Optical–Mid-infrared Period–Luminosity Relations for W UMa-type Contact Binaries Based on Gaia DR 1: 8% Distance Accuracy

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Abstract

W Ursae Majoris (W UMa)-type contact binary systems (CBs) are useful statistical distance indicators because of their large numbers. Here, we establish (orbital) period–luminosity relations (PLRs) in 12 optical to mid-infrared bands (GBVRIJHKs,W1,W2,W3,W4) based on 183 nearby W UMa-type CBs with accurate Tycho–Gaia parallaxes. The 1σ dispersion of the PLRs decreases from optical to near- and mid-infrared wavelengths. The minimum scatter, 0.16 mag, implies that W UMa-type CBs can be used to recover distances to 7% precision. Applying our newly determined PLRs to 19 open clusters containing W UMa-type CBs demonstrates that the PLR and open cluster CB distance scales are mutually consistent to within 1%. Adopting our PLRs as secondary distance indicators, we compiled a catalog of 55,603 CB candidates, of which 80% have distance estimates based on a combination of optical, near-infrared, and mid-infrared photometry. Using Fourier decomposition, 27,318 high-probability W UMa-type CBs were selected. The resulting 8% distance accuracy implies that our sample encompasses the largest number of objects with accurate distances within a local volume with a radius of 3 kpc available to date. The distribution of W UMa-type CBs in the Galaxy suggests that in different environments, the CB luminosity function may be different: larger numbers of brighter (longer-period) W UMa-type CBs are found in younger environments.

Key words: binaries: eclipsing – distance scale – stars: distances

Supporting material: machine-readable tables

1. Introduction

W Ursae Majoris (W UMa)-type contact binary systems (CBs) represent a class of short-period eclipsing binary systems. Unlike detached and semi-detached eclipsing binaries, the two components of W UMa-type CBs fill their Roche lobes. W UMa-type CBs are fainter and have shorter periods than early-type CBs. The radii of both components are correlated with their orbital periods. Based on Roche lobe theory (Eggleton 1983), the mean density is related to the orbital period, which can, in turn, be used to derive the period–luminosity–color relation (PLCR). Rucinski (1994) established the first accurate observational PLCR, eventually reaching a precision of 12% (Rucinski & Duerbeck 1997). Using near-infrared data, which are less sensitive to temperature, extinction, and metallicity variations than optical observations, Chen et al. (2016a) established the first accurate CB (orbital) period–luminosity relations (PLRs) based on 66 CBs. These PLRs have 10% (1σ) accuracy, which renders W UMa-type CBs a potential reliable statistical distance tracer. Characterized by properties similar to W UMa-type CBs, early-type CBs (Chen et al. 2016a) and red giant CBs (Muraveva et al. 2014) also obey PLRs, although the associated scatter is larger. Taking advantage of Tycho–Gaia astrometric solution (TGAS) parallaxes, studies based on W UMa-type CBs can potentially benefit significantly because of the large number of such objects in the solar neighborhood. Applying these parallaxes, Mateo & Rucinski (2017) found a (log P, Mv) PLR slope of −9.0 ± 0.4, which is in good agreement with the slope of −9.15 ± 0.12 from Chen et al. (2016a). However, some open questions still remain, such as the limiting distance precision and any applicable zero-point constraints.

W UMa-type CBs are one of the most numerous variables in the Galaxy since they cover the evolutionary phases of binaries with long orbital timescales. The General Catalog of Variable Stars (GCVS; Samus et al. 2017) lists 1131 CBs, while the All Sky Automated Survey (ASAS) Catalog of Variable Stars (Pojmanski et al. 2005) includes 5374 CB candidates. The largest CB sample available to date is based on the Catalina Survey and Catalina Survey Southern catalogs, which contain 30,710 and 18,803 CB candidates, respectively. In addition, hundreds of individual W UMa-type CBs are detected every year, so that a catalog of high-probability CBs with distance information can readily be constructed. The associated distance scale will benefit not only from constraining the absolute physical parameters of CBs, but also from the reduced uncertainties associated with the anticipated Gaia Data Release (DR) 2 parallaxes.

In this paper, we aim to establish PLRs for W UMa-type CB samples covering wavelengths from the optical to the near- and mid-infrared. We will evaluate the optimal accuracy of W UMa-type CBs as distance tracers. A complete catalog of CB candidates is compiled, and strict criteria to distinguish CBs from other types of variables are presented. The spatial distribution of CBs in our Galaxy is also discussed. In Section 2, we present the adopted data sets and our catalog. The steps taken to establish the twelve-band PLRs are discussed in Section 3. The distances to open clusters based...
2. Data

2.1. W UMa-type Contact Binaries with TGAS Parallaxes

For our CB sample, distance information is based on their TGAS parallaxes. TGAS contains two million stars with parallaxes (Gaia Collaboration et al. 2016a, 2016b), which includes all nearby CBs. The average random parallax uncertainty for the entire sample is 0.3 mas; even for the nearest CBs, the random uncertainty is still greater than 0.2 mas. In addition, the TGAS parallaxes are known to be affected by a systematic error of 0.3 mas, which cannot be reduced when dealing with small regions on the sky (see also Gaia Collaboration et al. 2016b, their Section 3). Since CBs are distributed randomly across the full sky, this systematic error is equivalent to the random uncertainty for the whole sample. The uncertainties pertaining to the CB PLRs are mainly owing to the propagation of the uncertainties associated with the parallax distances. To achieve high-accuracy PLRs, CBs with larger parallax uncertainties should consequently be eliminated. To ensure both sufficient numbers and small parallax uncertainties in our final CB sample, we selected objects within 330 pc ($\pi > 3$ mas) with parallax uncertainties of better than 7% (0.16 mag), resulting in a total sample size of 204. If we adopt a maximum systematic parallax error of 0.3 mas, the average total uncertainty in the distance modulus is 0.16 ± 0.05 mag for this sample.

