LIGHTCURVE ANALYSIS FOR FOUR NEAR-EARTH ASTEROIDS OBSERVED APRIL-JUNE 2023

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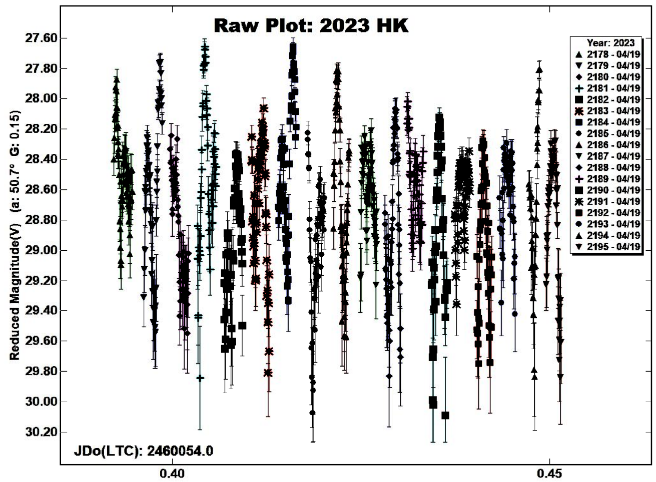
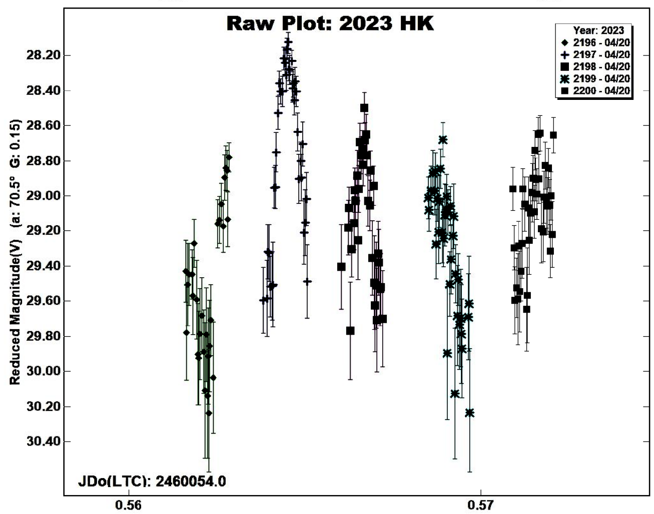
Lightcurves and amplitudes for four small near-Earth asteroids observed from Great Shefford Observatory during close approaches between April and June 2023 are reported. All are fast rotators with dominant periods shorter than 10 minutes and two are identified as having tumbling rotation.

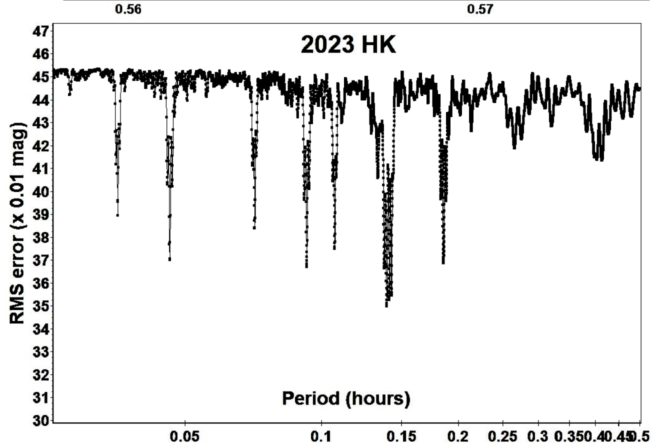
Photometric observations of near-Earth asteroids during close approaches to Earth between April and June 2023 were made at Great Shefford Observatory using a 0.40-m Schmidt-Cassegrain and Apogee Alta U47+ CCD camera. All observations were made unfiltered and with the telescope operating with a focal reducer at f/6. The 1K×1K, 13-micron CCD was binned 2×2 resulting in an image scale of 2.16 arc seconds/pixel. All the images were calibrated with dark and flat frames and *Astrometrica* (Raab, 2018) was used to measure photometry using APASS Johnson V band data from the UCAC4 catalogue (Zacharias et al., 2013). *MPO Canopus* (Warner, 2022), incorporating the Fourier algorithm developed by Harris (Harris et al., 1989) was used for lightcurve analysis.

