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V1100 Her – A W-TYPE OVERCONTACT ECLIPSING BINARY

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V1100 Her (= TYC 3092-1291-1= J174410.58+401650.7) was discovered to be variable by the ROTSE survey Akerlof et al. (2000). Sufficient data were available for them to classify it as an eclipsing binary of the EW type, and determine a period of 0.34694(4) days. Since then, numerous authors have reported times of minima (Nelson 2002, 2008, 2013a; Brát et al. 2008, 2011; Hübscher et al. 2010; Arena et al. 2011). Two early times of minima (Nelson 2002, 2008) led to equation (1):

$$\mathrm{JD_{hel}\,Min\,I} = 2452024.8148(18) + 0.3469283(1)\,E \tag{1}$$

The resulting eclipse timing (ET) diagram (a.k.a. $O-C$ diagram) is displayed in Fig. 1.

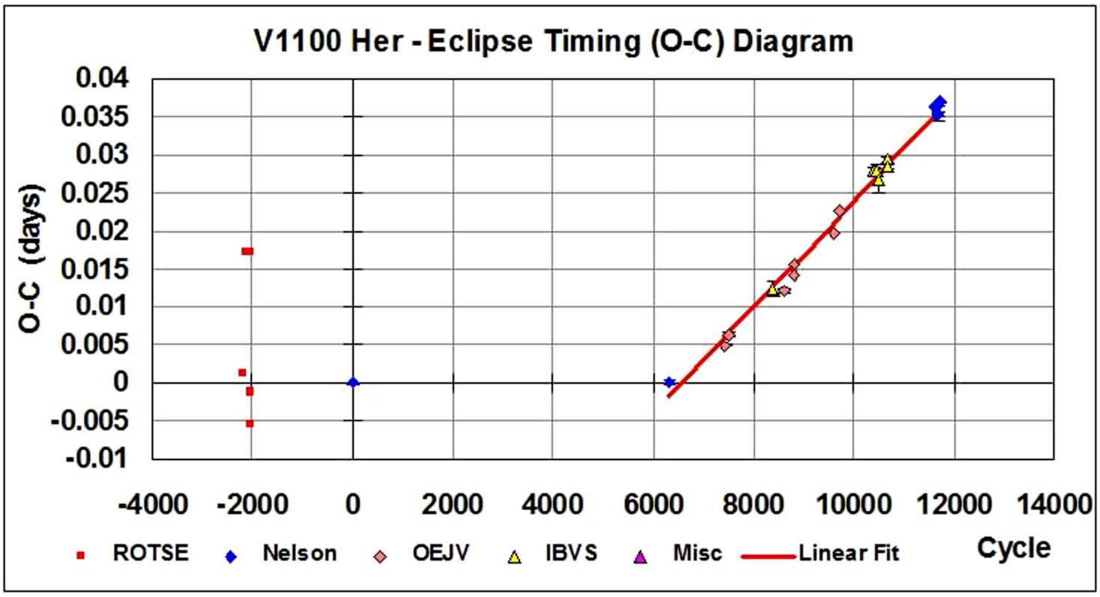

Figure 1. Eclipse timing diagram for V1100 Her using the elements of equation (1).

It seems to reveal a constant period from 1999 (cycle −2205) to 2007 (cycle 6327) but there are insufficient data points to make any realistic conclusions. After that there appears to be an episodic increase and a constant period until the last data points (in 2012). Least squares fitting of the 19 data points in the interval from 2007 to 2012 gives a period of 0.3469354(2) days; that and the last point in the plot (Nelson 2013a) were used in the elements of equation (2). The latter was used to phase all the data.

$$\mathrm{JD_{hel}\,Min\,I} = 2456089.8099(1) + 0.3469354(2)\,E \quad (2)$$

A further time of minimum, hitherto unpublished, is reported in Table 1 and plotted in Fig. 2.

Table 1. New time of minimum for V1100 Her.

HJD−2400000	Error (days)	Type	Filter
56569.6185	0.0003	I	R

An alternative fit, superimposing a sine function to the points since cycle 0, is plotted in Fig. 2 using the elements of equation (1).

