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A MODEL OF THE EARLY TYPE BINARY SYSTEM BF AURIGAE

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RESUMEN

Se presenta un modelo físicamente consistente para el sistema binario eclipsante, de tipo temprano BF Aur, basado en soluciones simultáneas de las curvas de luz y de velocidad radial. La estrella secundaria menos brillante y menos masiva (pero más caliente), es más pequeña aunque casi llena el lóbulo de Roche. El sistema no es, por lo tanto, un sistema Algol invertido. Los parámetros absolutos del sistema son: $M_h = 3.3\ M_\odot$, $M_c = 4.1\ M_\odot$, $T_h = 15600$ K, $T_c = 15400$ K, $R_h = 3.9\ R_\odot$, $R_c = 4.1\ R_\odot$. Se requiere información más detallada de la velocidad radial, antes de asegurar que el modelo es único.

ABSTRACT

A physically consistent model is presented for the early-type eclipsing binary system BF Aur, based on a simultaneous solution of its light and radial velocity curves. The less massive fainter (but hotter) secondary is smaller but almost Roche lobe filling component. The system is thus not reverse-algol. The absolute parameters of the system are found to be: $M_h = 3.3\ M_\odot$, $M_c = 4.1\ M_\odot$, $T_h = 15600$ K, $T_c = 15400$ K, $R_h = 3.9\ R_\odot$, $R_c = 4.1\ R_\odot$. More accurate radial velocity data are needed before uniqueness can be claimed for the model.

Key words: **BINARIES – ECLIPSING — BINARIES – SPECTROSCOPIC — STARS – FUNDAMENTAL PARAMETERS — STARS – INDIVIDUAL (BF AUR)**

1. INTRODUCTION

The photometric observations were carried out of the short period (P = 1.58^d) early type eclipsing binary BF Aur in the B and V filters by Schneller (1961), in the U, B and V filters by Mannino, Bartalio, & Biolchini (1964) and Zhang et al. (1993). Mammano, Margoni, & Stagni (1974) derived poor spectroscopic orbits of two similar B5V component stars. Using Wilson-Devinney (1971) program, Schneider, Darland, & Lenng (1979) and Kallrath & Kamper (1992) analysed Mannino et al.'s (1964) data and concluded that BF Aur is a semi-detached system. Mammano et al. (1974) noted that the fainter component is eclipsed at the primary minimum. This means the fainter component of BF Aur is slightly hotter. Based on this finding, and using the line ratios of Hg and He I 4388 in Popper's (1981) data, Kallrath & Kamper (1992) found a consistent solution with q = 1.05 and a lobe filling more massive but slightly cooler component. However, they used only the second half of the light curves (0.5 < phase < 1.0). Using the same data and same method of analysis, van Hamme (1993) found that BF Aur is fully detached, but very near to contact. The orbital period of the system was shown to be increasing about 0.01 sec/yr (see Zhang et al. 1993) indicating a mass transfer from less massive to more massive component, and that the lobe filling component should be the less massive one.

We observed BF Aur on 19 nights between August 1988 and March 1989 using the 30-cm Maksutov telescope of the Ankara University Observatory. A single-channel photometer with an EMI9789 QB photomultiplier and Johnson's UBV filters were used. The system was again observed during two full nights in 1996 using the same telescope with a SSP-5 photometer. BD + 41 1046 and BD + 41 1050 were used as comparison and check stars. A total of 547 observations were secured in each filter. New observations are available on request from the authors. The r.m.s. error of a single observation in the light curve is about 0.01^m in all pass bands. Preliminary analysis of these observations by Özdemir et al. (1996) lead to a detached (but very close to contact) solution for q = 0.97 and to a semi-detached solution with a Roche lobe filling primary for q = 1.06. In order to explain the period increase of the system, a solution restricted to a Roche lobe filling secondary was obtained, based on the same observations by Djurasevich et al. (1997) only for q < 1. In this solution, which was based on the independent analysis of the U, B and V observations; however, the slightly hotter component, which is eclipsed at the primary minimum, turns out to be more massive, smaller and fainter.

