NSVS 2569022: a peculiar binary among W UMa stars with extremely small mass ratios

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Received 2018 April 20; accepted 2018 May 28

Abstract Photometric observations of the W UMa binary NSVS 2569022 are presented. The light curve solution reveals that both components are of F spectral type (temperatures \( T_1 = T_2 = 6100 \) K). NSVS 2569022 undergoes a total eclipse of W subtype and the mass ratio is well-determined. Its extremely small value of only 0.077 implies that the target will probably experience instability and a possible merger. This value ranks NSVS 2569022 in sixth place among binaries with the smallest mass ratio. Based on an empirical relation of “period – total mass” for low mass-ratio binaries, we estimate the global parameters of NSVS 2569022: masses \( M_1 = 1.17 M_\odot \) and \( M_2 = 0.09 M_\odot \); radii \( R_1 = 1.19 R_\odot \) and \( R_2 = 0.38 R_\odot \); luminosities \( L_1 = 1.73 L_\odot \) and \( L_2 = 0.17 L_\odot \). An analysis of the characteristics of binaries with extremely low-mass ratios is made. NSVS 2569022 turns out to be a peculiar binary among W UMa stars with extremely small mass ratios due to its unexpectedly small fill-out factor of only 0.014 (slightly overcontact configuration).

Key words: binaries: eclipsing — binaries: close — stars: fundamental parameters — stars: individual (NSVS 2569022)

1 INTRODUCTION

The components of W UMa systems lie between the inner and outer Lagrangian equipotential surfaces. Because of the similarity in effective temperatures of their components, the eclipse depths are practically independent of their temperatures, but depend strongly on the mass ratio \( q \) as well as on orbital inclination \( i \) and degree of contact \( f \). The case is different for detached binaries where the differences in component temperatures have a significant effect on the eclipse depths (Rucinski 2001).

The study of W UMa stars is essential for modern astrophysics because they are probes that can be used for investigating the processes of tidal interaction, mass loss, mass transfer and angular momentum loss (Martin et al. 2011). However, the mechanism of energy transfer, the W phenomenon (in which the hotter component is the smaller star) and their future fate (tight binaries or merger) are still debatable problems for W UMa stars. Their solution requires knowledge of fundamental parameters for a number of such binaries.

The mass ratio is an important parameter for each binary star, particularly as it determines the W/A subtype of W UMa systems (Binnendijk 1970). However, the mass ratio is poorly determined based on photometric data of binaries which undergo partial eclipses (Rucinski 2001; Terrell & Wilson 2005). On the other hand, spectral data of W UMa stars are rarely available due to their faintness (Rucinski 2002). Moreover, even when W UMa stars have spectral observations, their spectral mass ratios are not precise due to the highly broadened and blended spectral lines (Frasca 2000; Bilir et al. 2005; Dall & Schmidtobreick 2005).
Firstly, Webbink (1976) established that there is a cut-off of mass ratio: for \( q < q_{\text{min}} \) the binary system quickly merges into a single, rapidly rotating star. Instability occurs when \( J_{\text{orb}} \approx 3 J_{\text{rot}} \). Rasio (1995) theoretically calculated \( q_{\text{min}} \simeq 0.09 \) for a contact binary containing two unevolved main sequence (MS) stars whose primary is mostly radiative (the value is bigger for a convective envelope). Li & Zhang (2006) found \( q_{\text{min}} \sim 0.071 - 0.076 \) assuming that W UMa systems rigorously comply with Roche geometry. For overcontact binaries, Arbutina (2007) determined theoretically \( q_{\text{min}} \sim 0.094 - 0.109 \). Later, by including the effects of higher central condensation due to rotation, Arbutina (2012) found \( q_{\text{min}} = 0.070 - 0.074 \) for overcontact binaries with fill-out factor \( f = 0 - 1 \). Jiang et al. (2010) argued that \( q_{\text{min}} \) depends on the primary mass and structure, and can reach up to 0.05. Yang & Qian (2015) even obtained \( q_{\text{min}} = 0.044 \). It was supposed that the lower limit of mass ratio depends on the fill-out factor \( f \) (Rasio 1995; Rasio & Shapiro 1995) but this dependence was not studied. The majority of the foregoing theoretical investigations has been invoked by the discoveries of several binaries with extremely low mass ratios \( (q_{\text{min}} < 0.09) \).

