

MASS FLOW IN THE O7f BINARY UW CANIS MAJORIS. II.

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ABSTRACT

The far-ultraviolet spectrum of the UW CMa was obtained from the Princeton telescope spectrometer on the *Copernicus* satellite at about phase 0.25 in order to supplement earlier observations of the same kind made near phase 0.75. Analysis of the data shows that the high-temperature gas giving rise to the P Cygni features in the far-ultraviolet spectrum is located primarily around the entire binary system and does not share in the motion of either component. The effects of radiation pressure on the Roche (Jacobian) equipotential surfaces and in generating a stellar wind are discussed.

Subject headings: stars: eclipsing binaries — stars: individual — stars: mass loss — stars: Of-type

I. INTRODUCTION

The far-ultraviolet spectrum of the O7f star HD 57060 (= 29 CMa = UW CMa) was first observed in 1973 by McCluskey, Kondo, and Morton (1975), hereafter referred to as Paper I. A brief review of the previous photometric and spectroscopic studies of this eclipsing binary is given in Paper I. The 1973 observations were obtained primarily near phase 0.75 and showed that the dominant features in the far ultraviolet spectral region (950–1560 Å) of this binary are P Cygni lines. From the strength of the absorption component of these lines, a mass loss rate of about $3 \times 10^{-6} M_{\odot}$ per year was deduced.

The current set of observations were obtained around 1975 January 30 near phase 0.25. These observations were made at this phase in order to compare them with the 1973 observations near phase 0.75 so that any phase dependence of the characteristics of the P Cyg lines might be detected. In addition, such a comparison would permit verification of the identification of several absorption lines as originating near the photosphere of the O7f star, as an easily measured Doppler shift will have occurred if this is the case.

II. OBSERVATIONS

The current observations were obtained with the U2 spectrometer of the *Copernicus* Princeton University telescope (Rogerson, Spitzer, *et al.* 1973). The U2 spectrometer had a resolution of 0.2 Å, and the spectral range observed was 1010–1510 Å. The time

interval of data acquisition extended from phases 0.10 to 0.36. Phases, listed in Table 1, were computed from the light elements:

$$\text{Primary Minimum} = \text{JD } 2440877^{\text{d}}563 + 4^{\text{d}}393485 E,$$

which incorporate the recent OAO-2 observations of the time of minimum by Eaton (1974).

With the exception of the expected orbital Doppler shifts of the O7f photospheric lines, the 1975 spectrum is nearly the same as the 1973 spectrum. No significant changes in the velocities of the P Cygni absorption lines occurred. The emission component intensities are about the same, although the absorption line intensities seem to be somewhat weaker. The velocities of the P Cygni emission lines seem to be less positive in 1975 than in 1973 for some ions. This point is discussed below. An unidentified absorption line at 1100 Å in 1973 shifted to 1098 Å in 1975, thereby establishing itself as a photospheric line of the O7f star with a stationary wavelength of 1099 Å.

To review the line identifications of Paper I, the photospheric lines detected are N III (1006, 1183, 1184 Å), possible He II (1084 Å), and the unidentified line (1099 Å), all associated with the O7f component. No features associated with the O-B companion have been detected in the far-ultraviolet. The P Cyg lines have been identified as C III (977, 1175 Å), S IV (1062, 1073 Å), P V (1117 Å), Fe III + Si IV? (1122 Å), P V + Si IV? (1128 Å), N V (1238, 1242 Å), Si IV (1393, 1402 Å), and C IV (1549 Å).

III. DISCUSSION

The change in the radial velocity of the photospheric absorption lines clearly establishes them as belonging to the O7f star. In both 1973 and 1975, the radial velocities observed agree with the velocities predicted

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TABLE 1
SPECTRUM OF UW CANIS MAJORIS

