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A survey of small fast rotating asteroids among the near-Earth asteroid population

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ABSTRACT

A survey of 62 small near-Earth asteroids was conducted to determine the rotation state of these objects and to search for rapid rotation. Since results for 9 of the asteroids were previously published (Pravec, P., Hergenrother, C.W., Whiteley, R.J., Šarounová, L., Kušnirák, P., Wolf, M. [2000]. Icarus 147, 477–486; Pravec, P. et al. [2005] Icarus 173, 108–131; Whiteley, R.J., Tholen, D.J., Hergenrother, C.W. [2002a]. Icarus 157, 139–154; Hergenrother, C.W., Whiteley, R.J., Christensen, E.J. [2009]. Minor Planet Bull. 36, 16–18.), this paper will present results for the remaining 53 objects. Rotation periods significantly less than 2 h are indicative of intrinsic strength in the asteroids, while periods longer than 2 h are typically associated with gravitationally bound aggregates. Asteroids with absolute magnitude (H) values ranging from 20.4 to 27.4 were characterized. The slowest rotator with a definite period is 2004 BW_{18} with a period of 8.3 h, while 2000 DO_8 and 2000 WH_{10} are the fastest with periods of 1.3 min. A minimum of two-thirds of asteroids with $H > 20$ are fast rotating and have periods significantly faster than 2.0 h. The percentage of rapid rotators increases with decreasing size and a minimum of 79% of $H \geqslant 24$ objects are rapid rotators. Slowly-rotating objects, some with periods as long as 10–20 h, make up a small though significant fraction of the small asteroid population. There are three fast rotators with relatively large possible diameters (D): 2001 OE_{84} with $470 \leqslant D \leqslant 820$ m (Pravec, P., Kušnirák, P., Šarounová, L., Harris, A.W., Binzel, R.P., Rivkin, A.S. [2002b]. Large coherent Asteroid 2001 OE84. In: Warmbein, B. (Eds.), Proceedings of Asteroids, Comets, Meteors – ACM 2002. Springer, Berlin, pp. 743–745), 2001 FE_{90} with $265 \leqslant D \leqslant 594$ m (Hicks, M., Lawrence, K., Rhoades, H., Somers, J., McAuley, A., Barajas, T. [2009]. The Astronomer's Telegrams, # 2116), and 2001 VF_2 with a possible D of $145 \leqslant D \leqslant 665$ m. Using the diameters derived from nominal absolute magnitudes and albedos, the remainder of the fast rotating population is completely consistent with $D \leqslant 200$ m. Even when taking into account the largest possible uncertainties in the determination of diameters, the remainder must all have $D \leqslant 400$ m. With the exceptions of 2001 OE_{84}, this result agrees with previous upper diameter limits for fast rotators in Pravec and Harris (Pravec, P., Harris, A.W. [2000]. Icarus 148, 589–593) and Whiteley et al. (Whiteley, R.J, Tholen, D.J., Hergenrother, C.W. [2002a]. Icarus 157, 139–154.

1. Introduction

Time-resolved photometric measurements are the best source of information on the spin state of small Solar System bodies. In the last two decades, the nearly ubiquitous use of CCD technology has led to an explosion in asteroid rotational data. A large number of Main Belt asteroids and many near-Earth asteroids (NEA) are now easy targets for CCD-equipped amateur astronomers, or professionals on small aperture telescopes. The large amount of available data has allowed the recognition of unusual types of rotational behavior including very fast rotation among the smallest asteroids (Pravec and Harris, 2000).

Most rotation period determinations are of the larger Main Belt asteroids, and these typically rotate with periods in the 4–12 h range (Pravec et al., 2002a). Before the 1990s no asteroids were known to rotate with periods shorter than 2.1 h. This strong bias against rapid rotation was taken as evidence that almost all asteroids were strengthless "rubble piles" that did not possess any inherent tensile strength (Harris, 1996). Asteroids with typical densities and rotation periods longer than 2.1 h can, in principle, be held together strictly by self-gravitation.

The profusion of NEAs discovered during the last decade has given researchers the opportunity to examine the spin rates of much smaller asteroids. Even before the publication of Harris (1996), the first example of a possible asteroid rotation period faster than 2.1 h was identified when 1995 HM was found to have a period of 1.6 h (Steel et al., 1997). 1998 KY_{26}, a 30 m wide NEA, was the first convincing case of fast asteroid rotation (Ostro et al., 1999). The rapid

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rotation period of 10.7 min suggests that 1998 KY_{26} is a monolithic body rotating under tension. In short order, seven additional fast rotating asteroids (FRA) were identified (Pravec et al., 2000; Whiteley et al., 2002a). These fast-rotating asteroids added weight to the suggestion that rapid rotation was the normal dynamical situation for asteroids with diameters smaller than 200 m.

In 1999, we started a survey of small asteroids with absolute magnitudes (*H*) greater than 20. Monthly observing runs were conducted using telescopes in southern Arizona in the 1- to 2-m size range. Results for 1998 WB_2, 1999 TY_2, and 1999 SF_{10} have previously been published in Pravec et al. (2000); 2000 AG_6, 2000 DO_8, 2000 EB_{14}, and 2000 HB_{24} in Whiteley et al. (2002a); 2000 WL_{107} in Pravec et al. (2005) and 2006 XY in Hergenrother et al. (2009). This paper presents observations and results for an additional 53 small asteroids observed between 2000 and 2007. Preliminary rotation periods and lightcurve amplitudes for 26 asteroids observed between 2000 and 2002 were previously published in Whiteley et al. (2002b). At that time, however, no lightcurves or details of observations were given. This paper will present final results and phased lightcurves for these objects as well as for 27 new objects from our survey.

A small number of objects were observed to be in a state of non-principal axis (NPA) rotation including 2000 WL_{107} (Pravec et al., 2005). Details and results for these additional objects are not presented in this paper and will be the topic of a future paper.

2. Observations

All observations were obtained with telescopes located in southern Arizona. The most utilized facility was the University of Arizona Kuiper 1.5-m Cassegrain reflector near Mount Bigelow (KUI). A smaller fraction of observations were obtained with the University of Arizona Bok 2.3-m located on Kitt Peak (BOK), the Smithsonian Astrophysical Observatory 1.2-m on Mount Hopkins (SAO), and the Vatican Advanced Technology Telescope (VATT) Lennon 1.8-m on Mount Graham (VAT). The telescope systems used to observe each asteroid are listed in Table 1.

All four telescopes were equipped with thinned Loral 2048×2048 CCDs with 15-μm pixels. The camera systems at the Kuiper 1.5-m (CCD32), the VATT 1.8-m (CCD26) and the Bok 2.3-m (CCD21) consisted of a single CCD detector. The 4Shooter mosaic camera on the SAO 1.2-m employed four CCD detectors though usually only a single detector ('chip 3') was used for lightcurve observations. In all cases, the Field-of-Views were on the order of $5' \times 5'$ to $10' \times 10'$ in size.

In every case, the telescope was tracked at the rate of the asteroid. To maximize the signal to noise ratio, most photometric lightcurve observations at the Kuiper 1.5-m were taken through a clear filter. When the clear option (denoted with a *N* in Table 1) was not available or the asteroid was sufficiently bright, observations were conducted through a Harris *R* filter. The filters used are listed in Table 1. Due to the short rotation periods careful attention was taken to keep exposure times short. Pravec et al. (2000) found that exposure lengths need to be shorter than 18.5% of the rotation period to prevent loss of information due to lightcurve smearing. Trial and error was used on an individual case to find a proper exposure length in order to prevent lightcurve smearing and period aliasing while maximizing signal. Color photometry was obtained with Harris *BVRI* filters for a subset of asteroids. Photometric reference stars from Landolt (1992) were observed at multiple airmasses on each night in order to determine the photometric zero point and extinction coefficient. In the case of the filter-less observations, the Harris *R* filter extinction coefficient was used.

All data were reduced with the IRAF software package. The images were bias-subtracted and flat-fielded with dome and sky flat images using tasks in the CCDRED package. The APPHOT package was used to perform aperture photometry of the asteroids and, if applicable, photometric standard stars. In order to compensate for variable seeing, the average FWHM was measured for each image and the photometric aperture was set to a radius of $2*$ FWHM. Sky background was measured with a circular ring aperture. The size of the ring aperture was selected in each case to properly measure the sky brightness and avoid contamination by background stars. The sky aperture was centered on the position of the measured source.

Period determination was conducted with the Asteroid Light Curve (ALC) software package (version 0.96) provided by P. Pravec. The ALC is a Windows-based program, which uses Fourier series analysis to search for rotation period solutions. The Fourier series fits were also used to determine the amplitude of each lightcurve. Unless otherwise noted in Section 3.1, a 4th-order fit was used for most period solutions. Observations were corrected for light travel time and changes in heliocentric distance (*r*), geocentric distance (Δ), and phase angle (α). During most observations, the change in phase angle was minimal and the standard $G = +0.15$ was assumed (Bowell et al., 1989). Observing circumstances are listed in Table 1.

3. Lightcurve analysis and results

Asteroids for which observations are presented in this paper are listed in Table 2. The table includes absolute magnitudes (*H*) listed by the Minor Planet Center in their orbit database, fitted rotation periods, error of the period, fitted lightcurve amplitudes, and reliability codes (*U*). Straightforward cases requiring no additional discussion are only presented in Table 2 and their respective phased lightcurve plots. Objects requiring additional discussion are summarized below in Sections 3.1, 3.2 and 3.3. Phased lightcurves are presented in Figs. 1–53. The zero point for each plot is set to 0 h UT on the date of the first observation and is given in Julian Date on each plot.

The Reliability Code (*U*) is a modification of the code presented in Lagerkvist et al. (1989). For this paper, *U* is defined in Table 3.

3.1. Good rotation period solutions ($U = 2$ or 3)

3.1.1. (54509) YORP = 2000 PH_5

(54509) YORP is an Apollo asteroid with a 1.005-year period and is one of only four definite objects that reside on a Sun–Earth horseshoe orbit (Wiegert et al., 2002; Margot and Nicholson, 2003; Brasser et al., 2004). Its orbital parameters suggest the possibility of an origin from within the Earth-Moon system (Margot and Nicholson, 2003). The very Earth-like orbital period allows for an annual series of close approaches to the Earth. As a result, it is the only small fast rotating asteroid that has been physically studied during two or more apparitions. The current cycle of close approaches resulted in bright ($V \leqslant 16$) apparitions from 2001 through 2004. After initial lightcurve observations it was recognized as a prime candidate for the detection of the Yarkovsky effect on its orbital motion and the Yarkovsky–O'Keefe–Radzievskii–Paddack (YORP) effect on its rotation state (Vokrouhlický and Capek, 2002; Vokrouhlický et al., 2005).

Radar observations from Goldstone in 2001 and Arecibo in 2004 and 2005 were able to resolve this object and directly determine a shape model. The models give consistent *a*:*b*:*c* axial ratios of ~149:130:96 m and a mean diameter of 113-m (Taylor et al., 2007). Lowry et al. (2007) reported rotation periods of 0.20290020 h and 0.20289985 h for the 2003 apparition. During the same apparition, we measured a rotation period of 0.2030 ± 0.0012 h and amplitude of 0.77 mags consistent with

Table 1
Observational circumstances.

