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AD Cancri: A Contact Binary with Components in Poor Thermal Contact

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Abstract We present the light curve and photometric solutions of the contact binary AD Cnc. The light curve appears to exhibit a typical O'Connell effect, with Maximum I brighter than Maximum II by 0.010 mag. in V. From 1987 to 2000, the light curve showed changes of shape: the depth of the primary eclipse increased by about 0.056^{m} while that of the secondary eclipse decreased by about 0.032^{m}, so the difference between the primary and the secondary eclipses increased by about 0.088^{m}, while there was no obvious variation in the O'Connell effect. Using the present and past times of minimum light, the changes in the orbital period of the system are analyzed. The result reveals that the orbital period of AD Cnc has continuously increased at a rate of $\frac{\mathrm{d}p}{\mathrm{d}t} = 4.4 \times 10^{-7}\,\mathrm{day\ yr^{-1}}$. The light curve is analyzed by means of the latest version of the Wilson-Devinney code. The results show that AD Cnc is a W-subtype contact binary with a small mass ratio of 0.267 and the two components are in poor thermal contact. AD Cnc has a component temperature difference exceeding 500 K, and exhibits a shallow contact of 3.6%. The asymmetry of the light curves is explained by the star spot model.

Key words: binaries: eclipsing — stars: starspots

1 INTRODUCTION

In a search for cluster variables in the region of the old galactic cluster M67, Kurochkin (1960) discovered the variability of AD Cancri, and identified the star as an RR Lyrae type variable with a period of 0.146373 d. Efremov et al. (1964) argued that AD Cnc is a W Ursae Majoris type system. The spectral type of the system was found to be K0 (Herbig 1961). Millis (1972) observed AD Cnc photoelectrically and obtained a V magnitude range of 13.1 − 13.4 as well as a $(B-V)$ color range of about 0.89–0.94. This color range is in agreement with the spectral type of K0. The General Catalogue of Variable Stars (1968, 1985), citing unpublished manuscripts of Kurochkin, gives two ephemerides, JD Hel Min. I = 2441363.8063

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+ 0.2771724 Ed in the third edition and JD Hel Min. I = 2443192.4300 + 0.28273824 Ed in the fourth edition. Samec & Bookmyer (1987a) observed this system photoelectrically and published B, V, R, I light curves, determined a V magnitude range of 13.13 − 13.51 and a $(B-V)$ color range of 0.88 − 0.96. They gave an improved ephemeris, JD Hel Min. I = 2446826.8767 + 0.28273731 Ed. An approximate check performed by Samec & Bookmyer (1987a) indicated that AD Cnc is not a member of M67. Subsequently, Samec et al. (1989) published photometric solutions of AD Cnc, and showed that AD Cnc is a W-subtype W UMa type contact binary with a mass ratio of 0.625.

Because photometric data of AD Cnc are quite rare, the system was included in the observational program of short period variables with the 100-cm reflecting telescope of the Yunnan Observatory.

2 OBSERVATIONS

The CCD photometry of AD Cnc in the V band was carried out on the night of January 28, 2000, with the PI1024 TKB CCD photometric system attached to the 100-cm reflecting telescope at the Yunnan Observatory. The effective field of view of the photometric system is 6.5 × 6.5 square arcmin at the Cassegrain focus and its BV color system approximates to the standard Johnson BV photometric system (Yang & Li 1999). The coordinates of the comparison star and the check star used are listed in Table 1. The comparison star and the check star are close enough to the variable star that they are all included in the same viewing field.

Table 1 Coordinates of the Variable, Comparison Star and Check Star

Star	R.A. (2000.0) h m s	Decl. (2000.0) ° ′ ″
Variable	08 46 21	10 19 59
Comparison star	08 46 16	10 16 00
Check star	08 46 33	10 19 48

The integration time for each image was 100 seconds. A total of 114 images in the V band was obtained. The aperture photometry package, IRAF, was used to reduce the images. The reduced results show that the magnitude difference between the check star and the comparison star was constant within a probable error of ±0.008 mag. Extinction corrections were not made since the comparison star is very close to the target star: their air-mass difference between never exceeded 0.0005 during the observations.

