Properties of massive stars in Galactic binary systems

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Resumen / En el marco del proyecto OWN, usamos datos espectroscópicos de alta resolución de la binaria masiva HD 54662 para medir velocidades radiales y desentramar los espectros de las dos componentes del sistema, que hemos clasificado como O6.5 Vz(n) y O7.5 Vz. Obtenemos una nueva solución orbital espectroscópica para el sistema, con un periodo de 5.50 ± 0.02 años. Usamos datos astrométricos publicados para calcular masas estelares absolutas de 24 ± 1 y $20 \pm 1\,M_\odot$ para las componentes A y B, respectivamente. Analizamos cuantitativamente los espectros desentramados con modelos FASTWIND de atmósferas estelares y calculamos masas evolutivas actuales usando la herramienta BONNSAI. Obtenemos masas evolutivas demasiado altas, lo cual podría estar relacionado con el problema de discrepancia de masas.

Abstract / Within the OWN project, we use high resolution spectroscopic data of the massive binary system HD 54662 to measure accurate radial velocities and disentangle the spectra of the two components, which we classify as O6.5 Vz(n) and O7.5 Vz. We obtain a new spectroscopic orbital solution of the system, with a period of $P = 5.50 \pm 0.02$ yr. We use published astrometric data to derive absolute stellar masses of 24 ± 1 and $20 \pm 1\,M_\odot$ for components A and B, respectively. We analyze quantitatively the disentangled spectra using FASTWIND stellar atmosphere models and infer current evolutionary masses using the BONNSAI tool. We find too high evolutionary masses, which could be related to the mass discrepancy problem.

Keywords / stars: massive — stars: binaries — stars: atmospheres — stars: fundamental parameters

1. Introduction

Massive stars are considered cosmic engines that shape the physical and chemical structure of their host galaxies. Several mechanisms, such as rotation and stellar winds, affect the life of these extreme objects. Multiplicity is a crucial factor in massive stars, since more than half of them are expected to be born in a binary or multiple system (Sana et al., 2013; Sota et al., 2014; Barbá et al., 2017), and it affects their evolution by means of binary interaction processes and mergers (Langer, 2012; de Mink et al., 2013).

HD 54662 is an O-type double-lined spectroscopic binary located in the Seagull Nebula complex. Its binary nature was first revealed by (Boyajian et al., 2007, hereafter B07), who estimated an orbital period of ~ 560 d. Recently, Le Bouquin et al. (2017, LB17 hereafter) used VLTI interferometric data and radial velocity (RV) measurements by B07 to derive a period of 2100 d, confirming that HD 54662 is one of the spectroscopic binaries with the longest periods known to date. These authors provided a 3D solution for the orbit, estimating excessively high absolute stellar masses of $316\,M_\odot$ and $58\,M_\odot$ for the primary and the secondary components, respectively. On the other hand, Mossoux et al. (2018, M18 hereafter) used new spectroscopic observations and the results from LB17 to derive absolute stellar masses below $10\,M_\odot$, too low for O-type stars.

In this work, we use high-quality, multi-epoch spectroscopic data in order to obtain a new orbital solution for HD 54662 and characterize the properties of both components of the system via stellar atmosphere and evolutionary models.

2. Observations

We have used the spectroscopic data gathered by the OWN Survey (Barbá et al., 2017), a project devoted to study the multiplicity status of Galactic massive stars. It has obtained more than 7 000 high-resolution, optical spectra of O-type and WR stars in the Southern hemisphere, using 2-m class telescopes in Chile (La Silla, Las Campanas and CTIO) and Argentina (CASLEO). For HD 54662, we have used ∼50 spectra with $R = 15\,000 - 50\,000$ and $S/N > 100$ with a good phase coverage (see Fig. 1 in Sec. 3.).

3. Spectral disentangling and orbital solution

HD 54662 has two components: one with broad lines (component A, which is the most massive of the system) and one with narrower lines (component B), which are highly blended. Using the iterative method by González & Levato (2006), we performed a spectral disentangling process to obtain the individual spectra of the components and accurate RV measurements (uncertainties below ~ 2 km s^{-1}). We used the MGB tool (Maíz Apellániz et al., 2012) to classify component A as O6.5 Vz(n) and component B as O7.5 Vz.