The photometric data we have access to consist of $(B - V)$ colors from the Tycho catalog, maximum V-band magnitudes ($V_{\text{max}}$) from the ASAS catalog, $G_{\text{mean}}$ magnitudes from Gaia DR 1, $RI$ magnitudes from the U.S. Naval Observatory (USNO)-B catalog (Monet et al. 2003), near-infrared $JHK_s$ data from the Two Micron All-Sky Survey (2MASS) catalog (Cutri et al. 2003), and W1, W2, W3, and W4 magnitudes from the Wide-Field Infrared Survey Explorer (WISE) catalog (Wright et al. 2010). The ASAS catalog covers mostly the sky, with V-band CB light curves in the range $8 < V < 14$ mag. For each object, more than 100 detections are recorded, so it is easy to determine both maximum and average magnitudes. Gaia DR 1 includes 10 billion objects with $G$-band mean magnitudes based on more than 100 detections each. The $G$ band is centered at 673 nm, and the filter has a width of 440 nm (Jordi et al. 2010). 2MASS provides single-epoch $JHK_s$ photometry but it includes the observations’ Julian dates, which can be converted to maximum magnitudes using template light curves. The details pertaining to our conversion from single epochs or mean magnitudes to the corresponding maximum magnitudes are discussed in Section 3.1. WISE is a full-sky survey undertaken in four mid-infrared bands: W1 (3.35 $\mu$m), W2 (4.60 $\mu$m), W3 (11.56 $\mu$m), and W4 (22.09 $\mu$m). WISE has 20–100 detections for each object, which means that the WISE catalog is a powerful tool to find and study variable stars. The limiting magnitudes in the four bands are 16.5, 15.5, 11.2, and 7.9 mag, respectively; except for the W4 band, all 194 W UMa-type CBs have sufficient signal-to-noise ratios for our analysis.

2.2. The Catalog of Contact Binaries

The GCVS contains 1131 CBs collected from individual studies. Those CBs represent a genuine CB sample because most of these CBs are well observed and carefully studied. The ASAS catalog lists 5374 CBs. This sample only includes a small number of incorrectly identified CBs, since the authors separated CBs from semi-detached binaries. In addition, they only collected about 100 CBs with amplitudes of less than 0.15 mag (Rucinski 2006) to avoid sample contamination. In recent years, the Catalina (Drake et al. 2014) and Catalina Southern (Drake et al. 2017) catalogs have yielded about 50,000 CB candidates covering the declination range $-70^\circ < \delta < 65^\circ$ but avoiding the Galactic plane. These latter catalogs reach down to at least $V = 19$ mag. Unlike the ASAS catalog, the Catalina catalogs do not distinguish between CBs and semi-detached binaries, and they also contain a number of low-amplitude CBs. Therefore, these CB candidates need further study.

The total number of CB candidates in our sample is 56,603, and the photometric data adopted cover the Gaia $G$ band, the near-infrared $JHK_s$ bands, and the mid-infrared W1 filters, since they are homogeneous and deep enough.

3. Twelve-band PLRs for W UMa-type Contact Binaries

Chen et al. (2016a) first determined the near-infrared $JHK_s$ CB PLRs based on 66 CBs with open cluster distances and Hipparcos parallaxes. In this paper, we aim to make the PLRs of W UMa-type CBs more complete, accurate, and convenient for follow-up use. First, photometric observations in the $G$ band and mid-infrared bands are introduced, since numerous detections are available in these filters. Johnson $BVRI$ magnitudes are added because they are widely used. Second, Chen et al. (2016a) only used maximum absolute magnitudes to establish their PLRs. In contrast, here we intend to establish PLRs based on both maximum and mean magnitudes. Although in theory only the maximum magnitude is related to the orbital period, a relation between the mean magnitude and the orbital period is obvious, because the dispersion between the maximum and mean magnitudes is only $\sigma = 0.05$ mag (see Section 3.1). However, the mean-magnitude PLR is more suitable for use with large-sample surveys with sparse period coverage, since mean magnitudes are easier and better determined than maximum magnitudes. Third, only W UMa-type CBs are considered, since the number of early-type CBs in our sample (16) is too small for further analysis.

3.1. Light-curve Analysis

To establish multiband PLRs, the most important problem we must overcome is the conversion from magnitude in a single epoch to the corresponding maximum magnitude. To address this problem, we first need to know how the light-curve shape changes with wavelength. Luminosity variations of CBs are caused by geometric eclipses of the two binary components. During an eclipse, the temperature change is very small, since the temperatures of both components are similar. Therefore, almost no light-curve shape variation occurs between different bands. This is contrary to the situation for pulsating stars, whose amplitude decreases with increasing wavelength. To make sure that this situation indeed applies to our CBs, we compared the W1 and V-band light curves for the 204 calibration CBs and found that they are in good agreement.
Since the light-curve shape does not change with wavelength, we can use the V-band light curve as our template light curve, and 2MASS magnitudes obtained at a given epoch can hence be converted to maximum magnitudes.

The second issue of importance is the conversion between the mean and maximum magnitudes. Statistically speaking, the difference between both magnitudes is proportional to the light-curve amplitude: \( \Delta = (0.361 \pm 0.001) \text{amp} + (0.016 \pm 0.000), \sigma = 0.017 \text{mag} \) for the 27,000 genuine CBs in the Catalina catalog. Based on this equation, \( \text{Gaia} \ G_{\text{mean}} \) magnitudes can be converted to \( G_{\text{max}} \) magnitudes. If the amplitude is not taken into account, the difference between the mean and maximum magnitudes is \( \Delta_1 = 0.14 \pm 0.05 \text{mag} \); the 0.05 mag dispersion will propagate to the scatter in the mean-magnitude PLR. For the USNO-B1, single-epoch RI magnitudes are used to derive the PLRs, because the observation times are not recorded. This will introduce a statistical error of \( \Delta_1/2 = 0.07 \text{mag} \) and a possible systematic bias of \( \Delta_1/\sqrt{183} = 0.01 \text{mag} \) if we assume that the 183 W UMa-type CBs with accurate TGAS parallaxes (see below) are equally distributed in phase. Since this bias is negligible and the statistical uncertainty is small, these RI PLRs are acceptable for inclusion in our analysis.

### 3.2. Period–Luminosity Relations

We selected 183 of the 204 CBs to determine the PLRs (see Table 1), excluding early-type CBs with long periods, log \( P > -0.25 \) [days], since they are rare, and short-period CBs, log \( P < -0.575 \) [days], since the latter are fainter than the other stars (Chen et al. 2016a; Mateo & Rucinski 2017). The period range covered by our CB sample spans approximately 0.3 days, which is similar to the range of RR Lyrae (Gaia Collaboration et al. 2017). The maximum-magnitude PLRs are shown in Figure 1. The absolute magnitudes were estimated based on the equation \( M_\lambda = m_\lambda - 5 \log(1000/\pi) + 5 - A_\lambda \), where \( \pi \) is the parallax in units of mas.

