

## Radial velocities for contact binary systems – I. W Ursae Majoris and AW Ursae Majoris

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**Summary.** Radial velocity observations obtained by a numerical cross-correlation technique are presented for the two W Ursae Majoris type contact binaries W UMa and AW UMa. Spectroscopic mass ratios are determined, for the first time in the case of AW UMa, and compared with the photometric values.

The results obtained show a significant discrepancy in the case of W UMa but good agreement for AW UMa, and it is suggested that a possible explanation is in terms of line distortion.

### 1 Introduction

This paper is the first in a short series in which radial velocity curves for several contact binaries of W Ursa Majoris type are determined. These systems have been well observed photometrically in recent years but they have been neglected spectroscopically on account of the difficulty of obtaining accurate data for such short-period binaries due to large rotational broadening and blending effects. Over 400 systems of this kind have been detected (Kukarkin *et al.* 1969) but only 21 of them have radial velocity curves, the majority of which are of poor quality as has been pointed out by Batten, Fletcher & Mann (1978).

In this investigation, the radial velocities of a number of these systems are obtained from higher dispersion spectra by means of a cross-correlation technique with the object of achieving more accurate results. The main aim of the work is to obtain improved mass ratios and to try to resolve the discrepancy between values deduced from spectroscopic work and those obtained from the models based on analysis of their light curves. This paper presents the results for the systems completed during the first series of observations. These are W UMa, the prototype of this class of binary systems, and AW UMa, which has the smallest known mass ratio.

### 2 Observations

The spectrograms were obtained at the Haute Provence Observatory using the coude spectrograph of the 193-cm reflector during the period 1979 April 11–19. The spectra have a dispersion of  $20 \text{ \AA mm}^{-1}$  and were obtained on baked IIA-O plates with an average exposure

Table 1. Measurements of radial velocity standards.

Star HD no.	SP	$V$ (km s <sup>-1</sup> )	$V \sin i$ (km s <sup>-1</sup> )	No. plates	Measured velocity (km s <sup>-1</sup> ) (mean $\pm$ sd)					
					CCF		LPF		LSM	
89449	F8IV	+ 6.5	16	3	+ 5.5	1.4	+ 6.2	0.8	+ 6.3	2.4
103095	G8V	-99.0	-	7	-98.8	4.7	-101.1	3.4	-	-
144579	G8V	-60.0	-	4	-60.3	4.9	- 61.8	3.2	-	-

CCF – Cross-correlation function method.

LPF – Computer assisted line profile fitting.

LSM – Long screw micrometer measurements.

time of about 25 to 30 min. Due to the short periods of these systems, this corresponds to a time resolution of approximately 0.05 of a cycle, which is not as good as had been expected because of the seeing conditions that prevailed during the observing run.

In addition to the spectra of the contact binaries, 14 plates of three IAU radial velocity standard stars (Sanford, Moore & Pearce 1950; Sanford & Pearce 1952; Pearce 1955) were obtained in order to provide a check on the accuracy of the system (Table 1) as well as standard spectra against which the programme spectra could be cross-correlated when determining the Doppler shifts.

### 3 Reductions

The high rotational broadening and possible line blending in the spectra of these contact binaries make it difficult to measure accurate Doppler shifts. In order to use the maximum amount of information contained within the spectrum and to obtain more objective results, the radial velocities were determined using a cross-correlation technique (Simkin 1974), the analogue form of which has been used successfully in radial velocity spectrometers (e.g. Griffin 1967; Da Costa *et al.* 1977; Baranne, Mayor & Poncet 1979).