LINE	λ_{LAB} (Å)	1973					1975				
		Phase	V_r (km s $^{-1}$)	V_m (km s $^{-1}$)	I_0/I_c		Phase	V_r (km s $^{-1}$)	V_m (km s $^{-1}$)	I_0/I_c	
S IV.....	A	1062.672	0.59	-840	-1460	0.13	0.11	-810	-1320	0.50	
	E			+490		1.44		+350		1.15	
S IV.....	A	1073.0	0.59	-750	-1420	0.12	0.12	-780	-1420	0.58	
	E			+510		1.60		+390		1.42	
He II.....	A	1084.942	0.71	+180?	...	0.45	0.12	-205	...	0.66	
Fe III + (Si IV)....	A	1123.7	0.74	-380	-780	0.59	0.15	-590	...	0.80	
	E			+160		1.10		0		1.22	
P V + (Si IV).....	A	1128.006	0.74	-210	-830	0.36	0.15	-430	-800	0.78	
	E			+640		1.14		+290		1.21	
C III.....	A	1175.7	0.76	-440	-1180	0.19	0.19	-490	-1200	0.64	
	E			+710		1.13		+360		1.39	
N III.....	A	1183.030	0.78	+220		0.60	0.19	-200	...	0.68	
N III.....	A	1184.544	0.78	+200		0.61	0.19	-200	...	0.68	
N V.....	A	1238.821	0.81	-830	-1630	0.12	0.25	-860	-1940	0.34	
N V.....	E	1242.804	0.81	+430		1.80	0.25	+470	...	1.43	
Si IV.....	A	1393.755	0.04	-830	-1450	~0	0.36	-830	-1700	0.76	
	E			+240		1.71		+230		1.71	
Si IV.....	A	1402.770	0.04	-750	-1230	~0	0.36	-800	-1600	0.57	
	E			+560		2.14		+260		1.80	

NOTE.—Table 1 is a comparison of radial velocities and relative line intensities in the far-ultraviolet spectrum of UW CMA near phases 0.25 and 0.75.

from the spectroscopic orbital elements. The O-B secondary component should not be detectable in the far-ultraviolet unless it is very nearly as hot as the primary star, so its undetectability is not unexpected. The absorption line at 1099 Å, attributable to the O7f star, proved very difficult to identify. There are several lines listed in various catalogs which are located near 1099 Å, but none of them, with one possible exception, appear consistent with the spectral type of O7f and the other observed lines. In the absence of any better candidates, we tentatively identify this line as Fe III at 1099.061 Å (Kelley and Palumbo 1973). The only problem with this identification is that numerous other Fe III lines occurring in this spectral region are not found.

Table 1 lists the laboratory wavelength, phase of observation, radial velocity of the line center, V_r , radial velocity of the blue edge of the P Cygni absorption component, V_m , and I_0/I_c , the ratio of the intensity of the line center to the continuum intensity for both the 1973 and 1975 observations. A comparison of the 1973 (phase 0.75) results with the 1975 (phase 0.25) results shows that the P Cyg absorption-line velocities have not changed. The radial velocity corresponding to the blue edge of these absorption features is also unchanged. The radial velocity of the center of the emission component seems to be significantly less positive in 1975 for S IV, Fe III, P V, and C III. This trend is not noted for N V and Si IV, but measurements are uncertain for these ions due to blending in the case of N V and the low intensity of the detectable continuum at the Si IV lines. The intensity of the emission lines relative to the continuum shows no significant change, but the P Cyg absorption is definitely weaker in 1975.

The behavior of the changes in emission-line

wavelength and the behavior of the P Cyg absorption strength are probably related. Presumably the center of the emission is shifted to longer wavelengths because of the shortward absorption. If the emission strengthened in 1975, the central wavelength would shift to shorter wavelength, i.e., toward the laboratory wavelength, and the absorption would be partially filled in by this increased emission and would weaken. However, the intensity of the emission relative to the continuum does not appear to have increased. On the other hand, the absorption may have weakened. This in turn would shift the center of the emission toward the laboratory wavelength as observed. It should again be noted that the expansion velocity of the material giving rise to the P Cygni features does not appear to have changed. In addition, note that the strengths of the O7f absorption lines show no changes larger than the errors in measuring them.

Two factors may be important in explaining the change in strength of the P Cygni absorption features. This variation may be related to phase. It is relatively minor, and any asymmetries in the outflow of mass from the O7f star and from the system, which could arise because of the companion star which is probably slightly more massive than this star, could easily give rise to such a phenomenon. Alternatively, since the two sets of observations are separated in time by 2 years, a variation in the outflow of mass from the O7f star may have occurred. At present it is impossible to ascertain the relative contributions of these effects.

