MY Serpentis: a high-mass triple system in the Ser OB2 association

C. Ibanoglu¹, Ö. Çakırılı¹†, E. Sipahi¹,

¹Ege University, Science Faculty, Astronomy and Space Sciences Dept., 35100 Bornova, İzmir, Turkey

ABSTRACT

We present spectroscopic observations of the massive multiple system HD 167971, located in the open cluster NGC 6604. The brighter component of the triple system is the overcontact eclipsing binary MY Ser with an orbital period of 3.32 days. The radial velocities and the previously published UBV data obtained by Mayer et al. (2010) and the UBVRI light curves by Davidge & Forbes (1988) are analysed for the physical properties of the components. We determine the following absolute parameters: for the primary star $M_p=32.23±0.54 \, M_\odot$, $R_p=14.23±0.75 \, R_\odot$; and for the secondary star $M_s=30.59±0.53 \, M_\odot$, $R_s=13.89±0.75 \, R_\odot$. Photoelectric times of minimum light are analysed under the consideration of the light-time orbit. The center-of-mass of the eclipsing binary is orbiting around the common center-of-gravity of the triple system with a period of 21.2±0.7 yr and with a projected semi-major axis of 5.5±0.7 AU. The mass function for the third star was calculated as 0.370±0.036 $M_\odot$. The light contributions of the third star to the triple system in the UBV pass-bands were derived and the intrinsic magnitudes and colors were calculated individually for the three stars. The components of the eclipsing pair were classified as O7.5 III and O9.5 III. The intrinsic color indices for the third star yield a spectral type of (O9.5-B0) III-1. This classification leads to constrain the inclination of the third-body orbit, which should be about 30°, and therefore its mass should be about 29 $M_\odot$. MY Ser is one of the rare massive O-type triple system at a distance of 1.65±0.13 kpc, the same as for the NGC 6604 embedded in the Ser OB2 association.

Key words: stars: binaries: eclipsing – stars: fundamental parameters – stars: binaries: spectroscopic – stars: late-type — stars: chromospheric activity
1 INTRODUCTION

Massive stars are known as progenitors of supernovae. The end-product of the supernova explosions are neutron stars or black holes which can be sources of strong gravitational waves. Therefore massive stars affect not only dynamical but also chemical evolution of the galaxies. They ionize the surrounding material and emit UV radiation. Almost at the beginning of their life they start to lose considerable amount of their material. Studies of physical characteristics of massive components of early-type double-lined eclipsing binaries are essential for understanding of the final stages of stellar evolution. The two components of an eclipsing binary system have the same age and chemical composition when they born but slightly different masses and radii and temperatures. Therefore, theoretical stellar models must be able to match their precisely determined physical properties for one age and chemical composition. This comparison for the detached eclipsing binaries leads to improvement in input physics and success of the treatment in stellar models of several physical phenomena, for example mass loss, mixing-length, convective core overshooting and opacity (Aparicio et al. 2007). In addition to this, some hints about the spin and orbital angular momentum exchange in close binaries due to mass-transfer and loss will be obtained.

Zinnecker & Yorke (2007) propose that the incidence of binary and multiple stars among the massive O-stars is much larger than that for solar-like stars. This difference in multiplicity properties is attributed to the differences in the star formation process between massive and low-mass stars. While low-mass stars may loose angular momentum by magnetic- and disk-related processes, these are ineffective in massive star formation due to short time scale of formation. Mason et al. (1998) estimate that O-star binary frequency is larger than 60%, even this may reach to 100 % as the gap in orbital periods between close and wide binaries is filled. They also note that most binaries occur in clusters and associations and that binaries are less common among field star and especially among young runaway stars. So far, many eclipsing binary systems have been discovered in the open clusters and associations. They not only offer determining the properties of the cluster but also allow one to calculate an accurate distance, age and chemical composition as a whole. Accurate physical parameters of stars, especially masses, radii and effective temperatures may only be determined from the analyses of multi-passband light curves and radial velocities. These analyses may also yield signs about the existence of additional components. Eclipsing binaries which are members of physically bounded multiple stellar systems provide additional con-
straints for the reliability of evolutionary models. The physical parameters that can be evaluated for the members of a multiple system should be represented by the same isochrone that fit the eclipsing pair. Recently, Torres, Andersen & Giménez (2010) collected astrophysical parameters of 94 detached non-interacting eclipsing binaries. Masses and radii of these stars have been determined with an accuracy of 3% or more. This sample includes only three high mass binaries with a component as massive as 27 M\(_\odot\).

