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Mass transfer and loss of the massive semi-detached binary AI Crucis *

Er-Gang Zhao[1,2,3], Sheng-Bang Qian[1,2,3], E. Fernández Lajús[4], Carolina von Essen[4] and Li-Ying Zhu[1,2,3]

[1] National Astronomical Observatories / Yunnan Observatory, Chinese Academy of Sciences, Kunming 650011, China; *zergang@ynao.ac.cn*

[2] Key Laboratory for the Structure and Evolution of Celestial Objects, Chinese Academy of Sciences, Kunming 650011, China

[3] Graduate University of Chinese Academy of Sciences, Beijing 100049, China

[4] Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, 1900 La Plata, Buenos Aires, Argentina; *eflajus@lilen.fcaglp.unlp.edu.ar*

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Abstract AI Crucis is a short-period semi-detached massive close binary ($P = 1.41771^{\rm d}$, Sp.=B 1.5) in the open cluster NGC 4103. It is a good astrophysical laboratory for investigating the formation and evolution of massive close binary stars via case A mass transfer. Orbital period variations of the system were analyzed based on one newly determined eclipse time and the others compiled from the literature. It is discovered that the orbital period of the binary is continuously increasing at a rate of $dP/dt = +1.00(\pm0.04) \times 10^{-7}$ d yr^{-1}. After the long-term increase is subtracted from the $O-C$ diagram, weak evidence indicates the presence of a cyclic oscillation with a period of 30.1 yr, which may reveal a very cool stellar companion in the system. The long-term period increase can be explained by mass transfer from the less massive component to the more massive one. This is in agreement with the semi-detached configuration of the binary, indicating that the system is undergoing a slow mass-transfer stage on the nuclear time scale of the secondary. However, it is found that the slow mass transfer is insufficient to cause the observed period increase, which suggests that the stellar wind from the hot component should contribute to the amount of period increase $dP/dt = +0.54 \times 10^{-7}$ d yr^{-1} that corresponds to a mass loss rate of $\dot{M}_1 = 2.72 \times 10^{-7}\, M_\odot$ yr^{-1}. It is estimated that the hot component lost a total mass of 4.1 $M_\odot$ during the slow mass-transfer stage and, thus, the evolution of the binary system should be changed greatly by the mass loss.

Key words: stars: binaries: close — stars: binaries : eclipsing — stars: individual (AI Crucis)— stars: early-type — stars: evolution

1 INTRODUCTION

Theoretical studies of binary evolution have suggested that short-period semi-detached massive binary stars are formed through case A mass transfer (the mass transfer is taking place during the

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main-sequence evolutionary stage of the mass loser) (e.g., Plavec et al. 1968; Horn et al. 1970). It is shown that mass transfer between the components and mass loss from the system are two key astrophysical processes which are needed to understand this evolution. However, details on the two processes are not well investigated. Up to now, a few massive semi-detached eclipsing binaries have been found where the less massive components are filling the critical Roche lobe. Some examples are V Pup (e.g., Andersen et al. 1983), MP Cen (Terrell et al. 2005), SX Aur (Bell et al. 1987a), and AI Cru (Bell et al. 1987b). They are observed in the slow phase of case A mass transfer and the roles of the current primary and the secondary components have been reversed. Orbital period changes of these eclipsing binary systems can provide invaluable information on the evolution of binary stars. In the paper, orbital period changes of AI Crucis are investigated. Then, based on the period variations, the presence of a very cool stellar companion, the mass transfer and mass loss, and, thus, the evolutionary state of the system are discussed.

AI Crucis (CPD $-60°$ 3273, CoD $-60°$ 3971) was found to be an eclipsing binary by Oosterhoff (1933) who derived a period of $P = 1.4177073^{\rm d}$. Subsequently, photometric solutions of the system were determined by Ollongren (1956), Giuricin et al. (1980), and Russo (1981). Russo (1981) concluded that AI Crucis was semi-detached with the secondary component in contact with its critical Roche lobe. Both photometric and spectroscopic observations of AI Crucis were obtained by Bell et al. (1987b) who estimated the spectral type of the primary to be B 1.5 and derived the masses of both components as 8.9 $M_\odot$ and 5.4 $M_\odot$. Ollongren (1956) noted that AI Crucis is a possible member of the open cluster NGC 4103, which was later confirmed by Bell et al. (1987b). The photometric solutions of AI Crucis by Bell et al. (1987b) revealed the semi-detached configuration of the system and concluded that it has probably passed through the rapid phase of Case A mass transfer.

