Unveiling asteroids: international observing project and amateur-professional connection

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Abstract

I review methods (other than spacecraft flybys) of obtaining detailed information on the shapes, spin states, and other characteristics of minor planets. Not directly resolvable asteroids can actually be imaged with these methods by making use of various data sources and modern mathematical techniques. Especially photometric observations play a key role in the construction of a large sample group of models representing the asteroid population. Amateur observers, in their turn, have an important and necessary role in providing such observations.

1 Introduction

Asteroids and comets form the largest and, perhaps paradoxically, the least well known population of celestial bodies in our solar system. The shortage of detailed information is mainly due to the fact that, because of the large interplanetary distances, disk-resolved images can be obtained only of a limited number of these targets. Nevertheless, our view of this population has started to change dramatically over the past few years. Spacecraft images and detailed radar observations, though very limited in their ability to cover the asteroid population, have already revealed to us that asteroids come in just about all possible shapes (from spheroids to 'dogbones'), configurations (from single bodies to contact or separate binaries or satellite systems), and structures (rubble piles, solid or fractured rocks, smooth or bombarded surfaces). The need for detailed information on a large sample of asteroids is thus now pressing, and fortunately it turns out that there are rich data sources readily available. I will discuss below how the present golden age of asteroid research applies also to amateurs, who now have, thanks to modern equipment and CCD cameras, a remarkable opportunity to participate in important scientific research.

In addition to their importance in completing the big picture of our solar system today, asteroids also carry important information from the past. They are, in a way, dinosaurs of the solar system. Unlike planets that are thoroughly moulded by various physical and geological processes, asteroids still contain material from the primordial stages. By studying their composition, structure, shapes, rotational states, and orbits, we can reconstruct much of the history of our system.

2 Asteroid models from remote sensing

Disk-resolvable direct images of asteroids are available only from flybys (e.g., Thomas et al. 1994, 1996; Zuber et al. 2000); there are some very crude low-resolution snapshots of the largest few asteroids taken with the Hubble Space Telescope, but we cannot expect much better resolution because of the physical limitations. Other methods of obtaining information (including radar) are indirect, so they constitute inverse problems. We never properly see the target, so we have to find a way of making a full model of it that explains the observations. In fact this is precisely what our brains do every day with the data from our senses, including images, so in that sense we all solve inverse problems all the time – we are just accustomed to doing it with instinct and experience, not mathematics. When we have to invoke mathematics, the first step is to solve the direct problem, i.e., to give detailed mathematical and physical rules accurately describing how the observed quantities are determined by the parameters describing the target and the observational circumstances. In our case, we are primarily interested in the rotational state, shape, and surface characteristics of the target. The second step is to check whether we can trace this originally one-way path back to the starting point. Usually it turns out that this cannot be done without some constraints and/or additional information, so the second step is considerably harder than the first one. This is why inverse problems are a very active field of study in applied mathematics. The third step is to make the actual backward trip for each target, starting with the real instrument readings and ending up with model figures and images on the computer display.

2.1 Photometric data

A previously much unused but major and easily available source of information on small solar system bodies consists of their photometric lightcurves, i.e., measurements of their total brightnesses that vary as the viewing/illumination geometry changes. We can now well say that the resolving capacity of lightcurve inversion lies, roughly speaking, between space telescope and radar, and its range extends from near-Earth to Jupiter Trojan asteroids (Kaasalainen et al. 2002c).

Let us first write the mathematical model describing an asteroid's brightness (Kaasalainen & Torppa 2001). This is done by integrating over all visible and illuminated surface patches of infinitesimal area $\mathrm{d}s$. In a coordinate frame fixed to the asteroid, the contribution $\mathrm{d}L$ to the total brightness $L = \int \mathrm{d}L$ is, at some point $\mathbf{r}$ on the surface (ignoring the trivial distance-squared factors),

$$\mathrm{d}L = S[\mu(\mathbf{r}), \mu_0(\mathbf{r})]\varpi(\mathbf{r})\,\mathrm{d}s, \tag{1}$$

