Peremennye Zvezdy (*Variable Stars*) **33**, No. 5, 2013

Received 09 July; accepted 17 July.

BVRI CCD Photometry of Two New Variable Stars in the Field of Seyfert 1 Galaxies Mrk 478 and Mrk 1513

V.T. Doroshenko

Southern station of the Moscow M.V. Lomonosov State University, Moscow, Russia, Nauchny, 98409 Crimea, Ukraine

CCD $BVRI$ photometry is presented for two new variable stars in the fields of the Seyfert galaxies Mrk 478 and Mrk 1513. The new variables change their brightness periodically, with the periods $P = 0\overset{d}{.}341$ and $P = 0\overset{d}{.}4422$ respectively, and it is possible that they belong to the close binary eclipsing stars of the W UMa type.

1 Introduction

In the course of studying comparison stars in the fields of several Seyfert galaxies, we found two variable stars. One of them is in the field of Mrk 478, and the other one is located in the field of Mrk 1513. For accurate photometry of galaxies, it is important to search for possible variable stars among the reference-star candidates selected in the AGN field in order to reject them as comparison stars. That is why we perform a study of stars in the fields of those AGNe which we have been observing at the Crimean Astrophysical Observatory from 2002 to the present time.

2 Observations and reductions

The CCD monitoring of Seyfert galaxies was performed in the prime focus of the 70-cm telescope of the Crimean Astrophysical Observatory using the Ap7p CCD camera. This camera has a 515 × 512-pixel chip. The field of view of our images is $15'' \times 15''$. The scale of images is $1\overset{''}{.}755$ per pixel. We used the B, V, R, $R1$, I filters. The transformation of our instrumental magnitudes to the standard Johnson–Cousins system was made using Stetson's Standard fields where star magnitudes are given in the BVR_cI_c system (Doroshenko et al. 2005a). It should be noted that the $R1$ filter is more similar to the I filter in the Cousins system. As a rule, for each object we made 4–6 series of exposures per night with each filter, while before and after that we obtained a single image to determine the bias and two images to find the dark current, with the largest exposure for the B filter. At least 4–6 flat-field (FF) images for each filter were usually obtained in twilight at sunset or sunrise for each change in the CCD setup at the telescope. The images for bias, dark current, and FF were cleared from spikes and then used in the standard procedure of CCD-image processing. All our photometric measurements were made by aperture photometry with respect to the star selected as a standard in the field of the galaxy. We used a circular aperture of $15''$ diameter to measure the signal from an object. The sky background was usually determined around each object in an annulus aperture. We took into consideration errors associated with photon statistics, with readout noise, with correlated changes in the bias, and errors associated with the distance between the measured object and the comparison star. The stars in the field of the two galaxies in question were calibrated earlier by Doroshenko et al. (2013).

3 Mrk 478, star 4

In the field of the Seyfert 1 galaxy Mrk 478 ($14^{\mathrm{h}}42^{\mathrm{m}}07\overset{\mathrm{s}}{.}47$, $+35°26'22\overset{''}{.}9$, J2000, 2MASS), we found a variable star No. 4 (USNO-A2.0 1200–07369079). It is circled in the finding chart (Fig. 1). Its coordinates are $\alpha = 14^{\mathrm{h}}42^{\mathrm{m}}00\overset{\mathrm{s}}{.}57$, $\delta = +35°28'07\overset{''}{.}6$ (J2000.0, UCAC4). The galaxy Mrk 478 is marked by two bars; the comparison and check stars are numbered.

