

LIGHTCURVE ANALYSIS FOR SIX NEAR-EARTH ASTEROIDS OBSERVED IN 2009 AND OCTOBER - DECEMBER 2024

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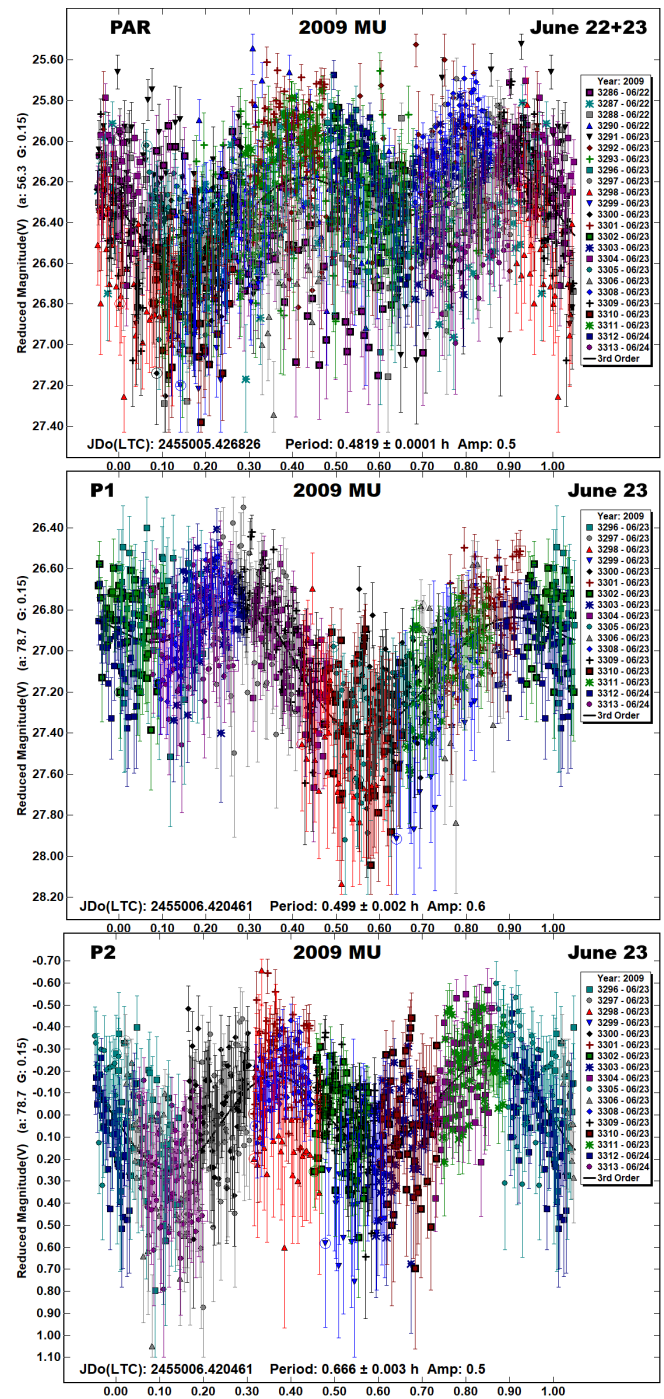
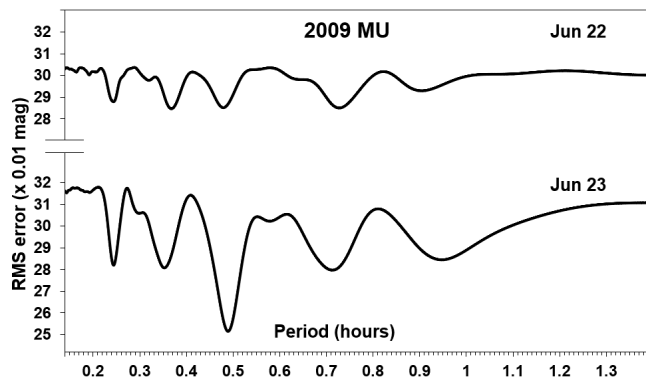
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Lightcurves and amplitudes for six near-Earth asteroids observed from Great Shefford Observatory during close approaches in June 2009 and October to December 2024 are reported. All are small objects with rotation periods 1 hour or shorter and four are identified as having tumbling rotation.

