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AL CASSIOPEIAE: AN F-TYPE CONTACT BINARY SYSTEM WITH A COOL STELLAR COMPANION

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ABSTRACT

According to the general catalog of variable stars, AL Cas was classified as an EW-type eclipsing binary with a spectral type of B and an orbital period of $P = 0.5005555$ days. The first photometric light curves of the close binary in the *B*, *V*, *R*, and *I* bands are presented. New low-resolution spectra indicate that its spectral type is about F7 rather than B-type. A photometric analysis with the Wilson–Devinney method suggests that it is a contact binary ($f = 39.3\%$) with a mass ratio of 0.61. Using 17 newly determined eclipse times together with those collected from the literature, we found that the observed−calculated ($O - C$) curve of AL Cas shows a cyclic change with a period of 86.6 yr and an amplitude of 0.0181 days. The periodic variation was analyzed for the light-travel time effect via the presence of a third body. The mass of the third body was determined to be $M_3 \sin i' = 0.29(\pm0.05)\ M_\odot$ when a total mass of 2.14 $M_\odot$ for AL Cas is adopted. It is expected that the cool companion star may have played an important role in the origin and evolution of the system by removing angular momentum from the central binary system during early dynamical interaction and/or late dynamical evolution. This causes the original detached system to have a low angular momentum and a short initial orbital period. Then it can evolve into the present contact configuration via a case A mass transfer.

Key words: binaries: close – binaries: eclipsing – stars: evolution – stars: individual (AL Cas)

Online-only material: supplemental data

1. INTRODUCTION

The light variability of AL Cas ($V = 12.3$) was discovered by Hoffmeister (1928). According to the general catalog of variable stars (Samus et al. 2011), it was classified as an EW-type eclipsing binary. Its light change is continuous and it is impossible to specify the exact times of onset and the end of eclipses. The depths of the primary and secondary minima are almost equal with a magnitude of about 0.7 in V (Kreiner et al. 2001). In several catalogs of close binary stars, AL Cas was listed as a B-type eclipsing binary (e.g., Reed, 2003; Pribulla et al., 2003; Malkov et al. 2006) with a short period of 0.50055550 days (Kreiner et al. 2001). If AL Cas is really a B-type star, it would have the shortest orbital period among B-type main-sequence close binaries. In this case, it is an important object for understanding the structure and evolution of early-type close binaries. However, since its discovery by Hoffmeister in 1928, apart from some eclipse times that were obtained, neither complete photoelectric or CCD light curves nor photometric investigations were published. In the present paper, we present the first complete CCD light curves in the *BVRI* bands. Our new low-resolution spectra reveal that it is an F7-type star rather than B-type. A detailed photometric analysis reveals that AL Cas is a normal contact binary with a third stellar companion. Finally, the formation and evolution of the system are discussed based on those obtained results.

2. NEW OBSERVATIONS OF AL Cas

AL Cas was observed from 2006 November 15 to 17 at the Mt. Suhora Observatory, using a CCD and the wide band, Johnson–Cousins *BVIR* filters, attached to the 60 cm Cassegrain telescope (Suhora telescope). Observations were reduced with the Image Reduction and Analysis Facility (IRAF)[7] to account for flat/bias/dark, then Cmunipack was used to extract magnitudes. It has DAOPHOT routine built in and aperture photometry for targets was applied. Two stars near AL Cas in the CCD field of view, GSC 4315 844 and GSC 4315 32, were chosen as the comparison star and the check star. Complete multicolor light curves were obtained on November 16 and 17 and are graphed in Figure 1. The light curves show typical EW light variation with a depth of both minima about 0.7 mag.