where ϖ and S are the albedo and the so-called light-scattering model of the surface; $\mu = \mathbf{E} \cdot \mathbf{n}(\mathbf{r})$ and $\mu_0 = \mathbf{E}_0 \cdot \mathbf{n}(\mathbf{r})$, where $\mathbf{E}$ and $\mathbf{E}_0$ are, respectively, unit vectors towards the observer (Earth) and the Sun at the moment of observation, and $\mathbf{n}(\mathbf{r})$ is the surface unit normal. Lambert's law, for example, is $S_\mathrm{L} = \mu\mu_0$, while the Lommel-Seeliger law is $S_\mathrm{LS} = S_\mathrm{L}/(\mu + \mu_0)$. Note that L is given in intensity units rather than magnitudes. In practice, brightness changes are ascribed almost completely to shape; potential albedo variegation over the surface can be separated from shape to some extent, but from physical considerations and spacecraft images we can expect such effects to be quite small. The integral is in practice computed by tessellating the surface into small planar facets and replacing the integral by a sum. In the inverse problem we solve for the parameters defining such a surface (i.e., $\mathbf{r}$) by minimizing with suitable optimization procedures the chi-square residual

$$\chi^2 = \sum_{i=1}^{N} (L_i^\mathrm{obs} - L_i)^2, \tag{2}$$

where L_i^obs and L_i are, respectively, the observed and modelled brightnesses at the N observation epochs.

Rotation parameters are easily introduced through rotation matrices transforming coordinates between the asteroid frame and a global frame such as the ecliptic or equatorial one (Kaasalainen et al. 2002c; also cf. Fairbairn 2003). For most asteroids these parameters are the direction of the spin axis and the sidereal rotation period. Some asteroids are precessing, i.e., their rotational states have not yet relaxed to the so-called principal-axis rotation due to energy dissipation in the tumbling asteroid material. Such precession can also be described mathematically and the corresponding parameters be included in the coordinate transform (Kaasalainen 2001). Lightcurve observations can also reveal binary asteroids revolving around each other (Pravec et al. 1998, Mottola & Lahulla 2000).

The direct problem is thus quite straightforward via (1). The inverse problem, however, is notoriously difficult, and has often been thought unsolvable. Indeed, it was something of a surprise to find out that, when merely natural and simple constraints are applied, the problem has a well-defined solution. The path to this solution is rather a winding one and involves a number of mathematical and physical considerations I will not discuss here (Kaasalainen & Torppa 2001,

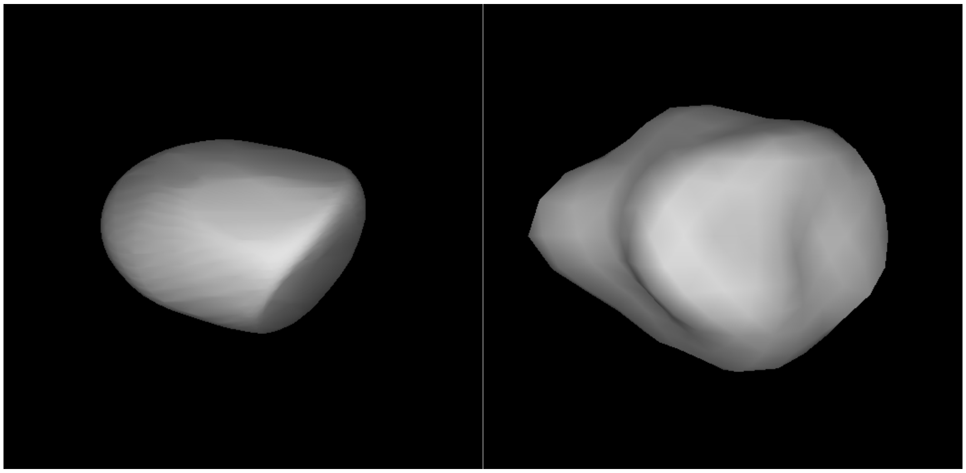

Figure 1: Equatorial views of the lightcurve-based models of asteroids 1580 Betulia (left) and 3908 Nyx (right).