Photometric observations of near-Earth asteroids during close approaches to Earth in June 2009 and October to December 2024 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 arcsec/pix. All the images were calibrated with dark and flat frames and *Astrometrica* (Raab, 2024) was used to measure photometry using APASS Johnson V band data from the UCAC4 catalogue (Zacharias et al., 2013) and G band data from the Gaia DR2 and DR3 catalogues. *MPO Canopus* (Warner, 2023), 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, 2025) or from wider searches unless otherwise noted. All size estimates are calculated using H values from the Small-Body Database Lookup (JPL, 2025b), using an assumed albedo for NEAs of 0.2 (LCDB readme.pdf file) and are therefore uncertain and offered for relative comparison only.

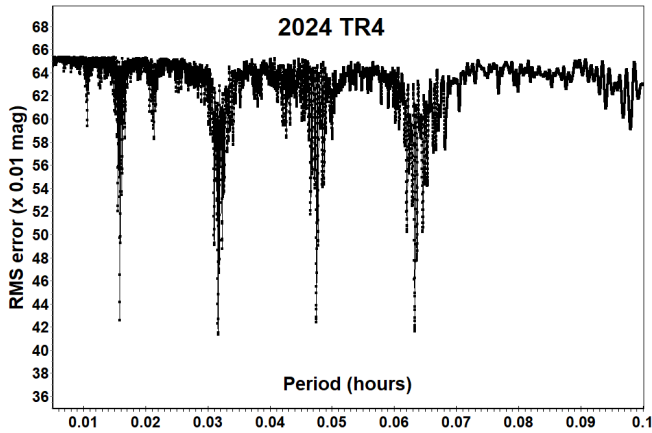
2009 MU. The Catalina Sky Survey discovered this Apollo ($H = 24.6$, $D \sim 36$ m) on 2009 Jun 19.3 UTC (Gajdos et al., 2009) and it made an approach to 2.3 Lunar Distances (LD) from Earth on 2009 Jun 24.7 UTC. It was observed for 2.8 h starting on 2009 Jun 22.93 UTC and then again for 2.1 h a day later, starting on 2009 Jun 23.92 UTC.



The viewing geometry changed appreciably between the two nights, with the distance decreasing from 5.5 to 3.1 LD, the apparent speed tripling to 100 arcsec/min and phase angle increasing from 56° to 79° . 2009 MU was about half a magnitude brighter on the second date but with shorter exposure times the SNR improved only slightly. Independent period spectrum plots from the 2 nights are given and show very similar minima, with the best fit at ~ 0.5 h, but with a related minima at ~ 0.25 h and another pair of minima at ~ 0.7 h and ~ 0.35 h. A best-fit phased lightcurve combining measurements from both nights is labelled PAR and gives a bimodal lightcurve with period of 0.4819 ± 0.0001 h, but with a large amount of scatter. The *MPO Canopus* Dual Period Search function was used to investigate possible tumbling, or non-principal axis rotation (NPAR) solutions suggested by the 0.35 h and 0.7 h minima in the period spectrum. Using the better-quality second

night, the best-fit NPAR solution gives periods of $P1 = 0.499 \pm 0.002$ h and $P2 = 0.666 \pm 0.003$ h. These lightcurves are labelled P1 and P2 but there are other possible solutions with poorer fits. With the span of observations on each night being < 3 h, not enough rotations are covered to determine a reliable solution and it is expected that it may be rated as $PAR = -2$ on the scale defined in Pravec et al. (2005) where NPA rotation is detected based on deviations from a single period but the second period is not resolved (Petr Pravec, personal communication).

2024 TR4. The ATLAS facility on Mauna Loa discovered this small Aten ($H = 26.9$, $D \sim 13$ m) on 2024 Oct 6.5 UTC. It made a very close pass to Earth, to 0.3 Lunar Distances (LD) on 2024 Oct 7.05 UTC (Buzzi et al., 2024). Observations were made for 1 h over a period of 3.4 h starting at 2024 Oct 6.80 UTC with 372 measurements being obtained. Apparent speed increased from 200 to 740 arcsec/min and exposures were reduced from 3.1 to 0.8 s to reduce image trailing. The period spectrum from an initial analysis indicates the best fit solution has a period of 0.031651 ± 0.000003 h (~ 1.9 min) and large 1.4 mag amplitude, but the resulting lightcurve labelled PAR shows strong indications of tumbling (NPA) rotation.



