Photometric study of AH Cnc, a W UMa-type system in M67

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ABSTRACT

We present time-series CCD photometry of AH Cnc, a W UMa-type binary system in the old open cluster M67. Over 3500 measurements in two filters were recorded on 15 nights from 2001 to 2004. From the data, 17 new times of minima for the eclipsing binary were obtained, based on which, a new ephemeris was derived. The orbital period of the system is refined as 0.36045754 days. A photometric analysis for the obtained light curves is performed based on the Wilson-Devinney code. The photometric solutions reveal a totally eclipsing contact configuration for AH Cnc. The photometric mass ratio is determined to be 0.149±0.002. The masses and radii of the components are estimated as $1.21 \pm 0.08 M_\odot$, $1.36 \pm 0.03 R_\odot$ for the primary and $0.18 \pm 0.02 M_\odot$, $0.62 \pm 0.02 R_\odot$ for the secondary, respectively. The evolutionary status of the contact system is briefly discussed.

Subject headings: stars: variable – binaries: eclipsing – stars: individual (AH Cnc) – open clusters: M67

1. INTRODUCTION

M67 is a well-studied old open cluster with an age similar to that of the Sun (Janes & Phelps 1994). It is noted for the richness in W UMa-type binaries and other types of variable stars. During the past two decades, much work has been done on the cluster searching for stellar variability through radial velocity surveys and time-series photometric studies (Mathieu et al. 1990, Gilliland et al. 1991, van den Berg et al. 2002, Stassun et al. 2002, Sandquist & Shetrone 2003). Up to now, there are at least four W UMa stars, one RS CVn variable BS (blue straggler), two δ Scuti pulsating BSs and a large number of miscellaneous variables known in the cluster. Investigation of the variability behaviors and physical properties of these variables can undoubtedly provide important information for us to understand the structure and evolution of these stars and the host cluster.

AH Cnc, as a relatively bright eclipsing binary with large amplitude of light variation, is the first known and most frequently observed in M67. Its variability was discovered by Kurochkin (1960). Efremov et al (1964) identified its W UMa nature. The orbital period of the system was deriv flat-bottom eclipse during the secondary minimum light, covering approximately 0.1 in orbital phase. Such a characteristic in the light curve of AH Cnc was recently confirmed by Sandquist & Shetrone (2003) through high-precision CCD photometry. By using the program NIGHTFALL (available in http://www.lsw.uni-heidelberg.de/users/rwichman/Nightfall.html), Sandquist & Shetrone (2003) had made a brief photometric analysis of the system. Their results revealed a total eclipse configuration for the contact system. The mass ratio of the system was refined to be about 0.16±0.033. Therefore, the physical nature of AH Cnc could be very different from ever known.

Furthermore, AH Cnc could be an important member of the star cluster. In the color-magnitude diagram of M67, it is found to be located just below the turn-off. Determination of its physical parameters and study of its evolutionary status are therefore very significant for us to understand the evolution of close binaries and related variable stars such as blue stragglers in the star cluster. This important object is worthy of further study.

As an important object of our project to search for new variable stars in open clusters (Zhang et al. 2002), M67 has been observed through long-term time-series CCD photometry. AH Cnc was one of the monitored objects. During these observations, a large number of measurements for the system have been collected. In the present paper, we shall report the results of the observations and a photometric analysis for the system based on the Wilson-Devinney code.

2. OBSERVATIONS AND DATA REDUCTIONS

All the observations were carried out at the Xinglong Station of the National Astronomical Observatories, Chinese Academy of Sciences. The observations were made in two runs in 2001 and 2003/04 observing seasons. The relevant information about the observations is given in Table 1. The 2001 observations were made from Feb. 16 to 19. The data were collected using the 60/90 cm Schmidt telescope equipped with a 2k×2k Aerospace Ford CCD camera. The CCD provides a field of view of about $1^o \times 1^o$, corresponding to an image scale of 1".67/pixel. It covered almost the whole field of the cluster. The cluster center was positioned at the center of the CCD frame. The photometry was all in a single BATC[9] i filter (centered at 6660Å, bandwidth = 350 Å) with the exposure time of 120 seconds. We obtained a total number of 336 useful images on four nights of this run.

