

LIGHTCURVE ANALYSIS FOR SIX NEAR-EARTH ASTEROIDS

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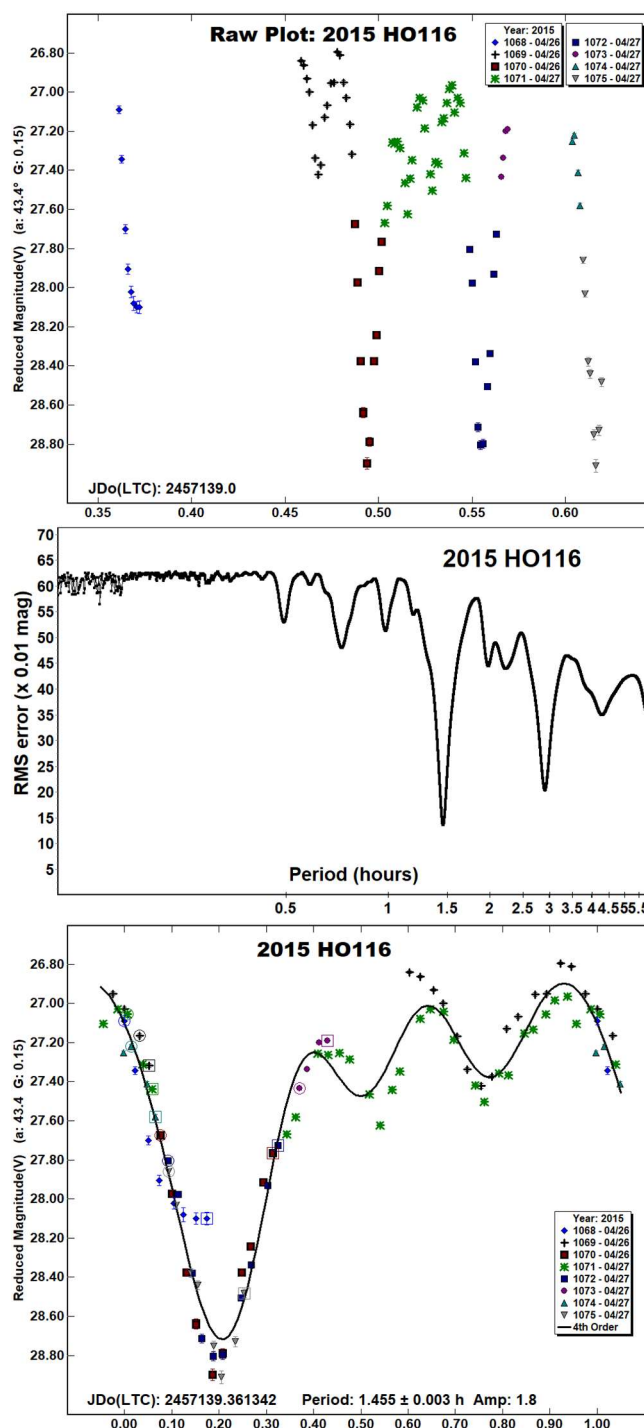
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Lightcurves and amplitudes for six near-Earth asteroids observed from Great Shefford Observatory during close approaches in 2015 and 2021 are reported: 2015 HO116, 2021 GG11, 2021 HC3, 2021 JR3, 2021 JB6 and 2021 KN2. All are fast or superfast rotators and two appear to show signs of tumbling.

Photometric observations of near-Earth asteroids during close approaches to Earth in April 2015 and 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 1Kx1K, 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. *MPO Canopus* (Warner, 2021), incorporating the Fourier algorithm developed by Harris (Harris et al., 1989) was used for lightcurve analysis.

