The Astronomical Journal, 129:979–984, 2005 February

PHOTOMETRIC STUDY OF AH CANCRI, A W UMa–TYPE SYSTEM IN M67

X. B. Zhang, R. X. Zhang, and L. Deng
National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Road, 100012 Beijing, China
Received 2004 July 29; accepted 2004 October 20

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, from 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 $1.21 \pm 0.08\ M_{\odot}$ and $1.36 \pm 0.03\ R_{\odot}$ for the primary and $0.18 \pm 0.02\ M_{\odot}$ and $0.62 \pm 0.02\ R_{\odot}$ for the secondary, respectively. The evolutionary status of the contact system is briefly discussed.

Key words: binaries: eclipsing — open clusters and associations: individual (M67) — stars: individual (AH Cancri) — stars: variables: other

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 its 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 in 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 blue straggler (BS), 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 understanding the structure and evolution of these stars and the host cluster.

AH Cnc, a relatively bright eclipsing binary with a large amplitude of light variation, is the first known and most frequently observed variable 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 derived to be 0.3604364 days (Eggen 1967). A spectral type of F7 V was assigned to the primary component by Mammano (1965) and confirmed later by Whelan et al. (1979). Whelan et al. (1979) contributed a complete study with photometry and spectroscopy. The first photometric solution for AH Cnc was obtained by Maceroni et al. (1984) based on the Wilson-Devinney method. Both of their studies suggested a partially eclipsed, W-type contact configuration for the system. The mass ratio was estimated to be in the range of 0.4–0.6. Because of the large deviations of the data, however, their results seemed to be very uncertain.

The time-series CCD photometry of Gilliland et al. (1991) produced a well-defined light curve of AH Cnc, which is quite different in shape from that obtained by Whelan et al. (1979). It presents a 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,[1] 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 any variable ever known.

Furthermore, AH Cnc could be an important member of the star cluster. In the color-magnitude diagram (CMD) of M67, it is found to be located just below the turnoff. 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 BSs 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 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 the 2001 and 2003–2004 observing seasons. The relevant information about the observations is given in Table 1. The 2001 observations were made from February 16 to 19. The data were collected using the 60/90 cm Schmidt telescope equipped with a $2\text{k} \times 2\text{k}$ Aerospace Ford CCD camera. The CCD provides a field of view of about $1^{\circ} \times 1^{\circ}$, corresponding to an image scale of $1''.67$ pixel^{-1}. 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 6660 Å, bandwidth = 350 Å) with the exposure

[1] Available at http://www.lsw.uni-heidelberg.de/users/rwichman/Nightfall.html.

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 1..................	3006.076–3006.421	85 cm	*V*	281
2004 Jan 2..................	3007.082–3007.421	85 cm	*V*	265
2004 Jan 3..................	3008.094–3008.422	85 cm	*V*	250
2004 Jan 4..................	3009.169–3009.422	85 cm	*V*	220

