Astronomy & Astrophysics manuscript no. 13153
November 12, 2009

Photometric survey of the very small near-Earth asteroids with the SALT telescope

II. Discussion of YORP

T. Kwiatkowski[1]

Astronomical Observatory, Adam Mickiewicz University, Słoneczna 36, 60-286 Poznań, Poland

ABSTRACT

Aims. A possibility of detection of the YORP effect in the population of the very small near-Earth asteroids is discussed. It is probable that due to their significant thermal conductivity, those of the objects which are on low inclination orbits experience a continuous spin-up/spin-down without the typical YORP cycles, and their spin axes are moved towards obliquities of 0° and 180°.
Methods. For all rapidly rotating near-Earth asteroids observed with SALT, as well as other such objects for which periods are known, future observing possibilities are identified. A statistically derived, approximate relation for the YORP spin-up/spin-down is then utilized to check which of the considered asteroids can be potentially used to detect this effect.
Results. It was found that for two asteroids, 2000 HB_{24} (if successfully recovered in 2014) and 1998 KY_{26}, rotation period changes due to YORP should be detectable in the future. A determination of obliquities of two other objects, 2001 AV_{43} and 2006 XY should also be possible. For the latter constraints on its pole position are obtained suggesting a prograde rotation and the spin axis obliquity $\epsilon \leq 50°$.

Key words. techniques: photometric – minor planets, asteroids

1. Introduction

This is the second paper in the series presenting the results of the photometric survey of very small near-Earth asteroids, which was carried out from January 2007 to March 2008. Its goal was to obtain lightcurves of tens of objects and derive their rotation periods and shape elongations. A detailed description of the data reduction and analysis was presented in Kwiatkowski et al. (2009b), which reported observations of an unusual near-Earth asteroid 2006 RH_{120}. A more systematic presentation of the results of the survey was started in Kwiatkowski et al. (2009a) (hereafter Paper I), which included 14 lightcurves of very small asteroids (VSAs), with diameters of $21\ \mathrm{m} \leq D \leq 94$ m and rotation periods of $77\ \mathrm{s} \leq P \leq 44$ min. Such objects are sometimes called Monolithic Fast Rotating Asteroids (MFRAs), but we prefer to use the broader term VSAs because we used only the criterion of size in our survey (selecting targets with the absolute magnitude of $H \geq 21.5$ mag). Moreover we are not sure that all fast-rotating VSAs are monolithic pieces of rocks. Further studies of their spin limits can help in explaining the internal structure of these bodies (Holsapple 2007).

Several mechanisms have been proposed in the past to explain the fast rotation of VSAs. Being a product of collisions in the Main Belt, they could obtain their rotational kinetic energy during ejection from the parent body. A numerical simulation of an impact disruption of an asteroid (Asphaug & Scheeres 1999) suggests that it is possible for small fragments of a collision to have rapid rotations. Also post-formation, non-destructive collisions, which are relatively frequent in the Main Belt could alter the rotation rates of VSAs (Farinella et al. 1992; Farinella et al. 1998). In the case of the VSAs belonging to near-Earth asteroids (NEAs) there are two other spin altering mechanisms, which are particularly effective in the inner solar system. These are close planetary encounters (Bottke et al. 1997) and YORP (Rubincam 2000). While first attempts of explaining the rapid spins of VSAs emphasized rotational energy transfer immediately after creation during impacts (Whiteley et al. 2002; Pravec et al. 2002), recent works tend to favour YORP as the dominant mechanism responsible for extremely short periods of many VSAs (Pravec et al. 2008; Rossi et al. 2009).

The YORP effect (Rubincam 2000; Vokrouhlický & Čapek 2002) is a torque induced on the rotating asteroid by the thermal radiation emitted by its surface. It can either spin it up or slow down its rotation as well as change the obliquity of its spin axis ϵ, which is an angle between the normal to the asteroid orbital plane and its rotation axis. It should not be confused with the dihedral angle γ, also known as obliquity, showing the orientation of the asteroid spin vector with respect to the plane of the solar phase angle.

Most of the studies of the YORP effect assume zero thermal conductivity of the asteroid surface, which can be realistic for large, regolith covered bodies, but does not work well for VSAs, which have bare-rock surfaces without any insulating layer. According to Delbò et al. (2007), the average thermal conductivity k of NEAs in the km-size range is $k = 0.03 \pm 0.01\ \mathrm{Wm^{-1}K^{-1}}$ with a clear trend to increase with decreasing size. For the $D = 0.3$ km Itokawa (which is the smallest NEA for which k has been measured), thermal conductivity is larger than $k = 0.1\ \mathrm{Wm^{-1}K^{-1}}$, and for smaller asteroids it approaches $k = 1\ \mathrm{Wm^{-1}K^{-1}}$ (see Delbò et al. 2007, Fig. 6). This is consistent with recently measured thermal conductivities of the stony meteorite samples, which were found to be $k = 0.5 - 1.9\ \mathrm{Wm^{-1}K^{-1}}$ (Consolmagno et al. 2009).

Send offprint requests to: T. Kwiatkowski,
e-mail: `tkastr@vesta.astro.amu.edu.pl`

Article published by EDP Sciences and available at http://www.aanda.org
To be cited as: A&A preprint doi http://dx.doi.org/10.1051/0004-6361/200913153

The role of finite surface thermal conductivity in the YORP effect has been studied by Čapek & Vokrouhlický (2004) who found out that it can substantially change previous conclusions. Specifically, the rotation rate changes appear to be near-independent on k, while the obliquity effect increases with increasing k. To derive a statistical characterization of YORP, Čapek & Vokrouhlický (2004) generated 200 Gaussian random spheres with effective diameters of $D = 2$ km, approximating shapes of real asteroids. All of them were assigned a period of rotation of 6 h and were assumed to revolve about the Sun on circular orbits with a semimajor axis $a = 2.5$ AU and zero inclination to the ecliptic. For each object an orbit-averaged rate of change of the spin and obliquity due to YORP were computed for different surface thermal conductivities k. Results showed that for $k = 0.1\,\mathrm{Wm}^{-1}\mathrm{K}^{-1}$, spin axes of 95% of objects were driven to become perpendicular to the orbital plane (where obliquities achieved asymptotic values $\epsilon = 0^\circ$ or $\epsilon = 180^\circ$). At the same time rotation rates were accelerated and decelerated with equal probability.

