

LIGHTCURVE ANALYSIS FOR TWO NEAR-EARTH ASTEROIDS OBSERVED IN JANUARY 2023

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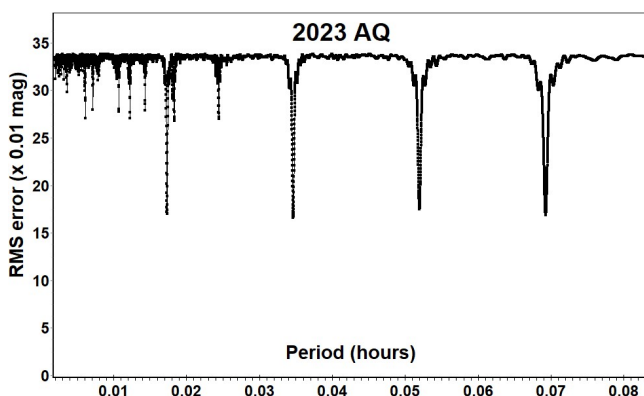
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Lightcurves and amplitudes for 2 small near-Earth asteroids observed from Great Shefford Observatory during close approaches in January 2023 are reported. Both are superfast rotators with periods shorter than 3 minutes, one with reliably detected tumbling rotation.

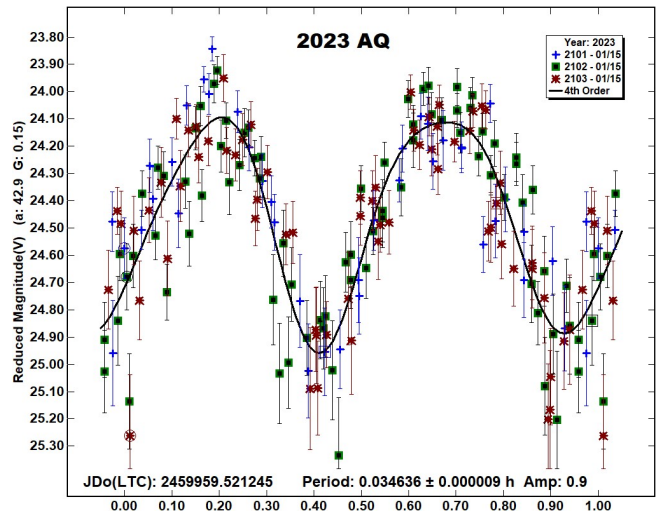
Photometric observations of near-Earth asteroids during close approaches to Earth in January 2023 were made at Great Shefford Observatory using a 0.40-m Schmidt-Cassegrain and Apogee Alta U47+ CCD camera. All observations were made unfiltered and with the telescope operating with a focal reducer at $f/6$. The $1K \times 1K$, 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) in *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.

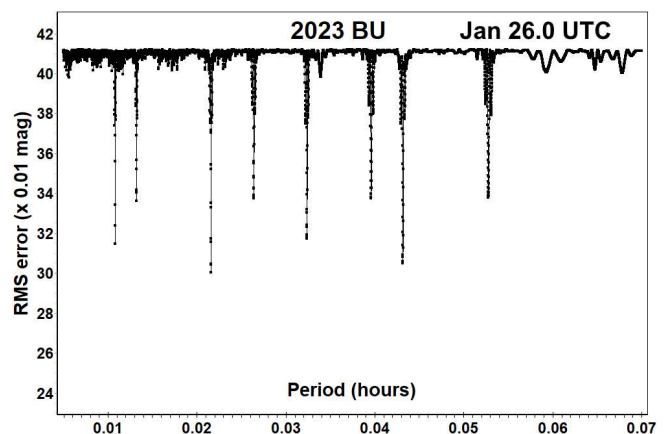
2023 AQ. This Apollo was discovered by the Mt. Lemmon Survey on 2023 Jan 13.53 UTC and made its closest approach 3.5 days later at 11 Lunar Distances (LD) from Earth (Melnikov et al., 2023). It was observed over a period of 1.6 h starting 2023 Jan 15.02 UTC when it was 17th mag and due to its apparent speed of 35 arcsec/min, exposures were limited to 15 seconds to keep trailing of the target within the measurement aperture of *Astrometrica*. Analysis with *MPO Canopus* reveals a relatively short, 124.7 second rotation period for an object with $H = 22.78$ (est. dia. ~ 83 m) and an amplitude of 0.9.

