

A NEW PHOTOMETRIC WORKFLOW AND LIGHTCURVES OF FIFTEEN ASTEROIDS

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A new data reduction workflow makes intense use of the recent ATLAS refcat2 catalog, with the intent of using every eligible comparison star available in the sky field of view. By applying this workflow to CCD observations made late 2019 and early 2020, we generated lightcurves and synodic rotation periods, also presented here, for fifteen asteroids of various families.

A new photometric reduction workflow is described which attempts to use all eligible comparison stars in an image's field of view. Lightcurves, synodic periods, and amplitudes are given for fifteen asteroids.

ATLAS refcat2 (Tonry et al 2018) as used in this work is a comprehensive catalog of Gaia astrometry and all-sky photometry in several passbands, each data point cross-calibrated across several advanced, recent photometric catalogs. The workflow was largely implemented by python automation scripts written by the author (Dose, 2020).

New Photometric Reduction Workflow

The new workflow begins by collecting all ATLAS catalog stars (typically ca. 200-800) within an image's field of view, and then screening them for appropriate magnitude, magnitude uncertainty, color index, lack of nearby interfering sources, and for catalog-stated non-variability and photometric quality. Each image will begin with typically 40-150 of these screened comparison "comp" star candidates. By visual inspection of numerous diagnostic plots, one then removes those comp stars with erratic photometric behavior, trending magnitudes, and the like, typically yielding 40-120 accepted comp stars for the session. Given that the ATLAS catalog is >99% complete to magnitude 16, this workflow benefits from including effectively all eligible comp stars offered by the sky.

The low-level aperture photometry engine applied here is adapted from the author's variable star observing programs (Dose, 2019), including a split-annulus sky-flux measuring algorithm adept at nullifying the effect of most cosmic rays and nearby light sources not visually detected.

Instrumental magnitudes for all accepted comp stars in all of a session's images are then submitted as dependent variable to mixed-model regression (Gelman and Hill, 2006) as implemented by the python package statsmodels. Extracted parameters include zero-point, parabolic vignetting, and, optionally, extinction, linear magnitude drift with time, and even transform. The mixed model is then applied in reverse to all asteroid instrumental magnitudes to give the final best estimates of catalog-basis, top-of-atmosphere asteroid magnitudes in Sloan r passband; these best magnitudes are already transformed and corrected for sky extinction. Modest image-to-image random fluctuations ("cirrus effect") are also accounted for and plotted as facilitated by mixed-model statistics.

A sequence of adjustments, mixed-model regression, diagnostic plotting, and asteroid magnitude extraction is iterated; adjustments include restricting comp star color and magnitude ranges to better match the target asteroid, as well as excluding outlier comp stars, outlier comp star observations, and/or entire images. Iterations continue until convergence; typically 2-4 iterations are needed. It is usually profitable to set uniform ranges to comp star magnitude and color ranges among all sessions of a campaign (all nightly sessions in one apparition for one asteroid), to minimize night-to-night artifacts arising solely from unnecessary variation in comp star selection.

This process directly yields best estimates of asteroid magnitude on catalog basis, that is, the session's lightcurve. These final, catalog-basis asteroid magnitudes are imported directly into *MPO Canopus* software (Warner, 2018b) for Fourier analysis. In *MPO Canopus*, magnitudes are adjusted for distances and for phase-angle dependence with an *H-G* model, using $G = 0.15$ unless otherwise specified.

By taking full advantage of the large number and high quality of ATLAS comp stars, the author finds that sessions of a given campaign match in reduced absolute magnitudes, that is, they seldom need any night-to-night magnitude offsets at all. In *MPO Canopus* terms, the DeltaComp values are zero for almost all sessions for the asteroids reported here. Exceptions occur for phase angles below about 1° , where the *H-G* correction model may miss intense opposition effects (e.g., from asteroid surface crystals with internal right angles). This limitation of the *H-G* model will result in inaccurate phase-angle corrections near zero phase even were one's measured magnitudes perfectly correct. That aside, and if the zero-adjustment findings hold up, the ability for a given asteroid to match many nights of photometry without arbitrary magnitude adjustments will prove especially helpful for studying asteroids with long periods. For wide phase-angle ranges, amplitude dependence on phase angle should probably be included as well (Zappalá et al., 1990).

The present workflow automatically generates ALCDEF-compliant files. All lightcurve data herein have been submitted to the ALCDEF database.

