Light curve solutions of six eclipsing binaries at the lower limit of periods for W UMa stars

Diana P. Kjurkchieva\textsuperscript{1}, Dinko P. Dimitrov\textsuperscript{2} and Sunay I. Ibryamov\textsuperscript{1,2}

\textsuperscript{1} Department of Physics, Shumen University, 115, Universitetska Str., 1712 Shumen, Bulgaria; d.kyurkchieva@shu-bg.net

\textsuperscript{2} Institute of Astronomy and National Astronomical Observatory, Bulgarian Academy of Sciences, 72, Tsarigradsko Shose Blvd., 1784 Sofia, Bulgaria

Received 2014 October 17; accepted 2015 February 2

Abstract Photometric observations are presented in \( V \) and \( I \) bands of six eclipsing binaries at the lower limit of the orbital periods for W UMa stars. Three of them are newly discovered eclipsing systems. The light curve solutions reveal that all short-period targets are contact or overcontact binaries and six new binaries are added to the family of short-period systems with estimated parameters. Four binaries have components that are equal in size and a mass ratio near 1. The phase variability shown by the \( V-I \) colors of all targets may be explained by lower temperatures on their back surfaces than those on their side surfaces. Five systems exhibit the O’Connell effect that can be modeled by cool spots on the side surfaces of their primary components. The light curves of V1067 Her in 2011 and 2012 are fitted by diametrically opposite spots. Applying the criteria for subdivision of W UMa stars to our targets leads to ambiguous results.

Key words: methods: data analysis — catalogs — stars: fundamental parameters — stars: binaries: eclipsing: individual (1SWASP J173828.46+111150.2, 1SWASP J174310.98+432709.6 \( \equiv \) V1067 Her, NSVS 11534299, NSVS 10971359, NSVS 11234970, NSVS 11234970, NSVS 11504202)

1 INTRODUCTION

Most W UMa stars consist of solar-type components that have orbital periods within 0.25 d < \( P \) < 0.7 d. They are recognized by continuous brightness variations and nearly equal minima. The short orbital periods of these binaries mean they have small orbits in which rotation is synchronized with revolution.

The statistics describing W UMa stars around the lower limit of their periods are quite poor (Terrell et al. 2012) because the period distribution of binaries reveals a very sharp decline below 0.27 days (Drake et al. 2014). Another reason is that these short-period binaries contain late-type stars and thus are faint objects that are difficult to study in detail.

However, short-period contact systems are important objects for modern astrophysics in at least two ways: (a) the empirical period-luminosity relation shown by W UMas allows one to use them as distance and population tracers; (b) these binaries are natural laboratories for the study of the late
stage of stellar evolution connected with the processes of mass and angular momentum loss, merging or fusion of stars, etc.

Lately, interest in binaries around the low-period limit has increased because they provide constraints on theories describing the formation and evolution of low-mass stars. Moreover, one of the hypotheses for the origin of hot Jupiters is that they are products of a protoplanetary disk formed by the merging of short-period, low-mass binaries via “magnetic braking” if a substantial amount of mass remains in orbit around the primary (Martin et al. 2011).

Fortunately, modern large stellar surveys during the last decade have allowed the discovery of binaries with shorter and shorter periods (Rucinski 2007; Pribulla et al. 2009; Weldrake et al. 2004; Maceroni & Rucinski 1997; Dimitrov & Kjurkchieva 2010; Norton et al. 2011; Nefs et al. 2012; Davenport et al. 2013; Lohr et al. 2014; Qian et al. 2014; Drake et al. 2014). The majority of the newly discovered binaries from space missions (Kepler, CoRoT, etc.) and ground-based projects (ASAS, SuperWASP, Catalina, LINEAR, NSVS, etc.) have been classified as contact systems. However, most of them need follow-up observations and study.

