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GRAVITY DARKENING IN SEMI-DETACHED BINARY SYSTEMS TT AURIGAE

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Abstract. From a light-curve analysis of the semi-detached close binary system TT Aur, the exponent of the gravity-darkening has been empirically estimated for the component filling the Roche lobe. In the analysis, the gravity-darkening coefficient for the component underfilling its Roche lobe has been fixed according to von Zeipel's (1924) value $\beta = 0.25$ for stars in hydrostatic and radiative equilibrium. The results of the present analysis show that the estimated empirical value of the gravity-darkening exponent is significantly greater than the one derived from existing theories by von Zeipel for radiative (hot systems) envelopes.

1. LIGHT-CURVE ANALYSIS

An ordinary semi-detached system of Algol-type consists of a main-sequence primary component inside its Roche lobe and a subgiant (or giant) secondary filling the Roche lobe. If the primary component is well deep inside its Roche lobe, the shape of the star is close to being spherical. In this case it is reasonable to fix the value of the gravity-darkening coefficient according to von Zeipel's (1924) value $\beta = 0.25$ for stars in hydrostatic and radiative equilibrium. The exponent of the gravity-darkening has been empirically estimated for the component filling the Roche lobe by the light-curve analysis. In this paper a modern computer programme (Djurašević, et al., 1998) has been used to analyze the photometric observations. The programme is based on the Roche model and the principles deriving from the paper by Wilson & Devinney (1971).

In the analysis of the light curves, instead of the often used and somewhat questionable practice of forming normal points, we used the original observational data in order to avoid negative effect of such normalization.

To achieve more reliable estimates of the model parameters in the programme for the light-curves analysis, we applied a quite dense coordinate grid having $72 \times 144 = 10368$ elementary cells per each star. The intensity and angular distribution of radiation of elementary cells are determined by the star's effective temperature, limb-darkening, gravity-darkening and by the effect of reflection in the system.

The star's size in the model is described by the filling coefficients for the critical Roche lobes $F_{h,c}$ of the primary and secondary components, respectively, which tell us to what degree the stars in the system fill their corresponding critical lobes. The subscripts (**h,c**) refer to the hotter (primary) and cooler (secondary) component respectively. For synchronous rotation of the components (tidal effects are present) these coefficients are expressed via the ratio of the star polar radii, $R_{h,c}$, and the corresponding polar radii of the critical Roche lobes, i.e., $F_{h,c} = R_{h,c}/R_{Roche_{h,c}}$.

For a successful application of the foregoing described model in the analysis of the observed light curves, the method proposed by Djurašević (1992) was used. By that method optimum model parameters are obtained through the minimization of $S = \Sigma(O - C)^2$, where $(O - C)$ is the residual between the observed (LCO) and synthetic (LCC) light curves for a given orbital phase. The minimization of S is effected in an iterative cycle of corrections of the model parameters. In this way the inverse-problem method gives us the estimates of system's parameters and their standard errors.

The values of the limb-darkening coefficients were derived from the star's effective temperature and surface gravity, according to the given spectral type, by using the polynomial proposed by Díaz-Cordovés et al., (1995). Following Rucinski (1969) and Rafert & Twigg (1980), the gravity-darkening coefficients of the stars, β, and their albedos, A, were set at the values of $\beta = 0.25$ and $A = 1.0$ for stars in hydrostatic and radiative equilibrium. In this particular case, as we mentioned earlier, the gravity-darkening coefficient is fixed for the primary component situated inside its Roche lobe.

In previous versions of our programme, there were two different possibilities in the application of the model regarding the treatment of the radiation law: the simple black-body theory, or the stellar atmosphere models by Carbon & Gingerich (1969) (CG). Our current version of the programme for the light-curve analysis employs the new promising Basel Stellar Library (BaSeL). We have explored the "corrected" BaSeL model flux distributions, consistent with extant empirical calibrations (Lejeune et al., 1997, 1998). By choosing and fixing the particular input switch, the programme for the light-curve analysis can be simply redirected to the Planck or CG approximation, or to the more realistic BaSeL model atmospheres.