Care must be taken when applying these conclusions to real asteroids because planetary perturbations can change their orbits disturbing the obliquity path towards asymptotic states. In the absence of YORP secular changes of the orbital ascending node can make the obliquity ϵ circulate with an amplitude of i (where i is the inclination of the orbit to the ecliptic plane). The timescale of such changes can be as short as $\sim$ 10 kyr, while the timescale of YORP for many VSAs can be 100 kyr or even 1 Myr. Obviously, this purely geometrical effect can be neglected for small inclination orbits.

So far YORP has been positively detected only for four near-Earth asteroids: (1862) Apollo (Kaasalainen et al. 2007; Ďurech et al. 2008b), (54509) YORP (Lowry et al. 2007; Taylor et al. 2007), (1620) Geographos (Ďurech et al. 2008a), and (3103) Eger (Ďurech et al. 2009), of which only (54509) belongs to VSAs (its diameter is about 100 m). To test our present understanding of YORP, particularly in the realm of VSAs, new observations are needed. In the next chapters we will first check which of the previously observed VSAs with periods shorter than 2.2 h will be available for studies in the near future, then discuss the possibility of detecting YORP from their lightcurves, and finally constrain the pole position of 2006 XY. The knowledge of asteroid pole coordinates is important in transforming the observed, synodic periods into sidereal ones, which evolve under YORP. What is more, if spin axes of statistically significant number of VSAs, especially those with small i, are found to be perpendicular to the planes of their orbits, this would confirm results of Čapek & Vokrouhlický (2004) about YORP effectively changing their obliquities.

2. Future apparitions

The problem with the very small NEAs is that most of them are observed as one-opposition objects. Subsequent close approaches to the Earth can happen on a time scale of several months to many decades, but even relatively frequent apparitions do not guarantee that the object will be accessible for extended studies. Many orbits of the NEAs are determined with too little accuracy to permit successful recovery during the next oppositions, and such objects are considered lost shortly after discovery. If rediscovered by any of the wide-field asteroid surveys, they can be linked back to their past apparitions and have their orbits improved so that they will not be lost again (Ted Bowell, personal communication).

In the near future new surveys will start operation, increasing our chances of rediscovering many NEAs. In the beginning of 2012 the Gaia space mission will start observations, and it should be able during its 10 years of operation to detect asteroids as faint as $V = 20$ mag (Tanga et al. 2007). The Pan-STARRS project (Jedicke et al. 2007) will go even deeper to $R = 24$ mag. The first of its four telescopes is currently at the beginning of its 3.5 year Science Mission (Chambers 2009), after which it will carry on routine observations. Similar survey to $r = 24.7$ mag will be carried out by LSST (Jones et al. 2009), which is supposed to start full science operations in 2017[1].

Because of these prospects it is reasonable to check if any of the objects described in Paper I will be passing close to the Earth in the next 20 years (June 2009 to June 2029). To make our review more complete we added other fast-rotating NEAs (with periods shorter than 2.2 h, the period reliability code $U \geq 2$ and diameters $D \leq 150$ m), taken from the LCDB (Warner et al. 2009). After removing (54509) YORP (it has already been extensively observed), 2006 RH_{120} (it is on a difficult Earth-like orbit) and 2008 TC_3 (which ended its life in the Nubian desert) we were left with 53 objects.

It was assumed that due to the rapid rotation of the considered objects successful photometry can be obtained for NEAs as faint as $V = 22$ mag, and this was the limit brightness in our search. Using the NEODyS[2] we first found, for a given asteroid, all close approaches of the nominal orbit to the Earth (at a distance $\leq$ 0.1 AU). Next, using the Minor Planet & Comet Ephemeris Service[3] (MPES) we computed a detailed ephemeris for the period of a close passage and chose the maximum brightness of the asteroid during that time.

Unfortunately, the orbits of most asteroids in our sample are known with low accuracy. To estimate the uncertainty of the calculated brightness three ephemerides were computed: for the nominal orbit, for the line-of-variation $LOV = -3\,\sigma$, and for $LOV = +3\,\sigma$. For each of them the asteroid maximum brightness was recorded even though the obtained magnitudes referred to different dates during the close approach. This gave a rough estimate of the accuracy of the results. In the case of two asteroids (2000 WN_{148} and 2000 EB_{14}) the MPES did not provide variant orbits. The OrbFit Package 3.3.2[4] was then used to compute, for each of the two objects, 100 clones, from which the $LOV = -3\,\sigma$ and $LOV = +3\,\sigma$ orbits were selected. For them, ephemerides for the dates of close passages were obtained and maximum magnitudes selected. For the sake of consistency of the results it was checked that the computations with the OrbFit gave the same magnitudes as those from MPES (for the test objects, for which MPES provided variant orbits).

Table 1 lists only those asteroids which were found to be observable during the next 20 years, at $V \leq 22$mag. The fourth column shows the $LOV = -3\,\sigma$ and $LOV = +3\,\sigma$ brightness, from which the uncertainty of V can be estimated.