Fig. 1 shows the disentangled spectra of both components. Residuals from the disentangling process are

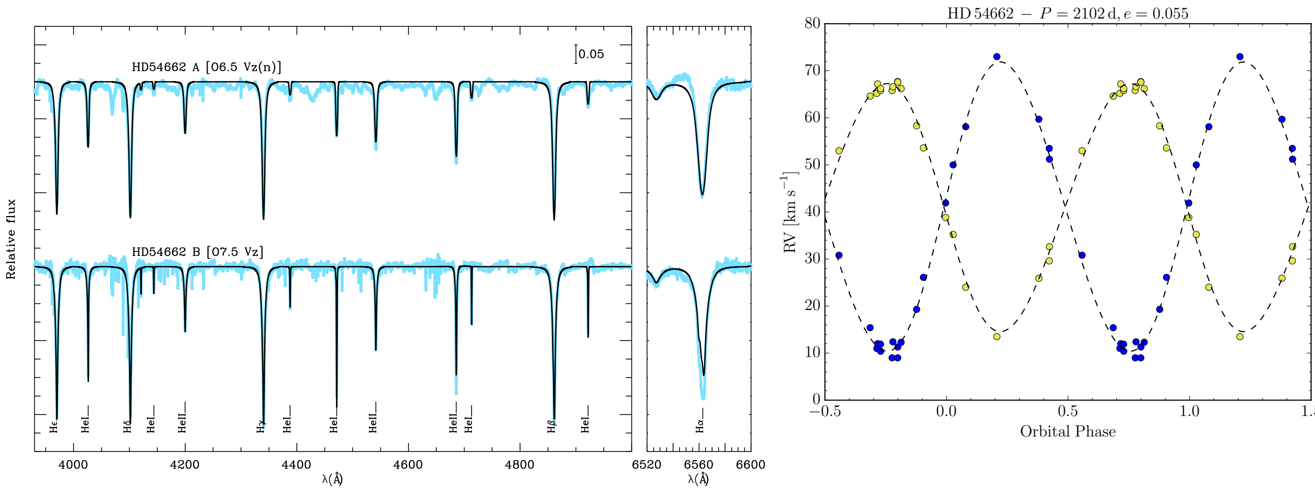

Figure 1: Results from the spectral disentangling and orbital solution. *Left:* Individual disentangled spectra of the components of HD 54662 (light blue). In black, best fitting FASTWIND spectrum from the quantitative spectroscopic analysis ($T_{\rm eff} = 39$ kK, log $g = 3.90$ dex for component A; $T_{\rm eff} = 39$ kK, log $g = 4.00$ dex for component B). Optical H and He diagnostic lines are indicated. *Right:* Spectroscopic orbital solution for HD 54662. RV measurements for components A (broad-lined) and B (narrow-lined) are plotted in yellow and blue, respectively.

present, mainly affecting the wings of the H Balmer lines, which is an important factor in the determination of surface gravities with synthetic spectra (see Sec. 4.).

We used RV measurements and the GBART code (improved version of Bertiau & Grobben, 1969, by F. Bareilles) to derive an orbital solution for the system (see Fig. 1, which shows a remarkably good fitting of the RV curve). We obtained a period of $P = 2012 \pm 9$ d, in agreement with previous results (LB17, M18). We derived RV semi-amplitudes of $K_{\rm A} = 26.4 \pm 0.3$ and $K_{\rm B} = 30.7 \pm 0.3$ km s^{-1}, which differ significantly from LB17 ($K_{\rm A} = 17.8 \pm 0.8$ and $K_{\rm B} = 98.0 \pm 18.0$ km s^{-1}) and M18 ($K_{\rm A} = 19.3 \pm 0.6$ and $K_{\rm B} = 22.9 \pm 0.7$ km s^{-1}). This discrepancy could be likely related to different assumptions in the Gaussian models used to fit the line profiles when measuring RVs.

Additionally, we used our RV estimates and the astrometric data from LB17 to compute a 3D solution for the orbit using the ORBIT* code by A. Tokovinin. We estimated an inclination angle of the orbit of $i = 75 \pm 0.5°$ (almost the same as LB17) and a distance to the system of 1087 ± 25 pc, in agreement with LB17 and Gaia DR2 (Bailer-Jones et al., 2018). We derived absolute stellar masses of 24 ± 1 and 20 ± 1 M$_\odot$ for components A and B, respectively, which are consistent with the expected stellar masses for O-type stars, and differ significantly with the results from LB17 and M18 due to the differences in the estimated RV semi-amplitudes.

4. Quantitative spectroscopic analysis

We performed a quantitative analysis of the individual spectra in order to estimate the physical properties of each component. In a first step, we characterized the broadening of the line profiles by means of the IACOB-BROAD tool (Simón-Díaz & Herrero, 2014). We used the O III λ 5592 line to derive a projected rotational velocity ($v \sin i$) of 160 and 40 km s^{-1} for components A and B, respectively. This remarkable difference in $v \sin i$ between both components of HD 54662 is one of various cases discovered within the OWN Survey (see,e.g. Putkuri et al., 2018). This phenomenon could be related to asynchronism or non-parallel rotation axes (see, e.g. Hut, 1981), representing a key factor to consider when modeling massive stars in binary systems.