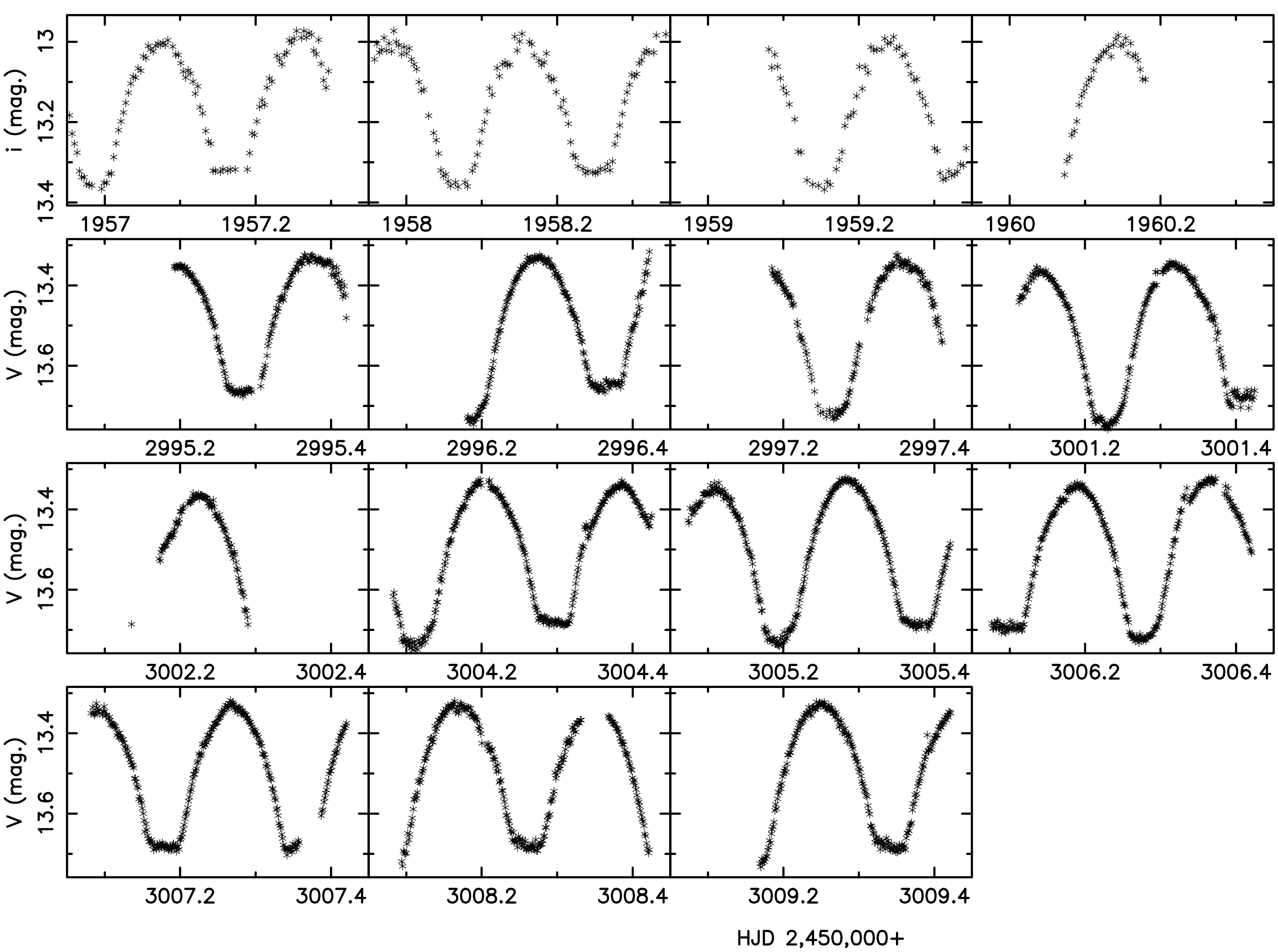

FIG. 1.—Time-series CCD photometry of AH Cnc.

TABLE 2
New Times of Minima for AH Cnc

JD (Heliocentric) (2,450,000+)	Epoch	$O-C$
51,956.9876	−2905.0	0.0023
51,957.1642	−2904.5	−0.0013
51,958.0662	−2902.0	−0.0004
51,958.2465	−2901.5	−0.0004
51,959.1478	−2899.0	−0.0002
52,995.2842	−24.5	0.0010
52,996.3640	−21.5	−0.0006
52,997.2642	−19.0	−0.0015
53,001.2290	−8.0	−0.0018
53,004.1135	0.0	−0.0009
53,004.2951	0.5	0.0004
53,005.1948	3.0	−0.0010
53,005.3747	3.5	−0.0013
53,006.2758	6.0	−0.0014
53,007.1818	8.5	0.0034
53,008.2609	11.5	0.0011
53,009.3435	14.5	0.0024

time of 120 s. We obtained a total number of 336 useful images on four nights of this run.

The 2003–2004 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 $6' \times 6'$, corresponding to a image scale of about 0."7 pixel^{-1}. 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 s. Useful data were collected on 11 nights from 2003 December 21 to 2004 January 4. Nearly 3000 CCD frames were recorded in the 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 that in Zhang et al. (2002). A absolute magnitude calibration was done according to deep photometry taken on the same field by Fan et al. (1996).