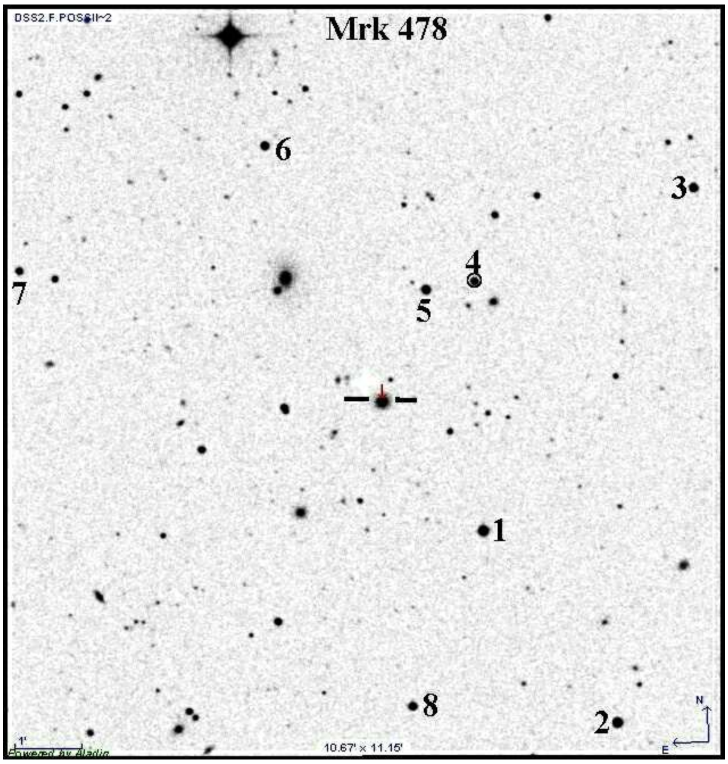

Figure 1.
The finding chart for the comparison stars in the field of Mrk 478. The size of the chart is $11' \times 11'$, north is at the top, east is to the left. The variable star No. 4 is circled, the galaxy is marked by two bars.

The $BVRR1I$ magnitudes of the selected stars are given in Doroshenko et al. (2013). Our photometry of stars in the Mrk 478 field was made relative to the star No. 1 with the aperture $A = 15''$, in the course of 32 nights from January 04/05, 2012 to July 19/20, 2012. As a rule, 4 images in each filter were obtained on each observing night, the time resolution for this galaxy being about 4.35 minutes. We used the χ^2 criterion to find variable stars. The χ^2 value per one degree of freedom (dof) was calculated from the light curves of the selected star. If the star under consideration is not variable, then χ^2 is close to 1. For variable stars, χ^2 should be significantly larger than 1. We concluded that the star No. 4 was a variable star with a high confidence level because χ^2 per dof was 13.1, 16.4, 21.7, 11.6, and 10.1 in the $BVRR1I$ bands, respectively, whereas the stars Nos. 1–3, Nos. 5–8 had $\chi^2 \leq 1$, and they can be used as check stars as well. The star No. 1 was calibrated using 4 nights in 2012 against the main reference stars in the fields of 14 different AGNe. Next, we calculated the unweighted mean values for these different calibrations. The mean magnitudes for the star No. 1 from 29 measurements are the following: $B = 14.429 \pm 0.005$, $V = 13.831 \pm 0.005$, $R = 13.472 \pm 0.003$, $R1 = 13.130 \pm 0.003$, and $I = 13.133 \pm 0.004$. Table 1, available electronically in the html version of this paper, presents the photometry of the star No. 4 in the Johnson–Cousins BVR_cI_c system. The mean V magnitude and color indices of the star No. 4 are the following: $B = 16^{\mathrm{m}}.227$, $V = 15^{\mathrm{m}}.574$, $R_c = 15^{\mathrm{m}}.193$, $I_c = 14^{\mathrm{m}}.829$, $B-V = 0^{\mathrm{m}}.654$, $V-R_c = 0^{\mathrm{m}}.380$, and $V-I_c = 0^{\mathrm{m}}.744$. This $B-V$ color index is characteristic of the F8–G0 spectral type if the star belongs to the main sequence and if the extinction in the direction of the star is rather small. The star can have an earlier spectral type if the extinction is appreciable. The amplitude of variability, derived from the averaged phased light curves, slightly decreases from B to I: Amp $B = 0^{\mathrm{m}}.135 \pm 0^{\mathrm{m}}.004$, Amp $V = 0^{\mathrm{m}}.136 \pm 0^{\mathrm{m}}.006$, Amp $R_c = 0.122 \pm 0^{\mathrm{m}}.004$, and Amp $I_c = 0^{\mathrm{m}}.111 \pm 0^{\mathrm{m}}.005$. Figure 3 shows the phased light curves for the star No. 4, plotted for the double period, $P = 0^{\mathrm{d}}.341$.

In addition to the observations made in Crimea, data for this star are also available in the 2013 release of the Catalina Sky Survey (Drake et al. 2009). The light curve in the CSS is obtained from observation without filter. However, to obtain more accurate values in the Johnson V band from V_{CSS}, the authors of the survey give transformation formulae depending on the color indices $(B-V)$ and $(V-R)$; I applied them. Photometry of the star No. 4 in the field of Mrk 478 from the Catalina Sky Survey is given in Table 2, available electronically in the html version, where Modified Julian Dates were transformed to Julian Dates and V_{CSS}, to standard V magnitudes using the the formula $V = V_{\mathrm{CSS}} + 0.91 \times (V-R)^2 + 0.04$, according to CSS prescripts.

