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A PHOTOMETRIC STUDY AND ANALYSIS OF AW URSAE MAJORIS

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ABSTRACT

New green and red light curves for the extremely low mass ratio contact binary AW UMa have been observed. These display intrinsic variability around primary minimum occurring with a time scale of a few days. Times of minimum light obtained over three seasons confirm the previously reported period change. A limiting light curve analysis indicates a change in the temperature of the secondary component and in the size of both components. Alternatively, the observations are consistent with a variable hot spot. The implications of these observations are discussed with respect to theories of contact binaries, particularly with regard to the stability of the A-type systems.

Subject headings: stars: eclipsing binaries — stars: individual — stars: W Ursae Majoris

I. INTRODUCTION

AW Ursae Majoris (BD +30°2163, HD 99946) was discovered to be a light variable by Paczyński (1964). He observed complete *UBV* light curves and found it to be a W UMa type eclipsing binary. Additional light curves and times of minimum light have been obtained by Kalish (1965), Dworak and Kurpińska (1975), Woodward, Koch, and Eisenhardt (1980), Istomin, Orlov, and Kulagin (1980), and Mikolajewska and Mikolajewski (1980). Two times of minimum light have been observed by Hart *et al.* (1979) and by Kurpińska-Winiarska (1980) and some observations were made near minimum by Ferland and McMillan (1976). A significant change in the period was noted by Woodward *et al.*

Analysis of the light curves of Paczyński using modern synthetic light curve techniques has been performed by Mochnacki and Doughty (1972), Ruciński (1973), Wilson and Devinney (1973), Lucy (1973), Binnendijk and Nagy (Binnendijk 1977), and Al-Naimiy (1978*b*), the last author also analyzing the light curve of Dworak and Kurpińska. Woodward *et al.* analyzed their light curves made at two different epochs. All found the binary to have an extremely low mass ratio, the lowest determined for a contact system.

A spectroscopic study by Paczyński revealed a single-lined spectroscopic binary with spectral type F0–F2 and phase-locked changes in the hydrogen line widths. A recent radial velocity study by McLean (1981, 1982) yielded a value for the mass ratio similar to that found photometrically. McLean used a cross-correlation technique to measure the radial velocities of both stars, arriving at a semiamplitude for star one similar to that obtained by Paczyński. Strömgren indices for AW UMa have been published by Ruciński (1976) and imply an unreddened spectral type of F1–F2, as do the *UBV* indices by Paczyński and by Eggen (1967). The CN-absorption measurements by Koch (1974) show no anomalies. The system is of the A-type according to the classification of Binnendijk (1970).

Eggen found that BD +30°2164 is a common proper motion companion to AW UMa, from which it is separated by 67″. This companion is 2.6 mag fainter than the variable.

Oshchepkov (1974) found some apparent evidence for a phase-dependent polarization, while a later study by Piirola (1975, 1977) found little change in polarization with phase. Hull (1980) made polarization measurements of AW UMa in 1974 and 1975 and found a phase dependence in the angle of polarization, with no clear phase dependence in the amplitude of polarization

II. OBSERVATIONS

AW UMa was observed on 15 nights in 1979 and 3 nights in 1980 at the Flower and Cook Observatory. In all, 1390 green (g) and 1288 red (r) observations were obtained in 1979, and 359 green and 365 red were obtained in 1980, using the Pierce-Blitzstein simultaneous two-channel, pulse-counting photometer mounted on the 38 cm stationary refractor. The detectors and the natural system characteristics are described by Blitzstein *et al.* (1980). A counting interval of 0.0004 days was used and the angular diameter of each focal plane diaphragm was 69″. The observations were not standardized to the *UBVRI* system. The simultaneous magnitude differences between the variable and comparison stars exist as File IAU (27), RAS-79 in the Royal

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Observations of AW UMa were also made on two nights in 1981 at the Rothney Astrophysical Observatory of the University of Calgary for the purpose of obtaining times of minimum light.

The comparison star for all these observations was BD +31°2270 which has been used by previous observers of this system. The variable and comparison stars are close together in the sky, and though the instantaneous differential extinction was always small, it was always evaluated and removed from the observations. The comparison star was checked on seven nights against BD +30°2165, the check star also used by Woodward, Koch, and Eisenhardt (1980) and was found to be satisfactorily constant.

III. TIMES OF MINIMUM AND PERIOD STUDY

Nine heliocentric times of minimum light were determined from the three seasons of observation. A computer program based upon the method of Kwee and van Woerden (1956) was used to calculate these times, which are listed in Table 1. These were then compared to the predicted times of minimum light according to the ephemeris determined by Dworak and Kurpińska (1975):

$$\text{Heliocentric Primary Minimum} = 2438044.7812 + 0.43873235E. \quad (1)$$

The residuals from this ephemeris are also listed in Table 1.

These times of minimum light were compared with those of the previously cited observers. Residuals based upon the above ephemeris for all photoelectrically observed times are plotted in Figure 1. Two results are apparent from the figure: the period of the system has changed, and the residuals of any one season show significant scatter.