In this paper we present photometric observations and light curve solutions for six binaries around the lower limit of orbital periods for W UMa stars. We chose to study such systems because the statistics of W UMa stars with periods around a quarter of a day are quite poor (Terrell et al. 2012). Three of our targets are known binaries: two binaries (1SWASP J173828.46+111150.2 and 1SWASP J174310.98+432709.6 = V1067 Her) are from the SuperWASP photometric survey (Pollacco et al. 2006) and one system (NSVS 11534299) is from the NSVS database (Wozniak et al. 2004). Also, three of our targets (NSVS 11234970, NSVS 11504202 and NSVS 10971359) are newly discovered binaries. Table 1 presents the coordinates of our targets and information on their light variability.

The plan of the paper is as follows: Section 2 gives information for our observations and data reduction; Section 3 describes the procedure of the light curve solution of our data; Section 4 contains analysis of the obtained results; Section 5 gives subclassification of the targets; Section Conclusions summarizes the main results of the study.

### 2 OBSERVATIONS

The CCD photometry of the targets was carried out in 2011–2012 at Rozhen National Astronomical Observatory (Bulgaria) with the 60-cm Cassegrain telescope using the FLI PL09000 CCD camera (3056 \times 3056 pixels, 12 μm pixel\(^{-1}\), field of 17.1′ \times 17.1′). The average photometric precision per data point is 0.005 mag in \(I\) band and 0.008 mag in \(V\) band. Table 2 presents the journal of our simultaneous \(VI\) observations. In addition we obtained several observations in \(BVI\) colors of targets 1, 3 and 4.

The photometric data were reduced by the IDL software package (including subroutine DAOPHOT). We used more than three standard stars in the observed fields (Fig. 1). Table 3 presents their colors: \(I\) from the USNO-B1.0 catalog and \(V\) from the GSC 2.3.2 catalog. The magnitudes of the targets in Table 3 correspond to their out-of-eclipse levels from our observations.
Table 2  Journal of the Rozhen Photometric Observations

| Target | Date       | Filter | Exposure [s] | Phase range          |
|--------|------------|--------|--------------|----------------------|
| 1      | 2011 July 10 | V, I   | 120,120      | 0.21–1.17            |
|        | 2011 Aug 03  | V, I   | 120,120      | 0.67–0.89            |
|        | 2011 Aug 21  | V, I   | 120,120      | 0.60–0.94            |
|        | 2012 June 02 | V, I   | 120,120      | 0.61–1.41            |
|        | 2012 June 03 | V, I   | 120,120      | 0.24–1.35            |
|        | 2012 July 07 | V, I   | 120,120      | 0.90–1.74            |
| 2      | 2011 Aug 11  | V, I   | 120,120      | 0.20–1.08            |
|        | 2011 Aug 19  | V, I   | 120,120      | 0.83–1.74            |
|        | 2012 June 04 | V, I   | 120,120      | 0.86–1.33            |
|        | 2012 July 08 | V, I   | 120,120      | 0.35–1.38            |
| 3      | 2012 Aug 04  | V, I   | 90,120       | 0.60–1.94            |
| 4      | 2012 Aug 05  | V, I   | 120,120      | 0.63–1.91            |
| 5      | 2012 Aug 06  | V, I   | 120,120      | 0.19–1.32            |
| 6      | 2011 July 08 | V, I   | 120,120      | 0.45–1.24            |
|        | 2011 July 11 | V, I   | 120,120      | 0.16–0.90            |

Table 3 Magnitudes of the Targets and Their Standard Stars

| Star (USNO B1) | GSC-ID | I [mag] | V [mag] | B [mag] |
|----------------|--------|---------|---------|---------|
| targ 1         | 0100100125 | 12.21   | 13.46   | 14.68   |
| st1 0100100125 | 12.67   | 13.41   |         |
| st2 0100100125 | 10.83   | 12.20   | 13.62   |
| st3 0099702419 | 11.04   | 12.49   | 14.15   |
| st4 0099702343 | 12.57   | 14.09   |
| st5 0099702387 | 11.85   | 13.12   | 14.10   |
| targ 2         | 0310001679 | 12.49   | 13.00   |
| st1 0310001679 | 13.45   | 13.66   |
| st2 0310001797 | 11.13   | 12.01   |
| st3 0310001604 | 12.45   | 13.66   | 14.33   |
| targ 3         | 1049-0454686 | 12.88   | 13.44   | 13.87   |
| st1 1049-0454686 | 12.45   | 13.33   |
| st2 1049-0454842 | 11.75   | 12.88   | 13.41   |
| targ 4         | 1095000807 | 12.63   | 13.19   | 14.79   |
| st1 1095000807 | 12.63   | 13.19   | 14.16   |
| st2 1095001223 | 10.98   | 12.27   | 13.70   |
| st3 1095000601 | 11.22   | 12.78   | 14.65   |
| st4 1095015899 | 10.66   | 11.33   | 11.93   |
| st5 109500781  | 10.88   | 12.38   | 14.02   |
| targ 5         | 002402305 | 10.71   | 12.13   |
| st1 0052401323 | 11.50   | 11.93   |
| st2 0052401783 | 11.94   | 13.32   |
| st3 0052402368 | 13.77   | 13.97   |

