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New evolutionary clues to understand the nature of massive stars

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Abstract

Massive stars play a pivotal role in shaping the Universe. However, comparisons between observational data and theoretical models of massive stars have given rise to long-standing and new discrepancies that have questioned our understanding of these objects. A main uncertainty arises from the overdensity of B-type supergiants (BSGs) located beyond the terminal-age main sequence, as predicted by the state-of-the-art evolutionary models. It remains unclear whether the width of the main sequence has to be redefined or if the overdensity is the result of overlapping populations following different evolutionary paths. Here, we outline some key findings from the first author's Ph.D. thesis, which aims at improving this situation by carrying out a holistic empirical study of the largest spectroscopic sample of BSGs analyzed to date. The results provide important clues about the nature of these objects and establish new constraints on the evolutionary models of massive stars.

1 Introduction

Despite representing a minority of stars, massive stars play a crucial role in the Universe. Their hot stellar winds, intense UV radiation, and extremely energetic life-ends all heavily influence their circumstellar and interstellar medium, becoming important drivers of the dynamical evolution of galaxies [18]. They are also the primary source of heavy-element production, contributing to the chemical enrichment of galaxies [20] and altering the chemical properties of the next generations of stars. Massive stars are also the progenitors of some of the most exotic and violent phenomena in the Universe, such as gamma-ray bursts or gravitational waves [26].

Despite their importance, comparisons between observational data and theoretical models of massive stars have revealed long-standing and new discrepancies that challenge our understanding of the properties and evolutionary nature of these objects. One of the main uncertainties arises from the overdensity of B-type supergiants (BSGs) located beyond the predicted terminal age of the main sequence (TAMS) [14] in the Hertzsprung–Russell (HR) diagram, where the relative number of objects should decrease significantly. It remains unclear whether the TAMS position needs to be re-adjusted in the models, altering the width of the main sequence, or if the observed overdensity arises from different overlapping populations following different evolutionary paths. These include stars evolving in the main sequence, returning from a post-red supergiant (RSg) phase [7], or resulting from binary interaction [6, 8].

It has been proposed that the observed lack of fast-rotating objects below a given effective temperature can be used to locate the end of the main sequence [29, 3]. However, the lack of these objects could also be a consequence of the theoretically predicted and widely accepted increase in mass-loss rates over the wind bi-stability region [28]. Nevertheless, some studies employing reduced samples have suggested that such an increase is not present [17, 13, 22].

To improve this situation and effectively compare empirical results with different theoretical predictions, statistically significant samples are required. In this regard, our work comprised the study of $\sim$750 Galactic BSGs, combining multi-epoch high-resolution spectroscopic data from the IACOB project and the ESO archive with Gaia distances, becoming the largest holistic empirical study of the physical and chemical properties of these objects performed to date.

2 Methodology

The quantitative spectroscopic analysis of the data has been carried out using two different semi-automated tools. The line-broadening analysis, used to derive the projected rotational velocity ($v \sin i$), was achieved using the `iacob-broad` tool [25]. Other parameters, including effective temperature ($T_{\rm eff}$), surface gravity ($\log g$), the wind-strength parameter ($\log Q$) and the surface abundances of helium (He), carbon (C), nitrogen (N), and oxygen (O), were obtained using a statistical emulator for FASTWIND [24, 27] synthetic spectra, combined with a Markov chain Monte Carlo method. Additionally, the multi-epoch spectra allowed for the identification of single- and double-line spectroscopic binaries in the sample. The distances to the stars were obtained from those quoted in [1] corrected for zero-point offset, and were used in combination with optical photometry (B, V) and infrared photometry (J, H, Ks) to derive the extinction (A_v) to each star. The radii and luminosities were calculated by using the observed V magnitudes together with the above information. The estimates of $\log Q$, combined with wind-terminal velocities from the literature and the derived radius, allowed us to obtain mass-loss rates [21].

