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Absolute dimensions and evolutionary status of UW CMa

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Summary. Photoelectric *B* and *V* light curves of close binary system UW Canis Majoris (O8.5 If + O–B) obtained by Doss are analysed. Combining the photoelectric elements and the spectroscopic orbit by Struve *et al.* absolute dimensions of the system are determined. The mass of the bright primary (O8.5 If) component is found to be $19.3M_{\odot}$ and that of the faint secondary to be $23.2M_{\odot}$. The primary has filled the Roche lobe and it is 1–2 mag over-luminous for its mass. The massive secondary component is most likely a main sequence star. Comparison with the theoretical evolutionary models of massive close binary systems undergoing case A of mass exchange indicate that UW CMa is close to the contact stage of evolution.

1 Introduction

UW Canis Majoris (O8.5 If + O–B) is one of the interesting massive early-type close binary systems. Pearce (1932) and Struve *et al.* (1958a) detected the spectrum of the fainter secondary component and found it to be more massive than the brighter primary – a situation similar to that found in HD 47129 and AO Cas (Abhyankar 1959). Spectroscopically, UW CMa has been studied in considerable detail, but not enough attention was paid to the study of light variations. Gaposchkin (1936) and Seyfert (1941) studied the light variations photographically; the only photoelectric observations of UW CMa available are the ones made by Doss (1967) at the Kodaikanal Observatory with the 20-cm Cooke refractor. In this paper the results of an analysis of the photoelectric observations of UW CMa are reported.

2 Light curves

The individual *B* and *V* observations listed by Doss (1967) are grouped into normal points and are given in Table 1. Phases listed in Table 1 are computed from the following ephemeris: JD Hel. min I = 2439164.176 + $4^{\mathrm{d}}.393423$E.

Primary depths are found to be 0.44 and 0.45 mag in *B* and *V* respectively. The depth of the secondary minimum is 0.39 mag in *B* and also in *V*. Colour index changes for the binary are insignificant throughout the cycle. The mean colour index $(B-V)$ is found to be -0.112 mag. The *B* and *V* light curves (Fig. 1) show that the ascending and descending

Table 1. Normal points.

Yellow observations of UW CMa

Phase	*V*	*N*	Phase	*V*	*N*	Phase	*V*	*N*
0.0020	5.289	4	0.2635	4.862	5	0.6432	4.969	4
0.0065	5.268	4	0.2830	4.847	5	0.6552	4.910	2
0.0151	5.224	3	0.3048	4.926	5	0.6630	4.912	4
0.0205	5.226	5	0.3138	4.919	3	0.6728	4.900	4
0.0224	5.276	4	0.3238	4.918	5	0.6822	4.844	4
0.0265	5.210	4	0.3535	4.988	5	0.7034	4.854	3
0.0313	5.169	6	0.3728	5.025	3	0.7316	4.840	5
0.0378	5.198	6	0.3996	5.067	4	0.7971	4.868	5
0.0426	5.167	7	0.4169	5.101	5	0.8365	4.881	2
0.0455	5.164	5	0.4737	5.214	5	0.8664	4.894	3
0.0513	5.156	5	0.4848	5.237	6	0.8854	4.997	4
0.0592	5.150	4	0.4967	5.243	3	0.9089	5.104	5
0.0728	5.084	6	0.5007	5.250	2	0.9280	5.089	4
0.0825	5.091	3	0.5139	5.248	2	0.9394	5.131	4
0.1006	4.989	2	0.5239	5.184	2	0.9716	5.278	2
0.1512	4.929	4	0.5337	5.150	2	0.9833	5.244	2
0.1750	4.888	5	0.5469	5.132	4	0.9896	5.301	4
0.1943	4.859	5	0.5546	5.139	3	0.9987	5.331	3
0.2513	4.854	5	0.5982	4.996	3			

