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PHOTOMETRIC ANALYSIS OF A NEAR-CONTACT BINARY, HL AURIGAE: EVIDENCE FOR A THIRD BODY

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ABSTRACT

A complete analysis of U, B, V photometric light curves of HL Aurigae is presented. Twelve new precision epochs of minimum light were determined. A period study spanning 45 years and utilizing more than 135 times of minimum light indicates that the period has remained essentially constant. The photometry has been standardized and our analysis includes corrections for interstellar reddening. We find that HL Aurigae is in a semidetached configuration with the primary component having a fillout of 95%. The primary and secondary components have spectral types of F1 V and G9 V, respectively, and a mass ratio of $\sim$0.8. The photometric solution gives a surprisingly large third light amounting to 18% in V, and 14% in U and B. Our calculations suggest the presence of an unresolved G2 V component separated by less than 340 AU from the close pair. Thus, we tentatively conclude that HL Aur is in an hierarchical triple star system, i.e., a close pair with a well-separated component. © *1997 American Astronomical Society.* [S0004-6256(97)02306-6]

1. INTRODUCTION

The eclipsing binary, HL Aurigae [S4727 Aur, GSC 3383 696 $\alpha(2000)=6^h19^m013.0^s$, $\delta(2000)=+49°42'07''$, galactic latitude: 15.49°], was discovered by Hoffmeister (1949) while conducting a massive photographic survey of Sonneberg Zone +40° plates. He listed no period, but classified it as an Algol-type (EA) variable with an amplitude of 1.0 mag. From 96 plate estimates, Kippenhahn (1953) classified it as a β Lyræ (EB) type variable. His light curves show the primary and secondary eclipse depths to be 1.1 and 0.35 mag, respectively. He calculated the following ephemeris:

$$\text{JD Hel Min. I}=2426365.309+0.6225058d\cdot E. \quad (1)$$

Kippenhahn (1955) later published fifteen times of minimum light along with a photographic light curve. That same year, Pfau (1995a, 1995b) published fourteen new times of minimum light, a finder chart, and a photographic light curve. HL Aur was then generally neglected until 1975, when it was added to the roster of stars being observed by both BBSAG and BAV teams (BBSAG #21 #103, BAV Mitt. #29, 36, 52, 56). Zhang *et al.* (1994) published sparse B, V photoelectric light curves formed from the 1990 and 1994 observing seasons and minima from six eclipses along with the following ephemeris:

$$\text{JD Hel Min. I}=2447913.3470+0.62250590d\cdot E. \quad (2)$$

They conclude the period has been constant for forty years. No light curve solutions appear in the literature.

2. OBSERVATIONS AND REDUCTIONS

HL Aur was observed as part of our ongoing study of observationally neglected near-contact eclipsing binaries. The observations were made on 1994 December 9–15 at Lowell Observatory, Flagstaff, Arizona. The 0.79 m Lowell reflector was used in conjunction with a thermoelectrically cooled S-13 type PMT and standard U, B, V filters. Integration times were varied to ensure 1% photometry. Further observations as referred to in Sec. 6 were performed by D. Caton using the Appalachian State 0.8 m reflector in conjunction with a thermoelectrically cooled CCD camera housing a 1k×1k Tektronix chip. About 50 unfiltered images were taken. The comparison [GSC 3383 1332: $\alpha(2000)=6^h19^m20.7^s$, $\delta(2000)=+49°21'36''$] and check [GSC 3383 1358: $\alpha(2000)=6^h19^m3.9^s$, $\delta(2000)=+49°24'35''$] were chosen from four nearby field stars. A finding chart made from the Digitized Sky Survey (DSS) is shown as Fig. 1, in which the variable, comparison, and check stars are designated V, C, and K, respectively. Our comparison star was a good color match to the variable with $\Delta(B-V)$ averaging 0.05 mag. Check minus comparison star measurements showed that the comparison star's light output remained constant during the observing interval. A total of 2655 observations were made (883 in the U filter, 886 in B, and 886 in