We also carried out a preliminary time-series analysis of our data using the software package PerSea. A comparison of the results with the published ones (Table 1) revealed two discrepancies.

(a) The published periods of targets 1 and 2 agreed well our data. However, the period of 0.24914 d for target 5 (see further Table 5) that we obtained was around 11% longer than the previous value (Table 1). This result is not so surprising because the follow-up observations of variable stars from different databases sometimes reveal different periods than the previous values (Norton et al. 2011;
Mighell & Plavchan 2013; Lohr et al. 2013; Kjurkchieva et al. 2014; Mayangsari et al. 2014). This is a consequence of the automated frequency analyses of the huge data sets. They were based on different approaches, which turned out to have different precisions for different types of variabilities. Moreover, sometimes they gave several different periods for each target (as well as false alarm detections of exoplanets).

(b) The amplitudes of variability for targets 1 and 2 turned out to be considerably larger than the previous ones. We assume that the reason for this discrepancy is the low spatial resolution of the previous photometric observations by small telescopes (13.7″ pixel$^{-1}$ for the SuperWASP survey and 14.4″ pixel$^{-1}$ for NSVS) that can blur the separation of two neighboring stars. A close nonva-
Table 4 The 2MASS Color Indices J–K and Corresponding Mean Temperatures \( T_m \) for the Targets

| Target | 1       | 2       | 3       | 4       | 5       | 6       |
|--------|---------|---------|---------|---------|---------|---------|
| J–K    | 0.645±0.033 | 0.590±0.024 | 0.749±0.030 | 0.750±0.026 | 0.558±0.034 | 0.618±0.031 |
| \( T_m \) | 4720±120   | 4930±140   | 4320±130   | 4320±110   | 5090±220   | 4810±130   |

An instrumental variable star may trigger a response from the same pixel during the photometric measurements of the variable star and thus reduce its amplitude of variability.

### 3 LIGHT CURVE SOLUTIONS

The shapes of the light curves (Figs. 2, 3, 4, 5, 6 and 7) implied that our targets are nearly contact or overcontact (OC) systems which was expected from their short orbital periods. The large amplitudes of their light variabilities mean that they are caused by eclipses.

It is well known that the determination of the mass ratio through the light-curve solution is an ambiguous approach compared with that by the radial velocity solution. However, the rapid rotation of components in short-period binaries is a serious obstacle to obtaining a precise spectral mass ratio from the measurement of their highly broadened and blended spectral lines (Bilir et al. 2005, Dall & Schmidtobreick 2005). On the other hand, their eclipse depths strongly depend on the potentials and the mass ratios.

Taking these considerations into account, we solved the Rozhen light curves of the six targets using the code PHOEBE (Prša & Zwitter 2005) by the following procedure.

We determined the mean temperatures \( T_m \) of the binaries (Table 4) by using their infrared color indices \( J–K \) from the 2MASS catalog and the color-temperature calibration of Tokunaga (2000).

At the first stage we adopted \( T_1 = T_m \) (a good approximation for contact binaries with close temperatures of the components) and searched for solutions with fixed \( T_1 \) by varying the initial epoch \( T_0 \), period \( P \), secondary temperature \( T_2 \), orbital inclination \( i \), mass ratio \( q \) and potential \( \Omega_{1,2} \).

