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UBV Photometry of the Massive Eclipsing Binary TT Aur

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Abstract: *UBV* observations of the massive binary system TT Aur were carried out mainly at the Turkish National Observatory (TUG). These observations, together with IUE spectra and times of eclipse minima collected from the literature, were used to study the system parameters.

Simultaneous solution of the light curves by the Wilson-Devinney code allows a semi-detached configuration with a slightly larger Roche-lobe filling secondary. This picture is supported by other evidence. The shoulders of the primary minimum suggest some excess absorption, in keeping with circumstellar material in the form of a disk-like structure around the primary component. The deeper primary minimum in the *U* filter may indicate a hotter region on the secondary-facing hemisphere of the primary.

The period variation of the system can also be related to the possible existence of a third component in a circular orbit around the system.

An alternative detached representation is also considered using optimal curve-fitting techniques. We appeal for further observations to help resolve some outstanding issues in this interesting massive binary.

Keywords: stars: mass loss — binaries: close — stars: individual (TT Aurigae) — techniques: photometric — techniques: miscellaneous

1 Introduction

Leavitt (1907) first detected the light variation of the 8.6–9.5 magnitude variable TT Aur on Harvard plates. The EB type light curve was produced from the photographic observations of Martin & Plummer (1916), and Jordan (1929). Joy & Sitterley (1931) carried out an early photometric and spectroscopic study of the system. They classified the primary companion as B3 spectral type, and noted a slightly later B–type secondary. Hilditch & Hill (1975) obtained intermediate–band *uvby* light curves. They estimated the most likely spectral type for the primary to be B2, and the secondary to be between B4 and B6, from their reddening-free data. Bell & Hilditch (1984), Wachmann, Popper & Clausen (1986) and Bell, Adamson & Hilditch (1987) obtained photometric solutions for TT Aur that appear mutually incompatible. Published light curves tend to show depressed shoulders to the primary minimum. This effect is also noticeable in our light curves. It may be due to a disk-like structure around the primary.

In the present study a simultaneous solution of new photoelectric U, B, V observations, the ultraviolet light curve formed by integrating low dispersion IUE spectra and times of minima collected from the literature, have been used to better our understanding of the TT Aur system.

2 Period Variation

The adopted period of TT Aur P_d is 1.332735d. From our observations we have obtained the following new times of minima:

$$\begin{aligned}
\text{HJD min I} &= 2450486.4438 \pm 0.0003\\
\text{HJD min I} &= 2451083.5091 \pm 0.0003\\
\text{HJD min I} &= 2451587.2873 \pm 0.0004\\
\text{HJD min II} &= 2450488.4431 \pm 0.0004\\
\text{HJD min II} &= 2451081.5089 \pm 0.0003\\
\text{HJD min II} &= 2451517.3183 \pm 0.0003.
\end{aligned}$$

These results were derived using the well-known method of Kwee & van Woerden (1956). A list of published times of minima of TT Aur was given by F. Agerer (1998, private communication). By combining all timing data we formed the O–C diagram of Figure 1, where the calculated estimates were obtained using Simon's (1999) elements.

The photometric times of minima show a sinusoidal variation superimposed on a parabolic variation of longer term. The sinusoidal variation, realized by Simon (1999), is probably due to an unseen third companion in the system. Orbital elements of this hypothetical third body have been determined and compared with Simon's results in Table 1. Here A^d is the semi-amplitude of the O–C changes in days; $V_{\rm rad}$ is the deduced third body's radial velocity amplitude.

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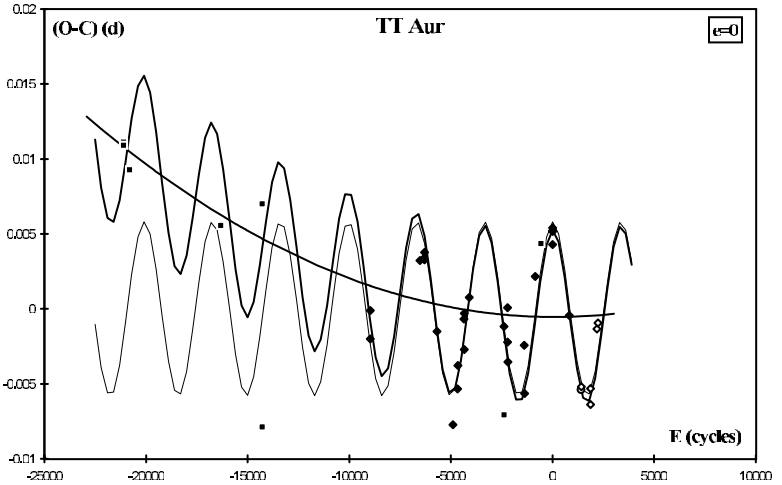


Figure 1 O–C diagram formed by the photoelectric (diamonds) and photographic (squares) eclipse minima of TT Aur. A sinusoidal variation superimposed and a long-term parabolic trend are shown by the best-fit solid lines. Open diamonds correspond to the new times of minima.

