Inversion of asteroid photometry from *Gaia* DR2 and the Lowell Observatory photometric database[★]

J. Ďurech¹, J. Hanuš¹, and R. Vančo^{1,2}

¹ Astronomical Institute, Faculty of Mathematics and Physics, Charles University, V Holešovičkách 2, 180 00 Prague 8, Czech Republic

e-mail: durech@sirrah.troja.mff.cuni.cz

² Czech National Team, Nádraží 549, Újezd u Brna 664 53, Czech Republic

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ABSTRACT

Context. Rotation properties (spin-axis direction and rotation period) and coarse shape models of asteroids can be reconstructed from their disk-integrated brightness when measured from various viewing geometries. These physical properties are essential for creating a global picture of structure and dynamical evolution of the main belt.

Aims. The number of shape and spin models can be increased not only when new data are available, but also by combining independent data sets and inverting them together. Our aim was to derive new asteroid models by processing readily available photometry.

Methods. We used asteroid photometry compiled in the Lowell Observatory photometry database with photometry from the *Gaia* Data Release 2. Both data sources are available for about 5400 asteroids. In the framework of the Asteroids@home distributed computing project, we applied the light curve inversion method to each asteroid to find its convex shape model and spin state that fits the observed photometry.

Results. Due to the limited number of *Gaia* DR2 data points and poor photometric accuracy of Lowell data, we were able to derive unique models for only ~1100 asteroids. Nevertheless, 762 of these are new models that significantly enlarge the current database of about 1600 asteroid models.

Conclusions. Our results demonstrate the importance of a combined approach to inversion of asteroid photometry. While our models in general agree with those obtained by separate inversion of Lowell and *Gaia* data, the combined inversion is more robust, model parameters are more constrained, and unique models can be reconstructed in many cases when individual data sets alone are not sufficient.

Key words. minor planets, asteroids: general – methods: data analysis – techniques: photometric

1. Introduction

The ESA *Gaia* mission (Gaia Collaboration 2016) was launched in December 2013 with the main aim being to provide accurate astrometry and photometry for more than a billion stars. *Gaia* systematically scans the whole sky and observes not only stars but also other point-like sources – asteroids. The second data release (DR2) from April 2018 (Gaia Collaboration 2018a) contains astrometric and photometric data for about 14 000 asteroids (Gaia Collaboration 2018b). The first analysis of *Gaia* asteroid photometry was published by Mommert et al. (2018), who performed a population-level study of asteroid shapes and pole orientations. Inversion of photometry of individual asteroids was done by Ďurech & Hanuš (2018). Because the number of *Gaia* DR2 measurements for individual asteroids is small, a successful inversion was possible only for a small fraction of asteroids released in DR2. In Ďurech & Hanuš (2018), we reconstructed spins and shapes of 173 asteroids.

The purpose of this paper is to further exploit DR2 asteroid photometry by combining it with complementary ground-based photometric data. Ideally, to maximize the scientific output of the information content of the data, all available photometry should

be processed together, but because photometric data are scattered in many individual sources, this is hard to do efficiently in practice. To take the first step, we combined what was readily available – Lowell and *Gaia* data. We present new shape and spin models and make them available on the Database of Asteroid Models from Inversion Techniques (DAMIT; Ďurech et al. 2010)¹.

2. Inversion of *Gaia* and Lowell photometry

We used a similar approach as in our previous works: Ďurech et al. (2007, 2009, 2016, 2018) and Hanuš et al. (2011, 2013). Namely, we used the light curve inversion method of Kaasalainen et al. (2001) to reconstruct the rotation parameters (rotation period P and the direction of the rotation axis in ecliptic coordinates λ, β) and convex shapes of asteroids. The method and its implementation are described in Hanuš et al. (2011). In short, the best model is defined as that with the best goodness of fit measured by χ^2 . The global minimum in χ^2 is found by scanning the relevant parameter space densely with gradient-based optimization of Kaasalainen et al. (2001). In practice, this is done with Asteroids@home distributed computing project (Ďurech et al. 2015).

