Shape models of asteroids based on lightcurve observations with BlueEye600 robotic observatory

Josef Ř. Durech, Josef Hanuš, Miroslav Brož, Martin Lehký, Raoul Behrend, Pierre Antonini, Stephane Charbonnel, Roberto Crippa, Pierre Dubreuil, Gino Farroni, Gilles Kober, Alain Lopez, Federico Manzini, Julian Oey, Raymond Poncy, Claudine Rinner, René Roy

Abstract

We present physical models, i.e., convex shapes, directions of the rotation axis, and sidereal rotation periods, of 18 asteroids out of which 10 are new models and 8 are refined models based on much larger data sets than in previous work. The models were reconstructed by the lightcurve inversion method from archived publicly available lightcurves and our new observations with BlueEye600 robotic observatory. One of the new results is the shape model of asteroid (1663) van den Bos with the rotation period of 749 hr, which makes it the slowest rotator with known shape. We describe our strategy for target selection that aims at fast production of new models using the enormous potential of already available photometry stored in public databases. We also briefly describe the control software and scheduler of the robotic observatory and we discuss the importance of building a database of asteroid models for studying asteroid physical properties in collisional families.

Keywords: Asteroids, rotation, Photometry

1. Introduction

The increasing amount of available photometric data for asteroids has led to hundreds of asteroid shape models that have been derived from these data. A common method of asteroid shape reconstruction from disk-integrated time-resolved photometry is the lightcurve inversion of Kaasalainen et al. (2001). The scientific motivation for reconstructing physical models of asteroids can be manifold: increasing the number of models for better statistical studies (Hanuš et al. 2016), debiasing the spin and shape distribution (Marciniak et al. 2015), or studying the spin distribution of collisional family members (Slivan et al. 2009, Hanuš et al. 2013, Kim et al. 2014), to name a few.

In order to uniquely determine asteroid’s sidereal rotation period, the direction of its rotation axis, and a convex shape approximation of its shape, lightcurves from different viewing and illumination geometries have to be observed. In practice it means that for a typical main-belt asteroid, we need to collect lightcurves from at least three apparitions. So to derive a new asteroid model, one has to either devote a significant amount of time to collect data from more apparitions, choose a near-Earth object that changes its geometry a lot during a single close approach, or use some archived data and combine them with new observations. For the purpose of this paper, we have chosen the last strategy and present new models of asteroids that were obtained by investing only minimum observing time and using mainly archived data.

We present our strategy of concentrating on those asteroids, for which there is a ‘subcritical’ number of
lightcurves available in the archives and adding observations from just one more apparition should lead to a unique model. A list of such candidates is published in every issue of the Minor Planet Bulletin (Warner et al. 2016, for example). We used the BlueEye600 telescope that we briefly describe together with the target selection algorithm in Sect. 1. In Sect. 2 we present our results – new or updated shape models of 18 asteroids. lightcurve

New lightcurves were obtained with the robotic observatory BlueEye600. We have developed an algorithm to assign priorities to individual asteroids, with the aim to maximize the number of new asteroid models that could be derived by adding new lightcurves to archived data. Therefore, we focused on asteroids for which older lightcurves existed and scheduled the observations according to priorities of observable asteroids and observing conditions.

1.1. Instrument description

The observatory is located in Ondřejov, Czech Republic ($\phi = 49^\circ 54' 34'', \lambda = 14^\circ 46' 48'', h = 515$ m). The telescope itself is a Ritchey–Chrétien system (Officina Stellare), with the primary mirror diameter $d = 600$ mm and the effective focal length $f = 3\,000$ mm, equipped with a 3-lens optical corrector. It produces a diffraction-limited images in a large field of view (50 mm), after a proper alignment; in practice the telescope is seeing limited. Seeing conditions at the site are not exceptional, the average value is about 2–3 arcsec. The secondary mirror also contains a 2nd (raw) focuser.

Instruments are located in the secondary focus, in particular focuser, derotator (Rotofocuser) off-axis guider with a 2nd camera filter wheel (FLI) and the main camera (Mii) using a E2V 42–40 CCD chip, with more than 90% quantum efficiency in VRI bands and the resulting FOV 0.52°.

The alt-azimuth mount (developed by Projectsoft) is of very rigid construction, equipped with torque motors and allows for fast motions with the angular velocity up to 45°/s and angular acceleration up to 45°/s².

1.2. High-level control software

The observatory can be controlled using a high-level software with the following basic architecture or parts: Aitel, Aiplan, Aiview, Projectsoft telescope and Projectsoft camera (see the simplified scheme in Figure 3). All communication between these software components is based on TCP/IP sockets. One can either send commands and their parameters to the lower-level software, specified according to ASCOL, MACOL and other protocols, or serialised objects (most importantly ‘cubes’, i.e. descriptions of observational blocks). The communication is transparent over the internet, or a secure VPN network, respectively.

The most important component is Aitel, the executive part running in real time and sending commands to the observatory. It is implemented in Python language as an object-oriented and fully asynchronous code. Functional schemes exist for all types of devices, which appear as classes in the code (see the example of Tel class in Figure 3). For every individual device there is an object, the instance of the corresponding class. The object-oriented language allows for an easy modifications and future development of other scientific applications.

The list of supported classes corresponding to types of hardware devices includes: Autofocus, Camera, Camera-Voltage, Converter, Cooling, Derotator, Dome, Filterwheel, Flap, Focus, Guider, Heating, Meteo, Meteodata, Slit, Tel, Voltage, Weather. Apart from them, we also have classes serving for configuration and TCP/IP communications: AscolClient, Config, CubeClient, CubeServer, MacolClient. There might be more objects of the same class. In particular, we use three objects ascol_client, i.e. instances of AscolClient class. The source code of the given class is devoted exclusively to a single device, because mutual dependencies are accounted for elsewhere — in the sequencer code. This strict distinction makes the code very clean.