Object	Date of observations (UT)	r (AU)	Δ (AU)	α (°)	V (mag)	Integration time (s)	Filter	Telescope
(54509) YORP	2003/07/29.28–29.32	1.027	0.017	48.9	15.8	10	R	KUI
1999 MN	2004/06/30.35–30.44	1.068	0.101	57.2	18.6	120	R	VAT
	2004/07/01.34–01.46	1.064	0.093	57.3	18.4	120	R	VAT
	2004/07/02.35–02.46	1.059	0.084	57.6	18.2	120	R	VAT
2000 UK_{11}	2000/11/02.12–02.19	0.993	0.012	86.6	18.7	30	N	BOK
2000 UO_{30}	2000/11/02.36–02.44	1.035	0.045	14.3	18.4	30	N	BOK
2000 WG_{10}	2000/11/23.20–23.23	1.021	0.044	39.1	19.2	30,36,40	N	KUI
2000 WH_{10}	2000/11/24.16–24.29	1.013	0.057	61.5	18.5	6–22	N	KUI
2000 WM_{10}	2000/11/23.34–23.36	1.026	0.040	11.9	19.5	30	N	KUI
2000 WS_{28}	2000/11/24.45–24.46	1.152	0.169	11.8	18.6	16–26	N	KUI
2000 WG_{63}	2000/12/04.22–04.24	1.003	0.033	56.2	17.8	10,12	N	KUI
2000 WJ_{107}	2000/12/03.42–03.44	1.093	0.111	13.2	20.0	12,30	N	KUI
2000 WN_{148}	2000/12/04.31–04.33	1.046	0.078	38.0	18.5	16,20	N	KUI
2000 WQ_{148}	2000/12/04.39–04.41	1.069	0.087	15.4	18.4	8	N	KUI
2001 CQ_{36}	2001/02/27.13–27.16	1.055	0.087	39.9	19.0	30–120	N	KUI
2001 DS_8	2001/02/27.22–27.31	1.125	0.136	5.6	19.1	30–92	N	KUI
2001 KU_{66}	2001/05/31.19–31.29	1.030	0.019	30.5	16.8	10,16	R	VAT
2001 SQ_3	2001/09/19.35–19.38	1.059	0.067	34.8	17.3	40	R	KUI
2001 UC_5	2001/10/24.38–24.47	1.049	0.061	26.4	16.5	22,26,30	N	KUI
2001 UF_5	2001/10/24.24–24.30	1.047	0.057	23.5	17.7	28,30	R	KUI
2001 VF_2	2001/12/09.37–09.54	1.124	0.169	32.2	18.1	60	R	KUI
2001 WH_1	2001/12/09.19–09.26	1.043	0.080	42.2	16.6	30,60	R	KUI
2001 WV_1	2001/11/21.23–21.33	1.018	0.046	48.1	17.7	11,12	N	KUI
2001 WJ_4	2001/11/20.15–20.23	0.992	0.006	39.1	17.7	30	N	KUI
2001 WR_5	2001/12/09.26–09.32	1.036	0.056	23.3	17.6	30,36	N	KUI
2001 XU_4	2001/12/14.19–14.29	1.057	0.076	18.0	19.2	40,60	R	BOK
2002 EC	2002/03/09.32–09.50	1.047	0.056	13.1	18.0	30,60	N	KUI
	2002/03/10.12–10.49	1.049	0.057	10.8	18.0	30	N	KUI
2002 UK_{11}	2002/11/05.23–05.40	1.131	0.148	18.6	18.8	120	N	KUI
2003 GA	2003/07/30.40–30.46	1.103	0.135	46.5	18.7	120	N	KUI
	2003/07/31.24–31.44	1.106	0.135	45.6	18.7	120	N	KUI
	2003/08/02.36–02.46	1.110	0.137	43.4	18.7	120	N	KUI
2003 SR_{84}	2003/09/27.36–27.47	1.005	0.007	72.5	17.8	60	R	SAO
2003 WT_{153}	2003/11/30.30–30.32	0.990	0.005	40.7	17.9	30	R	SAO
2004 BV_{18}	2004/01/27.32–27.36	1.001	0.017	17.6	18.0	17–23	R	KUI
2004 BW_{18}	2004/01/27.13–27.26	1.037	0.065	35.0	18.1	13–30	R	KUI
2004 BB_{75}	2004/01/30.42–30.53	1.021	0.053	45.4	18.5	17–120	R	KUI
2004 BE_{86}	2004/04/14.45–14.47	1.145	0.158	24.9	18.3	120–240	R	SAO
	2004/04/15.35–15.49	1.147	0.160	24.5	18.4	120	R	SAO
2004 GD	2004/04/15.24–15.30	1.034	0.032	18.1	17.2	11,15	N	SAO
2004 GD_2	2004/04/14.20–14.27	1.024	0.025	32.3	17.7	41,43	N	SAO
2004 HZ	2007/04/22.42–22.44	1.033	0.040	45.1	17.4	11	R	KUI
2004 KF_{17}	2004/05/31.17–31.21	1.020	0.007	11.8	15.9	27,30	N	SAO
2004 RQ_{10}	2004/10/14.26–14.47	1.196	0.216	20.6	19.0	120	R	KUI
	2004/10/15.39–15.46	1.202	0.222	20.6	19.0	120	R	KUI
2005 GB_{34}	2005/04/07.33–07.43	1.008	0.007	21.9	15.7	10	N	KUI
2006 AM_4	2007/01/29.44–29.50	1.015	0.037	36.3	16.2	10	R	KUI
2006 CL_9	2006/02/27.35–27.37	1.029	0.048	35.3	17.7	30	R	VAT
2006 DD_1	2006/02/23.12–23.15	0.991	0.002	26.7	13.8	10	R	KUI
2006 DR_{14}	2006/02/24.38–24.45	1.002	0.012	10.7	17.2	10,60,90	R	KUI
2006 HH_{56}	2006/05/01.34–01.37	1.040	0.034	18.7	17.7	20	N	VAT
2006 HU_{50}	2006/04/30.44–30.47	1.020	0.018	45.2	17.8	7	N	VAT
2006 HW_{50}	2006/05/01.30–01.34	1.039	0.038	33.6	18.8	29,30	N	VAT
2006 KC	2006/05/24.25–24.31	1.138	0.128	12.1	18.8	60	N	KUI
2006 KB_1	2006/05/22.31–22.34	1.054	0.042	9.9	18.3	60	N	KUI
2006 KS_{38}	2006/05/25.26–25.31	1.040	0.029	21.3	17.4	20	N	KUI
2006 MV_1	2006/06/20.26–20.29	1.021	0.007	41.9	17.7	10	N	KUI
2006 SF_{77}	2006/09/26.36–26.41	1.091	0.094	18.6	17.6	60	R	KUI
2007 DA	2007/02/17.54–17.55	1.081	0.101	21.6	18.6	10	R	KUI
2007 GQ_3	2007/04/20.28–20.34	1.059	0.079	44.6	18.3	11,20	N	KUI

the results of Lowry et al. (2007) (Fig. 1). This object has one of the best-determined rotation periods for any asteroid and is firmly classified as $U = 3$. The observations by Lowry et al. (2007) allowed the detection of changes in the rotation period due to the YORP effect.

3.1.2. 1999 MN

With an absolute magnitude (H) of 21.4, 1999 MN is at the upper brightness limit for fast rotation. Observations over three consecutive nights in July and August of 2004 show a clean $U = 3$ lightcurve with a rotation period of 5.494 ± 0.014 h and amplitude of 0.74 magnitudes (Fig. 2). A shorter period of 2.8 ± 0.1 h is published in Polishook and Brosch (2008) but their observations only spanned 1.62 h and did not cover an entire rotation. Since their period is roughly half the period we determined, it suggests their result is a sub-multiple of the actual period.

Ambiguities in lightcurve period determination are common when the data in question have error bars that are on the order of the lightcurve amplitude. The most common ambiguity is the uncertainty over whether a lightcurve period is a particular value, or is really twice that value. This 2:1 period ambiguity occurs in lightcurve determinations because the chi-squared of individual

Table 2
Light curve properties of the fast rotating asteroids.

Asteroid	*H* (mag)	Period (h)	Error (h)	Amplitude (mag)	*U*
(54509) YORP	22.7	0.2030	0.0012	0.77	3
1999 MN	21.4	5.494	0.014	0.74	3
2000 UK_{11}	25.3	0.02660	0.00004	0.28	2
		0.05320	0.00007	0.28	2
2000 UO_{30}	24.3	0.578	0.014	0.21	3
2000 WG_{10}	24.4	0.228	0.006	0.48	3
2000 WH_{10}	22.5	0.02221	0.00022	0.66	3
2000 WM_{10}	25.8	N/A	N/A	N/A	0
2000 WS_{28}	23.6	0.03646	0.00320	0.36	3
2000 WG_{63}	23.2	0.1383	0.0025	0.43	3
2000 WJ_{107}	23.8	N/A	N/A	>0.6	0
2000 WN_{148}	22.4	N/A	N/A	>0.3	0
2000 WQ_{148}	22.7	0.1659	0.0003	0.30	3
2001 CQ_{36}	22.6	N/A	N/A	N/A	0
2001 DS_{8}	22.7	0.531	0.025	0.46	3
2001 KU_{66}	24.1	0.874	0.02	0.55	3
2001 SQ_{3}	21.7	0.06248	0.00048	0.39	3
2001 UC_{5}	21.3	0.02931	0.00008	0.11	3
2001 UF_{5}	22.7	0.2612	0.0040	0.60	3
2001 VF_{2}	20.3	1.39	0.06	0.42	3
2001 WH_{1}	20.4	>8	N/A	>0.15	1
2001 WV_{1}	22.5	N/A	N/A	>0.5	0
2001 WJ_{4}	27.4	0.904	0.040	0.93	3
2001 WR_{5}	22.7	0.358	0.025	0.63	3
2001 XU_{4}	23.7	0.46	0.03	0.76	2
2002 EC	23.4	6.169	0.018	0.57	3
2002 UK_{11}	21.7	~8	N/A	~1.3	2
2003 GA	21.2	5.78	0.01	1.25	3
2003 SR_{84}	26.0	2.24	0.04	1.88	3
2003 WT_{153}	28.0	N/A	N/A	>0.2	0
2004 BV_{18}	25.9	0.05647	0.00040	0.22	3
2004 BW_{18}	22.5	8.29	0.03	0.22	2
2004 BB_{75}	23.1	>3	N/A	~0.4	1
2004 BE_{86}	21.3	2.424	0.007	0.68	2
		2.284	0.017	0.65	2
2004 GD	23.7	N/A	N/A	N/A	0
2004 GD_{2}	24.3	0.2354	0.0026	0.80	3
2004 HZ	22.6	N/A	N/A	N/A	0
2004 KF_{17}	26.1	0.249	0.008	0.34	3
2004 RQ_{10}	20.9	5.69	0.03	0.70	2
		5.16	0.02	0.69	2
		6.44	0.03	0.65	2
2005 GB_{34}	25.4	0.520	0.003	0.38	3
2006 AM_{4}	21.8	0.0847	0.0003	1.01	3
2006 CL_{9}	22.8	0.145	0.005	0.39	3
2006 DD_{1}	26.5	0.04563	0.00021	0.93	3
2006 DR_{14}	26.1	>8	N/A	>0.5	1
2006 HU_{50}	24.7	0.444	0.003	0.50	3
2006 HW_{50}	24.4	0.0291	0.0002	0.32	3
2006 HH_{56}	24.0	~0.7	N/A	~0.12	1
2006 KC	22.2	0.65	0.02	0.19	2
2006 KB_{1}	24.4	>4	N/A	>0.3	1
2006 KS_{38}	23.9	0.68	0.02	0.55	3
2006 MV_{1}	26.8	0.0951	0.0003	1.14	3
2006 SF_{77}	21.7	0.312	0.008	0.38	3
2007 DA	22.4	0.074	0.002	0.99	2
2007 GQ_{3}	22.0	0.0602	0.0004	0.54	3

fits is badly impacted by the use of low signal data in the Fourier fitting process. With lightcurve data that have error bars significantly smaller than the lightcurve amplitude (i.e. good quality data), the chi-squared of each individual Fourier Harmonic fit is highly diagnostic, and usually eliminates any uncertainty about which of the two periods is the best-fitting.

Low SNR data makes it difficult to utilize the chi-squared results to see differences in the quality of the fit between the two period solutions. When the lightcurve data error bars are the same size as the lightcurve amplitude, there is simply not enough information to tell which of the two possible periods is the correct one.