Extinction values were estimated for each CB individually, i.e., \( A_V = \rho_0 \int_0^1 \exp(-r) \sin(b)/H \, dr \) (c.f. Nataf et al. 2013; Mateo & Rucinski 2017), where \( b \) represents the object’s Galactic latitude and \( d \) is the distance derived from the corresponding TGAS parallax. \( H = 164 \) pc is the dust scale height (Nataf et al. 2013). This small scale height indicates that the dust is predominantly concentrated in the Galactic plane. The extinction is estimated based on the length of sightline through the dust distribution, and hence it reflects global extinction variations with distance \( d \) and Galactic latitude \( b \).

The mean density of the dust in the Galactic plane, \( \rho_0 = 0.54 \text{mag pc}^{-1} \), was estimated based on 2000 nearby open clusters (OCs) (Chen et al. 2016a), which span a similar (nearby) distance range to the CBs. Statistically speaking, the average extinction for our 183 CBs is \( A_V = 0.075 \pm 0.025 \text{mag} \). This is a reliable extinction value for an average distance of 183 pc. The extinction values in the other bands were estimated based on the relative extinction values \( A_\lambda/A_V \) from Rieke & Lebofsky (1985) and Jordi et al. (2010). The extinction model can be used to estimate the extinction values with 20% accuracy. Therefore, after the correction, the remaining systematic bias introduced by extinction variations is around 0.015 mag in the \( V \) band and 0.0015 mag in \( W_1 \). This is significantly smaller than the uncertainties in the PLRs.

The red lines in Figure 1 are the linear fits to the twelve-band \( M_\lambda \) versus log \( P \) trends. Their slopes and the intercepts obtained from application of the least-squares method are listed in Table 2 for both the maximum- and mean-magnitude PLRs. The numbers used to determine the PLRs are also included. Those objects that exceed the detection limit are excluded, but only for \( W_4 \). A comparison of the maximum- and mean-magnitude PLRs shows that the scatter in the mean-magnitude PLRs is somewhat larger, which is in accordance with the analysis in the previous section. We also adopted the bootstrap-sampling technique to explore possible variations in the coefficients and the PLR uncertainties. The best-fitting coefficients and \( 1\sigma \) uncertainties resulting from the application of the least-squares method were identical to those based on the least-squares method, except for the \( W_4 \) band. In the latter case, the PLRs resulting from the bootstrap-sampling technique are \( M_{W_4(\text{max})} = (-5.28 \pm 0.32) \log P + (-0.10 \pm 0.14), \sigma = 0.21 \text{mag} \), and \( M_{W_4(\text{mean})} = (-5.55 \pm 0.33) \log P + (-0.05 \pm 0.14), \sigma = 0.21 \text{mag} \). The differences with respect to the values returned by the least-squares method (Table 2) are negligible. Although maximum-magnitude PLRs are more accurate than mean-magnitude relations, mean-magnitude PLRs are more practical when dealing with large surveys or faint objects. For such data sets, light curves are usually sparsely covered and affected by large photometric uncertainties. Few or no good light curves are usually available to determine the maximum magnitudes.

By studying the PLRs in different bands, an obvious trend is found in the slopes and the scatter properties. The slopes increase with increasing wavelength, while the scatter decreases. We compare this behavior with that of the PLRs of classical Cepheids (Fouqué et al. 2007; Chen et al. 2017; Wang et al. 2018) in Figure 2. In the top panel, the slopes of the Cepheid PLRs decrease with wavelength, which is contrary to

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**Table 1**

| R.A. (J2000) (°) | Decl. (J2000) (°) | Period (day) | DM\text{Gaia} (mag) | err\text{Gaia} (mag) | Amp. (mag) | \( A_V \) (mag) | \( M_{\text{max}} \) (mag) | \( M_{\text{mean}} \) (mag) | \( B - V \) (mag) | \( M_{\text{max}} \) (mag) | \( M_{\text{mean}} \) (mag) | \( M_{\text{max}} \) (mag) | \( M_{\text{mean}} \) (mag) |
|-----------------|-----------------|-------------|--------------------|---------------------|-----------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 27.80248        | 43.81867        | 0.38303     | 6.686              | 0.118               | 0.53      | 0.10          | 4.362          | 4.043          | 0.823          | 3.728          | 3.408          | 2.959          |
| 31.83356        | 35.64064        | 0.38970     | 6.763              | 0.147               | 0.45      | 0.09          | 4.087          | 3.905          | 1.134          | 3.432          | 3.002          | 2.686          |
| 42.17014        | 13.74623        | 0.28234     | 5.493              | 0.065               | 0.27      | 0.05          | 4.787          | 4.917          | 0.917          | 4.707          | 4.357          | 3.954          |

**Note.**

\( DM_{\text{Gaia}} \) and err\text{Gaia} denote the distance modulus and its uncertainty derived from TGAS parallaxes; Amp. is the amplitude of the V-band light curve and \( A_V \) is the V-band extinction. \( M_{\text{max}} \) are the maximum absolute magnitudes in each band, while \( M_{\text{mean}} \) are the mean absolute magnitudes.

(This table is available in its entirety in machine-readable form.)
what we saw for the W UMa-type CBs. The reason for this is that Cepheids become redder when they increase in brightness, while W UMa-type CBs become bluer. In addition, Cepheids cover a larger magnitude range at long wavelengths, while W UMa-type CBs span a larger magnitude range at short wavelengths. We also found that the two trends become flat for wavelengths exceeding 2 μm (Ks band), which means that mid-infrared colors are insensitive to temperature. This is also found in the bottom panel: the 1σ scatter first decreases with increasing wavelength, but it becomes flat in the mid-infrared.

With regard to this scatter, temperature is one contributor, but the other contributors (such as extinction and metallicity variations) also decrease with increasing wavelength. The photometric and distance errors therefore do not depend on wavelength. This scatter represents the precision of variables as distance indicators if the external errors are well constrained. For Cepheids, the typical uncertainty is 0.10 mag (5%), while for W UMa-type CBs it is 0.16 mag (7%). Compared with Cepheids, W UMa-type CBs are not as well studied, so the reduction of this scatter is expected based on future studies.

Focusing on the scatter in the W UMa-type CB PLRs, in the optical the uncertainty is around 0.3 mag. To deal with this obvious dependence on temperature in the scatter, a second band is needed to establish PLCRs. A combination of the G and W1 bands yields the smallest uncertainty, $M_G(\text{max}) = -5.19 \log P + 1.17(G - W1)_0 - 0.19$, $\sigma = 0.16$ mag (7%) and $M_G(\text{mean}) = -5.02 \log P + 1.28(G - W1)_0 - 0.11$, $\sigma = 0.16$ mag (7%). For the V band, $M_V(\text{max}) = -5.27 \log P + 1.12(V - W1)_0 - 0.18$, $\sigma = 0.16$ mag (7%) and $M_V(\text{mean}) = -5.20 \log P + 1.19(G - W1)_0 - 0.09$, $\sigma = 0.16$ mag (7%). This also suggests that a 7% distance accuracy can be achieved by using this combination of G (V) and W1 magnitudes. Note that the parallax uncertainty is around 0.16 mag (see Section 2.1), so the best accuracy attainable is limited by that in the parallax distance. We are confident that the accuracy will benefit significantly from Gaia's five-year parallaxes, once made available.

