

EVOLVED CONTACT SYSTEMS OF SPECTRAL TYPE O. I. UW CANIS MAJORIS

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ABSTRACT

The light curves of UW CMa by Seyfert and by Ogata and Hukusaku were analyzed using the Wilson and Devinney approach. The system is found to be an evolved contact system. The unusual variations in the light curves may be caused by a highly nonuniform surface brightness of the common envelope. The photometric solution favors a mass ratio m_2/m_1 less than unity. The asymmetry in the radial velocity curves is not due to an eccentricity in the orbit but is caused by complicated effects arising from the closeness of the components. It is suggested that UW CMa has components of 46 and 34 $M_\odot$, making it one of the most massive contact systems known so far.

Subject headings: stars: early-type — stars: eclipsing binaries — stars: individual

I. INTRODUCTION

The early type binary UW CMa (= 29 CMa = HD 57060, O7f Ia + O) is one of the most interesting eclipsing systems. It was discovered to have a variable radial velocity by Frost (1906), and was found to be an eclipsing binary by Gaposchkin (1936). The spectroscopic orbit of the system has been investigated by Harper (1920); Pearce (1932); Struve and Sherman (1941); Struve *et al.* (1958); and Hutchings (1977). Photometric work has been reported by Gaposchkin (1936) and Seyfert (1941). Recently Ogata and Hukusaku (1977) obtained new photoelectric observations. Eaton (1977) is presently analyzing OAO photometry on this system. Detailed spectroscopic emission features and their interpretation have been published by McCluskey, Kondo, and Morton (1975); McCluskey and Kondo (1976); and Hutchings (1977). There are still many unresolved problems associated with this system: (1) there is an uncertainty in the mass ratio (0.75 by Pearce, 1.17 by Struve *et al.*, and 1.3 adopted by Hutchings); (2) the secondary minimum occurs at 0.5 phase whereas spectroscopic solutions generally indicate an eccentricity of 0.09 to 0.16 and a variety of arguments of perihelion (ω); (3) the absolute dimensions estimated by McCluskey, Kondo, and Morton suggest that the system is nearly in contact, which would favor a circular orbit; (4) there has been no reported period change, but the primary's radial velocity amplitude has shown significant changes through the years (Hutchings 1977). It was decided to reanalyze the existing observational material and investigate whether (i) the system is in

contact, (ii) the spectroscopic eccentricity is real, (iii) the period is constant, (iv) the existing observational evidence favors any particular mass ratio, and (v) the variation in the radial velocity amplitude of the primary indicates mass exchange between the components and/or mass loss from the system.

II. PHOTOMETRIC SOLUTIONS

To investigate whether this system is truly in contact, we adopted the Wilson and Devinney (1971) approach. Initially, we assumed that the system was detached. We started with the light curve program, using trial and error to obtain a set of parameters which marginally represented the observations. With this final set of trial parameters, we proceeded with the differential corrections program, starting with a detached configuration, mode 2 (see Leung and Wilson 1977 for a detailed description of the modes of operation), and let the calculations converge to a final solution. The solution usually went from the mode 2 configuration into a situation where one of the components overflowed its Roche surface. At this time, we changed to mode 4 or mode 5, in which the solution gradually evolved into a contact configuration. After that, we switched to mode 3. A final set of parameters was adopted when the corrections to the adjustable parameters were similar to or smaller than the probable errors.

Normal points were used for the analysis and were weighted according to the number of individual observations. We assumed that the gravity darkening coefficients $g_1 = g_2 = 1$; the bolometric albedos