By using those CCD photometric data, several times of minimum light were determined with a parabolic fitting method. To obtain more eclipse times, AL Cas was continuously monitored with the Suhora telescope and the 60 cm and the 1.0 m telescopes in the Yunnan observatories (YNO). The 60 cm and 1.0 m telescopes were equipped with a Cassegrain-focus multi-color CCD photometer where two Andor DW436 2K CCD cameras were used. Another nine epochs of minimum light were obtained. All of the eclipse times are listed in Table 1, where "N" refers to those obtained without filters. "Suhora" in the table represents the 60 cm Suhora telescope, while "YNO-60 cm" and "YNO-1.0 m" refer to the 60 cm and 1.0 m telescopes in YNO, respectively.

3. VARIATIONS OF THE $O - C$ DIAGRAM

All available times of minimum light before 2001 were compiled by Kreiner et al. (2001). After this collection, some eclipse times were published by Safar & Zejda (2002), Zejda (2002, 2004), Hübscher (2005, 2007, 2011), Hübscher

[7] IRAF is a collection of software written at the National Optical Astronomy Observatory (NOAO) geared toward the reduction of astronomical images in pixel array form.

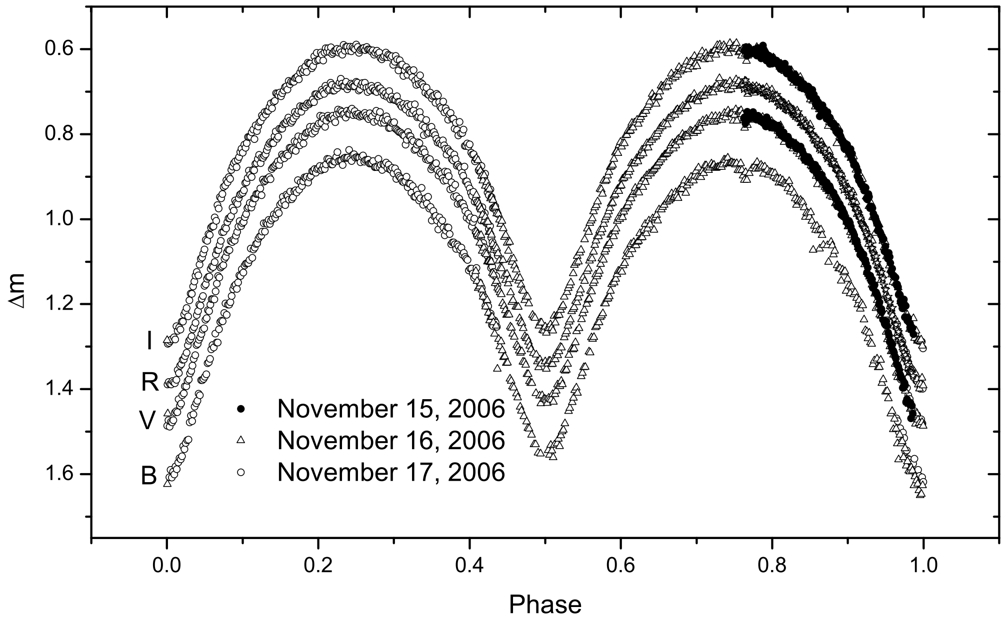

Figure 1. First CCD photometric light curves of AL Cas. The phases of the observations were calculated with the linear ephemeris: Min.I = 2454056.23792.5569 + 0.50055550 days × E where the orbital period is from Kreiner et al. (2001).

(Supplemental data of this figure are available in the online journal.)

Table 1
New CCD Times of Minimum Light for AL Cas

J.D. (Hel.) (days)	Error (days)	Min.	Filters	Telescopes
2454056.23819	0.00018	II	*B*	Suhora
2454056.23789	0.00017	II	*V*	Suhora
2454056.23770	0.00019	II	*R*	Suhora
2454056.23789	0.00018	II	*I*	Suhora
2454057.48879	0.00016	I	*B*	Suhora
2454057.48938	0.00014	I	*V*	Suhora
2454057.48939	0.00011	I	*R*	Suhora
2454057.48914	0.00012	I	*I*	Suhora
2454816.33508	0.00046	I	*R*	Suhora
2454828.59883	0.00021	II	*R*	Suhora
2454829.35017	0.00019	I	*R*	Suhora
2455916.06061	0.00019	I	*R*	YNO-60 cm
2455916.56057	0.00003	I	*R*	Suhora
2455917.06080	0.00013	I	*R*	YNO-60 cm
2456296.98397	0.00024	I	N	YNO-60 cm
2456644.12027	0.00011	II	N	YNO-1.0 m
2456645.12150	0.00019	II	N	YNO-1.0 m

