A PHOTOMETRIC STUDY OF FOUR RECENTLY DISCOVERED CONTACT BINARIES: 1SWASP J064501.21+342154.9, 1SWASP J155822.10-025604.8, 1SWASP J212808.86+151622.0, AND UCAC4 436-062932

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ABSTRACT
We present new, high-quality multicolor observations of four recently discovered contact binaries, 1SWASP J064501.21+342154.9, 1SWASP J155822.10-025604.8, 1SWASP J212808.86+151622.0, and UCAC4 436-062932, and analyze their light curves to determine orbital and physical parameters using the modeling program of G. Djurašević. In the absence of spectroscopic observations, the effective temperatures of the brighter components are estimated from the color indices, and the mass ratios are determined with the q-search method. The analysis shows that all four systems are W UMa type binaries in shallow contact configurations, consisting of late-type main-sequence primaries and evolved secondaries with active surface regions (dark or bright spots) resulting from magnetic activity or ongoing transfer of thermal energy between the components. We compare the derived orbital and stellar parameters for these four variables with a large sample of previously analyzed W UMa stars and find that our results fit it well.

Key words: binaries: eclipsing – stars: fundamental parameters – stars: individual (1SWASP J064501.21+342154.9, 1SWASP J155822.10-025604.8, 1SWASP J212808.86+151622, UCAC4 436-062932)

Supporting material: machine-readable table

1. INTRODUCTION

Low-temperature, short-period contact binaries, also known as W UMa stars, are among the most extreme and least understood stages of binary evolution and interaction. A remarkable feature of these stars is that, even for small mass differences (large differences between masses), the temperatures of components are typically close to equal (with differences in the order of 100 K), which is understood in terms of efficient heat transfer through a common convective envelope (Lucy 1968a, 1968b). Components of a close binary system may come in contact when the more massive (and thus more quickly evolving) star fills its Roche lobe during its normal post-main-sequence expansion, and deposits a large amount of material on its companion, which then in turn fills its own Roche lobe, so that a common envelope is formed. This and alternative evolutionary paths from detached to contact binaries are discussed in detail by Yakut & Eggleton (2005) and Eggleton (2006).

Light curves of W UMa stars are distinguished by continuous changes in brightness resulting from ellipsoidal variations, minima of nearly equal depths, and maxima that are not always symmetric. This difference in maximum light levels, sometimes referred to as the O’Connell effect (O’Connell 1951), is caused by inhomogeneity in the surface brightness distribution on one or both stars and is commonly associated with dark spots of magnetic origin.

W UMa stars are traditionally divided into two groups: A-type and W-types (Binnendijk 1970). In A-type systems, the more massive component is eclipsed in the primary (deeper) minimum, and in W-type systems, the less massive. In addition to that, A-types have smaller mass ratios and spectral types ranging from A to G, while W-types have larger mass ratios and spectral types from F to K. There is a long-standing debate in the literature on whether these two groups represent an evolutionary sequence (see, e.g., Gazeas & Niarchos 2006), but Yildiz & Doğan (2013) recently showed that the initial parameters from which the two types evolved are completely different. Lucy & Wilson (1979) introduced the additional B-type, or contact binaries in poor thermal contact, for variables of observational characteristics similar to other W UMa stars, but where the temperatures of components differ by more than 1000 K.

W UMa binaries make especially attractive subjects for photometric studies. With orbital periods typically shorter than 0.7 days (Hilditch 2001), several nights of observations are needed to obtain a complete light curve. For systems exhibiting high inclination, the mass ratios (necessary for a reliable orbital solution) can be inferred from purely geometric arguments even in the absence of complementary spectroscopic data (Terrell & Wilson 2005). Suitable modeling techniques can then be applied to the light curves in order to estimate the absolute stellar parameters for the individual components (see, e.g., Wilson 1994 for a review of modeling methods).

