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Photometric study and preliminary elements of the low-mass ratio W UMa system ASAS 021209+2708.3

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Abstract We present CCD B and V light curves, obtained in the year 2006, and a photometric solution of the low-mass ratio contact binary ASAS 021209+2708.3. With our data we were able to determine six new times of minimum light and refine the orbital period of the system to 0.3181963 days. The light curves are analyzed using the 2003 version of the Wilson-Devinney program and the analysis was performed with and without adding a spot on the surface of one star because the light curves appear to exhibit a typical O'Connell effect, with Maximum I brighter than Maximum II. The results show that ASAS 021209+2708.3 may be classified as an A-subtype W Ursae Majoris system with a small mass ratio $q = 0.1889$, a large over-contact degree of $f = 0.587$, a very small difference between the component temperatures of $\Delta T = 53$ K and an orbital inclination of $i = 81°$. It is known that deep ($f > 50\%$), low-mass ratio ($q < 0.25$) overcontact binary stars are a very important resource for understanding the phenomena of Blue Straggler/FK Com-type stars. The formations of Blue Straggler stars and FK Com-type stars are unsolved problems in stellar astrophysics. One of the possible explanations for their formation is from the coalescence of W UMa-type overcontact binary systems. The absolute dimensions of ASAS 021209+2708.3 are estimated and its dynamical evolution is inferred.

Key words: binaries: eclipsing – stars: fundamental parameters – stars: individual: ASAS 021209+2708.3

1 INTRODUCTION

W Urase Majoris type stars are cool short-period (usually $P < 1$ day) binary systems with both components filling the critical Roche lobe during their main-sequence evolutionary stage and sharing a common envelope. The formation and evolution of this type of binary star system are unsolved problems in astrophysics.

Deep, low-mass ratio overcontact binary stars are a group of W Ursae Majoris type binaries with mass ratios q less than 0.25 and their degrees of overcontact f larger than 50%. They are very important for the study of stellar astrophysics because they are in the final evolutionary stage of overcontact binary stars and may be the progenitors of single rapidly-rotating stars. Therefore, they provide valuable information on the dynamical evolution of overcontact binaries and on the formation of Blue Straggler (BS) stars and FK Com-type stars (Qian et al. 2005).

ASAS 021209+2708.3 (α_{2000} =02$^{\rm h}$12$^{\rm m}$09$^{\rm s}$, $\delta_{2000} = +27°08'19''$) was discovered to be variable during the All Sky Automated Survey, a long-term project dedicated to detecting and monitoring the variability of bright stars in a large area of the sky using fully automated instruments (Pojmanski 1997).

The ASAS observations were able to determine the type of light variation (an eclipsing binary) and the first preliminary ephemeris (1)

$$\text{Min.I} = \text{HJD}2452625.80 + 0.318197 \times E. \tag{1}$$

Detailed photometric analysis and an orbital period study of this system can provide invaluable information for the coalescence of binary systems but, unfortunately, the observations in our possession are insufficient to reveal any change in period.

2 OBSERVATIONS

A total of 406 filtered B and V CCD observations were carried out on several nights between JD 2454049 and JD 2454095 by one of us (MM) utilizing a 0.2m Schmidt-Cassegrain telescope equipped with a Kodak KAF 401E CCD Camera (768 × 512 pixel of 9 × 9 micron) and a 14 bit A/D converter, without an antiblooming gate. The resulting field of view is 11.7×7.8 arcmin with a pixel resolution of 0.9×0.9 arcsec. The frames were reduced using prism software by Cavadore and Gaillard; a self-developed sub-routine was used to perform the initial data reduction (dark subtraction, flat field division) and automatic aperture photometry of the target objects (variable, comparison and check stars) excluding images with a poor signal-to-noise ratio, generally less than 50, or with tracking errors. Measurements were made in the B and V bands using Johnson filters and transformed into standard differential magnitudes, as described by Cohen (2002), by means of a Microsoft Excel spreadsheet.