In the present work, in order to better understand the system we reanalysed the same photometric data together with the radial velocity curves by Mammano et al. (1974). All observational constraints were considered in the analysis. The resulting model is presented and discussed.

2. PERIOD VARIATION

Three eclipse minima were evaluated by Müyesseroğlu & Selam (1994) from the new light curves; other time of eclipse minimum (Min II HJD 2450095.24254) was obtained by Özdemir et al. (1996). All four times of minimum are the mean from observations in three filters. We collected altogether 131 times of eclipse minimum of BF Aur from the literature and used them in forming the (O–C) diagram (Figure 1), where the yearly mean of the visual data were considered. The C epochs were estimated by using the linear ephemeris by Zhang et al. (1993). The parabolic character of the (O–C) variation (Fig. 1) is verified after Zhang et al. (1993). A parabolic best fit to the (O–C) data yields the following quadratic ephemeris:

$$MinI(HJD) = 2449002.0253 + 1.58322519E +$$
$$\pm 9.3 \times 10^{-4} \quad \pm 2.5 \times 10^{-7}$$
$$1.77 \times 10^{-10} E^2$$
$$\pm 1.1 \times 10^{-11}$$

The rate of the period increase is found to be ΔP = 0.0071 sec/yr from the quadratic ephemeris. The period increase is explained by the mass transfer from the less massive to the more massive component. Thus, we would expect the less massive component to be filling the first critical Roche lobe and since the mass ratio is close to unity the system should be in the early stage of mass transfer, but the mass ratio should be already reversed, i.e., the system cannot be a reverse-algol.

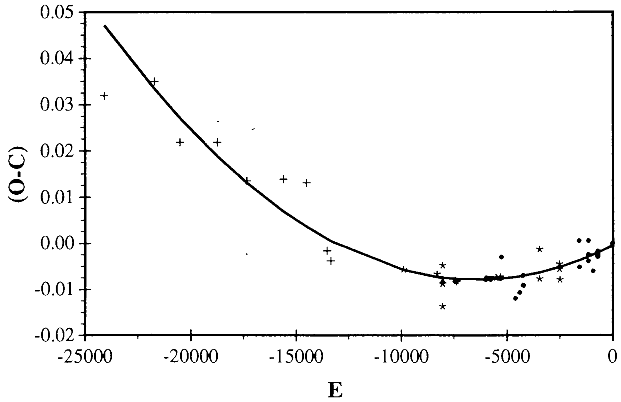

Fig. 1. The best parabolic fit representation of the (O–C) variation of BF Aur. + normal visual data, ⋆ photographic data, • photoelectric data.

3. OBSERVATIONAL CONSTRAINTS ON THE MODEL

Any model of the system BF Aur should be consistent with the following observational findings: (1) The fainter component of the system is eclipsed at the primary minimum (cf., Mammano et al. 1974; Kallrath & Kampe 1992). (2) The eclipsed component at the primary minimum should be the hotter component. (3) Combination of (1) and (2) indicates that the hotter component should be fainter. This, in turn, requires an occultation type primary minimum (i.e., $R_c > R_h$). (4) The spectral type B5V of the system corresponds to an effective temperature of about T = 15400 K for the larger more luminuous but cooler component. (5) The constancy of the color curves in all phases including the eclipses indicates nearly equal surface fluxes (and thus temperatures) for the component stars. The mean error in color measurements is about 0.02 mag, which corresponds to a B5V star within an error of about 1400 K in the temperature estimate. This figure should be an upper limit to the temperature difference between the component stars. (6) The period increase as discussed in the previous section requires a mass transfer from less massive to more massive component of the system. This, in turn, is the signature of the Roche lobe filling for the less massive component.