Kaasalainen et al. 2002c). The main results are that the rotation parameters can be deduced very accurately, and the *global* shape can be well inferred. This shape can be thought of as the convex shape best mimicking the silhouette of the body in all viewing directions. Detailed topographic/nonconvex features can seldom be confirmed using disk-integrated photometric data alone (Ďurech & Kaasalainen 2003). This is typical of any inverse problem: some information is often inevitably lost on the way, in this case due to the smoothing effect of integration over the disk. Our job is to make sure we gather everything that the information source has to offer. The important thing here is to have data from various observing geometries, and above all when the solar phase angle $\alpha = \arccos(\mathbf{E} \cdot \mathbf{E}_0)$ is not low, i.e., the shadowing effects revealing the shape are prominent. We show examples of the models and lightcurves of two near-Earth asteroids (NEAs) 1580 Betulia and 3908 Nyx in Figures 1-3.

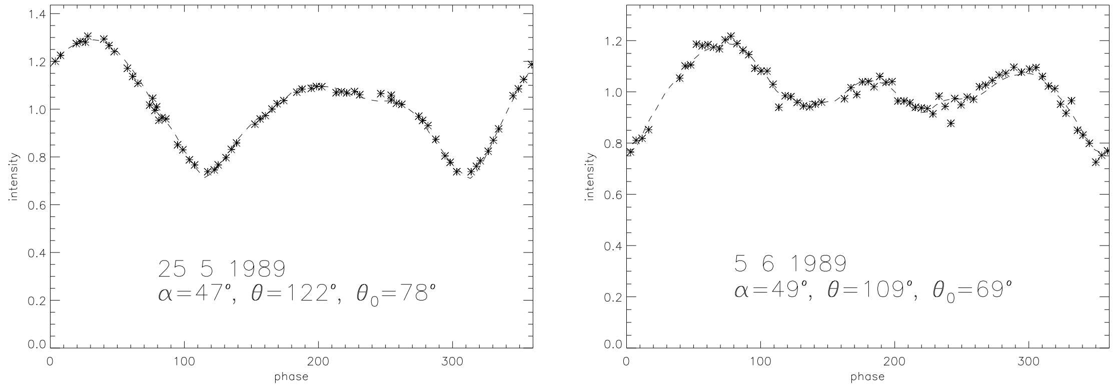

Figure 2: Two lightcurves of 1580 Betulia. Asterisks are the observed intensity points (in relative units), and the dashed line is the model fit, plotted against the rotational phase (in degrees). The polar angles of the Earth and the Sun, as seen from the asteroid, are θ and θ_0, respectively. The solar phase angle is given by α. Note the very rapid change of the lightcurve shape as the observing geometry changes, caused by the irregular shape and the high solar phase angle.

There are some 10 000 recorded lightcurves of several hundreds of objects (Lagerkvist et al. 2001), and the numbers are growing. We have so far built models of over eighty objects (e.g., Kaasalainen et al. 2002a,b, 2003; Slivan et al. 2003; Torppa et al. 2003), and at least as many can be analyzed in the near future with the aid of well-planned observations. NEAs are especially rewarding targets. Due to the quickly changing observing geometries, a comprehensive model of a NEA can often be constructed after an observation span of only a few months. In addition to NEAs, there are numerous main-belt asteroids (MBAs) for which only one or two more observation campaigns are needed to compile a good data set.