Using the *MPO Canopus* Dual Period Search function to find an NPAR solution is not entirely satisfactory, but the best-fit periods P1 and P2 are:

$P1 = 0.031645 \pm 0.000003$ h (~ 1.9 min), amplitude 1.4
 $P2 = 0.021327 \pm 0.000003$ h (~ 1.3 min), amplitude 0.9

Lightcurves for this NPAR solution are labelled P1 and P2. However, other solutions for the secondary period can be resolved, but these all appear to be linear combinations of the frequencies of the best-fit P1 and P2 periods, e.g.:

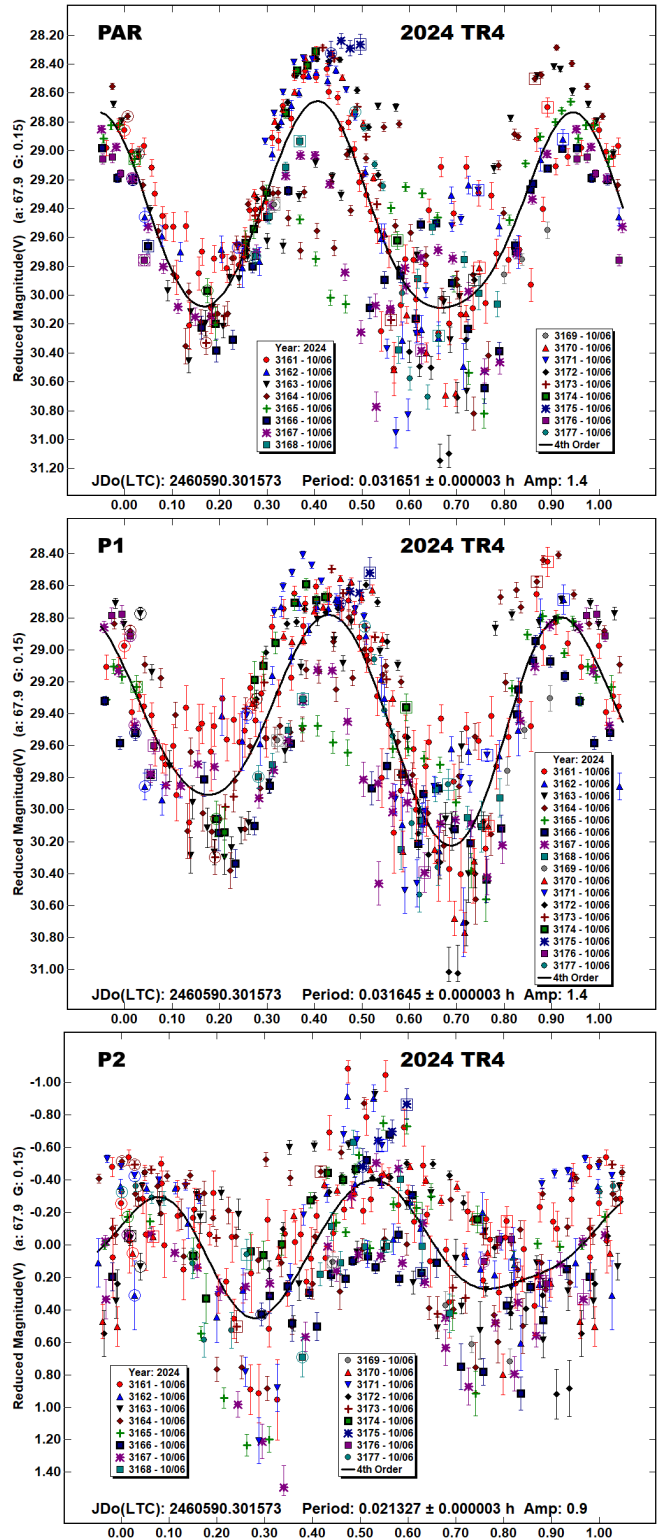
$P3 = 0.016099 \pm 0.000006$ h (~ 58 sec), amplitude 0.6
 $P4 = 0.018172 \pm 0.000005$ h (~ 1.1 min), amplitude 0.5
 $P5 = 0.025477 \pm 0.000006$ h (~ 1.5 min), amplitude 0.5

are linear combinations of the frequencies of P1 and P2, where:

$$\begin{aligned} 2/P2 - 1/P1 &= 1/P3 \\ 3/P2 - 1/P1 &= 2/P4 \\ 1/P1 + 1/P2 &= 2/P5 \end{aligned}$$

