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X-shooting ULLYSES: Massive stars at low metallicity

XV. On the metallicity dependence of B-supergiant mass-loss rates

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ABSTRACT

Context. Our limited understanding of the winds of massive stars hampers our ability to predict their evolution. We currently often rely on mass-loss rate prescriptions that show strong features that lack a firm empirical confirmation, such as the bi-stability jump. This bi-stability jump is a pronounced increase in mass loss in the decreasing temperature regime $T_{\text{eff}} \sim 28\text{--}21$ kK, i.e., spectral types B1–B2. Different prescriptions also give different metallicity dependences; these sometimes include a dependence on effective temperature, luminosity or both, that may also differ among prescriptions. Although recent papers have compared empirical results to prescriptions, a large observational sample of B stars for which the wind has been scrutinised over different metallicity ranges is still lacking.

Aims. Through the modelling of both ultraviolet (from the ULLYSES programme) and optical (from the XShootU programme) high-resolution spectra, we determined the stellar and wind parameters, including detailed clumping parameters, of 24 SMC B stars ranging in T_{eff} from 13 to 29 kK. By combining this sample with LMC studies, we compared the wind behaviour of B stars in two different metallicity regimes. We compared our results to common mass-loss rate prescriptions to test features present in these models and their metallicity dependence.

Methods. We have used the model atmosphere code FASTWIND and the genetic algorithm code Kiwi-GA to fit the UV and optical spectra simultaneously. This allows us to determine wind properties including clumping behaviour.

Results. The moderate to strong metallicity trends present in the mass-loss prescriptions ($\dot{M} \propto Z^{0.41-1.4}$) explored here overestimate the empirical metallicity dependence in the B-star regime, which appears very weak. Similarly to a previous study of B supergiants in the LMC, we do not find a sudden increase in mass-loss rate at approximately spectral type B1, but only a weak temperature trend. As in this LMC study, we show that on average around 40% of the wind mass is located in the wind medium between the clumps. Using other studies from this paper series, we compiled a sample of 80+ O and B stars in the SMC and LMC. From a comparison we find a clear difference in O- and B-type metallicity dependence.

Conclusions. The apparent lack of a bi-stability jump in the B-star regime and a very weak metallicity dependence for the same stars offers new empirical constraints to theoretical models of line-driven winds. As differences between these models are large (reaching orders of magnitude in parts of parameter space) such constraints are much needed. More studies exploring the mass-loss rates of B stars and cooler objects will be helpful to our understanding of hot star winds.

Key words. techniques: spectroscopic – stars: fundamental parameters – stars: massive – stars: mass-loss – stars: winds, outflows

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1. Introduction

Mass loss strongly impacts the evolution of massive stars (Josiek et al. 2024; Gormaz-Matamala et al. 2024), and hence an accurate implementation of this process in evolution codes is essential. The mass loss in hot massive stars is driven by the absorption and scattering of photons in spectral lines, supported by Thomson scattering on free electrons (Castor et al. 1975). As momentum transfer in line transitions dominates the process, relatively abundant atoms with many energy transitions, such as iron, are the main driving contributors. Currently, the mass-loss rates used in evolutionary modelling are prescriptions based on 1D models of the stellar atmosphere (Vink et al. 1999, 2001; Krtićka et al. 2021, 2024; Björklund et al. 2023). The most widely used prescription for stellar mass loss in the hot upper Hertzsprung–Russell diagram, and a benchmark, is the pioneering work by Vink et al. (2001), which features a bi-stability jump. This is a pronounced upward trend in mass-loss behaviour from ~ 28 kK down to 21 kK superimposed on a generally downward trend of mass loss with decreasing temperature, i.e., along the evolutionary sequence. The cause of this upward jump (with decreasing temperature) is thought to be the recombination to a lower ionisation stage of iron, Fe IV to Fe III, which, in principle, can increase the efficiency of line-driven winds as more line transitions become available in the region of the stellar flux maximum.

Tentative empirical evidence for a bi-stability jump may come from the temporal behaviour in mass-loss properties in luminous blue variable stars during their S Doradus-type excursions in the Hertzsprung–Russell diagram (Vink & de Koter 2002; Groh & Vink 2011). However, it has not been confirmed in regular B-type stars, even though multiple studies have investigated the temperature range covering the bi-stability jump over a large range of luminosities. In the Small Magellanic Cloud (SMC) these are (Trundle et al. 2004; Trundle & Lennon 2005; Bernini-Peron et al. 2024); in the Large Magellanic Cloud (LMC) (Verhamme et al. 2024), and in the Milky way (Crowther et al. 2006; Markova & Puls 2008; Rubio-Díez et al. 2022; de Burgos et al. 2024a). In recent years, a focussed spectroscopic study, that uses both ultraviolet (UV) and optical lines and takes into account the clumping behaviour of the winds (Verhamme et al. 2024; Alkousa et al. 2025) as well as a large-scale approach using optical spectroscopy that uses a more simplified model of the wind (de Burgos et al. 2024a) did not find compelling evidence for a bi-stability jump. All research groups come to the conclusion that the Vink et al. (2001) prescription should be used cautiously, as it may overestimate the mass loss by up to a factor of 10–100 for stars cooler than 25 kK, agreeing more closely with the trends predicted by Björklund et al. (2021); Krtićka et al. (2024).

As the wind is mostly driven by metals, such as carbon, nitrogen, oxygen, and iron-group elements, the mass-loss rate $\dot{M}$ is predicted to be metallicity dependent, specifically $\dot{M} \propto Z^{0.6-1.4}$ (Vink et al. 2001; Björklund et al. 2023; Krtićka et al. 2024). Spectroscopic studies confirm this behaviour for O stars (Mokiem et al. 2007; Backs et al. 2024). For B stars, however, recent in-depth studies at different metallicities that take a homogeneous approach and use data with the same spectral coverage and resolution while accounting for clumping are lacking. Hence, to date, theoretical results in this temperature range have not been comprehensively tested.

What complicates analyses of hot-star wind properties is that the mass-loss rates are found to depend on the degree of structure in the wind outflow. These density (and velocity)

inhomogeneities are referred to as wind clumping (e.g., Puls et al. 2008; Vink 2022). Only in the case that the scattering-dominated lines (notably resonance lines in the UV) and recombination-dominated lines (notably H α and He II $\lambda 4686$) can be modelled simultaneously is it possible to distinguish between clumping properties and mass-loss rate. To date, most studies have relied on optical/IR data alone (Trundle et al. 2004; Trundle & Lennon 2005; Markova & Puls 2008; Rubio-Díez et al. 2022; de Burgos et al. 2024a), and hence are affected by this degeneracy. Bernini-Peron et al. (2024) have the UV data needed to derive clumping parameters, but use a simplified clumping description that assumes that all wind mass is located in the dense regions of the wind and none in the interclump medium. At least for O stars, several studies in both the LMC and SMC accounting for a detailed description of clumping show that a significant fraction of the wind mass is located in the interclump region (Hawcroft et al. 2024a; Brands et al. 2022, 2025). A study of LMC B stars adopting the same clumping model shows that 40% of the wind mass is located in the medium between the clumps (Verhamme et al. 2024). What is currently lacking is a similar detailed study for SMC B stars to better understand the clumping behaviour over different metallicities.

The UV Hubble database, *UV Legacy Library of Young Stars as Essential Standards* (ULLYES) (Roman-Duval et al. 2020, 2025), and the follow-up optical X-Shooter/VLT observations of *Xshooting ULLYES* (XShootU) (Vink et al. 2023), secured high spectral resolution data of a sample of 250 O- and B-type stars in both the LMC and SMC to study mass loss in the hot upper Hertzsprung–Russell diagram in detail at different metallicities. The availability of high-quality optical and UV spectroscopy allows us to consistently derive essential stellar and wind parameters, such as terminal wind speed and clumping properties. This paper is part of a series in which the ULLYES sample has been studied using a fitting method that relies on a genetic algorithm (GA) and the spectral synthesis code FASTWIND (Puls et al. 2005; Verhamme et al. 2024; Backs et al. 2024; Hawcroft et al. 2024a; Brands et al. 2025). We focus on the results of the SMC B stars, and address the presence or absence of a bi-stability jump and the $\dot{M}(Z)$ dependence in the B-star regime, while also discussing trends found in the entire homogeneously studied sample of 84 stars over a T_{eff} regime from 12 to 60 kK.

We discuss the method of spectral analysis and the SMC sample in Sect. 2. Our results are presented in Sect. 3 and discussed in Sect. 4. We summarize our findings and draw conclusions in Sect. 5.

2. Method and sample

We studied the spectra of 24 hot stars in the SMC. In this section we give details on how we extracted this information from the spectra and how these spectra were obtained.

2.1. Sample

For this paper we analysed 24 SMC B-type stars ranging from spectral type B0 to B8. The stars are mostly supergiants, with a few bright giants and one giant star. The UV spectra are from the Hubble Space Telescope programme ULLYES (Roman-Duval et al. 2020, 2025) in which 250+ O- and B-type stars in the SMC and LMC were observed using the Space Telescope Imaging Spectrograph (STIS) and Cosmic Origins Spectrograph (COS). This sample was complemented with optical spectra obtained using the X-shooter spectrograph installed on the Very Large

Telescope in the XshootU programme (Vink et al. 2023; Sana et al. 2024). Although our aim was to select single B stars, the first nine epochs of the BLOeM survey, which has overlapping targets, showed AzV 488 to be a binary (Shenar et al. 2024; Britavskiy et al. 2025). It is possible that a radial velocity analysis of the full projected 25 epochs of this programme will reveal more of our targets to be binaries.

The UV spectral range of COS spans from 940 to 1783 Å with a spectral resolving power $R = 11\,000$ – $19\,000$ depending on the grating used. The STIS data cover 1141–2366 Å with $R = 30\,000$ – $48\,500$ depending on the grating. The UV data has a signal-to-noise ratio around 20 (for more details see Roman-Duval et al. (2025)). As our method only uses small line windows, we carried out local normalisation using the same method as Hawcroft et al. (2024b). For the optical spectra the full spectral range is 3100–8000 Å. This range is covered by two different arms; the UVB arm, which runs from 3300 Å to 5500 Å with $R = 6700$, and the VIS arm, which covers 5500–8000 Å with $R = 11\,400$. The optical spectra have a signal-to-noise ratio that is typically higher than 100; more details are available in Vink et al. (2023) (for details on the reduction and normalisation of the optical data, see Sana et al. (2024)). To facilitate the reproducibility of these results, we did not renormalise any spectral windows in the optical regime.

2.2. Model and fitting

We created synthetic spectra using the 1D stellar atmosphere and spectral synthesis code FASTWIND (Santolaya-Rey et al. 1997; Puls et al. 2005; Sundqvist & Puls 2018). FASTWIND solves for the state of the gas assuming non-local thermodynamic equilibrium (NLTE) in a spherically symmetric and stationary extended stellar envelope comprising both the photosphere and out-flowing wind. Here we use version 10.5 (see Puls et al. 2005; Rivero González et al. 2012; Sundqvist & Puls 2018; Carneiro et al. 2018), which accounts for the accumulative feedback effects from the multitudes of metallic spectral lines (e.g. C, N, O, Ne, Mg, Si, S, Ar, Fe, Ni) upon the radiation field and atmospheric structure by means of a computationally efficient statistical method. Only a part of these chemical elements are used for detailed spectroscopy (here H, He, Si, C, N, O). The lines of the remaining elements may blend with the diagnostic lines. The clearest cases of this are the iron lines that overlap with the carbon and silicon lines in the UV region. To ensure that we indeed fit the intended lines, we removed the non-modelled lines from the observed spectra. This method has been used in other recent analyses of early-type spectra (Brands et al. 2022; Verhamme et al. 2024; Baks et al. 2024; Brands et al. 2025).

Clump optical depths for the spectral lines are calculated from the input parameters using the Sobolev (1960) approximation. This means that we do not assume that clumps are either optically thin or thick; instead, we compute the opaqueness for all lines according to the structure parameters. For this ensemble of clumps, we evaluated the impact upon the ionisation balance and spectrum formation. For details on the version of FASTWIND used and details on the implementation of X-rays, we refer to Section 2.2 in Verhamme et al. (2024), where we use the exact same set-up, with the exception of the metallicity which is set to the SMC value of 0.2 times the solar metallicity, defined by Asplund et al. (2009). This commonly used scaling of the abundance of the SMC is not perfect as all elements scale differently compared to the Galactic abundance. For instance, the nitrogen abundance in the SMC, according to Vink et al. (2023), is 0.05

the galactic value. However, in this work, CNO are fitted, not scaled.

The FASTWIND models used here have 18 free wind and stellar parameters, which are constrained by comparing them to the UV plus optical spectra. The 18 parameters are effective temperature (T_{eff}), effective surface gravity (g_{eff}); helium abundance (Y_{He}); CNO abundances; upper limit on projected rotational velocity ($v_{\text{max,rot}} \sin i$); mass-loss rate ($\dot{M}$); terminal wind speed (v_{∞}); wind acceleration parameter (β); clumping factor (f_{cl}); interclump density in units of mean density ($f_{\text{ic}} = \rho_{\text{ic}}/\langle\rho\rangle$); velocity filling factor (f_{vel}); onset velocity of clumping as a fraction of terminal wind speed ($v_{\text{cl,start}}$); velocity at which full clumping is achieved ($v_{\text{cl,max}}$); maximum wind turbulence ($\max v_{\text{turb}}$), which starts at the set micro-turbulence ($v_{\xi} = 10$ km/s) at the transition point (0.1 times sound speed at the surface) and increases similarly to the clumping factor until it reaches $\max v_{\text{cl,max}}$; a transformation of the X-ray filling factor (f_{X}); and the maximum jump velocity (u_{∞}). We note that the radius is not one of the fit parameters because it is constrained using the temperature and the observed K -band magnitude.

The effective surface gravity is the measured surface gravity affected by the rotation of the star itself, which can be converted to the value we use to compute the stellar mass by $g_{\star} = g_{\text{eff}} + (v_{\text{rot}} \sin i)^2/R_{\star}$ (Herrero et al. 1992). We do not separate the mechanisms broadening spectral lines into macro-turbulence and rotational broadening as these are nearly impossible to separate for all but the fastest rotators (Sundqvist et al. 2013). Therefore, here we report total broadening, which includes the stellar macro-turbulence motion and the rotational speed. The reported value is therefore the upper limit for possible rotation. Both the wind acceleration parameter and the terminal wind speed determine the radial velocity field: $v(r) = v_{\infty}(1 - bR_{\star}/r)^{\beta}$ with $R_{\star}$ being the radius at the photospheric boundary and $b = 1 - (v_0/v_{\infty})^{1/\beta}$ ensures a smooth velocity transition from the (quasi-)hydrostatic atmosphere to the wind (Santolaya-Rey et al. 1997). v_0 is set to the standard value 0.1 times the sonic speed at T_{eff} . The clumping factor denotes the overdensity of the denser parts of the wind compared to the average, defined as $f_{\text{cl}} = \langle\rho^2\rangle/\langle\rho\rangle^2$. The velocity filling factor shows the fraction of the velocity field filled with clumps. In these FASTWIND models clumping does not start in the quasi-hydrostatic atmosphere, but instead the onset velocity ($v_{\text{cl,start}}$). From this onset velocity the clumping increases linearly with velocity until it reaches $v_{\text{cl,max}}$ (Verhamme et al. 2024, see Figure 16).

We included X-rays in most of our stars following a prescription explained in Carneiro et al. (2016), where the X-rays are created due to differential motion of material in the wind leading to shocks. The parameter f_{X} is defined as $f_{\text{X}} = 16e_s^2$, where e_s is the X-ray volume filling factor. Finally, u_{∞} is the maximum jump velocity, which sets the actual jump velocity to $u(r) = u_{\infty} [v(r)/v_{\infty}]^{1.45}$.