4. LIGHT AND RADIAL VELOCITY CURVE SOLUTION

We used the revised Wilson & Devinney (1971) eclipsing binary computer program in the simultaneous light and radial velocity curve solution of BF Aur. Initially we carried out the solutions of B and V light curves of the Ankara University Observatory. The large scatter in the radial velocity curves of Mammano et al. (1974) and the probable UV excess in the U light curve prompted us to exclude them initially from the simultaneous solution. The albedos and the gravity darkening exponents were fixed at their radiative values. The linear limb darkening coefficients were interpolated from the tables by Wade & Rucinski (1985).

By considering above mentioned observational constraints on the model and using the initial parameters according to van Hamme's (1993) solution, we run a detached mode of the light curve program, initially for our B and V light curves, separately. A visual inspection of the agreement between synthetic and observational light curves was performed in every run, and only after a satisfactory agreement in the maximum and minimum light levels, the differential correction program was initiated for the simultaneous solution of the B and V light curves and the radial velocity curves in semi-detached mode (according to the constraint 6 in § 3). We obtained a grid of solutions with fixed values of the mass ratio q between 0.8 and 1.6. Approximately 10 integrations were performed to obtain each solution. The adjustable parameters for a given q were: the inclination i, the non-dimensional potential Ω_c of the cooler but more luminuous component (the Ω_h was fixed to its first critical Roche lobe [see the constraint 6 in § 3]), the polar temperature T_h (the T_c of the more luminuous component was fixed according to B5V spectral type [see constraint 4 in § 3]), and the relative monochromatic luminosities (L_{1V}, L_{1B}). Before the final solution, the Ω_h was also left to be adjusted, and a better solution is obtained by a slightly ($\sim$ 3%) larger value of Ω_h.

The goodness of the fits χ^2 to the light curves, defined as the sum of the squared residuals $\chi^2 = \Sigma(I_o - I_c)^2$ were seen to be almost independent of the assumed q over a wide range around unity; however, the theoretical radial velocity curves do not represent well the observations for larger and smaller values of q. Consistent solutions for both q $\sim<$ 1 or q $\sim>$ 1 are possible. However, we found that the χ^2 is slightly ($\sim$ 2%) smaller for the solution around q $\cong$ 1.15. The parameter q = M_c/M_h is also larger than unity in the best fit light curve solutions by Schneider et al. (1979), Kalrath & Kamper (1992), and van Hamme (1993). We present in Table 1 the

TABLE 1

PHOTOMETRIC PARAMETERS OF BF AUR[a]

Parameter	Value
i (deg)	82.5 (5)
q	1.15 (5)
T_h (K)	15600 (150)
T_c^* (K)	15400
Ω_h^*	4.10 (3)
Ω_c	4.13 (3)
L_h (B)	0.479 (10)
L_h (V)	0.478 (10)
r_h (back)	0.372
r_h (side)	0.347
r_h (pole)	0.332
r_h (point)	0.409
$\overline{r}_h$	0.351
f_h	0.99
r_c (back)	0.393
r_c (side)	0.369
r_c (pole)	0.353
r_c (point)	0.428
$\overline{r}_c$	0.371
f_c	0.94
χ^2	0.010

[a] The probable errors in the last digits are given in parenthesis.

