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Implications of Boron Surface Abundances in Massive Stars

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Abstract

The evolution of massive stars can be influenced by rotationally induced internal mixing, for which surface boron abundances can serve as a key indicator. We compare rotating single star models to observational data from massive stars with boron observation. Through a Bayesian analysis, we find that about two-thirds of the stars in our sample are well represented by the models, confirming the existence of rotational mixing in radiative stellar envelopes. They were well represented by the models with 50% weaker rotational mixing than the widely adopted one. However, one-third of the stars, which are mostly boron-depleted slow rotators, do not fit the models, suggesting that these stars may have experienced a different boron depletion mechanism or formation channel, such as a binary merger.

Keywords: stars: abundances, stars: evolution, stars: massive, stars: rotation

1. Why Look at Boron?

Rotationally induced internal mixing is believed to affect the evolution of massive stars greatly (e.g., Meynet and Maeder, 1997; Heger et al., 2000). For example, fast rotating stars can experience quasi-chemically homogeneous evolution and evolve towards the long gamma-ray burst progenitors (Yoon and Langer, 2005). However, its efficiency has remained uncertain, and surface nitrogen abundances have been used to calibrate the efficiency (Heger et al., 2000; Yoon et al., 2006; Brott et al., 2011a). Compared to nitrogen, which gets enhanced in the core via the CNO-cycle and the transport of the enriched matter can be inhibited by the mean molecular weight gradient at the core-envelope interface, boron is a more fragile element such that it gets depleted near the surface via proton capture. Thus, upon rotational mixing, the surface abundance of boron changes faster than that of nitrogen, for it requires shallower mixing. This makes boron a more sensitive tracer of rotational mixing than nitrogen; stars first exhibit boron depletion then nitrogen enhancement at the surface (see their anti-correlation fig. 1 in Kaufer, 2010). Theis has been recognized and explored in many works Venn et al. (1996); Fliegner et al. (1996); Heger and Langer (2000); Mendel et al. (2006); Morel et al. (2008); Brott et al. (2009); de Mink et al. (2009); Frischknecht et al. (2010); Brott et al. (2011a); Proffitt et al. (2016, 2024).

2. Observational Sample vs. Stellar Models

Boron can be observable through B II $\lambda 1362$ resonance line and B III $\lambda 2066$ resonance doublet line in early B-type stars, requiring ultraviolet spectra obtained from space telescopes. To our knowledge, there are 90 early B-type stars on the main sequence in the Galaxy with boron observation (Venn et al., 1996; Proffitt and Quigley, 2001; Venn et al., 2002; Morel et al., 2006, 2008; Proffitt, 2015; Proffitt et al., 2016, 2024), and we use them as our observational sample and compiled their observationally derived stellar parameters such as effective temperature, luminosity, surface gravity, and rotational velocity. In this work, the parameters have been compiled from various literature sources. Notably, Proffitt et al. (2024) investigated stars in a Galactic open cluster NGC 3293, thus a homogeneous sample, and found practically the same results to ours. Figure 1 shows their locations in the Hertzsprung–Russell diagram along with their surface boron depletion factor and projected rotational velocities. We computed a dense grid of rotating single star models with MESA (Paxton et al., 2011, 2013, 2015, 2018, 2019) for a range of masses, rotational velocities, and rotational mixing efficiencies (f_c; `am_D_mix_factor` in MESA). All the input files and model data are available in Jin (2024). Then, we performed a Bayesian statistical analysis (Schneider et al., 2014) for the comparison between the single star models and our sample stars. For each star, we obtain a probability Π, which quantifies how compatible the observables are with the models.

Figure 2 shows the result of our Bayesian analysis for the stars in our sample. We found that the distribution shows a peak at $\Pi \sim 0.85$, around which most stars cluster, while a rather flat distribution is seen at $\Pi < 0.55$. This can be understood as follows: if a star has followed a single star path, the single star models should well reproduce its observables, resulting in a high Π value. Conversely, if a star has experienced a non-canonical event such as binary interaction, the single star models might not reproduce the observables, resulting in a low Π value. Given that we expect a non-negligible fraction of binary interaction products among massive stars (e.g., de Mink et al., 2014), it might be natural to find one group of stars at high Π and another at low Π. In our sample, we found that about two-thirds of the stars correspond to relatively high Π values of $\Pi > 0.6$ (first group) and the rest one-third to $\Pi < 0.55$ (second group). The stars in the first group have a wide range of rotational velocities and surface boron depletion factors, while the stars in the second group are mostly very slow rotators ($v \sin i < 50$ km/s) with too strong boron depletion for their rotation. These are the counterparts of nitrogen-enhanced slow rotators identified in the so-called Hunter diagram (surface nitrogen abundance versus projected rotational velocity) (e.g., Hunter et al., 2008; Brott et al., 2011b). Likewise, the boron-undepleted fast rotators might be the counterparts of nitrogen-enhanced fast rotators (in our framework, they belong to the first group with low f_c values). For simplicity, here I do not differentiate stars with surface boron abundance measurements and upper limits. In principle, the latter case can give lower values than the Π values presented in Fig. 2, possibly enlarging the second group. For more details about the physics assumptions, properties of the sample stars, statistical method, the choice of the boundary Π, and the treatment of the stars with surface boron abundance upper limits, see Jin et al. (2024).