The massive binary system MY Ser (HD 167971, V=7.65, U-B=-0.34, B-V=0.75 mag) is the central star of NGC 6604, which is listed by Humphreys (1978) among the visually most luminous O stars in the Galaxy. NGC 6604 is a young, compact open cluster lying at the core of the H II region S54 (Georgelin et al. 1973), in the Ser OB2 association (Forbes 2000). First photometric photometry made by Hiltner (1956) who classified it as O8f in the MK system. Later on Conti & Alschuler (1971) refined this classification as O7.5If, and Walborn (1972) as O8Ib(f)p. Yamashita & Nariai (1977) re-classified the star as O8Ibf. Its light variability was detected by Leitherer et al. (1984), and later, its eclipsing nature with an orbital period of 3.32 days was revealed by van Genderen (1985). Photometric and spectroscopic observations of the star were obtained by Leitherer et al. (1987). They derived the orbital period for the eclipsing pair as 3.32 days and classified the stars as O8I+O5-8V. They have also pointed out that a third component of spectral type O5-8V dominates the optical and the UV luminosity of the eclipsing pair. First attempt for the solution of the light curve is made by Davidge & Forbes (1988). They obtained UBVRI light curves and performed preliminary analyses of these curves assuming the light contribution of the third star as 63.3%, 31.55% and zero. Later on UBV passbands and their analyses are published by Mayer et al. (2010). They find light contribution of the third star in the U, B and V light curves as 55.2%, 56.5% and 56.7%, respectively. The radial velocities of both components of the eclipsing pair were revealed by Mayer, Drechsel & Brož (2011) using the ESO archive spectra. Combining the results of the radial velocity and light curves analyses they estimate the masses of the components as 37.4 and 34.8 M\(_\odot\).

In this paper we present new spectroscopic observations and radial velocities of both components of the eclipsing pair. By analysing the previously published light curves and the new radial velocities we obtain orbital parameters for the stars. Combining the results of these analyses we obtain absolute physical parameters of both components. In addition we reveal for the first time orbital parameters of the third-body’s orbit and the parameters of the third star.
2 DATA ACQUISITION

2.1 Spectroscopy

Optical spectroscopic observations of the MY Ser were obtained with the Turkish Faint Object Spectrograph Camera (TFOSC) attached to the 1.5 m telescope in July, 21–29, 2012, under good seeing conditions. Further details on the telescope and the spectrograph can be found at http://www.tug.tubitak.gov.tr. The wavelength coverage of each spectrum was 4000-9000 Å in 12 orders, with a resolving power of $\lambda/\Delta \lambda \sim 7000$ at 6563 Å and an average signal-to-noise ratio (S/N) was $\sim 120$. We also obtained high S/N spectra of four early type standard stars 21 Cyg, $\tau$ Her, HR 153 and 21 Peg for use as templates in derivation of the radial velocities.

The electronic bias was removed from each image and we used the 'crreject' option for cosmic ray removal. Thus, the resulting spectra were largely cleaned from the cosmic rays. The echelle spectra were extracted and wavelength calibrated by using Fe-Ar lamp source with help of the IRAF ECHELLE package, see Simkin (1974).

2.2 Light curves

The UBV and intermediate-passband photometric observations have been obtained in 1985 by Leitherer et al. (1987) in three observatories. Despite some gaps in the resulting light curve the overall-shape of the light curve is well-represented by their observations. Depth of the primary minimum is deeper only 0.03 mag and the phase interval between the two eclipses is about 0.5, giving an evidence of circular orbit. Almost the same epoch Davidge & Forbes (1988) performed photometric observations in the Cousins-Bessel UBVRI filters. They have published five-passband light curves as well as individual differential photometric measurements. The most outstanding feature in their light curves is the asymmetry, in particular, light level immediately following primary eclipse appears to be depressed. UBV photometry of MY Ser in seven seasons of the years from 1990 to 1994 is performed by Mayer et al. (2010). Fortunately, one can reach to their original data. In consequence, two original multi-passband data sets are available for the use in interpretations.

1 http://tug.tug.tubitak.gov.tr/rtt150_tfosc.php
3 ANALYSIS OF THE $O-C$ CURVE

Leitherer et al. (1987) found from the line spectrum that MY Ser is a triple system with two close eclipsing O stars and a distant companion also of spectral type O. They note that the third star is the most luminous component of the system both in the optical and the UV spectra. The third star has been angularly resolved for the first time by De Becker et al. (2012) using multi-epoch VLTI observations. Their observations provide direct evidence for a gravitational link between the eclipsing pair and the O8 supergiant. They measured separations between the components A and B (the eclipsing binary) vary from 8 to 15 mas over the three-year baseline. They suggest that the stars evolve on a wide and eccentric orbit which is not coplanar with the orbit of the inner eclipsing pair.

Since the photometric observations of the eclipsing pair go back to middle of 1980s the orbit of the eclipsing pair around the center-of-mass of triple system can be determined from the times of mid-eclipses. However, the orbital period of the eclipsing binary is too long to be obtained a complete minimum in a night in an observing site. The eclipse, from first to fourth contact, lasts about 20 hours. For this reason a few times of mid-eclipse was seen in the literature. They could be obtained from the observations at the near to mid-eclipse. Therefore we try to estimate mid-primary and mid-secondary eclipses using the observations obtained in the ingress and egress of the minima. For this reason, we performed a preliminary analysis of the light curves obtained by Mayer et al. (2010) and obtained the best fit representation of the observed light curves. Plotting the observations with the same scales that of the computed curve and determined the minimum time by shifting it along the time axis. We note that the shape of the light curve is assumed to be constant during the time base of the observations. As the best fit is obtained the time for mid-primary or mid-secondary eclipses are read off from the observations. Using this procedure we obtained 20 times for the mid-primary and 21 for the secondary eclipse. The times are given in Table 1 with those taken from O-C GATEWAY data-base in the literature. The uncertainties of the minima derived in this study are about a few hundredths of a day.

