

# LIGHTCURVES AND COLORS OF SEVEN SMALL NEAR-EARTH ASTEROIDS: 2023 LQ1, 2023 LT1, 2023 MC, 2023 VQ5, 2023 VE6, 2023 VF6, 2023 VV7

Jean-Baptiste Kikwaya Eluo  
Vatican Observatory  
V-00120 Vatican City of State  
jbkikwaya@arizona.edu; jbkikwaya@gmail.com

Carl W. Hergenrother  
Ascending Node Technologies, LLC  
Tucson, Arizona, USA

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We conducted two observation campaigns (2023 June 16-19 and 2023 November 11-13), during which we obtained photometric observations of seven small near-Earth asteroids. Lightcurves for six of the asteroids clearly showed rapid rotation, while one was inconclusive. We also computed BVRI colors for all seven asteroids to determine their taxonomy by computing color indexes and relative reflectances and comparing the results with published BVRI asteroid measurements, SMASS/SMASSII asteroid spectra.

Small near-Earth asteroid (NEA) lightcurve and color photometry were obtained with the Vatican Observatory's Vatican Advanced Technology Telescope (VATT), an aplanatic Gregorian telescope located at Mount Graham in southern Arizona with MPC code 290 (Kikwaya Eluo and Hergenrother, 2023). The VATT4K CCD camera equipped with a 4064×4064 detector and 15×15 μm pixels was used. The VATT4k covers the visible spectrum (300-1000 nm) with peak quantum efficiency at 450 nm. To reduce the readout time to 30 seconds, data were binned two by two, yielding a plate scale of 0.375 pixels.

For each observing campaign, ~200 bias images and about 10 to 90 images in each filter (B, V, R, and I) were obtained. Using the IRAF packages imred, ccdred, zerocombine, and flatcombine (Tody, 1986; Tody, 1993), a master bias and master flat were made and used to correct the data. Asteroid data were taken with the telescope tracking at the asteroid's rate of motion. Consequently, stars in the field were trailed and not useful for in-field relative photometry.

Therefore, on each night, standard stars were observed to compute a photometric zero point and extinction coefficient for each filter (Kikwaya Eluo and Hergenrother, 2023). The IRAF ccdphot, digiphot, and apphot packages were used to produce asteroid and standard star photometry (Hergenrother et al., 2009; Kikwaya Eluo et al., 2016, 2019, 2022). Each object was measured with an aperture set to two times the FWHM (Hergenrother et al., 2009; Kikwaya Eluo et al., 2016, 2019, 2022). The sky background was set to a radius of fifteen pixels and a width of ten pixels.

As we expected the asteroid to be a fast rotator, the filter sequence used for lightcurve and colors is V-R-I-B-V (Hergenrother et al., 2009; Kikwaya Eluo et al., 2016, 2019, 2022). To ensure that the rotation period was covered, we collected several images in V at the beginning of the sequence and then observed in R, I, and B filters. The number of images in the R, I, and B filters was usually equal to one-third of the number of images taken in V. At the end, we again observed a series of images in V. To compute the lightcurve and determine the rotation period of an asteroid, we used *ALC*, Petr Pravec's Asteroid Lightcurve software.

We also used *ALC* to determine the following color indexes: V-R, B-V, and V-I. Two-color plots (B-V versus V-R, and V-I versus V-R) were utilized to estimate the taxonomy of the object (Yoshida et al., 2004; Zellner et al., 1985; Dandy et al., 2002; Dandy et al., 2003). We used spectrophotometry to compute the relative reflectance normalized to V (reflectance at the V-band equal to 1) of each asteroid from its photometric color indexes (Holmberg et al., 2006; Kikwaya Eluo et al., 2016). To refine the taxonomy classification of the asteroid, we proceeded to compare its relative reflectance using the chi-squared method (Popescu et al., 2012; Popescu et al. 2016) with the observed asteroid spectra in the SMASS/SMASSII database as presented by Bus and Binzel (2002a,b). However, our data only covered the visible part of the spectra (Kikwaya Eluo & Hergenrother, 2023). The comparison uses the M4AST (Modeling for Asteroids) engine from the Paris observatory, <https://spectre.imcce.fr/m4ast/index.php/index/home>.

