LIGHTCURVE ANALYSIS FOR ELEVEN NEAR-EARTH ASTEROIDS

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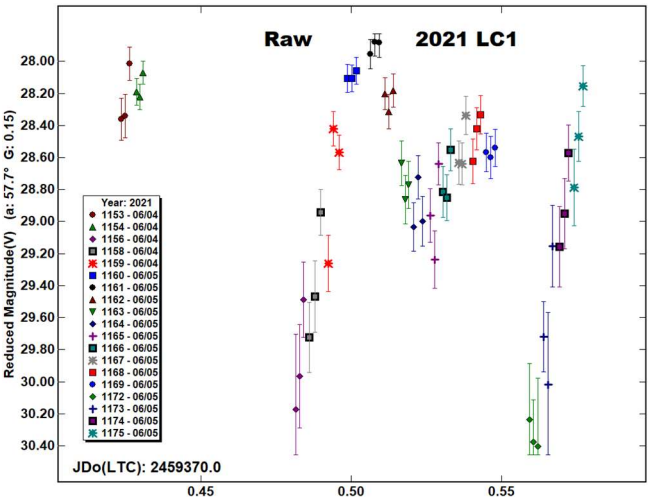
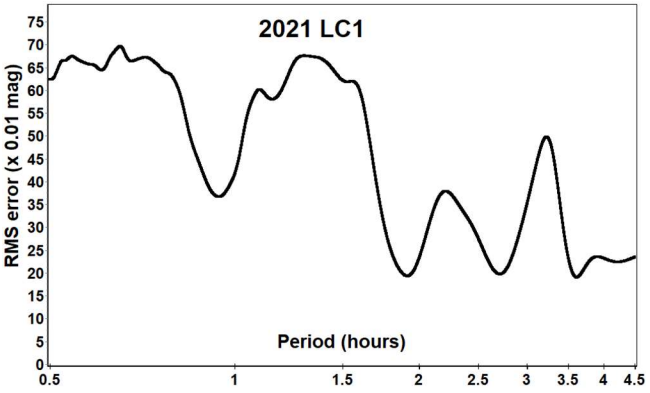
Lightcurves and amplitudes for eleven near-Earth asteroids observed from Great Shefford Observatory during close approaches in 2021 are reported: 2021 LC1, 2021 QB3, 2021 RA, 2021 RB1, 2021 RS2, 2021 RG19, 2021 TT10, 2021 US1, 2021 UW1, 2021 VL3 and 2021 VQ26. Most are fast or superfast rotators including two ultra-fast rotators with periods < 1 minute and one shows indications of tumbling.

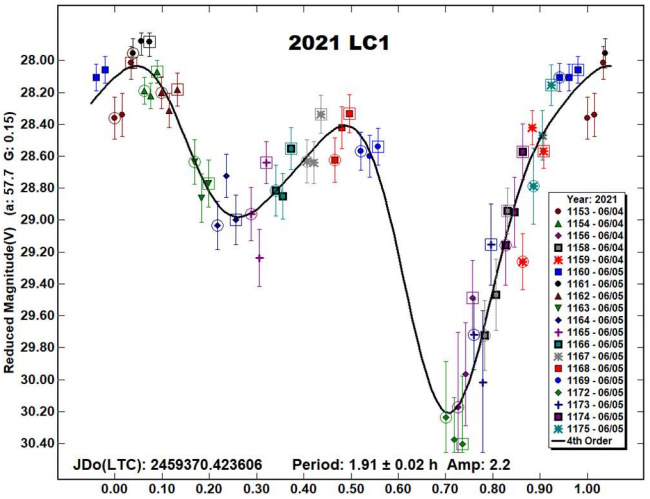
Photometric observations of near-Earth asteroids during close approaches to Earth between June and November 2021 were made at Great Shefford Observatory using a 0.40-m Schmidt-Cassegrain and Apogee Alta U47+ CCD camera. All observations were made unfiltered and with the telescope operating with a focal reducer at f/6. The 1K×1K, 13-micron CCD was binned 2×2 resulting in an image scale of 2.16 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) and G band data from the Gaia DR 2 catalogue (Brown et al., 2018). *MPO Canopus* (Warner, 2021), 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 (from here on referred to as LCDB; Warner et al., 2009), from searches via the Astrophysics Data System (ADS, 2021) or from wider searches. All size estimates are calculated using H values from the Small-Body Database Lookup (from here on referred to as SBDB; JPL 2021), using an assumed albedo for NEAs of 0.2 (LCDB readme.pdf file) and are therefore uncertain and offered for relative comparison only.

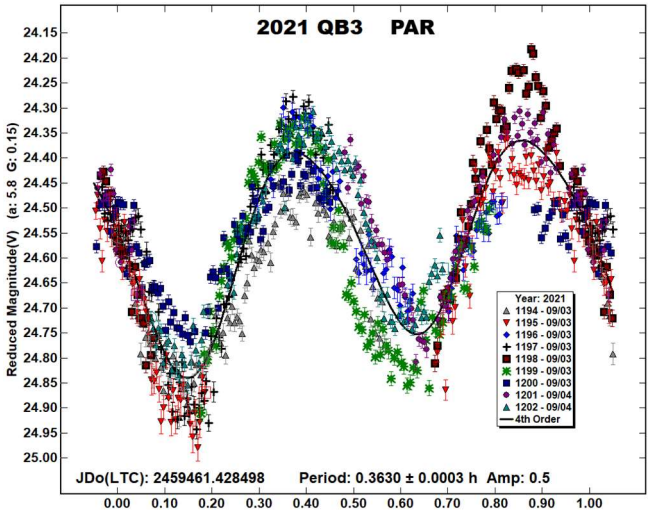
2021 LC1. The ZTF team at Palomar discovered this Aten 31 hours before an approach to 3 Lunar Distances (LD) on 2021 June 5.5 UTC (Pettarin et al., 2021). With H = 26.53 in the SBDB it has an estimated size of 15 m. It was observed for 3.7 h while still inbound, at a range of ~3.5 LD, about 12 hours before passing Earth. Its apparent speed increased from 115-133 arcsec/min during that time and exposures were limited to 5.6 s or shorter. The telescope was repositioned a total of 19 times during the session and although relatively faint on individual images, no short-term variation was obvious as it crossed individual fields, however longer term (tens of minutes) variation was noted. The images were then stacked using *Astrometrica*, with 3 stacks being formed from the images collected from each of the 19 separate fields with the maximum elapsed time from the start of the first exposure to the end of the last used in any stack being 165 s. The raw plot shows fragments of a lightcurve, with two ~2 mag amplitude rises and indications of three maxima over ~3.6 h. The period spectrum shows the first of the three most significant RMS minima at 1.9 h and this period is adopted to generate the bimodal phased plot, though as this implies there was only partial coverage of less than 2 revolutions, this solution should be regarded as uncertain.



