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Light Curve Changes in AH Cancri

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Abstract. Light curves of the W Ursae Majoris binary AH Cancri obtained in 1973 and 1988 show a remarkable change in shape. Earlier curves have rounded minima and eclipses appear to be partial; later curves have flat-bottomed minima indicating total eclipses. The 1973 curves are consistent with a system in overcontact with an orbital inclination of approximately 65°. Such a low inclination, however, is incompatible with the $0\overset{p}{.}1$-duration flat-bottomed eclipse seen in the more recent light curves. Intrigued by this puzzle we decided to make new photometric observations. We present CCD photometry in V and R obtained with the Southeastern Association for Research in Astronomy (SARA) 0.9-m and Buehler Observatory 0.4-m telescopes. We solve the new light curves and find a high-inclination ($i \approx 84°$), low-mass-ratio ($q \approx 0.145$) model fits the observations reasonably well. In the post-1988 light curves, limb darkening causes eclipses of the cooler star to be deeper than those of the hotter star. Times of minima suggest a possible third body interaction.

1. Introduction

AH Cancri ($V = 13\overset{m}{.}3$, $B - V = 0.53$, spectral type F7V, period $P = 0.36$ days) is a W Ursae Majoris (overcontact) binary in the old galactic cluster M67. Photometric and spectroscopic observations obtained by Whelan et al. (1979) in 1973 and 1975-1976, respectively, revealed the system to be of type W (the smaller, less-massive star has the higher surface temperature, see Binnendijk 1970), and the eclipses to be partial. The radial velocities show a large amount of scatter which make the spectroscopic mass ratio uncertain, with an estimated value in the range 0.42 to 0.75. The light curves indicate an orbital inclination between 65° and 68°. Maceroni, Milano & Russo's (1984) solution of the Whelan et al. (1979) light curves with the Wilson (1979) program gives an inclination $i = 62\overset{\circ}{.}94 \pm 0\overset{\circ}{.}50$ and a mass ratio $q = 0.61 \pm 0.01$. In 1988, Gilliland et al. (1991) obtained time-series photometry of AH Cnc as part of a photometric study of M67. The light curve (see their Fig. 5) now shows well-defined flat-bottomed secondary (shallower) eclipses, indicating *total* eclipses and an inclination considerably larger than 65°. Gilliland et al. briefly comment on this remarkable change in the shape of AH Cnc's light curve and wonder whether it could have been caused by a decrease in the size of the secondary component. More recent light curves obtained in 1997 (Table 1), 2001 (Zhou 2002) and 2002 (Table 2) appear to be of similar shape as the 1988 curves. Thus, AH Cnc seems to deserve the label "exotic". We present solutions of our 1997 and 2002 light curves and compare model parameters with those obtained from the 1973 curves.

2. New Photometry

We observed AH Cnc on February 7 and 10, 1997 with the Southeastern Association for Research in Astronomy (SARA) 0.9-m telescope located at Kitt Peak National Observatory. We used a CCD detector with a Kodak KAF 4200 (2048×2048) chip and Cousins R filter. Images were reduced using the MIRA reduction software package. A number of stars in the $9' \times 9'$ field were used as comparison stars. Standard errors of single observations are 0.005 mag. Differential magnitudes are listed in Table 1. In January–February, 2002, we obtained observations in V with the Buehler Planetarium Observatory 0.4-m telescope located in Fort Lauderdale, Florida. We used a Meade Pictor 1616 XTE camera (1536×1024 pixels, binned 2×2) and a standard Johnson V filter. Table 2 lists the V differential magnitudes. Standard errors of individual ΔVs are 0.02 mag, making the scatter in the V curve considerably larger than that in R.

Table 1. CCD Observations in R obtained in 1997[1]

HJD 2450480+	Δm	HJD 2450480+	Δm	HJD 2450480+	Δm	HJD 2450480+	Δm
6.69242	0.060	6.69410	0.063	6.69578	0.061	6.69746	0.062
6.69914	0.057	6.70082	0.061	6.70250	0.065	6.70418	0.061
6.70586	0.059	6.70889	0.059	6.71057	0.056	6.71225	0.055
6.71393	0.056	6.71561	0.052	6.71729	0.051	6.71897	0.045

Table 2. CCD Observations in V obtained in 2002[1]

HJD 2452000+	Δm	HJD 2452000+	Δm	HJD 2452000+	Δm	HJD 2452000+	Δm
291.73753	1.154	291.74271	1.095	291.74414	1.118	291.74527	1.091
291.74639	1.116	291.75132	1.128	291.75228	1.112	291.75326	1.073
291.75423	1.088	291.75521	1.137	291.75622	1.074	291.75720	1.095
291.75821	1.067	291.75918	1.096	291.76015	1.055	291.76114	1.073

3. Light Curve Solutions

Both the V and R light curves were solved simultaneously with the Wilson (1979) program, including an improved stellar atmosphere routine based on Legendre polynomials that have been fitted to Kurucz (1993) atmosphere models, and with bandpass-integrated fluxes instead of effective wavelength-fluxes (see Van

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[1] Tables 1 and 2 are available in their entirety at the World Wide Web address *http://www.fiu.edu/~vanhamme/ahcnc.htm.* Only portions are shown here for form and content.