The peak-to-peak scatter in the residuals is of the order of 0.003 days for seasons which have more than two observations of minima. The seasonal scatter may

TABLE 1

New Times of Minimum Light for AW Ursae Majoris

$JD_{\odot} - 2400000$	σ	E	$(O-C)$
43941.7714	±0.0001	13441	$-0^{d}0113$
43945.7190	0.0001	13450	−0.0123
43954.7158	0.0002	13470.5	−0.0095
43970.7281	0.0005	13507	−0.0109
44274.7702	0.0008	14200	−0.0104
44277.8396	0.0004	14207	−0.0121
44283.7634	0.0004	14220.5	−0.0112
44608.8622	0.0002	14961.5	−0.0131
44664.7993	0.0002	15089	−0.0143

be slightly greater after the apparent period change. There is no consistent differentiation between primary and secondary minima. Complications, which will be discussed in more detail in the next section, are readily apparent in the light curves obtained in this study. These can contribute to the scatter in the observed times of minimum. The complications in the 1979 light curves include asymmetries on individual nights in the interval between $0^{P}75$ and $0^{P}25$. On March 8–9 the green light curve is fainter by about 0.01 mag over the interval $0^{P}83$–$0^{P}86$ than over the phase-symmetric interval $0^{P}14$–$0^{P}17$. Similarly, on April 6–7 the green light curve is fainter by 0.01 mag over the interval $0^{P}82$–$0^{P}86$ than over the interval $0^{P}14$–$0^{P}18$. The mechanism causing these light differences may also be affecting the minima. From the observations of these two nights, an upper limit of ±0.004 days can be derived for the bias in the time of minimum light resulting from light curve distortion. Thus, light curve distortion can have a significant effect on the timing of minimum light, at least in the 1979 season. These asymmetries may be caused by a stationary fluctuation in the brightness of the common envelope, by streaming of gas between the components, or by nonsynchronous motion of circumstellar material.

The period change as displayed in Figure 1 may represent either (1) a change from one constant period to another constant period or (2) a continuously changing period.

The former explanation implies that the period changed between 1975 and 1978. Ephemerides appropriate before and after this change are as follows:

1963–1975: Hel. Pri. Min.

$$= \underset{\pm 4}{2438044.7813} + \underset{\pm 5}{0.43873231}E, \quad (2a)$$

1978–1981: Hel. Pri. Min.

$$= \underset{\pm 69}{2443576.7505} + \underset{\pm 50}{0.43872917}E. \quad (2b)$$

Similar results were obtained independently by Kurpińska-Winiarska. Representations derived from the two ephemerides are shown in Figure 1. These values indicate a period change of $\Delta P/P = -7 \times 10^{-6}$. Period changes of this magnitude are typical for W UMa binaries of the W type (Kreiner 1977) and for close binaries in general (Frieboes-Conde and Herczeg 1973). Such changes might be the result of mass loss from the system or mass transfer between the components. If mass is being transferred without loss, the mass transfer rate can be calculated from the equation (Ruciński 1974)

$$\frac{d \ln M}{dt} = \frac{q}{3(q^2-1)} \frac{d \ln P}{dt}, \quad (3)$$

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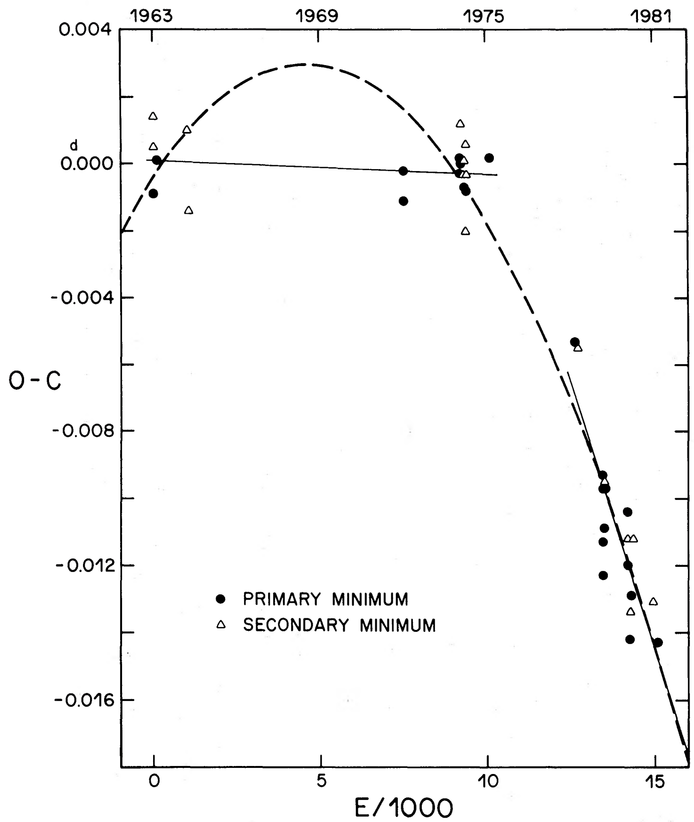

FIG. 1.—The $(O-C)$ diagram from AW UMa. The values are calculated according to eq. (1) of the text. The solid line segments represent the fit to two constant periods, and the dashed curve the fit to a continuously varying period.

where negative values of this rate indicate that the primary is the component donating the mass. Using the mass ratio $q=0.0716$ as given by Wilson and Devinney (1973) and Woodward, Koch, and Eisenhardt (1980), and total mass $M=3.5\ M_\odot$ based upon the inclination calculated in the above studies and the radial velocity results of Paczyński (1964), one finds that a single mass transfer from the more to the less massive component on the order of $6\times10^{-7}\ M_\odot$ would produce this period change. This amount is not too large for an occasional event. The period change due to mass loss from the system is more difficult to calculate and depends upon assumptions concerning the location and angular momentum of the lost mass.

To investigate the idea that the period is continuously changing, the residuals were fitted with a quadratic equation. A least-squares solution in this case results in the following ephemeris:

Hel. Pri. Min.

$$= \underset{\pm 6}{2438044.7808} + \underset{\pm 17}{0.43873382}E - \underset{\pm 11}{1.60}\times10^{-10}E^2. \qquad (4)$$

Solving for the period change one finds

$$\dot{P} = -7.3\times10^{-10} \text{ days per day}$$

$$= -3.2\times10^{-10} \text{ days per cycle.} \qquad (5)$$

This is similar in magnitude and sign to the period change found by Dreschel *et al.* (1977) for V1010 Oph, an early-type, evolved contact system (Leung and Wilson 1977).

