

ANALYSES OF NEW LIGHT CURVE OF AW URSAE MAJORIS

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ABSTRACT

New 4-bandpass light curves of the low-mass ratio, over-contact binary AW UMa have been observed and are described. A few times of minimum light and a significant recent period change are reported. Only small variations of the color indices are seen, but these are so situated in phase as to convey the idea of systemic complications rather than gravity-darkening effects. Small asymmetries of the light curves were removed and the symmetricized light curves were analyzed for the binary parameters. It is emphasized that agreement between the present and historical light curve solutions is not as good as it had been anticipated and that this is probably to be attributed to intrinsic variability of the system.

I. INTRODUCTION

AW UMa (BD +30°2163, HD 99946) was observed photoelectrically by Paczyński (1964) on seven nights and proved to be a new short-period eclipsing binary. Later observations and times of minimum light were discussed by Kalish (1965) and by Dworak and Kurpinska (1975). Eggen (1967) considered the common proper motion of AW UMa and BD +30°2164 and noted that no orbital motion has been observed in 50 years. A fraction of a light curve was published by Ferland and McMillan (1976).

Since 1970 Mochnecki and Doughty (1972), Ruciński (1973), Wilson and Devinney (1973), and Lucy (1973), have all analyzed Paczyński's light curves and showed that this binary displays the shallowest complete eclipses of all contact systems. It is, in fact, an over-contact binary of extremely low mass ratio.

Polarimetric observations by Oshchepkov (1974) seem to show a phase-locked variation for the p -parameter indicating some scattering centers within the binary system. Pirola (1977) concluded only that the polarization was possibly variable.

The spectral classification is given as F0-F2. Paczyński's radial velocity representation was rejected from Batten's (1967) compilation because of the possibility that only the light centroid of unresolved double lines had been measured. The analyses of the light curves make it clear, however, that the light ratio is of the order of 10:1 so that the system should be a single-line one. It is curious, therefore, that AW UMa does not appear in

Batten, *et al.* (1978). Some variability of the H line strengths does appear to be phase locked.

II. OBSERVATIONS

AW UMa was observed by E. J. W. on four consecutive nights in April 1974 at Kitt Peak National Observatory (KPNO) using the No. 3 41-cm reflector equipped with a dry ice-refrigerated 1P21 photomultiplier. In all, 427, 466, and 468 observations were obtained with the ultraviolet, blue and yellow filters, respectively. Each observation represents a 10-sec integration registered with a Brown strip-chart recorder. All ultraviolet observations taken with airmasses greater than 2.5 were discarded as there appeared to be a systematic change in these magnitude differences compared to measures at the same phase intervals made at smaller airmasses. On the first two nights standard stars were also observed and these results were analyzed at the Smithsonian Astrophysical Observatory.

The binary was also observed on three nights in 1978 by P.R.E. and R.H.K. at the Flower and Cook Observatory using the two-channel, pulse-counting Pierce-Blitzstein photometer mounted on the 38-cm (diaphragmed to 28-cm) stationary refractor and equipped with spectrally-matched RCA 4509 photomultipliers. The counting interval was 0.0004 days. The characteristics of these 752 observations are: $\lambda_{\text{eff}} \approx 6650 \text{ \AA}$, $\text{FWHM} \approx 1500 \text{ \AA}$.

The comparison star for all observations was BD +31°2270 ($V = +7.20$, $B-V = +0.46$, $U-B = -0.02$); UBV -magnitude and indices were measured by E. J. W. and are in very good accord with those of Paczyński. A check star BD +30°2165 was observed ten times by E. J. W. on her first two nights and yielded $V = +8.93$, $B-V$

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= +0.55, $U-B = +0.10$. The precision of the magnitudes and color indices for the comparison and check stars is ± 0.01 . There is no indication that the comparison star is variable.

