Massive Stars Near and Far
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Upper Mass-Loss Limits and Clumping in the Intermediate and Outer Wind Regions of OB stars

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Abstract. Mass-loss is a key parameter throughout the evolution of massive stars. In this work we probe the radial clumping stratification of OB stars in the intermediate and outer wind regions ($r \gtrsim 2R_*$; r, radial distance to photosphere), derive upper limits for mass-loss rates, $\dot{M}_{\rm max}$, and compare them to current theoretical mass-loss recipes implemented in evolutionary models. A key conclusion of our analysis regards the derived upper-limit mass-loss rates of B supergiants, independently of clumping, which calls for an urgent revision of the role recombination of iron-like elements plays in determining the mass-loss rates of objects that cross the bi-stability region, and a careful analysis of corresponding effects for stellar evolution models.

Keywords. stars: early-type, stars: atmospheres, stars: mass loss

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It is well known that the presence of inhomogeneities in stellar winds (*clumping*; see Puls et al. (2008) and references within) leads to severe discrepancies among different mass-loss rate diagnostics, and between empirical estimates and theoretical predictions (e.g. Fullerton et al. (2006)).

In this work, we derive the minimum radial stratification of the clumping, $f_{\rm cl}^{\rm min}(r)$, through the stellar wind of 25 OB starts, by using density-squared diagnostics, and the corresponding maximum mass-loss rate, $\dot{M}_{\rm max}$, normalising clumping factors to the outermost wind region ($f_{\rm cl}^{\rm far} = 1$) (Puls et al. (2006)). Finally, we compare the obtained $\dot{M}_{\rm max}$ to theoretical mass-loss rate recipes (Vink et al. (2000), 2001; hereafter V00 and V01) commonly implemented in current stellar evolution codes (MESA-Bonn, Geneva).

We find that the clumping degree for r $\gtrsim 2R_*$ decreases or stays constant with increasing radius, regardless of luminosity class or spectral type (22/25 in our sample). However, a dependence of the clumping degree on luminosity class and spectral type at the intermediate region relative to the outer ones has been observed: O supergiants present, on average, a factor 2 larger clumping factors than B supergiants (Fig. 1). In addition, we

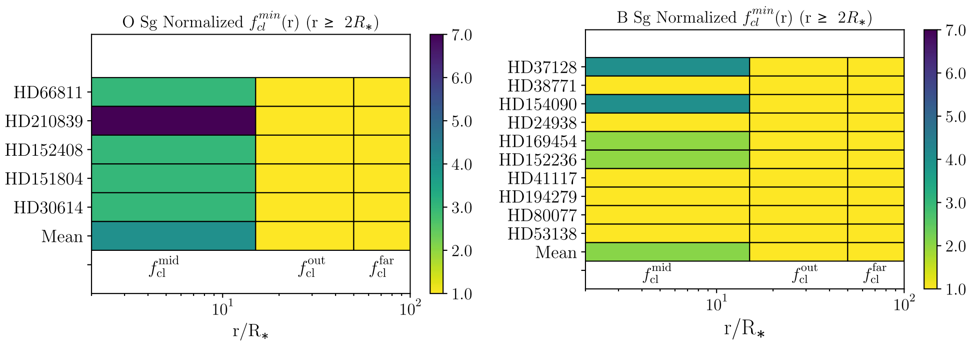

Figure 1. Derived individual minimum and average values of the clumping factors through the stellar wind for $r \gtrsim 2R_*$ for the O (left) and B (right) supergiants in our sample.

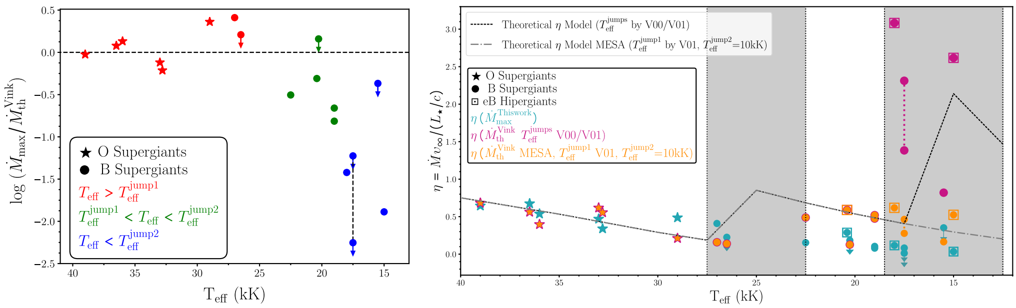

Figure 2. *Left:* this work empirical-maximum ($\dot{M}_{\rm max}$) to theoretical ($\dot{M}_{\rm th}^{\rm Vink}$) mass-loss rates ratio as a function of $T_{\rm eff}$ for the OB supergiants in our sample. $\dot{M}_{\rm th}^{\rm Vink}$ was computed via the recipes by V00 and V01, depending on the temperatures of the jumps (see legend). Arrows indicate upper limits and a dotted line joints two possible values for a given source. *Right:* empirical-maximum (clear blue) vs. theoretical (magenta and orange) wind performance numbers, η, as a function of $T_{\rm eff}$, for OB supergiants. Theoretical η where obtained using $\dot{M}_{\rm th}^{\rm Vink}$ recipes as they are implemented in Geneva and MESA evolution model and code, respectively. Dashed and dotted-dashed lines correspond to theoretical predictions for a source with log L/L$_\odot = 5.75$ and $M_* = 45 M_\odot$ for Z$_\odot$ from Geneva and MESA implementations, respectively. The shadowed regions are the first and second bi-stability jump zones as defined by V00.

find that the estimated $\dot{M}_{\rm max}$ for B supergiants is at least one order of magnitude (before finally decreasing) lower than the values usually adopted by stellar evolution models, whereas for O supergiants upper observational limits and predictions agree within errors (Fig. 2). This implies large reductions of mass-loss rates applied in evolution-models for B supergiants, independently of the actual clumping properties of these winds. However, hydrodynamical models of clumping suggest absolute clumping factors in the outermost radio-emitting wind on the order $f_{\rm cl}^{\rm far} \approx 4-9$ (Runacres & Owocki (2002)); assuming these values would imply a reduction of mass-loss rates included in stellar evolution models by a factor $2-3$ for O supergiants (above $T_{\rm eff} \sim 26.5$ kK) and by factors $6-200$ for B supergiants below the so-called first bi-stability jump (below $T_{\rm eff} \sim 22$ kK). While such reductions agree well with new theoretical mass-loss calculations for O supergiants (Björklund et al. (2021)), our empirical findings call for a thorough re-investigation of B supergiants mass-loss rates and their associated effects on stellar evolution.

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Supplementary material

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