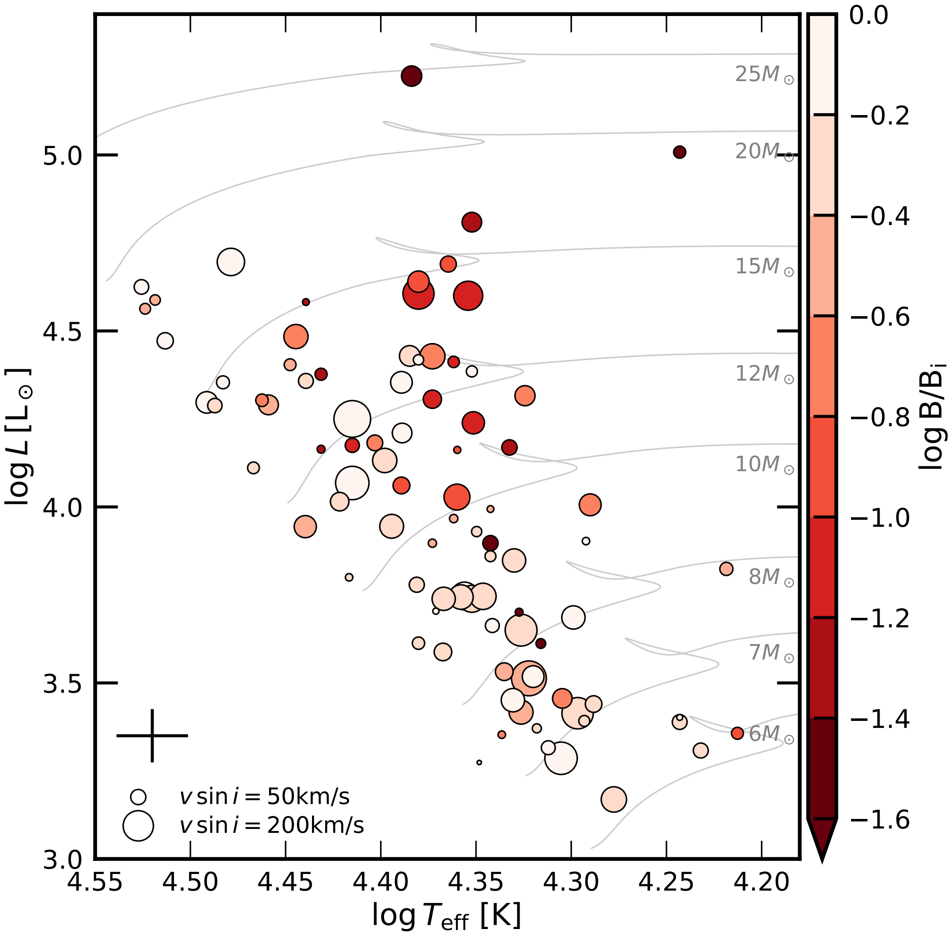

Figure 1: Stars in our dataset in the Hertzsprung–Russell diagram. The size of each circle represents the projected rotational velocity of the stars, while the face color indicates the boron depletion factor at the surface. The boron depletion factor is defined as the measured (or upper limits on) boron abundance divided by the initial value. Evolutionary tracks of non-rotating single star models are presented. The cross in the bottom left corner represents typical errors in the effective temperature and the luminosity.

