

LIGHTCURVE ANALYSIS FOR SEVEN NEAR-EARTH ASTEROIDS

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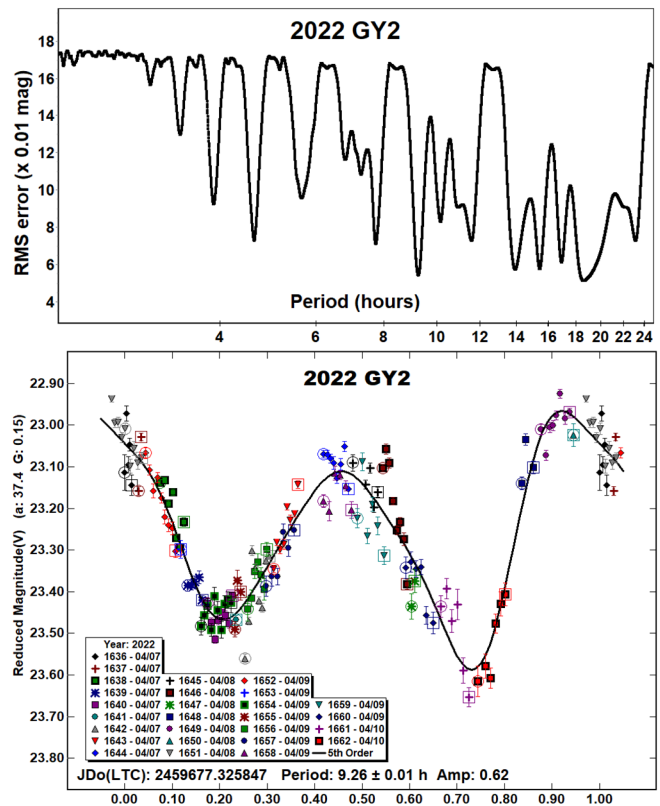
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Lightcurves and amplitudes for seven near-Earth asteroids observed from Great Shefford Observatory during close approaches between 2022 April and June are reported. Four are superfast rotators with periods $P < 1$ minute. The effects of lightcurve smoothing due to an inappropriately chosen exposure length are modelled for 2022 JL.

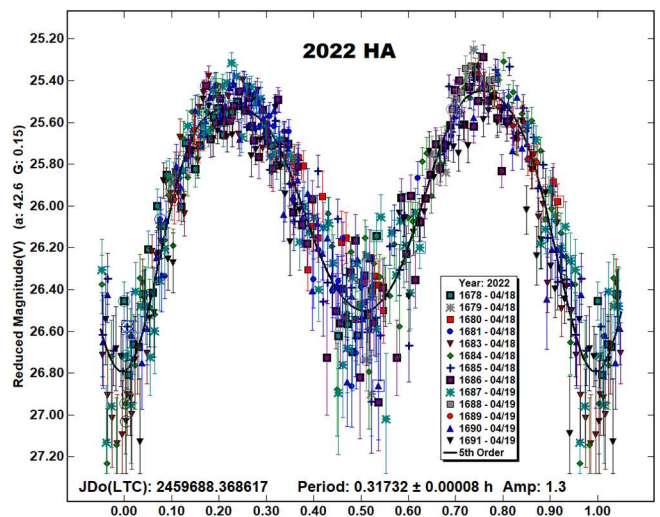
Photometric observations of near-Earth asteroids during close approaches to Earth between 2022 April and June were made at Great Shefford Observatory using a 0.40-m Schmidt-Cassegrain and Apogee Alta U47+ CCD camera. All observations were made unfiltered and with the telescope operating with a focal reducer at $f/6$. The $1K \times 1K$, 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.

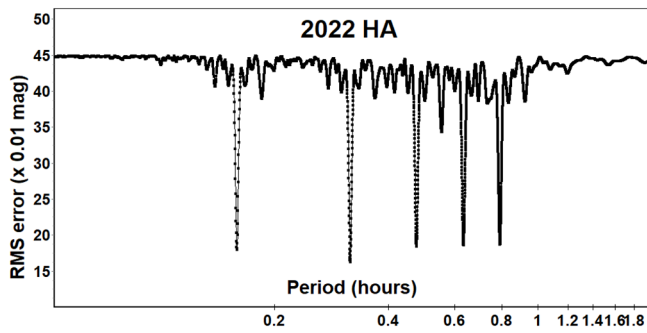
No previously reported results for any of the objects reported here have been found in the Asteroid Lightcurve Database (LCDB) (Warner et al., 2009), from searches via the Astrophysics Data System (ADS, 2022), or from wider searches unless otherwise noted. All size estimates are calculated using H values from the Small-Body Database Lookup (JPL 2022b), using an assumed albedo for NEAs of 0.2 (LCDB readme.pdf file) and are therefore uncertain and offered for relative comparison only.

2022 GY2. With $H = 21.7$ and a Minimum Orbit Intersection Distance (MOID) from Earth of 0.0011 au = 0.4 Lunar Distances (LD), this Apollo is classified by the Minor Planet Center as a PHA, a potentially hazardous asteroid, with an estimated diameter of ~135 m. It was a mag 15 discovery from the ATLAS-HKO, Haleakala site on 2022 Apr 7 (Serrano et al., 2022) and was observed over the next three nights, fading from mag +16.2 to +18.0 during that time. Initial measurement of the 2549 usable images obtained showed variation over several hours. The images were then stacked using *Astrometrica* to produce 154 data points, with each measurement typically combining 16 images. A period spectrum from continuous observation of 5.9 h on Apr 7, 4.4 h on Apr 8 and 4.8 h on Apr 9 indicated the lightcurve is probably bimodal with a period of 9.26 h with the data points covering almost the entire lightcurve. A quadrimodal solution at 18.5 h also fits the data but with the limited coverage, is rejected in favour of the shorter period. The longest effective exposure (Δt), from start of the first to the end of the last exposure in any one stack was 10.4 minutes and so $\Delta t / P = 0.019$, indicating that lightcurve smoothing due to the stacking process is negligible (Pravec et al., 2000).