We adopted coefficients of gravity brightening \( g_1 = g_2 = 0.32 \) and reflection effect \( A_1 = A_2 = 0.5 \) appropriate for late-type stars while the limb-darkening coefficients for each component and each color were automatically updated to the stellar temperature according to the tables of van Hamme (1993).

In order to reproduce the O’Connell effect we added cool spots on the stellar surfaces and varied spot parameters (longitude \( \lambda \), latitude \( \beta \), angular size \( \alpha \) and temperature factor \( \kappa \)). Moreover, the best fit in the two colors required a small contribution of third light \( l_3 \).

Finally, we searched for the best fits for fixed \( q \), spot parameters and third light contributions by adjusting the primary temperature \( T_1 \) slightly above \( T_m \) and correspondingly changed \( T_2 \), \( \Omega_{1,2} \) and \( i \).

Table 5 displays the results of our light curve solutions. The parameter errors are the formal PHOEBE errors. The synthetic light curves corresponding to the parameters from Table 5 are shown in Figures 2, 3, 4, 5, 6, 7 and 8 as continuous lines.

The results of our light curve solutions can be used for estimation of the global parameters of the targets (masses, radii and luminosities) using statistical relations and the supposition that their components are approximate main sequence (MS) stars.

### 4 ANALYSIS OF THE RESULTS

The analysis of the light curve solutions led to several conclusions.

1. All targets are almost contact (≈CB) or OC binaries. This result is expected taking into account the short periods of the binaries (Table 1).
Fig. 2 Light curves of target 1 in $V$ and $I$ bands (the $V$ data are shifted vertically by $1^m$ for better visibility) and their fits.

Fig. 3 Light curves of target 2 in $V$ and $I$ bands in 2011 (the $V$ data are shifted vertically by $0.3^m$ for better visibility) and their fits.

Fig. 4 Light curves of target 2 in $V$ and $I$ bands in 2012 (the $V$ data are shifted vertically by $0.3^m$ for better visibility) and their fits.

(2) The $q$ values are near 0.5 for two binaries (targets 1 and 6) and near 1 for the other ones. This result only refers to our sample and should be assumed to be accidental because the $q$ values of W UMa stars are rather evenly distributed (fig. 1 in Csizmadia & Klagyivik 2004).

(3) The stellar components are K spectral type. This is a natural consequence of the average infrared colors of the targets (Table 4).
Fig. 5 Light curves of target 3 in V and I bands (the V data are shifted vertically by 1 m for better visibility) and their fits.

Fig. 6 Light curves of target 4 in V and I bands (the V data are shifted vertically by 1 m for better visibility) and their fits.

Fig. 7 Light curves of target 5 in V and I bands (the V data are shifted vertically by 1 m for better visibility) and their fits.

(4) The temperature differences in the components of the binaries are below 630 K. The small temperature differences are expected for contact or OC systems and mean that their components are almost in thermal contact.

(5) Four targets (2, 3, 4 and 5) have components that are equal in size, and they have a mass ratio near 1. Hence, their components obey the same mass-radius relation.
Fig. 8 Light curves of target 6 in $V$ and $I$ bands (the $V$ data are shifted vertically by 0.2 m for better visibility) and their fits.