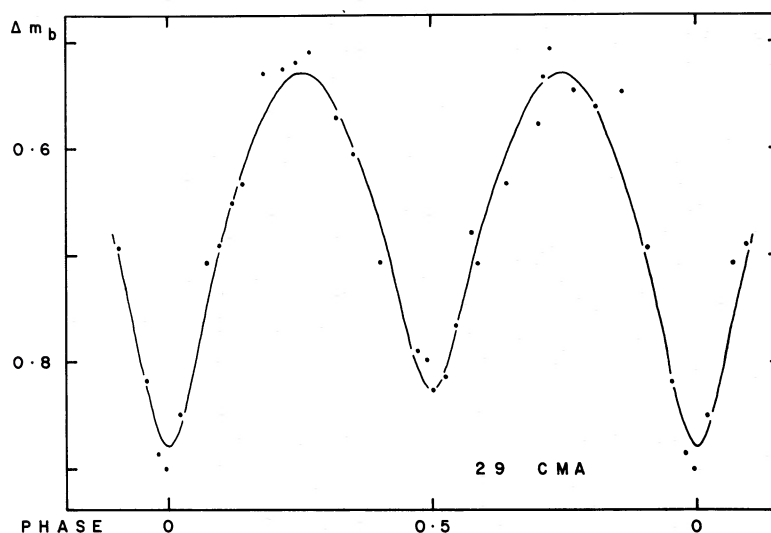


FIG. 1.—The photographic light curve of UW CMa by Seyfert (1941). The solid line is the computed light curve based on a contact configuration of mass ratio 0.751.

$A_1 = A_2 = 1$; the polar temperature of star 1, $T_1 = 43,000$ K; and the limb darkening coefficients $x_1 = x_2$ equal to 0.14 and 0.18 for the yellow and blue wavelengths, respectively (Carbon and Gingerich 1969). The adjustable parameters used were: inclination, i ; polar temperature of component 2, T_2 ; nondimensional surface potentials, Ω_1 and Ω_2 ; mass ratio, m_2/m_1 ; and luminosities of component 1, L_1 (yellow) and L_1 (blue). In the final (overcontact, mode 3) solutions, there is of course only one value of Ω to be adjusted.

Because of the complexity as well as the uncertainty of the light curve (in the case of Seyfert's photographic observations), the mass ratio could not be determined,

although the configuration is reliable (for discussion of this problem, see Leung and Schneider 1978).

In our approach, we have neglected the complicated effect of radiation pressure on potential surface, which may have substantial effect on extremely hot stars. McCluskey and Kondo (1976) discussed this problem as related to UW CMa.

a) Seyfert's Light Curve

The photographic observations by Seyfert were analyzed. As shown in Figure 1, the observations are very scattered and the coverage is poor. As is to be expected from data of this quality, no unique mass

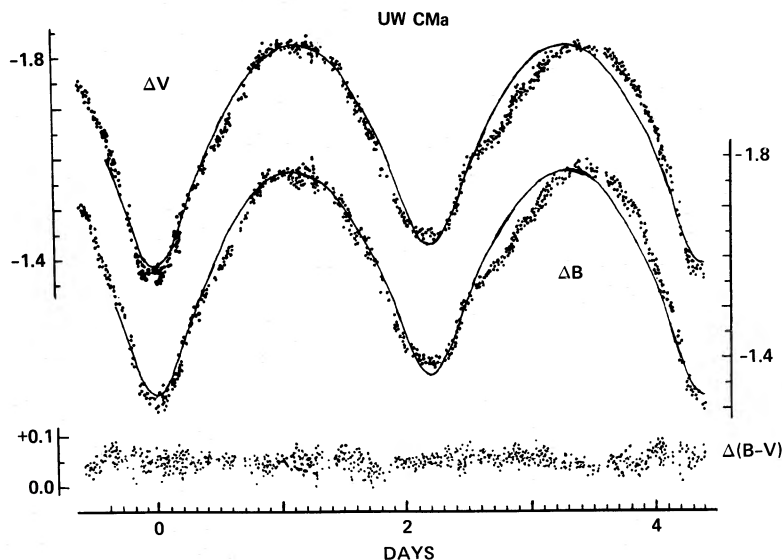


FIG. 2.—The yellow and blue photoelectric light curves of UW CMa by Ogata and Hukusaku (1977). Dots, individual observations. Solid lines, the computed light curves based on the photometric parameters in Table 1 (for mass ratio = 0.751).

ratio could be found. The observed light curve can be represented about equally well by either Pearce's or Struve and Sherman's mass ratio. The computed light curve for a contact configuration for a mass ratio of 0.751 is shown in Figure 1 as a solid curve. The computed curve agrees well with the observations except at the primary minimum and at the following maximum. These small deviations are not of great concern, as there is significant scatter in the observations.