Table I reports the absolute magnitude and orbital information of each asteroid. Table II contains the results of our observations.

| Object   | yyyy mm/dd | Phase | Delta (AU) | r (AU) | H    | a     | e     | i      | Bpab    | Lpab    | Grp    |
|----------|------------|-------|------------|--------|------|-------|-------|--------|---------|---------|--------|
| 2023 LQ1 | 2023 06/16 | 42.6  | 0.008      | 1.021  | 27.1 | 1.849 | 0.473 | 3.873  | 259.162 | 20.983  | Apollo |
| 2023 LT1 | 2023 06/19 | 34.6  | 0.013      | 1.026  | 26.9 | 1.232 | 0.332 | 8.249  | 253.633 | 11.490  | Apollo |
| 2023 MC  | 2023 06/18 | 15.9  | 0.036      | 1.051  | 25.7 | 0.894 | 0.393 | 1.679  | 265.314 | 8.460   | Aten   |
| 2023 VQ5 | 2023 11/11 | 23.8  | 0.009      | 0.999  | 27.7 | 0.737 | 0.356 | 5.689  | 60.003  | 1.387   | Aten   |
| 2023 VE6 | 2023 11/11 | 32.1  | 0.011      | 0.999  | 27.2 | 0.857 | 0.225 | 10.403 | 57.636  | -13.306 | Apollo |
| 2023 VF6 | 2023 11/11 | 24.9  | 0.019      | 1.007  | 27.2 | 0.920 | 0.118 | 8.993  | 35.270  | 2.281   | Aten   |
| 2023 VV7 | 2023 11/13 | 13.6  | 0.015      | 1.004  | 26.7 | 1.704 | 0.411 | 8.388  | 53.701  | 5.971   | Apollo |

Table I: Object name, date of observation, phase angle, delta (distance to the Earth in AU), r (distance to the Sun in AU), absolute magnitude, semi-major axis, eccentricity, inclination, Bpab, Lpab, and Grp (group the object belongs to) are reported.

| Object   | Period (hours)    | Amp(mag)      | B-V           | V-R           | V-I           | Tax. Class            |
|----------|-------------------|---------------|---------------|---------------|---------------|-----------------------|
| 2023 LQ1 | 0.1605+/-0.0002   | 0.249+/-0.075 | 0.805+/-0.076 | 0.433+/-0.091 | 0.715+/-0.063 | X-complex (Q,Xe,Cg)   |
| 2023 LT1 | 0.11620+/-0.00004 | 0.582+/-0.079 | 0.754+/-0.077 | 0.372+/-0.081 | 0.716+/-0.073 | C-complex (Cgh,Cg,C)  |
| 2023 MC  | -----             | -----         | 0.683+/-0.082 | 0.383+/-0.072 | 0.713+/-0.085 | C-complex (C,Cgh,Xc)  |
| 2023 VQ5 | 0.07130+/-0.00003 | 0.176+/-0.072 | 0.699+/-0.049 | 0.373+/-0.052 | 0.788+/-0.055 | X-complex (X,Xc,Xk)   |
| 2023 VE6 | 0.12724+/-0.00006 | 0.516+/-0.070 | 0.779+/-0.054 | 0.384+/-0.041 | 0.650+/-0.054 | C-complex (Cgh,Cg,O)  |
| 2023 VF6 | 0.1079+/-0.0002   | 0.290+/-0.088 | 0.789+/-0.053 | 0.366+/-0.058 | 0.752+/-0.059 | C-complex (Cgh,Cg,Xc) |
| 2023 VV7 | 0.3036+/-0.0004   | 0.623+/-0.103 | 0.774+/-0.051 | 0.536+/-0.049 | 0.944+/-0.062 | S-complex (Sv,L,S)    |

Table II: Rotation periods of 6 NEAs and colors and taxonomic classes of all 7 NEAs are reported.

**2023 LQ1.** The Catalina Sky Survey discovered this small,  $H = 27.1$  Apollo asteroid on 2023 June 15. On 2023 June 16, shortly before the asteroid passed 0.0068 au from Earth, we collected 10 B, 64 V, 10 R, and 9 I images to determine its rotation period, colors, and taxonomic class. Its lightcurve yielded a rotation period of  $0.1605 \pm 0.0002$  h with an amplitude of  $0.249 \pm 0.075$  magnitude, confirming fast rotation (Fig. 1). Images taken with the B, R, and I filters were used to compute the color indexes. 2023 LQ1's colors ( $B-V = 0.805 \pm 0.076$ ,  $V-R = 0.433 \pm 0.091$ ,  $V-I = 0.715 \pm 0.063$ ) fall between C-type and S-type, being more consistent with the X-complex (Fig. 14, 15). The comparison of its relative reflectance with the observed asteroid spectra yielded three matches: Q, Xe, and Cg (Bus and Binzel, 2002a, 2002b), with the chi-squared value for Q being less than 0.001 (Fig. 2).