Table 5 Parameters of the Light Curve Solutions for the Targets

| Parameter | 1 | 2 | 3 | 4 | 5 | 6 |
|-----------|---|---|---|---|---|---|
| $T_0$     | 2450000+ | 6091.94682 | 5785.294939 | 6144.364434 | 6145.36124 | 6146.46937 | 5751.49320 |
| $P$       | ±0.00021 | ±0.000151 | ±0.000208 | ±0.00011 | ±0.00021 | ±0.00021 |
| $q$       | 0.488±0.002 | 1.009±0.005 | 0.986±0.006 | 0.980±0.006 | 0.872±0.003 | 0.462±0.002 |
| $i$       | 66.85±0.09 | 75.68±0.21 | 74.36±0.26 | 79.4±0.2 | 56.3±0.4 | 66.8±0.2 |
| $T_1$     | 4900±48 | 5152±94 | 4600±90 | 4402±55 | 5150±61 | 4936±48 |
| $T_2$     | 4544±28 | 4626±56 | 3969±70 | 4219±54 | 5014±45 | 4423±37 |
| $\Omega_1$ | 2.843±0.004 | 3.640±0.012 | 3.615±0.009 | 3.717±0.013 | 3.548±0.014 | 2.785±0.005 |
| $\Omega_2$ | 2.843±0.004 | 3.640±0.012 | 3.615±0.009 | 3.717±0.013 | 3.550±0.008 | 2.785±0.005 |
| $r_1$     | 0.445 | 0.400 | 0.399 | 0.363 | 0.389 | 0.451 |
| $r_2$     | 0.319 | 0.399 | 0.396 | 0.338 | 0.365 | 0.317 |
| $l_1$     | 0.746 | 0.643 | 0.715 | 0.598 | 0.566 | 0.787 |
| $l_2$     | 0.254 | 0.357 | 0.285 | 0.402 | 0.434 | 0.213 |
| $l_2/l_1$ | 0.340 | 0.555 | 0.399 | 0.672 | 0.767 | 0.271 |
| fillout   | 0.033 | 0.229 | 0.209 | -0.045 | -0.0024 | 0.061 |
| fillout   | 0.033 | 0.229 | 0.209 | -0.045 | -0.003 | 0.061 |
| configuration | OC | OC | OC | ≃CB | ≃CB | OC |

Table 6 Parameters of the Cool Spots on the Targets

| Target | $\beta$ | $\lambda$ | $\alpha$ | $\kappa$ | $l_3$ |
|--------|--------|--------|--------|--------|-----|
| 1      | 122±1  | 297±1  | 17±1   | 0.83±0.01 | 0.029 (I) |
| 22011  | 90±1   | 90±1   | 20±1   | 0.80±0.01 | 0.066 (I) |
| 22012  | 90±1   | 270±1  | 20±1   | 0.80±0.01 | 0.034 (I) |
| 3      | 90±1   | 270±1  | 18±1   | 0.90±0.01 | 0.055 (I) |
| 4      | 90±1   | 270±1  | 10±1   | 0.90±0.01 | 0.085 (I) |
| 5      | 40±1   | 0±1    | 20±1   | 0.88±0.01 | 0.073 (V) |
| 6      | 90±1   | 90±1   | 15±1   | 0.90±0.01 | 0.057 (I) |

(6) Five targets exhibited the O’Connell effect that could be modeled by cool spots (Table 6) on the side surfaces of their primary components. The light curves of target 2 in 2011 and 2012 were fitted by diametrically opposite spots (visible at the second and first quadratures correspondingly). This result can be explained by differential rotation or by a new spot cycle. However, the equal sizes and temperatures of the two spots (Table 6) rather support the first supposition.
The modeling of the O’Connell effect in late-type stars by cool spots is the preferred approach by almost all authors. A cloud of circumstellar, absorbing matter that orbits the corresponding star may reproduce the O’Connell effect as a cool photospheric spot. However, only using photometric data (as is ordinarily the case) cannot resolve this ambiguity and one adopts modeling by spots.

(7) The cool spot on target 5 was invoked to reproduce the distortions in its light curve at the minima and maxima.

(8) The $V - I$ indices of the targets undergo orbital variability with reddening at the light minima (Fig. 9). The amplitudes of the $V - I$ curves are proportional to the light amplitudes (Table 7). This result means that the temperature on the back surface of the close stellar components is lower than those of their side surfaces.

(9) No target in our sample was identified as an X-ray source or H$_{\alpha}$ emission source. Thus, the low level of activity generally exhibited by W UMa stars was confirmed.

5 SUBCLASSIFICATION OF OUR TARGETS

The contact binary stars are divided into two subtypes, A and W, according to the following criteria: (a) the ratio $R/T$ (radius to temperature): the larger star is the hotter one for an A subtype system while the smaller star is the hotter one for a W subtype system (Binnendijk 1970); (b) temperature $T$ or spectral type: the A subtype systems are earlier than the W subtype binaries, whose components are G or K spectral type; (c) period $P$: the W subtype binaries have shorter periods of 0.22 to 0.4 days (Smith 1984); (d) mass ratio $q$: values for the A subtype are smaller than those for W subtype.

