LIGHTCURVE ANALYSIS FOR NINE NEAR-EARTH ASTEROIDS

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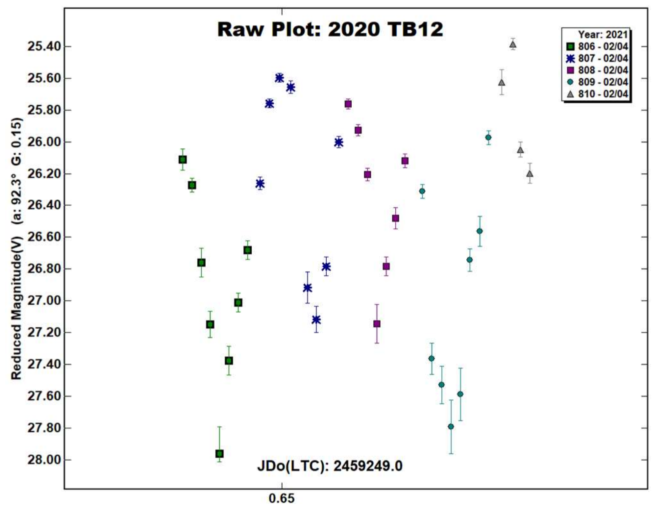
Lightcurves and amplitudes for nine near-Earth asteroids observed from Great Shefford Observatory during close approaches in 2021 are reported: 2020 TB12, 2020 YE5, 2021 AU, 2021 CO, 2021 DP, 2021 DX1, 2021 EB1, 2021 EX1 and 2021 FH. All have rotation periods faster than the 2.2h spin barrier and five appear to show signs of tumbling.

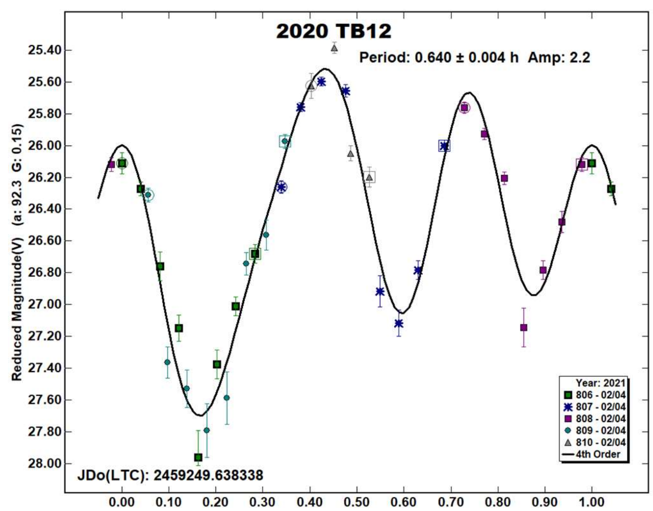
Photometric observations of near-Earth asteroids during close approaches to Earth during January - March 2021 were made at Great Shefford Observatory using a 0.40-m Schmidt-Cassegrain and Apogee Alta U47+ CCD camera. All observations were made unfiltered and with the telescope operating with a focal reducer at f/6. The 1K×1K, 13-micron CCD was binned 2×2 resulting in an image scale of 2.16 arcsec/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. *MPO Canopus* (Warner, 2021), incorporating the Fourier algorithm developed by Harris (Harris et al., 1989) was used for lightcurve analysis.

All the objects were discovered on or after the last available update of the LCDB (Warner et al., 2009) and therefore no previous results for any of the objects are contained therein. Searches of the Astrophysics Data System (ADS, 2021) have also not found any previously reported results for any of the nine objects. Other sources of information for previously reported results are listed against each object where appropriate.

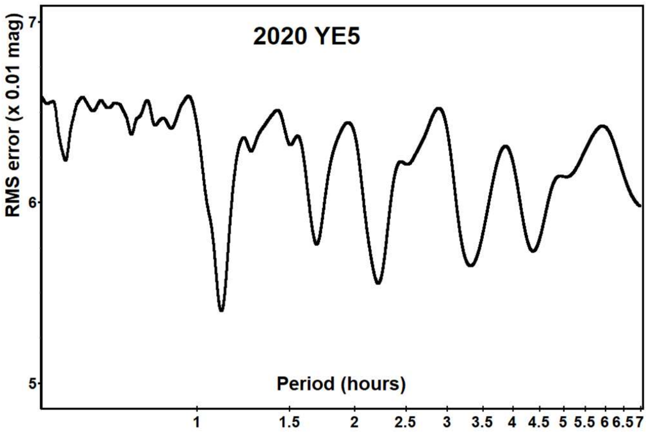
<u>2020 TB12</u>. Discovered on 2020 Oct 15 by Pan-STARRS1 (Mastaler et al., 2020), this Apollo made an approach to within 7 Lunar Distances (LD) on 2021 Feb 1 and was observed on 2021 Feb 4 for 1 hour at a range of 9 LD and at a phase angle of >90°. It is classed as a Potentially Hazardous Asteroid (PHA) by the Minor Planet Center (MPC, 2021a), PHAs defined as having a Minimum Orbit Intersection Distance (MOID) < 0.05 AU and $H < 22.0$. The MPC lists 2020 TB12 with MOID = 0.009 and $H = 21.7$, though JPL (2021) lists H as 22.16, just outside the PHA limit and the JPL value implies a diameter of ~108 m assuming a default NEO albedo of $p_v = 0.20$ (Warner et al., 2009).

