LIGHTCURVES, H-G CURVES AND COLOR INDICES FOR THREE MINOR PLANETS

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Photometric measurements were made for three main-belt asteroids based on CCD observations made from 2023 April through June. Phased lightcurves are presented, followed by phase-slope parameter analyses based on 30 nights of data. Three color indices were computed for each asteroid. All the lightcurve data have been submitted to the ALCDEF database.

CCD photometric observations of three main-belt asteroids were performed at Command Module Observatory (MPC V02) in Tempe, AZ. Images were taken using a 0.32-m *f*/6.7 Modified Dall-Kirkham telescope and an SBIG STXL-6303 CCD camera. A 'clear' glass filter was used for lightcurve and phase-slope (H-G) parameter observations, and photometric B, V, R, and I filters were used on one night to compute color indices. Exposure time for all the images was 60 seconds. The image scale after 2×2 binning was 1.76 arcsec/pixel. Table I shows the observing circumstances and period solution results. All of the images for these asteroids were obtained between 2023 April and June.

Images were calibrated using a dozen bias, dark, and flat frames. Flat-field images were made using an electroluminescent panel. Image calibration and alignment was performed using *MaxIm DL* software.

The data reduction and period analysis were done using *MPO Canopus* (Warner, 2023). The 45′×30′ field of the CCD typically enables the use of the same field center for three consecutive nights. In these fields, the asteroid and three to five comparison stars were measured. Comparison stars were selected with colors within the range of $0.5 < B\text{-}V < 0.95$ to correspond with color ranges of asteroids. In order to reduce the internal scatter in the data, the brightest stars of appropriate color that had peak ADU counts below the range where chip response becomes nonlinear were selected. *MPO Canopus* plots instrumental vs. catalog magnitudes for solar-colored stars, which is useful for selecting comp stars of suitable color and brightness.

Since the goal of this effort was to determine H-G parameters, magnitudes were reduced to Johnson V. Comparison star magnitudes were obtained from the ATLAS catalog (Tonry et al., 2018), which is incorporated directly into *MPO Canopus*. The ATLAS catalog derives magnitudes using a number of available catalogs. The consistency of the ATLAS comp star magnitudes and color-indices allowed the separate nightly runs to be linked often with no zero-point offset required.

A 9-pixel (16 arcsec) diameter measuring aperture was used for asteroids and comp stars. It was typically necessary to employ star subtraction to remove contamination by field stars. For the asteroids described here, RMS scatter on the phased lightcurves is noted, which gives an indication of the overall data quality including errors from the calibration of the frames, measurement of the comp stars, the asteroid itself, and the period-fit. Period determination was done using the *MPO Canopus* Fourier-type FALC fitting method (cf. Harris et al., 1989). Phased lightcurves show the maximum at phase zero. Magnitudes in the lightcurve plots are apparent and scaled by *MPO Canopus* to the first night. H-G curves were created with the utility in *MPO Canopus*, using average magnitudes from each session.

Asteroids were selected from the "Low Phase-Angle Opportunities" section in the *Minor Planet Bulletin* (Warner et al., 2023). These are bright asteroids with short periods and small amplitudes. The Asteroid Lightcurve Database (LCDB; Warner et al., 2009) was consulted to locate previously published results. All the new data for these asteroids can be found in the ALCDEF database.

H-G Parameters and Absolute Magnitudes

The H-G parameter is determined by plotting absolute magnitude against phase angle. This curve will be linear when the phase is larger than 7°, but bows upward at lower phase values due to the opposition effect. Fewer data points are required to define the linear portion of the curve. Each data point on an H-G curve represents a night of observations, after which the average magnitude was computed.

Determining average magnitude can be problematic for asteroids with rotation periods longer than the observing session. An asteroid with low orbital inclination is necessarily well away from opposition at large phase angles, and only available for observation for a portion of the night. High amplitudes with differing pairs of maxima and minima also introduce error into the determination of an average value. Viewing the night's data points on a phased lightcurve helps in locating time points to calculate average magnitude from a raw lightcurve.

Number	Name	20yy/mm/dd	Phase	L_{PAB}	B_{PAB}	Period(h)	P.E.	Amp	A.E.	Grp
19	Fortuna	23/04/14-06/07	*15.7,5.0	245	1	7.44306	0.00018	0.23	0.03	MB-I
150	Nuwa	23/04/11-06/07	*11.7,6.9	238	1	8.13374	0.00019	0.17	0.02	MB-O
423	Diotima	23/04/11-06/07	*13.5,5.9	241	3	4.77575	0.00006	0.18	0.03	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).