At the same time, the code is fully asynchronous, so there are no waiting cycles that would delay reaction of the program on changes of object states. The TCP/IP communications can be generally fragmented and we use the select module for sending and receiving packets, which minimizes the CPU load.
1.3. Planning of observations

In general, observable asteroids that are within the reach of the telescope are sorted according to their priority, that is assigned according to the preferences. The highest priority is given to those asteroids for which there are old lightcurves from more apparitions and still no unique model. In such cases, we expect to derive a unique model by enlarging the data set by just one or a few lightcurves from a new apparition. We also gave high priority to those asteroids for which a preliminary model existed but was based only on low-quality sparse photometry (Durech et al. 2016, for example). The confirmation of models based on sparse data from surveys is important because sparse data will dominate the field of lightcurve inversion just by sheer amount of data. By comparing models derived from sparse data with those from dense lightcurves, we will understand limitations of models based on sparse photometry.

The weight of the observation is a number $w \in [0; 10]$ from the given interval, which expresses our priority for the observation of the given asteroid. The respective computation is performed in Aiplan and the value is stored in the ‘cube’. The user can check the cube (and its weight) and possibly modify it with Aiview. Finally, Aitel sorts all the cubes according to the weight, in descending order, and selects the first one which is observable at the given time instant.

We use the following equation to compute the weight:

$$w = w_d \cdot f_{\text{airmass}} \cdot f_{\text{duration}} \cdot f_{\text{moonalt}} \cdot f_{\text{elong}} \cdot f_{\text{phase}} \cdot f_{\text{eclipse}} \cdot f_{\text{sn}} \cdot f_{\text{ucac}},$$

where $w_d$ denotes the weight according to our database of existing observations, which is independent of observational conditions, multiplied by factors $f \in [0; 1]$ dependent on observations. Namely $f_{\text{airmass}}$ denotes the factor corresponding to air mass (or height above the horizon), $f_{\text{duration}}$, duration of the observation in comparison with the rotation period, $f_{\text{moonalt}}$, height of the Moon, $f_{\text{elong}}$, elongation of the Moon, $f_{\text{phase}}$, phase of the Moon, $f_{\text{eclipse}}$, an eclipse by the Moon, $f_{\text{sn}}$, signal-to-noise ratio and $f_{\text{ucac}}$, encounters between the asteroid and stars according to UCAC4 catalogue (Zacharias et al. 2013).

1.3.1. Weights according to the database

The weights according to our light curve database and eventually Brian Warner’s database of periods (Warner et al. 2009) are assigned as follows:

- 10 – there is a non-physical shape model, the asteroid is on a ‘hot list’
- 9 – ‘hot list’ with a slightly lower weight
- 8 – known period, more poles, > 4 apparitions, ‘hot list’
7 – known period, more poles, 2 to 4 apparitions
6 – known period, more poles, single apparition, or unknown period, > 4 apparitions
5 – known period, only sparse data, the number of observations ≥ 100, or unknown period, 4 apparitions
4 – unknown period, 2 or 3 apparitions
3 – known period, only sparse data, the number of observations 70 to 99, or unknown period, 2 or 3 apparitions
2 – unknown period, only sparse data, the number of observations ≥ 100
1 – unknown period, only sparse data, the number of observations 70 to 99
0 – there is already a model in DAMIT database, unpublished model

The values of $w_d$ can be further increased or decreased by $w_i$ in the following specific cases: $w_1 = +3$: asteroid is a member of a major asteroid family (Nesvorný 2012, 2015); $w_2 = +2$: an ellipsoidal model exists; $w_3 = -3$: the asteroid is binary. The resulting weigth is then:

$$w'_d = \min\{w_d + \sum w_i, 10\}.$$

1.3.2. Factors depending on observational conditions

Factors $f$ are computed from the asteroid ephemeris and Moon ephemeris downloaded from the Minor Planet Center (MPC). We use a whole arc for this purpose, not only extremal values. The factor corresponding to air mass, or the height above the horizon, respectively, is defined as:

$$f_{\text{airmass}} = \frac{\int f(t) \sin h dt}{\int f dt},$$

where $t$ denotes time (Julian date), $h(t)$ height of the asteroid and $H(x)$ Heaviside step function. The factor would be $f_{\text{airmass}} = 1$, if there would be $h = 90^\circ$ during the whole observation (a kind of miracle), and $f_{\text{airmass}} = 0$ for $h \leq 0^\circ$.

The factor of duration is:

$$f_{\text{duration}} = \min\left[\frac{\int f(h - h_{\text{min}}) dt}{P/4}, 1\right],$$

where $h_{\text{min}}$ denotes the minimum height of the target (a technological limit or the local horizon) and $P$ the rotation period, if known; otherwise $f_{\text{duration}} = 1$.

The factor of Moon height is:

$$f_{\text{moonalt}} = 1 - \frac{\int f(h_{\text{C}}) \sin h_{\text{C}} k_{\text{full}} f_{\text{C}} (h - h_{\text{min}}) dt}{\int f(h - h_{\text{min}}) dt},$$

where $h_{\text{C}}$ denotes the angular height of the Moon and $f_{\text{C}}$ its phase. It is an equivalent of Eq. [1.3.2] but only for a limited time span, when the asteroid of interest is above the horizon. We also see, that a new Moon will not affect us ($f_{\text{C}} = 0$). The coefficient $k_{\text{full}} \approx 0.9$ is not unity, because we shall observe even during a full Moon in the zenith.