The mechanism for such a continuous period change may be mass exchange from the primary to the secondary or mass loss from the system. If mass is being transferred, then by the use of equation (3)

$$\dot{M} = 5.1\times10^{-8}\ M_\odot\ \text{yr}^{-1}. \qquad (6)$$

This leads to a characteristic lifetime of 7×10^7 years for all the mass to be transferred to the presently less massive star.

The "thermal relaxation oscillation" (TRO) theory of Lucy (1976), Flannery (1976), and Robertson and Eggleton (1977) predicts mass transfer from primary to secondary during the semidetached phase and from

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secondary to primary during the contact phase. This latter result is also found by Webbink (1976). The present analysis and the results of past studies of the system rule out a semidetached configuration. Thus, a contact configuration and a continuously decreasing period resulting from mass transfer from primary to secondary are in conflict with the predictions of the TRO theory, as it is presented to explain the systems in marginal contact. It is not known that the theoretical predictions for the general direction of the mass transfer change in the over-contact case. The "contact discontinuity" (DSC) theory of Shu, Lubow, and Anderson (1976, 1979) does not predict a direction for net mass transfer, although it can accommodate small period changes.

It is clear that the history of the times of minimum light can be reasonably well represented either by a change from one constant period to another constant period or by a continuously changing period.

The former explanation may be preferred for two reasons. The first is that one avoids having an extremum which is not represented by observations. Second, and more importantly, the new light curves show a level of activity not seen in the high-quality light curves obtained before 1975. This increased activity might receive a more consistent explanation when coupled with a mechanism which causes the period change. If one regards the period as having been smoothly changing, one must find a mechanism which induces the recent light curve activity but which does not have a major effect on the period.

To plot the 1979 and 1980 light curves we have used the following ephemeris:

$$\text{Hel. Pri. Min.} = 2443941.7717 + 0.43873212E, \quad (7)$$

which yielded a satisfactory fit to the minima over this 1 year of observation.

IV. LIGHT CURVES AND COLOR INDICES

The observations of the 1979 season were gathered together into one light curve for each bandpass; these are shown in Figure 2. The points which lie between approximately 0.P25 (the first maximum) and 0.P75 (the second maximum) define a highly repetitive light curve with good night-to-night overlap, especially in green. However, between 0.P75 and 0.P25, the points do not define a unique light curve, but rather indicate intrinsic variability in the system.

This region between 0.P75 and 0.P25 requires special discussion. The observations of different nights appear

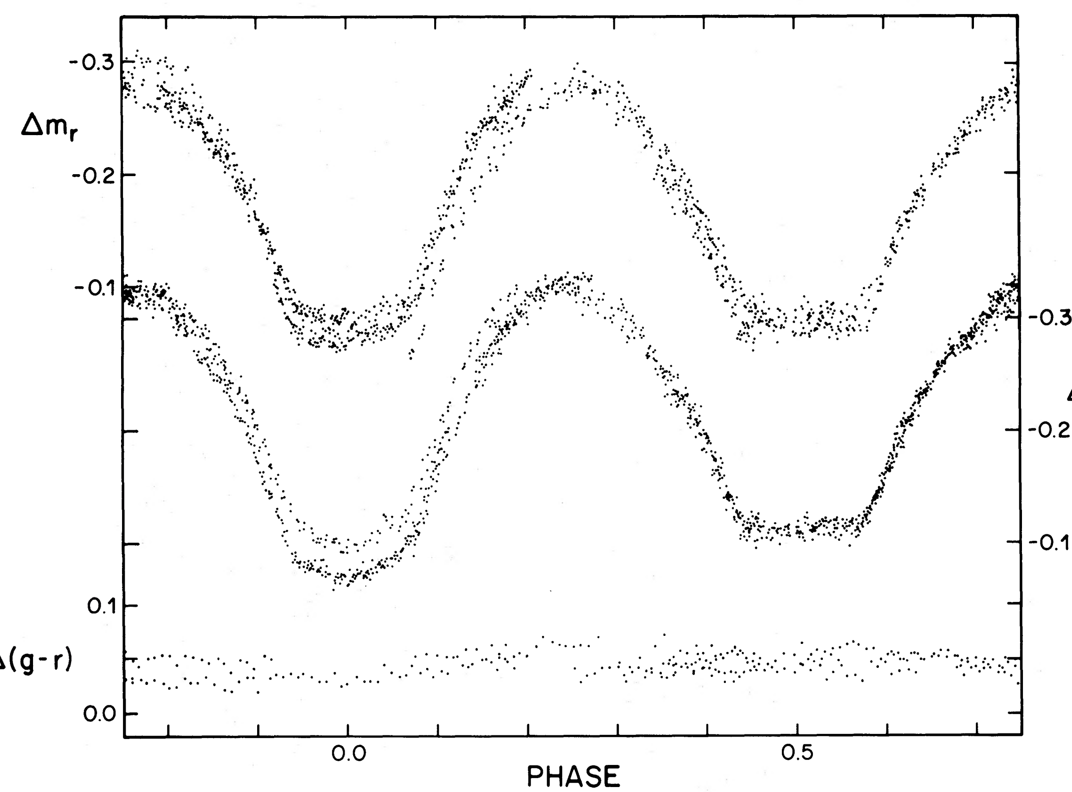

FIG. 2.—The observed differential red, green, and color curves of AW UMa for 1979

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TABLE 2

CHRONOLOGY OF OBSERVED INTRINSIC VARIABILITY IN 1979 LIGHT CURVES

Date (1979)	JD − 2400000	g	r
Mar 8–9	43941	faint	...
Mar 12–13	43945	...	median
Mar 15–16	43948	faint	faint
Mar 18–19	43951	...	bright
Apr 5–6........	43969	bright	median
Apr 6–7........	43970	bright	bright

as nested curves. On some nights, observations were made with only one bandpass, so there is not a one-to-one correspondence in time between red and green curves in this region. On nights when observations were made through both bandpasses, it was found that the observations that are relatively bright in one bandpass are associated with relatively bright data in the other bandpass. The shallowest curve through primary is for the night of April 6–7 in both bandpasses. The deepest curve through primary in the green is for March 8–9, and it is only slightly brighter than the observations of March 15–16 which begin at $0\overset{P}{.}07$. Observations were not made through the red bandpass on March 8–9 and thus a corresponding deepest curve through primary is not defined. However, the red observations of March 15–16 do show that the system was especially faint, and we expect that, had red observations been made on March 8–9, they also would have delineated a deep curve.