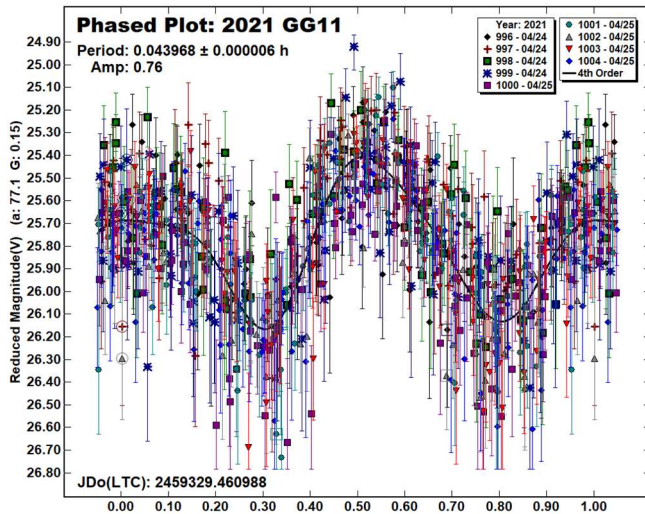
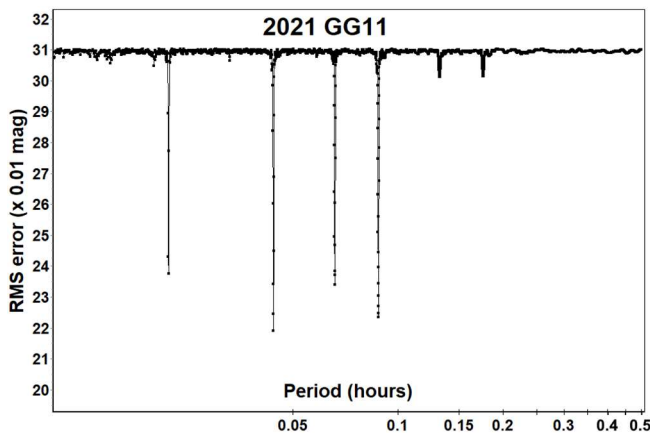
Unless otherwise noted, no previously reported results for any of the objects have been found in the LCDB (Warner et al., 2009), from searches via the Astrophysics Data System (ADS, 2021) or from wider searches.

2015 HO116. This Apollo object was discovered by the Catalina Sky Survey on 2015 Apr 25 (Nishiyama et al., 2015) two days before approaching Earth to within 1.7 Lunar Distances (LD). It was observed over a six-hour span starting on 2015 Apr 26.86 UTC as it brightened from 16th to 15th magnitude and the apparent speed against the sky increased from 150 to 275 arcsec/min. Exposures were limited to 1 and 2 seconds to keep trailing of the target well within the measurement annulus of *Astrometrica*. A total of 1404 images were taken, with the telescope being repositioned 45 times during the six hours. As no short-term magnitude variation was detected, but large variations were obvious over a period of tens of minutes, the *Astrometrica* Track and Stack function was used to combine on average groups of 15 individual exposures into a stacked image for photometry measurement, to increase the signal to noise ratio. The raw plot shows three deep minima with an apparent variation of shorter period and lower amplitude. To aid the analysis, the measurements were imported into separate sessions within *Canopus* by their placement within the raw curve rather than the more usual means of grouping measurements made from the same field of view into one session. The period spectrum shows a dominant solution at 1.455 h but phased solutions at that period (and at 2.91 h) fail to represent simple principal axis rotation well, the three deep minima are modelled well, but not the apparent minimum seen in the first set of measures, or the smaller ~ 0.6 mag amplitude variations away from the deep minima. Attempting to solve for a second period using the *Canopus* Dual-Period Search function was also unsuccessful. It is concluded that 2015 HO116 is tumbling, but neither period is resolved unambiguously and so it is expected to be rated as PAR = -1 (Non-Principal Axis rotation possible, but not conclusively) on the scale of Pravec et al. (2005).