All observations exist as File IAU(27). RAS-61 at the R.A.S. Library. Normal points composed from the in-

dividual observations are listed in Table I. The data of 22/23 April 1978 were used only for determining a time of minimum light and were not compiled into the normal points. The KPNO normals are typically composed of five observations which are consecutive in phase. Deviations from this distribution occur only for the two

TABLE I. Normal points for AW UMa in intensity scale.

Phase	I_V/I_C	Phase	I_V/I_C	Phase	I_V/I_C	Phase	I_V/I_C		
Ultraviolet									
0.0133	0.7848	0.2743	0.9917	0.4806	0.8102	0.7661	1.0066		
0.0229	0.7909	0.2841	0.9911	0.4922	0.8151	0.7829	0.9981		
0.0359	0.8068	0.2898	0.9829	0.5041	0.8108	0.8015	0.9872		
0.0471	0.8094	0.2969	0.9785	0.5155	0.8075	0.8157	0.9837		
0.0644	0.8190	0.3062	0.9757	0.5297	0.8108	0.8240	0.9765		
0.0758	0.8403	0.3133	0.9631	0.5405	0.8108	0.8332	0.9648		
0.0830	0.8450	0.3215	0.9574	0.5545	0.8159	0.8443	0.9530		
0.0928	0.8596	0.3313	0.9489	0.5703	0.8220	0.8530	0.9439		
0.1037	0.8832	0.3401	0.9363	0.5820	0.8349	0.8670	0.9184		
0.1134	0.9036	0.3485	0.9323	0.5936	0.8597	0.8833	0.9023		
0.1282	0.9249	0.3575	0.9212	0.6020	0.8712	0.8878	0.8928		
0.1412	0.9485	0.3620	0.9176	0.6160	0.8973	0.9015	0.8659		
0.1555	0.9560	0.3699	0.9079	0.6279	0.9071	0.9209	0.8330		
0.1652	0.9687	0.3784	0.8984	0.6417	0.9264	0.9331	0.8171		
0.1756	0.9819	0.3897	0.8810	0.6502	0.9334	0.9412	0.8122		
0.1878	0.9902	0.3975	0.8648	0.6638	0.9507	0.9560	0.8009		
0.1982	0.9970	0.4055	0.8518	0.6755	0.9563	0.9672	0.7973		
0.2167	0.9990	0.4181	0.8315	0.6974	0.9744	0.9810	0.7941		
0.2325	1.0000	0.4354	0.8188	0.7119	0.9818	0.9922	0.7859		
0.2444	0.9958	0.4488	0.8167	0.7253	0.9923				
0.2588	0.9978	0.4584	0.8162	0.7345	0.9945				
0.2676	0.9912	0.4686	0.8157	0.7509	1.0005				
Blue									
0.0085	0.7879	0.2358	0.9984	0.4088	0.8496	0.6047	0.8831	0.8494	0.9541
0.0156	0.7949	0.2465	0.9973	0.4187	0.8390	0.6173	0.8990	0.8596	0.9426
0.0225	0.7989	0.2615	0.9943	0.4267	0.8323	0.6308	0.9178	0.8775	0.9162
0.0354	0.8064	0.2688	0.9863	0.4351	0.8292	0.6425	0.9348	0.8859	0.8986
0.0466	0.8149	0.2782	0.9887	0.4423	0.8210	0.6527	0.9459	0.8940	0.8893
0.0652	0.8204	0.2861	0.9816	0.4529	0.8227	0.6649	0.9529	0.9126	0.8580