The O-C(I) residuals given in the third column of Table 1 are computed with the linear light elements,

$$HJD\ (Min\ I) = 2\ 445\ 554.9987 + 3^d.321615 \times E. \quad (1)$$

and are displayed graphically against the years in Fig.1. Despite large scatter in the O-C(I) residuals they indicate a slow decrease and a steeper increase, then a decrease again. At a first glance the variations of the residuals look like a distorted sine curve. Since the residuals for both minima
Table 1. Times of mid-eclipses for MY Ser and the O-C residuals (see text)

| HJD-2400000 | E   | O-C(I)     | O-C(II)    | Ref |
|-------------|-----|------------|------------|-----|
| 45555.0000  | 0.0 | 0.0013     | 0.0123     | 1   |
| 45937.0000  | 115.0 | 0.0157     | 0.0264     | 1   |
| 46230.9410  | 203.5 | -0.0063    | 0.0044     | 1   |
| 46232.6125  | 204.0 | 0.0044     | 0.0151     | 1   |
| 46235.94    | 205.0 | 0.0103     | 0.0210     | 2   |
| 46237.58    | 205.5 | -0.0105    | 0.0002     | 2   |
| 48059.47    | 754.0 | -0.0262    | -0.0163    | 2   |
| 48062.80    | 755.0 | -0.0178    | -0.0079    | 2   |
| 48067.7894  | 756.5 | -0.0108    | -0.0010    | 1   |
| 48069.43    | 757.0 | -0.0310    | -0.0212    | 2   |
| 48071.13    | 757.5 | 0.0082     | 0.0180     | 2   |
| 48449.7664  | 871.5 | -0.0195    | -0.0098    | 1   |
| 48453.11    | 872.5 | 0.0025     | 0.0122     | 2   |
| 48501.2700  | 887.0 | -0.0009    | 0.0087     | 1   |
| 48753.7130  | 963.0 | -0.0007    | 0.0089     | 1   |
| 49155.63    | 1084.0 | 0.0009     | 0.0103     | 2   |
| 49157.32    | 1084.5 | 0.0301     | 0.0395     | 2   |
| 49158.95    | 1085.0 | -0.0007    | 0.0087     | 2   |
| 49163.97    | 1086.5 | 0.0369     | 0.0463     | 2   |
| 49459.58    | 1175.5 | 0.0232     | 0.0324     | 2   |
| 52083.69    | 1965.5 | 0.0575     | 0.0664     | 2   |
| 52088.6490  | 1967.0 | 0.0341     | 0.0422     | 1   |
| 52455.68    | 2077.5 | 0.0267     | 0.0374     | 2   |
| 52460.66    | 2079.0 | 0.0242     | 0.0359     | 2   |
| 52495.54    | 2089.5 | 0.0273     | 0.0359     | 2   |
| 52500.52    | 2091.0 | 0.0249     | 0.0359     | 2   |
| 52744.69    | 2164.5 | 0.0562     | 0.0589     | 2   |
| 52782.88    | 2176.0 | 0.0476     | 0.0589     | 2   |
| 52872.54    | 2203.0 | 0.0240     | 0.0343     | 2   |
| 52877.53    | 2204.5 | 0.0316     | 0.0344     | 2   |
| 52935.63    | 2222.0 | 0.0033     | 0.0112     | 2   |
| 53056.87    | 2258.5 | 0.0044     | 0.0112     | 2   |
| 53189.76    | 2298.5 | 0.0298     | 0.0357     | 2   |
| 53413.97    | 2366.0 | 0.0308     | 0.0371     | 2   |
| 53556.76    | 2409.0 | -0.0086    | -0.0034    | 2   |
| 53571.71    | 2413.5 | -0.0059    | -0.0035    | 2   |
| 53576.68    | 2415.0 | -0.0173    | -0.0098    | 1   |
| 53795.93    | 2481.0 | 0.0051     | 0.0080     | 2   |
| 53830.80    | 2491.5 | -0.0018    | 0.0080     | 2   |
| 54192.87    | 2600.5 | 0.0121     | 0.0166     | 2   |
| 54247.61    | 2617.0 | -0.0545    | -0.0441    | 2   |
| 54530.62    | 2648.0 | -0.0146    | -0.0109    | 2   |
| 54355.59    | 2649.5 | -0.0270    | -0.0153    | 2   |
| 54559.90    | 2711.0 | 0.0037     | 0.0136     | 2   |
| 54574.85    | 2715.5 | 0.0064     | 0.0135     | 2   |
| 54637.95    | 2734.5 | -0.0042    | 0.0072     | 2   |
| 54672.87    | 2745.0 | 0.0388     | 0.0409     | 2   |
| 54888.69    | 2810.0 | -0.0461    | -0.0386    | 2   |
| 54906.96    | 2815.5 | -0.0450    | -0.0386    | 2   |
| 54941.87    | 2826.0 | -0.0120    | -0.0097    | 2   |
| 55129.54    | 2882.5 | -0.0132    | -0.0068    | 2   |

Ref: (1) O-C Gateway, (2) This study

follow almost the same behavior such a variation resembles a light-time effect, orbiting around a third-body. The time delay or advance of the observed eclipses caused by the influence of a third star can be represented by

\[
\Delta T = \frac{a_{12} \sin i_3}{c} \left\{ \frac{1 - e_3^2}{1 + e_3 \cos \nu_3} \sin [\nu_3 + \omega_3] + e_3 \sin \omega_3 \right\}
\]  