Lightcurves from the New Workflow

Fifteen asteroids were observed from Deep Sky West observatory (IAU V28) in northern New Mexico. Images were acquired with a 0.35-m SCT reduced to $f/7.7$, an SBIG STXL-6303E camera without binning and cooled to -35°C fitted with a Clear filter (Astrodon), on a PlaneWave L-500 direct-drive mount. The equipment is operated remotely via *ACP* software (DC-3 Dreams), running plan text files generated for each night by the author's python scripts (Dose, 2020). Most sessions were interleaved by cycling between the positions of 2-4 asteroids (and/or unrelated long-period variable stars for separate studies), as facilitated by the mount's rapid slews. Exposures longer than 120 seconds were autoguided. Time basis was standardized by *Meinberg* NTP service and monitor (Meinberg, 2020) against 4-6 remote NTP servers, continuously to within 2-10 milliseconds.

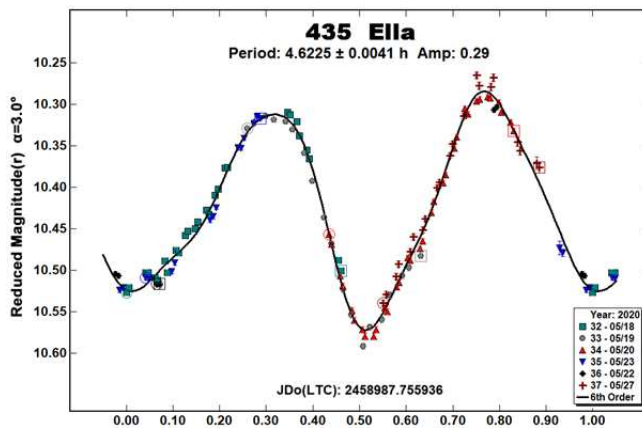
FITS images were plate-solved by *PinPoint* (DC-3 Dreams) and calibrated using temperature-matched, median-averaged dark images and recent flat images of a flux-adjustable flat panel. Every photometric image was visually inspected, and any images with poor tracking or with other light sources expected to overlap the target asteroid were simply excluded. Accepted photometry-ready images were submitted to the workflow presented above, producing the lightcurves presented here.

Number	Name	yyyy mm/dd	Phase	L_{PAB}	B_{PAB}	Period(h)	P.E.	Amp	A.E.	Grp
435	Ella	2020 05/18-05/27	*3.5, 1.2	244	-2	4.622	0.004	0.29	0.02	NYSA
768	Struveana	2019 10/21-11/17	*6.7, 6.7	40	0	10.744	0.006	0.32	0.02	MB-O
1074	Beljawska	2019 11/04-11/10	17.8, 15.9	86	1	6.286	0.002	0.31	0.02	THM
1130	Skuld	2019 10/27-11/03	*1.11, 3.27	35	0	4.808	0.001	0.26	0.02	FLOR
1592	Mathieu	2020 05/18-06/20	*9.4, 17.6	241	12	28.528	0.010	0.16	0.02	MB-O
2415	Ganesa	2020 05/19-06/25	3.0, 16.9	233	2	6.894	0.001	0.23	0.02	MB-M
3151	Talbot	2020 05/15-05/26	*6.6, 7.3	239	12	19.444	0.007	0.50	0.02	MB-O
3683	Baumann	2020 05/20-06/22	*7.6, 8.6	253	10	7.888	0.001	0.22	0.02	MB-O
3800	Karayusuf	2020 05/13-05/20	20.5, 19.0	236	19	2.232	0.001	0.14	0.02	MC
5534	1941 UN	2019 10/17-11/05	9.4, 19.4	10	2	14.402	0.004	0.17	0.02	MB-O
7910	Aleksola	2020 06/08-06/20	12.6, 18.1	242	9	6.416	0.002	0.20	0.02	MB-I
11190	Jennibell	2019 10/31-11/03	1.3, 3.1	35	0	3.429	0.003	0.32	0.04	FLOR
14923	1994 TU3	2019 10/27-10/31	6.9, 5.2	41	-5	2.653	0.001	0.13	0.02	PHO
39197	2000 XA	2019 10/23-10/31	*3.9, 4.1	32	-3	5.221	0.001	0.65	0.02	H
42196	2001 DE21	2019 10/29	1.9	32	-3	7.480	0.160	0.27	0.02	EOS

Table I. 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). Grp is the asteroid family/group (Warner et al., 2009).

435 Ella. This well-studied Nysa-family asteroid was found to have a synodic period of 4.6225 h, in agreement with published periods of 4.623 h (Barucci et al., 1992), 4.624 h (Piironen et al., 1998), 4.6233 h (Behrend, 2006), 4.64 h (Chang et al., 2016), and 4.621 h (Lang et al., 2018).