It is expected that 2024 TR4 may be rated as $PAR = -3$ (NPA rotation reliably detected with the two periods resolved. An ambiguity of the periods solution may be tolerated provided the resulting spectrum of frequencies with significant signal is the same for the different solutions.) (Petr Pravec, personal communication).

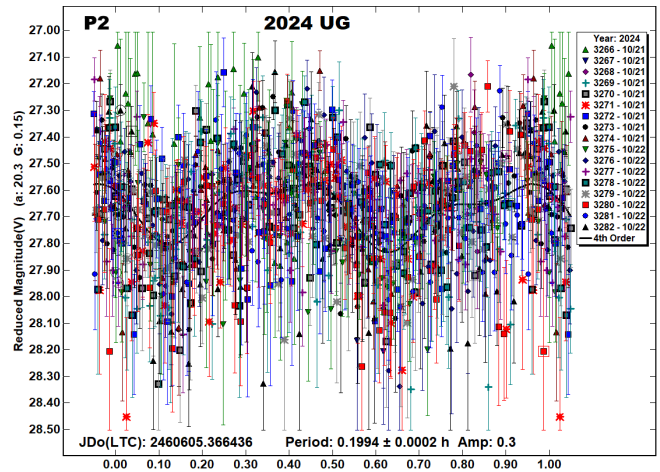
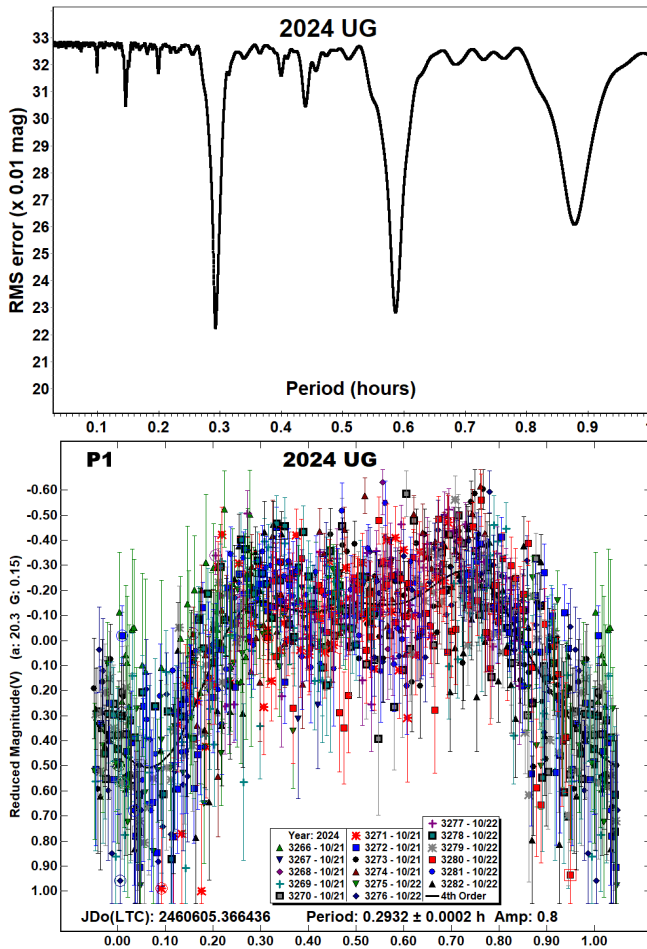
The NPAR solution indicates the full amplitude of the tumbling rotation is 2.3 mag. During the 1 h it was actively observed, 2024 TR4 completed 30 rotations of the P1 period and 44 rotations of the P2 period.