The factor of Moon elongation is:

$$f_{\text{elong}} = \frac{\int \left[\frac{1}{3} \left(1 - \cos e_{\text{C}}\right) H(h_{\text{C}}) f_{\text{C}} + H(-h_{\text{C}}) H(h - h_{\text{min}})\right] dt}{\int f(h - h_{\text{min}}) dt},$$

where $e_{\text{C}}$ is the elongation of the Moon and the asteroid. These combinations of the Heaviside functions guarantee that the factor is independent of $e_{\text{C}}$, if it is not above the horizon.

The factor of Moon phase is:

$$f_{\text{phase}} = \frac{\int \left[\frac{1}{3} - k_{\text{full}, f_{\text{C}}} H(h_{\text{C}}) + H(-h_{\text{C}}) H(h - h_{\text{min}})\right] dt}{\int f(h - h_{\text{min}}) dt},$$

where $f_{\text{C}}$ denotes the phase of the Moon, i.e. 1 for the full Moon and 0 for the new one.

The factor of an Moon eclipse, even thought quite improbable, is:

$$f_{\text{eclipse}} = \frac{\int f(h_{\text{C}} - \alpha_{\text{C}}) H(h - h_{\text{min}}) dt}{\int f(h - h_{\text{min}}) dt},$$

where $\alpha_{\text{C}}$ is the angular radius of the Moon (constant here). This approach can be also used when we want to eliminate possible reflections due to the Moon then we choose larger $\alpha_{\text{C}} \approx 1^\circ$.

The factor corresponding to the ratio $S_N$, i.e. the signal from asteroid over the noise from all possible sources, computed for the given maximal exposure time $\tau_{\text{exp}} \approx 180$ s, is:

$$f_{\text{sn}} = H_3\left\{\max\left[\min\left(\frac{S_N}{S_N\text{max}} \frac{S_N}{S_N\text{min}}, 1\right), 0\right]\right\},$$

where $H_3(x) \equiv 3x^2 - 2x^3$ is the Hermite polynomial of the third order; we choose some limiting values $\frac{S_N}{S_N\text{min}} \approx 5$, $\frac{S_N}{S_N\text{max}} \approx 100$.

A ‘cube’ for observation is generated only if the resulting $w > 0$, of course.

1.4. Observations and reductions

Photometric observations were mostly performed in the standard Kron-Cousins Rc filter. Exposure times were between 60 and 180 s, depending on the brightness of the target. The limiting magnitude is about 18 mag for the
longest exposures. We rather prefer to observe one or a few
targets per night with a high cadence to obtain a high total
signal (S/N) and to significantly constrain the shape
modelling. Our new light curve observations (together
with older ones) are summarised in Table 2. In 2016, we
observed 45 different objects for about 227 hours, and 26
additional objects in the same field of view for 105 hours.
In 2015, it was 11 objects for 197 hours. Only a subset
of these data were used in this work, thought, because for
many asteroids observed by BlueEye600 we still do not
have enough data to derive a unique shape model.

Basic reduction procedures are not automated. We use
a standard series of bias, dark-frame and flat-field correc-
tions. Optionally, we can apply a procedure to suppress
fringing if present (Snodgrass and Carry 2013). We then
perform an aperture photometry with C-Munipack1 vers.
1.1.26 software by Motl et al., essentially based on the
We also used sparse photometry from the US Naval Ob-
servatory in Flagstaff, Catalina Sky Survey Observatory
downloaded from the AstDyS), and the Lowell Photomet-
ic Database (Piironen et al. 2001) and the Asteroid
lightcurves archived in the Asteroid Photometry Datab-
Base, available through the Database of Asteroid Models from
Inversion Techniques (DAMIT3, Durech et al. 2010). The
new lightcurves observed with the BlueEye600 telescope
were also uploaded to the Asteroid Lightcurve Photometry
Database4 (Warner et al. 2011).

In total, we reconstructed 18 asteroid models, out of
which 10 are new models. The remaining 8 are updated
models of those based only on sparse photometry from the
Lowell Photometric Database and published by Durech
et al. (2016). In general, the updated spin solutions agree
within the expected errors with those based on only sparse
data, which further enhances reliability of models recon-
structed from sparse photometry. The mean difference of
poles between new and old models of the same asteroid
is ~ 16° of arc. The largest discrepancies are around 25°
with only one exception for the second pole solution for
(1320) Impala where the spin axis directions for the two
models differ by about 35°.

As an example, we show in Fig. 4 an updated model
of asteroid (955) Alstede, that was uniquely (up to the
ambiguity in the pole longitude) reconstructed from one
lightcurve and sparse data.

There are several members of asteroid families in our
small sample. Most importantly, (163) Erigone is the
largest remnant of the corresponding C/X type family (des-
ignated FIN 406, according to Family Identifier Number
defined by Nesvorný et al. 2015, in the inner belt. A very
interesting case is (918) Itha, the largest fragment of the
S-type Itha family (FIN 633), located in the so-called ‘pris-
tine zone’ of the main belt (2.832 to 2.956 au). This family
has an extremely shallow size-frequency distribution (cu-
mulative slope $q = 1.3 \pm 0.3$) which may indicate this is
actually a remnant of a very old disruption originated dur-
ing the Late Heavy Bombardment (Brož et al. 2013). There
are also three members of the Eos family (FIN 606) in our
sample: (608) Adolfine, (775) Lumiere, and (1095) Tulipa;
one member of Maria family (FIN 506): (616) Elly; and
one from Vesta (FIN 401): (2511) Patterson.