To search for a time scale for these intrinsic variations, we have composed a chronology of the relative variation on the nights when observations were made between $0\overset{P}{.}75$ and $0\overset{P}{.}25$. This is listed in Table 2, where "faint" refers to the deeper curves through minima, "bright" to the shallower curves, and "median" to those between. This chronology indicates an upper limit to a time scale from "faint" to "bright" on the order of 3–4 days, at least in red. A very short time scale such as 0.2 days can be ruled out by the fact that the nightly observations around primary minima appear as nested curves, with no intersection of the "bright" and "faint" curves.

The two maxima appear to differ in brightness by about 0.005 mag in green, with the first maximum being the brighter. The large scatter in the red observations at these phases, particularly from $0\overset{P}{.}75$ to $0\overset{P}{.}80$, prohibits one from measuring a meaningful difference in the heights of the two maxima in this bandpass. No obvious asymmetry appears in the observations between the first and second maxima in green, except for the slight difference in height of the two maxima; however, in red the interval from $0\overset{P}{.}28$ to $0\overset{P}{.}33$ is brighter by 0.010–0.015 mag than the interval from $0\overset{P}{.}67$ to $0\overset{P}{.}72$. The secondary minimum is total, with no obvious asymmetry in the interval of totality.

The individual observations of each night were gathered together in small groups, consisting typically of three successive observations, from which averages were made. The average red points were interpolated to the phases of the average green points, and differential $(g-r)$ indices were composed. These are also shown in Figure 2. The observations lie within a band of 0.03 mag and show some night-to-night variation but no significant phase-dependent variation. There are not enough data at primary minimum to decide if the slight apparent reddening is real, for on some nights the primary minimum was observed in only one bandpass.

The observations of the 1980 and 1981 seasons were made mainly to find new times of minimum light and complete light curves were not obtained.

Although light curves derived from studies prior to 1979 have not shown significant variation within a season, the light curves do show changes from season to season and changes with respect to my 1979 light curves. This later effect can be seen by a comparison of my g light curve with previous V light curves which are nearly complete: those of Paczyński (1964), Kalish (1965), Dworak and Kurpińska (1975) (restricted to observations of 1971), and Woodward, Koch, and Eisenhardt (1980).

Some of the properties of each of these V and g light curves can be parameterized in a relative fashion. The relative depths of the two minima (minimum I − minimum II) vary from +0.023 mag in the Woodward *et al.* light curve and +0.031 mag in Paczyński's light curve to +0.078 mag in Kalish's light curve, while observations presented here for the 1979 season vary from +0.016 mag to 0.044 mag due to the intrinsic variability in the depth of primary minimum. The relative heights of the two maxima (maximum I − maximum II) vary from −0.005 mag in Paczyński's light curve to +0.010 mag for Kalish's. The observations presented for the 1979 season imply a relative height of −0.005 mag. The depth of each minimum relative to its succeeding maximum has also varied from season to season, with those involving the primary minimum showing a greater range by a factor of 2. On the whole, the older V light curves are more similar to the fainter level of the g light curve of the 1979 season than to the brighter level.

An attempt was made to find some long-term periodicity in these season-to-season light curve changes, but none was found. Much of this previous discussion is summarized in Table 3, where NI, NII, XI, and XII denote the observed magnitudes at minimum I, minimum II, maximum I, and maximum II respectively.

Since the 1974 light curve of Woodward *et al.* was compiled during four consecutive nights, we cannot rule out intrinsic variability on longer time scales during that season. However, the observations of 1979 show signifi-

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TABLE 3

SUMMARY OF SEASONAL V AND g LIGHT CURVE CHANGES

Ref.	Season	NI−NII	XI−XII	XI−NI	XII−NII
Paczyński 1964	1963	+0.031	−0.005	−0.249	−0.213
Kalish 1965	1964	+0.078:	+0.010	−0.285:	−0.217
Dworak and Kurpińska 1975	1971	> +0.033	−0.008	< −0.280	−0.239
Woodward *et al.* 1980	1974	+0.023	+0.001	−0.243	−0.221
This paper (faint)	1979	+0.044	−0.005	−0.262	−0.213
This paper (bright)	1979	+0.016	−0.005	−0.234	−0.213

cant variation over a 4 day interval, and thus activity of the level seen in the present observations was probably absent from the system in 1974. The light curves of Paczyński, Kalish, and Dworak and Kurpińska (particularly that of 1971) were compiled from observations over intervals of several weeks and do not indicate intrinsic variability during these intervals. The red 1978 light curve of Woodward *et al.* is based on only two nights and thus does not rule out intrinsic variability during that season. In fact, since the observations were made following the change in period, we expect intrinsic variability in the light curves. Intrinsic variability was also noted by Istomin, Orlov, and Kulagin (1980) in their 1979 light curve, with the variability manifested in the phase interval from 0ᴾ30 to 0ᴾ50 between two successive nights.

Thus the evidence seems to be against the existence of variability on the scale of the 1979 observations during any of the 1974 or pre-1974 observations. However, season-to-season variations do exist during the entire photometric history of this system.