No previously reported results have been found in the Asteroid Lightcurve Database (LCDB) (Warner et al., 2009), from searches via the Astrophysics Data System (ADS, 2023) or from wider searches unless otherwise noted. All size estimates are calculated using H values from the Small-Body Database Lookup (JPL, 2023), using an assumed albedo for NEAs of 0.2 (LCDB readme.pdf file) and are therefore uncertain and offered for relative comparison only.

2023 HK. This Apollo (H = 27.2, est. size 11 m) was discovered by the Mt. Lemmon Survey on 2023 Apr 16.3 UTC four days before an approach to within 0.9 Lunar Distances (LD) from Earth (Carcano et al., 2023). It was observed for 1.4 hours starting 2023 Apr. 19.89 UTC, then 2.6 hours later for an additional 15 minutes. Its apparent speed increased from 220 to 440 arcsec/min and exposures were limited to 2.4 s, reducing to 1 s to keep trailing of the target within the measurement aperture of *Astrometrica*. Large brightness variations are apparent in the raw plots from the two observing periods and irregularly spaced maxima and minima can be seen in timescales of a few minutes, with an amplitude of at least 1.5 magnitudes. It is apparent that the rotation is likely to be tumbling and a period spectrum shows a number of potential solutions. A simple reduction, assuming principal axis rotation (PAR) gives a very unsatisfactory trimodal lightcurve with period 0.13905 ± 0.00005 h and amplitude of 1.0 magnitudes. Tumbling, or non-principal axis (NPA) rotation solutions derived using the *MPO Canopus* Dual Period Analysis function are also unsatisfactory, an example pair of lightcurves from one NPA solution is given, labelled P1 and P2 and displays obvious systematic trends in both curves.



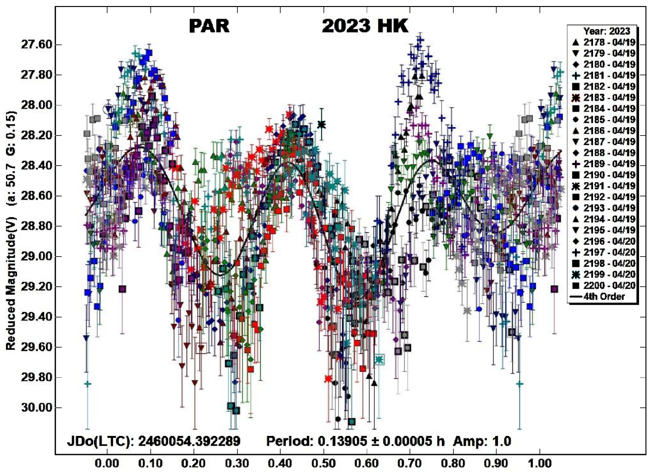


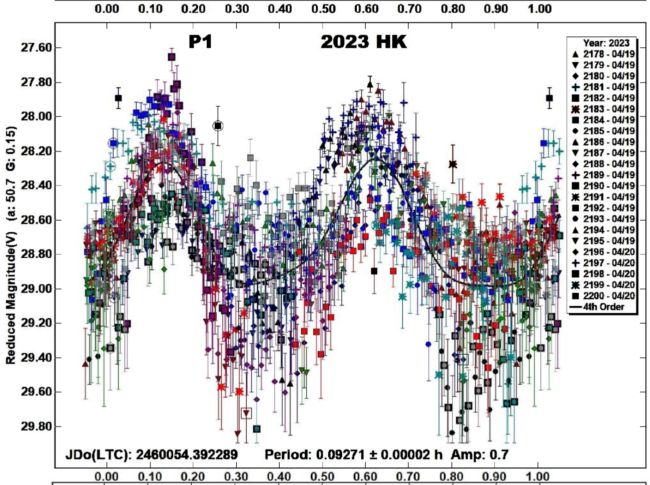


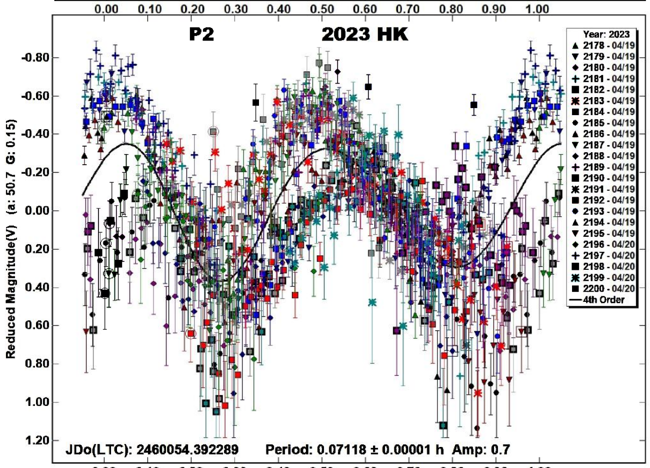
2023 HK is tumbling, and in a very excited state; there are high amplitudes also in linear combinations of the main frequencies (whichever they actually are). There are several significant periods in the data, but it is unclear which of them are real frequencies of the tumbler and which are linear combinations of the real frequencies. The candidate periods are:

0.0562 h (or half that)
0.0712 h (or half that)
0.0927 h (or half that)
0.2658 h (or half that)

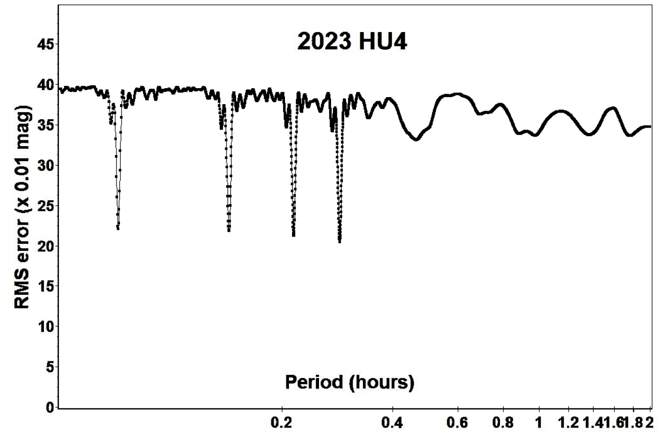
On the scale defined in Pravec et al. (2005) it is expected to be rated as PAR = -2 (NPA rotation detected based on deviations from a single period but the second period is not resolved) with periods in the range from 0.028 to 0.266 h (Petr Pravec, personal communication). The full amplitude suggested by the NPA solutions is ~1.5 magnitudes.



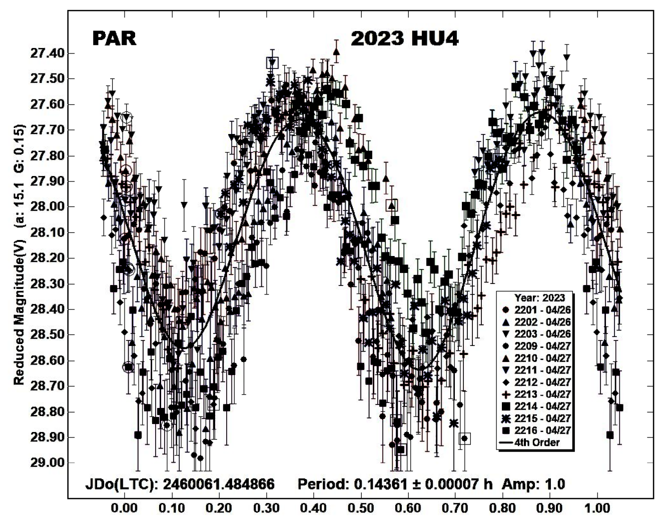




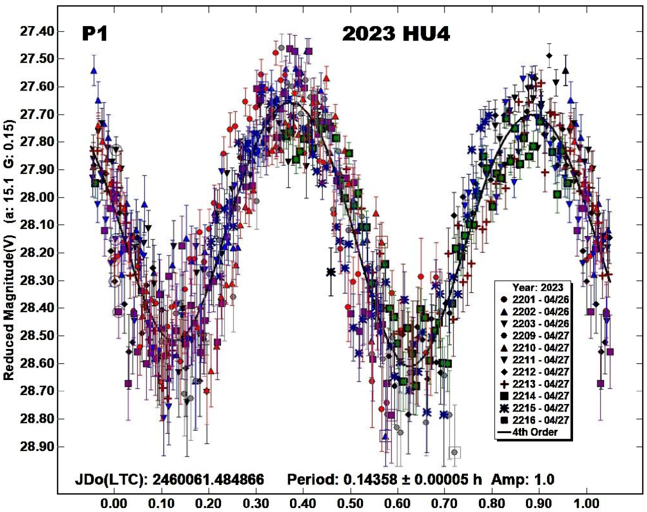
<u>2023 HU4</u>. The Catalina Sky Survey discovered this small Apollo (H = 26.8, est. size 13 m) on 2023 Apr. 25.2 UTC, 2 days before an approach to 1.4 LD (Bacci et al., 2023a). It was observed for 21 minutes starting on 2023 Apr. 26.98 UTC, then 40 minutes later observed for a further 56 minutes. During that time, it was 1.5 LD from Earth, its apparent speed accelerated from 132 to 145 arcsec/min. and exposures were kept between 3.6 and 3.9 s. A period spectrum indicates a number of potential solutions at multiples of 0.07 h.