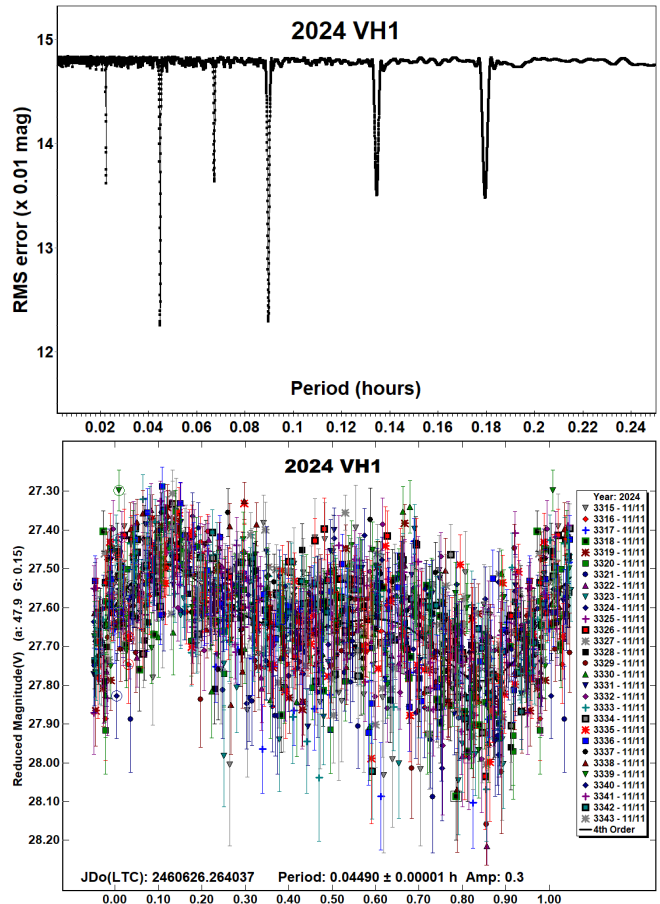
2024 UG. The ZTF collaboration discovered this Apollo ($H = 26.9$, $D \sim 12$ m) using the Palomar 1.2-m Schmidt on 2024 Oct 21.1 UTC (Bacci et al., 2024), less than 2 h after it had passed Earth at 2.7 LD. It was actively observed for 3.0 h over a period of 4.8 h starting at 2024 Oct 21.87 UTC. Apparent speed decreased from 80 to 70 arcsec/min and exposures were restricted to no more than 8.2 s to limit image trailing. Initial examination of the period spectrum shows a significant solution at 0.29 h, with related minima at integer multiples of half that value. Also present are a set of weak minima at integer multiples of 0.1 h. Tumbling was again suspected and the best-fit NPAR solution isolated using the *MPO Canopus* Dual Period Search function is:

$P1 = 0.2932 \pm 0.0002$ h, amplitude 0.8
 $P2 = 0.1994 \pm 0.0002$ h, amplitude 0.3

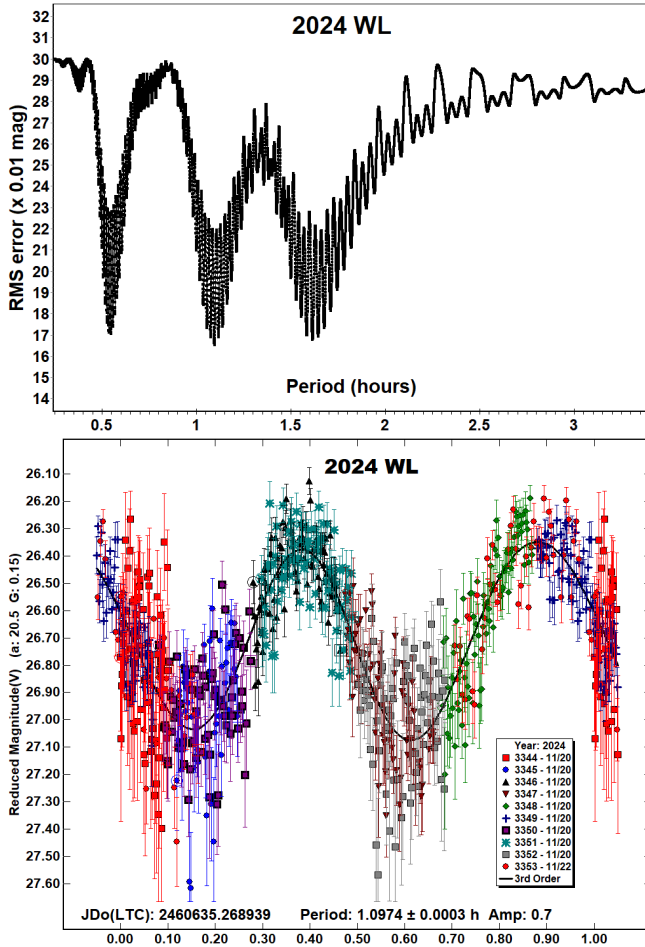
The corresponding lightcurves are labelled P1 and P2. Note that the periods are nearly but not exactly in 3:2 commensurability ($0.2932 / 0.1994 = 1.47$) and due to the 4.8 h span of observations covering 16 of the P1 rotation periods and 24 of the P2 rotation periods, the NPAR solution is expected to be reasonably secure, with a rating of PAR = -3 (NPA rotation reliably detected with the two periods resolved.) (Petr Pravec, personal communication.)