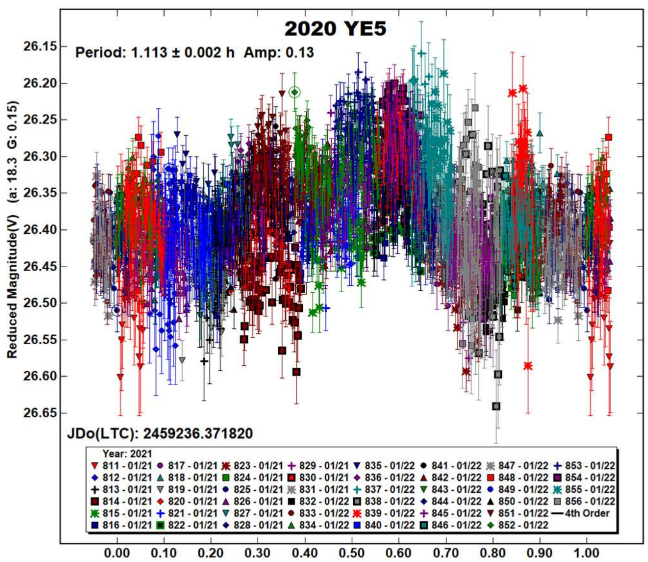
333 usable images were collected with exposures limited to 8 s due to the sky motion of 24 arcsec/minute. Large variations in magnitude were obvious over a period no shorter than several minutes, so the individual images were stacked using *Astrometrica* into 35 groups comprising a maximum of 10 images in each to enhance the signal to noise ratio. Individual stacks contained exposures over a time span of no more than 90 s. It is apparent from the raw plot that there are 5 unequal maxima and 4 minima, Canopus manages to represent the points well with a period of 0.640 ± 0.004 h but the curve suggests the likelihood of some tumbling being present, with none of the maxima or minima repeating. From this reduction it is therefore expected to be rated as PAR = -1 (Non-Principal Axis rotation possible, but not conclusively) on the scale of Pravec et. al. (2005). The only previously reported result located for 2020 TB12 (Pravec, 2021) lists it with a rating of PAR = -2 (NPA rotation detected based on deviations from a single period but the second period is not resolved) from observations made between 2021 Jan 8 - 15 and gives P_1 = 0.6294 ± 0.0001 h with a second period P_2 = 0.41951 ± 0.00005 h. The current analysis is therefore in reasonable agreement with the primary period from the earlier study.





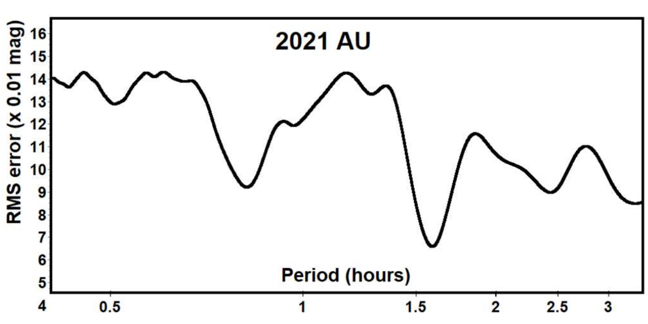
<u>2020 YE5</u>. This small, ~21 m diameter, Apollo object was discovered with the 6.5-m reflector at Las Campanas Observatory on 2020 Dec 18 (Sheppard et al., 2021) at mag +23 and made a close approach to 1.1 LD on 2021 Jan 22.6 UTC. It was followed during its approach, starting at 2021 Jan 21.87 UTC for 6.4 hours. During this interval its distance from Earth ranged from 2.0 to 1.6 LD and the apparent speed increased from 90 to 160 arcsec/min. Exposures were limited to a maximum of 4.1 s to keep trailing of the NEO within a 3-pixel radius annulus in *Astrometrica* and a total of 3237 measurements were made. The lightcurve is of low amplitude, implying a relatively spherical object or possibly pole-on aspect. Phase angle increased from 19° to 30° during the period observed.

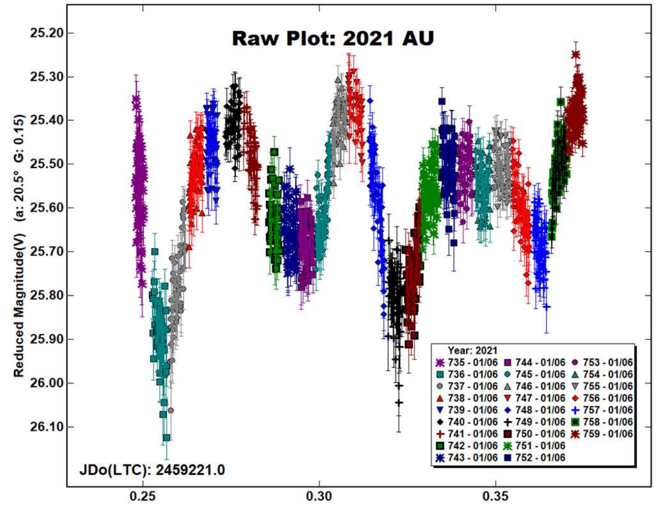


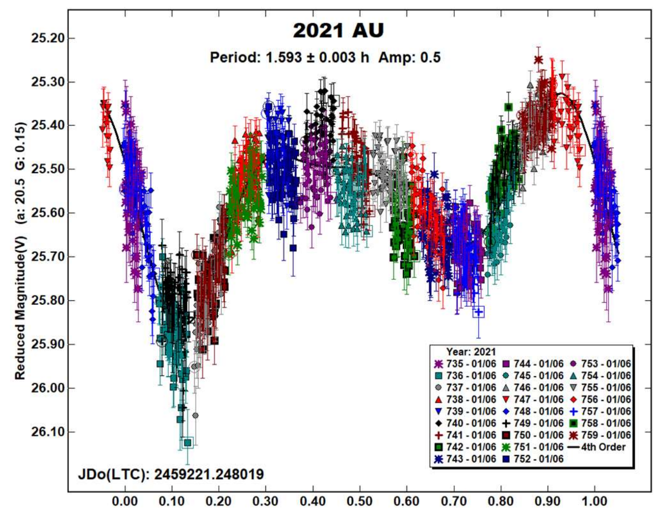


2021 AU. Another small (~39 m diameter) Apollo, discovered at 17th mag by the ATLAS 0.5-m reflector on Mauna Loa (Groeller et al., 2021) on 2021 Jan 4 and reached 15th mag during an approach to 3.5 LD on 2021 Jan 6.85 UTC. It was observed for 3 h at the point of closest approach, when the apparent speed was 114 arcsec/min and exposures were limited to 3.5 s to keep trailing short.