The combined light curve (CSS + Crimean data) in the V band is shown in Fig. 2, where the CSS data are plotted in red color and the Crimean data, in black color. The agreement between these data at close times is very good.

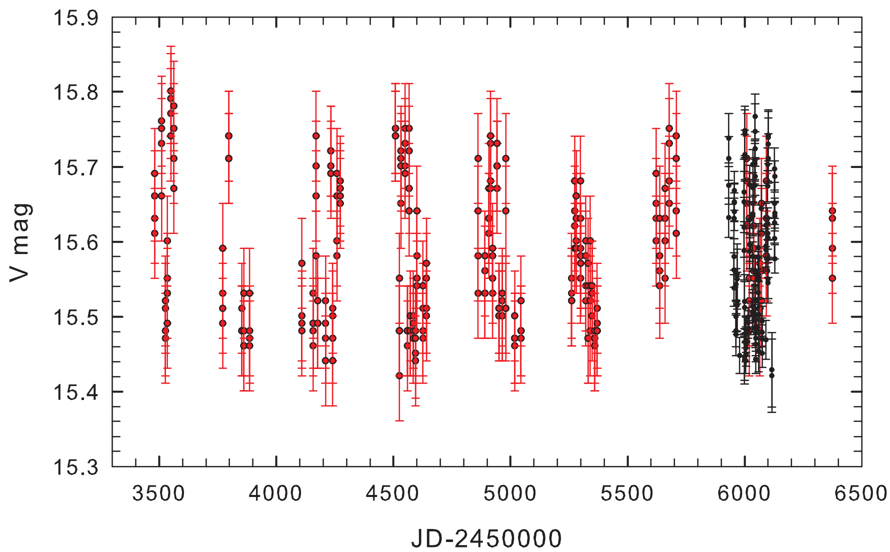

Figure 2.
The V-band light curve of the star No. 4, based on the Catalina Sky Survey (open circles with red error bars) and Crimean (open circles with black error bars) observations.

The Fourier analysis of the V light curve of this star revealed a peak at the frequency $\nu = 5.865037$ cycles/day ($P = 0^{\mathrm{d}}.1704946$). Figure 3 displays the Fourier spectrum for the V-band photometry of the star No. 4.

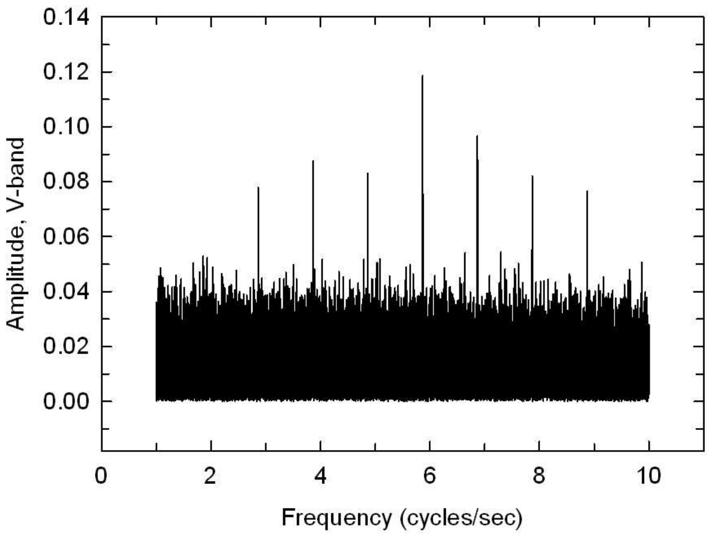

Figure 3.
The V-band power spectrum for the combined (CSS+Crimean) photometry of the star No. 4 in the field of Mrk 478.

The particular type of variability is difficult to determine from the photometric data only, without any spectroscopic information. However, taking into account the variability period and amplitude and the shape of the phased light curves for the period $P = 0\overset{d}{.}1705$, we can suppose that the star No. 4 may belong to eclipsing variable stars, namely, to the W UMa type of variable stars. In this case, the phased light curves plotted with the double period can give us a more definite information about the variable star type. Such curves for the star No. 4, with the period $P = 0\overset{d}{.}341$ day, are presented in Fig. 4. The phased light curves correspond to the elements: Min $= 2456004.473888 + 0\overset{d}{.}3409896 \times E$. The phased light curve in the V band shows a slight difference in the depths of brightness minima and resembles light curves of close binary eclipsing systems.

