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# THE STATUS OF GSC 3870-01172 AS A MEMBER OF A TRIPLE OR QUADRUPLE SYSTEM

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**Abstract**

New photometry and radial velocities of the eclipsing binary GSC 3870–01172 are reported. Simultaneous analysis of the data using the Direct Distance Estimation method yields the absolute parameters, as well as the distance to the binary. A comparison of the distances and proper motions indicates that the nearby star GSC 3870-01361 may be a third component of the system.

GSC 3890-01172 was identified as a candidate W Ursae Majoris (W UMa) eclipsing binary star by the Northern Sky Variability Survey (Hoffman et al., 2009). The observations reported herein confirm that the system is indeed a W UMa binary. Standardized photometric observations in 2013 and 2016 show that the system has partial eclipses and exhibits small night-to-night variations. Radial velocities measured for both components allow us to perform a simultaneous solution that includes the distance to the system as an adjustable parameter.

The photometric observations were made at the Sonoita Research Observatory near Sonoita, AZ using a 0.5 m folded Newtonian telescope and a Santa Barbara Instrument Group STL-6303 CCD camera with Johnson-Cousins $BV$ filters. The images were calibrated in the usual way by bias/dark subtraction and then flatfielding using IRAF (Tody, 1993). Instrumental magnitudes were then measured using PSF fitting with SExtractor (Bertin & Arnouts, 1996) and PSFEx (Bertin, 2011). Using the method described in Terrell et al. (2016), the instrumental magnitudes were transformed onto the standard system using APASS standards (Henden et al., 2012) from Data Release 9 (APASS DR9). The standard $BV$ magnitudes are available from the IBVS web site as file 6247-t2.txt.

From 2016 to 2018, spectroscopic observations were made with the 1.85 m Plaskett telescope at the Dominion Astrophysical Observatory in Victoria, British Columbia. The 21181 configuration of the spectrograph was employed with a grating of 1800 lines/mm, blazed at 5000 Å, giving a reciprocal linear dispersion of 10 Å/mm in the first order. The wavelengths ranged from 5000 to 5260 Å, approximately. Frame reduction was performed by the software RaVeRe (Nelson 2013). See Nelson (2010) and Nelson et al. (2014) for further details. Radial velocities were determined using the Rucinski broadening functions (Rucinski, 2004; Nelson, 2010) as implemented in the software Broad (Nelson, 2013; Nelson et al., 2014). Table 1 gives the details of the radial velocity observations.

Table 1: Radial Velocity Observations of GSC 3870-01172.

| DAO Image # | Mid Time (HJD−2400000) | Exposure (sec) | Phase at mid-exp.† | $V_1$ (km sec$^{-1}$) | $V_2$ (km sec$^{-1}$) |
|---|---|---|---|---|---|
| 16-01283 | 57493.86414 | 1800 | 0.229 | $-260.3 \pm 3.9$ | $79.4 \pm 5.2$ |
| 16-01334 | 57496.00532 | 3600 | 0.783 | $268.7 \pm 2.2$ | $-79.2 \pm 1.2$ |
| 16-01362 | 57497.00402 | 1000 | 0.841 | $229.8 \pm 2.2$ | $-62.1 \pm 2.3$ |
| 16-01364 | 57497.01913 | 1120 | 0.888 | $175.8 \pm 4.3$ | $-34.1 \pm 3.6$ |
| 16-01444 | 57498.90975 | 1200 | 0.675 | $228.3 \pm 3.9$ | $-64.6 \pm 3.8$ |
| 16-01446 | 57498.93979 | 3600 | 0.767 | $264.5 \pm 3.4$ | $-76.5 \pm 3.7$ |
| 16-01511 | 57504.96601 | 1000 | 0.216 | $-250.3 \pm 2.3$ | $68.3 \pm 3.5$ |
| 16-01513 | 57504.97996 | 1200 | 0.258 | $-254.5 \pm 1.8$ | $70.4 \pm 5.2$ |
| 17-03943 | 57854.80597 | 940 | 0.198 | $-245.7 \pm 1.2$ | $80.2 \pm 0.6$ |
| 18-05325 | 58233.78010 | 900 | 0.368 | $-175.1 \pm 3.9$ | $69.3 \pm 4.1$ |
| 18-05375 | 58234.84434 | 900 | 0.626 | $175.3 \pm 2.9$ | $-64.7 \pm 7.1$ |
| 18-05393 | 58235.01831 | 312 | 0.159 | $-211.0 \pm 5.5$ | $80.4 \pm 4.3$ |
| 18-05423 | 58235.99037 | 900 | 0.135 | $-202.1 \pm 3.7$ | $63.2 \pm 4.8$ |
| 18-05518 | 58242.89512 | 900 | 0.273 | $-253.5 \pm 3.6$ | $73.7 \pm 4.0$ |