---

1 http://c-munipack.sourceforge.net
2 http://alcdef.org
3 http://astro.troja.mff.cuni.cz/projects/asteroids3D
The slowest rotator with known shape. One of the new models – (1663) van den Bos – is particularly interesting because it has a very long rotation period of 748.7 hr, which is close to the synodic period of 740 ± 10 hr determined by Stephens and Higgins (2011). Although we cannot rule out some excitation of its rotation state, it cannot be very high because we obtained a model with the same period and similar pole directions from inversion of an independent set of calibrated sparse data from the Lowell Photometric Database. The shape model for one of the possible poles is shown in Fig. 5.

This asteroid is an S-type, with the geometrical albedo $p_V = 0.171 ± 0.018$ and diameter $D = (11.70 ± 0.05)$ km (Masiero et al. 2011). The time scale of YORP-effect-driven evolution (or doubling time) can be estimated as:

$$\tau_{\text{YORP}} = \tau_0 c^{-1}_{\text{YORP}} \left( \frac{a}{a_0} \right)^2 \left( \frac{D}{D_0} \right)^2 \left( \frac{\rho}{\rho_0} \right) = 990 \text{ Myr},$$

where $\tau_0 = 11.9$ Myr, $a_0 = 2.5$ au, $D_0 = 2$ km, $\rho_0 = 2.500$ kg m$^{-3}$ are the reference values from Čapek and Vokrouhlický (2004). Note that for decreasing the spin rate from an average value of $D = 10$ km asteroids, $\dot{\omega} \approx 5$ rev day$^{-1}$, down to the current value, one would need about 7 doubling times.

At the same time, we can estimate a collisional reorientation time scale as:

$$\tau_{\text{reor}} = B \left( \frac{\omega}{\omega_0} \right)^{\beta_1} \left( \frac{D}{D_0} \right)^{\beta_2} \approx 140 \text{ Myr},$$

where we used $B = 84.5$ kyr, $\omega_0 = 2\pi/P_0$, $P_0 = 5$ h, $\beta_1 = 5/6$, and $\beta_2 = 4/3$ according to Farinella et al. (1998). It means that the asteroid spin is currently rather driven by collisions than YORP. However, if the rotation was significantly faster in the past, the collisional time scale was most likely longer than $\tau_{\text{YORP}}$.

The time scale for damping of non-principal-axis rotation is of the order of (Hestroffer and Tanga 2006):

$$\tau_{\text{damp}} = \frac{\mu Q}{\rho K_1^2 (D/2)^2 \omega^3} \approx 10^6 \text{ Myr},$$

where we assumed $\rho = 2.500$ kg m$^{-3}$, $K_1^2 \approx 0.1$, and the value $\mu Q = 5 \times 10^{12}$ Pa (Harris 1994). In the current state, the damping thus seems negligible and from this point of view one would expect an excited state.

3. Conclusions

The new models we have obtained will further increase the number of asteroids for which a simple physical model exists. By building a database of such models, we can study the distribution of spins and shapes across the population. We will re-observe those targets, for which the current data sets are still not enough to build a unique model. The data obtained in the course of this project (together with other data) will be also used as independent observational constraints for dynamical models of asteroid families and their longer-term evolution, driven mostly by the Yarkovsky semimajor axis drift, chaotic diffusion in mean-motion resonances, eccentricity and inclination drift in secular resonances (Brož and Morbidelli 2013), random collisional reorientations, the YORP effect causing systematic changes of spin rates and spin poles (Hanuš et al.).
, or even spin-orbital resonances (Vokrouhlický et al. 2003).

Luckily, the current number of shape models in DAMIT database seems sufficiently high, in order to focus on individual families. For example, recent census of the Eos family shows there are at least 43 core and 27 halo asteroids (including background) with known spin orientations (Hanuš et al., in prep.). There are three more Eos family members in our list of models. Together with distributions inferred from Lowell photometric data, in particular the absolute values of (approximate) pole latitudes $|\beta|$ for 69 053 asteroids (Cibulková et al. 2016), they may represent very stringent constraints for dynamics of small ($D \approx 10^6$ km) asteroids.

Acknowledgements

The work of MB and JĎ was supported by the Grant Agency of the Czech Republic (grant no. 15-04816S). The computations have been done on the computational cluster Tiger at the Astronomical Institute of Charles University in Prague (http://sirrah.troja.mff.cuni.cz/tiger). The development of the observatory was supported by the Technology Agency of the Czech Republic (TA ČR), project no. TA 03011171, 'Development of Technologies for the Fast Robotic Observatories and Laser Communication Systems'.
Table 1: Rotational states and light curve summary of asteroids, for which we derived their shape models. The table gives ecliptic coordinates $\lambda_1$, $\beta_1$, $\lambda_2$, and $\beta_2$ of the two best-fitting pole solutions, sidereal rotational period $P$, the number of dense light curves $N_{lc}$ spanning $N_{app}$ apparitions, the number of sparse-in-time measurements $N_{sp}$, and the reference to the model.