There are two parameters not included in the list above, which we did not fit, but instead set to a chosen value. The first is the micro-turbulence, which may potentially have an impact on derived parameters. For this study, just as in the LMC B-star study by Verhamme et al. (2024), we set the micro-turbulence to $v_{\xi} = 10$ km/s. Tests have shown that the parameters we value most here, notably T_{eff} and $\dot{M}$, are not noticeably sensitive to v_{ξ} and vary only due to the randomness of the GA method when changing the micro-turbulence. The CNO abundances may be influenced by micro-turbulence, however only within error margins (see the appendices in Brands et al. 2022; Verhamme et al. 2024). The second fixed parameter is the Si abundance,

which is set to the abundance suggested by Vink et al. (2023). Unlike CNO, Si is not involved in the CN/CNO cycle and is not expected to change as the star evolves. Verhamme et al. (2024) find only minor changes in T_{eff} when fitting the Si abundance rather than keeping it to one value. Si is set to a number fraction of $\epsilon_{\text{Si}} = 6.72$, defined as $\epsilon_X = 12 + \log_{10}(n_X/n_H)$, i.e. $0.14 Z_{\odot}$ (Vink et al. 2023).

To fit these 18 parameters simultaneously we used a genetic algorithm (GA) as previously explored by Mokiem et al. (2005); Tramper et al. (2014); Abdul-Masih et al. (2019); Hawcroft et al. (2021). More specifically, here we use Kiwi-GA (Brands et al. 2022, 2025). In our fitting, we employed a two-step approach where we used the optical-only fits to inform the initial guess of the GA when fitting both UV and optical data (see Section 2.4 of Verhamme et al. 2024). The aim was to improve the stability of the method, while not influencing the results. The list of diagnostic spectral lines is given in Table E.1.

Though the methodology used follows Verhamme et al. (2024), we needed to adjust it in one respect as for a number of stars we were unable to determine the terminal wind speed. The spectral features that typically allow us to measure v_{∞} are the C IV 1550 and Si IV 1400 UV-resonance lines. For some of the cooler, low mass-loss rate stars the wind is insufficiently ionised to have these species abundantly present, thus removing their sensitivity to wind properties far into the outflow. An example of this is AzV 324 (B8 Ib) shown in Fig. A.1. Its effective temperature is too low to produce a C IV profile originating in the wind. The narrow observed profile is mostly of interstellar origin. The Si II-III lines show that the derived temperature is acceptable. Due to the version of FASTWIND that we used, we did not have access to the Al III features in UV, which might have given more constraints in these cases. Therefore, to obtain v_{∞} we resorted to using the SMC effective temperature-terminal wind speed relation of Hawcroft et al. (2024b) derived using stars hotter than 22 500 K,

$$v_{\infty} = 0.089 \cdot T_{\text{eff}} - 1560, \quad (1)$$

where v_{∞} is in km/s. This empirical formula yields negative wind speeds for stars cooler than 17 528 K. To avoid unrealistically low values, we required that v_{∞} is at least the effective escape speed at the stellar surface, i.e. $v_{\text{esc}}^2 = 2GM_*/(1 - \Gamma_e)/R_*$. Here M_* and R_* are stellar mass and radius and $\Gamma_e = \kappa_e L_*/(4\pi c GM_*)$ is the Eddington factor for electron scattering opacity (κ_e) only, with L_* the stellar luminosity.

The density in the wind scales as $\langle \rho \rangle \sim \dot{M}/v_{\infty}$. Therefore, if a star has a terminal velocity lower than its surface escape velocity, we overestimate the terminal wind speed. To recover the strengths of wind sensitive lines, set by $\langle \rho \rangle$, we therefore overestimate the mass-loss rate. This overestimation is modest. Assuming the actual terminal wind speed were $0.75 \cdot v_{\text{esc}}$, we would be overestimating the mass-loss rate by 0.1 dex. Typical error margins on the mass-loss rates are much higher, ranging from 0.3 to 0.6 dex.

3. Results

Here, we present the results of the spectral fitting of the sample of SMC stars described in Table 1. Examples of the fits of important diagnostic lines of four stars covering the full temperature range are shown in Fig. A.1.

The SMC sample is shown in the Hertzsprung–Russell diagram (Figure 1), marked as circles. Also in this figure is the LMC sample discussed in Verhamme et al. (2024) shown as partially

Table 1. Sample used in this paper.

Name	BLOeM ID ^a	SpT ^b	K_s [mag] ^c	Instrument
AzV 215	4-020	B0 Ia	13.04	FUSE, STIS
AzV 488	6-080	B0 Ia	12.24	FUSE, STIS
AzV 235	7-064	B0 Ia	12.28	FUSE, STIS
AzV 104		B0.5 Ia	13.73	FUSE, STIS
AzV 506		B0.5 II	14.12	FUSE, STIS
AzV 43		B0.5 III:n	14.48	COS
AzV 266		B0.7 Ia	12.91	FUSE, STIS
AzV 410		B0.7 Iab	13.83	COS, STIS
AzV 264	1-009	B1 Ia	12.75	FUSE, STIS
AzV 96	8-008	B1 Iab	12.95	FUSE, STIS
AzV 210		B1.5 Ia	12.79	FUSE, STIS
SK 191		B1.5 Ia	11.9	COS, FUSE, STIS
AzV 175		B1.5 Ib	13.89	COS, FUSE
AzV 18		B2 Ia	12.32	FUSE, STIS
AzV 374		B2 II	13.53	COS, FUSE, STIS
NGC330 ELS 4		B2.5 Ib	13.46	COS, STIS
AzV 234	4-066	B2.5 Ib	13.22	COS, STIS
AzV 22		B3 Ia	12.15	STIS
AzV 445		B3 Iab	12.94	COS, STIS
AzV 314		B3 Ib	13.23	COS, STIS
NGC330 ELS 2		B3 Ib	13.08	STIS
SK 179		B3 II	13.37	COS, STIS
AzV 343		B8 Iab	13.07	COS, STIS
AzV 324	1-062	B8 Ib	13.1	COS, STIS

Notes. (a) Corresponding BLOeM ID; (b) Spectral types from Bestenlehner et al. (2025); (c) K -band magnitudes compiled by Vink et al. (2023).

transparent star markers. Theoretical evolutionary pathways by Schootemeijer et al. (2019) are also plotted for initially 16, 25, and 40 $M_{\odot}$ stars with a metallicity of 0.2 $Z_{\odot}$. These tracks are for non-rotating stars and adopt a core-overshooting $\alpha_{\text{co}} = 0.33$ and semi-convection $\alpha_{\text{sc}} = 1$, following Brott et al. (2011). The luminosity range of our sample implies initial masses between about 15 and 50 $M_{\odot}$. The star's temperatures range from 12.5 to 30 kK. We find that the majority of the sample stars, among which all relatively low-mass sources, are located beyond the terminal age main sequence (TAMS) in the Hertzsprung gap. This conclusion on evolutionary status is, however, dependent on the adopted value for α_{co} . For instance, for $\alpha_{\text{co}} = 0$ the entire SMC sample is positioned beyond the TAMS. We note that this assessment of evolutionary status also ignores a potentially unnoticed binary interaction history (for more information on the effect of binary interaction on the evolution of massive stars, see Bellinger et al. 2024).

3.1. Stellar properties

The stellar and wind parameters are determined by fitting the spectral lines listed in Table E.1. For the seven atmospheric parameters of T_{eff} , g_{eff} , Y_{He} , $v_{\text{max,rot}} \sin i$, and CNO abundance the results are listed in Table 2. As magnesium lines are not considered, the effective temperature of the coolest stars is derived solely from Si II and He I. Additionally, the O II 4088 line blends with the Si IV 4088 line potentially causing a shift in the derived T_{eff} (de Burgos et al. 2024b). This causes the coolest stars to have higher T_{eff} uncertainties compared to the hottest stars. The surface gravity, from which the spectroscopic mass is derived, ranges from $\log_{10} g = 2.0 - 3.5$, with typical error margins of 0.1 dex. It is known that temperature and gravity are to some

Table 2. Photospheric parameters of the sample.

Object name	T_{eff} [K]	$\log_{10} g_{\text{eff}}$ [$\log_{10}(\text{cm/s}^2)$]	$Y_{\text{He}}[n_{\text{He}}/n_{\text{H}}]$	$v_{\text{max, rot}} \sin i$ [km/s]	ϵ_{C} [dex]	ϵ_{N} [dex]	ϵ_{O} [dex]
AzV215	29 300 ⁺²⁰⁰ ₋₆₀₀	3.25 ^{+0.05} _{-0.35}	0.16 ^{+0.02} _{-0.01}	92 ⁺¹ ₋₁₃	6.42 ^{+0.5} _{-0.4}	7.56 ^{+0.05} _{-1.75}	8.45 ^{+0.25} _{-0.85}
AzV488	25 900 ⁺¹⁸⁰⁰ ₋₁₄₀₀	2.7 ^{+0.2} _{-0.15}	0.2 ^{+0.04} _{-0.12}	78 ⁺⁵ ₋₁₃	7.02 ^{+1.2} _{-0.2}	6.56 ^{+1.05} _{-0.95}	7.3 ^{+1.4} _{-0.2}
AzV235	26 900 ⁺¹⁸⁰⁰ ₋₂₂₀₀	3.05 ^{+0.4} _{-0.05}	0.12 ^{+0.04} _{-0.02}	81 ⁺¹⁶ ₋₇	5.82 ^{+0.95} _{-0.25}	7.46 ^{+0.05} _{-0.65}	8.6 ^{+0.2} _{-0.7}
AzV104	27 800 ⁺⁶⁰⁰ ₋₄₀₀	3.2 ^{+0.1} _{-0.05}	0.12 ^{+0.02} _{-0.01}	90 ⁺⁶ ₋₁₄	7.87 ^{+0.45} _{-0.05}	7.56 ^{+0.05} _{-1.65}	7.95 ^{+0.35} _{-0.7}
AzV506	27 500 ⁺⁵⁰⁰ ₋₁₀₀	3.35 ^{+0.1} _{-0.05}	0.12 ^{+0.0} _{-0.04}	59 ⁺⁴ ₋₁	7.57 ^{+0.2} _{-0.05}	7.61 ^{+0.05} _{-1.65}	8.2 ^{+0.05} _{-0.95}
AzV43	26 600 ⁺¹³⁰⁰ ₋₄₀₀	3.05 ^{+0.15} _{-0.05}	0.12 ^{+0.04} _{-0.01}	234 ⁺³⁴ ₋₁	7.82 ^{+0.2} _{-0.1}	7.06 ^{+0.4} _{-1.0}	8.2 ^{+0.35} _{-0.15}
AzV266	23 900 ⁺¹³⁰⁰ ₋₁₅₀₀	2.7 ^{+0.25} _{-0.2}	0.22 ^{+0.04} _{-0.08}	78 ⁺⁶ ₋₁₇	6.27 ^{+0.4} _{-0.4}	6.06 ^{+0.6} _{-0.45}	8.05 ^{+0.4} _{-0.4}
AzV410	20 400 ⁺⁶⁷⁰⁰ ₋₁₀₀	2.75 ^{+0.6} _{-0.05}	0.09 ^{+0.03} _{-0.01}	120 ⁺²⁸ ₋₁₅	7.92 ^{+0.2} _{-0.3}	6.61 ^{+1.1} _{-1.0}	8.1 ^{+0.55} _{-0.55}
AzV264	22 000 ⁺¹⁸⁰⁰ ₋₁₇₀₀	2.6 ^{+0.1} _{-0.25}	0.16 ^{+0.05} _{-0.01}	71 ⁺²⁰ ₋₃	5.72 ^{+0.55} _{-0.35}	7.66 ^{+0.05} _{-0.8}	7.65 ^{+0.7} _{-0.1}
AzV96	23 200 ⁺⁸⁰⁰ ₋₅₀₀	2.7 ^{+0.1} _{-0.15}	0.2 ^{+0.06} _{-0.0}	73 ⁺¹² ₋₁₀	7.12 ^{+0.4} _{-0.3}	7.41 ^{+0.2} _{-1.3}	8.0 ^{+0.5} _{-0.55}
AzV210	22 800 ⁺¹⁷⁰⁰ ₋₂₀₀	2.6 ^{+0.2} _{-0.1}	0.19 ^{+0.04} _{-0.0}	75 ⁺¹³ ₋₁₃	7.02 ^{+0.65} _{-0.3}	7.11 ^{+0.35} _{-1.25}	8.2 ^{+0.1} _{-0.85}
SK191	22 400 ⁺⁸⁰⁰ ₋₈₀₀	2.55 ^{+0.2} _{-0.05}	0.23 ^{+0.0} _{-0.04}	72 ⁺¹⁶ ₋₁	7.57 ^{+0.55} _{-0.05}	6.61 ^{+0.05} _{-0.65}	7.3 ^{+0.35} _{-0.05}
AzV175	20 400 ⁺²⁰⁰ ₋₂₀₀	2.65 ^{+0.4} _{-0.15}	0.09 ^{+0.0} _{-0.02}	46 ⁺¹¹ ₋₃	8.07 ^{+0.15} _{-0.25}	7.31 ^{+0.25} _{-1.1}	7.7 ^{+0.85} _{-0.05}
AzV18	23 000 ⁺⁸⁰⁰ ₋₁₄₀₀	2.8 ^{+0.2} _{-0.25}	0.18 ^{+0.1} _{-0.02}	67 ⁺¹⁰ ₋₇	5.77 ^{+0.5} _{-0.4}	6.86 ^{+0.65} _{-1.1}	7.5 ^{+0.4} _{-0.2}
AzV374	21 800 ⁺⁸⁰⁰ ₋₁₀₀₀	2.9 ^{+0.2} _{-0.2}	0.08 ^{+0.02} _{-0.0}	69 ⁺¹ ₋₂₇	7.87 ^{+0.5} _{-0.2}	6.81 ^{+0.8} _{-0.25}	7.3 ^{+1.05} _{-0.45}
NGC330-ELS-04	20 300 ⁺⁷⁰⁰ ₋₇₀₀	2.6 ^{+0.2} _{-0.15}	0.14 ^{+0.05} _{-0.04}	49 ⁺¹³ ₋₁₁	7.82 ^{+0.45} _{-0.2}	6.91 ^{+0.5} _{-1.25}	6.6 ^{+1.35} _{-0.1}
AzV234	17 100 ⁺¹⁰⁰⁰ ₋₄₀₀	2.35 ^{+0.2} _{-0.1}	0.08 ^{+0.02} _{-0.01}	45 ⁺¹¹ ₋₅	8.12 ^{+0.35} _{-0.05}	6.31 ^{+0.55} _{-0.7}	7.1 ^{+1.25} _{-0.2}
AzV22	16 400 ⁺⁸⁰⁰ ₋₁₃₀₀	2.1 ^{+0.2} _{-0.2}	0.09 ^{+0.02} _{-0.01}	46 ⁺⁶ ₋₈	6.37 ^{+0.75} _{-1.0}	6.91 ^{+0.4} _{-1.2}	6.75 ^{+0.95} _{-0.25}
AzV445	15 600 ⁺⁷⁰⁰ ₋₇₀₀	2.3 ^{+0.15} _{-0.15}	0.065 ^{+0.04} _{-0.02}	41 ⁺⁶ ₋₁₅	7.72 ^{+0.35} _{-0.25}	6.46 ^{+0.8} _{-0.65}	7.3 ^{+1.1} _{-0.65}
AzV314	16 800 ⁺⁷⁰⁰ ₋₁₅₀₀	2.5 ^{+0.15} _{-0.25}	0.075 ^{+0.005} _{-0.045}	39 ⁺²¹ ₋₇	8.12 ^{+0.05} _{-0.65}	6.36 ^{+1.3} _{-0.75}	7.6 ^{+1.05} _{-0.7}
NGC330-ELS-02	16 900 ⁺⁹⁰⁰ ₋₁₀₀₀	2.45 ^{+0.15} _{-0.1}	0.09 ^{+0.0} _{-0.06}	44 ⁺⁴ ₋₈	6.42 ^{+0.75} _{-0.05}	6.51 ^{+0.6} _{-0.3}	7.85 ^{+1.0} _{-0.05}
SK179	14 500 ⁺⁶⁰⁰ ₋₆₀₀	2.35 ^{+0.15} _{-0.15}	0.09 ^{+0.04} _{-0.01}	116 ⁺¹⁵ ₋₆	7.57 ^{+0.35} _{-0.2}	6.96 ^{+0.75} _{-0.5}	7.45 ^{+1.6} _{-0.45}
AzV343	13 200 ⁺³⁰⁰ ₋₆₀₀	2.15 ^{+0.05} _{-0.15}	0.04 ^{+0.05} _{-0.0}	61 ⁺⁵ ₋₃	7.07 ^{+1.0} _{-0.25}	6.86 ^{+0.6} _{-0.4}	7.55 ^{+1.1} _{-0.35}
AzV324	13 100 ⁺⁵⁰⁰ ₋₅₀₀	2.15 ^{+0.15} _{-0.15}	0.09 ^{+0.04} _{-0.01}	42 ⁺¹⁸ ₋₂₈	7.67 ^{+0.7} _{-0.25}	5.81 ^{+1.2} _{-0.15}	7.3 ^{+1.75} _{-0.3}

Notes. For Y_{He} and $v_{\text{max, rot}} \sin i$ the errors are constrained from the optical-only fits as the allowed ranges of these parameters in optical plus UV fitting is limited in order to prevent unrealistic error bounds. The SMC base abundance of carbon, nitrogen, and oxygen is 7.42, 6.66, and 8.05, respectively (Vink et al. 2023).