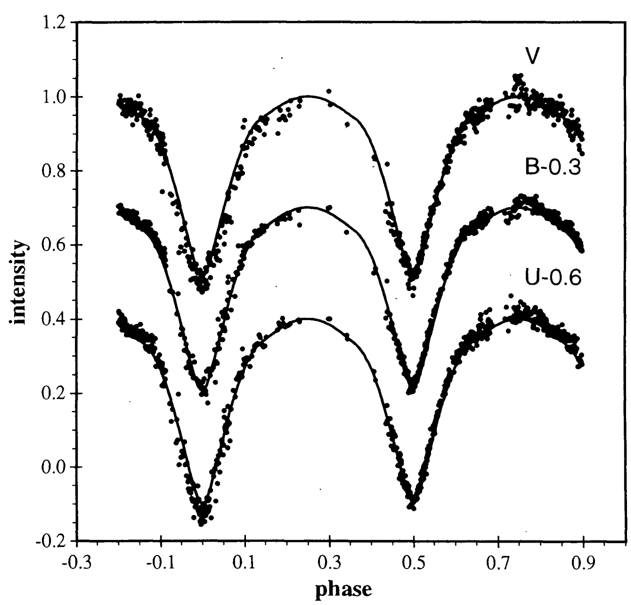

Fig. 2. The synthetic light curves (continuous lines) formed by the present best fit model among the observations.

TABLE 2

ABSOLUTE DIMENSIONS OF BF AUR

	Model A for $q > 1$			Model B for $q < 1$		
	Hotter Component		Cooler Component	Hotter Component		Cooler Component
$M/M_{\odot}$	3.25		4.12	4.10		3.22
$R/R_{\odot}$	3.89		4.12	3.77		4.09
f	0.99		0.94	0.92		0.99
T (K)	15600		15400	15400		15200
$a(R_{\odot})$		11.10			11.08	
$\overline{\rho}(cgs)$	0.078		0.083	0.108		0.067
log g (cgs)	3.77		3.83	3.90		3.72

parameters of the best simultaneous solution fit corresponding to q = 1.15, where the fractional radii are in terms of the distance a between the component stars, and the fill-out parameter f is defined in terms of the first and second critical non-dimensional potentials $\Omega_{1,2}$ (i.e., $f = (\Omega_1 - \Omega)/(\Omega_1 - \Omega_2)$. Figure 2 compares the synthetic curves formed by the present best solution fit with the photoelectric observations. The synthetic curve was also compared with the U light curve which was not well represented by the synthetic curve around mid-eclipse phases. Additional loss of light during the mid-eclipse phases of the U light curve is most likely caused by the eclipse of a hotter region around the first Lagrangian point (see also Djurasevic et al. 1997).

5. ABSOLUTE DIMENSIONS

The simultaneous solution (see Table 1) of our light and the radial velocity curves of Mammano et al. (1974) lead to an internally consistent set of absolute dimensions of BF Aur, which are listed in Table 2, as model A. For comparison, the model parameters by Djurasevic et al. (1997) were also listed in Table 2 as model B. The error estimates of the mass and radius in Table 2 are about 0.10. The error in temperatures should be about 1000–1500 K.

6. DISCUSSION AND CONCLUSION

The light curve solutions are in general less sensitive to the mass ratio, particularly around unity. However, the mass ratio is known to be a key parameter in the light curve solutions of eclipsing binary stars. For the system of BF Aur the old poor spectroscopic orbits derived by Mammano et al. (1974) show that the mass ratio is around unity (q = 1.0 ± 0.2), and it is not known if q < 1 or q > 1. Thus two consistent models of the system are possible with the present data; one for q < 1 and the other for q > 1. Both models satisfy the observational constraints of § 3 and represent the observations equally well. The model with q < 1 was presented by Djurasevic et al. (1997) and the other alternative model with q > 1 is obtained in the present work (Tables 1 and 2). Both models are almost semi-detached with the Roche lobe filling secondaries, and very close to marginal contact. The U observations provide good evidence that there should be a hotter region around the first Lagrangian point. This would be the impact region of the mass flow on the primary. The component stars are significantly oversized and closer to the terminal age of the main sequence. In the first model with q < 1 the Roche lobe filling less massive star is cooler and larger, while in the second model with q > 1 the Roche lobe filling less massive star is slightly hotter and smaller. In the present model with q > 1 the larger star is the more massive component. Of course the mass losing secondary can be the original primary and thus it does not obey the mass-radius relation. No further conclusion can be drawn with the present data. Only more accurate radial velocity data can help to select one of the models and to deduce the unique model of the system.

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