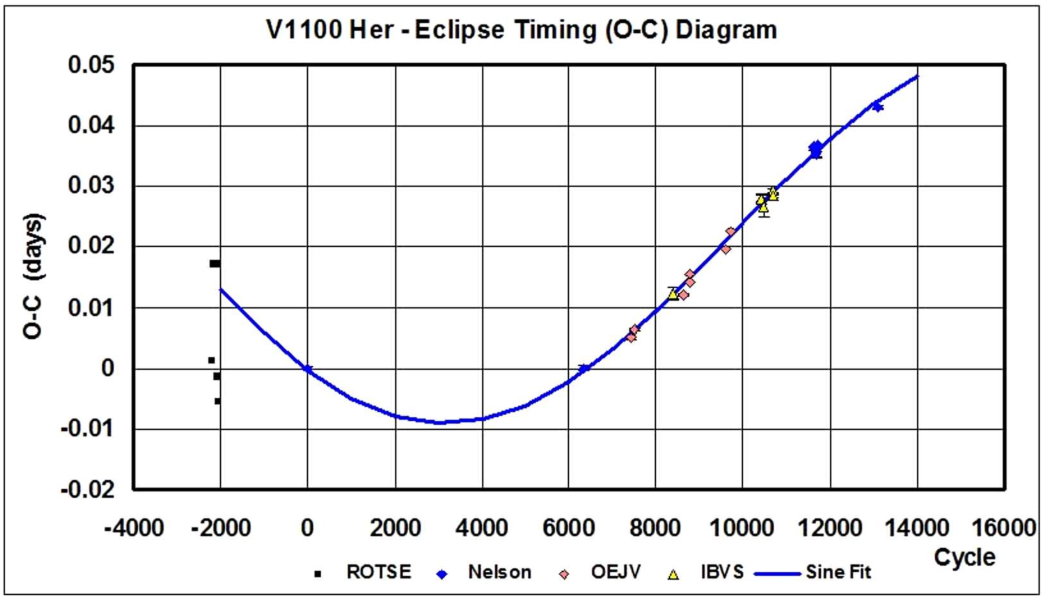

Figure 2. Eclipse Timing ($O-C$) diagram for V1100 Her (sine + linear fit).

The fit is in the form:

$$O - C = C_1 + C_2 n + C_3 \sin(C_4 n + C_5) \quad (3)$$

where $C_1 = 0.0255$ days, $C_2 = -3.8 \cdot 10^{-7}$ days/cycle, $C_3 = 0.0335$ days, $C_4 = 0.00023$ radians/cycle, $C_5 = 4.022$ radians, and n is the cycle number. Constant C_4 translates into a period $P_2 = 25.7$ years for the orbit of a possible third star. [Note that magnetic cycles may also cause cyclic variations in the periods of overcontact binaries – see, for example, Borkovits et al. (2005). However, this explanation is remote in this case, as the observational criteria have not yet been met (Applegate 1992, page 622, para 8).]

It must be admitted straight away that the sine fit is very speculative and liable to change with any new data. It may be completely false. On the other hand, it seems more physical than the scenario of a constant period followed by a sudden period change and then a new constant regime. Time will tell. This system is reminiscent of AC Boo (Nelson 2010a) where the period was constant from 1929 to 1982, followed by an episodic rise, followed by a period of increase at a constant rate since then.

See Nelson (2013b–updated annually) for the latest data and $O-C$ fit. Since V1100 Her has never had a full analysis, it was added to the author's observing programme.

A total of 153 frames in V, 145 in R_C (Cousins) and 143 in the I_C (Cousins) band were obtained by one of the authors (R.H.N.) at his private observatory in Prince George, BC, Canada in May and June of 2012. (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 2 (coordinates, and $B-V$, V magnitudes are from SIMBAD). The V magnitude for V1100 Her was taken from our own ensemble photometry at phases 0.25 and 0.75 using Tycho stars in the field as standards.

Table 2. Details of variable, comparison and check stars.