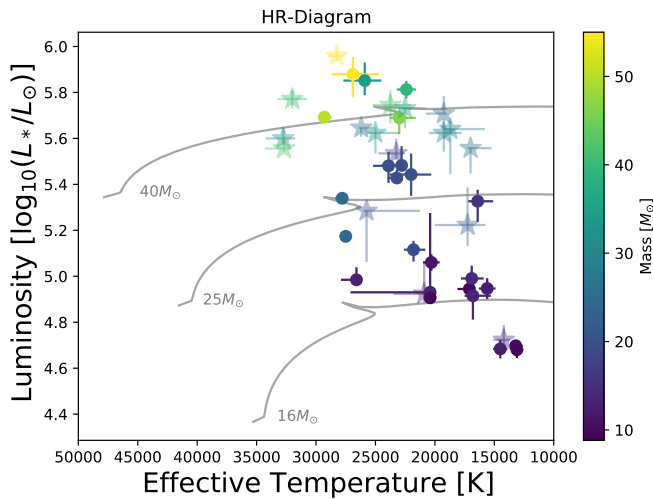


Fig. 1. Hertzsprung–Russell diagram showing the SMC sample (circles) and the LMC sample discussed in Verhamme et al. (2024) (stars). The symbol colour is a measure of the derived spectral mass. The non-rotating stellar evolution tracks are from Schootemeijer et al. (2019) and have $\alpha_{\text{co}} = 0.33$ and $\alpha_{\text{sc}} = 1$. The metallicity of the evolutionary tracks is set to $0.2 Z_{\odot}$.

extent degenerate, which impacts their uncertainties. Due to the statistical fitting process the errors quoted in this paper take these degeneracies into account automatically.

The maximum rotational velocity ranges from 40 to 120 km/s with one outlier at 230 km/s; the typical error margin is around 10 km/s. We note again that these values are a combination of macro-turbulence and rotational velocity. Determining the exact value of the macro-turbulence using the modest resolution of X-shooter is difficult and determining the macro-turbulence separately from the rotational velocity is almost impossible for all but the fastest of rotators (Sundqvist et al. 2013).

The helium abundance given is $Y_{\text{He}} = n_{\text{He}}/n_{\text{H}}$, i.e., the ratio of number density of He nuclei to H nuclei. Values range from lower than 0.08–0.23 with error margins typically not larger than 0.02. In three cases (AzV445, AzV314, and AzV343) the best fit helium abundance is below the Big Bang nucleosynthesis value of 0.08 (Schramm & Wagoner 1977). Even though they agree with this value within their 1σ uncertainty, we explore whether the helium abundance may impact other stellar properties. To this end, as a test we refitted these stars while preventing Y_{He} from going below a 0.08 threshold. This did not change the other parameters outside of the random variation due to the use of the GA method. The low Y_{He} is mostly found in the lower temperature stars. Undetected companions are known to potentially artificially lower the derived helium abundance, although for the one confirmed binary (AzV 488) this does not appear to be the case. The quoted CNO abundance is $\epsilon_x = 12 + \log_{10}(n_x/n_{\text{H}})$, where n_x is the number abundance of element x . We note that this convention implies that our quoted CNO abundances depend on the derived hydrogen, and hence helium abundance. Due to the small number of data points for CNO lines compared to

Table 3. Wind parameters of the sample.

Object name	$\log_{10} \dot{M} [\log_{10} (M_{\odot}/\text{yr})]$	$v_{\infty} [\text{km/s}]$	β	f_{cl}	f_{ic}	f_{vel}	$v_{\text{cl, start}} [v_{\infty}]$	$v_{\text{cl, max}} [v_{\infty}]$	$v_{\text{turb}} [v_{\infty}]$
AzV215	$-5.9^{+0.05}_{-0.4}$	1700^{+200}_{-50}	$1.15^{+0.45}_{-0.1}$	$10.0^{+19.0}_{-4.0}$	$0.15^{+0.45}_{-0.1}$	$0.45^{+0.1}_{-0.15}$	$0.01^{+0.06}_{-0.0}$	$0.15^{+0.18}_{-0.01}$	$0.08^{+0.11}_{-0.05}$
AzV488	$-5.85^{+0.05}_{-0.6}$	1400^{+100}_{-200}	$1.2^{+0.75}_{-0.05}$	$6.0^{+36.0}_{-1.0}$	$0.92^{+0.03}_{-0.38}$	$0.25^{+0.7}_{-0.22}$	$0.01^{+0.08}_{-0.01}$	$0.16^{+0.08}_{-0.07}$	$0.02^{+0.12}_{-0.02}$
AzV235	$-5.95^{+0.25}_{-0.05}$	1300^{+600}_{-250}	$2.6^{+0.05}_{-0.85}$	$26.0^{+1.0}_{-17.0}$	$0.42^{+0.58}_{-0.20}$	$0.38^{+0.25}_{-0.22}$	$0.08^{+0.01}_{-0.08}$	$0.24^{+0.11}_{-0.02}$	$0.3^{+0.07}_{-0.27}$
AzV104	$-7.35^{+0.35}_{-0.1}$	600^{+550}_{-150}	$2.25^{+0.2}_{-0.55}$	$17.0^{+33.0}_{-4.0}$	$0.02^{+0.02}_{-0.02}$	$0.18^{+0.05}_{-0.15}$	$0.03^{+0.05}_{-0.01}$	$0.3^{+0.08}_{-0.06}$	$0.4^{+0.00}_{-0.07}$
AzV506	$-7.4^{+0.05}_{-0.1}$	888^{+44}_{-10}	$1.75^{+0.2}_{-0.05}$	$19.0^{+9.0}_{-1.0}$	$0.02^{+0.02}_{-0.02}$	$0.02^{+0.08}_{-0.02}$	$0.07^{+0.04}_{-0.01}$	$0.18^{+0.12}_{-0.01}$	$0.37^{+0.01}_{-0.01}$
AzV43	$-7.45^{+0.05}_{-0.2}$	800^{+450}_{-50}	$1.25^{+1.85}_{-0.05}$	$26.0^{+3.0}_{-9.0}$	$0.08^{+0.08}_{-0.08}$	$0.1^{+0.5}_{-0.02}$	$0.07^{+0.02}_{-0.06}$	$0.2^{+0.01}_{-0.05}$	$0.39^{+0.01}_{-0.08}$
AzV266	$-6.7^{+0.2}_{-0.35}$	2250^{+300}_{-850}	$2.8^{+0.9}_{-0.35}$	$18.0^{+8.0}_{-13.0}$	$0.38^{+0.52}_{-0.22}$	$0.08^{+0.92}_{-0.08}$	$0.02^{+0.06}_{-0.02}$	$0.14^{+0.07}_{-0.04}$	$0.39^{+0.02}_{-0.14}$
AzV410	$-7.55^{+0.05}_{-1.8}$	423^{+428}_{-0}	$0.8^{+0.7}_{-0.35}$	$17.0^{+33.0}_{-15.0}$	$0.8^{+0.2}_{-0.75}$	$0.62^{+0.4}_{-0.6}$	$0.07^{+0.04}_{-0.07}$	$0.26^{+0.14}_{-0.05}$	$0.17^{+0.24}_{-0.09}$
AzV264	$-6.9^{+0.25}_{-0.3}$	1250^{+750}_{-600}	$2.65^{+1.05}_{-0.25}$	$19.0^{+17.0}_{-4.0}$	$0.88^{+0.12}_{-0.35}$	$0.2^{+0.77}_{-0.2}$	$0.01^{+0.06}_{-0.01}$	$0.23^{+0.15}_{-0.05}$	$0.13^{+0.22}_{-0.11}$
AzV96	$-6.85^{+0.05}_{-0.3}$	900^{+300}_{-50}	$1.25^{+2.25}_{-0.05}$	$34.0^{+13.0}_{-1.0}$	$0.38^{+0.6}_{-0.03}$	$0.6^{+0.4}_{-0.18}$	$0.01^{+0.07}_{-0.01}$	$0.1^{+0.23}_{-0.01}$	$0.26^{+0.11}_{-0.15}$
AzV210	$-7.0^{+0.25}_{-0.05}$	900^{+150}_{-150}	$2.05^{+0.3}_{-1.0}$	$24.0^{+26.0}_{-10.0}$	$0.82^{+0.18}_{-0.75}$	$0.65^{+0.35}_{-0.4}$	$0.07^{+0.02}_{-0.07}$	$0.19^{+0.13}_{-0.1}$	$0.11^{+0.24}_{-0.02}$
SK191	$-6.3^{+0.1}_{-0.2}$	550^{+50}_{-50}	$1.6^{+0.25}_{-0.2}$	$7.0^{+3.0}_{-5.0}$	$0.55^{+0.17}_{-0.25}$	$0.42^{+0.35}_{-0.15}$	$0.04^{+0.01}_{-0.02}$	$0.3^{+0.07}_{-0.01}$	$0.15^{+0.03}_{-0.04}$
AzV175	$-8.3^{+0.55}_{-0.05}$	200^{+550}_{-50}	$1.75^{+0.4}_{-0.3}$	$12.0^{+8.0}_{-1.0}$	$0.22^{+0.28}_{-0.22}$	$0.1^{+0.12}_{-0.08}$	$0.04^{+0.04}_{-0.01}$	$0.22^{+0.04}_{-0.09}$	$0.35^{+0.01}_{-0.16}$
AzV18	$-6.15^{+0.15}_{-0.15}$	1800^{+750}_{-1100}	$3.5^{+0.7}_{-0.9}$	$3.0^{+8.0}_{-2.0}$	$0.05^{+0.52}_{-0.05}$	$0.02^{+0.6}_{-0.02}$	$0.07^{+0.03}_{-0.07}$	$0.27^{+0.07}_{-0.09}$	$0.25^{+0.15}_{-0.13}$
AzV374	$-7.75^{+0.05}_{-0.5}$	492^{+97}_{-93}	$1.55^{+0.65}_{-0.3}$	$35.0^{+12.0}_{-12.0}$	$0.02^{+0.15}_{-0.02}$	$0.18^{+0.2}_{-0.12}$	$0.09^{+0.01}_{-0.08}$	$0.38^{+0.03}_{-0.06}$	$0.39^{+0.02}_{-0.12}$
NGC330-ELS-04	$-7.55^{+0.3}_{-0.3}$	500^{+150}_{-100}	$2.95^{+0.15}_{-0.7}$	$20.0^{+18.0}_{-12.0}$	$0.08^{+0.25}_{-0.08}$	$0.42^{+0.23}_{-0.4}$	$0.05^{+0.05}_{-0.03}$	$0.28^{+0.12}_{-0.1}$	$0.24^{+0.17}_{-0.11}$
AzV234	$-7.5^{+0.15}_{-0.35}$	292^{+70}_{-18}	$1.0^{+0.7}_{-0.25}$	$10.0^{+12.0}_{-4.0}$	$0.65^{+0.35}_{-0.18}$	$0.57^{+0.43}_{-0.45}$	$0.1^{+0.01}_{-0.08}$	$0.34^{+0.02}_{-0.06}$	$0.29^{+0.12}_{-0.02}$
AzV22	$-6.8^{+0.15}_{-0.3}$	650^{+500}_{-300}	$1.55^{+1.25}_{-0.4}$	$12.0^{+20.0}_{-8.0}$	$0.25^{+0.2}_{-0.2}$	$0.9^{+0.10}_{-0.52}$	$0.02^{+0.08}_{-0.02}$	$0.24^{+0.12}_{-0.14}$	$0.19^{+0.19}_{-0.08}$
AzV445	$-7.35^{+0.25}_{-0.25}$	308^{+36}_{-33}	$0.55^{+0.45}_{-0.1}$	$7.0^{+6.0}_{-6.0}$	$0.7^{+0.32}_{-0.15}$	$0.62^{+0.08}_{-0.6}$	$0.08^{+0.03}_{-0.07}$	$0.32^{+0.08}_{-0.01}$	$0.31^{+0.01}_{-0.28}$
AzV314	$-7.8^{+0.4}_{-0.55}$	357^{+47}_{-74}	$1.2^{+0.5}_{-0.75}$	$17.0^{+33.0}_{-12.0}$	$0.7^{+0.3}_{-0.65}$	$0.85^{+0.15}_{-0.85}$	$0.04^{+0.07}_{-0.03}$	$0.28^{+0.1}_{-0.18}$	$0.39^{+0.02}_{-0.32}$
NGC330-ELS-02	$-7.9^{+0.45}_{-0.3}$	450^{+250}_{-200}	$1.75^{+0.2}_{-0.85}$	$17.0^{+23.0}_{-15.0}$	$0.1^{+0.52}_{-0.05}$	$0.5^{+0.08}_{-0.35}$	$0.06^{+0.04}_{-0.06}$	$0.38^{+0.01}_{-0.18}$	$0.39^{+0.01}_{-0.21}$
SK179	$-7.25^{+0.15}_{-0.3}$	351^{+34}_{-27}	$0.95^{+0.15}_{-0.5}$	$2.0^{+9.0}_{-1.0}$	$0.82^{+0.18}_{-0.7}$	$0.55^{+0.45}_{-0.45}$	$0.07^{+0.03}_{-0.06}$	$0.28^{+0.07}_{-0.07}$	$0.13^{+0.25}_{-0.04}$
AzV343	$-7.62^{+0.03}_{-0.53}$	282^{+2}_{-29}	$0.95^{+0.45}_{-0.25}$	$6.0^{+5.0}_{-5.0}$	$0.28^{+0.22}_{-0.15}$	$0.5^{+0.15}_{-0.45}$	$0.04^{+0.05}_{-0.03}$	$0.38^{+0.02}_{-0.15}$	$0.14^{+0.08}_{-0.03}$
AzV324	$-7.4^{+0.3}_{-0.05}$	278^{+33}_{-38}	$0.52^{+0.18}_{-0.05}$	$1.0^{+3.0}_{-0.0}$	$0.42^{+0.48}_{-0.22}$	$0.35^{+0.3}_{-0.3}$	$0.01^{+0.09}_{-0.0}$	$0.25^{+0.15}_{-0.04}$	$0.19^{+0.13}_{-0.05}$

Notes. For stars lacking strong P Cygni lines, terminal wind speeds are obtained from the scaling law by [Hawcroft et al. \(2024a\)](#). These are given in grey. Additionally, any parameters for which the error margins cover the full allowed parameter range are shown grey as well. These values should be considered unconstrained.

other lines, the loss function (i.e. the root mean square error of approximation or RMSEA; see, e.g., [Steiger 2016](#)) does not change significantly when varying CNO. This causes the error margins on the CNO abundances to be relatively high ranging from 0.5 to 1.5 dex. The carbon abundance ranges from 6 to 8 dex, the nitrogen abundance from 6 to 7.5 dex, and the oxygen abundance from 7 to 8.5 dex. These should be assessed relative to the SMC baseline abundance of 7.42, 6.66, and 8.05, for C, N, and O, respectively ([Vink et al. 2023](#)). The errors could be reduced by fixing all parameters except for the abundances of interest and only fitting lines of those species, but this would ignore all degeneracies with other parameters. Because of the high uncertainty of the CNO abundances and the small influence of their lines on the fit function, CNO abundances are not the focal point of this paper (for a closer look into abundances of B-stars, see e.g. [Przybilla et al. 2006, 2008](#); [Urbaneja et al. 2017, 2023](#)). Here, we focus on the wind parameters. In estimating the error margins of a parameter, degeneracies with other parameters are automatically accounted for. Within the mass-loss rate error margin, for example, are models covering the full error margins of the CNO abundances.