0.0765	0.8406	0.2921	0.9771	0.4574	0.8172	0.6786	0.9598	0.9289	0.8313
0.0845	0.8568	0.3000	0.9760	0.4648	0.8225	0.6925	0.9769	0.9372	0.8137
0.0945	0.8760	0.3077	0.9658	0.4711	0.8208	0.7043	0.9832	0.9488	0.8064
0.1045	0.8888	0.3164	0.9608	0.4773	0.8158	0.7131	0.9852	0.9621	0.7970
0.1161	0.9087	0.3253	0.9561	0.4880	0.8136	0.7229	0.9969	0.9748	0.7965
0.1306	0.9334	0.3338	0.9403	0.4937	0.8207	0.7297	0.9989	0.9849	0.7970
0.1433	0.9433	0.3421	0.9364	0.5063	0.8148	0.7429	1.0074	0.9952	0.7923
0.1564	0.9580	0.3522	0.9353	0.5170	0.8133	0.7607	1.0024		
0.1644	0.9645	0.3590	0.9234	0.5317	0.8186	0.7751	1.0020		
0.1732	0.9742	0.3642	0.9154	0.5419	0.8178	0.7936	0.9918		
0.1796	0.9785	0.3721	0.9117	0.5581	0.8164	0.8106	0.9885		
0.1916	0.9852	0.3824	0.8967	0.5714	0.8281	0.8198	0.9851		
0.2009	0.9952	0.3925	0.8792	0.5842	0.8426	0.8296	0.9744		
0.2186	0.9950	0.3995	0.8688	0.5944	0.8635	0.8387	0.9617		
Yellow									
0.0077	0.7976	0.2281	0.9993	0.4045	0.8605	0.6008	0.8763	0.8453	0.9506
0.0151	0.8004	0.2422	0.9984	0.4140	0.8412	0.6149	0.8983	0.8535	0.9393
0.0219	0.7984	0.2550	1.0013	0.4234	0.8325	0.6268	0.9140	0.8705	0.9149
0.0349	0.8055	0.2664	0.9936	0.4326	0.8273	0.6404	0.9331	0.8835	0.9060
0.0461	0.8110	0.2731	0.9912	0.4415	0.8257	0.6467	0.9384	0.8890	0.8935
0.0633	0.8169	0.2831	0.9881	0.4508	0.8205	0.6606	0.9518	0.9036	0.8730
0.0748	0.8418	0.2888	0.9834	0.4562	0.8150	0.6715	0.9585	0.9233	0.8384
0.0818	0.8494	0.2957	0.9756	0.4624	0.8208	0.6870	0.9733	0.9331	0.8231
0.0915	0.8645	0.3050	0.9690	0.4694	0.8208	0.6988	0.9827	0.9424	0.8142
0.1031	0.8903	0.3120	0.9598	0.4745	0.8181	0.7106	0.9874	0.9574	0.8045
0.1127	0.8996	0.3203	0.9601	0.4866	0.8109	0.7182	0.9907	0.9688	0.8020
0.1271	0.9174	0.3302	0.9501	0.4914	0.8132	0.7262	0.9943	0.9810	0.8001
0.1401	0.9464	0.3386	0.9352	0.5030	0.8193	0.7357	0.9976	0.9891	0.8061
0.1543	0.9461	0.3473	0.9403	0.5144	0.8167	0.7536	0.9951	0.9964	0.8006
0.1618	0.9569	0.3563	0.9275	0.5284	0.8196	0.7680	1.0087		
0.1719	0.9701	0.3610	0.9257	0.5393	0.8188	0.7863	0.9958		
0.1771	0.9767	0.3685	0.9132	0.5533	0.8196	0.8038	0.9866		
0.1891	0.9821	0.3765	0.9057	0.5691	0.8289	0.8161	0.9851		
0.1959	0.9883	0.3888	0.8946	0.5808	0.8401	0.8252	0.9706		
0.2109	0.9938	0.3962	0.8757	0.5925	0.8600	0.8341	0.9633		