2. RESULTS AND CONCLUSIONS

In this paper the light-curve analysis is applied to the massive binary system of TT Aurigae (B2V+B4 ; $P \sim 1^d.333$). UBV observations (Demircan, 1999) made at the Ankara University Observatory and BV observations (Bell et al., 1987) were analyses with the fixed mass-ratio of the components $q = m_h/m_c = 0.678$ (Wachmann et al., 1986). Based on the spectral type of the components, B2 V+B4 (Kitamura and Nakamura, 1987), the value of $T_h = 24800K$ was taken as the temperature of the primary. The gravity-darkening exponent of the primary was fixed at $\beta_h = 0.25$, and as the albedos of the components the values of $A_h = A_c = 1.0$ were adopted. Other parameters of the system were estimated in the light-curve analysis. Here we used the "corrected" BaSeL model flux distributions and we assumed solar chemical abundance for the components of the system. This model approximation provides much better agreement between the individual U, B and V solutions than the simple black-body theory, or the stellar atmosphere models by Carbon & Gingerich (1969).

The present analysis of the observations of TT Aur enabled us to estimate the parameters of the system that are mutually consistent. The solutions indicate a semi-detached configuration in which the less-massive secondary fills its Roche lobe. They suggest also a quite possible mass-transfer from the less massive secondary toward the more massive primary.

Table 1 presents the results of the light-curve analysis while Fig. 1 gives a graphic presentation of these results. For the gravity-darkening exponent of the secondary we obtained the value $\beta_c \sim 0.6$, which is greater than twice the expected value $\beta = 0.25$ for stars in hydrostatic and radiative equilibrium. By applying a different model and method Kitamura and Nakamura (1987) found for this system $\alpha_c = 4 \times \beta_c = 3.84$, which is about 1.4 times greater than the value estimated in our present paper. We think that our Roche model is more adequate and that the method of optimization we applied is a direct and efficacious one. In our opinion this discrepancy between our and Kitamura and Nakamura's estimates of the gravity-darkening exponent is a consequence of the simplified model of the system and method used by the two authors.

Table 1. Results of the analysis of the TT Aur light curves obtained by solving the inverse problem for the Roche model. Gravity-darkening coefficient of the cooler secondary component (β_c) is a free parameter.

Quantity	U - filter	B - filter	V - filter	B - filter	V - filter
n	359	360	361	113	113
$\Sigma(O-C)^2$	0.1054	0.0819	0.0932	0.0068	0.0055
$q = m_c/m_h$	0.678				
T_h	24800				
β_h	0.25				
A_h	1.0				
A_c	1.0				
$f_h = f_c$	1.0				
T_c	19800 ±92	19911 ±103	20023 ±117	19960 ±70	19843 ±69
F_h	0.805 ±0.005	0.812 ±0.007	0.764 ±0.008	0.792 ±0.006	0.791 ±0.006
F_c	0.986 ±0.002	0.989 ±0.002	0.997 ±0.002	0.982 ±0.002	0.986 ±0.001
i	86.2 ±0.1	86.2 ±0.13	86.2 ±0.14	86.2 ±0.07	86.3 ±0.07
β_c	0.60 ±0.02	0.60 ±0.02	0.60 ±0.02	0.60 ±0.02	0.62 ±0.02
u_h	0.33	0.35	0.31	0.35	0.31
u_c	0.37	0.41	0.35	0.40	0.35
Ω_h	3.844	3.813	4.018	3.894	3.900
Ω_c	3.234	3.229	3.211	3.243	3.236
R_h [D=1]	0.313	0.316	0.297	0.308	0.308
R_c [D=1]	0.320	0.321	0.323	0.318	0.319
$L_h/(L_h+L_c)$	0.659	0.612	0.550	0.602	0.581