V. ANALYSIS

As previously described, the observations between 0ᴾ25 and 0ᴾ75 can be well represented by a single light curve in each color. However, between 0ᴾ75 and 0ᴾ25, the observations show night-to-night variations at the same phase and are represented by nested light curves in each color. It was decided to couple the "bright" and "faint" curves through the primary minimum with the single representative curve at 0ᴾ25 and 0ᴾ75 and thus form complete "bright" and "faint" light curves in each bandpass. Synthetic light curve solutions could then be attempted for each of these light curves. In this way, limits for the parameters of the system could be found. This analysis was begun with the g light curve because, as previously noted, it contains nearly complete curves along the upper and lower bounds of the region of light variation and also because it contains less scatter than the red light curve.

The g observations were gathered into average points within phase intervals of 0.01 centered about 0ᴾ00. This size interval served to define the flat portion of scondary minimum quite well. All the observations between 0ᴾ25 and 0ᴾ75 were used in forming the average points in this interval, and the observations of March 8–9 and April 6–7 were used to delineate the "faint" and "bright" light curves, respectively, between 0ᴾ75 and 0ᴾ25. The particular number of individual observations in each interval represented the weight of the average value. A correction of +0.328 mag was added to the g means in order to adjust the average of the two maxima to 0.000 mag. These were then converted to intensity ratios and are listed together with their weights for the faint green curve and for the bright green curve in Table 4.

The analysis was performed using the synthetic light curve and differential corrections program of Wilson and Devinney (1971). Initial values for the faint curve were derived from the final solution by Wilson and Devinney (1973) for the 1963 light curve of Paczyński (1964), with T_1 increased by 175 K to a value of 7175 K and T_2 increased by the same amount. Theoretical light curves were then calculated and differential corrections applied to the parameters. Mode 3 was used, as described by Leung and Wilson (1977), with synchronous rotation and the assumption that the atmosphere can be represented by a blackbody. The scatter in each light curve was assumed to be due to shot noise.

Several of the parameters were held fixed at their initial values. These were the mass ratio q ($=M_2/M_1$), the inclination i, and the limb-darkening coefficients $x_1=x_2$, for all of which Wilson and Devinney (1973) and Woodward, Koch, and Eisenhardt (1980) had calculated identical values. Also held constant were the polar temperature T_1 of star 1 (the more massive component) and the bolometric albedoes $A_1=A_2$. Thus, the parameters which were adjusted are the temperature T_2 of star 2, the surface potentials $\Omega_1=\Omega_2$, the luminosity L_1 of star 1, the gravity exponents $g_1=g_2$ ($=4\beta$), and the "third" light L_3.

It was found that the fit of the light curve depended only weakly on the gravity exponent over the range of values calculated in the first few iterations, so it was then decided to fix this parameter at its initial value of 0.45, as found by Wilson and Devinney (1973). The

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TABLE 4

Average Points for AW Ursae Majoris (1979) in Intensity Units

Phase	I_V/I_C	n
Green–Faint		
0.0006	0.7879	6
0.0092	0.7916	8
0.0203	0.7911	9
0.0307	0.7965	7
0.0392	0.7979	7
0.0499	0.8013	8
0.0595	0.8071	7
0.0697	0.8175	9
0.0797	0.8285	6
0.0899	0.8521	8
0.0999	0.8732	8
0.1083	0.8872	5
0.1422	0.9385	5
0.1499	0.9449	8
0.1594	0.9546	6
0.1696	0.9636	9
0.1790	0.9744	7
0.1899	0.9818	9
0.1992	0.9932	7
0.2097	0.9960	9
0.2182	0.9986	6
0.2300	1.0015	8
0.2398	1.0053	9
0.2516	1.0010	12
0.2594	1.0002	8
0.2680	0.9978	8
0.2797	0.9870	5
0.2912	0.9781	4
0.3022	0.9807	6
0.3108	0.9695	9
0.3214	0.9641	7
0.3303	0.9504	7
0.3402	0.9417	9
0.3507	0.9294	15
0.3608	0.9201	18
0.3710	0.9151	10
0.3797	0.9003	17
0.3902	0.8910	14
0.4007	0.8742	16
0.4100	0.8606	16
0.4198	0.8430	12
0.4299	0.8298	16
0.4406	0.8225	17
0.4501	0.8232	19
0.4608	0.8213	10
0.4700	0.8195	6
0.4799	0.8187	9
0.4880	0.8204	6
0.4996	0.8202	11
0.5094	0.8236	10
0.5193	0.8229	11
0.5293	0.8229	10
0.5396	0.8218	12
0.5496	0.8241	13
0.5599	0.8227	17
0.5707	0.8280	14
0.5808	0.8391	19
0.5895	0.8511	20
0.6000	0.8687	23
0.6103	0.8855	22
0.6203	0.8991	19
0.6306	0.9139	18
0.6389	0.9202	15
0.6501	0.9350	15

Phase	I_V/I_C	n
Green–Faint		
0.6596	0.9455	14
0.6680	0.9507	13
0.6798	0.9572	24
0.6897	0.9639	17
0.7004	0.9713	18
0.7102	0.9827	24
0.7194	0.9882	26
0.7304	0.9915	25
0.7395	0.9958	25
0.7501	0.9986	30
0.8120	0.9745	5
0.8188	0.9697	7
0.8306	0.9509	6
0.8390	0.9425	6
0.8492	0.9342	7
0.8603	0.9253	8
0.8702	0.9141	7
0.8795	0.8995	6
0.8904	0.8864	9
0.9004	0.8645	7
0.9101	0.8491	8
0.9209	0.8332	6
0.9289	0.8192	7
0.9410	0.8019	7
0.9504	0.7971	7
0.9590	0.7971	7
0.9699	0.7945	8
0.9794	0.7895	6
0.9902	0.7892	9
Green–Bright		
0.0093	0.8098	3
0.0198	0.8100	5
0.0312	0.8173	4
0.0412	0.8295	3
0.0480	0.8254	3
0.0597	0.8266	5
0.0694	0.8422	4
0.0811	0.8580	3
0.0904	0.8716	5
0.1009	0.8943	3
0.1093	0.9049	4
0.1176	0.9273	3
0.1301	0.9422	5
0.1416	0.9592	4
0.1527	0.9751	3
0.1595	0.9793	3
0.1663	0.9784	3
0.1793	0.9945	4
0.2516	1.0010	12
0.2594	1.0002	8
0.2680	0.9978	8
0.2797	0.9870	5
0.2912	0.9781	4
0.3022	0.9807	6
0.3108	0.9695	9
0.3214	0.9641	7
0.3303	0.9504	7
0.3402	0.9417	9
0.3507	0.9294	15
0.3608	0.9201	18
0.3710	0.9151	10