2 ORBITAL PERIOD VARIATIONS OF AI CRUCIS

Epochs and orbital periods of AI Crucis have been given by several authors (e.g., Ollongren 1956; Bell et al. 1987b) and are listed in Table 1. Ollongren (1956) and Bell et al. (1987b) pointed out that there is no reliable evidence for variations in the orbital period. All of the available times of light minimum were collected and were kindly provided by Kreiner (2006, private communication). A few unpublished times of light minimum were determined by Drs. Kosiek, P. & Ogloza, W. and one CCD eclipse time was from Paschke (2007). The original data are listed in the first column of Table 2. Those shown in the third column are the observed methods where "Pg" refers to photographic, "Pe" to photoelectric, and "CCD" to the Charged-couple device.

Table 1 Epochs and Orbital Periods of AI Crucis

Epochs	Orbital Period (d)	References
2423959.179	1.417722	Oosterhoff (1933)
2433466.3358	1.4177073	Ollongren (1956)
2433283.44995	1.4177183	Wood & Forbes (1963)
2446567.4063	1.4177112	Bell et al. (1987b)
2433466.3444	1.41771013	Kreiner et al. (2001)

One time of light minimum of AI Crucis, HJD 2454530.7030 (± 0.0005), was obtained by one of the co-authors (Dr. Fernández Lajús) on 2008 March 3. Those observations of AI Crucis were obtained with the HSH 0.6-m telescope at Casleo in Argentina. During the observation, the filter V was used and 500 images were obtained. The $(O-C)_1$ curve of AI Crucis was formed by using the linear ephemeris of Kreiner et al. (2001),

$$\text{Min.}I = 2433466.3444 + 1.41771013^{\rm d} \times E. \tag{1}$$

The corresponding $(O-C)_1$ diagram is plotted against epoch number in the upper panel of Figure 1 where crosses refer to photographic observations and open dots to photoelectric and CCD

Table 2 Times of Light Minimum of AI Crucis

JD.Hel. 2400000+	Errors (d)	Method	Min.	E	$(O-C)_1$ (d)	$(O-C)_2$ (d)	Residuals (d)
23959.194		Pg	I	–6706	+0.0137	+0.0049	
23976.175		Pg	I	–6694	–0.0178	–0.0266	
24285.273		Pg	I	–6476	+0.0194	+0.0114	
24292.342		Pg	I	–6471	–0.0001	–0.0081	
25351.381		Pg	I	–5724	+0.0094	+0.0040	
25354.218		Pg	I	–5722	+0.0110	+0.0056	
25361.294		Pg	I	–5717	–0.0016	–0.0070	
25378.325		Pg	I	–5705	+0.0169	+0.0115	
25714.294		Pg	I	–5468	–0.0114	–0.0160	
26114.112		Pg	I	–5186	+0.0123	+0.0086	
26471.395		Pg	I	–4934	+0.0324	+0.0294	
28687.239		Pg	I	–3371	–0.0046	–0.0035	
33466.3358	±0.0002	Pe	I	0	–0.0086	–0.0018	–0.0001
33466.3362		Pe	I	0	–0.0082	–0.0014	+0.0003
40676.8133	±0.0010	Pe	I	5086	–0.0051	+0.0018	+0.0005
46224.3175	±0.0003	Pe	I	8999	–0.0036	–0.0034	–0.0025
46557.4796	±0.0002	Pe	I	9234	–0.0014	–0.0018	–0.0012
46567.4063	±0.0001	Pe	I	9241	+0.0026	+0.0022	+0.0028
48363.6481	±0.0013	CCD	I	10508	+0.0057	+0.0017	+0.0004
48775.4938	±0.0023	CCD	II	10798.5	+0.0066	+0.0017	0.00000
52074.5125	±0.0022	CCD	II	13125.5	+0.0138	+0.0004	–0.0006
52102.1589	±0.0008	CCD	I	13145	+0.0148	+0.0013	+0.0003
52950.6583	±0.0008	CCD	II	13743.5	+0.0147	–0.0013	–0.0014
52966.9637	±0.0009	CCD	I	13755	+0.0165	+0.0004	+0.0004
54251.411	±0.0040	CCD	I	14661	+0.0184	–0.0018	–0.0006
54530.7030	±0.0005	CCD	I	14858	+0.0215	+0.0004	+0.0018

data. The corresponding $(O-C)_1$ values are listed in the sixth column of Table 2. It is found from Figure 1 that the orbital period of AI Crucis is variable. As shown in the upper panel of Figure 1, the general trend of the $(O-C)_1$ curve shows an upward parabolic change, indicating that the period is continuously increasing. By considering that the error of photographic observations is about 0.008^{d} and that of photoelectric and CCD (PC) data is about 0.001^{d}, we choose weights 1 for photographic data and 8 for PC observations.