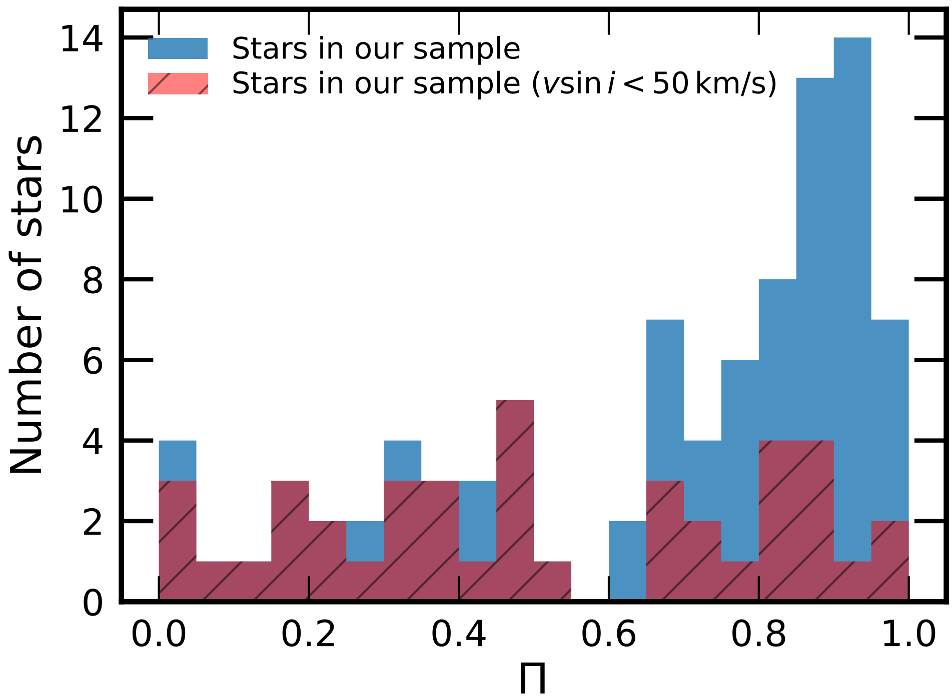

Figure 2: The distribution of Π (the probability quantifying how compatible the observables are with the model predictions) of all the stars in our sample is shown in blue, and the distribution corresponding to slow rotators $v\sin i < 50\,\mathrm{km\,s^{-1}}$ is shown in red (hatched).

3. Implications for the Rotational Mixing Efficiency and Binary Merger

Interestingly, for the stars in the first group, we found that the models with 50% weaker rotational mixing efficiency ($f_c = 0.017$) than the widely adopted value ($f_c = 0.033$) could well reproduce their observables. This is in line with the value of $f_c = 0.023$ obtained by Brott et al. (2011a) based on the surface nitrogen abundances of massive stars, advocating for weaker rotational mixing. Thus predictions from models based on the conventional rotational mixing strength should be taken with caution (e.g., the chemically homogeneous evolution channel for gravitational wave sources).

The stars in the second group are boron-depleted slow rotators. It is highly unlikely that all these stars are fast rotators seen near pole-on, and some of them have their equatorial rotational velocities measured, which are also very slow. We found that the fraction of stars with magnetic field detection is significantly higher in this group ($\sim 25\%$) than the first group ($\sim 9\%$), while the general incidence of magnetic stars in OB dwarfs is $\sim 7\%$ (Wade et al., 2014; Fossati et al., 2015). However, this statement should be taken with caution since the magnetic field analyses that we referred to are not homogeneous and may have significant observational biases (i.e., favoring field detection for slow rotators). A more complete sampling of spectropolarimetric data and magnetic field analysis on our sample stars will enable a statistically sound analysis. The merger model produced by Schneider et al. (2019), characterized by a slow rotator with a strong magnetic field, puts a binary merger as a promising channel for these unconventional stars, given various degrees of stellar mixing and mass loss that can happen during the process. Surface boron abundance might be used to get constraints on these uncertain processes, given its sensitivity to shallow mixing and mass loss.

We checked the binary or multiple-star status of our sample stars, if possible. To our knowledge, 27 stars are part of binary or multiple-star systems. About 70% of them belong to the first group, implying that they could be primary stars that have not yet experienced binary interaction (binaries are the "best single stars" in de Mink et al., 2011). Out of the 27 stars, 19 have measured periods. The stars in the closest binaries, which present orbital periods between 1.5 to 4 days, all belong to the first group. They do not show too much boron depletion, implying that tidal mixing has not been significant in these stars, if present at all.

4. Conclusions

We have compared rotating single star models newly computed with MESA with a sample of early B-type stars with boron observation in the Galaxy. Using a Bayesian framework, we have tested how well the models can reproduce the observables of the sample stars. We have identified two groups of stars: one (which includes two-thirds of the sample stars) that supports the role of rotational mixing in massive stars, but with a 50% weaker rotational mixing efficiency than the conventional value, and the other (which includes the remaining one-third of the sample stars) that mostly consists of boron-depleted slow rotators, requiring a different boron depletion mechanism or formation channel as an explanation. The slow rotation and high incidence of magnetic stars in the second group appear to support the binary merger scenario. As shown in this work, boron can offer a unique way to understand uncertain processes in massive star evolution such as rotational mixing and binary interaction.

Further Information

Conflicts of interest

The author declares that there is no conflict of interest.

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