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Asteroid photometry achieved with small telescopes

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Abstract. Despite very valuable information from space missions (NEAR, Hayabusa,...) extremely important data about asteroids are provided by photometric observations from ground-based telescopes. Because observations are so time-consuming, small telescopes (< 2 m) at professional observatories are mostly used. The community of amateur astronomers also perform extraordinary precise work using even smaller telescopes (> 0.2 m).

The results of short-term photometry are the rotational period and the amplitude of changes of brightness in a variety of solar phase angles. Medium-term photometry is able to cover eclipses/occultations of binary asteroids very well and to determine the parameters of the primary and the satellite. Long-term photometry detects amplitude variations in different apparitions, determines the direction of rotation axes and the sense of rotation and helps to create a 3D model of the asteroid's shape. By using photometric data from a wider time interval we can study the thermal YORP effect, which affects the trajectory and rotation of asteroids (mainly NEAs). It can be used also in the photometric survey of the paired asteroids.

Key words: asteroids – telescopes – photometry

1. Historical background

During the 18th century, astronomers were fascinated by a mathematical expression called Bode's law. It suggested there should be an undiscovered planet between orbits of Mars and Jupiter. When Sir William Herschel discovered Uranus in 1781, at a distance that corresponded to Bode's law, excitement about the law validity reached an all-time high. Many astronomers were convinced that a planet must exist between Mars and Jupiter.

On New Year's Day, 1801, Giuseppe Piazzi from the Palermo Observatory discovered *visually* what he believed to be the missing planet. The new body was named Ceres[1]. Between 1801 and 1808, astronomers tracked down another three minor planets smaller than Ceres within this region of space – Pallas, Juno, and Vesta. A 5th asteroid, Astraea, was discovered *visually* in 1845 and

[1]Follow-up observations rapidly established that it cannot be classed a planet due to its small diameter 940 km. Instead, it was classified as a *minor planet*. In 2006 Ceres together with Pluto and other big icy bodies were classified as *dwarf planets*.

interest in the asteroids as a new class of celestial objects began. In fact, since that time new asteroids have been discovered almost every year and until 1891 more than 300 asteroids were discovered *visually.*

Astrophotography was massively used since 1900 and asteroid discoveries rates sharply increased. Max Wolf pioneered the use of astrophotographic techniques to automate the discovery of asteroids, as opposed to older visual methods. With a Bruce double-astrograph (parallel 41-cm lenses and a $f/5$ focal ratio) he discovered more than 200 asteroids.

Now there are a number of telescopes with CCD cameras. Especially, small telescopes (any reflector with a primary mirror $< 2\,\mathrm{m}$ in diameter) dominate in the fields of comet and asteroid research, variable star photometry, and supernova and nova discovery. Even smaller telescopes with the increasingly sophisticated modern imaging instrumentation can be available to amateur astronomers, not only for astrophotography. Many of them gather high-quality scientific data.

Before the talk about interesting asteroid properties, let's write some words on asteroid search projects using $\sim$1-m telescopes, or smaller. In the past the most known two searching projects operated – NEAT (a 1.2-m telescope, California) and LONEOS (a 0.6-m Schmidt, Arizona). Currently still in operation – LINEAR (2× 1-m and 0.5-m telescopes, New Mexico), Catalina Sky Surveys/Siding Spring Survey (a 1.5-m telescope at Mt. Lemmon in Arizona, a 0.7-m Schmidt near Tucson in Arizona and a 0.5-m Uppsala Schmidt in Australia), Spacewatch (0.9-m and 1.8-m at Kitt Peak in Arizona), Pan-STARRS (4× 1.8-m telescopes in Hawaii). With astrometric observations from other observers all over the world, MPC Archive records more than 103 billion positions for more than 622 thousand asteroids[2]!

2. Photometric campaigns and projects

The *golden age* of asteroid photometry starts when Egon von Oppolzer observed on Dec. 20, 1900 the light variations of (433) Eros and explained them by rotation of its irregular shape.

In this section we want to present interesting photometric projects in which the small telescopes of professional observatories and amateurs play a key role.