Type of target	GSC 3092-	R.A. J2000	Dec. J2000	V Mags	$B-V$ Mags
Variable	1291	$17^\mathrm{h}44^\mathrm{m}10.588^\mathrm{s}$	$40°16'51''.15$	10.71	+0.61
Comparison	0934	$17^\mathrm{h}43^\mathrm{m}12.489^\mathrm{s}$	$40°08'58''.32$	10.94	+0.96
Check	1173	$17^\mathrm{h}43^\mathrm{m}14.686^\mathrm{s}$	$40°01'08''.01$	10.88	+0.34

For classification purposes, one of the authors (R.M.R.) took two low resolution spectra, on 2013 March 9 (HJD=2456360.4608) and 2013 June 22 (HJD=2456465.3077). He used the 1.85 m Plaskett telescope at the Dominion Astrophysical Observatory (DAO) in Victoria, British Columbia, Canada with the Cassegrain spectrograph in the 2131 configuration, resulting in a reciprocal dispersion of 60 Å/mm. The two spectra were very similar. The strength of the Calcium H&K lines, G-band, Hγ, Fe I 4384, Ca I 4227, and Hδ lines all indicated a F9 V$\pm$1 spectral classification for V1100 Her.

For radial velocity (RV) determination, the other author (R.H.N.) took 7 medium resolution spectra, also at the DAO, in April and September of 2011 using the same Plaskett telescope. In the 21181 configuration, the grating was 1800 lines/mm, blazed at 5000 Å and used in first order, with reciprocal dispersion = 10 Å/mm, and resolving power = 10,000. The camera was the SITe-2. The spectral range covered was from 5000 to 5260 Å, approximately.

R.H.N. then used the Rucinski broadening functions (Rucinski 2004) to obtain radial velocity curves (see Nelson et al. (2006) and Nelson (2010b) for details). A log of DAO observations and RV results is presented in Table 3. The results were corrected 9% up in this case to allow for the small phase smearing 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. (This matter will be fully explored in a forthcoming paper.)

Table 3. Log of DAO observations.

DAO Image #	Mid Time (HJD−2400000)	Exposure (sec)	Phase at Mid-exp	V_1 (km/s)	V_2 (km/s)
2537	55668.9002	3600	0.778	−58.7	277.60
2581	55670.9454	3600	0.673	−59.9	263.5
7954	55812.6763	3600	0.195	32.6	−281.9
7957	55812.7195	3600	0.320	40.9	−252.9
8011	55814.7589	3600	0.198	40.0	−295.5
8057	55815.8079	3600	0.222	24.6	−302.5
8181	55824.6473	3600	0.700	−48.2	285.7

A plot of two spectra of V1100 Her, #8057 (top) and #2537 (bottom), is given in Fig. 3.

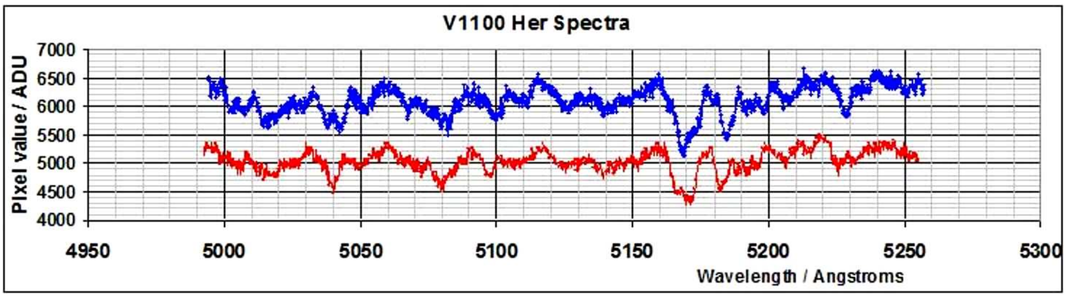

Figure 3. Two spectra of V1100 Her, at phases 0.222 (top) and 0.778 (bottom).

R.H.N. used the 2004 version of the Wilson-Devinney (WD) light curve and radial velocity analysis program with Kurucz atmospheres (Wilson & 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 F9 V, mentioned above, and a temperature $T_2 = 6093 \pm 200$ K were used. (The temperature of the secondary, T_2, was fixed because the secondary star, being larger, might be expected to dominate the flux from the system, and hence the spectral classification. This assertion is borne out by the values of $L_1/(L_1 + L_2)$ given in Table 5.)

