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MW UMA, A DETACHED BINARY: OBSERVATIONS AND ANALYSIS

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While studying the optical variability of ROSAT X-ray sources, Robb et al. (2002) found MW UMa (= GSC 4153-0634 = RXJ 114302+603435) to be a detached eclipsing binary of period 1.2347 days. They presented eight CCD times of minima, photometry, a light curve in R_C (Cousins), and a classification spectrum. The spectrum and the photometry yielded approximate spectral types of F6V +F9V. The full light curves in V, R_C, and I_C were kindly forwarded to the author.

During April of 2006, the author took five high resolution (10 Å/mm reciprocal dispersion) spectra at the Dominion Astrophysical Observatory (DAO) in Victoria, British Columbia, Canada; he then used the Rucinski broadening functions (Rucinski, 2004) to obtain radial velocity (RV) curves (see Nelson, et al., 2006a for details). The spectral range was 5004-5267 Å and the reciprocal dispersion, 10 Å/mm. A log of DAO observations and RV results is presented in Table 1.

Table 1:

DAO Image #	Mid Time (HJD-2400000)	Exposure (sec)	Phase at Mid-exp	V_1 (km/s)	V_2 (km/s)
3697	53847.9490	1422	0.778	122.2	-138.4
3720	53848.9623	3600	0.599	71.5	-84.5
3729	53849.7431	3600	0.231	-124.1	134.5
3731	53849.7853	3600	0.266	-122.9	138.0
3736	53849.8639	3600	0.329	-107.4	123.1

The following elements were used for phasing throughout (see Nelson, 2006b for the O-C relation):

$$\mathrm{JD\,Hel\,Min\,I} = 52402.3277(1) + 1.23475(80)\mathrm{E}$$

The author used the 2004 version of the Wilson-Devinney (WD) light curve and radial velocity analysis program with the Kurucz atmospheres (Wilson and Devinney, 1971, Wilson, 1990, Kallrath, et al., 1998) as implemented in the Windows software WDwint (Nelson, 2005) to analyze the data. To get started, a spectral type F6V mentioned above and a temperature $T_1 = 6514 \pm 240\,\mathrm{K}$ were used; interpolated tables from Cox (2000) which gave $\log g = 4.368$ were used; an interpolation program by Terrell (1994) gave the (van Hamme, 1993) limb darkening values; and finally, a logarithmic (LD = 2) law for the extinction coefficients was selected, appropriate for cooler stars (Bessell, 1979). Convective envelopes were chosen for both stars. (Radiative envelopes were later tried as a check but gave a poorer fit.)

Mode 2 (for detached stars) was chosen based on the general appearance of the light curves. Mindful that, for detached systems, stellar size is not well constrained by the light curves (Terrell, 2009), the author determined the flux ratio based on the areas under the (well-defined) peaks in the Rucinski broadening function (see Fig. 1). This is justified (Rucinski, 2008) because the Rucinski broadening functions (Rucinski, 2004) are linear. Values were taken for all the spectra; a mean value of $\text{Flux}_2/\text{Flux}_1 = 0.690 \pm 0.003$ (sd of mean) was obtained. (Note that this was for a wavelength band centred at 5136 Angstroms; it was taken to represent the *V* band, the closest available band.)

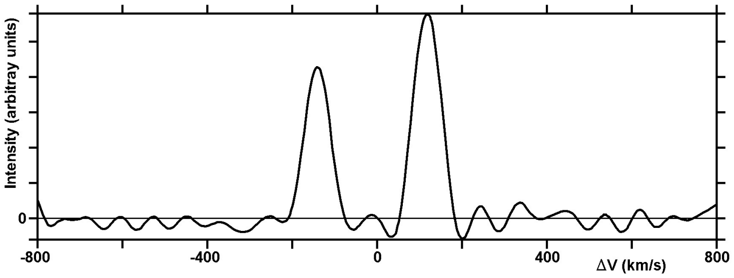

Figure 1. A Rucinski broadening function for MW UMa, image #3697.

During modelling, convergence was attained through the method of adjusting sets of uncorrelated parameters (fixed parameters are given in Table 2). In particular, the mass ratio $q = M_2/M_1$ was held fixed because this value (0.886 ± 0.003) was well determined from the RV curves; in contrast, it is not well constrained from the photometric data. Various starting values of Ω_1 were used and the DC procedure followed through to a best solution. The resultant flux ratios $= L_2/L_1$ were then found and compared to the required value of 0.690. In this way, the optimal value for Ω_1 was found and a consistent solution found.