The comparison star used was TYCHO2 1761.1578.1 ($m_V = 10.32$, $B - V = 0.98$), while TYCHO2 1761.2002.1 ($m_V = 11.70$, $B - V = 1.27$) served as the check star. The times of minima, presented in Table 1, are all heliocentric and determined by the Kwee & van Woerden (1956) method. These new data permit us to refine the orbital period as follows:

$$\text{Min.I} = \text{HJD}2452625.6409(34) + 0.3181963(8) \times E. \tag{2}$$

Table 1 CCD Time of Minima of ASAS 021209+2708.3

Band	JD(Hel.)+2400000	Epoch$_{(2)}$	(O-C)$_2$	Error
V	54062.4580	4515.5	0.0018	0.0025
V	54080.4333	4572.0	–0.0010	0.0026
B	54081.3877	4575.0	–0.0012	0.0038
B	54083.2978	4581.0	–0.0003	0.0021
B	54083.4583	4581.5	0.0011	0.0017
B	54095.3893	4619.0	–0.0003	0.0020

3 PHOTOMETRIC SOLUTION

In order to derive reliable geometric and astrophysical elements of the system, the present observations were analyzed with the 2003 version of the Wilson-Devinney (WD) program (Wilson & Devinney 1971; Wilson 1990, 1994; Wilson & van Hamme 2003). Analysis was done for the available B and V light curves with, respectively, 196 and 210 individual points. The preliminary solutions were determined by means of the synthetic light-curve program, and taken as starting solutions of the iterative process of the Differential Correction program. The convergence of the minimization procedure was obtained by means of the multiple subset method (Wilson & Biermann 1976).

We assumed that the system was in contact, employing the Mode 3 option of the computing code. Mode 3 is for overcontact binaries (W UMa stars) in which the six parameters Ω_2, g_2, A_2, L_2, x_2 and y_2 are not free. The spectral type information of the system was unavailable, so we made use of the color index $(B - V)$ = 0.79 derived from our observations and the tables of Flower (1996) to determine the temperature of the primary component (star eclipsed at Min.I), assumed to be 5307 K and the corresponding spectral class G8, which is a generally accepted spectral type for the primary component of EW type stars.

The bolometric and wavelength-dependent limb darkening coefficients ($x_{1\rm bolo} = x_{2\rm bolo}$, $y_{1\rm bolo} = y_{2\rm bolo}$, $x_{1BV} = x_{2BV}$), using the square root law (LD = 3), were taken from van Hamme (1993) for $\log g = 4.0$ and solar abundances. The gravity-darkening exponents were adopted to be $g_1 = g_2 = 0.32$ for the convective envelopes (Lucy 1967), and the bolometric albedos were $A_1 = A_2 = 0.50$ (Ruciński 1969). All of these parameters were not adjustable. A fine surface grid, N_1 = N_2 = 30, $N1L$ = $N2L$ = 25 and symmetrical partial derivatives for each of the adjustable parameters (ISYM = 1) were adopted during all calculations. The simple reflection model (Wilson 1990) was used with a single reflection (MREF = 1, NREF = 1). No third light was allowed, $l_3 = 0.0$, and a circular orbit and synchronous rotation were assumed.

The adjustable parameters were the inclination i, the mean surface temperature of the secondary component T_2, the non-dimensional surface potential $\Omega_1 (= \Omega_2)$, and the monochromatic luminosity of the primary component L_1.

Since a spectroscopically determined mass ratio, $q = m_2/m_1$, is not available, a search for a solution was made for several fixed values of q in the range between 0.1 and 3.5. A sufficient number of runs of the DC program was made until the sum of the residuals, $\sum(\rm res)^2$, showed a minimum and the corrections to the parameters became smaller than their probable errors. The solution for each value of q indicated that the best fitting was for $q = 0.20$, with $\sum(\rm res)^2 = 0.01806$, as shown in Figure 1.

Starting with the preliminary solution for $q = 0.20$, we performed a more detailed analysis with q being treated as an additional free parameter. After some iterations, the best set of parameters are finally derived and listed in Table 2 (unspotted). The corresponding theoretical light curves are shown in Figure 2 (solid lines). The phases of our observations were computed using the new ephemerids (2).