3.2. Wind properties

For the nine wind parameters of $\dot{M}$, f_{cl} , f_{ic} , f_{vel} , $v_{\text{cl, start}}$, $v_{\text{cl, max}}$, v_{∞} , β , and max v_{turb} of the results are listed in Table 3 with additional and derived parameters in Table 4. The top panel of

Figure 2 shows the terminal wind speed over T_{eff} ; the colour of the symbol is a measure of the Eddington factor for electron scattering. Only stars for which we extracted v_{∞} from our analysis are shown. We made a comparison to the empirical relation for SMC stars by [Hawcroft et al. \(2024b\)](#) (black line, with grey area showing the 1σ uncertainty). Except for four stars with relatively large uncertainties due to weak wind features, our values are within the uncertainty of the [Hawcroft et al.](#) relation, though on average somewhat larger. Appendix D gives more details on v_{∞} and a comparison of this sample with [Hawcroft et al. \(2024b\)](#) including a very weak effect of metallicity on v_{∞} . In the second panel of Figure 2, we show the wind acceleration parameter. Both the scatter (from 0.5 to 3.5) and the uncertainties (typically 0.25, but sometimes larger) in β are fairly large. Especially in the region from 20 to 25 kK the spread is large and uncertainties are sizeable. This might indicate that particularly here the β -law performs poorly. This could indicate that for this regime a different velocity-law prescription is needed, for example the δ -slow solution ([Curé 2004](#); [Curé et al. 2011](#)). The high β values only show for stars with low rotational velocity compared to their critical rotational velocity ($v_{\text{max, rot}} \sin i \leq 0.4 v_{\text{crit}}$), meaning they could potentially be classified as low Ω , high δ slow solutions ([Curé et al. 2011](#)). However, the v_{∞} of the slow solution typically shows terminal velocities of 100–200 km/s, which is lower than almost all of the sample.

For the case of AzV22 (B3 Ia), we show in Fig. B.2 the relation between clumping factor and mass-loss rate for the many

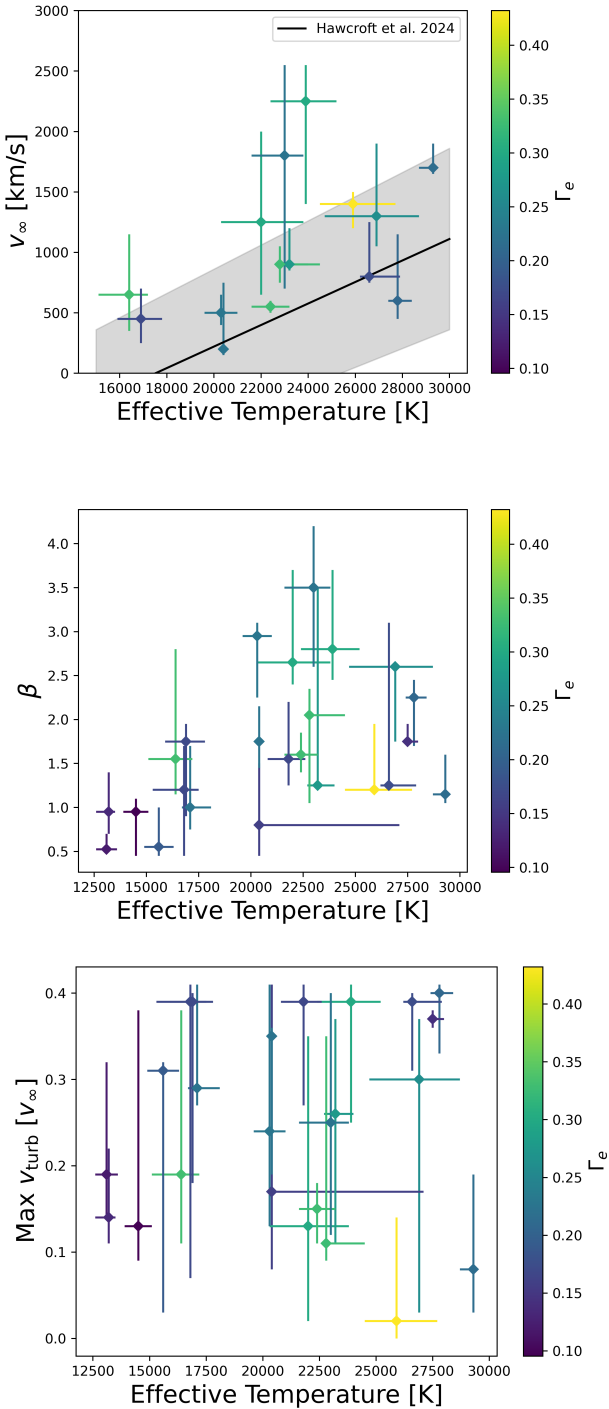


Fig. 2. Derived terminal velocities, wind acceleration parameter, and maximum wind micro turbulence, as function of effective temperature. The top panel excludes stars for which we adopted v_∞ from Hawcroft et al. (2024a) (shown in black with its 1σ uncertainty).

models calculated in the Kiwi-GA fitting run. The yellow region shows $(f_{cl}, \dot{M})$ combinations for which the fits are of good quality. It reveals that up to $f_{cl} \sim 20$ models of similar quality can be created by reducing the mass loss and increasing the clumping factor. This is expected for optically thin clumps embedded in a void interclump medium (e.g. Puls et al. 2020). We note, however, that for $f_{cl} \geq 20$ only a narrow range of mass loss is allowed for a wider range of, and more poorly constrained, clumping factors. This is the case for many of the objects. We find rather high

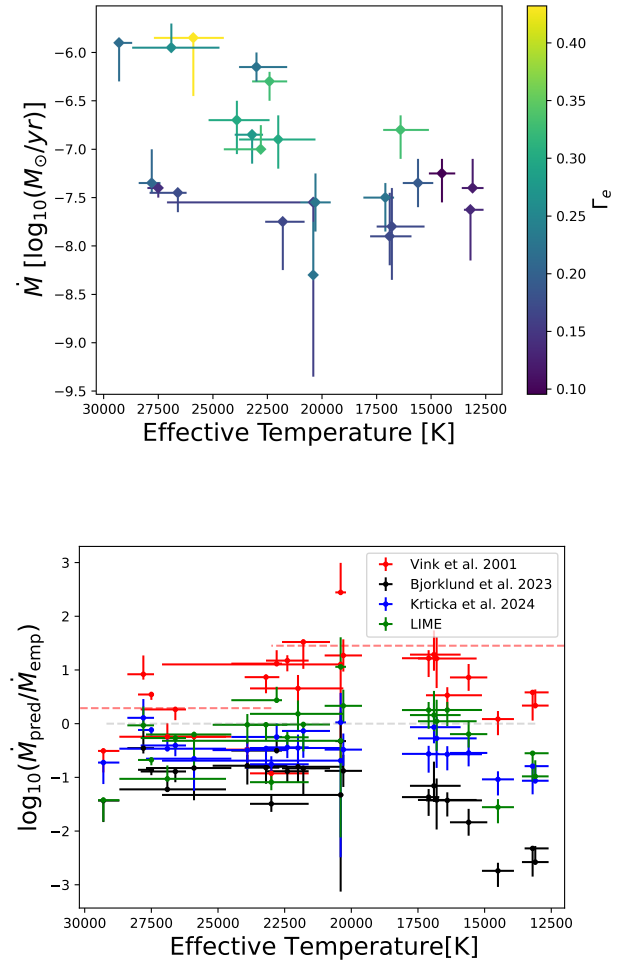


Fig. 3. Derived mass-loss rates for our sample as function of effective temperature. The top plot shows the derived mass-loss rates and the colour shows the derived classical Eddington parameter for each star. The bottom plot shows the logarithm of the ratio between the theoretical prescriptions by Vink et al. (2001); Björklund et al. (2023); Krtićka et al. (2024); Sundqvist et al. (2025) and the empirically found values. The red dashed line shows the average offset for the Vink et al., separated for stars on the hot side and the cool side of the jump. The grey line indicates where these values are equal.

error margins on the clumping parameters (see Fig. B.3) and reasonably low margins on the mass-loss rate (see Figure 3). For completeness, we present the clumping properties f_{cl} , f_{ic} , and f_{vel} in Fig. B.3. All three show a large spread accompanied by large uncertainties, with no apparent trends.

In the top panel of Figure 3, mass-loss rate as function of temperature is plotted. As our target stars span a sizeable range in luminosity and mass (strongly impacting $\dot{M}$; see e.g. Vink et al. 2001), we assessed our findings by comparing them directly to the predictions. This is shown in the bottom panel of the figure. On a star-by-star basis, we compare our results to four different prescriptions: in red to Vink et al. (2001), in black to Björklund et al. (2023), in blue to Krtićka et al. (2024), and in green to LIME (Sundqvist et al. 2025). For the comparisons we used the empirically derived spectroscopic mass, v_∞ , luminosity, and escape speed as input for the theoretical mass-loss estimate.

4. Discussion

Some of the relevance of the results we show in the last section only become clear when put in the context of the current

Table 4. Derived and X-ray parameters of all objects in our sample.

Object Name	$M_{\text{spec}}[M_{\odot}]$	$\log_{10}(L/L_{\odot})$	Radius $[R_{\odot}]$	Γ_e	$u_{\infty}[\text{km/s}]$	$\log_{10}(f_x)$	$\log_{10}(L_x/L_{\text{bol}})$
AzV215	50.24 ^{+0.04} _{-24.19}	5.69 ^{+0.0} _{-0.02}	27.49 ^{+0.27} _{-0.05}	0.22 ^{+0.18} _{-0.01}	667.5 ^{+87.5} _{-487.5}	-0.5 ^{+0.4} _{-0.05}	-5.83 ^{+0.29} _{-2.62}
AzV488	33.99 ^{+11.57} _{-5.19}	5.85 ^{+0.08} _{-0.06}	42.25 ^{+1.27} _{-1.51}	0.43 ^{+0.14} _{-0.1}	205.0 ^{+150.0} _{-75.0}	-1.05 ^{+0.75} _{-0.25}	-8.8 ^{+0.74} _{-0.63}
AzV235	68.2 ^{+82.56} _{-0.0}	5.88 ^{+0.08} _{-0.1}	40.4 ^{+1.93} _{-1.39}	0.26 ^{+0.0} _{-0.15}	117.5 ^{+87.5} _{-37.5}	0.9 ^{+0.05} _{-1.05}	-8.6 ^{+0.54} _{-1.23}
AzV104	24.76 ^{+2.58} _{-0.08}	5.34 ^{+0.02} _{-0.01}	20.33 ^{+0.13} _{-0.2}	0.21 ^{+0.0} _{-0.02}	180.0 ^{+112.5} _{-12.5}	0.5 ^{+0.3} _{-0.75}	-8.07 ^{+0.76} _{-0.25}
AzV506	24.39 ^{+2.53} _{-0.0}	5.17 ^{+0.02} _{-0.0}	17.17 ^{+0.0} _{-0.14}	0.140 ^{+0.003} _{-0.000}	255.0 ^{+75.0} _{-12.5}	0.0 ^{+0.05} _{-1.3}	-7.95 ^{+0.0} _{-1.04}
AzV43	13.15 ^{+3.53} _{-0.0}	4.98 ^{+0.05} _{-0.01}	14.76 ^{+0.1} _{-0.37}	0.17 ^{+0.0} _{-0.04}	205.0 ^{+500.0} _{-12.5}	-0.35 ^{+0.35} _{-0.3}	-8.52 ^{+1.84} _{-0.0}
AzV266	20.18 ^{+9.34} _{-4.54}	5.48 ^{+0.06} _{-0.07}	32.36 ^{+1.16} _{-0.91}	0.3 ^{+0.08} _{-0.06}	367.5 ^{+437.5} _{-37.5}	-0.4 ^{+0.3} _{-0.45}	-8.06 ^{+1.13} _{-0.45}
AzV410	13.18 ^{+17.51} _{-0.0}	4.93 ^{+0.35} _{-0.0}	23.57 ^{+0.0} _{-3.55}	0.16 ^{+0.11} _{-0.05}	380.0 ^{+462.5} _{-325.0}	-1.55 ^{+2.55} _{-0.45}	-8.14 ^{+1.31} _{-9.14}
AzV264	20.38 ^{+2.37} _{-5.92}	5.44 ^{+0.09} _{-0.09}	36.56 ^{+1.67} _{-1.56}	0.3 ^{+0.12} _{-0.04}	692.5 ^{+100.0} _{-412.5}	-0.35 ^{+0.4} _{-0.5}	-7.15 ^{+0.41} _{-0.85}
AzV96	20.0 ^{+2.35} _{-4.26}	5.43 ^{+0.04} _{-0.02}	32.32 ^{+0.33} _{-0.55}	0.28 ^{+0.08} _{-0.04}	355.0 ^{+112.5} _{-212.5}	0.3 ^{+0.05} _{-0.7}	-6.81 ^{+0.0} _{-1.96}
AzV210	19.5 ^{+6.61} _{-1.9}	5.48 ^{+0.08} _{-0.01}	35.64 ^{+0.09} _{-1.38}	0.33 ^{+0.03} _{-0.06}	255.0 ^{+362.5} _{-150.0}	-0.55 ^{+0.85} _{-1.1}	-8.52 ^{+1.45} _{-1.1}
SK191	39.21 ^{+16.2} _{-0.0}	5.81 ^{+0.04} _{-0.04}	54.0 ^{+1.02} _{-0.96}	0.33 ^{+0.0} _{-0.09}	405.0 ^{+112.5} _{-262.5}	-1.8 ^{+0.2} _{-0.2}	-8.32 ^{+0.41} _{-2.13}
AzV175	8.82 ^{+10.85} _{-1.76}	4.91 ^{+0.01} _{-0.01}	22.93 ^{+0.07} _{-0.07}	0.23 ^{+0.06} _{-0.12}	242.5 ^{+87.5} _{-137.5}	-0.5 ^{+0.75} _{-0.05}	-8.65 ^{+0.76} _{-1.55}
AzV18	46.48 ^{+18.04} _{-17.09}	5.69 ^{+0.04} _{-0.07}	44.43 ^{+1.54} _{-0.77}	0.23 ^{+0.12} _{-0.06}	542.5 ^{+200.0} _{-250.0}	-1.45 ^{+0.5} _{-0.4}	-8.02 ^{+0.26} _{-0.54}
AzV374	19.55 ^{+6.86} _{-5.66}	5.12 ^{+0.04} _{-0.05}	25.55 ^{+0.64} _{-0.47}	0.17 ^{+0.06} _{-0.04}	267.5 ^{+400.0} _{-12.5}	-0.1 ^{+0.9} _{-0.55}	-8.05 ^{+0.97} _{-0.34}
NGC330-ELS-04	11.45 ^{+4.49} _{-2.09}	5.06 ^{+0.04} _{-0.04}	27.65 ^{+0.5} _{-0.47}	0.23 ^{+0.04} _{-0.07}	480.0 ^{+350.0} _{-62.5}	-1.8 ^{+0.85} _{-0.1}	-8.94 ^{+1.21} _{-0.0}
AzV234	9.86 ^{+3.97} _{-0.91}	4.94 ^{+0.06} _{-0.02}	34.11 ^{+0.37} _{-1.06}	0.22 ^{+0.01} _{-0.07}	505.0 ^{+275.0} _{-62.5}	-1.65 ^{+0.3} _{-0.2}	-7.95 ^{+0.2} _{-0.38}
AzV22	15.85 ^{+5.12} _{-3.47}	5.33 ^{+0.05} _{-0.09}	57.55 ^{+2.81} _{-1.47}	0.33 ^{+0.01} _{-0.05}	N/A	N/A	N/A
AzV445	12.65 ^{+2.51} _{-2.15}	4.95 ^{+0.05} _{-0.05}	41.08 ^{+1.03} _{-0.96}	0.19 ^{+0.03} _{-0.02}	N/A	N/A	N/A
AzV314	13.73 ^{+3.11} _{-4.47}	4.92 ^{+0.04} _{-0.1}	34.16 ^{+1.91} _{-0.73}	0.17 ^{+0.05} _{-0.04}	N/A	N/A	N/A
NGC330-ELS-02	14.31 ^{+3.63} _{-0.7}	4.99 ^{+0.06} _{-0.07}	36.81 ^{+1.27} _{-1.03}	0.17 ^{+0.02} _{-0.02}	530.0 ^{+312.5} _{-12.5}	-1.15 ^{+1.35} _{-0.25}	-8.22 ^{+1.56} _{-0.22}
SK179	12.56 ^{+2.15} _{-1.6}	4.68 ^{+0.04} _{-0.04}	35.13 ^{+0.8} _{-0.75}	0.1 ^{+0.01} _{-0.01}	N/A	N/A	N/A
AzV343	10.39 ^{+0.17} _{-1.69}	4.7 ^{+0.02} _{-0.05}	43.06 ^{+1.1} _{-0.42}	0.13 ^{+0.01} _{-0.01}	N/A	N/A	N/A
AzV324	9.88 ^{+2.16} _{-2.21}	4.68 ^{+0.04} _{-0.04}	42.88 ^{+0.88} _{-0.84}	0.12 ^{+0.03} _{-0.02}	N/A	N/A	N/A

Notes. For the cooler stars we could not converge models that include X-ray luminosities, and hence we do not include X-rays. M_{spec} is computed using rotational velocity corrected $\log_{10} g_{\text{eff}}$.

latest results. Here we discuss how our results compare to popular mass-loss prescriptions and the effect of metallicity on the wind.