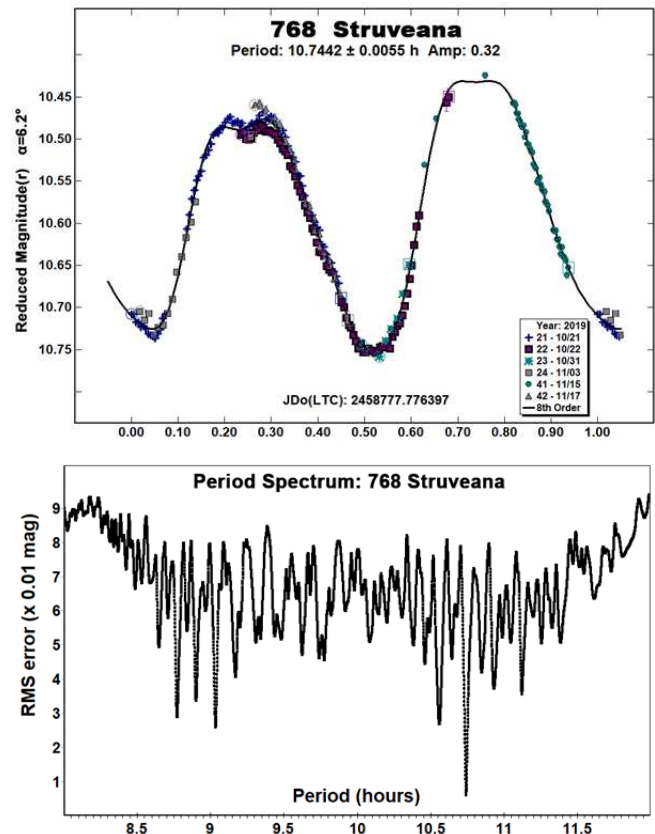
ATLAS comparison stars were abundant; in the new photometric workflow described above, comp stars for this asteroid averaged 57 in number, with every night employing at least 36. Fourier fit and phased plot used magnitudes obtained directly from the mixed-model regression, that is, without night-to-night magnitude adjustments beyond standard distance reductions and $H-G$ corrections. RMS error is 10 millimagnitudes.



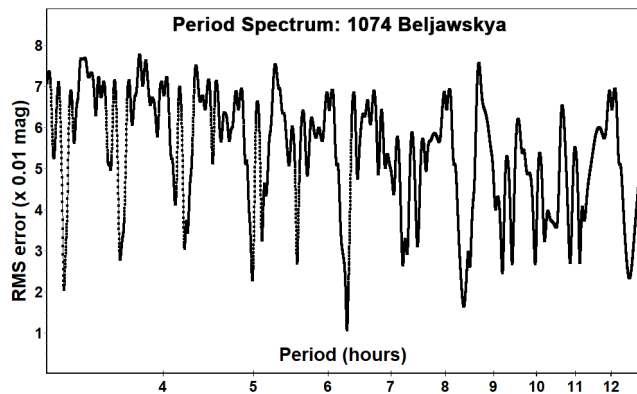
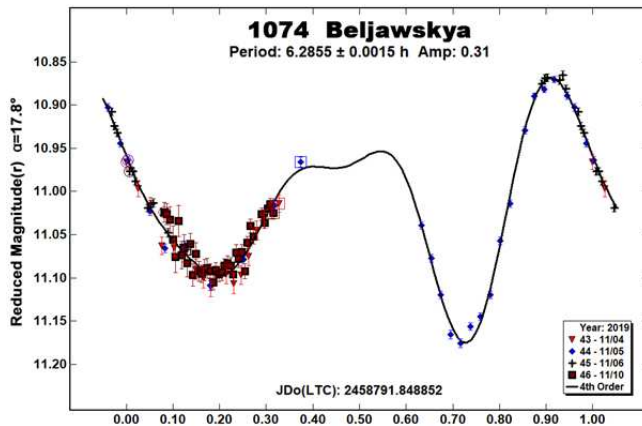
768 Struveana. For this outer main-belt asteroid, the LCDB lists two previous period determinations: 8.802 h (Gil-Hutton and Cañada, 2003) and 8.76 h (Behrend, 2007), with uncertainty code of 2+. However, the present data's deeper coverage, high amplitude to RMS-error ratio, and period spectrum all clearly favor a different synodic period of 10.7442 h. We note that our bimodal period differs from previous periods by one half-period per 24 hours. RMS error is 8 millimagnitudes.

The Fourier fit benefited from magnitude adjustments to two nights with very low phase angles: +0.040 magnitudes for Oct 31 (phase angle $\alpha = 1.47^\circ$) and +0.110 for Nov 3 ($\alpha = 0.29^\circ$). The other four nights with larger phase angles needed no such adjustment. As the two adjustments were limited to very low phase angles, were negative in magnitude (indicating brightening and thus requiring positive corrections), and were monotonic in scale with phase angle, they indicate a large opposition effect for which standard $H-G$ corrections fail to account.