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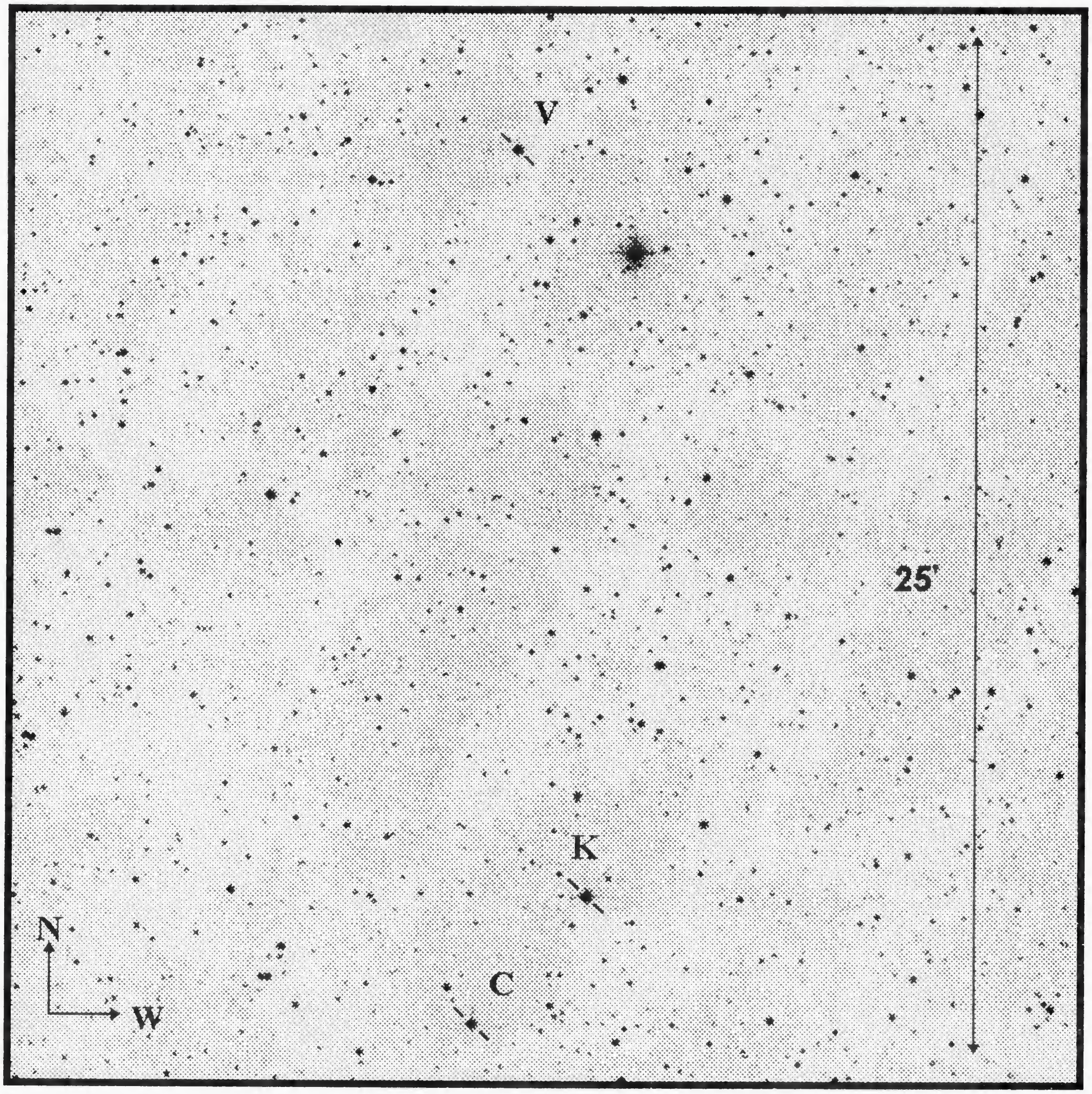

FIG. 1. Finding chart (modified from a Digitized Sky Survey image) of HL Auriga (V), the Comparison star (C), and the Check star (K).