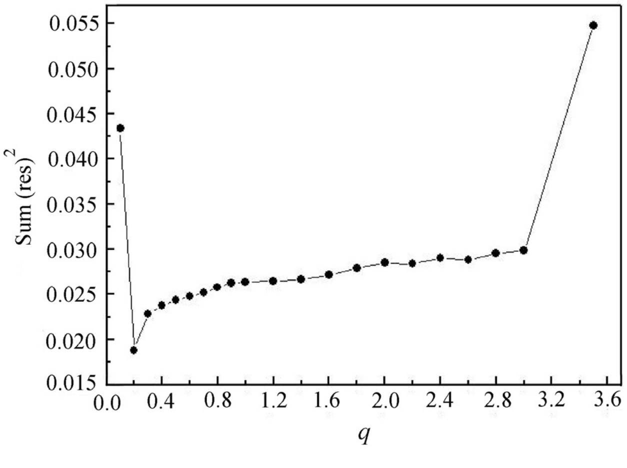

Fig. 1 Relation $\sum(\rm res)^2$ - mass ratio q in Mode 3 for ASAS 021209+2708.3.

Table 2 Light Curve Solutions for ASAS 021209+2708.3

Parameter	Spotted	Unspotted
i	80.963° ±0.033°	80.085° ±0.032°
T_1 (K)	5307*	5307*
T_2 (K)	5254 ± 12	5218 ± 16
f	0.587 ± 0.002	0.518 ± 0.004
$\Omega_1 = \Omega_2$	2.1340 ± 0.0033	2.1424 ± 0.0048
$q = m_2/m_1$	0.18894 ± 0.00218	0.18894 ± 0.00218
$A_1 (= A_2)$	0.50*	0.50*
$g_1 (= g_2)$	0.30*	0.30*
$L_{1V}/(L_1 + L_2)$	0.787 ± 0.001	0.783 ± 0.004
$L_{2V}/(L_1 + L_2)$	0.180 ± 0.005	0.171 ± 0.005
$L_{1B}/(L_1 + L_2)$	0.785 ± 0.001	0.779 ± 0.002
$L_{2B}/(L_1 + L_2)$	0.177 ± 0.003	0.168 ± 0.001
$X_{1V} = X_{2V}$	0.411*	0.411*
$X_{1B} = X_{2B}$	0.736*	0.736*
L_3	0	0
Primary Component		
r (pole)	0.5084 ± 0.0008	0.5068 ± 0.0013
r(side)	0.5606 ± 0.0012	0.5581 ± 0.0020
r(back)	0.5884 ± 0.0016	0.5851 ± 0.0027
Secondary Component		
r (pole)	0.2488 ± 0.0010	0.2459 ± 0.0037
r (side)	0.2618 ± 0.0012	0.2583 ± 0.0046
r (back)	0.3190 ± 0.0032	0.3113 ± 0.0121
$\mathrm{Lat}_{\mathrm{spot}}$	90°*	
$\mathrm{Long}_{\mathrm{spot}}$	260.77° ± 5.2°	
$\mathrm{Radius}_{\mathrm{spot}}$	29.96° ± 1.6°	
$\mathrm{TempFact}_{\mathrm{spot}}$	0.9021 ± 0.008	
$\sum(\mathrm{res})^2$	0.013237	0.018056

* assumed parameters

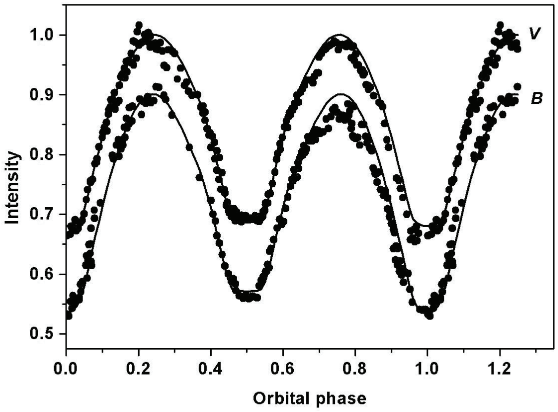

Fig. 2 CCD V and B light curves of ASAS 021209+2708.3 (points) and theoretical ones (lines). For convenience, the light curves are shifted by arbitrary amounts of intensity.

4 STAR-SPOT MODELS

It is clear that the theoretical light curves do not fit the observed ones very well, especially around the second maximum. The observed light curves are asymmetric, and show unequal quadrature heights, with Maximum I being 0.034 in V and 0.017 in B magnitudes brighter than Maximum II.