Observations of low mass ratio systems are valuable for understanding the dynamical evolution of binaries and the formation of blue stragglers and FK Com-type stars (Eggleton & Kiseleva-Eggleton 2001). In this paper, we present photometric observations of the eclipsing binary NSVS 2569022 (RA = \( 10^h10^m42.72^s \), Dec = \( +67^\circ39'32.4'' \), \( V = 10.1 \) mag) whose modeling shows that it is ranked sixth among W UMa systems with the smallest mass ratios. Gettel et al. (2006) classified NSVS 2569022 as an EW type with period \( P = 0.2877\text{891 d} \) and amplitude 0.21 mag.

2 OBSERVATIONS

CCD photometric observations of the target in Sloan \( g', i' \) bands were carried out on 2015 February 13 and 14 at Rozhen Observatory with the 30-cm Ritchey Chretien Astrograph (located in the IRIDA South dome) using an ATIK 4000M CCD camera (2048 × 2048 pixels, 7.4 \( \mu \)m/pixel, field of view 35 × 35 arcmin). The exposures in \( g' \) and \( i' \) were 30 and 60 s respectively, and the mean errors in the two filters were \( \sim 0.002 \) mag.

The standard procedure was used for reduction of the photometric data (de-biasing, dark frame subtraction and flat-fielding) by software AIP4WIN2.0 (Berry & Burnell 2005).

The light variability of the target was estimated with respect to nearby comparison (constant) stars in the observed field (ensemble photometry). A check star served to determine the observational accuracy and to check constancy of the comparison stars (Table 1). We performed ensemble aperture photometry with the software VPHOT. The magnitudes of the comparison and check stars were taken from the catalog APASS DR9 (Henden et al. 2016). The obtained instrumental magnitudes were transformed to standard ones as in Kjurkchieva et al. (2017).

3 MODELING

The photometric data were modeled using the PHOEBE code (Prša & Zwitter 2005; Prsa et al. 2011; Prša et al. 2016) which is based on the Wilson–Devinney (WD) code (Wilson & Devinney 1971; Wilson 1979, 1993). It allows simultaneous modeling of photometric data in a number of filters and provides a graphical user interface.

We determined in advance the temperature of NSVS 2569022 as \( T_{\text{m}} = 6100 \pm 50 \) K by comparing its low-resolution spectrum with a sample of Planck curves (Fig. 1). There are two deviations in the observed spectrum from the (normalized) Planck curves: protruding peak and steeper left branch (the same deviations that might be seen in a solar spectrum). The obtained spectral temperature of 6100 K is bigger than the photometric values (Table 2) determined by different color indices. The possible reason could be the use of data without de-reddening. For instance, the temperature corresponding to our original data is 5870 K (Table 2) while the de-reddening procedure led to \( g' - i' = 0.499 \) (Schlafly & Finkbeiner 2011) and correspondingly to a temperature of 6030 K, very close to the spectral value of 6100 K.

Fixed coefficients of gravity brightening \( g_1 = g_2 = 0.32 \) and reflection effect \( A_1 = A_2 = 0.5 \) appropriate for stars with convective equilibrium were assumed. Initially, we used a linear limb-darkening law whose coefficients for each component and each color were updated according to the tables in van Hamme (1993).
Table 1: Magnitudes of Standards