Phase	I_V/I_C	n
Green–Bright		
0.3797	0.9003	17
0.3902	0.8910	14
0.4007	0.8742	16
0.4100	0.8606	16
0.4198	0.8430	12
0.4299	0.8298	16
0.4406	0.8225	17
0.4501	0.8232	19
0.4608	0.8213	10
0.4700	0.8195	6
0.4799	0.8187	9
0.4880	0.8204	6
0.4996	0.8202	11
0.5094	0.8236	10
0.5193	0.8229	11
0.5293	0.8229	10
0.5396	0.8218	12
0.5496	0.8241	13
0.5599	0.8227	17
0.5707	0.8280	14
0.5808	0.8391	19
0.5895	0.8511	20
0.6000	0.8687	23
0.6103	0.8855	22
0.6203	0.8991	19
0.6306	0.9139	18
0.6389	0.9202	15
0.6501	0.9350	15
0.6596	0.9455	14
0.6680	0.9507	13
0.6798	0.9572	24
0.6897	0.9639	17
0.7004	0.9713	18
0.7102	0.9827	24
0.7194	0.9882	26
0.7304	0.9915	25
0.7395	0.9958	25
0.7501	0.9986	30
0.7602	0.9966	3
0.7707	1.0014	4
0.7803	0.9988	4
0.7893	1.0009	2
0.7996	0.9943	5
0.8089	0.9824	3
0.8206	0.9814	5
0.8303	0.9712	4
0.8420	0.9642	5
0.8504	0.9534	5
0.8628	0.9371	4
0.8705	0.9270	3
0.8785	0.9196	3
0.8901	0.9067	5
0.9007	0.8849	4
0.9127	0.8648	3
0.9204	0.8553	3
0.9272	0.8444	3
0.9398	0.8318	4
0.9489	0.8224	3
0.9603	0.8178	3
0.9690	0.8131	5
0.9797	0.8145	4
0.9897	0.8104	5
0.9990	0.8096	3

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TABLE 5

LIGHT CURVE PARAMETERS FOR AW URSAE MAJORIS

Parameter	G_f	G_b
i	79°1[a]	79°1[a]
$g_1=g_2$	0.45[a]	0.45[a]
$T_{1,\mathrm{pole}}$ (K)	7175[a]	7175[a]
$T_{2,\mathrm{pole}}$ (K)	6910±12	7146±22
ΔT_{pole} (K)	265	29
$A_1=A_2$	1.00[a]	1.00[a]
Ω	1.8261±0.0008	1.8461±0.0016
q	0.0716[a]	0.0716[a]
$L_1/(L_1+L_2)$	0.914±0.001	0.908±0.001
$x_1=x_2$	0.63[a]	0.63[a]
L_3	0.000[a]	0.000[a]
$r_{1,\mathrm{pole}}$	0.5669±0.0003	0.5606±0.0005
$r_{1,\mathrm{side}}$	0.6492±0.0005	0.6378±0.0009
$r_{1,\mathrm{back}}$	0.6680±0.0005	0.6553±0.0010
$r_{2,\mathrm{pole}}$	0.1887±0.0004	0.1799±0.0007
$r_{2,\mathrm{side}}$	0.1986±0.0004	0.1881±0.0008
$r_{2,\mathrm{back}}$	0.2670±0.0023	0.2303±0.0021
f	0.87	0.44

[a] Not adjusted in the solution.

solutions in which L_3 was adjusted did not yield satisfactory fits at secondary minimum, so L_3 was subsequently fixed at 0.000. After several iterations, a best fit to the observed faint g light curve was achieved. The adjusted parameters for this fit are listed as solution G_f in Table 5, together with their probable errors. The solution shows the system to be extremely over-contact, with a fill-out factor, relative to the inner and outer critical surfaces,

$$f=\frac{\Omega_{\mathrm{inner}}-\Omega}{\Omega_{\mathrm{inner}}-\Omega_{\mathrm{outer}}}=0.87.$$

The fit of this solution to the light curve is good and is displayed in Figure 3. However, in the region from 0P83 to 0P87 the observed light curve falls significantly below the theoretical one. This is the region of asymmetry in the light curve noted previously and is due to complications in the system which are not included in the modeling.

Initial values for the bright curve were the same as those of the faint curve except for the value of the common equipotential surface which was increased. The same parameters were initially held fixed as for the G_f solution, and $g_1=g_2$ and L_3 were later also fixed for the reasons already discussed for the faint curve.

After several iterations, a best fit to this light curve was achieved. These results are listed as G_b in Table 5. The fill-out factor in this case is 0.44. The synthetic light curve of solution G_b is also seen in Figure 3.

The fit in this case is good for most of the bright light curve, but is poor in the region 0P12 to 0P18. This is again a region of asymmetry in the observed light curve which must represent unmodeled complexities. The fit at the shoulders of secondary minimum is also poor.

A comparison of the two light curve solutions shows that they differ in their values of surface potential (thus radii of the stars) and T_2 (thus $\Delta T=T_1-T_2$). Solution G_f describes the stars as larger in size with a larger temperature difference between them and G_b describes them as smaller in size with a smaller temperature difference. Similar results were found in the initial trials during which the gravity exponents were allowed to vary. The slight difference in brightness at secondary minimum between the light curves produced by solutions G_f and G_b is well within the observational scatter.