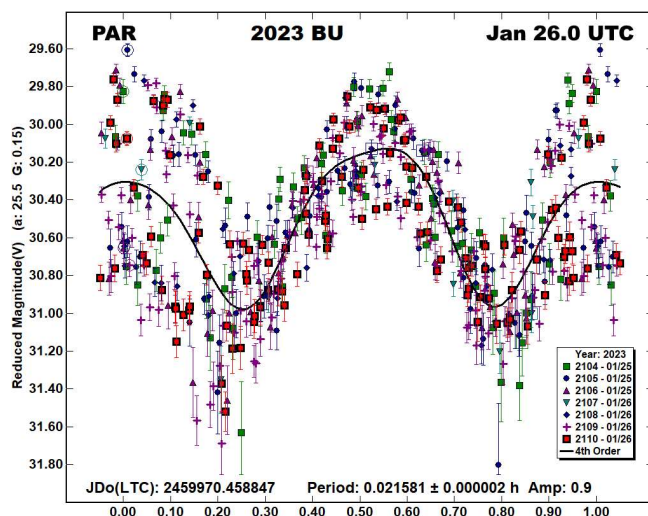


As well as the strong signals related to the derived period the period spectrum includes a number of weaker RMS minima which are all multiples of either 12.89 or 21.98 seconds and have similar strengths. These are suggestive of low amplitude tumbling motion but are discounted here as possible artifacts of the cadence of the exposures taken but also because any signal from real periodicity would be expected to be drastically degraded or completely obscured due to lightcurve smoothing for periods below ~ 0.0125 h, where the exposure length is potentially 1/3 or more of the indicated periods (Pravec et al., 2000).

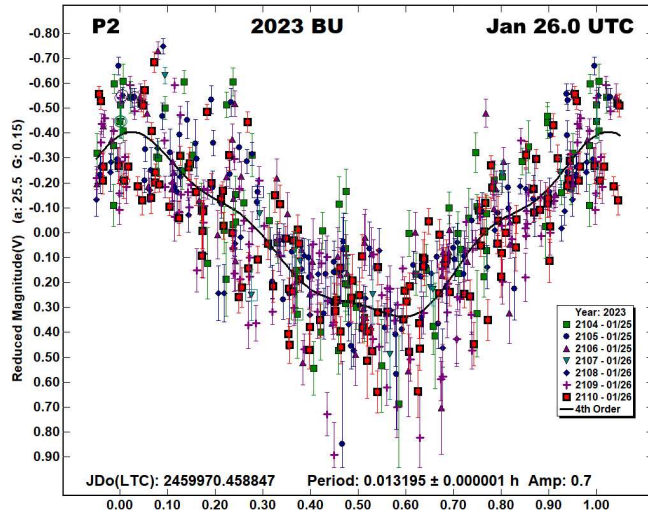
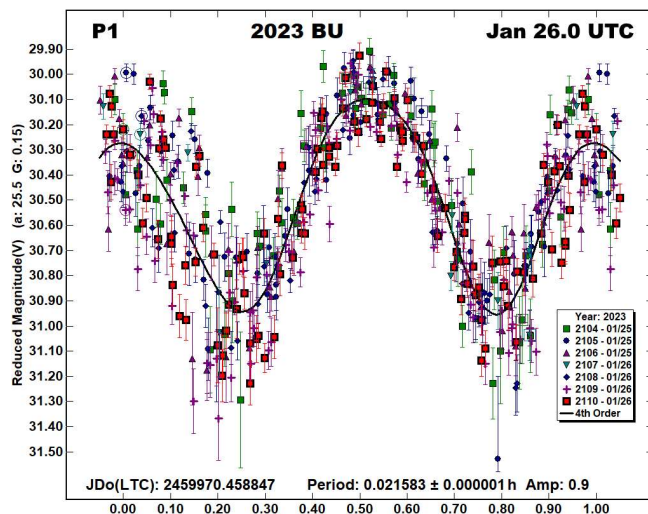