et al. (2005, 2009), Kotkova & Wolf (2006), Kim et al. (2006), and Brát et al. (2007, 2009). The $(O - C)_1$ values of those times of minimum light were computed with the following linear ephemeris given by Kreiner et al. (2001),

$$\text{Min.I(HJD)} = 2425303.5729 + 0.50055550 \text{ days} \times E, \quad (1)$$

where 2425303.5729 is the initial epoch, while 0.50055550 days is the orbital period. The corresponding $O-C$ diagram is shown in the upper panel of Figure 2 along with the epoch number E, where open circles represent the visual or photographic observations (hereafter "VP") and solid dots refer to eclipse times observed with the methods of photoelectric or CCD (hereafter "PC") photometry, respectively.

As shown in the upper panel of Figure 2, the linear ephemeris of AL Cas needs to be revised, and it appears that there is a cyclic variation as well. To satisfactorily describe the general trend of the $(O - C)_1$ curve, a combination (solid line in the upper panel) of a new linear ephemeris (dashed line in the same panel) and an additional cyclic variation is required. By using a least-squares method, we determined

$$\begin{aligned}\text{Min.I} = {} & 2425303.55676(\pm 0.00029) \\ & + 0.50055604(\pm 0.00000008) \times E \\ & + 0.0181(\pm 0.0028) \sin[0^{\circ}\!.0057(\pm 0.0001) \\ & \times E + 1^{\circ}\!.08(\pm 0^{\circ}\!.17)]. \end{aligned} \quad (2)$$

As displayed in Figure 2, the short-time scatter of the VP times is of about 0.02 days, while the errors for the PC data are usually less than 0.001 days. Therefore, during the analysis, the weighted least-squares method was used. The weight of 1 was assigned to the VP observations, while the weight of 20 was assigned to PC data.

The derived orbital period is slightly longer than that determined by Kreiner et al. (2001). The cyclic oscillation has an amplitude of 0.0181 days. By using $P_3 = (360^{\circ}/w) \times P$, the period of the cyclic change is determined to be $P_3 = 31614.0$ days = 86.6 yr, where $w = 0^{\circ}\!.0057$ is the frequency. The residuals from Equation (2) are displayed in the lower panel of Figure 2 where no changes can be traced, indicating that Equation (2) well describes the general $(O - C)_1$ trend. The $(O - C)_2$ diagram with respect to the new linear ephemeris in Equation (2) is shown in Figure 3, where the cyclic change can be seen more clearly.

4. PHOTOMETRIC SOLUTION WITH THE W-D METHOD

The spectral type of AL Cas was listed as B type in several catalogs (e.g., Reed, 2003; Pribulla et al., 2003; Malkov et al. 2006), and, if this is true, it would be the shortest binary among B-type main-sequence binaries. To check its spectral type, low-resolution spectra were obtained in 2012 September by using the 2.16 m telescope in the Xinglong station of the National Astronomical Observatory (NAO). During the observation, an Optomechanics Research, Inc., spectrograph and a Tecktronix

