The Potential of Combined Sparse Photometric Data in Asteroid Shape Modeling

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Abstract. We investigate the potential of the sparse data produced by the Catalina Sky Survey astrometric project (Catalina for short) in asteroid shape and rotational state determination. Although the photometric quality of the Catalina data, compared to the dense data, is significantly worse, it is in principle possible that these data are for some asteroids with high lightcurve amplitudes sufficient for a unique shape determination. Catalina data are available for \( \sim 180 \) asteroids which shape models were previously derived from different photometric data sets. For 12 asteroids from this sample, we derive their unique shape models based only on Catalina data. We compare the two independent shape models and discuss the reliability of models derived from only Catalina data. We also use Catalina data in shape modeling for asteroids with already known rotational period values and derive 12 unique models. We compare previously published periods with periods determined from the shape modeling.

Introduction

Orbital parameters are currently known for more than 400,000 asteroids. On the other hand, rotational states and shapes were determined only for a small fraction of them. In the Minor Planet Lightcurve Database\(^1\) [Warner et al., 2009], periods for \( \sim 3500 \) asteroids are stored. Convex shapes and spin axis directions were derived only for \( \sim 200 \) asteroids, these three-dimensional models of asteroids are available in the Database of Asteroid Models from Inversion Techniques\(^2\) (DAMIT, Řurech et al. [2010]) maintained by the Astronomical Institute of the Charles University in Prague, Czech Republic.

All asteroid models in DAMIT were derived by the lightcurve inversion method (LI). This gradient-based method is a powerful tool that allows us to derive basic physical properties of asteroids (the rotational state and the shape) from their disk-integrated photometry (see Kaasalainen and Torppa [2001]; Kaasalainen et al. [2001, 2002]).

Two different types of disk-integrated photometry are used: (i) dense-in-time, which typically consists of tens to a few hundreds of individual data points observed during one revolution (typically several hours), and (ii) sparse-in-time, where the typical separation of individual measurements is large compared to the rotation period. For sparse data, we usually have a few measurements per night as is the case of astrometric sky surveys. Based on the type of the photometry, we use the terms “dense lightcurves” and “sparse lightcurves”.

Our long-term strategy is to enlarge the number of asteroids with known shapes and rotational states because it can help us in understanding the physical processes that take place in the asteroid’s populations, such as Near Earth Asteroids (NEAs), Main Belt Asteroids (MBAs) or even asteroids in individual families (e.g., Koronis family, Slivan [2002]; Slivan et al. [2003]). Current distribution of periods and spin axes is the direct result of the evolution of these objects starting with their formation until the present time (several hundreds of Myr to \( \sim 4 \) Gyr for most studied asteroids). The knowledge of the shape can be used for several purposes, e.g.: (i) in the construction of a thermal model (e.g., Müller et al. [2011]), where values for geometric

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\(^1\)http://cfa-www.harvard.edu/iau/lists/LightcurveDat.html
\(^2\)http://astro.troja.mff.cuni.cz/projects/asteroids3D
albedo, size, and surface properties can be determined, (ii) a sample of real shapes instead of synthetic ones can be used for the statistical study of the non-gravitational forces (Yarkovsky\(^3\) and YORP effects), or (iii) in combination with occultations of stars by asteroids, when these events (observed for hundreds of asteroids) give us additional information about the shape (e.g. non-convexities) and can lead to a size estimation with a typical uncertainty of 10\% (see Durech et al. [2011]).

Most of the currently available photometric data were already used in the LI. The only significant exception are data from the Catalina Sky Survey astrometric project (Catalina for short). In this paper, we investigate these data with respect to the shape modeling by the LI – we want to find out if these data are for asteroids with high lightcurve amplitudes of a sufficient amount and quality for a unique shape determination, and if so, how reliable these asteroid models are. The investigation of sparse data capabilities and the reliability of derived models is important, because (i) it can lead to a determination of new asteroid models without a need of observing any additional photometric lightcurves, and (ii) in a few years, another huge amount of sparse data from three astrometric surveys will be available – from the Pan-STARRS (Panoramic Survey Telescope and Rapid Response System), and later also from the Gaia satellite, and the LSST (Large Synoptic Survey Telescope). Understanding the Catalina data with respect to the asteroid shape modeling will speed up future processing and use of new sparse data.

### Investigation of Catalina data

Our database of dense lightcurves consists of data for \(\sim 2000\) asteroids, these data were produced by tens of amateur or semi-professional observers. For \(\sim 100\) asteroids, these photometric data sets were sufficient for a unique shape model determination. Derivation of new models based on the dense data is now possible, only if new lightcurves are observed. Models based only on dense data are important in testing the reliability of models based on sparse data (due to possible comparison).