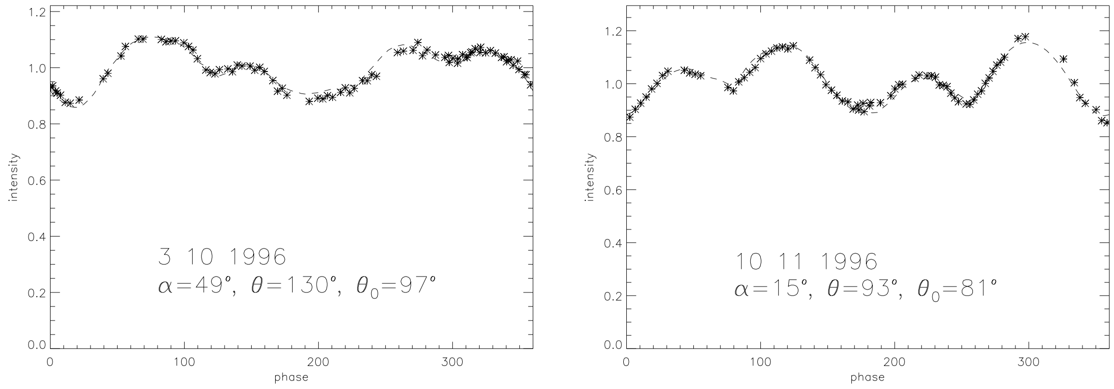

Figure 3: Two lightcurves of 3908 Nyx, together with the model fits.

2.2 Complementary data: radar, interferometry, occultations

There are other sources of information that are perhaps not as robust and easily available as photometry, but have a complementary character. Combining even a limited number of such data with photometry can result in a more detailed solution. We have recently started doing this with radar and interferometric observations and occultation timings. In the following I briefly list the basic models for these sources to show that the mathematical relationship between the model parameters and the observables is always quite straightforward. It is the backtracking that is the hard part.

Radar is a powerful tool for asteroid observations (Ostro et al. 2002). A delay-Doppler experiment not only measures the intensity of the reflected radar signal as a function of the Doppler frequency (different surface points have different radial velocities due to asteroid's rotation); it also measures the intensity as a function of (very accurately determined) time. This gives the radar depth coverage as parts of the body further away from the radar reflect the same signal back later. Now the observable 'coordinates' (d, D) (d for depth and D for apparent Doppler velocity in the radial direction away from the observer) and the surface point $\mathbf{r} = (x, y, z)$ in the asteroid's own coordinate system are related by

$$\begin{aligned} d &= -(x\cos\phi + y\sin\phi)\cos\delta - z\sin\delta, \\ D &= \omega\cos\delta\,(y\cos\phi - x\sin\phi), \end{aligned} \tag{3}$$

where ω is the angular speed of the asteroid's rotation about its axis, δ is the sub-radar latitude, i.e., the latitude of the radar as seen from the asteroid, and ϕ is the sub-radar longitude. The often shown radar 'image' of an experiment is a plot of the combined observed intensities of all visible surface patches in the (d, D)-plane, so it should never be mistaken for a snapshot of the target. For one such plot, there are still several surface patches that correspond to the same (d, D)-pixel. The "brightness" of one pixel is the integrated radar cross section (echo strength) of these patches, computed just as in (1) (now $\mu = \mu_0$ and $S \sim \mu^n$).

If there are delay-Doppler experiments for several epochs, and the latitude δ is different from zero, the many-to-one pixel mapping is different for different images, and one can use this to create a model of the target (Ostro et al. 2002). In practice, this results in standard least-squares optimization. For asteroids not close to the Earth, however, the echo power is usually not sufficient for depth resolution, so we get Doppler-only signal (also known as CW, continuous wave). Now the echo power for one frequency is given by integrating over surface patches corresponding to one D-bin. These data are usually not sufficient for reliable object modelling by themselves. Since their information is 'orthogonal' to photometry, they can be employed to give additional accuracy to models based on lightcurve inversion. An example of this is shown in Figure 4. A contact-binary type asteroid shows the waist between its two main parts in a Doppler profile, but lightcurves seldom carry information on such indentations unless they are very large and are observed at very high solar phase angles (Ďurech and Kaasalainen 2003).

