Asteroids: New Observations, New Models
Proceedings IAU Symposium No. 318, 2015
S. R. Chesley, A. Morbidelli, R. Jedicke & D. Farnocchia, eds.

doi:10.1017/S1743921315008492

WISE data and sparse photometry used for shape reconstruction of asteroids

Josef Ďurech[1], Josef Hanuš[2], Victor M. Alí-Lagoa[2], Marco Delbo[2] and Dagmara A. Oszkiewicz[3]

[1] Astronomical Institute, Faculty of Mathematics and Physics, Charles University in Prague, V Holešovičkách 2, 18000 Prague, Czech Republic
email: durech@sirrah.troja.mff.cuni.cz

[2] Laboratoire Lagrange, UMR7293, Université de la Côte d'Azur, CNRS, Observatoire de la Côte d'Azur, Blvd de l'Observatoire, CS 34229, 06304 Nice cedex 4, France

[3] Astronomical Observatory Institute, Faculty of Physics, A. Mickiewicz University, Słoneczna 36, 60-286 Poznań, Poland

Abstract. Asteroid disk-integrated sparse-in-time photometry can be used for determination of shapes and spin states of asteroids by the lightcurve inversion method. To clearly distinguish the correct solution of the rotation period from other minima in the parameter space, data with good photometric accuracy are needed. We show that if the low-quality sparse photometry obtained from ground-based astrometric surveys is combined with data from the Wide-field Infrared Survey Explorer (WISE) satellite, the correct rotation period can be successfully derived. Although WISE observed in mid-IR wavelengths, we show that for the period and spin determination, these data can be modelled as reflected light. The absolute fluxes are not required since only relative variation of the flux over the rotation is sufficient to determine the period. We also discuss the potential of combining all WISE data with the Lowell photometric database to create physical models of thousands of asteroids.

Keywords. methods: data analysis, techniques: photometric, minor planets, asteroids, infrared: solar system

1. Introduction

Inversion of asteroid lightcurves has become a standard method for asteroid shape determination from disk-integrated photometry (Kaasalainen *et al.* 2002; Ďurech *et al.* 2016). Apart from classical lightcurves, which are obtained by targeted photometry of individual asteroids, the so-called sparse photometry has become more important, mainly because of the huge amount of available data. As has been shown by Kaasalainen (2004), even data that are sampled much sparser than the rotation period can be used the same way as standard lightcurves as long as the whole sparse data set is internally calibrated. With current data sets, the production of new models from sparse data is not very efficient because the photometric accuracy of the data is low and one typically obtains many possible models that fit the data equally well. Nevertheless, hundreds of new asteroid models have been derived from sparse photometry alone or its combination with classical lightcurves (Ďurech *et al.* 2009; Hanuš *et al.* 2011, 2013, 2016). Combination of sparse data with lightcurves is efficient because sparse data cover a long interval of time and thus a wide range of geometries, whereas dense data better constrain the rotation period. However, compared to the large amount of sparse data (available essentially for all known asteroids), the number of asteroids with lightcurves is of the order of thousands (Warner *et al.* 2009).

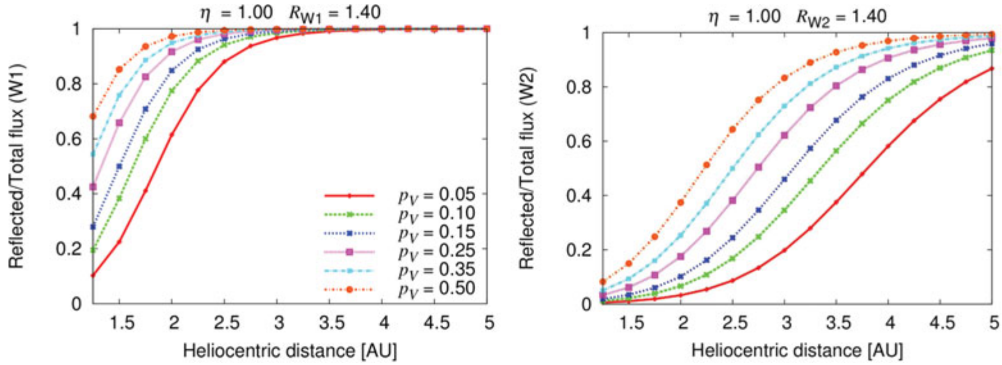

Figure 1. The ratio between the reflected flux and total (reflected and emitted) flux in W1 and W2 filters as a function of heliocentric distance for different values of geometric visible albedo p_V and fixed values of beaming parameter η and a ratio R_W between the geometric infrared and visible albedos (the fixed parameters of η and R_W are close to those of the S-type asteroid (3767) DiMaggio).