Hicks et al. (2010) confirmed the period near 5.5 h with observations made during the 2010 apparition. Their result of 5.482 ± 0.007 h is a close match to the 2004 period of 5.494 ± 0.014 h. The small difference in rotation period between

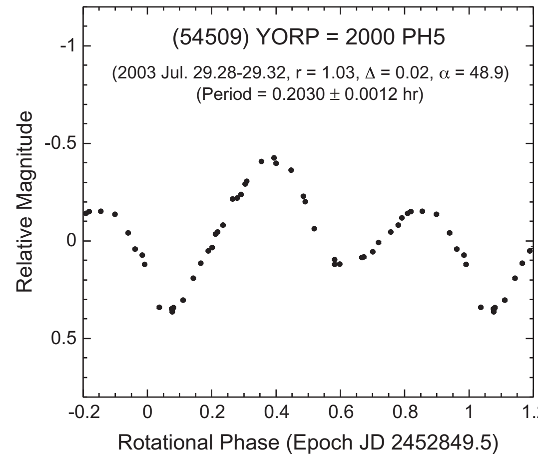

Fig. 1. Phased lightcurve of (54509) YORP. Magnitudes are relative to the mean magnitude of the lightcurve during the course of the observations. Observational circumstances and the derived rotation period and period error are included near the top of the figure. Error bars are plotted for each data point, though very small errors may be smaller than the point size. Plot details are similar for Figs. 1–53 except where noted.

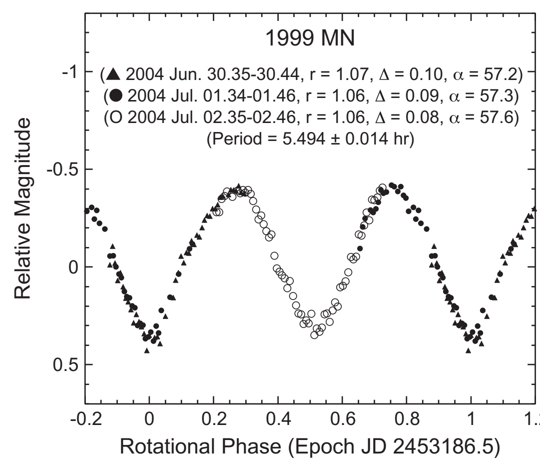

Fig. 2. Phased lightcurve of 1999 MN.

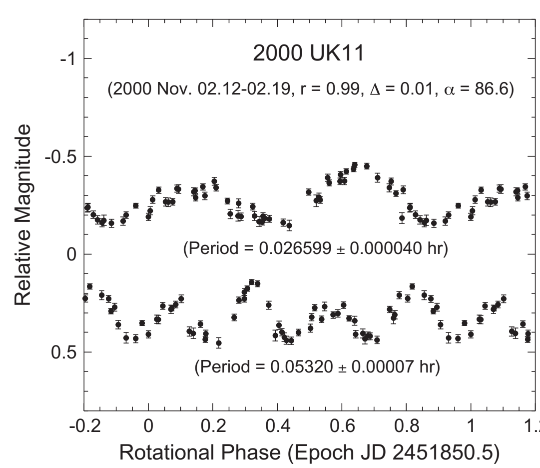

Fig. 3. Phased lightcurve of 2000 UK_{11}.

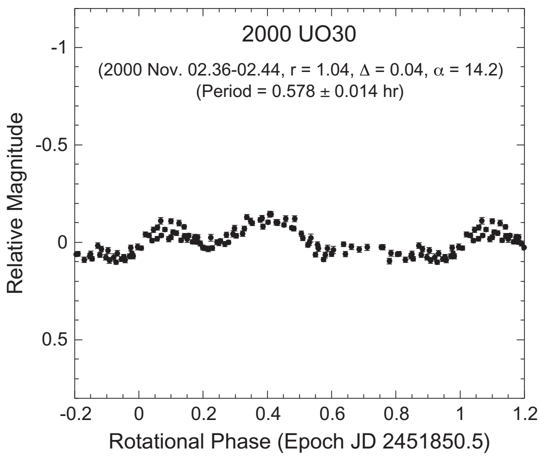

Fig. 4. Phased lightcurve of 2000 UO_{30}.

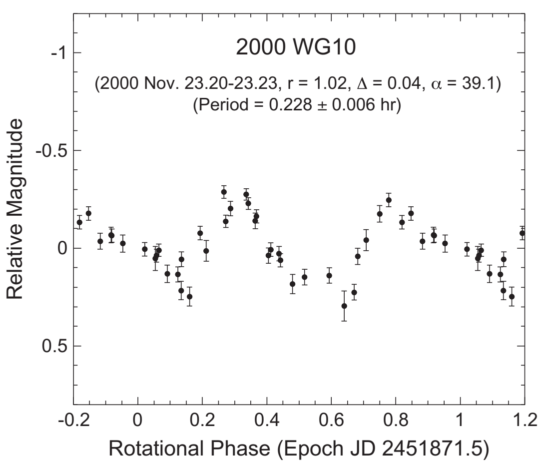

Fig. 5. Phased lightcurve of 2000 WG_{10}.

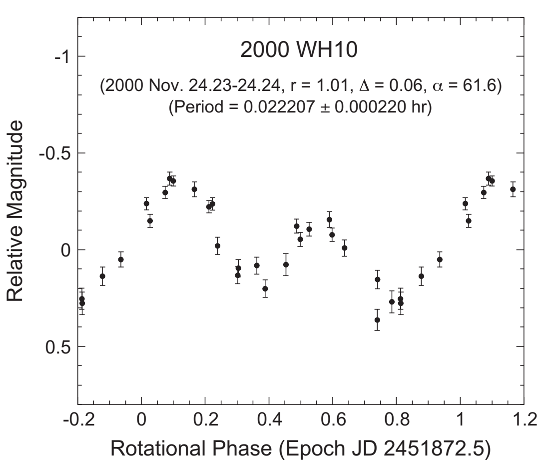

Fig. 6. Phased lightcurve of 2000 WH_{10}.

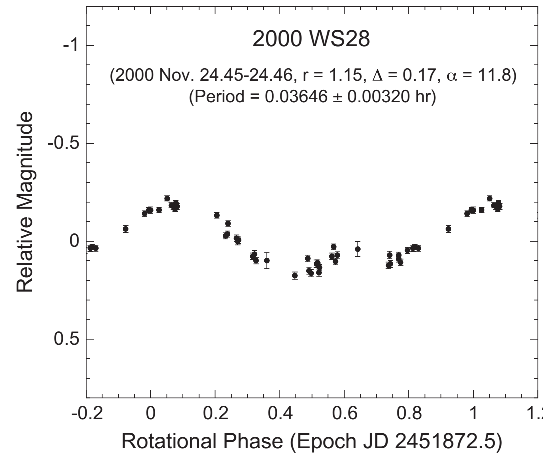

Fig. 7. Phased lightcurve of 2000 WS_{28}.

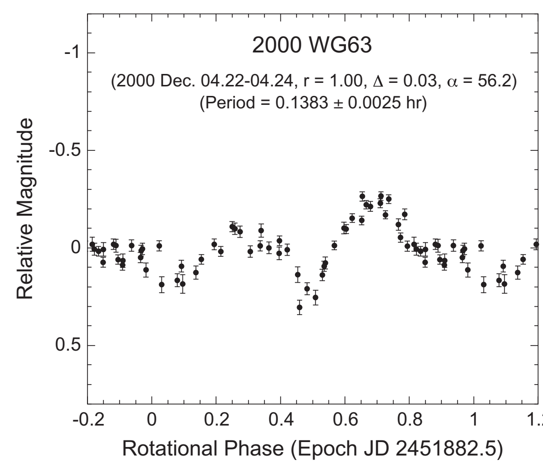

Fig. 8. Phased lightcurve of 2000 WG_{63}.

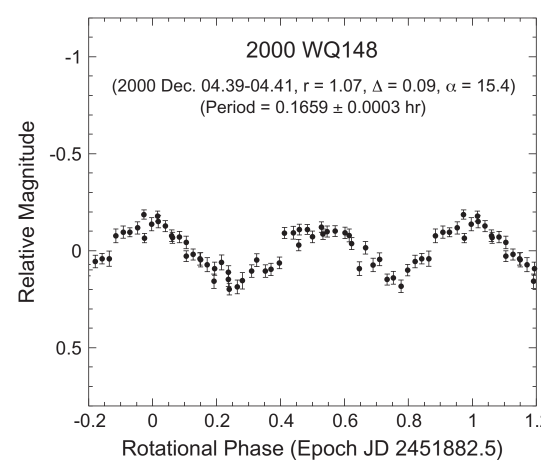

Fig. 9. Phased lightcurve of 2000 WQ_{148}.

2004 and 2010 may be due to YORP induced spin-up though the values are similar enough that a slight underestimate in the error of one or both solutions may explain the difference.

3.1.3. 2000 UK_{11}

Two period solutions are possible at 0.02660 ± 0.00004 h and 0.05320 ± 0.00007 h (Fig. 3). The shorter period displays a bimodal lightcurve while the longer period has a quadrumodal lightcurve. Both solutions have amplitudes of 0.28 magnitudes. Goldstone and Arecibo radar observations detected a rapid rotation period on the order of 3 min (0.05 h) and a small ~30 m diameter (Nolan et al., 2001). Fourier series fits and manual inspection of our data alone does not reveal which period is correct. Based on the period

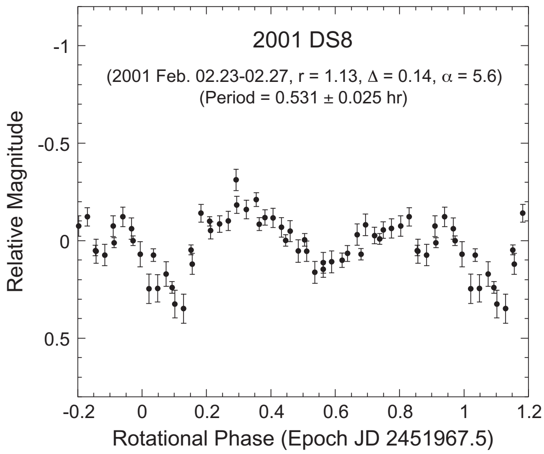

Fig. 10. Phased lightcurve of 2001 DS_8.

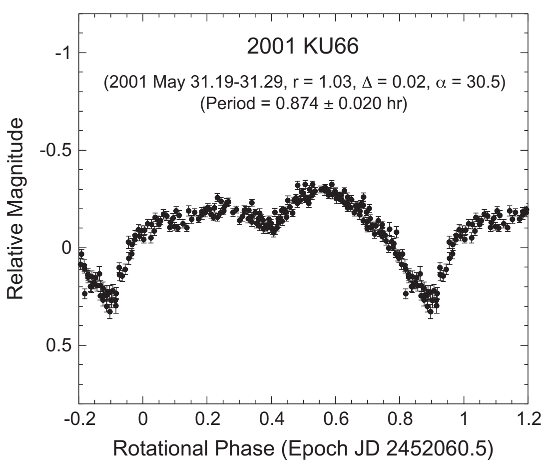

Fig. 11. Phased lightcurve of 2001 KU_{66}.

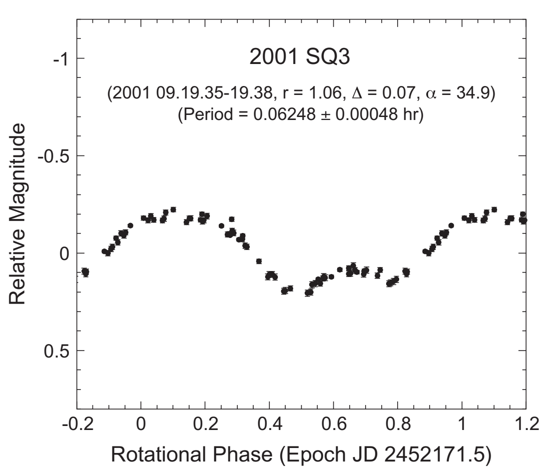

Fig. 12. Phased lightcurve of 2001 SQ_3.