In this study, we analyze the light curves of four newly discovered contact systems: 1SWASP J064501.21+342154.9 (hereafter J0645), 1SWASP J155822.10-025604.8 (hereafter J1558), 1SWASP J212808.86+151622.0 (hereafter J2128), and UCAC4 436-062932 (hereafter UCAC4) with the aim to determine their orbital and stellar characteristics. For this purpose, we obtained high-quality multicolor CCD observations from the 1.88 m telescope in the Kottamia Observatory in Egypt, and constructed binary star models that optimally fit these observations using the modeling program of G. Djurašević (Djurašević 1992a; Djurašević et al. 1998). With the exception of J0645 (which has recently been analyzed by Liu et al. 2014), the present work is the first in-depth study of these variables.
Our findings suggest that all four systems are contact binaries of W UMa type, with J0645, J1558, and UCAC4 belonging to the A-type, and J2128 to the W-type. In all four cases, we use dark or bright spots on one or both components to model the asymmetries of the light curves and improve the fit of the models to observations. The dark spots are interpreted in terms of surface magnetic activity, while the spots in the neck region to observations. The dark spots are interpreted in terms of temperature inhomogeneities arising from the ongoing exchange of thermal energy between the stars through the common envelope.

Below, we describe the details of the observations (Section 2) and light-curve analysis (Section 3), and discuss each system in turn (Sections 4–7).

2. OBSERVATIONS

Photometric observations of selected variables were carried out with the wide Bessell V, R, and I passbands closely matched to the classic Johnson-Cousins system, using the back-illuminated EEV CCD 42-40 camera with 2048 × 2048 pixels. The pixel size, scale, and total field of view are 13.5 μ, 0".305 pixel⁻¹, and 10 × 10 arcmin², respectively. The camera is attached to the Newtonian focus (f/4.84) of the 1.88 m reflector telescope of the Kottamia Astronomical Observatory (KAO) in Egypt, and kept at a temperature of −125 °C by liquid nitrogen cooling. For more details about KAO instruments, see Azzam et al. (2010).

Exposure times for J0645 were 60, 20, and 10 s for the V, R, and I passbands, respectively; 150, 80, and 60 s for J1558 and UCAC4; and 100, 40, and 20 s for J2128. All frames were reduced (bias-subtracted and flat-field corrected), and differential aperture photometry was performed using the software package C-Munipack. Finally, the magnitudes (variable minus comparison) and their errors were computed in each passband.

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(This table is available in its entirety in machine-readable form.)
Information about the variable, comparison, and check stars was obtained from the UCAC4 Catalog (Zacharias et al. 2012) and the NOMAD Catalog (Zacharias et al. 2005), and is listed in Table 1. The comparison and check stars were chosen so as to match as closely as possible the position, magnitude, and color of the corresponding program star.

Times of minima were calculated using the software package AVE (Barbera 1996) which is based on the method of Kwee & van Woerden (1956), and are given in Table 2. A preview of the light-curve data is given in Table 3, and the full light curves are available as machine-readable tables.

3. LIGHT-CURVE ANALYSIS

The analysis of the light curves was done using the program by Djurašević (1992a) generalized for the case of contact configurations (Djurašević et al. 1998), which implements a sophisticated and versatile binary star model based on Roche geometry. This program has been used and tested for more than two decades on a wide range of binary configurations (see, e.g., Djurašević et al. 2010, 2011; Mennickent et al. 2015). Its distinguishing features are the efficient approach to visibility detection during the eclipses, the treatment of the reflection effect, and the model optimization method. Namely, the

Figure 1. q-search results. Each point represents the quality of fit (the sum of squared $O - C$ residuals) for the candidate mass ratio. The insets zoom in on the regions around the best solution, and show the polynomial fit (solid line) used to find the minimum.
parameters of the model are estimated using the Marquardt-Levenberg algorithm (Marquardt 1963) with modifications described in detail in Djurašević (1992b) to minimize the sum of squared residuals between the observed \((O)\) and calculated \((C)\) light curves simultaneously in all passbands.

A comprehensive list of all model parameters can be found below. Note that we consistently refer to the more massive star as the primary component (with the subscript 1), so that mass ratio, \(q\), is always less than one. Unless stated otherwise, the reflection coefficients (albedos) and gravity-darkening exponents were kept fixed to their expected values for stars with convective envelopes (von Zeipel 1924; Lucy 1967). The effective temperature, corresponding to the average of local temperatures weighted by the areas of elementary surfaces, is estimated from the \(B - V\) color index (see Table 1) for the brighter component and adjusted as a free parameter for the other. Treatment of limb darkening follows the nonlinear approximation of Claret & Bloemen (2011), with the coefficients for the appropriate passbands interpolated from their tables based on the current values of effective temperature and effective gravity in each iteration. The reflection effect is accounted for by applying a temperature correction to affected elementary surfaces, which is calculated following the prescription of Khruzina (1985).