A weighted least-squares solution leads to the following quadratic ephemeris,

$$\begin{aligned} \mathrm{Min}.I &= 2433466.3376(\pm 0.0003) \\ &+ 1.41770911^{\mathrm{d}}(\pm 0.00000007) \times E \\ &+ 1.95(\pm 0.08) \times 10^{-10} \times E^2. \end{aligned} \tag{2}$$

The residuals from this equation are displayed in the lower panel of Figure 1. The quadratic term in Equation (2) indicates a long-term period increase at the rate of $dP/dt = +1.00(\pm 0.04) \times 10^{-7}\,\mathrm{d\,yr}^{-1}$, which corresponds to a period increase of 0.86 s per century.

The $(O-C)_2$ residuals of all PC times of light minimum with respect to the quadratic ephemeris in Equation (2) are shown in the upper panel of Figure 2 and are listed in the seventh column of Table 2. As displayed in Figure 2, a cyclic oscillation may exist. Using the least-squares method, the following equation,

$$\begin{aligned} (O-C)_2 &= 0.0002(\pm 0.0001) \\ &+ 0.0019(\pm 0.0005)\sin[0.0464^\circ \times E \\ &+ 266.7^\circ(\pm 12.8^\circ)], \end{aligned} \tag{3}$$

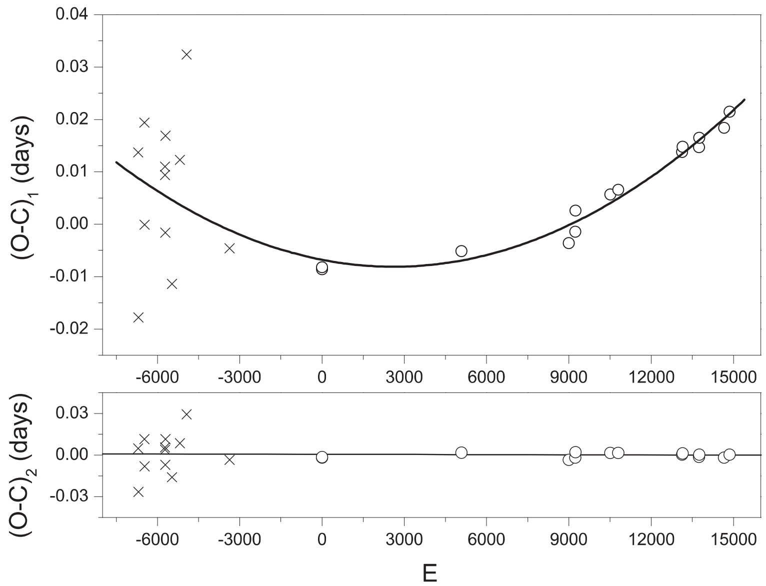

Fig. 1 $(O-C)_1$ curve of AI Crucis to computed with the linear ephemeris of Kreiner et al. (2001). The solid line in the upper panel refers to a continual period increase. The $(O-C)_2$ values from Eq. (2) are displayed in the low panel. Crosses refer to photographic data and open circles to photoelectric and CCD observations.

is derived. The sinusoidal term in Equation (3) reveals a small-amplitude periodic change with a period of $P_3 = 30.1$ yr and an amplitude of $A_3 = 0.0019^{\rm d}$ (± 0.0005). However, it needs more precise times of light minimum to be checked in the future.

3 MECHANISMS FOR THE PERIOD CHANGES

3.1 Mass Transfer between the Components

Photometric solutions derived by Russo (1981) and Bell et al. (1987b) suggest that AI Crucis was semi-detached where the secondary component is filling the critical Roche lobe. The increases in secular period deduced from the $O-C$ analysis can be interpreted by mass transfer from the less massive component to the more massive one. By comparing astrophysical parameters of AI Crucis with the stationary model by Horn et al. (1970), Bell et al. (1987b) show that AI Crucis has probably passed through the rapid phase of Case A mass transfer. The system is now in the slow phase of Case A mass transfer on the nuclear time-scale of the less massive component. The nuclear time-scale is as follows,

