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Photometric elements, absolute dimensions and evolutionary status of the eclipsing binary HU Tauri (HR 1471)*

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Abstract. The photometric elements of HU Tauri are derived from an analysis of its blue and visual light curves using the Wilson & Devinney (1971) light curve synthesis method. The photometric elements suggest that HU Tauri is a semidetached system and the primary minimum in its light curve is due to an occultation eclipse. Combining the photometric elements and spectroscopic orbital elements the absolute dimensions of the system are derived. The masses and radii of the B8 V primary and F8–G2 III–IV type secondary are found to be 4.68 $M_\odot$, 2.9 $R_\odot$ and 1.26 $M_\odot$, 3.34 $R_\odot$ respectively. The cool and less massive secondary has filled its Roche lobe and it is over luminous for its mass.

Key words: stars: binaries: close – stars: binaries: spectroscopic – stars: evolution of stars: individual: HU Tau (HR 1471) – stars: fundamental parameters

1. Introduction

The light variability of HU Tauri (HR 1471 HD 29365 = BV 312, V = 5.92, Sp.: B8V) was discovered by Strohmeier (1960). Strohmeier & Knigge (1960) found it to be an eclipsing binary with an orbital period of 2.056 days. Mammano & Margoni (1967) found the system to be a single lined spectroscopic binary. Parthasarathy (1979) detected the secondary component and derived its radial velocities. He found the mass ratio to be 0.269. Parthasarathy & Sarma (1980) obtained the blue and visual light curves and derived six epochs of minimum light. From an analysis of all the then available photoelectric times of minimum light they derived a new ephemeris: HJD 2441275.3166 + $2\overset{\mathrm{d}}{.}0563107$E. Parthasarathy (1979) analysed these light curves and determined the photometric elements of HU Tauri using the Russell & Merrill (1952) method. He has concluded that the primary minimum is an occultation eclipse, and HU Tauri is a semidetached system with the cool component filling its Roche lobe. Later Giuricin & Mardirossian (1981) analysed the B and V light curves of HU Tauri obtained by Parthasarathy & Sarma (1980). They used Wood's (1972) light curve synthesis model which treats the stars as triaxial ellipsoids.

Dumitrescu & Dinescu (1980) also obtained B and V light curves and analysed them using the method of Russell & Merrill (1952). They note that they find no special problems in the computation of the geometric and photometric elements. Ito (1988) also obtained B and V light curves of HU Tau and analyzed them with the Kitamura's (1965) incomplete Fourier method. More recently Dumitrescu & Suran (1993) analysed the light curves of HU Tau using the Wood's (1972) model. The photometric and geometric elements of HU Tau derived by Parthasarathy (1979), Dumitrescu & Dinescu (1980), Ito (1988) and Dumitrescu & Suran (1993) are in reasonable agreement with one another (Table 2) and they, all find that primary minimum is a partial occultation eclipse, and the orbital inclination $i \approx 78\overset{\circ}{.}$ However, Giuricin & Mardirossian (1981) find the orbital inclination $i = 90^\circ$ and the primary mininimum to be an annular transit. In order to resolve this uncertainty concerning the elements and the nature of the eclipses we have analysed the B and V light curves of HU Tau (Parthasarathy & Sarma 1980) using the synthetic light curve method of Wilson & Devinney (1971). The photometric elements thus obtained are combined with the spectroscopic orbital elements determined by Parthasarathy (1979) to derive the absolute dimensions. Preliminary results were reported earlier by Parthasarathy et al. (1993).

In this paper we give the results of the above mentioned analysis and also discuss the evolutionary stage of the components of HU Tau.