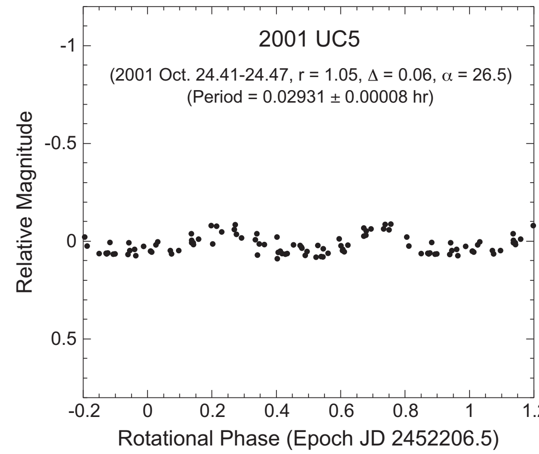

Fig. 13. Phased lightcurve of 2001 UC_5.

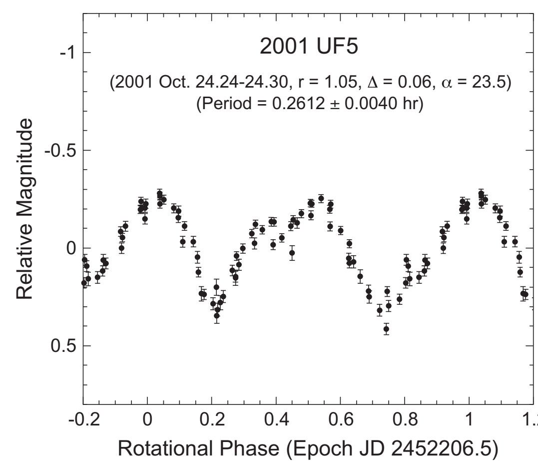

Fig. 14. Phased lightcurve of 2001 UF_5.

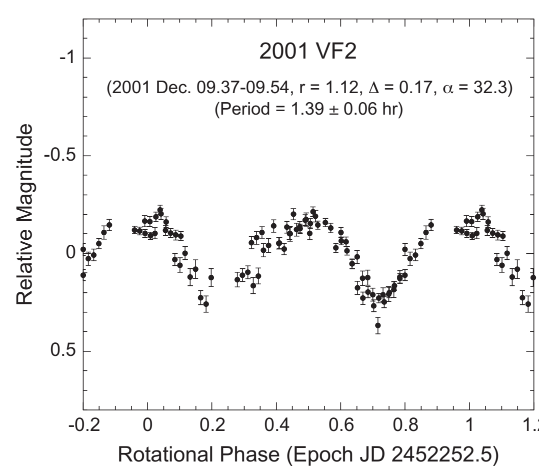

Fig. 15. Phased lightcurve of 2001 VF_2.

derived from the radar observations, the longer period (0.05320 h) is considered most likely. Future radar opportunities in 2005 and 2010 may allow the detection of Yarkovsky forces (Vokrouhlický et al., 2005).

3.1.4. 2001 UC_5

Observations were obtained over 2.25 h during a single night with exposures lengths of 22, 26 and 30 s. Only the shortest exposures (22 s) produced a clean solution suggesting the lightcurve was being smeared by the longer exposures. The solution derived

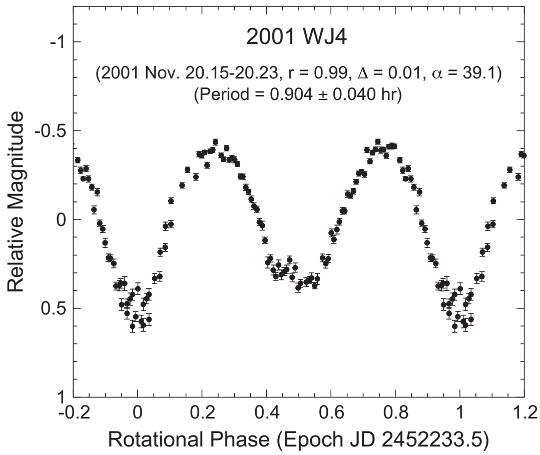

Fig. 16. Phased lightcurve of 2001 WJ_4.

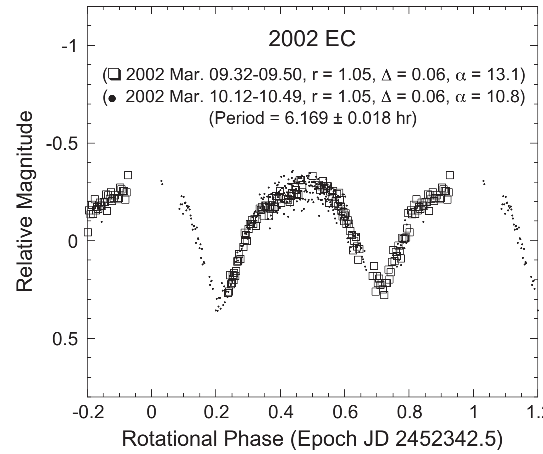

Fig. 19. Phased lightcurve of 2002 EC.

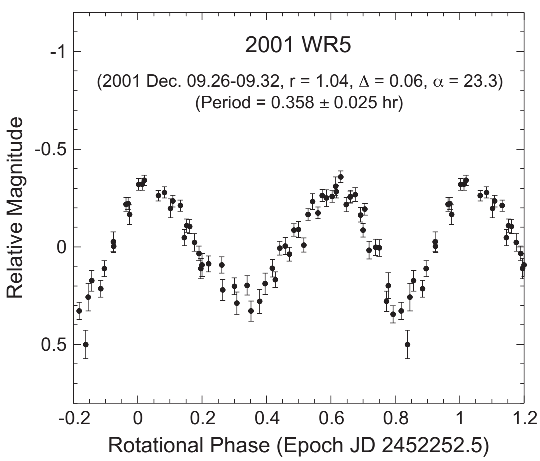

Fig. 17. Phased lightcurve of 2001 WR_5.

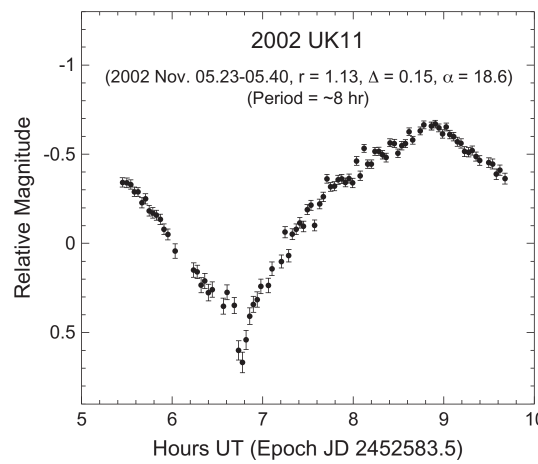

Fig. 20. Lightcurve of 2002 UK_{11}.

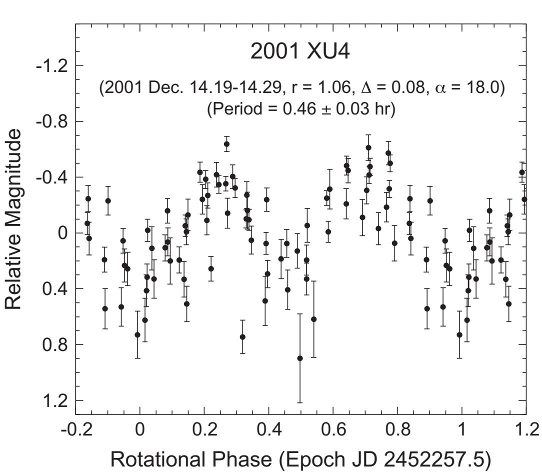

Fig. 18. Phased lightcurve of 2001 XU_4.

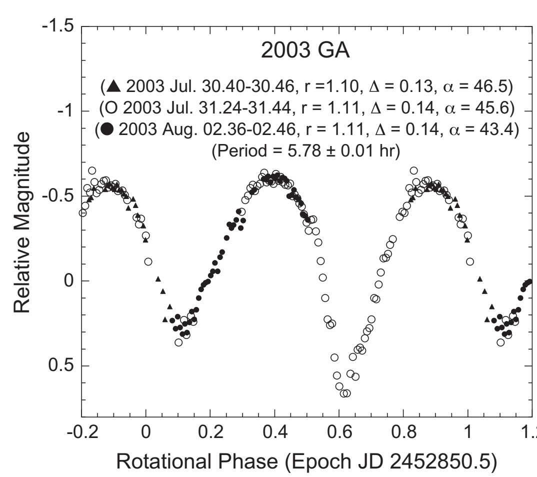

Fig. 21. Phased lightcurve of 2003 GA.

from the 22 s exposures is 0.02931 ± 0.00008 h with amplitude of 0.11 magnitudes (Fig. 13).

3.1.5. 2002 UK_{11}

2002 UK_{11} has an H value of 21.7 placing it in the transitional size range between fast and slow rotation. Observations over nearly 5 h clearly detected a single minimum and maximum roughly 2 h apart (Fig. 20). This suggests a period on the order of 8 h with high amplitude of no less than 1.3 magnitudes. A big deviation from symmetry is not expected for a high amplitude lightcurve observed at low phase angle of 18.6° (Pravec, P., personal communication, 2010).

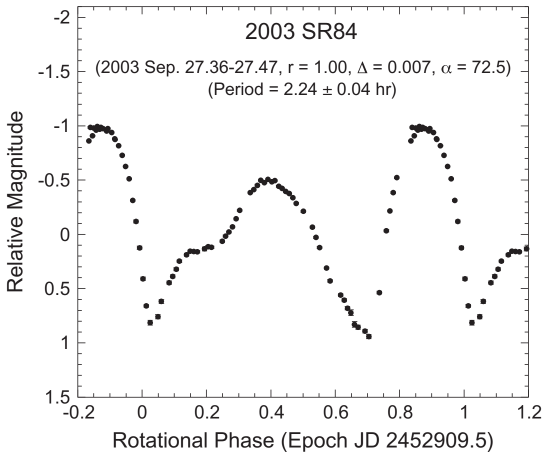

Fig. 22. Phased lightcurve of 2003 SR_{84}.

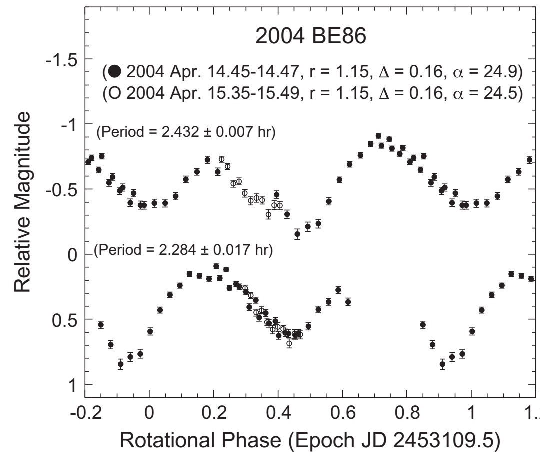

Fig. 25. Phased lightcurve of 2004 BE_{86}. Two possible rotation period solutions are plotted. Each solution is shifted along the Y-axis to avoid confusion.

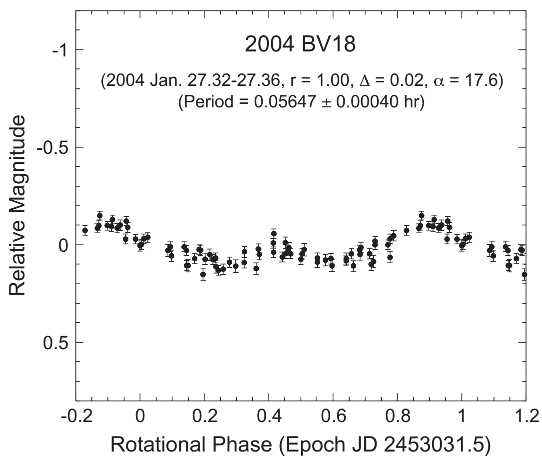

Fig. 23. Phased lightcurve of 2004 BV_{18}.