1. Point count—the total number of the observations spanning all the passbands.
2. \(\sum(O - C)^2\)—the final sum of squares of residuals between the observed (LCO) and synthetic (LCC) light curves (in magnitudes).
3. \(P\)—the orbital period, in days.
4. \(q = m_2 / m_1\)—the mass ratio of the components.
5. \(i\)—the orbital inclination (in degrees).
6. \(a_{\text{ORB}}\)—the orbital semimajor axis in units of solar radius.
7. \(\ell_3 / (\ell_1 + \ell_2 + \ell_3)\)—the contribution of uneclipsed (third) light to the total light of the system at the phase of the light-curve maximum (omitted when zero).
8. \(f_{\text{over}}\)—the degree of overcontact, or overflow (in percents), defined as \(f_{\text{over}} = 100 \frac{\Omega - \Omega_n}{\Omega_n - \Omega_e} \).

Figure 2. Parameter space mapping in the vicinity of optimal models. Each row corresponds to a star, and each column to a correlation between mass ratio and inclination (left), mass ratio and filling factor (middle), and inclination and filling factor (right). The quality of fit of synthetic to observed light curves, \(\Sigma(O - C)^2\), is color-coded with darker colors corresponding to smaller values (better fits), and the optimal solutions given in Tables 4–7 are represented with white crosses.
Properties of the Fit

| Summary of Modeling Results for J0645 |
|--------------------------------------|
| **Point Count** | 469 |
| **$\Sigma(O - C)^2$** | 0.0403 |

**System Parameters**

| Parameter | Value |
|-----------|-------|
| $P$       | $0.2486159$ |
| $q$       | $0.48 \pm 0.05$ |
| $d''$     | $88.8 \pm 0.5$ |
| $a_{\text{orb}} [\text{R}_{\odot}]$ | $1.7 \pm 0.2$ |
| $F$       | $1.019 \pm 0.001$ |
| $f_{\text{over}} [%]$ | $15.95$ |
| $\Omega_{2}$ | $2.7913$ |
| $\Omega_{\infty}$  | $2.8372, 2.5494$ |
| $\ell_{i} / (\ell_{1} + \ell_{2} + \ell_{i})$ | $0.000 \pm 0.002 \pm 0.002$ [R], $0.010 \pm 0.003$ [I] |

**Stellar Parameters**

| Parameter | Primary | Secondary |
|-----------|---------|-----------|
| $A$       | 0.5     | 0.5       |
| $\beta$   | 0.08    | 0.08      |
| $T_{\text{eff}} [K]$ | 4590 | 4720 $\pm 20$ |
| $L/(L_{1} + L_{2})$ | $0.619 \pm 0.621$ [R], $0.381 \pm 0.379$ [R], $0.625$ [I] | $0.375$ [I] |
| $R$ [$D = 1$] | $0.426$ | 0.305 |
| $M$ [$M_{\odot}$] | $0.7 \pm 0.2$ | $0.3 \pm 0.1$ |
| $R$ [$R_{\odot}$] | $0.76 \pm 0.07$ | $0.55 \pm 0.05$ |
| $\log_{10}(g)$ | $4.5 \pm 0.2$ | $4.5 \pm 0.3$ |
| $M_{\text{bol}}$ | $6.4 \pm 0.2$ | $7.0 \pm 0.3$ |

**Spot Parameters**

| Parameter | Spot 1 (Primary) |
|-----------|------------------|
| $T_{\text{spot}} / T$ | $0.96 \pm 0.01$ |
| $\theta$ ["] | $16 \pm 1$ |
| $\lambda$ ["] | $320 \pm 10$ |
| $\varphi$ ["] | $34 \pm 7$ |

9. $\Omega_{\infty}$ and $\Omega_{\infty}$—the dimensionless values of Roche potential at the inner and outer critical surfaces that contain the equilibrium points $L_{1}$ and $L_{2}$, respectively.