To investigate the situation further, the author made use of a contour-plotting routine in WDwint in which the best model served as the starting point, after which the program varied two parameters – in this case, Ω_1 and Ω_2 (the surface potentials of stars 1 and 2, resp.) – over a matrix of 100 preset values. For each value of these two parameters, it searched for a best fit varying other selected parameters (in this case, L_1, T_2, and inclination i) over two iterations or loops (each loop varying one parameter, making the correction, then on to the next parameter, then on to the third). Mass ratio, q, was kept fixed, as mentioned above. A long 'rift valley' in Ω_1–Ω_2 space resulted, in which low values of the sum of residuals ($\Sigma\omega^2_{\text{res}}$) nearly equaled that of the best solution all the way along the trough. (See Fig. 2.) This result underscored the need for independent flux ratio determinations obtained from the spectra, else the solution would be truly indeterminate. The lines of constant flux ratio (not shown) are lines of positive slope; the one for the required value neatly intersected the imaginary line along the trough for the best (spotted) solution (marked by a cross).

The author then ran a set of runs using the square root law (LD = 3), interacting with the above contour plot to get Ω_2 as a function of Ω_1. The best solution yielded a sum of the residues indistinguishable from the solution with LD = 2; further, there was no significant change in any of the output values.

Runs with non-zero eccentricity were attempted, but with the formal errors close to the final value of 0.001, circular orbits were adopted. Two separate runs were made: Model 0: no spots, and Model 1: spots of star 1. The final results for both models are given in Table 4. It may be seen that Model 1 (spots on star 1) gives a significantly lower residual than the unspotted model and a much better fit visually; hence it is adopted (but the unspotted results given for comparison). Note that the quoted errors are formal errors produced by the WD program; actual errors may be larger. Also the quoted error in T_2 is relative to T_1 – that is, it is the error in $(T_2 - T_1)$. The absolute error in T_1 is much larger, corresponding to half one spectral sub-class (so obviously, the absolute error in T_2 will be of the same order). Third light was tested for, but no significant differences from zero were found.

The fundamental parameters, using the results from Model 1 are given in Table 3. Also, the interstellar coefficient, $A_V = 0.19 \pm 0.09$ was taken from Robb, et al. (2002) to yield an estimate of the distance.

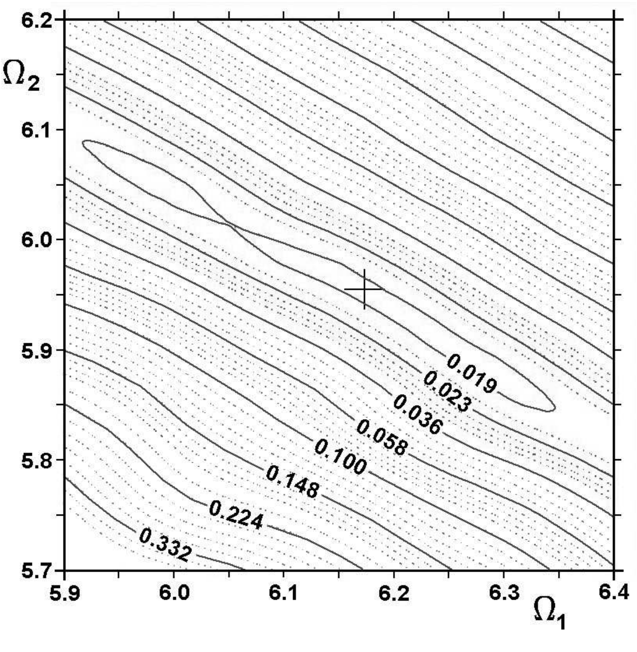

Figure 2. A contour plot of $\Sigma\omega^2_{\rm res}$ plotting Ω_1 versus Ω_1.

Table 2:

Quantity	Value		Error
	Star 1	Star 2	
g	0.320	0.320	[fixed]
A	0.500	0.500	[fixed]
x (bol)	0.639	0.644	[fixed]
y (bol)	0.241	0.225	[fixed]
x (V)	0.710	0.741	[fixed]
y (V)	0.275	0.257	[fixed]
x (R_C)	0.637	0.669	[fixed]
y (R_C)	0.285	0.271	[fixed]
x (I_C)	0.553	0.585	[fixed]
y (I_C)	0.276	0.264	[fixed]

Table 3:

Fundamental Quantity	Star 1 Tabular	Star 1 WD	Star 1 error	Star 2 Tabular	Star 2 WD	Star 2 Error
Sp. Type	F6 V	–	–	F9 V	–	–
Mass (M_0)	1.32	1.28	0.10	1.11	1.14	0.09
Radius (R_0)	1.26	1.23	0.01	1.14	1.18	0.01
$\log g$ (cgs)	4.36	4.36	0.004	4.37	4.35	0.004
Luminosity (L_0)	2.56	2.47	0.36	1.60	1.75	0.25
Distance (pc)	–	159	11	–	–	–