| Asteroid | $\lambda_1$ (deg) | $\beta_1$ (deg) | $\lambda_2$ (deg) | $\beta_2$ (deg) | $P$ (hours) | $N_{lc}$ | $N_{app}$ | $N_{sp}$ | Reference |
|----------|------------------|----------------|------------------|----------------|------------|----------|----------|----------|-----------|
| 114 Kassandra | 196 | −55 | 4 | −58 | 10.74358 | 24 | 8 | 322 | This work |
| 163 Erigone | 191 | −75 | 358 | −73 | 16.1403 | 5 | 2 | 331 | This work |
| 176 Iduna | 276 | −69 | 16.1402 | 483 | Durech et al. (2016) |
| 582 Olympia | 156 | 78 | 85 | 29 | 11.28783 | 9 | 3 | 360 | This work |
| 616 Elly | 219 | 68 | 83 | 24 | 11.28785 | 491 | Durech et al. (2016) |
| 775 Lumiere | 135 | 3 | 36.3635 | 104 | 6 | 443 | This work |
| 608 Adolphe | 342 | 43 | 171 | 30 | 8.34489 | 10 | 3 | 224 | This work |
| 549 Itha | 262 | 54 | 353 | 85 | 5.29770 | 19 | 3 | 284 | This work |
| 955 Alstede | 250 | 44 | 60 | 62 | 5.29770 | 368 | Durech et al. (2016) |
| 822 Lalage | 89 | 54 | 248 | 47 | 6.10300 | 14 | 6 | 250 | This work |
| 918 Itha | 343 | −74 | 133 | −75 | 3.346503 | 13 | 3 | 445 | This work |
| 955 Alstede | 59 | −59 | 249 | −72 | 3.47381 | 350 | Durech et al. (2016) |
| 1095 Tulipa | 64 | 57 | 246 | 23 | 5.18734 | 1 | 1 | 258 | This work |
| 1219 Britta | 54 | 38 | 240 | 13 | 5.18735 | 401 | Durech et al. (2016) |
| 1251 Hedera | 142 | 40 | 349 | 56 | 2.787153 | 11 | 3 | 356 | This work |
| 1320 Impala | 61 | −62 | 223 | −68 | 5.57557 | 21 | 3 | 231 | This work |
| 1378 Volodia | 72 | −62 | 241 | −66 | 5.57556 | 387 | Durech et al. (2016) |
| 1663 van den Bos | 271 | −53 | 115 | −62 | 19.9020 | 10 | 2 | 289 | This work |
| 2511 Patterson | 266 | −62 | 124 | −70 | 19.9021 | 414 | Durech et al. (2016) |
| 34817 Shiominemoto | 186 | −43 | 126 | −70 | 6.17081 | 9 | 2 | 213 | This work |
| 1380 Volodia | 151 | −57 | 254 | −70 | 6.17081 | 353 | Durech et al. (2016) |
Table 2: Light curve observations used for the shape model determinations. Our observations with the BE600 telescope were obtained by Martin Lehký.