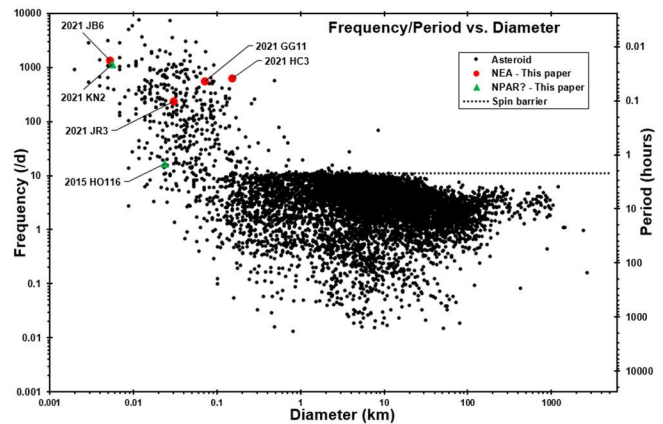
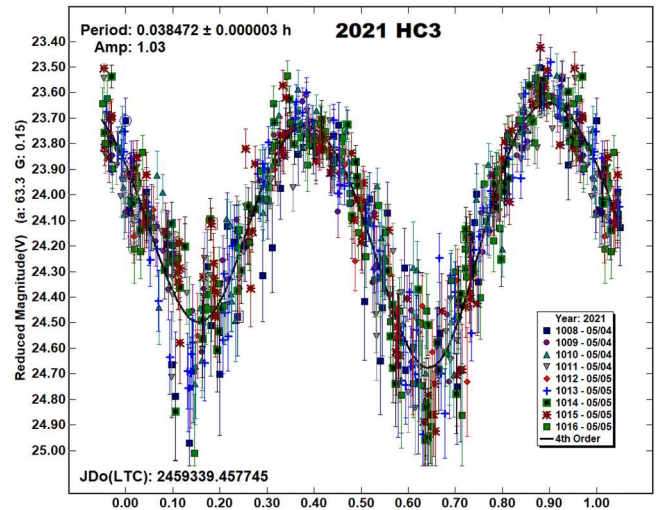
A lightcurve for 2015 HO116 has also been reported by Vaduvescu et al. (2018web), where a single clear maximum and apparent minimum were recorded during a short (probably < 1 h and possibly ~ 20 min) observing run starting at 2015 Apr 26.93 UTC (JD 2457139.43), i.e., completely within the six-hour span reported here, but probably entirely in the gap between *Canopus* sessions 1068 and 1069 (see the Raw plot). They report a 0.64 mag amplitude and a 0.45 ± 0.04 h monomodal or 0.90 ± 0.04 h bimodal period, flagged as tentative and to be regarded with caution, probably corresponding to quality code U ~ 1 . The form of their lightcurve appears to have similar amplitude and periodicity to the short period variation seen in *Canopus* sessions 1069 and 1071 of the raw plot and as such appears consistent with the result presented here.

2021 GG11. The SBDB (JPL, 2021) lists this Apollo with $H = 23.1$, equating to a diameter of ~ 71 m assuming an albedo of 0.20. It was discovered from the Mt. Lemmon station of the Catalina Sky Survey (CSS) on 2021 Apr 15, with pre-discovery positions reported from the Mt. Bigelow CSS station 2 days before (Kowalski et al., 2021) and it made an approach to within 5 LD of Earth on 2021 Apr 27. Its ephemeris magnitude was expected to peak at +17.7 between Apr 25 and 26, but it would be moving at twice the speed on the latter date, favouring photometric observation on the earlier night. This was obtained over a period of 3.3 hours starting at 2021 Apr 24.96 UTC when 2021 GG11 was moving at 30 arcsec/min, at a distance of just under 9 LD. The telescope was repositioned 8 times, exposure length for the first 4 sessions limited to 6 s but this was increased to 13 s for the last 4 as large magnitude variations were obvious over a period of 1-2 minutes, indicating that no significant lightcurve smoothing would result with the longer exposure (Pravec et al., 2000). A period spectrum shows potential solutions in the range of 1 - 8 minutes, with an asymmetric bimodal lightcurve of period 2.6 minutes giving the best fit. 2021 GG11 completed 74 rotations during the period of observation.