4.1. Comparison to current prescriptions

To further our understanding of mass loss in the SMC supergiant B-star regime, we compare our empirical $\dot{M}$ rates to several theoretical predictions. In the LMC and Galaxy, similar comparisons have already been made. Verhamme et al. (2024) using optical and UV data did not identify a jump in mass loss at about spectral type B1 in a sample of LMC B supergiants. de Burgos et al. (2024a) also did not find such a jump in an optical-only study of a large sample of Galactic B stars. In the bottom panel of Figure 3, we show the ratio of predicted to empirical mass-loss rate, i.e. $f_{p/e} = \dot{M}_{\text{pred}}/\dot{M}_{\text{emp}}$, in order to test how well four different theories recover our empirical mass-loss rates. We discuss separately how the theories of Vink et al. (2001), Björklund et al. (2023), Krtićka et al. (2024), and Sundqvist et al. (2025) compare to our results.

(1) Vink et al. (2001) is based on Monte Carlo simulations of photon–gas interactions, accounting for multiple-scattering effects, where the NLTE state of the gas is computed using the Sobolev approximation and the mass-loss rate is constrained

from global energy conservation assuming a preset β -type velocity structure (see also Vink et al. 1999; Vink et al. 2000). For $T_{\text{eff}} \geq 25$ K our empirical estimates are in fair agreement with these predictions, yielding $f_{p/e} = 2.0 \pm 0.9$. For stars cooler than 25 kK, however, the prescription yields mass-loss rates that exceed the empirical values by an average factor of 30 ± 17 . This ratio at temperatures below the bi-stability jump is similar to the LMC findings by Verhamme et al. (2024). This sizeable difference between the offset for stars on the cool and hot side of the jump location strongly suggests that the bi-stability jump is not present in this sample. To allow a comparison to prescriptions that are limited in their prediction range, we also computed an average for all stars above 18 kK: $f_{p/e} = 25 \pm 17$.

(2) Björklund et al. (2023) computed dynamical models by deriving the radiative acceleration from NLTE radiative transfer in the co-moving frame and solving the steady-state equation of motion. Hence, they predict both wind mass-loss rate and velocity structure. A comparison to our empirical data does not reveal a clear discontinuous behaviour at about 25 kK. $f_{p/e} = 0.12 \pm 0.02$, i.e. the predictions underestimate the mass loss by about a factor of eight. No temperature dependence in $f_{p/e}$ was found also for the LMC sample of Verhamme et al. (2024) where the theoretical values are on average a factor of two lower than the empirical values. The larger offset for SMC stars relative to LMC stars may point to a too strong dependence of mass loss on

metallicity in the Björklund et al. (2023) models. The Björklund et al. models do not probe temperatures below 15 kK, whereas three of our target stars are in this regime (SK179, AzV343, AzV324). However, we cannot identify which part of this discrepancy may have a physical cause and which may be the result of extrapolation of the predictions. For these three, the offset is several orders of magnitude. However, when only including stars with T_{eff} above 18 kK, the average offset is very similar ($f_{p/e} = 0.16 \pm 0.03$).

(3) Krtićka et al. (2024) compute dynamical models with similar approximations to those by Björklund et al. (2023), for example though differences in treatment of atomic data, non-explicit energy levels, and the use of the Sobolev approximation in the inner region to compute bound-bound rates, neglecting velocity curvature effects, and the location of the wind critical point, might lead to slightly differing results. For instance, while the fitting formula of Björklund et al. does not have a bi-stability jump, the Krtićka et al. predictions feature a very localised bump setting in below 20 kK and peaking at about 13 kK, albeit with relatively small (compared to Vink et al. 2001) amplitude. We note that our sample poorly probes the location of this predicted bump at low temperatures. For the full temperature range, $f_{p/e} = 0.42 \pm 0.06$. This is significantly better than for the previous two predictions. For all stars hotter than 18 kK, $f_{p/e} = 0.48 \pm 0.08$. The Krtićka et al. (2024) models underpredict $\dot{M}$ in the full temperature range. Similarly to Björklund et al., this underestimation becomes worse for the coolest stars.

(4) Sundqvist et al. (2025) provide the web tool LIME¹ to compute mass loss for arbitrary compositions from the modified (Pauldrach et al. 1986) Castor-Abbott-Klein theory (CAK; Castor et al. 1975) as formulated by Gayley (1995), adopting LTE flux-weighted line opacities (Poniatowski et al. 2022) to compute line-force parameters at the critical point. For the full sample an average offset of $f_{p/e} = 1.3 \pm 0.3$ is found, when limiting the comparison to stars $T_{\text{eff}} > 18$ kK, the comparison stays the same $f_{p/e} = 1.3 \pm 0.3$. For the coolest T_{eff} stars the mass loss is still underestimated. The latter may (in part) be the result of extrapolation, as the recommended T_{eff} parameter range is 18–60 kK. On average in both regimes LIME performs significantly better than other predictions.

Empirical evidence for a bi-stable behaviour of stellar winds of hot stars was first presented by Lamers et al. (1995), who identified a jump in the terminal wind velocity divided by the surface escape speed of galactic B1 supergiants. A jump-like behaviour was also found for SMC stars (Bernini-Peron et al. 2024). Crowther et al. (2006), however, reported a more gradual trend for galactic stars, though with large scatter. Here we combine the samples of all studies utilising the same collection data, and a similar methodology as utilised in this paper (Backs et al. 2024; Hawcroft et al. 2024a; Verhamme et al. 2024; Brands et al. 2025). These are all for LMC and SMC samples, while Lamers et al. (1995); Crowther et al. (2006) are galactic studies. Figure 4 shows $v_{\infty}/v_{\text{esc}}$ over T_{eff} for our full sample. Here v_{esc} is defined as the escape speed from the stellar surface with the radiative acceleration provided by electrons subtracted ($v_{\text{esc}}^2 = 2GM_{\star}(1 - \Gamma_e)/R_{\star}$). Unlike the study of 18 SMC B stars by Bernini-Peron et al. (2024), we do not find a jump in $v_{\infty}/v_{\text{esc}}$. Instead, similar to the conclusion of Crowther et al., we find a linear increase of $v_{\infty}/v_{\text{esc}}$ with T_{eff} . The linear trend shows no clear offset between LMC and SMC objects and appears to flatten somewhat at a value of about 3 for the hottest stars.

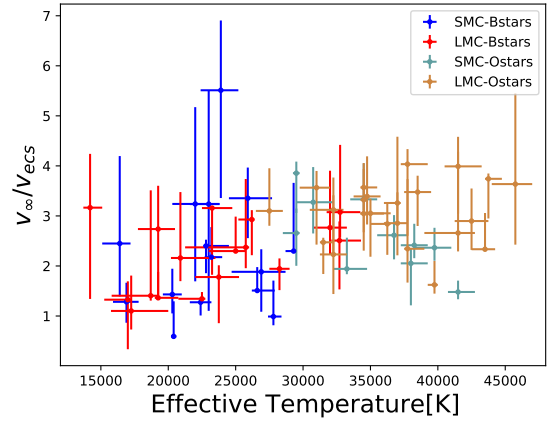


Fig. 4. Terminal wind speed divided by escape speed plotted over temperature. The mass used to determine the escape speed is the effective spectral mass. The values shown here are a combination of the stars studied in Backs et al. (2024); Hawcroft et al. (2024a); Verhamme et al. (2024); Brands et al. (2025), and the sample studied here.

This behaviour can be seen in Figure D.2. One should note that this parameter depends on the spectroscopic mass, for which both random and systematic uncertainties may be large (Herrero et al. 1992). This results in many observable trends within the uncertainties, making it a difficult empirical metric to use.

4.2. Effects of metallicity and temperature on mass loss

Combining the present work with the four studies mentioned above using a similar atmosphere analysis methodology, specifically the same detailed treatment of wind structure including a clumping description using f_{cl} , f_{ic} and f_{vel} (Backs et al. 2024; Hawcroft et al. 2024a; Verhamme et al. 2024; Brands et al. 2025), allows us to explore how mass loss depends on metallicity for different effective temperature and luminosity ranges. These studies combined cover temperatures in the range 13–60 kK and luminosities in the range $10^{4.7} - 10^6 L_{\odot}$, in the LMC and SMC metallicity environments at $Z_{\text{LMC}} = 0.5 Z_{\odot}$ and $Z_{\text{SMC}} = 0.2 Z_{\odot}$.

A practical way of doing this is by means of the mechanical momentum of the wind modified by the square root of the radius:

$$D \equiv \dot{M} v_{\infty} \sqrt{R_{\star}/R_{\odot}}. \quad (2)$$

The advantage of this modified wind momentum is that in the CAK theory it can be expressed as a function of luminosity only for reasonable line-force parameters (Kudritzki & Puls 2000).

Figure 5 shows four comparison plots of the $D(L_{\star})$ of the subsets of the sample, with all values in cgs units. The orange crosses are all of the LMC O stars with a luminosity above $10^{5.2} L_{\odot}$ by Brands et al. (2025) and Hawcroft et al. (2024a), green crosses the SMC O stars from Backs et al. (2024), the red crosses the LMC B-stars from Verhamme et al. (2024), and the blue crosses are the SMC B stars presented in this paper. For the LMC-O stars we removed all the stars from Hawcroft et al. (2024a) that have a luminosity below $10^{5.2} L_{\odot}$ as they exhibit what is known as the weak wind problem. To quantify the differences between the subsamples we fit them with a linear wind momentum luminosity relation,

$$\log_{10} D = \log_{10} D_0 + x \cdot \log_{10}(L_{\star}/L_{\odot}). \quad (3)$$

As in Backs et al. (2024), we use an orthogonal distance regression method (ODR; Boggs 1987) to derive the best fit values

¹ The line-driven-wind iterative mass-loss estimator tool LIME is available at <https://lime.ster.kuleuven.be/>

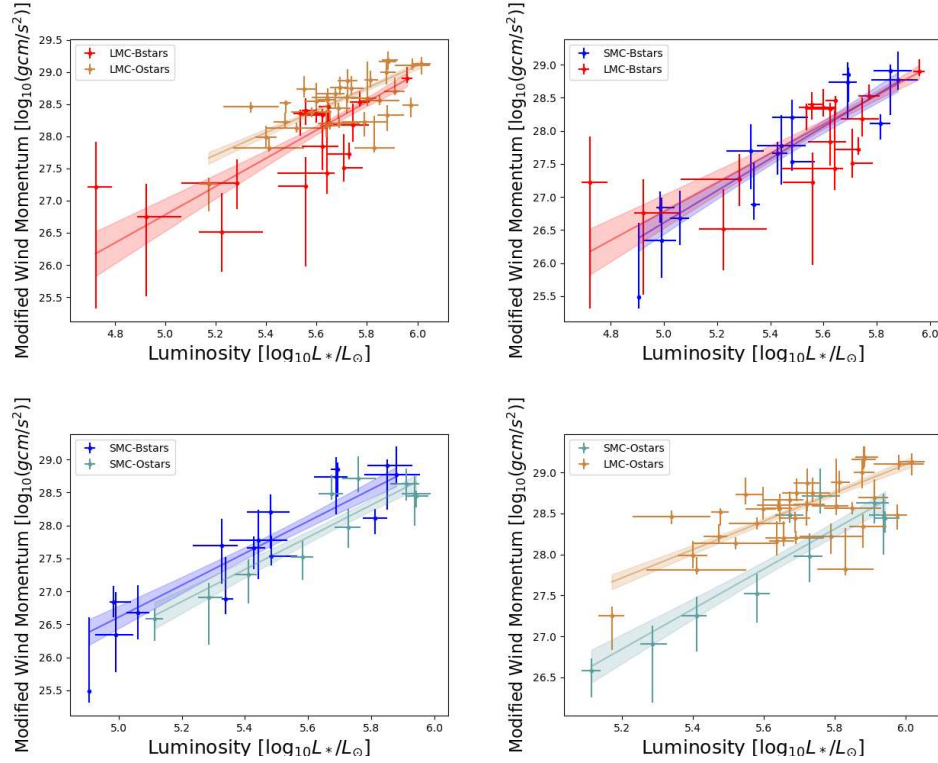


Fig. 5. Modified wind momentum vs luminosity from this study and previous SMC and LMC studies in this line of papers (Hawcroft et al. 2024b; Backs et al. 2024; Verhamme et al. 2024; Brands et al. 2025). The fits were performed using an ODR method. The error margins shown reflect the 1σ uncertainty.

Table 5. Fit values for Equation (3) for the four different datasets.

	$\log_{10} D_0$	x
LMC O-star	18.7 ± 0.9	1.7 ± 0.2
LMC B-star	15.8 ± 2.0	2.2 ± 0.4
SMC O-star	14.1 ± 1.8	2.4 ± 0.3
SMC B-star	14.5 ± 1.6	2.4 ± 0.3

and the 1σ error. These are listed in Table 5 and shown in the respective panels of Figure 5 using colours matching the star symbols.

Two surprising findings immediately stand out. First, there is only a minor difference in wind momentum between O stars and B stars in the SMC (Figure 5 bottom left panel), and only a modest difference in the LMC (top left), suggesting a weak direct temperature dependence of the mass-loss rate. Second, the wind momentum of LMC B stars matches the wind momentum of the SMC B stars for similar luminosities (top right), while there is a clear difference in D between the LMC and SMC O stars (bottom right). When making similar panels for the mass-loss rate versus luminosity, we see that the SMC B stars have a higher mass-loss rate when compared to the SMC O stars (Figure C.3), which is in conflict with all prescriptions as well.

Our findings for the B-star regime are at odds with the mass-loss recipes discussed above. The fit formula presented in Vink et al. (2001) yields $\dot{M} \propto Z^{0.64}$ for B stars and $\dot{M} \propto Z^{0.69}$ when taking into account the terminal wind speeds dependence on metallicity. The dependence of $\dot{M}$ on metallicity in the Björklund et al. (2023) prescription even steepens at lower temperatures:

for B stars at 20 kK it scales as $\dot{M} \propto Z^{1.4}$, while for O stars at 35 kK the mass-loss rate scales as $\dot{M} \propto Z^{0.95}$. The Krtićka et al. (2024) prescription has a more intricate relation with metallicity, which depends on both T_{eff} and luminosity. At a typical value $\log_{10}(L/L_{\odot}) = 5.5$ and $T_{\text{eff}} > 25$ kK it is found that $\dot{M} \propto Z^{0.41}$, and similarly to the Björklund et al. (2023) it becomes stronger towards lower temperatures. Because of the differences between $\dot{M}(Z)$ trends in our findings and in theory, we have compared our results to those of previous studies that cover the same stars. The direct comparisons are discussed in Appendix C and are overall in agreement.