TABLE I. (Continued).

Phase	I_V/I_C	Phase	I_V/I_C	Phase	I_V/I_C	Phase	I_V/I_C
				Red			
0.0036	0.7960	0.2585	0.9895	0.5231	0.8365	0.7803	0.9910
0.0228	0.8021	0.2829	0.9931	0.5434	0.8353	0.8020	0.9922
0.0468	0.8120	0.3036	0.9760	0.5631	0.8443	0.8218	0.9696
0.0635	0.8219	0.3224	0.9602	0.5828	0.8647	0.8410	0.9440
0.0847	0.8544	0.3429	0.9357	0.6033	0.8918	0.8667	0.9170
0.1023	0.8831	0.3639	0.9184	0.6261	0.9278	0.8834	0.8959
0.1228	0.9104	0.3836	0.8894	0.6434	0.9412	0.9031	0.8651
0.1436	0.9340	0.4033	0.8649	0.6620	0.9582	0.9233	0.8267
0.1633	0.9471	0.4194	0.8437	0.6829	0.9711	0.9435	0.8129
0.1821	0.9750	0.4445	0.8421	0.7025	0.9813	0.9626	0.8038
0.2027	0.9944	0.4631	0.8403	0.7229	0.9973	0.9827	0.7984
0.2238	0.9999	0.4835	0.8422	0.7434	1.0000		
0.2436	0.9981	0.5033	0.8386	0.7633	0.9971		

normals flanking zero phase which may contain 4, 5, or 6 measures depending on the filter. The Pennsylvania normals encompass observations within windows of 0.02P and are of individual weights. The weights are accounted for in the analyses of the light curves.

III. TIMES OF MINIMUM LIGHT

Among the observations reported here, there are several which pass through minimum light. These were analyzed by the procedure developed by Kwee and van Woerden (1956) and the heliocentric times of minimum light are listed in Table II. All published times of minimum light have been collected and, together with those of Table II, have been subjected to the ephemeris of Dworak and Kurpiska. The residuals from this constant period ephemeris are shown in Figure 1. Phases for the KPNO observations were computed from:

$$\text{Hel. Pr. Min.} = 2442150.4385 + 0.43873234E, \quad (1)$$

which accounts satisfactorily for a constant period through about $E = +10000$. From Dworak and Kurpiska's ephemeris, the Pennsylvania observations show a mean residual of -0.00537 days, which implies a significant period shortening over no more than 2500 cycles. Period changes are certainly known among the subclass of A-type (Binnendijk 1977) contact binaries, but the magnitude of this period change for AW UMa is large. Since the two nights representing the Pennsylvania measures span only 15 cycles, phases for these observations were adequately calculated from:

TABLE II. Times of minimum light for AW UMa.

J.D. (hel.)	E
2442151.7539 \pm 0.0001	+9361
2442152.8495 \pm 0.0001	9363.5
2442153.7287 \pm 0.0002	9365.5
2443580.70074 \pm 0.00006	12618
2443621.7220 \pm 0.0001	+12711.5

$$\text{Hel. Pr. Min.} = 2443580.70074 + 0.43873234E. \quad (2)$$

The normal points of the light curves are shown in Figure 2. Secondary minimum is clearly total without any obvious slope to the interval of totality, and it is a reasonable inference that the primary eclipse is annular.

IV. COLOR INDICES AND LIGHT CURVES

The UBV indices of AW UMa agree within ± 0.01 for the Paczyński and KPNO light curves. As expected for an early F-type star, the $(U-B)$ -index shows only very small variations through the cycle. It does, however, become about 0.01 more positive through phase intervals 0.85–0.93, 0.99–0.12, and 0.36–0.52. These variations must express systemic complications which are phase locked. The $(B-V)$ -index also shows only small variations through the cycle. It is more negative by about 0.01 near phase 0.75 than near 0.25 phase and, with respect to its value at phase 0.75, becomes more positive by 0.015 over the phase interval, 0.93–0.02. Obviously, this too is not the conventional gravity reddening seen at the conjunctions of contact binaries but, rather is an expression of some systemic complications. The mean indices imply an unreddened F2-system. Because the light curves were

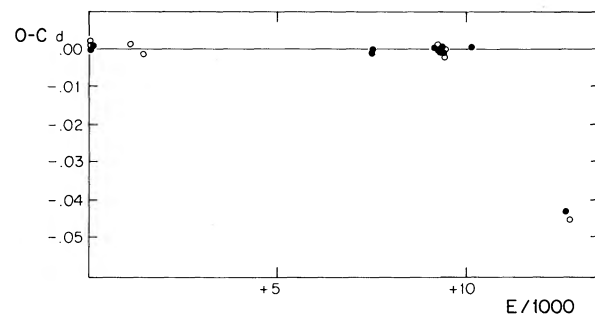


FIG. 1. The residuals from the constant period ephemeris of Dworak and Kurpiska for all observed times of minimum light. Filled and open circles refer to primary and secondary minima, respectively.