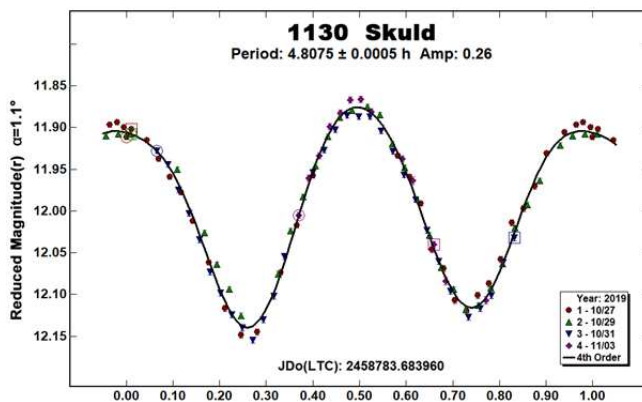
Trial corrections with G values other than the MPC standard of $G = 0.15$ did not reduce need for extra nightly adjustments of data taken at very low phase angles. The phased plot does suggest some increase in amplitude with phase angle (Zappalá et al., 1990).



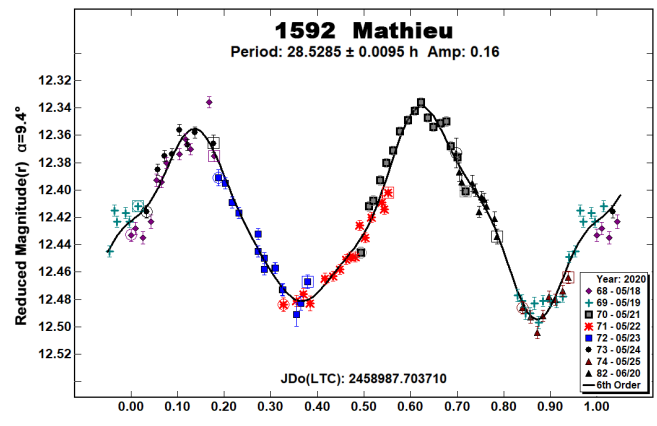
1074 Beljawska. This very early lightcurve effort of the author's for this Themis asteroid suffered imperfect phase sampling, but even so it captured both of its brightness minima and yielded a provisional bimodal synodic rotation period of 6.2855 h, matching one known published survey period of 6.285 h (Waszczak et al., 2015). On average, 48 ATLAS comp stars were applied to each image; no night-to-night magnitude adjustments were needed. RMS error is 10 millimagnitudes.



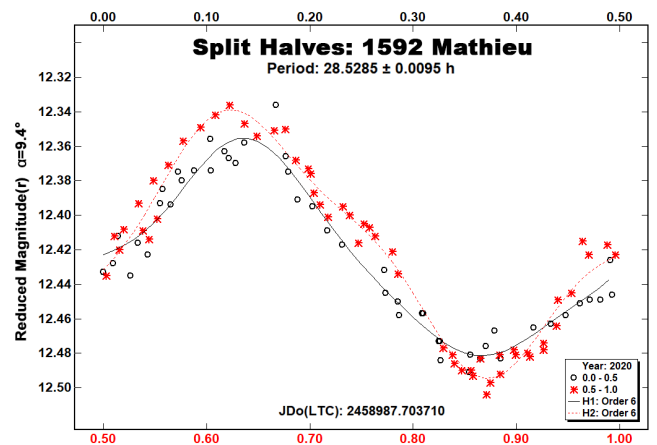
1130 Skuld. This well-studied Flora asteroid was found to have synodic rotation period of 4.8075 h, matching published periods of 4.75 h (Behrend, 2004), 4.807 h (Buchheim, 2010), 4.810 h (Robinson, 2011), 4.8079 h (Kryszczyńska et al., 2012), 4.8096 h (Behrend, 2017), and 4.8058 h (Behrend, 2019). Nightly magnitude adjustments were made for two nights at very low phase angles: $+0.010$ for Oct 27 ($\alpha = 1.11^\circ$), and $+0.060$ for Oct 29 ($\alpha = 0.19^\circ$), almost certainly arising from opposition effects inadequately accounted for by $H-G$ correction. RMS error is 8 millimagitudes.



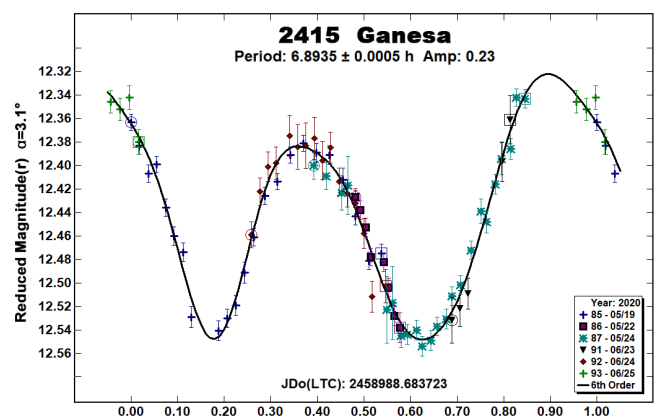
1592 Mathieu. This Flora asteroid was observed over eight nights spanning a month. Its synodic period is clearly bimodal and of duration 28.5285 h, consistent with a published monomodal period of 14.23 h (Warner, 2006) and a survey estimate of 28.4821 h (Durech et al., 2016). No nightly magnitude adjustments were made; RMS error is 9 millimagitudes.