V). Our individual standardized observations will be included in the archive of photometric data at the Centre de Donnees astronomiques de Strasbourg (CDS). The observations were transformed to the standard system in the usual manner (Hardie 1962). Extinction coefficients were determined from nightly measurements of the comparison star. Transformation coefficients were calculated from seven to eight Landolt (1983) *U*, *B*, *V* photometric standard stars which were measured each night of the observing interval. When the coefficients were applied to the standard stars, their standard magnitudes were reproduced with probable errors of ± 3 to ± 13 mmag. Mean standard magnitudes of the comparison and check stars along with those for the variable at quadratures are given in Table 1, with values accompanied by probable errors in the last decimal place given in parentheses. Interstellar reddening estimates were made using a color–color plot for the comparison star. We found $E(B-V)=0.14$ mag which corresponds to an $A_v=0.44$ mag. From this, we determined a distance ~340(40) pc for the variable. The comparison and check stars showed reddening-corrected spectral types of F1 V and F6 V, respectively (Popper 1980; Bessell 1976, 1979; Schmidt-Kaler 1982).

3. PERIOD ANALYSIS

We determined four epochs of minimum light made during one secondary and three primary eclipses. The Hertzs-

TABLE 1. Standard magnitudes of HL Aur, Comparison, and Check stars.

Star	V	B-V	U-B	Phase
Comparison	10.780	0.460	0.117	-
Check	10.316	0.593	0.109	-
Variable	11.686	0.617	0.051	0.00
	10.799	0.517	0.035	0.25
	11.247	0.469	0.042	0.50
	10.805	0.518	0.051	0.75

TABLE 2. Unpublished epochs of minimum light, HL Aur.

JD (Hel.) 2400000+	Minimum	Cycles	(O-C)	Observer
45660.8163	II	-6483.5	0.0040	JS
45664.8624	I	-6477.0	0.0039	JS
45684.7763	I	-6445.0	-0.0024	JS
45686.6488	I	-6442.0	0.0026	JS
45699.7206	I	-6421.0	0.0017	JS
45729.6000	I	-6373.0	0.0009	JS
45731.7790	II	-6369.5	0.0011	JS
49695.8909(3)	II	-1.5	-0.0027	PO
49696.8232(1)	I	0.0	-0.0041	PO
49698.6900(7)	I	3.0	-0.0048	PO
49701.8021(5)	I	8.0	-0.0053	PO
50110.7961(5)	I	665.0	0.0026	DC

Notes. -- SH - J. Shaw (1996), PO - Present Observations, DC - D. Caton (1996)

prung (1928) method was used to determine the first two primary minima while the bisection of chords technique (Henden & Kaitchuck 1990) was used to determine the last primary and one secondary epoch of minimum light. These are listed in Table 2 as mean times from the three pass bands. More than 135 timings of minimum light, spanning a 45 years, were collected from sources referred to in Sec. 1. This gives a rather continuous coverage to the observational record, except for an 18 year gap (1957–1975). Included in Table 2 are seven previously unpublished epochs of minimum light, provided to us by Shaw (1996). They are means from 5 pass bands taken with a dry ice cooled photoelectric photometer in conjunction with the University of Georgia 0.6 m reflector. A further epoch of minimum light was obtained by Caton (1996).

All available epochs of minima were introduced into a weighted least squares calculation. From this, we obtained the following improved linear ephemeris:

$$\text{JD Hel Min.} = 2449696.8273(20) + 0.6225056(2)d \cdot E. \tag{3}$$

Photographic and visual minima were given weights of 0.05 and photoelectric minima were weighted 1.0. The residuals are given as (O−C) in Table 2 and are shown in Fig. 2. The later epochs exhibit much smaller residuals and suggest interesting oscillations, each about 10 years in duration. This might be due to solar-like activity cycles. No other period changes are discernible, except that there is a slight trend in the O−C's as we look toward earlier epochs. The quadratic ephemeris is

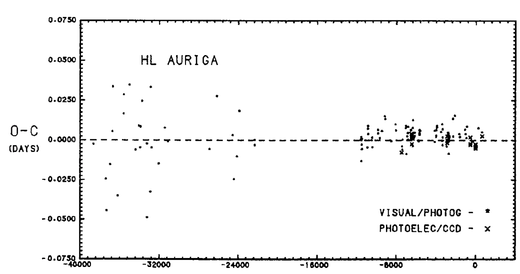

FIG. 2. Period behavior of HL Aur as determined from our improved linear ephemeris [Eq. (3)].