(2)
Table 2. Orbital parameters for the third component of MY Ser.

| Parameter | Value |
|-----------|-------|
| $T_1$ (HJD) | 2445554.9626 ± 0.0034 |
| $P_1$ (d) | 3.321616 ± 0.000002 |
| $A_3$ (d) | 0.032 ± 0.005 |
| $e_3$ | 0.53 ± 0.05 |
| $w_3$ | 294 ± 30 |
| $a_{12}\sin i_3$ (AU) | 5.5 ± 0.7 |
| $P_3$ (yr) | 21.2 ± 0.7 |
| $T_3$ (HJD) | 2455592 ± 547 |
| $\Sigma(O-C)^2$ | 0.0167 |

where $a_{12}$ is the semi-major axis of the eclipsing pair’s orbit around the barycenter and $i_3$, $e_3$, $\omega_3$ are the inclination, eccentricity and longitude of the periastron of the third-body orbit, respectively. The semi-amplitude of the light-time effect is $A_3 = a_{12}\sin i_3/c$, where $c$ is speed of light. The only parameter varying with time in Eq.2 is the true anomaly, $\nu_3$, of the third-body. The resulting ephemeris is given by

$$T_{ec} = T_1 + EP_1 + \Delta T$$

where $T_1$ is the starting epoch, $E$ is the integer eclipse cycle number and $P_1$ is the orbital period of the eclipsing binary. First we estimated the initial parameters using the trial-and-error method. Then, a linear least squares fit is applied in order to obtain five independent variables $A_3, T_3, P_3, e_3, \omega_3$ for the third-body orbit plus two variables $T_1$ and $P_1$ for the eclipsing binary. The parameters are given Table 2 with their standard deviations. Subtracting the contribution of the light-time we obtained the O-C(II) residuals and plotted in the bottom panel of Fig. 1. This solution indicates that MY Ser revolves around the common center-of-gravity with a third-body. The orbit is highly eccentric, amounting 0.53. Using the projected semi-major of 5.5 AU and a period of 21.2 yr the mass function of the third star is calculated as $0.370 \pm 0.036 M_\odot$.

The first O-C analysis confirms that there is a gravitational connection between the MY Ser and the third-star as suggested by De Becker et al. (2012). The radio light curve obtained by Blomme et al. (2007) reaches to maximum close to 1988-1989 and minimum between 1995 and 1999. The maximum radio flux density to the orbital phase close to periastron passage, when the separation between the eclipsing pair and the third-star, is thus confirmed by the O-C analysis of the eclipsing pair.
Figure 1. Residuals for the times of minimum light of MY Ser with respect to the linear light elements. The continuous curve represents the light time effect. In the bottom panel the O-C(II) residuals, after subtracting the light-time, are shown.

4 RADIAL VELOCITIES

To derive the radial velocities, the eight spectra obtained for the system are cross-correlated against the template spectra of standard stars on an order-by-order basis using the FXCOR package in IRAF (Simkin 1974). The spectra showed three cross-correlation peaks in the quadratures, one for each component of the triple system. Thus, the peaks are fitted independently with a Gaussian profile to measure the velocities and their errors for the individual components. If the three peaks appear blended, a triple Gaussian was applied to the combined profile using de-blend function in the task. For each of the eight observations we then determined a weighted-average radial velocity for each star from all orders without significant contamination by telluric absorption features. Here we used as weights the inverse of the variance of the radial velocity measurements in each order, as reported by FXCOR.

The heliocentric radial velocities for the primary ($V_p$), the secondary ($V_s$) components and also for the third star ($V_t$) are listed in Table 3, along with the dates of observations and the corresponding orbital phases computed with the new ephemeris given above. The velocities in this table have been corrected to the heliocentric reference system by adopting a radial velocity value for the template stars. The radial velocities are plotted against the orbital phase in Fig. 2, together with the error bars. We analysed all the radial velocities for the initial orbital parameters using the RVSIM software program (Kane, Schneider, & Ge 2007). Figure 2 shows the best-fit orbital solution to the radial velocity data. The results of the analysis are as follow:
Figure 2. Radial velocities for the components of MY Ser. Symbols with error bars show the radial velocity measurements for the components of the system (primary: open circles, secondary: filled circles).

Table 3. Heliocentric radial velocities of MY Ser and the third star. The columns give the heliocentric Julian date, the orbital phase (according to the ephemeris in §3), the radial velocities of the three components with the corresponding standard deviations.

| HJD 2400000+ | Phase | Star 1 V_pσ | Star 2 V_sσ | Star 3 V_tσ |
|-------------|-------|--------------|--------------|--------------|
| 56130.3678  | 0.8034| -275 3 -4 10 | -275 3 -4 10 | -275 3 -4 10 |
| 56131.3096  | 0.0869| 132 7 -37 5 | 132 7 -37 5 | 132 7 -37 5 |
| 56132.3140  | 0.3893| 153 4 -41 9 | 153 4 -41 9 | 153 4 -41 9 |
| 56135.2888  | 0.2849| 246 3 -43 7 | 246 3 -43 7 | 246 3 -43 7 |
| 56136.3513  | 0.6048| -278 3 -27 8 | -278 3 -27 8 | -278 3 -27 8 |
| 56137.2779  | 0.8837| 247 3 -30 6 | 247 3 -30 6 | 247 3 -30 6 |

$\gamma = -14.5 \pm 3.2$ km s$^{-1}$, $K_1 = 265 \pm 4$ and $K_2 = 279 \pm 4$ km s$^{-1}$ with circular orbit. Using these values we estimate the projected orbital semi-major axis and mass ratio as: $a \sin i = 35.72 \pm 0.54$ R$_{\odot}$ and $q = \frac{M_2}{M_1}=0.949 \pm 0.028$.