An unequal quadrature light level, namely the O'Connell effect (O'Connell 1951), is found in many eclipsing binaries and explained by several physical mechanisms, such as the presence of additional orbital mass (also known as third light), a hot spot due to the impact from mass transfer between the components (Lee et al. 2006), a cool spot that may be connected with magnetic activity with the same nature as solar magnetic spots (Mullan 1975) and the circulation effect (Zhou & Leung 1990).

In order to improve the fit to the light curve, we ran a new light curve solution with the WD program, this time including a possible third light source, but found that the code always returned negative values for this parameter. So the asymmetry of the light curve is not caused by the third light. It is probably caused by the star spot(s) and/or the circulation effect in the common envelope. The circulation effect indeed can be replaced by the spot(s) effect (Li et al. 2001).

We therefore tested the two spot models: a hot spot on the more massive primary star due to impact from mass transfer between the components and a cool spot on the secondary star caused by magnetic activity. When a hot spot on the primary component was assumed, the solution did not show an appreciable improvement in the light curve fitting.

New DC calculations, assuming the presence of a cool spot at fixed latitude 90° (i.e., on the equator) on the surface of the secondary component, have been made. The other spot parameters, including longitude ϕ, angular radius γ, and the temperature factor $T_{\rm s}/T_{*}$, were treated as free parameters. This model could explain the decrease of brightness in the phase interval 0.70–0.85 and the spot assumption gives fairly good fittings to the asymmetry and variations of the light curves of ASAS 021209+2708.3 as shown in Figure 3 for the spotted final fit (lines), but the physical nature of the spot model is still open for discussion.

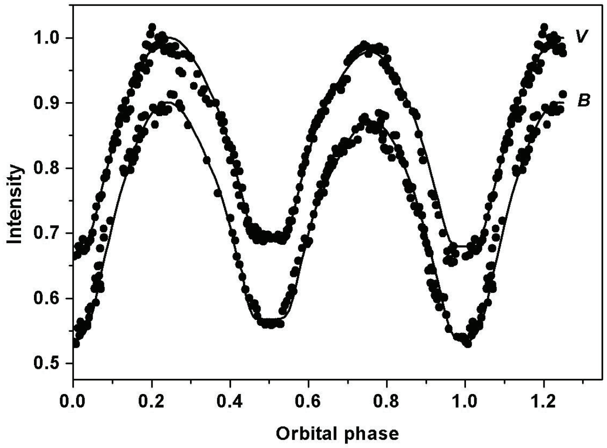

Fig. 3 Same as Fig. 2, but for the lines represent the best fit obtained when adding a cool spot to the secondary component.

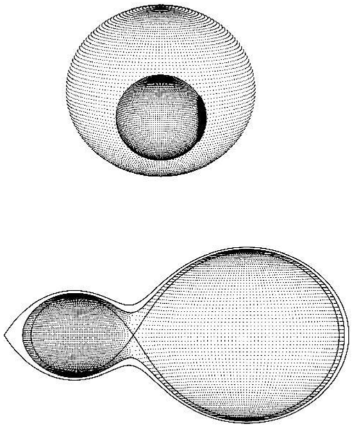

Fig. 4 Aspect of ASAS 021209+2708.3 at 1.00 of orbital phase. The larger and more massive star is eclipsed (*upper*) and the configuration of the components of the system in the orbital plane is shown (*bottom*), according to our solution.

The parameters obtained are given in Table 2 (spotted). It should be noted that the errors of the parameters provided by the WD solutions are unreliably small because of correlations (Maceroni & Rucinski 1997).

According to our results and properties of some similar low-mass ratio overcontact binary stars (e.g. XY Boo, V410 Aur), the system has been found to be an A-subtype W Ursae Majoris variable star in the overcontact configuration, showing a significant over-contact degree ($f = 0.587$) with a small temperature difference between the components ($\Delta T = T_1 - T_2 = 53\,\mathrm{K}$) and a small mass ratio of $q = 0.1889$. Close binaries with a deep common envelope are in thermal contact and they have eclipses of almost equal depth. The primary (deeper) minimum occurs when the larger, more massive star is eclipsed by its smaller, less massive companion (Binnendijk 1965, 1970). Their common envelope substantially exceeds the Roche inner contact surface (Fig. 4).