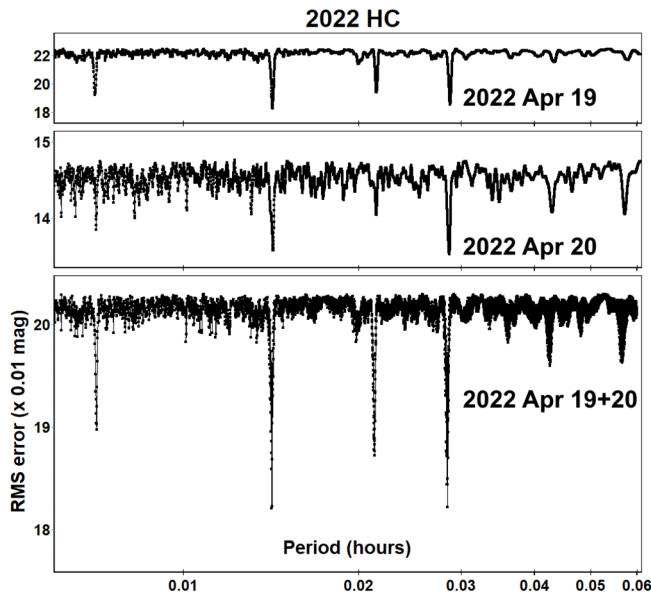


2022 HA. This Aten, with an estimated diameter of ~40 m, was discovered by the ZTF team at Palomar on 2022 Apr 18.37 UTC, just three hours before a close approach to within 7 LD of Earth (Bacci et al., 2022a). It was observed for 5.8 h starting at 2022 Apr 18.87 UTC and initial 4 s exposures did not show any significant variability between consecutive images. With the apparent motion of 50 arcsec/min, exposures were then lengthened to 10 s and 585 usable images obtained. Although relatively faint at mag +17, conditions were good and the resulting lightcurve reveals a large amplitude and rotation period of 19 minutes, meaning that 18 revolutions occurred during the observing session.

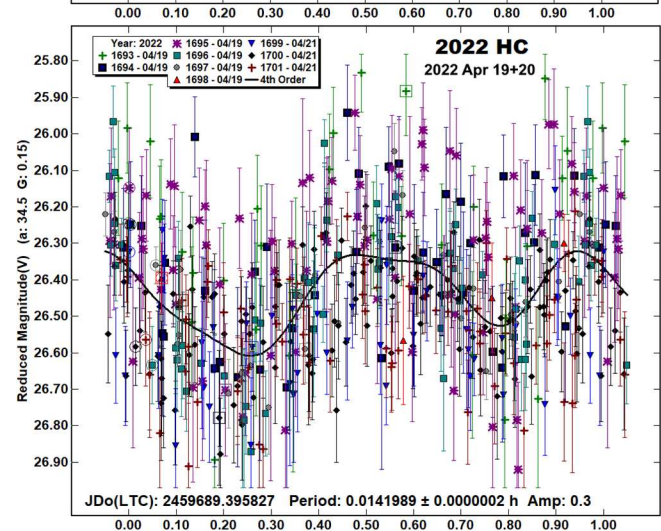
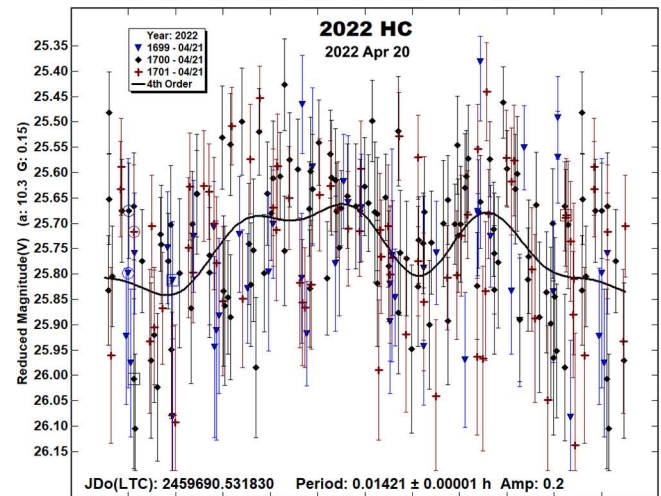
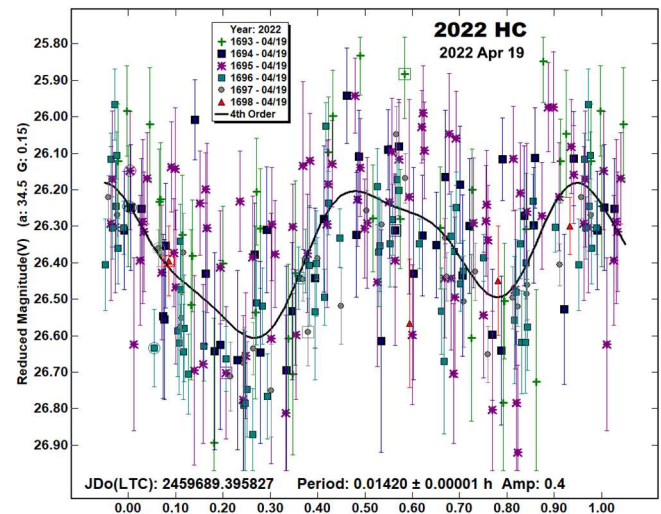