For five asteroids, which are marked in bold, the fourth column gives similar numbers. This is because the ephemerides of these objects are known with a positional accuracy of better than 1°. It also means they will not have to be recovered.

Table 1 contains 24 out of 53 asteroids, which means that a significant number of objects belonging to the fast-rotating VSAs can potentially be recovered and observed again in the next 20 years. If we are more restrictive and accept only the

---

[1] http://lsst.org/lsst/science/timeline, last accessed 2009-07-18

[2] http://newton.dm.unipi.it/neodys/

[3] http://www.cfa.harvard.edu/iau/MPEph/MPEph.html

[4] http://adams.dm.unipi.it/orbmaint/orbfit/

Table 1. Future observing opportunities of fast rotating VSAs for which periods with $U \geq 2$ are known. Date is given in the YYYY-MM-DD order and V is the maximum asteroid brightness during the approach, computed from the nominal orbit. ΔV, given as a range, is an estimate of the brightness uncertainty, obtained from variant orbits with $LOV = \pm 3\sigma$.

Asteroid	Date	V [mag]	ΔV [mag]	Asteroid	Date	V [mag]	ΔV [mag]
2007 DD	2010-06-04	22.1	(22.1, 22.1)	2001 UF5	2016-04-05	20.1	(27.2, 26.7)
	2011-07-13	20.8	(20.8, 20.8)	2002 GD10	2017-11-02	21.9	(22.0, 21.8)
2000 WN148	2010-12-01	20.5	(18.2, 23.5)		2021-10-23	21.5	(21.7, 21.3)
2000 EB14	2011-02-23	20.2	(22.1, 24.2)		2025-10-15	21.6	(21.3, 21.8)
2008 DG4	2011-11-19	18.9	(25.8, 25.3)	2000 UO30	2017-11-12	21.0	(18.8, 22.3)
2007 TU18	2011-12-05	21.6	(23.3, 24.9)	2007 KE	2017-12-19	18.5	(22.9, 22.2)
2000 YA	2011-12-25	15.4	(15.6, 16.5)	2006 XY	2017-12-21	17.0	(14.7, 18.2)
2001 AV43	2013-11-13	18.7	(18.6, 18.9)	2007 LT	2018-06-14	20.6	(23.5, 22.0)
2001 SQ3	2014-03-07	20.7	(20.7, 20.7)	2007 RQ12	2019-09-13	18.0	(24.0, 24.8)
	2015-09-27	20.3	(20.3, 20.3)	**2004 FH**	2021-02-21	19.9	(20.0, 19.9)
	2021-03-14	18.5	(18.5, 18.5)	2007 DX40	2022 08 27	21.3	(25.8, 26.3)
	2022-10-03	21.5	(21.5, 21.5)		2026-02-25	21.4	(26.2, 26.3)
	2028-03-17	16.2	(16.2, 16.2)	1998 WB2	2024-04-02	18.8	(24.3, 23.8)
2000 HB24	2014-05-01	17.4	(16.9, 18.2)	2000 WQ148	2024 04 11	16.6	(26.1, 23.8)
	2017-06-10	20.0	(20.5, 20.3)		2026 12 12	17.5	(26.0, 27.6)
	2020-07-02	21.6	(19.2, 22.0)	**1998 KY26**	2024-05-27	20.0	(20.0, 20.0)
	2028-05-17	19.1	(17.7, 19.3)	1995 HM	2025-06-04	19.9	(20.3, 19.5)
	2029-08-06	18.8	(19.4, 18.4)	2007 VV83	2026-11-04	19.9	(19.7, 20.1)
2001 WR5	2016 01 04	19.4	(18.3, 20.5)				

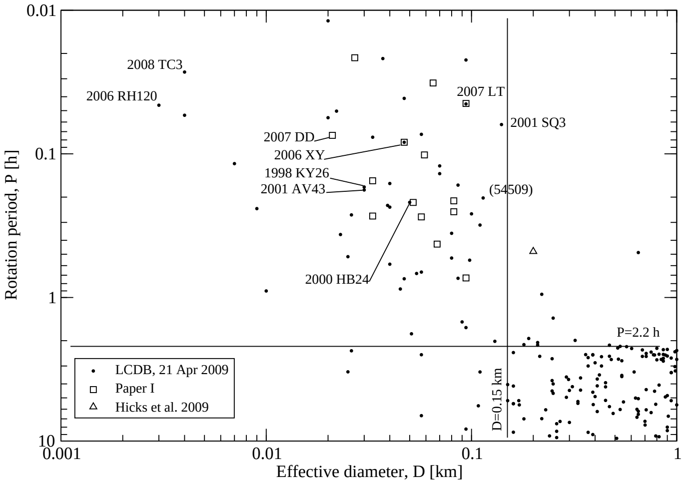

Fig. 1. Rotation periods vs effective diameters for all asteroids presented in Paper I as well as for the objects cataloged (till 21 Apr 2009) in the LCDB database. Selected objects, which are mentioned in the text, are indicated.

asteroids where the expected magnitudes (both nominal and $LOV = \pm 3\sigma$ ones) are not greater than 22 mag, we still end up with 12 potentially observable objects. This is on a level of 20%, and in the future this percentage should grow, as many more very small NEAs will be discovered and followed-up.

3. Rotation of asteroids and YORP

The rotational properties of asteroids are best visible on the $\log D$–$\log P$ plot which shows a relationship between rotation periods and sizes. In Fig. 1 we show periods (with the reliability code $U \geq 2$) for all asteroids available in the LCDB (Warner et al. 2009) as well as a newly observed $D = 200$ m near-Earth asteroid 2001 FE_{90} (Hicks et al. 2009), limiting the scope to $D < 1$ km and $P < 10$ h. It also includes new results presented in Paper I. The new points, marked by squares, fit well in the already existing cluster in the center of the plot. There are two squares and dots that coincide: one pair denotes 2006 XY, which can be found both in LCDB (the Dec 2006 data) and in our survey (the Jan 2007 lightcurves in Paper I). Another pair indicates two different asteroids: 2001 WV_1 and 2007 LT, which do have similar periods of rotation, but can be quite different in their sizes given the approximate nature of their effective diameters.