Blue observations of UW CMa

0.0016	5.165	3	0.2457	4.735	4	0.5544	4.972	3
0.0053	5.161	4	0.2621	4.732	5	0.5891	4.832	2
0.0156	5.114	4	0.2740	4.738	4	0.6376	4.989	5
0.0210	5.139	6	0.2903	4.771	4	0.6602	4.766	6
0.0241	5.087	5	0.3160	4.780	4	0.6772	4.736	5
0.0284	5.053	3	0.3341	4.782	3	0.7067	4.771	5
0.0317	5.067	3	0.3560	4.886	4	0.7422	4.752	3
0.0369	5.069	6	0.3726	4.887	3	0.7930	4.716	3
0.0411	5.074	6	0.4013	4.972	5	0.8292	4.769	5
0.0435	5.061	5	0.4226	4.985	3	0.8591	4.782	2
0.0498	5.056	5	0.4715	5.076	4	0.8819	4.838	5
0.0543	4.998	3	0.4787	5.131	3	0.9006	4.895	3
0.0728	4.974	3	0.4830	5.112	3	0.9101	4.929	3
0.0820	4.958	3	0.4880	5.110	2	0.9263	4.864	2
0.1051	4.892	3	0.4960	5.102	2	0.9392	4.977	4
0.1510	4.803	4	0.4999	5.136	3	0.9722	5.118	4
0.1710	4.771	3	0.5135	5.154	2	0.9846	5.145	3
0.1828	4.783	3	0.5308	5.047	3	0.9904	5.172	3
0.1932	4.737	2	0.5466	5.015	4	0.9987	5.184	2

branches of both the minima are not symmetrical; in particular in the secondary minimun the fall to minimum is less steep than the rise. Light curves indicate a circular orbit contrar to the orbit derived from the spectroscopic data (Struve *et al.* 1958a). This anomalou orbital eccentricity and the asymmetric light variations are the result of gas streams in th system.

3 Rectification of the light curves

To normalize the outside eclipse light to unity, values of 4.850 and 4.732 mag are subtracte from the *V* and *B* normal points respectively. A reasonable preliminary value of 48° for th external tangency θ_e was determined by a graphical method (Russell & Merrill 1952

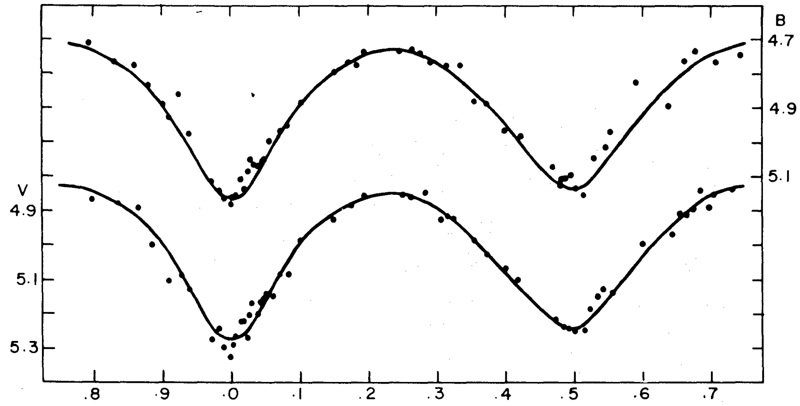

Figure 1. Light variations of UW CMa. The filled circles are observed normal points and the solid line is the computed curve.

Normal points in the phase interval 48 to 132° and 228 to 312° are represented by a formula of the form:

$$l = A_0 + \sum_{n=1}^{4} A_n \cos(n\theta) + \sum_{n=1}^{4} B_n \sin(n\theta).$$