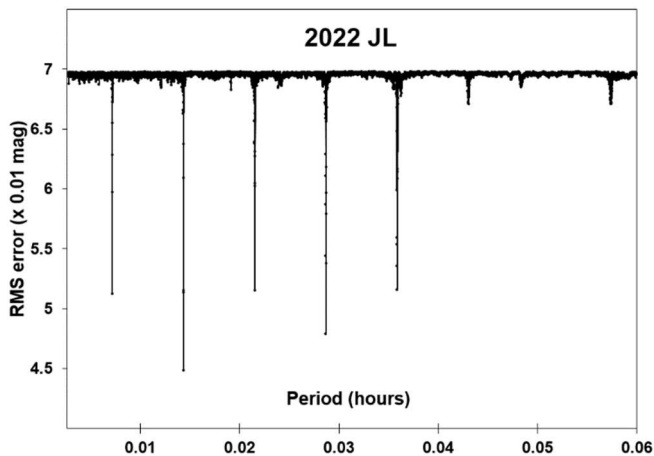
2022 HC. This was a discovery made on 2022 Apr 19.52 UTC by the 1.05-m Schmidt at the Tokyo-Kiso station, about eight hours after an approach to 3 LD of Earth (Bacci et al., 2022b). With $H = 25.1$, its estimated diameter is ~ 28 m. Observations were made on 2022 Apr 19.92 UTC for 78 min when its sky motion was 90 arcsec/min and again on Apr 21.05 UTC for 62 min when sky motion had decelerated to 30 arcsec/min. Although fading as it receded from Earth, the 1.2 mag decrease in brightness due to changing geometry was partially offset by the expected ~ 0.8 mag brightening due to the phase angle reducing from 34° to 10° . On both nights, it was relatively faint, with significant noise in the measurements, but, especially on the first date, very short-term magnitude variations were obvious. Exposures were limited to between 2-6 s on the first date and 8 s on the last. Independent period spectra from the two dates are given here, together with a solution combining data from both dates, showing that very similar periodicities are detected in the data from the two nights.



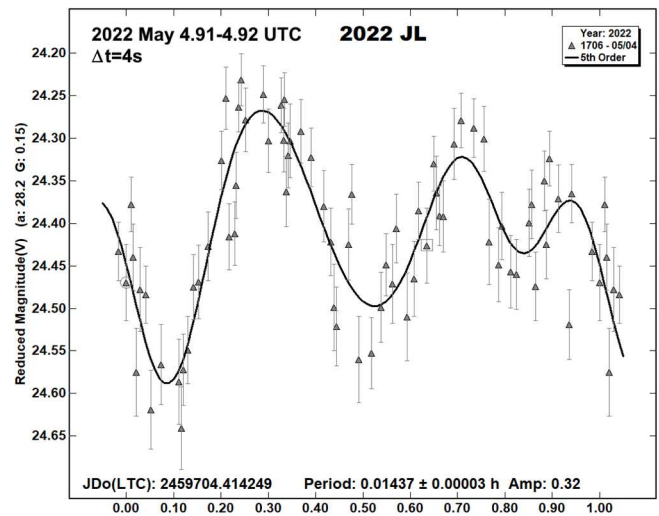
Although the lightcurves are very noisy, as expected the amplitude is seen to decrease as the phase angle reduced. The lightcurve from the combined nights indicates that the period is 51 seconds and that 91 and 72 revolutions, respectively, would have occurred during the periods of observation on the two nights.



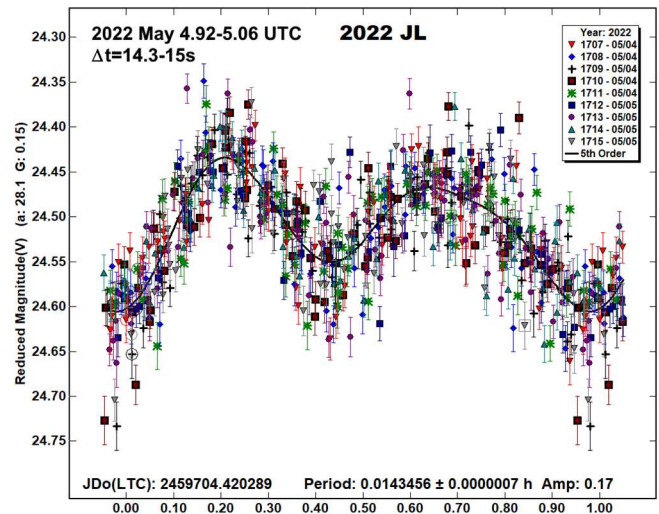
2022 JL. Another Apollo, it was discovered at mag +16 by the Catalina Sky Survey on 2022 May 3 (Melnikov et al., 2022a) just a few hours past its closest approach to 6 LD. With $H = 23.36$, it has an estimated size of ~ 63 m. Even though receding from Earth, with increasing elongation from the Sun and decreasing phase angle, its magnitude peaked about 0.5 mags brighter two days after discovery. It was observed for 7.5 minutes starting on 2022 May 4.91 UTC to measure astrometry and with motion of 35 arcsec/min, 72 usable images were obtained with 4 s exposures. Images were visually checked for any rapid change in brightness but nothing was obvious. Exposures were then increased immediately afterwards to 14.3-15 s, for an extended run of 3.3 h to gather images for photometry. When both set of images were measured it was obvious that the rotation period was actually very short. The linearly scaled period spectrum spanning 10 s to 3.6 minutes indicates the best fitting solution has a rotation period of $P = 0.014$ h (52 s).