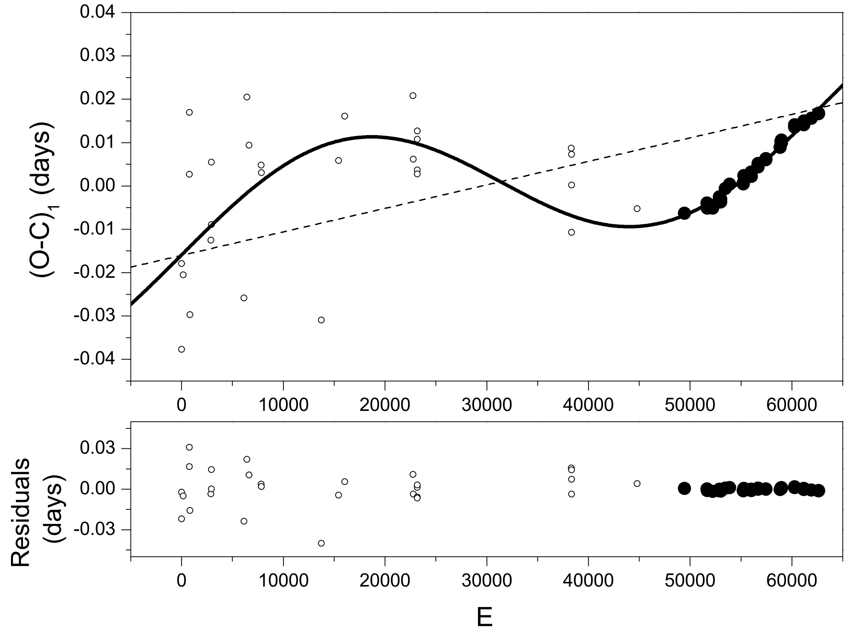

Figure 2. $(O - C)_1$ curve of AL Cas with respect to the linear ephemeris by Kreiner et al. (2001). The solid line refers to a combination of a new ephemeris and a cyclic period variation. The dashed line represents the new linear ephemeris. Residuals from Equation (2) are displayed in the bottom panel. Open circles refer to visual or photographic data, while solid circles refer to photoelectric and CCD observations.

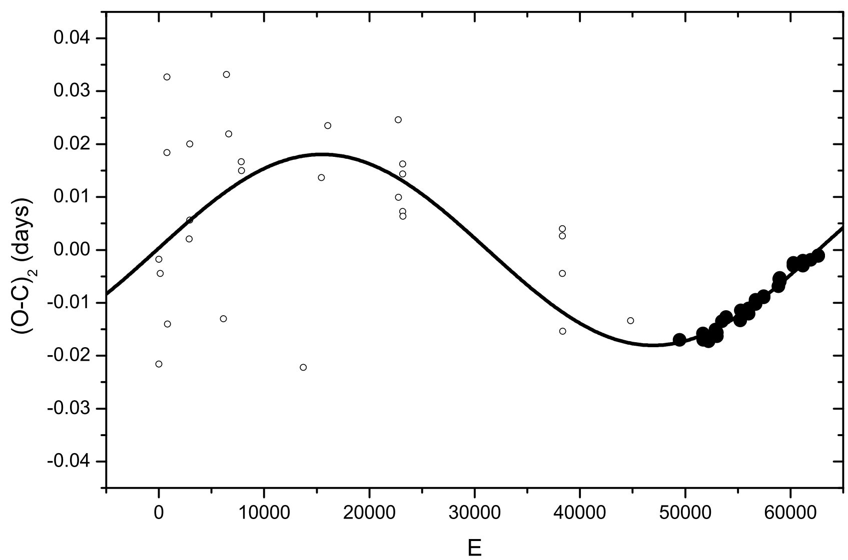

Figure 3. $(O - C)_2$ diagram of AL Cas calculated with the linear ephemeris in Equation (2). The solid line represents the cyclic period variation. Symbols are the same as those in Figure 2.

1024 × 1024 CCD were used. These spectroscopic data have a two-pixel resolution of 4.88 Å. The spectroscopic data were reduced using standard procedures and packages in IRAF. Several spectral are show in Figure 4. Based on the Ca II *H*-, *K*-, and *G*-band lines, we estimated that the spectral type of AL Cas is about F7 rather than B-type.

