LIGHTCURVES AND SPIN RATES OF EARTH CO-ORBITAL ASTEROIDS

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We present photometric optical lightcurves and derived rotation periods for a sample of seven Earth co-orbital asteroids: 2008 WM64 (2.356 ± 0.033 h), 2016 AU8 (4.698 ± 0.013 h), 2000 EE104 (13.324 ± 1.135 h), 2018 EB (2.600 ± 0.437 h), 2014 KZ44 (2.797 ± 0.596 h), 2016 JP (3.288 ± 0.224 h), and 2014 KQ76 (2.953 ± 0.063 h). These observations were carried out at the Bulgarian National Astronomical Observatory - Rozhen using the FoReRo2 instrument attached on the 2mRCC telescope.

Asteroids co-orbital with the Earth - broadly defined as those with an average heliocentric distance of 1 au - present special challenges to surveys. Because of the very slow net Earth-relative motion from one revolution to the next, they can remain far from our planet and close to the Sun's location in the sky for many decades. As a result, observational completeness for this type of orbit is generally lower than for other near-Earth asteroids (Tricarico, 2017). When an object of this type is discovered, it typically offers a few brief annually-recurring apparitions when it is bright enough to allow physical characterisation. Afterwards, the accumulated Keplerian drift will place it out of reach of observational scrutiny for many decades hence.

Photometric observations of selected Earth co-orbital asteroids were carried out from the Bulgarian National Astronomical Observatory - Rozhen. We used the Focal Reducer Rozhen or “FoReRo2” instrument attached on the 2-m RCC telescope. The asteroid targets and their observational circumstances are presented in Table 1.

The data were reduced by applying standard bias and flat-field corrections followed by aperture photometry to produce the lightcurve for each object shown in Fig. 1. To determine their periods and amplitudes, we fit the lightcurves from single or multiple nights to Fourier series of different orders, typically between 3 and 5, using Levenberg-Marquardt nonlinear least-squares minimisation (Press et al., 1992) and assuming a double-peaked lightcurve. Zero-point offsets for different nights and different filters were included as free parameters in the fit to allow us to adjust more precisely the different parts of the lightcurves and determine more accurately the amplitude. A refined period search was then performed over a narrow range around the initial solution to estimate more accurately the period. In the following, we present an object-by-object analysis of our photometric data.

<u>(418849) 2008 WM64</u> (H=20.6) is an Apollo asteroid. It has a previously published rotation period of P=2.40 ± 0.02 h (Rowe, 2018; Warner, 2018a). Our analysis of the new observations shows a period of P=2.356 ± 0.033 h, consistent with the previous estimate given the statistical uncertainty. The $\chi 2$ period search clearly shows only one minimum suggesting a unique period solution from our data.

<u>(512245) 2016 AU8</u> (H=19.9) is an Aten asteroid with a previously published rotation period of P=4.516 ± 0.002 h (Warner and Stephens, 2019a). Our analysis of the new observations yields a period of P=4.698 ± 0.013 h. The new solution has a small uncertainty even though it is based on partial lightcurve coverage and is slightly longer than the previous estimate. The $\chi 2$ period search shows only one minimum which again suggests a unique period solution.

<u>(138175) 2000 EE104</u> (H=20.4) is an Apollo asteroid suspected to have boulders with diameters of larger than 10 m distributed along its orbit (Lai et al., 2017). Jewitt (2020) finds no evidence for co-moving companions or a dust particle trail and report a B-V colour of 1.16 ± 0.04 which they interpret as intermediate between C-class and S-class asteroids. The mean B-R colour is consistent with that measured for Jovian Trojan and D-type asteroids. Asteroids can shed material from their surface and onto heliocentric orbit if they rotate once every few hours or faster (Pravec et al., 2010; Jacobson and Scheeres, 2011). Here we obtained a rotational period of P=13.324 ± 1.135 h using data from 3 observing nights in 2018 and 2019. We employed the period search routine within the DAMIT software package (Durech et al., 2010) to combine observations from the different nights taking into account the mutual positions of the Sun, the Earth and the object for each individual measurement. The obtained period for this object is quite slow and far from the spin-barrier (Pravec and Harris, 2000), and it is therefore unlikely that spin-induced mass shedding due to the asteroid’s present rotational state is responsible for any existing orbit-sharing material.