2. Analysis of the light curves

The photometric observations of HU Tauri (Parthasarathy & Sarma 1980) were grouped into 96 normal points in yellow (Table 1a – Table 1 is only available in electronic form) and

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* Tables 1a and 1b are aviable electronically at the CDS (via ftp 130.79.128.5)

Table 2. Earlier photometric solutions of HU Tau

Parameter	Parthasarathy (1979)[a]	Dumitrescu and Dinescu (1980)[a]	Giuricin and Mardirossian (1981)[b]	Ito (1988)[c]	Dumitrescu and Suran (1993)[b]
Primary minimum	Oc	Oc	Tr	Oc	Oc
T_h (K)	–	–	12 000	–	12 000
T_c (K)	–	–	4820	–	6433
i	77°.1	78°.4	89°.3	77°	78°.2
r_h	0.221	0.171	0.283	0.18	0.207
r_c	0.284	0.214	0.198	0.28	0.296
L_h	$V = 0.880$	0.802	0.972	–	0.819
	$B = 0.891$	0.831	0.990	–	0.871

[a] Russell–Merrill method, [b] Wood's WINK (computer model), [c] Kitamura's incomplete Fourier method.

Table 3. Elements of HU Tau derived using the Wilson & Devinney (1971) method

Element	Combined B, V solution keeping all parameters as adjustable	Combined B, V solution keeping $T_{e,h}$ and q fixed
$T_{e,h}$ (K)	13 600±90	11 400[a]
$T_{e,c}$ (K)	5740±16	5340±20
i^0	77.99±0.06	78.58±0.06
q	0.282±0.002	0.269[a]
r_h Pole	0.2157±0.0013	0.2340±0.0013
Point	0.2182±0.0014	0.2375±0.0014
Side	0.2171±0.0013	0.2359±0.0013
Back	0.2179±0.0014	0.2370±0.0014
r_c Pole	0.2567±0.0013	0.2534±0.0013
Point	0.3732±0.0014	0.3689±0.0014
Side	0.2672±0.0013	0.2638±0.0013
Back	0.2999±0.0014	0.2964±0.0014
$L_h/L_h + L_c$	0.8469±0.016	0.8981± 0.016
	0.8913±0.016	0.9334±0.016
$L_c/L_h + L_c$	0.1531	0.1019
	0.1087	0.0666
l_3	0	0
x_h^*	0.42	0.42
	0.50	0.50
x_c^*	0.58	0.58
	0.75	0.75
$*A_h = A_c$	1.0	1.0
G_h^*	0.25	0.25
G_c^*	0.08	0.08

[a] Fixed parameters.

101 normal points in blue (Table 1b). The normal points can be transformed to the standard system using the transformation equations $\Delta V = \Delta v = 0.068\Delta(B - V)$ and $\Delta(B - V) = 1.478\Delta(b - v)$. The light curves are analysed using the Wilson & Devinney (1971) light curve synthesis method. The preliminary elements used for the present analysis are taken from Parthasarathy (1979). All the earlier photometric solutions of HU Tau are given in Table 2. Throughout our analysis, the coefficients A_h and A_c, (albedoes), G_h and G_c (gravity exponents) and x_h and x_c (limb darkening coefficients) were kept as fixed parameters (Table 3). Initially the following parameters were treated as adjustable: i the orbital inclination, Ω_h the surface potential, q the mass ratio, L_h the relative monochromatic luminosity, $T_{e,h}$ the effective temperature of the primary (hot component), $T_{e,c}$ the effective temperature of the secondary (cool component), and l_3 the third light. With these fixed and adjustable parameters a number of runs of the Wilson & Devinney program for detached system (code 2) and semidetached system (code 5) were made till the sum of the residuals $\sum w(O - C)^2$ showed a minimum and the corrections to the parameters became smaller than their probable errors.

From the above mentioned analysis of the light curves of HU Tau we find that it is a semidetached system and the primary minimum is due to an occultation eclipse. If we consider that the primary minimum is due to a transit then the solution requires the orbital inclination $i = 90^\circ$. In such a situation we expect the primary minimum to show annular phase and the secondary minimum to show the totality phase. However, our light curves and the light curves obtained by Turner & Kurutac (1979) and Ito (1988) are found to show minima with no annular or totality phase, which indicates that the eclipses are partial and the orbital inclination $i < 90^\circ$. In fact the earlier solutions (Parthasarathy 1979; Dumitrescu & Dinescu 1980; Ito 1988; and Dumitrescu & Suran 1993) and also the present solution yield the orbital inclination $i = 78^\circ$.