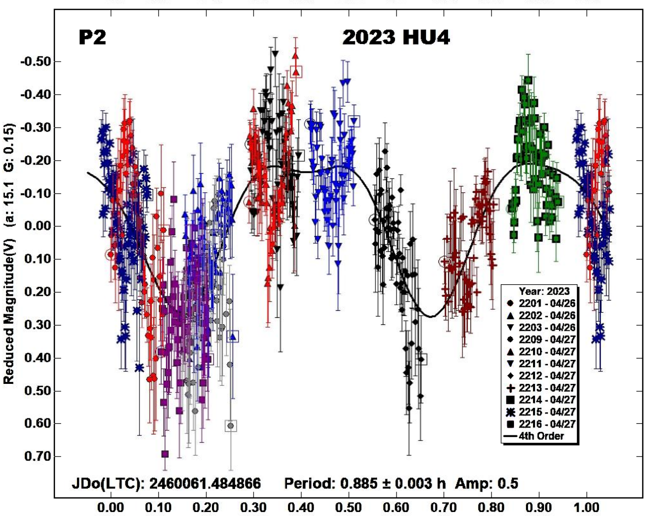


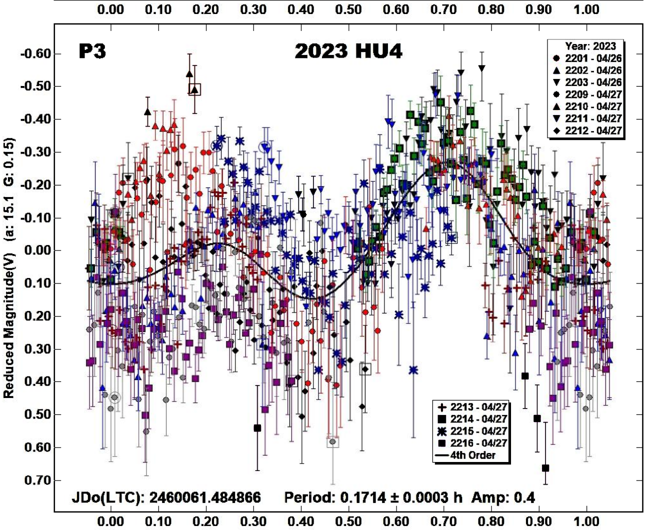
Initial analysis in *MPO Canopus* shows a strong 1 magnitude amplitude lightcurve with a period of 0.14361 ±0.00007 h, but some indications of systematic trends in the data points can be seen in the plot labelled PAR.



The *MPO Canopus* Dual Period Analysis function was used to check whether tumbling motion could be detected and the best fit was obtained with the dominant main period of 0.14358 ± 0.00005 h and a secondary period of 0.885 ± 0.003 h, see plots labelled P1 and P2. However, another solution, with somewhat larger residuals was also obtained, again identifying the same dominant P1 period, but with a secondary period of 0.1714 ± 0.0003 h, see plot labelled P3. It is noted that the frequencies of these candidate solutions are related, i.e., 1/P1 - 1/P2 = 1/P3. The dominant P1 period is well determined but the second period is ambiguous, either of the P2 or P3 periods are possible. However, it is expected that on the scale defined in Pravec et al. (2005) this may still be rated as PAR = -3, (NPA rotation reliably detected with the two periods resolved. There may be some ambiguities in one or both periods) (Petr Pravec, personal communication). The full amplitude suggested by the NPA solutions is 1.3 magnitudes.