From the observations, three times of minimum light were derived by using a parabola fitting. The new times of minimum light and the photoelectric times published by other authors are listed in Table 2; the $(O–C)_1$ values were calculated by means of the light element formula given by Samec and Bookmyer (1987a),

$$\mathrm{Min.I} = \mathrm{HJD}\,2446826.8767 + 0.28273731^{\mathrm{d}}\,E\,. \tag{1}$$

From the photoelectric times of minimum light collected in the references and the new ones derived here, and the minima computed with the above ephemeris we obtain the $(O–C)_1$ values plotted in Fig. 1. This diagram shows that the orbital period of AD Cnc has continuously increased since 1970. A quadratic ephemeris determined by a least squares fitting to the photoelectric minima gives,

$$\text{Min.I} = \text{HJD}\,2446826.8749(6) + 0.28272724(8)^{\text{d}} E + 1.7(4) \times 10^{-10} E^2\,, \tag{2}$$

which is used to compute the (O–C)$_2$ values in Table 2. This ephemeris shows that the orbital period of AD Cnc has continuously increased. Using the coefficient of the square term of Eq. (2), we calculate a continuous period increase of $\frac{\Delta p}{p} = 3.4 \times 10^{-10}$, i.e., $\frac{\mathrm{d}p}{\mathrm{d}t} = 4.4 \times 10^{-7}$ day yr^{-1}. From the photoelectric timings of minimum light obtained by Samec & Bookmyer (1987a) and the present work, a linear ephemeris is obtained

$$\text{Min.I} = \text{HJD}\,2451572.2169(5) + 0.28272999(2)^{\text{d}}\,E\,, \tag{3}$$

which is used to compute the phases of our observations.

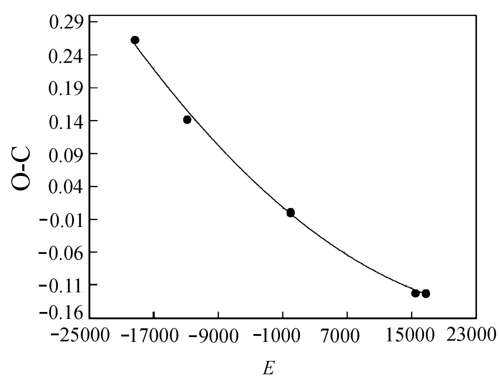

Fig. 1 Period changes of AD Cnc.

Table 2 The Times of Minimum Light of AD Cnc

HJD 2400000+	Min.	(O–C)$_1$	(O–C)$_2$	Reference
41363.8063	I	0.2626	0.0085	GCVS, 1968
43192.4300	I	0.1414	–0.0138	GCVS, 1985
46823.7661	I	–0.0005	–0.0012	Samec and Bookmyer, 1987b
46823.9082	II	0.0002	0.0019	Samec and Bookmyer, 1987b
46826.8769	I	0.0002	0.0020	Samec and Bookmyer, 1987b
46827.7244	I	–0.0005	–0.0005	Samec and Bookmyer, 1987b
46827.8670	II	0.0007	0.0026	Samec and Bookmyer, 1987b
50508.5558	I	–0.1262	–0.0215	Krobusek, 1997a
50520.5746	II	–0.1237	–0.0188	Krobusek, 1997b
51202.3969	I	–0.1224	–0.0048	Agerer and Hubscher, 2000
51572.0756	II	–0.1227	0.0010	this paper
51572.2166	I	–0.1231	0.0007	this paper
51572.3586	II	–0.1225	0.0013	this paper

A total of 114 data points in yellow light as been obtained. Tables 3 lists the Heliocentric Julian Day, and magnitude difference between the variable and the comparison. The light curve of the system is shown by the filled circles in Fig. 2. The light curves appear to exhibit a typical