Number	Name	yyyy mm/dd	Phase	L_{PAB}	B_{PAB}	Period(h)	P.E.	Amp	A.E.	Grp
418849	2008 WM64	2017 12/25	36.9	96	19	2.356	0.033	0.62	-	APO
512245	2016 AU8	2018 01/19	42.5	90	6	4.698	0.013	0.39	-	ATE
138175	2000 EE104	2018 11/09	66.3	100	8	-	-	-	-	APO
138175	2000 EE104	2019 01/01	19.5	108	14	-	-	-	-	APO
138175	2000 EE104	2020 01/02	17.9	104	14	13.324	1.135	0.82	-	APO
	2018 EB	2018 10/06	75.6	52	-10	2.600	0.437	-	-	APO
468909	2014 KZ44	2019 05/30	47.0	254	43	2.797	0.596	-	-	ATE
522684	2016 JP	2020 04/25,27	53.3	240	21	3.288	0.224	0.23	-	ATE
468910	2014 KQ76	2020 04/25	44.7	228	25	2.953	0.063	0.12	-	APO

Table I. Observing circumstances and results. The phase angle is given for the first date. $\mathbf{L_{PAB}}$ and $\mathbf{B_{PAB}}$ are the approximate phase angle bisector longitude/latitude at mid-date range (see Harris et al., 1984). **Grp** is the asteroid family/group (APO-Apollo, ATE-Aten).

2018 EB (H=21.9) is an Apollo asteroid. It has a previously published rotation period of P=3.16 ± 0.01 h (Warner and Stephens, 2019b). Our analysis of the new observed lightcurve shows a period of P=2.600 ± 0.437 h. This is based on partial lightcurve coverage which, together with the large scatter in the data, is responsible for the relatively high uncertainty. Nevertheless, the $\chi 2$ period search shows only one deep minimum which suggests a unique solution for the period.

(468909) 2014 KZ44 (H=20.4) is an Aten asteroid with no previously published rotation period. Our analysis of the new photometric data shows a period of P=2.797 ± 0.596 h. The large uncertainly is due to high photometric scatter as well as less-than-full lightcurve coverage. Its $\chi 2$ period search shows one single-peaked solution but a poorly-defined double-peaked solution. Here we present the double-peaked lightcurve obtained from the Fourier fitting routine.

(522684) 2016 JP (H=21.1) is a small Aten-class asteroid. There are two series of observations published previously which yielded quite different rotation periods. The first photometric observations suggested a very long period of 37.4 ± 0.1h (Warner, 2018b) but more recent observations (Pravec, 2019) yield a much shorter period, 3.2905 ± 0.0003h. Our observations show a period of P=3.288 ± 0.224h thus strongly supporting the latter estimate. The $\chi 2$ period search shows multiple minima between values of 3 and 5 h. We chose the optimal solution by visual inspection of all individual lightcurves with different period solutions and by using as criteria the better overlapping of the different nights for a double-peaked lightcurve.

(468910) 2014 KQ76 (H=21.5) is an Apollo asteroid. It has no previously published rotation period. Our analysis of the new observations shows a period of P=2.953 ± 0.063 h. The $\chi 2$ period search shows only one deep minimum which suggests a unique solution from our data.

Acknowledgements

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References

Durech, J.; Sidorin, V.; Kaasalainen, M. (2010). "DAMIT: a database of asteroid models." *A&A* **513**, A46.

Harris, A.W.; Young, J.W.; Scaltriti, F.; Zappala, V. (1984). "Lightcurves and phase relations of the asteroids 82 Alkmene and 444 Gyptis." *Icarus* **57**, 251-258.

Jacobson, S.A.; Scheeres, D.J. (2011). "Dynamics of rotationally fissioned asteroids: Source of observed small asteroid systems." *Icarus* **214**, 161-178.

Jewitt, D. (2020). "138175 (2000 EE104) and the source of interplanetary field enhancements." *The Planetary Science Journal* **1**, 33.

Lai, H.R.; Russell, C.T.; Wei, H.Y.; Connors, M.; Delzanno, G.L. (2017). "Possible potentially threatening co-orbiting material of asteroid 2000EE104 identified through interplanetary magnetic field disturbances." *Meteoritics and Planetary Science* **52**, 1125-1132.

Pravec, P.; Harris, A.W. (2000). "Fast and slow rotation of asteroids." *Icarus* **148**, 12-20.

Pravec, P. and 25 colleagues (2010). "Formation of asteroid pairs by rotational fission." *Nature* **466**, 1085-1088.

