The IACOB project: searching for empirical signatures of binarity in fast-rotating Galactic O stars and B supergiants.

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Abstract: Rotation is one of the important parameters affecting the evolution and final fate of massive stars. Still the origin of fast-rotating stars in the massive OB domain remains unclear. Although the high spin rates detected in about 20-30% of these stars could just be an imprint of the star formation process, alternative scenarios – supported by the fact that the majority of massive stars are born in binary or multiple systems – propose that most of them are the result of binary interaction. The understanding of binary evolution in massive stars, as well as the impact that it can have on the stellar spin of the two individual components as the system evolve, has been a hot topic in the last decade. In this work, we aim at investigating the binary status of a statistically meaningful sample of Galactic fast-rotating O stars and B supergiants by performing a comprehensive multi-epoch radial velocity analysis of new high quality spectroscopic observation gathered in the framework of the IACOB project. Our ultimate objective is to provide solid empirical constraints to be considered by any theoretical attempt to investigate the impact and characteristics of binary evolution in the massive star domain.

The origin of fast-rotating stars

*from a theoretical point of view

de Mink et al. (2011, 2013)

1. Single star spin-up during the star formation process (the fraction of stars F_r~20%);

   product: effectively single fast-rotating star;

2. Binary interaction:

   a) mergers,

   product: effectively single fast-rotating star (F_r~10%);

   b) short-period binaries (tides mechanism, F_r~50%),

   P=2-3 days

   product: eclipsing binary system with a significant rotational mixing effect in the fast-rotating star;

   c) post-interaction binaries (mass transfer, F_r ~20%)

   P=5 days – several months

   product: **(i)** a stripped helium star (donor) with fast rotating gainer, if the initially more massive component (donor) explode as a supernova, **(ii)** the fast rotating gainer may become a walk/runaway star or **(iii)** the explosion may result a binary system with the fast rotating gainer and compact object (black hole or neutron star).

The origin of fast-rotating stars

*from an empirical point of view

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In order to examine these theoretical predictions, it is critical to obtain meaningful empirical information about the potential single/binary (and runaway) nature of these stars. Of particular interest is, e.g., to know what is the percentage of each of these type of objects among OB fast rotators and, in the case of binaries which kind of companion they have. Surface abundance may also provide useful hints.

To this aim, we gathered high quality multi-epoch spectroscopy for a sample of 27 Galactic O-type stars with a projected rotational velocity (vsini) above 200 km/s, and 7 evolved B supergiants (Sgs) with vsini > 100 km/s (all of them located in the fast tail of the corresponding spin rate distribution, see Fig. 1).

For each star, we have 15-20 spectra covering a typical time-span of several months an obtained with a cadence ranging from 1-2 days to a few weeks.

Working sample: 27 O-type stars (*v*sin*i* > 200 km/s) + 7 B Sgs (*v*sin*i* > 100 km/s)