Fourier coefficients obtained from the least-squares solution for $n = 2$ are listed in Table 2 along with their probable errors. In the case of the B light curve, the sine terms are fairly small indicating the absence of asymmetry in the two maxima. Coefficients listed in Table 2 show that Al (the differential reradiation coefficient), the coefficient of the $\cos\theta$ term, is positive and large which is contrary to theory. In several W UMa type systems and few early-type systems, Al is found to be positive when analysis is restricted to terms up to $\cos 2\theta$ and $\sin 2\theta$. Merrill (1970) has shown that a valid estimate of the reflection effect can be obtained by including higher harmonics in the analysis of the outside eclipse light variations of W UMa systems. In the case of UW CMa, whose light curve is similar to that of a W UMa system, we find that Al is positive and increased in magnitude when the analysis was carried with $n = 3$ and 4 in the above equation. In both cases the coefficients of the $\cos 3\theta$ term is significant and positive. There is no general theory to account for the positive values of Al in the outside eclipse light variations. The cases may be manifold. The shape of the stars may deviate from the ellipsoidal model and/or the observed light variations are significantly affected by the gas streams and the gaseous envelope around the system.

The light curves were rectified by the method of Russell & Merrill (1952). Rectification was carried for both reflection and ellipticity using the equation

$$l_r = \frac{l_{obs} - B_1 \sin\theta - B_2 \sin 2\theta + C_0 - A_1 \cos\theta + C_2 \cos 2\theta}{(A_0 + C_0) + (A_2 + C_2)\cos 2\theta}$$

Table 2. Coefficients for light outside eclipses of UW CMa.

Filter	A_0	A_1	A_2	B_1	B_2
V	+ 0.8922	+ 0.0333	−0.1162	−0.0131	+ 0.0058
	± 74	± 67	± 105	± 32	± 40
B	+ 0.8885	+ 0.0266	−0.1191	−0.0083	+ 0.0024
	± 110	± 101	± 157	± 48	± 60

where $C_0 = 3C_2 = 0.09 \sin^2 \theta_e$. The photometric ellipticity coefficient z was calculated fror expressions given by Russell & Merrill (1952). A mean value of 0.25 for z is adoptec Rectification of phase is made using the equation

$$\sin^2 \Theta = \frac{\sin^2 \theta}{1 - z \cos^2 \theta}.$$

4 Solution of the light curves

Before proceeding with the solution itself, the character of the eclipse needs to be deteı mined. From the observed light curves it can be seen that the eclipses are partial. Th spectral type and radial-velocity data of UW CMa indicate that the most luminous, and als hotter, component is the star eclipsed at principal minimum and must also be the larger c the two. Also from the χ functions (Merrill 1950) it is found that the primary minimum i due to transit eclipse. Depth and shape relations were obtained for each minimum from th rectified V and B light curves. No unique intersection of depth relation with shape relatio was found. Therefore, using k, α_0^{oc} and α_0^{tr} found from the depth relation, a series of thec retical light curves in B and V were computed with k ranging from 0.70 to 0.97 with a interval of 0.03. Each time the computed light curves were derectified and were compare with the observed light variations. After obtaining a reasonable agreement between th observed and computed light curves, the rectified eclipse depths were slightly adjusted an the above-mentioned procedure of light curve computation was repeated. The final gec metric and photometric elements, which represent the observed light variations satisfactoril are listed in Table 3 and the computed light curve is shown in Fig. 1. The present photc metric solution can be considered as a preliminary one in view of the large positive value c the reflection coefficient Al, asymmetric light curve and spectroscopic evidence for th presence of gas streams in the system. Computations were also made assuming that th primary minimum is due to an occultation eclipse, but the agreement between observed an computed light curves was not satisfactory.

5 Absolute dimensions

The geometrical and physical parameters of the system given in Table 4 are computed b combining the photometric elements listed in Table 3 and the following spectroscop orbital elements obtained by Struve *et al.* (1958a).

$K_1 = 222.7$ km/s
$K_2 = 185$ km/s
$a_1 \sin i = 1.338 \times 10^7$ km
$f(m) = 4.977$.

Spectral type and effective temperature for the brighter component are taken from Conti Alschuler (1971) and Conti (1975) respectively. The masses of the components determine from the radial-velocity amplitudes and from the mass function are as follows:

	$M_1/M_\odot$	$M_2/M_\odot$
from K_1 and K_2	19.3	23.2
assuming the mass ratio $q = 1$	27.7	27.7
assigning mass for the primary component (Conti & Burnichon 1975)	30	29

Table 3. Geometric and photometric elements.