To further increase the number of unique models derived form sparse data, we tested the possibility to combine sparse photometry collected in the Lowell Observatory database with data from Wide-field Infrared Survey Explorer (WISE) mission (Wright *et al.* 2010). Although the WISE data were observed in mid-IR wavelengths, they show flux variations due to rotation similar to those of visual reflected data. Using optical lightcurves to correct thermal infrared fluxes (assuming analogy of thermal and optical data) has been done by Delbó *et al.* (2003); Harris *et al.* (2005), for example. In the following we discuss a new possibility of treating mid-IR data the same way as reflected light and we show a typical result for one test case.

2. Inversion of combined data sets

2.1. *Lowell photometric database*

The largest source of calibrated photometry of asteroids is the Lowell Observatory photometric database (Bowell *et al.* 2014). It consists of photometry of asteroids provided to the Minor Planet Center (MPC) by the largest surveys that was re-calibrated in the V band using the accurate photometry of the Sloan Digital Sky Survey. Details about the data reduction and calibration can be found in Oszkiewicz *et al.* (2011). Data are available for $\sim 326,000$ asteroids with the photometric accuracy of about 0.15–0.20 mag. There are several hundreds of photometric points for each asteroid. The length of the observing interval is $\sim$ 10–15 years.

The data are processed by means of the lightcurve inversion method in the framework of the distributed computing project Asteroids@home (Ďurech *et al.* 2015) and preliminary shape models are published online†. The final models are being prepared for publication (Ďurech *et al.*, in prep.). However, because of the poor photometric accuracy of the data, the number of reliable models (hundreds) is only a small fraction of the hundreds of thousands asteroids that have been analyzed. These data were also combined with dense lightcurves and hundreds of new models were derived (Hanuš *et al.* 2016).

† `http://asteroidsathome.net`

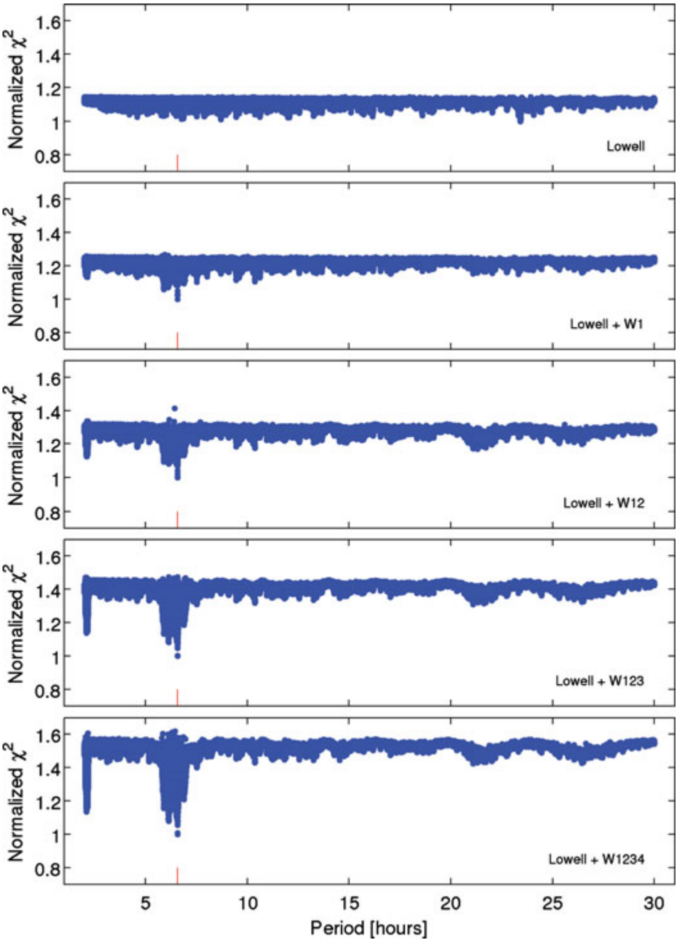

Figure 2. Periodograms for each data set. As more WISE data are added to Lowell data (Lowell + W1234 means Lowell photometry combined with WISE data from all four filters), the minimum at $P = 6.58$ h becomes more apparent.