Number	Name	H	H err	G	G err	B-V	B-V err	V-R	V-R err	R-I	R-I err
19	Fortuna	7.241	0.012	0.163	0.022	0.706	0.015	0.355	0.012	0.349	0.030
150	Nuwa	8.508	0.009	0.110	0.017	0.681	0.043	0.377	0.013	0.349	0.023
423	Diotima	7.531	0.011	0.160	0.020	0.664	0.019	0.368	0.013	0.332	0.016

Table II. Absolute magnitudes, phase-slope parameters, and color indices.

A tutorial and an associated spreadsheet created by Lorenzo Franco were instrumental in creating H-G curves. Using these tools, the author created a spreadsheet that computes average magnitude and the midpoint time for each night. These values are brought into the H-G Calculator utility in *MPO Canopus*. Input for the utility is average V magnitude with no H-G adjustment and mid-point time and date for the night. Knowing the asteroid's designation, the utility calculates absolute magnitude and phase, which are then plotted on the H-G curve. Values of *H* and *G* are reported in Table II.

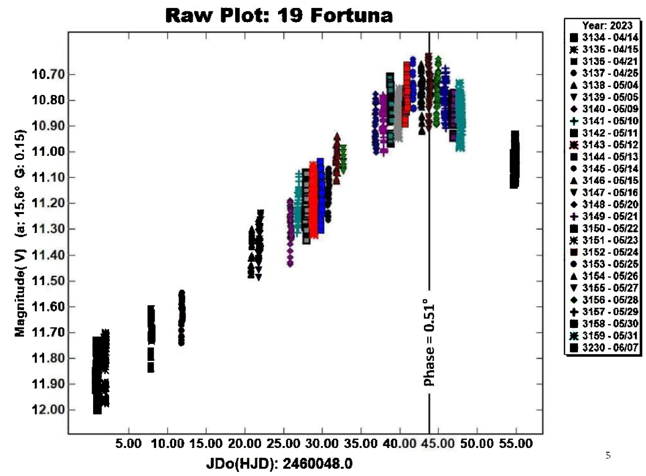
Color Indices

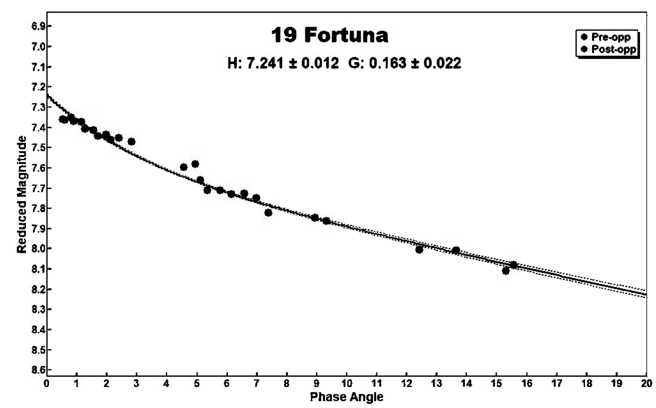
The method for computing color indices involved making a single full night of observations through photometric filters. Photometry is done in the usual fashion, producing sets of B, V, R, and I magnitudes for each visit. These magnitudes are subtracted to produce three color indices, B-V, V-R, and R-I. The averages and standard deviations of the color indices throughout the night are then calculated.

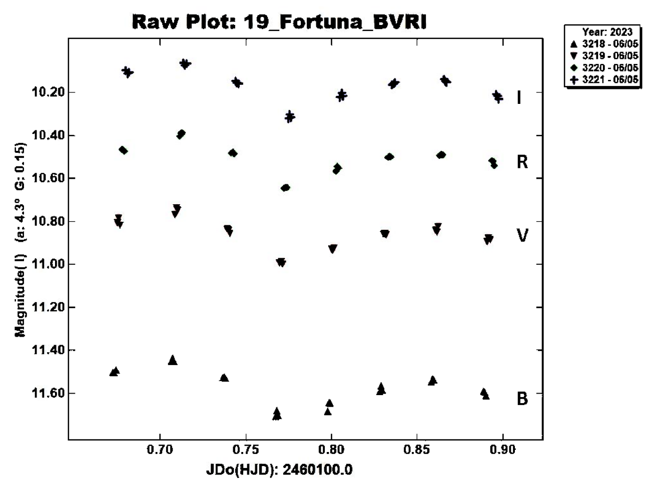
For each asteroid, a trio of images was taken consecutively in each filter, and the sets of magnitudes were binned. Each of the three asteroids in these observations had eight or nine visits throughout the night of 2023 June 5. Results are summarized in Table II. Published B-V color indices for the asteroids were found in the Planetary Data System site (Tedesco, 2020), and are compared to this work in the text below.