b) Ogata and Hukusaku's Light Curves

Photoelectric light curves in the standard Johnson yellow and blue filters were published by Ogata and Hukusaku (1977). Their light curves are reproduced in Figure 2 (the dots represent individual observations). Several conclusions can be drawn from inspecting these light curves: (1) the primary minimum is symmetric and the descending branch of the secondary minimum appears normal; (2) the secondary minimum occurs at 0.5 phase; (3) the ascending branch of the secondary minimum is clearly not smooth; and (4) the maximum following this branch is displaced from the normal 0.75 phase. In light of the extreme complexity of the light curves, we analyzed the observations with three independent approaches: (1) including all observations; (2) omitting phases 0.57 (2.5 days) to 0.74 (3.3 days) on the ascending branch of the secondary minimum; and (3) omitting phases 0.57 (2.5 days) to 0.93 (4.1 days) which includes the displaced maximum.

Attempts were made to find solutions using several values of the initial mass ratio. As was noticed in several other systems (Leung and Schneider 1978), a unique value for the mass ratio could not be deter-

mined. For a given value for the mass ratio, the three approaches gave essentially the same solution (within 1–2%, depending on the parameters). As expected, none of the solutions can fit either the ascending branch or the displaced secondary maximum, since neither is associated with normal binary behavior. In this study, we adopted the solutions derived from approach 3, where the observations from phases 0.57 to 0.93 were omitted, for the reasons mentioned.

Since the mass ratio cannot be determined, we will report five sets of self-consistent photometric parameters for the three published mass ratios: 0.751 of Pearce, 1.173 of Struve and Sherman, and 1.3 of Hutchings; also two intermediate values, 0.9 and 1.0. The photometric parameters associated with these mass ratios together with their internal probable errors are collected in Table 1. The locations of these solutions in the (mass ratio, surface potential)-plane is shown in Figure 3. Notice that all the points fall between the inner and outer contact boundaries. (This is also true for the other cases attempted.) This indicates that although the photometric mass ratio for UW CMa is not determined, a contact configuration is fairly certain.

The parameters i , T_2 , luminosity ratio L_2/L_1 , and ratio of radii r_2/r_1 for the five different mass ratios are shown in Figure 4. The inclinations agree within twice the probable error, while the secondary polar temperatures agree within the probable error.

The luminosity ratio (in the visible) and the ratio of radii get larger as the mass ratio increases. Since the polar temperature of the secondary remains around 40,000 K for the assumed polar temperature of 43,000 K for the primary, the increasing luminosity ratio is due solely to the increasing ratio of radii. It is an

TABLE 1
PHOTOMETRIC SOLUTIONS OF UW CANIS MAJORIS FOR ASSUMED MASS RATIOS*

PARAMETER	m_2/m_1				
	0.751†	0.90	1.00	1.173‡	1.30§
$L_1/(L_1 + L_2)$ yellow.....	0.594 ± 0.019	0.541 ± 0.012	0.529 ± 0.010	0.494 ± 0.011	0.469 ± 0.010
$L_1/(L_1 + L_2)$ blue.....	0.596 ± 0.013	0.524 ± 0.013	0.531 ± 0.011	0.496 ± 0.012	0.471 ± 0.010
i (degrees).....	70.21 ± 0.32	69.84 ± 0.36	69.63 ± 0.41	68.71 ± 0.42	68.98 ± 0.34
$\Omega_1 = \Omega_2$	3.231 ± 0.016	3.505 ± 0.015	3.622 ± 0.014	3.813 ± 0.023	4.036 ± 0.033
T_1 (K).....	43000 ^a	43000 ^a	43000 ^a	43000 ^a	43000 ^a
T_2 (K).....	39194 ± 984	41126 ± 775	39524 ± 570	39496 ± 65	39720 ± 610
r_1 (pole).....	0.3946 ± 0.0025	0.3754 ± 0.0021	0.3722 ± 0.0019	0.3685 ± 0.0029	0.3556 ± 0.0040
r_1 (side).....	0.4186 ± 0.0030	0.3964 ± 0.0026	0.3953 ± 0.0024	0.3907 ± 0.0037	0.3758 ± 0.0050
r_1 (back).....	0.4563 ± 0.0046	0.4329 ± 0.0038	0.4342 ± 0.0036	0.4399 ± 0.0063	0.4221 ± 0.0083
r_2 (pole).....	0.3471 ± 0.0025	0.3579 ± 0.0021	0.3722 ± 0.0019	0.3948 ± 0.0029	0.3990 ± 0.0039
r_2 (side).....	0.3656 ± 0.0031	0.3769 ± 0.0026	0.3935 ± 0.0024	0.4203 ± 0.0037	0.4244 ± 0.0051
r_2 (back).....	0.4070 ± 0.0049	0.4146 ± 0.0039	0.4342 ± 0.0036	0.4661 ± 0.0059	0.4662 ± 0.0076
Ω_{inner}	3.331	3.586	3.750	4.027	4.223
Ω_{outer}	2.905	3.088	3.207	3.468	3.657
% overcontact.....	23.5	16.3	23.6	28.3	33.0

