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# V363 And – A DETACHED ECLIPSING BINARY

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V363 And (= TYC 2305-272-1 = HIP 7122 = SAO 54757) is listed in the General Catalogue of Variable Stars (Samus et al., 2007-2012) as a $\beta$ Lyrae (EB) type with an epoch of 2448500.3980, a period of 1.27799 days and a spectral type of A2. Its photometric variability was discovered from the data of the Hipparcos mission. Accordingly, it was added to the author's observing programme.

The first task was to establish the proper elements (epoch, period) for phasing. All available eclipse timings—together with two new timings—are listed in Table 1.

**Table 1.** All available eclipse timings for V363 And.

| Source | Type | HJD−2400000 | Error (d) | Detector | Filters |
|---|---|---|---|---|---|
| Selam et al. (2003) | II | 52855.2955 | 0.0002 | Photomultiplier | B, V |
| Aksu et al. (2005) | II | 52925.3790 | 0.0007 | Photomultiplier | B, V |
| Senavci et al. (2007) | I | 53640.3931 | 0.0005 | Photomultiplier | B, V |
| Senavci et al. (2007) | I | 53649.3501 | 0.0006 | Photomultiplier | B, V |
| Paschke (2011) | I | 55856.413 | 0.01 | CCD | ?? |
| This work | II | 56545.8793 | 0.0003 | CCD | V, R, I |
| This work | I | 56547.7958 | 0.0005 | CCD | V, R, I |

These yielded the eclipse timing (ET) diagram (a.k.a. O–C diagram) of Fig. 1. (The value labelled 'BAD?' is the third timing in Table 1 and was not included in the least-square fit.)

The least-squares best fit relation to fit the curve was found to be:

$$\mathrm{HJD\,(min\,I)} = 2456547.7963(6) + 1.2779742(3)\,\mathrm{E} \tag{1}$$

Accordingly, these elements were used for all phasing.

In September of 2011, the author took 10 medium resolution spectra at the DAO. The grating (#21181) was 1800 lines/mm, blazed at 5000 Å and used in first order, reciprocal linear dispersion = 10 Å/mm, resolving power = 10000. The camera used was the SITe-2. The spectral range covered was from 4995 to 5256 Å, approximately.

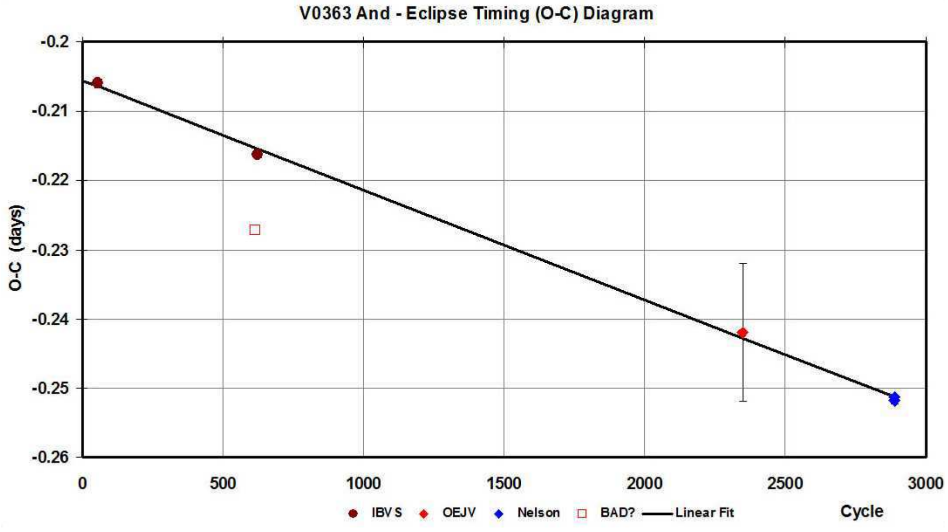

**Figure 1.** Eclipse timing diagram for V363 And.

The author then used the Rucinski broadening functions (Rucinski, 2004) to obtain radial velocity (RV) curves (see Nelson, et al. (2006) and Nelson (2010) for details). A log of DAO observations and RV results is presented in Table 2. In order to correct for the small phase smearing, the RVs were increased by 1% (in this case) in the following way: the RVs were divided by the factor $f = (\sin X)/X$ (where $X = 2\pi t/P$ and $t$ = exposure time, $P$ = period). For spherical stars, the correction is exact; in other cases, it can be shown to be close enough for any deviations to fall below observational errors.