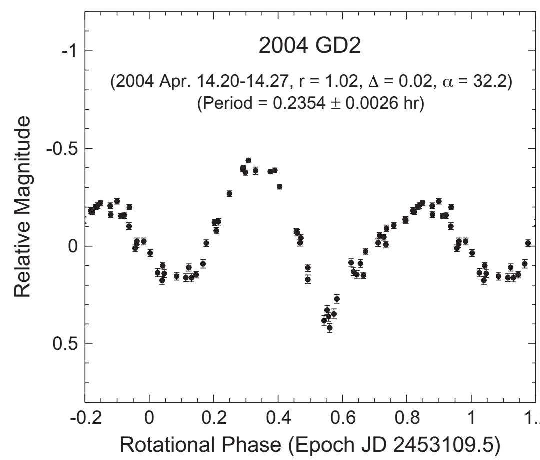

Fig. 26. Phased lightcurve of 2004 GD_2.

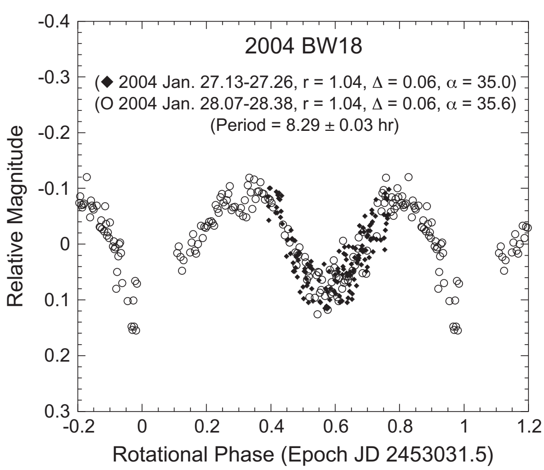

Fig. 24. Phased lightcurve of 2004 BW_{18}.

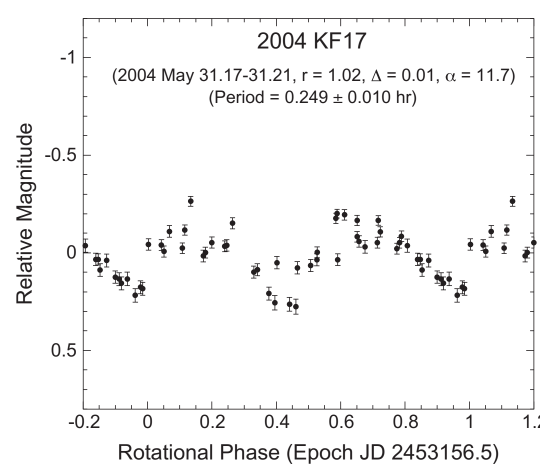

Fig. 27. Phased lightcurve of 2004 KF_{17}.

As a result we can be confident that the period of 2002 UK11 is close to 8 h allowing a *U* value of 3 to be assigned.

3.1.6. 2003 SR_{84}

2003 SR_{84} is a not a fast rotator even though it is one of the smallest objects we observed with $H = 26.0$. Observations over ~2.6 h appear to cover more than a single rotation. The best-fit solution is a period of 2.3 ± 0.1 h and amplitude of 1.88 magnitudes (Fig. 22). Phasing the lightcurve shows discrepancies where the observations overlap. The large amplitude and clean lightcurve leave little doubt that the period is on the order of 2.2–2.4 h. The phased lightcurve discrepancies suggest the possibility of complex

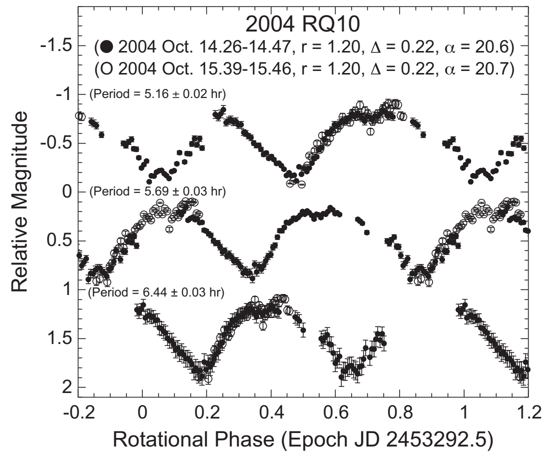

Fig. 28. Phased lightcurve of 2004 RQ_{10}. Three possible rotation period solutions are plotted. Each solution is shifted along the Y-axis to avoid confusion.

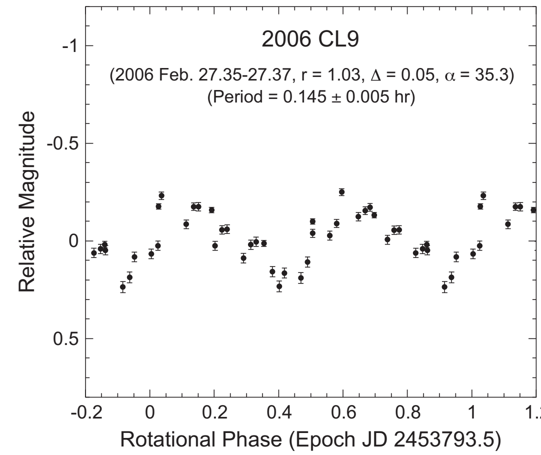

Fig. 31. Phased lightcurve of 2006 CL_9.

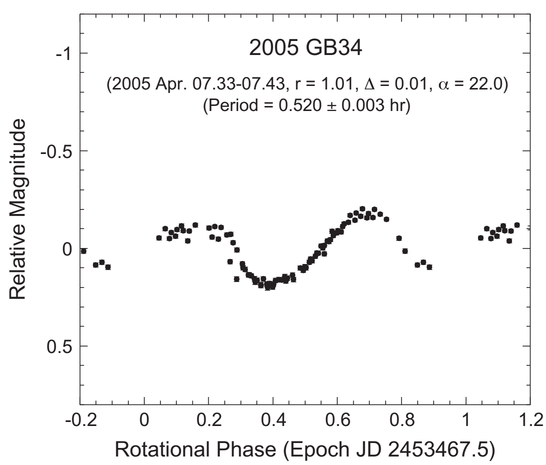

Fig. 29. Phased lightcurve of 2005 GB_{34}.

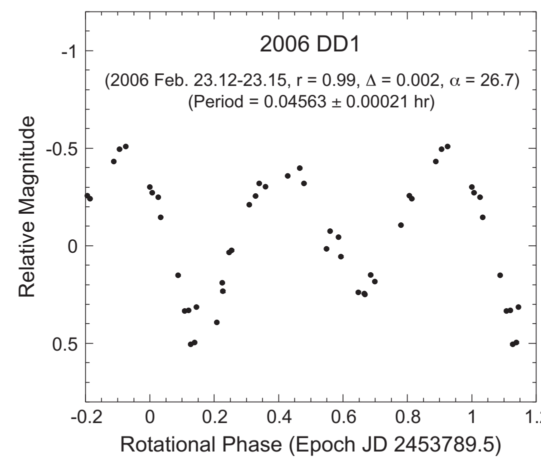

Fig. 32. Phased lightcurve of 2006 DD_1.

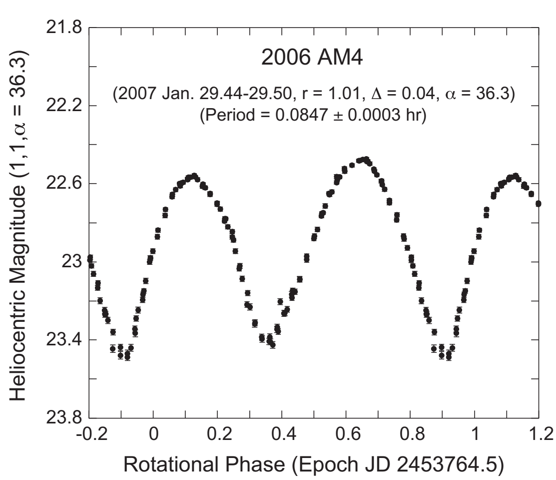

Fig. 30. Phased lightcurve of 2006 AM_4.

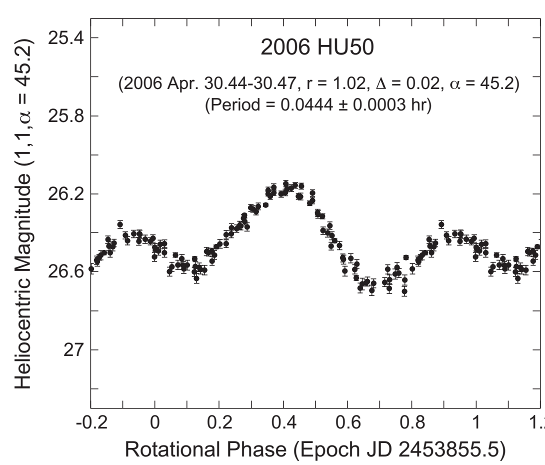

Fig. 33. Phased lightcurve of 2006 HU_{50}.

rotation or uncorrected observational effects such as incorrect airmass extinction determination or a change in transparency due to light clouds. A rotation period published on the Ondrejov Observatory NEO Program website (www.asu.cas.cz/~ppravec/newres.txt) gives a period of 2.352 ± 0.006 h which is consistent with our result.

3.1.7. 2004 BE_{86}

2004 BE_{86} was observed over two nights. A complete rotation was not observed on either night with observations from the second night spanning only ~0.5 h. Combining data from each night yields two possible rotation periods at 2.284 ± 0.017 and

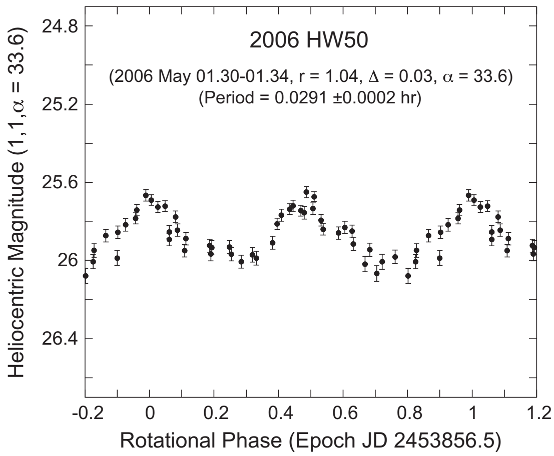

Fig. 34. Phased lightcurve of 2006 HW_{50}.

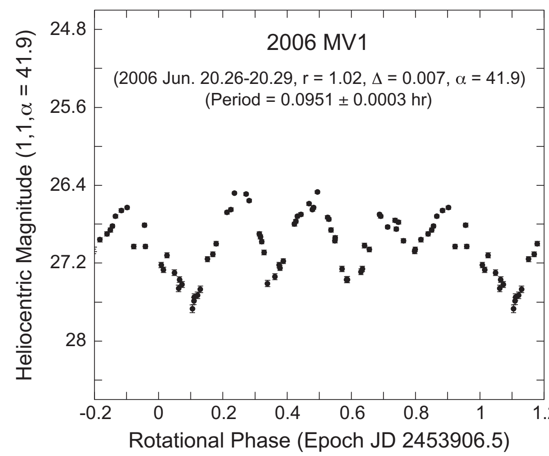

Fig. 37. Phased lightcurve of 2006 MV_1.

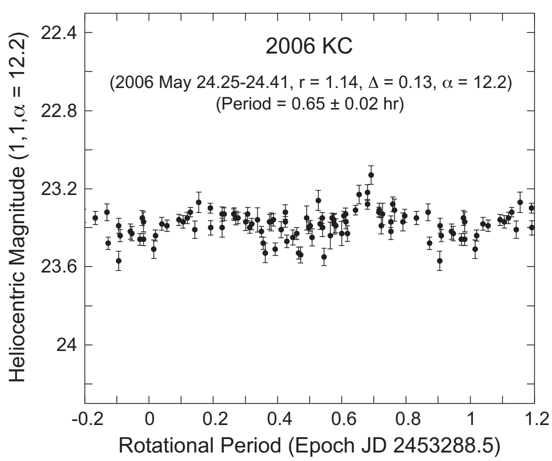

Fig. 35. Phased lightcurve of 2006 KC.