$$\tau_{\rm N} = 10^{10} M_2/L_2, \tag{4}$$

where M_2, R_2, and L_2 are the mass, the radius, and the luminosity of the less massive component. With the physical parameters determined by Bell et al. (1987b), the nuclear time-scale of the secondary star can be calculated to be $\tau_{\rm N} = 3.63 \times 10^7$ yr, which corresponds to a mass transfer rate of $dM_2/dt = M_2/\tau_{\rm N} = 1.49 \times 10^{-7}\, M_\odot\,{\rm yr}^{-1}$. By using the following equation,

$$\frac{\dot{P}}{P} = 3\dot{M}\Big(\frac{1}{M_2} - \frac{1}{M_1}\Big), \tag{5}$$

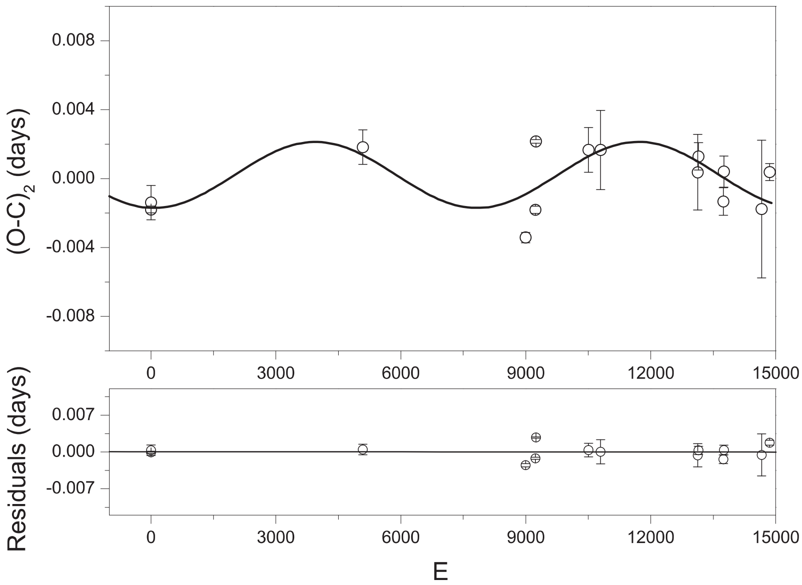

Fig. 2 $(O-C)_2$ residuals for AI Crucis after the continuous increase was removed from the whole period change. The solid line refers to a possible cyclic period oscillation.

the period increase caused by the slow mass transfer should be $dP/dt = +0.46 \times 10^{-7}$ d yr^{-1}, which is much smaller than the observed increase rate $dP/dt = +1.00 \times 10^{-7}$ d yr^{-1}. Another mechanism should contribute to the amount of period increase $dP/dt = +0.54 \times 10^{-7}$ d yr^{-1}.

3.2 The Combination of Mass Transfer and Mass Loss

The analysis in the previous subsection suggests that a conservatively slow mass transfer rate from the secondary to the primary is insufficient to explain the observed rate of period increase. Another mechanism that can cause the orbital period increase is the mass loss from the more massive component that is detached from the critical Roche lobe (e.g., Russo 1981; Bell et al. 1987b). The spectral type of the primary is estimated to be B 1.5 by Bell et al. (1987b) and mass loss from the component is expected via stellar wind. By assuming the rest period increase $dP/dt = +0.54 \times 10^{-7}$ d yr^{-1} is caused by mass loss via stellar wind, a calculation with the equation,

$$\frac{\dot{P}}{P} = -\frac{2\dot{M}_1}{M_1 + M_2}, \tag{6}$$

where M_1 and M_2 are the masses of the primary and the secondary, respectively, leads to a mass loss rate of $dM_1/dt = 2.72 \times 10^{-7}\, M_\odot$ yr^{-1}. Most probably, the observed period increase is caused by a combination of mass transfer from the secondary to the primary and mass loss via stellar wind from the more massive primary.

3.3 The Presence of Unseen Tertiary Components

AI Crucis is composed of two early-type component stars that presumably contain a convective core and a radiative envelope. This suggests that the small-amplitude period oscillation cannot be explained by the magnetic activity cycle mechanism, which is usually proposed to explain the cyclic period changes of solar-type binary stars (e.g., Applegate 1992; Lanza et al. 1998). Therefore, a plausible explanation of the periodic change of the orbital period is the light-travel time effect via the presence of a tertiary component (e.g., Borkovits & Hegedüs 1996; Chambliss 1992). By considering that the third body is moving in a circular orbit, the projected radius of the orbit $a'_{12}\sin i'$ of the eclipsing pair rotating around the mass center of the triple system was computed with the equation,