| Asteroid | Date        | $N_{LC}$ | Observer/Telescope                  |
|----------|-------------|----------|-------------------------------------|
| 114 Kassandra | 1979-03 – 1980-07 | 2        | Harris and Young (1989)               |
|          | 1981-09 – 1981-09 | 2        | Harris et al. (1992)                 |
|          | 1988-04 – 1988-04 | 3        | Hutton and Blain (1988)              |
|          | 1993-05 – 1993-05 | 2        | Piironen et al. (1998)              |
|          | 2006-6-24.0    | 1        | Roberto Crippa, Federico Manzini     |
|          | 2006-6-27.0    | 1        | Roberto Crippa, Federico Manzini     |
|          | 2006-6-30.0    | 1        | Roberto Crippa, Federico Manzini     |
|          | 2006-7-11.0    | 1        | Roberto Crippa, Federico Manzini     |
|          | 2006-7-21.0    | 1        | Roberto Crippa, Federico Manzini     |
|          | 2006-7-21.9    | 1        | Roberto Crippa, Federico Manzini     |
|          | 2006-8-06.9    | 1        | Roberto Crippa, Federico Manzini     |
|          | 2006-8-08.9    | 1        | Roberto Crippa, Federico Manzini     |
|          | 2011-8-29.9    | 1        | René Roy                             |
|          | 2011-8-31.0    | 1        | René Roy                             |
|          | 2011-9-17.0    | 1        | René Roy                             |
|          | 2011-9-19.0    | 1        | René Roy                             |
|          | 2016-08-02.1   | 1        | Martin Lehký                         |
|          | 2016-08-14.0   | 1        | Martin Lehký                         |
|          | 2016-08-18.0   | 1        | Martin Lehký                         |
| 163 Erigone | 1980-12 – 1981-01 | 3        | Harris and Young (1989)               |
|          | 2016-11-20.8   | 1        | Martin Lehký                         |
|          | 2016-12-29.8   | 1        | Martin Lehký                         |
| 176 Iduna | 2007-09 – 2007-10 | 3        | Warner (2008)                        |
|          | 2015-01-07.7   | 1        | Julian Oey                           |
|          | 2015-01-14.7   | 1        | Julian Oey                           |
|          | 2015-01-17.7   | 1        | Julian Oey                           |
|          | 2015-01-23.5   | 1        | Julian Oey                           |
|          | 2015-01-29.6   | 1        | Julian Oey                           |
|          | 2016-04-29.9   | 1        | Martin Lehký                         |
| 582 Olympia | 1986-01 – 1989-12 | 10       | Schober et al. (1993)                |
|          | 2006-11-13.6   | 1        | Julian Oey                           |
|          | 2006-11-21.6   | 1        | Julian Oey                           |
|          | 2013-05 – 2013-08 | 87       | Pilcher et al. (2014)                |
|          | 2016-04-30.0   | 1        | Martin Lehký                         |
|          | 2016-04-30.9   | 1        | Martin Lehký                         |
|          | 2016-05-02.9   | 1        | Martin Lehký                         |
| 608 Adolfine | 2006-10-14.9   | 1        | Raymond Poncy                        |
|          | 2006-10-24.9   | 1        | Raymond Poncy                        |
|          | 2006-10-26.9   | 1        | Raymond Poncy                        |
|          | 2006-10-27.9   | 1        | Raymond Poncy                        |
|          | 2013-02-03.9   | 1        | Roberto Crippa, Federico Manzini     |
|          | 2006-10-11.0   | 1        | Roberto Crippa, Federico Manzini     |
|          | 2006-10-15.9   | 1        | Roberto Crippa, Federico Manzini     |
|          | 2006-10-26.9   | 1        | Roberto Crippa, Federico Manzini     |
|          | 2016-08-31.9   | 1        | Martin Lehký                         |
| Asteroid | Date       | N\textsubscript{LC} | Observer/Telescope |
|----------|------------|-------------------|-------------------|
| 616 Elly | 2010 01 – 2010 02 | 2 | Warner (2010) |
|          | 2010 02 – 2010 02 | 2 | Durkee (2010) |
|          | 2014 02 – 2014 02 | 2 | Parafes (2014) |
|          | 2014 02 – 2014 02 | 4 | Stephens (2014) |
|          | 2014 02 – 2014 03 | 8 | Klinglesmith et al. (2014) |
|          | 2016-10-04.8 | 1 | Martin Lehký |
| 775 Lumiere | 1983 05 – 1983 05 | 3 | Binzel (1987) |
|          | 2001-09-20.0 | 1 | René Roy |
|          | 2001-09-26.0 | 1 | René Roy |
|          | 2001-09-31.0 | 1 | René Roy |
|          | 2001-08-27.1 | 1 | René Roy |
|          | 2003-03-23.9 | 1 | Claudine Rinner |
|          | 2005-07-07.1 | 1 | Stephane Charbonnel, Pierre Dubreuil |
|          |            |                  | Alain Lopez, Gilles Kober |
|          | 2006-10-15.0 | 1 | Raymond Poncy |
|          | 2006-10-24.9 | 1 | Raymond Poncy |
|          | 2006-10-26.9 | 1 | Raymond Poncy |
|          | 2006-10-27.8 | 1 | Raymond Poncy |
|          | 2016-09-25.9 | 1 | Martin Lehký |
| 822 Lalage | 1992 09 – 1992 09 | 2 | Wisniewski et al. (1997) |
|          | 2009 10 – 2009 10 | 2 | Higgins (2011) |
|          | 2014 01 – 2014 01 | 2 | Stephens (2014) |
|          | 2014 02 – 2014 03 | 6 | Klinglesmith et al. (2014) |
|          | 2016-12-29.0 | 1 | Martin Lehký |
| 918 Itha | 2011 06 – 2011 06 | 4 | Oey et al. (2012) |
|          | 2011 06 – 2011 07 | 3 | Folberth et al. (2012) |
|          | 2016-08-24.0 | 1 | Martin Lehký |
|          | 2016-12-03.8 | 1 | Martin Lehký |
| 955 Alstede | 2016-03-17.9 | 1 | Martin Lehký |
| 1095 Tulipa | 1983 02 – 1983 02 | 1 | Binzel (1987) |
|          | 2005-04-15.0 | 1 | Ondřejov |
|          | 2005-04-29.0 | 1 | Ondřejov |
|          | 2005-04-28.0 | 1 | Pierre Antonini, Raoul Behrend |
|          | 2005-05-15.0 | 1 | Pierre Antonini, Raoul Behrend |
|          | 2005-05-26.9 | 1 | Pierre Antonini, Raoul Behrend |
|          | 2005-05-32.0 | 1 | Pierre Antonini, Raoul Behrend |
|          | 2005-06-02.0 | 1 | Pierre Antonini, Raoul Behrend |
|          | 2005-06-01.9 | 1 | Gino Farroni |
|          | 2005-05-32.0 | 1 | Gino Farroni |
|          | 2016-06-24.0 | 1 | Martin Lehký |
| 1219 Britta | 1983 09 – 1983 12 | 12 | Binzel (1987) |
|          | 2014 01 – 2014 01 | 4 | Stephens (2014) |
|          | 2014 02 – 2014 03 | 4 | Klinglesmith et al. (2014) |
|          | 2016-10-30.9 | 1 | Martin Lehký |
| 1251 Hedera | 2007 07 – 2007 10 | 9 | Oey (2008) |
|          | 2016-08-08.0 | 1 | Martin Lehký |
Table 2: continued.

| Asteroid    | Date            | $N_{LC}$ | Observer/Telescope            |
|-------------|-----------------|----------|-------------------------------|
| 1320 Impala | 2006 05 – 2006 05 | 3        | Warner (2006)                 |
|             | 2016 03 – 2016 04 | 5        | Benishek (2016)               |
|             | 2016-05-08.0    | 1        | Martin Lehky                  |
| 1380 Volodia| 2016-09-24.0    | 1        | Martin Lehky                  |
| 1663 van den Bos | 2010 09 – 2010 11 | 32   | Stephens and Higgins (2011)    |
|             | 2010 10 – 2010 11 | 4       | Ruthroff (2011)               |
|             | 2016-05-12.0    | 1        | Martin Lehky                  |
| 2511 Patterson | 2016-12-03.9   | 1        | Martin Lehky                  |
| 34817 Shiominemoto | 2003 07 – 2003 07 | 2       | Warner (2004)                 |
|             | 2006 12 – 2006 12 | 2       | Warner (2007)                 |
|             | 2011 11 – 2011 11 | 3       | Warner (2012)                 |
|             | 2015 02 – 2015 02 | 4       | Stephens (2015)               |
|             | 2016-08-31.0    | 1        | Martin Lehky                  |
Table 3: List of observers, their locations and telescope specifications.