The 2003/04 observations were performed on the 85 cm reflector at the Xinglong Station with a AP7P 512×512 CCD camera. With a field of view of about 6'×6', corresponding to a image scale of about 0".7/pixel. The field of view covered only a part of the cluster. A single Johnson V filter was used. The exposure time was set at 90 seconds. Useful data were collected on 11 nights from Dec. 21, 2003 to Jan. 4, 2004. Nearly 3000 CCD frames were recorded in V band.

The preliminary processing of all the CCD frames was performed with the standard routines in the IRAF/CCDPROC package. The photometry of the 2001 observations was performed in a similar manner as Zhang et al. (2002). A absolute magnitude calibration was done according to a deep photometry taken on the same field by Fan et al. (1996).

For the 2003/04 observations, the photometry was extracted using the DAOPHOTII package (Stetson 1987, 1996). For the purpose of differential photometry, we firstly choose a number of brighter stars which have good seeing and were detected in all of the CCD frames as the reference candidates. Two stars, S1072 (V=11.30, V-I=0.71) and S1084 (V=10.49, V-I=1.05) were finally defined as the most appropriate objects employed as comparison and check stars for this observation. The average deviation of different magnitude between the comparison and check stars is generally less than 0.005 mag. In this way, all the photometry measurements of AH Cnc were extracted and were corrected into the standard V magnitude

3. PERIOD AND THE LIGHT CURVES

In Figure 1, we plot the light curves obtained from the above observations. We have obtained a total 17 light curves including 8 primary and 9 secondary eclipses. By using the K-W method (Kwee & van Woerden 1956), the times of minimum light corresponding to each of the eclipses were derived. They are given in Table 2. With these times of minima, we could perform a period analysis of the system. The new linear ephemeris based on these times of minima is determined as:

$$HJD_{Min.I} = 2453004.1144(\pm 0.0003) + 0.36045754(\pm 0.00000020) \times E$$

The Epoches and O-C residuals calculated with the new ephemeris are given in Table 2. The period determined by this study agrees well with the result of 0.360452 days from van den Berg (2002) but obviously longer than those obtained early by Eggen (1967) (0.3604364 days) and Whelan et al. (1979) (0.3604423 days). Since the data published for AH Cnc available for period analysis is very rare, it is impossible to yield a definite quadratic ephemeris, thus we are not sure whether the period of the system is undergoing long-term increase.

With the newly derived ephemeris, we computed the phases for all the measurements. The phased i and V band light curves are formed as shown in Figure 2. In Table 3, we list the main feature parameters of the light curves. In which, $\bar{m}_{max}$ is the average magnitude at maximum light, Δm_p and Δm_s are the depths of the primary and the secondary eclipses, respectively.

The general feature of the light curves is typical of W UMa systems. Comparing with the light curves previously published, we find that it is similar to those of Gilliland (1991) and Sandquist & Shetrone (2003) and quite different with that of Whelan et al (1979). Firstly, each of our i and V band light curves presents a flatter-bottom secondary eclipse covering approximately 0.1 in phase, this possibly indicates a total-eclipse configuration for the system. Meanwhile, the flatter secondary eclipse is obviously shallower than the rounded primary one by 0.05 mag. in V and 0.03 mag. in the i band, respectively. It implies that the system could be more likely an A-type W UMa binary as suggested by Sandquist & Shetrone (2003). Moreover, we note that most of the light curves show slightly asymmetry and variations from one epoch to another. Short-term changes of the light curves with a timescale of several days can also be found by inspecting Figure 1. It is likely due to some frequently surface spot activities as regarded by Sandquist & Shetrone (2003).

4. PHOTOMETRIC SOLUTIONS

To perform the photometric analysis by means of the Wilson-Devinney method, the light curves were combined into normal points with the average interval of 0.08 in phase. The 1992 version of the WD code (Wilson & Devinney 1971; Wilson 1979, 1990) was employed. Since the 2003/04 observations have higher photometric precisions and contain more measurements, we begin with the V band light curve at first.

