Testing the inversion of Gaia photometry of asteroids

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We studied the performance of the *Gaia* inversion algorithm under different scenarios. The test consisted of feeding the algorithm with several sets of photometric simulations for ten thousand asteroids having different spin axis orientations, rotational periods and shapes, including binaries. We used the *Gaia* mission simulator to generate the observational epochs, while the brightnesses were generated using a Z-buffer standard graphic method. It was found that results are biased against asteroids presenting low lightcurve amplitude and low pole latitudes. The analysis of the inversion results led to the confirmation that synchronous binary systems can be successfully modelled with a simple triaxial ellipsoid body. On the basis of these simulations, it was also possible to develop strategies for binary asteroid detection. The presented quantitative results include the semi-major axis values of the triaxial ellipsoid model with a high probability of hosting binary systems. We also present the Gaia-Groundbased Observation Service for Asteroids (*Gaia-GOSA*), which aims to support ground-based observation campaigns of asteroids.

1 Introduction

Asteroids are crucial objects for the study of the origin and evolution of the Solar System. Models containing asteroids' spin, shape and rotational state are necessary to investigate the physics of these minor bodies. In order to derive such models, photometry is by far the most fruitful observational technique. The usual format of this data for one apparition (the period during which the asteroid is observable from the Earth) is basically dozens of photometric measurements collected during few nights. As a result, the rotational period of the asteroid is well covered but the quantity of information of the body shape is limited, as the viewing geometry is practically constant during this period. Consequently, to obtain a unique spin and shape solution, we need a set of a few tens of dense lightcurves obtained under different viewing geometries. This observational constraint is significantly limiting the number of objects for which we have observations sufficiently dense to derive a complex shape of the body. Around 100 asteroid models have been obtained basing on this classic photometric data. Enlarging the number of derived models using this method requires the organization of observational campaigns, potentially resulting in few tens of new models per year.

During the last years, some observatories around the world have started sky surveys mainly focused to detect new Near-Earth Objects (NEOs) or to improve their orbit determination (e.g. U.S. Naval Flagstaff, Catalina Sky Survey, La Palma). As a by-product of these astrometric survey programs a huge amount of sparse-in-time photometric measurements for tens of thousands of asteroids have been retrieved. For each object some tens of discrete measurements were collected for different observation geometries and illuminations. Generally, the photometric accuracy of such surveys is rather low, at the order of ∼0.1 mag in the majority of cases. But still, this accuracy has been proved to be enough to retrieve valuable information of the asteroid physical properties (e.g. Hanuš J. et al., 2013). Combining these datasets with dense lightcurves allowed increasing the modelled population of asteroids from 100 (classical photometry) to 400 (combination of classical and sparse photometric data).

Gaia observations will generate a similar set of sparse photometric measurements during its expected lifetime of – at least – five years. But *Gaia* data will include many more objects (are expected for ∼300.000 asteroids, Mignard F. et al., 2007) and will be of higher quality (the photometric accuracy is estimated to be ∼0.01 mag for asteroids up to 18 magnitude, and ∼0.03 mag up to 20 magnitude, Cellino A. et al., 2006). As a result of this enormous amount of new data, we expect to derive asteroid models for more than 10.000 objects. This means an improvement of two order of magnitudes from our actual knowledge, and is expected to have a direct impact on the Solar System formation theories, as a statistically large sample of objects with known properties may reveal physical effects which play an important role for the whole population.

Among these results, new discoveries are also expected. One particularly interesting case are the asteroids with satellites. Such systems are specially appreciated by the Solar System researchers as they give a unique opportunity to derive the mass of the components directly from the third Kepler's law. For this reason, they are invaluable targets for studies on internal structure and composition, and therefore it is crucial to develop techniques enabling to detect them among *Gaia* photometry.