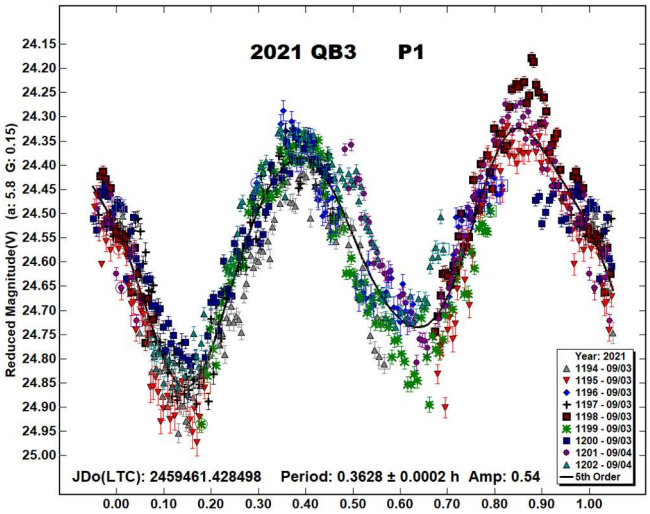


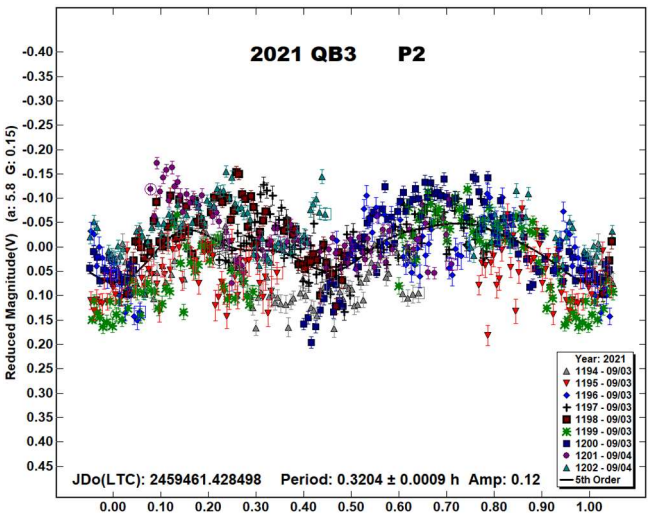


2021 QB3. The SBDB lists this Apollo with H = 23.77, equating to a diameter of ~52 m. It was an ATLAS-MLO discovery from 2021 Aug 31.3 UTC (Melnikov et al., 2021a) and made an approach to 1.7 LD of Earth on 2021 Sep 3.0 UTC, reaching mag +13 for 40 hours following that passage. 811 images were obtained over a period of 2.1 h starting 2021 Sep 3.93 UTC using exposures of 5.2 and 5.6 s and an initial solution resulted in a bimodal lightcurve of period 0.3630 h with an amplitude of 0.5. This figure is marked as PAR (Principal Axis Rotation) but shows strong indications of low amplitude non-principal axis rotation.

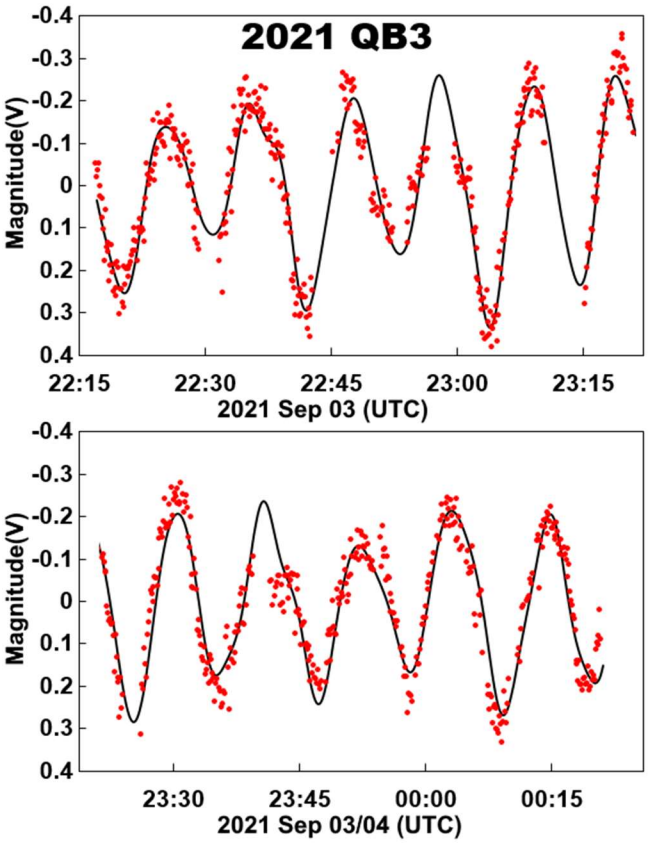


An attempt to solve for two periods in Canopus using its Dual-Period search functionality resulted in a second period of 0.3206 h with amplitude 0.12 being derived, the two lightcurves given here marked as P1 and P2.