The radial velocities of the third star vary from -4 to -43 km s$^{-1}$. Since the observations were obtained in successive eight nights, these changes should be arisen from the measurement errors, due to the blending of the three lines. The average radial velocity is determined as $-26 \pm 13$ km s$^{-1}$.

5 LIGHT CURVES AND THEIR ANALYSES

As we quoted in §1 the optical photometric studies of MY Ser were made by Leitherer et al. (1987) in the UBV, by Davidge & Forbes (1988) in the UBVRI and by Mayer et al. (2010) in the UBV. The original data of the latter two studies were published for use of other investigators. Davidge & Forbes (1988) obtained 1 520 points in the five passbands. The standard deviations of differential brightnesses were given as 0.014 mag in U, 0.005 mag in B, and 0.006 mag in V, R, and I. Although there are some gaps the shape of the light curve was revealed. The UBV photometric
observations of Mayer et al. (2010) were obtained between 1990-1994, which contain 3 042 points. Their three passbands light curve are almost complete. They did not give standard deviations of their observations. We estimate accuracies of differential observations from the maxima about 0.010 in U, 0.009 in B, and 0.010 mag in V-passband. The light curves are shown in Fig. 3.

Most commonly used code for modeling the light curves of the eclipsing binaries is that of Wilson & Devinney (1971). This code was up-dated and implemented in the PHOEBE code of Prša & Zwitter (2005). One of the main difficulties in this modeling is determination of individual effective temperatures of both stars. Generally used practice is to estimate effective temperature...
of primary star and determine that of the secondary star. Effective temperature of the primary star could be estimated from its spectra or color indices. However, spectrum of an eclipsing binary is a composite spectra of both stars. In some cases decomposition of the spectra is almost impossible. Similarly the color indices are also include colors of both stars. If the stars of an eclipsing binary have similar properties, i.e. their temperatures and luminosities are very close, it is difficult task to estimate their contribution to the total luminosity of the system.

The average colors are measured by Leitherer et al. (1987) as \( U-B = -0.34 \pm 0.02 \), \( B-V = 0.75 \pm 0.01 \), \( V-R = 0.52 \pm 0.01 \), \( V-I = 1.05 \pm 0.01 \) mag. They point out that the colors remain constant independently of the phase. In addition, infrared colors \( J-H = 0.205 \pm 0.05 \), \( H-K = 0.177 \pm 0.05 \) mag are given in the 2MASS catalog (Cutri et al. 2003). The quantity \( Q = (U - B) - (E(U - B)/(E(B - V)))(B - V) \) is independent of interstellar extinction. The average value obtained is \( (E(U - B)/(E(B - V)) = 0.72 \pm 0.03 \) (Johnson & Morgan 1953);(Hovhannessian 2004)). We compute the reddening-free index as \( Q = -0.88 \pm 0.03 \). The values of index were calculated by Hovhannessian (2004) beginning from O8 to G2 spectral type for the luminosity classes between main-sequence and supergiants. As pointed out by Johnson & Morgan (1953) this quantity is almost constant between O8 and B0. Both calibrations yield an approximate spectral type of the triple system as O9. A preliminary analysis of the light curves obtained by Mayer et al. (2010) yields \( \log g = 3.6 \) for both stars of the eclipsing pair which indicates that they should be luminosity class of III, i.e. giants. Using the calibration of Martins, Schaerer, & Hillier (2005) for the stellar parameters of galactic O stars we obtained a spectral type of O(7.5±0.5)III for the more massive and O(9.5±0.5) III for the less massive secondary component of MY Ser. The effective temperatures are estimated as 34 000±1 000K and 30 000±1 000K for the primary and secondary stars, respectively. Thus, the intrinsic color of \( (B - V)_0 = -0.30 \pm 0.01 \) mag and the interstellar reddening \( E(B - V) = 1.05 \pm 0.01 \) mag are estimated.

Logarithmic limb-darkening coefficients were interpolated from the tables of van Hamme (1993). They are updated at every iteration. The gravity-brightening coefficients \( g_1 = g_2 = 1.0 \) and albedos \( A_1 = A_2 = 1.0 \) were fixed for both components, as appropriate for stars with radiative atmospheres. Since the preliminary analysis indicates that both stars fill their corresponding Roche lobes synchronous rotations were adopted and Mode 6 was used in the solution. This mode is used for the contact systems, e.g., both stars fill their limiting Roche lobes. The adjustable parameters in the light curves fitting were the orbital inclination \( i \), the effective temperature of the secondary star \( T_{eff2} \), the luminosity of the primary \( L_1 \), the third-body light contribution \( l_3 \) and the zero-epoch offset. The parameters of our final solution are listed in Table 4. The uncertainties assigned to the adjusted parameters are the internal errors provided directly by the code. In the
Table 4. Results of the simultaneous analyses of the Mayer’s UBV, and Davidge & Forbes’s UBVRI light curves for MY Ser.