In this paper we describe some tests performed on the preparation of the scientific exploitation of *Gaia* photometric measurements of asteroids. The analysis of the results for the case of single and binary asteroids are presented. Besides, we describe the *Gaia*-GOSA service, a tool specifically developed to coordinate asteroid observational campaigns, with the aim of enhancing the Solar System science coming out from *Gaia*.

2 Inversion of Gaia photometry of single asteroids

The *Gaia* inversion code was build under one main constraint: CPU efficiency, in order to deal with the unprecedentedly great amount of data to be analysed. This forced the *Gaia* Solar System Group to find a compromise between the number of parameters used for solving the inversion problem, and the goodness of this solution. As a result, the solution implemented in the *Gaia* data pipeline is a triaxial ellipsoid representation of the asteroid shape, which is able to give us an idea of the real body's shape with just 2 parameters (i.e. the size ratios between its axes).

Such an approximation should be sufficient for the majority of cases, but it may also be the source of potential bias introduced by inversion failures under certain circumstances. We have generated synthetic observations for ten thousand asteroids,

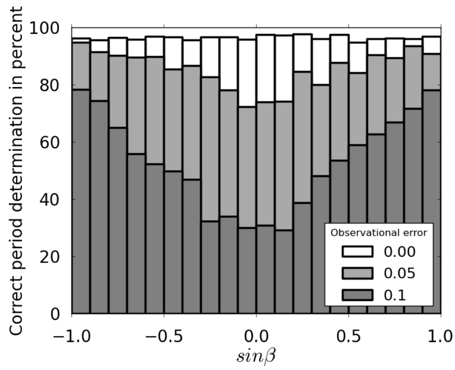

Fig. 1: Correct period determination in percert versus asteroids' initial pole latitude for different values of the Gaussian noise added to the *Gaia* photometric simulations.

in order to feed the inversion algorithm and study the results. We have used the *Gaia* mission simulator developed at the Observatoire de la Côte d'Azur (OCA) to generate the observational epochs. The period distribution within the population was generated following a Maxwellian distribution like the one described in P. et al. (2002). The disk-integrated photometry simulations have been generated using a Z-buffer standard graphic method described by Catmull E. et al. (1974). The computations were executed using the Poznań observatory cluster, which consist of 27 workstations equipped with a six-core AMD processors (3 GHz).

At first we tested the algorithm computing brightnesses under ideal assumptions (triaxial ellipsoid, geometric scattering law, no tumbling or binary asteroids, etc). For this ideal case, pole (within 5 degrees of the true value) and shape (within 5 per cent of the true axis ratio) were correctly found for more than 99 per cent of inversion runs.

The good results obtained in the control test allowed us to be confident with the methodology used. However, we cannot expect the inversion of the real observations obtained by *Gaia* to have such a high reliability. Thus, we contaminated our photometric simulations with Gaussian noise with different values of σ, and we repeated the inversion process for each case. The results presented two different biases: 1) population bias, 2) inversion reliability bias. The first one is connected with the warnings obtained from the results control system. The number of rejected solutions is not homogeneously distributed, as the majority of them are concentrated around the ecliptic plane (low pole latitudes). The second bias is affecting the reliability of the obtained results. For $\sigma \geq 0.03$ the results reliability is becoming proportional to the asteroid's pole latitude, being worse for the low pole latitudes. Worth noting that the inversion solutions studied are the ones accepted by the algorithm's warning system, thus the first and the second bias are superimposed. The reliability bias is increasing with the photometric noise, as can be seen in Fig. 1.

3 Inversion of Gaia photometry of binary asteroids

We performed simulations of *Gaia* observations of synchronous binary asteroids using a modified version of the Poznań simulator. We used the same number of asteroids (10.359), with their spin axis directions also uniformly distributed. The orbits and, consequently, the transit epochs were considered to be the same as for the single cases. However, the rotation period distribution used in the single asteroid case would not be realistic for the binary population. Thus the rotation period population was created using a pseudorandom generator with values from 11 to 50 hours mimicking the observed boundaries (D. & N., 2006). The shape representation of binary asteroids consist of two triaxial ellipsoids, with the axes ratio values generated as for the single population, which are mutually orbiting in a synchronous system. The size relation between both components was also generated with a pseudorandom procedure with values $0.7 < r_2/r_1 < 1$, which corresponds to the observed boundaries of synchronous systems known.