The solution obtained by keeping all the parameters as adjustable is given in Table 3. This solution yields the effective temperature of the primary (hot star) $T_{e,h}$ = 13 600 K which is much higher than that obtained from the spectral type (the spectral type of the primary is B8V according to Cowley et al. 1969) and $T_{\rm eff}$ calibration (de Jager & Nieuwenhuijzen 1987; Bohm-Vitense 1981). For a B8V star de Jager & Nieuwenhuijzen (1987) find $T_{\rm eff}$ = 11 429 K and Bohm-Vitense finds $T_{\rm eff}$ = 12 000 K. The light curve solution is expected to be

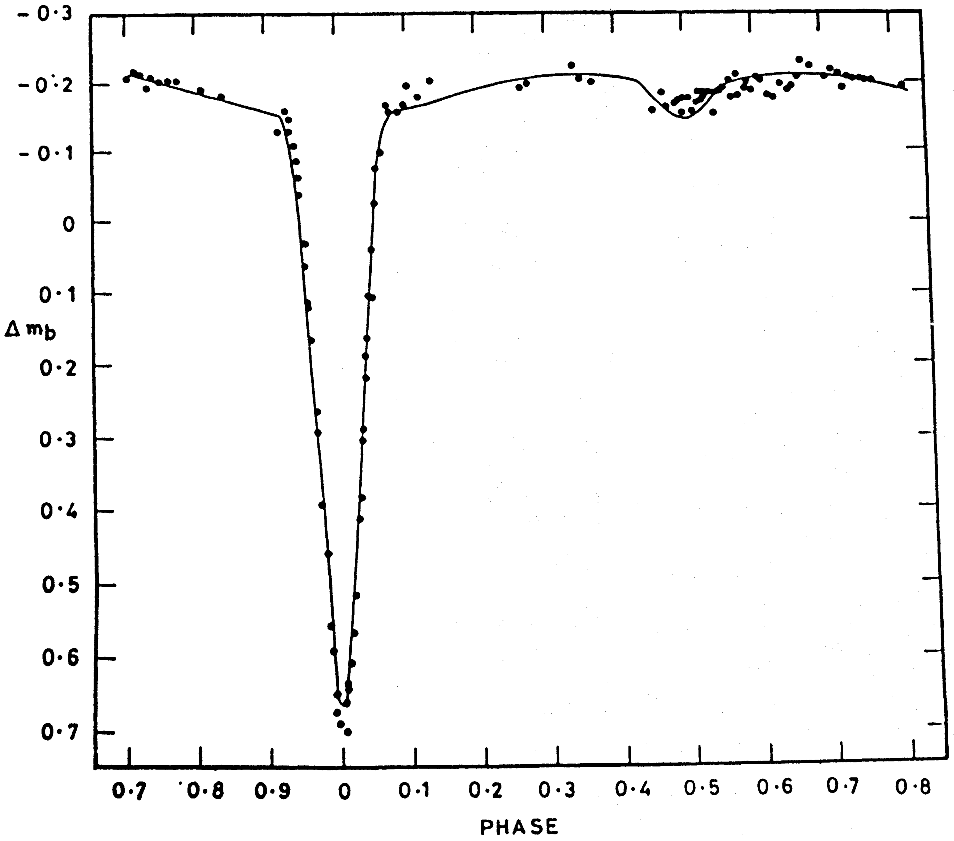

Fig. 1a. Observed (filled circles, Table 1) and synthetic (dark line) light curves of HU Tau. The synthetic light curves are for the semidetached case with the primary minimum due to an occultation (blue light curve)