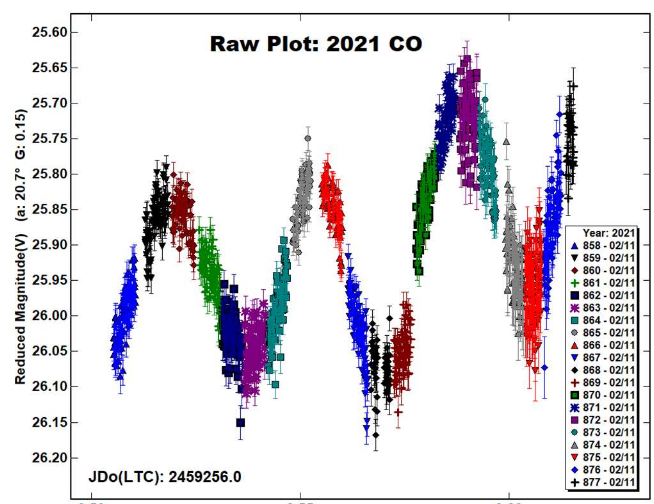
The raw plot from *MPO Canopus* shows 0.5 mag variations peaking every ~45 minutes and suggestive of a bimodal solution. However, the secondary maxima show significant differences in amplitude and shape of curve, especially on the descending slope, indicating that the body may be tumbling. A phased bimodal solution gives a period of 96 min, implying less than two rotations were observed, insufficient to resolve NPA rotation and so it is expected to be rated as PAR = -1.

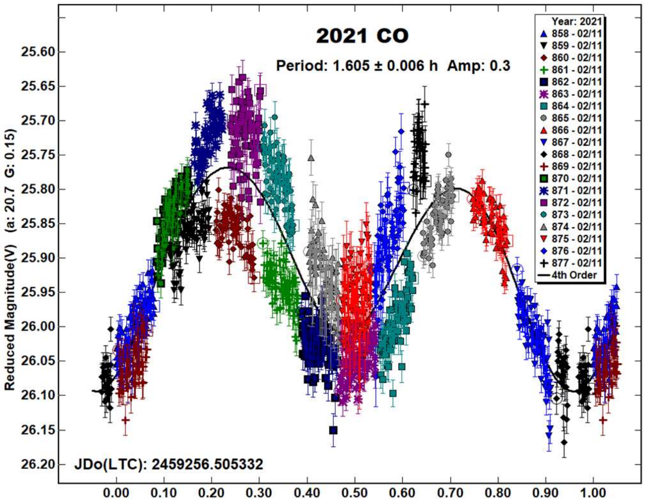






2021 CO. This was a discovery by the Catalina Sky Survey on 2021 Feb 5 (Wierzchos et al., 2021) and made a close approach to 0.95 LD on 2021 Feb 11.64 UTC. The SBDB (JPL, 2021) lists it with H = 25.3, implying a size of ~26 m. It was observed for 2.6 h from 2021 Feb 11.00 UTC when it was 14th mag and moving at 100+ arcsec/min, with exposures kept to a maximum length of 3.8 s.

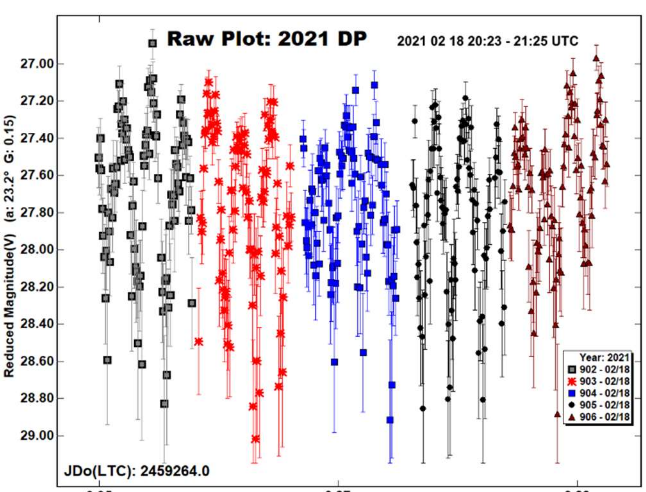


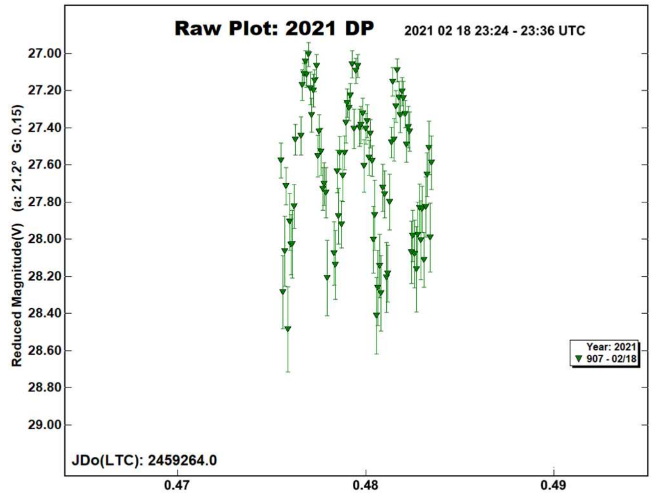


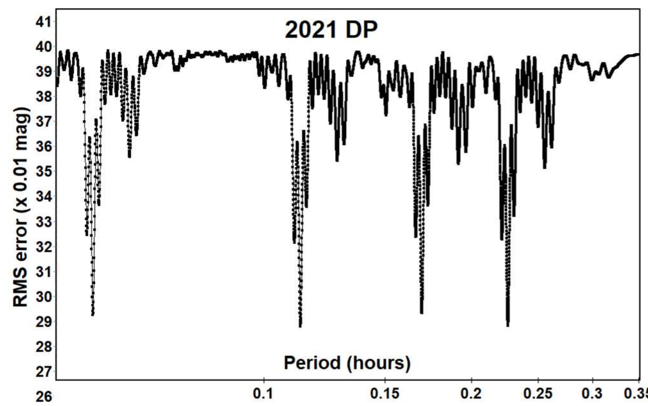
Strong variations are shown on the raw plot, but similarly to 2020 TB12 and 2021 AU, although a dominant periodic variation is evident, there are significant deviations from what would be expected if it were in simple principal axis rotation. The period of observation covers 3 maxima and minima, not enough to properly characterise the variations, therefore this is expected to be another candidate for rating as PAR = -1.