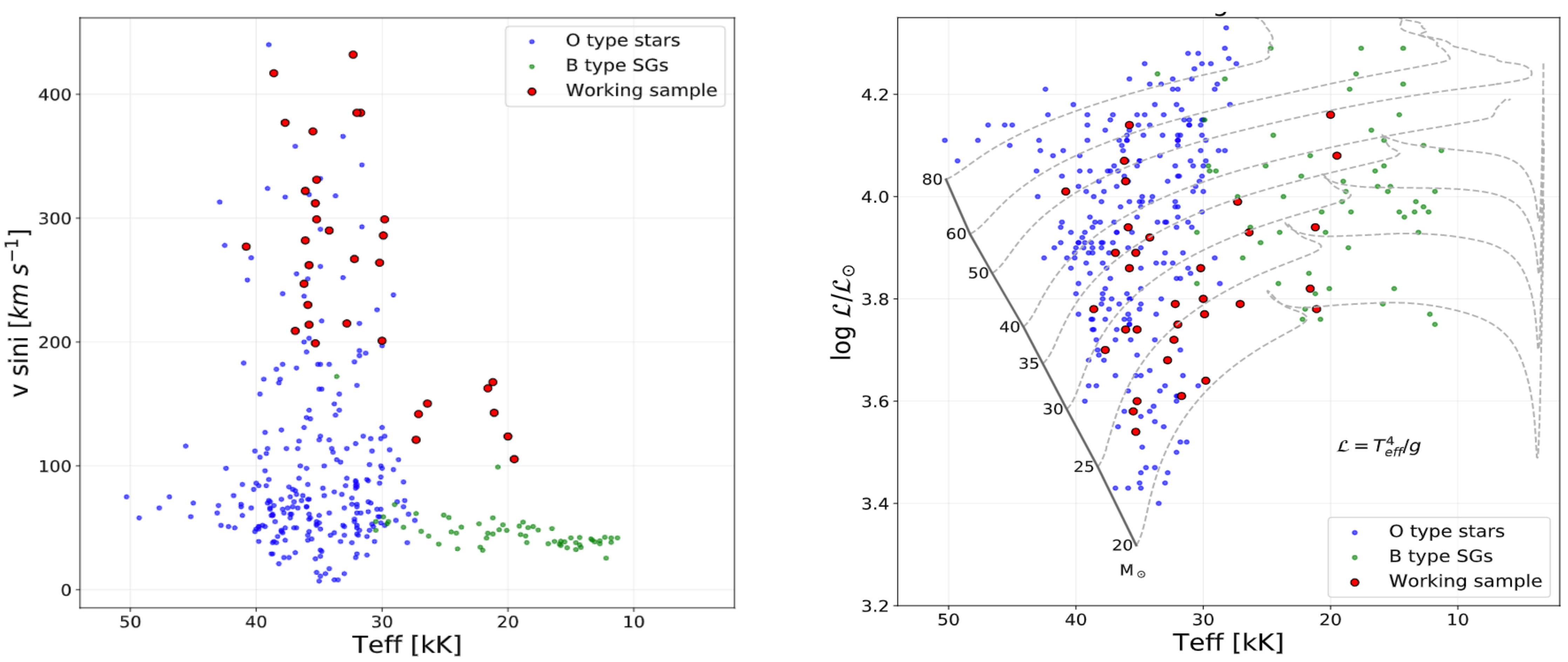

Fig.1: Distribution of our working sample of fast rotating O stars (27) and BSgs (7) in the *v*sin*i* - T_{eff} diagram (left) and the spectroscopic HR diagram (right, *Langer & Kudritzki 2014*). For reference, we also include the full sample of likely single and SB1 O-type stars (285) and B Sgs (68) observed and spectroscopically analyzed to date in the framework of the IACOB project (*Simón-Díaz et al. 2017, Holgado et al. 2020*). Location of the ZAMS and evolutionary tracks in the right panel from Brott et al. (2011, $v_{eq,ini}$=0)

Methodology and preliminary results (I)

We obtained radial velocity (RV) estimates for all the multi-epoch spectra of each star in our working sample of fast rotators by using a cross-correlation technique. As template, we used a synthetic rotationally broadened HeI line profile.

The spectroscopic binary (SB) status of each star was established by visual inspection of the detected type of line profile variability (LPV). If the displacement of the diagnostic line profile in one or several epochs was obvious, and clearly differentiated from LPV originated by stellar oscillations we marked the star as SB1. If we noticed a significant variable asymmetry in the line profiles we considered the star as SB2/LPV? whenever the star was not a clear SB2.

RV curves where complemented with information about the runaway nature of the stars, as established from the study of their proper motions (*Maíz Apellániz et al. 2018*). We also searched for eclipsing binary (EB) signatures in the TESS light curves.