In general terms, the results obtained are similar to the ones described for the single asteroid simulations with a photometric error of $\sigma = 0.04$. A total of 6.535 solutions were accepted by the inversion algorithm (63% of the simulated asteroids). The reliability of the rotational period determination is also biased against low pole latitudes. However, the wrong period determinations appears to be higher than for the single asteroids results for high pole latitudes, with almost 20% of the inversion results with a wrong solution. The distribution of the percentage of correct solutions as a function of the number of *Gaia* transits and the pole latitude is also following the same scheme as in the single case. However, the number of generated solutions is smaller, as the number of warning flags is higher compared to the singular case.

The number of transits is specially crucial for the detection of binary systems, as the greater the number of transits, the higher the probability of catching a mutual event. In order to estimate the impact of the mutual events on the *Gaia* photometry simulations, the drop in magnitude (Δmag_i) was analytically calculated for each single measurement, including the eclipses and the shadowing effects. Next the arithmetic mean of the mutual events (Δm) was calculated by adding all the magnitude drops and dividing by the number of transits (N) when they were observed:

$$\Delta m = \frac{1}{N} \sum_{i=1}^{N} \Delta mag_i. \tag{1}$$

The results of these calculations allowed to understand better the behaviour of the inversion algorithm. For the majority of binary systems simulated, the impact of the mutual events in the *Gaia* photometric simulations was almost negligible. In particular, 4.783 asteroids (73% of the results accepted by the inversion algorithm) had a mean $\Delta m < 0.02$ mag. For the modelling purposes, this means that the effects of the mutual events were comparable to the noise level. On the other hand, in case of weakly elongated bodies, the lack of mutual events implies a lightcurve with low amplitude. As previously stated, this is the worst scenario for an inversion problem with sparse data, as several solutions might generate equivalent fits. Regarding the rest of the results, 1.065 asteroids (16% of the results accepted) had a mean between $0.02 < \Delta m < 0.04$ mag, only 308 (5% of the results accepted) had $0.04 < \Delta m < 0.06$ mag, and 379 (6% of the results accepted) had a strong impact on the photometry having $\Delta m > 0.06$ mag.

The most interesting result was found to be connected with the distribution of the semi-axes ratios. A histogram showing a comparison between the semi-major axes obtained for the single and binary populations is shown in Fig. 2. Despite both results being similar, the mean is slightly shifted to a higher value for the binary results. This effect is related to the lack of observed mutual events discussed previously. However,

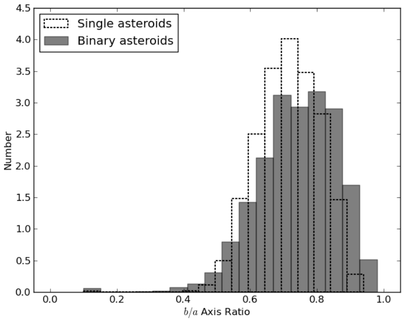

Fig. 2: Histograms comparing the distribution of the semi-major axis found in the inversion of the single and binary simulations.

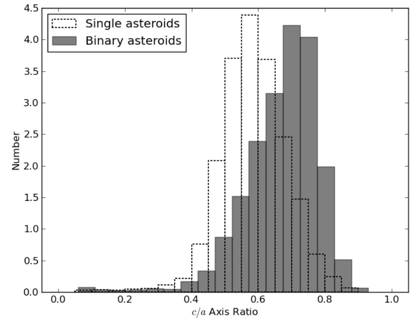

Fig. 3: Histograms comparing the distribution of the semi-minor axis found in the inversion of the single and binary simulations.

a longer tail can be observed for small values of the b/a axis ratio. A small fraction of the results include ratios smaller than $b/a < 0.5$ whereas such values were practically not existing in the single asteroids results. These results correspond to the systems with observed mutual events.

