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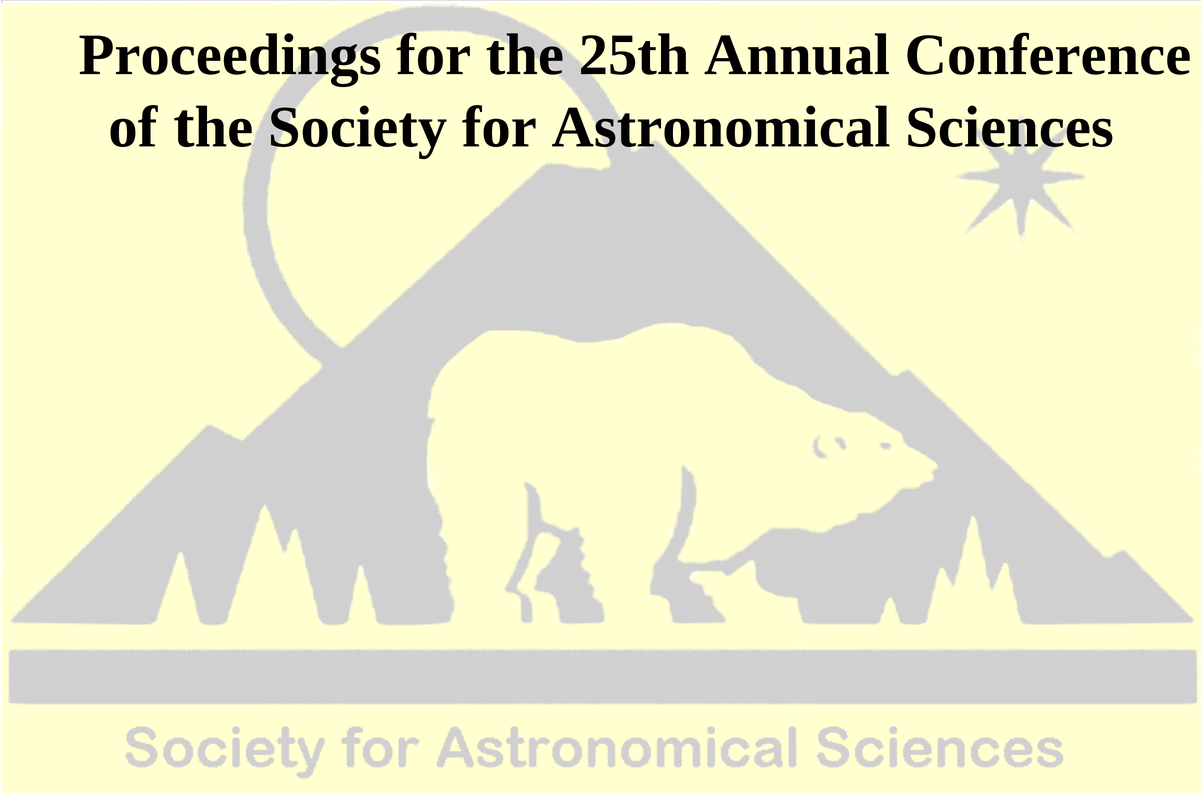

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Follow-up Data for Large Photometric Surveys

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Abstract

Contrary to what one might think, amateur photometry will become increasingly important and considerably more time-efficient in the era of extensive astronomical surveys. Appended to a sparsely sampled data sequence, even one ‘traditional’ dense lightcurve of an asteroid will boost the reliability of the resulting physical model significantly. Amateur observers have the chance to obtain thousands of well-defined spin and shape models of asteroids in the near future as the data from surveys such as Pan-STARRS and LSST start flowing in. This is a unique opportunity to map the asteroid population: no other observing mode can reach such a vast number of targets.

