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HL Aurigae: A near-contact binary system

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Abstract. Photoelectric observations of HL Aur were carried out with the 60 cm reflector of Beijing Astronomical Observatory in 1990 and 1994, and the first photoelectric BV light curves were obtained along with a newly derived ephemeris. The period of the system appears to be constant over the past 65 years. Using the Wilson-Devinney program a photometric analysis of the B and V light curves is performed. It is evident that HL Aur is a near-contact binary with a mass ratio of $q = m_2/m_1 = 0.722 \pm 0.011$. The primary component of the system is essentially in contact with its Roche lobe, while the secondary is detached but nearly in contact with its lobe. It is found that the components of the system are slightly evolved and located near the terminal-age main sequence. The binary is consistent with the general evolutionary picture for near-contact systems.[1]

Key words: stars: HL Aur — binaries: eclipsing

1. Introduction

HL Aur was discovered to be a variable star by Hoffmeister (1949). Kippenhahn (1953) classified it as a β Lyr-type star with the primary and secondary eclipse depths of 1.10 mag and 0.35 mag respectively. He deduced the first ephemeris and an orbital period of $P = 0.6225058$ days. Kippenhahn (1955) also published 15 times of minimum and a complete photographic light curve. Almost at the same time, a total of 14 times of minimum were secured by Pfau (1955), and he also obtained an ephemeris similar to that given by Kippenhahn (1955).

Subsequent times of minimum have been published by many authors (Tsesevitch 1956; Quester 1978; Locher 1979; Fernandes 1983; Moscher & Kleikamp 1989, 1990), but most of them being visual or photographic observations except those by Fernandes which were photoelectric. After an observational information of HL Aur supplied by us (1994), Gray & Samec (1995) published photoelectric UBV light curves and four times of minimum. Götz & Wenzel (1961) gave its spectral type to be F4. In general, little attention was paid to this system in the past.

In our search of probable near-contact binary systems, the short period eclipsing binary HL Aur was put on the observational program. In this paper, we present our first photoelectric light curves of HL Aur as well as a photometric analysis.

2. Observations

In 1990 January and 1994 January-March, photoelectric observations were made with the 60 cm reflector and a single-channel photon-counting photometer at the Xinglong station of the Beijing Astronomical Observatory (BAO). Three primary and three secondary minima were observed in these two seasons. In 1994, a total of 129 observations in V and 122 in B were secured, covering well a full light curve.

The comparison and check stars were carefully chosen and a finding chart for them was published by Zhang et al. (1994). Table 1 presents the coordinates and UBV values of the comparison and check stars. All the observations were corrected for differential atmospheric extinction and transformed into the standard UBV system. In order to eliminate the probable influence caused by the colour difference between HL Aur and the comparison star used, secondary extinction coefficients were adopted in the data reduction. The probable errors for a single observation are estimated to be 0.008 mag in V and 0.010 in B, respectively.

Table 2 lists our new determinations of the times of minimum by the K-W method. The differential magnitudes between the variable and comparison stars are given in Tables 3a and b. The characteristics of the light curves of this system are given in Table 4.

3. Period

A total of 48 times of minimum are collected in Table 5. We assigned different weights: 1, 2, and 10, for visual, photographic and photoeletric observations, respectively.

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[1] Tables 3 and 5 are only available at the CDS via anonymous ftp 130.79.128.5 or via http://www.ed-phys.fr

Table 1. The coordinates and UBV values of the comparison and check stars

	α_{2000}	δ_{2000}	V	$B-V$	$U-B$
Comparison star	$06^{\rm h}17^{\rm m}55'$	$49°45'26''$	10.94 ± 0.03	1.65 ± 0.06	2.20 ± 0.08
Check star	06 17 24	49 36 48	10.97 ± 0.03	0.50 ± 0.01	0.07 ± 0.02

Table 2. New times of minima of HL Aur

JD(Hel.) 2400000+	colour	Min.	m.e.
47911.1722	V	II	0.0015
47911.1728	B	II	0.0013
47913.3470	V	I	0.0001
47913.3470	B	I	0.0002
47915.2162	V	I	0.0015
47915.2154	B	I	0.0007
49360.9873	V	II	0.0015
49362.2291	V	II	0.0006
49362.2274	B	II	0.0008
49363.1609	V	I	0.0005
49363.1616	B	I	0.0004

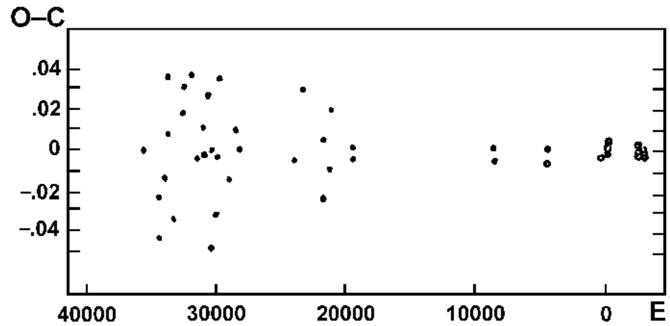

Fig. 1. The O − C diagram of the minimum times of HL Aur, the dots represent visual or photographic observations and the small circles represent photoelectric observations

A weight of 5 is given to the time of minimum derived from somewhat incomplete observations.