2.2. *WISE*

The Wide-field Infrared Survey Explorer mission (Wright *et al.* 2010) observed asteroids during its cryogenic mission in four filters (we denote them W1, W2, W3, and W4) at isophotal wavelength 3.4, 4.6, 11, and 22 μm, respectively (Mainzer *et al.* 2011). While W3 and W4 fluxes consist of almost entirely thermal flux and have been used in thermophysical models to infer physical properties of selected asteroids (Alí-Lagoa *et al.* 2014; Rozitis *et al.* 2014; Hanuš *et al.* 2015, for example), the W1 and W2 filters are mixture of reflected and emitted flux. The ratio between reflected and emitted flux depends on the geometric albedos in visible and infrared and on the heliocentric distance (Fig. 1). Contrary to thermophysical modelling, only relative changes of the flux during the rotation are important for our purposes, because even relative variations carry information about the rotation period. Also the thermal data in W3 and W4 filters show the same periodicity as the visual lightcurves with negligible phase shift (see an example in Fig. 5). The sampling of WISE data is typically about ten points per filter in a day or two, which makes them semi-sparse, a compromise between the densely sampled lightcurves and sparsely sampled photometry from surveys.

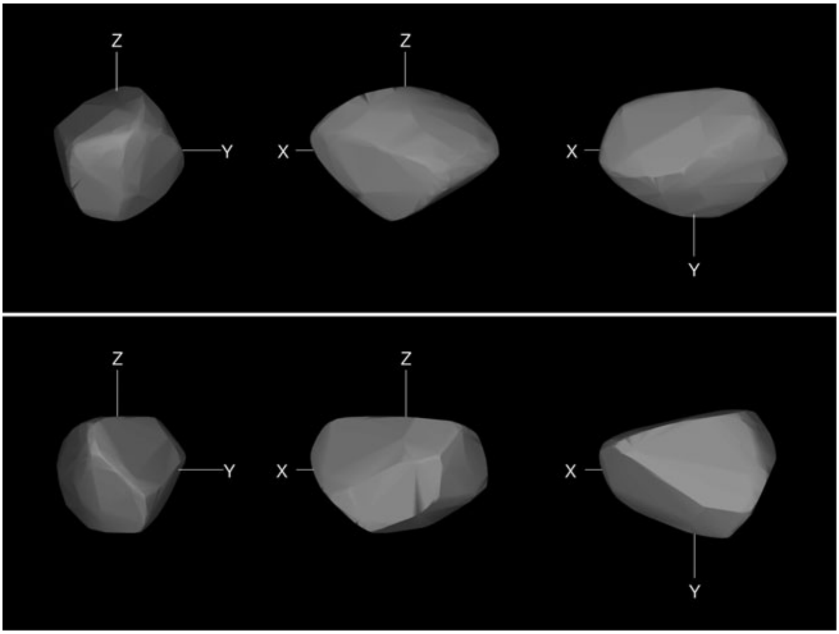

Figure 3. Two shape models of (3767) DiMaggio reconstructed from Lowell and WISE data from all four filters. The corresponding poles are $(\lambda, \beta) = (146°, -36°)$ and $(311°, -45°)$ for top and bottom model, respectively.

2.3. *Example – asteroid (3767) DiMaggio*

We have carried out many tests with combined Lowell and WISE data to see what kind of results we get if we use the WISE data as visual photometry. The results show that in most cases the optimization algorithm finds the correct period and corresponding shape/spin solution because, although the number of WISE measurements is low, the data sample the typical rotation periods of the order of hours well.

As an example, we show here results for asteroid (3767) DiMaggio. It is a main belt asteroid with semimajor axis 2.6 au. There are more that 400 points in the Lowell database from years 1998–2011 and more than 20 points in each WISE filter observed at a heliocentric distance of 2.67 au. For the period search, we used a fast ellipsoid approach where the shape is approximated by a triaxial geometrically scattering ellipsoid (Kaasalainen & Ďurech 2007). It makes the computation of disk-integrated brightness fast compared to the convex approach, because the brightness can be computed analytically (Connelly & Ostro 1984). The periodograms for each data set (Lowell data alone and their combination with W1–4 filters) are shown in Fig. 2. For Lowell data only, the correct period (known from dense lightcurves to be around 6.58 h, Almeida *et al.* 2004; Waszczak *et al.* 2015, and Behrend's web†) is hidden in many local minima. Adding increasingly more WISE data makes the correct period stand out more clearly. For this period of 6.57885 ± 0.00001 h, we used the convex lightcurve inversion of Kaasalainen *et al.* (2001) and found two equally good (measured by the χ^2 of the fit) possible pole solutions with ecliptic longitude λ and latitude β of $(\lambda, \beta) = (146 \pm 6°, -36 \pm 7°)$ and $(311 \pm 8°, -45 \pm 10°)$. The ambiguity in pole ecliptic longitude is often present in inversion of disk-integrated data and is caused by the the fact that geometry of the problem is limited close to the ecliptic