† Phases computed using the ephemeris parameters in Table 2 for the third body solution.

The *BV* light curves and the new radial velocities were analysed simultaneously with the 2013 version of the Wilson–Devinney program (WD; Wilson & Devinney, 1971; Wilson, 1979; Wilson, 2008). We assumed a value of 0.32 for the gravity darkening exponents of both stars and a value of 0.5 for the bolometric albedos, consistent with convective envelopes as expected from the surface temperatures of both components. Limb darkening coefficients were automatically computed at each iteration from the Van Hamme (1993) tables and the square-root limb darkening law gave substantially better results in the fits as compared to the logarithmic law. Weights for the various light and velocity curves were determined automatically by WD at each iteration.

WD mode 3, appropriate for overcontact binaries, was used in the solution process. The system exhibits partial eclipses so we cannot determine a photometric mass ratio with any reasonable degree of certainty (Terrell & Wilson, 2005), but the system is double-lined and thus a spectroscopic mass ratio can be determined. The radial velocities allow us to determine the absolute scale of the system and thus the luminosity of the system. Our standard magnitudes of the system can be converted into physical flux units via the calibrations of Wilson et al. (2010), enabling the distance to be a free parameter in the simultaneous light/velocity curve solution. See Wilson (2008) for details on this direct distance estimation (DDE) procedure. The lower mass star is eclipsed at primary minimum, making this a W-type system.

The system shows mild asymmetries in the light curves and we used a cool spot on star 2 to model them. The determinacy of spot parameters from light curve solutions is known to be fraught with difficulties, so we performed extensive tests using a combination of grid searches through the spot parameter space, as well as a genetic algorithm optimizer coupled with WD. In all, approximately $10^6$ light curves were computed. Once various minima were discovered in the search, traditional differential corrections (DC) solutions were performed with WD to zero in on the local minima.

The initial solution assumed no third light and determined a distance to the binary of $107.4 \pm 0.2$ pc. The adjusted ($a$, $V_\gamma$, $i$, $T_1$,$T_2$, $q$, $\Omega$, HJD$_0$, $P$, $\dot{P}$, and $\log(d)$) and derived

Table 2: Parameters from the light/velocity curve solution. Errors on the adjusted parameters are the internal errors from the least squares solution.