10. $A$, $\beta$—the albedo and the gravity-darkening exponent of the component.

11. $T_{\text{eff}}$—the effective temperature of the component (in kelvins).

12. $F$—the filling factor of the component, defined as the ratio between the stellar polar radius and the polar radius of the critical Roche surface. In contact systems, this quantity is the same for both stars and we treat it as a system parameter.

13. $\Omega$—the dimensionless surface potential of the component.

14. $L/(L_{1} + L_{2})$—the contribution of the component to the total luminosity of the system.

15. $R$—the polar radius of the component in units of separation.

16. $M$, $R$—the mass and the mean radius of the component in solar units.

17. $\log g$—the logarithm (to base 10) of the effective gravity of the component in CGS units.

18. $M_{\text{bol}}$—the absolute bolometric magnitude of the component.

19. $T_{\text{spot}} / T$—the ratio between the temperature of the spot and the local temperature of the star.

20. $\theta$, $\lambda$, $\varphi$—the angular radius, longitude, and latitude of the spot (in arc degrees).

Of particular interest is the determination of the mass ratios. In the absence of spectroscopic observations and radial-velocity studies for these recently discovered variables, the mass ratios were estimated from photometric data only, using the so-called $q$-search method (illustrated in Figure 1). This approach entails making a sequence of simplified, preliminary models (that, for example, do not include spots or the third light contribution) with different values of mass ratio, selected so as to uniformly cover a reasonable range; in this study, the $q$-search is performed from $q = 0.1$ to 1.0. These models are then optimized to fit the observations as well as possible by adjusting the major orbital and stellar parameters (inclination, filling factors, temperatures), but not the mass ratio itself, which is kept fixed at its initial value. The quality of the fit, quantified with the sum of squared residuals between the observed and calculated light curves, $\Sigma(O - C)^2$, is then plotted against the mass ratio for each trial value of $q$. Since the mass ratio affects the relative sizes of the components, it has an appreciable effect on the shape of the light curve, especially in systems with inclinations high enough to produce total eclipses. For this reason, we expect that the quality of fit will significantly increase as the trial values of $q$ approach the actual mass ratio. The minimum of the $q$-search curve, representing the best mass ratio, is found by fitting a low-order polynomial through the points (insets on Figure 1).

Then the procedure is repeated for a finer sampling of trial values of $q$ in a region near this minimum. The model with the best candidate mass ratio is finally optimized with the full set of parameters, $q$ included.

The stability of these solutions was tested with a heuristic scan of the surrounding parameter space. We chose three pairs of highly correlated parameters ($q - i$, $q - F$, and $i - F$) and made two-dimensional grids of perturbed models with 50 values along each dimension (2500 models per grid) in the range of $\pm 5$% from the values in the final solution found by the $q$-search. The other key parameters (primary or secondary temperature and the sizes, locations, and contrasts of the spots) were perturbed at random in the same $\pm 5$% range. All of these models were then optimized for a best fit to the observations, and the goodness of achieved fit can be used to examine the parameter space. This is illustrated in Figure 2, which shows the $q - i$, $q - F$, and $i - F$ model grids as contour plots where the quality of fit is color-coded so that darker colors correspond to smaller values (better fit) and vice versa. Finally, we picked the best parameter combinations from these plots (the ones with the smallest $\Sigma(O - C)^2$, shown in Figure 2 as white crosses), and used them as initial values for one last model optimization. It is this final model that is presented in subsequent sections on individual stars.

To derive the absolute system parameters, the mass of the brighter component was estimated based on the spectral type—color index calibration from Lang (1992), assuming the star is on the main sequence. The mass of the other component can then be calculated from the mass ratio. Knowing the total mass

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6 Some parameters have natural limits (i.e., the inclination cannot be greater than 90° and the filling factor cannot be less than one in contact configuration). In such cases the range of perturbations is smaller and asymmetric.
and the period of the system, we derive the orbital separation from the third Kepler's law.