2024 VH1. This Apollo ($H = 26.6$, $D \sim 14$ m) was a Pan-STARRS 2 discovery from 2024 Nov 03.3 UTC (Heogner et al., 2024) which made an approach to 1.3 LD nine days later on 2024 Nov 12.34 UTC. It was observed on its final approach for 3.1 h starting at 2024 Nov 11.76 UTC when it was at 1.7 LD from Earth, reaching an apparent speed of 158 arcsec/min and exposures were reduced from 4.4 to 3.2 s during the session. A period spectrum shows a well-defined set of related minima, all being integer multiples of 0.0225 h and a lightcurve of the best-fit period of 0.04490 ± 0.00001 h (~ 2.7 min) is given. 2024 VH1 completed 69 rotations during the time it was under observation.



2024 WL. The ATLAS telescope at Mauna Loa discovered this Apollo ($H = 25.8$, $D \sim 21$ m) on 2024 Nov 20.4 UTC (Galli et al., 2024) some 15 h after it had passed Earth at 3 LD. It was observed for 1.8 h starting on 2024 Nov 20.77 UTC and again for 30 min starting 2024 Nov 21.99 UTC. Combining both sets of measurements indicates a best-fit solution at 1.0974 ± 0.0003 h with an amplitude of 0.7 but, with the limited coverage spanning only 1.7 rotations on the first date and 0.5 rotations on the second, this result is necessarily somewhat uncertain.