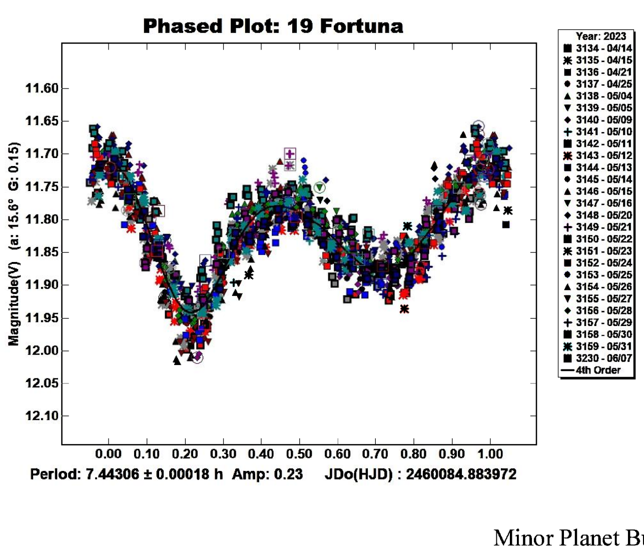
19 Fortuna is an inner main-belt asteroid, discovered in 1852 by John Russell Hind at London. Its rotation period is well-characterized, with the most recent result being from Vernazza et al. (2021), who computed 7.443224 ± 0.000005 h. Images were gathered on 27 nights in a 55-day interval, yielding 1417 data points. A period of 7.44306 ± 0.00018 h was calculated, agreeing with previous assessments. The amplitude of the lightcurve is 0.23 mag, with an RMS error on the fit of 0.030 mag.

Observations of this minor planet began on 2023 April 14, when the phase angle was -15.56°, reaching a minimum of 0.51° on May 27. Post-opposition data was gathered through June 7, when the phase angle reached 5.11° (a negative value is before opposition). A plot of all raw data with no H-G correction is provided, as well as the H-G curve. The computed value of *G* is 0.163 ± 0.022, in line with the LCDB level of 0.162 ± 0.03 (Pravec et al., 2012). Absolute magnitude, *H*, is 7.241 ± 0.012 mag, roughly agreeing with Pravec's 7.152 ± 0.02 mag.







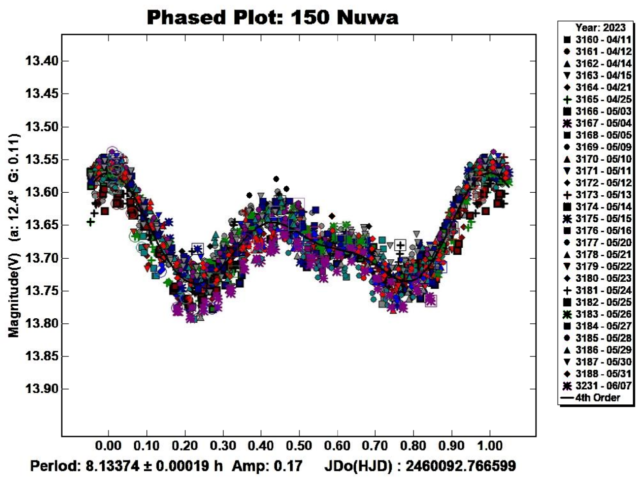


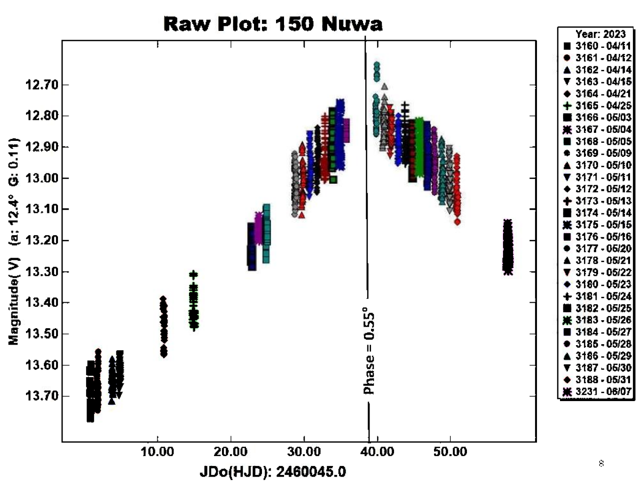
Tedesco shows B-V of 0.719 ± 0.014 mag. Eight visits of collecting sets of three points in the four filters were made during a 6-hour interval on 2023 June 5. They produced B-V of 0.706 ± 0.015 mag. The two other color indices are V-R = 0.355 ± 0.012 and R-I = 0.349 ± 0.030. These values are consistent with a carbonaceous (Type C or G) asteroid, as tabulated by Shevchenko and Lupishko (1998).