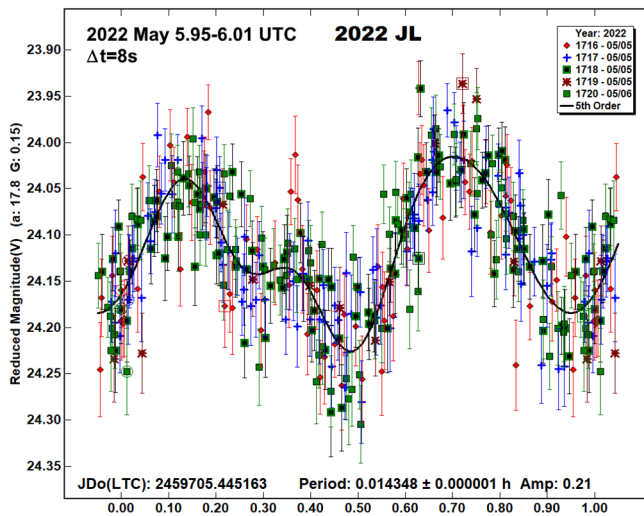
This result implies the exposure length, Δt , during the photometry run was long enough to cause significant lightcurve smoothing, where $\Delta t/P$ reached 0.290. The next night provided another opportunity to observe 2022 JL and this time exposure length was set at 8 s, where $\Delta t/P = 0.155$ was chosen as a good compromise between maximising signal to noise ratio (at $\Delta t/P = 0.185$) and minimising lightcurve smoothing (Pravec et al., 2000). The resulting lightcurves, from exposure lengths of 4 s, then 14.3-15 s, both from 2022 May 4.91-5.06 UTC, and finally 8 s from 2022 May 5.95-6.01 UTC, show the effects of lightcurve smoothing on the shape of the lightcurve due to the different exposure lengths, the rotation period itself being secure in each analysis. Three independent phased reductions are given, the first, with $\Delta t = 4$ s shows a small minimum occurring at phase = 0.84 and a third maximum at phase = 0.94 in what would otherwise be a bimodal lightcurve, with amplitude 0.32.



The second set of observations, with $\Delta t = 14.3-15$ s was started by chance about 8.7 minutes = 10.1 rotations later than the start of the first lightcurve, so the main features are similarly positioned in the two phased diagrams. There is no dip at the equivalent point in the second lightcurve, at phase = 0.75, indeed the Fourier curve shows a small hump in the overall descent between phase 0.64 and 0.98. The amplitude is also significantly smaller at 0.17.



The third phased plot, centred on 2022 May 5.98 UTC, with $\Delta t = 8$ s and with a different zero point for the phased curve, does again show the small minimum, this time at phase = 0.28 and a small increase in overall amplitude from the previous lightcurve, at 0.21.



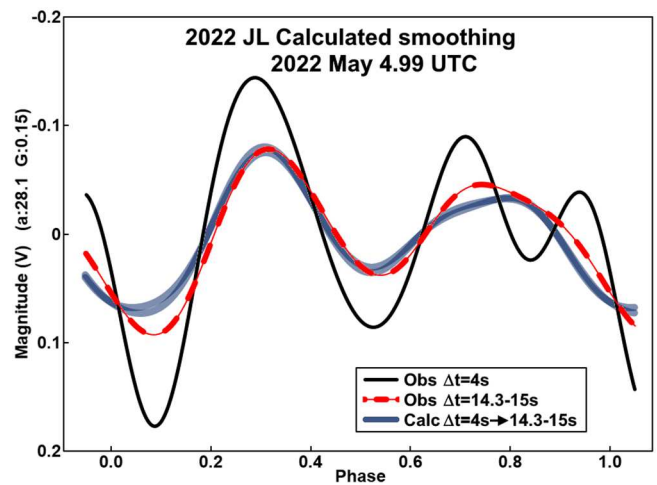
To model the effects of lightcurve smoothing, the factors $f_1 - f_5$ that would be expected to reduce the first five Fourier coefficients of the true lightcurve for the range of exposures used were calculated and are listed in Table I, together with the corresponding fraction of the rotation period.

Δt	$\Delta t/P$	f_1	f_2	f_3	f_4	f_5
4	0.077	0.99	0.96	0.91	0.85	0.77
8	0.155	0.96	0.85	0.68	0.48	0.27
14.3	0.277	0.88	0.57	0.19	-0.10	-0.21
15	0.290	0.87	0.53	0.14	-0.13	-0.22

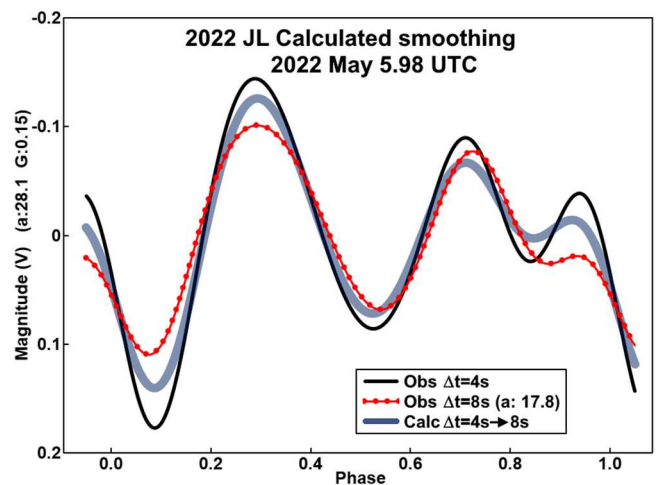
Table I. Factors f_n reducing the strength of the first five harmonics in the lightcurve of 2022 JL for exposure length values of Δt (seconds) and rotation period of 51.64 s. (see Pravec et al., 2000).