**Table 2.** Log of DAO observations.

| DAO Image # | Mid Time (HJD−2400000) | Exposure (sec) | Phase at mid-exp | V1 (km/s) | V2 (km/s) |
|---|---|---|---|---|---|
| 7833 | 55808.7963 | 3600 | 0.741 | 151.3 | −127.3 |
| 7895 | 55810.8335 | 3600 | 0.335 | −114.7 | 131.5 |
| 7945 | 55811.9451 | 1800 | 0.205 | −124.5 | 147.5 |
| 7995 | 55813.8675 | 1800 | 0.709 | 131.5 | −138.4 |
| 8063 | 55815.8617 | 1800 | 0.270 | −136.9 | 141.2 |
| 8065 | 55815.8840 | 1800 | 0.287 | −129.7 | 141.8 |
| 8102 | 55816.9864 | 1200 | 0.150 | −106.7 | 123.8 |
| 8116 | 55817.7711 | 1800 | 0.764 | 146.6 | −131.5 |
| 8121 | 55817.7932 | 1800 | 0.781 | 142.7 | −128.9 |
| 8127 | 55817.8497 | 1800 | 0.825 | 131.6 | −119.2 |

In fitting two simple sine functions to the data, an overall rms deviation of 3.4 km/s was noted. These two best-fit functions yielded the following parameters:

$$K_1 = 141.0 \pm 1.0\,\mathrm{km/s},\ \mathrm{K}_2 = 139.6 \pm 0.9\,\mathrm{km/s},\ \text{and}\ \mathrm{V}_\gamma = 6.6 \pm 4.3\,\mathrm{km/s}.$$

In September-October of 2013, the author took a total of 775 frames in $V$, 737 in $R_C$ (Cousins) and 771 in the $I_C$ (Cousins) band at his private observatory in Prince

George, BC, Canada. (The telescope was a 33 cm f/4.5 Newtonian on a Paramount ME mount; the camera was an SBIG ST-10XME. Standard reductions were then applied. The comparison and check stars are listed in Table 3. The coordinates and magnitudes are from the Tycho Catalogue, Hog, et al., 2000.)

**Table 3.** Details of variable, comparison and check stars.

| Type<br>of target | GSC<br>2305- | R.A.<br>J2000 | Dec.<br>J2000 | $V$ (Tycho)<br>mag | $B-V$<br>mag |
|---|---|---|---|---|---|
| Variable | 0272 | $01^{\mathrm{h}}31^{\mathrm{m}}46^{\mathrm{s}}.573$ | $+36^\circ05'37''.99$ | 9.06 | 0.25 |
| Comparison | 0270 | $01^{\mathrm{h}}31^{\mathrm{m}}50^{\mathrm{s}}.457$ | $+36^\circ03'40''.07$ | 9.90 | 1.02 |
| Check | 1196 | $01^{\mathrm{h}}31^{\mathrm{m}}09^{\mathrm{s}}.6886$ | $+36^\circ04'56''.961$ | 11.12 | 0.98 |

In view of the number of data points, the author binned the data into phase bins of width 0.01. He then used the 2004 version of the Wilson-Devinney (WD) light curve and radial velocity analysis program with Kurucz atmospheres (Wilson and Devinney, 1971, Wilson, 1990, Kallrath et al., 1998) as implemented in the Windows front-end software WDwint (Nelson, 2009) to analyze the data. To get started, a spectral type A2 (SIMBAD; no reference given) was used. If the system were main sequence, this would correspond to a temperature $T_1 = 9000$ K (Cox, 2000). However, best-fit models using this temperature yielded masses of 1.70 $M_\odot$, too low for the interpolated standard value of 2.50 $M_\odot$ given in Cox (2000). From an inspection of the interpolated table, a spectral type of A8-9 was found to yield masses of 1.75 and 1.67 solar masses, respectively more in keeping with the computed values. Therefore a temperature of $T_1 = 7554 \pm 255K$ (the mean of 7640 and 7468) and $\log \mathrm{g} = 4.285 \pm 0.003$ [cgs] (the mean of 4.284 and 4.286) were adopted. (The errors correspond to an error of one spectral sub-class.) An interpolation program by Terrell (1994, available from Nelson 2009) gave the Van Hamme (1993) limb darkening values; and finally, a square root (LD = 3) law for the limb-darkening coefficients was selected, appropriate for hotter temperatures (ibid).