Because ad libitum computations can be done with the web-tool LIME (Sundqvist et al. 2025), we can explore its $\dot{M}(Z)$ dependence in considerable depth. Figure C.4 shows the trends in different temperature brackets. Interestingly, the metallicity's effect on mass-loss rate has a clear temperature dependence. For instance, at $\log_{10}(L/L_{\odot}) = 5.8$ LMC stars with $T_{\text{eff}} = 20$ kK have a mass-loss rate only 1.2 times higher than their SMC counterparts. In comparison, at the same luminosity at $T_{\text{eff}} = 40$ kK an LMC star is found to have a mass-loss rate 1.7 times higher than a similar SMC star. We further note that LIME retrieves accurately the difference in mass-loss rate between LMC and SMC O stars also found in Backs et al. (2024).

Although the weak metallicity dependence of LIME for B stars warrants deeper investigation, our considerations suggest it may be related to the conditions at the wind critical point. As discussed in Sundqvist et al. (2025), it is generally found from LIME that carbon, nitrogen and oxygen play a more important role in determining the mass-loss rate than previously thought, in particular for cooler objects that are some distance from the Eddington limit. As CNO lines are generally quite strong (and often saturated), the direct dependence on metallicity becomes

less prominent than when the more numerous and weaker iron-group lines dominate. Similarly, Krtićka et al. (2025) find a weaker metallicity dependence of the mass-loss rate for stars with T_{eff} around 20–27 kK. Krtićka et al. (2025) show that CNO are the dominant species for line driving in the T_{eff} range from 20 to 27 kK, where an Fe contribution seems particularly low. This effect becomes more pronounced at lower metallicity.

4.3. Clumping parameters

As introduced in Sect. 2.2, five parameters describe the clumping properties (f_{cl} , f_{ic} , f_{vel}) and radial development of clumping ($v_{\text{cl,start}}$, $v_{\text{cl,max}}$). Figure B.3 shows that the clumping parameters of the SMC sample are very scattered and generally have a high degree of uncertainty. Similarly to the LMC sample (Verhamme et al. 2024), there are no clear trends between any stellar or wind parameters and clumping parameters. Although all clumping parameters have a measurable impact on the mass-loss rate, comparatively the impact of f_{cl} is largest. As the errors in the GA fitting approach take into account degeneracies among the parameters, all trends – including those in mass loss – are real despite a possible degeneracy, notably between $\dot{M}$ and f_{cl} .

The large error margins and the lack of trends in clumping characteristics as a function of stellar and wind properties is possibly related to a clumping formalism that does not adequately characterise the physical structure of clumping. Similar conclusions are drawn by Verhamme et al. (2024); Brands et al. (2025). In contrast to the current two-component medium used in FASTWIND, the results from multi-dimensional radiation hydrodynamics (Moens et al. 2022; Debnath et al. 2024) suggest a distribution of densities that more closely resembles a log-normal distribution around a mean. A hint that such a local density distribution is indeed a better physical description may be visible in the relatively high values of f_{ic} (for which the weighted average is ≈ 0.4). A similar result for f_{ic} was also reported for LMC stars by Verhamme et al. (2024). The importance of interclump density has also been marked by Zsargó et al. (2008); Puebla et al. (2016) for its role in producing super-ionised lines. However, they required a low interclump density.

5. Summary and conclusion

The primary objective of the photosphere and wind analysis of the 24 B stars in the SMC presented in this work was to empirically determine the presence or absence of a bi-stability jump in mass loss at early B spectral types. As our sample covers a wide range of luminosities, we searched for a jump behaviour with temperature in the ratio of predicted to empirical mass loss (see Fig. 3). No bi-stability feature in the spectral range B1–3 was found. In the range 16–30 kK, the predictions by the web tool LIME (Sundqvist et al. 2025) lack a bi-stability jump or bump and recover the empirical $\dot{M}$ values most closely.

For stars with spectral type later than B3 ($T_{\text{eff}} \approx 17$ kK), for which only a few data points are available, theory tends to strongly underpredict $\dot{M}$. For the Vink et al. (2001) rates, the differences between empirical and theoretical mass-loss rates are small at $T_{\text{eff}} \approx 17$ K. However, their strong overprediction at 20 kK implies a decline that is too steep compared to observations. It remains to be explored whether this is the result of extrapolation beyond the parameter space of validity of the predictions or points to shortcomings in the theory or models used to analyse the observations.

The derived wind clumping parameters are uncertain and show a large scatter. Found as well in other studies (including the LMC B-star analysis by Verhamme et al. 2024), it was suggested in Verhamme et al. (2024); Brands et al. (2025) that this behaviour might point to shortcomings in the representation of clumping behaviour in FASTWIND. Specifically, the large value of the local interclump density relative to the local mean density, $f_{\text{ic}} \sim 0.4$, potentially points to a breakdown of the assumption of a two-component density structure. Instead of high-density clumps and a very low-density interclump medium, a more continuous distribution may be more realistic. Multi-dimensional hydrodynamical simulations, which naturally clump and need no ad hoc clumping parameters point to the same conclusion (e.g. Driessen et al. 2022).

One of the main strengths of the combined ULLYSES (Roman-Duval et al. 2020, 2025) and XshootU (Vink et al. 2023) programmes, which are securing ultraviolet and optical spectra of large samples of LMC and SMC stars, is the comprehensive coverage of hot stars in the upper Hertzsprung–Russell diagram. Now that focussed studies have constrained the stellar and wind properties of over 80 stars in the temperature range 15–60 kK using uniform methodologies that address both clumping and mass loss (Hawcroft et al. 2024a; Backs et al. 2024; Verhamme et al. 2024; Brands et al. 2025), we were able to search for trends in wind properties with spectral type and metallicity. This yielded two surprising findings: (1) The modified wind-momenta (D) for SMC O-type and B-type stars are very similar. In the LMC, the O stars have somewhat higher D values. When considering mass-loss rate the SMC B stars even surpass the SMC O stars. (2) The mass-loss rates of B-type stars only very weakly depend on metallicity. The physical meaning of this result requires further exploration. Interestingly, the predictions by the recently published web tool LIME (Sundqvist et al. 2025), which computes mass-loss rates using line-force parameters specifically tailored to exact stellar and wind properties, predict a significantly weaker metallicity dependence for B stars relative to O stars. This offers a means to explore the physical reason(s) for this effect, which may be related to differences in the strength and elemental species of the dominant wind driving spectral lines near the wind critical point. Though for B stars the Z dependence appears weak, this may change when going to sub-SMC metallicity.

Data availability

The fits of all SMC B-supergiants discussed here and the distribution of the GA models are available at <https://zenodo.org/records/17725648>.

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References

- Abdul-Masih, M., Sana, H., Sundqvist, J., et al. 2019, *ApJ*, **880**, 115
- Alkousa, T., Crowther, P. A., Bestenlehner, J. M., et al. 2025, *A&A*, **699**, A314
- Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, *ARA&A*, **47**, 481
- Backs, F., Brands, S. A., de Koter, A., et al. 2024, *A&A*, **692**, A88
- Bellinger, E. P., de Mink, S. E., van Rossem, W. E., & Justham, S. 2024, *ApJ*, **967**, L39
- Benesty, J., Chen, J., Huang, Y., & Cohen, I. 2009, in *Noise Reduction in Speech Processing*, eds. I. Cohen, Y. Huang, J. Chen, & J. Benesty (Berlin, Heidelberg: Springer), 1
- Bernini-Peron, M., Sander, A. A. C., Ramachandran, V., et al. 2024, *A&A*, **692**, A89
- Bestenlehner, J. M., Crowther, P. A., Hawcroft, C., et al. 2025, *A&A*, **695**, A198
- Björklund, R., Sundqvist, J. O., Puls, J., & Najarro, F. 2021, *A&A*, **648**, A36
- Björklund, R., Sundqvist, J. O., Singh, S. M., Puls, J., & Najarro, F. 2023, *A&A*, **676**, A109
- Boggs, J. E. 1987, *Phys. Chem. Minerals*, **14**, 407
- Brands, S. A., Koter, A. d., Bestenlehner, J. M., et al. 2022, *A&A*, **663**, A36
- Brands, S. A., Backs, F., de Koter, A., et al. 2025, *A&A*, **697**, A54
- Britavskiy, N., Mahy, L., Lennon, D. J., et al. 2025, *A&A*, **698**, A40
- Brott, I., de Mink, S. E., Cantiello, M., et al. 2011, *A&A*, **530**, A115
- Carneiro, L. P., Puls, J., Sundqvist, J. O., & Hoffmann, T. L. 2016, *A&A*, **590**, A88
- Carneiro, L. P., Puls, J., & Hoffmann, T. L. 2018, *A&A*, **615**, A4
- Castor, J. I., Abbott, D. C., & Klein, R. I. 1975, *ApJ*, **195**, 157
- Crowther, P. A., Lennon, D. J., & Walborn, N. R. 2006, *A&A*, **446**, 279
- Curé, M. 2004, *ApJ*, **614**, 929
- Curé, M., Cidale, L., & Granada, A. 2011, *ApJ*, **737**, 18
- de Burgos, A., Keszthelyi, Z., Simón-Díaz, S., & Urbaneja, M. A. 2024a, *A&A*, **687**, L16
- de Burgos, A., Simón-Díaz, S., Urbaneja, M. A., & Puls, J. 2024b, *A&A*, **687**, A228
- Debnath, D., Sundqvist, J. O., Moens, N., et al. 2024, *A&A*, **684**, A177
- Driessen, F. A., Sundqvist, J. O., & Dagore, A. 2022, *A&A*, **663**, A40
- Evans, C. J., Lennon, D. J., Walborn, N. R., Trundle, C., & Rix, S. A. 2004, *PASP*, **116**, 909
- Gayley, K. G. 1995, *ApJ*, **454**, 410
- Gormaz-Matamala, A. C., Cuadra, J., Ekström, S., et al. 2024, *A&A*, **687**, A290
- Groh, J. H., & Vink, J. S. 2011, *A&A*, **531**, L10
- Hawcroft, C., Sana, H., Mahy, L., et al. 2021, *A&A*, **655**, A67
- Hawcroft, C., Mahy, L., Sana, H., et al. 2024a, *A&A*, **690**, A126
- Hawcroft, C., Sana, H., Mahy, L., et al. 2024b, *A&A*, **688**, A105
- Herrero, A., Kudritzki, R. P., Vilchez, J. M., et al. 1992, *Atmos. Early-Type Stars*, **401**, 21
- Josiek, J., Ekström, S., & Sander, A. A. C. 2024, *A&A*, **688**, A71
- Krtićka, J., Kubát, J., & Krtićková, I. 2021, *A&A*, **647**, A28
- Krtićka, J., Kubát, J., & Krtićková, I. 2024, *A&A*, **681**, A29
- Krtićka, J., Kubát, J., & Krtićková, I. 2025, *A&A*, **702**, A9
- Kudritzki, R.-P., & Puls, J. 2000, *ARA&A*, **38**, 613
- Lamers, H. J. G. L. M., Snow, T. P., & Lindholm, D. M. 1995, *ApJ*, **455**, 269
- Markova, N., & Puls, J. 2008, *A&A*, **478**, 823
- Moens, N., Poniatowski, L. G., Hennicker, L., et al. 2022, *A&A*, **665**, A42
- Mokiem, M. R., Koter, A. d., Puls, J., et al. 2005, *A&A*, **441**, 711
- Mokiem, M. R., de Koter, A., Vink, J. S., et al. 2007, *A&A*, **473**, 603
- Owocicki, S. P., & Rybicki, G. B. 1984, *ApJ*, **284**, 337
- Pauldrach, A., Puls, J., & Kudritzki, R. P. 1986, *A&A*, **164**, 86
- Pauli, D., Oskinova, L. M., Hamann, W.-R., et al. 2025, *A&A*, **697**, A114
- Poniatowski, L. G., Kee, N. D., Sundqvist, J. O., et al. 2022, *A&A*, **667**, A113
- Przybilla, N., Butler, K., Becker, S. R., & Kudritzki, R. P. 2006, *A&A*, **445**, 1099
- Przybilla, N., Nieva, M.-F., & Butler, K. 2008, *ApJ*, **688**, L103
- Puebla, R. E., Hillier, D. J., Zsargó, J., Cohen, D. H., & Leutenegger, M. A. 2016, *MNRAS*, **456**, 2907
- Puls, J., Urbaneja, M. A., Venero, R., et al. 2005, *A&A*, **435**, 669
- Puls, J., Markova, N., Scuderi, S., et al. 2006, *A&A*, **454**, 625
- Puls, J., Vink, J. S., & Najarro, F. 2008, *A&A Rev.*, **16**, 209
- Poniatowski, L. G., Sundqvist, J. O., & Sen, K. 2020, *A&A*, **642**, A172
- Rivero González, J. G., Puls, J., Najarro, F., & Brott, I. 2012, *A&A*, **537**, A79
- Roman-Duval, J., Fischer, W. J., Fullerton, A. W., et al. 2025, *ApJ*, **985**, 109
- Roman-Duval, J., Proffitt, C. R., Taylor, J. M., et al. 2020, *Res. Notes AAS*, **4**, 205
- Rubio-Díez, M. M., Sundqvist, J. O., Najarro, F., et al. 2022, *A&A*, **658**, A61
- Sana, H., Tramper, F., Abdul-Masih, M., et al. 2024, *A&A*, **688**, A104
- Sander, A. A. C., Bouret, J. C., Bernini-Peron, M., et al. 2024, *A&A*, **689**, A30
- Santolaya-Rey, A. E., Puls, J., & Herrero, A. 1997, *A&A*, **323**, 488
- Schootemeijer, A., Langer, N., Grin, N. J., & Wang, C. 2019, *A&A*, **625**, A132
- Schramm, D. N., & Wagoner, R. V. 1977, *Ann. Rev. Nucl. Part. Sci.*, **27**, 37
- Shenar, T., Bodensteiner, J., Sana, H., et al. 2024, *A&A*, **690**, A289
- Sobolev, V. V. 1960, *Moving Envelopes of Stars* (Cambridge: Harvard University Press)
- Steiger, J. H. 2016, *Struc. Eq. Model. Multidisciplinary J.*, **23**, 777
- Sundqvist, J. O., & Puls, J. 2018, *A&A*, **619**, A59
- Sundqvist, J. O., Simón-Díaz, S., Puls, J., & Markova, N. 2013, *A&A*, **559**, L10
- Sundqvist, J. O., Debnath, D., Backs, F., et al. 2025, *A&A*, **703**, A284
- Tramper, F., Sana, H., de Koter, A., Kaper, L., & Ramírez-Agudelo, O. H. 2014, *A&A*, **572**, A36
- Trundle, C., & Lennon, D. J. 2005, *A&A*, **434**, 677
- Trundle, C., Lennon, D. J., Puls, J., & Dufton, P. L. 2004, *A&A*, **417**, 217
- Urbaneja, M. A., Kudritzki, R. P., Gieren, W., et al. 2017, *AJ*, **154**, 102
- Urbaneja, M. A., Bresolin, F., & Kudritzki, R.-P. 2023, *ApJ*, **959**, 52
- Verhamme, O., Sundqvist, J., de Koter, A., et al. 2024, *A&A*, **692**, A91
- Vink, J. S. 2022, *ARA&A*, **60**, 203
- Vink, J. S., & de Koter, A. 2002, *A&A*, **393**, 543
- Vink, J. S., & Sander, A. A. C. 2021, *MNRAS*, **504**, 2051
- Vink, J. S., de Koter, A., & Lamers, H. J. G. L. M. 1999, *A&A*, **350**, 181
- 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
- Vink, J. S., Mehner, A., Crowther, P. A., et al. 2023, *A&A*, **675**, A154
- Zsargó, J., Hillier, D. J., Bouret, J.-C., et al. 2008, *ApJ*, **685**, L149

Appendix A: Fitting example

Figure A.1 shows an example of some of the lines fit over the temperature domain. These stars range from B0-B8.

Appendix B: Exploration of potential correlations

In this section we have compiled additional figures which explore the clumping behaviour of the sample closer.