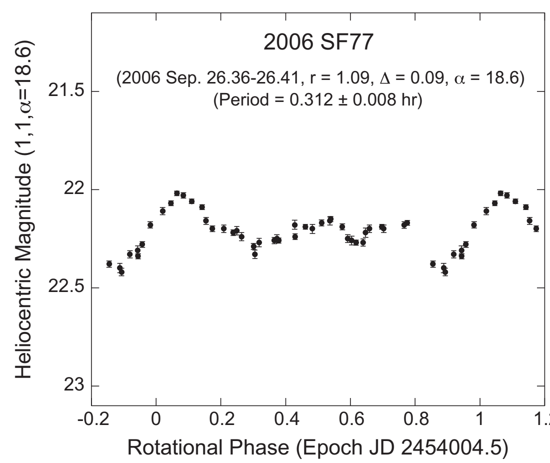

Fig. 38. Phased lightcurve of 2006 SF_{77}.

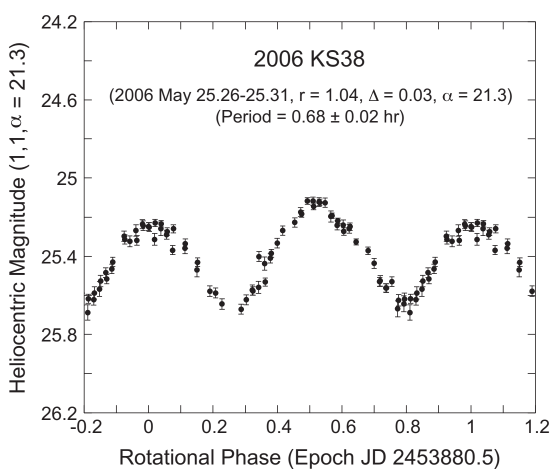

Fig. 36. Phased lightcurve of 2006 KS_{38}.

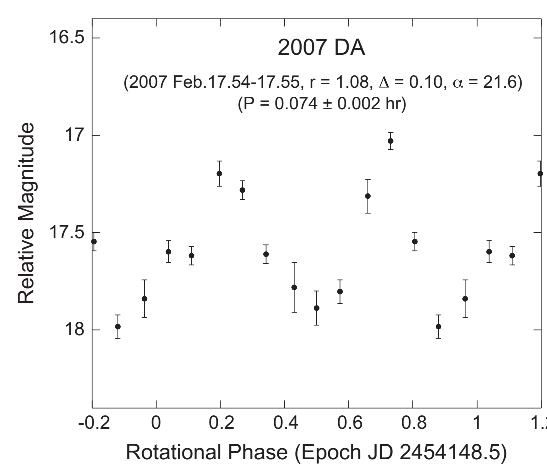

Fig. 39. Phased lightcurve of 2007 DA.

2.432 ± 0.007 h (Fig. 25). The 2.284 h period does not result in complete coverage of the lightcurve. As a result of the ambiguity in the period, this asteroid has been assigned a *U* value of 2.

3.1.8. 2004 RQ_{10}

Observations of 2004 RQ_{10} were acquired on two consecutive nights. Coverage was insufficient on either night to span an entire rotation. Combining data from each night results in three possible periods of 5.16 ± 0.02 h, 5.69 ± 0.03 h, and 6.44 ± 0.03 h (Fig. 28). All three periods produce clean lightcurves with two minima and maxima. A 5 or 6 h rotation period is not unusual for an object with $H = 20.9$ since this is larger than the majority of fast rotators. A $U = 2$ has been assigned to this object.

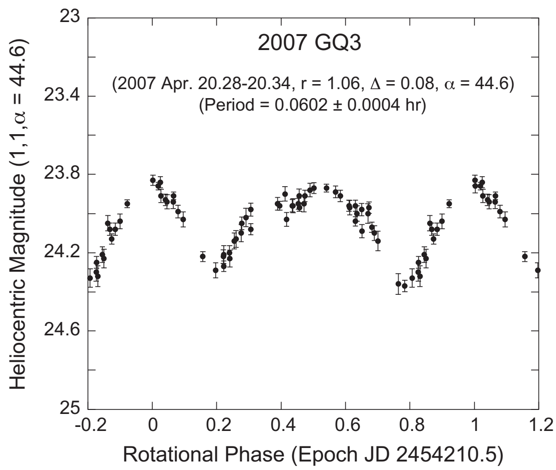

Fig. 40. Phased lightcurve of 2007 GQ_3.

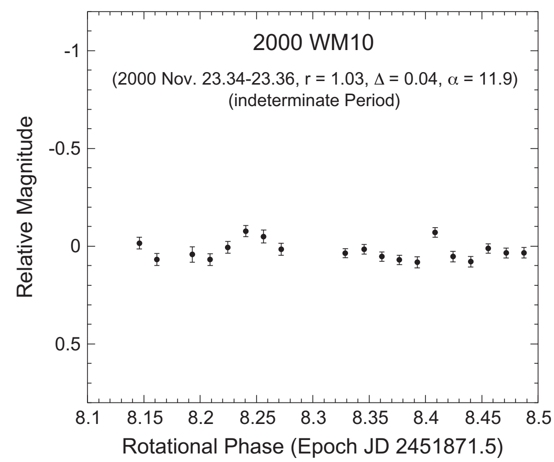

Fig. 41. Lightcurve of 2000 WM_{10}.

3.1.9. 2006 KC

A rotation period of 0.65 ± 0.02 h produces a noisy lightcurve with amplitude of 0.19 magnitudes (Fig. 35). The high error of the individual observations (~0.04 mag) relative to the amplitude decreases our confidence in the period. A U value of 2 is assigned to 2006 KC. Filter photometry was conducted in the *BVRI*-bands. The resulting color indices of $B–V$ = +0.84 ± 0.16, $V–R$ = +0.50 ± 0.07, and $V–I$ = +0.50 ± 0.07 are consistent with a S-type taxonomy.

3.1.10. 2006 KS_{38}

A clean U = 3 lightcurve with a rotation period of 0.68 ± 0.02 h and amplitude of 0.55 magnitudes was observed for this object (Fig. 36). Filter photometry was conducted in the *BVRI*-bands. The resulting color indices of $B–V$ = +0.67 ± 0.08, $V–R$ = +0.38 ± 0.03, and $V–I$ = +0.75 ± 0.09 are consistent with a C- or X-type taxonomy.

3.1.11. 2006 MV_1

2006 MV_1 displays one of the most interesting lightcurves observed by our survey. A fitted rotation period of 0.0951 ± 0.0003 h and amplitude of 1.14 magnitudes produces a phased lightcurve with four maxima/minima pairs (Fig. 37). Multiple and sub-multiple periods do not produce a clean lightcurve and can be ruled out. The repeatability of the lightcurve over ~0.8 h, or ~8 rotations, indicates no obvious NPA rotation. A single-period quadrumodal lightcurve with amplitude 1.14 magnitudes is unusual and defies easy explanation (Pravec, P., personal communication, 2010). The possibility of a beat between rotation frequency and the sampling rate was investigated. The data presented in Fig. 37 are 10 s clear filter exposures taken at ~35.5 s intervals. Other observations in the *BVRI*-bands and 30 s clear filter exposures had sampling intervals of ~35.5, ~35.5, ~56.2, ~45.8, and ~56.2 s, respectively. All sampling rates produce a similar consistent lightcurve so the rotation period is assigned a U value of 3. Filter photometry was conducted in the *BVRI*-bands. The resulting color indices of $B–V$ = +0.76 ± 0.10, $V–R$ = +0.44 ± 0.10, and $V–I$ = +0.77 ± 0.15 are consistent with the C, X, and S type asteroids. The large errors for each color index preclude a definitive taxonomy.

3.1.12. 2006 SF_{77}

A phased lightcurve produced from observations of 2006 SF_{77} yield a rotation period of 0.312 ± 0.008 h and amplitude of 0.38 magnitudes (Fig. 38). The clean unambiguous lightcurve is assigned a U value of 3. Filter photometry was conducted in the *BVRI*-bands. The resulting color indices of $B–V$ = +0.65 ± 0.02, $V–R$ = +0.36 ± 0.01, and $V–I$ = +0.77 ± 0.03 are consistent with a C-type taxonomy.

3.1.13. 2007 DA

2007 DA was observed on the night of its discovery, 2007 February 17 UT. The object was placed on the Minor Planet Center Near Earth Object Confirmation Page (NEOCP) as twilight was starting at the Kuiper 1.5-m. This resulted in only 12 min of observation before the sky became too bright. A solution displaying a reasonably clean lightcurve with a period of 0.074 ± 0.002 h was found (Fig. 39). Though the lightcurve looks realistic, the short arc of observations places some doubt on the period and results in a U value of 2.

3.2. Uncertain or indeterminate rotation period solutions (U = 0 or 1)

In the following cases, it is apparent that an incomplete lightcurve was observed. This was due to an arc of observations shorter than the rotation period. Though a rotation period cannot be determined, the lightcurve allows us to place some constraints on a possible period.

3.2.1. 2001 WH_1

2001 WH_1 was observed for 1.4 h during which a maximum and a possible minimum in brightness were observed (Fig. 45). These observations suggest that 2001 WH_1 has a rotation period greater than 8 h and amplitude greater than 0.15 magnitudes. Its size (H = 20.4) is larger than that expected for fast rotation so a period of many hours is expected.

3.2.2. 2004 BB_{75}

The photometry acquired on this object over 2.5 h has a low signal-to-noise (Fig. 48). Even with the noisy data, the photometry suggests a maximum and minimum was observed about an hour apart.

3.2.3. 2006 DR_{14}

Observations over 1.5 h show a steady fading trend of ~0.5 magnitudes (Fig. 51). Since no extrema was observed we can only state that 2006 DR_{14} has a rotation period greater than ~4 h and amplitude greater than ~0.5 magnitudes. At H = 26.1, 2006 DR_{14} is one of the smallest objects sampled as part of this survey.

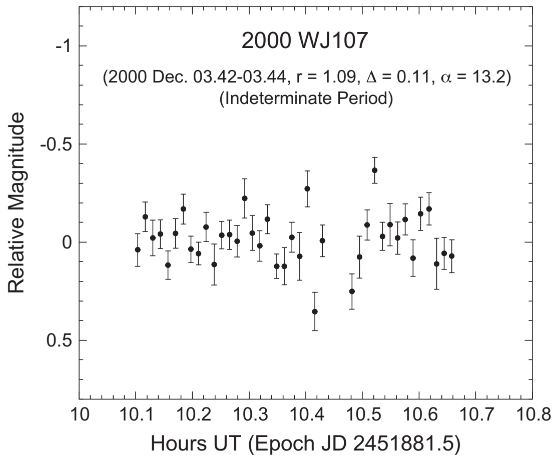

Fig. 42. Lightcurve of 2000 WJ_{107}.

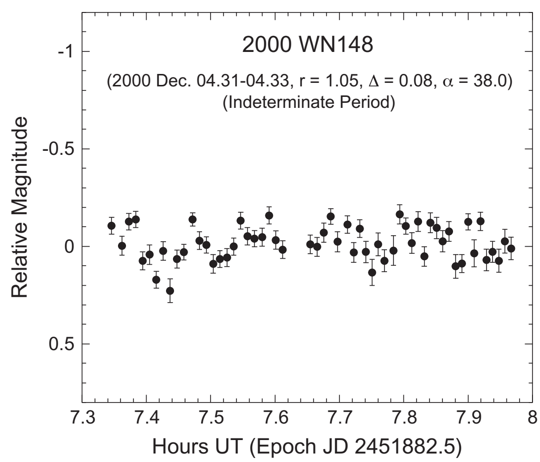

Fig. 43. Lightcurve of 2000 WN_{148}.