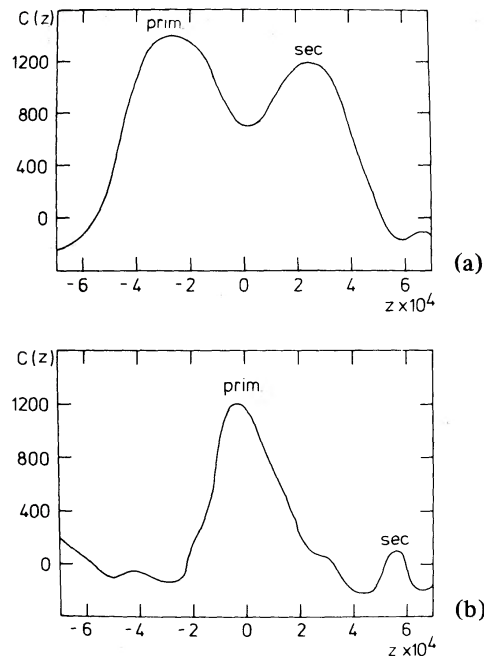
The Joyce Loebel microdensitometer at the University Observatory, St Andrews was used to scan the spectrograms. This is controlled by a Nova 820 mini-computer programmed in FORTH (Moore & Rather 1974) which was also used for the data reduction (McLean 1981). Details of the system and reduction packages available were presented at a recent image-processing conference (Davenhall *et al.* 1980). The digitized spectral data are then processed by Fourier noise filtering (Brault & White 1971), normalized to the continuum, and a wavelength calibration obtained by fitting a least-squares polynomial in terms of the wavelength to the measured position of the comparison arc lines (Peterson 1979). All plates were scanned in the manner, Fe comparison spectrum (side 1), stellar spectrum, Fe comparison spectrum (side 2). The Doppler shift between the observed and rest wavelengths can be represented as a linear displacement with the spectrum plotted as a function of  $\log \lambda$ , where the shift is given by

$$z = \log [1 + v/c] .$$

The radial velocity of a star may be determined by cross-correlating the stellar spectrum under study  $S(\log \lambda)$  with that of a standard or prototype spectrum  $P(\log \lambda)$ , which is of similar spectral type, with known radial velocity and preferably obtained on the same spectrograph under the same conditions of seeing and extinction.

The cross-correlation function

$$C(z) \equiv \int P(\log \lambda) S(\log \lambda + z) d(\log \lambda)$$



**Figure 1.** Examples of cross-correlation functions for representative spectra of the contact binaries. (a) W UMa (phase = 0.75). (b) AW UMa (phase = 0.21).

has a maximum value when the spectrum  $S(\log \lambda)$  has been shifted by the amount  $z$  so that it coincides with  $P(\log \lambda)$ . In the case of a binary system, two peaks will be observed in this function and their positions will give the velocity of each component. An example of this is shown in Fig. 1.

Variations of up to half of one letter class between the spectral types of the standard and programme spectra only increases the noise rather than altering the overall shape of the cross-correlation function. A spectrogram of the radial velocity standard HD 89449 (F5) was used as the standard spectrum for both W UMa (F8–G0) and AW UMa (F0–F2). In practice, it was found necessary to use the section of spectrum  $\lambda\lambda 4125\text{--}4325$  which did not contain the hydrogen lines which are heavily blended and so strong that they would otherwise dominate and distort the cross-correlation function.

Examination of the spectra showed that the weaker metallic lines were unblended at all phases away from the eclipses so that line blending would not affect the velocities obtained. It should also be noted that there were no Ca II emission features visible in the spectra of either system at the time of observation.

The internal accuracy of the reduction technique is about  $1\text{--}2\text{ km s}^{-1}$  but a more realistic estimate of the external error was obtained by the repeated measurement of several plates which gave a standard deviation of  $2\text{--}3\text{ km s}^{-1}$  for the radial velocity standards and  $8\text{--}10\text{ km s}^{-1}$  for the contact binaries. In addition, measurement of several plates using a long-screw micrometer and also by computer-aided line-profile fitting established that there is no systematic deviation from the standard radial velocity system (Table 1).

The solution to the radial velocity curves obtained was carried out using Irwin's (1973) differential-correction version of Wilson's (1941) method, in which the mass ratio and systemic velocity are obtained by a least-squares technique. It is then possible to derive the values of the semi-amplitudes  $K_1$  and  $K_2$ . In practice, data points near eclipse are removed as some distortion due to rotational velocity may be present. The assumption of circular orbits is made on the basis of the appearance of the light curves in which the secondary

eclipse occurs at phase 0.5. This would be expected on account of the tidal interaction between the components of a contact system.