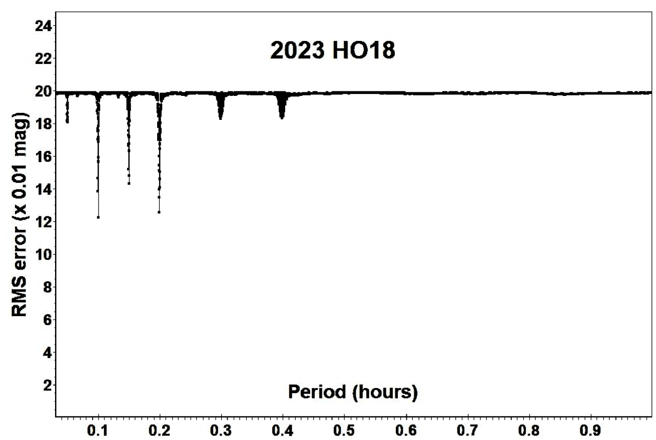


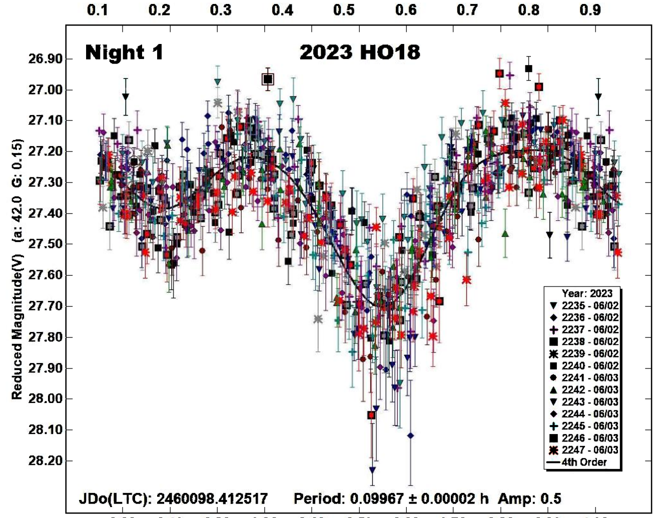


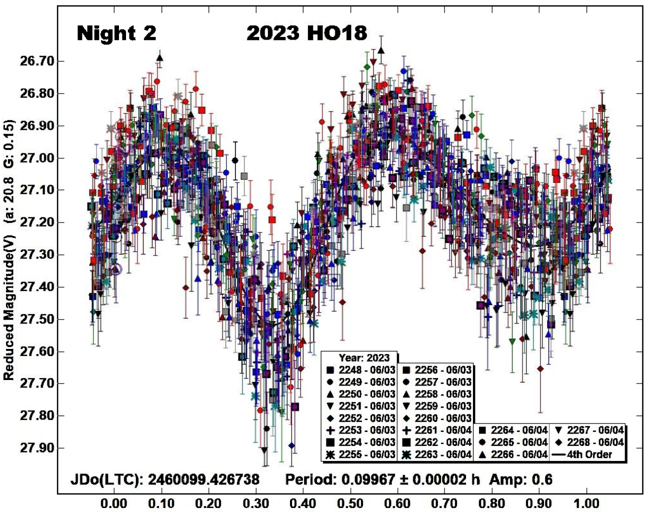
<u>2023 HO18</u>. With H = 25.5 and an est. diameter of 24 m this Apollo is the largest of the objects reported here. It was discovered by the Mt. Lemmon Survey on 2023 Apr. 22.4 UTC at magnitude 22, and a close approach to 1.2 LD occurred more than a month later on 2023 June 4.7 UTC (Bacci et al., 2023b). It was observed for 4.0 h starting on 2023 June 2.91 UTC and again for 2.7 h starting on 2023 June 3.93 UTC. On the first night it was at a distance of 2.2 LD and 1.4 LD on the second with the apparent speed increasing from 36 to 92 arcsec/min. Exposures were reduced from 14 to 5.7 s as the speed increased. A period spectrum shows a minimum at 0.04984 h and at multiples of ×2, 3, 4, 6 and 8 of that value. Separate best fit solutions from the two nights give very similar bimodal lightcurves:

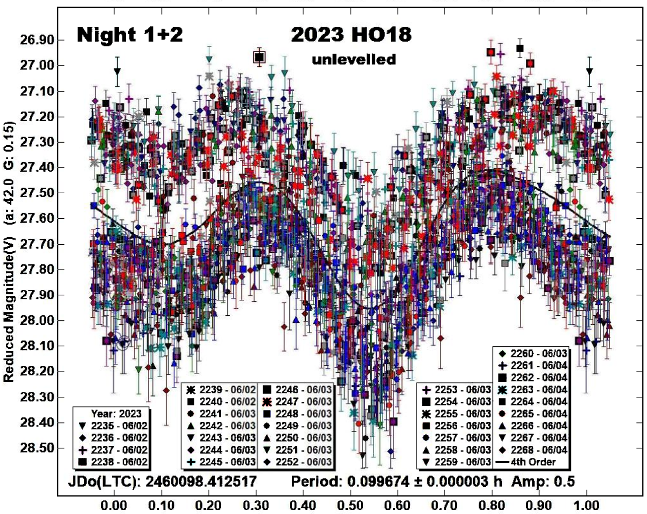
Night 1: Period 0.09967 ± 0.00002 h, amplitude 0.5
Night 2: Period 0.09967 ± 0.00002 h, amplitude 0.6