The uncertainties in absolute orbital and stellar parameters provided in Tables 4–7 and throughout the text are derived from the formal fitting errors, assuming an error of one subtype in the determination of spectral type.

Now we present the results of our work for each system in turn.

Figure 3. Observed (LCO) and synthetic (LCC) light curves and the final $O - C$ residuals of J0645, with $\Delta(V - R)$ and $\Delta(R - I)$ color curves and the graphic representation of the model described in Section 4 at the orbital phases 0.00, 0.30, 0.60, and 0.85.
Properties of the Fit

| Property                          | Value       |
|----------------------------------|-------------|
| Point Count                      | 466         |
| &\sum(O - C)^2                   | 0.2101      |

System Parameters

| Parameter | Value       |
|-----------|-------------|
| P         | 0.2600776   |
| q         | 0.65 ± 0.08 |
| i [°]     | 78.3 ± 0.3  |
| \omega_{\text{eff}}[\text{R}_{\odot}] | 2.2 ± 0.2   |
| F         | 1.010 ± 0.001 |
| f_{\text{over}} [%] | 6.92 |
| \Omega_{\text{in}}, \Omega_{\text{out}} | 3.1524, 2.7763 |
| \Omega_1, 2 | 3.1264 |

Stellar Parameters

| Parameter | Primary | Secondary |
|-----------|---------|-----------|
| A         | 0.5     | 0.5       |
| \beta     | 0.08    | 0.08      |
| \text{T}_{\text{eff}} [K] | 6200 | 5970 ± 20 |
| L/(L_1 + L_2) | 0.637 [V], 0.635 [R], 0.363 [V], 0.365 [R], 0.632 [I] | 0.368 [I] |
| R [\text{D} = 1] | 0.396 | 0.325 |
| \text{M} [M_\odot] | 1.3 ± 0.2 | 0.8 ± 0.3 |
| \text{R} [R_\odot] | 0.94 ± 0.06 | 0.77 ± 0.05 |
| \text{log}\text{g}(\text{g}) | 4.6 ± 0.2 | 4.6 ± 0.2 |
| \text{M}_{\text{out}} | 4.6 ± 0.2 | 5.2 ± 0.2 |

Spot Parameters

| Parameter | Spot 1 (Primary) |
|-----------|------------------|
| \text{T}_{\text{spot}}/\text{T} | 1.04 ± 0.02 |
| \theta [°] | 18 ± 5 |
| \lambda [°] | 351 ± 6 |
| \varphi [°] | 0.0 ± 0.4 |

4. J0645

The variability of J0645 was discovered by Norton et al. (2011), who measured a period of 0.22105 days, a maximum of 14.11 mag and the depth of minima of 0.35 in the V band. Later, Lohr et al. (2012) determined that the orbital period is 0.2486159 days, and that is the value used in this study.

J0645 was recently observed and studied in more detail by Liu et al. (2014), who found a photometric mass ratio of q = m_2/m_1 = 0.474, a degree of overcontact of f_{\text{over}} ≈ 15%, minor third light contribution in the I band and a small dark spot with a considerable temperature contrast (\text{T}_{\text{spot}}/\text{T}_\text{s} = 0.8) on the larger, cooler, and more massive star.\footnote{Note that Liu et al. (2014) denote the larger, cooler, and more massive star eclipsed in the deeper minimum with subscript 2, while we denote it with subscript 1.}

We observed J0645 on 2013 February 7 and measured times of minimum light on three other nights (2013 January 4 and 5, and February 8). A preliminary analysis of these data was done by Essam et al. (2013), who manually tweaked the major system parameters to get a visually good fit of the calculated light curves to the observations, with the aim of providing rough first estimates. Such a procedure is hard to replicate, verify, and reproduce, which is why we reanalyze the same data in this work, using the results of Essam et al. (2013) as the starting point for our automatic model optimization.

The light curves were folded using the following ephemeris:

\[ \text{Min}_1[\text{HJD}] = 2456331.3940(2) + 0.2486159 \times E. \] (1)

The mass ratio of q = m_2/m_1 = 0.48, determined by the q-search method (Figure 1, top left), can be considered reliable given the total eclipse, which constrains the orbital inclination to within a couple degrees from an edge-on orientation. This result is in remarkably good agreement with the value calculated by Liu et al. (2014). In our solution, the system is in a contact configuration with f_{\text{over}} ≈ 16% and has nearly identical temperatures of the components (ΔT ≈ 130 K).