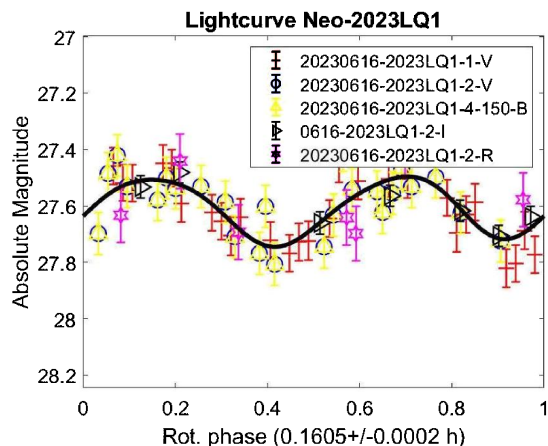


Figure 1. Lightcurve of 2023 LQ1 phased to a period of  $0.1605 \pm 0.0002$  h.

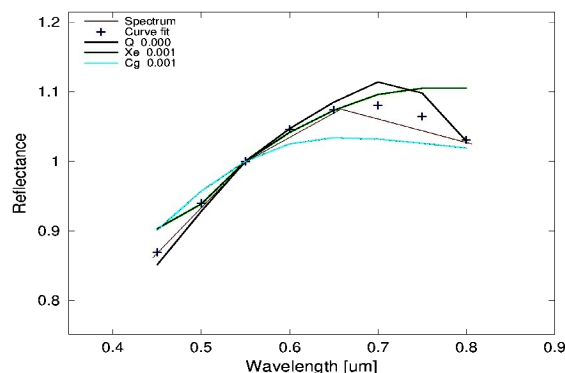


Figure 2. Relative reflectance of 2023 LQ1 compared with SMASS spectra using the chi-squared method (Bus and Binzel, 2002a, 2002b).

**2023 LT1.** 2023 LT1 is an Apollo asteroid with an absolute magnitude of 26.9. Eighty-four V-band images were obtained on 2023 June 19 UT. The rotation period is  $0.11620 \pm 0.00004$  h with an amplitude of  $0.582 \pm 0.079$  mag, confirming it is a fast rotator (Fig. 3). Images were also obtained in B, R, and I for computing colors:  $B-V = 0.754 \pm 0.077$ ;  $V-R = 0.372 \pm 0.081$ ; and  $V-I = 0.716 \pm 0.073$ . 2023 LT1 is identified as a C-type from both the two-axis color plots (Fig. 14, 15), and comparison with SMASS/II asteroid spectra showed a chi-squared value of less than 0.0001 with Cgh, Cg, and C taxonomies (Fig.4).

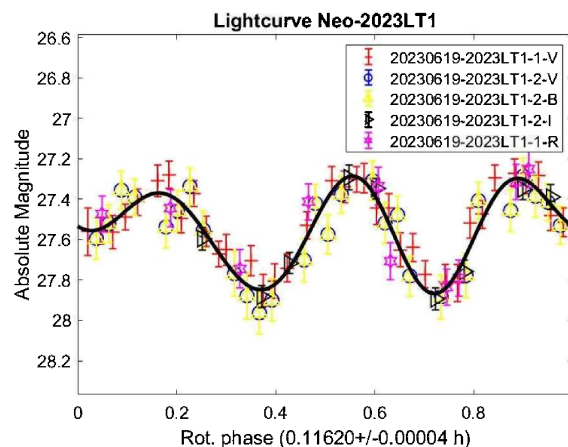


Figure 3. Lightcurve of 2023 LT1 phased to a period of  $0.11620 \pm 0.00004$  h.

