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Asteroids@home—A BOINC distributed computing project for asteroid shape reconstruction

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HIGHLIGHTS

- Asteroids@home is a distributed computing project.
- It runs in the framework of Berkeley Open Infrastructure for Network Computing.
- Shape models of asteroids are reconstructed from disk-integrated photometry.

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ABSTRACT

We present the project Asteroids@home that uses distributed computing to solve the time-consuming inverse problem of shape reconstruction of asteroids. The project uses the Berkeley Open Infrastructure for Network Computing (BOINC) framework to distribute, collect, and validate small computational units that are solved independently at individual computers of volunteers connected to the project. Shapes, rotational periods, and orientations of the spin axes of asteroids are reconstructed from their disk-integrated photometry by the lightcurve inversion method.

1. Introduction

With more than 500,000 discovered objects, asteroids form a large population of small bodies in the solar system that was affected by all processes that were acting during the formation and evolution of the solar system. By studying asteroids, we can reveal the history and current state of our cosmic neighborhood. In general, study of asteroids can be done either in situ by spacecrafts or by remote-sensing techniques. In situ measurements are limited to only a very small sample of all asteroids that are direct targets of spacecraft missions or fly-by opportunities. However, remote-sensing techniques are, in principle, feasible for most of the known population. Although the level of information we are able to get from remote sensing is inevitably much lower than from a detailed spacecraft mission, the basic physical properties can be successfully obtained for a substantial part of the asteroid population.

One of the main sources of information about asteroid shapes and spin states (i.e., rotational periods and spin axis directions) is their disk-integrated photometry that is available for all known asteroids. Because asteroids have irregular shapes and rotate, the amount of light reflected towards the observer at Earth varies with asteroid's rotation—we observe a lightcurve. An effective method to reconstruct asteroid shapes and spin states from their lightcurves (so called lightcurve inversion) has been developed by Kaasalainen and Torppa (2001) and Kaasalainen et al. (2001).

In the following sections, we describe our project of distributed computing named Asteroids@home that is aimed for solving the lightcurve inversion problem for a substantial part of the asteroid population.

2. Asteroid lightcurve inversion

A method for lightcurve inversion was developed by Kaasalainen et al. (2001). It uses all available photometric data to reconstruct a convex shape model of an asteroid (together with its sidereal rotation period and the spin axis direction) that provides the best fit to the data. The review of the method can be found in Kaasalainen et al. (2002). Its mathematical stability and uniqueness was proved by Lamberg and Kaasalainen (2001) and its results were independently confirmed by disk-resolved images (Marchis et al., 2006;

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Hanuš et al., 2013a), stellar occultation data (Ďurech et al., 2011), or spacecraft images (Keller et al., 2010).

Although real asteroids have in general complex shapes with (sometimes large) concavities, their lightcurves can be successfully reproduced with convex shapes. Nonconvex models are an alternative to convex ones, but they lack the mathematical uniqueness and stability and in practice they are needed only when high-quality lightcurves observed at high solar phase angles or disk-resolved data are available. In this sense, convex models should be taken as approximations to the real shapes of asteroids.

Since the publication of the method, models of about 500 asteroids were derived by this technique (Ďurech et al., 2009; Ďurech et al., 2011; Hanuš et al., 2011, 2013b; Marciniak et al., 2011, for example); most of them are publicly available in the Database of Asteroid Models from Inversion Techniques (DAMIT[1], Ďurech et al., 2010). At this site, the source codes for the lightcurve inversion called `convexinv` can be downloaded. This code written in the c programming language is a default version of the shape optimization and is widely used by the scientific community. Only minor changes related to input/output file format were necessary to satisfy the BOINC specifications. Recently, the `convexinv` program has been also modified to (i) deal with disk-resolved data and nonconvex features of the shape (Carry et al., 2012), (ii) changing rotation rate to model the YORP effect (Ďurech et al., 2008), or (iii) excited rotation state (Kaasalainen, 2001; Pravec et al., 2014).

The lightcurve inversion code uses the Levenberg–Marquardt algorithm to converge to a local minimum in χ^2, where χ^2 is a usual measure of difference between the observed and modeled brightness L taking into account the errors σ:

$$\chi^2 = \sum_i \left(\frac{L_{\mathrm{obs}}^{(i)} - L_{\mathrm{model}}^{(i)}}{\sigma_i} \right)^2 . \quad (1)$$

For each epoch corresponding to the ith observation, the brightness $L_{\mathrm{model}}^{(i)}$ is computed as a sum of contributions from surface elements that are illuminated by Sun and seen by the observer. The orientation of the model in inertial space is determined by the direction of the spin axis given in ecliptic longitude λ and latitude β, and the rotation period P. The shape is represented as convex polyhedron and parametrized by spherical harmonics. The coefficients of spherical harmonics series are optimized together with the spin parameters to get the lowest value of χ^2 (for more details see Kaasalainen et al. (2002)). Depending on the resolution of the shape (degree and order of the spherical harmonics series), the number of parameters to be optimized is typically between 20 and 90.