From the GCVS 4 designation and from the shape of the light curve mode 2 (detached binary) was used. Convergence by the method of multiple subsets was reached in a small number of iterations. Radiative envelopes for both stars were used, appropriate for hotter stars (hence the values of gravity exponent, g = 1.00 and albedo, A = 1.00 were used for each). The limb darkening coefficients are listed in Table 4.

**Table 4.** Limb darkening values from Van Hamme (1993).

| Band | x1 | x2 | Y1 | y2 |
|---|---|---|---|---|
| Bol | 0.210 | 0.224 | 0.525 | 0.512 |
| V | 0.120 | 0.132 | 0.684 | 0.675 |
| $R_C$ | 0.070 | 0.084 | 0.634 | 0.625 |
| $I_C$ | 0.026 | 0.040 | 0.563 | 0.548 |

During the initial stages of modelling, it was discovered that no solution was possible without third light (see below). It was tempting to add a spot to improve the fit of the computed solution at the shoulders of the secondary minimum; however, the fit improved only very slightly at the expense of adding four new parameters. Therefore, the spot was abandoned.

The model is presented in Table 5. Note again that the quoted error in $T_2$ listed above, output by the WD program, refers to the error relative to $T_1$. This error, when added statistically to the error in $T_1$ quoted below, yields an absolute error of 85 K for $T_2$ (see Table 6). If the error in classification is a full spectral sub-class, the estimated errors in $T_1$ and $T_2$ would rise to 255 K.

Detailed reflections were eventually used, with nref = 3, but little or no change in parameters ensued. The binned and unbinned light curve data and the their fits are displayed in Figures 2 and 3, respectively.

**Table 5.** Wilson-Devinney parameters.

| WD Quantity | Binned Value | Binned error | Unbinned Value | Unbinned error | Unit |
|---|---|---|---|---|---|
| $q = M_2/M_1$ | 0.9896 | 0.0038 | 0.9896 | 0.0036 | — |
| Temperature $T_1$ | 7554 | [fixed] | 7554 | [fixed] | K |
| Temperature $T_2$ | 7534 | 7 | 7529 | 4 | K |
| Potential $\Omega_1$ | 4.722 | 0.013 | 4.725 | 0.007 | — |
| Potential $\Omega_2$ | 4.939 | 0.017 | 4.938 | 0.011 | — |
| Inclination, $i$ | 72.83 | 0.13 | 72.83 | 0.08 | deg |
| Semi-maj. axis $a$ | 7.463 | 0.017 | 7.463 | 0.024 | s.u. |
| $V_\gamma$ | 6.60 | 0.28 | 6.60 | 0.43 | km/s |
| Phase shift | -0.0002 | 0.0003 | -0.0002 | 0.0002 | — |
| 3rd light EL3 ($V$) | 0.019 | 0.008 | 0.019 | 0.005 | — |
| 3rd light EL3 ($R$) | 0.029 | 0.008 | 0.029 | 0.005 | — |
| 3rd light EL3 ($I$) | 0.036 | 0.009 | 0.036 | 0.004 | — |
| $L_1/(L_1+L_2)$ ($V$) | 0.5366 | 0.0022 | 0.5367 | 0.0012 | — |
| $L_1/(L_1+L_2)$ ($R_C$) | 0.5354 | 0.0022 | 0.5354 | 0.0013 | — |
| $L_1/(L_1+L_2)$ ($I_C$) | 0.5495 | 0.0022 | 0.5341 | 0.0012 | — |
| $r_1$ (pole) | 0.2656 | 0.0010 | 0.2654 | 0.0006 | s.u. |
| $r_1$ (point) | 0.2822 | 0.0013 | 0.2819 | 0.0008 | s.u. |
| $r_1$ (side) | 0.2707 | 0.0011 | 0.2705 | 0.0006 | s.u. |
| $r_1$ (back) | 0.2781 | 0.0012 | 0.2779 | 0.0007 | s.u. |
| $r_2$ (pole) | 0.2497 | 0.0012 | 0.2498 | 0.0009 | s.u. |
| $r_2$ (point) | 0.2623 | 0.0015 | 0.2625 | 0.0011 | s.u. |
| $r_2$ (side) | 0.2537 | 0.0013 | 0.2538 | 0.0009 | s.u. |
| $r_2$ (back) | 0.2595 | 0.0014 | 0.2596 | 0.0010 | s.u. |
| $\Sigma\omega\,\mathrm{res}^2$ | 0.00300 | — | 0.0538 | — | — |