The r light curve was then analyzed to see if it was consistent with the results for the g light curves. The r observations were averaged in a fashion similar to the g ones, except that no r observations exist for the night of March 8–9 to define a faint red curve through primary minimum. Thus, only a solution for the bright red light curve could be examined. The results obtained from the bright g light curve were used to calculate a synthetic light curve appropriate for the r observations. A theoretical limb-darkening coefficient of 0.50 for stars of this temperature and wavelength was adopted from the table of Al-Naimiy (1978*a*). Since the wavelength-independent parameters were fixed at the values determined in solution G_b, the only parameter left to determine was L_1, and this was adjusted using the differential corrections program.

The fit was not nearly as good as that for the green light curves. The observed points fall slightly below the theoretical curve through secondary minimum, although this can be corrected by increasing T_2. The deviation of the synthetic light curve from the observed points was especially large in the regions 0P10–0P18 and 0P76–0P90, as was easily forecast from the observed light curve. It is not anticipated that the fit can be improved significantly by fitting the upper green and red light curves simultaneously, for the red light curve is brighter in these regions than can be modeled. Since we did not seek a best fit to the red light curve independent of the green one but only a check of its consistency with the solution obtained for the green light curve, we have not listed the parameters for this solution nor displayed the resulting light curve. Although the fit is not nearly so good, it appears that the results obtained for the bright r light curve are consistent with the g light curves.

The following picture results from the synthetic light curve analysis of the observed light curves. The bright curves through primary minimum can be synthesized by using a higher T_2 and more positive surface potential than those calculated for the faint curve in g. The consistency of the light level through the secondary minimum implies that it is mainly T_2 and not T_1 which varies. The derived change in the common equipotential surface leads to a change in the surface area of star 2

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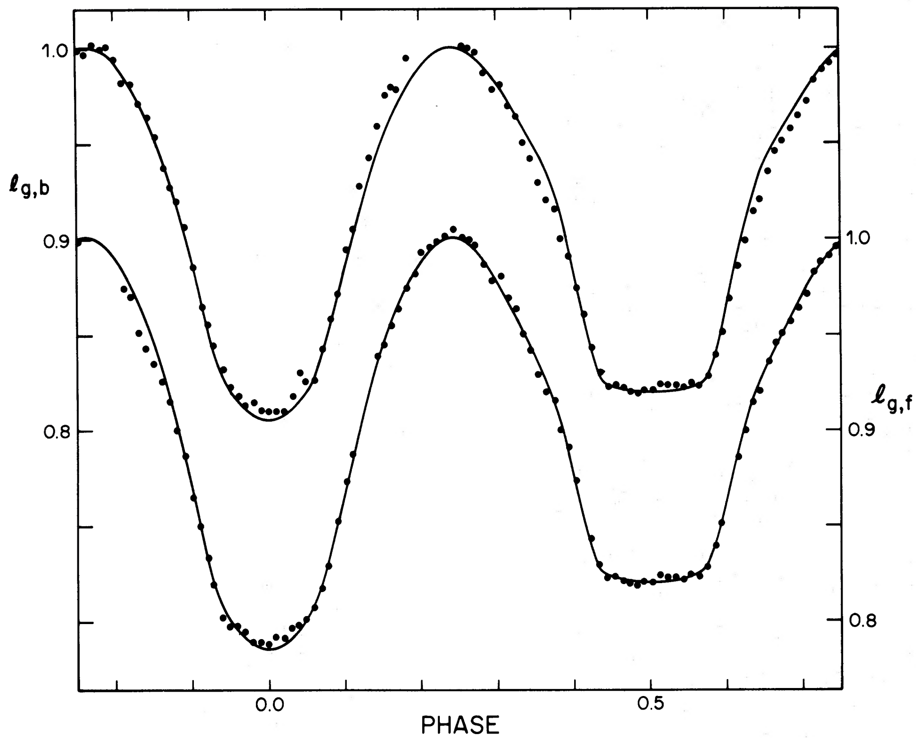

FIG. 3.—The fit of the theoretical light curves of solutions G_f and G_b to the observed green average points

which is larger by a factor of 3.6 than the change in the surface area of star 1.

Normalized synthetic radial velocity curves were also generated by the Wilson-Devinney synthetic light curve program, based upon the light distribution of these distorted stars. Although the eccentricity is assumed to be equal to zero, the radial velocity curve of star 1 is grossly asymmetric about 0^{P}25 and 0^{P}75. McLean (1982) has slightly revised his earlier results by constraining the phases to agree with the photometric ephemeris. Using his revised value for the semiamplitude of star 1, reasonably good agreement exists between his observations and the synthetic curves. No attempt was made to use the radial velocity observations to improve upon the values of any of the light curve parameters.

The light curve parameters derived from this study can be compared with those of previous studies which used the same method. The G_f parameters show good consistency with those of Wilson and Devinney (1973): L_1 and ΔT are within 1 p.e. and Ω within 3 p.e. of their values. Note that this consistency exists even though their solution was based upon mode 1 (T_2 constrained to produce continuity in surface brightness across the neck connecting the two components), while the present solution was arrived at with mode 3 (constraint on T_2 removed). Their solution implies a fill-out factor $f = 0.74$. There is a significant difference, however, in the value of Ω between G_f and the Woodward, Koch, and Eisenhardt (1980) solution calculated using mode 3. Their solution yields $f = 0.30$. L_1 and ΔT are again consistent within 1 p.e.