5 ESTIMATED ABSOLUTE ELEMENTS OF ASAS 021209+2708.3

Mass is not an easily determinable stellar parameter, especially for overcontact binaries. It can only be obtained by knowing both photometric and spectroscopic elements. However, as shown in Gazeas (2009), physical parameters of contact binaries are closely correlated with the orbital period and mass ratio. Therefore we made an estimation of the mass of the primary star $M_1 = 1.15M_\odot$ and both of the absolute radii, $R_1 = 1.18M_\odot$ and $R_2 = 0.58M_\odot$. From the derived mass ratio, $m_c/m_h = q = 0.18894$ and the assumed mass of $1.15M_\odot$ for m_h, the mass of the secondary component has been derived as $0.22M_\odot$, while luminosities were calculated using the well known formulae (Milano & Russo 1983).

The computed absolute elements of ASAS 021209+2708.3, as reported in Table 3, are used to estimate the evolutionary status of the system by means of the mass-radius diagram (Fig. 5).

It can be seen that the radius of the primary component corresponds to the value for zero age main sequence (ZAMS) stars of the same mass; in fact, if the primary component could be at the ZAMS location, its radius should be 1.09 $R_\odot$ (Awadalla & Hanna 2005), according to the present estimated radius of 1.18 $R_\odot$ and an evolutionary degree of 1.09, i.e. basically a ZAMS star (Liu & Yang 2000). The secondary component lies above the ZAMS, due to the fact that the energy transfer from the primary to the secondary makes it oversized and overluminous for its mass (Webbink 2003).

Table 3 Estimated Absolute Elements for ASAS 021209+2708.3

Primary Star	Secondary Star
mass ($M_\odot$) =1.15	mass ($M_\odot$)= 0.22
radius ($R_\odot$) = 1.18	radius ($R_\odot$) = 0.58
log ($L/L_\odot$) = 0.0	log ($L/L_\odot$) $= -0.64$
A ($R_\odot$) = 2.18	A ($R_\odot$) = 2.18

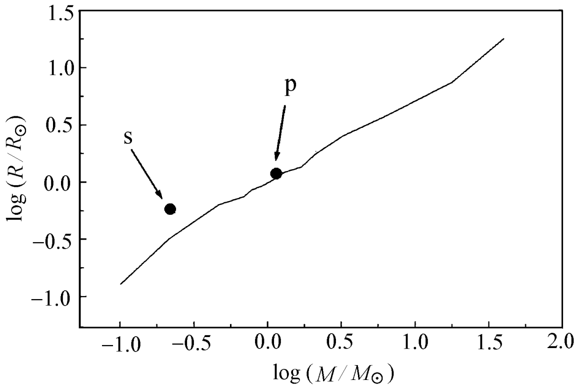

Fig. 5 Location of the primary and secondary components of ASAS 021209+2708.3 on a $\log M - \log R$ diagram. The solid line shows the ZAMS.

6 DISCUSSION AND CONCLUSIONS

From the photometric solution of the B and V light curves of ASAS 021209+2708.3 and using the W-D code, we conclude that the system is in a deep contact with a filling factor of about 0.58. It is an A-subtype W Ursae Majoris variable star, with a low-mass ratio $q = 0.188$. Overcontact systems with small mass ratios and deep contacts are interesting and play an important role in the study of the structure and evolution of binaries.

If a thermal relaxation oscillation (TRO) is the underlying dynamical mechanism in these systems then the high mass ratio phase is one extreme of the TRO cycle (contact phase) evolving towards a semi-detached phase. Detailed modeling shows that W UMa binaries will ultimately become a single star configuration system, and hence the high mass ratio system has to lose a significant portion of inherent mass and angular momentum in order to become a low mass ratio system, which must have relatively small periods (Sriram & Vivekananda Rao 2010).