| Parameter | No $3^{rd}$ Body | With $3^{rd}$ Body |
|---|---|---|
| $a$ ($R_\odot$) | 2.308 ± 0.006 | 2.281 ± 0.006 |
| $V_\gamma$ (km sec$^{-1}$) | 3.1 ± 0.3 | 3.2 ± 0.3 |
| $i$ (deg) | 76.1 ± 0.1 | 76.6 ± 0.1 |
| $T_1$ (K) | 5459 ± 6 | 5492 ± 6 |
| $T_2$ (K) | 5315 ± 4 | 5333 ± 4 |
| $\Omega_1$ | 6.83 ± 0.03 | 6.98 ± 0.04 |
| $q$ | 3.23 ± 0.02 | 3.35 ± 0.03 |
| HJD$_0$ | 2456415.51108 ± 0.00008 | 2456415.51107 ± 0.00008 |
| $P$ (d) | 0.326651 ± 0.0000001 | 0.326651 ± 0.0000001 |
| $\dot{P}$ | $1.7 \pm 0.2 \times 10^{-9}$ | $1.8 \pm 0.2 \times 10^{-9}$ |
| $log(d)^\dagger$ | 2.031 ± 0.001 | 2.034 ± 0.001 |
| $M_1$ ($M_\odot$) | 0.366 ± 0.003 | 0.343 ± 0.004 |
| $M_2$ ($M_\odot$) | 1.18 ± 0.01 | 1.15 ± 0.01 |
| $R_1$ ($R_\odot$) | 0.672 ± 0.002 | 0.636 ± 0.002 |
| $R_2$ ($R_\odot$) | 1.137 ± 0.008 | 1.132 ± 0.009 |
| $L_{B,1}$ ($L_\odot$) | 0.290 ± 0.003 | 0.290 ± 0.003 |
| $L_{B,2}$ ($L_\odot$) | 0.69 ± 0.01 | 0.70 ± 0.01 |
| $L_{V,1}$ ($L_\odot$) | 0.336 ± 0.003 | 0.333 ± 0.003 |
| $L_{V,2}$ ($L_\odot$) | 0.84 ± 0.01 | 0.85 ± 0.01 |
| Spot longitude (rad) | 0.6 ±0.1 | 0.6 ±0.1 |
| Spot co-latitude (rad) | 2.71 ±0.03 | 2.69 ±0.03 |
| Spot radius (rad) | 0.26 ±0.04 | 0.26 ±0.03 |
| Spot temperature (rad) | 0.8 ±0.1 | 0.8 ±0.1 |

$^\dagger$ Distance $d$ to the binary in parsecs.

parameters (masses, radii and bandpass luminosities) are shown in Table 2.

The *Gaia* DR2 distance is 108.3 ± 0.3 pc (Gaia Collaboration et al., 2018). We note that since binarity can affect the parallax determined by *Gaia* and DR2 does not include processing for binarity (Lindegren et al., 2018), this value may be revised in future *Gaia* data releases. For now we assume that since the binary components are very close, the parallax, and thus distance, is reasonably accurate for comparison to the distance derived from our analysis. Attempts to resolve the discrepancy between the two distance measurements by adjusting the interstellar extinction were not successful without unreasonably large extinction values, given the close distance and high galactic latitude of the system. Third light was also investigated and gave more reasonable results. Because of strong parameter correlations and the fact that the system only has partial eclipses and light curve asymmetries, we decided to fix third light at values appropriate for a grid of main sequence stars of various effective temperatures and solve for the full parameter set, including the distance, rather than allowing third light to adjust. The radii of the third bodies were computed via the $T_{\rm eff}$-$R$ relation in Boyajian et al. (2012) and then the LC program from WD was used to compute the flux from the third body, which was then added to the DC input file. Because of the strong correlations between some of the spot parameters, we adjusted only one at a time (along with all of the other non-spot parameters), doing three DC iterations and then switching to another spot parameter for another three iterations, rotating through all four spot parameters. This approach to dealing with parameter correlations is similar to that described by Wilson and Biermann (1976).