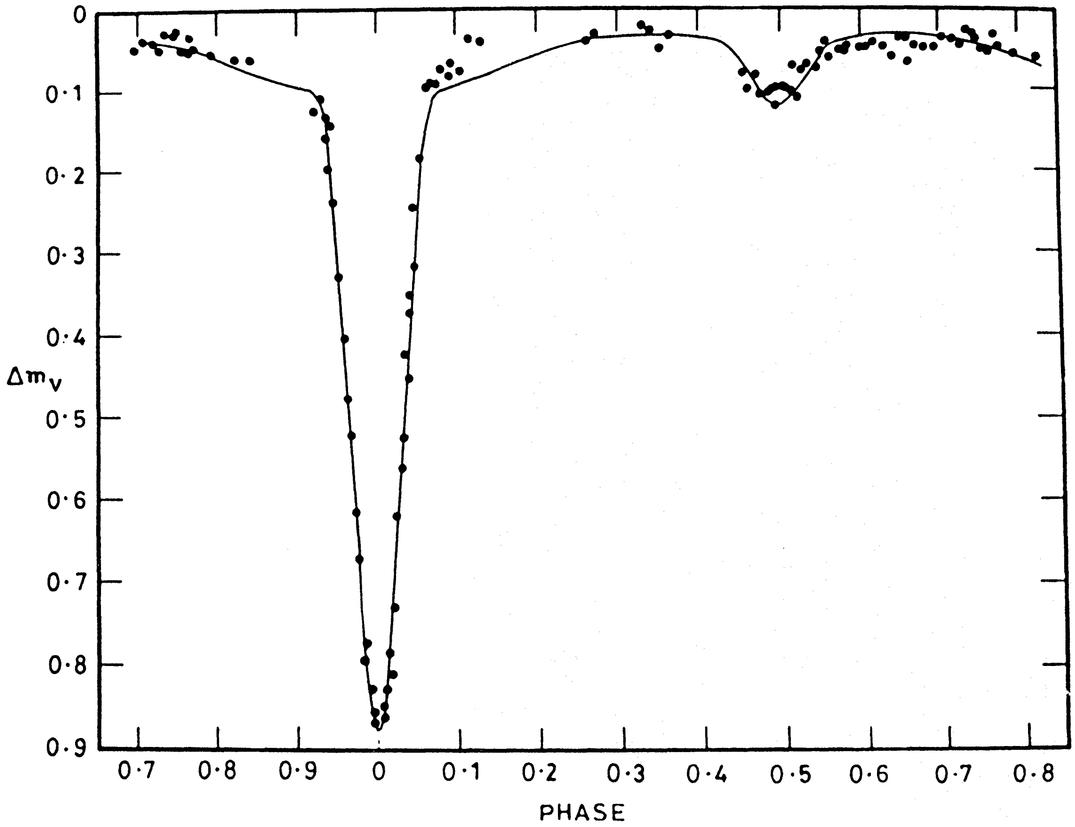

Fig. 1b. Same as Fig. 1a (visual light curve)

more reliable if we consider the effective temperature of the primary $T_{\rm e,h}$ and the mass ratio q as fixed parameters. We fixed $T_{\rm e,h}$ = 11 400 K and the mass ratio q = 0.269 (deterimined by Parthasarathy (1979) from spectroscopy) and carried out the analysis of the light curves using the Wilson & Devinney (1971) program with code 5 (semidetached system). The final elements are given in the last column of Table 3. The light curves computed with the final elements and the observations are shown in Figs. 1a and 1b. The final elements are in agreement with the photometric solutions obtained by Parthasarathy (1979), Dumitresc & Dinescu (1980), Ito (1988) and Dumitrescu & Suran (1993) (Table 2).