The horizontal line marks a 2.2 h spin limit for a gravitationally bound body (Pravec & Harris 2000). As can be seen, most asteroids[5] larger than about 150 m have periods longer than 2.2 h, while many VSAs display a significantly faster rotation. We will leave a more detailed analysis of this plot to the next paper in the series, where more new periods of VSAs observed with SALT will be reported, and focus on the YORP effect.

Similarly to Pravec et al. (2008) we can use the results of Čapek & Vokrouhlický (2004) to estimate the rate of the period change in the case of the fast rotating asteroids presented in Paper I. As found by Čapek & Vokrouhlický (2004), the median value of the rotation period doubling time t_d (computed at asymptotic obliquities of 0° and 180°) was 11.9 Myr (with 75% of objects having $4\,\mathrm{Myr} < t_\mathrm{d} < 16\,\mathrm{Myr}$). The period doubling time t_d can be easily scaled to smaller diameters D, shorter periods P and orbits of smaller semiaxes a using the relation: $t_\mathrm{d} \sim a^2\, D^2\, P^{-1}$, which is a consequence of the basic physics of YORP (Rubincam 2000). For our purposes it is also more convenient to replace t_d with $|\dot{P}| = P t_\mathrm{d}^{-1}$, where we use the absolute value to account for both the increase and decrease of P. Since Čapek & Vokrouhlický (2004) computed t_d for the asymptotic obliquities, where $|\dot{P}|$ is the largest, it is more realistic to replace $|\dot{P}|$ with $|\langle\dot{P}\rangle|$, which is the rate of change of the period averaged over all possible obliquities. According to numerical integrations of YORP performed by Vokrouhlicky et al. (and quoted in Pravec et al. (2008)), $|\langle\dot{P}\rangle|$ is usually 1.5-2 times lower than $|\dot{P}|$, so we will adopt $|\langle\dot{P}\rangle| \approx 0.5|\dot{P}|$.

---

[5] Recently Masiero et al. (2009) reported six Main Belt asteroids which are larger than 150 m and have spins shorter than 2.2 h, but this result, according to the authors, is still uncertain and so these objects are not presented in Fig. 1

Combining this we have:

$$t_d = 2.85 \times 10^6\ a^2 D^2 P^{-1} \mathrm{yr}, \quad (1)$$

but since $|\dot{P}| = P\, t_{\mathrm{d}}^{-1}$ and $|\langle\dot{P}\rangle| \approx 0.5\, |\dot{P}|$ we obtain:

$$|\langle\dot{P}\rangle| \approx 10^{-7}\ P^2 D^{-2} a^{-2}\ \mathrm{h/yr}, \quad (2)$$

where P is given in hours, D in kilometers and a in AU. From this equation it is evident that to make the influence of YORP independent on P it would be best to work with $|\langle\dot{P}\rangle|/P^2$. Such a parameter was used by Pravec et al. (2008), whose $|\langle\dot{f}\rangle|$ has exactly the same meaning. In other works the fractional change of P in time was used ($\Delta P/P_0$ per year) even though it depends on P. Here we will stay with $|\langle\dot{P}\rangle|$, which is the easiest to operate with in our situation.

Of course, $|\langle\dot{P}\rangle|$ suggests only the order of magnitude of the true value of $\dot{P}$ (and does not determine its sign). A slightly better approximation would be an interval bracketing $\dot{P}$. Since $|\langle\dot{P}\rangle|$ is inversely proportional to t_d and for 75% of objects 4 Myr $< t_{\mathrm{d}} <$ 16 Myr, in most cases $\dot{P}$ should lie in the interval from $2/3\, |\langle\dot{P}\rangle|$ to $3|\langle\dot{P}\rangle|$.

To check Eq. 2 we can see how well it approximates $\dot{P}$ due to YORP, determined from observations of (1862) Apollo (Ďurech et al. 2008b), (54509) YORP (Lowry et al. 2007), (1620) Geographos (Ďurech et al. 2008a), and (3103) Eger (Ďurech et al. 2009). Such a comparison is presented in Table 2, which provides the parameters necessary to compute $|\langle\dot{P}\rangle|$: the semimajor axis of the asteroid orbit a, its effective diameter D, and the rotation period P. We also list the uncertainty of P and $\dot{P}$ derived from observations. In the last column $\langle\dot{P}\rangle$ is given. As we can see, the observed values are generally not smaller than the statistically derived ones. The only exception is (54509), for which $\langle\dot{P}\rangle$ is slightly greater then $\dot{P}$. In fact, since its obliquity was found to be close to one of the asymptotic states ($\epsilon = 173°$), our estimated value $\langle\dot{P}\rangle$ should be doubled. We do not assume the knowledge of the spin axis for the discussed asteroids, however, and to treat them all on an equal basis we will use Eq. 2 to select new candidates for YORP detection.

The second part of Table 2 lists selected VSAs with already known rotation periods, which – according to Table 1 – can be potentially observed during the next 20 years (they have either good orbits or should be bright enough to allow recovery). A comparison of the rotation period accuracy σ_P with $\Delta P = \langle\dot{P}\rangle\Delta t$, where Δt is the time span, separating two apparitions, and ΔP is the estimated change of P due to YORP, allows one to judge whether the detection of YORP could be possible.