Models of W UMa systems (Li et al. 2004, 2005) have shown that W UMa systems evolve into contact binaries with extreme mass ratios and then evolve into single, fast-rotating stars (FK Com stars) or blue stragglers due to Darwin's instability and its orbital angular momentum can be expressed as $J_{\rm orb} = 3J_{\rm spin}$ (Hut 1980; Eggleton & Kiseleva-Eggleton 2001); deep $f > 50\%$, low-mass ratio ($q < 0.25$) overcontact binary stars may be the progenitors of blue straggler / FK Com-type stars.

One possible evolution of ASAS 021209+2708.3 is from the present low-mass ratio and deep-contact binary into a single rapid-rotation star, just like the systems of GR Vir (Qian & Yang 2004), FG Hya (Qian & Yang 2005), and AW UMa (Pribulla et al. 1999). However, the available observations are insufficient to reveal any period changes. That could explain the decrease of the mass ratio of the binary system and therefore the evolution into a rapidly-rotating single star.

The absolute dimensions of ASAS 021209+2708.3 cannot be determined directly because radial velocity observations are unavailable. Astrophysical parameters for the two components of ASAS 021209+2708.3 are presented in Table 3 based on the period-mass relation by Gazeas (2009).

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References

Awadalla, N. S., & Hanna, M. A. 2005, Journal of Korean Astronomical Society, 38, 43

Binnendijk, L. 1965, Veroeffentlichungen der Remeis-Sternwarte zu Bamberg, 27, 36

Binnendijk, L. 1970, Vistas in Astronomy, 12, 217

Cohen, L. 2002, Computing and Using CCD Transformation Coefficients, AAVSO Information Sheet (see *http:www.aavso.org*)

Eggleton, P. P., & Kiseleva-Eggleton, L. 2001, ApJ, 562, 1012

Flower, P. J. 1996, ApJ, 469, 355

Gazeas, K. D. 2009, Communications in Asteroseismology, 159, 129

Hut, P. 1980, A&A, 92, 167

Kwee, K. K., & van Woerden, H. 1956, Bull. Astron. Inst. Netherlands, 12, 327

Lee, J. W., Lee, C.-U., Kim, C.-H., & Kang, Y. W. 2006, Journal of Korean Astronomical Society, 39, 41

Li, L., Han, Z., & Zhang, F. 2004, MNRAS, 355, 1383

Li, L., Han, Z., & Zhang, F. 2005, MNRAS, 360, 272

Li, L., Liu, Q., Zhang, F., & Han, Z. 2001, AJ, 121, 1091

Liu, Q., & Yang, Y. 2000, A&A, 361, 226

Lucy, L. B. 1967, ZAp, 65, 89

Maceroni, C., & Rucinski, S. M. 1997, PASP, 109, 782

Milano, L., & Russo, G. 1983, MNRAS, 203, 235

Mullan, D. J. 1975, ApJ, 198, 563

O'Connell, D. J. K. 1951, Publications of the Riverview College Observatory, 2, 85

Pojmanski, G. 1997, Acta Astronomica, 47, 467

Pribulla, T., Chochol, D., Rovithis-Livaniou, H., & Rovithis, P. 1999, A&A, 345, 137

Qian, S., & Yang, Y. 2004, AJ, 128, 2430

Qian, S., & Yang, Y. 2005, MNRAS, 356, 765

Qian, S., Yang, Y., Soonthornthum, B., et al. 2005, AJ, 130, 224

Ruciński, S. M. 1969, Acta Astronomica, 19, 245

Sriram, K., & Vivekananda Rao, P. 2010, Research in Astronomy and Astrophysics, 10, 159

van Hamme, W. 1993, AJ, 106, 2096

Webbink, R. F. 2003, in 3D Stellar Evolution, Astronomical Society of the Pacific Conference Series, vol. 293, eds. S. Turcotte, S. C. Keller, & R. M. Cavallo, 76

Wilson, R. E. 1990, ApJ, 356, 613

Wilson, R. E. 1994, PASP, 106, 921

Wilson, R. E., & Biermann, P. 1976, A&A, 48, 349

Wilson, R. E., & Devinney, E. J. 1971, ApJ, 166, 605

Wilson, R. E., & van Hamme, W. 2003, Computing Binary Stars Observables, the 4th edition of the WD program (*ftp.astro.ufl.edu, dicrectory pub/wilson/lcdc2003*)

Zhou, D., & Leung, K. 1990, ApJ, 355, 271