By the least squares method we obtain the following new linear ephemeris:

$$\text{JD(Hel).MinI} = 2447913.3462 + 0^{\rm d}\!.62250560 \times E. \quad (1)$$
$$\pm \quad 11 \qquad\qquad 8$$

From the photoelectric times of minimum a linear ephemeris is derived as follows:

$$\text{JD(Hel).MinI} = 2447913.3460 + 0^{\rm d}\!.62250577 \times E. \quad (2)$$
$$\pm \quad 6 \qquad\qquad 22$$

The O-C values of the times of minimum are calculated from Eq. (1) and plotted in Fig. 1. It was found that the period of HL Aur appears to be constant over the past 65 years even though the visual and photographic observations display large scatter in the O − C diagram.

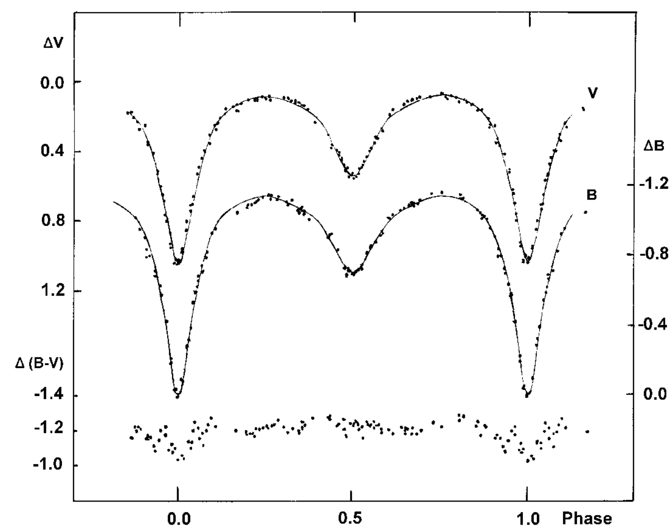

Fig. 2. BV light curves and the synthetic light curves based on the photometric solutions of HL Aur. The synthetic light curves are shown with solid lines

4. Photometric solutions

Based on the ephemeris (1), the observations of 1994 were combined into a single orbital cycle and the light curves of HL Aur in both V and B are shown in Fig. 2. The light curve of the system is essentially symmetric, although the average light level seems to be slightly brighter at phase 0.75 than at 0.25. The primary-ecilpse depth is 0.98 in V and 1.06 in B, the secondary-eclipse depth is 0.47 in V and 0.45 in B.

In the following photometric analysis, the observations are further combined into 59 normal points in V and 51 points in B, respectively. The new, 1992 version of the Wilson-Devinney computing code (Wilson & Devinney 1971; Wilson 1990) is employed to perform the photometric solution of the B and V light curves simultaneously. In the Roche model, from the calibration of the statistical relations between stellar spectral/luminosity classes and effective temperature (de Jager & Nieuwenhuijzen 1987) the temperature of component 1 was fixed at $T_1 = 6792$ K, corresponding to spectral type F4 (Götz & Wenzel 1961). The gravity-darkening coefficients are adopted to be $g_1 = g_2 = 0.32$ (Lucy 1967), and the bolometric albedo

Table 4. The light curve characteristics of HL Aur

	MaxI($\phi = 0.25$)	MaxII($\phi = 0.75$)	ΔMinI	ΔMinII	MaxI − MaxII
V	11.02	11.00	0.98	0.47	0.02
B			1.06	0.45	0.02
$B-V$	0.42	0.42			

to be $A_1 = A_2 = 0.50$ (Rucinski 1969) in accordance with the assumed stellar convective envelope. From the tables in Al-Naimiy (1978) the limb-darkening coefficients are taken to be $x_1 = 0.60$, $x_2 = 0.63$ for the V band and $x_1 = 0.73$, $x_2 = 0.80$ for the B band. The adjustable parameters are: the inclination i, the polar temperature of the secondary component T_2, the nondimensional surface potentials Ω_1 and Ω_2, the luminosity of the primary (component 1) star L_1 and the mass ratio $q = m_2/m_1$. Unfortunately, no photometric or spectroscopic information on the mass ratio q is available. In search of an approximate mass ratio, we carried out test solution by assuming mass ratio $q_i = m_2/m_1 = 0.30$, 0.50, 0.60, 0.65, 0.70, 0.75, 0.80, 0.85, 0.90, 1.05, 1.45, 2.0, and 2.5.