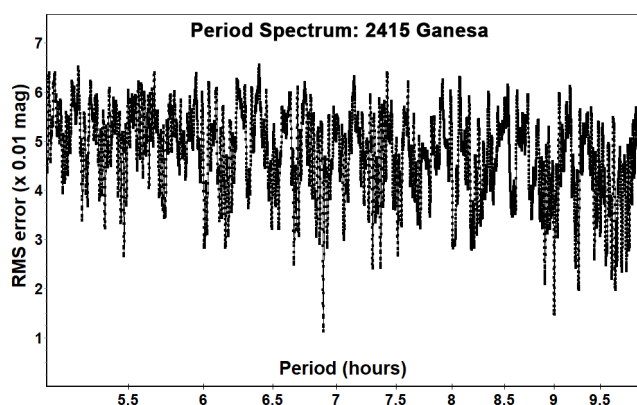
The split-halves plot supports bimodality. Higher-frequency structure in the lightcurve, evident even at this low amplitude, suggests that this asteroid's shape model might profitably be revisited.



2415 Ganesa. This middle main-belt asteroid has an apparent synodic period of 6.8935 h. Applying a G value of 0.09 rather than the default 0.15 value markedly improved the Fourier fit. No nightly magnitude adjustments were made; RMS error is 11 millimagitudes.

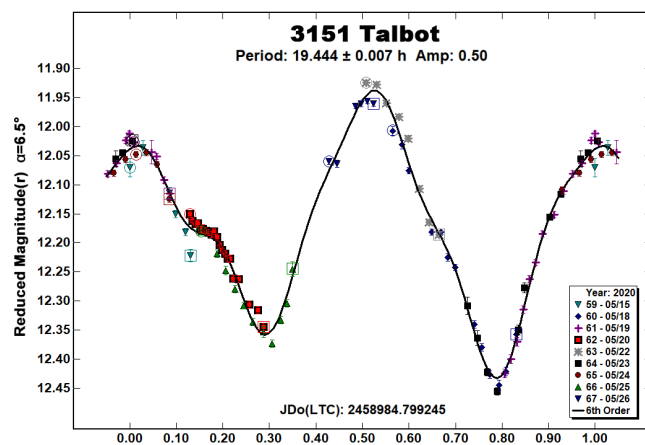


Our rotation period result differs from one published result of 8.0 h (Sarneczky et al., 1999) and from a survey finding (marked ambiguous in LCDB) of 2.67 h (Chang et al., 2016), notably close to 1/3 of the Sarneczky result. The earlier 8.0-h period does not appear in the present period spectrum: it is notably an alias of the present result by a half-cycle per 24 hours.

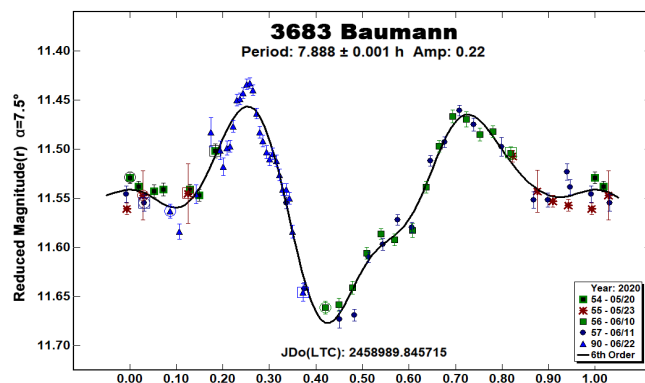


3151 Talbot. This outer main-belt asteroid was found to have a synodic rotation period of 19.444 h, in good agreement with published period of 19.49 h (Ferrero, 2011) and a survey estimate of 19.499 h (Pál et al., 2020). No nightly magnitude adjustments were made; RMS error is 16 millimagnitudes.

This is the first lightcurve reported near its phase angle bisector latitude of 12° , so with the PAB latitude range filled in and the newly secure period, this asteroid may merit new shape modeling.

