INVESTIGATIONS OF ASTEROIDS IN PULKOVO OBSERVATORY

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ABSTRACT. Observational Astrometry Laboratory and Ephemeris Provision Sector of Pulkovo Observatory carry out a joint multipurpose research on asteroids belonging to various groups. Astrometric and photometric observations are done using ZA–320M and MTM–500M telescopes located at Pulkovo and in Northern Caucasus mountains, correspondingly. We obtain lightcurves that allow us to determine spin parameters and shapes of asteroids. Their color indices and taxonomy classes are derived from wideband filter observations. Improvement of asteroid orbits is achieved by doing positional measurements. Orbital evolution of asteroids is modelled, taking into account also non-gravity forces, including light pressure and Yarkovsky effect. NEAs, as well as binary asteroids, take an important place in our investigations. Quasi-satellites of Venus, Earth, and Mars are new targets of our research, one of the examples being 2012 DA14 that approached Earth in early 2013; many MTM–500M observations of this asteroid were obtained around the date of approach.

1. TELESCOPES

Observational Astrometry Laboratory of Pulkovo Observatory carries out observations with two small robotic telescopes. ZA–320M ($D = 32$ cm, $F = 320$ cm) is installed at Pulkovo observatory (Saint Petersburg). MTM–500M ($D = 50$ cm, $F = 410$ cm) is located in Northern Caucasus mountains near Kislovodsk at the altitude of 2070 m. Both telescopes are equipped with CCD cameras and $BVRI$ filters.

2. SOFTWARE

CCD images are processed by Apex II software (Devyatkin et al., 2010) developed at Pulkovo Observatory as an all-purpose astronomical image analysis platform. Apex II automatic asteroid pipeline comprises the following basic steps: calibration (including synthesis and application of dark and flatfield frames and cosmetic correction); sky background flattening; object detection; deblending; centroiding by PSF fitting; flux measurement using aperture, PSF, and optimal techniques; rejection of false detections; matching to reference catalog (USNO–A2, USNO–B1, Tycho–2, HIPPARCOS, UCAC4, 2MASS, XPM, user catalogs); astrometric reduction by a set of standard plate models; matching uncorrelated objects to the list of Solar system bodies (EPOS package is used to provide solar system object ephemerides, see below); report creation in one of the standard formats (e. g. MPC). There is a capability to mark objects and reference stars in a visual manner using the dedicated graphical interface.

To calculate the motion of solar system bodies, we use EPOS software (L'vov, Tsekmeister, 2012), also developed at Pulkovo. The software provides several kinds of celestial mechanics calculations and visualization modes, including ephemerides, $\mathrm{O}-\mathrm{C}$, orbit determination and improvement, and modelling the motion of solar system bodies in the various coordinate systems.

3. ASTEROID INVESTIGATIONS

From our observations, we get astrometric positions of asteroids for improvement of their orbits. Also, we do numerical modelling of orbital evolution of asteroids, taking into account both gravity and non-gravity effects (light pressure, Yarkovsky effect, close approaches to planets). Lightcurves obtained from photometric observations allow us to estimate parameters of rotation of asteroids, while $BVRI$

magnitudes provide their color indices and (in some cases) help us to estimate their taxonomy classes.

We focus on observations of the following types of asteroids: near-Earth asteroids, binary and multiple systems, asteroids named after Pulkovo astronomers, and several other types. We take part in the international campaigns for asteroid observations, like the ground-based follow-up of GAIA mission targets. A new prospective direction of our research are asteroids that are quasi-satellites of inner planets. Some of the recent results for asteroids that approached Earth are shown below.

4. ASTEROID (367943) DUENDE = 2012 DA14

The asteroid had a very close approach (27700 km) to Earth on 15.02.2013. It was a target of GAIA follow-up training observational campaign. We obtained 436 astrometric positions with the average accuracy of $0.''46$ in right ascension and $0.''23$ in declination. Three color indices were estimated from $BVRI$ observations: $B-V = 0.^m86 \pm 0.^m15$, $V-R = 0.^m39 \pm 0.^m04$, $R-I = 0.^m36 \pm 0.^m03$. Based on these values, we estimated the possible Tholen taxonomy class of Duende – either G or C.