* Assuming $A_1 = A_2 = 1$; $g_1 = g_2 = 1$; and $x_1 = x_2$ equal to 0.14 and 0.18 for yellow and blue, respectively (linear limb darkening coefficients derived from the grid model atmosphere of Carbon and Gingerich 1969, for $T = 34,000$ K and $\log g = 5$).

† Pearce 1932.

‡ Struve *et al.* 1958.

§ Hutchings 1977.

^a = Assumed value.

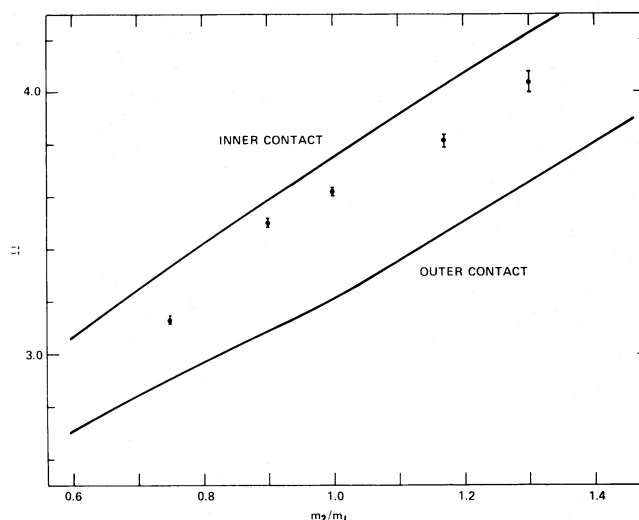


FIG. 3.—(Mass ratio, contact potential)-diagram of UW CMa. The five photometric solutions are represented by dots with error bars.

observational fact that the secondary spectra are quite faint and difficult to detect. This observational constraint imposes that L_1/L_2 (visual) must be less than unity (or $r_1/r_2 < 1$). In other words, the mass ratio has to be less than unity for a contact configuration.

The computed light curves for the five assumed mass ratios show only small differences ($\sim 2\%$) at the primary and secondary minima. A comparison between the observed light curves of Ogata and Hukusaku and the computed light curves assuming a mass ratio of 0.751 is shown in Figure 2. As expected, the greatest departure occurs at the unusual section of

the ascending branch and the displaced maximum. The computed light curves are shallower at primary minimum I and deeper at secondary minimum II. The observed secondary minimum II is relatively broad. Obviously, the peculiar light curves must be due to some very complicated structure and/or nonuniform brightness distribution of the common envelope. No normal binary model can reproduce this complex behavior.

In summary, the analysis of Ogata and Hukusaku's observations indicates that (1) UW CMa is in contact, which implies that its orbit is almost certainly circular, (2) the inclination is about 69° , (3) the secondary's polar temperature is about 40,000 K (which agrees with the observed spectral type O), or 3000 K cooler than the primary (assumed 43,000 K), and (4) the mass ratio m_2/m_1 is most likely less than unity.