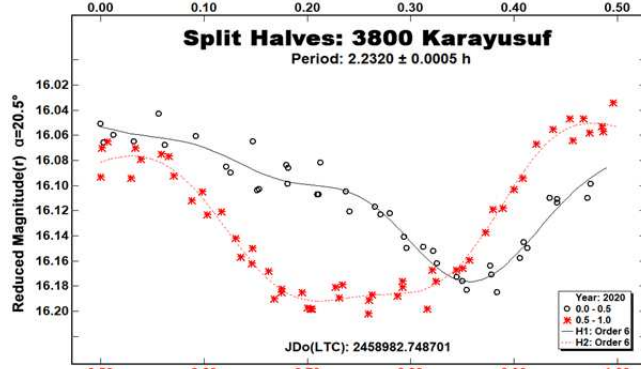
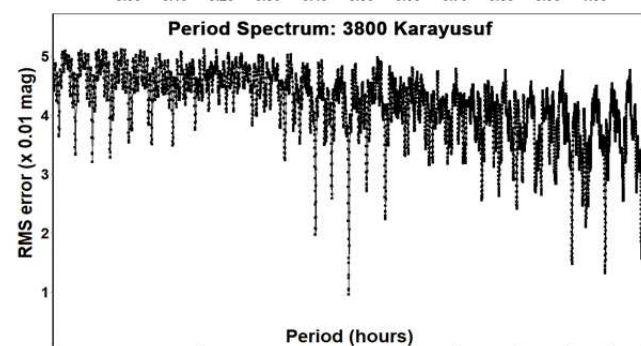
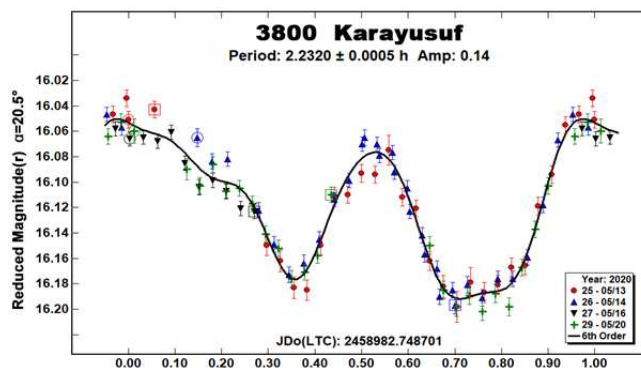


3683 Baumann. This outer main-belt asteroid was found during its favorable 2020 opposition to have a bimodal synodic period of 7.888 h, or half of a previously reported period of 15.758 h derived from sparse photometry (Waszczak et al., 2015).



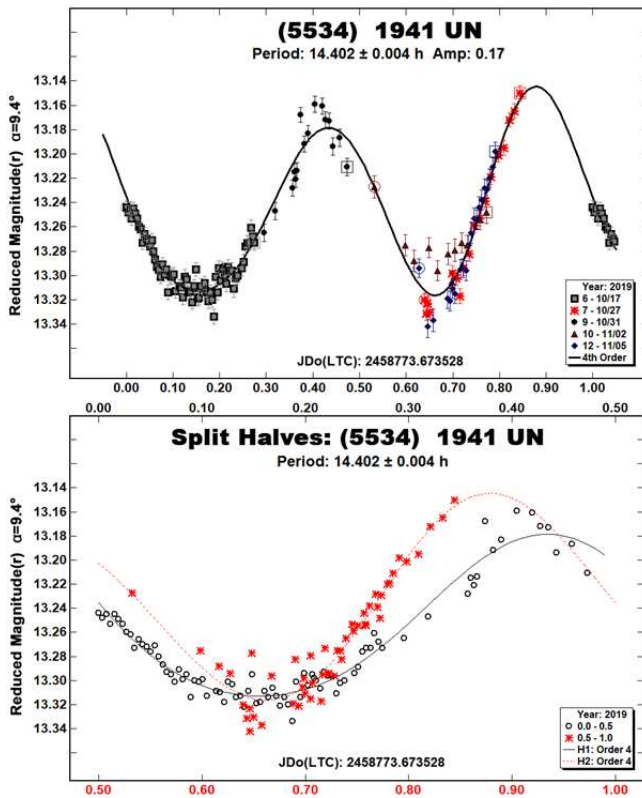
No nightly adjustments were made; RMS error is 15 millimagnitudes. The data suggest somewhat higher amplitude at the higher phase angle of June 22 (Zappalá et al., 1990).

3800 Karayusuf. This rapidly rotating and well-studied Mars-crosser was found to have synodic rotation period of 2.232 h, in excellent agreement with published periods of 2.2319 h (Warner, 2008), 2.232 h (Warner, 2010), 2.221 h (Warner 2014), 2.2318 h (Franco et al., 2018), 2.232 h (Klinglesmith and Erin, 2018), 2.2319 h (Skiff, 2018), and 2.2328 h (Warner 2018a). No nightly magnitude adjustments were made; RMS error is 10 millimagnitudes. Period-search and split-phase plots support a bimodal lightcurve over unimodal or higher-mode interpretations.