4 Mrk 1513=II Zw 136, star 9

Mrk 1513 is a well-known Seyfert 1 galaxy ($21^{\mathrm{h}}32^{\mathrm{m}}27\overset{s}{.}82$, $+10°08'19\overset{''}{.}3$, J2000, 2MASS). The finding chart for the star No. 9 and other stars selected for photometry is shown in Fig. 5. The coordinates of the star No. 9 (GSC 1123–00250) are $\alpha = 21^{\mathrm{h}}32^{\mathrm{m}}42\overset{s}{.}60$, $\delta = +10°09'19\overset{''}{.}5$ (J2000.0, UCAC4).

The stars selected as the comparison star candidates are numbered. Their $BVRR1I$ magnitudes are presented in Doroshenko et al. (2013). The photometry of stars in the Mrk 1513 field was made relative to the star No. 3 with the aperture $A = 15''$, in the course of 82 nights in 2010–2012. The comparison star No. 3 was calibrated during 5 good (in the photometrical sense) nights in 2010. Thirty-six estimates of its brightness were made with respect to the main stars in 12 different galaxies, which were observed on the same nights as Mrk 1513. The BVR_cI_c magnitudes of the comparison star No. 3 are the following: $B = 14.738 \pm 0.013$, $V = 13.839 \pm 0.009$, $R_c = 13.321 \pm 0.007$, and $I_c = 12.902 \pm 0.006$. The magnitudes of other stars were also computed relative to the star No. 3 using all observational nights. The mean magnitudes of the star No. 9 are $B = 13\overset{m}{.}685$, $V = 13\overset{m}{.}077$, $R_c = 12\overset{m}{.}709$, $R1 = 12\overset{m}{.}405$, $I_c = 12\overset{m}{.}416$; the mean color indices are $(B - V) = 0\overset{m}{.}608$, $(V - R_c) = 0\overset{m}{.}368$, $(V - I_c) = 0\overset{m}{.}661$. The color indices of

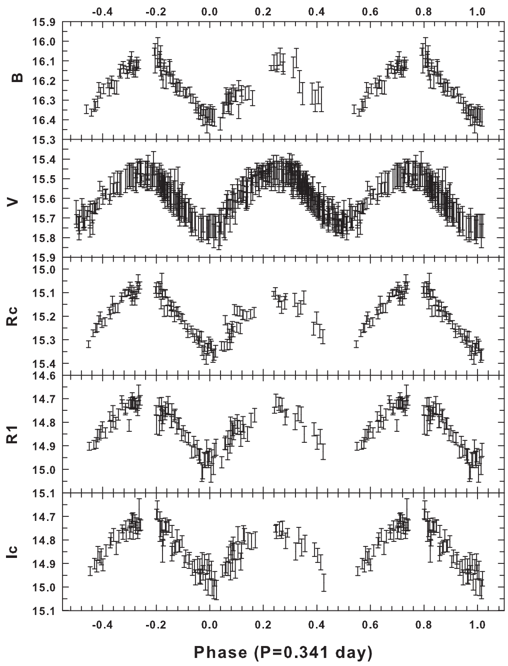

Figure 4.
The phased light curves for the star No. 4 plotted with the period $P = 0.^{\rm d}341$. In the V band, the CSS and Crimean data were used. Only Crimean data are presented in the other bands.

this star are in general agreement with the spectral type F2–G0, if this star belongs to the main sequence and if the extinction in the direction of the star is small enough.

The Crimean photometry of the star No. 9 is presented in Table 3, available electronically in the html version of this paper.

The χ^2 values calculated for light curves of the star No. 9 are significantly higher than 1: $\chi^2 B = 16.9$, $\chi^2 V = 20.7$, $\chi^2 R_c = 30.5$, and $\chi^2 I_c = 19.6$, compared to other selected stars, which have $\chi^2 \sim 1$. This fact indicates the variability of the star No. 9. The amplitudes of variability of the star No. 9 are the following: Amp $B = 0.^{\rm m}049 \pm 0.^{\rm m}016$, Amp $V = 0.^{\rm m}048 \pm 0.^{\rm m}012$, Amp $R_c = 0.^{\rm m}047 \pm 0.^{\rm m}012$, and Amp $Ic = 0.^{\rm m}045 \pm 0.^{\rm m}011$. The uncertainties were computed using a Monte-Carlo simulation.