Though AL Cas was discovered more than 80 yr ago, no photometric solutions were published. Based on our observations, complete light curves in the *B*, *V*, *R*, and *I* bands were obtained and are shown in Figure 1. In all, 593 data points in *B*, 822 in *V*, 820 in *R*, and 817 in *I* were obtained. As shown in Figure 1, the light curves in four colors are typical EW-type where light variation is continuous and has a very small difference between the depths of the two minima. These properties reveal tidally distorted components and both of the components have similar temperatures. To derive photometric elements and to understand the evolutionary state of the binary star, the obtained light curves were analyzed simultaneously with the Wilson–Devinney (W-D) method (Wilson & Devinney 1971).

According to the spectral type of F7, the temperature for star 1 (star eclipsed at the primary minimum light) was fixed as $T_1 = 6400\,K$. We assume convective outer envelopes for both components. The bolometric albedo $A_1 = A_2 = 0.5$ (Rucinski 1969) and the values of the gravity-darkening coefficients $g_1 = g_2 = 0.32$ (Lucy 1967) were used. To treat the limb darkening in detail, we took logarithmic functions. The corresponding bolometric and passband-specific limb-darkening coefficients are chosen from van Hamme's (1993) table and are listed in Table 2, where all of the fixed parameters are shown. First, we assumed that the bolometric and passband-specific limb-darkening coefficients of both components are equal. After determining the temperature of the secondary star, the values

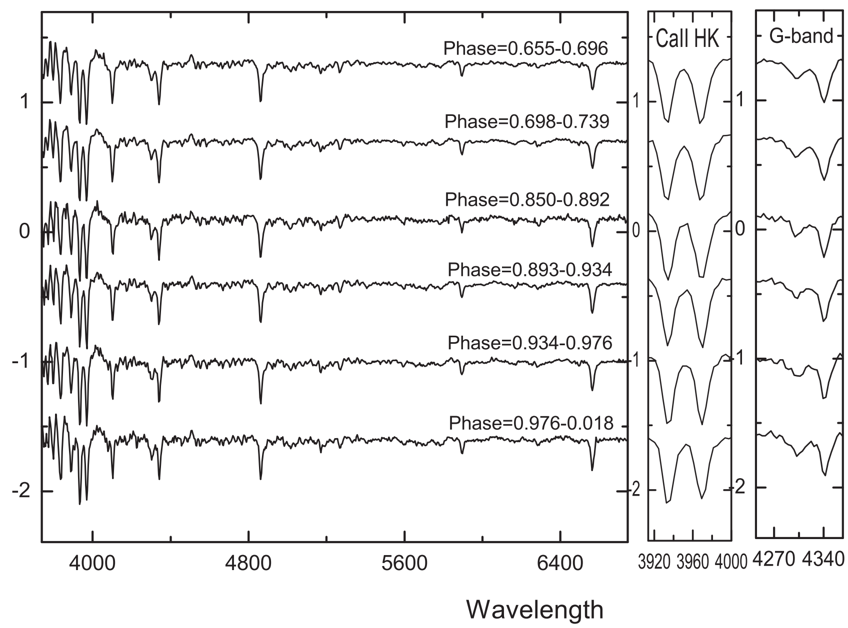

Figure 4. Low-resolution spectra obtained by the 2.16 m telescope at Xinglong station of the NAO.

Table 2
Fixed Parameter during Photometric Solution

Parameters	Values
$g_1 = g_2$	0.32
$A_1 = A_2$	0.5
x_{1bol}	0.123
x_{2bol}	0.144
y_{1bol}	0.559
y_{2bol}	0.577
x_{1B}	0.281
x_{2B}	0.351
y_{1B}	0.604
y_{2B}	0.538
x_{1V}	0.108
x_{2V}	0.144
y_{1V}	0.697
y_{2V}	0.673
x_{1R}	0.021
x_{2R}	0.053
y_{1R}	0.713
y_{2R}	0.695
x_{1I}	−0.035
x_{2I}	−0.007
y_{1I}	0.682
y_{2I}	0.668
T_1	6400 K