In Fig. 2, where we present the peak-to-peak amplitude of detected variability in RV as a function of *vsini* for all the stars in the sample, we also summarize the compiled information about their LPV/SB/runaway nature. The same information is presented in the spectroscopic HR diagram in Fig. 3.

In addition, we compiled information about surface He abundances in the complete sample (fast rotators + reference sample) of O-type stars (Fig. 4).

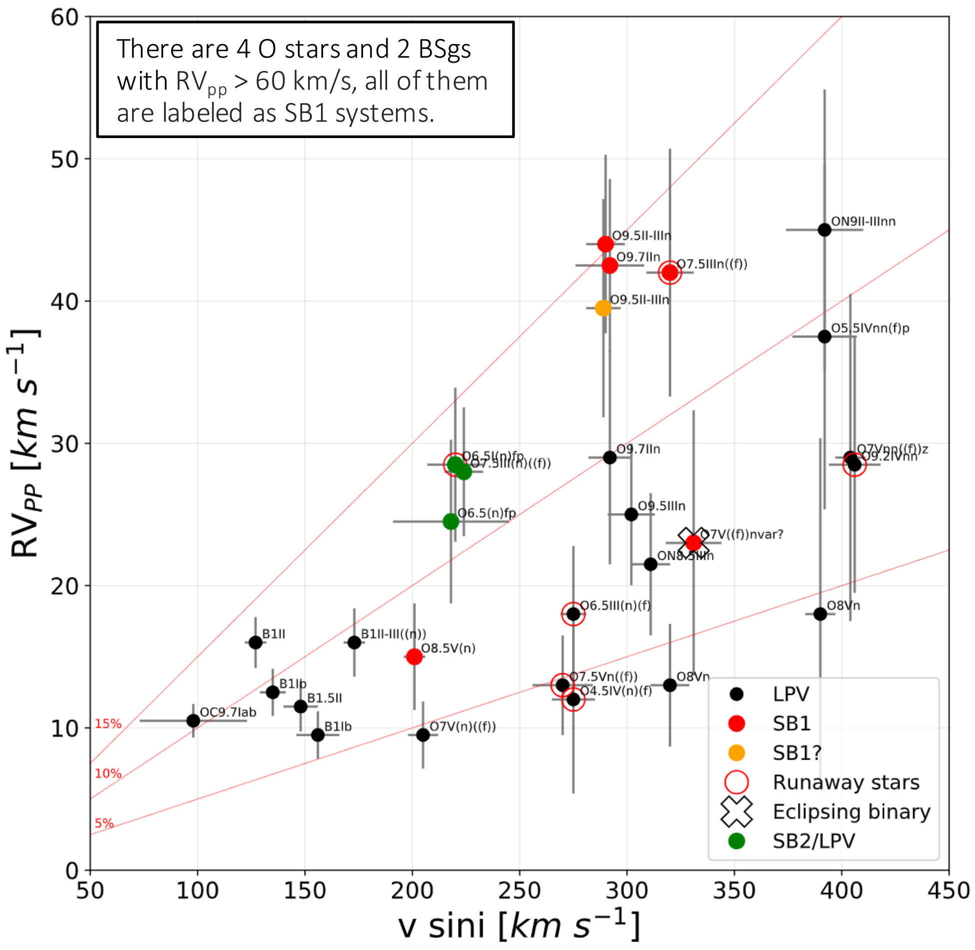

Fig.2: Distribution of the working sample of stars in the RV_{pp} – *vsini* diagram (zoomed in the RV_{pp} < 60 km/s region). Notes on the compiled information regarding the SB/EB/runaway nature of the stars is indicated in the bottom right corner. Spectral classification of each star is depicted close to the corresponding symbol. Red lines indicate the percentage of the global broadening of the line profile (due to rotation) represented by the detected RV_{pp}.