2023 BU. Discovered by G. Borisov at MARGO, Nauchnij, Crimea 5 days before an exceptionally close approach to 3,600 km above the Earth's surface on 2023 Jan 27.02 UTC (Zoltowski et al., 2023). With $H = 29.7$ it has an estimated dia. of ~ 3 m and was 17th mag when observed over a period of 3 h starting 2023 Jan 25.96 UTC and as bright as 12th mag the next night, the night of closest approach, when it was followed for 42 min starting at 2023 Jan 26.93 UTC. Exposures were 10 and 12 s on the first night when the apparent speed reached 26 arcsec/min, but with the speed reaching 1700 arcsec/min on the second night exposures of 0.6, reducing to 0.4 s were utilised. 2023 BU trailed no more than 11 arcsecs, allowing all the images on both nights to be measured with a standard aperture in *Astrometrica*. The telescope needed repositioning 7 times on the first night and 16 times on the second. The reduction in *MPO Canopus* from 501 measurements on the first night reveals a dominant period of 77.69 s but with large systematic trends, the best fit lightcurve here labelled PAR for Jan 26.0 UTC.



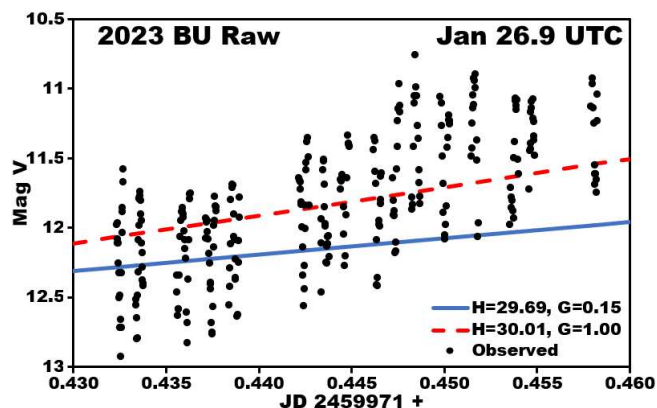


This curve is strongly suggestive of tumbling or non-principal axis (NPA) rotation and a period spectrum covering solutions from 18 - 252 s and labelled Jan 26.0 UTC shows two sets of linearly spaced minima, in multiples of 38.85 and 47.51 s. The *MPO Canopus* Dual Period Analysis function was used to try and resolve periods due to the effects of NPA rotation and the resulting best fit periods are a bimodal period of 77.70 s ($= 2 \times 38.85$) of amplitude 0.9 and a monomodal period of 47.50 s with amplitude 0.7. These lightcurves are labelled P1 and P2 for Jan 26.0 UTC.