Interpolated tables from Cox (2000) gave $\log g = 4.367$; an interpolation program by Terrell (1994, available from Nelson 2009) gave the Van Hamme (1993) limb darkening values; and finally, a logarithmic (LD=2) law for the limb darkening coefficients was selected, appropriate for temperatures < 8500 K (ibid.). (The stated error in T_1 corresponds to one half spectral sub-class.)

From the GCVS 4 designation and from the shape of the light curve mode 3 (overcontact binary) mode was used. Early on, it was noted that the maxima between eclipses were unequal. This is the O'Connell effect (Davidge & Milone 1984, and references therein) and is usually explained by the presence of one or more star spots. Accordingly, one was added first to star 1, and this gave good results. (Moving the spot to star 2 gave poorer results and was abandoned.)

Convergence by the method of multiple subsets was reached in a small number of iterations. (The subsets were: (a, L_1), (T_1, Ω_1, q), and ($V_{\rm gam}$, i, q). The spots were handled separately.) Convective envelopes for both stars were used, appropriate for cooler stars (hence values gravity exponent, $g = 0.32$ and albedo, $A = 0.500$ were used for each). Detailed reflections were used, with $n_{\rm ref} = 3$. The limb darkening coefficients are listed in Table 4. There are certain uncertainties in the process (see Csizmadia et al. 2013; Kurucz 2002). On the other hand, the solution is weakly dependent on the exact values used.

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

Band	x_1	x_2	y_1	y_2
Bol	0.644	0.641	0.226	0.235
V	0.739	0.721	0.259	0.271
R_C	0.667	0.648	0.272	0.280
I_C	0.583	0.565	0.264	0.271

The model is presented in Table 5. (Note that estimating the uncertainties in temperatures T_1 and T_2 is somewhat problematic. A common practice is to quote the temperature difference over half a spectral sub-class (assuming that the classification is good to one spectral sub-class, which precision might be rare). In addition, various different calibrations have been made (Cox 2000, page 388-390 and references therein; and Flower 1996), and the variations between the various calibrations can be significant. In our case the classification is ± 1 one sub-class. Therefore, we propose to assign an uncertainty of ± 200 K to the absolute temperatures of each, which would roughly span this range. The modelling error in temperature T_1, relative to T_2, is indicated by the WD output to be much smaller, around 4 K.)

Table 5. Wilson-Devinney parameters.

WD Quantity	Value	Error	Unit	W-D Quantity	Value	Error	Unit
Temperature T_1	6362	200	K	$L_1/(L_1+L_2)$ (V)	0.2011	0.0016	—
Temperature T_2	6093	[fixed]	K	$L_1/(L_1+L_2)$ (R_C)	0.1961	0.0014	—
$q = M_2/M_1$	6.227	0.010	—	$L_1/(L_1+L_2)$ (I_C)	0.1921	0.0011	—
Potential Ω_1=Ω_2	10.271	0.011	—	r_1 (pole)	0.2374	0.0008	orb. rad.
Inclination, i	68.3	0.3	deg	r_1 (side)	0.2497	0.0009	orb. rad
Semi-maj. axis a	2.56	0.01	sol.rad.	r_1 (back)	0.3075	0.0027	orb. rad
V_γ	-5.6	0.7	km/s	r_2 (pole)	0.5190	0.0005	orb. rad
Spot co-latitude	82	10	deg	r_2 (side)	0.5754	0.0007	orb. rad
Spot longitude	94	5	deg	r_2 (back)	0.6016	0.0009	orb. rad
Spot radius	47	2	deg	Phase shift	-0.0007	0.0004	—
Spot temp factor	0.958	0.005	—	$\omega^2_{\rm res}$	0.00387	—	—

The light curve data and the fitted curves are depicted in Fig. 4. The presence of third light was tested for, but found not to be significant.

The RVs are shown in Fig. 5. A three-dimensional representation from Binary Maker 3 (Bradstreet 1993) is shown in Fig. 6.