| Parameter                  | Mayer et al. (UBV) | Davidge & Forbes (UBVRI) |
|----------------------------|--------------------|--------------------------|
| i                          | 73.76±0.08         | 77.98±0.30               |
| T_{eff,1} (K)              | 34 000±0.00        | 34 000±0.00              |
| T_{eff,2} (K)              | 29 350±0.00        | 29 750±0.115             |
| Ω_1 = Ω_2                 | 3.667±0.021        | 3.667±0.021              |
| r_1                        | 0.3825±0.0016      | 0.3825±0.0016            |
| r_2                        | 0.3733±0.0017      | 0.3733±0.0017            |
| \(L_{1}(L_{1}+L_{2})U\)   | 0.578±0.002        | 0.570±0.006              |
| \(L_{1}(L_{1}+L_{2})B\)   | 0.569±0.002        | 0.563±0.006              |
| \(L_{1}(L_{1}+L_{2})V\)   | 0.568±0.002        | 0.562±0.006              |
| \(L_{1}(L_{1}+L_{2})R\)   | 0.562±0.007        | 0.562±0.007              |
| \(L_{1}(L_{1}+L_{2}+L_{3})U\) | 0.388±0.002    | 0.472±0.006              |
| \(L_{1}(L_{1}+L_{2}+L_{3})B\) | 0.395±0.002    | 0.483±0.005              |
| \(L_{1}(L_{1}+L_{2}+L_{3})V\) | 0.406±0.002    | 0.485±0.006              |
| \(L_{1}(L_{1}+L_{2}+L_{3})R\) | 0.495±0.005    |                      |
| \(L_{1}(L_{1}+L_{2}+L_{3})I\) | 0.484±0.005    |                      |
| \(\sum_{N=1}^{N} (O - C)^2\) | 0.2176           | 0.2127                   |
| σ                          | 0.0085             | 0.0118                   |

last three lines of Table 4 sums of squares of residuals \(\sum (O - C)^2\), number of data points \(N\), and standard deviations \(σ\) of the observed light curves are presented, respectively. The computed light curves are compared with the observations in Fig. 3. We also applied Mode 3, suitable for the over contact binaries, the orbital parameters did not vary considerably but the sum of squares of the residuals is slightly increased.

Wilson (1992) suggestion about the unit of third light was to express it in the light curve of the triple system at a definite orbital phase. The values of \(l_3\) in units of total triple system light were estimated at the reference phase 0.25, from the Mayer et al.’s light curves, to be 0.388±0.002, 0.395±0.002 and 0.406±0.002 in U, B, V passbands, respectively. The light contributions of the third star from the Davidge and Forbes’ light curves are found to be 0.472±0.006, 0.483±0.005, 0.485±0.006, 0.495±0.005, and 0.484±0.005 in U, B, V, R and I passbands. Its contribution increases towards the longer wavelengths except the I-passband. Our spectra show that the light contribution of the third star to the total light is about 0.39 at the \(λ\) 6563. It is in a good agreement with that obtained from the analysis of Mayer et al.’s light curves.

6 RESULTS AND DISCUSSION

Combining the results of radial velocities and light curves analyses we have calculated the absolute parameters of the stars. Separation between the components of eclipsing pair is calculated as \(a = 36.69±0.20 R_\odot\). The fundamental stellar parameters for the components such as masses, radii, luminosities are listed in Table 5 together with their formal standard deviations. The stan-
Table 5. Properties of the MY Ser components

| Parameter          | Primary          | Secondary         |
|--------------------|------------------|-------------------|
| Mass (M_⊙)        | 32.23±0.54       | 30.59±0.53        |
| Radius (R_⊙)      | 14.23±0.75       | 13.89±0.75        |
| T_{eff} (K)       | 34 000±1000      | 29 350±1000       |
| log (L/L_⊙)       | 5.383±0.069      | 5.302±0.054       |
| log g (cgs)        | 3.640±0.046      | 3.638±0.047       |
| (v sin i)_{calc.} (km s^{-1}) | 214±11         | 210±11            |

The standard deviations of the parameters have been determined by JKTABSDIM\(^2\) code, which calculates distance and other physical parameters using several different sources of bolometric corrections (Southworth et al. 2005). The mass for the primary of M_p = 32.23 ± 0.54M_⊙ and secondary of M_s=30.59±0.53M_⊙ are consistent with O(7-8)III and O9.5III stars.

We estimate the interstellar reddening of E(B-V)=1.05 mag which is consistent with that of 1.02 mag obtained by Barbon et al. (2000) for the cluster NGC 6604. Using this value and the apparent visual magnitude of the triple system as V=7.65 given by Leitherer et al. (1987) and taking into account their contributions we find apparent visual magnitudes of the three stars as V_p=8.83, V_s=9.13 and V_3=8.63 mag. The bolometric corrections are adopted from Martins, Schaerer, & Hillier (2005) as -3.20, -2.80 for the primary and secondary stars, respectively. In Table 6 we present magnitudes corrected for interstellar absorption, color indices of the three stars as well as the derived distances for the components of the eclipsing binary system. Absolute bolometric magnitude of the Sun is taken as 4.74. The distances for the primary and secondary star found to be 1 645±133 and 1 640±143 pc, respectively. The distance to the NGC 6604 has been subjected to the various studies. Moffat & Vogt (1975) derived a distance of 1.64 kpc, while Barbon et al. (2000) estimated a distance of 1.7 kpc. Our result is consistent with the earlier values. The distance determination is, of course, depended upon the total apparent magnitude of the multiple system. It varies from 7.37 (Mayer et al. (2010)) to 7.65 mag. Leitherer et al. (1987). If we adopt the former the distance to the system is reduced to 1 445 pc, decreased by about 12%.