Table 1. Orbital elements of the hypothetical third body in TT Aur

	This work	Simon (1999)
Period	4465 d	4465 d (12.2 years)
e	0	0.296
ω°	–	346.9
A^d	0.0058	0.00545
$V_{\rm rad}$ (km s^{-1})	27.8	–
Δ(AU)	12.5	–
L_3 (L$\odot$)	1.7	–

Table 2. Masses of third body for different orbital inclinations

Inclination (°)	Mass (M$_\odot$)
30	2.5
60	1.4
90	1.2

Table 2 gives mass estimates for the third body for different inclinations. If we assume a coplanar orbit to that of TT Aur and adopt $i = 88°$, the mass and luminosity of the third body should be about 1.18M$_\odot$ and 1.7L$_\odot$. The fractional contribution to the overall light of such a body would be negligible (L$_3$ $\sim$ 0.00025 $L_{\rm TTAur}$). On this basis, the third body's light should not noticeably affect the light curves of TT Aur.

3 The Light Curves

The *UBV* light curves (Figure 2) were formed mainly from observations carried out using the 40 cm Cassegrain (Utrecht) telescope at the TUBITAK National Observatory (TUG) during 1997 (seven nights), supplemented by two nights with the 30 cm Maksutov telescope at the Ankara University Observatory in 1996. The 40 cm TUG telescope was used with a standard SSP-5 photometer and an SSP-5A on the 30 cm Maksutov. These single channel uncooled photometers have side-on Hamamatsu R1414 photomultipliers and near standard *UBV* filter sets. The control of the photometer heads, data acquisition and reduction functions were carried out with software prepared by Muyesseroğlu (1992) (AUO) and Keskin (1996) (TUG). Further details of observational procedure are available on request (cf. also http://www.tug.tubitak.gov.tr/).

The main comparison star (C1) was BD +39°1191 (=SAO 57677), with occasional checks on BD +38°1005 (=SAO 57581; C2). During the course of these observations, the star C2 was discovered to be variable, showing a light decrease of $\sim$1.5 mag (Ak, 1997).

In addition to the new *UBV* data, IUE spectral data were also studied. Doppler shifts, equivalent widths, depths and areas of the bright lines were investigated. Derived values were found to show a phase dependence. Integration of the low dispersion continua between 1225 Å $< \lambda <$ 1975 Å yields a very smooth light curve, where the primary is much deeper and the secondary shallower in comparison to the optical light curves.

3.1 Semi-detached Model

These light curves have been fitted simultaneously, using a recent version of the Wilson-Devinney code (Wilson 1992). During this curve-fitting, certain parameters were fixed to reliably known values. These parameters are: the spectroscopic mass ratio, $q = 0.668$ (Popper & Hill 1991); the temperature of the primary, $T_1 = 23\,400$ K, appropriate to spectral type B2V (Wachmann et al. 1986); linear limb-darkening coefficients (Wade & Rucinski 1985); bolometric albedo $A_{1,2} = 1.0$; gravity-brightening coefficients $g_{1,2} = 1.0$; and rotation parameter $F_{1,2} = 1.0$.