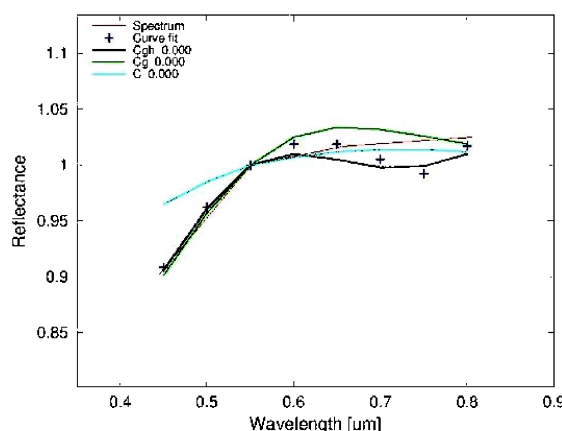


Figure 4. Relative reflectance of 2023 LT1 compared with observed asteroid spectra using the chi-squared method.

**2023 MC.** 2023 MC is an Aten asteroid with an absolute magnitude of 25.7. Sixty-four images were collected in the V filter to determine the lightcurve of 2023 MC. The lightcurve results were ambiguous, suggesting that 2023 MC may be a slow rotator or a very rapid rotator with a period unresolved by our 60 s exposures. The color indexes were  $B-V = 0.683 \pm 0.082$ ,  $V-R = 0.383 \pm 0.072$ , and  $V-I = 0.713 \pm 0.085$ , consistent with 2023 MC being a member of the C-complex (Fig. 14, 15). A C-type taxonomy was confirmed by comparison with SMASS/II spectra, revealing close matches (Chi-squared value  $< 0.001$ ) with C and Cgh types (Fig. 5).

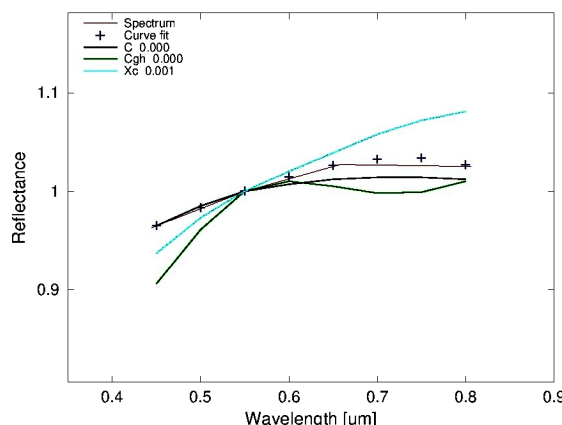


Figure 5. The relative reflectance of 2023 MC matches three taxonomies: C, Cgh, and Xc.

**2023 VQ5.** 2023 VQ5 is an Aten asteroid with an absolute magnitude of 27.7. We observed three long series in the V filter on November 11 UT: one at the beginning of the color sequence and two at the end for a total of ninety images. The lightcurve shows a rotation period of  $0.07130 \pm 0.00003$  h with a small amplitude of  $0.176 \pm 0.072$  mag (Fig. 6). The object appears to be a rapid rotator. Still, the low amplitude relative to the uncertainty of the individual observations casts doubt as to whether the 0.07130 h solution is correct.

The color indexes of  $B-V = 0.699 \pm 0.049$ ,  $V-R = 0.373 \pm 0.052$ , and  $V-I = 0.788 \pm 0.055$  suggest an X-complex taxonomy for 2023 VQ5 (Fig. 14, 15). This is confirmed by the comparison between the relative reflectance of 2023 VQ5 and the SMASS asteroid spectra (Bus and Binzel, 2002a, 2002b) that yielded three solutions with a chi-squared value of less than 0.001 (X, Xc, and Xk) (Fig. 7).

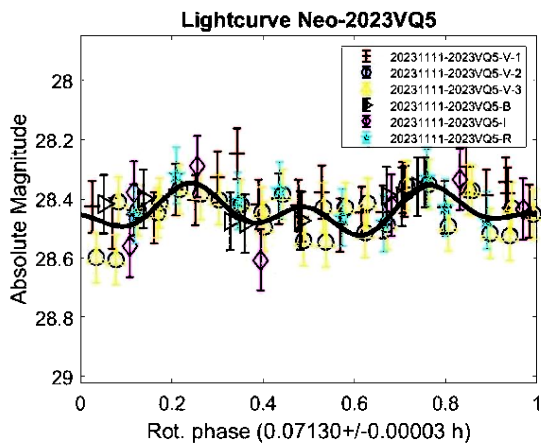


Figure 6. Lightcurve of 2023 VQ5 phased to a period of  $0.07130 \pm 0.00003$  h.