Using EPOS, we have modelled the orbital evolution of this asteroid and got some interesting results. Duende orbits the Sun near 1:1 mean motion resonance with Earth and sometimes closely approaches the latter, which changes its orbital parameters. The latest closest approaches were in 2004 and 2013 (see Fig. 1). At the moments of approaches, orbital elements changed abruptly.

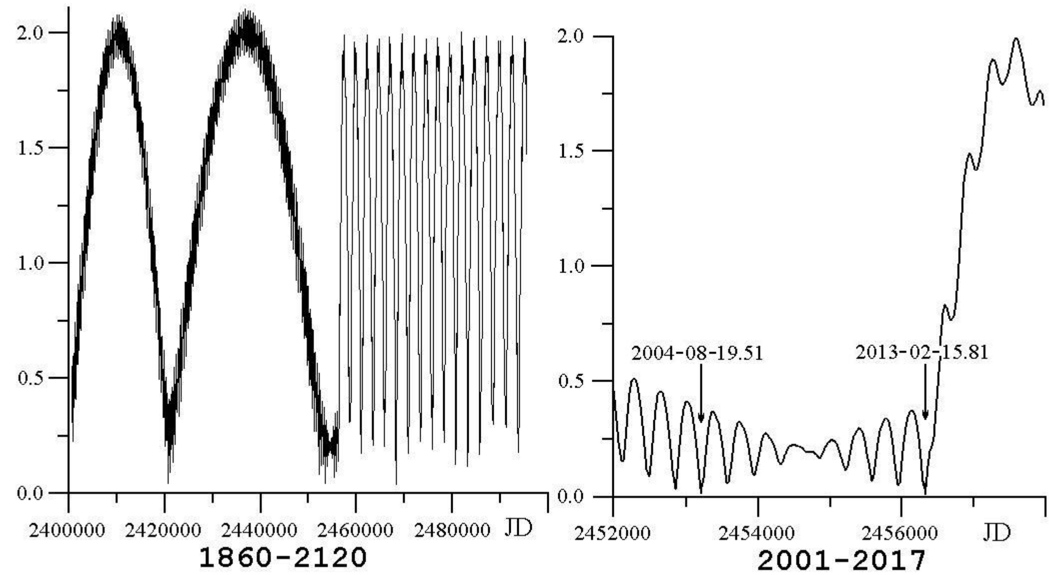

Figure 1: Geocentric distance (in AU) of Duende over 160 years (left) and on a shorter timescale (right). Arrows indicate the moments of closest approaches to Earth.

Moreover, the asteroid even changes the type of its orbit with respect to Earth. Let us use a rotating coordinate system with X axis going from Sun towards Earth. The possible types of Duende trajectory are shown in Fig. 2. However, this result is extremely sensitive to small changes in orbital elements at the initial moment of calculations. When using pre-April 2013 MPC elements, Duende changes the type of its orbit three times from circulating orbit to a horseshoe one and then (possibly) to the one of an Earth's quasi-satellite. Taking a more recent set of elements leads to the asteroid maintaining a circulating orbit, but moving in the opposite direction with respect to Earth and escaping from 1:1 resonance as a result of the 2013 approach.

We obtained two lightcurves for Duende: on February 16 and 19 2013. Each of them is about 10 hours long, which should roughly correspond to one rotation period, considering their shape. Unfortunately, these two fragments do not allow one to reliably determine the period. Comparing with lightcurves observed by other teams reveals a certain degree of coincidence. However, there are also lightcurves not overlapping with ours in time that do not match ours assuming the period of 9 to 11 hours. This is an indication of a quite complex rotation of the asteroid during approach.