Csizmadia & Klagyivik (2004) introduced H subtype systems (H/A and H/W) with a large mass ratio ($q \geq 0.72$), whose energy transfer is less efficient than that in other types of contact binary stars. They found that the different subtypes of W UMas are located in different regions on the mass ratio – luminosity ratio diagram but above the line $\lambda = q^{4.0} (\lambda = l_2/l_1)$ representing the mass-luminosity relation for MS stars (fig. 1 in Csizmadia & Klagyivik 2004).

The subclassification of our targets according to the foregoing criteria is presented in Table 8. It reveals that almost all targets simultaneously belong to at least two subclasses. Only target 3 is deeply below the line representing the mass-luminosity relation for MS stars (the uninhabited place).
This result means that the proposed criteria and subdivisions are ambiguous and, of course, that the stellar world is richer than one expects.

6 CONCLUSIONS

We obtain light curve solutions of six binaries with periods around 0.25 d, the lower limit of periods for W UMa stars. Three of the targets are newly discovered eclipsing systems.

The solutions reveal that all the systems are contact or OC binaries.

The colors of the investigated systems become redder at the light minima. Such a behavior may mean that the temperatures of the back surfaces of the close components are lower than those of their side surfaces.

The mass ratios of the targets are grouped around values 0.5 and 1 and those with a mass ratio near 1 have components that are equal in size.

Five targets exhibit the O’Connell effect that can be modeled by cool spots on the side surfaces of their primary components. The light curves of V1067 Her in 2011 and 2012 are fitted by diametrically opposite spots.

Applying the criteria for subclassification of W UMa stars to our targets leads to ambiguous results. New criteria are necessary for subclassifying the numerous W UMa systems.

This study adds six new systems with estimated parameters to the family of short-period binaries. They could help to improve statistics describing the relations between stellar parameters for low-mass stars.

Acknowledgements This research was partly supported by funds provided by projects RD 02-263 administered by the Scientific Foundation of Shumen University.

This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. This research also has made use of the SIMBAD database, operated at CDS, Strasbourg, France, NASA’s Astrophysics Data System Abstract Service, and the USNOFS Image and Catalogue Archive operated by the United States Naval Observatory, Flagstaff Station (http://www.nofs.navy.mil/data/fchpix/). The authors are grateful to the anonymous reviewer for the useful suggestions and notes.

References

Bilir, S., Karataş, Y., Demircan, O., & Eker, Z. 2005, MNRAS, 357, 497
Binnendijk, L. 1970, Vistas in Astronomy, 12, 217
Blattler, E., & Diethelm, R. 2000, Information Bulletin on Variable Stars, 4966, 1
Csizmadia, S., & Klagyivik, P. 2004, A&A, 426, 1001
Dall, T. H., & Schmidtobreick, L. 2005, A&A, 429, 625
Davenport, J. R. A., Becker, A. C., West, A. A., et al. 2013, ApJ, 764, 62
Dimitrov, D. P., & Kjurkchieva, D. P. 2010, MNRAS, 406, 2559

Table 8 Subclassification of the Targets

| Criterion/target | 1 | 2 | 3 | 4 | 5 | 6 |
|------------------|---|---|---|---|---|---|
| T/R              | A | A | A | A | A | A |
| T               | W | W | W | W | W | W |
| P               | W | W | W | W | W | W |
| q               | A | W | W | W | W | A |
| q, l2/l1        | A | H/A | ? | H/A | H/W | A |

This result means that the proposed criteria and subdivisions are ambiguous and, of course, that the stellar world is richer than one expects.

6 CONCLUSIONS

We obtain light curve solutions of six binaries with periods around 0.25 d, the lower limit of periods for W UMa stars. Three of the targets are newly discovered eclipsing systems.

The solutions reveal that all the systems are contact or OC binaries.

The colors of the investigated systems become redder at the light minima. Such a behavior may mean that the temperatures of the back surfaces of the close components are lower than those of their side surfaces.

The mass ratios of the targets are grouped around values 0.5 and 1 and those with a mass ratio near 1 have components that are equal in size.