The radial velocities are shown in Fig. 4. A three dimensional representation from Binary Maker 3 (Bradstreet, 1993) is shown in Fig. 5.

The WD output fundamental parameters and errors are listed in Table 6. Most of the errors are output or derived estimates from the WD routines. The fill factor $f = (\Omega^I - \Omega)/(\Omega^I - \Omega^O)$, where $\Omega$ is the modified Kopal potential of the system, $\Omega^I$ is that

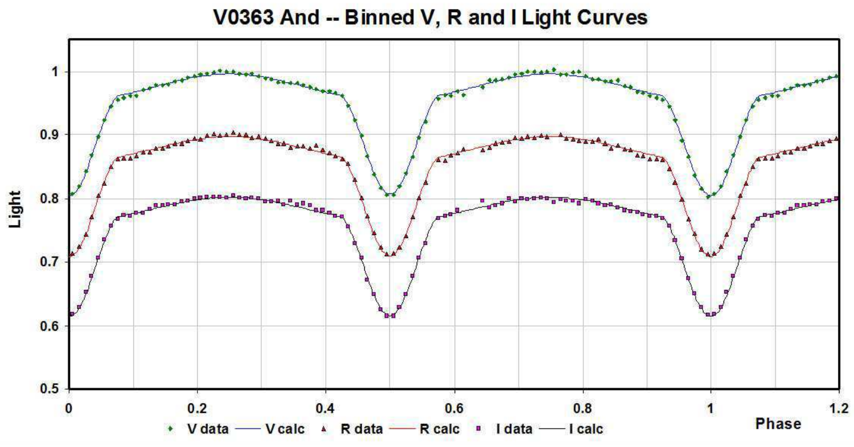

**Figure 2.** V363 And: $V$, $R_C$, and $I_C$ light curves – binned data and WD fit.

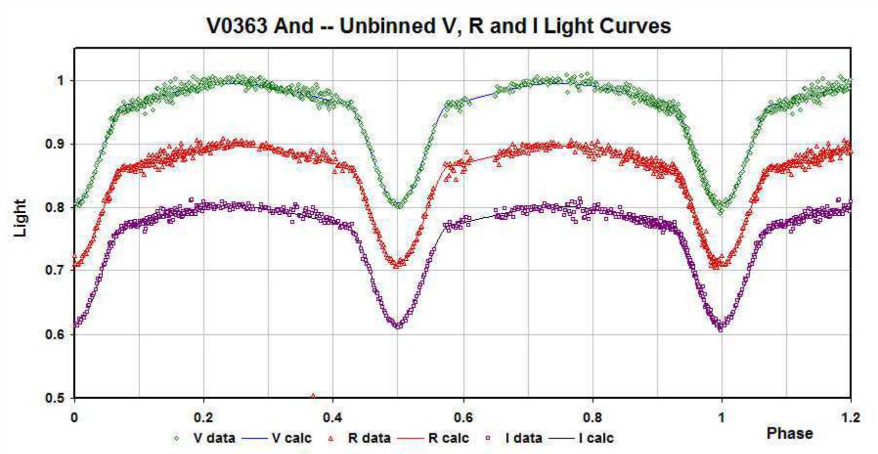

**Figure 3.** V363 And: $V$, $R_C$, and $I_C$ light curves – unbinned data and WD fit.

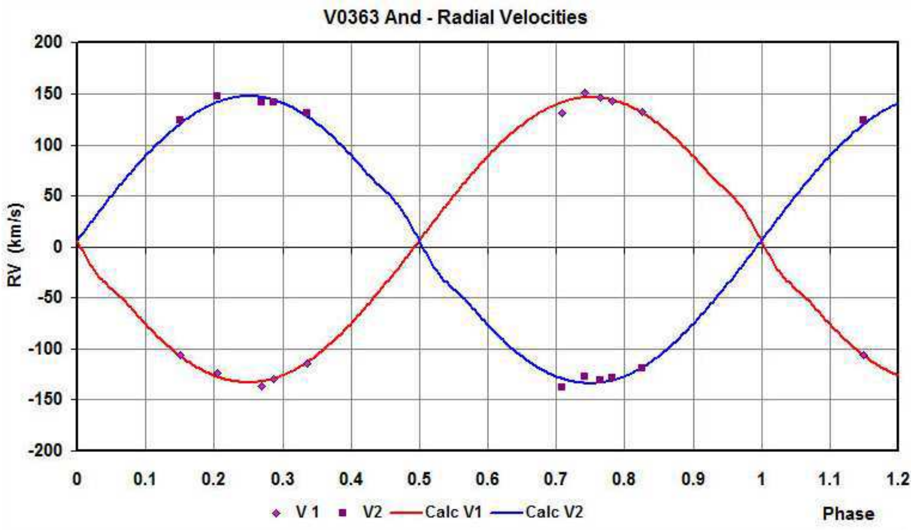

**Figure 4.** V363 And: radial velocity curves – data and WD fit.

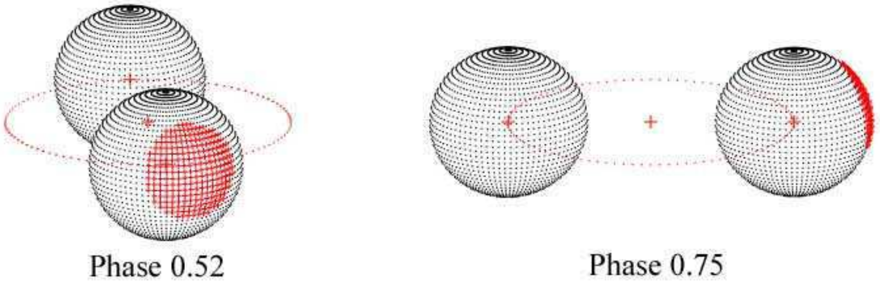