¹ <http://astro.troja.mff.cuni.cz/projects/asteroids3D>

[★] Table A.1 is only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsarc.u-strasbg.fr/viz-bin/cat/J/A+A/631/A2>

We used two sources of asteroid photometry: the Lowell Observatory photometry database, which contains re-processed photometry from the largest ground-based surveys reported to the Minor Planet Center (Oszkiewicz et al. 2011; Bowell et al. 2014), and *Gaia* DR2 (Gaia Collaboration 2018b). While both sources contain asteroid disk-integrated photometry, their precision and cadence are very different.

Lowell data are available for approximately 330 000 asteroids, and they cover more than a decade from 1998 to 2011. Magnitudes are given for *V* filter, and typically there are hundreds of measurements for a single object. What makes this data set problematic and not very efficient regarding inversion is low accuracy of photometry, which is typically only 0.1–0.2 mag. On the contrary, *Gaia* data (magnitudes in *G* band) are very accurate with errors of 0.01 mag. Their disadvantage is that they cover only a limited time interval of 22 months in 2014–16 and the number of measurements per asteroid is low. From 14 000 asteroids reported in DR2, only about 5500 have at least ten observations. Therefore, separate inversion of either Lowell or *Gaia* data alone is not very efficient. In our previous publications, we derived 328 new models from Lowell data (Durech et al. 2016) and 129 new models from *Gaia* DR2 (Durech & Hanuš 2018). However, it is straightforward to combine both data sets and invert them together. For example, we successfully combined Lowell data with WISE thermal observations in Durech et al. (2018).

We selected all asteroids with photometric measurements in the Lowell Observatory database and in *Gaia* DR2. We required that the number of *Gaia* observations was greater than or equal to ten. Together, the combined data set consisted of 5412 asteroids.

2.1. Weights and thresholds

Because Lowell and *Gaia* data have very different photometric accuracy, it is necessary to weight them differently when computing χ^2 . Formally, χ^2 is computed as a sum of squares of residuals between model and data divided by measurement errors. However, reliable errors of individual measurements are not known and are often dominated by errors other than Gaussian random noise. Therefore, we minimize a relative goodness-of-fit value

$$\chi_{\text{rel}}^2 = \sum_{\text{Gaia}} (I_i^{\text{obs}} - L_i^{\text{model}})^2 + w \sum_{\text{Lowell}} (L_j^{\text{obs}} - L_j^{\text{model}})^2, \quad (1)$$

where the total χ^2 is composed of two parts weighted by w . If we assume that a typical uncertainty of Lowell photometry is 0.1 mag and that of *Gaia* is 0.01 mag, the weight of Lowell data with respect to *Gaia* should be $w = 0.01$. To check the sensitivity of our results to the particular choice of w , we also tested values $w = 0.05$ and 0.1 (Table 1).

The best-fit model is defined as having the lowest χ_{rel}^2 . The period parameter space is typically full of other local minima. We accept the global minimum χ_{min}^2 as a unique solution if all other models with different parameters have χ^2 values higher than $\chi_{\text{tr}}^2 = (1 + k \sqrt{2/\nu}) \chi_{\text{min}}^2$, where ν is the number of degrees of freedom and k is selected such that it produces the maximum number of correct solutions while giving a negligible number of false positive solutions. The smaller k , the closer χ_{tr}^2 is to χ_{min}^2 and the more models are accepted as reliable. At the same time, small k increases the number of false positive solutions. If k is large, χ_{tr}^2 is significantly larger than χ_{min}^2 and the global minimum has to be deep with respect to other minima to be accepted as a unique solution of the inverse problem. Thus, large k minimizes the number of false positive solutions but also the number

Table 1. Comparison between our best-fit periods and LCDB periods for different setups of k and w .

k	Convex models						Ellipsoids	
	$w = 0.01$		$w = 0.05$		$w = 0.1$		$w = 0.01$	
1	287	87%	198	92%	151	95%	710	90%
1/2	522	86%	403	86%	326	88%	997	85%
1/3	641	83%	513	82%	453	82%	1215	78%

Notes. Each cell of the table contains the number of models with uniquely determined period and the fraction (in percent) of those models for which the period was correct, i.e., the same (within $\pm 10\%$) as that in the LCDB.

of accepted models. The value of k is set based on a trade-off between these two trends. For example, in Durech et al. (2018) we used $k = 1/2$, in Durech & Hanuš (2018) we used $k = 1$.