The test solution for each assumed q_i value started from the detached model (mode 2), but after a few runs in the iteration, the system converged into a semi-detached configuration with component 1 in contact with the inner critical equipotential surface of the binary system. Then computing mode 4 was used instead of mode 2 until a final convergent solution was reached. Figure 3 represents the sum of the weighted residuals, Σ_i for each assumed mass ratio q_i. It is found that the mass ratio of the system is most likely somewhere around $q = 0.75$, at which the test solution gives the smallest residuals in the $\Sigma - q$ diagram. With this probable mass ratio we started again and let it be adjusted freely along with other adjustable parameters. In the last few runs the parameters g_1, g_2 and x_1 in both V and B bands are also made adjustable. However, A_1, A_2 and x_2 seem to be not adjustable and no convergent values could be found for them. The final test converged into two slightly different solutions with nearly the same parameters and the same Σ value at $q = 0.722$ for HL Aur, depending on the last mode (2 or 4) of the W-D program we used. Solution 1 indicates that the system is a detached binary with Ω_1 very close to $\Omega_{\rm inn}$ while solution 2 tells us that the system has a semi-detached configuration with the primary in contact with its Roche lobe. The two solutions are set out in Table 6. The theoretical light curves based on solution 2 is shown in Fig. 2 and the configuration of the system is given in Fig. 4. Almost the same theoretical light curve and configuration as those in Figs. 2 and 4 could be found for HL Aur based on solution 1. Figure 2 displays a good, full-orbit fitting between the theoretical and observed light curves.

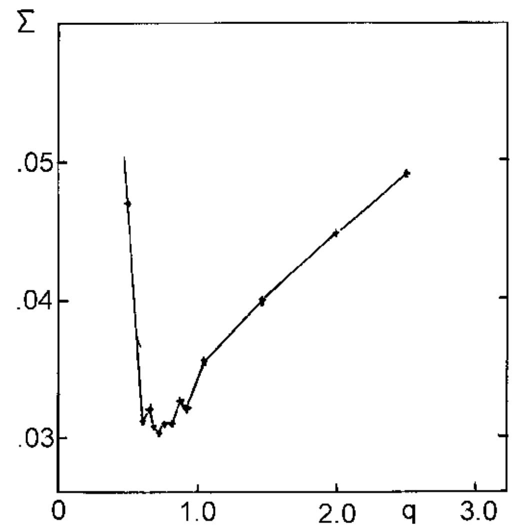

Fig. 3. The behaviour of Σ as a function of the mass ratio q

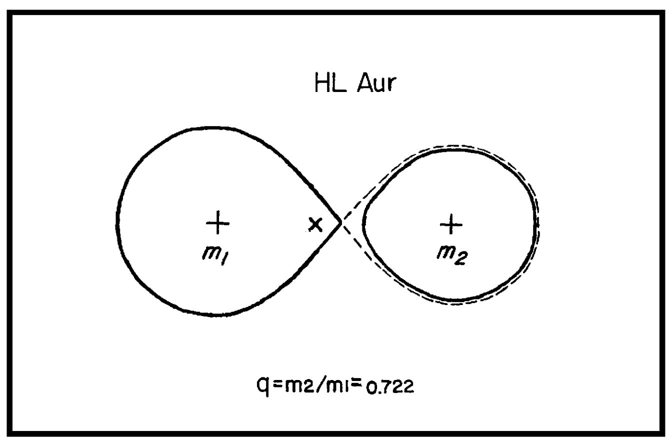

Fig. 4. The configuration of HL Aur

5. Discussion

(1) In our photometric analysis, HL Aur is found to be a near-contact binary system. The primary component is in contact or almost in contact with its Roche lobe and the secondary is inside but very close to its Roche lobe. The values of the filling factor of Roche lobe $r_1/r_{1,\rm inn}$ and $r_2/r_{2,\rm inn}$ are derived to be 0.9970 and 0.9442 from solution 1, and 1.00 and 0.9483 from solution 2, respectively.