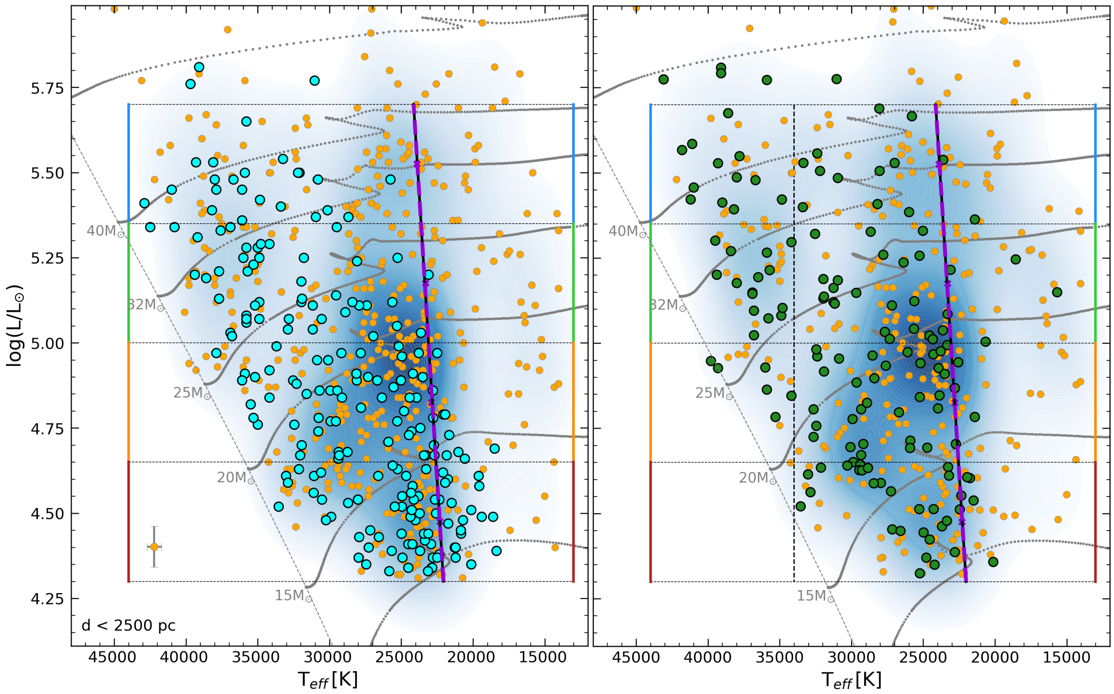

Figure 1: HR diagrams of the analyzed BSGs including also the results of O-type stars from [11, 12]. Left panel: stars located within the first 2500 pc from the solar neighborhood, separated in fast-rotating ($v \sin i > 100\,\mathrm{km s^{-1}}$; cyan circles) and regular stars. Right panel: stars in the complete sample for which three or more spectra are available, indicating with green circles indicating SB1 systems. In both panels, the evolutionary tracks are taken from the MIST web-tool for solar metallicity and no initial rotation. The dashed purple line indicates the adopted TAMS.

3 Results and discussion

We performed the quantitative spectroscopic analysis on ~750 Galactic BSGs of which the majority have reliable distances and luminosities. The parameter space covered by the sample ranges between 35–15 kK in $T_{\rm eff}$ and 4.3–6.0 dex in $\log(L/L_\odot)$. The left panel of Fig. 1 shows the distribution of stars in the HR, including also the results of O-type stars from [11, 12].

From the sample of BSGs, we were able to obtain upper limits on mass-loss rates for 116 of them. Our results showed no increase in the mass-loss rates over the bi-stability region. Therefore, we argued that the lack of fast-rotating stars, which we observed within our sample below ~21 kK (see Fig. 2), cannot be explained by the jump in mass-loss rates and is more likely connected with stars reaching the TAMS (see below). Moreover, we strongly recommend a reassessment of the standard prescriptions presently employed.

We investigated the location of the TAMS within our sample based on the drop in the relative number of objects. This task can be interpreted as the continuation of the work led by [9] and [4]. To achieve that, we first reduced potential observational biases by selecting

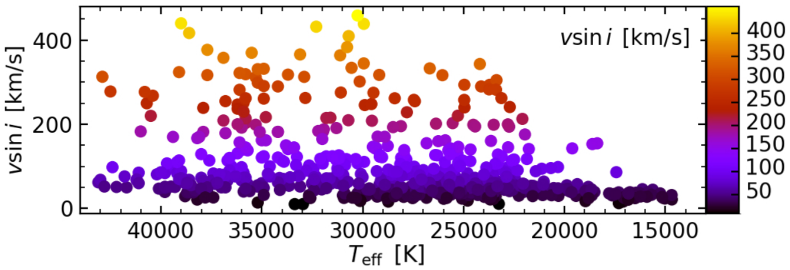

Figure 2: Distribution of $v \sin i$ against $T_{\rm eff}$ for the O-stars and BSGs included in Fig. 1.