We also made an attempt to model the asteroid rotation based solely on our two lightcurves, both

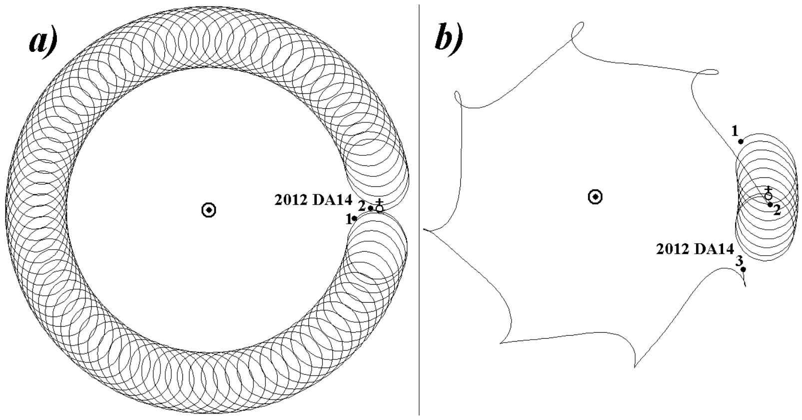

Figure 2: The possible types of Duende trajectory with respect to Earth in the rotating coordinate system: *a)* horseshoe orbit; *b)* quasi-satellite (1–2) and circulating (2–3) orbit.

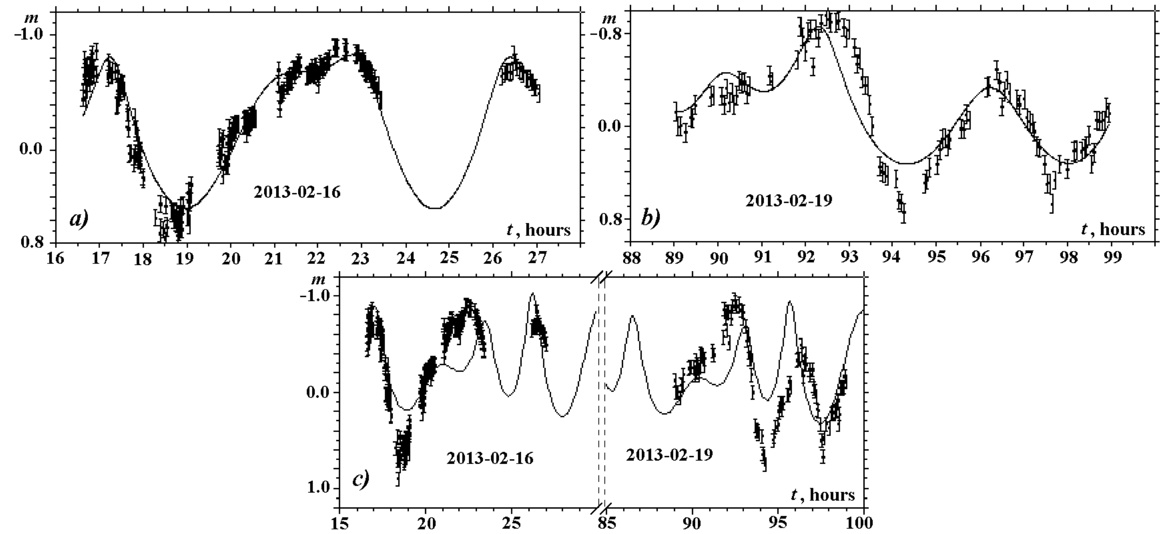

Figure 3: Model lightcurves of Duende (solid lines) superimposed over the observation data from ZA–320M and MTM–500M. *a)* and *b)* two separate datasets; *c)* lightcurve from two combined datasets.

taken separately and combined. The resulting model lightcurves and observed points are shown in Fig. 3. The modelling suggests that the ratio of "photometric" ellipsoid axes is 10:2:1, whereas the ratio of the axes of asteroid body is 4:2:1. Therefore, Duende shape greatly differs from ellipsoid and, possibly, its albedo is non-homogeneous. The axis of rotation of the asteroid has moved by 52° between these two sets of observations. Hence, Duende tumbled near the time of approach. We are currently calculating a model that incorporates all available lightcurves.