| Label | Star ID | RA   | Dec    | $g'$ | $i'$ |
|-------|---------|------|--------|------|------|
| Target | NSVS 2569022 | 10 10 42.72 | +67 39 32.40 | 10.357 | 9.784 |
| Chk   | UCAC4-789-020996 | 10 11 02.25 | +67 37 17.16 | 13.412 | 12.301 |
| C1    | UCAC4-789-021025 | 10 13 01.97 | +67 45 25.22 | 11.525 | 10.859 |
| C2    | UCAC4-790-020961 | 10 08 55.89 | +67 49 49.73 | 12.668 | 11.473 |
| C3    | UCAC4-789-021011 | 10 12 04.17 | +67 30 36.75 | 12.687 | 11.161 |
| C4    | UCAC4-789-021009 | 10 11 57.27 | +67 39 46.56 | 12.270 | 11.604 |
| C5    | UCAC4-788-021201 | 10 11 15.26 | +67 35 07.06 | 13.006 | 11.907 |
| C6    | UCAC4-788-021202 | 10 11 18.72 | +67 32 27.09 | 12.065 | 11.508 |
| C7    | UCAC4-788-021204 | 10 11 48.18 | +67 28 03.79 | 11.987 | 10.812 |

Table 2: Target Temperature from Photometric Observations (without de-reddening)

| Index | Value | $T$ | Color-T relation | Source |
|-------|-------|-----|------------------|--------|
| J − K | 0.417 | 5650 | | Cox (2000) |
| $B_T − V_T$, $B_T − J$, $V_T − H$, $V_T − K$, $J − K$ | 0.560 | 5800 | | Ammons et al. (2006) |
| B − V | 0.576 | 5760 | | Worley & Lee (2011) |
| V − Ic | 0.693 | 5750 | | Worley & Lee (2011) |
| $g' − i'$ | 0.799 | 5460 | | Droge et al. (2006) |
| $g' − i'$ | 0.573 | 5870 | | Covey et al. (2007) |

Table 3: List of Known Binaries with $q < 0.082$

| Target | $q$ | $f$ | $P$ (d) | $dP/dt$ (d yr$^{-1}$) | $T$ | Reference |
|--------|-----|-----|---------|-------------------|-----|-----------|
| V53 (M4) | 0.060* | 0.308448705 | +2.90×10$^{-7}$ | 9800 | Kaluzny et al. (2013) |
| V857 Her | 0.065* | 0.38222952 | | 8300 | Qian et al. (2005) |
| SX Crv | 0.066+ | 0.3166 | | 6200 | Rucinski et al. (2001) |
| ASAS J083241+2332.4 | 0.0715+ | 0.3165992 | −1.67×10$^{-7}$ | 6300 | Zola et al. (2004) |
| AW UMa | 0.075+ | 0.311329 | +8.854×10$^{-7}$ | 6500 | Sriram et al. (2016) |
| NSVS 2569022 | 0.077* | 0.43873 | −1.42×10$^{-5}$ | 7000 | Pribulla et al. (2009) |
| V870 Ara | 0.082 | 0.399722 | | 6000 | Szalai et al. (2016) |

Notes: The symbol * means photometric mass ratio (for total eclipses) and the symbol + means spectral mass ratio.

Since the light curve shapes (Fig. 2) implied an overcontact configuration, we employed the model “Overcontact binary not in thermal contact.”

To search for a fit, we fixed $T_1 = T_m$ and varied simultaneously the initial epoch $T_0$, period $P$ (around its known value), secondary temperature $T_2$ (around $T_m$), orbital inclination $i$, mass ratio $q$ and potential $\Omega$. The data in two bands were modeled simultaneously.

In order to reproduce the light curve distortion, we added a cool spot whose parameters (longitude $\lambda$, latitude $\beta$, angular size $\alpha$ and temperature factor $\kappa$) were adjusted.

After reaching the best fits, we also carried out solutions for quadratic and logarithmic limb-darkening laws, but they did not lead to better fits, so we further present the results corresponding to a linear limb-darkening law.