Since the more massive star is also the one eclipsed in the deeper minimum, J0645 belongs to the A-type of W UMa binaries according to our solution. The late spectral types of the components and the low total mass suggest that it might belong to the W-type instead, which is how Liu et al. (2014) classify it; but we could not find a solution as good as the one presented here for that configuration. Liu et al. (2014) assign the zero orbital phase (the “primary minimum”) to the total eclipse, while we assign it to the partial, but slightly deeper eclipse, which accounts for the difference. Minima of virtually equal depth are no rarity among W UMa stars, and in such cases only a radial-velocity study can lift the ambiguity between the subtypes with certainty.

There is a noticeable asymmetry in the light curves before and after the primary minimum, which is well accounted for by including in the model a small dark spot with the temperature contrast of T_{\text{spot}}/T_\text{s} = 0.96 on the primary star. Although the location of this spot differs by about 30° in longitude from the spot in the solution of Liu et al. (2014), which is of smaller size and greater temperature contrast, these results are qualitatively similar and point to surface activity of a magnetic nature on the primary star.

The fit of the synthetic light curve to the observations can be slightly improved by allowing for the presence of uneclipsed (third) light and treating it as a free parameter of the model. The contribution of third light is nearly negligible, at \ell_3/(\ell_1 + \ell_2 + \ell_3) ≈ 0.0 in the V band and 0.01 in the R and I bands; however, it confirms the results obtained by Liu et al. (2014).

Our findings are summarized in Table 4 and Figure 3, which shows the observed and simulated light curves with residuals, the color curves, and the representation of the model at several orbital phases.

5. J1558

J1558 was found to be a variable star by Norton et al. (2011), who reported a period of 0.23008 days, a maximum of 13.77 mag and the depth of minima of 0.18 in the V band. Lohr et al. (2012) gives an improved period of 0.2600776 days, which is the value used in this study. To our knowledge there have been no other observations or studies of J1558 to date, making this the first quantitative analysis of the variable.

Our observations of J1558 were made on three nights (2014 May 22, and June 17 and 18). The following ephemeris was used to fold the light curve to orbital phases:

\[ \text{Min}_1[\text{HJD}] = 2456826.3430(3) + 0.2600776 \times E. \] (2)

As in the case of J0645, the analysis of the light curves of J1558 begins with the determination of the mass ratio. The q-
search (Figure 1, top right) gives the value of $q = m_2/m_1 = 0.65$. Assuming this mass ratio, the system is in contact configuration with $f_{over} \approx 7\%$ and the orbital inclination of $i \approx 78^\circ$. With the more massive star eclipsed in the primary minimum, J1558 is an A-type W UMa binary.

The temperature of the primary component was determined from the $B-V$ color index and kept fixed at $T_1 = 6200$ K, while the optimization of the model results with $T_2 = 5970$ K. The fit of the model to the observations could be significantly improved by allowing the albedos of the components to be

Figure 4. Observed (LCO) and synthetic (LCC) light curves and the final $O-C$ residuals of J1558, with $\Delta(V-R)$ and $\Delta(R-I)$ color curves and the graphic representation of the model described in Section 5 at orbital phases 0.15, 0.30, and 0.80.
adjusted as free parameters. This resulted in albedos higher than theoretical values for stars with convective envelopes, which is an indication of the possible presence of a bright spot in the neck region. Indeed, a model with such a spot (and albedo values fixed to their theoretical values) fits the observations remarkably well. We interpret this finding as a consequence of ongoing thermal exchange between the components through the neck region of the common envelope.

The stellar and orbital parameters of J1558 resulting from our analysis are summarized in Table 5 and Figure 4, which details the observed and simulated light curves, color curves, and the appearance of the system in different phases.

6. J2128

The variability of J2128 was again discovered by Norton et al. (2011), who measured a period of 0.22484 days, a maximum of 14.49 mag, and a depth of 0.47 for the primary and 0.34 for the secondary minimum in the V band. Lohr et al. (2012) report an improved period of 0.2248416 days, and that is the value used in this study. The present work is to our knowledge the first quantitative analysis of this variable.

