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LIGHTCURVES OF ASTEROIDS: SPIN, 3-D SHAPE, DENSITY

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Abstract. The study of the physical properties of asteroids, spin and 3-D shape, is the first step in understanding their formation and the mechanisms that dictate their evolution. The 3-D shape is indeed required to compute precisely the density, the only quantity that tells us about the internal structure from *remote sensing*, which is at the crux of the question of the location of formation. Bodies accreted far from the Sun contain volatiles elements (ices) and are less dense. Similarly, the spin orientation is key in triggering the orbital Yarkovsky drift effect, which ultimately delivers meteorites to the Earth. Observations by amateur astronomers and professional astronomers are complementary to study these properties. Lightcurves provided by amateurs combined with high-angular resolution images obtained by professionals with 8m class telescopes allow detailed modeling of asteroids. In this proceeding, we describe the motivations to study asteroid physical properties, describe several on-going professional-amateur observing campaigns, and illustrate then with a few results.

Keywords: Planetary sciences, asteroids, photometry, lightcurves

1 Introduction

Asteroids are the left-overs of the blocks that accreted 4.5 Gyrs ago to build the terrestrial planets. Their current orbital and compositional distribution results from their primordial distribution in the accretion disk, from the dynamical events that shaped the solar system (in particular planetary migrations, Bottke et al. 2002), and from their slow evolution since then. Indeed, if the limited size of asteroids precludes any internal activity, collisions fragment them and release pristine material into orbit. Moreover, the Yarkovsky effect (describing the slow orbital drift due to the delayed thermal emission along their rotation, see Vokrouhlický et al. 2015) spreads orbital structures, bluring the original distribution.

This is why the study of the physical properties of asteroids, in particular their size, orientation, 3-D shape, and density, is crucial. The density is the only parameter that tells us about their internal structure: homogeneous or differentiated, with or without volatiles (Carry 2012). This structure is closely related to the time and place of their formation. Schematically: early formation, with the quantity of radioactive elements (in particular Al^{26}) that allowed differentiation; or formation far from the Sun, with volatiles present in their interior. In parallel, the size and orientation are the main parameters that dictate the dynamical evolution through the Yarkovsky effect, injecting material into resonances with giant planets that place them onto planet-crossing orbits, resulting in meteorite falls on Earth (Carry et al. 2016; Granvik & Brown 2018).

Since the 2000s and the work by Kaasalainen et al. (2002), we can determine the spin orientation and 3-D shape (although only its convex hull) from optical lightcurves taken under many different Sun-asteroid-observer geometries, i.e., several apparitions. These shapes have no diameter and cannot describe concavities (the craters). To do so, lightcurves must be combined with disk-resolved data (Carry et al. 2010, 2012), such as the stellar occultation or direct imaging, the later requiring adaptive-optics cameras mounted on 4–8m telescopes.

These two complementary aspects: a) easy and numerous access to *small* apertures over long timescales (i.e., several years) and b) access to *large* apertures, are the foundation of the successful collaborations between professional and amateur astronomers (hereafter ProAm) that have developed in the past two decades.

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2 Examples of ProAm collaborations in the field

2.1 Density of asteroids

From the analysis of the surface properties such as reflectance spectra or albedo, it is possible to make inferences on composition. These observables however tell us only about surface composition, which may or may not be reflective of the bulk composition of the body (Elkins-Tanton et al. 2011). From the compilation of the density of 287 small bodies, Carry (2012) listed several trends in density and macroporosity (the amount of voids larger than the typical micrometer-sized cracks of meteorites) depending on the dynamical and compositional classes, and diameter, following the earlier works of Britt et al. (2002) and Consolmagno et al. (2008). The largest asteroids (mass above 10^{20} kg) are apparently compact bodies without any macroporosity. This contrasts strongly with the other less massive bodies that all present at least 20% macroporosity.

From the combination of disk-resolved images obtained with the largest telescopes on Earth (ESO VLT, W. M. Keck, Geminis) with numerous lightcurves acquired by dedicated amateur astronomers, we have recently studied the shape and density of several large asteroids belonging to different compositional classes. The availability of the SPHERE new generation extreme-adaptive-optics camera mounted on the ESO VLT has even recently changed this field, allowing the study of the main surface features (above 20–25 km) such as impact craters (Marsset et al. 2017b).