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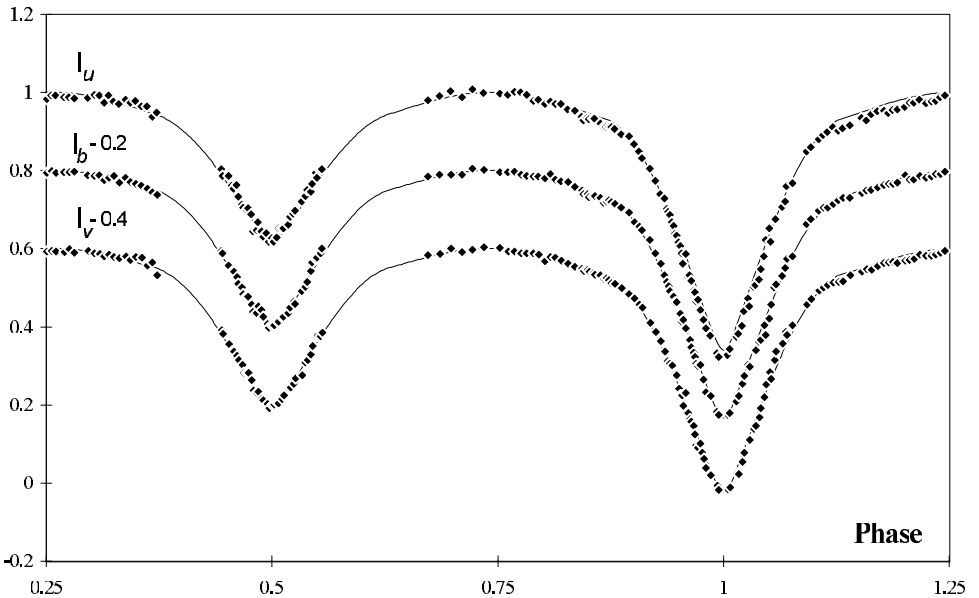


Figure 2 Simultaneous *UBV* TUG observations of TT Aur are here shown together with the semi-detached model discussed in Section 3.1. These (and subsequent) light curves plot relative flux levels against orbital phase.

We applied the semi-detached mode (W-D mode 5) in this analysis. Such a model is suggested by the long-term trend of period increase that can be associated with a Roche lobe overflow mechanism. Light curves of TT Aur also tend to show absorption effects in the primary minimum, which may also relate to mass transfer. The deeper primary minimum in the U filter may point to a hotter region on the secondary-facing hemisphere of the primary. The UV (IUE) light curve was also fitted with this model. Iterations were controlled visually, by inspection of the goodness of fit of the theoretical and observational light curves. The corresponding solution is listed in Table 3. The theoretical light curve corresponding to this solution is shown as Figure 2, together with normalized *UBV* data points, and also in Figure 3, which includes the UV (IUE) observations and corresponding radial velocity data.

TT Aur has some resemblance to the early type close binary DM Per, whose period variation was interpreted in terms of a standard Case B type Roche lobe overflow process (Murad & Budding, 1984). In such a regime one may write, for the period variation due to mass transfer,

$$\Delta P/P = -9\eta s((2x-1)/(1-x)/R_2) \times (P_d/365.25), \quad (1)$$

where $\Delta P/P$ is the fractional change of period, η is the density of the surface layer of the mass-losing star as a fraction of its mean density, R_2 is the mean radius of this star, x is the value of M_2 expressed in terms of the mass of the entire system, and s is the annual rate of surface expansion of the mass-losing star. If we substitute in the appropriate numbers, as in Murad & Budding (1984), we will find a representative relative period variation $\Delta P/P$ of about 3×10^{-9}. Period variations of this order can be observed for classical Case B Algols in the earlier stages of the semi-detached condition (cf. e.g. U Cep; Kreiner 1978). However, this is considerably greater than the observed value for TT Aur of $\sim 6 \times 10^{-11}$ (Section 2).

In considering the period variation in relation to the semi-detached hypothesis, we would note the following points. (i) The surface expansion rate s is a sensitive function of the initial mass of the loser (unknown but here

Table 3. WD solutions for TT Aur

Parameter	Value	p. e. (±)
a (R⊙)	11.64	0.07
i(°)	77.6	0.4
q	0.668	fixed
T_1	23400	fixed
T_2	18000	180
Ω_1	3.541	0.02
Ω_2	3.188	0.009
$r_{1,\mathrm{pole}}$	0.344	0.002
$r_{1,\mathrm{point}}$	0.387	0.003
$r_{1,\mathrm{side}}$	0.356	0.002
$r_{1,\mathrm{back}}$	0.372	0.003
$r_{2,\mathrm{pole}}$	0.323	0.001
$r_{2,\mathrm{point}}$	0.447	0.03
$r_{2,\mathrm{side}}$	0.337	0.002
$r_{2,\mathrm{back}}$	0.369	0.002
$L_1/(L_1+L_2)(U,B,V)$	0.69, 0.66, 0.64	
$L_2/(L_1+L_2)(U,B,V)$	0.31, 0.34, 0.35	
$L_1(U,B,V)$	8.7, 8.3, 8.1	
$L_2(U,B,V)$	3.95, 4.35, 4.45	
$x_1(U,B,V)$	0.31, 0.28, 0.24	fixed
$x_2(U,B,V)$	0.37, 0.34, 0.30	fixed
$L_3(U,B,V)$	0.0	
$A_1 = A_2$	1.0	
$g_1 = g_2$	1.0	
$F_1 = F_2$	1.0	
χ^2 (mag)	0.04	