Ratio of the radii		k	0.843
Semiaxes of the greater star		a_g	0.431
		b_g	0.388
		c_g	0.357
Semiaxes of the smaller star		a_s	0.363
		b_s	0.345
		c_s	0.330
Orbital inclination corrected for polar flattening		j	63°.5
		B	V
Limb darkening coefficient (assumed)		0.4	0.4
Fractional light of the greater star	L_g	0.77	0.81
Fractional light of the smaller star	L_s	0.23	0.19

Table 4. Dimensions and physical parameters.

	Primary		Secondary
Mass	$19.3 M_\odot$		$23.2 M_\odot$
a (separation)		$39.3 R_\odot$	
Radius	$15.4 R_\odot$		$13.6 R_\odot$
Roche radius	$14.3 R_\odot$		$15.6 R_\odot$
Spectral type	O8.5 If		O–B
T_{eff}	33 500 K		
M_{bol}	−8.8		−6.6

Struve *et al.* (1958a) derived the radial-velocity amplitude K_2 of the secondary component from the velocity measurements of the absorption line He I 5876. They found that the line intensity of He I 5876 changes drastically with phase and it is near the limit of visibility when the secondary is receding from the observer. Because of these complications, and the large scatter in the velocities of the secondary component, the error in the derived mass could be large. However, we adopt the masses determined from K_1 and K_2 rather than those estimated from the mass function which involves assuming mass for the primary (O8.5 If) component.

From the masses and radii of the components given in Table 4 we find that the brighter primary component has filled the Roche lobe and it is less massive than the fainter secondary. Also the primary is 1–2 mag overluminous for its mass if we assign a value of −10 for M_{bol} (absolute bolometric magnitude) obtained from the recent calibrations by Panagia (1973) and Conti (1975). From the brightness difference between the two components (Table 3), after correcting for reflection effect, M_{bol} of the secondary was found to be −6.6, whereas mass, radius and spectral type (O–B) indicate a value of −8.5. The secondary component appears to be underluminous for its mass.

6 Evolutionary status

There are at least a dozen early-type systems now known to have massive and underluminous secondary components. But here we consider massive O type semidetached systems having some characteristics similar to UW CMa. Systems listed in Table 5 share the following common properties:

(1) The radial-velocity amplitude of the faint secondary component is less than that of the bright primary.

Table 5. Peculiar O-type systems.

	Period (days)	Spectral type	$M_1/M_\odot$	$M_2/M_\odot$	$R_1/R_\odot$	$R_2/R_\odot$	$(R_1/R_\odot)_{crit}$	$(R_2/R_\odot)_{crit}$	$M_{1, bol}$	$M_{2, bol}$	Reference
HD 47129	14.4	O7.5 IIIf + O	58	64	–	–	43.8	45.9	–7.8	–7.8	1, 3
UW CMa	4.4	O8.5 If + O	19.3	23.2	15.4	13.6	14.3	15.6	–8.8	–6.6	
AO Cas	3.5	O9.5 III + O9.5 III	17.8	22.7	11.5	9.5	12.0	13.4	–7.9	–7.5	1, 4
V 448 Cyg	6.5	B1 Ib + O9.5 V	17.5	22.4	16.5	7.8	16.3	18.3	–6.8	–7.3	2, 5

(1) Abhyankar (1959).
(2) Ashbrook (1942).
(3) Hutchings & Cowley (1976).
(4) Hutchings & Hill (1971).
(5) Petrie (1956).

(2) The secondary component is more massive and underluminous for its mass and the primary component is either normal or overluminous for its mass.

(3) The bright primary component has filled the Roche lobe. (In the case of HD 47129 the picture is not clear.)