Pravec, P. (04.06.2019). Ondrejov Asteroid Photometry Project. *http://www.asu.cas.cz/~ppravec/newres.txt*

Press, W.H.; Teukolsky, S.A.; Vetterling, W.T.; Flannery, B.P. (1992). "Nonlinear Models." In *Numerical recipes in C. The art of scientific computing*, 681–688. Cambridge University Press, New York.

Rowe, B. (2018). *Minor Planet Bull.* **45**, 292-294.

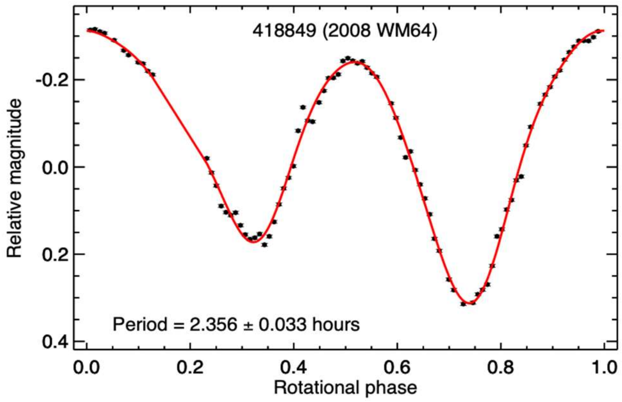
Tricarico, P. (2017). "The Near-Earth asteroid population from two decades of observations." *Icarus* **284**, 416–423.

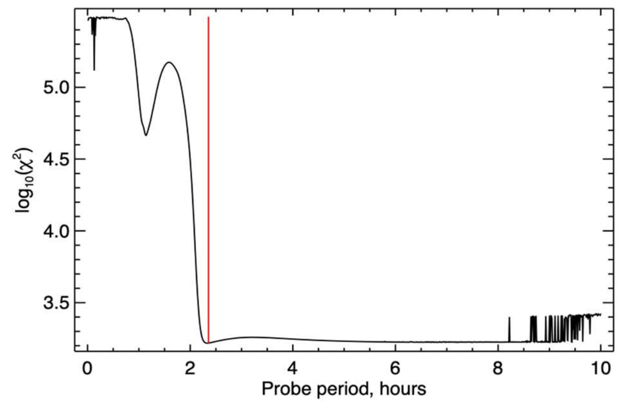
Warner, B.D. (2018a). *Minor Planet Bull.* **45**, 138-147.

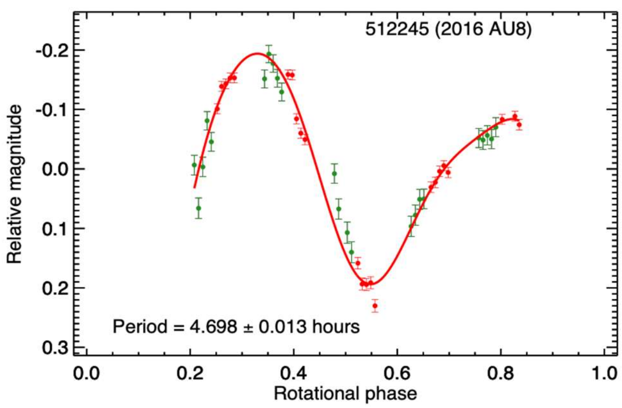
Warner, B.D. (2018b). *Minor Planet Bull.* **45**, 366-379.

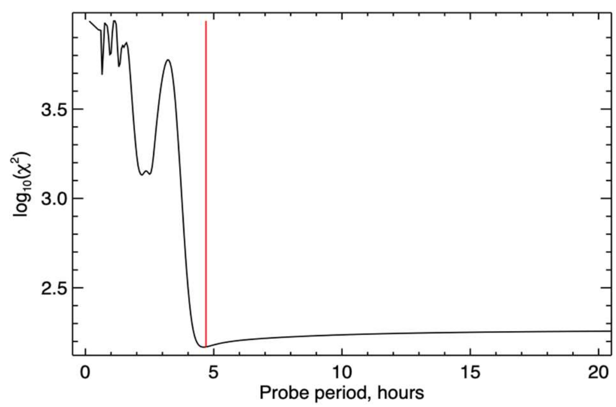
Warner, B.D.; Stephens, R.D. (2019a). *Minor Planet Bull.* **46**, 144-152.