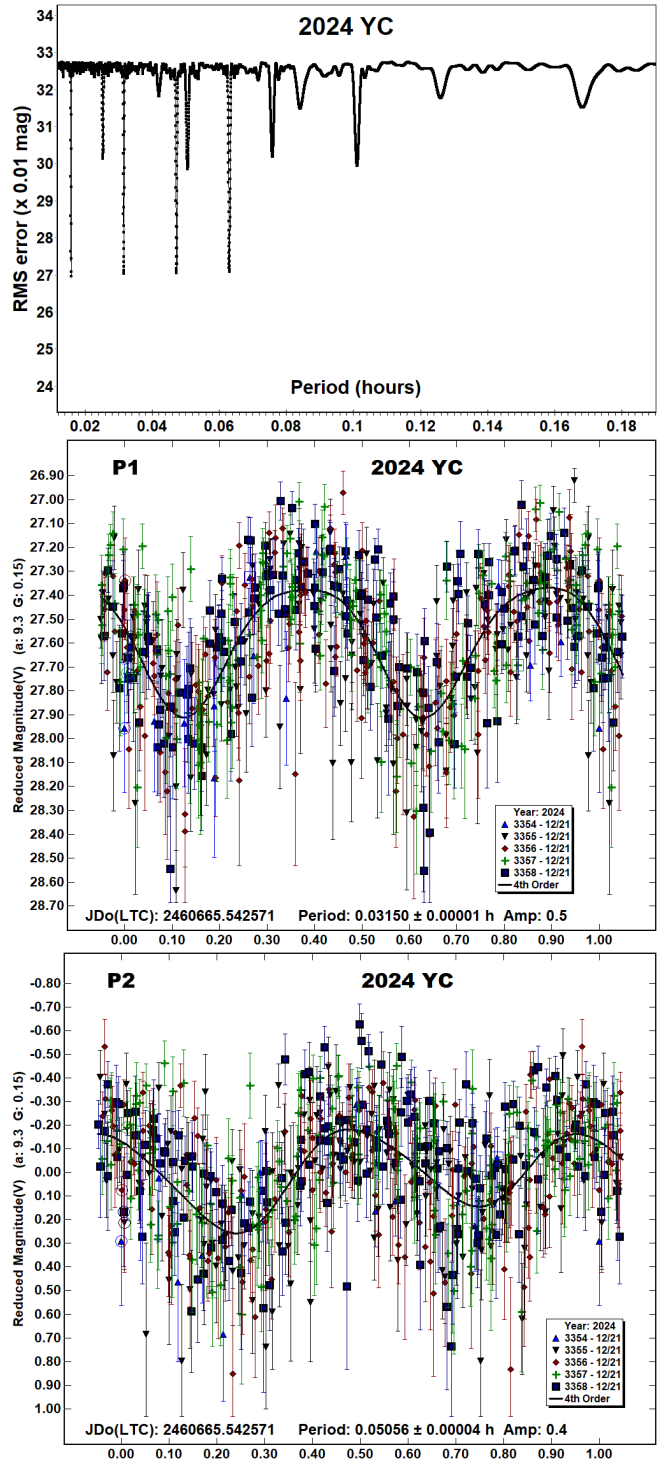
2024 YC. Another discovery of an Apollo ($H = 27.3$, $D \sim 10$ m) from the ATLAS Mauna Loa site (Kamel et al., 2024), this is listed as a virtual impactor by Sentry (JPL, 2025a) with a single low probability event in the year 2112. It made an approach to within 1.6 LD of Earth on 2024 Dec 23.0 UTC and was observed for 1.6 h starting 2024 Dec 21.04 UTC. A linearly plotted period spectrum shows several independent sets of equally spaced minima indicating that tumbling rotation is likely. The two strongest sets are at integer multiples of 0.01575 h and 0.02526 h, with a weaker set at multiples of 0.04209 h. The *MPO Canopus* Dual Period Search function located the best-fit pair of NPAR periods to be:

P1 = 0.03150 ± 0.00001 h (~ 1.9 min), amplitude 0.5
 P2 = 0.05056 ± 0.00004 h (~ 3.0 min), amplitude 0.4

The resulting lightcurves are bimodal and are given here labelled P1 and P2. A weaker NPAR solution has the same dominant P1 period with a second period, P3 = 0.0841 ± 0.0002 h (~ 5.0 min) and it is noted that the frequency of the P3 period is a linear combination of the frequencies of P1 and P2, where: $1/P1 - 1/P2 \approx 1/P3$. It is not possible to determine whether the main apparent

frequencies are the real frequencies of rotation and precession for the tumbler or just linear combinations of them. Nevertheless, it is expected that 2024 YC may be rated as PAR = -3 (NPA rotation reliably detected with the two periods resolved. An ambiguity of the periods solution may be tolerated provided the resulting spectrum of frequencies with significant signal is the same for the different solutions (Petr Pravec, personal communication).

The NPAR solution indicates the full amplitude of the tumbling rotation is 1.0 mag. 2024 YC completed 51 rotations of the P1 period and 31 of the P2 period during the 1.6 h it was under observation.



Number	Name	Integration times	Max intg/Pd	Min a/b	Pts	Flds
2009 MU		2, 6	0.003	1.3*	1643	24
2024 TR4		0.8–3.1	0.040 ¹	2.1*	372	17
2024 UG		2.5–8.2	0.011 ¹	1.9	987	17
2024 VH1		2–4.4	0.027	1.1*	1366	29
2024 WL		3.5–20	0.005	1.6	711	10
2024 YC		4–6	0.053 ¹	2.0	582	5

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°, 1 = Calculated using the shorter of the NPAR periods.

Acknowledgements

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This work has made use of data from the European Space Agency (ESA) mission Gaia (<https://www.cosmos.esa.int/gaia>), processed by the Gaia Data Processing and Analysis Consortium (DPAC, <https://www.cosmos.esa.int/web/gaia/dpac/consortium>). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement.