### 3.3. The PLR Zero Point

Except for the uncertainty, the zero point is the other parameter that can be used to evaluate the potential usefulness of a PLR. To detect differences in the zero point, different PLRs based on independently determined distances are needed. We compare the JHKs PLRs with those of Chen et al. (2016a), which are based on open cluster distances and Hipparcos parallaxes. In Figure 1, the cyan data points represent the 55 CBs from Chen et al. (2016a), while the red dashed lines are their best fits. No obvious zero-point differences are found. Statistically, the zero-point differences between this paper and Chen et al. (2016a) are $\Delta J = -0.04 \pm 0.23$ mag, $\Delta H = 0.00 \pm 0.20$ mag, and $\Delta K_s = 0.00 \pm 0.21$ mag.
parameters of the Galactic Mid-infrared PLRs

| Filter (λ) | N  | $a_λ$ | $b_λ$ | σ   |
|------------|----|--------|--------|-----|
| W1         | 183| $-5.67 \pm 0.17$ | $-0.15 \pm 0.08$ | 0.16 |
| W2         | 183| $-5.73 \pm 0.18$ | $-0.15 \pm 0.08$ | 0.16 |
| W3         | 182| $-5.45 \pm 0.17$ | $-0.08 \pm 0.08$ | 0.16 |
| W4         | 67 | $-5.29 \pm 0.35$ | $-0.10 \pm 0.15$ | 0.21 |
| G          | 183| $-8.53 \pm 0.33$ | $0.05 \pm 0.15$  | 0.31 |
| B          | 183| $-10.63 \pm 0.52$ | $0.07 \pm 0.23$  | 0.48 |
| V          | 183| $-8.93 \pm 0.38$ | $0.05 \pm 0.17$  | 0.35 |
| R          | 183| $-7.98 \pm 0.33$ | $0.06 \pm 0.15$  | 0.31 |
| I          | 183| $-7.45 \pm 0.31$ | $0.00 \pm 0.14$  | 0.28 |
| J          | 183| $-6.76 \pm 0.22$ | $-0.16 \pm 0.10$ | 0.21 |
| H          | 183| $-5.89 \pm 0.20$ | $-0.07 \pm 0.09$ | 0.18 |
| Ks         | 183| $-5.79 \pm 0.19$ | $-0.11 \pm 0.08$ | 0.17 |

Table 2

The derived distance moduli are denoted as $DM_G$, $DM_{W1}$, and $DM_{W2}$ in Table 3. The error pertaining to the distance modulus is the larger of the statistical errors for the different CBs in a given cluster and the uncertainty propagating from the PLR, $σ = σ_{PLR}/\sqrt{N}$. Compared with the distances determined using the open cluster method, the differences are $DM_G-DM_{i4} = -0.02 \pm 0.16$ mag and $DM_{W1}-DM_{i4} = 0.00 \pm 0.08$ mag. The maximum deviation of 1% in these distance scales shows that both calibrations are in good mutual agreement. In particular, the W1 distances are a little better than the $G$-band distances in Figure 3. The two clusters located at more than their 1σ uncertainties from the one-to-one relation suggest that, at optical wavelengths, PLR distances are sensitive to extinction and metallicity variations.

5. 27,000 W UMa-type Contact Binaries with an 8% Distance Accuracy

CBs are not only found in open clusters, but they are also the most numerous variable stars in the field. In this section, we collected a sample of 55,603 CB candidates from the GCVS, ASAS, and Catalina catalogs (see Section 2.2) and determined their distances based on PLRs. With known distances and light-curve solutions, the absolute masses and radii can be estimated. These parameters are important to constrain the evolution of CBs (Stepišić 2006; Yıldız & Doğan 2013). In addition, with access to tens of thousands of CBs with reliable distances, they can be used to constrain the zero points, in anticipation of Gaia DR 2.
5.1. Fourier Analysis to Select High-probability W UMa-type Contact Binaries

Before measuring the distances, contaminating objects must be eliminated. As discussed in Section 2.2, CBs in the ASAS catalog are distinguished from semi-detached eclipsing binaries, but they are still mixed with other types of variables. CBs in the Catalina catalog contain both semi-detached eclipsing binaries and other types of variables. Although CB samples in the ASAS and Catalina catalogs have already been selected by other authors (Pojmanski et al. 2005; Drake et al. 2014, 2017), we further refined the CB sample based on light-curve analysis. Note that our application of any selection criterion is aimed at reducing contamination rather than identifying genuine CBs, since the latter is impossible based on our current data. Nevertheless, this approach is sufficiently reliable for statistical purposes. A fourth-order Fourier series decomposition, \( f = a_0 + \sum_{i=1}^{4} a_i \cos(4\pi i t/P + \phi_i) \), was used to analyze the W-band light curves. Here, \( P \) is the orbital period for eclipsing binaries and twice the (pulsation) period for other types of variable stars. Compared with the Fourier analysis conducted by Rucinski (1993), phase information is introduced to distinguish eclipsing from pulsating variables. Note that \( a_1 \) and \( a_2 \) in this paper are equivalent to, respectively, the absolute values of \( a_2 \) and \( a_4 \) of Rucinski (1993). We used the parameters \( P, R_{21} = a_2/a_1 \), and \( \phi_{21} = \phi_2 - 2\phi_1 \) to select W UMa-type CBs:

\[
-0.60 < \log P [\text{day}] < -0.25, \quad (1)
\]

\[
a_2 < a_1(a_1 + 0.125), \quad (2)
\]

\[
R_{21} < 0.5 - 0.5|\phi_{21} - 2\pi|. \quad (3)
\]

The first criterion limits the period range, since PLRs would overestimate the absolute magnitudes of CBs with periods outside of this range. This period criterion will also reduce contamination by variables with long periods and symmetric light curves; see Figure 4(c). The second criterion results from the theoretical work of Rucinski (1993), which aimed to distinguish CBs from semi-detached and detached eclipsing binaries. Unlike CBs, detached binaries exhibit unequal minima in their light curves, which increase the ratio \( a_2/a_1 \). In Figure 4(a), the red line is the boundary separating CBs (with EW-type light curves) and detached binaries (EA-type light curves) based on the Catalina Southern catalog. Note that in that catalog, CBs and detached eclipsing binaries are mixed with semi-detached eclipsing binaries, because semi-detached eclipsing binaries are not explicitly selected.