O'Connell effect, with Maximum I 0.010 mag. (V) brighter than Maximum II. Some parameters of the light curves in the V band are listed in Table 4, from which one can see obvious variation in the light curves. A comparison between the V light curves obtained in (Samec & Bookmyer 1987a) and the present work will reveal that the depth of the primary eclipse has increased by about $0.056^{\rm m}$ while that of the secondary eclipse has decreased by about $0.032^{\rm m}$, so that the difference of eclipsing depth between the primary and the secondary eclipses has increased by about $0.088^{\rm m}$ while the O'Connell effect has not shown any obvious changes.

Table 3 CCD Photometric Observations of AD Cnc in the V Band

JD. (HEL) 2451572+	Δm	JD. (HEL) 2451572+	Δm	JD. (HEL) 2451572+	Δm	JD. (HEL) 2451572+	Δm	JD. (HEL) 2451572+	Δm
0.0609	–0.670	0.1334	–0.902	0.2014	–0.587	0.2669	–0.860	0.3328	–0.755
0.0683	–0.638	0.1361	–0.904	0.2042	–0.551	0.2695	–0.878	0.3355	–0.729
0.0711	–0.628	0.1389	–0.912	0.2071	–0.521	0.2722	–0.896	0.3383	–0.716
0.0761	–0.594	0.1416	–0.915	0.2098	–0.490	0.2762	–0.915	0.3410	–0.681
0.0789	–0.602	0.1444	–0.917	0.2126	–0.477	0.2790	–0.921	0.3529	–0.650
0.0815	–0.606	0.1471	–0.914	0.2153	–0.467	0.2819	–0.928	0.3556	–0.610
0.0866	–0.633	0.1498	–0.912	0.2181	–0.470	0.2848	–0.930	0.3586	–0.608
0.0893	–0.665	0.1526	–0.910	0.2209	–0.479	0.2879	–0.927	0.3613	–0.595
0.0920	–0.685	0.1553	–0.903	0.2237	–0.496	0.2911	–0.929	0.3644	–0.620
0.0948	–0.703	0.1580	–0.893	0.2268	–0.533	0.2938	–0.927	0.3714	–0.654
0.0976	–0.724	0.1609	–0.877	0.2296	–0.563	0.2965	–0.922	0.3741	–0.675
0.1004	–0.748	0.1659	–0.858	0.2323	–0.595	0.2995	–0.914	0.3769	–0.685
0.1033	–0.759	0.1686	–0.854	0.2350	–0.621	0.3023	–0.907	0.3796	–0.707
0.1061	–0.776	0.1713	–0.845	0.2378	–0.650	0.3050	–0.900	0.3823	–0.752
0.1088	–0.790	0.1741	–0.824	0.2405	–0.687	0.3077	–0.899	0.3883	–0.785
0.1115	–0.810	0.1785	–0.801	0.2432	–0.706	0.3105	–0.886	0.3910	–0.789
0.1143	–0.830	0.1824	–0.780	0.2460	–0.740	0.3133	–0.875	0.3938	–0.822
0.1170	–0.846	0.1850	–0.751	0.2490	–0.750	0.3160	–0.857	0.3970	–0.825
0.1197	–0.861	0.1871	–0.731	0.2523	–0.787	0.3187	–0.849	0.3997	–0.858
0.1226	–0.865	0.1901	–0.707	0.2554	–0.806	0.3214	–0.825	0.4024	–0.853
0.1253	–0.873	0.1931	–0.685	0.2582	–0.818	0.3243	–0.803	0.4052	–0.877
0.1280	–0.888	0.1959	–0.656	0.2609	–0.825	0.3270	–0.794	0.4079	–0.882
0.1308	–0.893	0.1986	–0.614	0.2636	–0.841	0.3301	–0.780		

