*Massive Stars Near and Far*
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# The clumped winds of the most massive stars

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**Abstract.** The core of the cluster R136 in the Large Magellanic Cloud hosts the most massive stars known. The high mass-loss rates of these stars strongly impact their surroundings, as well as the evolution of the stars themselves. To quantify this impact accurate mass-loss rates are needed, however, uncertainty about the degree of inhomogeneity of the winds ('wind clumping'), makes mass-loss measurements uncertain. We combine optical and ultraviolet HST/STIS spectroscopy of 56 stars in the core of R136 in order to put constraints on the wind structure, improving the accuracy of the mass-loss rate measurements. We find that the winds are highly clumped, and use our measured mass-loss rates to test theoretical predictions. Furthermore we find, for the first time, tentative trends in the wind-structure parameters as a function of mass-loss rate, suggesting that the winds of stars with higher mass-loss rates are less clumped than those with lower mass-loss rates.

**Keywords.** stars: early-type, stars: atmospheres, stars: mass loss, galaxies: Magellanic Clouds

## 1. Introduction

The young, massive star cluster R136 inside the Large Magellanic Cloud (LMC) hosts a rich population of massive stars, including the most massive stars known

(Bestenlehner et al. 2020; Crowther et al. 2010). Nine stars within this cluster have a mass around or exceeding 100 solar masses, reaching 300 solar masses for the most massive one. These extremely massive stars strongly impact their surroundings through their high ionising fluxes and powerful stellar winds (e.g. Weaver et al. 1977). Furthermore, the mass-losses resulting from these winds impact the stars themselves by altering their evolution and subsequent endpoints (e.g. Langer 2012).

Accurate measurements of the mass-loss rates are crucial for understanding the impact of the stellar winds. However, measurements of these rates are uncertain, in large part due to uncertainty about the degree of inhomogeneity of the winds, often referred to as 'wind clumping' (see e.g. Puls et al. 2008, for a review). In this work, we analyse optical and ultraviolet (UV) spectroscopy of R136, allowing us to study in detail the mass-loss rates and wind structure. For the first time, we study wind structure properties over a wide range of stellar properties, covering late to early O-stars, and three WNh stars.

## 2. Observations

R136 lies inside the Tarantula Nebula, a region extensively studied in the VLT-FLAMES Tarantula Survey (Evans et al. 2011), in which optical spectra of about 800 massive stars were taken and analysed. However, due to crowding, the cluster R136 has been excluded from this survey. To complement the VFTS survey, R136 has been observed in optical and UV with HST/STIS (PI: Crowther, Proposal ID: 12465). These observations were previously analysed by Crowther et al. (2016), who focus their analysis on the UV part of the data set and in particular on the He II $\lambda$1640 emission, and by Bestenlehner et al. (2020), who use the optical part of the data only, deriving detailed stellar parameters, ages, abundances and masses. The present study combines the optical and UV spectra and focuses on the wind properties.

## 3. Methods

We analyse the spectra of 56 stars using the model atmosphere code FASTWIND, version 10.3.1 (Santolaya-Rey et al. 1997; Puls et al. 2005; Rivero González et al. 2012; Carneiro et al. 2016; Sundqvist & Puls 2018). FASTWIND is a code that is tailored to hot stars with winds. It stands out in terms of speed, allowing for the computation of many models; one model can be computed in about 15-45 minutes on a single CPU.

In our analysis, we take into account a non-smooth wind, in which the clumps (regions of over-density) can become optically thick. This can lead to porosity effects, which may affect the line profiles and hence affect the mass-loss rate measurements. In FASTWIND the clumped wind is implemented by means of a two-component formalism. Fig. 1 contains a schematic explanation of the different wind structure properties.

For each star, we fit the temperature, surface gravity, helium abundance, projected rotational velocity, wind acceleration parameter $\beta$, terminal velocity, mass-loss rate and clumping factor $f_{\rm cl}$, a measure for the degree of inhomogeneity of the wind. If the data quality allowed (which was the case for 39 out of 56 stars), we also fitted the nitrogen en carbon abundance, as well as detailed wind structure parameters: the clumping onset velocity $v_{\rm cl,onset}$, the interclump density contrast $f_{\rm ic}$, the velocity-porosity $f_{\rm fvel}$ and the wind turbulence $v_{\rm windturb}$.