(4) Except in the case of V448 Cyg the spectral lines of the secondary are strongest at the phases when the secondary is approaching the observer (Struve *et al.* 1958b; Sahade 1962). This implies a stream of gaseous matter flowing from the brighter primary towards the secondary.

Sahade (1962) interpreted that the secondary component in these systems is old and is evolving towards the left in the HR diagram, while the primary (less massive and luminous component) is evolving to the right. This evolutionary scheme is not compatible with the recent studies of evolution of massive close binary systems (Paczynski 1971; Kippenhahn 1969 and Massevitch, Tutukov & Yungelson 1976). Systems listed in Table 5 are semi-detached with a mass ratio close to unity and the mass-losing components are approximately 1–2 mag overluminous for their mass. These properties indicate that UW CMa and similar systems are undergoing case A mass exchange. Benson's (1970) calculations showed that a majority of binaries undergoing case A mass exchange form contact systems. Mass exchange from the primary onto the secondary forces the secondary to expand and mass loss from the system decreases the separation between the components, leading to the contact stage. Recently Kippenhahn & Meyer-Hofmeister (1977) have shown that, during mass exchange, the star which is receiving mass increases its volume and the chance that two stars do not come in contact is diminished drastically. The orbital period, masses and critical period ($P_{\rm crit}$ from Fig. 7 of Kippenhahn & Meyer Hofmeister 1977) of UW CMa and similar systems (Table 5) indicate that they are almost in the contact phase of evolution. The mass-gaining secondary components in these systems are most likely main sequence stars of spectral types earlier than their mass-losing companions.

Ulrich & Burger (1976) and Flannery & Ulrich (1977) showed that shortly after contact the system enters a phase of rapid mass loss through the outer Lagrangian point L_2; further, the decrease in separation induced by the loss of angular momentum accelerates the mass loss rate. From ultraviolet observations McCluskey, Kondo & Morton (1975) and McCluskey & Kondo (1976) estimated a mass loss rate of about $3 \times 10^{-6} M_\odot$ per year. Hutchings (1976, 1978) gives a maximum rate of mass loss of the order $1.5 \times 10^{-5} M_\odot$/yr. This mass loss rate implies a period variation of the order of 0.1 s/yr. In due course, because of mass loss from the O8.5 If component, the close binary system UW CMa may pass through the stage having characteristics similar to BD +40° 4220 (Bohannan & Conti 1976) before ending up as a Wolf–Rayet binary system.

The cause for the underluminosity of the secondary component in the systems listed in Table 5 is not clear. From the rotational velocities of the primary components (Conti & Ebbets 1977) we find that they are rotating synchronously. The spectral lines of the secondary component seen and measured at several phases indicate that their rotational velocities are comparable to the rotational velocities of the primary components. In fact uniform rotation is expected to change the luminosity very little. Spectroscopic evidence for the existence of large-scale circumstellar matter in these early-type systems indicates that the apparent underluminosity could be due to electron scattering by a high-density electron cloud close to the secondary component. Observations do suggest the existence of such an electron cloud; for example the recent polarization measurements of AO Cas (Rudy & Kemp 1976 and Pfeiffer 1976) a system very much similar to UW CMa. Another observational evidence for the effect of gaseous matter on the secondary component can be cited here. The recent *OAO-2* observations of UW CMa (Eaton 1978) show that the secondary eclipse becomes deeper than the primary eclipse in the far ultraviolet. A similar phenomenon was observed in β Lyr by Kondo, McCluskey & Houck (1971). This indicates that the observed light variations are not just due to mutual eclipses of two simple stars. The gaseous matter close to the secondary component seems to radiate significantly in the far ultraviolet which comes into full play during the secondary minimum.

More quantitative information on the variation of absorption- and emission-line intensities of UW CMa with orbital phase and polarization measurements are needed to study the distribution of circumstellar matter in the orbital plane and its effect on the brightness of the secondary component. Multi-colour narrow-band photoelectric observations and analysis with light-curve synthesis techniques are highly desirable.

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