The light curves of the star No. 9 tend to fainter brightness with time. This is clearer seen in the B band. I have found that the star No. 9 changes its brightness periodically. The Fourier analysis of the BVR_cI_c light curves of this star revealed the maximum peak at the frequency $\nu = 4.52279$ cycles/day ($P = 0.^{\rm d}2211$); Fig. 6 demonstrates this power spectrum. It should be noted that the points in 2012 correspond to the minimum brightness on the phased light curve. It is quite possible that the depth of minimum varies with time.

Just as in the case of the star No. 4 in the field of the galaxy Mrk 478, discussed above, it is also difficult to determine accurately the variability type of the star No. 9. However, if we suppose that the star is in a close binary system, then the phased light curve plotted for the doubled period, $P = 0.^{\rm d}4422$ (Fig. 7), shows that the depth of the first and second minima are different, but the heights of the maxima are approximately the same. This fact may indicate that the star belongs to the W UMa type with the elements Min $= 2455513.69110 + 0.4422 \times E$. Further studies are required to investigate the stationarity of the orbit or to find out whether there are any systematic changes of the minima depths in time.

5 Conclusion

We found two new variable stars that change their brightness periodically. The star No. 4 in the field of Mrk 478 varies with the period $P = 0\overset{d}{.}341$, and the star No. 9 in the field of Mrk 1513 varies with the period $P = 0\overset{d}{.}4422$. It is possible that these stars belong to the class of close binary eclipsing systems.

Acknowledgements. I thank the anonymous referee for helpful remarks, Drs. V.P. Goranskij and A.A. Slyapnikov for useful discussion. This work was supported by the grant 12-02-01237-a from the Russian Foundation for Basic Research.

Drake, A.J., Djorgovski, S.G., Mahabal, A., et al. 2009, *Astrophys. J.*, 696, 870
Doroshenko, V.T., Sergeev, S.G., Merkulova, N.I., et al. 2005a, *Astrophysics*, 48, 156
Doroshenko, V.T., Sergeev, S.G., Merkulova, N.I., et al. 2005b, *Astrophysics*, 48, 304
Doroshenko, V.T., Sergeev, S.G., Efimov, Yu.S., et al. 2013, *Astrophysics*, in press

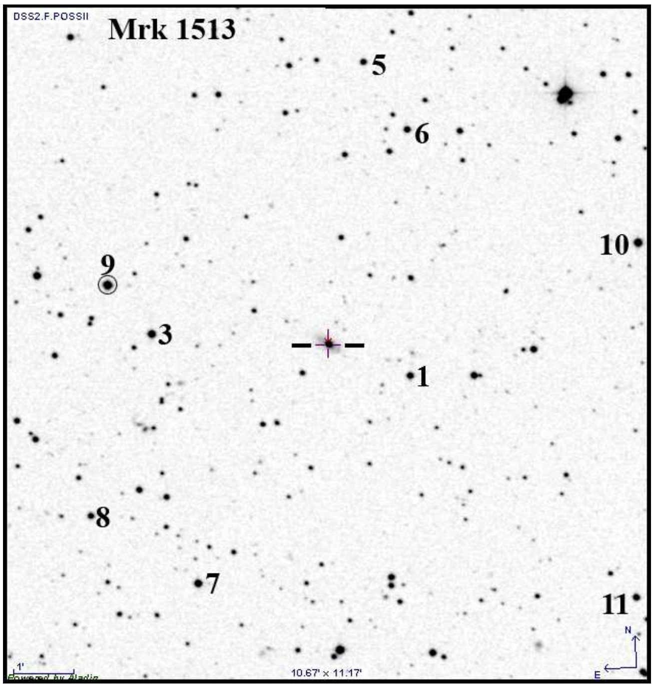

Figure 5.
The finding chart for the selected stars in the field of Mrk 1513. The size of the chart is $11' \times 11'$, north is at the top, east is to the left. The variable star No. 9 is circled; the galaxy is marked by two bars.