The third criterion above is first introduced in this paper. It can be used to exclude short-period variables with asymmetric light curves, such as RRc and RRd Lyras, and to reduce contamination by \( \delta \) Scuti and rotating variable stars (see Figures 4(b) and (c)). To apply this criterion, the upper limit of \( R_{21} = 0.5 \) is converted from the second criterion using \( a_1 = 0.75/2 \text{mag} \); 0.75 mag is usually the maximum amplitude of CBs. The phase difference \( \phi_{21} \) is either 0 or \( 2\pi \) in ideal conditions (we used \( 2\pi \) throughout to render an uninterrupted spread of CBs in Figures 4(b) and (c)) because of the symmetric light curves (regular eclipses) associated with CBs. However, photometric uncertainties and possible surface activity, or the presence of a third object, would cause \( \phi_{21} \) to deviate from \( 2\pi \). The extent of this deviation increases with decreasing half main amplitude \( a_1 \) (\( R_{21} \)). We set the extent of the deviation (slope) such that it covers the triangular distribution of CBs in the three catalogs (see Figure 4(d)) and thus determined this criterion.

Following the application of our three criteria, the fractions of high-probability W UMa-type CBs in the ASAS, Catalina Southern, and Catalina catalogs are 56\%, 64\%, and 49\%, respectively. With regard to the first two catalogs, most W UMa-type CBs candidates are excluded based on their periods, while in the last catalog, some candidates are excluded based on their light-curve shapes. This distinction is reliable, since the Catalina catalog is deeper and contains a number of low-amplitude CB candidates, which are easily mixed with other types of variables.

### Table 3
Comparison of Distance Moduli

| ID         | DM_G (mag) | DM_B (mag) | DM_V (mag) | E(B–V) (mag) | DM_O (mag) | References |
|------------|------------|------------|------------|--------------|------------|-------------|
| NGC 188    | 11.35 ± 0.16 | 11.36 ± 0.10 | 11.46 ± 0.14 | 0.09        | 11.35      | 1           |
| NGC 2682   | 9.26 ± 0.18  | 9.47 ± 0.10  | 9.47 ± 0.10  | 0.01        | 9.57       | 2           |
| NGC 2158   | 12.88 ± 0.23 | ...         | ...         | 0.33        | 12.78      | 3           |
| NGC 1245   | 12.28 ± 0.23 | 12.56 ± 0.12 | 12.96 ± 0.27 | 0.17        | 12.94      | 4           |
| Berkeley 39| 12.58 ± 0.18 | 12.95 ± 0.14 | 12.96 ± 0.27 | 0.17        | 12.94      | 4           |
| NGC 6791   | 13.25 ± 0.18 | ...         | ...         | 0.16        | 13.09      | 5           |
| NGC 6819   | 11.91 ± 0.16 | 11.94 ± 0.19 | ...         | 0.14        | 11.88      | 5           |
| NGC 7789   | 11.42 ± 0.16 | 11.30 ± 0.28 | 11.39 ± 0.17 | 0.28        | 11.27      | 6           |
| NGC 2099   | ...         | 11.49 ± 0.17 | 11.57 ± 0.18 | 0.23        | 11.57      | 7           |
| NGC 6705   | 11.52 ± 0.23 | ...         | ...         | 0.42        | 11.37      | 8           |
| Collinder 261 | 12.26 ± 0.14 | ...         | ...         | 0.34        | 12.14      | 3           |
| Melotte 66 | 13.18 ± 0.32 | ...         | ...         | 0.16        | 13.20      | 9           |
| NGC 7142   | 11.93 ± 0.23 | 11.90 ± 0.17 | 11.95 ± 0.18 | 0.35        | 11.80      | 10          |
| NGC 6939   | 11.28 ± 0.18 | 11.23 ± 0.24 | 11.23 ± 0.26 | 0.31        | 11.27      | 3           |
| NGC 7044   | 12.38 ± 0.16 | 12.42 ± 0.12 | 12.53 ± 0.18 | 0.70        | 12.43      | 11          |
| NGC 2044   | 13.14 ± 0.32 | ...         | ...         | 0.08        | 13.07      | 12          |
| NGC 2184   | 9.00 ± 0.32  | 9.03 ± 0.17  | 9.02 ± 0.18  | 0.10        | 8.97       | 3           |
| Ruprecht 56| 7.85 ± 0.32  | 8.19 ± 0.17  | 8.20 ± 0.18  | 0.12        | 8.16       | 3           |
| Praesepe   | 6.25 ± 0.32  | 6.22 ± 0.17  | 6.22 ± 0.18  | 0.01        | 6.36       | 3           |

References. (1) Chen et al. (2016b), (2) Geller et al. (2015), (3) Kharchenko et al. (2016), (4) Bragaglia et al. (2012), (5) Wu et al. (2014), (6) Wu et al. (2007), (7) Hartman et al. (2008), (8) Santos et al. (2005), (9) Kassis et al. (1997), (10) Straizys et al. (2014), (11) Sagar & Griffiths (1998), (12) Jacobson et al. (2011).
Unlike CBs in clusters, for $W_G$ distances are more accurate than the corresponding optical panel shows the results for the  

ments, we recommend that only DM distance moduli and their uncertainties are listed in Table 4. The average uncertainty $\sigma$ corresponding value is around 0.05 mag. Considering all these  

weight distance becomes $DM$ $\sigma$ $\sigma_{DM}$ the average distance becomes $DM = \sum(DM_i/\sigma_{DM}^2)/\sum(1/\sigma_{DM}^2)$, where the weight $\sigma_i$ is the error in the PLR in a given band $i$. The uncertainty $\sigma_{DM}$ is the larger of the DMs’ standard deviation and the external PLR uncertainty of 0.16 mag. The average distance moduli and their uncertainties are listed in Table 4. Given the unknown extinction affecting individual measurements, we recommend that only $DM_W$ and the average distance moduli DM based on the application of multiple bands be used (see the discussion of extinction below). Table 4 also contains information as to whether the CBs obey the criteria discussed in Section 5.1 (“Selection”) as well as their multiband photometric magnitudes. 