The differences between semi-minor axis results are even more noticeable. The mean of the binary results is clearly shifted to a higher value. A histogram showing a comparison between the semi-minor axes obtained for the single and binary populations is shown in Fig. 3. This shift to higher values is also due to the absence of mutual events for the majority of observed systems.

Besides, a cluster of solutions is formed in the region comprised by $0.5 < b/a < 0.7$ and $0.1 < c/a < 0.3$, as shown in Fig 4. These solutions correspond to systems with mutual events observed and having a wrong determination of the pole orientation. The inversion algorithm tends to choose very low values of the semi-minor axis in order to compensate for the wrong determination of the pole. Therefore, despite knowing that solutions in this area might be wrong, they could indicate that the asteroid can potentially be a binary system.

4 Gaia-Groundbased Observation Service for Asteroids

In order to lay the foundations for a worldwide collaborative network of observers, we have created a web service called *Gaia*-Groundbased Observation Service for Asteroids (*Gaia*-GOSA), which is available at www.gaiagosa.eu. The service has been funded under the ESA Contract No. 400011266014/NL/CBi: "Gaia-GOSA: An interactive service for asteroid follow-up observations". The main goal of *Gaia*-GOSA service is to support observers in preparation and planning asteroid photometric observations, so that they can generate valuable data of selected targets under scientific criteria. Such data will result in a standardised catalogue with physical information of asteroids ready to be used for enhancing the final *Gaia* Solar System release. Any registered user of the service is able to easily create an account, acquire the list of observation targets (in accordance with the *Gaia* observations) adapted for the specific user's instrument and observation site. The *Gaia* transit predictions have been obtained from a collaboration with the Observatoire de la Côte d'Azur (OCA) which has the leadership of Solar System processing and simulations in *Gaia*-DPAC (CU4,

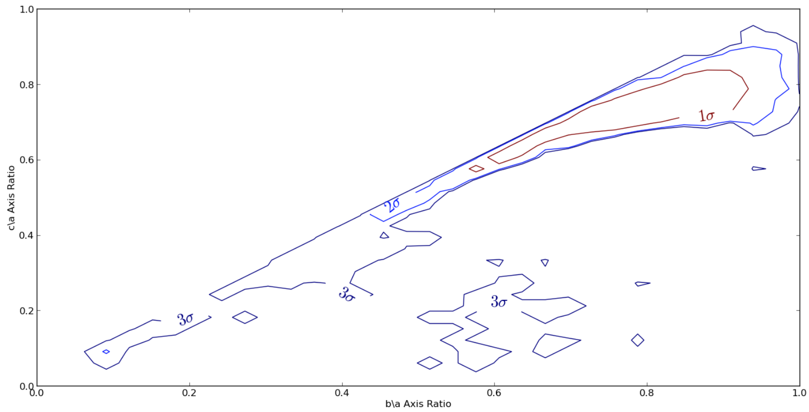

Fig. 4: Diagram obtained after subtracting the single population histogram from the binary population histogram. The plot shows the areas of the semi-axes' results with a higher probability of finding a binary asteroid among the inversion results.

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5 Conclusions

The tests performed with the *Gaia* inversion algorithm allowed us to confirm that the adopted approach (i.e. genetic algorithm with triaxial ellipsoid shape model) is valid under the *Gaia* photometric accuracy (∼0.01 magnitude). However, a bias against the asteroid's pole latitude was found in the inversion solutions of photometric datasets with a larger photometric error. This result is valid for both simulated datasets, using single and binary shape models. We also compared the results obtained with each simulation set and we defined strategies to optimize the seach for binary system among the expected *Gaia* results. In particular, we found that some regions of the models semi-axis histogram have a higher probability of hosting synchronous binary systems.

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