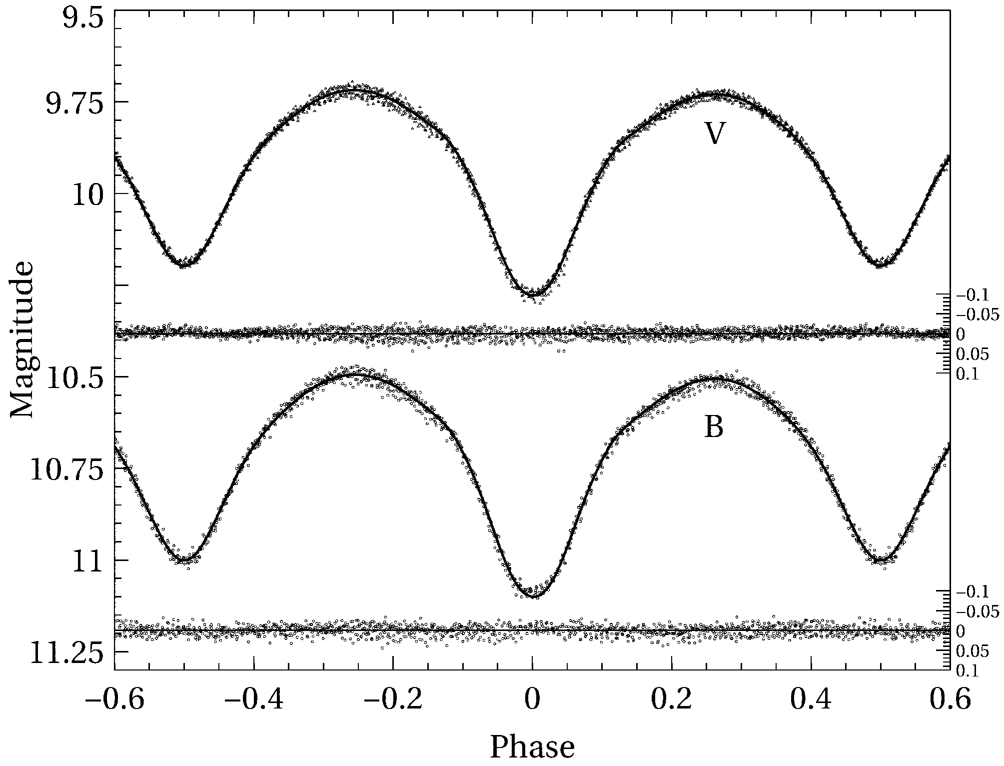


**Figure 1.** The fits to the $B$ and $V$ light curves of GSC 3870-01172. The residuals are plotted below each light curve.

The third body that resulted in a distance to the binary equal to the *Gaia* value was one with $T_{\rm eff}$=3750 K and $R = 0.514R_{\odot}$, making it a late K-type star. The adjusted and derived parameters for this solution are also shown in Table 2. Figure 1 shows the fits to the light curves and Figure 2 shows the fits to the radial velocity curves for the third body solution. Of the two solutions in Table 2, we favour the one that includes the third body for two reasons, while again noting the previously discussed caution about binarity affecting the *Gaia* DR2 parallax. Overcontact binaries are known to have a high frequency of third bodies (Pribulla & Rucinski, 2006) and the statistics are consistent with the hypothesis that all overcontact systems originated in multiple systems. Secondly, although the time baseline of our observations is small, we do find a statistically significant period change and this could be due to the influence of a third body.

GSC 3870-01361 (hereafter, "the companion") is about 46″ away from GSC 3870-01172 and the *Gaia* DR2 parallax puts it at 107.6±0.3 pc, *i.e.* at essentially the same distance as the binary, with a projected separation of about 4900 AU. The *Gaia* proper motions of the binary (15.98±0.05 mas yr$^{-1}$ in right ascension and 30.83±0.06 mas year$^{-1}$ in declination) and the companion ($15.99 \pm 0.05$ mas year$^{-1}$ and $30.61 \pm 0.05$ mas year$^{-1}$) are also very nearly equal. We measured the radial velocity of the companion on HJD 57854.85551 and found it to be $1.6 \pm 1.5$ km sec$^{-1}$, very close to our measured systemic velocity of the binary. Given that the companion's distance, proper motion and radial velocity are