It can be seen that the factors for $\Delta t = 14.3$ and 15 s are significant, e.g., for the normally dominant 2nd harmonic its strength will be almost halved, the 3rd harmonic reduced to less than 20% of its true strength and for the 4th and 5th harmonics, the factors are negative, indicating that their contribution to the smoothed lightcurve will be in the opposite sense of their true value.

Taking the observed $\Delta t = 4$ s curve as the least affected by smoothing, its calculated Fourier coefficients were adjusted by $1/f$ to approximate the true coefficients before smoothing. These were then reduced using the factors f_n for values of $\Delta t = 14.3$ and 15.0 s on the first night and $\Delta t = 8$ s on the second night to produce estimates of the smoothing of the $\Delta t = 4$ s curve due to the longer exposure times. The “Calculated smoothing” phased plot for May 4.99 UTC shows Fourier curves taken directly from the *MPO Canopus* reductions of the $\Delta t = 4$ s measurements (thin black line) and $\Delta t = 14.3 - 15$ s (dashed red line). Two almost coincident thicker blue lines are calculated from the $\Delta t = 4$ s curve by applying the factors for $\Delta t = 14.3$ and 15.0 s as described above, simulating how the $\Delta t = 4$ s curve would appear if the longer exposures had been used.

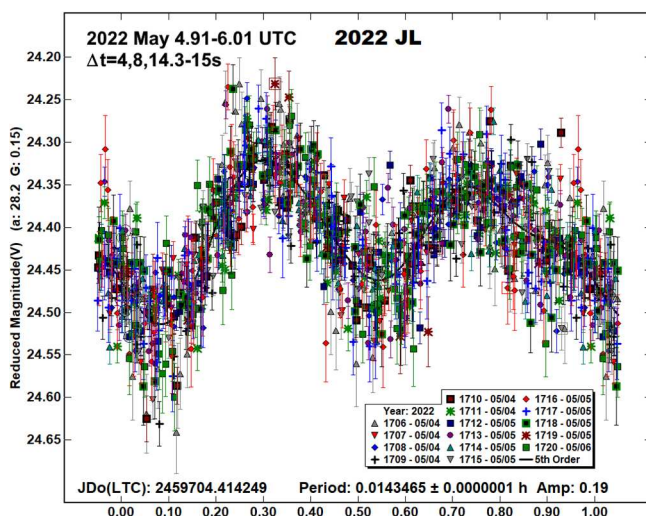


The calculated curve represents the observed lightcurve for $\Delta t = 14.3-15$ s well, including the disappearance of the small minimum at phase = 0.84 and a reduction in amplitude to 0.15. A similar phased diagram for May 5.98 UTC shows the equivalent comparison of the observed curves for $\Delta t = 4$ s (thin black line) and 8 s (dotted red line) together with a thick blue line calculated from the $\Delta t = 4$ s curve by applying the factors for $\Delta t = 8$ s.



The $\Delta t = 4$ s feature at phase = 0.84 is evident in the calculated curve but reduced in scale. As expected, the calculated overall amplitude is reduced due to smoothing, to 0.27, though not as much as the observed amplitude of 0.21 for the $\Delta t = 8$ s curve. However, on that second night, 2022 JL was at phase angle $a = 17.8^\circ$, and therefore the amplitude observed on that date would be expected to be somewhat smaller than the previous night, when $a = 28.1^\circ$.

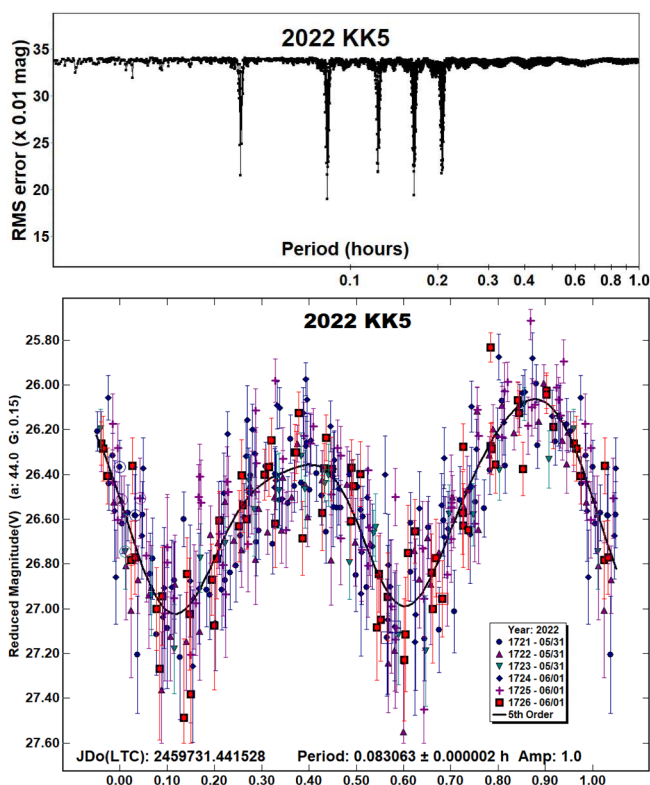
Using the measurements from both nights, the period is further refined, though the lightcurve shape has extra scatter due to the different degrees of lightcurve smoothing. Small zero-point adjustments with an RMS of 0.06 were applied to the 15 *MPO Canopus* sessions (for each time the telescope was repositioned), to reduce the overall scatter.