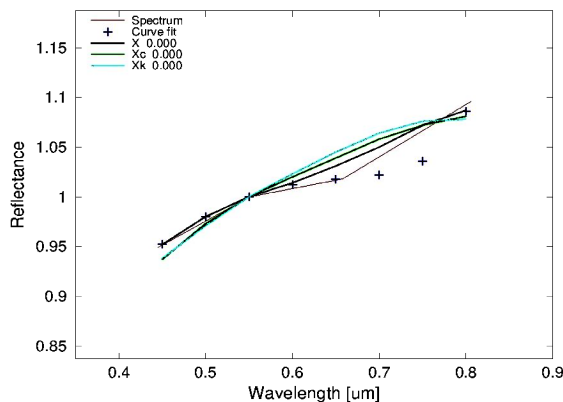


Figure 7. Relative reflectance of 2023 VQ5 compared with observed asteroid spectra using the chi-squared method.

**2023 VE6.** 2023 VE6 is an Aten asteroid with an absolute magnitude of 27.2. On November 11 UT, V images were obtained to construct a lightcurve of 2023 VE6. It yielded a rotation period of  $0.12724 \pm 0.00006$  h with an amplitude of  $0.516 \pm 0.070$  mag (Fig. 8). We found  $B-V = 0.779 \pm 0.054$ ,  $V-R = 0.384 \pm 0.041$ , and  $V-I = 0.650 \pm 0.054$ , showing that 2023 VE6 falls within the C-type taxonomy class according to the two-color plots (Fig. 14, 15). The comparison with observed asteroid spectra using the chi-squared method suggested a possible match between the relative reflectance of 2023 VE6 and asteroid spectra for Cgh, Cg, and O types. Two of these three solutions (Cgh, Cg) are clearly from the C-complex (Fig. 9).

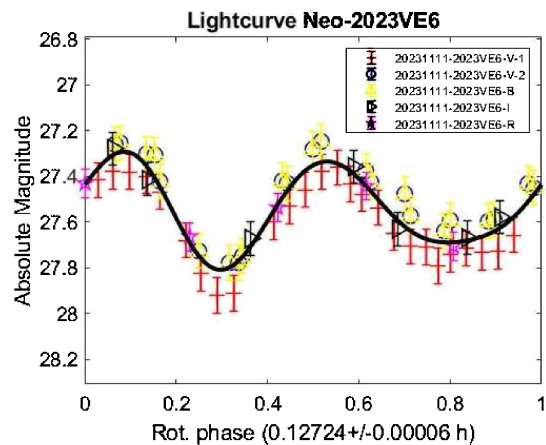


Figure 8. Lightcurve of 2023 VE6 phased to a period of  $0.12724 \pm 0.00006$  h.

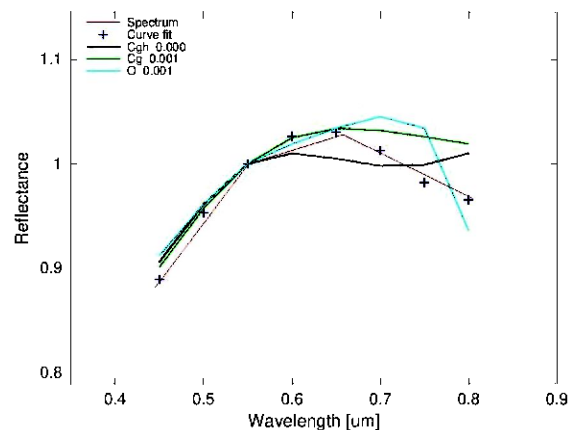


Figure 9. Among the observed spectra matching 2023 VE6 with a chi-squared value less than 0.001 are the Cgh, Cg, and O types (Bus and Binzel, 2002a, 2002b).