From the fractional luminosities of the components given in Table 3 and using $\Delta(B-V) = -0.364$ (outside the eclipse at $\sim$ 0.25 phase) and also using the $B-V = +0.31$ for the comparison star HR 1472 we find $(B-V)_{\rm pri} = -0.095$ and $(B-V)_{\rm sec} = +0.408$. The $(B-V)$ colour of the primary component is in agreement with its B8V spectral type (Cowley et al. 1969) and the effective temperature $T_{\rm e,h}$ = 11 400 K (Table 3) (Bohm-Vitense 1981; Schmidt-Kaler 1982). The $(B-V)_{\rm sec}$ color and radius of the secondary indicates that it is a F5 III-IV star.

The light curves show an asymmetry. There is a slow decline of light from 0.7 phase to 0.9 phase. However, near 0.1 phase there is a steep rise (Figs. 1a and 1b). This asymmetry may be due to the presence of gas stream between the components, most likely from the secondary to the B8V primary. The Hα profiles in the spectrum of HU Tau at various phases also suggest the presence of gas streams indicating mass loss and/or transfer from the cool secondary component (Parthasarathy 1979).

Table 4. Absolute dimensions of HU Tau

	Primary component (hot)	Secondary component (cool)
$M/{\rm M}_\odot$	4.68±0.14	1.26±0.03
$R/{\rm R}_\odot$	2.90±0.04	3.34±0.04
$\log L/{\rm L}_\odot$	2.105±0.063	0.910±0.038
$M_{\rm bol}$	−0.57±0.16	2.42±0.10
$M_{\rm v}$	0.00±0.16	2.63±0.10

3. Absolute dimensions

Parthasarathy (1979) determined the spectroscopic orbital elements and absolute dimensions of the system. We have redetermined the absolute dimensions using the final photometric elements obtained from the present analysis (Table 3 last column) and the spectroscopic orbital elements. The absolute dimensions of HU Tau (Table 4) suggest that the late type secondary component has filled its Roche lobe and it is over luminous for its mass. For a B8 main sequence star the mass and radius are 3.8 M$_\odot$ 3.0 R$_\odot$ respectively (Schmidt-Kaler 1982). The derived values of mass and radius for the primary component (B8V) of HU Tau are 4.68 M$_\odot$ and 2.9 R$_\odot$ respectively (Table 4). The calibrations of Popper (1980) and Andersen (1991) also sugest 3.5 M$_\odot$ for a B8V star. The mass of the primary appears to be slightly larger than that predicted from the calibrations of Popper (1980) and Andersen (1991) which are based on detached systems with main sequence components. The hot primary components of δ Lib (primary A0V, orbital period 2.3 days) and U Sagittae (primary B8V, orbital period 3.38 days) are similar to the B8V primary of HU Tau and also show similar trend. These two systems have well determined absolute dimensions. The mass of the B8V star of U Sagittae is 5.7 M$_\odot$ and the mass of the A0V primary of δ Lib is 4.9 M$_\odot$. These values are larger than those predicted from the calibrations of Popper (1980) and Andersen (1991). This indicates that in some of the Algol systems the primary components (hot component) are slightly under luminous for their mass and show slightly later spectral type compared to that inferred from the calibrations of Popper (1980) and Andersen (1991) based on the detached systems.