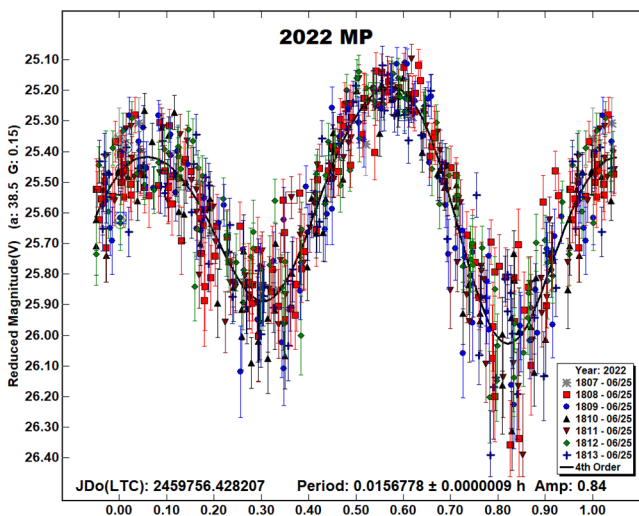
Mid-time	Δt	Pts/ Flds	Span (h)	Period(h)	P.E	Rotns	Amp
4.92	4	72/1	0.12	0.01437	0.00003	8	0.32
4.99	15	630/9	3.34	0.0143456	0.0000007	232	0.17
5.98	8	362/5	1.56	0.014348	0.000001	108	0.21

Table II. Details of periods of observation of 2022 JL, where Mid-time is the day in 2022 May (UTC), Δt is the longest exposure utilized (seconds), Pts is the number of data points used in the reduction, Flds is the number of times the telescope was repositioned to different fields, Span is the time from first to last measurement used, Rotns is the number of rotations completed during the Span and Amp is the Amplitude from the Fourier curve derived from the observations.

2022 KK5. This Apollo was another discovery made by the 1.05-m Schmidt at the Tokyo-Kiso station, first detected on 2022 May 29.56 UTC at mag +17 and less than four hours after an approach to within 3.5 LD of Earth (Melnikov et al., 2022b). Pre-discovery astrometry was reported from the Catalina Sky Survey from 2.4 days before and orbit solutions from Sentry (JPL 2022a) list 2022 KK5 as a virtual impactor with the earliest possible impact predicted for May 2043 with a probability of 1 in 7,700. It was observed from Great Shefford on 2022 May 31.96 UTC and 2022 June 1.98 UTC, on both occasions for just over one hour and on both nights large amplitude magnitude variations were apparent over a timescale of a few minutes. It had faded by about 0.5 mag on the second night as it receded from Earth but on both nights was visible on all images, where exposures ranged from 8 to 16 seconds. The period spectrum shows the best fit solution has a period of just under 5 minutes and the lightcurve indicates an amplitude of nearly 1 magnitude. About 13 rotations occurred during the first period of observation and 14 rotations during the second. Assuming a phase-relation slope parameter $G = 0.15$, the absolute magnitude (H) derived from the solution is 24.87 ± 0.19 which implies a diameter about 10% larger than the ~ 28 m diameter inferred from the value of $H = 25.09 \pm 0.40$ given in the Small-Body Database Lookup (JPL 2022b).



2022 MP. This Aten was discovered at mag 18 at the ATLAS Mauna Loa facility on 2022 June 21 (Bacci et al., 2022c). It was observed on 2022 June 21 and June 22 and was seen to show large magnitude variations in 10s of seconds but was too faint for reliable photometry. When 2022 MP was next observed, on 2022 June 25, it was within 0.1 mags of its peak brightness for the apparition at mag +16.