The orbit of 2007 DD is well known, which makes it possible to accurately check the observing conditions during its two future apparitions. Unfortunately during the 2010 close approach this asteroid will move along the Milky Way and will not leave it until its brightness drops to $V = 24$ mag. In 2011 the observing conditions will be much more favorable except that it will achieve the maximum brightness of $V = 20.8$ during the full moon. Also, the path on the sky will not be long enough to allow determination of the spin axis and shape. Even though $|\langle\dot{P}\rangle|$ is quite large for 2007 DD, the low accuracy of the period determined in 2007 as well as the difficulty with obtaining its spin axis in 2011 does not warrant success for YORP detection in this case.

During the 2010-2011 time span there will be close approaches of four other asteroids with known periods (see Table 1). Since their orbits are uncertain, they will have to be recovered. Given the predicted low maximum brightness during the apparitions, it is quite probable that they will pass the Earth unnoticed. The situation is better with 2000 YA, which during its 2011 apparition will reach the maximum brightness of $V = 15 - 16$ mag. Even though its ephemeris is uncertain and the exact observing circumstances cannot be checked, it is possible it will be successfully recovered. Unfortunately it is not a good candidate for YORP detection since its rotation period is known with rather low accuracy, and there will be no further close approaches in the near future.

The ephemeris of 2001 AV$_{43}$ for its 2013 apparition is accurate enough to predict that from September 2013 to March 2014 it will make a long arc on the sky which should make it possible to derive its accurate spin axis and shape. While the predicted $|\langle\dot{P}\rangle|$ is too small for a determination of the YORP spin-up/slowdown, its orbital inclination of only $i = 0.3°$ suggests YORP could have pushed its spin axis towards one of the asymptotic states. The determination of the pole position of 2001 AV$_3$ could test this hypothesis.

From 2014 to 2028 there will be five close approaches of 2001 SQ$_3$ which would make it a good candidate for YORP detection if its $|\langle\dot{P}\rangle|$ was not that small. However, there is another reason why this asteroid should be studied. On the $\log D - \log P$ plot (Fig. 1) it is located near the theoretically predicted spin limit at which rotational fission or mass shedding can happen (Holsapple 2007). While in 2015 the Milky Way will make the observations of 2001 SQ$_3$ impossible, it will be accessible for two months in 2014 and two in 2021 for extended observations at different locations on the sky. Another favorable apparition will happen in 2028. Apart from photometry it would be desirable to obtain spectra of this asteroid to determine its taxonomy and albedo.

Another asteroid in Table 1 which is close to the spin limit is 2007 LT. This object, however, needs recovery during its approach in 2018, which can be problematic due to the predicted maximum brightness of 20.6 mag and a large uncertainty of this value.

A pattern of close approaches can also be noticed in the case of 2000 HB$_{24}$. Its recovery should be possible in May 2014, when it will reach $V = 18$ mag, providing its galactic latitude is not too small (its present ephemeris is not accurate enough to check this). If successfully located, this asteroid will give us a good opportunity for YORP detection. The change of the rotation period due to YORP during 15 years should reach $\simeq 50 \times 10^{-6}$ h, which should be easy to measure. Subsequent apparitions will make it possible to obtain an accurate spin axis and shape. Since the orbital inclination of 2000 HB$_{24}$ is only $i = 3°$, chances are its spin axis may be close to one of the asymptotic states.

2006 XY will come back in 2017, eleven years after the first photometric observations in December 2006. Since its brightness at this time will be $V = 15 - 18$ mag, there should be no problem with its recovery. New photometric data combined with two lightcurves from Dec 2006 (Hergenrother et al. 2009) and Jan 2007 (Paper I) should allow to refine the approximate pole position obtained so far (see Sec. 4 in this paper), remove ambiguity from the already known rotation period and allow the translation of synodic periods into sidereal ones. During eleven years YORP should alter the sidereal period by about 10^{-6} h – a value comparable to $3\,\sigma$ accuracy, with which the period of 2006 XY has been obtained from the 2006/2007 apparition. Even if during the 2017 opposition the period is determined with higher accuracy, it may not be possible to detect YORP by comparing the 2006/2007 and 2017 results. It should be feasible, however, to check if its obliquity ϵ is close to one of the asymptotic states (the orbital inclination of 2006 XY is $i = 4°$).

In Table 1 there is also an asteroid (2004 FH) that displays a non-principal axis rotation. It will be observable at $V \leq 20$ mag during one week in February 2021. Because of its tumbling rotation it cannot be used for YORP detection nor determination of spin axis/shape.

In 2024 there will be a close approach of 1998 KY_{26} – an asteroid for which a good ephemeris is known and rotation period of which has been accurately determined. In fact, 1998 KY_{26} will pass the Earth even earlier, in 2013, but then its maximum brightness is estimated to be only $V = 23.4$ mag. At this time it will be observable twice: during the dark time in March ($V = 24$ mag) and in October ($V = 23.7$ mag). In the meantime it will be either fainter or close to the Galactic center. Given the short, 10 min rotation period of 1998 KY_{26}, it will be a very difficult object for successful photometric observations in 2013 – even with a 8-10 m telescope.

Čapek & Vokrouhlický (2004) computed the YORP effect for 1998 KY_{26}, using its radar shape, but not knowing the pole position they could only give the value averaged over all obliquities, which is $\langle \dot{P} \rangle = \pm 5 \times 10^{-6}$ h/yr. It is close to the result which was obtained from Eq. 2 and listed in Table 2. Čapek & Vokrouhlický (2004) concluded that the 2024 apparition of 1998 KY_{26}, brightness of which should then reach $V = 20$ mag, will give us a good opportunity to measure YORP because the change of the rotation period from 1998 to 2024 should amount to 10^{-4} h. However, the observations during this apparition will not be easy. The asteroid will cross the Galactic center and will then pass close to the Moon. After a short period of observability at the beginning of June 2024 (about 10 days) it will approach the Sun. Still, the arc of 60° on the sky should make it possible to determine its spin axis, which should not be difficult because of its known shape.