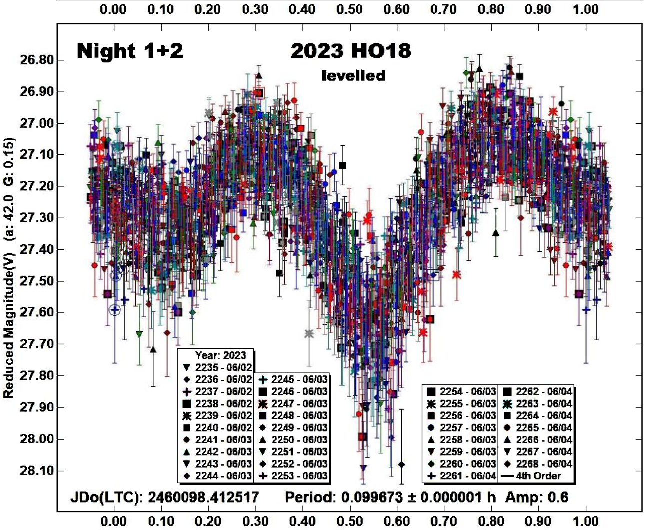
However, combining both nights with an assumed value of G = 0.15 in the H-G system results in a zero-point difference of ~0.4 magnitudes between the two nights as shown in the plot labelled Night 1+2 unlevelled. The phase angle reduced from 41.8° to 39.5° on Night 1, further reducing from 20.3° to 17.1° on Night 2. The observed magnitude of 2023 HO18 did not brighten as much as the H-G photometric model using G = 0.15 would predict for the changing phase angle. Attempts to solve for a value of G were unsuccessful, even with values of G ≫ 1. The plot labelled Night1+2 levelled was made by adjusting the zero points of the 34 individual sessions in *MPO Canopus* to minimise the overall scatter of the lightcurve, the average adjustment between the two nights was 0.44 mag, with the zero-point adjustments within the Night 1 sessions having an RMS of 0.041 and the adjustments for Night 2 an RMS of 0.047. The levelled lightcurve results in a period of 0.099673 ± 0.000001 h and amplitude 0.6 and indicates that 34 rotations were observed on Night 1 and 27 on Night 2.