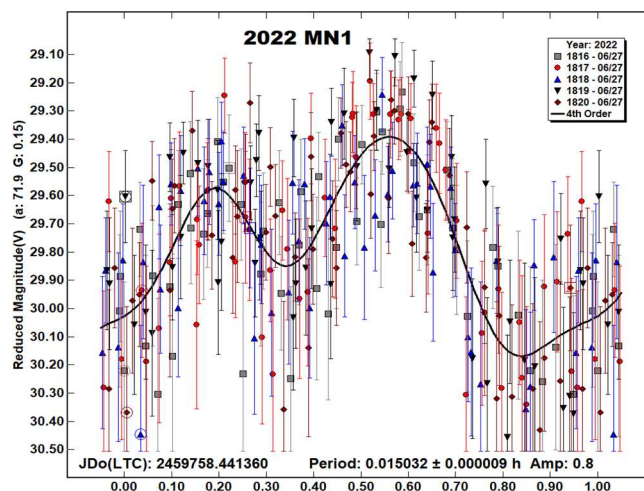
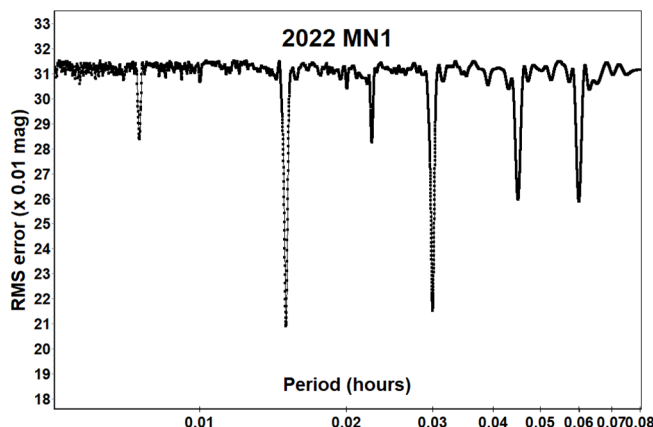
	2022 mm/ dd	Phase	L _{PAB}	B _{PAB}	Period(h)	P.E.	Amp	A.E	H
2022 GY2	04/07-04/10	37.4-28.7	181	2	9.26	0.01	0.6	0.1	21.69
2022 HA	04/18-04/19	42.5-47.5	198	20	0.31732	0.00008	1.3	0.2	24.39
2022 HC	04/19-04/21	34.3-9.9	203	9	0.0141989	0.0000002	0.3	0.3	25.10
2022 JL	05/04-05/06	28.2-17.3	223	12	0.0143465	0.0000001	0.32*	0.08*	23.38
2022 KK5	05/31-06/02	43.9-45.0	255	22	0.083063	0.000002	1.0	0.3	25.09
2022 MP	06/25-06/25	38.4-38.3	261	15	0.0156778	0.0000009	0.8	0.2	23.97
2022 MN1	06/27-06/27	71.9-73.0	248	24	0.015032	0.000009	0.8	0.3	27.30

Table III. 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 $\sqrt{2} \times (\text{lightcurve RMS residual})$. H is the absolute magnitude at 1 au from Sun and Earth taken from the Small-Body Database Lookup (JPL, 2022b). Note: * Values are taken from the lightcurve from 2022 May 4.91-4.92 UTC (with minimal lightcurve smoothing).

A set of 6 and 8 second exposures were obtained over a period of 1.6 h and the analysis of the 573 usable images shows a large amplitude asymmetrical bimodal lightcurve with a period of 56.4 seconds, indicating that 101 rotations occurred during image capture. About 76% of the images were from 6 s exposures, the remainder 8 s. The 6 and 8 s exposure lengths as a fraction of the period are 0.106 and 0.142, respectively, and therefore no significant smoothing of the lightcurve shape is to be expected (Pravec et al., 2000). The 6 s exposure length is likely to have caused the observed amplitude to be ~ 0.07 mags less than the real amplitude and the 8 s exposure length equivalently ~ 0.15 mags less, both reductions being smaller than the likely error in amplitude of 0.16 due to measurement uncertainty.

2022 MP was also observed by Radar from Goldstone on 2022 June 25 (Benner, 2022), where it is noted that T. Lister had reported a rotation period of 28 s (or possible 56 s) and a lightcurve amplitude of 0.5 magnitudes. These figures are in good agreement with the results determined in this paper. The Radar result includes the statement, “If we adopt the preliminary period of 28 seconds reported by T. Lister, then the bandwidth of ~ 300 Hz places a lower bound on the maximum pole-on extent of 23 meters (or double that if the period is 56 seconds).” Taking the 56 s period derived in this paper and a value of $H = 23.97 \pm 0.31$ (JPL, 2022b), the size estimate of 46 m implies an albedo of 0.23 ± 0.06 for 2022 MP.

2022 MN1. The Pan-STARRS 2 team discovered this Apollo at mag +22 almost exactly one week before it passed Earth at 0.9 LD (Wainscoat et al., 2022). With $H = 27.3$, its diameter is ~ 10 m. It was followed during its approach on 2022 June 27 for 28 minutes, when it was mag +17, at a range of 1.3 LD, and moving at 160 arcsec/min. Exposures were limited to 3.2 s or less to keep trailing of the object within the measurement annulus of *Astrometrica*.



Although relatively faint, it was showing obvious variations in brightness between consecutive images taken with a cadence of 4-5 s and a period spectrum indicates the best fit to the data is a solution with a period of 54 s. The overall RMS residual of the lightcurve is 0.2 mag, contributing to another rather noisy lightcurve.

Integration Times					
Name	Min/Max	intg/Pd	a/b	Pts	Flds
2022 GY2	621 ²	0.019	1.3	154	27
2022 HA	9.6-10.1	0.009	1.7	585	13
2022 HC	2-8	0.157	1.2	469	9
2022 JL	4-15	0.290	1.2	1064	15
2022 KK5	8-16	0.054	1.5	348	6
2022 MP	6, 8	0.142	1.4	573	7
2022 MN1	3.1, 3.2	0.059	1.3	264	5

Table IV. 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 (Kwiatkowski et al., 2010), the number of data points used in the analysis and the number of times the telescope was repositioned to different fields. Note: Σ = Longest elapsed integration time for stacked images (start of first to end of last exposure used).