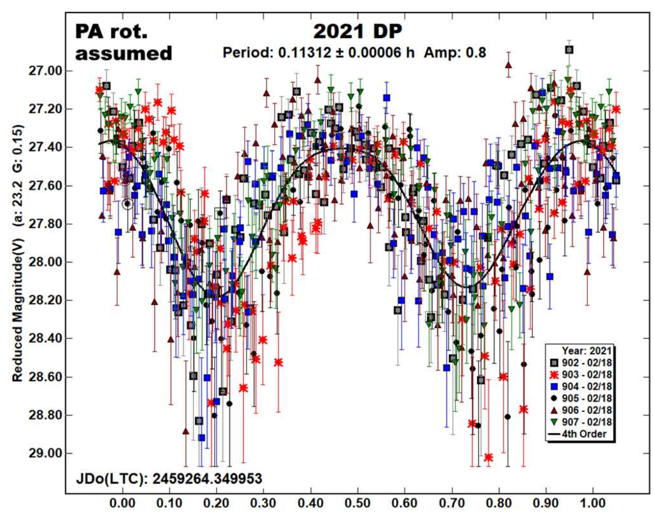
2021 DP. A ZTF team discovery from Palomar (Dupouy et al., 2021), this small ~14-m sized Apollo had passed Earth at 2.9 LD about 4 hours before discovery on 2021 Feb 18. It was under observation from Great Shefford for 61 minutes that same day, the telescope being repositioned five times due to the sky motion of 19 arcsec/min. Two hours later it was observed again for a period of 12 minutes. Large regular variations in brightness are evident in the raw plots from both periods of observation.

However, the height of maxima appears to vary semi-regularly and suggests the possibility of some non-principal axis rotation. The period spectrum indicates the dominant variation has a period of 0.11312 h and a phased plot labelled "PA rot. assumed" shows the resulting bimodal lightcurve assuming principal axis rotation, with significantly more scatter than the individual data point error bars would imply.

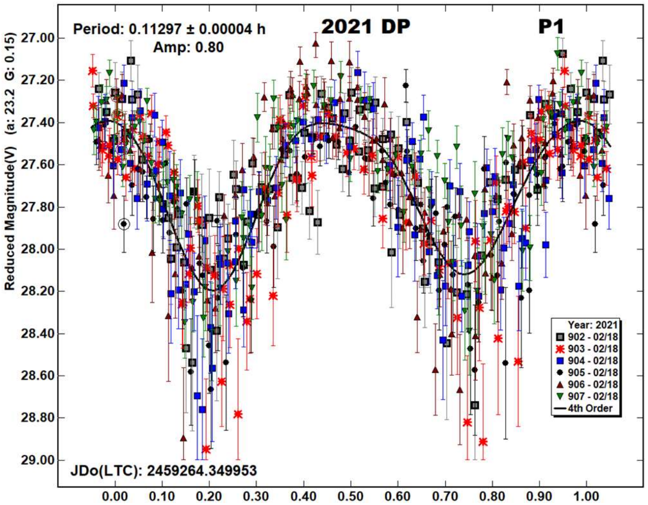


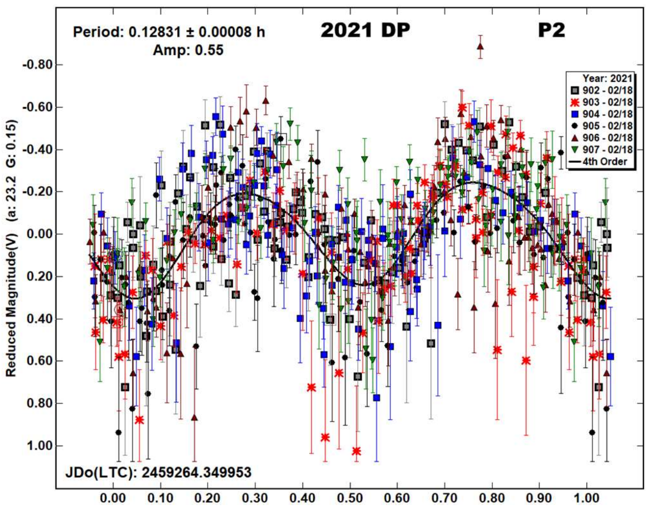






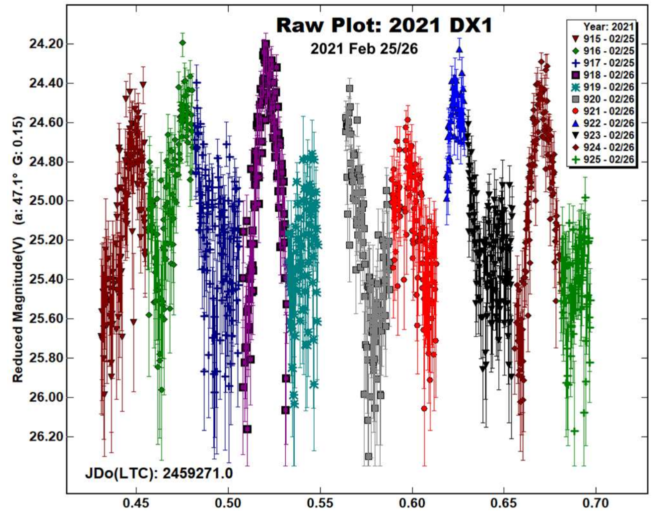
The Dual-Period Search function within *MPO Canopus* was used to see if removing the effect of the dominant lightcurve would reveal any residual NPAR periodicity. After several iterations the dominant variation was refined to 0.11297 ± 0.00004 h with an amplitude of 0.80 mags, and a second period revealed with an almost sinusoidal bimodal lightcurve with period 0.12831 ± 0.00008 h and amplitude 0.55 mags. Phased lightcurves are given for these, labelled P1 and P2.