For the 2003–2004 observations, the photometry was extracted using the DAOPHOT II package (Stetson 1987, 1996). For the purpose of differential photometry, we first choose a

TABLE 3
Main Feature Parameters of the Light Curves of AH Cnc

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

number of brighter stars that 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 and 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 to 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 of 17 light curves, including eight primary and nine 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

$$\mathrm{HJD_{Min}} = 2,453,004.1144(\pm 0.0003) + 0.36045754(\pm 0.00000020)E.$$

The epochs 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 is 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 are very rare, it is impossible to yield a definite quadratic ephemeris; thus, we are not sure whether the period of the system is undergoing a long-term increase.

With the newly derived ephemeris, we computed the phases for all the measurements. The phased i- and V-band light curves

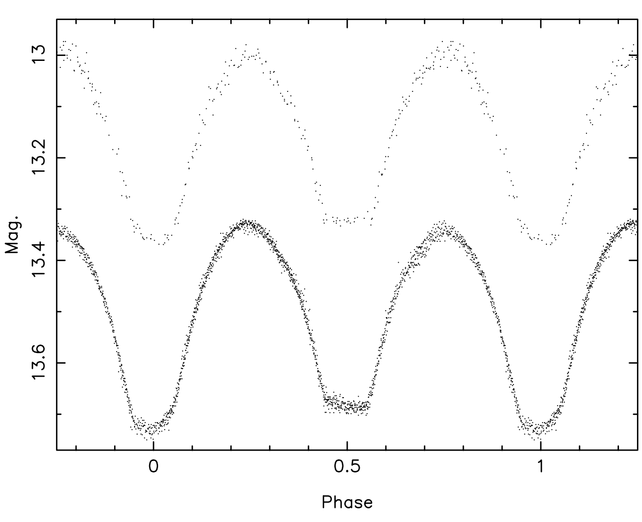

Fig. 2.—Phased i- (*top*) and V-band (*bottom*) light curves of AH Cnc obtained in 2001 and 2003–2004.

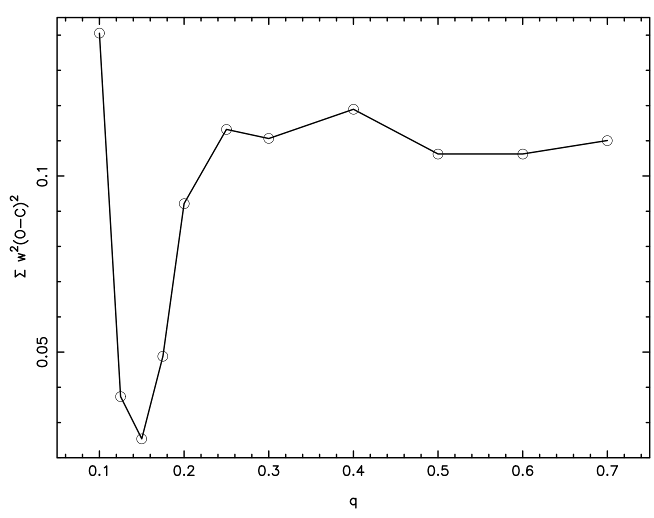

Fig. 3.—Diagram of $\sum w^2(O-C)^2$ vs. q of test solutions for the 2003–2004 light curve.

TABLE 4
PHOTOMETRIC SOLUTIONS FOR AH Cnc

Parameter	Light Curve 2001 BATC i (6600 Å)	Light Curve 2003-2004 V Band
T_1 (K)	6300[a]	6300[a]
T_2 (K)	6297 ± 20	6354 ± 7
$q = m_2/m_1$	0.148 ± 0.002	0.149 ± 0.001
i (deg)	84.30 ± 0.68	82.80 ± 0.35
$A_1 = A_2$	0.50[a]	0.50[a]
$g_1 = g_2$	0.32[a]	0.32[a]
$x_1 = x_2$	0.52[a]	0.63[a]
$\Omega_1 = \Omega_2$	2.0394 ± 0.0018	2.0370 ± 0.0007
$r_{1, \rm pole}$	0.5240 ± 0.0005	0.5249 ± 0.0002
$r_{1, \rm side}$	0.5825 ± 0.0008	0.5840 ± 0.0003
$r_{1, \rm back}$	0.6078 ± 0.0009	0.6098 ± 0.0004
$r_{2, \rm pole}$	0.2315 ± 0.0006	0.2336 ± 0.0002
$r_{2, \rm side}$	0.2435 ± 0.0007	0.2460 ± 0.0003
$r_{2, \rm back}$	0.3009 ± 0.0020	0.3071 ± 0.0009
$L_1/(L_1 + L_2)$	0.837 ± 0.002	0.830 ± 0.0001
$\Omega_{\rm in}$	2.1004[a]	2.0976[a]
Latitude$_{\rm spot}$ (deg)	90[a]	90[a]
Longitude$_{\rm spot}$ (deg)	271.1 ± 08	79.8 ± 0.3
Radius$_{\rm spot}$ (deg)	6.7 ± 0.7	8.8 ± 0.2
$T_{\rm spot}/T_1$	0.85 ± 0.04	0.76 ± 0.01