Figure B.1 shows the correlation between many of the resulting wind parameters. This plot shows the Pearson correlation coefficient (Benesty et al. 2009) between the different derived parameters not including the stars for which we could not determine v_∞ . We account for the error margins on the parameters by computing the correlation matrix 1000 times each time using randomly selected values according to a Gaussian distribution based on the best fit and the error margins. When averaging this result we can determine an error margin on this correlation by computing the standard deviation. Figure B.1 uses red to show positive linear correlations and blue to show negative correlation. If the numbers are printed in grey the standard deviation of the correlation is larger than the determined mean correlation.

Some of the expected correlation are clearly retrieved. There is a positive clear mass-loss rate, T_{eff} and v_∞ , T_{eff} correlation as expected. This results, logically, in a correlation between v_∞ and $\dot{M}$ as well. The positive correlation between f_{ic} , $\dot{M}$, and Γ_e is not immediately obvious. The two positive correlations are related as the mass-loss rate correlates with the Eddington factor for obvious reasons. A high mass-loss rate resulting in a high f_{ic} might be related to the amplification rate of line de-shadowing instability being inversely correlated to the optical depth of the line (Owocki & Rybicki 1984). Therefore, increasing the mass-loss rate reduces the effect of the line de-shadowing instability. This correlation seems to mostly be driven by the highest Γ_e star, when removed the mean correlation drops to 0.25 only slightly above the standard deviation.

Appendix C: Comparative tests to previous studies

In this paper, we appear to have shown that the mass-loss rates of B stars do not depend on metallicity. This result is not in line with some of the basic assumptions of line-driven winds. As a result, we extensively compared our results to other papers which study similar stars. Here we show how our results compare to several other studies which studied some of the same stars.

The SMC B star results of Bernini-Peron et al. (2024) uses identical data. In total there are 13 stars which are studied in both this paper and the sample of Bernini-Peron et al. (2024). Even though that paper uses a very different method we can still compare the mass-loss rates. Bernini-Peron et al. (2024) does not use a GA method or another systematic fitting method instead using a 'by-eye' fit manually tuning models to find a good fit. As a result, deriving error margins of the 'by-eye' fit is difficult. Bernini-Peron et al. (2024) use their expertise to estimate an error margin which they apply to the full sample. Instead of FASTWIND Bernini-Peron et al. (2024) use CMFGEN to produce the spectra and assume optically thin clumps. CMFGEN, like FASTWIND, takes into account a whole range of elements in different ionisation stages to determine the temperature stratification, but unlike the version of FASTWIND we used, CMFGEN is able to produce spectral lines of heavier elements such as aluminium and iron to use in determining wind behaviour. By using

the 'by-eye' method they are still forced to focus on a limited number of lines, most of which are also included here, with the notable exception of a UV Al III line and magnesium lines as we mentioned above. The UV Al III line could allow for v_∞ determination to cooler temperatures and the Mg lines give a more accurate T_{eff} at $T_{\text{eff}} < 15$ kK as we already mentioned. Despite all these differences, figure C.1 shows that there is in general a very good agreement between the derived mass-loss rates between this paper and Bernini-Peron et al. (2024). For all stars except SK 179 there is significant overlap in the error margin between this paper's mass-loss rates and those derived by Bernini-Peron et al. (2024). The difference between our derived v_∞ and Bernini-Peron et al. (2024) is higher than the error margins in 4 cases. Certainly for the cooler stars this can be explained by our lacking of the Al III lines, which is represented by our large error margins as well. We also compared other parameters which agree well, however we find that $\log_{10} g_{\text{eff}}$ and T_{eff} is consistently higher in this paper when compared to Bernini-Peron et al. (2024) (see figure C.2). However for all but 3 of the stars they do still have an overlap in error margins. A similar agreement between the methods was also shown on a sample of three O stars (Sander et al. 2024).

Even when comparing to previous studies using different data we find relatively strong agreement. Trundle et al. (2004) is an optical only study on 8 SMC B stars of which 6 have also been studied in this paper (AzV215, AzV104, SK191, AzV210, AzV18, AzV22). The $\log_{10} g_{\text{eff}}$ and T_{eff} agree within error margin for all stars, but AzV215 for which we find $T_{\text{eff}} = 29300^{+200}_{-600}$ K, $\log_{10}(g) = 3.25^{+0.05}_{-0.35}$, while Trundle et al. (2004) finds $T_{\text{eff}} = 27000 \pm 1000$ K, and $\log_{10}(g_{\text{eff}}) = 2.9 \pm 0.1$. Here we see the effective surface gravity still overlaps, but we find a higher T_{eff} with a very low uncertainty. The mass-loss rates agree within error margins for all stars, but AzV18. We find $\log_{10}(\dot{M}) = -6.15 \pm 0.15[\log_{10} M_\odot/\text{yr}]$ and Trundle et al. (2004) derives $\log_{10}(\dot{M}) = -6.64 \pm 0.05[\log_{10} M_\odot/\text{yr}]$. Even this difference is not worrying, considering the difference in studied lines and would not effect our conclusions. Trundle & Lennon (2005) is another optical only study for which some terminal wind speeds were known from Evans et al. (2004). This study has 2 stars in common with this study (AzV264, AzV96). Within error margins the T_{eff} , surface gravity, and the mass-loss rates agree. These comparisons show that although the resulting conclusions of our derived mass-loss rates are surprising the derived parameters themselves are similar to previous studies of these stars.

Finally we also decided to compare to the empirical prescription by Pauli et al. (2025), which uses a Γ_e dependence instead of a T_{eff} , mass, and luminosity dependence. We note an average $f_{p/e} = 1.3 \pm 0.4$ for the SMC B stars, and an average $f_{p/e} = 1.2 \pm 0.9$ for the SMC O stars. The LMC systematically does worse with an average ratio of LMC O stars of $f_{p/e} = 3.6 \pm 1.0$ and $f_{p/e} = 3.4 \pm 2.4$ for LMC B stars. The results for the SMC seem to be comparable with the results LIME (Sundqvist et al. 2025) provides. The LMC, in comparison, is overestimated and with a significant scatter. The success of this prescriptions is not entirely surprising as it is based on previous empirical studies which this paper, as shown above, is in agreement with.

Appendix D: v_∞ behaviour

From previous theoretical works we expect an existing, but weak v_∞ metallicity dependence. Vink & Sander (2021), using a Monte Carlo approach, find $v_\infty \propto Z^{0.19}$. Björklund et al. (2021), on the other hand find a relation indistinguishable from zero

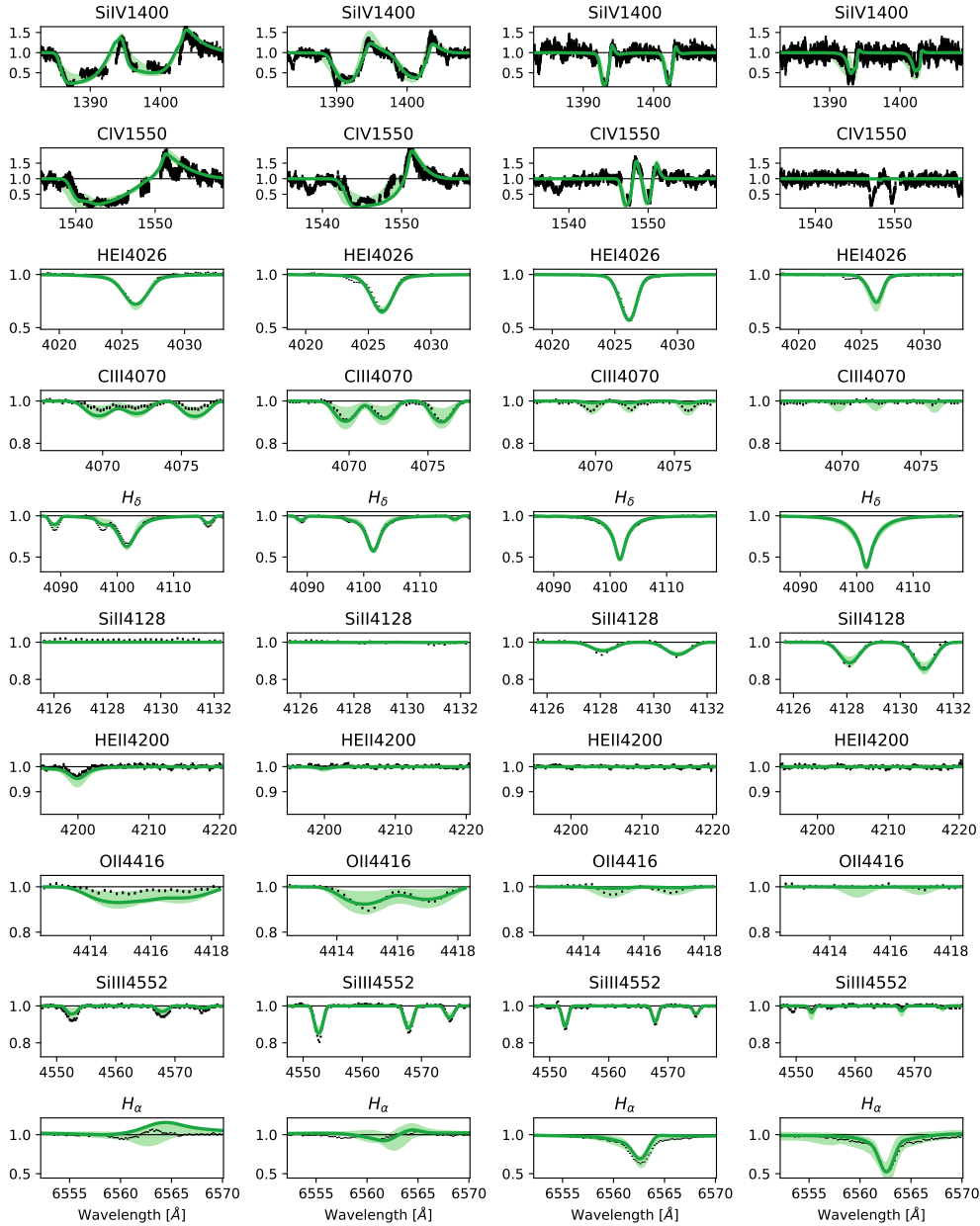


Fig. A.1. Presentation of normalised line fits to (from left to right) AzV215 (B0 Ia), AzV96 (B1 Iab), AzV234 (B2.5 Ib), and AzV324 (B8 Ib). The corresponding effective temperatures are 29.3, 23.2, 17.1, and 13.1 kK, respectively. Data is shown in black; the dark green line denotes the best fit and the light green region the 1- σ uncertainty region.

($v_{\infty} \propto Z^{-0.10 \pm 0.18}$). However, they do note some potential issues with their terminal wind speeds.

We compare the previously determined v_{∞} , T_{eff} relation through a Sobolev exact integration technique (Hawcroft et al. 2024b) with the combined results of this work with Backs et al. (2024); Hawcroft et al. (2024a); Verhamme et al. (2024); Brands et al. (2025). Table D.1 shows the results of our ODR fit and the fit of Hawcroft et al. (2024b), both using a simple linear fitting law,

$$v_{\infty} = a \cdot T_{\text{eff}} - b. \quad (\text{D.1})$$

It is clear that both the slope and the offset for the LMC is almost identical although we retrieve a lower 1- σ error margin. The SMC slope is different between the two studies, but for the

Hawcroft et al. (2024b) results still within error margins. The fits are plotted in the upper panel of figure D.1, which show that the smaller slope is caused mostly by some hot SMC O stars which have a lower v_{∞} in comparison to the LMC O stars with the same T_{eff} . Up to 35 kK the v_{∞} dependence on T_{eff} of the SMC appears mostly equal to that of the LMC. We also plot the Hawcroft et al. (2024b) results over the same results in the lower panel of figure D.1, showing that their retrieved results still function within error margins. When fitting the full sample with a new Z dependence,

$$v_{\infty} = a T_{\text{eff}} \cdot (Z/Z_{\odot})^c - b, \quad (\text{D.2})$$

we find that $a = (8.5 \pm 0.2) \cdot 10^{-2} \frac{\text{km}}{\text{s K}}$, $b = 1080 \pm 55 \frac{\text{km}}{\text{s}}$, and $c = (-0.9 \pm 1.1) \cdot 10^{-2}$. We note here that the Z -dependence is within

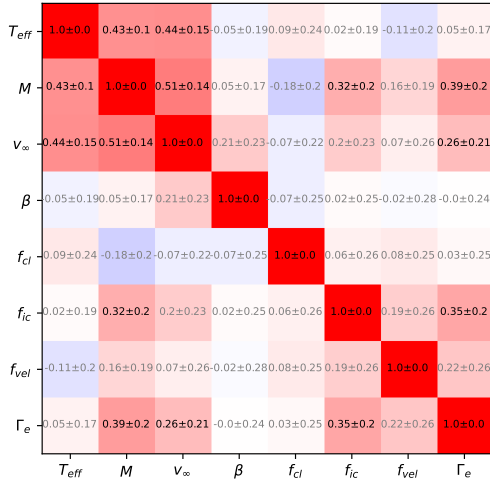


Fig. B.1. Correlation plot for wind parameters. The colour shows how positive (red) or negative (blue) the Pearson correlation coefficient is. If the standard deviation is larger than the derived correlation the values are written in grey.

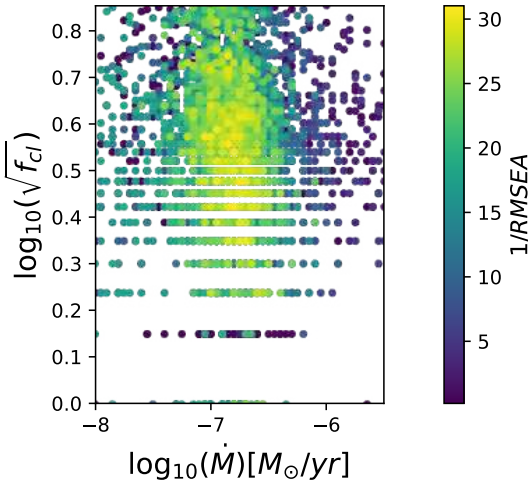


Fig. B.2. Mass loss versus clumping factor correlation plot for AzV22 (B3 Ia). The symbol colour yields the quality of the fit expressed as the inverse of the root mean square error of approximation. We plot the $\sqrt{f_{\text{cl}}}$ to emulate the expected clumping relation $f_{\text{cl}}(\rho_{\text{uncl}})^2 = \langle \rho^2 \rangle$ (Puls et al. 2006), although this correlation only holds for optically thin clumping and a constant clumping factor, both of which are not true here. For the same reason we plot this relation in a log-log scale.

error margins equal to zero, showing the lack of Z dependence of the terminal wind speed. This result was also hinted at in Bernini-Peron et al. (2024), where the found v_{∞} , T_{eff} relation was suggested to be not impacted by metallicity. Here they compared their found relation for the SMC B stars and found it remarkably similar to the LMC relation of Hawcroft et al. (2024b).