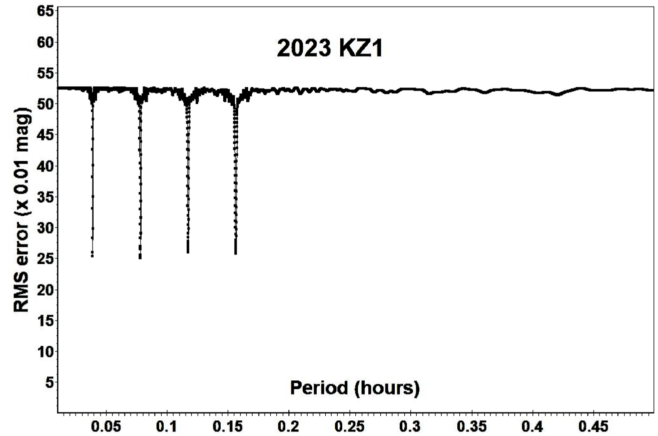


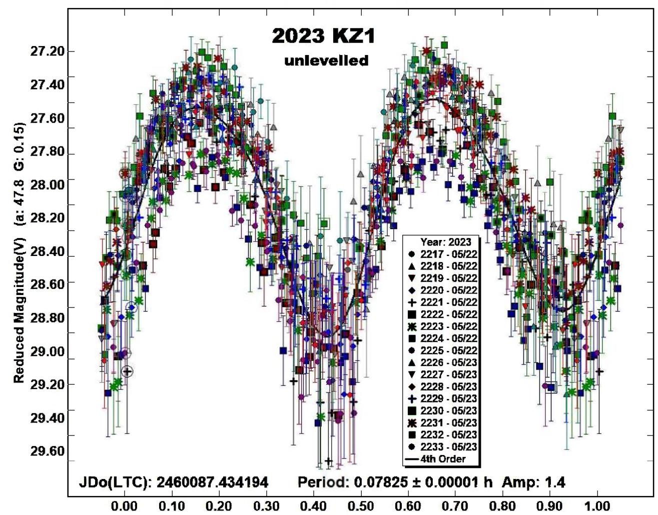




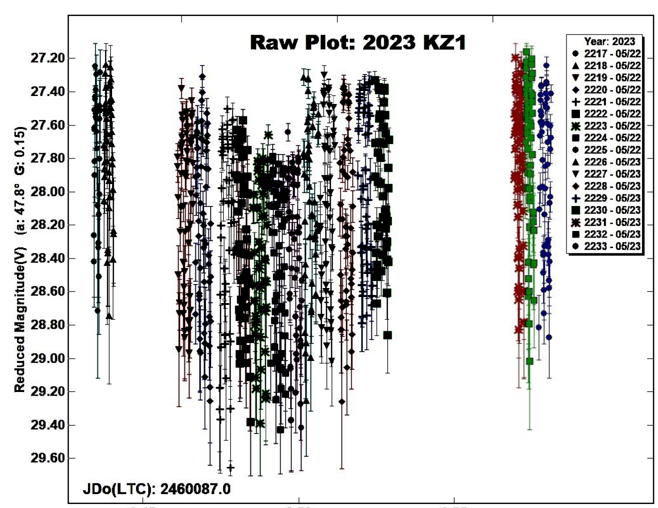


2023 KZ1. Another small Apollo, with H = 26.3, est. dia. 17 m, was discovered by the Catalina Sky Survey on 2023 May 22.4 UTC (Bacci et al., 2023c). It passed Earth at 1.0 LD on 2023 May 23.65 UTC and was under observation for 2.7 h over a 3.5 h period starting at 2023 May 22.93 UTC when it was at 2 LD. The apparent speed increased from 78 to 115 arcsec/min and exposure lengths were kept between 2 and 6 seconds throughout. A period spectrum shows a well-defined set of minima, with the best fit at 0.078 h producing a bimodal lightcurve with amplitude 1.4, shown in the plot labelled 2023 KZ1 unlevelled.





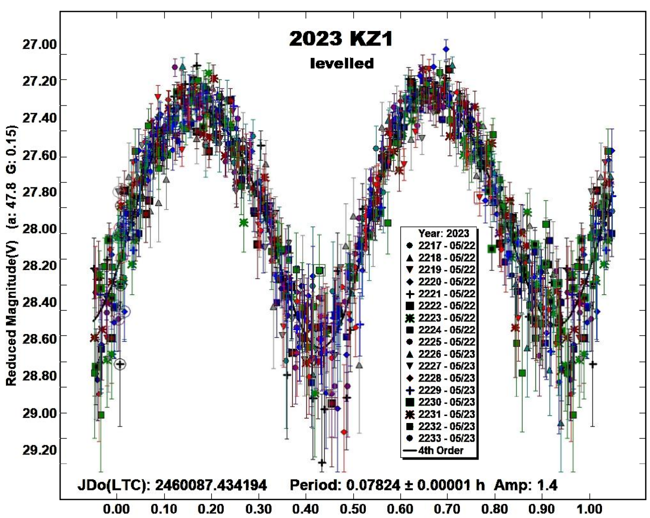
There are some trends in the data points that indicate there may be some tumbling motion present and further analysis with the *MPO Canopus* Dual Period function indicated a possible long secondary period. This variation can be seen in the raw plot, with one apparent minimum during the 3.5 h it was being observed.



Number	Name	Integration times	Max intg/Pd	Min a/b	Pts	Flds
	2023 HK	1-2.4	0.004	1.6*	1065	23
	2023 HU4	3.6-3.9	0.008	2.4	660	11
	2023 HO18	5.7-12.6	0.035	1.3	1828	34
	2023 KZ1	2-6.2	0.022	1.7*	864	17

Table I. Ancillary information, listing the integration times used (seconds), the fraction of the period represented by the longest integration time (Pravec et al., 2000), the calculated minimum elongation of the asteroid (Zappala et al., 1990), the number of data points used in the analysis and the number of times the telescope was repositioned to different fields. Note: * = Value uncertain, based on phase angle > 40°.

However, the span of observations is not long enough to determine whether this is real tumbling motion or an effect of the changing aspect or conditions during the period of observation and so it is expected that 2023 KZ1 may be rated as PAR = -1 (NPA rotation possible, i.e., deviations from a single period are seen, but not conclusively) on the scale defined in Pravec et al. (2005). A lightcurve removing the apparent long-period variations by adjusting the zero-points of the 17 individual sessions to minimise the RMS residual of the fit is labelled 2023 KZ1 levelled and gives the period as 0.07824 ± 0.00001 h with amplitude 1.4 and indicates 34 rotations were observed.