We do not obtain these parameters one by one, but fit them simultaneously. With up to 14 free parameters for one fit, this requires an efficient exploration of the parameter space. To this end, we developed a genetic algorithm called KIWI-GA†, using elements of the algorithms of Charbonneau (1995), Mokiem et al. (2005), and Abdul-Masih et al. (2021). Genetic Algorithms operate based on the principles of natural selection and survival of the fittest, and they are particularly suitable for efficient search in large parameter spaces.

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† `https://github.com/sarahbrands/Kiwi-GA`

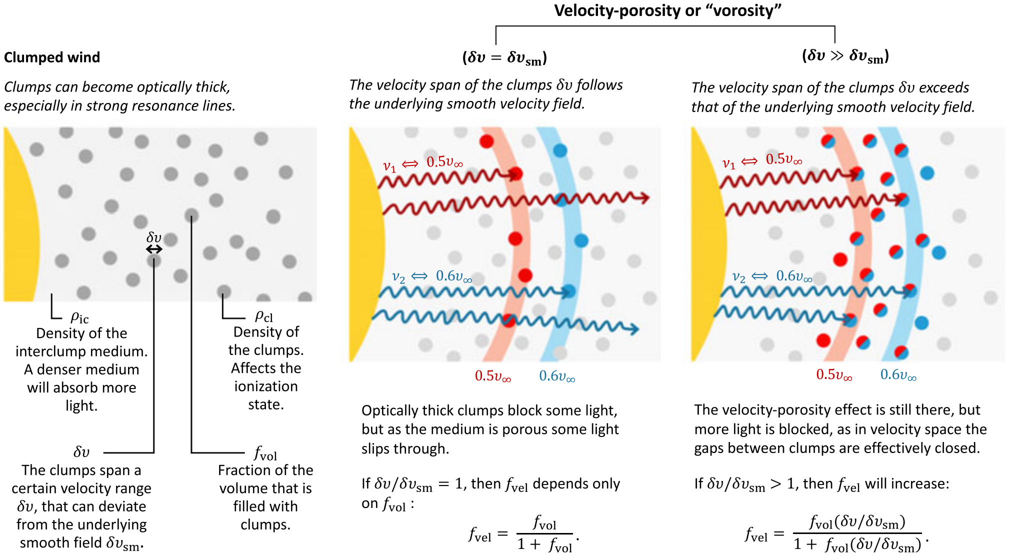

**Figure 1.** Illustration of the effects of clumping, porosity and velocity-porosity. Credit: Brands et al. (A&A, 663, A36, 2022), reproduced with permission © ESO.

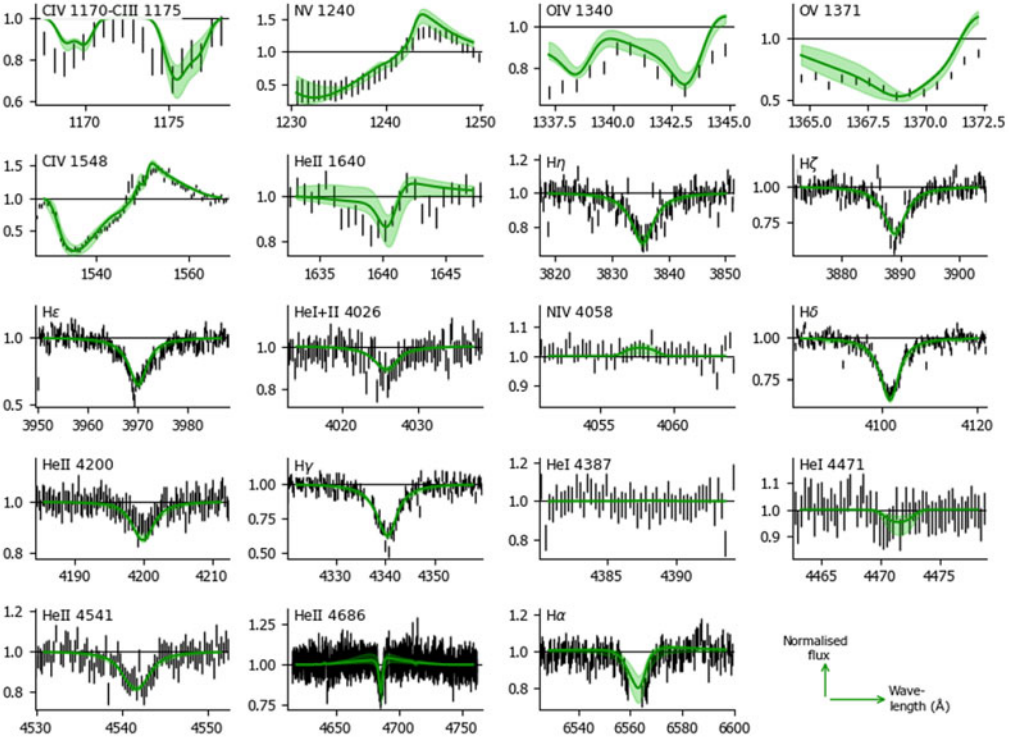

**Figure 2.** Diagnostic lines in the UV and optical of the star H35. Overlaid are the best fitting model (solid line) and the family of best fitting models (corresponding to 95% confidence intervals on the fitted parameters, shaded region). Credit: Brands et al. (A&A, 663, A36, 2022), reproduced with permission © ESO; figure adapted.