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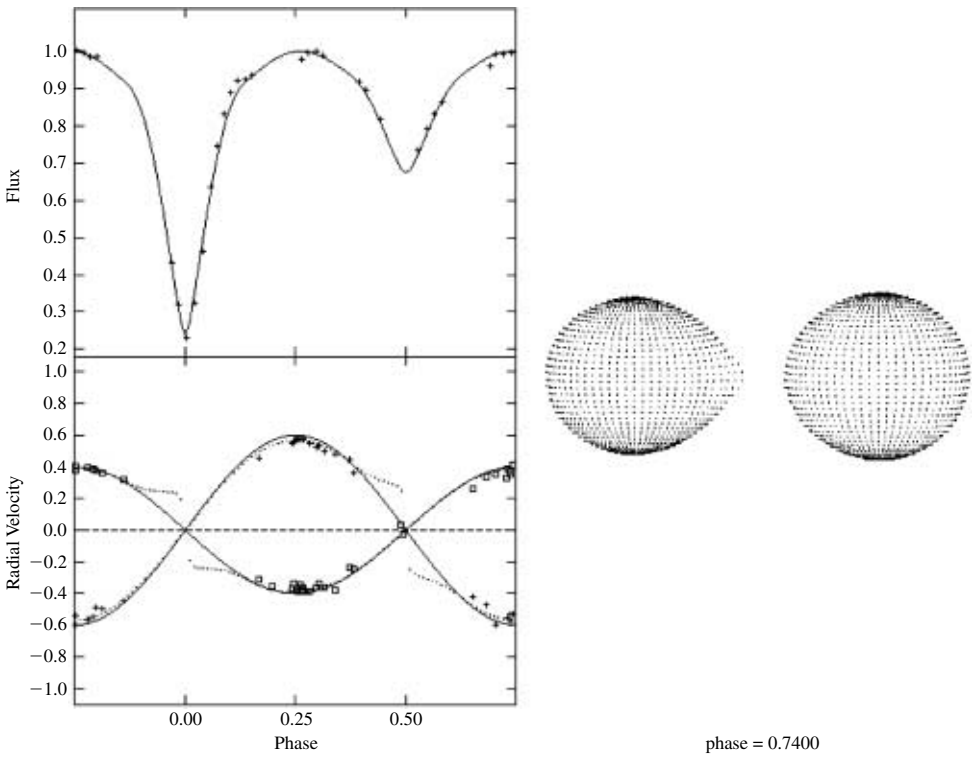


Figure 3 Simultaneous light curve solutions of the system TT Aur with a semi-detached model, together with normalized observation points. The upper left panel shows the UV (∼1600 Å) light curve, extracted from IUE records; the lower left panel shows the radial velocity data of Popper & Hill (1991), fitted with the derived model. These are given as fractions of the total radial velocity amplitude of the close binary (430 km s^{-1}). The panel on the right shows a corresponding Wilson & Devinney (1971) (WD) type representation. This diagram was produced using Bradstreet's (1993) *Binary Maker*^{TM} software.

assumed ∼7M$_\odot$). (ii) The role of momentum exchange with the third body complicates the problem. (iii) Not all Algols necessarily follow the Case B model (cf. e.g. Tout & Eggleton 1988). (iv) For spectral types earlier than mid-B the role of radiation pressure becomes increasingly dominant, whereupon the foregoing simple formula will no longer apply (cf. e.g. Plavec 1989; Mazzali et al. 1992; Drechsel et al. 1995).

3.2 ILOT models

Superficially, TT Aur also has some likeness to the bright early-type system VV Ori (Budding & Najim 1980). Although a semi-detached configuration is suggested by other evidence, as mentioned, we also examined the curve-fit of a detached model, utilizing the Information Limit Optimization Technique (ILOT) (cf. Budding 1993). Previously fixed parameters were set to the same values as for the W-D fitting. It became clear that, whether or not the secondary photosphere is in contact with the surrounding Roche lobe, both stars must occupy large fractions of these lobes, so that some mass transfer, at least of coronal material, can be expected. The ILOT fittings are summarized in Table 4. Error estimates are derived from inverting the determinacy Hessian for four parameters in the vicinity of the χ^2 minimum. Other things being equal, the SD configuration, entailing somewhat larger stars, requires a somewhat lower inclination to compensate for otherwise-introduced changes of shape to the light curves. Note here the difference between the inclination values of Tables 3 and 4 is appreciably bigger than their formal errors. This difference (∼4°) is a better indication of real uncertainties than the formal errors, which build in assumptions about the strict validity of the model.