Acknowledgements

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Number	Name	2023 mm/ dd	Phase	L_{PAB}	B_{PAB}	Period(h)	P.E.	Amp	A.E	PAR	H
	2023 HK	04/19-04/20	50.5-72.3	208	31	0.09271	0.00002	0.7	0.4	-2	27.2
						0.07118	0.00001	0.7	0.4		
	2023 HU4	04/26-04/27	15.0-11.8	209	0	0.14358	0.00005	1.0	0.2	-3	26.8
						0.885	0.003	0.5	0.2		
						0.1714	0.0003	0.4	0.2		
	2023 HO18	06/02-06/04	41.8-17.1	244	12	0.099673	0.000001	0.6	0.2		25.5
	2023 KZ1	05/22-05/23	47.7-42.2	243	23	0.07824	0.00001	1.4	0.2	-1	26.3

Table II. Observing circumstances and results. The phase angle is given for the first and last date. If preceded by an asterisk, the phase angle reached an extrema during the period. LPAB and BPAB are the approximate phase angle bisector longitude/latitude at mid-date range (see Harris et al., 1984). Amplitude error (A.E.) is calculated as √2 × (lightcurve RMS residual). PAR is the expected Principal Axis Rotation quality detection code (Pravec et al., 2005) and H is the absolute magnitude at 1 au from Sun and Earth taken from the Small-Body Database Lookup (JPL, 2023).

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LIGHTCURVES AND COLORS OF FOUR SMALL NEAR-EARTH ASTEROIDS: 2020 BV14, 2023 HH3, 2023 HT3, 2023 KQ

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Photometric observations of four small, potentially fast-rotating near-Earth asteroids (NEAs) were conducted in April and May 2023. Lightcurves for three NEAs and BVRI colors for all four NEAs are reported. A relative reflectance was computed and compared with observed asteroid spectra (from SMASS and SMASSII) for each asteroid. Also, the comparison was performed with lab spectra of meteorites from the Brown University Reflectance Experiment Laboratory.

We used the Vatican Observatory's Vatican Advanced Technology Telescope (VATT), an f/1.0 telescope with a primary mirror of 1.8-m in diameter and a 0.38-m f/0.9 secondary mirror with MPC code 290 located at Mount Graham in southeastern Arizona. We used VATT4k, a CCD camera with 4064×4064 15×15 µm pixels. The data were binned two by two to reduce readout time to 30 seconds and yield a plate scale of 0.375 arcsec/pixel. VATT4K covers the visible spectrum (300-1000 nm) and has a quantum efficiency that peaks at 450 nm.

For each observing run, we took around 200 bias images and 15 dome-flat images in each filter (B, V, R, and I). The IRAF imred, ccdred, zerocombine, and flatcombine packages (Tody, 1986) were used to create a master bias and master flat in each filter. Asteroid observations were tracked at the rate of each asteroid. On each night, standard stars were observed to find a photometric zero point and extinction coefficient for each filter. We used the IRAF ccdphot, digiphot, and apphot packages for the photometry reduction. The aperture was set to twice the FWHM (Hergenrother et al., 2009; Kikwaya et al., 2019, 2022). A circular ring with a 15-pixel radius and width of 10 pixels was set to measure the sky background. We used the following filter sequence: V-R-I-B-V to get the lightcurve and colors (Fedorets et al., 2017; Tricarico, 2017; Schunova-Lilly et al., 2017). To ensure the entire lightcurve is covered, we took several V images at the sequence's beginning and end. The number of B, V, and R images is usually a third of V images. We used ALC, Petr Pravec's Asteroid Lightcurve software, to determine the lightcurve and rotation period. For colors, we computed the color indexes V-R, B-V, and V-I. To estimate the taxonomy of the object, we compared them with two-color plots (V-R versus B-V and V-R versus V-I) (Yoshida et al., 2004; Zellner et al., 1985). We computed the relative reflectance of the object

Object	yyyy mm/dd	Phase	Delta (AU)	r (AU)	H	a	e	i	Bpab	Lpab	Grp
2020 BV14	2023 04/21	25.0	0.051	1.051	23.43	2.101	0.521	2.773	197.944	6.023	Apollo
2023 HH3	2023 04/24	35.4	0.014	1.016	27.14	2.251	0.606	6.477	196.107	-6.072	Apollo
2023 HT3	2023 04/24	36.5	0.048	1.044	24.05	0.814	0.330	25.739	195.991	10.077	Aten
2023 KQ	2023 05/22	24.2	0.034	1.043	24.91	0.857	0.225	10.403	227.638	-2.218	Aten

Table I: Object name, date of observation, phase angle, delta (distance to the Earth in AU), r (distance to the Sun in AU), absolute magnitude, semi-major axis, eccentricity, inclination, Bpab, Lpab, and Grp (group the object belongs to) are reported.