The final values of the fitted parameters are:

$$T_0 = 2457068.471732(88);$$
$$P = 0.287797(4) \text{ d};$$
$$\Omega = 1.88729(5);$$
$$q = 0.0777(3);$$
$$i = 76.29(8)^{\circ};$$
$$T_2 = 6100(25) \text{ K}.$$
To estimate the global parameters of the target, we used the empirical relation $M_{\text{tot}} = 0.5747 + 2.3734 \times P$ of Yang and Qian (2015) derived from a sample of 46 low mass-ratio binaries with $q \leq 0.25$. We calculated $M_{\text{tot}}$ of NSVS 2569022 as 1.258 $M_\odot$, which enables computation of the global parameters: orbital axis $a = 1.98 R_\odot$; masses $M_1 = 1.168(13) M_\odot$ and $M_2 = 0.090(2) M_\odot$; radii $R_1 = 1.188(8) R_\odot$ and $R_2 = 0.378(6) R_\odot$; luminosities $L_1 = 1.727(13) L_\odot$ and $L_2 = 0.175(9) L_\odot$.

4 ANALYSIS OF THE RESULTS

The main results from the light curve solution are as follows:

(1) We determine the initial epoch of the target. The known value of its orbital period agrees well with our data.

(2) The stellar components indicate an F spectral type.

(3) The target undergoes total eclipse.
NSVS 2569022 has a slightly overcontact configuration with fill-out factor 0.014 (Fig. 3).

The target is of W subtype.

The different light levels at the two quadratures are reproduced by a cool spot on the primary component with angular size of $10''$ and temperature factor of 0.9.

The solution of NSVS 2569022 turned out to be only mildly sensitive to the component temperatures and orbital inclination $i$, but very sensitive to the mass ratio $q$ and potential $\Omega$. The attempts to obtain a fit with $\Omega$ close to $\Omega_2$, corresponding to big fill-out factor $f$, were not successful.

NSVS 2569022 has an extremely small mass ratio. It was determined photometrically based on fitting the wide total eclipse and may be adopted with great confidence. This conclusion is supported by the coincidence of values of photometric ($q_{ph}$) and spectral ($q_{sp}$) mass ratios for totally-eclipsed binaries established by the investigation of a sample of low mass-ratio ($q \leq 0.25$) systems (Table 1 in Yang & Qian (2015)).

The values of stellar masses in NSVS 2569022 support the conclusion of Arbutina (2012) that extremely low mass ratio W UMa systems (with $q \leq 0.1$) represent an interesting class of objects in which a “normal,” approximately one solar mass MS star, is in contact with a significantly less massive companion, $M_2 \sim 0.1 M_\odot$.

According to the empirical relation $J_{rot}/J_{orb} = 0.5104 - 3.7738 \times q + 8.2817 \times q^2$ for low mass-ratio overcontact binaries (Yang & Qian 2015), NSVS 2569022 should have ratio $J_{rot}/J_{orb} = 0.269$. This value is close to but smaller than the cut-off of 0.33.

### Table 4: Eclipse Times

| Type | HJD time | Source |
|------|----------|--------|
| I    | 2457067.32025 ± 0.00014 | this work |
| II   | 2457068.52861 ± 0.00014 | this work |
| II   | 2457068.61689 ± 0.00014 | this work |
| II   | 2457449.66042 ± 0.00018 | AAVSO |
| II   | 2457461.74881 ± 0.00017 | AAVSO |
| I    | 2457473.69294 ± 0.00042 | AAVSO |

The target is faint and invisible in the spectra. Hence, an important possibility to determine global parameters of low mass-ratio systems is to study those cases which undergo total eclipses.

Analysis of the information in Table 3 led to the following conclusions:

1. Binaries with extremely low mass ratios exhibit periods of 0.29–0.45 d. This result means that there are probably two types of progenitors for the merger: ultrashort-period binaries and binaries with extremely small mass ratios.

2. The components of binaries with extremely low mass ratios are of intermediate spectral types with $6000 \, K < T < 9800 \, K$, i.e. there are no late-type stars among them (in contrast to ultrashort-period binaries which are very late stars). Moreover, there is a trend for the target temperature to decrease with mass ratio increase (Table 3).