The appearance of the eclipses in our data shows that AH Cnc is likely an A-type rather than a

Table 1: JOURNAL OF THE TIME-SERIES CCD PHOTOMETRY OF AH CNC IN 2001-2004

Date (UT)	HJD(2,450,000)	Telescope	Filter	N$_{obs}$
2001 Feb. 16	1956.953-1957.297	60/90 cm	i	93
2001 Feb. 17	1957.957-1958.344	60/90 cm	i	101
2001 Feb. 18	1959.080-1959.343	60/90 cm	i	62
2001 Feb. 19	1960.072-1960.180	60/90 cm	i	34
2003 Dec. 21	2995.033-2995.422	85 cm	V	184
2003 Dec. 22	2996.181-2996.422	85 cm	V	207
2003 Dec. 23	2997.185-2997.411	85 cm	V	160
2003 Dec. 27	3001.112-3001.425	85 cm	V	260
2003 Dec. 28	3002.175-3002.290	85 cm	V	99
2003 Dec. 30	3004.083-3004.425	85 cm	V	285
2003 Dec. 31	3005.074-3005.421	85 cm	V	293
2004 Jan. 01	3006.076-3006.421	85 cm	V	281
2004 Jan. 02	3007.082-3007.421	85 cm	V	265
2004 Jan. 03	3008.094-3008.422	85 cm	V	250
2004 Jan. 04	3009.169-3009.422	85 cm	V	220

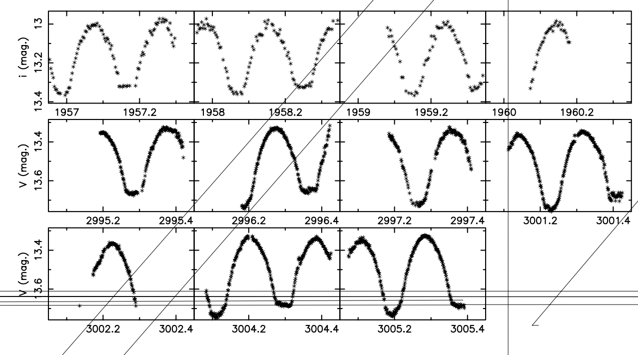
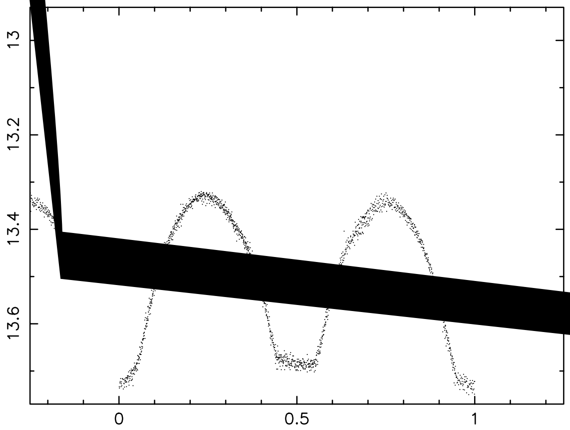


Table 2: NEW TIMES OF MINIMA FOR AH CNC

JD(Hel) 2,450,000+	Epoch	O-C
51956.9876	-2905.0	0.0023
51957.1642	-2904.5	0.0013
51958.0662	-2902.0	0.0004
51958.2465	-2901.5	[illegible].0004
51959.1478	-2899.0	-[illegible].0002
52995.2842	-24.5	[illegible]0010
52996.3640	-21.5	-[illegible]0006
52997.2642	-19.0	-[illegible]0015
53001.2290	-8.0	-[illegible]0018
53004.1135	0.0	-0[illegible]009
53004.2951	0.5	0.[illegible]004
53005.1948	3.0	-0.[illegible]010
53005.3747	3.5	-0.0[illegible]13
53006.2758	6.0	-0.0[illegible]14
53007.1818	8.5	0.0[illegible]34
53008.2609	11.5	0.00[illegible]1
53009.3435	14.5	0.00[illegible]4