Table 4 Parameters of the V Light Curve of Ad Cnc

Obs. date	1987	2000	Difference
Max.I – Min.I	–0.408	–0.462	0.054
Max.II – Min.I	–0.394	–0.452	0.058
Max.I – Min.II	–0.362	–0.328	–0.034
Max.II – Min.II	–0.348	–0.318	–0.030
Max.I – Max.II	–0.014	0.010	–0.024
Min.I – Min.II	0.046	0.134	–0.088

3 PHOTOMETRIC SOLUTIONS

Photometric solutions were obtained using the Wilson-Devinney program which included a new reflection treatment, an option to use non-linear limb-darkening laws and adjustable spot parameters. All the observations were used in the solutions. The convergence of the minimization procedure is obtained by the method of multiple subsets (Wilson & Biermann 1976).

The adopted parameters in the solutions are as follows: for Star 1 (the star eclipsed at Min.I), a temperature of 5164 K, which corresponds to a $B-V$ color of 0.88 (Donald & Thomas 1968), limb darkening coefficients $x_1 = x_2 = 0.740$ for the V band (Claret et al. 1990), gravity darkening coefficients $g_1 = g_2 = 0.320$ (Lucy 1967) and albedos ($A_1 = A_2 = 0.500$) (Rucinski 1969). The adjustable parameters are the orbital inclination, ι, the mean temperature of Star 2, T_2, the potential of the components, Ω_1 and Ω_2, and the monochromatic luminosity of Star 1, L_1 (the Planck function is used to compute the luminosity).

Solutions were worked out for a series of fixed values of the mass ratio $q = m_2/m_1$ (0.40, 0.50, 0.60, 0.70, 0.80, 1.20, 1.40, 1.60, 2.00, 2.40, 2.80, 3.20, 4.00, and 5.00). Assuming that initially it was a detached system, the differential corrections started from the contact Mode 2, but the converged solutions were always obtained from Mode 3. The resulting sum of residuals, Σ, of the converged solution for each value of q indicated that the fitting was best for $q = 4.00$ (see Fig. 3). At this point, the set of the adjustable parameters was expanded to include the mass ratio q, which converged to the value $q = 3.74431$, in the final solution. The filling factor, $f = 0.035$, was based on the expression $(\Omega_{\rm in} - \Omega)/(\Omega_{\rm in} - \Omega_{\rm out})$ that varies from 0 to unity from the inner to the outer critical surface. This solution indicates that AD Cnc is a W-subtype W UMa binary with a shallow degree of contact, because the primary eclipse is occultation (the smaller secondary component is eclipsed). The photometric parameters are listed in the second column (unspotted) of Table 5. The computed light curve according to these (unspotted) parameters is shown by the solid lines in Fig. 2.

While the overall fit of the computed light curves is quite satisfactory, Fig. 2 shows obvious distortions in the observed light curves that point to surface inhomogeneities of the components. Unequal quadrature light level, namely, the O'Connell effect, is known in many eclipsing binaries and several suggestions have been made to explain this effect by various authors. For AD Cnc, the observed distortion, with Maximum II fainter than Maximum I, may result from either a cool or a hot region on either component. We tested for groups of dark or hot spots on either star. Eventually, two converged solutions were found: one with a cool spot on star 2, one with a hot spot on star 2. These solutions are labeled Dark 2 and Hot 2 in Table 5. Also listed in Table 5 are the spot parameters (co-latitude, θ, longitude, ϕ, angular radius γ, all in degrees, and the temperature factor T_s/T_*, with T_* being the local effective temperature of the surrounding photosphere). The solution labeled Dark 2, i.e., the one with a cool spot on the primary (= more massive) star 2, turns out to be of a slightly better quality than the other one. The corresponding computed light curves are shown by the solid lines in Fig. 4. From Fig. 4 alone we could conclude that the O'Connell effect for AD Cnc is due to a cool area appearing on the surface of the primary component.