| Observer          | Observatory                                           | Telescope specification                                      |
|-------------------|--------------------------------------------------------|-------------------------------------------------------------|
| Roberto Crippa    | Tradate, Italy (B13)                                   | Reflector 0.65m, F/D=5, Apogee Alta 1001, KAF-1001ME        |
| Federico Manzini  | Sozzago, Italy (A12)                                   | D=0.40m F/D=5, Hisis 33                                     |
| Martin Lehký      | Ondřejov Observatory, Czech Republic (557)             | BlueEye 600                                                 |
| René Roy          | Observatoire de Blauvac, Blauvac, France (627)         | D=0.312m, Hisis 22, KAF-400                                 |
| Julian Oey        | Kingsgrove, NSW, Australia (E19)                       | D=0.25m Schmidt-Cassegrain, F/D=5.2, SBIG ST-402ME CCD      |
| Raymond Poncy     | Le Crès Observatory, Le Crès, France (177)             | D=0.20m F/D=3.3                                             |
| Claudine Rinner   | 224 Ottmarsheim, France (224)                          | D=0.305m F/D=10, ST8e, KAF1602E, KAF3200me                  |
| Stephane Charbonnel| Observatoire de Durtal, Durtal, France (949)           | D=0.30m, F/D=3.5, KAF-400                                   |
| Pierre Antonini   | Observatoire des Hauts Patys, Bédoin, France (132)     | D=0.305m, F/D=2.6 , NJP160, MCMT2, KAF-400                   |
References

Benishek, V. 2016. Lightcurves and Rotation Periods for 14 Asteroids. Minor Planet Bulletin 43, 339–342.

Binzel, R.P. 1987. A photoelectric survey of 130 asteroids. Icarus 72, 135–208.

Bowell, E., Oszkiewicz, D.A., Wasserman, L.H., Muinonen, K., Pentilä, A., Trilling, D.E., 2014. Asteroid spin-axis longitudes from the Lowell Observatory database. Meteoritics and Planetary Science 49, 95–102. [1310.3617]

Brož, M., Morbidelli, A., 2013. The Eos family halo. Icarus 223, 844–849. [1302.1447]

Brož, M., Morbidelli, A., Bottke, W.F., Rozeňhal, J., Vokrouhlický, D., Nesvorny, D., 2013. Constraining the cometary flux through the asteroid belt during the late heavy bombardment. Astronomy and Astrophysics 551, A117. [1301.6221]

Čapek, D., Vokrouhlický, D., 2004. The YORP effect with finite thermal conductivity. Icarus 172, 526–536.

Cibulková, H., Dušek, J., Vokrouhlický, D., Kaasalainen, M., Oszkiewicz, D.A., 2016. Distribution of spin-axes longitudes and shape elongations of main-belt asteroids. Astronomy and Astrophysics 596, A57. [1610.02790]

Dušek, J., Sidorin, V., Kaasalainen, M., 2010. DAMIT: a database of asteroid models. Astronomy and Astrophysics 513, A46. [1010.2943]

Dušek, J., Hanuš, J., Oszkiewicz, D., Vancó, R., 2016. Asteroid models from the Lowell photometric database. Astronomy and Astrophysics 587, A48. [1607.02999]

Durkee, R.I. 2010. Asteroids Observed from the Shed of Science Observatory: 2009 October - 2010 March. Minor Planet Bulletin 37, 125–127.

Farinella, P., Vokrouhlický, D., Hartmann, W.K., 1998. Meteorite Delivery via Yarkovsky Orbital Drift. Icarus 132, 378–387.

Folberth, J., Casimir, S., Dou, Y., Evans, D., Foukles, T., Haenfling, M., Kuhn, P., White, A., Ditteon, R., 2012. Asteroid Lightcurve Analysis at the Oakley Southern Sky Observatory: 2011 July-September. Minor Planet Bulletin 39, 51–55.

Hanuš, J., Brož, M., Dušek, J., Warner, B.D., Brinsfield, J., Durkee, R., Higgins, D., Koff, R.A., Oey, J., Pilcher, F., Stephens, R., Strabla, L.P., Ulisse, Q., Girelli, R., 2013. An anisotropic distribution of spin vectors in asteroid families. Astronomy and Astrophysics 559, A134. [1309.4296]