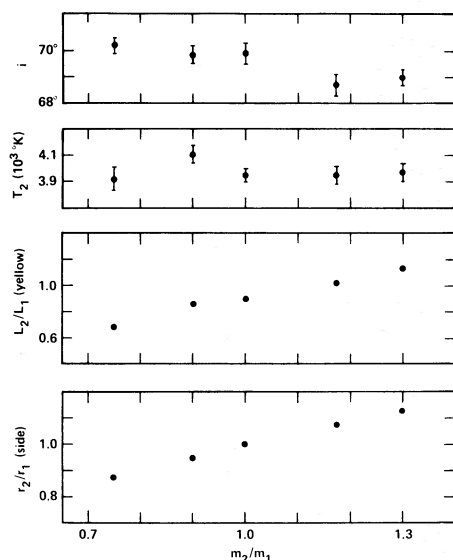


FIG. 4.—The parameters: inclination i , secondary temperature T_2 , luminosity ratio L_2/L_1 , and ratio of radii r_2/r_1 for the five assumed mass ratios m_2/m_1 for UW CMa.

III. THE RELIABILITY OF THE SPECTROSCOPIC ECCENTRICITY FOR CLOSE SYSTEMS

There is some degree of asymmetry in the radial velocity curve of UW CMa. It has been interpreted by spectroscopists as an orbital eccentricity. Previous works and their findings for the eccentricity and argument of perihelion, respectively, are: 0.16 and 38° by Harper; 0.16 and 38° by Pearce; 0.06 and 52° by Struve and Sherman; 0.09 and 42° by Struve *et al.*; and 0.09 and 35° by Hutchings. It is suspected that for a contact system such as UW CMa reflection effects, tidal distortions, and eclipses will have substantial effects on the observed radial velocity. Thus one would not expect the radial velocity curve to be sinusoidal or symmetric even when the orbit is circular. This is also true for very close systems (semi-detached or detached). For example, it was reported that the contact system V1073 Cyg (A3, Leung and Schneider 1978) had large distortions in its radial velocity curve, but the eccentricity was found to be

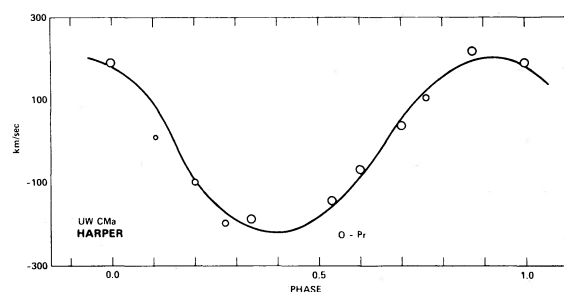


FIG. 5.—Radial velocity curve of UW CMa by Harper (1920). *Smooth line*, the computed radial velocity curve based on $K_1 = 218 \text{ km s}^{-1}$, $\gamma = -12.1 \text{ km s}^{-1}$, $e = 0$, and the photometric solution listed in Table 1.

zero instead of the 0.115 reported spectroscopically. A method for handling the effects of distortion on a radial velocity curve has been published by Wilson and Sofia (1976). We adopt their approach and used their subroutines for our analysis.

The radial velocity amplitudes of the primary component, K_1 , and the velocities of UW CMa for the last 50 years are collected by Hutchings (1977, Table 3; or see legends to Figs. 5–9 of this paper). The effect of the distortions on the radial velocity curve can be calculated from the quantities in Table 1 and the K_1 's. The corrections typically vary from -34 to $+12 \text{ km s}^{-1}$ through the cycle. These values are quite large. Thus the radial velocity curve is not sinusoidal even though the orbit is circular.

Theoretical radial velocity curves assuming a circular orbit and including reflection effects, tidal distortions, and eclipses were computed for three different mass ratios. The computed curves were also normalized to the appropriate K_1 's for the five different published epochs. A comparison between the observed and computed radial velocity curves are shown in Figures 5–9. The observations are shown