Number	Name	yyyy mm/dd	Phase	L _{PAB}	B _{PAB}	Period(h)	P.E.	Amp	A.E.	PAR	H
2009 MU		2009 06/23–06/24	78.6, 82.2	-121	25	0.499	0.002	0.6	0.3	-2	24.6
						0.666	0.003	0.5	0.3		
2024 TR4		2024 10/06–10/06	67.8, 61.8	38	21	0.031645	0.000003	1.4	0.5	-3	26.9
						0.021327	0.000003	0.9	0.5		
2024 UG		2024 10/21–10/22	20.3, 16.0	21	5	0.2932	0.0002	0.8	0.3	-3	26.9
						0.1994	0.0002	0.3	0.3		
2024 VH1		2024 11/11–11/11	47.6, 54.5	47	26	0.04490	0.00001	0.3	0.2		26.6
2024 WL		2024 11/20–11/22	*20.6, 5.6	54	-1	1.0974	0.0003	0.7	0.2		25.8
2024 YC		2024 12/21–12/21	9.2, 10.1	87	4	0.03150	0.00001	0.5	0.3	-3	27.3
						0.05056	0.00004	0.4	0.3		

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. L_{PAB} and B_{PAB} are the approximate phase angle bisector longitude/latitude at mid-date range (see Harris et al., 1984). Amplitude error (A.E.) is calculated as $\sqrt{2} \times$ (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, 2025b).

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LIGHTCURVES AND COLORS OF FIVE SMALL NEAR-EARTH ASTEROIDS: 2024 SY6, 2024 TU, 2024 TK1, 2024 TX13, 2024 UF9

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September 2024 and October 2024 observation campaigns resulted in photometric observations of five small near-Earth asteroids. Lightcurves of three asteroids (2024 SY6, 2024 TU, and 2024 TK1) clearly indicated rapid rotation, and those of two others (2024 TX13, and 2024 UF9) remained inconclusive. Color indices of all five asteroids were computed and were used to produce two-color plots to determine the taxonomy class of each of them, and in addition to compute their relative reflectance, which was compared to asteroid spectra (from SMASS and SMASSII) to refine the primary taxonomy classification.

We collected data with the Vatican Advanced Technology Telescope (VATT), the Vatican Observatory’s telescope with MPC code 290 located on Mount Graham in southeastern Arizona. VATT is an f/1.0 telescope with a primary mirror of 1.0 m in diameter and a 0.38-m f/0.9 secondary mirror. The instrument used was a CCD camera called VATT4k with the resolution of 4064×4064 pixels and a pixel size of 15×15 μm. Given the normal readout time of 60 seconds, we chose to bin the images two by two to reduce this to 30 seconds, yielding a plate scale of 0.375 arcsec/pixel. VATT4k covers the visible spectrum going from 300 nm to 1000 nm with a maximum quantum efficiency at 450 nm.

For each observing run, after collecting scientific data we corrected the images with master-bias, and master-flat. While the master-bias is generated from two hundred bias images using *ccdproc*, *imred*, *ccdred*, and *zerocombine* IRAF packages, the master-flat for B, V, R, and I is made from fifteen images on each filter through *imred*, *ccdred*, and *flatcombine* IRAF packages (Tody, 1986; Hergenrother et al., 2009; Kikwaya Eluo et al., 2019, 2022; Kikwaya Eluo and Hergenrother, 2024). We tracked each asteroid following its non-sidereal rate (Hergenrother et al., 2009). Consequently, stars in the field appeared smeared and could not be used for photometry. Instead, for each night we observed a certain number of standard stars in different airmasses (from 1.1 to 2.0) to compute a zero point and an extinction coefficient in each filter to apply to the asteroid according to the following formula: object (in Mag) = (zero point (in Mag) + observed object (in Mag)) - Object airmass * extinction coefficient (Hergenrother et al., 2009; Kikwaya Eluo et al., 2019, 2022; Kikwaya Eluo and Hergenrother, 2024). We set a circular ring with a 15-pixel radius, and a width of ten pixels for the background to measure the sky. We took twice the FWHM as the aperture to measure the asteroid.