2.1. Collaborative Asteroid Lightcurve Link (CALL)

The main purpose is to allow doing asteroid photometry and lightcurve sharing to coordinate efforts so that the best use of observing time can be made and to keep the asteroid community informed in a timely way. The web site provides pages to where the observer can reserve an asteroid for observation. This lets other observers know that other observer is working on it and either find another target or to request a collaboration in order to gather more data sooner. Service

[2]http://www.minorplanetcenter.net/iau/lists/ArchiveStatistics.html

allows also submission of the results of the asteroid lightcurve observations so that they are available to others prior to formal publication. The CALL site includes subpages to provide lists of potential targets for upcoming and recent past 3-month periods and other sites dedicated to asteroid lightcurve efforts.

The observers can publish individual lightcurves (one at a time or in bulk) in the journal *The Minor Planet Bulletin* which is indexed by the ADS and found in the libraries of major observatories and institutions around the world.

2.2. Database of Asteroid Models from Inversion Techniques (DAMIT)

It is a database of three-dimensional models of asteroids computed using inversion techniques. The database and the web interface is operated by the Astronomical Institute of the Charles University in Prague, Czech Republic. A paper describing DAMIT was published by Ďurech *et al.* (2010). Asteroid models are derived using the lightcurve inversion method (Kaasalainen, Torppa, 2001; Kaasalainen *et al.*, 2001) and this is combined with other inversion techniques. Some of them have been further refined or scaled using adaptive optics images, infrared observations, or occultation data. A substantial number of the models were derived also using sparse photometric data from astrometric databases. For each asteroid there is a list of the ecliptic coordinates of its spin axis, its sidereal rotation period, the reference to the original publication, and other parameters and comments related to the model. Observers can find and use there an inversion software developed by M. Kaasalainen and J. Ďurech.

2.3. Photometric Survey for Asynchronous Binary Asteroids

The goal of the survey is to discover asynchronous binary asteroids among small NEAs, MCs, and inner MBAs, and to do this in a controlled way that allows to simulate selection effects and biases in the obtained sample. Targeted are asteroids with $D < 10\,\mathrm{km}$ ($H \geq 12$) in near-Earth, Mars-crossing, and inner-main belt ($a < 2.5\,\mathrm{AU}$) orbits. Smaller objects are to be preferred but the minimal requirement of photometric errors of 0.03 mag or smaller is to be held. Occasionally there are asteroids with suspicion of the YORP effect and paired asteroids and interesting NEAs with radar inspection.

2.4. Koronis Family Asteroids Rotation Lightcurve Observing Program

The main aim is studying the spin properties of members of the Koronis family, which are thought to be shattered remains of a single body that was catastrophically disrupted by a collision. The Koronis family is a part of the main belt of asteroids between Mars and Jupiter (a family member (243) Ida was visited by the Galileo spacecraft in 1993). Most of the Koronis member lightcurve periods known so far are between about 6 hours and 18 hours. With enough lightcurve data it's possible to determine not only the object's rotation period but also its spin axis orientation, the direction of spin about the axis, and a first-order estimate of the object's shape. Analysis of rotation lightcurves has revealed that the spin vector orientations of several members of the largest Koronis family asteroids are unexpectedly aligned in obliquity, which has led to the suggestion that thermal effects might be responsible. New observations are needed to determine spin vectors of the remaining large Koronis family members.

3. Photometric data in databases

Asteroid physical properties, mainly photometric, users can find in some databases. But some of them are inconsistent, not updated regularly. We recommend the following:

- *LCDB* – A listing of asteroid lightcurve parameters and other information, e. g., estimated/measured diameters, absolute magnitudes, phase slope parameters, albedos, semi-major axis, orbital eccentricity, and orbital inclination, family by name, rotation period, and more. A summary set of tables is distributed annually for general use along with special versions for the Planetary Data System (PDS), the ITA in St. Petersburg, Russia (Ephemerides of Minor Planets), and the Minor Planet Center. The database contains photometric information for more than 4 500 asteroids. LCDB has its own on-line query form and the user can retrieve all columns from the LCDB Summary table and can limit results to a specific group, size, and/or rotation period. The on-line query returns a table with a radio button in each row. Select one of the rows and click a button to display all entries tied to the select object from the Details, Ambiguous, Binary, Spin Axis, Tumbling, and Color Index tables. Detailed description is in the paper by Warner *et al.* (2009).
- *APC* – A successor to the Standard Asteroid Photometric Catalogue (SAPC) previously hosted and developed at the University of Helsinki. It's an open web-interface to an asteroid lightcurve database serving as a public forum for observers and researchers alike to exchange and share related data. APC matches modern standards, but also introduced a bunch of new technical solutions that basically make the entire system easier to maintain. The database currently holds 6 414 lightcurves consisting of 224 636 distinct observations covering a total of 725 different asteroids.
- *DAMIT* – At present, the database contains 648 models of 381 asteroids. For each asteroid there are provided the polyhedral shape model, the sidereal rotation period, the spin axis direction, and the photometric data. The database is updated when new models are available or when already published models are updated or refined.

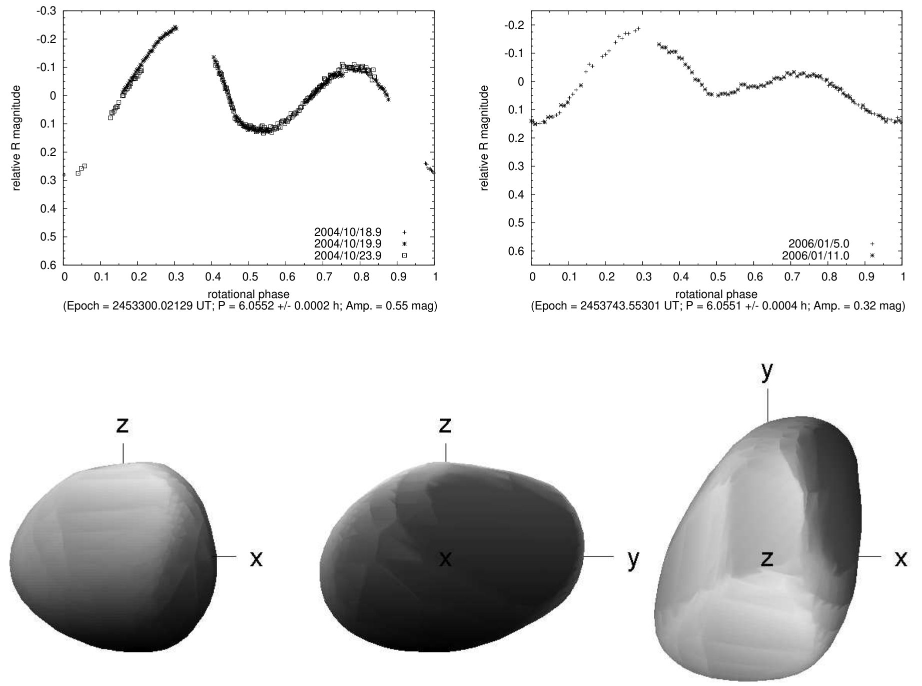

Figure 1. Composite lightcurves of asteroid (787) Moskva from year 2004 and 2006 and its 3D convex shape model. Ecliptic coordinates of the spin axis are $(122°, +27°)$.

4. Binary, ternary, multiple systems and tumblers

The fraction of binary asteroids in the asteroid population is not negligible. According to Pravec *et al.* (2006) it is about $15 \pm 4\,\%$ for the near-Earth population, and probably of the same order for small MBAs. A particularly useful aspect about binaries is that they can help us estimate their densities even if we can only measure their lightcurves. This is because the lightcurves give the orbital period of the system and its approximate relative size scale: how large the distance between the components is relative to their sizes (Scheirich, Pravec, 2009). For disk-resolved data, we can obtain both the mass and the size scale (and hence the density). Binaries are thus especially important in studying the structure and composition of asteroids.