BaSeL approximation of the stellar atmosphere ($[Fe/H]_{h,c} = 0.0$ - accepted metallicity of the components)

Note: n - number of observations, $\Sigma(O-C)^2$ - final sum of squares of residuals between observed (LCO) and synthetic (LCC) light curves, $q = m_c/m_h$ - mass ratio of the components, T_h - temperature of the hotter component, β_h - gravity-darkening coefficient of the hotter component, $A_h = A_c = 1.0$ - albedo coefficients of the components, $f_h = f_c = 1.00$ - nonsynchronous rotation coefficients of the components, T_c - temperature of the cooler component, $F_{h,c}$ - filling coefficients for critical Roche lobes of the hotter primary (h) and cooler secondary (c), i - orbit inclination (in arc degrees), β_c - gravity-darkening coefficient of the cooler secondary component, $u_{h,c}$ - limb-darkening coefficients of the components, $\Omega_{h,c}$ - dimensionless surface potentials of the primary and secondary, $R_{h,c}$ - polar radii of the components in units of the separation [D=1] between the component centres and $L_h/(L_h + L_c)$ - luminosity of the hotter star.

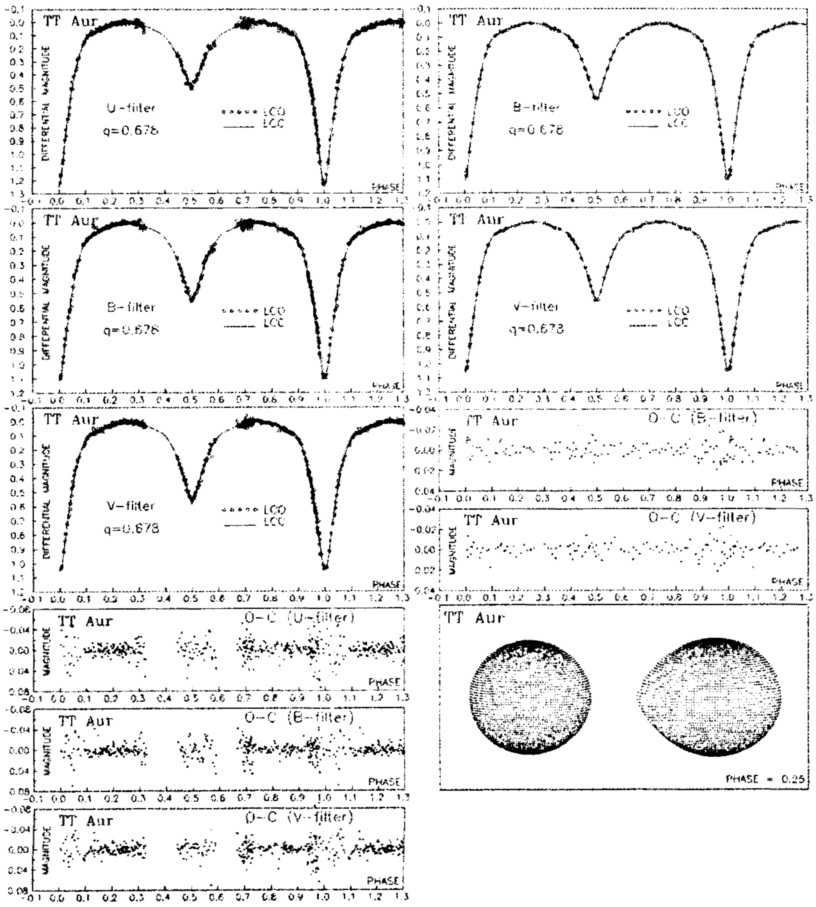

Fig. 1. Observed (LCO) and final synthetic (LCC) light curves of TT Aur with final O-C residuals obtained by analyzing two sets of U B V and B V observations and with the view of the system at the orbital phase 0.25, obtained with the parameters estimated by analyzing the observations.

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