To test which values of k and w are best for our case of inversion of Lowell and *Gaia* data, we tried three values of $k = 1, 1/2, 1/3$ and $w = 0.01, 0.05, 0.1$. The results are given in Table 1. For different values of k and w , we counted the total number of accepted models. We then selected those accepted models that had reliable (uncertainty code $U \geq 3$) periods listed in the Light Curve Database (LCDB) of Warner et al. (2009), version from November 20, 2018, and compared that period with the value we obtained from inversion of Lowell and *Gaia* data. We assumed that our model was correct if the relative difference between periods was less than 10%. The relative fraction of correctly determined periods is listed in Table 1. For the final analysis, we adopted values $w = 0.01, k = 1/3$ for convex models and $k = 1$ for ellipsoids. The fraction of incorrect periods is not negligible ($\sim 15\%$) but most of these incorrect periods do not pass further reliability checks, which include comparison between periodograms based on convex models (with different resolution) and ellipsoids, visual verification of the data fits, rotation around the shortest axis, and so on (for more details see Durech et al. 2018, Fig. 3).

2.2. Comparison with *Gaia*-only models

In Durech & Hanuš (2018), we derived rotation periods and pole directions for 129 asteroids from *Gaia* DR2 data. All these asteroids were included also in our new *Gaia* and Lowell combined data set so that we could compare results based on only *Gaia* photometry with those based on combined photometry. From the 129 models, 74 were in agreement – having the same rotation period and pole direction (within the uncertainty intervals). Only two models were completely different: (1540) Kevola and (15 496) 1999 DQ3. For Kevola, *Gaia*-only data produced a model that was incorrect. With the combined data set, the new rotation period of 20.08 h is consistent with the period given in the LCDB. For asteroid (15 496), the new rotation period of 88.295 h was one of local minima in the *Gaia*-based periodogram, the global minimum was at 81.21 h.

In another eight cases, rotation periods were the same but pole directions were different – typically prograde or retrograde differences – which was likely because *Gaia* data were not sufficient to determine the pole correctly.

In the remaining 45 cases, we did not retrieve any unique model based on combined photometry because the best-fit models did not pass reliability checks. The reasons were: a non-unique period in 17 cases, more than two pole solutions in 20 cases, and an incorrect inertia tensor in 8 cases.

Table 2. Updated spin states of incorrect DAMIT models.

Asteroid		λ_1	β_1	λ_2	β_2	P	Light curves
Number	Name	[deg]	[deg]	[deg]	[deg]	[h]	
208	Lacrimosa	16	60	202	61	14.08574	Binzel (1987), Slivan & Binzel (1996), Stephens (2014), USNO, <i>Gaia</i> DR2 Barucci et al. (1994), USNO, <i>Gaia</i> DR2 Stephens (2013), Devogèle et al. (2017), USNO, <i>Gaia</i> DR2 Hanuš et al. (2018), Lowell, <i>Gaia</i> DR2
526	Jena	16	50	194	54	11.87655	
1332	Marconia	59	26	240	26	32.11995	
4800	Veveri	94	−9	274	16	6.214858	

Notes. For each asteroid, two possible pole directions in the ecliptic coordinates (λ, β) and the sidereal rotation period P are given. Sources of light curves and sparse photometry used for model reconstruction are listed in the last column.