Table 3
Photometric Parameters for AL Cas

Parameters	Photometric Elements	Errors
q (M_2/M_1)	0.610	±0.003
Ω_{in}	3.0818	...
Ω_{out}	2.7256	...
T_2	6316K	±32K
i	80.57	±0.05
$L_1/(L_1 + L_2)$ (B)	0.6253	±0.0004
$L_1/(L_1 + L_2)$ (V)	0.6201	±0.0004
$L_1/(L_1 + L_2)$ (R)	0.6178	±0.0004
$L_1/(L_1 + L_2)$ (I)	0.6158	±0.0002
$\Omega_1 = \Omega_2$	2.9418	±0.0042
r_1(pole)	0.4203	±0.0008
r_1(side)	0.4499	±0.0011
r_1(back)	0.4902	±0.0018
r_2(pole)	0.3390	±0.0011
r_2(side)	0.3584	±0.0014
r_2(back)	0.4082	±0.0027
The degree of contact (f)	39.3%	±1.2%
$\Sigma\omega(O - C)^2$	0.0026	

of x_{2bolo}, y_{2bolo}, x_{2B}, y_{2B}, x_{2V}, y_{2V}, x_{2R}, y_{2R}, x_{2I}, and y_{2I} were redetermined according to its real temperature. The adjustable parameters were the orbital inclination i; the mean temperature of star 2, T_2; the mass ratio q ($q = M_2/M_1$); the band-pass luminosity of star 1, L_{1B}, L_{1V}, L_{1R}, and L_{1I}; and the dimensionless potential of star 1 ($\Omega_1 = \Omega_2$, mode 3 for contact configuration).

Since no mass ratios for AL Cas were obtained in previous literature, a q-search method was used to determine its mass ratio. We focus on searching for photometric solutions with a mass ratio from 0.1 to 3.0. However, it was found that no converged solutions were obtained when $q < 0.4$, and solutions were carried out for a series of values of the mass ratio. For each value of q, the calculation began at mode 2 (detached mode) and we discovered that the solutions usually converged to contact configuration. The relation between the resulting sum Σ of the weighted square deviations and q is plotted in Figure 5. A minimum value was obtained at $q = 0.64$. Therefore, we chose the initial value of the mass ration q as 0.64 and made it an adjustable parameter. Then, we performed a differential correction until it converged and final solutions were derived. The photometric solutions are listed in Table 3. The corresponding theoretical light curves are plotted in Figure 6.

5. DISCUSSIONS AND CONCLUSIONS

Although AL Cas was discovered as a variable star more than 80 yr ago, it was neglected for photometric study. The orbital period of AL Cas is about a half day and it is difficult to obtain complete light curves at one observational site. This may be the reason why no complete light curves for the binary

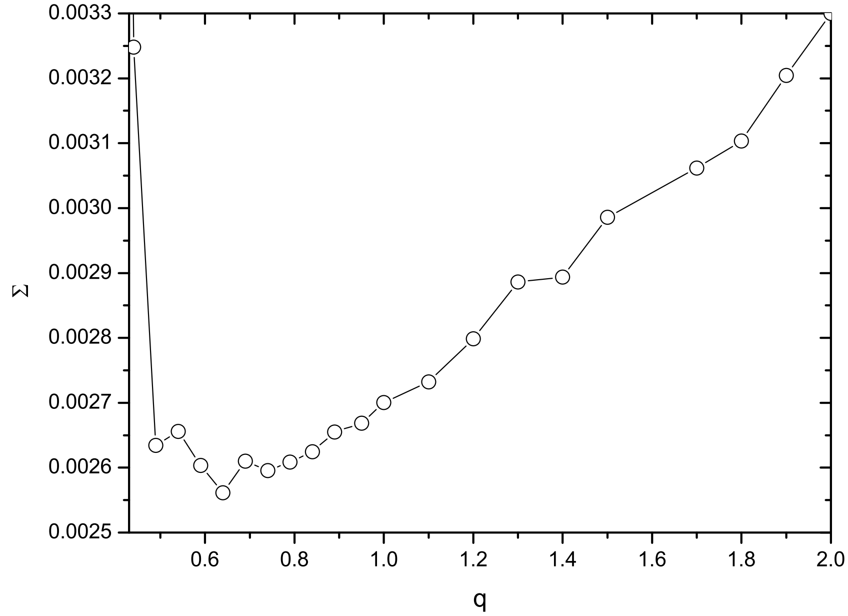

Figure 5. Relation between Σ and q for AL Cas, where Σ is the resulting sum of weighted square deviations. It is shown that a minimum is at $q = 0.64$.