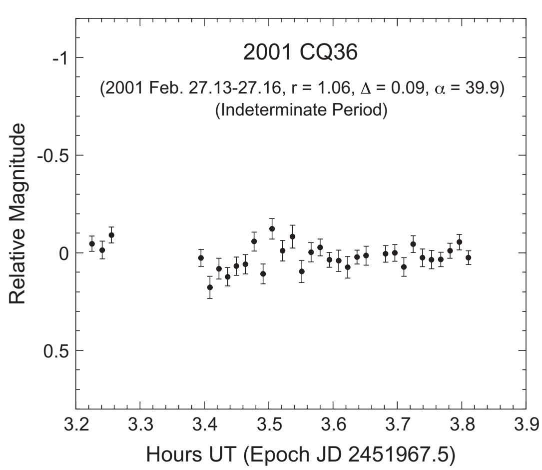

Fig. 44. Lightcurve of 2001 CQ_{36}.

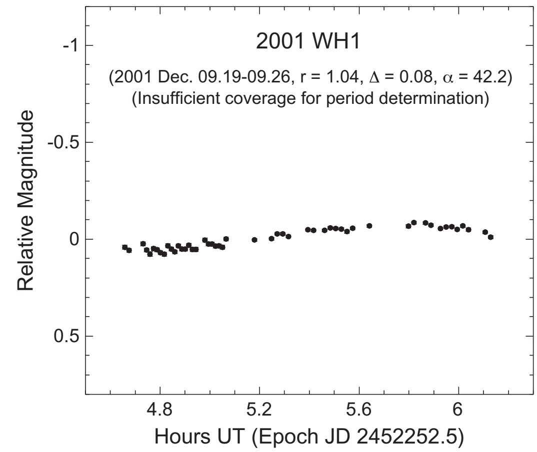

Fig. 45. Lightcurve of 2001 WH_1.

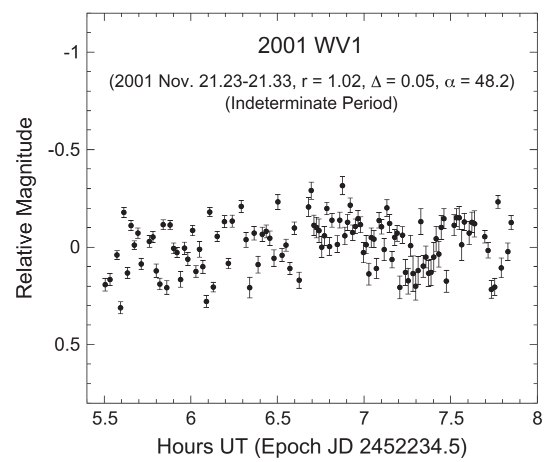

Fig. 46. Lightcurve of 2001 WV_1.

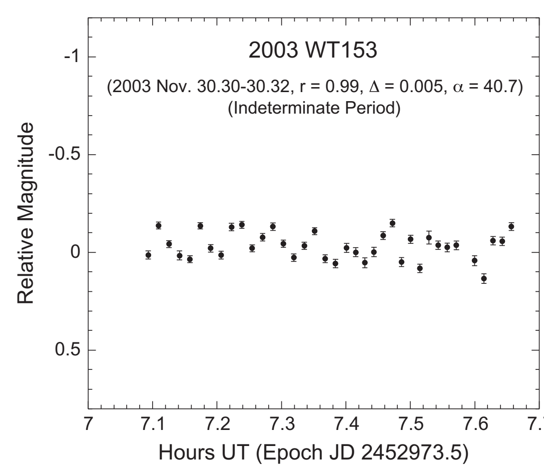

Fig. 47. Lightcurve of 2003 WT_{153}.

3.2.4. 2006 HH_{56}

Two maxima and a single minimum were observed over 0.6 h (Fig. 52). A second minimum may have been seen at the end of the observational arc but this is not conclusive. The low apparent amplitude raises doubts as to whether an extrema were observed. If the extrema are real then the rotation period is on the order of ~0.7 h with an amplitude of ~0.12 magnitudes.

3.2.5. 2006 KB_1

This object faded by ~0.3 magnitudes over 0.9 h (Fig. 53). Since no extrema were observed, the photometry suggests that 2006 KB_1 is not a fast rotator and has a rotation period greater than or equal to 4 h.

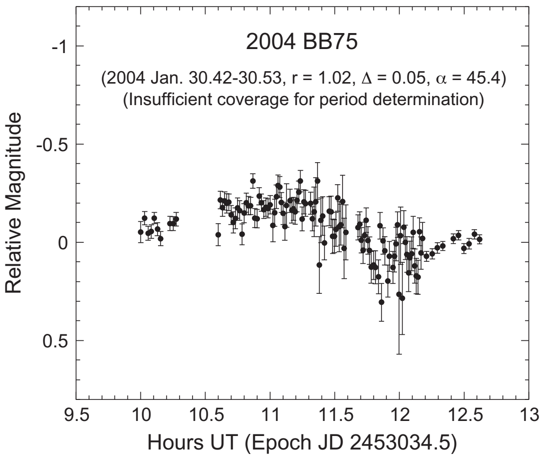

Fig. 48. Lightcurve of 2004 BB_{75}.

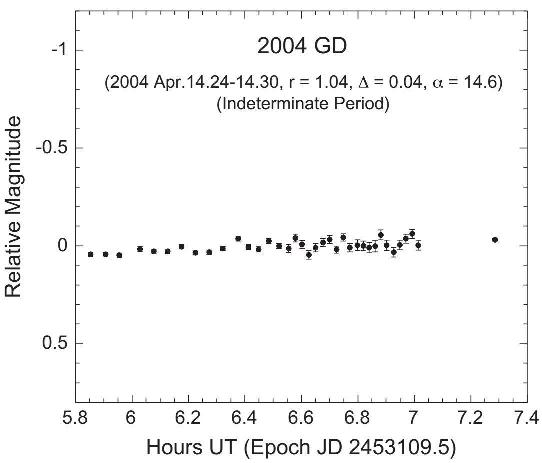

Fig. 49. Lightcurve of 2004 GD.

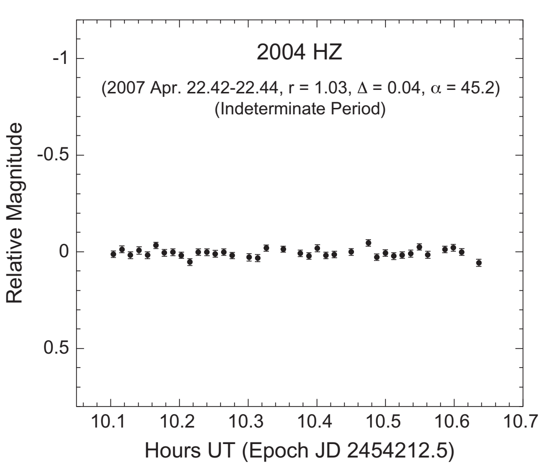

Fig. 50. Lightcurve of 2004 HZ.

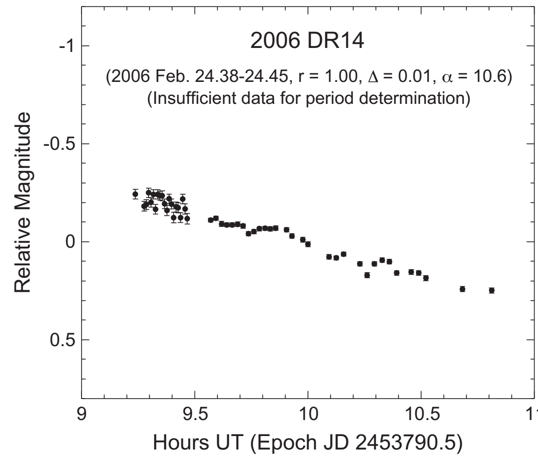

Fig. 51. Lightcurve of 2006 DR_{14}.

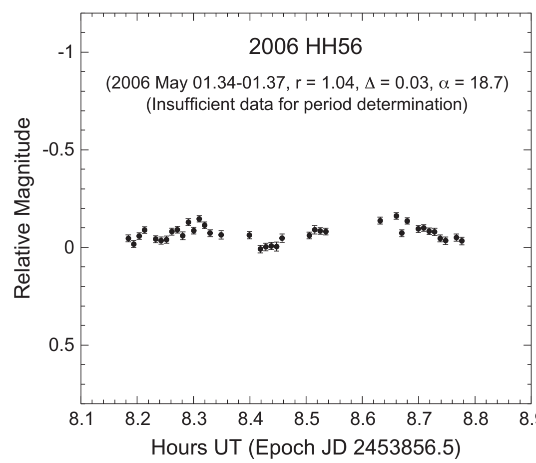

Fig. 52. Lightcurve of 2006 HH_{56}.

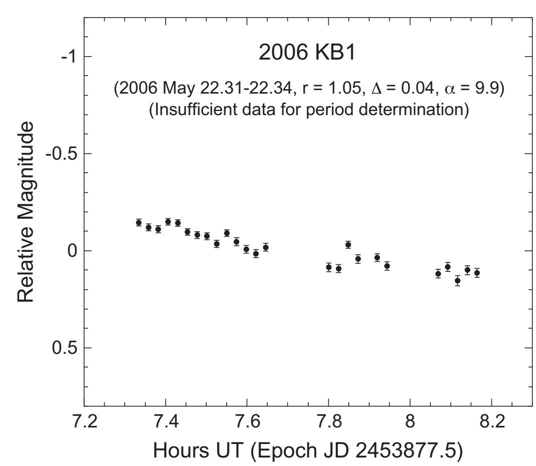

Fig. 53. Lightcurve of 2006 KB_1.

3.2.6. 2000 WM_{10}, 2001 CQ_{36}, 2004 GD, and 2004 HZ

These asteroids have indeterminate rotation periods. Indeterminacy may be due to a number of factors including periods many times longer than the arc of observations, small amplitudes making it difficult to detect photometric changes due to rotation, low signal-to-noise photometry or very rapid rotation periods that are not being properly sampled by the exposure lengths used. An additional four asteroids, 2000 WJ_{107}, 2000 WN_{148}, 2001 WV_1, and 2003 WT_{153}, also have indeterminate rotation periods. In these cases, the photometric errors are small suggesting the exposure time may be a significant fraction of the rotation period.

Table 3
Definition of rotation period uncertainty (U) codes. Modified from Lagerkvist et al. (1989).

U code	Description
0	No result can be derived from the data
1	Result based on fragmentary lightcurve(s), may be wrong
2	Result based on less than full coverage, so that the period may be wrong by 30% or so. Also used to indicate cases where an ambiguity exists as to the number of extrema between light curves. Hence the results may be wrong by an integer ratio
3	Secure result with no ambiguity, full lightcurve coverage

4. Discussion

Results from this survey were combined with all previously published rotation periods and lightcurve amplitudes. The source of the previously published data is the Asteroid Lightcurve Database (LCDB) maintained by A.W. Harris, B.D. Warner and P. Pravec at the MinorPlanet.Info website (http://www.minorplanet.info/lightcurvedatabase.html) (Warner et al., 2009). The 2010 November version of the database is used. Not all results included in the LCDB have undergone peer review, though in the case of many amateur contributions their lightcurves are posted on their respective websites allowing review. This review identified a few questionable results, which are not included in this paper. Rotation period results for (1897) Hind, (2981) Chagall, (3729) Yangzhou, (4917) Yurilvovia, (7436) Kuroiwa, (7603) Salopia, (12205) 1981 EZ_{26}, (19979) 1989 VJ and 2005 UE_1 were discarded following inspection of their published lightcurves. Higley (2008) claims that his results for 2005 PJ_2 are suspect and require further confirmation. As a result this object was also discarded from our study. In all of the cases above, the objects were much larger than $H = 22$ with claimed periods of under 2 h.