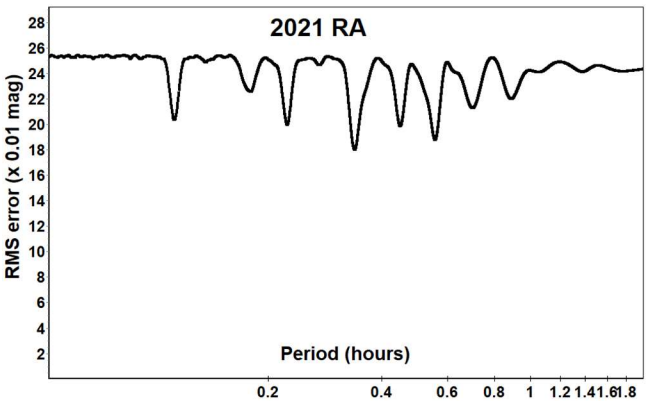


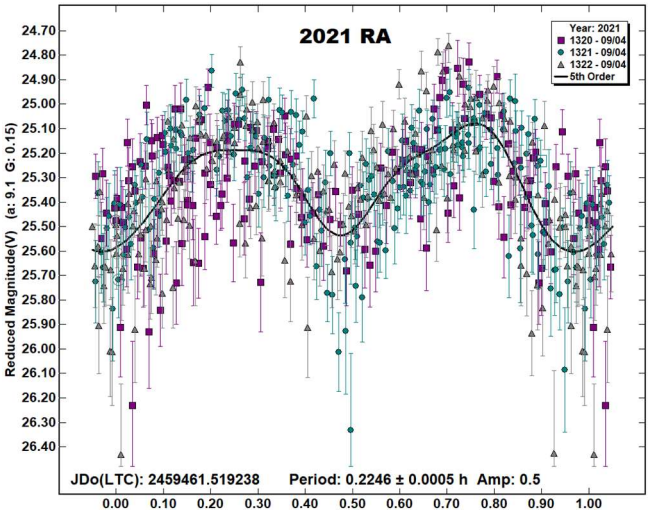


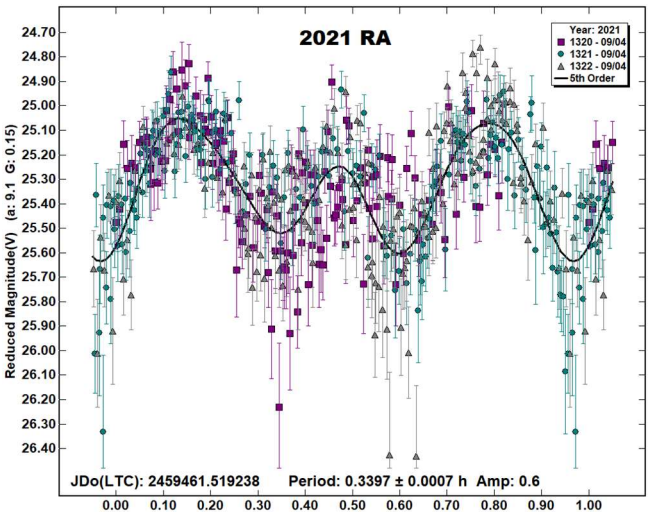
The large scatter in the P2 lightcurve and the reduced but still remaining systematic trends in the P1 lightcurve indicate problems with the NPAR fit and a plot of the measurements with the calculated curve from the NPAR solution superimposed shows the observed variations are represented only moderately well. It is expected that 2021 QB3 may be rated with a PAR code of -2 "NPA rotation detected based on deviations from a single period but the second period is not resolved" (Petr Pravec, personal communication).



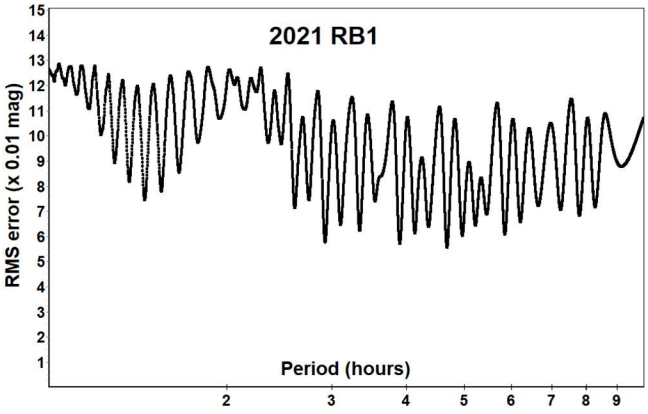
2021 RA. This Apollo was discovered at mag +15 and declination -44° on 2021 Sep 2.05 UTC by the SONEAR team in Brazil, already receding after an approach to within 3 LD some 13 h beforehand (Foglia et al., 2021a). The value of H given in the SBDB is 24.70, suggesting an approximate diameter of 34 m. It had already faded by about 1 mag when observed from Great Shefford starting at 2021 Sep 4.02 UTC. Over a period of 1.65 h, 531 exposures of 8 s duration were taken with the telescope needing repositioning 3 times. The period spectrum indicates a solution at 0.34 h gives the best fit, the resulting trimodal lightcurve is given as well as a bimodal solution at 0.22 h, but the shorter period is clearly an inferior fit.