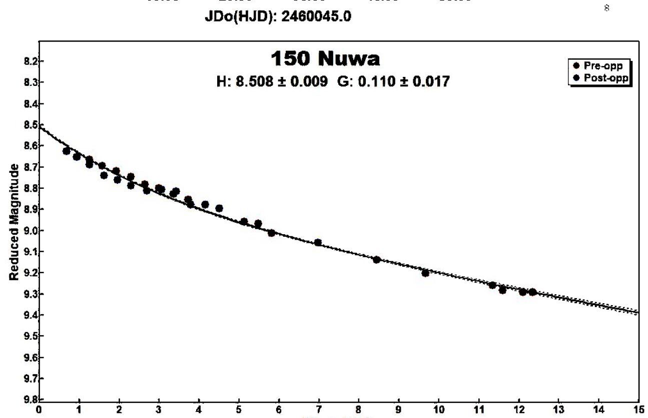
150 Nuwa is an outer main-belt asteroid, which was discovered by James Craig Watson in 1875 at Ann Arbor. The most recent calculation of the well-known rotation period is that of Hanus et al. (2016), who published a sidereal period of 8.13456 ± 0.000005 h. A total of 1625 images were taken in 30 nights, producing a period of 8.13374 ± 0.00019 h, in good agreement with Hanus' and other results. The amplitude is 0.17 ± 0.023 mag.

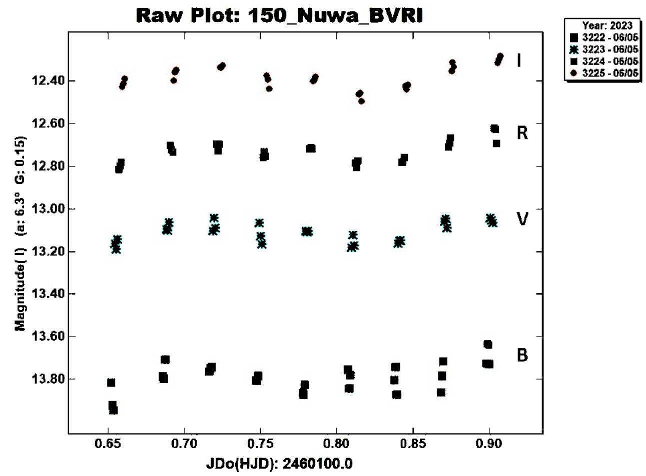
150 Nuwa was observed between 2023 April 11 and June 7, when the phase angle varied from -12.34° and 6.98°, reaching a minimum of 0.55° on May 19. Most G values reported in the LCDB appear to be simply the default value of 0.15, but Nugent et al. (2016) published $G = 0.12$. The result of this analysis is $G = 0.110 \pm 0.017$. Nugent shows H = 8.46 mag, while these 2023 observations produce a result of $H = 8.508 \pm 0.009$ mag.

Analysis of observed from nine visits resulted in B-V = 0.681 ± 0.043 mag, Tedesco's result is B-V = 0.706 ± 0.065. This is also in line with a Type C asteroid. V-R is 0.377 ± 0.013 and R-I is 0.349 ± 0.023.