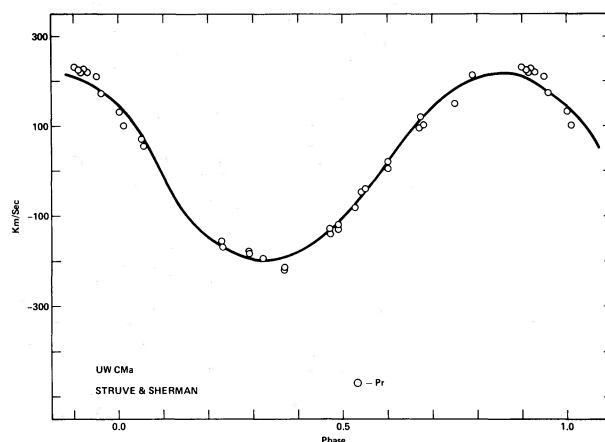


FIG. 7.—Radial velocity curve of UW CMa by Struve and Sherman (1941). *Smooth line*, the computed radial velocity curve based on $K_1 = 216 \text{ km s}^{-1}$, $\gamma = 9.3 \text{ km s}^{-1}$, $e = 0$, and photometric parameters listed in Table 1.

as circles for the primary component and as filled circles for the secondary component. The computed radial velocity curves are represented by continuous curves for the primary, and by broken lines for the secondary. There are only small differences in the primary curves for the three assumed mass ratios (corresponding to about twice the width of the line in places). Therefore, only the curve for the primary radial velocity for a mass ratio of 1.0 is shown in each of the figures. It is obvious from the graphs that the computed curves are not sinusoidal in shape. The computed primary radial velocity curves fit the observed asymmetry quite well. For Pearce's observations (Fig. 6), if K_1 is reduced from 217 to 207 km s^{-1} , the computed curve would go through all the observations much better. The agreement between all the observed and computed radial velocity curves is very

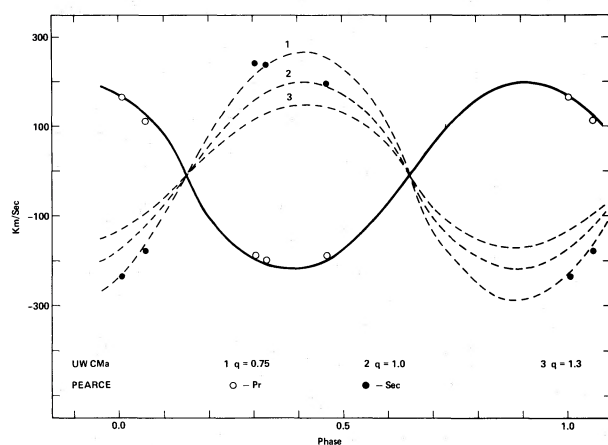


FIG. 6.—Radial velocity curve of UW CMa by Pearce (1932). *Smooth lines*, the computed radial velocity curves based on $K_1 = 217 \text{ km s}^{-1}$, $\gamma = -10.6 \text{ km s}^{-1}$, $e = 0$, and photometric solutions listed in Table 1 for three assumed mass ratios of 0.751, 1.0, and 1.3.

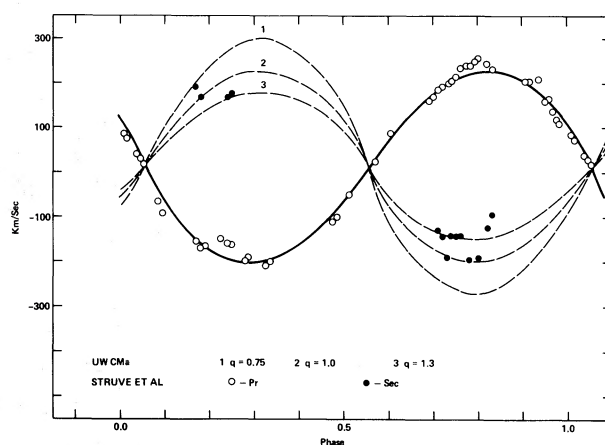


FIG. 8.—Radial velocity curves of UW CMa by Struve et al. (1958). *Smooth curves*, the computed radial velocity curves based on $k = 223 \text{ km s}^{-1}$, $\gamma = 13.5 \text{ km s}^{-1}$, $e = 0$, and photometric solutions in Table 1 for three different mass ratios.