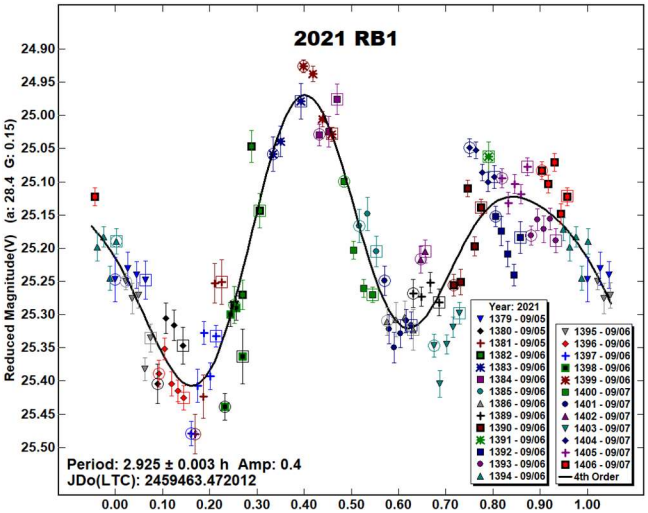




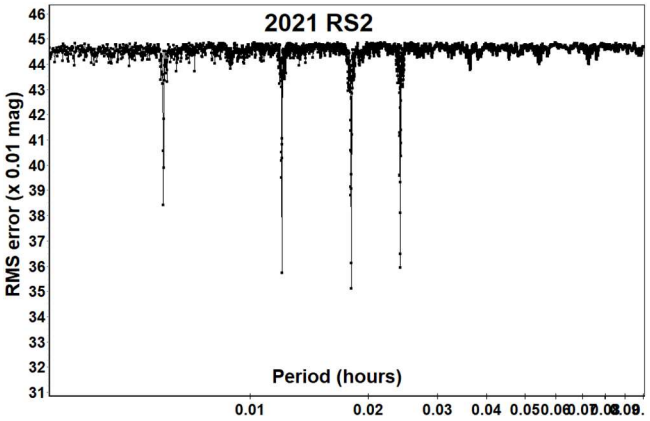


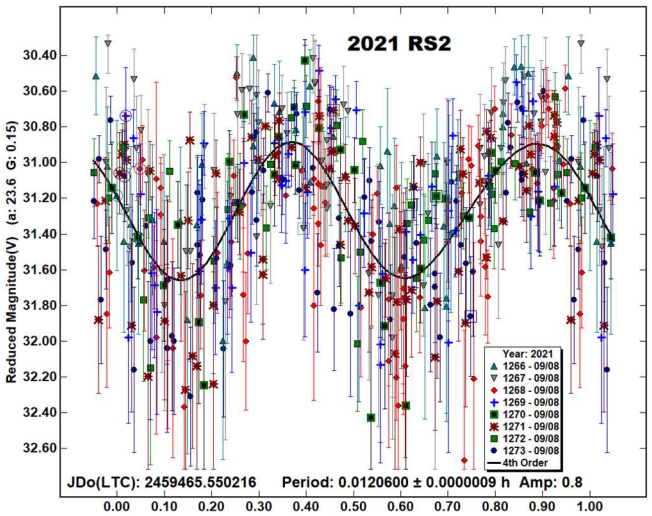
2021 RB1. Another discovery by the SONEAR team in Brazil, this Amor object was found on 2021 Sep 5.2 UTC and passed Earth at 8 LD about 30 hours later (Foglia et al., 2021b). The SBDB lists it with H = 24.06, equating to an approximate diameter of 46 m. It was under observation for 2.4 h starting at 2021 Sep 5.97 UTC and again for 3.9 h starting 2021 Sep 6.90 UTC and a total of 2527 images were obtained with exposures ranging from 2 - 7 s. 2021 RB1 was 16th mag throughout that period, sky conditions were occasionally only fair. The resulting noisy lightcurve from measuring individual images revealed no short period variation but did show a ~0.4 mag amplitude variation over the several hours it was observed on each of the two nights. The images were then combined into 109 stacked images and measured using *Astrometrica* before analysing with *MPO Canopus*. The period spectrum, covering the range 1 - 10 h reveals multiple solutions giving similar fits to the data in the range 2.5 - 6 h, the strongest bimodal solution, at 2.925 h is adopted here as the most plausible. The maximum elapsed time from the start of the first exposure to the end of the last used in any stack was 200 s, significantly less than the derived period, indicating lightcurve smoothing was negligible (Pravec et al., 2000).



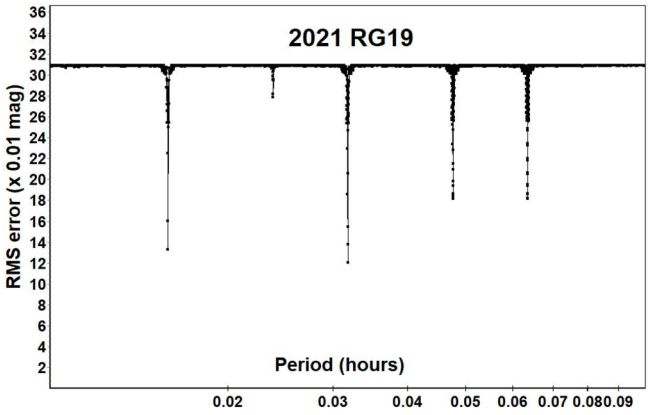


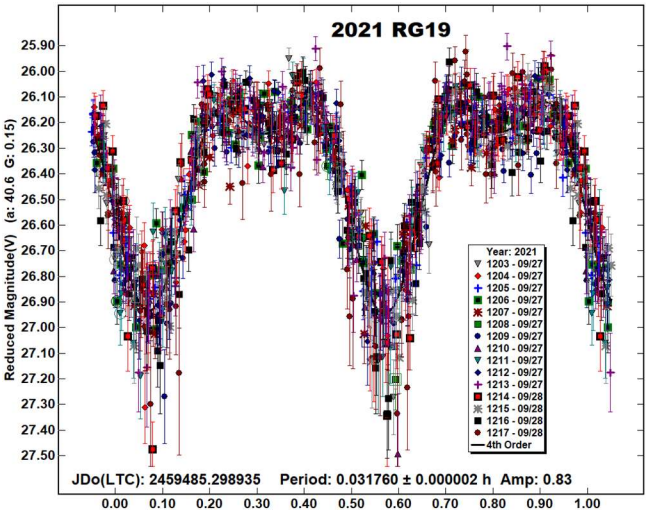
2021 RS2. The SBDB lists this Apollo with an H value of 30.35, suggesting a diameter of just 3 m and it was discovered by the Mt. Lemmon survey on 2021 Sep 7.26 UTC, 25 hours before making a very close approach to Earth at a distance of 0.06 LD (Melnikov et al., 2021b). It was under observation, initially for 15 mins starting at 2021 Sep 8.05 UTC, then 1.4 hours later for a further 55 mins and during that period halved its distance from Earth, to 0.56 LD. Exposures were kept between 4 and 5.6 s as the apparent speed increased from 40 to 100 arcsec/min. The apparent magnitude brightened from +18 to +17 and the amount of noise in the resulting photometric measures is large. However, especially during the latter stages, large variations in magnitude were obvious between consecutive exposures, taken with a cadence of ~6 s. The period spectrum covering periods from 11 to 360 s shows a set of very sharply defined RMS minima, the trimodal solution at 0.01809 h giving the lowest RMS figure, but only different to the bimodal solution's RMS by 0.01 mag and with the overall amount of noise in the measures being ~0.35 mag the bimodal solution at 0.012 h is selected here as being the most likely. This indicates that during the 1.4 h it was being observed it completed 119 revolutions. With the longest exposures used being 12.9% of the rotation period the amplitude attributable to the second harmonic would have been reduced due to lightcurve smoothing by 0.09 mag (Pravec et al., 2000), considerably less than the observed uncertainty in the amplitude.