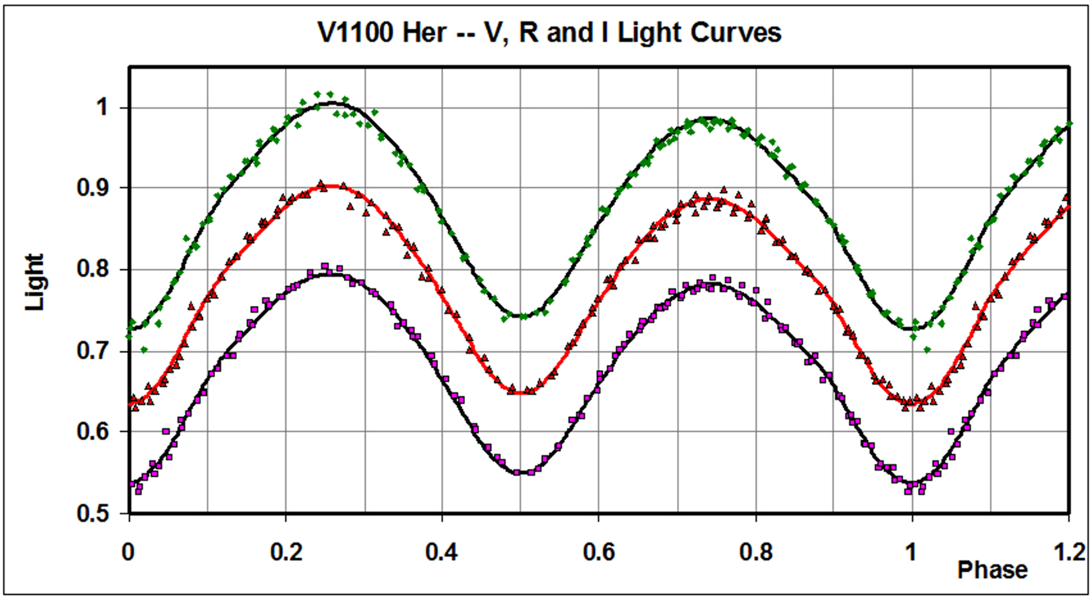

Figure 4. V1100 Her: V, R_C, and I_C light curves – data and WD fit.

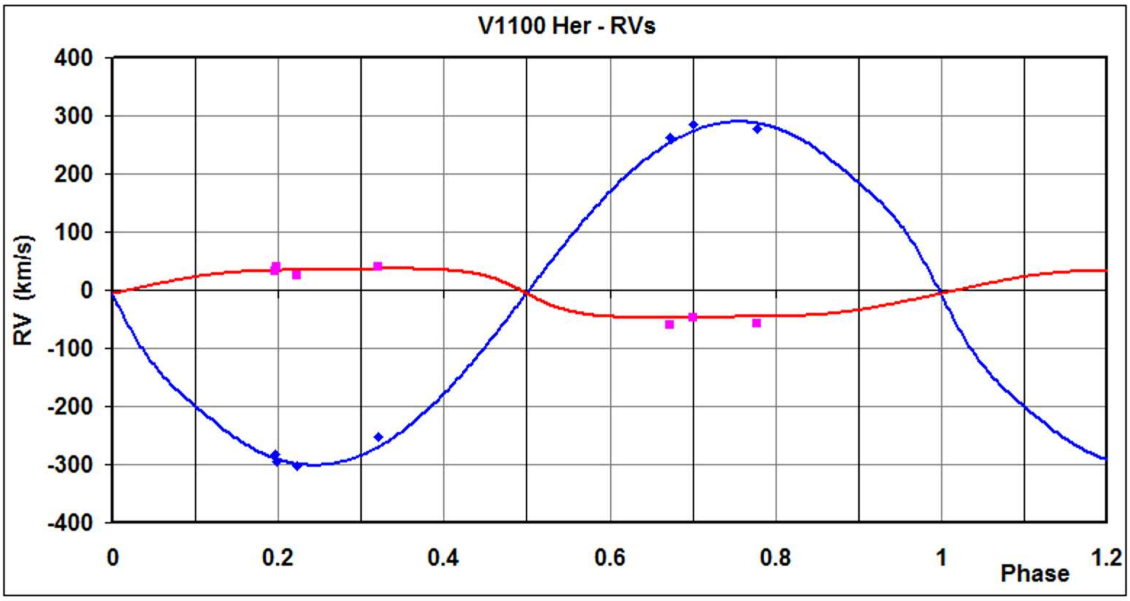

Figure 5. V1100 Her: radial velocity curves – data and WD fit.