† `http://obswww.unige.ch/~behrend/page_cou.html`

https://doi.org/10.1017/S1743921315008492 Published online by Cambridge University Press

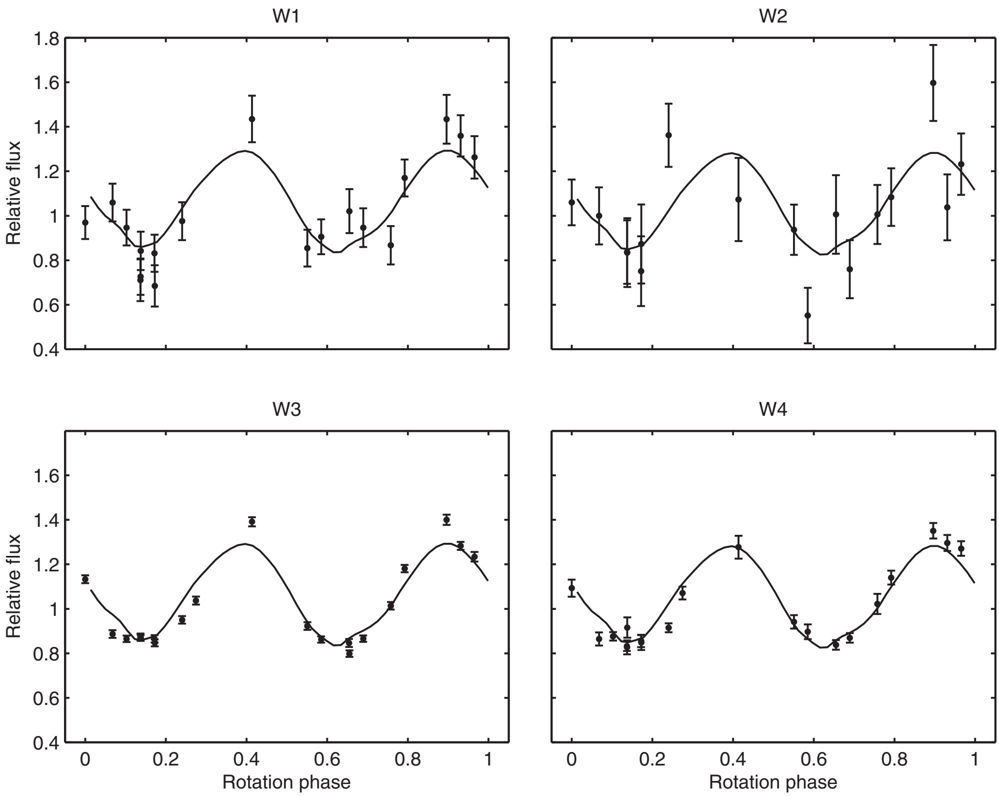

Figure 4. Comparison between observed (treated as reflected) and modelled lightcurves of asteroid (3767) DiMaggio in four WISE filters. The solid lightcurve is the same for all filters as our simple model assumes by definition) and was computed using the first model in Fig. 3.

plane (Kaasalainen and Lamberg 2006). The shape models are shown in Fig. 3. The fit to WISE data is shown in Fig. 4.

According to Masiero *et al.* (2011), the visual geometric albedo of asteroid DiMaggio is $p_{\mathrm{V}} = 0.20$, the beaming parameter $\eta = 1.00$, and the IR albedo $p_{\mathrm{IR}} = 0.31$. This corresponds to the ratio between the geometric infrared and visible albedos $R = 1.55$ (cf. Fig. 1). With these parameters, the ratio of the reflected over total (reflected + emitted) flux is ∼98% for W1 and ∼40% for W2 filters. This means that the flux in W1 filter is almost pure reflected light, and the flux in W2 is an even mixture of the reflected and emitted components. The lightcurves computed for the shape model, its spin parameters, the hemispherical bolometric albedo 0.07, thermal inertia 50 and 200 $\mathrm{J\,m^{-2}\,s^{-1/2}\,K^{-1}}$, and medium surface roughness are shown in Fig. 5. The emitted components were computed by the thermophysical model of Delbo *et al.* (2007); Delbo (2004) (see also Delbo *et al.* (2016) for a review on thermophysical modelling). All lightcurves were normalized to unit mean flux to see the differences in their shapes. What is important for our simplified model is that although the details of lightcurves in different filters are different, the overall amplitudes are similar and there is no important phase shift between the lightcurves. This justifies our simplified approach to model the thermal data as relative reflected light.