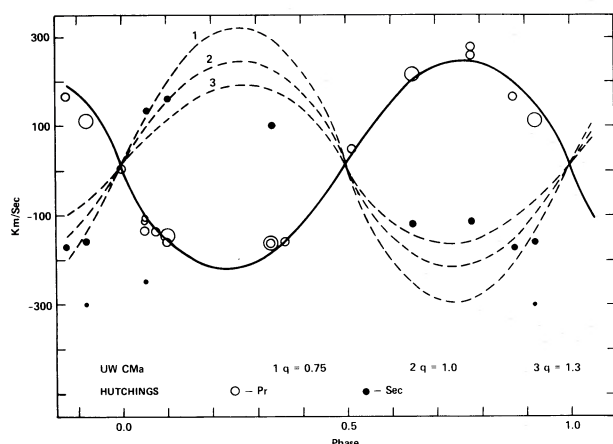


FIG. 9.—Radial velocity of UW CMa by Hutchings (1977). Smooth curves, the computed radial velocity curves based on $K_1 = 242 \text{ km s}^{-1}$, $\gamma = 13.7 \text{ km s}^{-1}$, $e = 0$, and photometric parameters in Table 1 for three different mass ratios. The size of the symbol is proportional to the weight of the observation.

satisfactory. Thus we conclude that the observed asymmetry in the radial velocity curves results from the distortions mentioned above and not from an orbital eccentricity.

What about the radial velocity curve of the secondary? Pearce's observations indicate a mass ratio of about 0.75 (Fig. 5, broken curve 1). The observations of Struve *et al.* (Fig. 8, between broken curves 2 and 3) indicate a mass ratio around 1.2, which is about the same value they adopted. For Hutchings's observations (Fig. 9), the result is not conclusive: four observations fit a mass ratio of 0.75 well, but the other three suggest a value of 1.5! Hutchings reported a value of 1.3.

We feel that the evidence above (§§ II and III) suggests that the mass ratio is less than unity. How do these larger values arise? If the primary is much more luminous than the secondary, the effects of line blending will increase the mass ratio if the data are not properly rectified. We suspect that the lines attributed to the secondary do not represent the true orbital motion of the star. The mass exchange in the common envelope may have a strong effect on the appearance of the secondary spectrum.

IV. PERIOD STUDY

It has been reported that a large mass loss ($3\text{--}8 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$) is taking place in UW CMa (McCluskey, Kondo, and Morton 1975; Hutchings 1977). This process should be reflected in a change in period (McCluskey *et al.* suggest a lengthening of 0.05 s yr^{-1}). Unfortunately, only two photometric times of minimum have been published: Seyfert (1941) and Ogata and Hukusaku (1977).

To determine if any period change has taken place, we supplemented these two observations with spectroscopic measurements by Harper (1920); Pearce (1932), Struve and Sherman (1941), and Struve *et al.* (1958).

TABLE 2
TIMES OF MINIMUM OF UW CANIS MAJORIS

Time of Minimum	Epoch	$O - C$	Source
2,417,240.938...	-4312	-0.048	Harper 1920, Fig. 5
2,424,982.272...	-2550	+0.102	Pearce 1932, Fig. 6
2,429,814.869...	-1450	-0.049	Struve and Sherman 1941, Fig. 7
2,429,814.947...	-1450	+0.029	Seyfert 1941
2,436,185.306...	0	-0.052	Struve <i>et al.</i> 1958, Fig. 8
2,442,424.014...	1420	+0.018	Ogata and Hukusaku 1977

The following assumptions were made: (1) the orbit has been circular over the period of observation, (2) the published γ velocities are reliable, and (3) the primary minimum occurs when the computed radial velocity curves (see § III) cross the γ velocity. We extracted the times of minimum from Figures 5–9 and they are listed in Table 2. A least squares analysis suggests the following light elements:

$$\begin{aligned} \text{Primary minimum} &= 2436185.358 + 4.393407E \\ &\pm 0.043 \pm 0.000019. \end{aligned}$$

This result is in close agreement with the first determination (4.3934, Harper) and the most recent (4.39341, Ogata and Hukusaku). There appear to be no systematic deviations from these elements, although the typical errors for a given observation are rather large, ± 0.05 . We can see no evidence for a period change. However, we cannot rule out a change on the scale suggested by McCluskey *et al.*, as the accumulated change from Harper's 1916 observations to the present is only slightly larger than the probable error.