Table 4:

Quantity. –	Model 0 (no spot)	Model 1 (spot on 2)	Error –	Quantity. –	Model 0 (no spot)	Model 1 (spot on 2)	Error –
T_1 (K)	6514	6514	130	L_2/L_1 (V)	0.670	0.690	-
T_2 (K)	6026	6112	22	a (solar radii)	6.48	6.49	0.008
Ω_1	6.27	6.17	0.02	V_γ (km/s)	-0.7	-0.7	0.3
Ω_1	5.89	5.95	0.02	r_1 (pole)	0.185	0.189	0.001
$q = M2/M1$	0.886	0.886	0.005	r_1 (point)	0.188	0.192	0.001
i (deg)	82.90	82.78	0.05	r_1 (side)	0.186	0.190	0.001
Spot Lat (deg)	na	90	30	r_1 (back)	0.188	0.191	0.001
Spot Lng (deg)	na	185	2	r_2 (pole)	0.183	0.180	0.001
Spot Rad. (deg)	na	74	5	r_2 (point)	0.186	0.184	0.001
Spot Temp fac	na	0.992	0.004	r_2 (side)	0.186	0.182	0.001
$L_1/(L_1+L_2)$ (V)	0.592	0.592	0.002	r_2 (back)	0.186	0.183	0.001
$L_1/(L_1+L_2)$ (R)	0.578	0.581	0.002	$\Sigma\omega^2_{\rm res}$	0.02140	0.01832	–
$L_1/(L_1+L_2)$ (I)	0.567	0.571	0.002				

The resultant V light curves are displayed in Figs. 3 and 4 together with the residuals, and the radial velocity curves, in Fig. 5. A 3-dimensional representation from Binary Maker 3 (Bradstreet, 1993) is displayed in Fig. 6. Fits for all colours are found in the on-line version in Figs. 7-8.

The validity of spots resulting from WD analysis is, in the opinion of the author, tenuous. Spots are added because they yield significant improvements to the fit (as happened here). One needs to use care, however, as the unrestrained addition of spots can, in principle, fit anything!

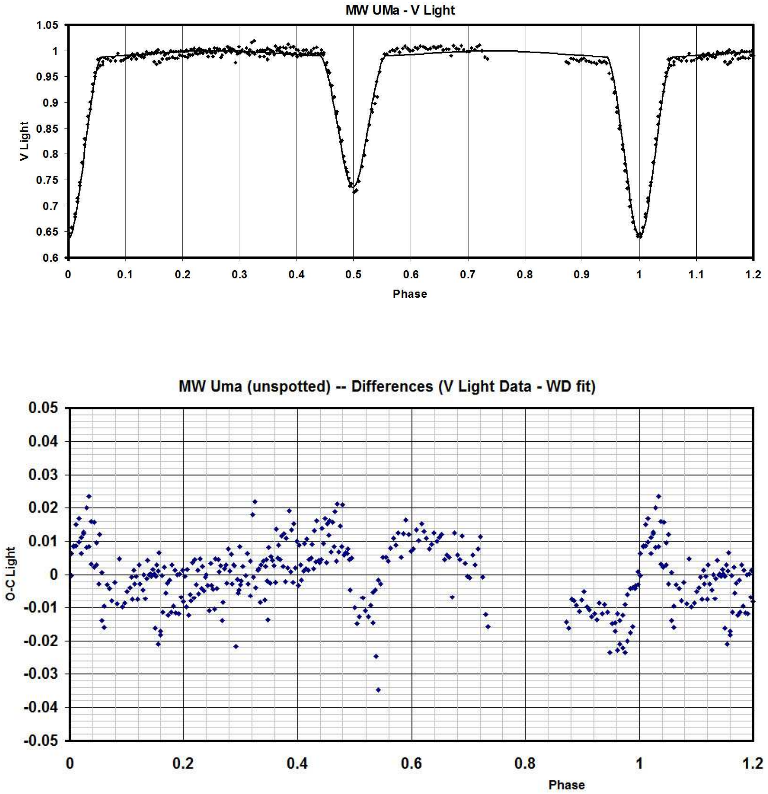

Figure 3. Photometric Data and WD Output (V, top panel), residual (bottom panel) – Model 0 (no spot)