Hamme et al. 2001). Time (instead of phase) was used as the independent variable which allowed the Least-Squares program to determine ephemeris parameters (zero-epoch T_0, period P, and dP/dt) together with the other binary parameters. Furthermore, by selecting initial T_0-values near observed minima, improved estimates for these minima were obtained (Table 3).

Table 3. New Times of Minima for AH Cnc

2450486.88152 ± 0.00017
2450489.76562 ± 0.00017
2452291.85353 ± 0.00059
2452333.66358 ± 0.00035

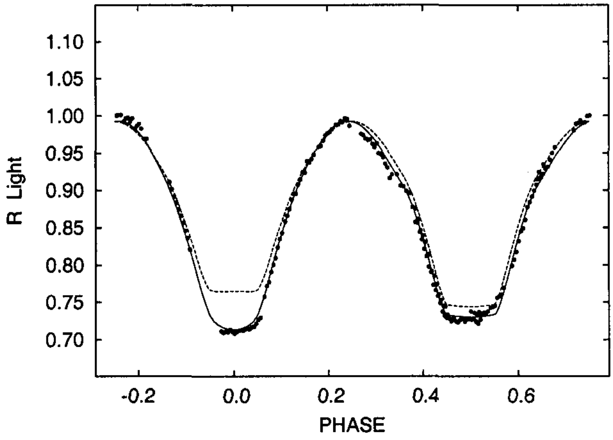

Figure 1. Observations in *R* of AH Cnc made in 1997 and the fitted curve. The dashed line is the computed curve without limb-darkening.

Both the 1997 *R* and 2002 *V* curves were solved simultaneously. Table 4 lists parameters for two solutions, one with dP/dt fixed at zero, the other with dP/dt as a free parameter. Fig. 1 shows the observed and computed light curves versus phase. The fit is reasonably good, except for the bottom of the *R* primary minimum, where the fitted curve lies systematically above the observations. There are indications of night-to-night variations in the light curve (note the apparent jump in light level around phase $0\overset{\mathrm{P}}{.}5$ corresponding to data obtained at two different nights). Note also the relatively small mass ratio ($q = 0.14525 \pm 0.00064$) which is needed to make the less massive component sufficiently small to produce the $0\overset{\mathrm{P}}{.}10$-wide flat bottom secondary (photometrically less deep) eclipse at phase $0\overset{\mathrm{P}}{.}5$. The less massive star (star 2), eclipsed at that phase, is the hotter star, confirming the W-type status of AH Cnc. The deeper minimum (here at phase $0\overset{\mathrm{P}}{.}0$) corresponds to an eclipse of the cooler star. Normally, this eclipse would be the shallower one; however, strong limb-darkening effects deepen the eclipse considerably. The effect of limb-darkening is shown in Fig. 1 where the dashed line is the computed light curve with no limb-darkening. It is important to note that the ephemeris of Table 4 has a zero-epoch T_0 which corresponds to an eclipse of the more massive star, whereas the ephemeris in Whelan et al.

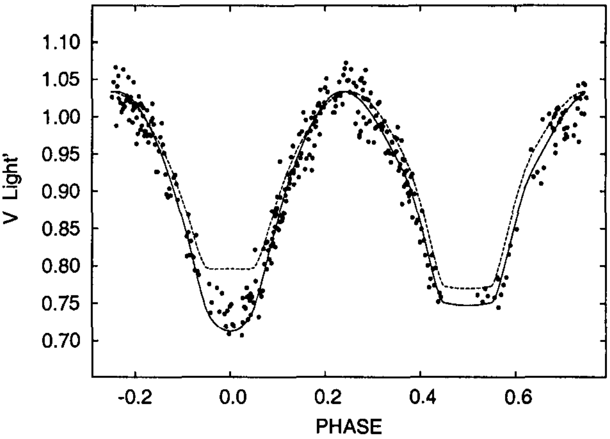

Figure 2. *V* observations of AH Cnc made in 2002 and fitted curve. The dashed line is the computed curve without limb-darkening.

(1979) has its zero-epoch set at a time when the less massive star is eclipsed and the more massive star is in front. The ephemeris of Table 4 is, therefore, half a period out of phase with the Whelan et al. ephemeris.

4. Discussion

A solution of the *V* and *B* normal-points light curves made from the Whelan et al. (1979) data by Maceroni, Milano, & Russo (1984), and kindly provided to us by C. Maceroni, essentially confirms their parameters. Our best fit of the 1973 normal-point curves gives $i = 63^\circ\!.01 \pm 0^\circ\!.51$, a photometric mass ratio $q = 0.601 \pm 0.016$, and a standard deviation of the fit of 0.02371 (in units of total light at phase $0^{\mathrm{P}}\!.25$). The mass ratio, however, is not well determined. We find other nearly equally deep local minima in parameter space corresponding to different values of q. For example, there is a solution with $i = 69^\circ\!.0 \pm 1^\circ\!.4$ and $q = 0.1522 \pm 0.0019$, and a standard deviation of the fit of 0.02367. Hence, the 1973 light curves do not exclude a lower mass ratio and the secondary's size need not have changed between 1973 and 1988; however, the curves do insist on an inclination of less than 70°. The radial velocities of Whelan at al. (1979) seem to prefer a larger mass ratio but their large scatter prevents any firm conclusions. The Whelan et al. original photometric data, and not the normal points, should be reexamined in detail. Thus far we have been unable to obtain these original data. New spectroscopic observations are strongly urged.