Table 3: MAIN FEATURE PARAMETERS OF THE LIGHT CURVES OF AH CNC

Band	BATC i	V
$\bar{m}_{max}$	13.00	13.33
Δm_p	0.37	0.38
Δm_s	0.32	0.35



W-type system, implying that the deeper eclipse could be the transit of the massive star by the less-massive one. Thus we define the massive primary component as star 1, and the less-massive component as star 2 in the following analysis. The temperature of the primary was set at T_1 = 6300K according to its spectral type through the calibration of Cox (2000). The gravity darkening exponents were taken to be $g_1 = g_2 = 0.32$ from Lucy (1967), and albedos were adopted as $A_1 = A_2 = 0.5$ following Rucinski (1969). The limb-darkening coefficients were taken as $x_1 = x_2 = 0.63$ based on the result from Diaz-Cordoves et al. (1995). The adjustable parameters are the orbital inclination i, the mean temperature of the secondary star T_2, the potentials Ω_1, Ω_2 of the components, and the non-dimensional luminosities L_1 and L_2.

The mass ratio q=M_2/M_1 (the most sensitive parameter for light curve synthesis) of AH Cnc still remains uncertain. The early studies from Whelan et al. (1979) and Maceroni et al. (1984) yielded a range of mass ratio from 0.4 to 0.7 for the system. The recent work by Sandquist & Shetrone (2003) gave a much smaller value of 0.157. In general, to match a light curve with a total eclipse, it requires a low mass ratio. Thus the result of Sandquist & Shetrone (2003) could be more reliable. To search for an approximate mass ratio, however, we made a set of test solutions at the outset. The test solutions were computed at a series of assumed mass ratios, q, with the values from 0.1 to 0.8. At each assumed mass ratio, the DC program started from mode 2 (detached) and rapidly ran into mode 3 (contact). After several runs in iteration, a converged solution was reached for each assumed q. Figure 3 plots the relation between the resulting sum of weighted residuals $\sum w^2(O-C)^2$ and the assumed q for all the test solutions. It is shown that the solutions are very sensitive to the mass ratio, and the most probable solution would be around q=0.15. Starting from the solution at q=0.15, we ran the DC code again and let the mass ratio be adjusted freely along with the other adjustable parameters and got the best-fitting solution.

Adopting the solution obtained above as the initial input, the unspotted synthesis was also made for the 2001 light curve. After that, the spot model was employed. We placed one spot on the primary component. The co-latitude of the spot was fixed at 90^o (i.e. on the equator). The other three parameters of the spot, longitude, temperature T_s, and radius r_s were calculated by adjusting the theoretical light curves to fit approximately the observed distorted light curves. In this way, we obtained the final photometric solutions for both the i and V-band light curves. The results are given in Table 4. In Figure 4, we plot the light curves as well as their best fittings based on the final solutions. As the amount of the individual data is too large, we present here the normal points for the V band light curve.

5. RESULTS AND DISCUSSIONS

Based on the W-D code, we have modelled the light curves obtained by the CCD photometry. The solutions carried out for each individual light curve match each other very well. It confirmed the total-eclipse contact configuration for the AH Cnc. The system is found to be in deep contact with a filling factor of about 0.65. From our photometric solutions, the orbital inclination is determined to be about $83^o.5 \pm 1^o.5$, and the mass ratio of the system is derived to be about 0.15. Our results are in broad agreement with Sandquist & Shetrone (2003) through the program NIGHTFALL.