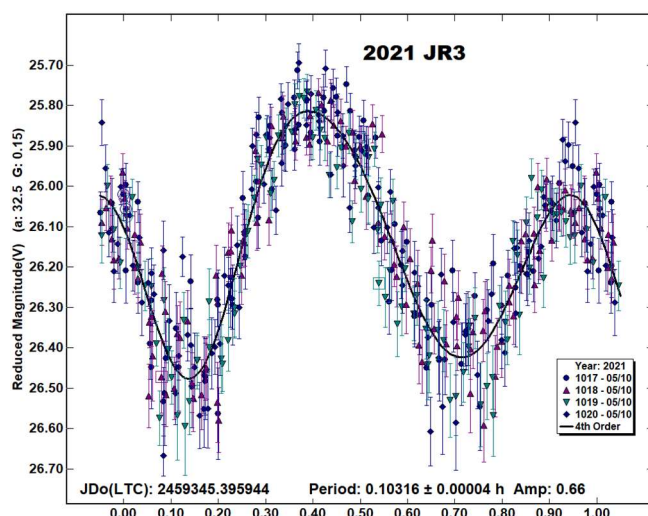


2021 HC3. This is the largest of the objects being reported, with the SBDB giving a value of $H = 21.59$ and with an assumed albedo of 0.20 suggesting a diameter of ~ 143 m. It was discovered by the ATLAS 0.5-m reflector on Haleakala (Pruyne et al., 2021) on 2021 Apr 30 and approached Earth to 19 LD on 2021 May 4. Photometry was obtained over a 2.6 h period on the night of closest approach

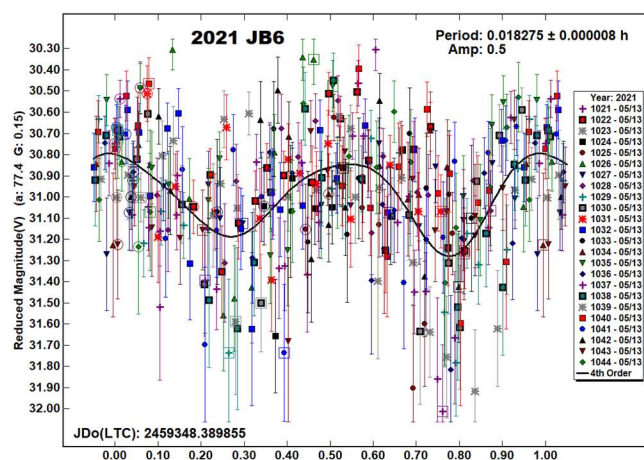
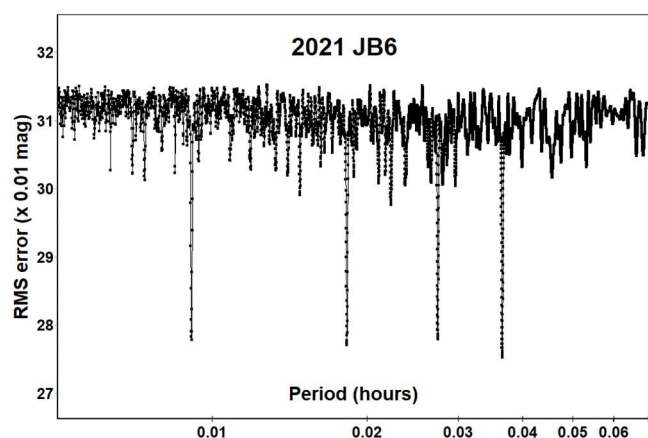
and again, obvious magnitude variations within 1 minute were seen during image collection. Sky motion was 44 arcsec / min and exposures were limited to 9 s to reduce image trailing. Reduction in *Canopus* reveals a 1 mag amplitude bimodal lightcurve of period 2.3 minutes, indicating that 67 full revolutions occurred during the period of observation. The Frequency/Period vs. Diameter diagram, based on LCDB data (Warner et al., 2009) shows 2021 HC3 as a relatively large superfast rotator, which must have non-zero tensile strength, being well beyond the 2.2 h spin barrier and with $H < 22$ is positioned at the start of the range of small asteroids (0.15 km < $D < 10$ km) where superfast rotators become much less common.