## 4 Results

### 4.1 W UMa

There have been several previous determinations of the radial velocity curves for this system (Adams & Joy 1919; Popper 1950; Struve & Horak 1950; Binnendijk 1967; Worden & Whelan 1973) which show a large variation in the spectroscopic elements obtained. The most recent of these by Worden & Whelan ascribe this to inaccuracies arising from difficulties in

Table 2. Radial velocity observations of W UMa.

Plate no.	Hel J.D. 2443900. +	Phase	Primary velocity (km s <sup>-1</sup> )	Secondary velocity (km s <sup>-1</sup> )
V4254	75.3186	0.65	-105	+138
V4255	75.3344	0.69	-142	+196
V4256	75.3532	0.75	-194	+186
V4257	75.3728	0.81	-140	+210
V4258	75.3969	0.88	-95	+147
V4259	75.4169	0.94	-70	+32
V4260	75.4457	0.02	-24	-
V4261	75.4740	0.11	+58	-185
V4262	75.5044	0.20	+72	-294
V4263	75.5274	0.27	+42	-263
V4272	76.3240	0.66	-140	+126
V4273	76.3460	0.72	-175	+200
V4274	76.3622	0.77	-178	+207
V4275	76.3864	0.84	-146	+216
V4276	76.3989	0.88	-103	+139
V4278	76.4352	0.99	-65	-
V4279	76.4664	0.08	+21	-166
V4280	76.4885	0.15	+44	-230
V4281	76.5114	0.22	+92	-257
V4282	76.5385	0.30	+84	-284

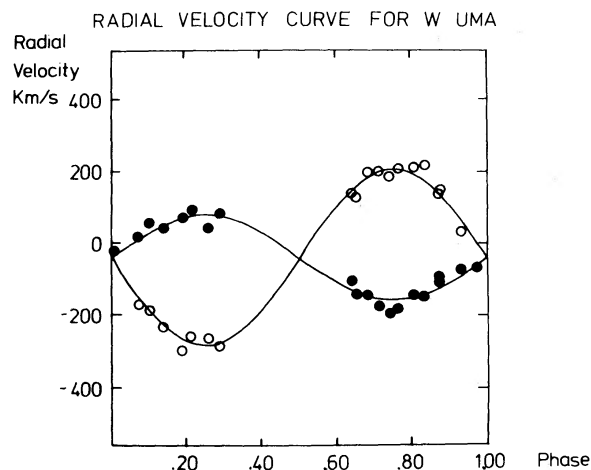


Figure 2. Radial velocity observations and solution for W UMa. Filled circles represent the primary component and open circles the secondary. The solid lines are the adopted solution.

**Table 3.** Spectroscopic elements for W UMa.

Element	Unit	Worden & Whelan (1973)	Present work
$P$	day	0.333638 (assumed)	
$V_0$	$\text{km s}^{-1}$	$-42.3 \pm 3$	$-37.8 \pm 4$ (s.d.)
$K_1$	$\text{km s}^{-1}$	$131.3 \pm 2$	$119 \pm 6$
$K_2$	$\text{km s}^{-1}$	$243.0 \pm 3$	$244 \pm 9$
$a_1 \sin i$	$10^6 \text{ km}$	$0.60 \pm 0.01$	$0.55 \pm 0.03$
$a_2 \sin i$	$10^6 \text{ km}$	$1.11 \pm 0.02$	$1.12 \pm 0.04$
$a \sin i$	$10^6 \text{ km}$	$1.72 \pm 0.03$	$1.67 \pm 0.05$
$M_1 \sin^3 i$	$M_\odot$	$1.18 \pm 0.05$	$1.11 \pm 0.11$
$M_2 \sin^3 i$	$M_\odot$	$0.64 \pm 0.03$	$0.54 \pm 0.05$
$(M_2 + M_1) \sin^3 i$	$M_\odot$	$1.82 \pm 0.06$	$1.65 \pm 0.02$
$M_2/M_1$	–	$0.54 \pm 0.03$	$0.49 \pm 0.03$

