in this way the first "ground truth" in asteroid polarimetry.

3. The Barbarians

The discovery of the peculiar polarimetric properties of the asteroid (234) Barbara, the prototype of the so-called "Barbarian" asteroids, dates back to 2006 (Cellino et al. 2006). Since then, a small number of other objects displaying the same polarimetric characteristics have been discovered. Up to a couple of years ago, only a handful of Barbarians were known. The peculiar feature of Barbarians is an unusually large "negative polarization branch", namely the interval of phase angles at which the plane of linear polarization turns out to be parallel to the plane of scattering (the plane containing the Sun, the observer and the asteroid). More recently, it was discovered that Barbarian asteroids are also peculiar due to the property of exhibiting very large abundances of the spinel mineral in their reflectance spectra (Sunshine et al. 2008). This suggests that Barbarians might be among the most ancient and most primitive solid bodies currently present in our solar system, because it is possible that they originally accreted during the very early epochs of formation of the first planetesimals. Their rarity could be interpreted as being due to the fact that only a few objects belonging to this first generation of planetesimals have been lucky enough to survive the early processes that led to the removal of 99% of the planetesimals initially accreted between Mars and Jupiter, according to modern models of the formation and early evolution of our planetary system.

An important recent discovery has been that one dynamical family of asteroids, named after the high-inclination asteroid (729) Watsonia, is composed of Barbarian asteroids (Cellino et al. 2014). This opens new possibilities for a better physical characterization and interpretation of these objects by means of polarimetric, as well as visual and near-IR spectroscopy, with promising implications for an improvement of our general understanding of the early phases of Solar system's history.

4. Spectro-polarimetry

The first pioneering attempts to apply the technique of spectro-polarimetry to asteroid studies have recently been carried out, with some interesting results (Bagnulo et al. 2015). Spectropolarimetry not only provides simultaneously spectral reflectance and phase-dependent polarimetric data, but it also provides information about the relation existing between the degree of linear polarization and wavelength. According to preliminary results, the measured gradient of linear polarization as a function of wavelength can be used to distinguish between objects belonging to different albedo classes. Moreover, some variation of this polarization gradient which is observed at different phase angles seems to be able to put some important new constraints to present theories of light-scattering phenomena from planetary surfaces. If early results will be confirmed, spectropolarimetry might soon become the best and fastest technique to achieve a satisfactory physical characterization of asteroid surfaces, the most important limitation being that of the need of large telescopes to obtain useful data for faint objects.

5. Summary and conclusions

We are seeing in these years a general process of Renaissance of asteroid polarimetry. Some important results recently obtained in this field indicate that the study of polarimetric properties of small solar system bodies is one of the most powerful tools at our disposal for the purposes of physical characterization of these bodies, There can be some immediate applications in the field of developing defense systems against the hazard posed by possible impacts with near-Earth objects. In particular, polarimetry can be very effective as a technique to quickly infer the albedo (and hence the size) of potentially hazardous bodies a short time after their discovery. Moreover, polarimetry is also important for taxonomic classification purposes. A first interesting application will be to test the future taxonomic classification that is expected to come from data obtained by the Gaia mission. In particular, it will be possible to confirm whether the sampling of the blue part of the reflectance spectrum performed by Gaia will be effective in producing a distinction between asteroids belonging to the current B taxonomic class, and asteroids that were previously classified as F-class. The latter objects, now included in the modern *B*-class due to lack of sectroscopic data at blue wavelengths, are known to exhibit well-defined polarimetric properties that clearly distinguish them with respect to other low-albedo taxonomic classes (Belskaya et al. 2005).

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