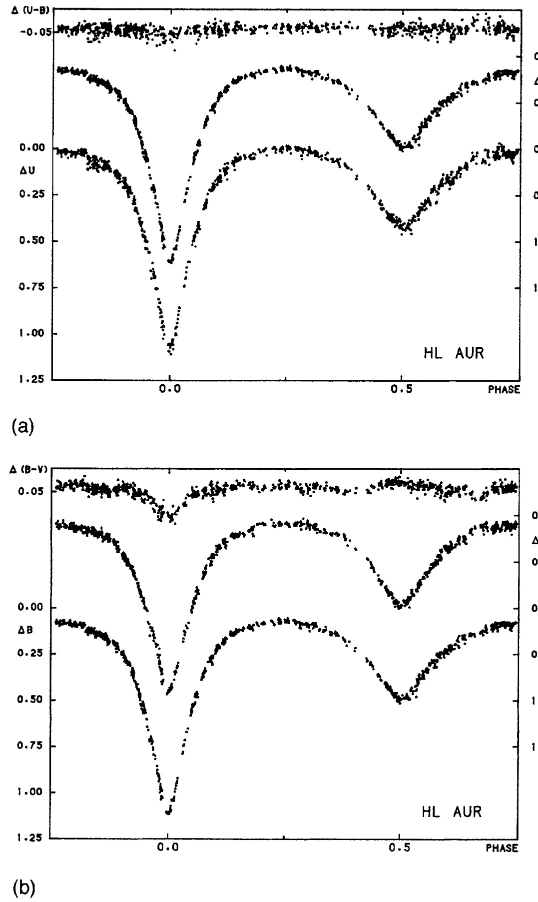

FIG. 3. U, B, and V light curves of HL Aur as defined by the individual observations.

$$\text{JD Hel Min.} = 2449696.8263(8) + 0.6225052(2)d \cdot E - 3(1) \times 10^{-11} \cdot E^2. \tag{4}$$

The quadratic term in Eq. (4) [which, if taken at face value, would imply a $dP/dt = -3(1) \times 10^{-8}$ d/y] has a magnitude of only $\sim 2\sigma$ and is not highly significant. Both ephemerides give nearly the same present period and epoch. We conclude, as did Zhang *et al.* (1994), that the period has essentially remained constant over the 45-year interval of available observations. However, high scatter in the early timings and the gap in the observations seem to preclude a conclusive determination of the system's period behavior.

4. LIGHT CURVES

The U, B, V light curves of HL Aur as defined by the individual observations are plotted in Fig. 3 as Δmag versus phase. The probable error for a single observation in U, B, and V is ± 10, ± 6, and ± 7 mmag, respectively. The light curves reveal that HL Aur is in a state of near or shallow contact with nearly continuous changes in the light in the out-of-eclipse portions of the light curve. This indicates severe gravitational and rotational distortions in the stars. There may be a slight O'Connell effect with the maximum at phase 0.25 (Max I) being higher than that at phase 0.75. The effect in U is at the 2% level, while it is at the 1% level (on

TABLE 3. Light-curve characteristics of HL Aur.

Standard ΔMag at Minima and Maxima:				
Phase	**0.00 (Min I)**	**0.25 (Max I)**	**0.50 (Min II)**	**0.75 (Max II)**
ΔU	1.056	-0.001	0.433	0.017
ΔB	1.110	0.069	0.496	0.076
ΔV	0.935	0.048	0.496	0.054
Δ(U-B)	-0.054	-0.070	-0.063	-0.054
Δ(B-V)	0.175	0.021	0.000	0.022

Comparison of Minima:	I	II	Diff.
Depth (U) from Max. at Phase 0.25:	1.057	0.434	0.623
Depth (U) from Max. at Phase 0.75:	1.039	0.416	0.623
Average Depth (U):	1.048	0.425	0.623
Depth (B) from Max. at Phase 0.25:	1.041	0.427	0.614
Depth (B) from Max. at Phase 0.75:	1.034	0.420	0.614
Average Depth (B):	1.038	0.424	0.614
Depth (V) from Max. at Phase 0.25:	0.887	0.448	0.439
Depth (V) from Max. at Phase 0.75:	0.881	0.442	0.439
Average Depth (V):	0.884	0.445	0.439