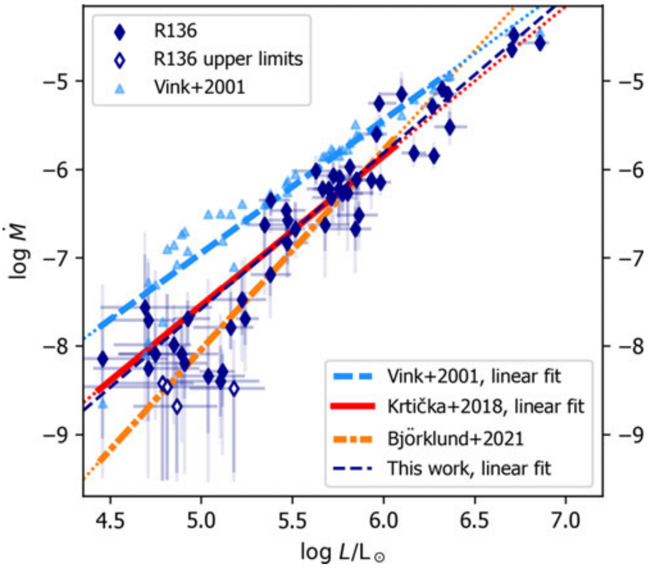

**Figure 3.** Observed and predicted mass-loss rates as a function of luminosity. Diamonds show our observed values, with light and dark error bars corresponding to 67% and 95% confidence intervals, respectively, thin dashed line the best fit to these values. Thick dashed, solid, and dot-dashed lines show theoretical predictions of Vink et al. (2001), Krtička & Kubát (2018), and Björklund et al. (2021), respectively. Credit: Brands et al. (A&A, 663, A36, 2022), reproduced with permission © ESO; figure adapted.

With the combination of Fastwind and Kiwi-GA we analyse all stars in the sample and constrain the free parameters listed above, including mass-loss rates and wind structure parameters. Fig. 2 shows the spectrum and best fitting models of H35 (spectral type: O3 V), for which we fitted 12 free parameters.

## 4. Mass-loss rates & wind structure parameters

Figure 3 shows a comparison of the observed mass-loss rates to the theoretical predictions of Vink et al. (2000, 2001), Krtička & Kubát (2018), and Björklund et al. (2021). Overall, the prediction of Krtička & Kubát (2018) matches our observations best, outperforming the other two in the regime where mass-loss impacts evolution the most ($\log L/\mathrm{L}_\odot > 5.3$). The observed values in the intermediate luminosity regime ($5.3 < \log L/\mathrm{L}_\odot \leq 6.25$) are about a factor two lower than the often used Vink et al. (2001) prescription. This is in line with other studies (Bouret et al. 2005, 2012; Fullerton et al. 2006; Puls et al. 2006; Cohen et al. 2010; Sundqvist et al. 2011; Šurlan et al. 2012; Rauw et al. 2015).

Simultaneously with mass-loss rate, we measure the wind structure parameters $f_{\rm cl}$, $f_{\rm ic}$, $f_{\rm vel}$ and $v_{\rm cl,onset}$. For the first time, these quantities are measured for a wide range of spectral types. Figure 4 shows the obtained values for these quantities against mass-loss rate. Tentative trends in the wind structure parameters as a function of mass-loss rate can be seen: the stars with the highest mass-loss rates seem to have smoother, albeit still clumpy, winds. Comparing these with the measurements of Hawcroft et al. (2021), who study a Galactic sample, we find that they generally agree well. However, the mass-loss rates of the sources studied by Hawcroft et al. (2021) span only a small range, and therefore their study confirms nor contradicts the trends we find. The trends we find thus need to be further investigated in the future.