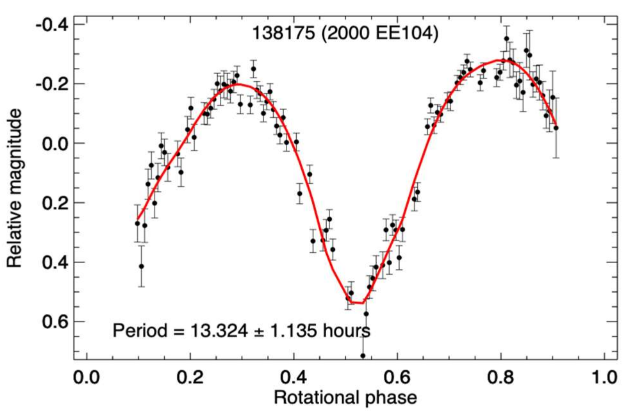
Warner, B.D.; Stephens, R.D. (2019b). *Minor Planet Bull.* **46**, 423-438.

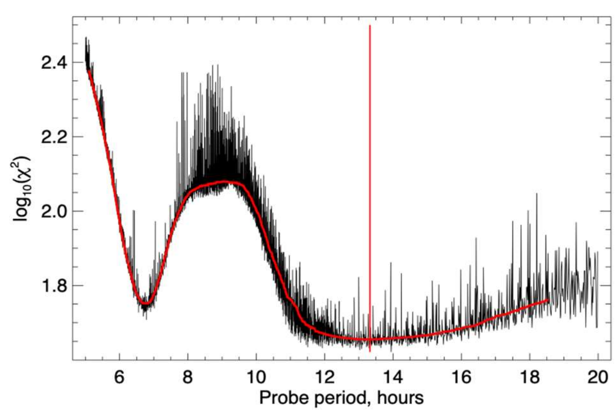

418849 (2008 WM64)
Period = 2.356 ± 0.033 hours
Relative magnitude
Rotational phase

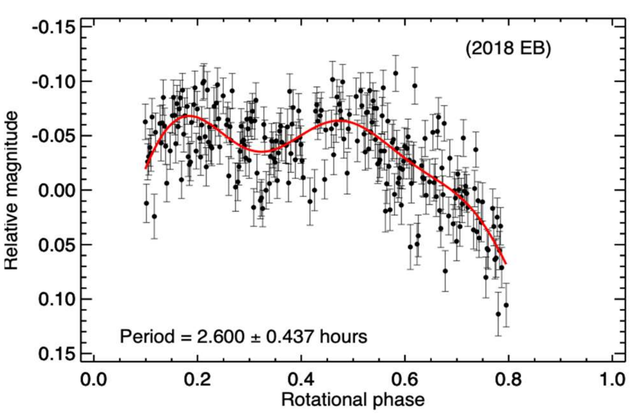

$\log_{10}(\chi^2)$
Probe period, hours

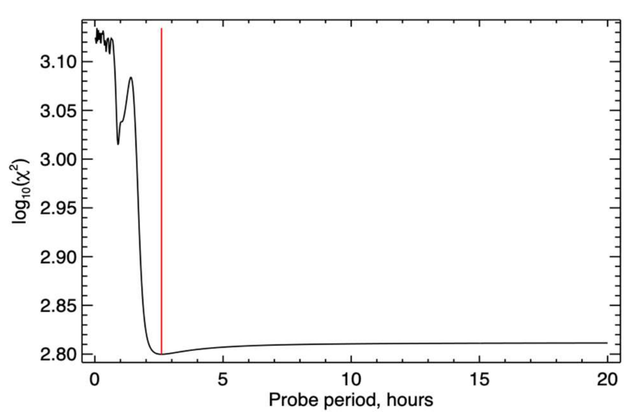

512245 (2016 AU8)
Period = 4.698 ± 0.013 hours
Relative magnitude
Rotational phase


$\log_{10}(\chi^2)$
Probe period, hours


138175 (2000 EE104)
Period = 13.324 ± 1.135 hours
Relative magnitude
Rotational phase