Preliminary results (II)

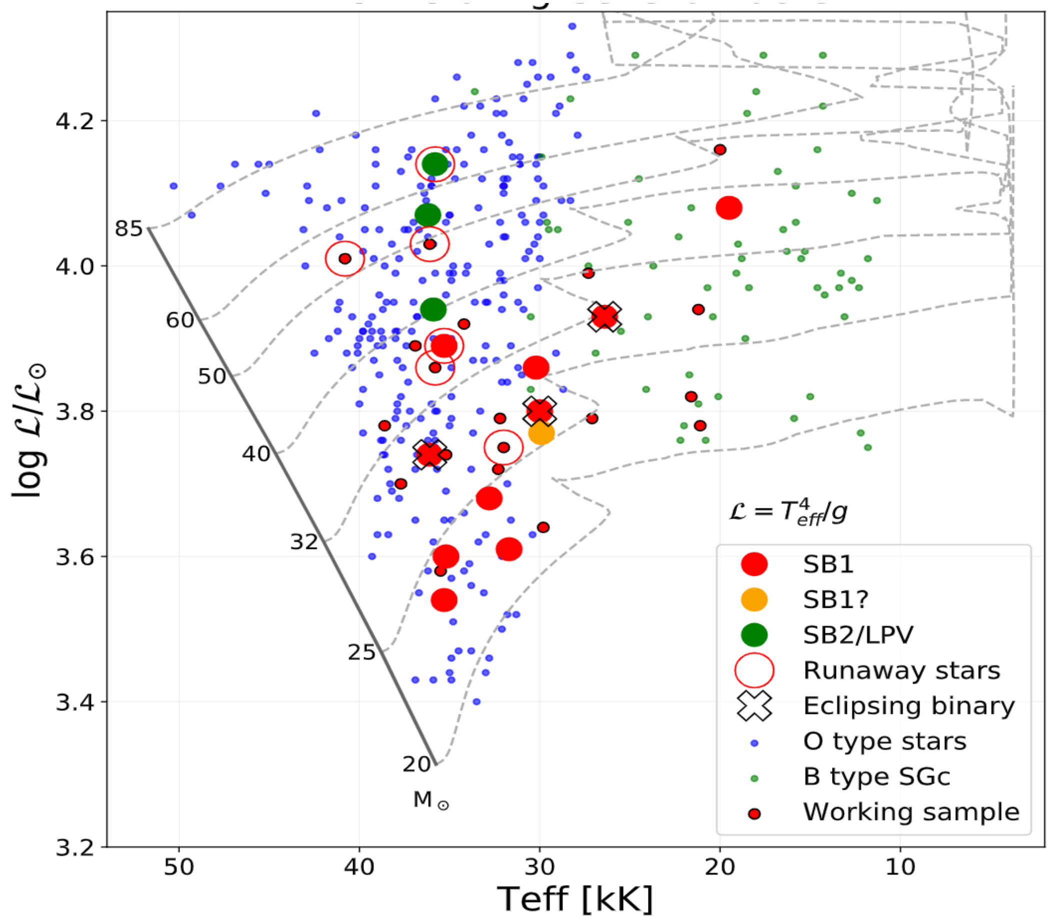

Fig. 3: Summary of compiled information about identified SB/EB/runaway systems in the spectroscopic HR diagram. Non rotating evolutionary tracks from *Ekström et al. (2012)* plotted for reference