Hanuš, J., Dušek, J., Oszkiewicz, D.A., Behrend, R., Carry, B., Delbo, M., Adam, O., Afonina, V., Anquetin, R., Antonini, P., Arnold, L., Audejean, M., Aurard, P., Bachschmidt, M., Baduel, B., Barborti, E., Barroy, P., Baudouin, P., Berard, L., Berger, N., Bernasconi, L., Bosch, J.G., Bouley, S., Bozhinova, I., Brinsfield, J., Brunetto, L., Canau, G., Caron, J., Carrier, F., Casalnuovo, G., Casulli, S., Cerda, M., Chalamet, L., Charbonnel, S., Chinaglia, B., Cikota, A., Colas, F., Coliac, J.F., Collet, A., Coloma, J., Condat, M., Conseil, E., Costa, R., Crippa, R., Cristofanelli, M., Dameridji, Y., Debaccker, A., Decock, A., Déhais, Q., Deléage, T., Delmelle, S., Demeautis, C., Dróżdż, M., Dubos, G., Dulcamara, T., Dumont, M., Durkee, R., Dymock, R., Escalante del Valle, A., Esseiva, R., Esteban, M., Fauchez, T., Fauchez, M., Fauchez, M., Fauchez, S., Fauvaud, M., Hirsch, R., Hodosan, G., Hren, M., Hygate, A., Innocent, N., Jacquinot, H., Jawahar, S., Jehin, E., Jerosimic, L., Klotz, A., Koff, W., Kornoš, P., Kurtuskiewicz, E., Kraft, P., Krugly, K., Kugel, F., Labrevoir, O., Lecacheux, J., Lehky, M., Leroy, Á., Lesquerbault, B., Lopez-Gonzales, M.J., Lutz, M., Mallecot, B., Manfroid, J., Manzini, F., Marciniak, A., Martin, A., Modave, B., Montanuit, R., Montier, J., Morelle, E., Morton, B., Mottola, S., Naves, R., Nemenyi, J., Oey, J., Ogloza, W., Paella, M., Pallares, H., Peyrot, A., Pilcher, F., Pirene, J.F., Pirón, P., Poliščík, M., Polotto, L., Poncy, R., Previt, J.P., Reğinier, F., Renaud, D., Ricci, D., Richard, F., Rinner, C., Risoldi, V., Robillard, D., Romeuf, D., Rousseau, G., Roy, R., Ruthoff, J., Salom, P.A., Salvador, L., Sanchez, S., Santana-Ros, T., Scholz, A., Séné, G., Skiff, B., Sobkowiak, K., Sogor, P., Soldán, F., Spiričak, A., Splanska, E., Sposetti, S., Starkey, D., Stephens, R., Stiepen, A., Stoss, R., Strajnic, J., Teng, J.P., Tumo, G., Vagnozzi, A., Vanoutryve, B., Vugnon, J.M., Warner, B.D., Waucomont, M., Wertz, O., Wiener, M., Wolf, M., 2016. New and updated convex shape models of asteroids based on optical data from a large collaboration network. Astronomy and Astrophysics 586, A108. [1510.07422]

Harris, A.W., 1994. Tumbling asteroids. Icarus 107, 314–364.

Harris, A.W., Young, J.W., 1989. Asteroid lightcurve observations from 1979-1981. Icarus 81, 314–364.

Harris, A.W., Young, J.W., Dockweiler, T., Gibson, J., Poutanen, M., Bowell, E., 1992. Asteroid lightcurve observations from 1981. Icarus 95, 115–147.

Hestroffer, D., Tanga, P., 2006. Asteroids from Observations to Models, in: Souchay, J. (Ed.), Dynamics of Extended Celestial Bodies and Rings, p. 89. astro-ph/0507158

Higgins, D., 2011. Period Determination of Asteroid Targets Observed at Hunters Hill Observatory: May 2009 - September 2010. Minor Planet Bulletin 38, 41–46.

Hroch, F., 1998. Computer Programs for CCD Photometry, in: Dusek, J. (Ed.), 20th Stellar Conference of the Czech and Slovak Astronomical Institutes, p. 30.

Hutton, R.G., Blain, A., 1988. V+B Photoelectric Photometry of Asteroid 114 Kassandra. Minor Planet Bulletin 15, 39.

Kaasalainen, M., Lamberg, L., 2006. Inverse problems of generalized projection operators. Inverse Problems 22, 749–769.

Kaasalainen, M., Torppa, J., Muinonen, K., 2001. Optimization methods for asteroid lightcurve inversion. II. The complete inverse problem. Icarus 153, 37–51.

Kim, M.J., Choi, Y.J., Moon, H.K., Byun, Y.I., Brosch, N., Kaplan, M., Kaynar, S., Uysal, Ö., Güzel, E., Behrend, R., Yoon, J.N., Mottola, S., Hellmich, S., Hinse, T.C., Eker, Z., Park, J.H., 2014. Rotational Properties of the Maria Asteroid Family. Astronomy and Astrophysics Journal 147, 56. [1311.5318]

Klingselmsith, M.A., Hanowell, J., Risley, E., Turk, J., Vargas, A., Warren, C.A., 2014. Lightcurves for Inversion Model Candidates. Minor Planet Bulletin 41, 139–143.

Marciniak, A., Pilcher, F., Oszkiewicz, D., Santos-Ros, T., Urakawa, S., Fauvaud, S., Kankiewicz, P., Tychonie, L., Fauvaud, M., Hirsch, R., Horbowicz, J., Kamiński, K., Konstanciak, I., Kurtuskiewicz, E., Murawiecka, M., Nadolny, J., Nishiya, K., Okumura, S., Poliščík, M., Richard, F., Sakamoto, T., Sobkowiak, K., Stachowski, G., Trela, P., 2015. Against the biases in spins and shapes of asteroids. Planetary and Space Science 118, 256–266.

Masiero, J.R., Mainzer, A.K., Gray, T., Bauer, J.M., Cutri, R.M., Dailey, J., Eisenhardt, P.R.M., McMillan, R.S., Spahr, T.B., Skrutskie, M.F., Thoulen, D., Walker, R.G., Wright, E.L., DeBaun, E., Elsbury, D., Gautier, I.T., Gomillion, S., Wilkins, A., 2011. Main Belt Asteroids with WISE NEOWISE. I. Preliminary Albedos and Diameters. Astrophysical Journal 741, 68. [1109.4096]

Nesvorny, D., 2012. Nesvorny HCM Asteroid Families V2.0. NASA Planetary Data System 189.

Nesvorny, D., 2015. Nesvorny HCM Asteroid Families V3.0. NASA Planetary Data System 234.