We observed it in VRI on 2013 August 28 and captured two new minima, given in Table 2. The light curve was folded to orbital phases according to this ephemeris:

$$\text{Min}_1(\text{HJD}) = 2456533.4807(5) + 0.2248416 \times E.$$ (3)

In the analysis of the light curves of J2128, the mass ratio was again estimated with the $q$-search method (Figure 1, bottom left), which is somewhat problematic in this case, considering the relatively low orbital inclination resulting from the best-fitting model ($i \approx 73^\circ$). The $q$-search was done for a rather large range of possible mass ratios and, although the value of $q = m_2/m_1 = 0.40$ is the best estimate we can give with the available data, this result is to be taken with a degree of caution until it is confirmed in a radial-velocity study. The mass ratio of $q = 0.40$ puts the system in a contact configuration with $f_{\text{over}} \approx 12\%$.

The color index $B - V = 1.157$ corresponds to a main-sequence star with the effective temperature of $T_1 = 4350\,\text{K}$, and it is assigned to the brighter of the two components, which is, in this case, the larger and more massive, but cooler primary. The temperature of the secondary is calculated as a free parameter of the model and has a value of $T_2 = 4800\,\text{K}$. Since it is the less massive star that is eclipsed in the primary minimum, we classify J2128 as a W-type W UMa binary.

Both the light curves and the color curves show significant asymmetries, which indicate the presence of spots on the stars. The optimally fitting model assumes dark spots on both components of the system, located at relatively large latitudes. The larger spot, with the temperature contrast of $T_\text{spot}/T_2 = 0.85$ is located in the polar region of the secondary star and has the greater contribution to the light-curve asymmetry. The spot on the other component is of similar temperature contrast but of smaller size. Even with these spots, the fit of the model to the observations turns out to be significantly better when the exponents of gravity darkening are adjusted as free parameters. This results in the value of $\beta_2 = 0.17$ for the secondary component, while the optimal exponent for the primary corresponds to the expected theoretical value of $\beta_1 = 0.08$. The higher value of the gravity darkening exponent for the secondary star can be interpreted as a consequence of the presence of the large dark spot.

These findings are summarized in Table 6 and Figure 5, where the observed and simulated light curves are shown together with the color curves and the representation of the system in several orbital phases.

### 7. UCAC4

UCAC4 is a newly discovered binary star. Its variability was noticed and reported by one of us (Essam 2014) in the field of view for observation of J1558. The orbital period is 0.361456 days, the maximum is 15.74 mag and the light-curve amplitude is 0.71 mag in the V band. Dedicated observations were conducted on three nights (2014 May 22, and June 17 and 18). The four recorded times of minimum light are given in Table 2, and this is the ephemeris used to fold the light curve to phases:

$$\text{Min}_1(\text{HJD}) = 2456827.4687(2) + 0.361456 \times E.$$ (4)

Such as in the previous cases, the mass ratio of UCAC4 was determined by the $q$-search (Figure 1, bottom right). The value of $q = m_2/m_1 = 0.40$ that we obtained can be considered reliable because the system has a high orbital inclination.
(i \approx 87^\circ) and shows total eclipses. The light-curve analysis indicates that this system is in a shallow contact configuration with \( f_{\text{over}} \approx 8\% \).

The more massive star is the one eclipsed in the primary minimum, making UCAC4 an A-type W UMa binary. This is at odds with the late spectral types and the low total mass, but,
as in the case of J0645, we assigned the zero of orbital phase to the deeper eclipse and adopted the model that best fits the light curves.

The temperature of the primary component was estimated to be $T_1 = 4590$ K from the $B - V$ color index, and the optimal model gave $T_2 = 4580$ K for the temperature of the secondary. Adjusting the albedos as free model parameters significantly improved the fit to the observations, resulting in smaller albedo values than expected from theory. Similarly, as in the case of J1558, this was taken to indicate the existence of one or more cool spots in the neck region of the binary. After fixing the albedos to their theoretical values and adding two cool spots in the neck region, model optimization converged to a solution in which both spots are of relatively large dimensions, but with a small temperature contrast $(T_{\text{spot}}/T_{1,2} = 0.94)$. Without these active regions, we could not find an optimal fit of the model to the observations. Such anomalous temperature distribution in the neck region can again be interpreted in terms of exchange of thermal energy between stars that, regardless of very different masses $(q = 0.4)$, have nearly the same temperatures $(\Delta T \approx 10$ K).