The stationary radial velocities of the P Cygni absorption lines indicate that the gas cloud giving rise to these lines is not closely situated near either component but surrounds the entire binary system. A recent theoretical study (Kondo and McCluskey 1976) of the effects of radiation pressure on the Roche

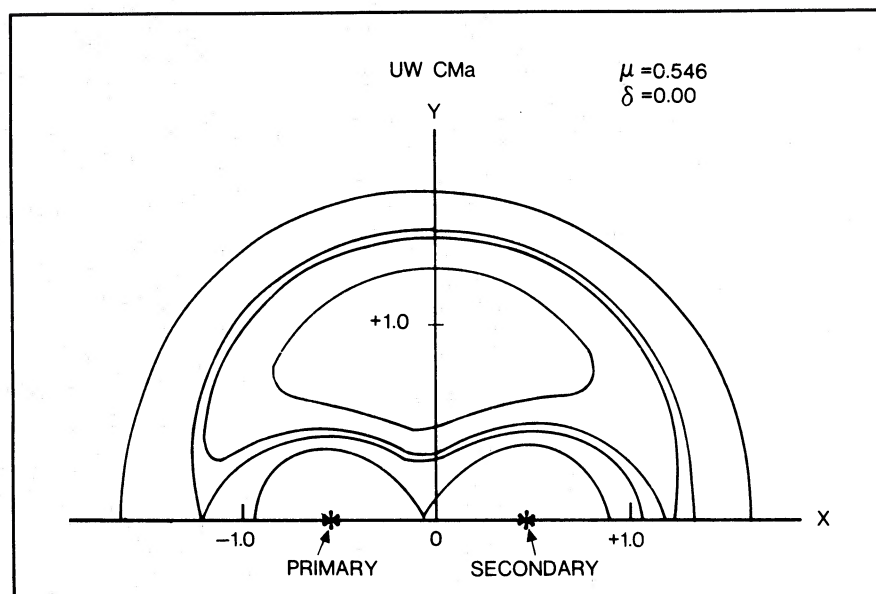


FIG. 1.—Equipotential surfaces for UW CMa. The parameter δ is the ratio of the radiation pressure force to the gravitational force for the O7f star. The parameter μ is the ratio of the mass of the O-B companion, which is the more massive but less luminous star, to the total mass of the system. The O7f star is to the left of the y -axis, and the distance between the stars is defined to be unity.

equipotential surfaces in a close binary system where one of the components is sufficiently hot (earlier than B0–B1) to create such a pressure, together with theoretical studies of stellar winds in early-type stars (e.g., Lucy and Solomon 1970; Castor, Abbott, and Klein 1975), suggest that this is to be expected in a system such as UW CMa. Following the work of Schuerman (1972), we have calculated the equipotentials for UW CMa with and without radiation

pressure. These respective cases are shown in Figures 1 and 2. The Roche critical surface, the traditional figure eight, is not present when the radiation pressure force is nonzero. As Figure 2 shows, the critical lobe opens behind the cooler component. The mass which flows through the inner Lagrangian point, L_1 , will have easy access to a region of space enveloping the entire system rather than tending to be limited to the region of the cooler star. As discussed in Kondo and

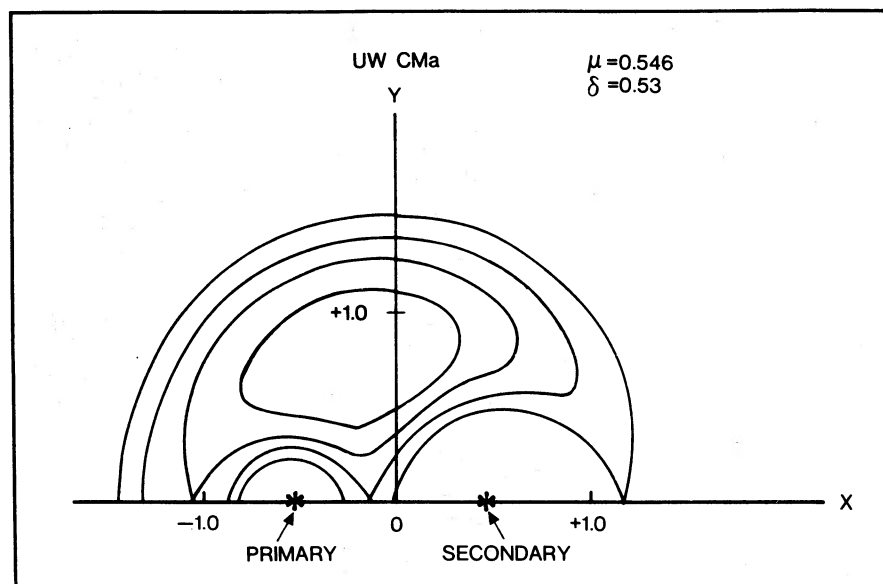


FIG. 2.—Same as Fig. 1. Note the effect of radiation pressure on the critical Roche lobe as compared with Fig. 1.