2.3. Comparison with DAMIT models

After processing all of the approximately 5500 asteroids for which we had photometric data from both sources, we obtained models for 1142 asteroids that passed all tests. Out of these, 367 were already in DAMIT. Similarly as in Ďurech et al. (2016, 2018) we compared spin solutions of our new models with those in DAMIT. Although DAMIT models cannot be treated as completely independent because in many cases they were reconstructed also from Lowell data (Ďurech et al. 2016, 2018), they can be to some extent used for consistency checks. The agreement with DAMIT models was good, most of the asteroids had the same spin solution within the expected uncertainty intervals. There were only four clearly incorrect solutions with completely different periods and 11 cases for which the periods were very similar (relative difference $\sim 10^{-4}$) but they corresponded to different local minima and thus the poles were significantly different ($>60^\circ$ apart). However, it was not clear which model was correct because in many of these 11 cases, the DAMIT model was based on sparse data only (Hanuš et al. 2016) or combination of Lowell and WISE data (Ďurech et al. 2018). In another few cases, the formal discrepancy between pole directions of new and DAMIT models was caused by the fact that they were mirror shape solutions with a difference in the pole ecliptic longitude of $\lambda \pm 180^\circ$.

When comparing our new results with DAMIT, we realized that four DAMIT models were incorrect. The updated models reconstructed from all available light curves and sparse photometry are listed in Table 2.

(208) *Lacrimosa*. The new model has prograde rotation while previous studies published retrograde models (Slivan et al. 2003; Ďurech et al. 2011). This was caused by the slightly incorrect sidereal period of the published solution.

(526) *Jena*. The model published by Hanuš et al. (2016) lists an incorrect rotation period of 9.52 h because the best-fit period was searched only near the value of 9.474 h reported by Barucci et al. (1994). The new model with a period 11.88 h is clearly better and fits well not only the light curves of Barucci et al. (1994) but also sparse USNO and *Gaia* photometry.

(1332) *Marconia*. Model in DAMIT published by Ďurech et al. (2016) was reconstructed from only Lowell Observatory data and its rotation period was 19.2 h. According to our new analysis of Lowell and *Gaia* data, the correct rotation period is 32.1 h, which agrees with the value published by Devogèle et al. (2017).

(4800) *Veveri*. The rotation period determined by Hanuš et al. (2018) of 7.14 h is incorrect. Our new analysis of light

curves from Hanuš et al. (2018), Lowell, and *Gaia* photometry gives a rotation period of 6.21 h.

2.4. New spin and shape models

In total, we derived new models for 775 asteroids. Many of them had their rotation period listed in the LCDB and in most cases the LCDB period agreed with our value. However, we identified 23 asteroids for which we obtained a model with a period that was clearly different from the value in the LCDB. We checked the original sources of LCDB records for all discrepant cases with uncertainty code $\geq 2+$. In 13 cases, we realized that our model was incorrect because the LCDB period was reliable and did not agree with our solution. We removed these asteroids from the list of new models. In some cases, however, even for $U = 3$, the LCDB period seemed not robust enough to reject our solution. The spin parameters of our models, LCDB period values with possible notes, and the number of data points we used for inversion are listed in Table A.1 (available at the CDS). Shape models and photometric data are available also through DAMIT.

We also derived simple single-period models for asteroids that are in fact (according to independent photometric observations) in a non-principal axis rotation state. Apparently, our principal-axis-rotation model is good enough given the quality and coverage of the data to fit the main period in light curves of some tumblers. For example, our principal-axis-rotation model of (5247) Krylov has the rotation period of 82.291 h, which is the most prominent period of its light curves given by a combination of two physical periods of free precession: $1/82.291 \approx 1/68.15 \text{ h} - 1/396.30 \text{ h}$ (Lee et al. 2017, 2018).

3. Conclusion

The set of 762 new asteroid models that we reconstructed from combined inversion of Lowell and *Gaia* DR2 photometry significantly increases the total number of asteroids with known spin state and shape. Although the sample of models in Table A.1 may contain erroneous models, their fraction should not be higher than a few percent. The results we publish can be used for the analysis of the distribution of spins and shapes of asteroids in the main belt, collisional families, and other sub-populations. However, detailed models of individual asteroids require dense light curves observed under various geometries that better constrain the shape and spin parameters.

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