Our results are summarized in Table 7 and in Figure 6, where the observed and modeled light curves, the color curves, and the appearance of the model in several orbital phases can be inspected.

8. COMPARISON WITH OTHER W UMA BINARIES

To put these new variables in context with other W UMa stars, we used data from two relatively recent catalogs of well-studied eclipsing binaries, combined with the findings made within our own group over the past decade for comparison.

From the catalog of Awadalla & Hanna (2005), we took the spectroscopic mass ratios, orbital periods, and separations, as well as absolute masses, radii, temperatures, and luminosities of the components for 75 W UMa stars. From the catalog of Deb & Singh (2011), we took the same quantities for 48 W UMa stars, of which 25 are new (not contained in the first catalog). In both catalogs, the B-type variables were omitted. To this sample, we added 17 W UMa stars studied by our group during the last decade, of which 6 are new (not contained in any of the two catalogs).

All the stars in this sample have mass ratios, separations, and spectral types determined from spectroscopic observations; and of all of them were “solved” for orbital and stellar parameters using modeling techniques based on the Roche model. In this sense, the sample is homogeneous, and since we only wanted to see how close or far the parameter derivations for J0645, J1558, J2128, and UCAC4 are from the bulk of other W UMa stars in the literature, no attempt was made at statistical analysis. We plotted several important correlations between stellar parameters from the sample, and examined the positions of our four stars in those plots, as shown in Figure 7.

In the top panel, the spectroscopic mass ratio $q = m_2/m_1$ (where $m_1$ is always the more massive star) is plotted against the ratio of radii, $r = r_2/r_1$. The four stars from this study are plotted using photometric mass ratios that we determined. The nearly linear relation between mass ratios and size ratios that can be expected in contact binaries (Terrell & Wilson 2005) is clearly visible and our variables do not deviate from it.

In the middle and bottom panels, the mass–luminosity and temperature-luminosity relations are plotted for the primary and secondary components. The zero-age main-sequence calibrations taken from Cox (2000) are shown for reference. Here too our stars do not deviate far from the catalog sample. J1558 seems to be the youngest and least evolved among our targets, but a serious discussion of ages and evolutionary states must be left for some future investigation when more data become available.

The segregation between the two subtypes of WUMa stars is evident to varying degrees in different plots of Figure 7. J0645 (classified as an A-type here, and as a W-type by Liu et al. 2014), J2128 (W-type), and UCAC4 (A-type) form a loose group, while J1558 (A-type) is clearly set apart; this might be another indication that J0645 and UCAC4 are in fact W-types. On the other hand, the regions they occupy are not completely devoid of A-types either. This issue could easily be resolved in a radial-velocity study.

9. RESUME

We secured high-quality multicolor light curves of four recently discovered binary stars: J0645, J1558, J2128, and UCAC4, and conducted a photometric analysis using the
The binary star model of G. Djurašević to determine the orbital and stellar properties of the systems to the best accuracy possible in the absence of complementary spectroscopic data. Our results indicate that all four systems are W UMa type binaries with active regions (dark and bright spots) that are interpreted either as signs of magnetic activity, or when found in the neck region, as a consequence of ongoing exchange of thermal energy between the components.

A comparison with a large sample of well-studied W UMa stars from the literature shows that the derived absolute parameters of our four targets are roughly within expected ranges. Note, however, that without spectroscopic studies, which...
are needed for a completely reliable determination of spectral types, the mass ratio and the orbital separation in an eclipsing binary, the absolute stellar parameters of our targets found in this work, are to be considered preliminary. A combined spectroscopic and photometric study of these stars would be an important next step for the understanding of low-temperature contact binaries and we invite researchers with access to relevant facilities to undertake the necessary spectroscopic observations.

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