Fortunately, the third star in the HD 167971 system has been angularly resolved by De Becker et al. (2012). Their multi-epoch VLTI observations provided evidence for a gravitational link between the third star and the close eclipsing pair. The separation between the third star and the eclipsing binary has been varied from 8 to 15 mas over the three-year baseline. Although limited interferometric measurements are available they suggest that the components evolve on a wide and very eccentric orbit, probably e ≥ 0.5. Using near infrared luminosity ratio of 0.8 they suggest spectral...
types for the stars in the close binary between O6 and O7 main-sequence stars. As a result they assumed an (O6.5V+0.6.5V)+O8I spectral classification for the stars in the HD 167971.

In §3 we presented parameters of the third-body orbit. Since the O-C curve was however only poorly covered by minimum times and the times were very uncertain the parameters given in Table 2 were not well established. Even a preliminary set of parameters for the third-body orbit is obtained the parameters appear to support the interferometric measurements. The orbital period about the center-of-gravity with the third-star is derived as 21.2±0.7 yr, $a_{12}\sin i_3=5.5\pm0.7$ AU and $e=0.53\pm0.05$. Using the projected semi-major axis and the period of the third-body orbit we estimate a mass function for the third star as $f(m)=0.370\pm0.036M_\odot$. Since the masses of the eclipsing pair’s components are derived as 32.23 and 30.59 solar masses and the eclipsing pair orbiting around common center-of-mass with a period of 21.2 yr the mass of the third star can easily be calculated from the mass function. The mass of the third body has been computed as 12.70, 15.0 and 28.8 $M_\odot$ for the inclination of 90, 60 and 30 degrees, respectively. A plausible inclination of the third-body should be smaller than 30 degree when the light contribution is taken into account. Assuming an inclination of 30 degrees we estimate separation between the third-body and eclipsing pair as 8.07 and 26.26 AU, when they are at the periastron and apastron on their orbits, respectively. They correspond to linear angular separations of 4.9 and 15.9 mass for a distance of 1 650 pc. They are in good agreement with the interferometric measurements between 8.7 and 15.1 mas, obtained by De Becker et al. (2012). Unfortunately, the four interferometric measurements were made in two epochs, e.g. in 2008 and 2011. We derived the semi-amplitude of the radial velocity of the eclipsing pair’s gravity center as $K_{12}=9\pm1$ km s$^{-1}$. Therefore, the semi-amplitude of the radial velocity of the third star should be about 20 km s$^{-1}$. This result is in a good agreement with the measured average radial velocities of -26±13 km s$^{-1}$ for the third star.

The roughly inferred intrinsic magnitudes and color indices are already presented in Table 6. With the color indices of $(U-B)_0=-1.080$ and $(B-V)_0=-0.275$ mag the third star appears to be later spectral type than both components of the eclipsing binary. Its intrinsic colors yield a spectral type close to B0 giant or supergiant. If it is a (O9.5-B0)III star its absolute visual magnitude and bolometric correction are deduced as -5.10 and -2.84 mag from the calibrations of Martins, Schaerer, & Hillier (2005). Using the intrinsic apparent visual magnitude of 5.36 we obtained a distance to the third star as 1 280 pc. If it were a supergiant, i.e. (O9.5-B0)I, its distance would be 2 130 pc. For an extreme case, if the third star is assumed to be a main-sequence star then it would lie at a distance about 7 00 pc. These comparisons point out that the third star’s luminos-
ity class is between giant and supergiant. It could also be explained by a (O9.5-B0)III-I star at the same distance as the binary.

The three lines are well separated at the quadratures of the eclipsing pair. We measured equivalent widths (EW) of the third star’s $\text{He I} \ 4471$ and $\text{He II} \ 4541$ lines. The average logarithmic ratio of the equivalent widths (EW) of the third star’s is about $1.19 \pm 0.17$, which corresponds to a B0-type star (van der Hucht 1996). On the other hand the ratio between the $\text{Si IV} \ 4088$ and $\text{He I} \ 4143$ lines is obtained as $0.34 \pm 0.04$. This value corresponds to III-I luminosity class stars. The ratios of the selected spectral lines confirm our spectral classification from the intrinsic color indices.

De Becker et al. (2012) estimated spectral types for the stars in close binary O6.5V, assuming that luminosity ratios should be similar for both bolometric and K-band luminosities. They also noted that for a giant luminosity class the close binary components should not be earlier than O8 spectral type. They propose for an O8I for the third-star. On the other hand, Leitherer et al. (1987) reported that the O supergiant is the most luminous and dominates the optical and UV spectra. However, our analysis of the Mayer et al. (2010) light curves show that luminosity ratios are 0.63, 0.65 and 0.68 in the U, B and V-passband. These ratios are obtained as 0.89, 0.94, 0.94, 0.98 and 0.94 from the UBVRI light curves of Davidge & Forbes (1988). In contrary to the De Becker et al. (2012), we find that eclipsing binary is brighter than the third star. The same result is also confirmed by the spectra we obtained around the $H_\alpha$. Perhaps, future spectroscopy will reveal more about its possible nature.

