Massive Stars Near and Far
Proceedings IAU Symposium No. 361, 2024
J. Mackey, J. S. Vink, & N. St-Louis, eds.
doi:10.1017/S1743921322003271

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

M. M. Rubio-Díez[1,2], J. O. Sundqvist[3], F. Najarro[2], A. Traficante[4], J. Puls[5], L. Calzoletti[4] and D. Figer[6]

[1]Facultad de Ciencias, Universidad de Alcalá, Alcalá de Henares, Madrid, Spain
email: mmar.rubio@uah.es

[2]Centro de Astrobiología, CSIC-INTA, Torrejón de Ardoz, Madrid, Spain

[3]Instituut voor Sterrenkunde, KU Leuven, Leuven, Belgium

[4]IAPS-INAF, Roma, Italy

[5]Universitäts-Sternwarte München, München, Germany

[6]Center for Detectors, Rochester Institute of Technology, Rochester, New York, USA

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

---

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

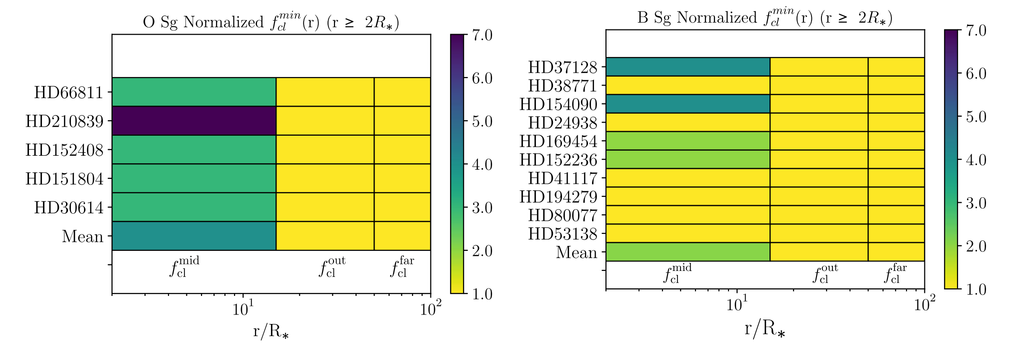

Figure 1. Derived individual minimum and average values of the clumping factors through the stellar wind for $r \gtrsim 2R_*$ for the O (left) and B (right) supergiants in our sample.

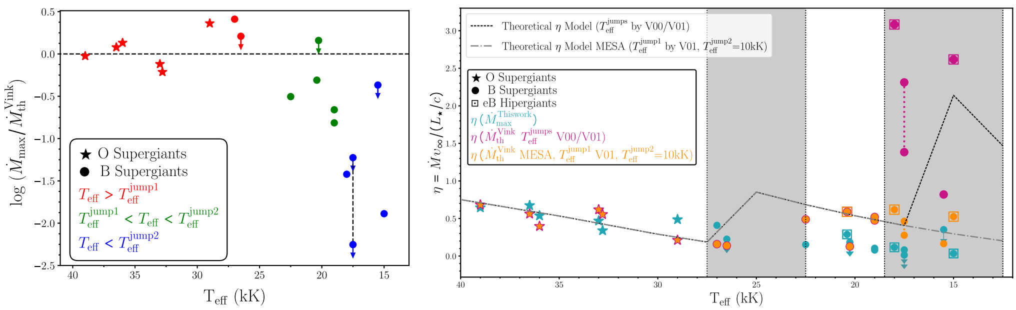

Figure 2. *Left:* this work empirical-maximum ($\dot{M}_{\rm max}$) to theoretical ($\dot{M}_{\rm th}^{\rm Vink}$) mass-loss rates ratio as a function of $T_{\rm eff}$ for the OB supergiants in our sample. $\dot{M}_{\rm th}^{\rm Vink}$ was computed via the recipes by V00 and V01, depending on the temperatures 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.

https://doi.org/10.1017/S1743921322003271 Published online by Cambridge University Press

Supplementary material

To view supplementary material for this article, please visit http://dx.doi.org/10.1017/S1743921322003271.

Acknowledgements.- M.M.R-D acknowledge financial support through the Community of Madrid in the framework of the Pluriannual Agreement with the University of Alcalá in the line of action "Stimulus to Excellence for Permanent University Lecturers (EPU-INV/2020/008)", through Spanish grants ESP2017-86582-C4-1-R and PID2019-105552RB-C41 (MINECO/MCIU/AEI /FEDER), and from the Spanish State Research Agency (AEI) through the Unidad de Excelencia "María de Maeztu"-Centro de Astrobiología (CSIC-INTA) project No. MDM-2017-0737.

References

Björklund, R., Sundqvist, J. O., Puls, J., & Najarro, F., 2021, *A&A*, 648, A36
Fullerton, A.W., Massa, D.L. & Prinja, R.K., 2006, *ApJ*, 637, 1025
Puls, J., Markova, N., Scuderi, S., et al., 2006, *A&A*, 454, 625
Puls, J., Vink, J.S. and Najarro, F., 2008, *A&A Rev*, 16, 209
Runacres, M. C. & Owocki, S. P., 2002, *A&A*, 381, 1015
Vink, J. S., de Koter, A., & Lamers, H. J. G. L. M., 2000, *A&A*, 362, 295
Vink, J. S., de Koter, A., & Lamers, H. J. G. L. M., 2001, *A&A*, 369, 574