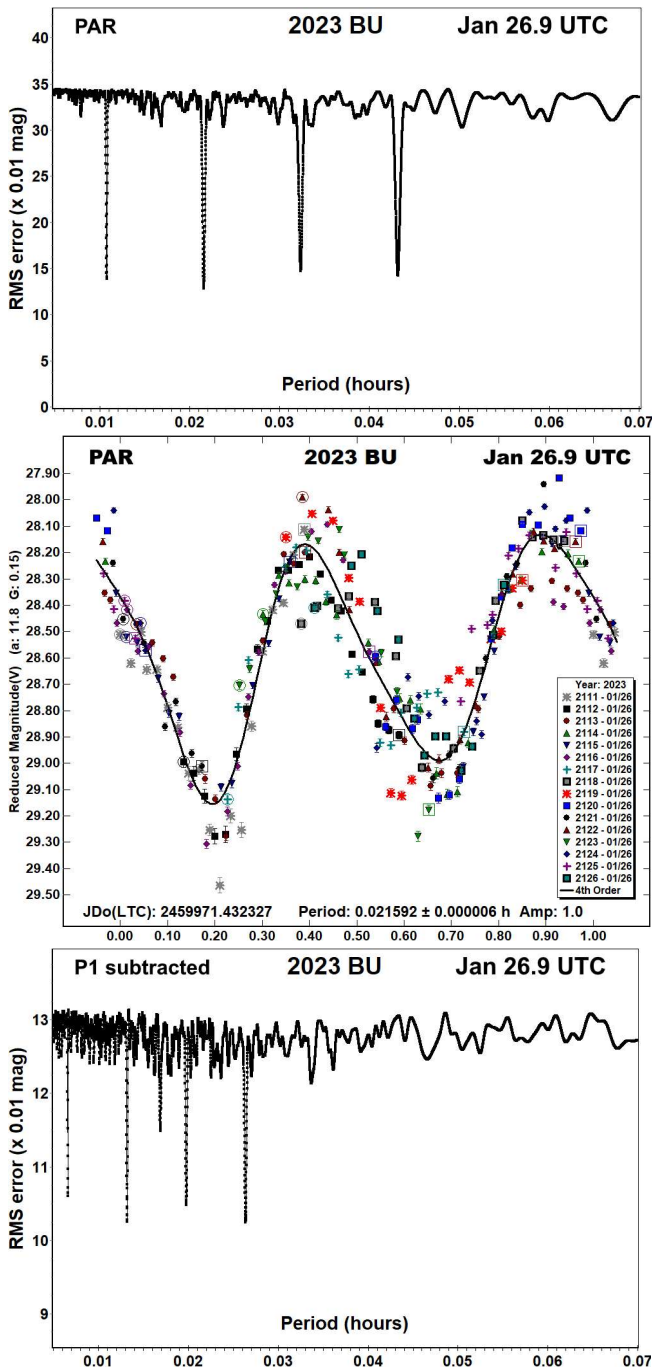


It is noted that the longest exposures used, of 12 s duration are 0.154 P1 and 0.253 P2. Lightcurve smoothing needs to be considered, where the optimal exposure length to maximise signal strength with minimal smoothing for a bimodal lightcurve of period P is determined to be $0.185 P$ and where exposures longer than $0.185 P$ would start to smooth and distort the lightcurve (Pravec et al., 2000). The factor of 0.154 for the P1 curve is safely below the optimal value and is estimated to reduce the amplitude of the P1 curve to ~85% of its actual value. The value of 0.253 for the P2 period is also not expected to cause serious lightcurve smoothing, as the strength of the dominant 1st harmonic for this monomodal curve is estimated to only be reduced to ~90% of its actual value, less affected by lightcurve smoothing than the P1 curve.

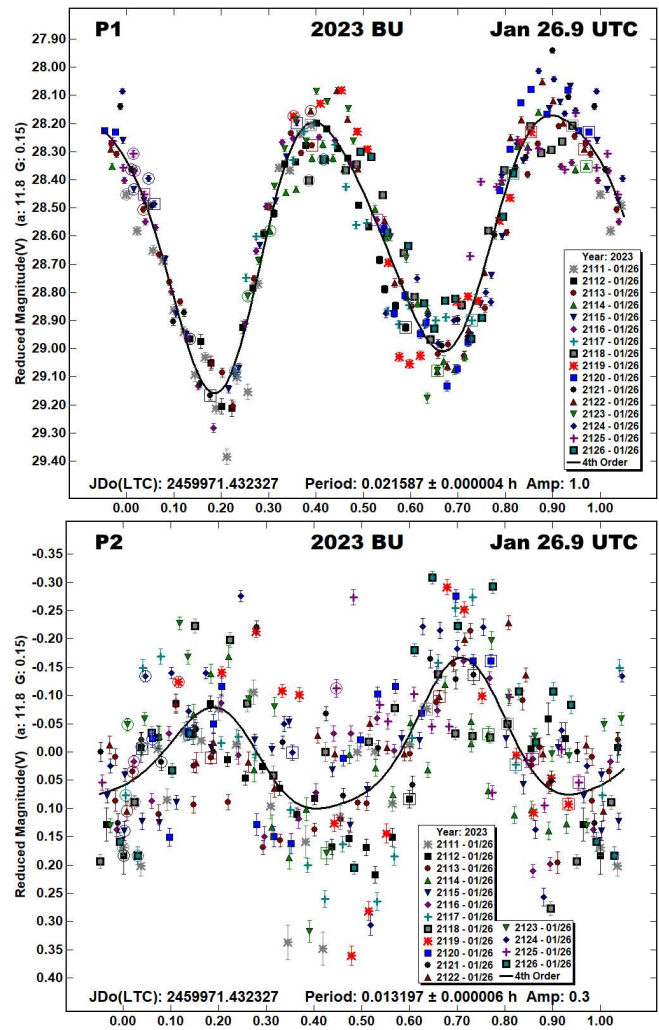
The analysis of 281 measurements from the second night, during the close approach, was not straightforward. In the 42 minutes 2023 BU was under observation the phase angle doubled from 10.1 to 20.5° as the distance reduced from 0.097 to 0.071 LD. The ephemeris magnitude, using the SBDB values of $H=29.69$ and $G=0.15$ does not represent the observed magnitude or the change in magnitude well, indeed the H/G system is not able to reproduce the observed changes. The diagram labelled Raw plots the observed magnitudes uncorrected for phase and distance (black dots), together with the SBDB magnitude formula (solid line) and also a solution assuming $G = 1.0$ and fitting $H = 30.01$ by least squares (dashed line). Neither magnitude formula represents the observed brightening well.