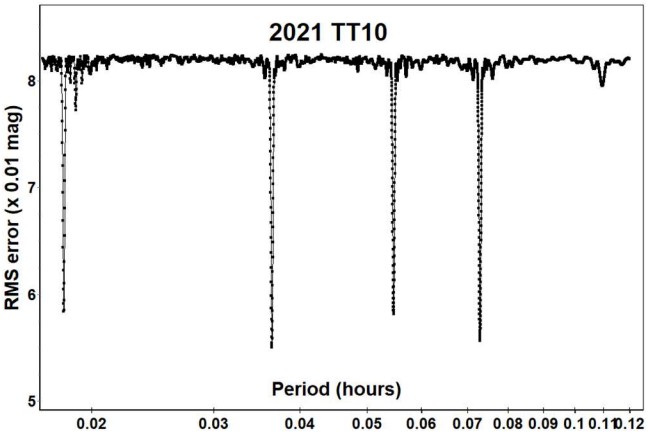


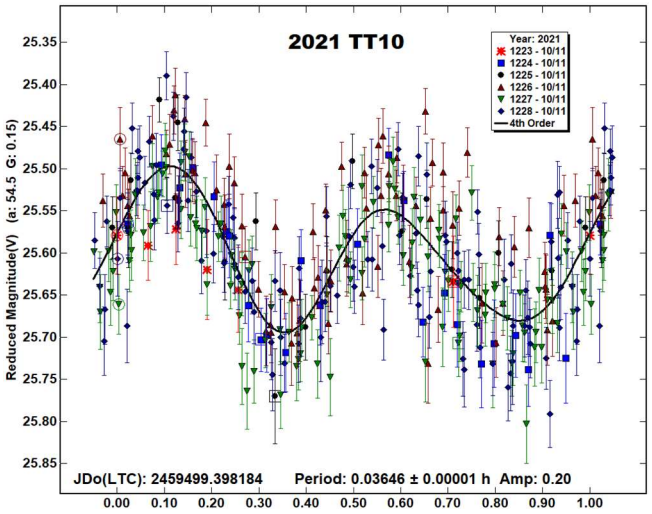
2021 RG19. The Pan-STARRS team discovered this Apollo at mag +22, with over two weeks lead time before it made an approach to 2 LD of Earth on 2021 Sep 28.92 UTC (Bulger et al., 2021). It was observed for 1.7 h starting at 2021 Sep 27.80 UTC and two hours later observed for another 2.0 h, when it was 16th mag and at a range of 4 LD. 1084 images were obtained with exposures ranging from 5.3 - 7.1 s with the telescope being repositioned 15 times due to the apparent speed, accelerating from 55 to 75 arcsec/min. The SBDB value of H = 24.73 translates to an approximate diameter of 34 m. 2021 RG19 could be seen to fade abruptly about every minute on individual images and the period spectrum shows the strongest solution at 0.031760 h (= 1.9 min.) is bimodal with a 0.8 mag amplitude. Over the 3.7 h of data collection, 2021 RG19 completed 116 rotations.