The ILOT values of χ^2, with the given number of degrees of freedom (168 for each light curve), and the given nominal accuracy of each datum ($\Delta l = 0.008$), show that these detached model fittings are, statistically, as probable as the semi-detached one (cf. e.g. Pearson & Hartley 1954). This adopted standard deviation dispersion for the normal points (i.e. Δl) is in broad keeping with both the normal statistical expectation that $\chi^2/(N-\nu) \sim 1$ and the observed scatter of individual observations of the comparison stars. Here it should be noted, however, that the greatest discrepancies in the light curves are systematic, and in certain regions of the light curves. Hence, neither the SD nor detached models are complete representations of the data. The detached model result was checked by Bradstreet's (W-D-based) Binary Maker$^{(TM)}$. Results are shown, for comparison, in Figure 4.

4 Absolute Parameters

Absolute parameters of the system were computed from the data given in Tables 3 and 4, using the revised radial velocities of the system from Popper & Hill (1991).

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Table 4. ILOT solutions for TT Aur

Parameter	Value	p. e. (±)
$i(^\circ)$	81.6	0.8
q	0.668	fixed
T_1	23 400	fixed
T_2	18 000	180
$r_{1,\,\mathrm{side}}$	0.389	0.005
$r_{2,\,\mathrm{side}}$	0.280	0.005
$m_{0,\,\mathrm{ref}}(U, B, V)$	7.512, 8.321, 8.547	0.010
$L_1/(L_1 + L_2)(U, B, V)$	0.81, 0.79, 0.75	
$L_2/(L_1 + L_2)(U, B, V)$	0.19, 0.21, 0.25	
$x_1(U, B, V)$	0.31, 0.28, 0.24	fixed
$x_2(U, B, V)$	0.37, 0.34, 0.30	fixed
$L_3(U, B, V)$	0.0	
$A_1 = A_2$ black body	1.0	
$g_1 = g_2$	1.0	
χ^2 (U, B, V)	189.4, 157.5, 180.0	
$N - \nu$	168, 168, 168	
Δl	0.008	(adopted)

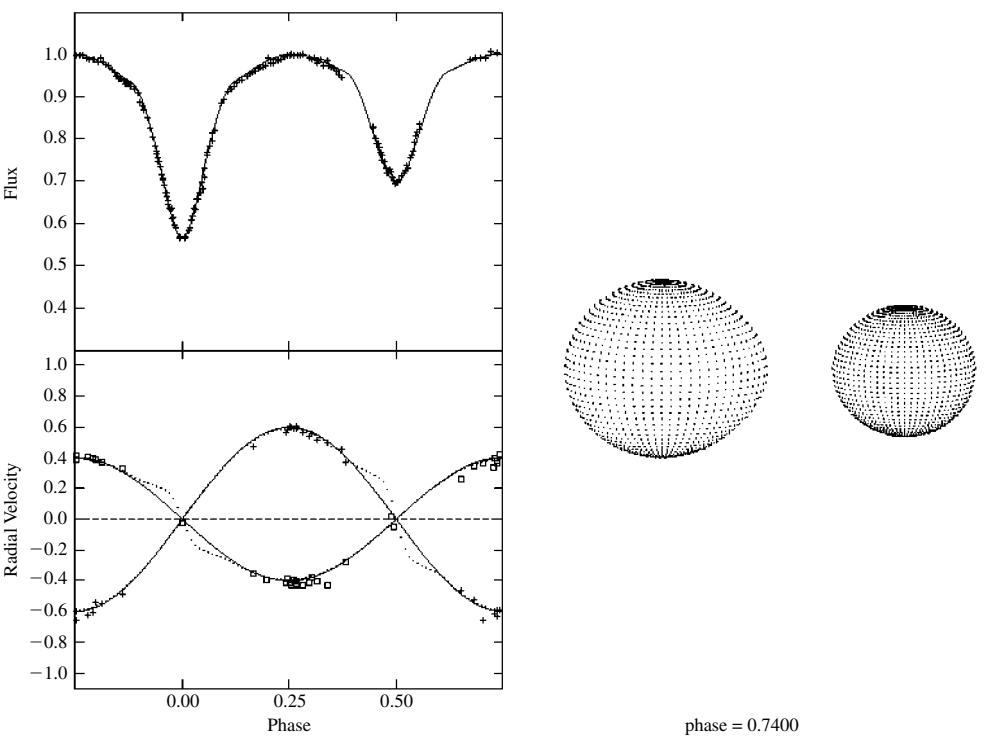


Figure 4 Light curve solutions of the system TT Aur with a detached model, derived by the ILOT curve-fitter and illustrated by means of Bradstreet's Binary Maker$^{(TM)}$, using the ILOT parameters. The light curve in the upper left panel is the *B* one of Figure 2, otherwise the diagram follows the format of Figure 3.