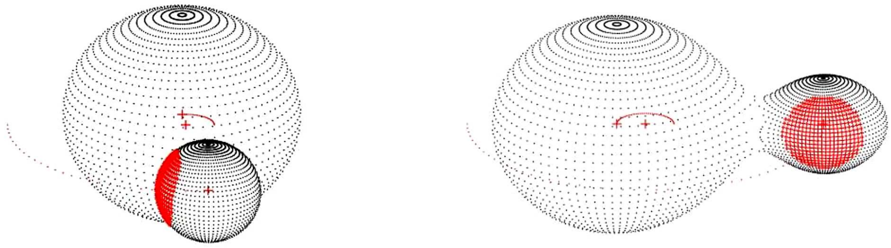

Figure 6. Binary Maker 3 representation of the system – at phases 0.52 and 0.75.

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-out factor $f = (\Omega^{\rm I} - \Omega)/(\Omega^{\rm I} - \Omega^{\rm O})$, where Ω is the modified Kopal potential of the system, $\Omega^{\rm I}$ is that of the inner Lagrangian surface, and $\Omega^{\rm O}$, that of the outer Lagrangian surface, was also calculated.

Table 6. Fundamental parameters.

Quantity	Value	Error	Unit
Temperature, T_1	6362	200	K
Temperature, T_2	6093	200	K
Mass, M_1	0.258	0.034	$M_\odot$
Mass, M_2	1.609	0.019	$M_\odot$
Radius, R_1	0.67	0.01	$R_\odot$
Radius, R_2	1.45	0.01	$R_\odot$
$M_{\rm bol,1}$	5.23	0.02	mag
$M_{\rm bol,2}$	3.76	0.02	mag
$\log g_1$	4.19	0.01	cgs
$\log g_2$	4.32	0.01	cgs
Luminosity, L_1	0.67	0.01	$L_\odot$
Luminosity, L_2	2.58	0.05	$L_\odot$
Fill-out factor	0.159	0.010	—
Distance, r	241	9	pc

To determine the distance r in column 2, we proceeded as follows: first the WD routine gave the absolute bolometric magnitudes of each component; these were then converted to the absolute visual (V) magnitudes of both, $M_{\rm V,1}$ and $M_{\rm V,2}$, using the bolometric corrections BC = −0.160 and −0.170, respectively. The latter were taken from interpolated tables in Cox (2000). The absolute V magnitude was then computed in the usual way, getting $M_{\rm V} = 3.68 \pm 0.03$ magnitudes. The apparent magnitude in the V passband was $V = 10.71 \pm 0.014$, taken from our ensemble photometry at phases 0.25 and 0.75 using Tycho stars in the field (Hog et al. 2000) as standards. The colour excess (in $B - V$) was obtained in the usual way, by subtracting the tabular value of $B - V$ (for that spectral class) from the observed (Tycho) value. This gave $E(B - V) = 0.06$ magnitudes. However, reference to the dust tables of Schlegel et al. (1998) revealed a value of $E(B - V) = 0.0395$ for those galactic coordinates. Since the $E(B - V)$ values have been derived from full-sky far-infrared measurements, they therefore apply to objects outside of the Galaxy;

this value of $E(B-V)$ so derived then represents an upper limit for closer objects within the Galaxy. Hence a lower value of $E(B-V) = 0.033$ was adopted. Galactic extinction was obtained from the usual relation $A_{\rm V} = R \cdot E(B-V)$, using $R = 3.1$ for the reddening coefficient. Hence, distance $r = 241$ pc was calculated from the standard relation:

$$r = 10^{0.2(V-M_V-A_V+5)} \text{ parsecs.} \tag{4}$$

The errors were assigned as follows: $\delta M_{\rm bol,1} = \delta M_{\rm bol,2} = 0.02$, $\delta {\rm BC}_1 = \delta {\rm BC}_2 = 0.012$ (the variation of 1.5 spectral sub-classes), $\delta V = 0.04$, $\delta E(B-V) = 0.02$, all in magnitudes, and $\delta R = 0.1$. Combining the errors rigorously yielded an estimated error in r of 9 pc.