2021 JR3. This Apollo was discovered at 17th mag from the Piskés-tető Mountain Station of the Konkoly Observatory in Hungary on 2021 May 9.9 UTC, with 21st mag pre-discovery positions from May 1st reported from Mt. Lemmon (Pettarin et al., 2021). It passed the Earth at 2 LD on 2021 May 12.08 UT and was best placed for photometry from Great Shefford on the night of May 10 when it was 16th mag, 5 LD away and moving at 45-50 arcsec / min. It was observed for 1 h 16 m, allowing 411 exposures of 8 - 9 s duration to be obtained. Analysis in *Canopus* revealed a bimodal lightcurve with a rotation period of 6.2 min, indicating 12 revolutions had been observed. It is listed with $H = 24.95$ (JPL, 2021), implying a diameter of ~ 31 m.



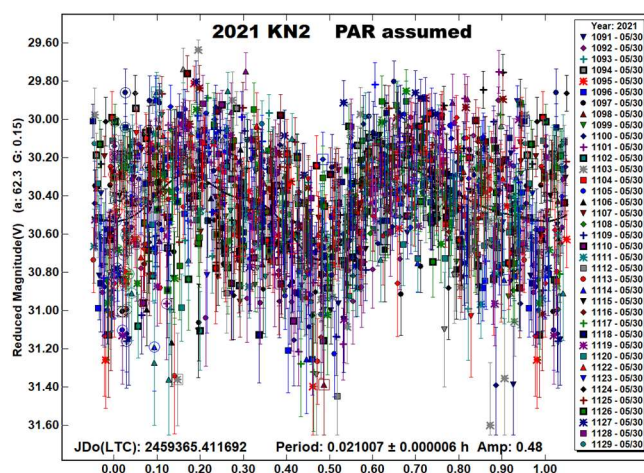
2021 JB6. A very small Apollo with an estimated diameter of ~ 5 m was discovered as a mag +22 object by the Pan-STARRS 1 team on 2021 May 8.3 UTC, 5.6 days before it made a very close pass to Earth at 0.27 LD (Beniyama et al., 2021a). It was only bright enough for photometry on the night of closest approach and was observed for 66 minutes starting at 2021 May 13.890 UTC. It was well placed, at an altitude of $+73^\circ$, decreasing to $+61^\circ$, but at a distance of 0.29 LD, decreasing to 0.26 LD (topocentric) it was moving very fast, speed increasing from 918 to 1086 arcsec/min during the period of observation and the telescope needed to be repositioned 24 times due to the fast motion. Exposures were reduced from 1 s down to 0.6 s to ensure trailing of the target was kept within the measurement annulus in *Astrometrica* and so even though 2021 JB6 was 16th mag, due to the short exposures the measurements are rather noisy. A period search in *Canopus* only found short period solutions, the four strongest shown in the period spectrum being monomodal at 0.009 h, increasing to quadrimodal at 0.037 h. The quadrimodal solution is marginally the strongest, but with the large amount of noise present, the bimodal solution at 0.018 h is preferred. 2021 JB6 completed 60 revolutions during the period of observation.



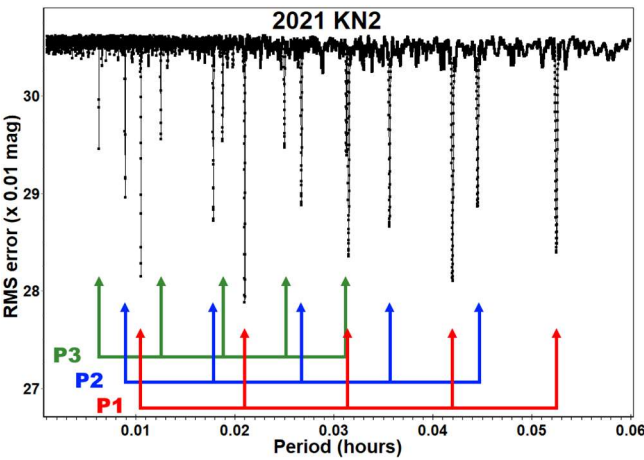
2021 KN2. Another very small Apollo, listed with $H = 28.6$ in the SBDB (JPL, 2021), equating to a likely size of ~ 6 m, assuming an albedo of 0.2. It was discovered with the 1.05-m Schmidt at the Tokyo-Kiso observatory on 2021 May 30.55 UTC (Beniyama et al., 2021b) when already just 1.2 LD from Earth and 13 hours later it passed Earth at 0.38 LD. Pre-discovery positions extending the observed arc by 3 hours were reported by the ATLAS team.