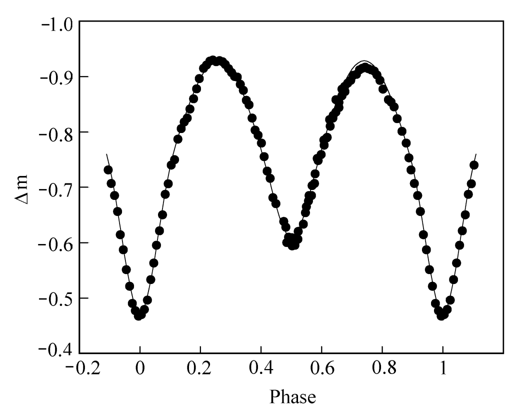

Fig. 2 Light curve of AD Cnc. Filled circles are the observations and the line is the computed light curve of the unspotted solution given in Table 5.

Table 5 Photometric Solutions of AD Cnc

Parameters	Unspotted	Dark 2	Hot 2
$q = m_2/m_1$	3.7443 ±0.0064	3.7460 ±0.0050	3.7667 ±0.0052
i	65.55±0.20	65.69 ±0.18	65.87 ±0.13
T_1 (K)	5164	5164	5164
T_2 (K)	4609 ±11	4595 ±11	4650 ±9
Ω	7.3979±0.0081	7.3961±0.0065	7.4432±0.0051
Ω (in)	7.5851	7.5872	7.6138
Ω (out)	2.2464	2.2464	2.2470
f	0.035	0.036	0.032
$L_{1V}/(L_{1V}+L_{2V})$	0.3651±0.0016	0.3693 ±0.0013	0.3514±0.0019
$x_{1V} = x_{2V}$	0.740	0.740	0.740
$A_1 = A_2$	0.500	0.500	0.500
$g_1 = g_2$	0.320	0.320	0.320
r_1 (pole)	0.2647±0.0004	0.2649 ±0.0002	0.2631 ±0.0003
r_1 (side)	0.2772 ±0.0005	0.2775 ±0.0003	0.2754 ±0.0004
r_1 (back)	0.3207 ±0.0011	0.3213±0.0005	0.3177±0.0007
r_2 (pole)	0.4759 ±0.0005	0.4762 ±0.0005	0.4754±0.0003
r_2 (side)	0.5166 ±0.0008	0.5169 ±0.0006	0.5157±0.0004
r_2 (back)	0.5447 ±0.0010	0.5452 ±0.0009	0.5434 ±0.0005
Σ	0.004642	0.003179	0.003646
ϕ		80.8±0.5	86.1 ±0.7
θ		284.2 ±1.1	56.8 ±1.9
γ		9.5 ±0.3	10.9±0.4
T_s/T_*		0.91±0.02	1.17±0.03

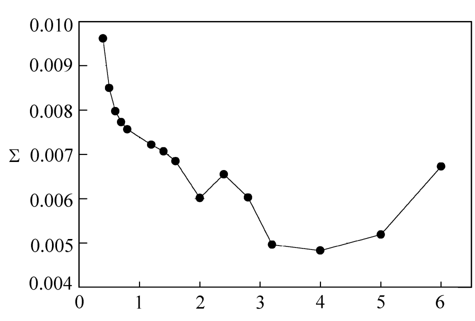

Fig. 3 Variance of the computed fit as a function of the mass ratio q.

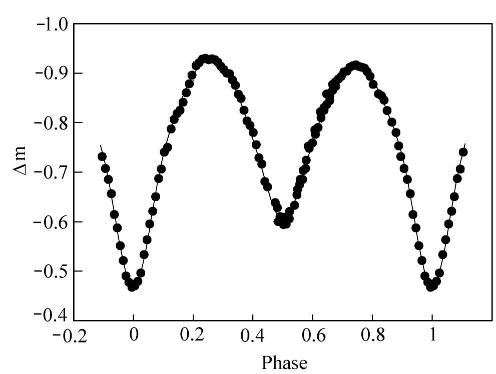

Fig. 4 AS in Fig. 2, but for the solution with a spot on the primary component.