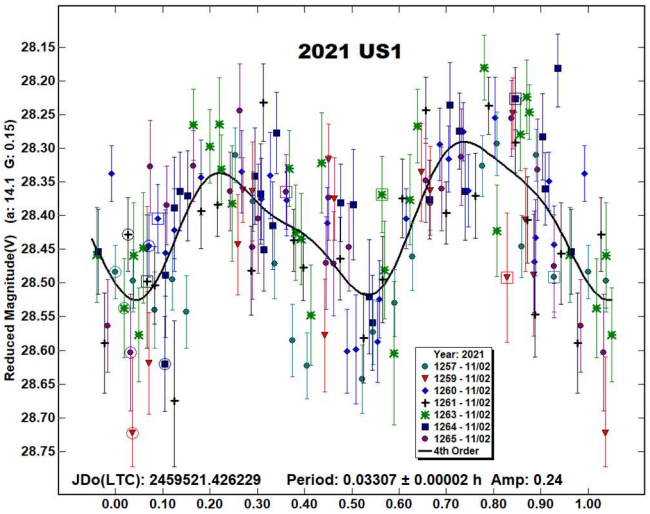




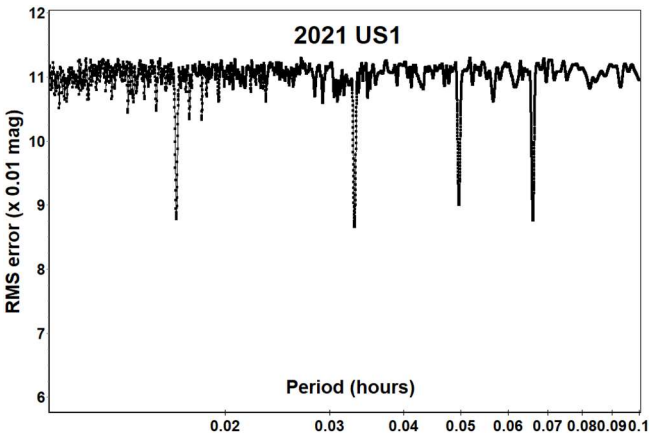
2021 TT10. The Mauna Loa ATLAS telescope discovered this Apollo on images taken on 2021 Oct 11.4 UTC, 4 hours after an approach to 1.7 LD from Earth (Bacci et al., 2021a). Pre-discovery positions were subsequently reported by the Catalina Sky Survey from 2 hours before closest approach, some 76° distant from the ATLAS positions. With the SBDB listing 2021 TT10 with a value of H = 23.41 this is likely to be the largest of the objects being reported here, with an estimated size of 62 m. It was observed for 2.1 h on the discovery date when it was 16th mag and moving at 20 arcsec/min. Exposures ranged from 7 - 12 s and 350 images were taken, with the telescope being repositioned 6 times. Analysis with Canopus revealed only short period solutions and the period spectrum, covering the range 1 - 7.2 min shows the strongest solution at 0.03646 h. The phased lightcurve indicates a low amplitude bimodal curve. The longest exposure as a fraction of the period is 0.09 and therefore no significant lightcurve smoothing is expected to be present (Pravec et al., 2000). 58 revolutions were completed during the period of observation.



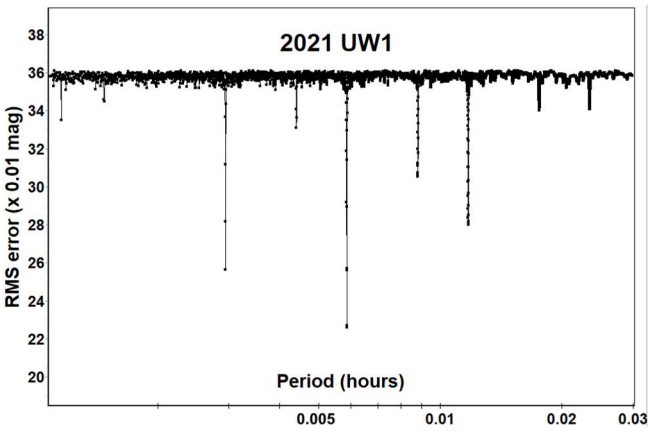


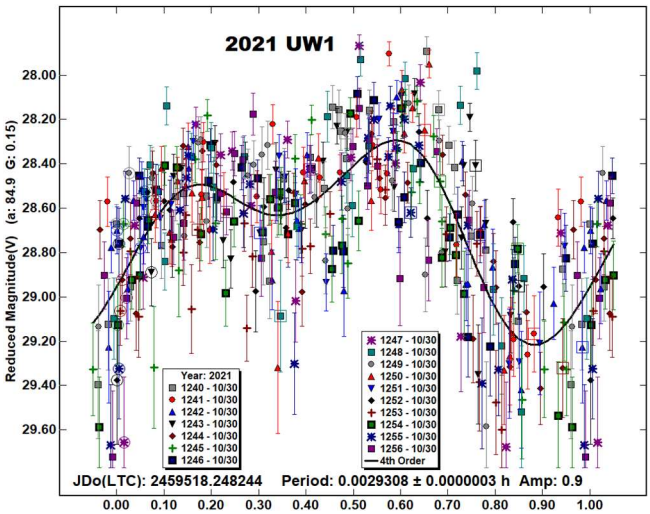


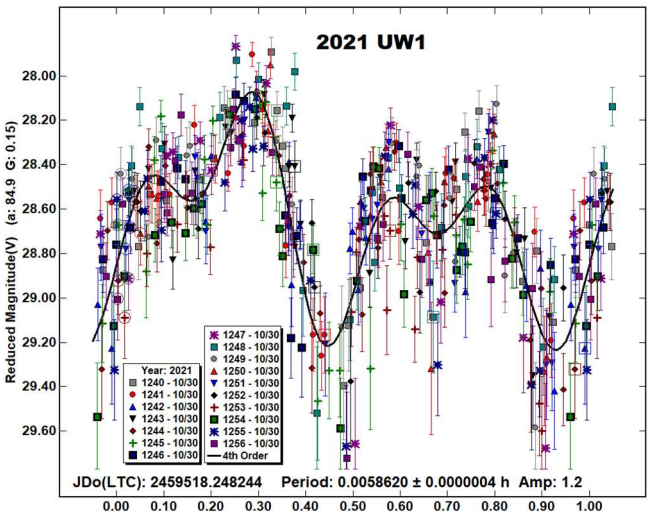
2021 US1. Another Apollo, discovered by the Mt. Lemmon survey on 2021 Oct 26.1 UTC on its way in to an approach to within 2 LD on 2021 Nov 2.97 UTC (Panterotto et al., 2021). It was observed for 1.3 h through the point of closest approach, apparent speed was not excessive, at 43 arcsec/min, with the telescope requiring repositioning 7 times, but it was rather faint at mag +17. The SBDB gives the value for absolute magnitude H as 27.79, inferring a diameter of approximately 8 m. 645 images were obtained with exposures of 2, 4 and 6 s and these measured and used to produce a lightcurve in *MPO Canopus*. As expected, there was a large amount of noise in the measurements but a bimodal solution with period 119 s was apparent. The optimal exposure to record the strongest signal for a minor planet with a bimodal lightcurve and rotation period of P is 0.185 P (Pravec et al., 2000), in this case 0.185 × 119 s = 22 s. The images from each of the 7 fields were examined and divided up into sets for stacking with *Astrometrica*, each set chosen so that the elapsed time from start of the first exposure to end of the last was 22 s or less. This resulted in 151 stacks combining on average 4.3 images in each. The measurements from these stacks were then imported into Canopus and the resulting period spectrum showing the solution at 0.03307 h being the strongest. The likely effect of forcing the effective integration time to be 0.185 P is to decrease the amplitude due to the second harmonic by 0.06 mag (Pravec et al., 2000), indicating that the amplitude without any lightcurve smoothing would be ~0.30 mag.