Comparison Between Maxima:					
Filter	U	B	V	U-B	B-V
Difference (Max II - Max I)	0.018	0.007	0.006	0.011	0.001
Average Of Maxima	0.008	0.072	0.051	-0.064	0.022

the same order as the photometric precision) in B and V. Although mass accretion may be implied, we must remember that this type of asymmetry is often seen in contact binaries and is due to star spot activity. The secondary minima is asymmetric, due to this distortion.

Specific characteristics of the ΔU, ΔB, and ΔV light curves appear in Table 3. Magnitudes displayed in this table were determined from means about the phase in question.

5. PHOTOMETRIC SOLUTIONS

Synthetic light curve solutions were calculated with the Wilson–Devinney (WD) Code (Wilson & Devinney 1971; Wilson 1990, 1994). The U, B, V light curves were solved simultaneously in order to better fix temperature-related phenomena such as surface temperatures, light values, and spots. The curves were weighted in accordance with the standard

TABLE 4. Synthetic light-curve parameters for HL Aur.

Parameter	**Model I (Unspotted)**	**Model II (3^{rd} Light)**	**Model III (3^{rd} Light / Spotted)**
λ_U (nm)	360	360	360
λ_B (nm)	440	440	440
λ_V (nm)	550	550	550
x_{1U} , x_{2U}	0.522 , 0.724	0.522 , 0.724	0.522 , 0.724
x_{1B} , x_{2B}	0.642 , 0.865	0.642 , 0.865	0.642 , 0.865
x_{1V} , x_{2V}	0.652 , 0.997	0.652 , 0.997	0.652 , 0.997
g_1 , g_2	1.00 , 0.32	1.00 , 0.32	1.00 , 0.32
A_1 , A_2	1.00 , 0.50	1.00 , 0.50	1.00 , 0.50
$xbol_1$, $xbol_2$	0.641 , 0.643	0.641 , 0.643	0.641 , 0.643
$ybol_1$, $ybol_2$	0.242 , 0.161	0.242 , 0.161	0.242 , 0.161
i (°)	80.6(1)	85.7(1)	85.7(2)
T_1 , T_2 (K)	6562 , 5363(4)	6562 , 5360(3)	6562 , 5351(1)
Ω_1 , Ω_2	3.679(9) , 3.331	3.682(13) , 3.490	3.673(3) , 3.482
q (m_2 / m_1)	0.750(6)	0.843(8)	0.838(2)
$L_1 / (L_1 + L_2)_U$	0.791(4)	0.795(5)	0.798(4)
$L_1 / (L_1 + L_2)_B$	0.748(5)	0.752(5)	0.755(5)
$L_1 / (L_1 + L_2)_V$	0.705(4)	0.709(6)	0.712(5)
ϕ	0.0001(1)	0.9999(1)	0.0001(1)
$l_{3(U)}$	0.00	18.0(3)	18.04(3)
$l_{3(B)}$	0.00	14.1(3)	14.18(2)
$l_{3(V)}$	0.00	14.1(4)	14.14(3)
r_1 , r_2 (pole)	0.3369(8) , 0.3323(6)	0.3466(7) , 0.3419(8)	0.3471(7) , 0.3415(7)
r_1 , r_2 (side)	0.3491(9) , 0.3480(8)	0.3612(8) , 0.3585(9)	0.3617(8) , 0.3579(7)
r_1 , r_2 (back)	0.3650(7) , 0.3797(9)	0.3824(9) , 0.3899(8)	0.3830(9) , 0.3894(7)
f_1, f_2	91% , 100%	95% , 100%	95% , 100%
Spot Location	-	-	Primary
Spot Colatitude	-	-	90°(23)
Spot Longitude	-	-	268° (2)
Spot Radius	-	-	28°(12)
Spot Temp. Factor	-	-	1.016(11)
Spot Temperature (K)	-	-	6667(72)
Σwr^2	0.1635086	0.1183353	0.1062678