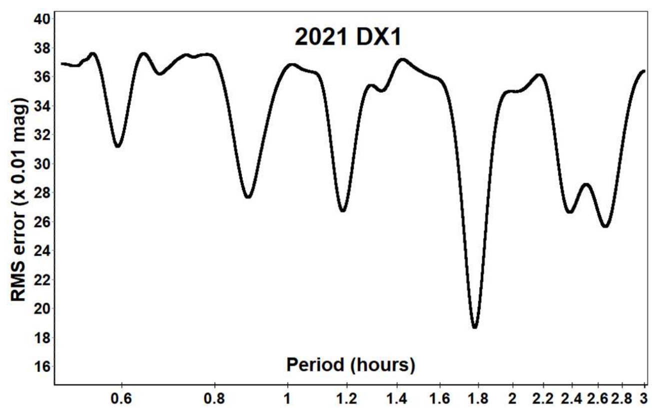


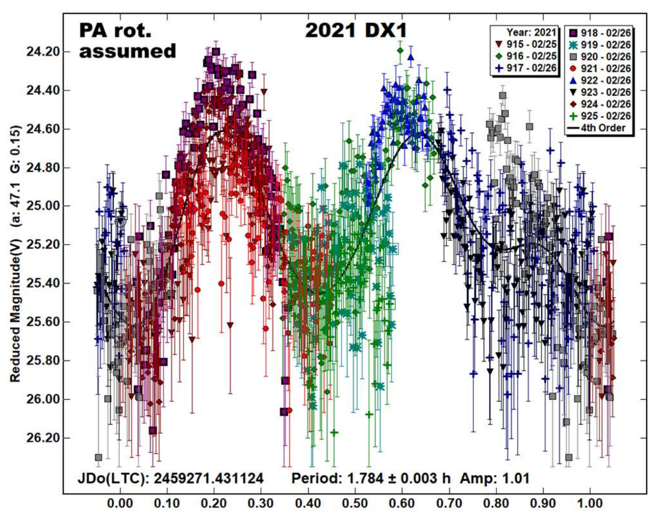
Although there is still a large amount of noise in the data points both periods are well resolved, helped by the large amplitudes and number of rotations covered. The *MPO Canopus* Dual Period Search is designed to find multiple periods in binary asteroid systems, not to determine lightcurve parameters for tumbling asteroids and the frequencies derived here may be linear combinations of the real frequencies, which would need a physical model of the NPA rotation to be constructed to properly resolve. However, this is expected to be rated as PAR = -3, i.e., NPA rotation reliably detected with the two periods resolved. There may be some ambiguities in one or both periods. (Petr Pravec, personal communication).

2021 DX1. This was a 17th mag discovery by the Catalina Sky Survey on 2021 Feb 20 (Bacci et al., 2021) which remained at a similar brightness for nearly two weeks following. With $H = 23.0$ it has an estimated diameter of ~75 m. 2021 DX1 was observed for 6.4 h starting 2021 Feb 25.9 UTC and 1087 16-s exposures were obtained. Conditions were poor, with the 98% illuminated Moon only 55° away, however, large amplitude variations over a period of tens of minutes were obvious during data collection. The raw plot shows regular variations but with significant differences in the shape of the curve and varying heights of maxima indicating non-principal axis rotation is likely.

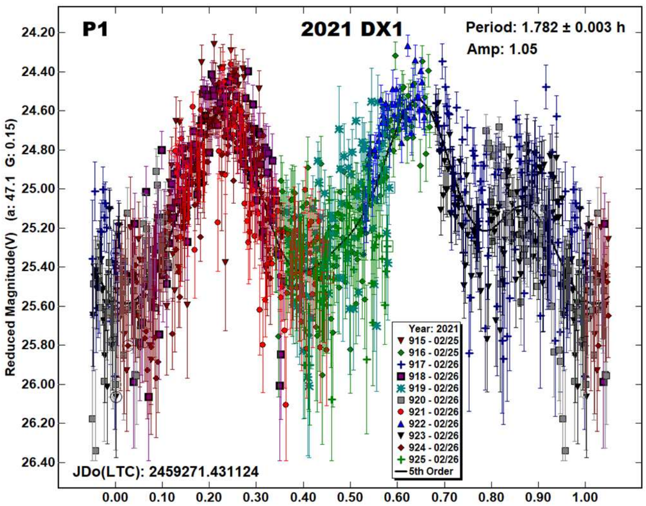


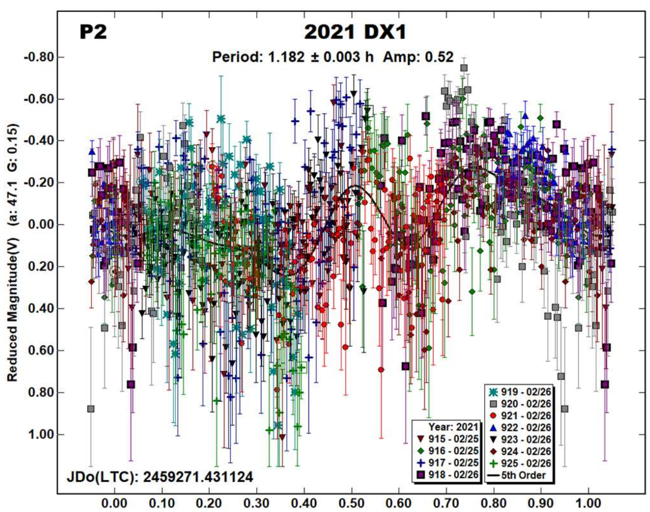
Assuming just principal axis rotation is present results in a period spectrum indicating a best fit period of 1.784 h and a bimodal phased lightcurve, labelled 'PA rot. assumed'.