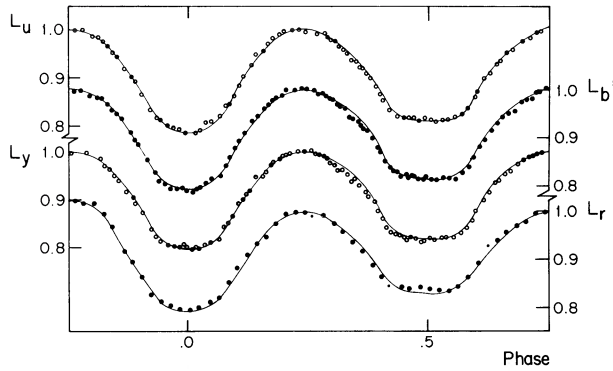


FIG. 2. From top to bottom, the intensity-scale ultraviolet, blue, yellow, and red normal points of Table I with the theoretical light curves from the solutions of Table IV drawn through them.

observed at different times, no attempt was made to form a ($V-R$)-index.

The light curves are slightly asymmetric. Empirically-evaluated terms with a $\sin \theta$ -dependence were used to remove these asymmetries and their coefficients, B_1 are given in Table III. The ultraviolet and visual coefficients are not in good agreement with those appropriate to Paczyński's light curve. Hence, some time-variable complexity must exist in AW UMa.

V. ANALYSIS AND DISCUSSION

Study of the KPNO normals was begun by initializing the parameters for the blue and yellow light curves at the values found for Paczyński's observations by Wilson and Devinney except for T_1 which was increased to 7175 K. For the ultraviolet normals, the wavelength-dependent parameters were initialized by extrapolating the weak trends from the yellow and blue evaluations. Theoretical light curves were then calculated by the Wilson-Devinney code and least-squares improvements to the evaluations of the parameters were pursued essentially in the manner described by Leung and Wilson (1977). Mode 3 of the code was used invoking synchronous rotation at all times. Both the black body and stellar atmosphere options were explored in fitting the observations. Among the three light curves, 18 iterations of the differential correction procedure were completed and they yield the results shown in Table IV and plotted through the observations in Figure 2. Each parenthesized quantity in Table IV represents the probable error of the last figure of the value for a light curve parameter.

The familiar tight correlations among i , q , and L_3 ,

TABLE III. Coefficients of $\sin \theta$ asymmetry for AW UMa.

Light Curve	B_1
Ultraviolet	-0.004
Blue	-0.004
Yellow	-0.0005
Red	-0.007

which usually degrade the conditioned determinacy of these parameters, are diminished for AW UMa since the eclipses are complete. The correlations among L_1 , g , T_2 and x remain, however. Most of the weight of the evaluations goes into L_1 and T_2 so that the determinacies of g and x are relatively poor.

In yellow and blue light, consistency at the 3σ -level with the former studies of Paczyński's data exists for every parameter except Ω . Furthermore, it has been possible to obtain a representation of the ultraviolet light curve that is consistent with the yellow and blue ones by using the black body approximation. This consistency could not be attained by using the model atmosphere feature of the code upon the ultraviolet light curve with the temperature difference which was found appropriate for the yellow and blue curves. The march with wavelength of the fractional stellar luminosities and limb darkening is satisfactory. Even though this general satisfaction exists, there remain systematic errors in the fitting to the observations: over most of the branches of secondary minimum, the theoretical light curves are too bright by as much as 0.008 mag. It was not possible to remove this misfit by manipulating the limb darkening or albedo or the stellar temperatures and it must be attributed to some unknown complication. The general description of AW UMa, revealed by the UBV data, is that of a true binary (i.e., at the level of about 1%, there is no contribution to the systemic light from a third source) whose secondary member overfills its Roche lobe by about 7.5% in units of the orbital radius, and whose primary member is in contact with its Roche lobe.