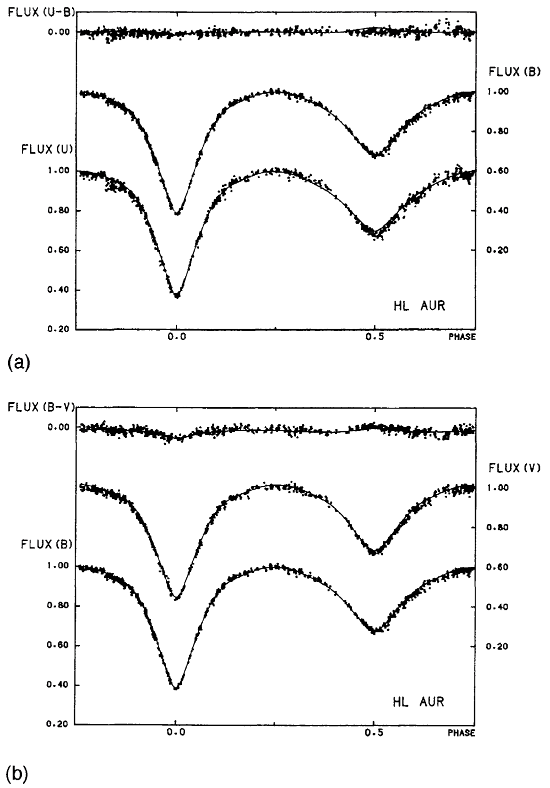

FIG. 4. U, B, and V flux-scale light curves, normalized to unity at phase 0.75 (Max II) with calculated synthetic light curves overlaid for Model II.

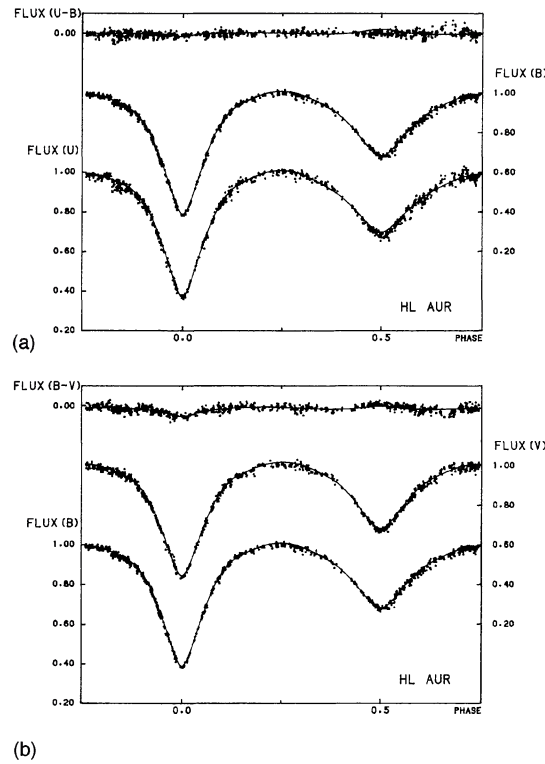

FIG. 5. U, B, and V flux-scale light curves, normalized to unity at phase 0.75 (Max II) with calculated synthetic light curves overlaid for Mode III.

deviation of a single observation. The temperature of the primary component was fixed in accordance with the photometry, and later adjusted with clues from the light curve solutions. Linear and bolometric limb darkening coefficients (x_1, x_2, $x_{\rm bol}$, and $y_{\rm bol}$) were determined from tables by Van Hamme (1993). Standard values of bolometric albedos (Rucinski 1969, 1973) and gravity darkening coefficients (Lucy 1967) for both radiative (primary) and convective (secondary) type stars were used.