Using the *MPO Canopus* Dual-period search function designed for binary asteroids, to find one period, subtracting its effect to find a second period, then using that to refine the first period and repeating, the dominant 1 mag amplitude period was sharpened up to 1.782 h and a second period of 1.182 h revealed, with a 0.5 mag amplitude, these lightcurves labelled 'P1' and 'P2'.

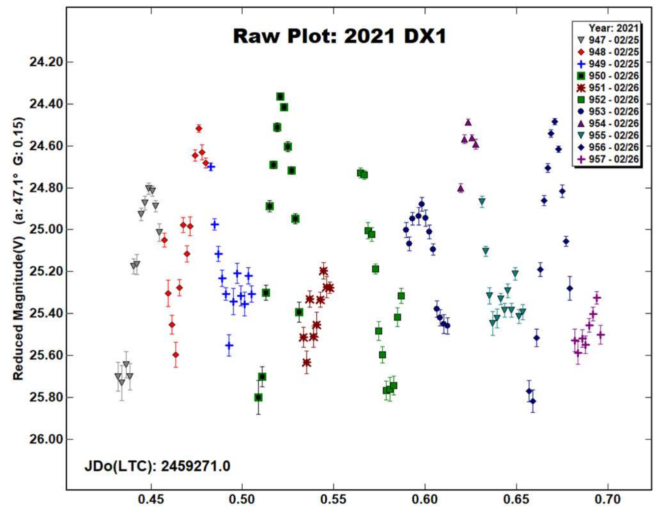


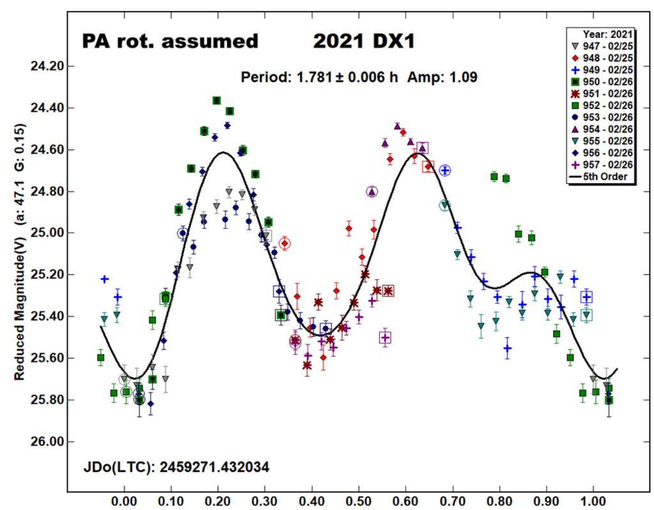


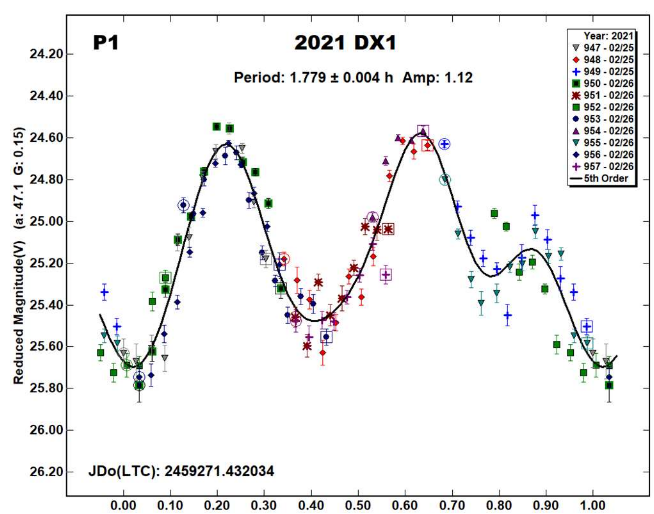
The raw lightcurve and 'PA rot. assumed' phased curve show evidence of NPA rotation and the 'P1' phased curve improves the fit of the data. However, the 2nd period is less well defined and it is expected that this will be rated as PAR = -2, i.e., NPA rotation detected based on deviations from a single period but the second period is not resolved. (Petr Pravec, personal communication).

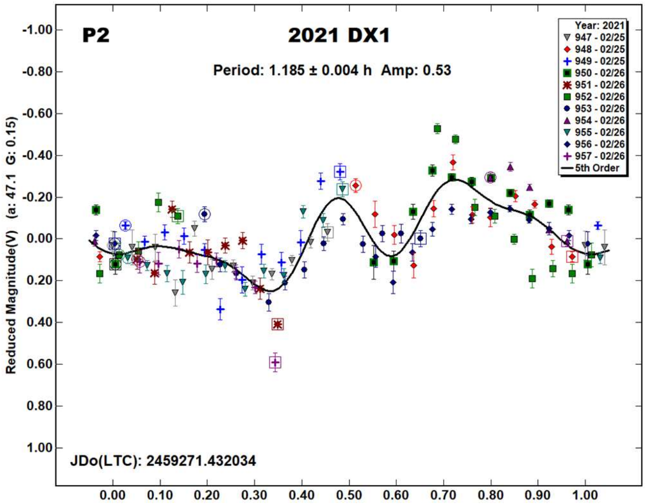
The same issues with interpreting the *MPO Canopus* Dual-period search function for tumblers discussed for 2021 DP also apply here. It is also noted that it is likely the errors derived for the individual periods in a dual-period search are understated for tumbling objects as the periods are derived separately and sequentially, rather than the two being derived simultaneously within the same reduction.