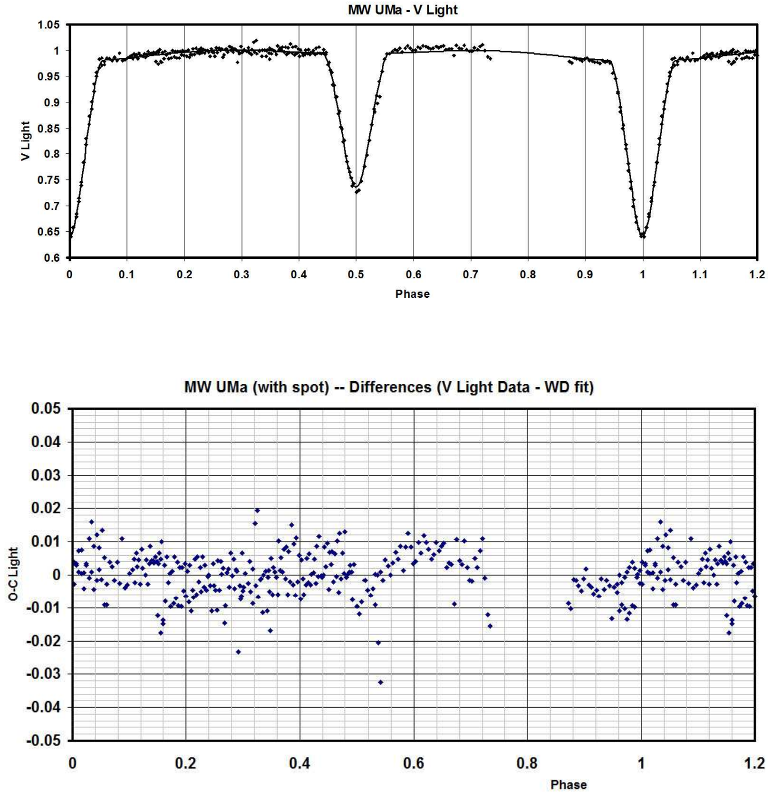

Figure 4. Photometric Data and WD Output (V, top panel), residual (bottom panel) – Model 1 (with spot)

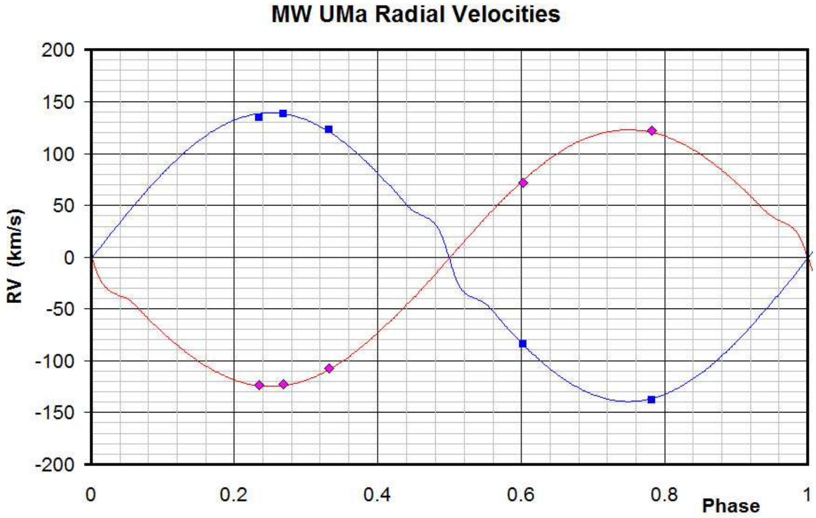

Figure 5. Radial Velocity Data and WD Output

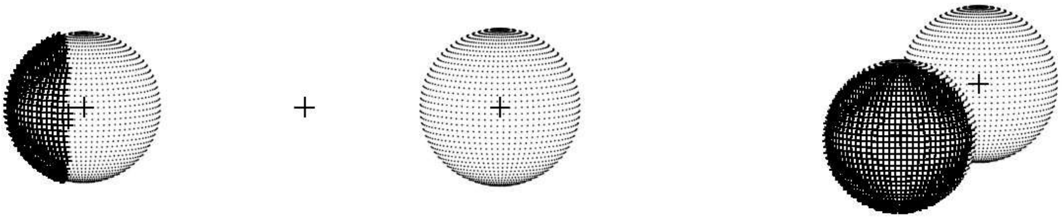

Figure 6. Binary Maker depiction of the system at phases 0.75 and 0.97 respectively

In conclusion, MW UMa is a detached binary with temperatures of about 6500 and 6100 K, and luminosities of about 2.6 and 2.5 solar units respectively. Reference to the evolutionary tracks of Schaller et al. (1992) for Y = 0.300 and z = 0.020 reveals that both stars are unevolved from the main sequence.

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