$$a'_{12}\sin i' = A_3 \times c, \tag{7}$$

where A_3 is the amplitude of the $O-C$ oscillation and c is the speed of light. The results are $a'_{12}\sin i' = 0.33(\pm 0.09)$. Then, by using the parameters derived by Bell et al. (1987b), a computation with the following equation,

$$f(m) = \frac{4\pi^2}{GP_3^2} \times (a'_{12}\sin i')^3, \tag{8}$$

leads to an extremely small mass function of $f(m) = 0.000039\,M_\odot$. G and P_3 in Equation (8) are the gravitational constant and the periods of the $O-C$ oscillations. Finally, the values of the masses and the orbital radii of the third components for different values of i' were estimated by the use of the following equation,

$$f(m) = \frac{(M_3\sin i')^3}{(M_1+M_2+M_3)^2}. \tag{9}$$

The relations between the orbital inclinations and the masses of the third bodies are plotted in Figure 3. It is shown that the lowest mass of the tertiary companion is $0.2\,M_\odot$, and most probably it is a very cool stellar companion.

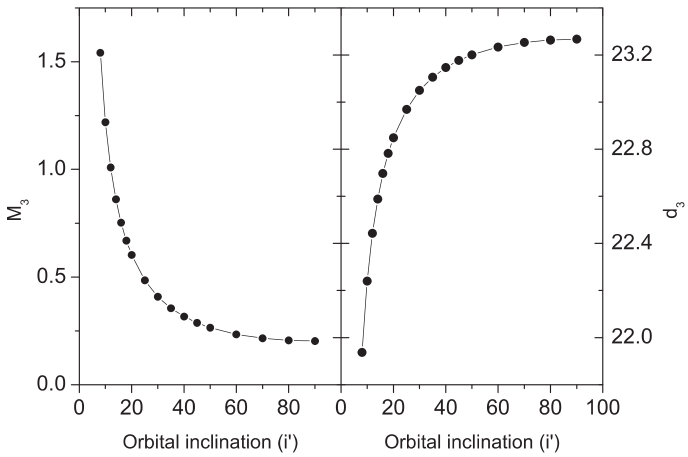

Fig. 3 Relations between the orbital inclinations i' and the mass and the radius of the tertiary companion in the short-period close binary AI Crucis.

4 DISCUSSION AND CONCLUSIONS

Based on the analysis of the $O-C$ diagram, it is found that the orbital period of AI Crucis is increasing at a rate of $dP/dt = +1.00(\pm 0.04) \times 10^{-7}$ d yr^{-1}. This is in good agreement with the semi-detached configuration with a lobe-filling secondary of the system, indicating that the binary has passed through a rapid phase of Case A mass transfer and is now in a slow phase of Case A mass transfer on the nuclear time-scale of the secondary. However, we discovered that a conservatively slow mass transfer is insufficient to cause the observed rate of period increase. The mass loss from the detached massive primary (Sp=B 1.5) via stellar wind should contribute to the period increase. The observed period increase is the result of a combination of mass transfer from the secondary to the primary and mass loss via stellar wind from the massive primary. The derived mass loss rate is $dM_1/dt = 2.72 \times 10^{-7}\,M_\odot\,\mathrm{yr}^{-1}$.

AI Crucis is a member of the open cluster NGC 4103 with an age of 2.5×10^7 yr (e.g., Bell et al. 1987b; Wesselink 1969). As discussed by Bell et al. (1987b), the model for AI Crucis before mass-ratio reversal may have involved a 9 $M_\odot$ primary and a 6.6 $M_\odot$ secondary with a period of about 1.3 days. After a time interval of 10^7 yr, the rapid phase of Case A mass transfer occurred which lasted on the order of 10^5 yr. These properties mean that AI Crucis has been in the slow phase of Case A mass exchange for 1.5×10^7 yr. With the rate of mass loss from the more massive component being $dM_1/dt = 2.72 \times 10^{-7}\,M_\odot\,\mathrm{yr}^{-1}$, the system should have lost a total mass of 4.1 $M_\odot$ during this evolutionary stage. Therefore, the evolution of the system should be greatly changed by the mass loss. The small-amplitude period oscillation can be explained by light-travel time effect via the presence of a cool stellar companion like those observed in other massive close binary stars, e.g., BH Cen, V701 Sco (Qian et al. 2006), V382 Cyg, and TU Mus (Qian et al. 2007). However, as for AI Crucis, more data are required to check this conclusion.

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