**Figure 5.** Binary Maker 3 representation of the system – at phases 0.52 and 0.75.

of the inner Lagrangian surface, and $\Omega^O$, that of the outer Lagrangian surface, was also calculated.

**Table 6.** Fundamental parameters.

| Quantity | Value | Error | unit |
|---|---|---|---|
| Temperature, $T_1$ | 7554 | 255 | K |
| Temperature, $T_2$ | 7534 | 255 | K |
| Mass, $M_1$ | 1.722 | 0.026 | $M_\odot$ |
| Mass, $M_2$ | 1.704 | 0.025 | $M_\odot$ |
| Radius, $R_1$ | 2.03 | 0.01 | $R_\odot$ |
| Radius, $R_2$ | 1.90 | 0.01 | $R_\odot$ |
| $M_{bol}$, 1 | 2.09 | 0.02 | mag |
| $M_{bol}$, 2 | 2.24 | 0.02 | mag |
| Log $g_1$ | 4.06 | 0.01 | cgs |
| Log $g_2$ | 4.11 | 0.01 | cgs |
| Luminosity, $L_1$ | 12.0 | 0.2 | $L_\odot$ |
| Luminosity, $L_2$ | 10.5 | 0.2 | $L_\odot$ |
| Distance, $r$ | 280 | 12 | pc |