The spot assumption can give fairly good fittings to the asymmetry and variations of the light curves of AH Cnc. But the physical nature of the spot model is still open for discussion. Besides the long-term (in years) changes, we have noted very short time-scale (in days) variations in the light curves. This phenomena is hard to explained by the solar-like activities of the system. Consideration of the large filling factor of the contact system, we suggest that there might be probable mass outflow from the system, and which might

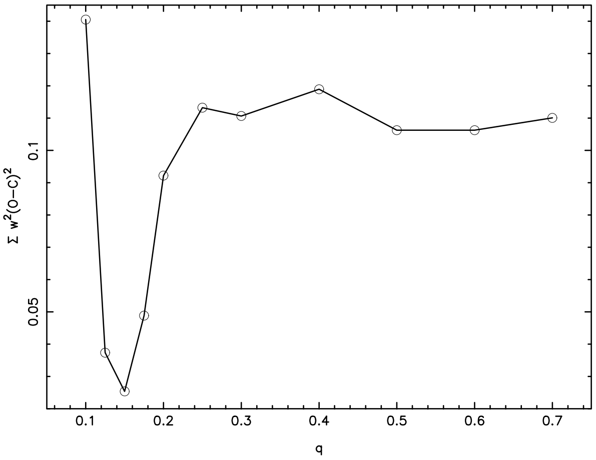


Fig. 3.— The diagram of $\sum w^2(O-C)^2$ vs. q of test solutions for the 2003/04 light curve.

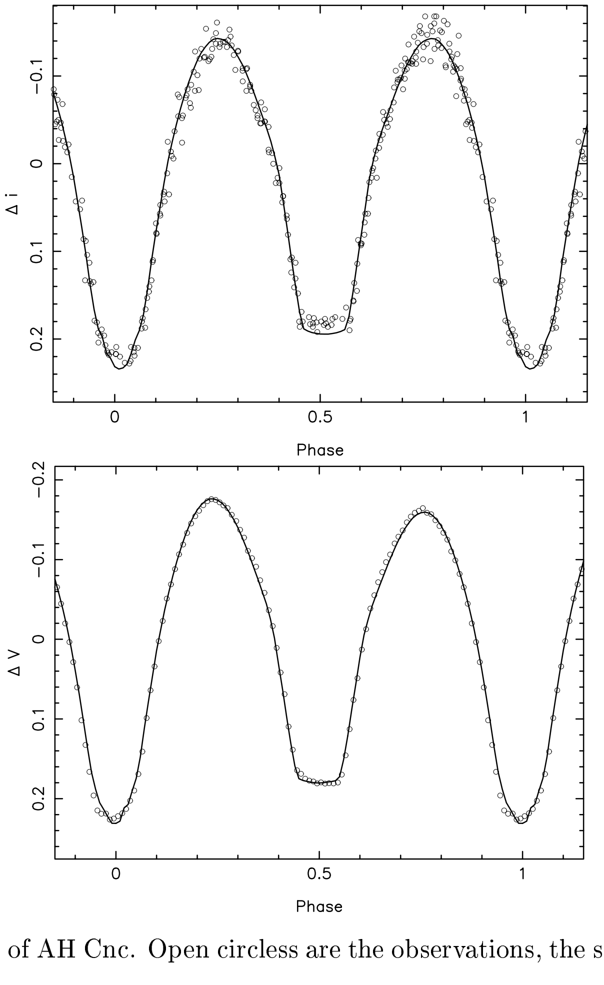


Fig. 4.— Light curve fittings of AH Cnc. Open circless are the observations, the solid lines are the theoretical light curves

Table 4: PHOTOMETRIC SOLUTIONS FOR AH CNC

Parameter	LC 2001 BATC i (6600Å)	LC 2003/04 V band
T_1 (K)	6300*	6300*
T_2 (K)	6297±20	6354±7
q=m2/m1	0.148±0.002	0.149±0.001
i (degree)	84.30±0.68	82.80±0.35
$A_1 = A_2$	0.50*	0.50*
$g_1 = g_2$	0.32*	0.32*
$x_1 = x_2$	0.52*	0.63*
$\Omega_1 = \Omega_2$	2.0394±0.0018	2.0370±0.0007
$r_{1,pole}$	0.5240±0.0005	0.5249±0.0002
$r_{1,side}$	0.5825±0.0008	0.5840±0.0003
$r_{1,back}$	0.6078±0.0009	0.6098±0.0004
$r_{2,pole}$	0.2315±0.0006	0.2336±0.0002
$r_{2,side}$	0.2435±0.0007	0.2460±0.0003
$r_{2,back}$	0.3009±0.0020	0.3071±0.0009
$L_1/(L_1 + L_2)$	0.837±0.002	0.830±0.0001
Ω_{in}	2.1004*	2.0976*
Latitude$_{spot}$	90^o*	90^o*
Longitude$_{spot}$	$271^o.1 \pm 0^o.8$	$79^o.8 \pm 0^o.3$
Radius$_{spot}$	$6^o.7 \pm 0^o.7$	$8^o.8 \pm 0^o.2$
T_{spot}/T_1	0.85 ± 0.04	0.76 ± 0.01