From the presented review it is evident that there are only two VSAs with known periods for which a detection of YORP during the next 20 years can be expected: 1998 KY_{26} and, if recovered, 2000 HB_{24}. For both of them, as well as for 2001 AV_{43} and 2006 XY, it should also be possible to derive the obliquity ϵ. On the other hand, a thorough study of 2001 SQ_3 would be desirable, including the spectroscopic characterization of its surface.

A special group of NEAs, that were not mentioned yet, are Earth co-orbitals. They sometimes visit the Earth every year for about a decade. (54509), for which YORP has been successfully measured, belongs to this group. Some of them can transfer to a quasi-satellite (QS) orbit in the vicinity of the Earth. Currently there are two quasi-satellite asteroids which are small enough to be regarded as VSAs (given a natural uncertainty of the effective diameters). These are (164207) 2004 GU_9 ($D = 0.18$ km) and 2006 FV_{35} ($D = 0.15$ km). Quite coincidentally, both of them approach the Earth every year in March and display a similar maximum brightness of about 20.5 mag). Contrary to some other Earth co-orbitals, they will remain on QS orbits for the next thousand years (Wajer 2008), which makes them good targets for extended observations. Their spins are not known, but most asteroids of such diameters rotate with periods longer than 2 h (Fig. 1). This means they require longer observing runs for an accurate spin determination.

4. Spin axis of 2006 XY

Determination of the spin axis and shape of asteroids from photometry traditionally requires at least three lightcurves obtained at different observing geometries. So far, for asteroids smaller than $H = 21.5$ mag, only one object has its spin axis determined. It is (54509) YORP, whose physical model is based on combined radar and optical observations (Taylor et al. 2007). So far no other VSA with a known rotation period was observed photometrically in the past at more than one position in the sky. In this situation 2006 XY is a notable exception and even though it has been observed photometrically at only two, instead of three, geometries, its lightcurves can be used to constrain the position of its rotation pole.

A generic method to derive poles and shapes by means of a lightcurve inversion has been presented by Kaasalainen et al. (2001) and Kaasalainen et al. (2002). It uses all lightcurve points and is able to derive a detailed shape of the asteroid. There are simpler algorithms, however, which give similar results in case of the spin axis position and require less input data. These so-called epoch-amplitude methods use lightcurve amplitudes and timings of the lightcurve extrema to obtain the sidereal period of rotation, pole coordinates and a triaxial ellipsoid shape, that best approximates the asteroid body. While the shape derived in this way is a rough approximation of the asteroid body (and is sometimes referred to as a *photometric shape*), the period and pole position are obtained with good accuracy. A side-by-side application of the lightcurve inversion and the epoch-amplitude methods can be found in Kaasalainen et al. (2003), where the model of a (25143) Itokawa is presented. The sidereal period and the pole position of the asteroid obtained with both methods were the same within the formal uncertainties.

In order to constrain the pole position of 2006 XY we used an epoch-amplitude method described in Kwiatkowski (1995). The input data were based on two lightcurves: the first from 16 Dec 2006 (Hergenrother et al. 2009) and the second, being a composite of three nights, from 12-19 Jan 2007 (Fig. 4 in Paper I). The average amplitudes of these lightcurves were 0.95 ± 0.1 mag and 0.8 ± 0.1 mag, respectively, and the (light-time corrected) time span between them was $\Delta T_1 = 27.91744 \pm 0.00005$ d (or $\Delta T_2 = 27.91918 \pm 0.00005$ d if the first maximum on the 16 Dec lightcurve was assumed to be identical with the second maximum on the 12-19 Jan lightcurve).

In its original form the epoch-amplitude method uses a model with five parameters: the sidereal period of rotation $P_{\rm sid}$, the ecliptic coordinates of the pole $\lambda_{\rm p}, \beta_{\rm p}$ and the shape of the triaxial ellipsoid a/b and b/c, rotating about the shortest c axis. In case of 2006 XY we first used the amplitude part of the algorithm, scanning the whole celestial sphere with trial poles and at each step adjusting the a/b parameter of the model shape so that the χ^2_A was minimum (χ^2_A was obtained as a sum of the squared residuals in amplitudes divided by $\sigma^2_A = 0.01 \mathrm{mag}^2$). The b/c parameter was kept constant at 1.1, as it weakly influences model amplitudes. Results are presented in Fig. 2C, which shows selected isolines of the χ^2_A value (χ^2_A=1,2,5) for different trial pole ecliptic coordinates. As can be seen, there are two large, symmetric areas in the sky, where the asteroid pole can be located. There are also another two small regions at the opposite ecliptic latitudes, which are close to the ecliptic pole. Thus far the conclusion can be drawn that the observed amplitudes suggest the spin axis of 2006 XY is closer to the ecliptic pole than to the ecliptic plane.

The search for the asteroid pole was repeated using the epoch part of the algorithm. This was possible because the accuracy of two solutions for the synodic period of 2006 XY, obtained in Paper I (see Table 2) was high enough to compute unambiguously the number of asteroid rotations between Dec 2006 and Jan 2007. It was also found that a difference between the syn-

Table 2. Period changes due to YORP for selected asteroids. a is the orbital semimajor axis and D denotes the effective diameter. For the first four objects P is the sidereal period of rotation, while for the rest it is a synodic one. σ_P is a standard deviation of P, $\dot{P}$ is the observed rate of change of P, while $\langle\dot{P}\rangle$ is a theoretically predicted, approximate rate of change of P.