$\log_{10}(\chi^2)$
Probe period, hours


(2018 EB)
Period = 2.600 ± 0.437 hours
Relative magnitude
Rotational phase


$\log_{10}(\chi^2)$
Probe period, hours

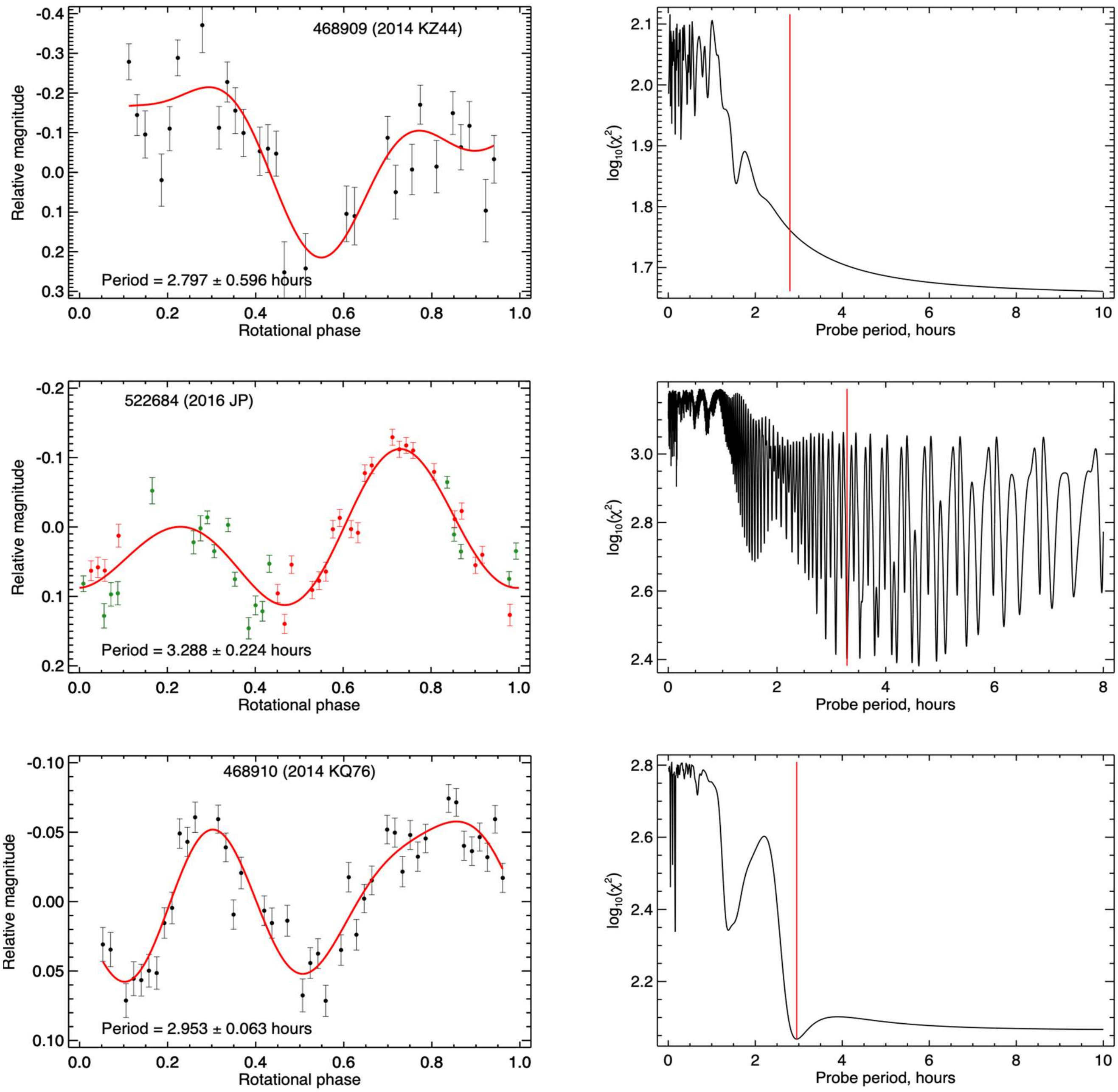


Figure 1: ***The left column*** presents the lightcurves of observed Earth co-orbitals asteroids. Different colours represent data obtained on different nights except for 2016 AU8 where they represent different filters - Sloan g′ and r′. The Fourier fit is presented with a red line. For 2000 EE104 we present the observations only for one night (2020 01/02) with the fit computed using all 3 nights. ***The right column*** presents the χ^2 period search. The preferred solution is marked with a vertical red line. For 2000 EE104 we did running average smoothing and found the global minimum of the χ^2 hence the solution of the period.