* assumed

be the cause of the short-term changes in the light curve of AH Cnc

The Wilson-Devinney approach in the analysis of a light curve with high photometric accuracy can in general yield a reliable mass ratio for the binary system. Based on the photometric solution derived for AH Cnc, here we try to estimate the absolute elements and, hence, discuss the evolutionary status of the system.

The radial velocities for AH Cnc obtained early by Whelan et al. (1979) were very uncertain ($K_1 = 100 \pm 15kms^{-1}, K_2 = 138 \pm 15 - 240 \pm 20kms^{-1}$), from which the yielded spectroscopic mass ratio does not agree with ours. It is not possible for us to derive trustworthy masses of the component stars directly. As a certain member of the open cluster M67, fortunately, the distance modulus of the star is well defined. Starting from the distance modulus, we can estimate the total bolometric luminosity and hence deduce the main parameters of the binary system. Adopting $(m - M)_V = 0.72 \pm 0.05$ for M67 (Sandquist 2004), V_{max}=13.33 (Table 3) and BC=-0.15 corresponding the spectral type of F7V (Cox, 2000), along with the photometric solution from Table 4 as well as the known orbital period, the absolute elements of AH Cnc were calculated and given in Table 5.

The mass of the primary component is derived to be 1.21$M_\odot$, which is slightly less than that of a turn-off star (about 1.25 $M_\odot$) in M67. This result in turn agrees with the position of the system on the color-magnitude diagram. The values of M_1, R_1 and L_1 match the spectral type of F7V very well. The secondary component, with a very low mass, is obviously an evolved star which presents a large radius and over-luminosity comparing with main sequence stars with the same mass. Meanwhile, the secondary has a surface temperature almost equal to the primary, and is unacceptably high with repsect to its mass. We conclude that the secondary component could not be a normal star, and the system might be formed through mass exchange after mass ratio reverse. It is very likely that the secondary was the massive component of the system, whose original mass could be larger than the turn-off mass. If this is the case, probable mass outflow and hence the angular momentum loss from the system would have played important role. To examine this hypothesis, however, more observations especially the high precision spectroscopy of the system are needed.

6. SUMMARY

We have presented the time-series CCD photometry of AH Cnc, a famous W UMa system in the open cluster M67. We have obtained complete phase coverage in two filters. The orbital period and ephemeris of the binary were refined. The light curve of AH Cnc is confirmed to be of A sub-type with a flat secondary minimum. By using the Wilson-Devinney code, we have computed the photometric solutions for each light curve. The results reveal a total-eclipsed contact configuration for the binary system. The mass ratio of the system is determined as 0.149±0.002. Taking our photometric solution along with the distance modulus of the cluster, we have deduced the absolute parameters of the component stars. The values of mass,

Table 5: ABSOLUTE PARAMETERS FOR AH CNC

Parameter	Primary	Secondary
Mass($M_\odot$)	1.21±0.08	0.18±0.02
Radius($R_\odot$)	1.36±0.03	0.62±0.02
Luminosity($L_\odot$)	2.62±0.12	0.54±0.06

radius and luminosity derived for the primary component match the star's spectral type as well as its position in the cluster CMD very well. It is suggested that the primary component is very likely a normal main-sequence star, while the secondary could be much evolved. The binary system might be formed through mass exchange.

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