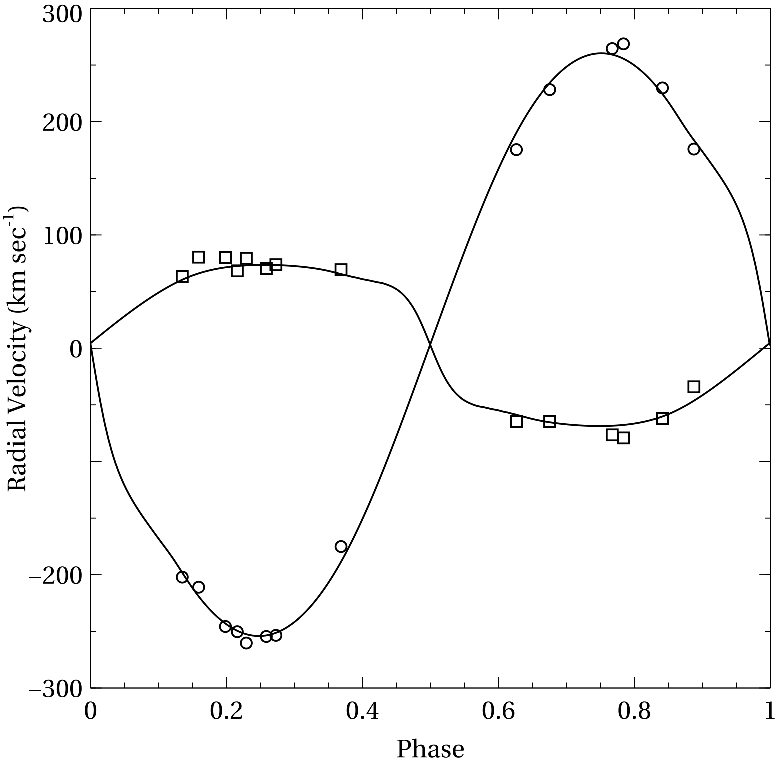


**Figure 2.** The fits to the radial velocity curves curves of GSC 3870-01172. The sizes of the error bars on the radial velocities are approximately the same size as the points.

nearly the same as GSC 3870-01172, we conclude that it is physically associated with the binary, making this at least a triple system, and potentially a quadruple system if our analysis of the eclipsing binary data indicating the presence of an unresolved body orbiting the binary is correct.

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References:

Bertin, E., 2011, *ASP Conf. Ser.*, **442**, 435
Bertin, E., Arnouts, S., 1996, *A&A Suppl. Ser.*, **117**, 393 DOI
Boyajian, T., et al., 2012, *ApJ*, **757**, 112 DOI
Gaia Collaboration, et al., 2018, *A&A*, **616**, 1 DOI
Henden, A. A., Levine, S. E., Terrell, D., Smith, T. C., Welch, D., 2012, *JAAVSO*, **40**, 430
Hoffman, D.I., Harrison, T.E.,, McNamara, B.J., 2009, *AJ*, **138**, 466 DOI
Lindegren, L., et al., 2018, *A&A*, **616**, 2 DOI

Nelson, R.H., 2010, ”Spectroscopy for Eclipsing Binary Analysis” in The Alt-Az Initiative, Telescope Mirror & Instrument Developments (Collins Foundation Press, Santa Margarita, CA), R.M. Genet, J.M. Johnson and V. Wallen (eds.)
Nelson, R.H., 2013, Software by Bob Nelson, `https://www.variablestarssouth.org/bob-nelson/`
Nelson, R. H., Şenavcı, H.V. Baştürk, Ö., Bahar, E., 2014, *New Astronomy*, **29**, 57 DOI
Pribulla, T., Rucinski, S., 2006, *AJ*, **131**, 2986 DOI
Rucinski, S. M., 2004, *IAUS*, **215**, 17
Terrell, D., Gross, J., Cooney, W.R., 2016, *IBVS*, **6166**
Terrell, D., Wilson, R.E., 2005, *Ap&SS*, **296**, 221 DOI
Tody, D., 1993, *ASP Conf. Ser.*, **52**, 173
Van Hamme, W., 1993, *AJ*, **106**, 2096 DOI
Wilson, R.E., 1979, *ApJ*, **234**, 1054 DOI
Wilson, R.E., 2008, *ApJ*, **672**, 575 DOI
Wilson, R.E., Biermann, P., 1976, *A&A*, **48**, 349 DOI
Wilson, R.E., Devinney, E.J., 1971, *ApJ*, **166**, 605 DOI
Wilson, R.E., Van Hamme, W., Terrell, D., 2010, *ApJ*, **723**, 1469 DOI