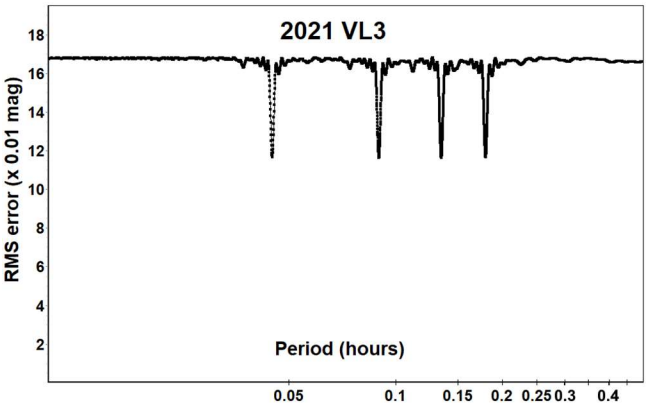
2021 UW1. This Apollo was another discovered by the Mt. Lemmon Survey, one day after 2021 US1 and due to pass Earth at 1 LD on 2021 Oct 30.85 UTC (Bacci et al., 2021b). It was observed for 43 minutes within 2 hours of closest approach at large phase angles (85 - 90°) with the apparent speed increasing from 420 to 440 arcsec/min and exposure lengths were limited to 0.9 s throughout. A total of 396 measurable images were obtained and large variations in brightness were obvious between consecutive exposures, indicating a very fast rotation period. The period spectrum shows a number of ultra-fast solutions below 60 s, the strongest being at 0.0058620 h (= 21 s) and the next strongest at half that value at 0.0029308 h. Both lightcurves are given here, but the longer period with a more complex curve appears to fit the data significantly better and is adopted here as the correct period. 2021 UW1 has an estimated diameter of 17 m based on the value of H = 26.15 in the SBDB. It completed 121 revolutions during the time it was under observation.

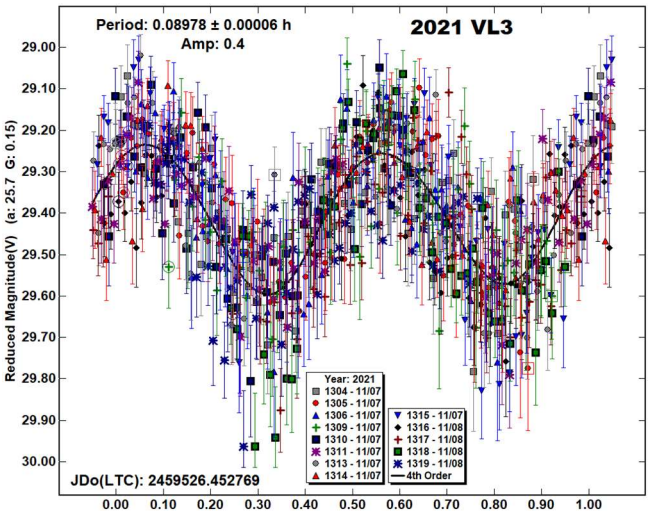




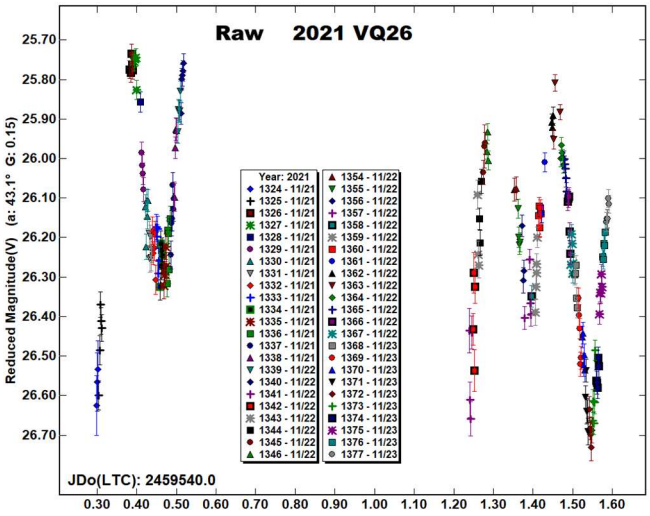


2021 VL3. This Apollo was discovered by the ATLAS telescope on Haleakala on 2021 Nov 7.45 UTC, 22 hours before passing Earth at 0.4 LD (Barni et al., 2021). The SBDB lists it with H = 28.43, equating to an estimated size of 6 m. It was observed for 1.4 h starting at 2021 Nov 7.95 UTC at 15th mag and with the apparent speed increasing from 160 to 190 arcsec/min during that period the telescope had to be repositioned 13 times, resulting in 745 measurable images being obtained, taken with exposures ranging between 2.3 and 2.7 s. Small adjustments to the zero-points of the 13 sessions were made in *MPO Canopus* to minimise the overall RMS fit of the lightcurve, with the RMS of those adjustments being 0.056 mag. The RMS of the four potential solutions revealed in the period spectrum are equal to within 0.0004 mag and the bimodal lightcurve is presented here with a period of 5.4 minutes and amplitude of 0.4.