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References

- ADS (2022). Astrophysics Data System.
<https://ui.adsabs.harvard.edu/>
- Bacci, P.; Maestrupieri, M.; Tesi, L.; Fagioli, G.; Coffano, A.; Marinello, W.; Micheli, M.; Pizzetti, G.; Soffiantini, A.; Buzzi, L.; Ikari, Y.; Dupouy, P.; Emmerich, M.; Melchert, S.; Koch, B.; and 40 colleagues (2022a). “2022 HA.” *MPEC* **2022-H08**.
<https://minorplanetcenter.net/mpec/K22/K22H08.html>
- Bacci, P.; Maestrupieri, M.; Tesi, L.; Fagioli, G.; Buzzi, L.; Beniyama, J.; Ikari, Y.; Emmerich, M.; Melchert, S.; Koch, B.; Lindner, P.; Jahn, J.; Urbanik, M.; Birtwhistle, P.; Gerhard, C.; and 11 colleagues (2022b). “2022 HC.” *MPEC* **2022-H12**.
<https://minorplanetcenter.net/mpec/K22/K22H12.html>
- Bacci, P.; Maestrupieri, M.; Tesi, L.; Fagioli, G.; Dupouy, P.; Urbanik, M.; De Pieri, A.; Holmes, R.; Linder, T.; Horn, L.; Losse, F.; Birtwhistle, P.; Sioulas, N.; Lombardo, M.; Lombardo, K.; and 13 colleagues (2022c). “2022 MP.” *MPEC* **2022-M35**.
<https://minorplanetcenter.net/mpec/K22/K22M35.html>
- Benner, L.A.M. (2022). “Goldstone Radar Observations Planning: (441987) 2010 NY65, 2022 LV, and 2022 MP.”
<https://echo.jpl.nasa.gov/asteroids/2010NY65/2010NY65.2022.goldstone.planning.html>
- 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.
- Harris, A.W.; Young, J.W.; Bowell, E.; Martin, L.J.; Millis, R.L.; Poutanen, M.; Scaltriti, F.; Zappala, V.; Schober, H.J.; Debehogne, H.; Zeigler, K. (1989). “Photoelectric Observations of Asteroids 3, 24, 60, 261, and 863.” *Icarus* **77**, 171-186.
- JPL (2022a). Sentry: Earth Impact Monitoring.
<https://cneos.jpl.nasa.gov/sentry/>
- JPL (2022b). Small-Body Database Lookup.
https://ssd.jpl.nasa.gov/tools/sbdb_lookup.html
- Kwiatkowski, T.; Buckley, D.A.H.; O’Donoghue, D.; Crause, L.; Crawford, S.; Hashimoto, Y.; Kniazev, A.; Loaring, N.; Romero Colmenero, E.; Sefako, R.; Still, M.; Vaisanen, P. (2010). “Photometric survey of the very small near-Earth asteroids with the SALT telescope - I. Lightcurves and periods for 14 objects.” *Astron. Astrophys.* **509**, A94.
- Melnikov, S.; Hoegner, C.; Laux, U.; Ludwig, F.; Stecklum, B.; Bacci, P.; Maestrupieri, M.; Tesi, L.; Fagioli, G.; Aschi, S.; Pettarin, E.; Kowalski, R.A.; Christensen, E.J.; Fay, D.; Fazekas, J.B.; and 32 colleagues (2022a). “2022 JL.” *MPEC* **2022-J30**.
<https://minorplanetcenter.net/mpec/K22/K22J30.html>
- Melnikov, S.; Hoegner, C.; Laux, U.; Ludwig, F.; Stecklum, B.; Beniyama, J.; Wada, S.; Pettarin, E.; Hogan, J.K.; Gray, B.; Rankin, D.; Shelly, F.C.; Dupouy, P.; Jahn, J.; Holmes, R.; and 13 colleagues (2022b). “2022 KK5.” *MPEC* **2022-K158**.
<https://minorplanetcenter.net/mpec/K22/K22KF8.html>
- Pravec, P.; Hergenrother, C.; Whiteley, R.; Sarounova, L.; Kusnirak, P.; Wolf, M. (2000). “Fast Rotating Asteroids 1999 TY2, 1999 SF10, and 1998 WB2.” *Icarus* **147**, 477-486
- Raab, H. (2018). *Astrometrica* software, version 4.12.0.448.
<http://www.astrometrica.at/>
- Serrano, A.; Christensen, E.J.; Farneth, G.A.; Fazekas, J.B.; Fuls, D.C.; Gibbs, A.R.; Grauer, A.D.; Groeller, H.; Hogan, J.K.; Kowalski, R.A.; Larson, S.M.; Leonard, G.J.; Rankin, D.; Seaman, R.L.; Shelly, F.C.; and 42 colleagues (2022). “2022 GY2.” *MPEC* **2022-G114**.
<https://minorplanetcenter.net/mpec/K22/K22GB4.html>
- Wainscoat, R.; Wells, L.; Burdullis, T.; Weryk, R.; Bulger, J.; Lowe, T.; Schultz, A.; Smith, I.; Chambers, K.; Dukes, T.; Chastel, S.; de Boer, T.; Fairlamb, J.; Gao, H.; Huber, M.; and 7 colleagues (2022). “2022 MN1.” *MPEC* **2022-M61**.
<https://minorplanetcenter.net/mpec/K22/K22M61.html>
- Warner, B.D.; Harris, A.W.; Pravec, P. (2009). “The Asteroid Lightcurve Database.” *Icarus* **202**, 134-146. Updated 2021 Dec.
<https://minplanobs.org/mpinfo/php/lcdb.php>
- Warner, B.D. (2022). MPO Software, *MPO Canopus* version 10.8.6.9. Bdw Publishing, Eaton, CO.
- Zacharias, N.; Finch, C.T.; Girard, T.M.; Henden, A.; Bartlett, J.L.; Monet, D.G.; Zacharias, M.I. (2013). “The Fourth US Naval Observatory CCD Astrograph Catalog (UCAC4).” *Astron. J.*, **145**, 44-57.