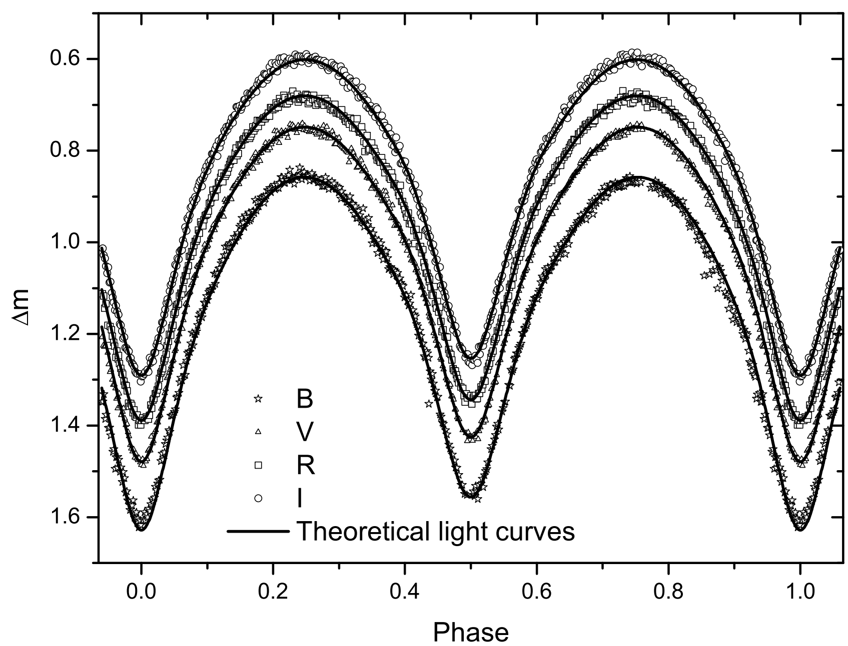

Figure 6. Observational data points (open cycles, squares, triangles, and stars) and theoretical light curves (solid lines) calculated by using the W-D method for AL Cas.

were published. The first complete multicolor light curves of the variable are obtained in the *BVRI* bands. As shown in Figure 1, the light curves are symmetric, indicating that they are suitable to be used for determining photometric parameters. Our photometric solutions reveal that AL Cas is a contact binary system with a contact degree of $f = 39.3\%$. The geometrical structures of AL Cas at phases of 0.0, 0.25, 0.50, and 0.75 are displayed in Figure 7. The derived mass ratio is $q = 0.61$. The orbital inclination of the binary is about $i = 80.57$, suggesting that it is a total eclipsing binary and the determined parameters are reliable. The new low-resolution spectra of AL Cas indicate that its spectral type is about F7 type rather than B type. If we assume that the mass of the primary component is $M_1 = 1.33\, M_\odot$ (Cox 2000), the mass of the secondary was estimated as $M_2 = 0.81\, M_\odot$ with the derived mass ratio. The spectral types of two other contact binaries, RT LMi and GR Vir, are also F7 (Rucinski et al. 2000; Rucinski & Lu 1999). The masses of the primary components in the two binaries were determined as $M_1 = 1.29\, M_\odot$ and $M_1 = 1.36\, M_\odot$ (Qian et al. 2008b; Qian & Yang 2004). This suggests that the mass estimation for the primary component in AL Cas is reasonable.