1. Introduction

Photometric data from amateur astronomers have played a well-recognized and increasingly important role in planetary studies for several years now. This meeting is a prime manifestation of the fact. The pro-am collaboration has perhaps three main components. In historical order these are:

1. Period analysis for more than 1000 asteroids, including the detection of many binary systems.
2. Full physical (spin, shape and scattering) modelling from combined datasets, also with data other than photometric (including, e.g., radar, stellar occultations, thermal infrared, and adaptive optics).
3. A vast quantity of physical models using accurately calibrated photometry from large surveys (Pan-STARRS, LSST, etc.) as the main database.

Item I has resulted in statistically important catalogues by Harris, Pravec, and others. Despite the inevitable observational selection effects, we are beginning to have some idea of the period distribution of asteroids. Item II has produced the first reasonably large (more than 100 objects) catalogue giving us some idea what asteroids are really like: how their spin axes are distributed in space, what kinds of shapes and irregularities they exhibit, what are their actual (spin/shape corrected) solar phase curves like, what can we say about their surface properties, etc. We now have several ‘ground truths’ from space missions, laboratory studies, etc. (Kaasalainen et al. 2001, Kaasalainen 2005, Marchis et al. 2006) from which we know that photometric modelling gives a good global portrait of the target. Similarly, we know that combining thermal infrared observations with these models yields, e.g., accurate estimates of surface regolith properties (Mueller et al. 2005). The models can even be used for getting a colour map of the surface using data at different wavelengths and thus gain some insight on mineral distributions (Nathues et al. 2005). The spin properties can reveal evolutionary surprises (Slivan et al. 2003), in particular in connection with the YORP effect from thermal radiation (Vokrouhlicky et al. 2004 and references therein).

While the level of detail from ground-based observations cannot reach that of in situ space missions, the latter are going to remain few in number. Photometry alone has the chance to give us a well representative and statistically significant coverage of the physical properties of the whole asteroid population and its subpopulations. In this context item III, the topic I will discuss here, will actually blow up the bank.

2. Large surveys and Sparse Photometry: a New Era in Astronomy

Observational astronomy is going through a change of paradigm. Rather than picking an individual target and sitting on it, we first scan the skies and record everything. Such surveys will give us the first proper global celestial map, with a vast number of targets for which we have preliminary characteristics available. From this catalogue (from hundreds of thousands of asteroids to a billion stars) we can then pick targets for closer individual scrutiny. This change is not unlike the advent of aerial photography in geographic studies a century ago: the globe was soon mapped without having to send explorers all over the place. Only now the scale of the mapping is entirely different, starting from solar system objects and reaching through the Galaxy and beyond. Ground-based and satellite surveys such as Pan-STARRS, Gaia, and LSST will completely change our way of viewing the universe. Also, since we record just about everything we can, the selection effects and biases are not nearly as strong as with predetermined target lists.

So everything is going to change, and asteroid science not the least. Originally the asteroid survey mode was intended for astrometry, especially with the determination of the orbits of near-Earth objects in mind, and this mode of operation has already been in use for some time (LINEAR and LONEOS). The new surveys, with Pan-STARRS in the forefront, will make use of the rapid developments in optical and data processing equipment not only to produce much larger quantities of data much faster, reaching considerably fainter targets – they will also obtain more accurate details. A particular feature of this is the possibility to have calibrated sparse photometric sequences over several years. Sparse means that the data points are typically separated by hours, days or even weeks. Typical Pan-STARRS sequences (or cadences, as the parlance goes) range from 50 to 500 or more points per 10 years per asteroid for tens of thousands of objects (Durech et al. 2006). Gaia will produce somewhat more sparsely distributed points over five years for a few times smaller target group (Kaasalainen 2004). In both cases, the calibration accuracy is expected to be better than 0.01 mag.

It is at first sight almost counterintuitive that sparse sequences are sufficient for asteroid modelling as shown in Kaasalainen (2004) and Durech et al. (2006). After all, the sampling interval is for most targets much longer than the sidereal period, so ordinary time series methods such as Fourier or power spectrum analysis (used for determining the periods of traditional lightcurves) are completely useless. The reason for the sufficiency is that the underlying well-defined mathematical model is highly constraining: only a certain type of an object can create a given sparse sequence as long as there are enough points at various observing geometries. In fact, sparse sequences are handled just like the ordinary lightcurve inversion problem: the mathematical model takes care of ‘filling the gaps’. Now we just have to scan a wide range of potential periods as the rotation period is not apparent in the data before the actual modelling.