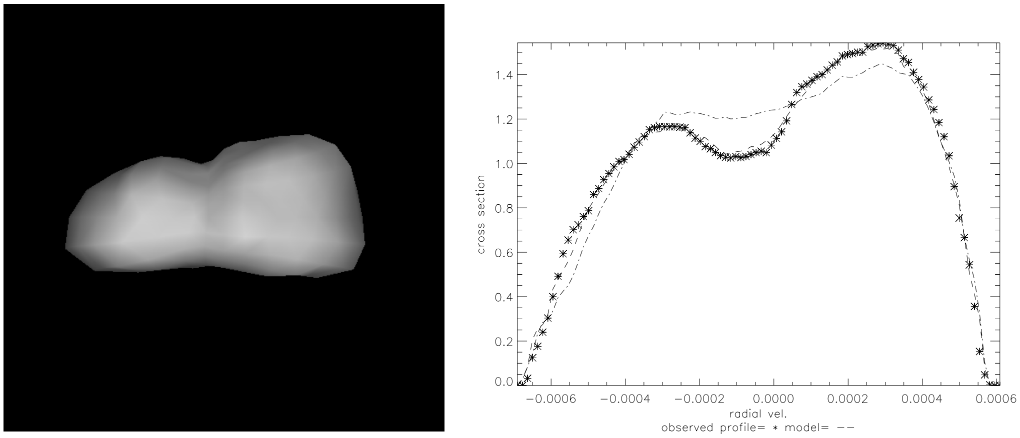

Figure 4: A test shape and its Doppler radar profile (asterisks), together with the fits from a lightcurve+radar-based model (dashed line) and lightcurves-only model (dot-dash).

Interferometry is another major remote sensing technique. It is based on the fact that even though the target cannot be resolved, its nonvanishing angular size inevitably disturbs the optical standard interference pattern that would be obtained from a pointlike source. The disturbances have a much larger angular width than the source. The disturbed pattern is a convolution of the undisturbed one with the plane-of-sky image of the target. Denoting the plane-of-sky distance along the scanning direction by x we have

$$P(x) = \frac{1}{L} \int\int I(u,v)\, T(x - u\cos\gamma + v\sin\gamma)\,\mathrm{d}u\,\mathrm{d}v, \tag{4}$$

where we integrate over the plane-of-sky image intensity $I(u,v)$ of the target (u, v are the chosen plane-of-sky coordinates), $T(x)$ is the standard interference pattern strength, and γ is the plane-of-sky tilt angle between x- and u-directions. The final pattern P is normalized with the target's total disk-integrated brightness $L = \int\int I(u,v)\,\mathrm{d}u\,\mathrm{d}v$. The model image distribution $I(u,v)$ is directly given by the plane-of-sky projections of the surface facets and their brightnesses $\mathrm{d}L$ from (1), so the interferometric case is simply an extension of the photometric one, and the inverse problem can be handled accordingly. One cannot reconstruct an image from one scanning session, but we can use all available data from several dates and geometries to make a full model.

We use, for example, the Fine Guidance Sensor interferometry with the Hubble Space Telescope with two orthogonal scanning directions (Hestroffer et al. 2002, Tanga et al. 2003). Interferometric data are, of course, obtained much less often than photometric data, so again they alone are not sufficient for modelling in practice, but they are a valuable addition to photometric information.

Timings of stellar occultations by asteroids are gathered almost exclusively by amateur astronomers. These are rather fragile and fortuitous events, but in principle contain snapshots profiles of the target if well observed. Here the direct problem is again easily expressed. For a given occultation timing Δt from some epoch, the proper observed quantities (coordinates of a "profile point") can be written as

$$(\xi, \eta) = [\hat{\mathbf{s}}_\xi \cdot (\mathbf{x} + \Delta\mathbf{v}\Delta t), \hat{\mathbf{s}}_\eta \cdot (\mathbf{x} + \Delta\mathbf{v}\Delta t)], \tag{5}$$

where $\mathbf{x}$ is the observer's position on the Earth in the sidereal equatorial frame, given by $\mathbf{x} = (R\cos\beta\cos\theta, R\cos\beta\sin\theta, R\sin\beta)$ (with R the local Earth radius, β the latitude, and θ the local sidereal time), $\Delta\mathbf{v}$ denotes the differential space velocity $\mathbf{v}_{\mathrm{Earth}} - \mathbf{v}_{\mathrm{asteroid}}$, and the silhouette plane projection unit vectors can be chosen to be