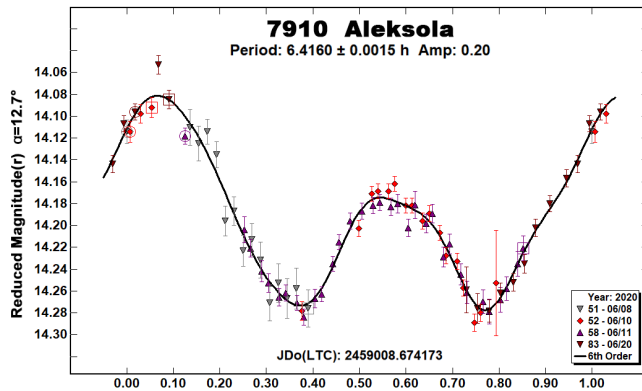


We saw no evidence of 3800 Karayusuf's being binary, though these observations were brief.

(5534) 1941 UN. Photometry on outer main-belt asteroid strongly indicates a synodic rotation period of 14.402 h. The LCDB lists one previous period of 4.10 h (LCDB-Zeigler). Neither that period nor any period less than 14.4 h gave a credible Fourier fit to the current five nights of photometric data, not even a "fit by exclusion" to the admittedly uneven phase coverage of this early effort. No nightly magnitude adjustments were made; RMS error is 11 millimagnitudes. The two halves of the phased lightcurve plot might appear similar, but a split-halves plot confirms a bimodal interpretation.

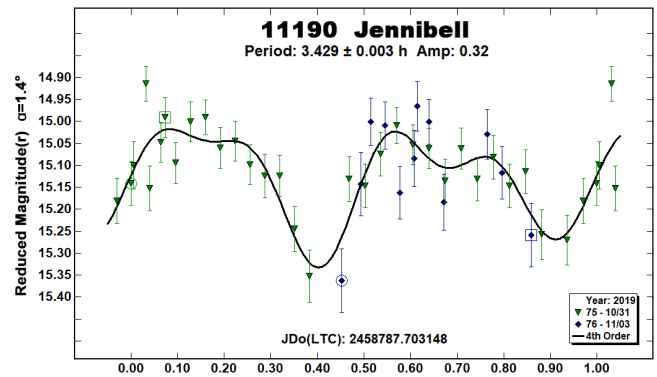


7910 Aleksola. The lightcurve for this inner main-belt asteroid during its favorable 2020 apparition is decidedly bimodal, with the two brightening events differing in scale by a factor of two.



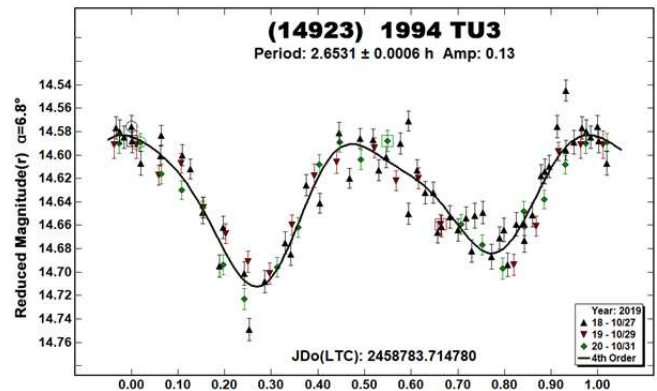
The current lightcurve requires a synodic period of 6.4160 h; the only previous period found was a survey-derived period of 6.41852 h (Pál et al., 2020) but marked as ambiguous in the LCDB. Adjusting the G value from the standard 0.15 to 0.40 markedly improved the Fourier fit without nightly magnitude adjustments; RMS error is 10 millimagnitudes.

11190 Jennibell. This Flora-family asteroid was located as a very faint signal in two nights of images targeting (1130) Skuld. The lightcurve appears bimodal with synodic period 3.428 h. RMS error to a 4th order Fourier fit is 63 millimagnitudes, but its short period affords complete phase coverage, and both bimodal brightness minima were clearly located. The author found no previous reports of rotational period for this asteroid.