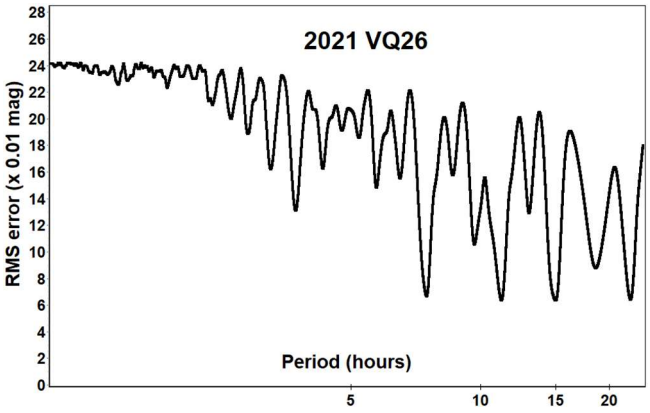




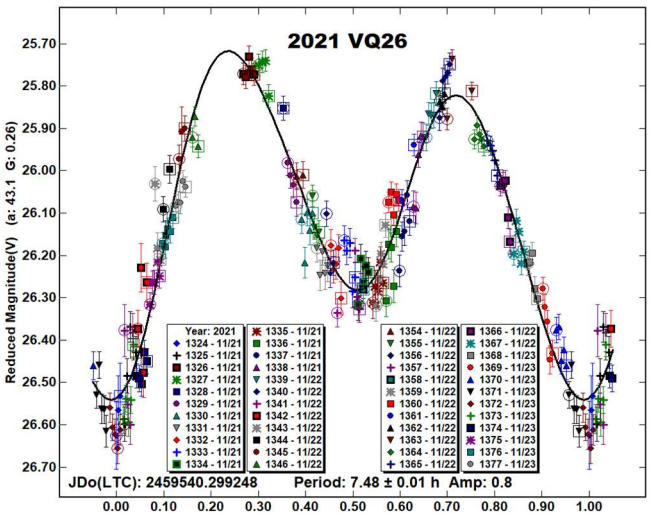
2021 VQ26. The Mt. Lemmon survey discovered this Apollo on 2021 Nov 15.1 UTC about 1 week before an approach to 4.6 LD (Buzzi et al., 2021). It was observed extensively from Great Shefford starting on 2021 Nov 21.8 for 5.3 h and 2021 Nov 22.7 UTC for 8.4 h with a total of 3837 measurable images being obtained, with the telescope being repositioned 47 times, the apparent magnitude rose from +16 to +15 over the two nights. With an apparent speed of 63 - 70 arcsec/min exposures were kept to 6.1 s or shorter. On initial examination no very short-term magnitude changes was evident but variation was seen over tens of minutes, so the images were then stacked in *Astrometrica* with the time from start of first exposure to end of last exposure in any one stack being kept to 240 seconds or less. The last three sessions measured (numbered 1375, 1376 and 1377 in the following plots) would not solve with the UCAC4 catalogue, instead G-band magnitudes were measured using the Gaia DR 2 catalogue and converted to V band by using the adjustment of 0.28 used by the MPC (MPC, 2021). A raw plot, with the observed magnitudes reduced to unit distance and adjusted for phase angle, assuming the phase slope parameter G = 0.15 indicates that an almost complete rotation with unequal minima may have been captured on the second night, assuming a bimodal curve. The partial curve on the first night includes one minimum, with a similar shape to the first minima on the second night, though it appears to be about 0.1 mag brighter. However, the phase angle decreased from 43.0 - 37.9° on the first night but had reduced to 21.4 - 17.2° on the second night, so levelling between the two nights will be sensitive to the value of G adopted in the HG magnitude system parameters used in the reduction.



The period spectrum over a range of 1 – 24 h shows a set of similar RMS minima starting with a bimodal solution at 7.6 h, which with the limited coverage obtained is chosen as likely to be the correct period.



MPO Canopus was used to vary the value of G to minimise the fit between the two nights of data, the best fit was obtained using G = 0.26 and is given here:



Acknowledgements

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Number	Name	Integration times	Max intg./ Period	Min a/b	Points	Fields
	2021 LC1	165Σ	0.024	2.0	57	19
	2021 QB3	5.2-5.6	0.010	1.5	811	9
	2021 RA	8	0.007	1.5	531	3
	2021 RB1	200Σ	0.019	1.2	109	26
	2021 RS2	4-5.6	0.129	1.5	439	8
	2021 RG19	5.3-7.1	0.062	1.4	1084	15
	2021 TT10	7,8,12	0.091	1.1	350	6
	2021 US1	22Σ	0.185	1.2	151	7
	2021 UW1	0.9	0.043	1.3	396	17
	2021 VL3	2.3-2.7	0.008	1.2	745	13
	2021 VQ26	240Σ	0.009	1.5	199	47

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).

Number	Name	yyyy mm/ dd	Phase	L_{PAB}	B_{PAB}	Period(h)	P.E.	Amp	A.E	PAR	H
	2021 LC1	2021 06/04-06/05	57.5,63.8	233	23	1.91	0.02	2.2	0.4		26.53
	2021 QB3	2021 09/03-09/04	5.6,8.0	344	-2	0.3628	0.0002	0.5	0.1	-2	23.77
						0.3204	0.0009	0.1	0.1		
	2021 RA	2021 09/04-09/04	9.1,9.2	346	-1	0.3397	0.0007	0.6	0.3		24.70
	2021 RB1	2021 09/05-09/07	28.5,30.3	357	3	2.925	0.003	0.4	0.1		24.06
	2021 RS2	2021 09/08-09/08	23.1,24.9	348	12	0.0120600	0.0000009	0.8	0.5		30.35
	2021 RG19	2021 09/27-09/28	40.4,43.6	11	20	0.031760	0.000002	0.8	0.2		24.73
	2021 TT10	2021 10/11-10/11	54.5,54.9	23	28	0.03646	0.00001	0.2	0.1		23.41
	2021 US1	2021 11/02-11/02	14.0,14.8	47	2	0.03307	0.00002	0.2	0.1		27.79
	2021 UW1	2021 10/30-10/30	85.2,90.3	358	21	0.0058620	0.0000004	1.2	0.3		26.15
	2021 VL3	2021 11/07-11/08	26.5,23.3	35	-7	0.08978	0.00006	0.4	0.2		28.43
	2021 VQ26	2021 11/21-11/23	43.0,17.1	52	11	7.48	0.01	0.8	0.1		24.33

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. L_{PAB} and B_{PAB} 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 Lookup (JPL, 2021).