stars located within 2500 pc of distance, reaching ∼70% completeness for all-sky targets with respect to the Alma Luminous Star III reference catalog (see the left panel of Fig. 1). We used a cumulative distribution function to identify the $T_{\rm eff}$ values of the drop in relative number of stars as a function of luminosity. We found that the position of the drop changes from 22 kK for the lowest luminosities to 24 kK for the higher ones, which we adopted as a new adopted TAMS (indicated with a purple line in both panels of Fig. 1). This result implies that, in contrast to the classical belief, B0-B2-type supergiants would still be main-sequence objects. Furthermore, our results provide strong empirical constraints for improving stellar evolution models, particularly the core overshooting parameter, which significantly affects the width of the main sequence. Additionally, we found that the percentages of detected single-line spectroscopic binaries decrease by 25% when crossing the TAMS (see the green circles on the right panel of Fig. 1), which is qualitatively also the case for double-line spectroscopic binaries, further supporting our proposed TAMS location (see also [16]). We found that the lack of fast-rotating objects closely follows the drop in relative number (see the cyan circles on the left panel of Fig. 1), and it is probably the result of stars reaching the TAMS and their critical rotational velocity.

As for O-type stars [5, 12], the distribution of $v \sin i$ values against $T_{\rm eff}$ in the BSG domain has a low-$v \sin i$ component and a tail of fast rotators ($v \sin i > 100\,{\rm km\,s^{-1}}$). The lack of surface braking of the low-$v \sin i$ component within the full $T_{\rm eff}$ range, plus the constant percentage of fast-rotating objects and the associated upper envelope of values above ∼21 kK, all indicate a very efficient angular momentum transport mechanism between the core and the surface of massive stars [12, 2]. We also interpret the larger fraction of slowly-rotating stars compared to the fast-rotating ones and the apparent decrease in $v \sin i$ of the former group with decreasing $T_{\rm eff}$ as an indicator that massive stars may enter the main sequence with low to mild initial rotations ($v \sin i / v_{\rm crit} \lesssim 0.2$). This would be further supported under the assumption that fast-rotating stars mainly result from binary interaction, as already suggested by several authors [6, 12].

We derived and compared spectroscopic masses ($M_{\rm sp}$) with evolutionary masses ($M_{\rm ev(HR)}$) to find objects with indications of having gained or lost mass at some point during their evolution. This includes stars that have undergone a blue-loop evolution [7], such as post-RSgs, which experience important mass-loss episodes during the RSG phase. However, our results first showed a systematic mass discrepancy [10] reaching $M_{\rm sp}/M_{\rm ev(HR)}$ ∼50% for stars within the main sequence and ∼30% for stars located after the TAMS. Assuming stars near the mean mass discrepancy as “normal” and those separated more than 3σ as “peculiar”, our results do not suggest the presence of post-RSgs within our sample, which has important implications for our understanding of massive star evolution.

We combined all available information, including the estimates of surface abundances, to also investigate the presence of stars that may have evolved through binary interactions [23]. Our results evidenced two interesting groups of stars. One that comprises objects that display helium surface enrichment ($Y_{\rm He}$ >0.13), of which the majority are fast-rotating and SB1 systems, being potential candidates for having received processed material from a post-main sequence companion [15]. The other interesting group is located immediately after the TAMS and above the $25M_\odot$ track. On average, the ∼20 stars in this group have $10M_\odot$ more than those objects located in the symmetrically opposite position with respect to the TAMS, and are our strongest candidates for being mass gainers (e.g., through mass transfer or merging) [19]. Furthermore, a preliminary analysis of the surface abundances of carbon, nitrogen, and oxygen indicates that these objects also exhibit higher N/O and N/C ratios compared to stars with similar $T_{\rm eff}$ and $\log(L/L_\odot)$ values that do not display helium-enriched atmospheres. Multi-epoch observations for 70% of these candidates also discard the presence of companions.

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