[a] Assumed.

are formed as shown in Figure 2. In Table 3, we list the main feature parameters of the light curves, where $\bar{m}_{\rm max}$ is the average magnitude at maximum light and 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 et al. (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. It implies that the system could more likely be an A-type W UMa binary as suggested by Sandquist & Shetrone (2003). Moreover, we note that most of the light curves show slight 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. This is likely due to frequent surface spot activities, as suggested 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 an average interval of 0.08 in phase. The 1992 version of the WD code (Wilson & Devinney 1971; Wilson 1979, 1990) was employed. Since the 2003–2004 observations have higher photometric precisions and contain more measurements, we begin with the V-band light curve.

The appearance of the eclipses in our data shows that AH Cnc is likely an A-type rather than a 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 $T_1 = 6300$ K 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 and Ω_2 of the components, and the nondimensional 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 ratios 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, matching a light curve with a total eclipse 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 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

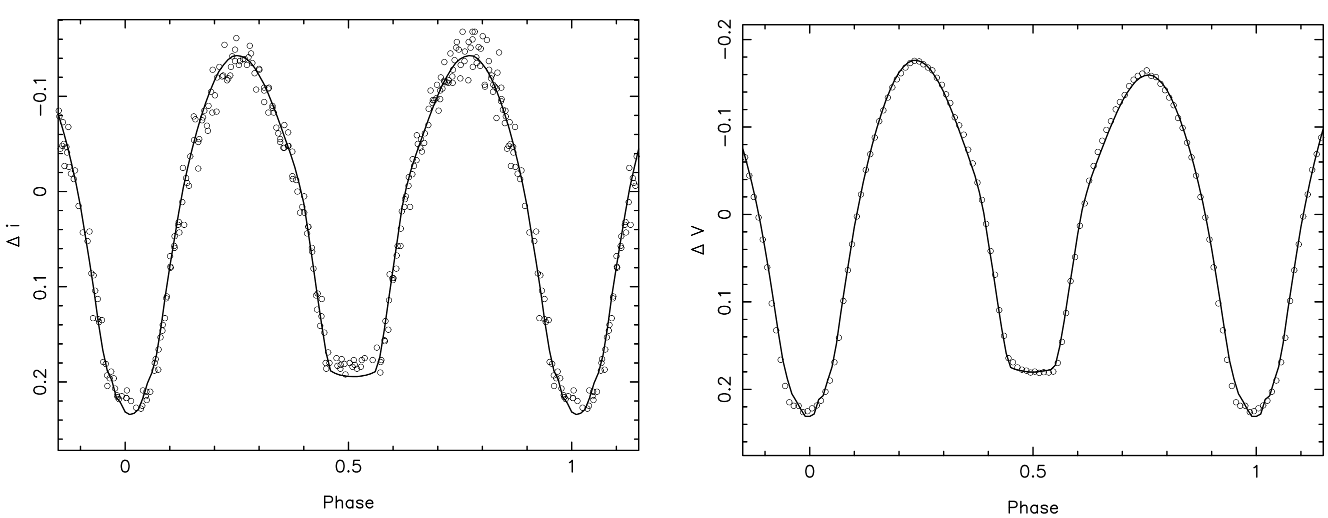

FIG. 4.—Light-curve fittings of AH Cnc. Open circles are the observations; the solid lines are the theoretical light curves.