**2023 VF6.** 2023 VF6 is an Apollo asteroid with an absolute magnitude of 27.2. Three sets of V images were obtained on November 11 UT: one at the beginning of the observation sequence (V-R-I-B-V) and two at the end. We used these images to construct the lightcurve of 2023 VF6, yielding a rotation of  $0.1079 \pm 0.0002$  h with an amplitude of  $0.290 \pm 0.088$  mag (Fig. 10). Observations of 2023 VF6 with filters R, B, and I helped to compute its color indexes:  $B-V = 0.789 \pm 0.053$ ,  $V-R = 0.366 \pm 0.058$ , and  $V-I = 0.752 \pm 0.059$ . The two-axes-color plots showed that 2023 VF6 belongs to C-type asteroids (Fig. 14, 15), and it was confirmed by the solutions given by comparing the relative reflectance of 2023 VF6 using the chi-squared method with the observed asteroid spectra (Bus and Binzel, 2002a, 2002b). Among the three solutions Cgh, Cg, and Xc which matched the relative reflectance of 2023 VF6 with a chi-squared value less than 0.001, two belong to the C-complex (Fig. 11).

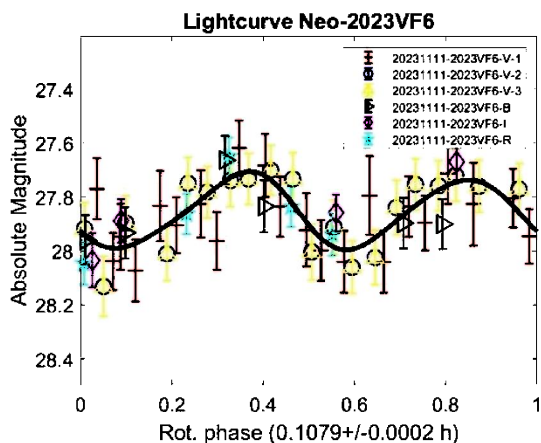


Figure 10. Lightcurve of 2023 VF6 phased to a period of  $0.1079 \pm 0.0002$  h

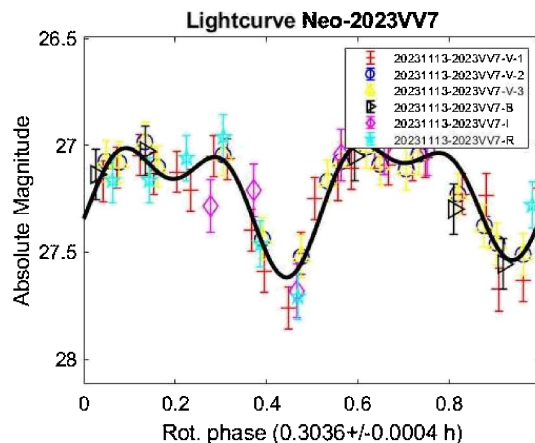


Figure 12. Lightcurve of 2023 VV7 phased to a period of  $0.3036 \pm 0.0004$  h.

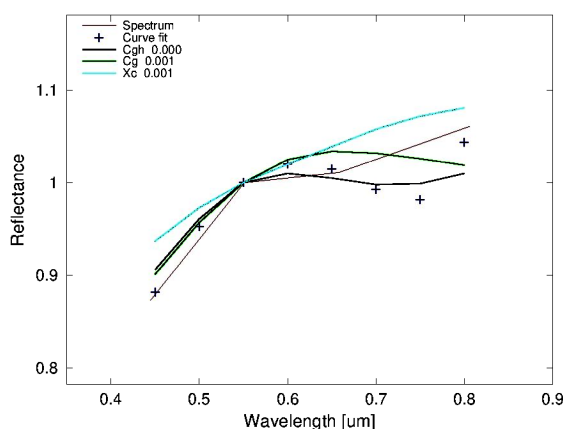


Figure 11. Relative reflectance of 2023 VF6 compared with observed asteroid spectra using the chi-squared method.

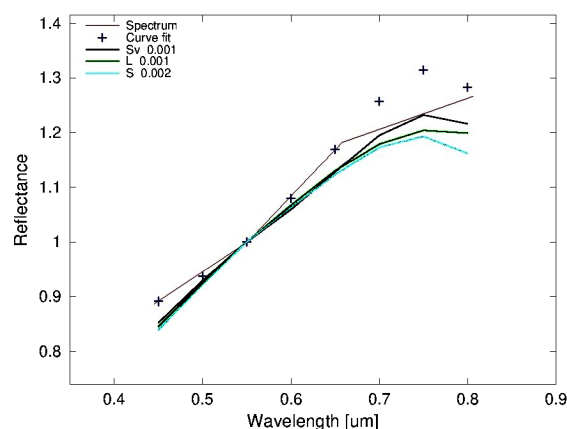


Figure 13. Relative reflectance of 2023 VV7 compared with observed asteroid spectra using the chi-squared method.