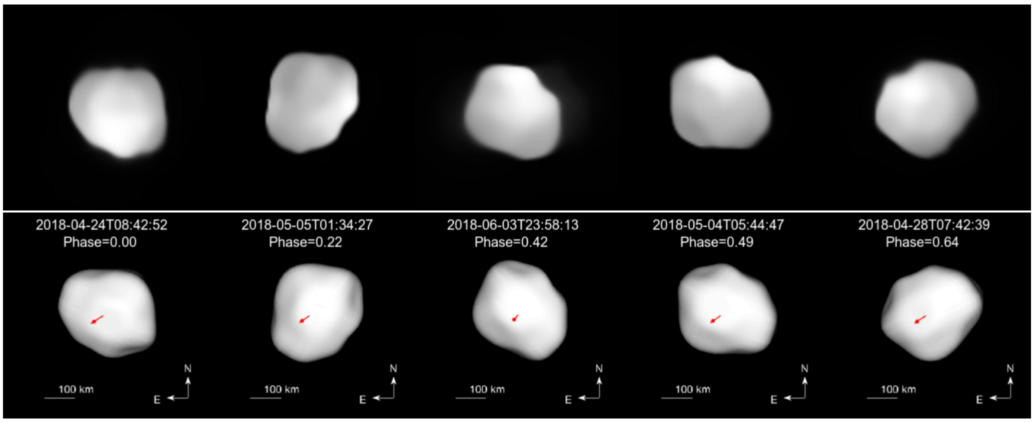

Fig. 1. Top: Images of (16) Psyche obtained with SPHERE/ZIMPOL. **Bottom:** Corresponding views of the 3-D shape model. Figure adapted from Viikinkoski et al. (2018)

Differentiation in P-types (87) Sylvia and (107) Camilla? Both (87) Sylvia and (107) Camilla are P-type asteroids, with a suggested link with interplanetary dust particles (IDPs, the main constituents of comets, see Vernazza et al. 2015). Two moons were discovered from high-angular and high-contrast imaging around each, allowing the determination of the mass and gravitational quadrupole (J_2) from the study of the moon orbits (Berthier et al. 2014; Pajuelo et al. 2018). In parallel, these images combined with lightcurves, both from historical records by professionals and recently by amateurs, allowed the reconstruction of the 3-D shape models of Sylvia and Camilla. The availability of both their mass and their volume provided their density, both around 1,300 kg· m^{-3}, hinting either at high macroporosity or presence of volatiles, most likely water ice. Furthermore, if these bodies were homogeneous, their J_2 would be much larger than measured dynamically, revealing the presence of a denser core surrounded by a less dense shell, i.e., a differentiated interior.

On the link between large bodies and impact families, the S-types (6) Hebe and (89) Julia. Using the enhanced angular resolution provided by the newly commissioned SPHERE/ZIMPOL camera on the ESO VLT, we have recently reconstructed the 3-D shapes of the S-types (6) Hebe (Marsset et al. 2017a) and (89) Julia (Vernazza et al. 2018). In the case of Hebe, not a single large crater or basin was identified, arguing strongly against the proposed origin of H ordinary chondrites from Hebe (around which no dynamical family has been unambiguously identified) by Gaffey & Fieber-Beyer (2013). Thus, the H chondrites are most likely originating from another parent body (Marsset et al. 2017a). The case of Julia is quite the opposite: there is an identified dynamical family related to Julia, with a peculiar distribution in the semi-major axis *vs* inclination

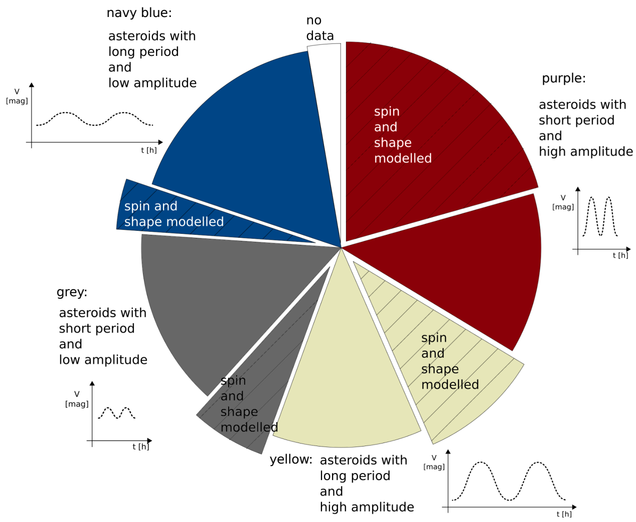

Fig. 2. Statistics of periods and amplitudes of bright main-belt asteroids. Marked areas show percentage of spin and shape modelled targets. Figure adapted from (Marciniak et al. 2018)

plane. The 3-D shape model reveal the presence of a large crater in the southern hemisphere of Julia, which can be linked with the family (Vernazza et al. 2018).