Currently available sparse photometry is accessible via the Asteroids – Dynamic Site database\(^4\) (AstDyS), where data from hundreds of astrometric observatories are stored. The photometry is mostly a by-product of astrometric measurements and in most cases, asteroid magnitudes are given to only one decimal place, so the accuracy is 0.1 mag at best. Whether this is sufficient for a unique shape model determination for a reasonable number of asteroids was studied in Hanuš et al. [2011]. The authors have found 7 observatories with quality data and used these data in combination with dense lightcurves for asteroid shape modeling (they derived 80 asteroid shape models). The most accurate sparse photometry is from the U.S. Naval Observatory in Flagstaff (USNO-Flagstaff station). These data were already studied in Durech et al. [2009], where convex shape models for 24 asteroids were determined. The biggest disadvantage of the USNO-Flagstaff station data is that they are available only for about 1000 brightest asteroids.

The largest amount of sparse photometry was observed by the Catalina Sky Survey astrometric project. These data were already used in the LI by Hanuš et al. [2011] (see also for more details about their processing or outliers removal), but only in combination with other photometric data, their typical photometric accuracy was \(\sim 12\%\). Although this accuracy seems low, the data are valuable for asteroids with lightcurve amplitudes higher than \(\geq 0.3\) mag, which represents almost a half of all asteroids (based on the lightcurve data of the Minor Planet Lightcurve Database). For \(\sim 6000\) asteroids, there are more than 100 data points available. Such amount of data points can, in principle, already lead to a unique shape model determination because

\(^3\)a thermal force acting on a rotating asteroid

\(^4\)http://hamilton.dm.unipi.it/astdys/
we usually have 55 unknown parameters (49 coefficients of the shape expansion into spherical harmonic functions, 3 parameters of the rotational state and 3 phase function parameters). To determine the reliability of possible models derived only from Catalina photometry, we used asteroid models previously derived from independent photometric data sets (typically from a set of dense lightcurves or a combination of dense lightcurves with sparse photometry from the USNO-Flagstaff station), which are stored in DAMIT database. These models (∼ 200) are mostly based on large photometric data sets and their reliability was carefully tested (several tests are listed in the work by Hanuš et al. [2011]). For most asteroids with unique models, Catalina data were also available. Therefore, it was possible to apply the LI to these data and try to derive independent asteroid models. Because of the poor quality and low amount of individual data points of Catalina data, we were able to successfully derive only 12 unique models. In 5 cases, the corresponding models were clearly wrong (they differed in the period value, the difference was typically more than one hour). In Table 1, we list rotational parameters (sidereal rotational periods and orientation of the spin axes) for 7 asteroids for which models in DAMIT database and their corresponding models derived only from Catalina data were similar.

In order to test the reliability of models based only on Catalina data, we used also the a priori information about the periods. For some asteroids, we (i) knew their synodic periods, (ii) had only Catalina data (there exists their dense lightcurves, but we did not have them in an electronic form), and (iii) were able to derive their models near the published period (we searched the solution on a short period interval with the expected period $P$ in the middle, typically $P \pm 5\% P$). For these asteroids, we searched the solution also on a larger period interval of 2–100 hours (as we always do if the period is unknown). In 12 cases, a unique model was found using the short period interval. For 7 asteroids, the corresponding solution was reproduced also on a larger period interval. For 4 asteroids, we did not get a unique solution on the extended period interval, and a formally correct but clearly different solution was found for one asteroid.

On Fig. 1, we show a periodogram of asteroid (5647) 1990 TZ, where for each initial period value a $\chi^2$-value corresponding to the best shape model and pole direction (a local minimum in the multi-dimensional parameter space) is plotted. This model computation was based on 87 individual measurements from Catalina, derived period $P = 6.13867$ h is in agreement with period $P = 6.141$ h reported in Bembrick and Bolt [2003].

<table>
<thead>
<tr>
<th>Asteroid</th>
<th>DAMIT $P$ [h]</th>
<th>DAMIT $\lambda$ [$^\circ$]</th>
<th>DAMIT $\beta$ [$^\circ$]</th>
<th>Reference</th>
<th>Catalina $P$ [h]</th>
<th>Catalina $\lambda$ [$^\circ$]</th>
<th>Catalina $\beta$ [$^\circ$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>685 Hermia</td>
<td>50.387</td>
<td>29</td>
<td>79</td>
<td>Hanuš et al. [2011]</td>
<td>50.387</td>
<td>52</td>
<td>71</td>
</tr>
<tr>
<td>1022 Olympiada</td>
<td>3.83359</td>
<td>39</td>
<td>17</td>
<td>Warner et al. [2008]</td>
<td>3.83357</td>
<td>49</td>
<td>27</td>
</tr>
<tr>
<td>1419 Danzig</td>
<td>8.11957</td>
<td>22</td>
<td>76</td>
<td>Hanuš et al. [2011]</td>
<td>8.11958</td>
<td>11</td>
<td>56</td>
</tr>
<tr>
<td>2156 Kate</td>
<td>5.62215</td>
<td>49</td>
<td>74</td>
<td>Hanuš et al. [2011]</td>
<td>5.62212</td>
<td>45</td>
<td>71</td>
</tr>
<tr>
<td>3678 Mongmanwai</td>
<td>4.18297</td>
<td>125</td>
<td>−65</td>
<td>Hanuš et al. [2011]</td>
<td>4.18297</td>
<td>130</td>
<td>−68</td>
</tr>
<tr>
<td>4483 Petofi</td>
<td>4.33299</td>
<td>107</td>
<td>40</td>
<td>Hanuš et al. [2011]</td>
<td>4.33300</td>
<td>99</td>
<td>36</td>
</tr>
</tbody>
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Table 1. Comparison of rotational parameters (sidereal rotational period $P$ and ecliptic longitude $\lambda$ and latitude $\beta$ of the spin axis direction) between adopted models from DAMIT database and their corresponding models derived only from Catalina data. For all these 7 asteroids, both models were similar. In several cases, ambiguous “mirror” pole solutions are present.
Discussion and conclusions