5. ASTEROID 2014 HQ124

The asteroid had a 0.0086 AU approach with Earth on 08.06.2014. It was a target of GAIA FUN SSO training campaign as well. Also, there was a sub-campaign for synchronous observations of the asteroid during its close approach for the purpose of triangulation.

We have got 84 astrometric positions from our observations, with an average accuracy of $0.''19$ in right ascension and $0.''26$ in declination. 18 positions were observed at the planned epochs simultaneously with other observatories. We also obtained lightcurves from these observations. Due to a rapid motion of the asteroid across the sky, the resulting accuracy is very moderate ($\approx 0.^{m}08$).

6. ASTEROID 2013 TV135

The asteroid had a 0.045 AU approach to Earth on 17.09.2013. Again, it was a training GAIA FUN SSO campaign target. We have obtained 335 astrometric positions from our observations, with an average accuracy of $0.''28$ in both right ascension and declination. Furthermore, we have obtained 5 lightcurves. Using their average values, we made an attempt to construct a phase curve of the asteroid and estimate its absolute magnitude and slope parameter ($G = -0.06 \pm 0.03$, $H_R = 18.^m7 \pm 0.^m2$). However, phase angle was too large ($\approx 50°$) to obtain a reliable estimate. Using our lightcurves spanning two weeks, we were able to accurately determine the rotation period of the asteroid: $P = 2.^h3512 \pm 0.^h0004$ (see Fig. 4).

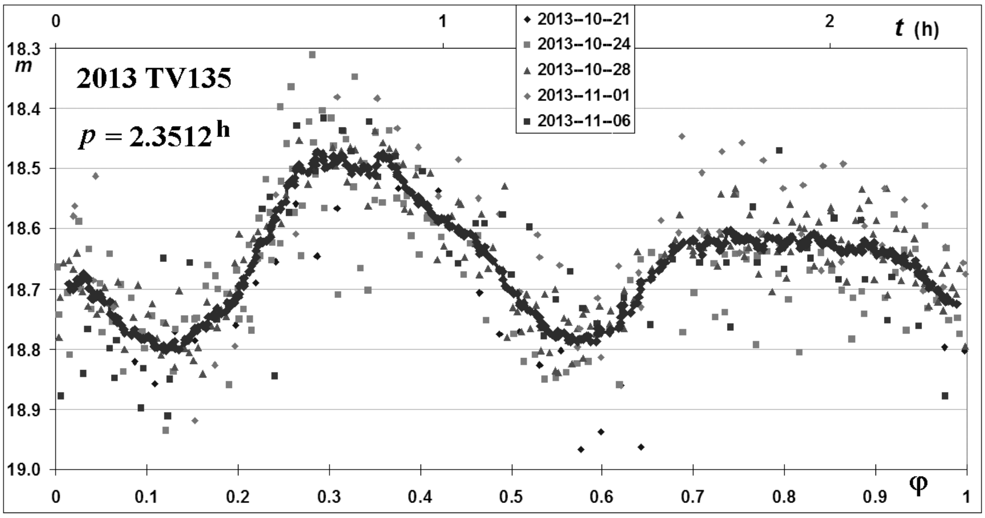

Figure 4: Lightcurve of 2013 TV135 phased with the period of $2.^h3512$ derived from our observations. It comprises 5 individual fragments obtained on MTM–500M.

7. ASTEROID 251346

The asteroid had a 0.049 AU approach to Earth on 22.01.2014. 120 astrometric positions with an average accuracy of $0.''23$ in right ascension and $0.''12$ in declination and 4 lightcurves were obtained. Unlike the previous example, here we used the known period $P = 2.^h718$ determined by other researchers (Hicks, Ebelhar, 2014; Warner, 2014) to combine the separate lightcurves. Our observations confirmed the above value.

8. REFERENCES

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