As of July 2013, there are 235 objects with companions: 225 binaries, 9 triple systems, and the sextuple system of Pluto, for 248 companions total. These systems include the following: 46 near-Earth asteroids (2 with two satellites each), 18 Mars crossing asteroids, 88 main-belt asteroids (5 with two satellites each), 4 Jupiter Trojan asteroids, and 79 trans-Neptunian objects (2 with two satellites, 1 with five satellites).

Most asteroids rotate along the shortest axis in the principal state with the lowest energy, some asteroids exhibit complex *tumbling* and their rotation state can be described as free precession. These cases can be modelled by the same inversion techniques as *standard* asteroids with a more complicated description of their rotation (Kaasalainen, 2001).

Another deviation from a simple rotation state is caused by the YORP effect. In the long term, this effect tilts the rotation axis with respect to the orbital plane and changes the rotation period. The change in the direction of the rotation axis is slow compared to the interval of observation. However, the secular change of the rotation period is relatively fast and has already been detected on some targets (Ďurech *et al.*, 2008).

5. YORP

The Yarkovsky effect is a force acting on a rotating body in space caused by the anisotropic emission of thermal photons, which carry momentum. That is, the surface of the object takes time to become warm when first illuminated; and takes time to cool down when illumination stops. The YORP (Yarkovsky-O'Keefe-Radzievskii-Paddack) effect is a second-order variation on the Yarkovsky effect which changes the rotation rate of an asteroid. The term was coined by D. P. Rubincam in 2000. Thermal radiation of small asteroids can secularly decelerate or accelerate their rotation rate. This interesting phenomenon was recently detected in the case of five small near-Earth asteroids – (1620) Geographos (Ďurech *et al.*, 2008), (1862) Apollo (Kaasalainen *et al.*, 2007), (6489) Golevka (Chesley *et al.*, 2003), (25143) Itokawa (Ďurech *et al.*, 2008), and (54509) 2000 PH5 (Lowry *et al.*, 2007). The YORP theory was also advanced, suggesting the effect may have an important role also in the long term evolution of the orbital elements of small asteroids. For instance, the YORP effect is assumed to have a dominant role in formation of binary asteroid systems. Because the theory was confirmed by only five direct detections, it would be important to extend the sample of objects.

6. Paired asteroids

The new study shows that many of binary asteroids do not remain bound to each other but go their separate ways, forming two asteroids in orbit around the Sun when there previously was just one. Vokrouhlický, Nesvorný (2008) report the first observational evidence for pairs of main-belt asteroids with bodies in each pair having nearly identical orbits. They note that the existence of ~ 60 pairs cannot be reconciled with random fluctuations of the asteroid orbit density and rather suggests a common origin of the paired objects. Next, they propose that the identified pairs formed by: (i) collisional disruptions of km-sized and larger parent asteroids; (ii) YORP-induced spin-up and rotational fission of fast-rotating objects; and/or (iii) splitting of unstable asteroid binaries.

Photometric observations started to characterize the spin properties of 20 primaries reveal that primaries of pairs with small secondaries rotate rapidly, while primaries of pairs with large secondaries show significantly slower rotations. The measurement fits precisely with a theory developed in 2007 by D. Scheeres. His theory predicts that if an asteroid splits in two by rotational fission, the pair can only escape from each other if the smaller one is less than 60 percent of the size of the larger asteroid (Pravec *et al.*, 2010).

7. Conclusion

Apart from a few asteroids directly imaged by spacecraft (NEAR, Hayabusa), remote sensing techniques (ground-based observations) are the main source of information about the basic physical properties of asteroids, such as the size, the spin state, or the spectral type. The most widely used time-resolved photometry provides data that can be used for deriving spin states, multiplicity and shapes. In the past ten years, asteroid lightcurve inversion has led to more than three hundred asteroid models.

Because this type of photometric observations are so time-consuming, small telescopes at professional observatories are mostly used. The community of amateur astronomers also performs extraordinary precise work using even smaller telescopes. They have now a great chance to participate in Solar System exploration and help to make the asteroid population well known.

In this paper we reviewed in short the most important aspects of the research of the asteroids. This part of the Solar System is not just big chunks of rock, but has the dynamic ability to evolve. The more we learn about them, the more exciting they are.

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