We remind the reader that the CBs in our global sample are located in the solar neighborhood (ASAS) and at high Galactic latitudes ($|b| > 20^\circ$; Catalina survey), where the interstellar extinction is very small, even in the $V$ band. To evaluate the extinction properties, the color excess $E(G−W1) = (G−W1) − (G − W1)_0$ was determined for all CBs individually by calculating the difference between their observed and intrinsic colors. For our final sample of 27,318 CBs, the average color excess is $E(G − W1) = 0.156 ± 0.274$ mag, which corresponds to $A_V = 0.19 ± 0.33$ mag for the extinction law adopted here. 

Our distances were determined in two ways, i.e., based on the $W1$ band alone and on a combination of the $GJHK$ bands. Both methods are insensitive to the actual extinction. The former method is affected by a relative extinction $A_{W1} = 0.05A_V$; while for the latter, $A_{GJHKW1} = 0.1A_V$. In fact, even if we had not corrected these 27,318 CBs for the effects of extinction, the impact on the determination of the final distance modulus is $E = 0.010 ± 0.016$ mag (0.4%) for the $W1$-based distances and $E = 0.019 ± 0.033$ mag (0.9%) for the multiband distances. These systematic and statistical uncertainties are both much lower than the distance uncertainty introduced by the scatter in the PLR (0.16 mag), which implies that the impact of extinction variations is negligible. Our extinction correction aims to exclude any global trends in the extinction properties and thus at reducing the statistical uncertainties. Although accurate extinction measurements for individual CBs are not available, the global distribution of our sample distances is expected to be improved compared with their corresponding distances obtained without corrections applied. 

The extinction equation introduced in Section 3.2, $A_V = \rho_0 \int_0^l \exp(-r|\sin(b)|/H)dr$, was adopted to estimate the individual extinction values for all CBs in our sample. The adopted distances were based on the $W1$ apparent distance moduli, which are mostly reddening-free on account of this filter’s long wavelength. To verify the applicability of this equation, we calculated the average corrected extinction value for our 27,318 CBs, i.e., $A_V = 0.194 ± 0.080$ mag. This value is in full accordance with the observed value $A_V = 0.19 ± 0.33$ mag, which means that we are indeed justified in correcting for the average extinction trend using this global equation. The $A_{W1}$ extinction values are included in Table 4; we
do not provide the individual $A_V$ values because of the larger intrinsic variations at this wavelengths.

Finally, 27,318 of the 55,603 CB candidates obey the selection criteria and have distance information based on multiband photometry. For these W UMa-type CBs, the average distance uncertainty is 0.168 mag, which corresponds to a precision of 8\%. To study the spatial distribution of these CBs in Galactic coordinates, the distances were decomposed into a distance component along the Galactic plane and a vertical component perpendicularly to the plane. The vertical component was then converted to Galactocentric distances by assuming $R_0 = 8.3 \pm 0.2$ (stat.) $\pm 0.4$ (syst.) kpc (de Grijs & Bono 2016). The numbers of CB candidates in each $0.1 \times 0.1$ kpc$^2$ box were counted and are shown in the top left-hand panel of Figure 5. We find that almost all CBs within 1 kpc have been detected, except for those objects located in a region close to the plane, which was not covered by the Catalina survey. CBs are powerful distance tracers out to 3 kpc.

An asymmetric distribution of CBs above and below the Galactic plane is found. However, this result is not conclusive, since their velocity information is not known. The average orbital periods were estimated if the number of CBs in a given selection box exceeded 10. From the period distribution in the top right-hand panel of Figure 5, it follows that the longer-period CBs are located closer to the Galactic plane. For W UMa-type CBs within $|z| < 0.5$ kpc, the periods are typically longer than 0.35 days. In the (vertically) outer regions, the periods are on average shorter than 0.35 days. This is in accordance with CBs in open clusters, where longer-period CBs are found in younger open clusters (Chen et al. 2016a).

The bottom panels of Figure 5 show the distributions of the periods and absolute magnitudes $M_2$ of all 27,318 W UMa-type CBs as well as the equivalent measurements based on the ASAS catalog only. The distribution of CBs in the ASAS catalog was discussed in detail by Rucinski (2006). Compared with the ASAS CBs, our full sample is characterized by typically shorter periods and fainter magnitudes. The main reason for this difference is that CBs in the Galactic thick and thin disks are distributed differently. In the young thin disk, long-period CBs encompass a larger fraction of the overall sample. A second reason is that the shallow limiting magnitude of ASAS ($V \sim 14$ mag) prevents the detection of shorter-period CBs.

6. Systematic Uncertainties and Improvements

6.1. PLR Systematics

In this section, we discuss the systematic uncertainties associated with the adoption of our set of PLRs for statistical analysis. Systematic effects include perturbations owing to tertiary companions, contamination, and metallicity corrections.

Many CBs have tertiary companions (Chambliss 1992; Hendry & Mochnacki 1998), which would render systems brighter. Only tertiary companions associated with nearby CBs can be found on the basis of light travel time effects in long-term O–C studies; these are subsequently resolved by spectral studies. We evaluate to extent to which tertiary companions

Figure 4. (a) $\phi_2$ vs. $\phi_1$ diagram. The black and pink data points are W UMa CBs (EW type) and detached eclipsing binaries (EA type), while the red line corresponds to $\phi_2 = a_1 (\phi_1 + 0.125)$. (b) and (c) $R_1$ vs. $\phi_{21}$ and $\phi_{21}$ vs. log $P$ (day) diagrams for different types of variable stars in the Catalina Southern catalog. Black: W UMa-type CBs; red: RRab; green: RRe; blue: RRd; pink: EA-type eclipsing binaries; blue pluses: rotating variable stars; cyan circles: long-period variables. (d) $R_1$ vs. $\phi_{21}$ diagram for W UMa-type CBs in the Catalina (blue), the Catalina Southern (black), and the ASAS (green) catalogs. The red lines are the same as those in panel (b).
affect the PLRs based on an analysis of nearby CBs. D'Angelo et al. (2006) performed a spectroscopic search for faint ($V < 10$ mag) tertiaries in CB systems. They found that approximately 25% of CBs have tertiaries with luminosities higher than 0.9% of those of the CB systems as a whole. The mean and median luminosity ratios of the tertiaries in this study are 11% and 2%, respectively. If these luminosity ratios are representative for a large sample of CBs, the influence of tertiaries on the resulting CB distances is less than 3%. If additional distance information that allows us to exclude outliers is available, the effects will decrease to 0.5%. A case in point: distances based on CBs in open clusters are statistically identical to those determined using the clusters’ intrinsic photometric properties (see Section 4).
Although CBs have characteristic light curves, they are nevertheless easily mixed with other variables, particularly when their amplitudes are low or for poor-quality light curves. In Figure 4(c), CBs are located close to Type c RR Lyrae (RRc) and rotating stars. Compared with RRab Lyrae, the light curves of RRc Lyrae are more symmetric and have lower amplitudes. To distinguish RRc Lyrae from CBs, Drake et al. (2014) adopted three criteria based on the objects’ periods, amplitudes, and color differences. They concluded that the fraction of RRc Lyrae that are misidentified as CBs is only on the order of 1%. RRc Lyrae are some 2 mag brighter than CBs for different periods. Therefore, contamination leads to larger CB distances on the order of 1% (0.02 mag).