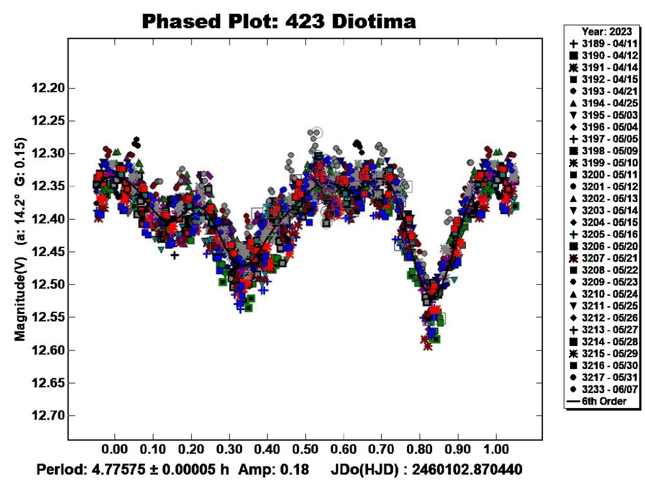


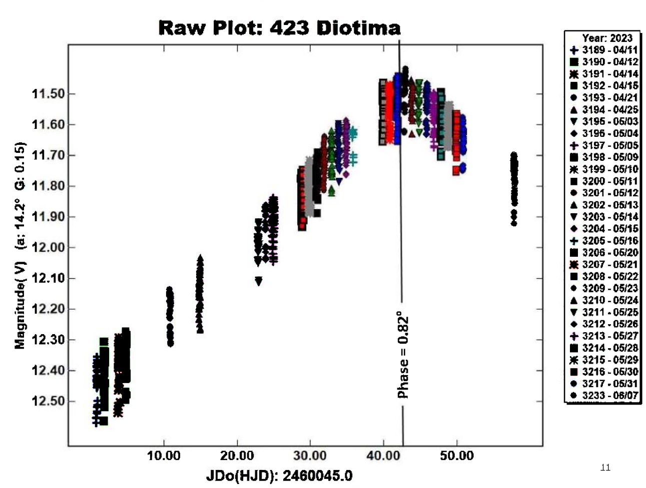




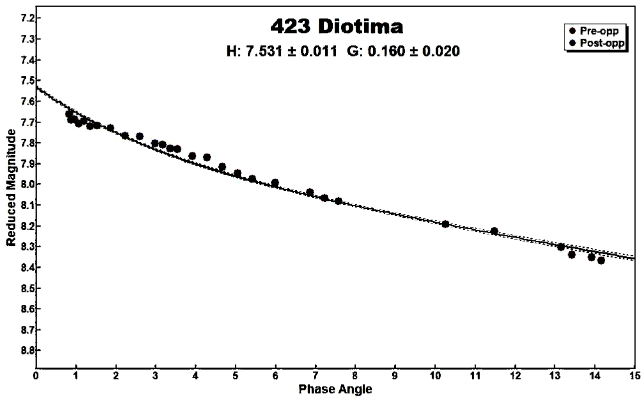


423 Diotima belongs to the Eos family. It was discovered by Auguste Charlois in 1896 from Nice. Hanus et al. (2018) published a sidereal period of 4.775377 ± 0.000002 h. During 30 nights, 1662 images were taken. The synodic period solution is 4.77575 ± 0.00006 h, agreeing with previous values. The amplitude of the lightcurve is 0.18 mag, and the RMS error on the fit is 0.029 mag.

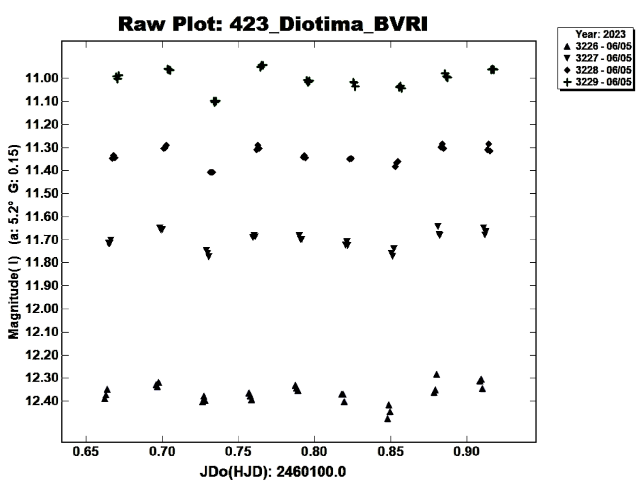




423 Diotima was also observed from 2023 April 11 through June 7. Phase angle ranged from -14.16° to 5.98° during this interval, with a minimum of 0.82° on May 23. The LCDB shows a wide range of values of *G*. Nugent et al. (2015) published *G* = 0.12 and *H* = 7.23 mag. The phase-slope parameter, *G*, from this analysis is 0.160 ± 0.020. Absolute magnitude, *H*, is 7.531 ± 0.011 mag, which is several tenths of a magnitude fainter than values in the LCDB.



423 Diotima was also visited nine times on 2023 June 7. A B-V color index of 0.664 ± 0.019 mag was computed, which compares favorably with Tedesco's 0.668 ± 0.011 mag. Color indices for V-R and R-I are 0.368 ± 0.013 mag and 0.332 ± 0.016 mag. The color indices again correlate well with a Type C asteroid.



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