In a second step, we utilized IACOB-GBAT (Simón-Díaz et al., 2011) to determine mean values and uncertainties for stellar parameters (effective temperatures, surface gravities, helium abundances and wind parameters, see Sec. 5.). This automatic tool is based on a large grid of precomputed FASTWIND (Santolaya-Rey et al., 1997; Puls et al., 2005) stellar atmosphere models. Fig. 1 shows the synthetic models from the grid that best fit the individual spectra.

Stellar radii, spectroscopic masses and luminosities were computed using IACOB-GBAT by means of the absolute magnitudes in the V-band, which were estimated using the apparent magnitude of the system (m$_V = 6.21$, see Ducati, 2002), the brightness factors from the disentangling process and our estimation of distance (Sec. 3.). We used the Bayesian tool BONNSAI (Schneider et al., 2014) to compute current evolutionary masses (see Sec. 6.).

5. Properties and evolutionary status of HD 54662

We obtained effective temperatures ($T_{\rm eff}$) of 39.1 ± 1.0 and 39.0 ± 0.6 kK, and surface gravities (log g) of 3.90 ± 0.10 and 4.00 ± 0.10 for components A and B, respectively. These results slightly differ with those from M18, who obtained 37.5 ± 1.0 and 37.7 ± 1.0 kK for $T_{\rm eff}$, and 3.81 ± 0.10 and 3.96 ± 0.10 for log g, for components

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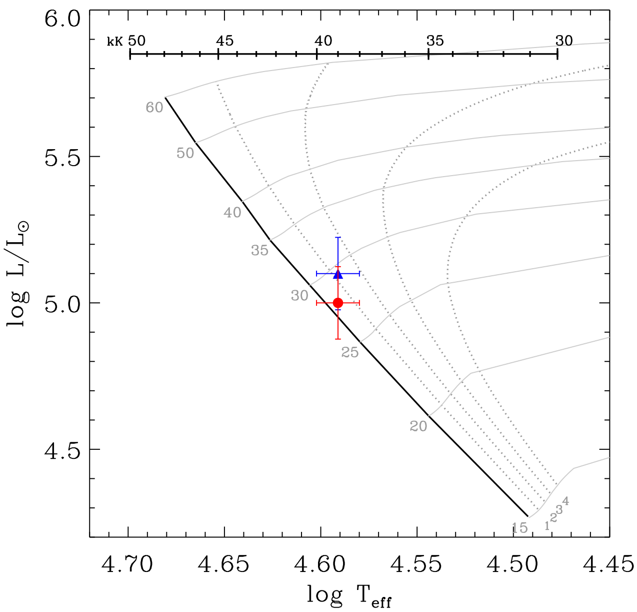

Figure 2: Location of both components of HD 54662 in the Hertzsprung–Russell diagram. The blue triangle and the red circle correspond to the primary and secondary components, respectively. Evolutionary tracks and isochrones for single stars with solar metallicity are taken from Brott et al. (2011), with an initial rotational velocity of $v_{ini} = 166\,{\rm km\,s^{-1}}$. Initial stellar masses (in solar masses) and ages (in Myr) are shown. The thick black isochrone corresponds to the *Zero Age Main Sequence* (ZAMS).

Table 1: Dynamical, spectroscopic and evolutionary masses for both components of HD 54662.

Stellar mass	A	B	Unit
$M_{\rm dyn}$	24 ± 1	20 ± 1	$M_\odot$
$M_{\rm sp}$	24 ± 5	19 ± 5	$M_\odot$
$M_{\rm ev}$	30 ± 2	28 ± 2	$M_\odot$

A and B, respectively. Differences in the disentangling process and the distortions of the line profiles, as commented in Sec. 3., could explain this discrepancy.

Fig. 2 shows the position of the stars of HD 54662 in the H–R diagram. Both components are very young objects (with ages ~ 1 Myr), in agreement with their Vz characteristic (Sabín-Sanjulián et al., 2014; Arias et al., 2016). The young age of HD 54662 makes a tidal synchronization or mass transfer improbable, so the inconsistency of the rotational velocities between both components (Sec. 4.) could be related to their formation process.

6. Mass discrepancy

In this work we have used three different methodologies to estimate stellar masses (see Table 1): *dynamical masses*, using RV measurements and astrometric data by LB17; *spectroscopic masses*, using FASTWIND stellar atmosphere models, and *evolutionary masses*, using evolutionary models from Brott et al. (2011).

Dynamical and spectroscopic masses agree within the error bars. However, evolutionary masses are $\sim$20 – 50 % higher than the other masses in both stars, which could be related to the long-standing *mass discrepancy problem* (Herrero et al., 1992, 2002). Sabín-Sanjulián et al. (2017) and Markova et al. (2018) have recently shown that evolutionary masses tend to be higher than the spectroscopic ones in the low mass regime ($M_* \lesssim 20 -$ $30\,{\rm M_\odot}$), and the discrepancy is present in environments of different metallicities. A detailed quantitative study of a large number of binaries is needed to reach a compelling conclusion on the mass discrepancy problem.

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