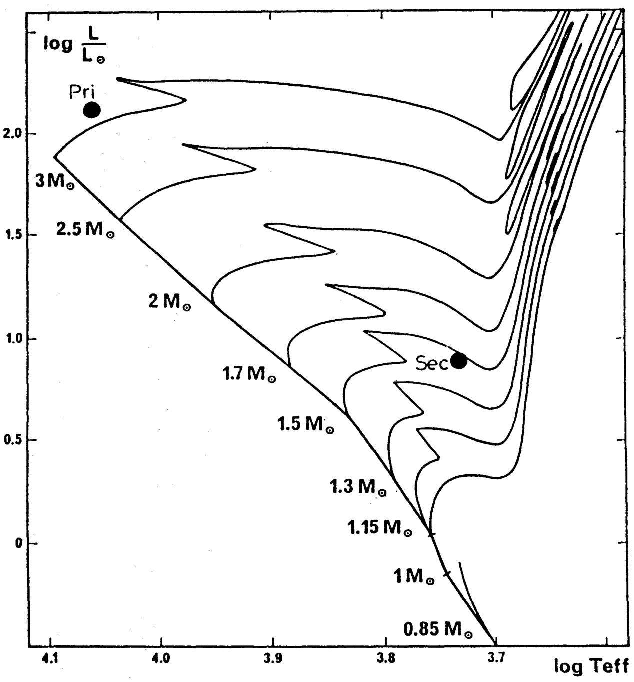

Fig. 2. The location of the primary (Pri) and secondary (Sec) components of HU Tau in the log L versus log $T_{\rm e}$ diagram. The evolutionary tracks of low mass stars (Maeder & Maynet 1988) of population I composition with initial masses 0.85 M$_\odot$ to 3.0 M$_\odot$ are shown

4. Evolutionary status

In order to understand the evolutionary status of the system we compared the location of the primary and secondary in the log $T_{\rm e}$ versus log L (luminosity is computed using $L = 4\pi R^2 \sigma T_{\rm e}^4$) diagram (Fig. 2) with the evolutionary tracks of Maeder & Meynet (1988) computed for stars of population I composition with initial masses 3.0 M$_\odot$ and 1.3 M$_\odot$. The location of the secondary in Fig. 2 indicates that it is over luminous for its mass. The luminosity and the spectral type of the (B8V) primary is in reasonable agreement with that expected from a 3 $M_\odot$ main sequence. However, the derived mass is 4.68 $M_\odot$ (Table 4). The primary (hot) components of δ Lib, U Sagittae, TU Mon and V356 Sgr are also under luminous and have cooler spectral types for their masses (Giuricin et al. 1983). The primary component of TT Hya is also found to show a similar trend (Vivekananda Rao & Sarma 1994). Recently Sarna & De Greve (1994) critically reviewed the absolute dimensions of U Sagittae and concluded that the spectroscopic mass ratio is sensitive to the interaction effects which could be the source of the problem in these semidetached systems. Possibly the primary (hot) component has accreted matter only in the recent past as a result of mass transfer from the Roche lobe over flow of the secondary and therefore the structure of the primary components in these systems may be different from that of single stars of similar mass.

Recently De Greve et al. (1985), Sarna (1993), and Sarna & De Greve (1994) investigated the evolutionary status of Algol systems TV Cas, β Per and U Sagittae respectively. They found that only non-conservative evolution gives reasonably good agreement with the observed parameters of these systems. They also find the initial orbital periods for these systems to be around $\sim$ 1.6 days. They also find that during the evolution the system loses 6 percent (U Sagittae) to 15 percent (β Per) of initial total mass and 2 percent (U Sagittae) to 30 percent (β Per) of its initial total angular momentum. The observed parameters of HU Tau are within the range of the observed parameters TV Cas, β Per and U Sagittae and therefore HU Tau evolutionary status may be similar to that of U Sagittae (Sarna & De Greve 1994) and β Per (Sarna 1993). However, Sarna (1993) states that because of the uncertainties in the orbital and physical data for β Per, the estimated initial parameters can be affected by an error as large as 20 percent. Compared to β Per the orbital and physical data of HU Tau is not as accurate as that of β Per. The initial orbital period of HU Tau may be around $\sim$ 1.6 days and the initial mass ratio may be around 1.1 and the system may have lost about 7 percent of the initial total mass.

5. Conclusions

From an analysis of the light curves of HU Tauri using the Wilson & Devinney (1971) light curve synthesis method we find that it is a semidetached system. The primary minimum is found to be due to an occultation eclipse. The absolute dimensions derived from combining the photometric and spectroscopic orbital elements suggests that the less massive secondary (cool component) has filled its Roche lobe and is over luminous for its mass. The primary (hot component) appears to be slightly under luminous for its mass.

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