Both described and performed tests (comparison with models from DAMIT and with the previously determined periods) show that unique asteroid models can be derived from only Catalina photometric data. In 7 cases out of 12, the solution was in well agreement with a model based on a different and higher data set. The dispersion in the pole directions of these models, their physical parameters are listed in Table 1, was ≤ 30 deg, that is a rather small value considering the poor quality of the Catalina data. These 7 models based only on Catalina data globally well matched the more detailed models from DAMIT. From this point of view, Catalina data, which represents the largest dataset of sparse photometry with photometric accuracy theoretically sufficient for a unique shape determination, seem to be promising for the asteroid shape modeling. Unfortunately, several clearly wrong models that fulfilled our conditions on a unique solution were derived. Similar problem occurred in the second test, where we compared the derived models with their previously known periods. One model was clearly incorrect.

For each tested asteroid we had a priori information about its shape model or at least its rotational period, so we were able to easily validate models from Catalina data. In reality, we do not have such information and so, possible unique models based on Catalina data are not reliable with a current configuration of the LI.

There are several possible explanations why we derived incorrect models from the Catalina data: (i) data for asteroids with low amplitudes are more noisy, (ii) low amount of data (with respect to the number of free parameters), (iii) systematic errors of the survey. In cases (i) and (ii), the data are poor, contain not enough information about the period and shape, and could produce a random solution with an unrealistic rms value (the fit is “too perfect”). We used probably too much parameters describing the shape. Oszkiewicz et al. [2011] show that photometric data sets from astrometric stations (such as Catalina) exhibit magnitude variations with apparent V-band magnitude. For the brightest asteroids, the images are saturated, and for the faintest, the background subtraction is imperfect. This consequence of (iii) is probably partially visible in our data – most of the incorrect models are brighter (have higher absolute magnitudes) than the correct ones. We are not able to distinguish between the effects of the amplitude and the noise from each other only from the sparse data without a model computation, so there is no way how to detect the case (i). The amount of data sufficient for a correct unique shape determination is dependent mainly on the time epochs (geometry of observations) and also on the signal-to-noise ratio, which we do not know. So, the sufficient amount of sparse measurements strongly varies from one asteroid to the other.
Sparse data from the Catalina Sky Survey are low efficient in unique model determination and seem more accurate for less brighter asteroids. Incorrectly determined models could be indicated by unrealistic rms values, but not generally. Since we derived several unique models that were clearly incorrect, we need to check more carefully the stability of the solutions and use more tests to detect false solutions. We can, for example, vary the resolution of the shape parametrization (lower the shape resolution), the step in period, or the number of iterations. This is an aim of future work.

Possible models based on Catalina data are good candidates for follow-up observations, new dense photometry should help in the detection of incorrect solutions and should lead to more detailed shape models.

Our method assumes a single body in a relaxed rotation state (rotates around the principal axis with the maximum momentum of inertia). Objects like tumblers or binary asteroids are not identified by the used form of the LI, their model determination usually fails because the single period model cannot handle the more complex period features. The only exception are fully synchronous close binary systems with similar-sized components, such as 91 Antiope. These objects are reproduced as highly elongated single bodies, and because they have typically high lightcurve amplitudes, they could be easily present in the possible sample of models based on Catalina data.

Finding an infallible test for detecting the false solutions derived from Catalina data could allow us determination of shapes and physical parameters for tens of asteroids. While the LI is more successful for asteroids with higher lightcurve amplitudes, the derived sample of asteroid parameters will be significantly biased. For example, shapes will be more elongated than it is usual in the whole population. Careful de-biasing of the model sample will be necessary before its use in any statistical studies and physical interpretations.

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References
HANUŠ AND ĎURECH: THE POTENTIAL OF SPARSE DATA