The $O - C$ diagram displayed in Figure 3 indicates a cyclic variation with a period of 86.1 yr. As plotted in Figures 2 and 3, both the primary and the secondary times of the minimum light follow the same general trend of the $O - C$ variation, which indicates that the oscillation in the $O - C$ curve cannot be explained by apsidal motion via eccentric orbits of the two binary stars. As discussed by several authors (e.g., Liao & Qian 2010; Qian et al. 2013a, 2013b), this kind of cyclic changes can plausibly be explained by the light-travel time effect (LTTE).

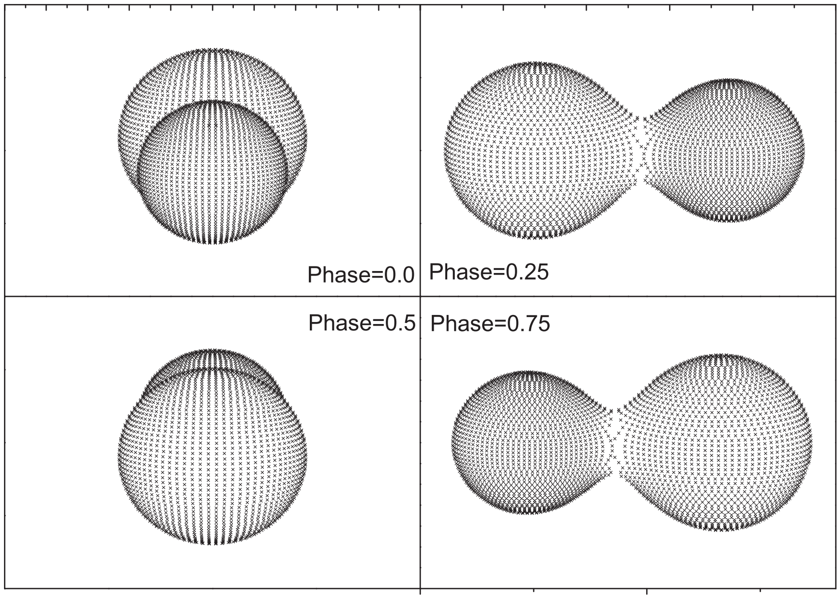

Figure 7. Contact configurations of AL Cas at phases 0.0, 0.25, 0.50, and 0.75.

Table 4
Parameters of the Tertiary Component in AL Cas

Parameters	Values	Units
P_3	86.6(±1.5)	years
A_3	0.0181(±0.0028)	days
e	0.0	assumed
$a'_{12} \sin i'$	3.14(±0.49)	AU
$f(m)$	$4.1(\pm 0.8) \times 10^{-3}$	$M_\odot$
$M_3 \sin i'$	0.29(±0.05)	$M_\odot$
$a_3(i' = 90°)$	23.2(±2.6)	AU

Therefore, we analyze the cyclic change for LTTE via the presence of a tertiary component (e.g., Borkovits & Hegedüs 1996). As displayed in Figures 2 and 3, the sine-like changes of the $O - C$ curves suggest that the eccentricities of the orbit of the tertiary component are close to zero. With the same method used by Qian (e.g., Qian et al. 2013a, 2013b), the parameters of the third body are determined and are shown in Table 4.

The mass of the tertiary companion is $M_3 \sin i' = 0.29(\pm 0.05)\ M_\odot$. To check the presence of the third body, during the photometric solution, we also included third light as one of the adjusted parameters. However, the results suggest that the third light is negligible, indicating that the orbital inclination of the third body cannot be extremely low and it should be a faint object with a mass close to $M_3 \sim 0.29\ M_\odot$. It contributes a very small light to the total system in the optical band when comparing with the luminous binary components. The presence of the additional stellar component in the binary system may play an important role for the formation and evolution by removing angular momentum from the central binary during the early dynamical interaction or late evolution. As discussed by Qian et al. (2007a, 2007b, 2008a, 2013a), this causes the central close binaries to have a lower angular momentum and a shorter initial orbital period. In this way the initially detached binaries can evolve into contact configuration via a case A mass transfer during their main-sequence evolutionary stage.

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