$$\begin{aligned} \hat{\mathbf{s}}_\xi &= (-\sin\delta\cos\alpha, -\sin\delta\sin\alpha, \cos\delta), \\ \hat{\mathbf{s}}_\eta &= (\sin\alpha, -\cos\alpha, 0), \end{aligned} \tag{6}$$

where α and δ are the right ascension and declination of the occulting star. The corresponding projection point of a surface point $\mathbf{r}$ of an asteroid model is simply

$$(\xi_{\mathrm{mod}}, \eta_{\mathrm{mod}}) = (\hat{\mathbf{s}}_\xi \cdot \mathbf{r}_{\mathrm{eq}}, \hat{\mathbf{s}}_\eta \cdot \mathbf{r}_{\mathrm{eq}}) + (\xi_0, \eta_0), \tag{7}$$

where $\mathbf{r}_{\mathrm{eq}}$ is $\mathbf{r}$ transformed to the equatorial coordinate system by the rotation parameters, and (ξ_0, η_0) is some offset. The inverse problem consists of adjusting the model $\mathbf{r}$ and rotation parameters such that the theoretical profile line coincides with the observed profile points as well as possible. Now even some large concave formations are resolvable in principle, and we also get the size scale of the target directly as with radar and interferometry.

There are some other remote sensing sources as well, most notably thermal infrared observations and polarimetry. The former is, again, closely related to ordinary photometry, but in this case we also have to invoke a thermal model to explain the transfer of heat in the surface material, which brings us to slightly less well known practical physics. The same applies even more to polarimetry: models of the polarization states caused by the surface material are as yet virtually nonexistent.

3 Amateur observations are important

A revolutionarily efficient practice in photometry is the extensive (and intensive) use of small telescopes. Accurate CCD photometry of targets brighter than about 15 mag is quite feasible with relatively inexpensive telescopes less than 40 cm in aperture. Even high-quality telescopes of only 20 cm or somewhat smaller are still useful. This means that there are at least hundreds of instruments in the world equipped for the asteroid modelling project. Most remarkably, many of these are operated by dedicated and skilful amateur astronomers. Best amateurs can routinely make observations on a par with small professional observatories at an automated level (or actually surpass them – so far, only amateurs have been able to deliver a desired lightcurve overnight with complete instrumental reductions!). Amateur observations are thus just as important as professional ones – occultation timings or lightcurve data from a 20-cm telescope are analyzed simultaneously with those from the large Arecibo radio telescope or the Hubble Space Telescope! It is also important to note that getting good photometric coverage for hundreds of asteroids takes thousands of hours of telescope time. This makes amateur observers indispensable: it would be physically impossible to get enough observing time from professional telescopes for this project. What is more, this observing mode is extremely flexible and unbureaucratic. Amateurs can also perform intensive observing campaigns on a specific target – this is often useful during one apparition of a NEA (see, e.g., Koff et al. 2002). Two examples of very good amateur observations of relatively bright MBAs are shown in Figure 5. The data are consistent and have very little noise even though they were obtained with a small telescope.

A natural form of organization for asteroid lightcurve observers is a flexible network mainly communicating over the Internet. I list here a few hubs of this network; links and people cited on these sites form a natural guide for those interested in the subject. An introduction to the project, an alert list of good asteroid targets, some publications, and other material are presented on the