In conclusion, the fundamental parameters of this system have been determined. One of these is the mass ratio, defined by the WD routine as $q = {\rm m}_2/{\rm m}_1$. Since, for W-type systems, the star eclipsed at primary minimum is the less massive one, here we have $q > 1$. However, many authors define q' to be less than 1 in both cases (and equal to ${\rm m}_1/{\rm m}_2$ here). So therefore, for V1100 Her, $q' = 0.161$. This makes V1100 Her a low mass ratio system. All available W-type systems with $q < 0.2$ are listed in Table 7 for comparison.

Table 7. Some low mass ratio W-type overcontact eclipsing binaries.

Star	Spectral Type	T_1 (K)	T_2 (K)	q' (spectr.)	q' (photom.)	f	Spectr. Ref.	Photom. Ref.
V0902 Sgr	~F6-7 V	6200	6256	—	0.132	0.39	—	1
UY UMa	G0?	5486	5900	—	0.133	0.05	—	2
TV Mus	G0-1 V	5980	6088	0.135	0.15	0.13	3	4
EF Dra	F9 V	6000	6054	0.16	0.16	0.455	5	6
V1100 Her	F9 V	6362	6093	0.161	0.161	0.159	7	7
AH Aur	F7 V	6215	6272	0.169	0.169	0.625	8	9
OU Ser	F9-G0 V	5960	6380	0.173	0.173	0.307	10	11
V0728 Her	F3 V	6622	6787	0.181	0.181	0.71	12	12

(1) Samec & Corbin (2002); (2) Yang et al. (2001); (3) Hilditch et al. (1989); (4) Pribulla et al. (2003); (5) Lu & Rucinski (1999); (6) Pribulla et al. (2001); (7) This paper; (8) Rucinski & Lu (1999); (9) Vaňko et al. (2001); (10) Rucinski et al. (2000); (11) Pribulla & Vaňko (2002); (12) Nelson et al. (1995)

It is seen from Table 7 that V1100 Her is most like TV Mus in terms of its mass ratio and fill-out factor. This is further borne out by the diagram of Fig. 7 in which we plot the fill-out factor f versus the mass ratio q using data taken from Csizmadia & Klagyivik (2004). The reader will note the clustering of points within the interval $q = 0.3$ to 0.7 and also for $f < 0.3$. This is typical of W-type overcontact binaries, which are known to display marginal contact (Lucy 1976). However, as mentioned, V1100 Her has a lower than normal mass ratio for a W-type (Binnendijk 1965). Therefore the newly derived results for V1100 Her can be added as 'grist for the mill' in efforts to understand the formation and evolution of this type of star.

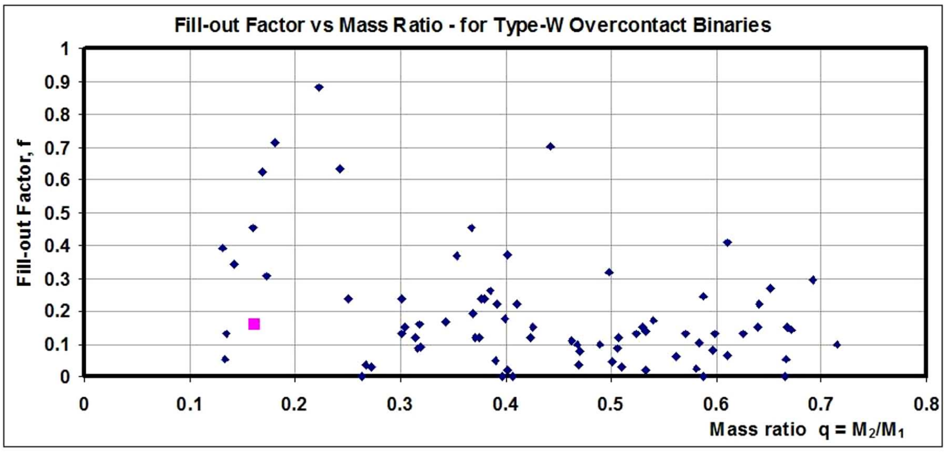

Figure 7. The values of the fill-out factor f are plotted versus mass ratio $q = M_2/M_1$ for W-type overcontact binaries using data from Csizmadia & Klagyivik (2004). The square denotes V1100 Her.

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