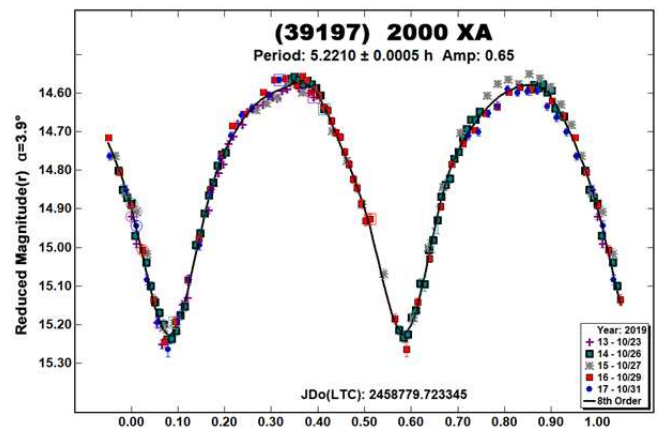


(14923) 1994 TU₃. This Phocaea asteroid was found to have a bimodal synodic rotation period of 2.6531 h, with low amplitude of 0.13 magnitudes (Sloan r). No nightly magnitude adjustments were made; RMS error is 17 millimagnitudes.

The present result differs strikingly from published periods of 30 h (Behrend, 2001) and 7.3 h (Warner, 2009). The current photometric data do not allow for a proper test of the 30 h period, but no period between 6 and 10 hours gave a credible Fourier fit to the present data obtained over three nights.



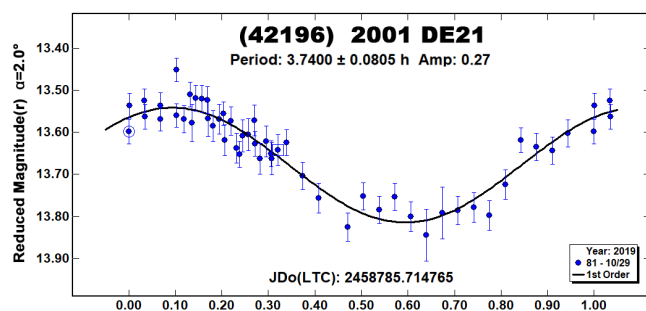
(39197) 2000 XA. This Hungaria asteroid was observed during its favorable 2019 opposition. The synodic rotation period was found to be 5.2210 h, agreeing with published periods of 5.221 h (Waszczak et al., 2015) and 5.2238 h (Benishek, 2020). RMS error is 18 millimagnitudes.



The fundamental period appears well established; at this large amplitude, the bimodal interpretation is almost certainly correct (Harris et al., 2014). The next opposition mid-2021 will be a magnitude fainter and satisfactory only for the Southern Hemisphere.

(42196) 2001 DE21. This Eos asteroid was located as a faint signal in one night of images targeting (39197) 2000 XA. The synodic fundamental was measured as 3.74 h, suggesting a bimodal synodic period of 7.48 h. The author found no previously published period. RMS error is 34 millimagnitudes.

The 4.9-hour observing session covered the fundamental but not the bimodal period, so while the fundamental period appears secure, later observations will be needed to confirm the modality. The next favorable opposition occurs 2024 October.



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Planning and processing software for this project was written in the python language, whose interpreter is provided without cost by the Python Foundation. This project's computations also made extensive use of several supporting packages also provided without cost, notably the pandas, ephemeris, matplotlib, requests, and statsmodels packages; the author thanks the package authors as well for their significant effort and offerings without which this work would have been infeasible.

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See specific asteroid lightcurve data via: <http://vizier.u-strasbg.fr/viz-bin/VizieR-3?-source=J/AJ/150/75/table4>

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LIGHTCURVE PHOTOMETRY OPPORTUNITIES: 2020 OCTOBER-DECEMBER

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We present lists of asteroid photometry opportunities for objects reaching a favorable apparition and have no or poorly-defined lightcurve parameters. Additional data on these objects will help with shape and spin axis modeling using lightcurve inversion. We also include lists of objects that will or might be radar targets. Lightcurves for these objects can help constrain pole solutions and/or remove rotation period ambiguities that might come from using radar data alone.

We present several lists of asteroids that are prime targets for photometry during the period 2020 October-December.

In the first three sets of tables, "Dec" is the declination and "U" is the quality code of the lightcurve. See the latest asteroid lightcurve data base (LCDB from here on; Warner et al., 2009a) documentation for an explanation of the U code:

<http://www.minorplanet.info/lightcurvedatabase.html>

The ephemeris generator on the CALL web site allows you to create custom lists for objects reaching $V \leq 18.0$ during any month in the current year and up to five years in the future, e.g., limiting the results by magnitude and declination, family, and more.

http://www.minorplanet.info/PHP/call_OppLCDBQuery.php

We refer you to past articles, e.g., Warner et al. (2009b) for more detailed discussions about the individual lists and points of advice regarding observations for objects in each list.

Once you've obtained and analyzed your data, it's important to publish your results. Papers appearing in the *Minor Planet Bulletin* are indexed in the Astrophysical Data System (ADS) and so can be referenced by others in subsequent papers. It's also important to make the data available at least on a personal website or upon request. We urge you to consider submitting your raw data to the ALCDEF database. This can be accessed for uploading and downloading data at

<http://www.alcdef.org>