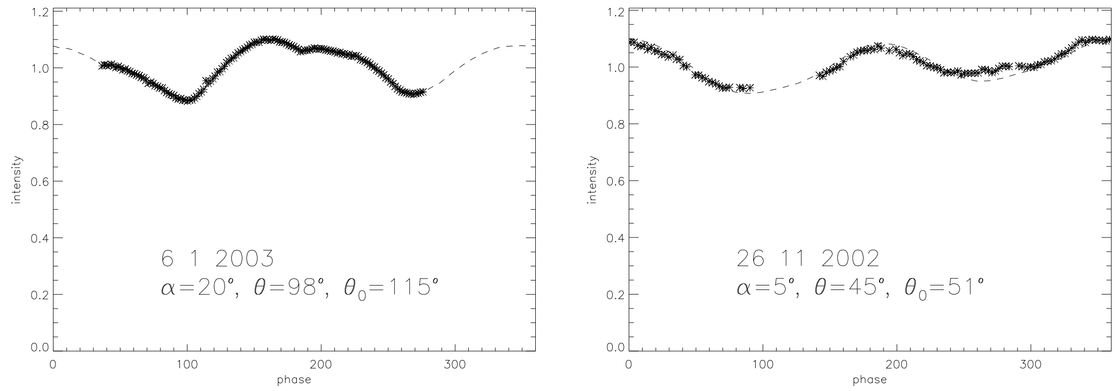

Figure 5: Two lightcurves of 37 Fides and 129 Antigone by R. Kowalski, obtained with an 18-cm Maksutov telescope and an SBIG ST-7E CCD camera.

webpages of our project on inverse problems in astronomy (`www.astro.helsinki.fi/∼kaselain`). Once the equipment is there, making actual scientific observations of an asteroid is quite straightforward after some practice. An excellent link containing plenty of advice and other links is Brian Warner's CALL (Collaborative Asteroid Lightcurve Link) site `www.MinorPlanetObserver.com/astlc/default.htm`. Another informative link is Richard Kowalski's ALPO (Association of Lunar and Planetary Observers) asteroid observing program site `www.bitnik.com/mp/alpo/`. Information on occultation timings is given on the IOTA (International Occultation Timing Association) pages `www.lunar-occultations.com/iota/asteroids/astrndx.htm`.

The first stage of photometric asteroid observations is to get the first few lightcurves of a target, enabling one to get the first estimate of its rotation period and perhaps some hints of its shape character. Rotation periods are already known for hundreds of asteroids, and it is possible to draw important statistical inferences from such a set (Pravec et al. 2002).

The second stage is to get more lightcurves at new apparitions, thus providing information at new viewing/illumination geometries. An efficient way of getting the most of one asteroid apparition is to obtain two lightcurves at the largest useful solar phase angles (to get a meaningful part of the period covered; more than one night is good for this), and one at a smaller phase just to get as long a stretch as possible. The high phase angles are important for reaching maximal shadowing effects (and light-scattering behaviour different from the simple near-geometric mode near opposition). A dense lightcurve sequence contains a wealth of information and helps to rule out errors. Several tens of points per rotation period are the optimum, so an automatic observation mode is necessary. A good practice is to eliminate potential systematical errors by observing on two adjacent or at least nearby nights, particularly if the rotation period is not short enough for overlapping rotational phases during one night. In this way one can be sure that possible features in the lightcurve are really repeated and not artificial.

Finally, sending the observations to be analyzed is very easy. The data can be sent by email (in a flexible format) to me or to Brian Warner (or to anyone else who is gathering and forwarding observations to us to be analyzed); we are also in the process of building an automated Internet-service for this purpose. The observer always gets author credit in the paper where the data are published.

4 Conclusions and encouragement

Solar system bodies are fascinating already from the point of view of data acquisition as few astrophysical targets offer such a wide repertoire of data sources. We live in the golden era of planetary research, and particularly for small solar system bodies this era has just begun. Amateur observers have now a great chance to participate in solar system exploration and help to make the asteroid population as well known as the larger planets.

While "what do they look like" is the natural prime incentive for acquiring photometric data, the follow-up question "why do they look like that" is just as important. When we have a large number of asteroid shape and spin models at our disposal, we can draw important statistical inferences on the origins and evolution of this population. To mention just one example, Slivan et al. (2003) used these methods to investigate the curious clustering of the spin states of small (20-40 km) members in the Koronis asteroid family. Recent results (Vokrouhlicky et al. 2003) suggest that such clustering could generally take place in this size region in the outer asteroid main belt at low inclinations. If evidence for this is found in the overall asteroid population, we will have important new clues to dynamical evolution particularly due to the so-called YORP (Yarkovsky-O'Keefe-Radzievskii-Paddack) thermal radiation pressure effect.

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