The detached model conforms to typical main sequence values for early type stars, as may be seen in the comparisons of Popper (1980). Although the derived masses are somewhat lower than typical for early main sequence stars of types comparable to those adopted, the mass ratio (0.67) is in keeping with a near-main sequence configuration. Low masses might reflect the difficulties of deriving accurate radial velocities for such rapidly rotating stars. It is similar with the adopted temperatures and correspondingly derived luminosities. Thus, while the temperature ratio (0.77) concurs with a near-main sequence configuration, the adopted values (cf. Figueiredo, de Greve & Hilditch 1994) are higher than typical. The radii, on the other hand, being relatively insensitive to the masses, are close to normal main sequence stars of similar types. The separately derived absolute magnitude values are also close to main sequence values.

5 Discussion

Our light curve analysis differs from the older ones in two ways. Firstly we used a revised mass ratio, taken

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Table 5. Absolute parameters for TT Aur*

Parameter	Primary	Secondary
$M(\odot)$	7.2 ± 0.1	4.80 ± 0.03
	6.9, *8.9*	4.6, *5.2*
$R(\odot)$	4.16 ± 0.03	4.21 ± 0.03
	4.47, *4.29*	3.22, *3.20*
T K (adopted)	23 400 (B2.5V)	$18\,000 \pm 180$ (B5IV)
	21 500	*15 500*
$L\odot$	$(4.6 \pm 0.02) \times 10^3$	$(1.6 \pm 0.2) \times 10^3$
	5.4, *3.5*	0.97, *0.53*
a $(\odot)$	4.66 ± 0.03	6.98 ± 0.14
	4.60	6.90
$\langle\rho\rangle$ (g cm^{-3})	0.14 ± 0.02	0.091 ± 0.003
	0.11	0.19
log g (cgs)	4.05 ± 0.02	3.87 ± 0.02
	3.98	4.08
M_V	-2.13 (mag)	-1.47 (mag)
	-2.29, *-2.5*	-1.10, *-1.2*
d(kpc) (adopted)	1.1	1.1

*SD solutions given on first line; D solutions on second; MS comparisons follow in italics. $E_{(B-V)} = 0.29$, adopted from Wachmann et al. (1986), and $R = A_V/E_{(B-V)} = 3.2$ assumed.

from Popper & Hill (1991), who took account of distorting effects in the broad and overlapping line profiles in such OB type double-lined binaries. Secondly, our simultaneous solutions are based on new photometry of TT Aur.

The solution presented in Table 3 shows a semi-detached configuration. As a result, the secondary component can be expected to be transferring material onto the primary. The long-term period increase of $P = 1.6 \times 10^{-3}$ sec y^{-1}, obtained from O–C analysis of the times of minimum, points to a semi-detached model with mass transfer from the secondary. Previous light curves, and ours, show an absorption effect in the shoulders of the primary minimum, in agreement with mass transfer in this semi-detached model. Also, the 12.2 year period sinusoidal variation of times of minima, superposed on the longer term period increase, may be caused by either a third body in the system or an episodic nature to the mass loss and transfer.

The solution presented in Table 4 corresponds to a detached model. While the curve-fit allows feasibility to such a model, there are systematic irregularities in the light curves, which would be more in keeping with mass-transfer effects in a semi-detached scenario. While the detached model stars are both close to main sequence, it is also clear that these stars must be relatively very close, so we should naturally expect some interactive effects to have started with such proximity.

TT Aur is a special example of a close eclipsing binary system consisting of a pair of young and massive stars. The evidence studied in this paper points to interesting interactive effects, but, by itself, does not convincingly resolve between physically somewhat different, alternative representations. We will continue to observe and analyse TT Aur and we appeal to others for further observations. For example, satellite UV or IR data may help to get a clearer understanding of this interesting binary by establishing the amount of circumbinary matter.

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