3. The extremely low mass ratios (Table 3) as a rule are accompanied by big fill-out factors ($f > 0.27$). However, our target almost has contact configuration ($f \sim 0.014$) and represents a major exception.

The anonymous referee attracted our attention to the very recent work of Liu et al. (2018) who suppose a new mechanism of long-term period variations for W UMa-type contact binaries. Under this mechanism, $f$ is oscillating. That means contact binary systems with an extremely small $q$ can have very different $f$, nearly from 0 to 1. This result can explain why the fill-out factor of NSVS 2569022 could be so small.

4. Some binaries with extremely low mass ratios show long-term sinusoidal modulation (Sriram et al. 2016), probably due to a third body, but most of them reveal secular change in the orbital periods, increasing or decreasing (Table 3). Theoretical and evolutional study is necessary to explain which factor(s) determine the two alternatives. The secular period variability may be an indication of instability. Probably sometimes it is con-

5. EXTREMELY LOW MASS RATIO

The most important peculiarity of NSVS 2569022 is its extremely low mass ratio of 0.077. This result implies that the target will probably experience instability and possible merger.

So far, only six binaries with $q < 0.082$ have been identified (Table 3). Three of them have mass ratios $q_{ph}$ determined photometrically, from their total eclipses (as our case). One should consider that the determination of $q_{sp}$ for extremely small mass-ratio binaries is very difficult: on one hand the primary radial velocity is negligible, and on the other hand the secondary component is faint and invisible in the spectra. Hence, an important possibility to determine global parameters of low mass-ratio systems is to study those cases which undergo total eclipses.

![Image](https://via.placeholder.com/150)
Table 5: List of Binaries with $q < 0.19$