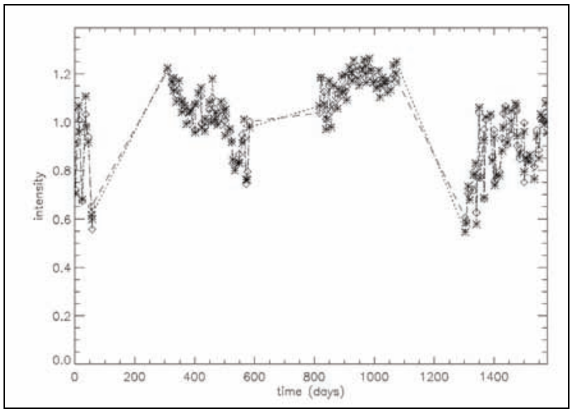

Figure 1. A typical sequence from a groundbased survey (asterisks and dotted line) with the model fit (diamonds and dashed line).

A typical requirement is some 100 well-distributed data points over five years for main-belters, while for NEAs even less is sufficient (Kaasalainen 2004). The calibration accuracy should be at least around 0.05 mag, so the new surveys can indeed meet the requirements. The surveys can make use of data at smaller solar elongations than those typical for ordinary lightcurves since only one point is needed at a time; thus the geometry coverage is wider (i.e., the observational gaps between apparitions are narrower). This is why the observation geometry range of ground-based surveys is not really very much smaller than that of satellite-based ones. For example, Pan-STARRS can reach solar elongations slightly less than 60 degrees, while Gaia’s minimum is at about 45 degrees. Fig. 1 shows a typical photometric sequence of a main-belt asteroid from a simulated ground-based survey, together with the model fit. The connecting lines are added just for viewing convenience – of course, the brightness does not change linearly between the points. Fig. 2 shows the correct result of the trial period scan.

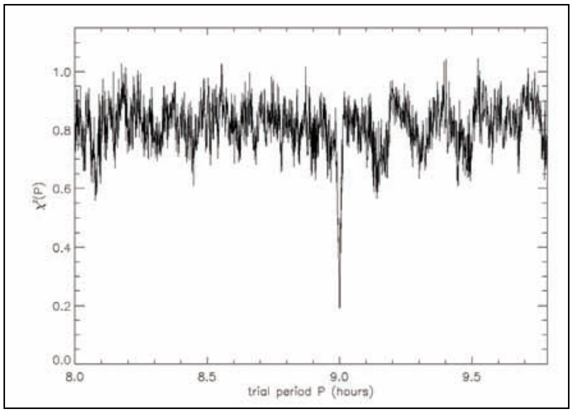

Figure 2. Chi-square as a function of the trial period has a global minimum at the correct value even though the period is not apparent in the data.

Despite the rather strong calibration noise of 0.04 mag, the model from this sequence has a pole direction only a few degrees away from the correct one, and the shape model well represents the rough global features of the object.

3. Amateur Contributions

Of course one cannot expect to get too much out of a handful of data points, especially if a number of these are noisier than expected (there are bound to be several outliers no matter what the engineers say). The models from sparse photometry are rough and in many cases (mildly) nonunique. This is where follow-up observations and thus amateur contributions come in.