We began modeling this system by assuming no complications such as spots or third light. Starting parameters were obtained with the aid of Binary Maker 2.0 (Bradstreet 1992). Our first runs were done in detached mode, which resulted in the secondary filling its Roche lobe and the primary component under filling. Thus, we used mode 5 of the WD code to model this system in a semidetached configuration. Because the eclipses are partial, modeling of the light curves resulted in a family of solutions. We therefore performed a parameter search, focused on the mass ratio ($q=\mathscr{M}_2/\mathscr{M}_1$). The best solution is listed as Model I in Table 4. Model I did not give a good fit to either the shape of the primary maximum or the depth of the primary eclipse. Before including a spot in our calculations, we made the usual test for third light. Interestingly, significant third-light contributions were found (18% in V and 14% in U and B). This will be discussed further in the next section. This solution is given as Model II in Table 4 and is shown graphically in Fig. 4. Since our third-light results were quite reasonable, we proceeded to model the asymmetry in Max I by a spot. This solution, which is an improvement over Model II in terms of goodness of fit, is given as Model III in Table 4 and is shown graphically in Fig. 5. Dark (cool) spot solutions were also attempted but were found to converge with residuals much worse (200%–300%) than those of Model 1.

6. THE NATURE OF THE THIRD LIGHT

The de-reddening of the third light yielded three possible solutions [intersections on the $(B-V)$–$(U-B)$ diagram] corresponding to a $B-V$ of $+0.62$, $+0.20$, and -0.20 mag. These are consistent with G2 V, A7 V, or B3 V spectral types, respectively. From our photometry and light curve solutions, we determined the V magnitude of the third light to be 12.6. This is concordant with the G2 V star at the same distance as the binary. If we assume typical temperatures (Popper 1980) and absolute magnitudes (Allen 1973), the distance to the A and B-type stars would be ~ 800 and ~ 1500 pc, respectively. In order to further examine these possibilities, CCD images were taken by Caton (1996). No stars were observed to approximately 17 mag within $1'$ of HL Aur. Thus, the third body was not resolved. From the size of our seeing disks, we estimate that the star must be within $1''$ of the variable. Consequently, a field star would have to lie in a cone of volume 0.003, 0.013, or 0.2 pc^3 (for a G, A, or B star, respectively). The *a priori* probability of a chance alignment is $<2\times 10^{-5}$. By contrast, the *a priori* probability that the HI Aur system contains a third member is much higher: ~30% of all systems with at least two components contain three or more stars (Orlov & Titov 1992).

To stay within 1″ of the binary, the G2 V star could be separated by up to ~340 AU and have an orbital period in excess of 1000 years. An orbital period of a few hundred years would be consistent with our O−C study (which covers only 45 years). Therefore, we conclude, tentatively, that HL Aur is a triple-star system, but more work is needed to confirm this result.

7. CONCLUSION

Our analysis indicates that HL Aur consists of F1 V and G9 V components in a near contact configuration with a possible third star of spectral type ~G2 V The G9 V component is filling its Roche lobe while the hotter component has a 95% fill-out. A large, 28° radius, superluminous region or bright spot was modeled on the primary component with a mean temperature difference of only 100 K. This probably arises from magnetic activity (i.e., a plage).

More than a dozen studies of near-contact binaries have appeared in the literature over the past decade. Some have addressed particular systems while others have explored their over all evolutionary status. In particular, HL Aur is listed in Shaw's (1994) study of near-contact binaries, but it is not given a sub classification. First, we find that HL Aur may not meet Shaw's $r/a<0.9$ ''near contact'' criteria for the sum of the components radii, since the point radii are 0.409(1) for the primary component and 0.482(21) for the secondary component (for Model III). Second, the binary is closest the V1010 Oph classification with a slightly oversized secondary, and Max I>Max II, with its primary component near filling (95%) its Roche Lobe. However, the asymmetry is not a result of mass accretion onto the secondary from a Roche Lobe filling primary, but rather star spot activity. This system is some what unique in that the components are rather similar in spectral types, straddling closely the Sun's spectral classification. The high rotational velocities greatly increase the stellar dynamo effect so components exhibit greatly enhanced and rapidly evolving solar-like activity. Thus, HL Aur may represent a new interesting group, solar type contact and near contact binaries, which should be studied closely as solar laboratories.

Spectroscopic observations are needed to better understand this interesting system. Radial velocity curves would not only give a definitive mass ratio for the binary but allow the determination of absolute masses for the components. High-resolution interferometric observations are suggested to confirm the existance of the unresolved tertiary component. Finally, it is clear that continued photometric monitoring of solar-like activity is needed.

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