V. VARIATION OF THE PRIMARY RADIAL VELOCITY AMPLITUDE, K_1

Changes in the primary radial velocity amplitude, K_1 , were reported by Hutchings (1977). These values

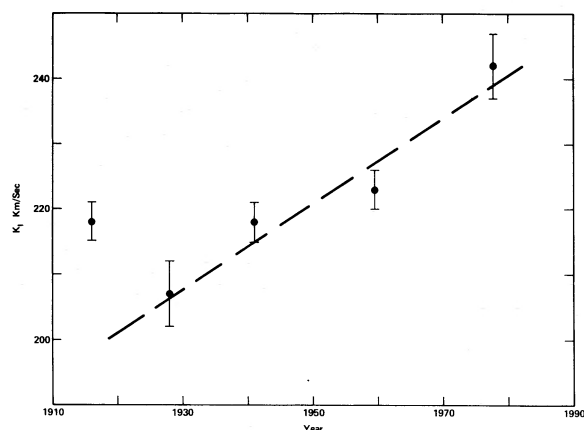


FIG. 10.—The changes of the primary radial velocity amplitude of UW CMa through the years.

are plotted in Figure 10 (note that we adopted $K_1 = 207 \text{ km s}^{-1}$ for Pearce's observations; see § III). If Harper's result is ignored, K_1 appears to be linearly increasing with time (*dotted line*). If Harper's measurement is used, then K_1 remained constant during the earlier observations and subsequently increased about 10% in the last 20 years. Hutchings noted that such an increase would require such a large rate of mass transfer that a mass exchange explanation would be unreasonable. This phenomenon is quite puzzling, and we plan to obtain new spectroscopic observations to verify Hutchings's result.

VI. ABSOLUTE DIMENSIONS

Since the mass ratio and the secondary radial velocity curve are highly uncertain, it will not be possible to derive unique absolute dimensions for UW CMa. A set of possible values was derived from the primary radial velocity curves, period, and assumed mass ratios together with their appropriate photometric solutions; these are listed in Table 3. It is our

TABLE 3
ABSOLUTE DIMENSIONS UW CANIS MAJORIS

PARAMETER	q		
	0.751	1.173	1.30
$m_1 (m_\odot)$	45.7	18.5	15.2
$m_2 (m_\odot)$	34.3	21.7	19.7
$A (R_\odot)$	48.7	38.7	37.0
$R_1 (R_\odot)$	20.4	15.1	13.9
$R_2 (R_\odot)$	17.8	16.3	15.7
$T_1 (\text{K})$	43,000	43,000	43,000
$T_2 (\text{K})$	39,194	39,496	39,720
$L_1 (10^5 L_\odot)$	12.8	7.0	6.0
$L_2 (10^5 L_\odot)$	6.8	5.8	5.3

opinion that the lower value of the mass ratio (see § II) is more reliable. Thus we suggest the masses of the components are most likely 46 and $34 M_\odot$. The radii are 20 and $18 R_\odot$. This system has the largest total mass of any known contact binary. In all cases (Table 3) the radii are much bigger than the zero-age main-sequence radii for their masses. Thus UW CMa is an evolved contact system.

VII. CONCLUSIONS

Both Seyfert's and Ogata and Hukusaku's light curves suggest that UW CMa is a contact system. The absolute dimensions of the components indicate that the system is evolved. The unusual light curves lead to an interpretation of a highly nonuniform surface brightness in the common envelope resulting from the mass flow. In very close contact systems, the asymmetry in the radial velocity curves is caused by tidal distortion, reflections, and eclipses, not by an orbital eccentricity. It is suggested that the mass ratio is most likely less than one. The period of UW CMa seems to be stable, but more photometric determinations of the times of minimum will be required to settle this important question.

There is an indication that the amplitude of the primary radial velocity curve may be increasing, but again more sophisticated spectroscopic observations are urgently needed to settle this problem as well as the problem of the spectroscopic mass ratio.

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