A second approach to fitting the bright light curves through primary minimum would be to locate a "brighter than normal" region on the system. This bright region or spot would be located so that it contributes maximum light at 0^{P}00, very little light around 0^{P}25 and 0^{P}75, and no light between the first and second maxima. Rough calculations show that the bright g curve could be fitted by beginning with the parameters of G_f and adding a bright spot on the back of star 2. Some sample parameters which yield rough agreement are: a spot area of 10% of the area of star 2 and a spot temperature of 9500 K, or a spot area of 20% of the area of star 2 and a spot temperature of 8300 K. The red light curve also indicates consistency with these parameters. Thus, another interpretation to the intrinsic variability is the existence of a localized hot spot of varying brightness on the back side of star 2.

VI. SUMMARY AND DISCUSSION

It is evident that changes occur in AW UMa: the period has changed, the light curves showed intrinsic variability in the course of the 1979 season, and there have been seasonal changes in the light curves.

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Changes in the systemic period and light curve are common features of the W-type contact systems. However, past studies of other A-type systems seemed to reveal little period change or light curve change. It has been concluded that the A-type systems are in thermal equilibrium in contrast to the W-types (Ruciński 1973; Lucy 1976; Wilson 1978). An exception, however, is AK Her, which has recently been observed and analyzed by Woodward and Wilson (1977). The spectral type of the primary of AK Her is given as F2 from its spectrum and F7–F8 on the basis of its color indices. The system has displayed intrinsic variations in one season of an order similar to those displayed by AW UMa, most notably around primary minimum. Seasonal variability is also found. AK Her shows period changes, and Woodward and Wilson have interpreted these as due either to the orbit of the eclipsing pair about an unseen companion or to mass exchange.

An analysis of the variable light curve has yielded a range of values for some of the parameters of AW UMa. Using the average sizes and temperatures of the two stars as found in this study, together with $q=0.0716$, $i=79^\circ.1$, and the Paczyński (1964) spectroscopic results, one arrives at the approximate value for the absolute visual magnitude of $+2.0$ for the system. This is about 0.8 mag brighter than the value of a main-sequence star of this spectral type (Allen 1973) and is consistent with the conclusion of Wilson that the system is evolved. Eggen (1967) found the binary to be 0.2 mag above the main sequence based upon fitting the common proper motion companion to the main sequence. The derived value for the mass of star 1 is approximately 3.3 ± 1.0 $M_{\odot}$, much larger than that expected for a main-sequence star of this spectral type.

The structure and evolution of contact binaries has been discussed recently by several investigators. Lucy (1976), Flannery (1976), and Robertson and Eggleton (1977) have found from theoretical studies that, due to an inability to attain thermal equilibrium, a zero-age W UMa system would be expected to break contact periodically and become a semidetached system. Mass flow would then proceed from primary to secondary, and a system of marginal contact would eventually arise again. When the contact is again established, mass flow would reverse from the secondary to the primary. These "thermal relaxation oscillations" are thought to occur on a time scale of 10^7 years. A stable state of equilibrium is found to exist, however, for systems in which at least one of the components has evolved on a nuclear time scale. This is thought to be the case for the A-type systems, for which Wilson found larger than zero-age main-sequence radii. AW UMa itself was one of the systems for which he demonstrated this. According to the TRO theory, in the conservative case one would expect the systems to evolve toward smaller mass ratios in order to allow for the evolutionary expansion of the primary while still maintaining marginal contact (Lucy and Wilson 1979). This theory appears to have only mixed success in explaining the observations of AW UMa. This system, as we have seen, is in deep contact and evolved and yet there are several indications that it is not in equilibrium. The period change shows some evidence of mass flow from primary to secondary, so even an appeal to the model appropriate to W-type systems is not consistent. However, the very low mass ratio for this evolved system is consistent with the predictions of the TRO theory. Perhaps the very low mass ratio and the disparate masses of the two stars require a modification in these ideas to explain successfully a system so extreme as AW UMa.

The DSC theory is also not in complete agreement with the observations. The authors of the theory suggest that matter is transferred between the stars by a process which may cause erratic period changes. This could account for the observed change in period. Refinements of this theory predict that the gravity darkening follows the von Zeipel law with a gravity exponent equal to 1.00 for spectral types earlier than F5 (Anderson and Shu 1977). Although this was not a strongly determined parameter in our limiting light curve analysis and we eventually fixed it at a value of 0.45, test solutions indicate a value for the gravity exponent much less than 1.00. In the initial iterations in which the value of the gravity exponent was adjusted with the differential corrections program, the new values of the exponent were less than 0.45. An attempt to fit the faint green curve with the gravity exponent fixed at 1.00 led to a solution whose sum of the weighted square of the residuals was 20% larger than that of solution G_f, and which produced too much curvature in the region of totality in the light curve. This solution with $g_1 = g_2 = 1.00$ also yielded the much larger temperature difference of $\Delta T = 600$ K. Although this is not a strong test, the derived value of the gravity exponent is not that predicted by the theory. The "contact discontinuity" theory of Shu, Lubow, and Anderson (1976, 1979) as presently developed makes fewer observable predictions than the TRO theory, and thus we can say little more with regard to it.

Two models for the intrinsic light variation have been advanced from this study of the light curves. In the first model, resulting from the limiting light curve analysis, star 2 varied in temperature, and the entire system, especially star 2, varied in size. These varied in such a way as to imply that star 2, or at least the outer region of star 2, was unstable. When the system expanded in size, it came near to filling its outer Lagrangian surface, and perhaps some material actually overflowed and escaped from the system, probably through L_2. A new polarization study might give evidence for this material.

The second model incorporated a hot spot of varying brightness on the back of star 2. Mechanisms to create this spot may be mass transfer from the primary to the

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secondary, circulation currents in the common envelope which intersect on the back of star 2, or prominence activity. However, the presence of Hα emission which one would expect from prominence activity has not been observed (McCook 1980). Whatever the mechanism, it must contain a variable component.

It will be useful to continue to obtain times of minimum light annually so that the history of the period and any future change of the period can be documented.

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