Other possible contaminants are rotating BY Dra variables and RS CVn variables. The light variations of BY Dra variables are caused by strong surface activity and rotation. However, they have a typical rotational speed of 3–5 km s\(^{-1}\), which implies that the majority of these stars have periods longer than a day. Based on the GCVS sample, the contamination fraction is less than 1% in terms of the objects’ periods. Combined with the differences between BY Dra stars and CBs in the shapes of their light curves (i.e., \(\phi_{21}\) in Figure 4), the associated contamination of our CB sample is less than 0.2%. The absolute magnitudes of BY Dra stars (Strassmeier et al. 1993) are similar to or a little fainter than those of CBs, so the effect of BY Dra contamination on the CB distances is negligible. RS CVn variables are close binaries with strong surface activity. They are usually found in relatively longer-period detached and semi-detached binaries. The period overlap of GCVS-based RS CVn and CB samples is approximately 3%. By adding a light-curve selection criterion, this fraction decreases to 0.6%. Since RS CVn stars have similar luminosities to CBs, the effect of this type of contamination on CB distances is also negligible.

Finally, metallicity effects on the CB PLRs are not well studied because of the prevailing limited sample sizes. Based on Chen et al. (2016a), however, CBs will become brighter by about 0.2 mag in the near-infrared when the metallicity decreases by 1 dex in [Fe/H]. No systematic deviations are apparent when we determine the distances to CBs using the mean solar abundance, but a correction is needed for metal-poor or metal-rich environments.

6.2. Improvement of the PLRs

The accuracy of the CB PLRs is 7%, which is expected to be further improved based on more detailed studies. In this section, we discuss possible ways to improve the achievable distance accuracy.

The scatter in the CB PLR is composed of the scatter in the mass–luminosity relation of the primary star, the temperature–luminosity relation, the scatter in the mass ratio \(q\), the orbital inclination \(i\), and the fill-out factor \(f\). The detection of discontinuous or nonlinear components of this scatter is helpful to establish a more accurate PLR. The primary stars of CBs are similar to main-sequence stars; the latter obey a widely accepted mass–luminosity relation. The scatter in the temperature–luminosity relation decreases significantly from the optical to the infrared regime.

We focus on the contributions of the latter three to the scatter here. The mass ratio \(q\) determines the size and area of the
system’s Roche lobe. Based on the approximate radius of the Roche lobe (Eggleton 1983; Yakut & Eggleton 2005), the areas of the inner and outer Roche lobes increase significantly for \( q < 0.2 \). The actual area for CBs is a function \( S(q, f) \), which covers a region between the inner and outer Roche lobes. The fill-out factor \( f \) represents the degree by which the inner Roche lobe is exceeded; overcontact binaries have positive values. For the same mass ratio, CBs with larger fill-out factors are brighter. Since CBs are tidally distorted, their polar radii are usually smaller than the radii on the side and back, which lead to high luminosities for relatively low orbital inclinations.

We performed an observational test based on 41 of our 183 CBs using these three bits of information. We estimated the deviations of the PLRs, e.g., \( \Delta M_{W1} = M_{W1} - M_{W1(PLR)} \). The \( W1 \) and \( G \) bands were used to represent infrared and optical filters, respectively. A local linear kernel smoothing regression method was adopted to determine the nonlinear relation among \( \Delta M_{W1} \), \( \Delta M_{G} \), and \( q, i, f \). The data points were divided into five bins along the \( x \) axis; we ignored any bin containing fewer than two data points. In Figure 6, the blue and red dashed lines are the mean-magnitude deviation and the local best-fitting line, respectively. Comparing the two lines, local nonlinearities can be found. In the \( q \) panels (top), an obvious luminosity excess is found in both the optical and the infrared for \( q < 0.2 \). In the \( i \) panels (middle), a luminosity excess is found in the optical but it is not seen in the infrared for \( 60^\circ < i < 72^\circ \). In the \( f \) panels (bottom), gradually increasing trends with \( f \) are visible. In addition, the excesses found for the global mean magnitudes \( \Delta M_{W1} = -0.045 \) mag and \( \Delta M_{G} = -0.061 \) mag for our 41 overcontact binaries imply that overcontact binaries are systematically brighter than near-contact binaries. In conclusion, CBs with \( q < 0.2 \) indeed deviate from the bulk PLRs; CBs with \( 60^\circ < i < 72^\circ \) may also deviate from the PLRs, although not obviously so; the brightness of CBs increases as the fill-out factor increases. These results should be better constrained not only by employing accurate distances, but also by including more CBs with homogeneous light-curve solutions.

With regard to improvement based on improved external conditions, better and independent distances are expected to better constrain both the zero points of and the scatter in the PLRs. Compared with Cepheids and RR Lyrae, the PLRs of CBs are more difficult to constrain because of the small sample sizes currently available. \textit{Gaia} Data release 2 will provide better parallaxes (0.07 mas precision) for more CBs within 1 kpc of the Sun. Novel studies of CBs in open and globular

Figure 6. Magnitude deviations as a function of (top) mass ratio \( q \), (middle) orbital inclination \( i \), and (bottom) fill-out factor \( f \). Black dots denote our 41 CBs, while the blue lines represent the mean-magnitude deviation. The red dashed lines are the best-fitting line based on the application of a local linear kernel smoothing regression method.
clusters are also expected to pick up, since clusters provide not only independent distances, but also age and chemical abundance information.