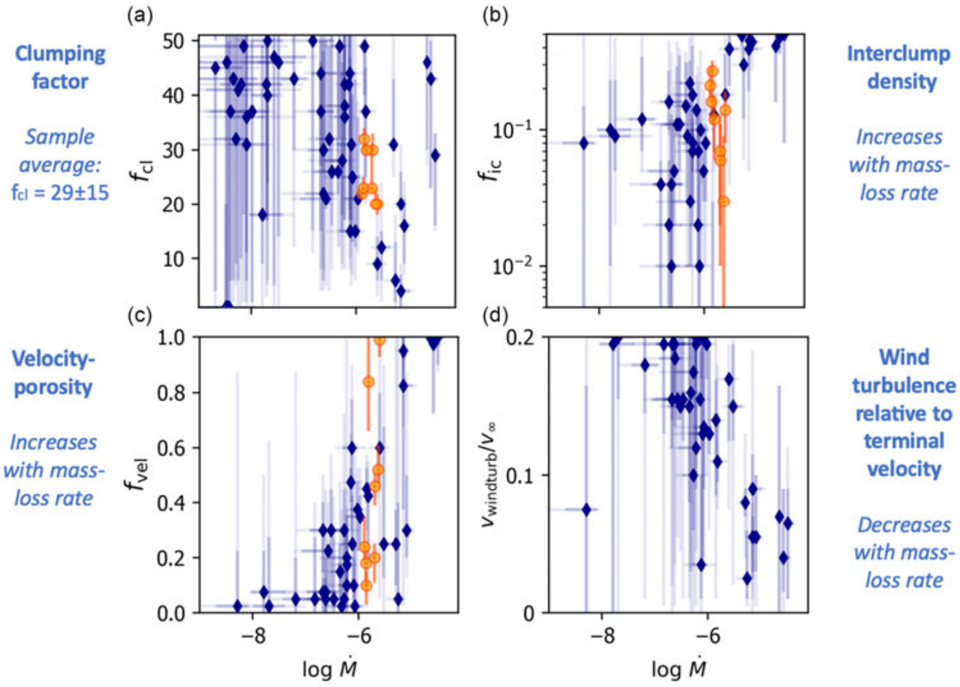

**Figure 4.** Measured wind structure parameters as a function of mass-loss rate. Diamonds are the values of R136 obtained in this study, with light and dark error bars corresponding to 67% and 95% confidence intervals, respectively. Circles Galactic observations of Hawcroft et al. (2021), error bars corresponding to 95% confidence intervals. Credit: Brands et al. (A&A, 663, A36, 2022), reproduced with permission © ESO; figure adapted.

## 5. Summary & Outlook

We simultaneously analysed the optical and UV spectra of 56 massive stars in the core of R136, and investigated the mass-loss rates and wind structure for a wide range of spectral types, covering the full O-star range and three WNh stars. We find that the mass-loss rates are in good agreement with the prescription of Krtička & Kubát (2018). We find high clumping factors for most of our stars. Furthermore we observe, for the first time, tentative trends in the wind structure parameters as a function of mass-loss rate. These trends require further investigation; the UV and optical spectra of the ULLYSES and XshootU projects are very well suited for this purpose, and analyses are currently being carried out.

## Supplementary material

To view supplementary material for this article, please visit http://dx.doi.org/10.1017/S1743921322002277.

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## Discussion

BRANKICA KUBÁTOVÁ: Did you check uniqueness of the obtained results, concerning clumping parameters? Could it happen in your calculation that combinations of different clumping parameters gives similar good fit with observations?

SARAH BRANDS: I checked this to some extent by running single models and comparing them, and each of the clumping parameters seems to have a different behaviour for different lines, so that degeneracy can be broken. But the signal to noise of this data is moderate, so I think it would be good to study this further with (higher signal to noise) ULLYSSES data, to be sure of this.

BRANKICA KUBÁTOVÁ: I think that is really important. One more question, which elements do you include in the FASTWIND calculation? When you talk about abundances you mention only carbon and nitrogen, but did you use some more elements?

SARAH BRANDS: Carbon and nitrogen are the ones that I have as free parameter. Helium is fixed but I fitted that from optical only spectra. The other elements are in there but are fixed. This includes also iron.

PACO NAJARRO: I have a question regarding the clumping. Do you use a structure for the clumping, in the sense that it is variable throughout the wind, or is it constant?

SARAH BRANDS: Clumping starts at a certain point in the wind, which is also a free parameter, and then it increases linearly until 0.3 of the terminal velocity. That is how it is implemented.

PACO NAJARRO: So it goes linearly, and doesn't grow exponentially with the velocity?

SARAH BRANDS: Indeed, it is a linear behaviour.