| Target       | $q$  | $f$  | $P$ (d) | $dP/dt$ (d yr$^{-1}$) | $T$   | Reference               |
|--------------|------|------|---------|------------------------|-------|-------------------------|
| AW CrB       | 0.101| 0.75 | 0.3609  | $+3.58 \times 10^{-7}$ | 6100  | Broens (2013)           |
| DN Boo       | 0.103| 0.64 | 0.4476  |                        | 6100  | Šenavči et al. (2008)   |
| ASASJ082243+1927 | 0.106| 0.72 | 0.28    |                        | 6000  | Kandulapati et al. (2015) |
| V1911 Cyg   | 0.107| 0.68 | 0.31337 | $+4.5 \times 10^{-7}$  | 6500  | Rucinski et al. (2008); Zhu et al. (2011) |
| CK Boo       | 0.11 | 0.72 | 0.355134| $+9.79 \times 10^{-8}$ | 6400  | Yang et al. (2012)      |
| FG Hya       | 0.112| 0.85 | 0.3278  | $-1.96 \times 10^{-7}$ | 6000  | Lu & Rucinski (1999); Qian & Yang (2005) |
| GR Vir       | 0.12+| 0.78 | 0.346978| $-4.32 \times 10^{-7}$ | 6200  | Rucinski & Lu (1999); Qian & Yang (2004) |
| DZ Psc       | 0.13 | 0.897| 0.3661278| $+7.43 \times 10^{-7}$ | 6200  | Yang et al. (2013)      |
| V776 Cas     | 0.138| 0.77 | 0.4404  |                        | 6700  | Rucinski et al. (2001); Zola et al. (2004) |
| V345 Gem     | 0.142| 0.73 | 0.274736| $+5.88 \times 10^{-8}$ | 6200  | Yang et al. (2009)      |
| V710 Mon     | 0.143| 0.60 | 0.4052  | $+1.95 \times 10^{-7}$ | 6000  | Yang et al. (2009)      |
| V410 Aur     | 0.143–0.183| 0.52 | 0.36634699| $+8.22 \times 10^{-7}$ | 5900  | Yang et al. (2005)      |
| HV Aq        | 0.145| 0.56 | 0.3734  | $-8.84 \times 10^{-8}$ | 6500  | Li & Qian (2013)        |
| XY LMi       | 0.148| 0.74 | 0.43688773| $-1.67 \times 10^{-7}$ | 6100  | Qian et al. (2011)      |
| EM Psc       | 0.149| 0.95 | 0.34395922| $+3.97 \times 10^{-6}$ | 5100  | Qian et al. (2008)      |
| ASAS J1130313010.9| 0.15 | 0.50 | 0.270969|                        | 6000  | Pribulla et al. (2009)  |
| TYC 3836-0854-1| 0.15 | 0.76 | 0.3961  |                        | 6000  | Acerbi et al. (2014)    |
| V728 Her     | 0.16 | 0.81 | 0.44625 | $+1.92 \times 10^{-7}$ | 6600  | Erkan & Ulaş (2016)     |
| AH Aur       | 0.165| 0.75 | 0.4941  |                        | 6300  | Gazeas et al. (2005)    |
| TV Mus       | 0.166| 0.74 | 0.4456794|                        | 5900  | Qian et al. (2005)      |
| AH Cnc       | 0.168| 0.58 | 0.3604412| $+3.99 \times 10^{-7}$ | 6300  | Qian et al. (2006)      |
| IK Per       | 0.17 | 0.60 | 0.67603467| $-2.5 \times 10^{-7}$ | 8600  | Zhu et al. (2005)       |
| TYC 1337-1137-1| 0.172| 0.76 | 0.475511|                        | 7800  | Liao et al. (2017)      |
| CU Tau       | 0.177| 0.50 | 0.41341521| $-1.81 \times 10^{-6}$ | 5900  | Qian et al. (2005)      |
| V728 Her     | 0.179| 0.71 | 0.4713  | $-1.81 \times 10^{-6}$ | 6700  | Nelson et al. (1995)    |
| Y Sex        | 0.180| 0.64 | 0.4198  |                        | 6100  | McLean & Hilditch (1983); Yang & Liu (2003) |
| MW Pav       | 0.182| 0.51 | 0.7950  |                        | 6700  | Lapasset (1980); Rucinski & Duerbeck (2006) |
| XY Boo       | 0.185| 0.56 | 0.3705524| $+6.25 \times 10^{-7}$ | 6300  | Yang et al. (2005)      |
| V2388 Oph    | 0.186| 0.77 | 0.8023  |                        | 6900  | Rucinski et al. (2002); Yakut et al. (2004) |
| TYC 3836-0854-1| 0.19 | 0.79 | 0.415547|                        | 7800  | Acerbi et al. (2014); Liao et al. (2017) |
| HV UMa       | 0.19 | 0.62 | 0.7108  |                        | 7200  | Csák et al. (2000)      |

Notes: The symbol * means only photometric mass ratio (for total eclipses) and the symbol + means only spectral mass ratio.

Besides the cases of extremely low mass ratio (Table 3), we found studies of around 30 W UMa binaries with small mass ratios ($q < 0.19$). We summarize their characteristics ($q, f, P, T$) in Table 5. Most of the targets might also be found in the list of Yang & Qian (2015) but our sample does not contain systems with photometric mass ratio of partially eclipsed targets due to their poorly determined mass ratio.

Table 5 also presents information about the period variability of the binaries with $q < 0.19$. It turns out that almost all of them exhibit secular period increase/decrease and some undergo quasiperiodic variation, superimposed on a secular period change.

The trends (1–4) established for binaries with the smallest mass ratios (Table 3) are approximately valid for targets with mass ratio in the range 0.1–0.19 (Table 5), but there are several exceptions with longer periods ($P > 0.45$ d) and lower temperatures ($T < 6000$ K). Moreover, for the second sample there is a rather strong trend for the target temperature to increase with the mass ratio increase (Table 5).