The M-type (16) Psyche target of the NASA Psyche mission a mesosiderite? M-type asteroids have been associated with the metallic cores of differentiated planetesimals, destructed long time ago by collisions. The NASA Discovery mission Psyche is designed to explore the M-type asteroid (16) Psyche to investigate this hypothesis. The very high-angular resolution images provided by the SPHERE instrument (Fig. 1) have allowed to refine its density estimate to $3{,}990 \pm 260\,\mathrm{kg\cdot\,m^{-3}}$ (Viikinkoski et al. 2018). This value is incompatible at the $3\,\sigma$ level with any known iron meteorite (which density lays in the range 7,000–8,000 $\mathrm{kg\cdot\,m^{-3}}$). The density of Psyche however appears fully consistent with that of stony-iron meteorites such as mesosiderites (density around $4250\,\mathrm{kg\cdot\,m^{-3}}$).

2.2 Counteracting the selection effects in asteroid studies

As described above, the physical properties of asteroids are the basis for theories describing Solar System formation and evolution with collisions, resonances, and thermal forces influencing those minor bodies (e.g., Rubincam 2000; Morbidelli et al. 2009) Large asteroids are considered to be the most primordial leftovers from planet formation, so studying them provides valuable clues on the conditions and processes influencing planetesimals. However the population of well-studied asteroids is burdened with strong selection effects. Therefore, the aforementioned theories are likely incomplete, being based on non-representative samples of various asteroid populations. The majority of spin and 3D shape models available today are for asteroids with fast rotation, elongated shape, and with extreme spin axis obliquity (Marciniak et al. 2015).

The selection effects that we focus on act against asteroids with long periods (P>12 hours) of rotation and small amplitudes (a_{max} <0.25 mag) of brightness variations (see Fig. 2). They can influence what is now known about asteroid spin vs. size distribution, evolution and ages of asteroid families, their thermal properties, and on asteroid spin axis orientations, influenced by thermal recoil force called YORP effect. The newest findings suggest, e.g., that thermal inertia is larger for slowly rotating asteroids, allowing to study deeper sub-regolith layers (Harris & Drube 2016). However there are very few long-period asteroids with available thermophysical parameters, because of lack of spin and shape models for slow rotators.

Motivated by these facts, a large, long-term photometric campaign is underway, aimed at reducing these observational biases against long-period asteroids with lightcurves of small amplitudes (Marciniak et al. 2015). Its aim is to obtain scaled spin and shape models of this class of "difficult" objects, with additional properties like thermal inertia and surface roughness, when joining optical and thermal infrared data form space observatories.

For the needs of the project, an international network of around 20 observatories has been set up with small, 0.5-m class, telescopes placed worldwide, from Europe, through the Americas, to east Asia, including the T60 telescope of Pic du Midi Observatory. This allows for an effective coordination of the observing campaign, e.g. for asteroids with periods close to 12 or 24 hours. The coordination is effectively done through a web-based planner service. Over the last 5 years, around 10 000 hours of data has been gathered, resulting in full composite lightcurves and period determinations for around 60 of our targets each year, where many occurred to have different values from the ones widely accepted in LCDB database maintained by Warner et al. (2009) (see Marciniak et al. 2015, 2018).

Among the main results of the campaign are asteroid spin and shape models that were scaled in kilometers by stellar occultation fitting, and also by thermophysical modelling, with consistent results. The thermal inertia values have also been determined and occured to follow the trend of growing thermal inertia with period. Using thermal infrared data also allowed to break the mirror spin axis ambiguity in some cases (Marciniak et al. 2018). This project is an example of a successful ProAm collaboration. Some of the participating observers are dedicated amateur astronomers, providing valuable data on many more targets than it would be possible using only telescopes owned by professional institutions. Our targets are mainly large and bright main belt asteroids that are surprisingly little studied though. Anyone interested in joining our project is welcome*.

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