4 CONCLUSIONS AND DISCUSSION

From the present observations and analyses, we have reached the following conclusions. 1) The shape of the light curves of AD Cnc has displayed considerable variation. From 1987 to 2000 the depth of the primary eclipse increased by about 0.056^{m} while the depth of the secondary eclipse decreased by about 0.032^{m}, so that the difference in depth between the primary and the secondary eclipses increased by about 0.088^{m} while the O'Connell effect did not show very obvious variations. 2) Since 1970 the orbital period of AD Cnc has continuously increased at a fractional rate of $\frac{\Delta p}{p} = 3.4 \times 10^{-10}$. 3) AD Cnc is a W-subtype W UMa contact binary with the two components in poor thermal contact. AD Cnc has a component temperature difference exceeding 500 K, and exhibits a shallow contact of 3.6%. This system can be considered as an example of contact binaries with the components in poor thermal contact.

The present solutions give a mass ratio of 0.267, which differs greatly from the mass ratio of 0.625 given by Samec et al.(1989). Samec et al. used a starting value of $q = 0.5$ so their final value 0.625 could be a local converged solution. From Fig. 3, one can see that two extreme values occur in the variance versus mass ratio curve. A second minimum of the variance Σ occurs when $q = 2.0$ (in the DC program of Wilson- Devinney code, q is defined as $q = m_2/m_1$, m_1 being the mass of the component eclipsed at the primary eclipse) corresponding to a mass ratio of 0.5 in the normal definition of the mass ratio. However, the best fit occurs when $q = 4.0$ corresponding to a mass ratio of 0.25 in the normal definition. Therefore, the present solution may be better than that obtained by Samec et al. (1989).

The spectroscopic data for AD Cnc are inadequate, so it is necessary to adopt the method introduced by Maceroni & van't Veer (1996) to infer the physical parameters of the system. With their method the total mass and total luminosity of the system can be derived and then from the photometric value of the mass ratio one can easily derive the physical parameters. The set of absolute dimensions of AD Cnc so derived are: $M_1 = 0.90\,M_\odot$, $M_2 = 0.24\,M_\odot$, $R_1 = 0.96\,R_\odot$, $R_2 = 0.55\,R_\odot$, $L_1 = 0.37\,L_\odot$ and $L_2 = 0.19\,L_\odot$.

AD Cnc possesses an EB-type light curve but its orbital period and color index $(B-V)$ fall in the range occupied by W UMa type contact systems. The solutions presented above show that this system is a contact binary with components in poor thermal contact. The obtained temperature difference between components is about 550 K. The degree of geometrical contact is only about 3.6%, defined by the expression $(\Omega_{in} - \Omega)/(\Omega_{\mathrm{in}} - \Omega_{\mathrm{out}})$. The ratio of bolometric luminosities of the components is about 0.51. This value is by a factor of 100 higher than the ratio which would be expected on the basis of the mass-luminosity relation for main sequence stars. This suggests that there is a large energy transfer between the components of AD Cnc.

Besides AD Cnc, at least 16 EB-type contact binaries with temperature difference between two components more than 400 K (W Crv, WZ Cep, BE Cep, CN And, FT Lup, V747 Cen, AG Vir, V1010 Oph, BL And, V1073 Cyg, TY Men, XZ Leo, UV Lyn, V432 Per, S And and ϵ CrA) have been observed and analyzed. Systems of this kind are interesting from the point of view of the "thermal relaxation oscillation theory" (Lucy & Wilson (1979) and references therein). According to this theory, unevolved W UMa systems undergo oscillations about a state of marginal contact. During each cycle of these hypothetical oscillations, a system spends some time in the semidetached configuration with the more massive component filling its Roche lobe. In the phase when thermal contact between components does not exist or is week, the system exhibits an EB-type light curve. AD Cnc and the other contact binaries with greater temperature differences between the components are some important systems to test this theory.

In the light of the present photometric solutions, AD Cnc is a W-subtype contact with the two components in poor thermal contact. In view of the importance to the study of the contact nature of the system, spectroscopic data of AD Cnc are very much to be desired.

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