Asteroid	a	D	P	σ_P	$\dot{P}$	$\langle\dot{P}\rangle$
	[AU]	[km]	[h]	10^{-6} [h]	10^{-6} [h/yr]	10^{-6} [h/yr]
(1620) Geographos	1.2	2.5	5.223336	2	−0.75	±0.3
(1862) Apollo	1.5	1.4	3.065447	3	−1.2	±0.2
(3103) Eger	1.4	2.5	5.710150	6	−0.7	±0.3
(54509) YORP	1.0	0.1	0.20290046	0.01	−0.3	±0.4
2007 DD	1.0	0.02	0.07429	70	—	±1
1998 KY_{26}	1.2	0.03	0.1783583	7	—	±2
2006 XY	1.5	0.05	0.0829783	0.3	—	±0.1
			0.0831226	0.4	—	
2000 HB_{24}	0.8	0.05	0.2176	600	—	±3
2000 YA	2.4	0.06	0.6658	100	—	±2
2001 AV_{43}	1.3	0.03	0.1701	500	—	±2
2001 SQ_3	1.1	0.14	0.06248	50	—	±0.02

odic and sidereal period of rotation should not be greater than the accuracy of the derived synodic period.

During a scan over the celestial sphere, at each trial pole the sidereal period of rotation was adjusted. At the start we took the first solution for the sidereal period of 2006 XY, and assumed that its true period should not differ by more than $\pm 3\sigma$ from it. This was a rather week constraint on the pole coordinates and limited the spin axis position to a large area on the sky. Fig. 2A shows a plot of χ^2_E isolines (drawn at $\chi^2_E = 1, 2, 5$ obtained from the squared residuum in the time span ΔT divided by $\sigma^2_E = 2.5 \times 10^{-9}$ d^2). Interestingly, a very similar plot was obtained when the second solution for the period of 2006 XY was used (Fig. 2B).

The final plot in Fig. 2D shows results of the simultaneous fit in amplitudes and epochs and was obtained by superposition of Fig. 2A and Fig. 2C (this was possible because both χ^2_A and χ^2_E were related to the standard deviations of the amplitudes and the time span, respectively). As a result only one region was obtained where the asteroid pole can be located. It indicates the prograde rather than retrograde sense of the rotation and suggests the ecliptic coordinates $\lambda_\mathrm{p}, \beta_\mathrm{p}$ of the spin axis of 2006 XY are, approximately, $30° < \lambda < 160°$ and $40° < \beta < 90°$. The ecliptic coordinates λ_o,β_o of the pole of the orbit of 2006 XY about the Sun can be easily obtained as $\lambda_\mathrm{o} = \Omega + 270°$ and $\beta_\mathrm{o} = 90° - i$, where $\Omega = 258°$ is the longitude of the ascending node and $i = 4°$ is the inclination of the orbit to the ecliptic. The pole of the orbit is thus located at $\lambda_\mathrm{o} = 166°, \beta_\mathrm{o} = 86°$ which is well inside of the solution area in Fig. 2D. It also means the obliquity of 2006 XY is $\epsilon \leq 50°$. If we assume the rapid rotation of 2006 XY is due to YORP, then the same effect should also influence the asteroid obliquity moving its spin axis towards one of the poles of its orbit. It is thus possible that the true pole of 2006 XY is not far from λ_o,β_o. This possibility can be used when planning new observations of 2006 XY in 2017.

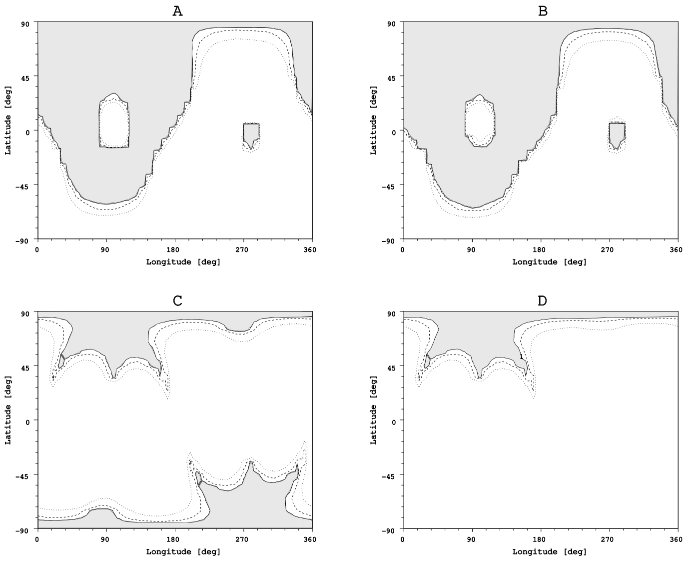

Fig. 2. Constraints on the pole position of 2006 XY. Two upper plots (A and B) were obtained from the epochs method, the lower-left plot (C) was obtained from the amplitude method and the lower-right plot (D) is the result from the simultaneous fit in both epochs and amplitudes. The continuous lines refer to $\chi^2 = 1$, the dashed lines mark the $\chi^2 = 2$ area, while the dotted lines refer to $\chi^2 = 5$.

5. Conclusions

The photometric survey of very small near-Earth asteroids with the SALT telescope extended the database of the known fast-rotating VSAs by 14 new objects (including the unusual asteroid 2006 RH_{120}, not discussed in Paper I), and there are currently 56 of them known (not counting 5 VSAs discovered in the Main Belt). Their studies are difficult because many of them are not available for observations during several apparitions. Future wide-field surveys like Gaia, Pan-STARRS and LSST can discover many new objects in this class and help determine their accurate orbits by the follow-up observations, but even now there are VSAs which will come close to the Earth in the near future. While there are several reasons why VSAs should be observed (one of them are their spin limits, which are connected with their internal structure), the detection of YORP is particularly dependent on frequent close approaches.