measurement. Indeed, their solution with a large number of data points and good time resolution gave a significant improvement in accuracy. Their spectra were at a dispersion of  $63 \text{ \AA mm}^{-1}$  and were measured using an oscilloscope comparator whereas in the present work a higher dispersion of  $20 \text{ \AA mm}^{-1}$  was used and a more objective numerical technique was employed to determine the radial velocities. On the other hand, we have poorer time resolution and fewer data points.

The individual observations are given in Table 2 and Fig. 2 while the resulting spectroscopic elements are in Table 3.

The important parameter, the mass ratio, can be seen to be slightly lower than that obtained by Worden & Whelan, but it is in much better agreement with their determination than earlier investigations. Similarly, the systemic velocity is slightly different, but it is likely that the differences are due to errors of measurement rather than any variation in the system itself.

**Table 4.** Radial velocity observations of AW UMa.

Plate no.	Hel. J.D. 2443900.+	Phase	Primary velocity ( $\text{km s}^{-1}$ )	Secondary velocity ( $\text{km s}^{-1}$ )
V4247	74.4965	0.68	– 5	– 349
V4248	74.5261	0.74	+16	– 381
V4249	74.5478	0.79	– 16	– 435
V4292	78.4820	0.76	+12	– 450
V4293	78.4912	0.78	0	– 389
V4294	78.4995	0.80	+12	– 433
V4295	78.5087	0.82	+27	– 443
V4296	78.5191	0.85	0	– 447
V4297	78.5287	0.87	– 29	– 295
V4298	78.5404	0.89	+ 5	–
V4305	80.3370	0.99	– 3	–
V4306	80.3607	0.04	– 26	–
V4307	80.3819	0.09	– 51	+ 263
V4308	80.4036	0.14	– 32	+ 303
V4309	80.4357	0.21	– 65	+ 374
V4310	80.4661	0.28	– 62	+ 381
V4311	80.4961	0.35	– 55	+ 303
V4312	80.5257	0.42	– 40	+ 305
V4313	80.5578	0.49	+ 1	–
V4319	81.3473	0.29	– 25	+ 373

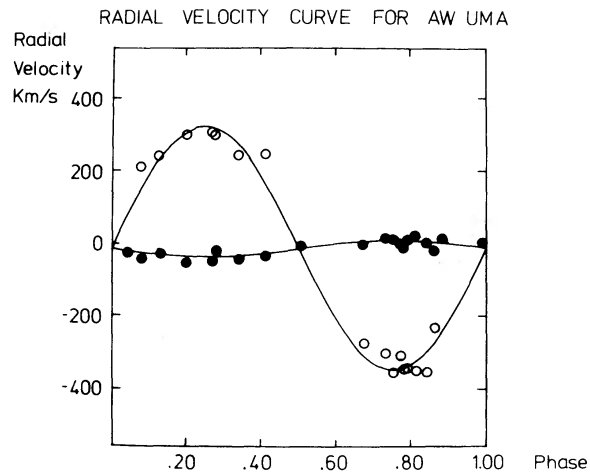


Figure 3. Radial velocity observations and solution for AW UMa. Filled circles represent the primary component and open circles the secondary. The solid lines are the adopted solution.

#### 4.2 AW UMa

The only previous spectroscopic study of this system was by Paczynski (1964) after the system was discovered to be a W UMa type variable. At that time, only the unresolved H $\delta$  and H $\gamma$  lines could be measured so that the single velocity curve that was obtained was rather inconclusive. In this study, however, the much weaker secondary spectrum was detected. The secondary velocities are less accurate due to the extreme weakness of the features since the light ratio is of the order 10:1, but it was only the use of a cross-correlation technique which enabled a useful measurement to be obtained at all.