With the large amount of noise present, especially in the P_2 curve, as an exercise, a separate determination was made by stacking the 1087 images to improve the signal to noise ratio. With both periods being > 1 h, a maximum of 10 contiguous images were combined, resulting in the longest effective elapsed time in a single data point being no greater than 2.7 minutes. Therefore, Integration time / Period = 0.04, less than the 0.185 value beyond which smearing of the lightcurve would be expected to occur (see Table I and Pravec et al., 2000). The stacking resulted in a total of 118 data points and these were used to generate equivalent plots to the unstacked reduction (raw, PA rot. assumed, P_1 and P_2), given here to demonstrate that although the underlying curves are easier to see in the stacked versions, there is no practical change to the results, differences between the best-fit periods in the stacked and unstacked results are insignificant.



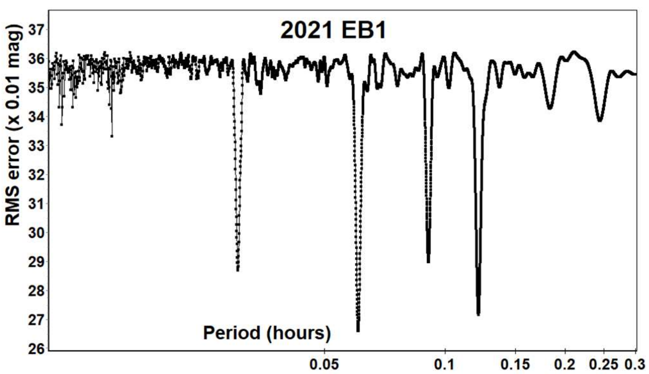


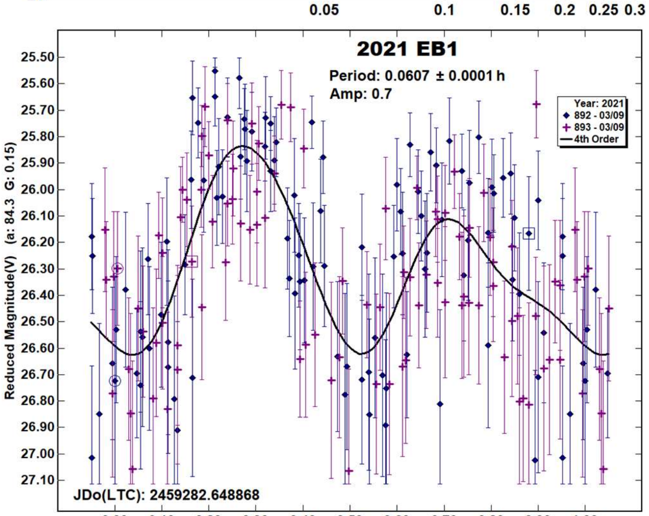




2021 DX1 is listed by Pravec (Pravec, 2021) with a rating of PAR = -3 (NPA rotation reliably detected with the two periods resolved) and gives P_1 = 1.18879 ± 0.00009 h and P_2 = 1.7678 ± 0.0002 h, from observations obtained between 2021 Mar 6-10, these periods being in good agreement with the results in this paper.

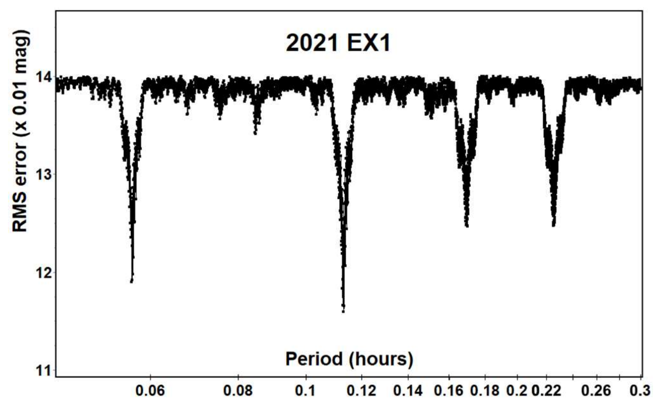
2021 EB1. This Apollo object, estimated diameter ~59 m was discovered by the Catalina Sky Survey at 19th mag on 2021 Mar 6 and announced with pre-discovery positions from Pan-STARRS1 and 2 dating back to 2021 Feb 10 (Melnikov et al., 2021). It passed Earth at 8.6 LD on 2021 Mar 11.2 UTC but due to increasing phase angle was predicted to be brightest 2 days beforehand at mag +18.8 (MPC, 2021c).

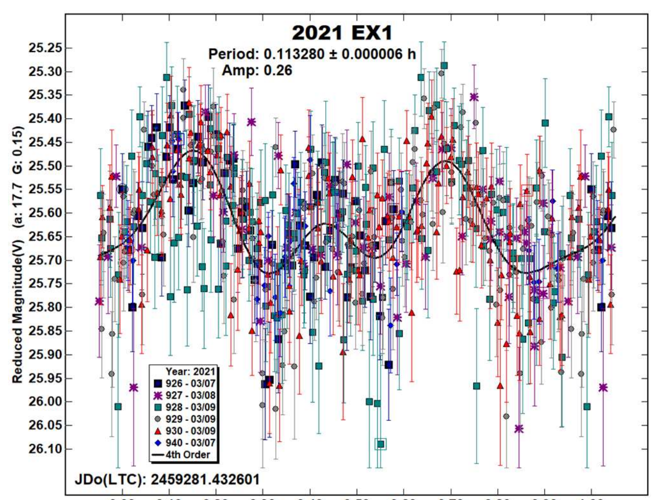




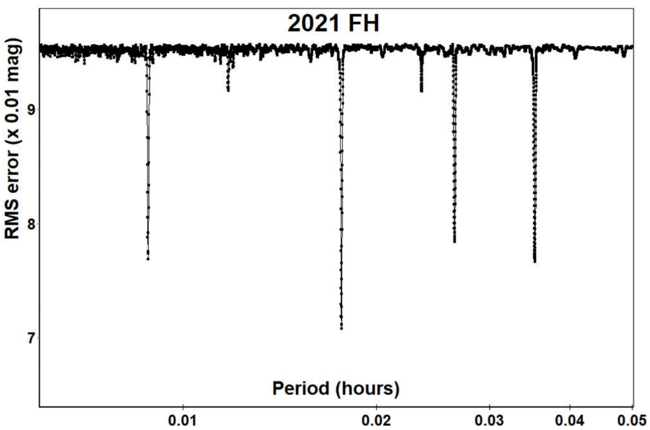
When observed on 2021 Mar 9.15 UTC it was showing large variations in magnitude, taking about 2 minutes to vary from peak to peak and at brightest was about 1 mag brighter than the ephemeris prediction. It was followed for 52 minutes and was visible throughout on individual 10-s exposures, though faint at minimum. The resulting phased lightcurve is noisy but shows a bimodal curve with a period of 3.6 minutes. It completed 14 revolutions during the period of observation.