Presently there are two fast-rotating VSAs, for which changes of their periods, due to YORP, should be detectable in the near future. 2000 HB_{24}, if recovered in 2014, will present a sequence of close approaches during the next 20 years, during which the change of period due to YORP should be detectable. 1998 KY_{26}, for which a radar shape is already known, will be observable in 2024 and provide another opportunity for the study of YORP. For other VSAs with known short periods, which will be recovered during their close approaches to the Earth, a detection of period changes due to YORP can be very difficult or impossible. However, their observations, if well planned, can result in the determination of their spin axes. This has already been done in the case of (54509) and, preliminary, for 2006 XY. The obliquity of (54509) was found to be $\epsilon = 173^{\circ}$, and for 2006 XY it is less than 50°. If obliquities of more fast-rotating VSAs are found to be close to the asymptotic values this will provide an independent prove of YORP at work as it was already done in the case of the spin vector alignment of the Koronis family asteroids (Vokrouhlický et al. 2003).

There is one more asteroid that should draw attention. 2001 SQ_3 is close to the theoretically predicted spin limit and will be observable during apparitions in 2014, 2021 and 2028. Both photometric and spectroscopic observations of this object would then be desirable to help determine its spin axis, shape, albedo, size and taxonomic type.

Acknowledgements. The author would like to thank Ireneusz Włodarczyk for his help in computing ephemerides for the asteroids. A referee, David Vokrouhlický, made helpful comments which improved the paper. This research made extensive use of the Minor Planet Ephemeris Service, the Horizons System, and NEODyS.

References

Asphaug, E. & Scheeres, D. J. 1999, Icarus, 139, 383
Bottke, W. F., Richardson, D. C., & Love, S. G. 1997, Icarus, 126, 470
Chambers, K. C. 2009, BAAS, 213, 270
Consolmagno, G., Opeil, C. P., & Britt, D. T. 2009, in AAS/Division for Planetary Sciences Meeting Abstracts, Vol. 41, 50.05
Delbò, M., Dell'Oro, A., Harris, A. W., Mottola, S., & Mueller, M. 2007, Icarus, 190, 236
Farinella, P., Davis, D. R., Paolicchi, P., Cellino, A., & Zappala, V. 1992, A&A, 253, 604
Farinella, P., Vokrouhlický, D., & Hartmann, W. K. 1998, Icarus, 132, 378
Hergenrother, C. W., Whiteley, R. J., & Christensen, E. J. 2009, Minor Planet Bulletin, 36, 16
Hicks, M., Lawrence, K., Rhoades, H., et al. 2009, The Astronomer's Telegram, 2116, 1
Holsapple, K. A. 2007, Icarus, 187, 500
Jedicke, R., Magnier, E. A., Kaiser, N., & Chambers, K. C. 2007, Proceedings of the International Astronomical Union, 2, 341
Jones, R., Chesley, S., Connolly, A., et al. 2009, Earth, Moon, and Planets, 105, 101
Kaasalainen, M., Kwiatkowski, T., Abe, M., et al. 2003, A&A, 405, L29
Kaasalainen, M., Torppa, J., & Muinonen, K. 2001, Icarus, 153, 37
Kaasalainen, M., Torppa, J., & Piironen, J. 2002, Icarus, 159, 369
Kaasalainen, M., Ďurech, J., Warner, B. D., Krugly, Y. N., & Gaftonyuk, N. M. 2007, Nature, 446, 420
Kwiatkowski, T. 1995, A&A, 294, 274
Kwiatkowski, T., Buckley, D. A. H., O'Donoghue, D., et al. 2009a, A&A, submitted
Kwiatkowski, T., Kryszczynska, A., Polinska, M., et al. 2009b, A&A, 495, 967
Lowry, S. C., Fitzsimmons, A., Pravec, P., et al. 2007, Science, 316, 272
Masiero, J., Jedicke, R., Ďurech, J., et al. 2009, Icarus, 204, 145
Pravec, P. & Harris, A. W. 2000, Icarus, 148, 12
Pravec, P., Harris, A. W., & Michalowski, T. 2002, Asteroids III, 113
Pravec, P., Harris, A. W., Vokrouhlický, D., et al. 2008, Icarus, 197, 497
Rossi, A., Marzari, F., & Scheeres, D. J. 2009, Icarus, 202, 95
Rubincam, D. P. 2000, Icarus, 148, 2
Tanga, P., Delbò, M., Hestroffer, D., Cellino, A., & Mignard, F. 2007, Advances in Space Research, 40, 209
Taylor, P. A., Margot, J., Vokrouhlický, D., et al. 2007, Science, 316, 274
Čapek, D. & Vokrouhlický, D. 2004, Icarus, 172, 526
Ďurech, J., Vokrouhlický, D., Kaasalainen, M., et al. 2008a, A&A, 489, L25
Ďurech, J., Vokrouhlický, D., Kaasalainen, M., et al. 2008b, A&A, 488, 345
Ďurech, J., Vokrouhlický, D., Polishook, D., et al. 2009, in AAS/Division for Planetary Sciences Meeting Abstracts, Vol. 41, 56.04
Vokrouhlický, D., Nesvorný, D., & Bottke, W. F. 2003, Nature, 425, 147
Vokrouhlický, D. & Čapek, D. 2002, Icarus, 159, 449
Wajer, P. 2008, LPI Contributions, 1405, 8122
Warner, B. D., Harris, A. W., & Pravec, P. 2009, Icarus, 202, 134
Whiteley, R. J., Tholen, D. J., & Hergenrother, C. W. 2002, Icarus, 157, 139