The individual observations are given in Table 4 and Fig. 3 and the computed elements in Table 5. A comparison with Paczynski's values of  $K_1$  and  $V_0$  is not appropriate, considering the uncertainty introduced by measuring the light centroid of unresolved double lines.

### 5 Discussion

It is a common result that the mass ratios obtained from spectroscopic data disagree significantly with the values from the analysis of light curves or, more recently, from solutions using the light-curve synthesis technique. When one compares the values obtained in this paper with the photometric values listed in Table 6 it can be seen that the mass ratio for

Table 5. Spectroscopic elements for AW UMa.

Element	Unit	Paczynski (1964)	Present work
$P$	day	0.438732 (assumed)	
$V_0$	km s <sup>-1</sup>	- 1 $\pm$ 2	- 17 $\pm$ 7 (s.d.)
$K_1$	km s <sup>-1</sup>	28 $\pm$ 3	29 $\pm$ 8
$K_2$	km s <sup>-1</sup>	—	423 $\pm$ 80
$a_1 \sin i$	10 <sup>6</sup> km	—	0.18 $\pm$ 0.05
$a_2 \sin i$	10 <sup>6</sup> km	—	2.56 $\pm$ 0.48
$a \sin i$	10 <sup>6</sup> km	—	2.74 $\pm$ 0.93
$M_1 \sin^3 i$	$M_\odot$	—	3.94 $\pm$ 1.22
$M_2 \sin^3 i$	$M_\odot$	—	0.27 $\pm$ 0.10
$(M_1 + M_2) \sin^3 i$	$M_\odot$	—	4.21 $\pm$ 1.29
$M_2/M_1$	—	—	0.07 $\pm$ 0.02

**Table 6.** Photometric mass ratios.

System	$q_{\text{phot}}$	Author
W UMa	$0.400 \pm 0.005$	Hutchings & Hill (1973)
	$0.428 \pm 0.006$	Mochnecki (1972)
	$0.428 \pm 0.005$	Nagy (1974)
	$0.45 \pm 0.02$	Hilditch (1981)
AW UMa	$0.079 \pm 0.008$	Mochnecki & Doughty (1972)
	$0.0716 \pm 0.0005$	Wilson & Devinney (1973)
	$0.0795 \pm 0.0005$	Lucy (1973)
	$0.0766 \pm 0.0008$	Nagy (1974)

W UMa is still significantly higher whereas that for AW UMa is in surprisingly good agreement, perhaps fortuitously so, considering the possible error in the secondary velocities.

It has been suggested that the presence of a third body (Whelan, Mochnecki & Worden 1974) would explain the discrepancy in the case of W UMa but, of course, this could not be invoked in every case. It cannot, however, be discounted at this stage until the behaviour of the period variations is established from the behaviour of the times of minima.

The problems associated with measuring radial velocities from broad and blended spectral lines in contact binaries have been investigated by Hutchings (1973), who found that the measured spectroscopic mass ratios may not be reliable. This is due to line-profile distortion as a result of variable temperature, gravity, surface brightness and the velocity distribution due to rotation over the visible surface of the two non-spherical stars. Thus, the measured velocities do not correspond to those of the centres of mass rotating in a Keplerian orbit around their common centre of gravity.

Hutchings computed line profiles taking into account the variation of surface parameters and the geometry from a previous model which has been used for light curve synthesis (Hutchings & Hill 1973). One of the systems discussed was W UMa, and Hutchings found that although line blending was no problem for the metallic lines, the stellar distortion led to an overestimate of  $K_1$ . His model for this system has a mass ratio of 0.40 which gave a predicted spectroscopic value of 0.47, which is in better agreement with the observed values. Unfortunately, this procedure has not been carried out for AW UMa. However, since the mass ratio is so small, it might be plausible to expect that stellar distortion is likely to be less significant in altering the ratio of the semi-amplitudes so that the spectroscopic value will be closer to the photometric value as, indeed, has been found. We consider that this technique of computing synthetic radial velocity curves, in addition to light curves, is the most promising approach to explain the mass-ratio discrepancies for the majority of systems, although the possibility of a third body is not ruled out in the case of W UMa. This technique should be extended to many more systems.