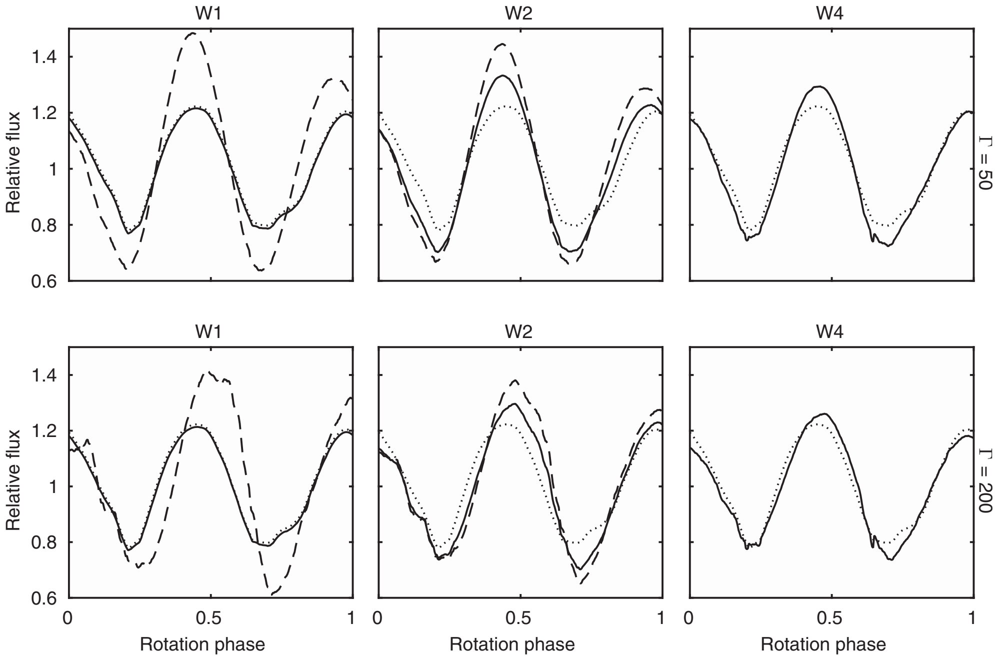

Figure 5. Comparison of normalized reflected and thermal emitted flux for shape model of (3767) in four WISE filters. The dotted curve on all six subplots is the classical lightcurve in reflected light. The solid curve is the total flux that is composed from reflected (dotted curve) and emitted (dashed curve for W1 and W2 filters). All curves are normalized such that their mean flux is 1. The ratio between reflected/emitted is high for W1, W2 filters and almost zero for W3 and W4 filters. The fluxes were computed for two values of thermal inertia Γ using the derived model of DiMaggio (Fig. 3) and the geometry corresponding to WISE observations.

3. Future

All the tests that we have made so far (similar to that for asteroid DiMaggio mentioned above) show that WISE data carry robust information about the rotation period of the asteroid that is coded in the variations of the flux caused by the changing projection of the shape. In many cases, it is possible to correctly reconstruct the rotation period from combined Lowell and WISE data even if both data sets are not sufficient alone. This opens a new possibility to find the rotation period and corresponding shape/spin model for tens of thousands of asteroids because for so many asteroids we have both WISE and Lowell data. The real number of models derivable from this approach, their reliability, possible systematic errors in shape and pole direction, and the number of false positive solutions is currently under study – we are processing the Lowell and WISE data in the framework of the Asteroids@home project (Ďurech *et al.* 2015).

Acknowledgments

The work of JĎ was supported by the grant 15-04816S of the Czech Science Foundation. JH greatly appreciates the CNES post-doctoral fellowship program. JH, VAL and MD were supported by the project under the contract 11-BS56-008 (SHOCKS) of the French Agence National de la Recherche (ANR). DO was supported by the grant NCN 2012/S/ST9/00022 Polish National Science Center. This publication also makes use of data products from NEOWISE, which is a project of the Jet Propulsion

Laboratory/California Institute of Technology, funded by the Planetary Science Division of the National Aeronautics and Space Administration.

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