Even just one additional dense lightcurve would be of great help in at least the following cases:

1. *There is more than one possible period fitting the sparse data*. This happens if the number of sparse data points is subcritical. The number is a complicated function of survey strategy and technical choices and can thus vary a lot. (This may also happen with faint targets for which data are noisy, but then the magnitude range is usually out of the reach of amateur observers.) Several targets will be in this class. Also, since the number of objects is so large, each target will only be given some standard computer time for analysis. Most of this time is spent in period scanning, and some targets will run out of the allocated pipeline time for period search as there will be both very fast and very slow rotators. Such targets will thus be flagged with 'period not found' and saved for later analysis. Additional lightcurves will help to determine what the actual period region is.
2. *Even if the period is known, there may be more than one independent pole solution*. This, again, happens with slightly too small sparse datasets. Here one should note that for objects moving close to the plane of the ecliptic there are always two dependent poles with roughly the same ecliptic latitudes and longitudes some 180 degrees apart. This ambiguity cannot be solved by photometric means, regardless of the method.
3. *There are sparse data points that just cannot be fitted.* This usually means that the target is a binary (mutual events affect some data) or a tumbler (or otherwise somehow strange and thus interesting), or the points are just outliers. A dense lightcurve can help in clearing the matter. We expect several targets to be flagged for follow-up observations in this manner.
4. *Quality and reliability check*. Even if everything seems to be fine with the sparse data analysis and we get a full model, we must do random checks to make sure that essentially the same model pops out from the combined sparse and dense datasets. If the models are different, we have overlooked something.
5. *More detail needed*. If the object seems to be strangely shaped, we need more data points to get additional details.

4. How to Contribute

The exact way of contributing to the above cases depends on the survey in question. The earliest upcoming survey is going to be Pan-STARRS (MOPS, moving object processing system), so I take it as an example. Our (viz. the authors of Durech et al. 2006 as well as other MOPS team members) first task after first light (expected early 2007) is to check the performance of the photometric equipment and systems (cases 3 and 4 above). During the first couple of years there will not be enough data for proper modelling, but we can check that the sequences from previously modelled targets are consistent (i.e., are fitted well with the existing model). This will give the first idea of the typical calibration noise level as well as of the size and frequency of outliers. From the second year on we can start to combine the sequences with separate lightcurves and thus have the first pipeline test with a large number of targets as one or more lightcurves and at least rough period estimates are available for over 1000 asteroids. This will further reveal the actual noise and outlier properties (as well as eventually produce the first preliminary models of new targets). Thus amateur data will be used very early in the survey.

After the first three or four years we should expect to begin to have sufficient data for full modelling, so there will be a steady flow of flags for the cases mentioned above. The analysis procedure (pipeline) will be trained to flag such targets automatically. We plan to have a website for the flagged targets for which follow-up observations are needed. This list will grow long, so there will be plenty of targets to choose from. All this should be automated, of course, as maintaining such a website manually will soon become impossible.

5. Discussion

Combining dense lightcurves with sparse photometric data offers a unique opportunity to obtain a large set of reliable asteroid models, thus mapping the physical properties of asteroids en masse for the first time. Amateur observers are an invaluable data source because the number of follow-up targets is large. This approach makes photometry very time-efficient: a single lightcurve can remove ambiguities and greatly reduce the error limits of the solution. When the data sequences from surveys become publicly available on the Internet, the lightcurve observer can immediately perform the modelling using the analysis procedures that will soon be released as open software. Thus a lucky observer can, after only a few hours' observations, actually see for the first time what a 'new' asteroid looks like on the computer screen. The ultimate goal and reward is, of course, the big picture, census and history record of the whole asteroid population.

6. References

Durech, J., Grav, T., Jedicke, R., Kaasalainen, M., Denneau, L., Asteroid models from Pan-STARRS photometry (2006). Earth, Moon, and Planets, in press.

Kaasalainen, M., Torppa, J., Muinonen K., Optimization method for asteroid lightcurve inversion. II. The complete inverse problem (2001). Icarus 153, 37.

Kaasalainen, M., Physical models of large number of asteroids from calibrated photometry sparse in time (2004). Astron. Astrophys. 422, L39.

Kaasalainen, S., Kaasalainen, M., Piironen, J., Ground reference for space remote sensing: Laboratory photometry of an asteroid model (2005). Astron. Astrophys. 440, 1177.

Marchis, F., Kaasalainen, M., Hom, E., Berthier, J., Enriquez, J., Hestroffer, D., Shape, size and multiplicity of main-belt asteroids. I. Keck adaptive optics survey (2006). Icarus, in press.