For the red light curve the parameters were initialized to the values finally obtained for the yellow observations. No attempt was made to improve the values of i , T_1 , and q beyond those already evaluated. The results of seven differential correction iterations with the black body option appear in Table IV and among the observations of Figure 2. Since, even after the removal of the $\sin \theta$ correction, the red light curve remains asymmetric with

TABLE IV. Light curve parameters for AW UMa.

Parameter	Ultraviolet/Blue/Yellow	Red
$A_1 = A_2$	1.00 (assumed)	1.00 (assumed)
$g_1 = g_2$	0.62 (6)	0.63 (5)
T_1	7175K (assumed)	7175K (assumed)
T_2	6875K (50K)	6560K (90K)
L_1	0.932(5)/0.909(6)/0.909(6)	0.925(10)
L_2	0.068/0.091/0.091	0.075
$x_1 = x_2$	0.76(6)/0.66(6)/0.63(6)	0.50 (9)
L_3	0.005(12)/0.008(8)/0.006(8)	0.00 (assumed)
i	79.1 (4)	79.1 (assumed)
Ω	1.8527(8)	1.821(2)
q	0.0716(5)	0.0716 (assumed)
$r_{1,pole}$	0.559 (2)	—
$r_{1,point}$	0.750	—
$r_{1,side}$	0.633(2)	—
$r_{1,back}$	0.651(2)	—
$r_{2,pole}$	0.177(2)	—
$r_{2,point}$	—	—
$r_{2,side}$	0.185(2)	—
$r_{2,back}$	0.221(2)	—

secondary advanced in phase earlier than the half-period point, it is inevitable that the fitting of this light curve will be less successful than for the three earlier light curves. Parameter errors are higher for red than for the other bandpasses, but there also exist systemic discrepancies: the polar temperature difference is greater and the modified Roche potential is smaller for the red than for the other light curves. In general, however, the red light curve also describes AW UMa as an over-contact binary with Ω essentially the value for outer contact for the given mass ratio.

In general, the analyses of all these light curves are formally less determinate than the representations by Wilson and Devinney of Paczyński's two light curves. For the present red observations this can be attributed to the easily recognized complexity of the light curve, which complexity is the reason that derived stellar radii are not given for this bandpass in Table IV. It is a reasonable conjecture that the complexity of this light curve is in some way associated with the recent period change. It is hardly likely, however, that only the stellar radii themselves have changed. It is much more likely that, even if the radii have really changed, other changes in the surface temperature distribution and in patterning of circumstellar gas have also occurred.

A more fundamental difficulty exists in that the representation of the KPNO light curves has formally no better precision than Wilson and Devinney were able to achieve for Paczyński's data. Although the asymmetry terms are different for the two epochs of observation, it is not possible *a priori* to prefer one set of data to the other on the basis of simplicity. One might have expected that the KPNO observations should be the less complicated ones since they describe a system closer to inner (rather than outer) contact than does Paczyński's light curve. One may also note that the Keplerian period was certainly the same for both epochs. As far as can be un-

derstood at present, there is no resolution of these paradoxical results. However, it is felt that these confusions forbid formal presentation of stellar radii and masses (in units of the solar values). The most temperate point of view seems to be that the Wilson and Devinney values are indicative ones but that the intrinsic variability of the binary has, thus far, prevented accurate understanding of its complexity. Until these complexities are confidently removed, the absolute stellar parameters will be more elusive than the formal solution of light curves would indicate.

Among others, Wilson (1978) and Lucy (1976), have emphasized the stability of the light curves and periods of A-type contact binaries and interpreted this to mean that these systems have attained thermal equilibrium. AW UMa is an A-type object, albeit of extreme mass ratio, and its intrinsic variability emphasizes the need to develop a long history for such systems before accepting this assertion.

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