To determine the distance $r$, the following procedure was followed: first the WD routine gave the absolute bolometric magnitudes of each component; these were then converted to the absolute visual magnitudes of both, $M_{V,1}$ and $M_{V,2}$, using the bolometric correction BC $= -0.108$. The latter datum was taken from interpolated tables in Cox (2000). The absolute $V$ magnitudes of the total system were then determined by the usual rules for addition, getting $M_V = 1.518 \pm 0.037$ magnitude. The apparent magnitude in the $V$ passband was $9.06 \pm 0.02$ magnitudes taken from the Tycho catalogue (Hog et al., 2000) and converted to the Johnson system (Kidger, no date) yielding $V = 9.01 \pm 0.02$ magnitude. However, the author's ensemble magnitude (taken using all the Tycho stars as standards and at phases 0.25 and 0.75) yielded $V = 8.91 \pm 0.02$ magnitudes. This was considered more reliable because it was not known at what phase the Tycho value was determined.

It was then necessary to estimate the galactic extinction $A_V = R \cdot E[B-V]$ where $E[B-V] = (B-V)_{\text{obs}} - (B-V)_{\text{tables}}$ is the colour excess, and $R =$ the reddening coefficient. (The value 3.1 was adopted.) Unfortunately, the Tycho B and V values lacked the precision to give meaningful results (unreasonable values near $A_V = 0.2$ were obtained). Fortunately, the dust maps of Schlegel et al (1998) (images available at Schlegel et al., (2013)) provided a maximum value of $E[B-V] = 0.051$ magnitudes[1] for the galactic coordinates of V363 And. Adopting that value, distances were obtained from the standard relation:

$$r = 10^{0.2\times(V-M_V-A_V+5)} \text{ parsecs}$$

The errors were assigned as follows: $\delta M_{bol,1} = \delta M_{bol,2} = 0.02$, $\delta BC_1 = \delta BC_2 = 0.017$ (1.5x the variation of a spectral sub-class), $\delta V = 0.02$, $\delta E(B-V) = 0.026$, all in magnitudes, and $\delta R = 0.1$. Combining the errors rigorously yielded estimated errors in $r$ of 17 pc. It was noted that the result was not overly sensitive to the value of $E[B-V]$ that was chosen. Dropping the value of $E[B-V]$ to half the Schlegel et al.'s value raised the distance by only 10 pc.

Van Leeuwen (2007), in a new reduction of Hipparcos data, derived a parallax value of $2.18 \pm 1.02$ mas, which yields a distance of $r = 459 \pm 214$ pc. The value for the distance presented here certainly lies within this large range. Also (as pointed out by an anonymous referee) it is not clear whether the Hipparcos value is valid for binary systems.

Reference to the evolutionary tracks of Schaller et al. (1992) for metallicity $Z = 0.02$ (approximately solar) and the derived masses revealed a reasonable fit at age $8.7 \cdot 10^8$ years for the luminosities and temperatures (see Table 7).

**Table 7.** Luminosities and temperatures compared to theoretical evolved values of Schaller et al. (1992).

| Star | Mass ($M_\odot$) | Luminosity this paper | Luminosity Schaller | Temperature this paper | Temperature Schaller |
|---|---|---|---|---|---|
| 1 | 1.722 | 12.0 | 10.80 | 7554 | 7544 |
| 2 | 1.704 | 10.5 | 10.17 | 7534 | 7537 |

In conclusion, this detached system of two stars, nearly equal in mass, is evolved and has an approximate age of $8.7 \cdot 10^8$ years. The luminosity of each star falls close to the theoretical value; discrepancies may result from differences in the metallicity from the assumed value of $Z = 0.02$.

An anonymous referee has pointed out that the primary is close to the delta Scuti instability strip and hence it is a candidate to $\delta$ Scuti stars in eclipsing binaries (Soydugan et al., 2006), and the star was also observed to search for$\delta$ Scuti-like pulsations for a short time (Liakos et al., 2012).

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[1] Since the $E[B-V]$ values were derived from the far-infrared all-sky images, this means that the former apply for a light path from the observer all the way through the Galaxy (in the specified direction), and therefore represent an upper limit for the appropriate value for a star lying somewhat closer than the far edge. The error estimate in this quantity has been set to 50% of this value, and is then an appreciable contributor to the overall error in $r$.

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