1457 images suitable for photometric measurement were obtained over a 2.73 h period starting 2021 May 30.91 UTC. With the speed increasing from 415 to 755 arcsec/min the telescope had to be repositioned 61 times and exposures were reduced from 1.4 to 0.6 s to keep trailing of the target within the measurement annulus in *Astrometrica*. As with 2021 JB6, the very short exposures used have resulted in measurements with relatively low S/Nr.

An initial reduction of the lightcurve in *Canopus*, assuming principal axis rotation (diagram labelled PAR assumed), indicated a period of 0.02101 h, but with even more scatter in the solution than would have been expected from the amount of noise in the measurements:

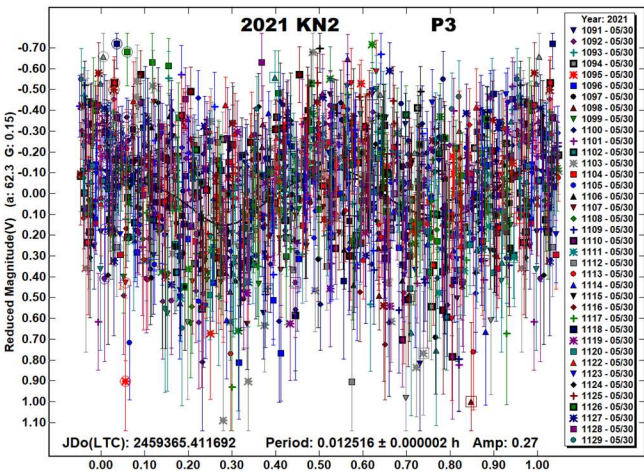
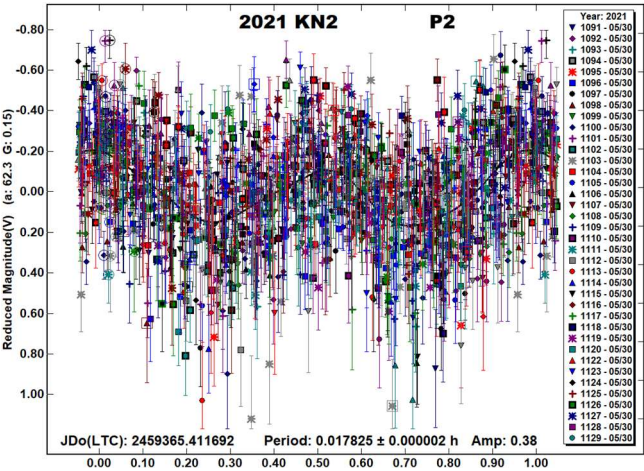
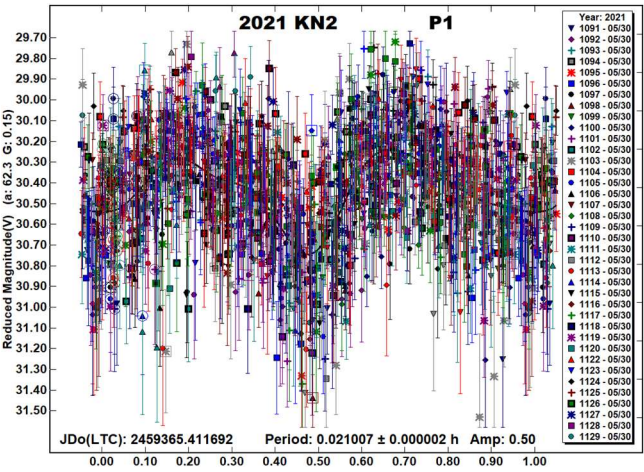