NGC 6604 is located in a rich part of the Milky Way in the constellation Serpens. Its galactocentric distance is about 6.9 kpc, which places it on the outer boundary of the Carina–Sagittarius arm, about 65 pc above the galactic plane. Reipurth (2008) suggest that NGC 6604 forms the densest part of the wider Ser OB2 association, which contains about 100 OB stars. His studies show that the age of the cluster is about 4-5 Myr and star formation is still ongoing in the association.

Figure 4 shows the components of MY Ser in the log $T_{\text{eff}}$-log $L/L_\odot$, log $T_{\text{eff}}$-log $g$ and mass-log $g$ planes. The evolutionary tracks and isochrones for the $Z=0.014$ with mass-loss are adopted from Ekström et al. (2012). While the location of the more massive companion in the $T_{\text{eff}}$-log $L/L_\odot$ and log $T_{\text{eff}}$-log $g$ is consistent with the models for single stars with an age of about 4 Myr the secondary star appears to lower temperature with respect to its mass with an age of about 6 Myr. Three components of the massive multiple system HD 167971 seem to have same age about 4 Myr. These age estimates are consistent with that proposed by Reipurth (2008) for the open cluster NGC 6604. Hilditch et al. (1996) discussed the properties of six O to B0 detached
Figure 4. Locations of the components of MY Ser on the a) log $T_{\text{eff}}$-log $L/L_\odot$, b) log $T_{\text{eff}}$-log $g$ and c) mass-log $g$ planes. Evolutionary tracks and isochrones are adopted from Ekström et al. (2012) for $Z=0.014$ with mass-loss, labelled in age (Myr). Location of the third star on the log $T_{\text{eff}}$-log $L/L_\odot$ diagram is also shown at the panel (a, b, and c) with triangle symbol.

binaries. They concluded that the masses and radii for the components in these systems are all in agreement with the theoretical models of solar composition. However, O-star temperature should be reduced by an average of about 1 000 K to obtain in agreement with the models. In the case of MY Ser the secondary star, in contrary to their result, seems to have lower temperature by about 3 000 K.

MY Ser appears to have just filling the entire outer contact surface with fill-out factor of 0.99. As suggested by Mayer et al. (2010), who determined a fill-out factor of 0.50, MY Ser is an over-contact binary.

7 CONCLUSION

HD 167971 is one of the rare triple system with massive components. Analysis of the radial velocities and light curves suggest that the inner binary consists of an O7.5 III and O9.5 III stars. The spectral type of the third star is estimated as O9.5 between giant and supergiant luminosity.
Table 6. The intrinsic apparent visual magnitudes, color indices, spectral and distances for the components of MY Ser. The intrinsic magnitudes and color indices for the third-star and HD 167971 stellar system are given in columns 4 and 5, respectively.

| Parameter | Primary | Secondary | Third-body | Total |
|-----------|---------|-----------|------------|-------|
| U (mag)   | 4.109±0.00 | 4.449±0.00 | 4.007±0.00 | 2.980±0.00 |
| B (mag)   | 5.237±0.00 | 5.559±0.00 | 5.087±0.00 | 4.079±0.00 |
| V (mag)   | 5.583±0.00 | 5.859±0.00 | 5.362±0.00 | 4.383±0.00 |
| U-B (mag) | -1.128±0.00 | -1.090±0.00 | -1.080±0.00 | -1.099±0.00 |
| B-V (mag) | -0.326±0.00 | -0.320±0.00 | -0.275±0.00 | -0.304±0.00 |
| Sp.Type   | O(7.5±0.5) III | O(9.5±0.5) III | — | — |
| Mbol     | -8.718±0.00 | -8.015±0.00 | — | — |
| BC (mag)  | -3.20±0.00 | -2.80±0.00 | — | — |
| Mv (mag)  | -5.518±0.00 | -5.215±0.00 | — | — |
| V-Mv (mag)| 11.081±0.00 | 11.074±0.00 | — | — |
| d (pc)    | 1645±133 | 1640±143 | — | — |

classes. The times for mid-primary and mid-secondary eclipses are analysed for the first time for the parameters of the third-body orbit. The gravitational link between the MY Ser and a third-star is confirmed.

Using our estimation of $E(B-V)$ and $A_v$, we determined a distance of about 1 650 pc which is in agreement with the distance of the open cluster NGC 6604. The properties of the components of MY Ser are compared with theoretical models. While the locations of the more massive primary component on the effective temperature-luminosity, effective temperature-gravity and mass-gravity planes are consistent with the models the less massive secondary star appears to have lower temperature with respect to its mass. Both components of MY Ser locate on the mass-gravity plane, that matched very well with an isochrone of 4 Myr. The ages suggested for NGC 6604 range from 4 to 6 Myr. Our results yield that the age of the close binary, is close to 4 Myr, and thus NGC 6604, where star formation still is going on.

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