To analyse the lightcurve, the 16 separate sessions were levelled by adjusting the zero-points of each session to minimise the overall RMS fit, this lightcurve is labelled PAR for Jan 26.9 UTC and results in a period of 77.73 s with amplitude 1.0. The degree of scatter due to tumbling visible in the first night appears to be much reduced and additionally, a period spectrum from the second night, labelled PAR for Jan 26.9 UTC shows little evidence of the secondary signals detected the night before. To further investigate, the Dual Period Analysis function was again used, to subtract the effect of the dominant 77.73 s period from the second night and this produced a period spectrum labelled P1 subtracted, showing RMS minima at multiples of 23.76 s. An NPA solution for the second night produces lightcurves labelled P1 and P2 for Jan 26.9 UTC, giving the dominant period at 77.71 s with amplitude of 1.0 and a weaker secondary, bimodal lightcurve with amplitude of 0.3 and a period of 47.51 s, very similar to the 47.50 s monomodal period determined from the measurements obtained for the previous night.



Lightcurves for 2023 BU have appeared on Twitter from San Marcello Pistoiese Observatory, IAU code 104 (Bacci, 2023web) and Northolt Branch Observatory, IAU code Z80 (Wells and Bamberger, 2023web), both from observations made around 2023 Jan 26.8 - 26.9 and both indicating principal axis rotation with a period of 0.0216 ± 0.0001 h, with 104 giving an amplitude of 0.91 and Z80 an amplitude of 0.84. These PAR results are in good agreement with the P1 NPAR results in this paper for Jan 26.0 UTC of period 0.021583 ± 0.000001 h, amplitude 0.9 and for Jan 26.9 UTC of period 0.021587 ± 0.000004 h and amplitude 1.0.



It is concluded that 2023 BU is tumbling and that the main period of 77.70 s is well established, but the other apparent period, of 47.50 s is actually one of a few possible solutions for the second period. The amplitudes of the harmonics related to the frequency $1/47.50$ s change dramatically between the two nights (it is predominated by the 1st harmonic on the first night, but by the 2nd harmonic on the second night) suggests that it may be actually a linear combination of the two real frequencies rather than the other real frequency, but this is unsure without full physical modelling. However, on the scale defined in Pravec et al. (2005) it still warrants a coding of PAR = -3, i.e., “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).

Number	Name	Integration times	Max intg/Pd	Min a/b	Pts	Flds
2023	AQ	14.6–14.9	0.119	1.4*	184	3
2023	BU	0.4–12	0.253	1.9	782	23

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°.

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	AQ	01/15	42.8–43.6	136	–8	0.034636	0.000009	0.9	0.2		22.8
2023	BU	01/25–01/26	*25.5–24.6	123	3	0.021583	0.000001	0.9	0.2	–3	29.7
						0.013195	0.000001	0.7	0.2		

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, 2023).