7. Conclusions

In this paper, 183 nearby W UMa-type CBs with accurate TGAS parallaxes were used to determine the twelve-band $GBVRIJHK,W1,W2,W3,W4$ PLRs. Maximum-magnitude PLRs as well as mean-magnitude PLRs were presented. The 1σ PLR dispersions decrease from optical to mid-infrared wavelengths, with the lowest dispersion of 0.16 mag found in the $W1$ band. Combining the $G$ and $W1$ bands, the PLR exhibits a scatter 0.16 mag, which means that W UMa-type CBs can anchor distances to a 7% accuracy. Since W UMa-type CBs are one of the most numerous variable stars in the solar neighborhood, they could be important distance indicators, second only to classical Cepheids. No obvious zero-point differences are found for the near-infrared PLRs between this paper and Chen et al. (2016a). The PLR of early-type CBs will be better studied in the future based on larger samples with independent distance estimates. Since OB-type CBs are brighter than classical Cepheids, it is important to know the distances out to which early-type CBs can be traced.

Applying the PLRs to W UMa-type CBs in 19 OCs, the CBs’ PLR distances agree well with the corresponding distances based on the open cluster method. In particular, $W1$-band distances are better than their $G$-band counterparts, since the former are insensitive to extinction and metallicity variations. A catalog of 55,603 CBs candidates has been compiled. Fourier decomposition was used to distinguish W UMa-type CBs and other types of variable stars. To reduce the uncertainties, distances based on a combination of optical, near-, and mid-infrared distances were determined. Ultimately, 27,318 of the 55,603 CB candidates are high-probability W UMa-type CBs for which we can achieve an 8% distance accuracy. This is the largest sample with accurate distances in the local volume, within a radius of 3 kpc. It is useful to calibrate the zero points of other distance tracers and constrain the absolute parameters of W UMa-type CBs.

We study the spatial distribution of 27,318 W UMa-type CBs. Long-period W UMa-type CBs tend to be located preferentially close to the Galactic plane. This is in accordance with the properties of W UMa-type CBs in open clusters. Compared with W UMa-type CBs in the ASAS catalog, the full sample contains more short-period and faint W UMa-type CBs. This suggests that in different environments, the luminosity function of W UMa-type CBs may be different. Increased numbers of W UMa-type CBs in the Galactic plane are expected to facilitate better studies of the formation and evolution of W UMa-type CBs.

Possible systematic uncertainties introduced by tertiary companions, contamination, and metallicity differences are discussed in the context of applying the resulting PLRs to measure distances. The relations between the PLRs on the one hand and $q, i, f$ on the other are discussed. The availability of better and more independent distances is expected to further constrain both the zero points of and the scatter in the CB PLRs.

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References

Bragaglia, A., Gratton, R. G., Carretta, E., et al. 2012, A&A, 548, 122
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Chambliss, C. R. 1992, PASP, 104, 663
Chen, X. D., de Grijs, R., & Deng, L. C. 2016a, ApJ, 832, 138
Chen, X. D., de Grijs, R., & Deng, L. C. 2017, MNRAS, 464, 1119
Chen, X. D., Deng, L. C., de Grijs, R., et al. 2016b, AJ, 152, 129
Cutri, R. M., Skrutskie, M. F., van Dyk, S., et al. 2003, The 2MASS Catalogue of Point Sources, NASA/IPAC Infrared Science Archive. (Univ. Massachusetts IPAC/Caltech)
D’Angelo, C., van Kerkwijk, M. H., & Rucinski, S. M. 2006, AJ, 132, 650
de Grijs, R., & Bono, G. 2016, ApJS, 227, 5
Drake, A. J., Djorgovski, S. G., Catelan, M., et al. 2017, MNRAS, 469, 3688
Drake, A. J., Graham, M. J., Djorgovski, S. G., et al. 2014, ApJS, 213, 9
Eggleton, P. P. 1983, ApJ, 268, 668
Fouqué, P., Arriagada, P., Storm, J., et al. 2007, A&A, 476, 73
Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al., 2016a, A&A, 595, A2
Gaia Collaboration, Clementini, G., Eyer, L., et al. 2017, A&A, 605, A79
Gaia Collaboration, Prusti, T., de Bruijne, J. H. J., et al. 2016b, A&A, 595, A1
Geller, A. M., Latham, D. L., & Mathieu, R. D. 2015, AJ, 150, 97
Hartman, J. D., Gauld, B. S., Holman, M. J., et al. 2008, ApJ, 675, 1233
Hendry, P. D., & Mchonacki, S. W. 1998, ApJ, 504, 978
Jacobson, H. R., Friel, E. D., & Pilachowski, C. A. 2011, AJ, 141, 58
Jordi, C., Gebran, M., Carrasco, J. M., et al. 2010, A&A, 523, A48
Kaisis, M., Janes, K. A., Friel, E. D., & Phelps, R. L. 1997, AJ, 113, 1723
Kharchenko, N. V., Piskunov, A. E., Schilbach, E., Röser, S., & Scholz, R.-D. 2016, A&A, 585, 101
Mateo, N. M., & Rucinski, S. M. 2017, AJ, 154, 125
Monet, D. G., Levine, S. E., Canzian, B., et al. 2003, AJ, 125, 984
Muraveva, T., Clementini, G., Maceroni, C., et al. 2014, MNRAS, 433, 432
Nataf, D. M., Gould, A., Fouque, P., et al. 2013, ApJ, 769, 88
Pojmanski, G., Pilecki, B., & Szyczygiel, D. 2005, A&A, 55, 275
Rieke, G. H., & Lebofsky, M. J. 1985, ApJ, 288, 618
Rucinski, S. M. 1993, PASP, 105, 694
Rucinski, S. M. 1994, PASP, 106, 462
Rucinski, S. M. 2006, MNRAS, 368, 1319
Rucinski, S. M., & Duerbeck, H. W. 1997, PASP, 109, 1340
Sagar, R., & Griffiths, W. K. 1998, MNRAS, 299, 1
Samus, N. N., Kazarovets, E. V., Durlevich, O. V., Kireeva, N. N., & Pastukhova, E. N. 2017, ARep, 61, 80
Santos, J. F. C., Jr., Bonatto, C., & Bica, E. 2005, A&A, 442, 201
Stepien, K. 2006, AcA, 56, 199
Straižys, V., Maskoliūnas, M., Boyle, R. P., et al. 2014, MNRAS, 437, 1628
Strassmeier, K. G., Hall, D. S., Fekel, F. C., & Scheck, M. 1993, A&AS, 100, 137
Wang, S., Chen, X. D., de Grijs, R., & Deng, L. 2018, ApJ, 852, 78
Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, AJ, 140, 1868
Wu, T., Li, Y., & Hecker, S. 2014, ApJ, 786, 10
Wu, Z.-Y., Zhou, X., Ma, J., et al. 2007, AJ, 133, 2061
Yakut, K., & Eggleton, P. P. 2005, ApJ, 629, 1055
Yildiz, M., & Doğan, T. 2013, MNRAS, 430, 2029