McCluskey (1976), this is somewhat academic in the case of an Of star. The radiation pressure has been assumed to arise solely from electron scattering in the equipotential calculations. This leads to a value of δ , the ratio of radiation pressure force to gravitational force, equal to 0.53 for the O7f star. Castor, Abbott, and Klein (1975) have shown that radiation pressure in the spectral lines of abundant elements can easily give a value of δ equal to or greater than unity. Thus, the Roche equipotentials are essentially of no importance in determining the mass flow or other system parameters. The mass flow is determined by the nature of the stellar wind created by the O7f star with the companion star and orbital angular momentum of the system causing deviations from a purely spherically symmetric outflow of mass. The fact that the P Cygni lines show no dramatic change at phase 0.25 as compared with phase 0.75 would seem to indicate that such perturbations are relatively small as regards the shape of the expanding circumbinary gas cloud. The observed expansional velocities and the mass loss rate of about $3 \times 10^{-6} M_{\odot}$ per year calculated for UW CMa in Paper I are in excellent agreement with the theoretical results advanced by Castor, Abbott, and Klein (1975).

The OAO-2 ultraviolet light curves (Eaton 1974) which showed an increase in the relative depth of the secondary minimum toward the shorter ultraviolet wavelengths may be partially accounted for in terms of the contribution of radiation from the hot circumbinary gas cloud. The viewing effect of an ellipsoidal emitting gas cloud, such as that discussed by Kondo and McCluskey (1974), could also explain the OAO-2 photometric results.

The UW CMa system is a close binary system undergoing a phase of fairly rapid mass loss. If a stellar wind is the dominant mechanism of mass loss, the matter leaving the O7f star attains the velocity of escape of the system close to the photosphere (Castor, Abbott, and Klein 1975). This implies that only a fraction of the mass is transferred to the O-B star. If the rate at which the period of revolution, about 4^d39, is changing is determined, it might be possible to determine the value of this fraction.

In a ground-based mass-loss survey, Hutchings (1976) has found a mass-loss rate of $8 \times 10^{-6} M_{\odot}$ per year for UW CMa, a result in good agreement with the value of $3 \times 10^{-6} M_{\odot}$ per year given in Paper I considering the differences between our methods. Hutchings (1975a) has also found an inverse correlation between mass loss and the strength of P Cygni features in *Copernicus* far-ultraviolet spectra of early-type supergiants and notes (Hutchings

1975b) that our UW CMa results agree with that trend.

In Paper I, we adopted a mass of about $20 M_{\odot}$ for the O7f star and $24 M_{\odot}$ for the companion by combining spectroscopic and photometric studies of UW CMa. Because of the difficulty in detecting the spectrum of the companion star and the shallowness of the eclipses, these values must be regarded as provisional. Morton (1975) brought to our attention a paper by Conti and Burnichon (1975) in which the masses of O and B-type stars are discussed. This study indicates that an O7f star should have a mass of about $30\text{--}35 M_{\odot}$. Hutchings (1976) plots a number of O and B-type stars, including UW CMa, on a theoretical H-R diagram. By comparing their position in this diagram with theoretical evolutionary tracks, their masses may be estimated. If an absolute bolometric magnitude of -10 is adopted for the O7f star, its mass would be about $50 M_{\odot}$ while a value of -9 yields a mass of $30 M_{\odot}$. Since these values of the absolute bolometric magnitude probably bracket the correct value, it seems possible that UW CMa is overluminous for its mass. If the O7f star is a post-main-sequence star, it is probably undergoing the later stages of case A mass exchange (Plavec 1970), and could easily be 1–2 mag overluminous.

Very little work has been done on mass flow in close binaries, particle or hydrodynamical, when the flow velocities are considerably higher than the orbital velocities of the stars. An exception is the interesting study of Limber (1971) on asymmetries in the envelopes of Wolf-Rayet stars in close binary systems.

We are currently computing the effect of radiation pressure on particle trajectories in the restricted three-body problem incorporating the effects of the two stars having eccentric orbits. This approach should lead to a qualitative estimate of the fraction of mass accreted by the companion star.

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