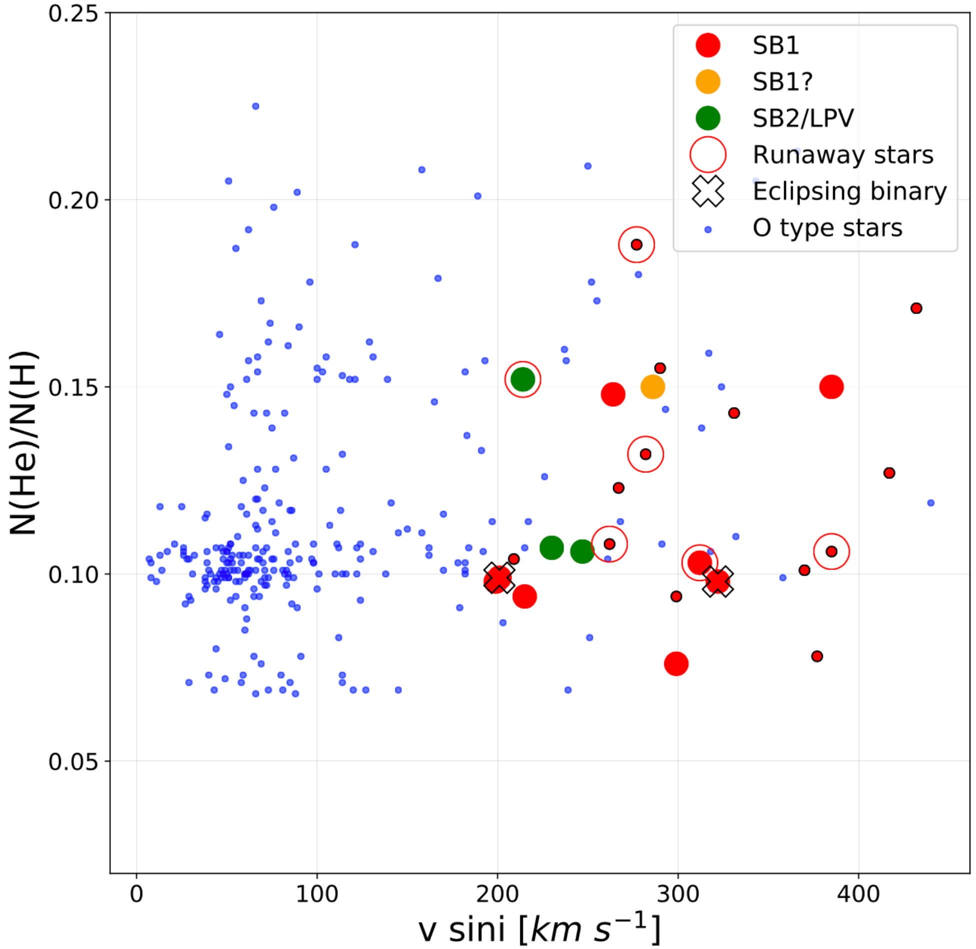

Fig. 4: Distribution of surface He abundances for the working and reference samples of O-type stars as a function of *vsini*. (adapted from Holgado 2019, PhD thesis)

Highlights

In this work we present preliminary results of our investigation of a statistically significant sample of fast-rotating O-type stars and B-type supergiants using multi-epoch spectroscopy. This is the first step towards a comprehensive study of physical and evolutionary properties of fast-rotating stars in the OB domain.

We gathered useful empirical information about kinematics (proper motions, radial velocities) and, in the case of the O-type stars, surface He abundance. From a preliminary analysis of this information we can draw the next preliminary conclusions:

1) we found 13 SB1/candidates for SB2 systems among our sample of 27 fast-rotating O-type stars, which means that ~50% of fast rotators are actual binaries; this binary fraction appears to be higher respect to the non fast-rotating O type stars (~35% according to Sana et al. 2013);

2) by including the runaway stars in this statistic the percentage of actual and post-interacting binaries will be ~60% in the O stars domain;

3) we find a significant spread in the surface He abundances for our sample of O type fast-rotating stars with different cases of binary status and kinematic regimes, which indicates the absence of prominent chemical composition patterns. Thus we can not clearly separate the evolutionary scenarios by using only one physical property for this type of stars.

Further investigation is required for the B type fast rotators. Thus we excluded them from our preliminary conclusions so far.

The results presented here point to different evolutionary pathways for fast rotators and further investigation of their physical properties will shed the light on their role in the evolution and the effect of rotation in physics of massive stars.