Yang and Qian (2015) found empirical relation $f = 1.176 - 5.276 \times q + 11.64 \times q^2$ for their sample of low
mass-ratio deep-contact binaries. According to this relation, NSVS 2569022 should have \( f = 0.84 \).

The data from Table 3 and Table 5 reveal that the stars with mass ratio within the range 0.10–0.19 have deep-contact configurations (fill-out 0.5–0.9) while the binaries with extremely small mass ratio within the narrow range 0.06–0.08 have fill-out factors in the wide range 0.01–0.84 (Fig. 4). NSVS 2569022 is a record holder with a slightly overcontact configuration.

6 CONCLUSIONS

The main results from modeling of our photometric observations for the W UMa binary NSVS 2569022 are: (i) the target undergoes a wide total eclipse and its mass ratio is determined with great confidence; (ii) the stellar components are of G spectral types; (iii) NSVS 2569022 has a slightly overcontact configuration (with fill-out factor \( f = 0.014 \)); (iv) it is of W subtype; and (v) the mass ratio of only 0.077 ranks NSVS 2569022 in sixth place among binaries with the smallest mass ratio. It implies that the target probably will experience instability and possible merger.

NSVS 2569022 is a peculiar binary with an extremely small mass ratio but a slightly overcontact configuration.

Acknowledgements This research was supported partly by project DN 08/20 of the Scientific Foundation of the Bulgarian Ministry of Education and Science as well as by project RD-08-142 of Shumen University. The research was conducted with support of the private IRIDA Observatory (www.irida-observatory.org).

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 has also made use of the SIMBAD database, operated at CDS, Strasbourg, France, and the NASA Astrophysics Data System Abstract Service. The authors are very grateful to the anonymous referee for the valuable notes and recommendations.

References

Acerbi, F., Barani, C., & Martignoni, M. 2014, New Astron., 31, 1
Ammons, S. M., Robinson, S. E., Strader, J., et al. 2006, ApJ, 638, 1004
Arbutina, B. 2007, MNRAS, 377, 1635
Arbutina, B. 2012, Publications de l’Observatoire Astronomique de Beograd, 91, 391
Berry, R., & Burnell, J. 2005, The Handbook of Astronomical Image Processing (Richmond: Willmann-Bell), 684, 1
Bilir, S., Karataş, Y., Demircan, O., & Eker, Z. 2005, MNRAS, 357, 497
Binnendijk, L. 1970, Vistas in Astronomy, 12, 217
Broens, E. 2013, MNRAS, 430, 3070
Butters, O. W., West, R. G., Anderson, D. R., et al. 2010, A&A, 520, L10
Şenavcı, H. V., Nelson, R. H., Özavcı, I., Selam, S. O., & Albayrak, B. 2008, New Astron., 13, 468
Covey, K. R., Ivezić, Ž., Schlegel, D., et al. 2007, AJ, 134, 2398
Cox, A. N. 2000, Introduction, ed. A. N. Cox, Allen’s Astrophysical Quantities, ed. A. N. Cox (New York: AIP Press)
Csik, B., Kiss, L. L., Vinkó, J., & Alfaro, E. J. 2000, A&A, 356, 603
Cutri, R. M., Skrutskie, M. F., van Dyk, S., et al. 2003, VizieR Online Data Catalog, 2246
Dall, T. H., & Schmidtobreick, L. 2005, A&A, 429, 625
Droege, T. F., Richmond, M. W., Sallman, M. P., & Creager, R. P. 2006, PASP, 118, 1666
Eggleton, P. P., & Kiseleva-Eggleton, L. 2001, ApJ, 562, 1012
Erkan, N., & Ulaş, B. 2016, New Astron., 46, 73
Field, T. 2011, in Bulletin of the American Astronomical Society, 43, American Astronomical Society Meeting Abstracts #217, 431.04
Frasca, A. 2000, in SARG at TNG: Perspectives for the Year 2000, eds. R. G. Gratton & R. U. Claudi, 83