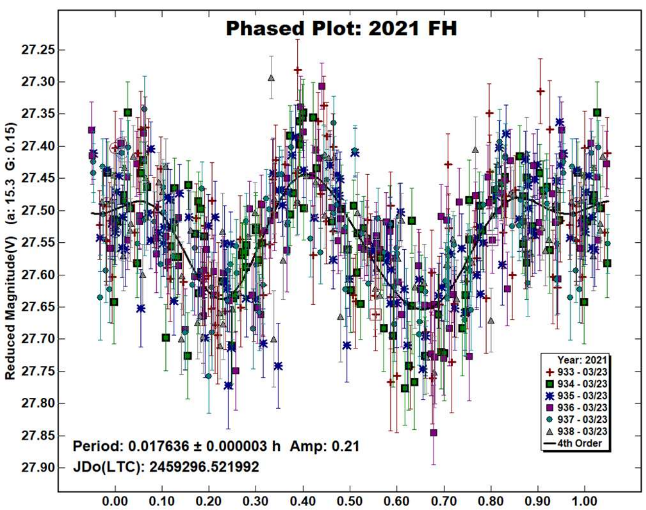
2021 EX1. A 15th mag discovery from the Piszkés-tető Mountain Station of the Konkoly Observatory in Hungary on 2021 Mar 7.9 UTC (Foglia et al., 2021), 30 hours after passing Earth at 3 LD. Thanks to the speed with which the observers identified and reported their discovery and the effectiveness of the NEOCP system at the Minor Planet Center (MPC, 2021b), the first images at Great Shefford were obtained less than 20 minutes after the time of the first reported discovery position. Unfortunately, conditions soon deteriorated and a span of only 48 minutes of photometry was possible, with cloud interruptions. The next night 2021 EX1 had faded about 1 mag, but a more extensive set of images in better conditions was obtained. Solving the lightcurve using just the 85 measurements obtained on the first night results in a period of 0.1129 ± 0.0004 h and solving using the 475 measures from the second night gives a period of 0.1131 ± 0.0001 h. The phased lightcurve is the result of using all measures from both nights after making small adjustments to the zero points of the sessions over the two nights, with the RMS of those corrections being 0.058 mag.





2021 FH. Another small (~14 m diameter) Apollo, discovered at Mt. Lemmon on 2021 Mar 18 (Brucker et al., 2021). 2021 FH passed Earth at 0.6 LD on 2021 Mar 23.7 UTC and was under observation from Great Shefford for 83 minutes starting at 2021 Mar 23.02 UTC when it was within 2 LD, its sky motion increased from 60 to 72 arcsec / min during the period. In case superfast rotation was present exposures were kept short, reducing from 6.5 to 5.6 s during the session, which also allowed for trailing of the target to be kept constant and within the measurement annulus in *Astrometrica*. A small amplitude, bimodal superfast rotation period of 63.5 s is evident and indicates that 78 revolutions occurred during the period of observation.





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Name	Integration Times	Max intg./ Period	a/b	Min Points	Fields
2020 TB12	90Σ	0.04	1.7	35	5
2020 YE5	1-4.1	0.001	1.1	3237	46
2021 AU	1.5,3.5	0.001	1.3	1321	25
2021 CO	2.9-3.8	0.001	1.2	1360	20
2021 DP	5.4,5.7	0.01	1.6	459	5
2021 DX1	16	0.004	1.4	1087	11
2021 EB1	10	0.05	1.2	194	2
2021 EX1	5,6,7	0.02	1.1	560	6
2021 FH	5.6-6.5	0.10	1.1	563	6

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 (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).

Name	yyyy mm/ dd	Phase	L_{PAB}	B_{PAB}	Period(h)	P.E.	Amp	A.E	PAR	H
2020 TB12	2021 02/04-02/04	92.4,92.2	138	47	0.640	0.004	2.2	0.1	-1	22.2
2020 YE5	2021 01/21-01/22	18.6,29.7	130	-9	1.113	0.002	0.13	0.07		25.8
2021 AU	2021 01/06-01/06	20.3,22.4	96	-2	1.593	0.003	0.5	0.1	-1	24.4
2021 CO	2021 02/11-02/11	20.8,25.7	131	-4	1.605	0.006	0.3	0.1	-1	25.3
2021 DP	2021 02/18-02/18	23.2,21.1	151	11	0.11297	0.00004	0.8	0.2	-3	26.6
					0.12831	0.00008	0.6	0.2		
2021 DX1	2021 02/25-02/26	47.2,45.7	170	21	1.782	0.003	1.1	0.1	-2	23.0
					1.182	0.003	0.5	0.2		
2021 EB1	2021 03/09-03/09	84.3,84.7	170	44	0.0607	0.0001	0.7	0.3		23.5
2021 EX1	2021 03/07-03/09	25.6,26.3	164	13	0.113280	0.000006	0.26	0.10		24.9
2021 FH	2021 03/23-03/23	15.2,13.9	177	4	0.017636	0.000003	0.21	0.05		26.7

Table II. Observing circumstances and results. Where two lines are given, these include two periods determined for NPA rotation. 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). 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 Browser (JPL, 2021).

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