iterations, 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. 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° (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. Since 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 modeled the light curves obtained by the CCD photometry. The solutions carried out for each individual light curve match each other very well. This confirms the total-eclipse contact configuration for 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 $83\overset{\circ}{.}5 \pm 1\overset{\circ}{.}5$, and the mass ratio of the system is derived to be about 0.15. Our results are in broad agreement with those of Sandquist & Shetrone (2003) from 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 timescale (in days) variations in the light curves. This phenomena is hard to explain by the solar-like activities of the system. Considering the large filling factor of the contact system, we suggest that there might be probable mass outflow from the system, which might be the cause of the short-term changes in the light curve of AH Cnc.

The Wilson-Devinney approach to 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 ($K_1 = 100 \pm 15$ km s^{-1}, $K_2 = 138 \pm 15 - 240 \pm 20$ km s^{-1}), so their 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 to the spectral type of F7 V (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 are given in Table 5.

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

The mass of the primary component is derived to be 1.21 $M_\odot$, which is slightly less than that of a turnoff star (about 1.25 $M_\odot$) in M67. This result in turn agrees with the position of the system on the CMD. The values of M_1, R_1, and L_1 match the spectral type of F7 V very well. The secondary component, with a very low mass, is obviously an evolved star, which presents a large radius and overluminosity compared 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 respect to its mass. We conclude that the secondary component could not be a normal star and that the system might be formed through mass exchange after themass ratio reverses. It is very likely that the secondary was the massive component of the system, with an original mass that could have been larger than the turnoff mass. If this is the case, probable mass outflow and hence angular momentum loss from the system would have played an important role. To examine this hypothesis, however, more observations, especially high-precision spectroscopy of the system, are needed.

6. SUMMARY

We have presented 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 subtype 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, 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, whereas the secondary could be much evolved. The binary system might be formed through mass exchange.

This research is supported by the Chinese National Science Foundation through grant 10173013. The authors are grateful to the referee for his valuable comments.

REFERENCES

Cox, A. N., ed. 2000, Allen's Astrophysical Quantities (4th ed.; New York: Springer), 388
Diaz-Cordoves, J., Claret, A., & Gimenez, A. 1995, A&AS, 110, 329
Efremov, Y. N., Khopolov, P. N., Kukarkin, B. V., & Sharov, A. S. 1964, Inf. Bull. Variable Stars, 75
Eggen, O. J. 1967, MmRAS, 70, 111
Fan, X. H., et al. 1996, AJ, 112, 628
Gilliland, R. L., et al. 1991, AJ, 101, 541
Janes, K. A., & Phelps, R. L. 1994, AJ, 108, 1773
Kurochkin, N. E. 1960, Astron. Tsirk., 212, 9

Kwee, K. K., & van Woerden, H. 1956, Bull. Astron. Inst. Netherlands, 12, 327
Lucy, L. B. 1967, Z. Astrophys., 65, 89
Maceroni, C., Milano, L., & Russo, G. 1984, A&AS, 58, 405
Mammano, A. 1965, in Third Coll. Var. Stars, Kl. Veröff. Remeis-Sternw., 4, 52
Mathieu, R. D., Latham, D. W., & Griffin, R. F. 1990, AJ, 100, 1859
Rucinski, S. M. 1969, Act. Astron., 19, 245
Sandquist, E. L. 2004, MNRAS, 347, 101
Sandquist, E. L., & Shetrone, M. D. 2003, AJ, 125, 2173
Stassun, K. G., van den Berg, M., Mathien, R. D., & Verbunt, F. 2002, A&A, 382, 899
Stetson, P. B. 1987, PASP, 99, 191
———. 1996, PASP, 108, 851
van den Berg, M., Stassun, K. G., Verbunt, F., & Mathien, R. D. 2002, A&A, 382, 888
Whelan, J. A. J., Worden, S. P., Rucinski, S. M., & Romanishin, W., 1979, MNRAS, 186, 729
Wilson, R. E. 1979, ApJ, 234, 1054
———. 1990, ApJ, 356, 613
Wilson, R. E., & Devinney, E. J. 1971, ApJ, 166, 605
Zhang, X. B., Deng, L., Tian, B., & Zhou, X. 2002, AJ, 123, 1548