An examination of the period spectrum showed 15 minima in the range 0.006 - 0.0525 h (22.5 - 189 s) and the *Canopus* Dual-Period search function, seeded with 0.02101 h as the main period, resulted in two bimodal periods being resolved, $P_1 = 0.021007$ h and $P_2 = 0.017825$ h (diagrams labelled P1 and P2). Multiples of the values of $P_1/2$ and $P_2/2$ can be identified as the strongest 10 of the 15 minima, these indicated by arrows labelled P1 and P2 in the linearly scaled Period Spectrum diagram:



The remaining 5 minima were equally spaced, and apparently multiples of 0.006 h, so another Dual-Period search was done, starting with the P1 value and forcing *Canopus* to resolve a period near .012 h (the likely bimodal value amongst the unidentified 5 minima). The resulting lightcurve labelled P3 has a period of 0.012516 h. The three derived periods, their formal errors and amplitudes are:

P1 = 0.021007 ± 0.000002 h, amplitude = 0.50
P2 = 0.017825 ± 0.000002 h, amplitude = 0.38
P3 = 0.012516 ± 0.000002 h, amplitude = 0.27



A Dual-Period solution using P1 and P2 gives the best fit to the data points but solutions for P1/P3 and also P2/P3 have similar fits, with the P2/P3 solution producing the largest RMS residuals, but these being only 8% larger than the P1/P2 result.

2021 KN2 is definitely tumbling and the three frequencies, 1/P1, 1/P2 and 1/P3 are linearly related, one of them is a linear combination of the other two, e.g.:

$$1/P1 = 2/P3 - 2/P2$$

and in rotations:

$$28 P1 = 33 P2 = 47 P3$$

but without more data it is not clear which two of the periods are real periods of the tumbler and which one is only their linear combination. It is therefore expected this may be rated as PAR = -2 tending to -3. (Petr Pravec, personal communication). The slowest rotation period, of 75.6 s (P1) implies at least 129 rotations were completed during the 2.73 h of observation.

Number	Name	Integration	Max intg./	Min	Points	Fields
		times	Period	a/b		
2015	HO116	134 [±]	0.026	2.1	91	45
2021	GG11	13	0.082	1.2	530	5
2021	HC3	8.8, 8.9	0.064	1.4	681	9
2021	JR3	8.1–8.7	0.023	1.4	411	4
2021	JB6	0.6–1.0	0.015	1.1	346	24
2021	KN2	0.6–1.4	0.031	1.2	1457	61

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).

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Acknowledgements

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Number	Name	yyyy mm/ dd	Phase	LPAB	BPAB	Period(h)	P.E.	Amp	A.E	PAR	H
2015	HO116	2015 04/26–04/27	22.1, 43.5	218	17	1.455	0.003	1.8	0.2	–1	25.5
2021	GG11	2021 04/24–04/25	77.1, 78.8	196	36	0.043968	0.000006	0.8	0.3		23.13
2021	HC3	2021 05/04–05/05	63.3, 65.0	217	34	0.038472	0.000003	1.0	0.2		21.59
2021	JR3	2021 05/10–05/10	32.4, 33.7	214	4	0.10316	0.00004	0.7	0.1		24.95
2021	JB6	2021 05/13–05/13	79.5, 95.1	219	42	0.018275	0.000008	0.5	0.3		28.78
2021	KN2	2021 05/30–05/31	60.2, 86.1	232	32	0.021007	0.000002	0.5	0.3	–2/–3	28.63
						0.017825	0.000002	0.4	0.3		
						0.012516	0.000002	0.3	0.3		

Table II. Observing circumstances and results. Where more than one line is given, these include 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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