Five targets exhibit the O’Connell effect that can be modeled by cool spots on the side surfaces of their primary components. The light curves of V1067 Her in 2011 and 2012 are fitted by diametrically opposite spots.

Applying the criteria for subclassification of W UMa stars to our targets leads to ambiguous results. New criteria are necessary for subclassifying the numerous W UMa systems.

This study adds six new systems with estimated parameters to the family of short-period binaries. They could help to improve statistics describing the relations between stellar parameters for low-mass stars.

Acknowledgements This research was partly supported by funds provided by projects RD 02-263 administered by the Scientific Foundation of Shumen University.

This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. This research also has made use of the SIMBAD database, operated at CDS, Strasbourg, France, NASA’s Astrophysics Data System Abstract Service, and the USNOFS Image and Catalogue Archive operated by the United States Naval Observatory, Flagstaff Station (http://www.nofs.navy.mil/data/fchpix/). The authors are grateful to the anonymous reviewer for the useful suggestions and notes.

References

Bilir, S., Karataş, Y., Demircan, O., & Eker, Z. 2005, MNRAS, 357, 497
Binnendijk, L. 1970, Vistas in Astronomy, 12, 217
Blattler, E., & Diethelm, R. 2000, Information Bulletin on Variable Stars, 4966, 1
Csizmadia, S., & Klagyivik, P. 2004, A&A, 426, 1001
Dall, T. H., & Schmidtobreick, L. 2005, A&A, 429, 625
Davenport, J. R. A., Becker, A. C., West, A. A., et al. 2013, ApJ, 764, 62
Dimitrov, D. P., & Kjurkchieva, D. P. 2010, MNRAS, 406, 2559
Drake, A. J., Djorgovski, S. G., García-Álvarez, D., et al. 2014, ApJ, 790, 157
Hoffman, D. I., Harrison, T. E., & McNamara, B. J. 2009, AJ, 138, 466
Kjurkchieva, D. P., Dimitrov, D. P., & Ibryamov, S. I. 2014, Information Bulletin on Variable Stars, 6113, 1
Lohr, M. E., Hodgkin, S. T., Norton, A. J., & Kolb, U. C. 2014, A&A, 563, A34
Lohr, M. E., Norton, A. J., Kolb, U. C., et al. 2012, A&A, 542, A124
Lohr, M. E., Norton, A. J., Kolb, U. C., et al. 2013, A&A, 549, A86
Maceroni, C., & Rucinski, S. M. 1997, PASP, 109, 782
Martin, E. L., Spruit, H. C., & Tata, R. 2011, A&A, 535, A50
Mayangsari, L., Priyatikanto, R., & Putra, M. 2014, in American Institute of Physics Conference Series, 1589, 37
Mighell, K. J., & Plavchan, P. 2013, AJ, 145, 148
Nefs, S. V., Birkby, J. L., Snellen, I. A. G., et al. 2012, MNRAS, 425, 950
Norton, A. J., Payne, S. G., Evans, T., et al. 2011, A&A, 528, A90
Pollacco, D. L., Skillen, I., Collier Cameron, A., et al. 2006, PASP, 118, 1407
Pribulla, T., Rucinski, S. M., DeBond, H., et al. 2009, AJ, 137, 3646
Prša, A., & Zwitter, T. 2005, ApJ, 628, 426
Qian, S.-B., Jiang, L.-Q., Zhu, L.-Y., et al. 2014, Contributions of the Astronomical Observatory Skalnate Pleso, 43, 290
Rucinski, S. M. 2007, MNRAS, 382, 393
Smith, R. C. 1984, QJRAS, 25, 405
Terrell, D., Gross, J., & Cooney, W. R. 2012, AJ, 143, 99
Tokunaga, A. T. 2000, Infrared Astronomy, in Allen’s Astrophysical Quantities, ed. A. N. Cox (New York: AIP Press; Springer), 143
van Hamme, W. 1993, AJ, 106, 2096
Weldrake, D. T. F., Sackett, P. D., Bridges, T. J., & Freeman, K. C. 2004, AJ, 128, 736
Woźniak, P. R., Vestrand, W. T., Akerlof, C. W., et al. 2004, AJ, 127, 2436