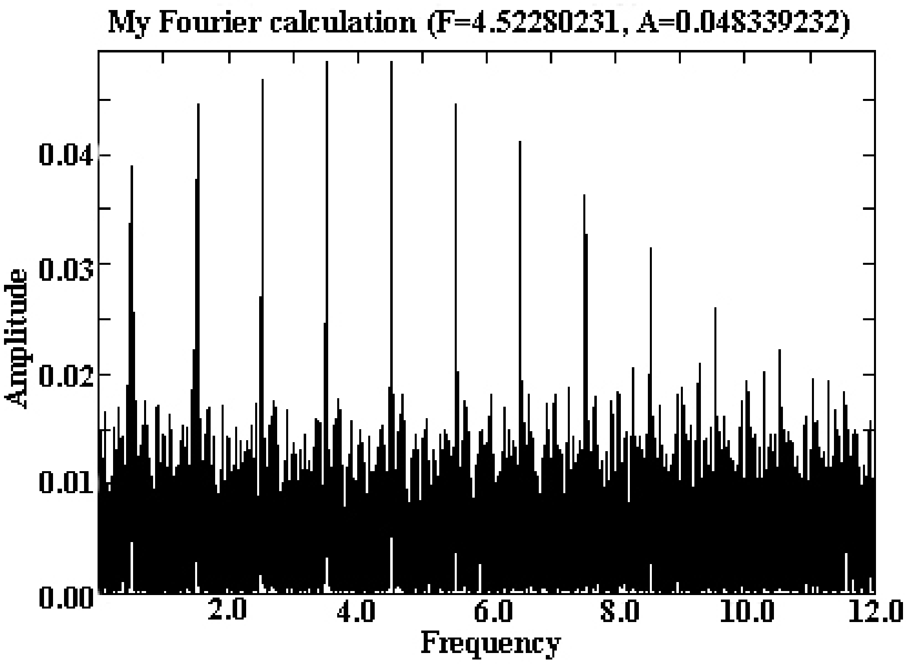

Figure 6.
The power spectrum for the V-band photometry of the star No. 9 in the field of Mrk 1513.

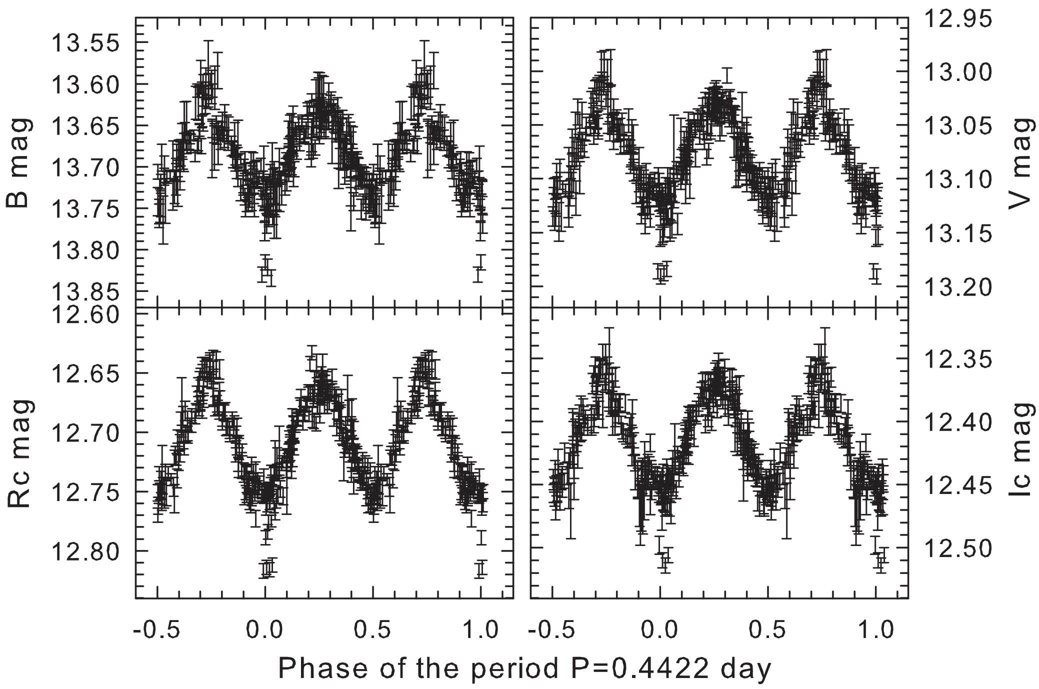

Figure 7.
The phased light curves for the star No. 9 in the field of Mrk 1513, plotted with the period $P = 0\overset{d}{.}4422$.