There are two questionable datasets that contain a significant number of rapid fast rotating asteroids. Dermawan (2004) conducted a deep survey of sub-kilometer sized asteroids in the Main Belt. They found that ~27% of Main Belt asteroids with diameters between 0.5 and 2.0 km were rapid rotators with periods less than 2 h. Warner et al. (2009) conducted an independent analysis of the Dermawan (2004) results. Their analysis of the Main Belt fast rotators suggests that the rapid rotation results are spurious and due to fitting lightcurves to noise rather than real signal.

The Thousand Asteroid Light Curve Survey (TALCS) also presents evidence of a population of rapid rotators among Main Belt asteroids with diameters in the range of $0.4\ \mathrm{km} \leqslant D \leqslant 10\ \mathrm{km}$ (Masiero et al., 2009). The TALCS authors question the accuracy of these rapid spin rates because "the light curve amplitude for these objects is close to the level of the photometric noise in the TALCS data sample." If the six suspected TALCS rapid rotator results are legitimate, the debiased distribution of Masiero et al. (2009) expects no more than ~4% of Main Belt asteroids in the sampled size range to be rapid rotators, significantly lower than the fraction of the population suggested by Dermawan (2004). Due to the questionable nature of the results in Dermawan (2004) and Masiero et al. (2009), they will not be considered for this paper. The possibility of a sizable population of rapid rotators among the sub-kilometer and larger population of Main Belt asteroids is a topic that requires additional investigation

4.1. Rotation periods of the fast rotating asteroids

The rotations periods of 3170 asteroids are plotted against absolute magnitude (H) and diameter in Figs. 54 and 55, respectively. From the largest Kuiper Belt objects down to asteroids with $H \sim 20$, all but three objects have rotation periods greater than 2.00 h. The virtual impactor (144898) 2004 VD_{17} with $H = 18.9$ and diameter of ~320 m is an E-type NEA with a rotation period of 1.99 h (de Luise et al., 2007). A period of this length is not much faster than the periods of many other asteroids with diameters greater than ~200 m. More obvious examples of rapid rotation among objects of this size are 2001 FE90, an A-type, $H = 20.1$ NEA with a rotation period of 0.478 h or 28.66 min (Hicks et al., 2009) and 2001 OE_{84}, an S-type, $H = 18.3$ NEA with a rotation period of 0.486 h or 29.19 min (Pravec et al., 2002b).

For objects smaller than H of 20, the ratio of rapid to slow rotation is reversed as seen in Figs. 56 and 57. We have observed 62 objects that are smaller than $H = 20.0$ including the 53 presented in this paper and nine objects (1998 WB_2, 1999 SF_{10}, 1999 TY_2, 2000 AG_6, 2000 DO_8, 2000 EB_{14}, 2000 HB_{24}, 2000 WL_{107}, 2006 XY) previously published in Pravec et al. (2000), Whiteley et al. (2002a), Pravec et al. (2005) and Hergenrother et al. (2009). The slowest rotator with a definite period is 2004 BW_{18} with a period of 8.29 ± 0.03 h while 2000 DO_8 and 2000 WH_{10} are the fastest with periods of 0.021730 ± 0.000002 h and 0.022207 ± 0.000220 h, respectively. Both objects rotate slower than 2008 HJ which has the shortest known rotation period at 0.0118 ± 0.0001 h (Miles, 2008). These rotation periods are still longer than period limits of 0.0055–0.0083 h suggested by the global "binding" strength of meter-sized meteorite-dropping fireballs (Brown et al., 2004). As more asteroids in the 1–10 m size range are observed, observed rotation periods may approach the Brown et al. (2004) limit.

4.2. Absolute magnitude of rapid rotators

The lightcurves presented in this paper include both conclusive and inconclusive results. This allows an interpretation of the ensemble properties of small fast rotating asteroids with few but well documented biases. In contrast, published observations of small asteroids may be incomplete. We do not know how many objects were observed but not entered into the public record due to inconclusive results. For this reason, our analysis will focus on the 62 objects observed during our survey.

The asteroids observed by our survey range in absolute magnitude from $H = 20.4$–27.4. These H values correspond to diameter on the order of 18–450 m for a typical C-type albedo of

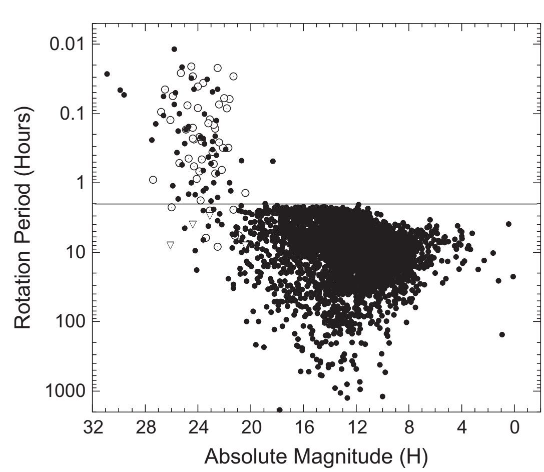

Fig. 54. The rotations periods of 4294 asteroids plotted against absolute magnitude (H). Filled circles are previously published data in the Asteroid Lightcurve Database (LCDB) maintained by A.W. Harris, B.D. Warner and P. Pravec at the MinorPlanet.Info website (Warner et al., 2009). Open circles represent data from this paper. Downward pointing triangles present lower limits for uncertain cases from this paper. The horizontal line marks the canonical limit between gravity- and strength-dominated regions (2.0 h).

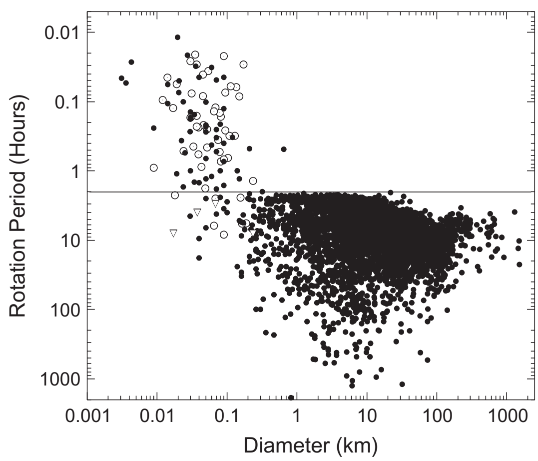

Fig. 55. The rotations periods of 4294 asteroids plotted against diameter. The source of data and plot details are the same as in Fig. 54.

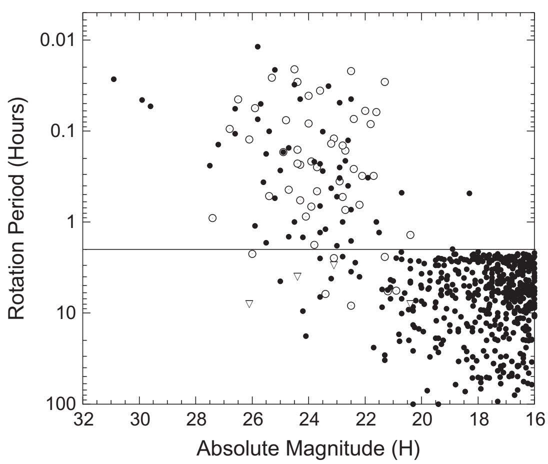

Fig. 56. The rotations periods of asteroids with $H \geqslant 16.0$ plotted against absolute magnitude (H). The source of data and plot details are the same as in Fig. 54.

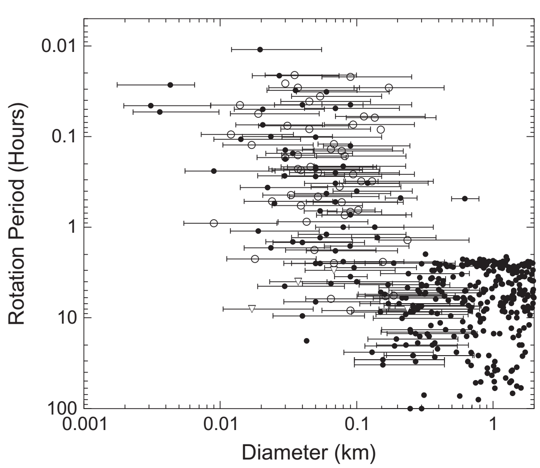

Fig. 57. The rotations periods of asteroids with $H \geqslant 16.0$ plotted against diameter. Error bars for the diameter estimate are based on the uncertainty in the absolute magnitude and albedo of each object (see Section 4.3 for details). The source of data and plot details are the same as in Fig. 54.

0.06 and 10–220 m for a typical S-type albedo of 0.22. For those objects with reliable rotation periods, the percentage of rapid rotators is 78% or 42 of 54. An additional eight asteroids have indeterminate rotation periods. As stated in Section 3.2 these results may be due to unresolved rapid rotation, very slow rotation, low lightcurve amplitude, or low signal-to-noise. Though some of these objects may be rapid rotators, the assumption of non-rapid rotation for all eight gives a rapid rotation percentage of 68% or 42 of 62. Thus, a minimum of two-thirds of asteroids with $H > 20$ are fast rotating with periods significantly faster than 2.0 h.

Limiting the study to asteroids with $H \geqslant 22$ gives similar results. Fast rotators make up 77% or 37 out of 48 objects with reliable periods. Assuming all objects with indeterminate periods are non-fast rotators produces a minimum percentage of fast rotators of 60% or 37 of 62. Looking only at asteroids with $H \geqslant 24$ finds a higher percentage of fast rotators; 86% or 19 of 22 objects with reliable periods and 79% or 19 of 24 periods if we include indeterminate periods. Clearly four-fifths of asteroids smaller than $H = 24$ are fast rotators. Non-fast rotators, some with periods as long as 10–20 h, make up a small though significant fraction of the small asteroid population.

4.3. Diameters of fast rotators

Absolute magnitude (H) is often used as a proxy for diameter. Its usefulness is limited for two reasons. One, though H is a measure of the total reflected light from an asteroid, a direct relationship between H and diameter is not possible without some knowledge of an asteroid's albedo. Known values for albedo can vary by a factor of ten. Two, H is a measure of the total reflected light at a phase angle of 0°. Most observations of near-Earth asteroids are made at much larger phase angles resulting in an assumed extrapolation to 0° phase angle. For many of the objects in this study, both the absolute magnitudes and diameters are uncertain.

There are few fast rotating asteroids with well-determined diameters. In all of these cases, this is the result of radar observations. For objects with no directly determined diameters, we have determined a range of effective diameters based on H. As stated above, the Minor Planet Center derived H values are extrapolated from higher phase angles with an assumed phase parameter, G, of +0.15 (Bowell et al., 1989). This value for G is the average for bright Main Belt asteroids and may be in error for any particular object (Lagerkvist and Magnusson, 1990). To account for this we have assumed H values are in error by ±0.4 magnitudes. The effective diameters listed in the LCDB lightcurve database have been used in Figs. 55 and 57. When the actual albedo is not known assumed values are used for the following taxonomies; 0.06 for C-types, 0.18 for X-types, 0.22 for S-types, 0.30 for E-types, 0.40 for V-types, and 0.22 for asteroids without a known taxonomy. In Fig. 57 asteroids with $H > 20$ are plotted with their range of possible diameters. Objects with no known taxonomy and X-types have an albedo range of 0.04–0.40 to cover most possibilities. S-types have an albedo range of 0.18–0.26 while C-types have ranges of 0.03–0.09.

Three fast rotators have relatively large possible diameters, 2001 OE_{84} with a diameter between $470 \leqslant D \leqslant 820$ m (Pravec et al., 2002b), 2001 FE_{90} with a diameter between $265 \leqslant D \leqslant 594$ m (Hicks et al., 2009) and 2001 VF_2 with a diameter between $145 \leqslant D \leqslant 665$ m. The remainder of the fast rotators is consistent with diameters under 400 m. Using the diameters based on the nominal absolute magnitudes and albedos, the remainder is consistent with diameters under 200 m. With the exception of 2001 OE_{84} and 2001 FE_{90}, this result agrees with previous upper diameter limits for fast rotators in Pravec and Harris (2000) and Whiteley et al. (2002a).

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