Table 6. Photometric solutions of HL Aur

Mode	Detached		Semi-detached	
	5500 Å	4500 Å	5500 Å	4500 Å
$L_1/(L_1+L_2)$	0.766 ± 0.011	0.793 ± 0.010	0.766 ± 0.011	0.793 ± 0.012
x_1	0.555 ± 0.060	0.782 ± 0.047	0.555 ± 0.067	0.782 ± 0.063
x_2	0.630*	0.800*	0.630*	0.800*
i	$84.^{\circ}88 \pm 0.07$		$84.^{\circ}75 \pm 0.24$	
$q = m_2/m_1$	0.722 ± 0.008		0.722 ± 0.011	
g_1	0.310 ± 0.065		0.310 ± 0.065	
g_2	0.293 ± 0.055		0.293 ± 0.047	
A_1	0.50*		0.50*	
A_2	0.50*		0.50*	
	Comp.1	Comp.2	Comp.1	Comp.2
T	$6792K$*	$5683 \pm 0015K$	$6792K$*	$5678 \pm 0016K$
Ω	3.2883 ± 0.0084	3.3993 ± 0.0107	3.2811*	3.3900 ± 0.0150
$r_{\rm pole}$	0.3825 ± 0.0015	0.3129 ± 0.0020	0.3835	0.3141 ± 0.0012
$r_{\rm point}$	0.5113 ± 0.0030	0.3785 ± 0.0025	0.5335	0.3819 ± 0.0030
$r_{\rm side}$	0.4034 ± 0.0019	0.3253 ± 0.0024	0.4046	0.3267 ± 0.0014
$r_{\rm back}$	0.4326 ± 0.0025	0.3495 ± 0.0032	0.4343	0.3514 ± 0.0019
$\Omega_{\rm inn}$	3.2811*		3.2811*	
Σ	0.0297		0.0300	

* assumed.

(2) The surface temperature difference between the two components is computed to be about $\Delta T = 1110$ K and the temperature of the secondary is derived as $T_2 = 5680$ K, corresponding to a spectral type of G3–4 (de Jager & Nieuwenhuijzen 1987).

(3) Knowing the period, relative radii,and mass ratio we obtain the mean density of the two components as $\overline{\rho}_1 = 0.43$ g cm^{-3} and $\overline{\rho}_2 = 0.59$ g cm^{-3} (see Table 7) via the formula of Mochnacki (1981). For zero-age main sequence stars with spectral types F4 and G4, the average density should be about 1.1 and 1.6, and for terminal-age main sequence stars with the same spectral types it should be 0.45 and 0.65, respectively. Therefore, the two components are approximately the same value as the terminal-age main sequence stars of the same spectral types, respectively. It means that the two components are slightly evolved and located near the terminal-age main sequence.

(4) According to the statistical study by Zhai et al. (1989) the ratio of mean density for the two components is close to unity in near-contact binary systems, this is in marked contrast with the classical Algol systems for which the density ratio of the two components are usually near a value of ~ 0.30. The above-obtained density ratio between the two components of HL Aur is consistent with the general evolutionary picture for near-contact binary systems (Zhai et al. 1989).

(5) From our photometry the luminosity of the primary component makes some 4/5 of the total output of the system. Differential magnitude measurements between the comparison and standard stars give a colour index $B-V$ of HL Aur as 0.42 during the maximum. If we consider that the coordinates of this system are close to the Galactic equator, and the de-reddened $B-V$ value is smaller than 0.42, then, from the density -colour diagram for near-contact semi-detached binaries with spectral types A–F (Zhai et al. 1989; Mochnacki 1981) we see that the primary component of this system is most likely located near the terminal age main sequence.

From the criteria described above we may conclude that the system is a near-contact binary with the primary component just filling or close to its Roche lobe and the secondary near its Roche lobe, but from the O-C diagram of the times of minimum rapid mass transfer does not appear to have occurred in this system. According to the criteria given by Shaw (1990, 1994) the secondary component could be more evolved than the primary, but in our view the components of HL Aur seem to be in nearly the same evolutionary stage. Because the mass transfer has just started , the mass transferred from the primary to the secondary component is apparently not sufficient to speed up the evolutionary process of the secdonary, which appears still to be located near the terminal-age main sequence.

The criterion needs further study and test by future photometric and spectroscopic observations.

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Table 7. The mean density of the component stars and relative parameters of HL Aur

Code	$r_1/r_{\rm inn}$	$r_2/r_{\rm inn}$	$\overline{\rho}_1$(g cm^{-3})	$\overline{\rho}_2$(g cm^{-3})	$\overline{\rho}_2/\overline{\rho}_1$	$\overline{\rho}_1/\overline{\rho}_2$
Model 2	0.9970	0.9442	0.431	0.593	1.376	0.727
Model 4	1.0000	0.9483	0.427	0.585	1.370	0.730

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