**2023 VV7.** 2023 VV7 is an Apollo asteroid with an absolute magnitude of 26.7. On November 13 UT, we observed 2023 VV7 with a V filter and gathered around 70 images to construct its light curve. The V photometry yielded a rotation period of  $0.3036 \pm 0.0004$  h with an amplitude of  $0.623 \pm 0.103$  mag, confirming that 2023 VV7 is a fast rotator (Fig. 12). Additional images in R, I, and B were obtained to help in computing the color indexes:  $B-V = 0.774 \pm 0.051$ ,  $V-R = 0.536 \pm 0.049$ , and  $V-I = 0.944 \pm 0.062$ . The two-axis color plots ( $B-V$  versus  $V-R$ ,  $V-I$  versus  $V-R$ ) show 2023 VV7 falling between S- and D-types, though closer to the S-type than D-type, suggesting that 2023 is more likely a member of the S-type taxonomy class (Fig. 14, 15). This is confirmed by comparing the relative reflectance of 2023 VV7 and the observed asteroid spectra as collected by SMASS and SMASSII (Bus and Binzel, 2002a, 2002b). Three solutions are given (Sv and L with a chi-squared value of 0.001, S with a chi-squared value of 0.002), suggesting that 2023 VV7 belongs to the S-type taxonomy class (Fig. 13).

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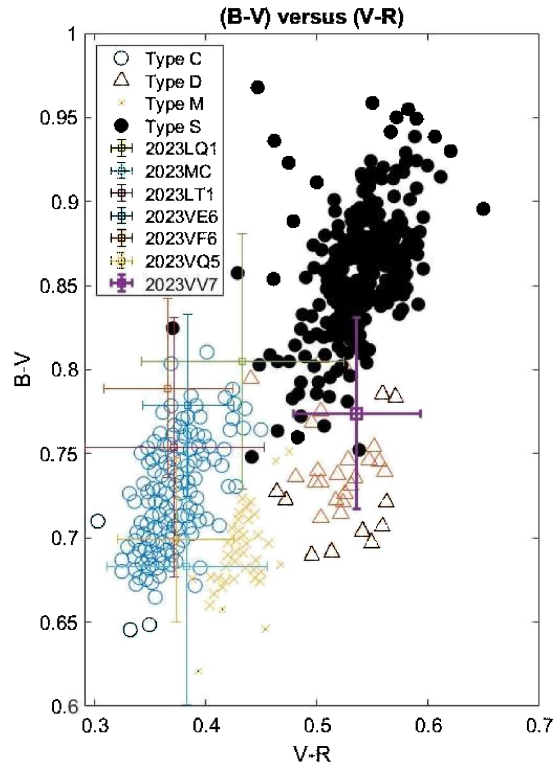


Figure 14. Two-color B-V versus V-R plot for all 7 NEAs.

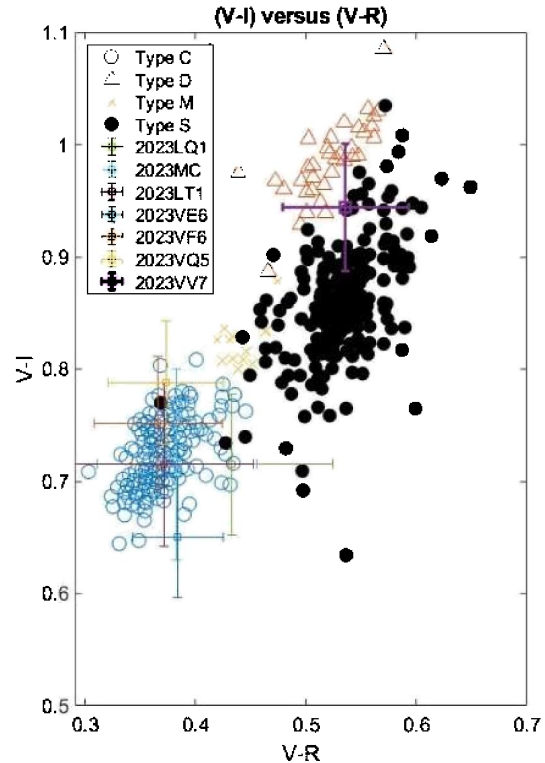


Figure 15. Two-color V-I versus V-R plot for all 7 NEAs.