To find the global minimum, however, we need to start at many initial points in the parameter space to go through all relevant local minima and then select the solution with the lowest χ^2. Convergence of the shape towards the local minimum is robust, so the initial shape can be always a sphere, for example, while the initial spin and period parameters have to cover the whole parameter subspace. The number of initial pole directions is usually ten (isotropically distributed in ecliptic coordinates), which is enough for a safe convergence into the global minimum in the spin subspace. What makes the problem time consuming is a large number of closely packed local minima in the period subspace. The local minima are separated by about $0.5P^2/\Delta T$, where P is the rotation period and ΔT is the length of the time interval covered by observations (Kaasalainen, 2001). For a typical set of lightcurves sufficient for inversion (tens of lightcurves observed during several apparitions), the rotation period can be estimated very accurately without any modeling from the period analysis of the signal. Then the interval of periods that has to be searched for the global minimum is narrow and the process is fast. However, with the data that are sparse in time with respect to the rotation period, the classical Fourier-based or phase dispersion minimization methods cannot be used and the rotation period cannot be easily estimated from the lightcurve data. The sparse-in-time photometry is typically provided by all-sky astrometric surveys (Catalina, Pan-STARRS, Gaia satellite, for example). With a typical rotation period of several hours and ∼15 years of observations, we have to test hundreds of thousands initial periods to be sure not to miss the global minimum.

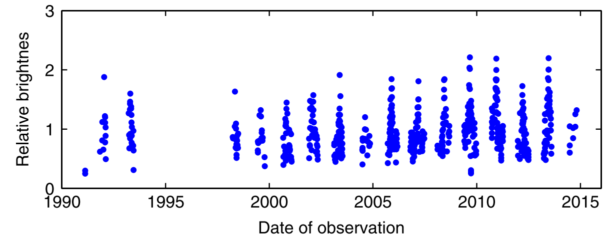

Fig. 1. Sparse-in-time photometry of asteroid (243) Ida downloaded from AstDyS. There are 700 individual photometric points observed during 17 apparitions. The brightness was reduced to unit distance from Earth and Sun.

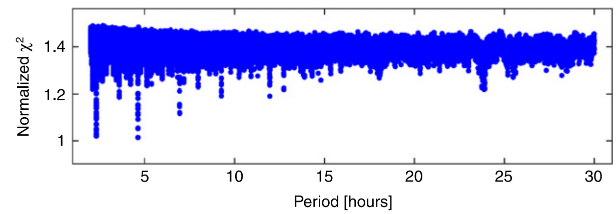

Fig. 2. Period search results for asteroid (243) Ida for sparse photometry (Fig. 1). Each point corresponds to the local minimum in the parameter space. The lowest χ^2 corresponds to the best-fit model for period $P = 4.633631$ h.

As an example of sparse-in-time photometry and a corresponding model, we present results for asteroid (243) Ida. The photometry obtained by sky surveys and downloaded from AstDyS[2] site is shown in Fig. 1. The brightness was reduced to the unit distance from Earth and Sun. The groups of points correspond to individual apparitions. The periodogram is shown in Fig. 2, it consists of about 240,000 points. There are two clear minima with the lowest χ^2 at 4.634 and 2.317 h. The best-fit model corresponds to the period 4.634 h and is shown in Fig. 3. The model is compared with the real shape of Ida as reconstructed from the fly-by images obtained by Galileo probe (Thomas et al., 1996). The pole direction from sparse data is $(\lambda, \beta) = (255\pm4°, -59\pm5°)$ in J2000.0 ecliptic coordinates, which is not far from the value $(263°, -67°)$ derived by Davies et al. (1996). The difference between these two poles is 9° of arc, which is within a typical uncertainty of the pole direction expected from models based on sparse data. The period $P = 4.633631\pm0.000005$ h is close to the value 4.633638 ± 0.000002 h of Kaasalainen et al. (2001) based on a set of 40 lightcurves from 1988 to 1993. Fig. 3 also illustrates a typical accuracy of the shapes derived from sparse photometry: they are only a rough approximation of the real (in general unknown) shape and cannot provide any surface details, but rather only global characteristics. They can be further refined with dense lightcurves or other complementary data. The relative accuracy of the period determination is however high, depending mainly on the length of the interval of observations. A typical uncertainty of the pole direction is 10°–20°, depending mainly on the number of brightness measurements, their photometric accuracy, and the number of apparitions.

[1] http://astro.troja.mff.cuni.cz/projects/asteroids3D.

[2] http://hamilton.dm.unipi.it/astdys.