Could AH Cnc's inclination have increased by approximately 14° as the result of a gravitational interaction with a third object? An eclipse-timings analysis suggests that AH Cnc's period is changing (see Fig. 3, left). When we fit a quadratic ephemeris to the minima we obtain[2] a dP/dt of $8.06 \pm 0.99\ 10^{-10}$ and

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[2] Based on data spanning more than 40 years; the negative dP/dt of Table 2 has a time base line of only 5 years.

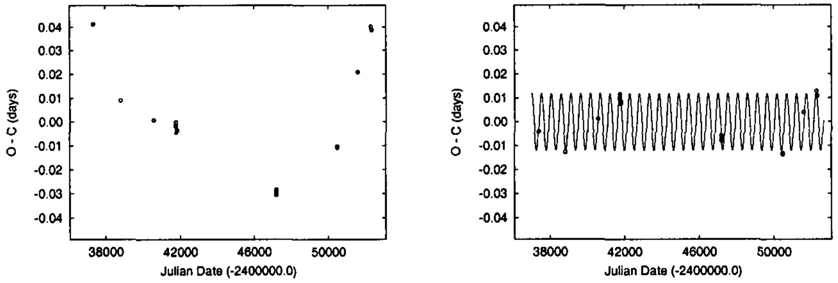

Figure 3. *Left:* $O - C$ residuals of AH Cnc minima with respect to a least squares fitted linear ephemeris ($\sigma = 0.025\,\mathrm{d}$). *Right:* Residuals with respect to a quadratic ephemeris ($\sigma = 0.010\,\mathrm{d}$) and the fitted sinusoid ($\sigma = 0.003\,\mathrm{d}$).

the residuals show a cyclic variation which is fitted well by a sinusoid of period 526.29±0.88 days and semi-amplitude 0.0119±0.0010 days (Fig. 3, right). Could this be the signature of a light-time effect caused by a third body? A third body with the right orbital characteristics might perturb AH Cnc's inclination and explain the changing light curve morphology. Dynamical three-body calculations exploring this possibility are under way. Note however, the number of minima is small and our results could be spurious. Future observations will be needed to confirm or rule out the third body hypothesis.

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Table 4. Light Curve Solutions

Parameter	$dP/dt = 0$	dP/dt Free
T_0 (HJD)	$2451585.00265 \pm 0.00018$	2451585.0209 ± 0.0074
P_0 (days)	$0.360453160 \pm 0.000000061$	0.3604502 ± 0.0000012
dP/dt	0.0	$-1.63 \pm 0.66\,10^{-8}$
i (°)	83.83 ± 0.70	84.08 ± 0.83
g_1, g_2	0.32, 0.32	0.32, 0.32
F_1, F_2	1.0, 1.0	1.0, 1.0
T_1 (K)	6250	6250
T_2 (K)	6358 ± 16	6355 ± 15
A_1, A_2	0.5, 0.5	0.5, 0.5
Ω_1	2.0394 ± 0.0039	2.0394 ± 0.0045
Ω_2	2.0394 ± 0.0039	2.0394 ± 0.0045
$q = M_2/M_1$	0.14525 ± 0.00064	0.14525 ± 0.00070
$L_1/(L_1 + L_2)_R$	0.8321 ± 0.0015	0.8323 ± 0.0014
$L_1/(L_1 + L_2)_V$	0.8302 ± 0.0021	0.8305 ± 0.0021
$l_3\,(R)$	0.0	0.0
$l_3\,(V)$	0.0	0.0
$x_1(bolo)$	0.642	0.642
$y_1(bolo)$	0.231	0.231
$x_2(bolo)$	0.642	0.642
$y_2(bolo)$	0.231	0.231
$x_1(R)$	0.654	0.654
$y_1(R)$	0.279	0.279
$x_1(V)$	0.816	0.816
$y_1(V)$	0.209	0.209
$x_2(R)$	0.654	0.654
$y_2(R)$	0.279	0.279
$x_2(V)$	0.816	0.816
$y_2(V)$	0.209	0.209
r_1 (pole)	0.5234 ± 0.0011	0.5234 ± 0.0012
r_1 (side)	0.5813 ± 0.0017	0.5813 ± 0.0019
r_1 (back)	0.6058 ± 0.0021	0.6058 ± 0.0024
r_2 (pole)	0.2280 ± 0.0019	0.2280 ± 0.0022
r_2 (side)	0.2394 ± 0.0024	0.2394 ± 0.0027
r_2 (back)	0.2923 ± 0.0065	0.2923 ± 0.0073

T_1 is based on the F7V spectral type. Limb darkening coefficients (x, y) are for a square-root limb darkening law and determined by interpolation in tables by Van Hamme (1993).