Accurate spectroscopic data are needed for many more systems to improve our understanding of this class of binary system. To this end, spectroscopic data have been obtained for several more systems and reduction of this data is currently in progress.

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## References

- Adams, W. S. & Joy, A. H., 1919. *Astrophys. J.*, **49**, 186.  
 Baranne, A., Mayor, M. & Poncet, J. L., 1979. *Vistas Astr.*, **23**, 279.  
 Batten, A. H., Fletcher, J. M. & Mann, P. J., 1978. *Publs Dom. Astrophys. Obs.*, **15**, no. 5.  
 Binnendijk, L., 1967. *Publs Dom. Astrophys Obs.*, **13**, no. 3.  
 Brault, J. W. & White, O. R., 1971. *Astr. Astrophys.*, **13**, 169.  
 Da Costa, G. S., Freeman, K. C., Kalnajs, A. J., Rodgers, A. W. & Stapinski, T. E., 1977. *Astr. J.*, **82**, 810.  
 Davenhall, A. C., Bunclark, P. S., Fraser, C. W., McLean, B. J., Stapleton, J. R. & Stewart, G. C., 1981. *J. British Interplanetary Soc.*, in press.  
 Griffin, R. F., 1967. *Astrophys. J.*, **148**, 465.  
 Hilditch, R. W., 1981. *Mon. Not. R. astr. Soc.*, **196**, 305.  
 Hutchings, J. B., 1973. *Astrophys. J.*, **180**, 501.  
 Hutchings, J. B. & Hill, G., 1973. *Astrophys. J.*, **179**, 539.  
 Irwin, J. B., 1973. *Astrophys. J.*, **179**, 241.  
 Kukarkin, B. V., Kholopov, P. N., Efremov, Yu. N., Kukarkina, N. P., Kurochka, N. E., Medvedeva, G. I., Perova, N. B., Fedorovich, V. P. & Frolov, M. S., 1969—. *The General Catalogue of Variable Stars*, and supplements.  
 Lucy, L. B., 1973. *Astrophys. Space Sci.*, **22**, 381.  
 Mochnecki, S. W., 1972. *Bull. Am. astr. Soc.*, **4**, 399.  
 Mochnecki, S. W. & Doughty, N. A., 1972. *Mon. Not. R. astr. Soc.*, **156**, 51.  
 McLean, B. J., 1981. *Thesis*, in preparation.  
 Moore, C. H. & Rather, E. D., 1974. *Astr. Astrophys.*, **15**, 529.  
 Nagy, T. A., 1974. *PhD thesis*, University of Pennsylvania.  
 Paczynski, B., 1964. *Astrophys. J.*, **69**, 124.  
 Pearce, J. A., 1955. *Trans. IAU* **9**, 441.  
 Peterson, D. M., 1979. *Publs astr. Soc. Pacif.*, **91**, 546.  
 Popper, D. M., 1950. *Publs astr. Soc. Pacif.*, **62**, 115.  
 Sanford, R. F., Moore, J. H. & Pearce, J. A., 1950. *Trans. IAU* **7**, 312.  
 Sanford, R. F. & Pearce, J. A., 1952. *Trans. IAU* **8**, 452.  
 Simkin, S. M., 1974. *Astr. Astrophys.*, **31**, 129.  
 Struve, O. & Horak, H. G., 1950. *Astrophys. J.*, **112**, 178.  
 Whelan, J. A. J., Mochnecki, S. W. & Worden, S. P., 1974. *Mon. Not. R. astr. Soc.*, **168**, 31.  
 Wilson, O. C., 1941. *Astrophys. J.*, **93**, 29.  
 Wilson, R. E. & Devinney, E. J., 1973. *Astrophys. J.*, **182**, 539.  
 Worden, S. P. & Whelan, J. A. J., 1973. *Mon. Not. R. astr. Soc.*, **163**, 391.