Although, as noted in the main text, the indicator of $v_{\infty}/v_{\text{esc}}$ is a tenuous one, due to major uncertainties. We also plot here two fits of the relation in figure D.2. We fit a linear function to the full sample regardless of metallicity up to $T_{\text{eff}} = 25$ kK as a very rough estimate to where we expect the increase to stop. We note that data points with low error margins have a higher weight when determining the linear fit. Therefore the most noticeable points at low T_{eff} , with a high $v_{\infty}/v_{\text{esc}}$ and high error margins are only weakly impacting the fit. The fit of stars with $T_{\text{eff}} >$

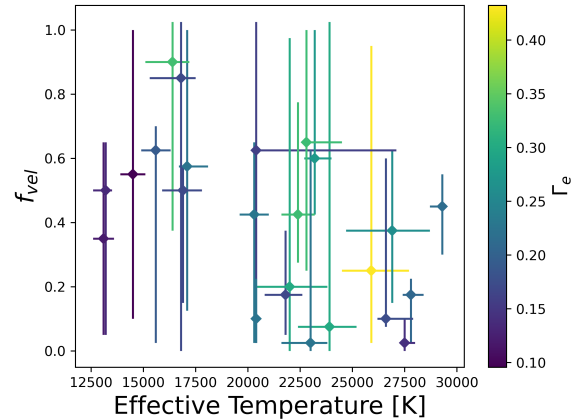
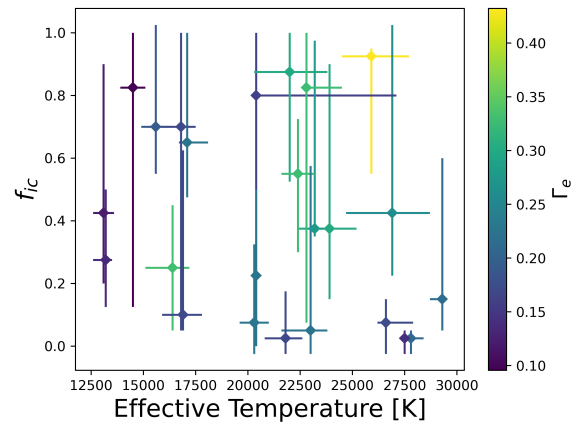
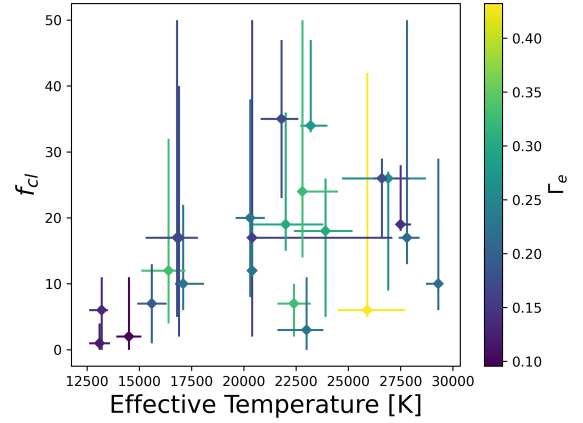


Fig. B.3. Clumping parameters with respect to the effective temperature. The panels from top to bottom show the clumping factor, interclump density (in units of mean density), and velocity filling factor. The colour indicates the derived Γ_e for the stars.

25 kK are also plotted. We also overplot the original Lamers et al. (1995) result.

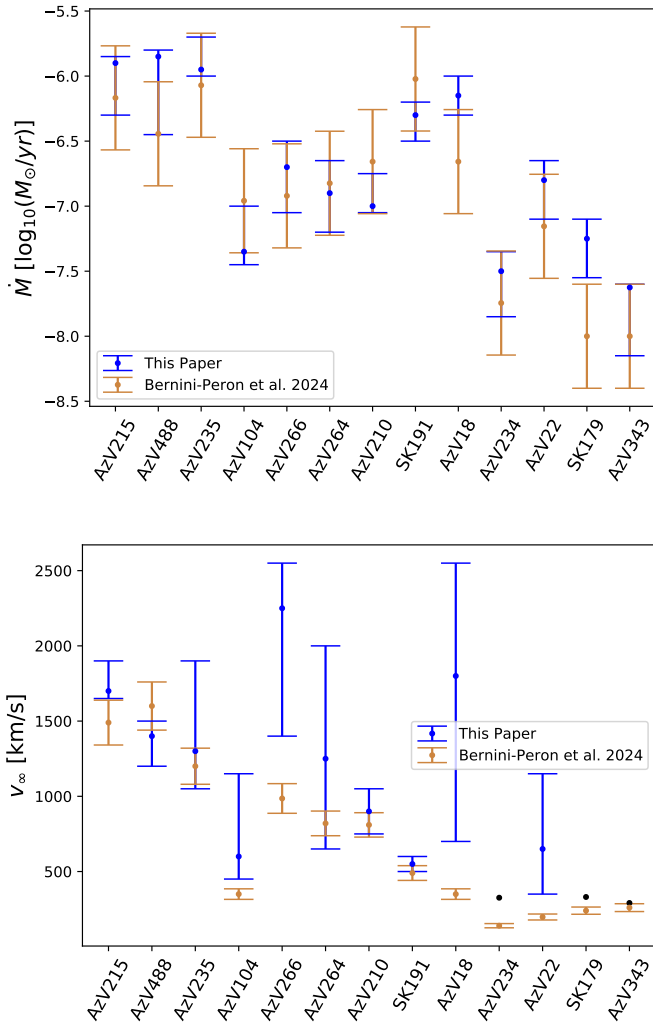


Fig. C.1. Comparison between derived mass-loss rates and terminal velocities. Here we show a comparison of the derived mass-loss rates and terminal wind speeds between all stars this paper shares with [Bernini-Peron et al. \(2024\)](#). In blue we show the results of this paper, while orange shows the results of [Bernini-Peron et al. \(2024\)](#). The black points in the v_{∞} show the assumed terminal wind speeds, where we could not derive a satisfactory v_{∞} .

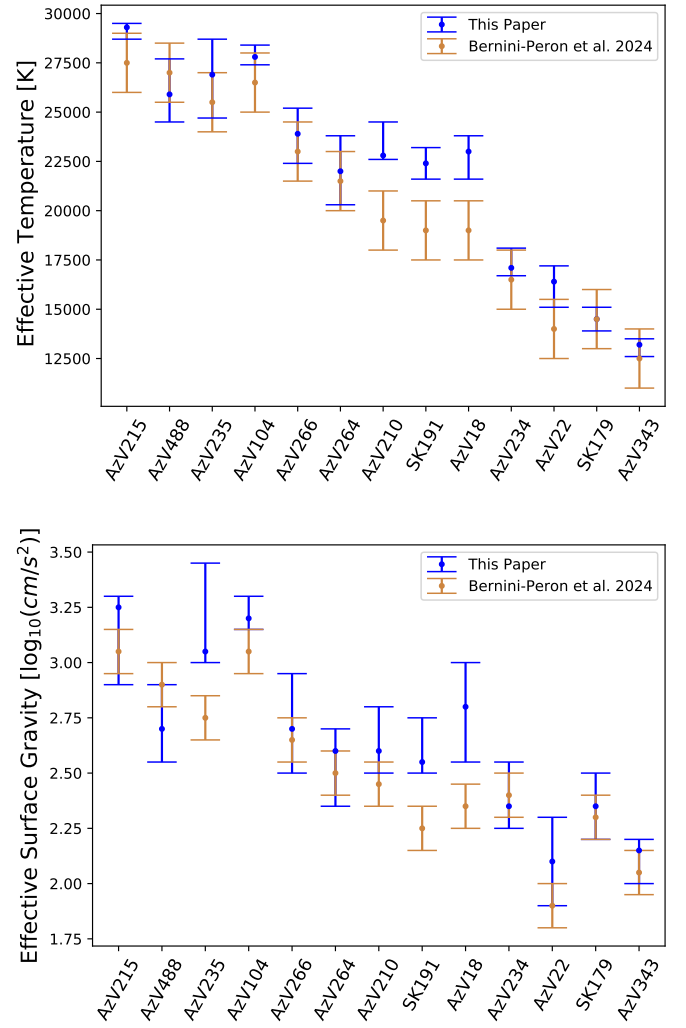


Fig. C.2. Comparison between derived T_{eff} and $\log_{10} g_{\text{eff}}$. Here we show a comparison of the derived T_{eff} (top figure) and the surface gravity (bottom figure) between all stars this paper shares with [Bernini-Peron et al. \(2024\)](#). In blue we show the results of this paper, while orange shows the results of [Bernini-Peron et al. \(2024\)](#).

Table D.1. Fits of v_{∞} with T_{eff} .

This work	a [$\text{km} \cdot \text{s}^{-1} \text{K}^{-1}$]	b [$\text{km} \cdot \text{s}^{-1}$]
SMC stars	$(7.9 \pm 0.3) \cdot 10^{-2}$	993 ± 99
LMC stars	$(8.8 \pm 0.2) \cdot 10^{-2}$	1083 ± 66
Hawcroft et al. 2024		
SMC stars	$(8.9 \pm 1.1) \cdot 10^{-2}$	1560 ± 420
LMC stars	$(8.8 \pm 0.4) \cdot 10^{-2}$	1200 ± 150

Note: We compared the v_{∞} , T_{eff} fit of this sample with the results of [Hawcroft et al. \(2024b\)](#). The fit formula is given by formula 1.

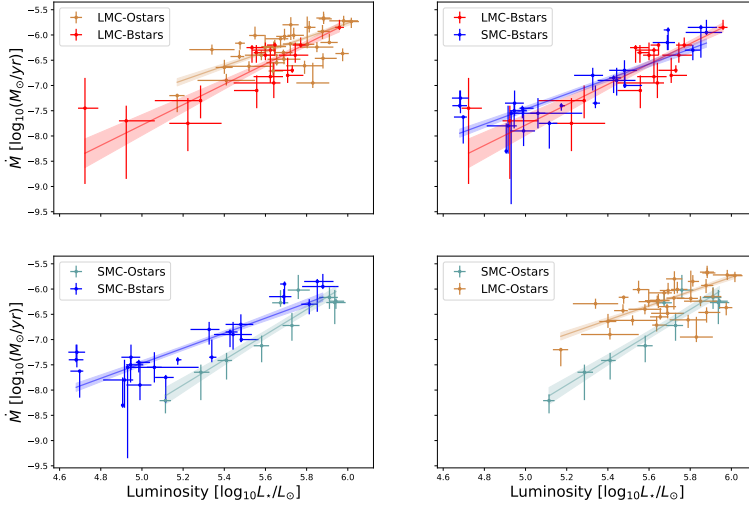


Fig. C.3. Mass-loss rate comparisons. These plots all show the mass-loss rate vs the luminosity from this study and the previous SMC and LMC studies in this series of papers (Hawcroft et al. 2024b; Backs et al. 2024; Verhamme et al. 2024; Brands et al. 2025). The fits were performed using an ODR method. The error margins shown are the 1 σ uncertainty.

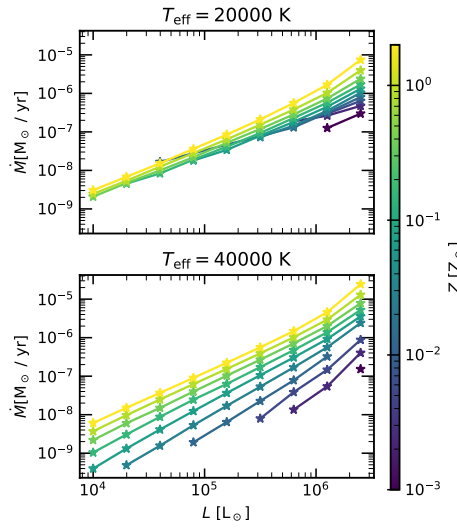


Fig. C.4. LIME mass-loss predictions as function of luminosity for different metallicities and temperatures. Each panel shows a T_{eff} value. The coloured lines from blue to yellow are for $\log_{10}(Z/Z_{\odot}) = -3, -2.6, -2.3, -1.9, -1.5, -1.2, -0.8, -0.4, -0.07, 0.3$.

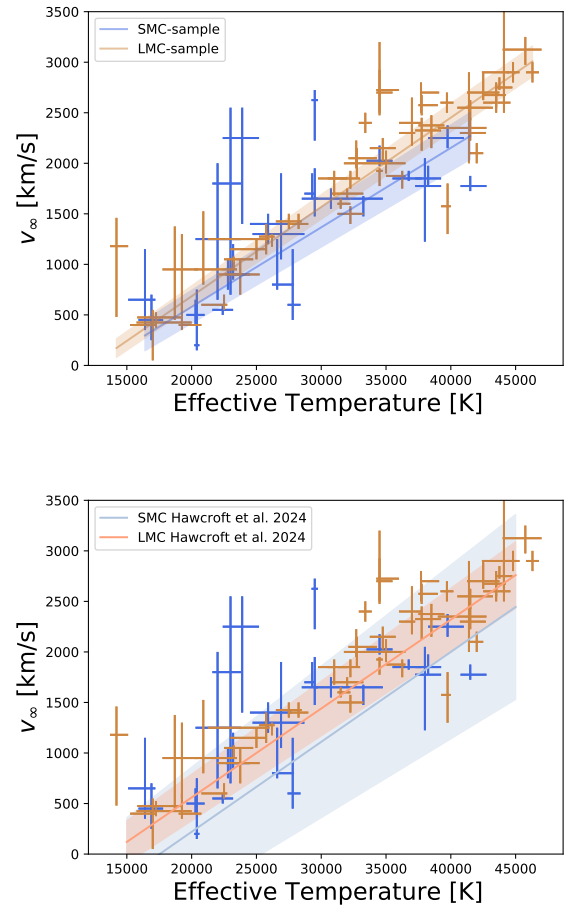


Fig. D.1. Relation between T_{eff} and v_{∞} . The top panel shows the combined results from Backs et al. (2024); Verhamme et al. (2024); Hawcroft et al. (2024a); Brands et al. (2025) and a fit separating the SMC and LMC sample. The bottom panel shows the same sample but with the results of Hawcroft et al. (2024b) overplotted.

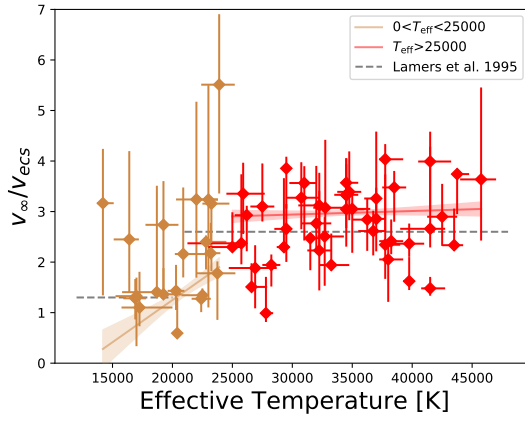


Fig. D.2. $v_{\infty}/v_{\text{esc}}$ over T_{eff} . We show the full sample including all results from Backs et al. (2024); Hawcroft et al. (2024a); Verhamme et al. (2024); Brands et al. (2025) which are fitted by two linear functions. The orange line fits only the stars up to $T_{\text{eff}} = 25$ kK, while the red line fit stars with $T_{\text{eff}} > 25$ kK. The dashed lines are the initial results from (Lamers et al. 1995).

Si III	4552.6, 4567.8, 4574.8	Si III 4552
C III	4647.4, 4650.2, 4651.5	C III N III COLD/HOT
N III	4634.1, 4640.6, 4641.9	C III N III COLD/HOT
O II	4638.9, 4641.8,	C III N III COLD
	4661.6, 4676.2	
He II	4685.6	He II 4686
N III	4858.7, 4859.0, 4861.3,	H β
	4867.1, 4867.2, 4873.6	
He II	4859.1	H β
H I	4861.4	H β
He I	4921.9	He I 4922
He II	5411.3	He II 5411
O III	5592.3	O III 5592
C III	5695.9	C III 5695
He I	5875.6	He I 5875
He II	6527.1	He II 6527
He II	6559.8	H α
H I	6562.8	H α
C II	6578.1, 6582.9	C II 6578
He I	6678.2	He II 6683
He II	6682.8	He II 6683
He I	7065.2	He I 7065

Note: The first column shows the atom and its ionisation stage responsible for the transition. The second column shows the corresponding wavelength with possible multiplets. The third column shows where to find this line in the fit summary which is available on Zenodo.

Appendix E: Line list

Table E.1. Detailed list of all spectral lines which are fitted.

Ion	Wavelength [Å]	Line window
C IV	1168.9, 1169.0	C IV 1196b
C III	1174.9, 1175.3, 1175.6 1175.7, 1176.0, 1176.4	C IV 1169b
Si IV	1393.8, 1402.8	Si IV 1400
C IV	1548.2, 1550.8	C IV 1550
O III	3961.6	H ϵ
He I	3964.7	H ϵ
H I	3970.1	H ϵ
He II	4025.4	He I 4026
He I	4026.2	He I 4026
C III	4068.9, 4070.3	C III 4070
O II	4069.6, 4069.9, 4072.16, 4075.86	C III 4070
S IV	4088.9, 4116.1	H δ
N III	4097.4, 4103.4	H δ
H I	4101.7	H δ
Si II	4128.1, 4130.9	Si II 4128
N III	4195.8, 4200.1, 4215.77	He II 4200
He II	4199.6	He II 4200
C II	4267.0, 4267.3	C II 4267
He II	4338.7	H γ
H I	4340.5	H γ
O II	4317.1, 4319.6, 4366.9	H γ
N III	4345.7, 4332.91	H γ
N III	4379.0, 4379.2	He I 4387
He I	4387.9	He I 4387
O II	4414.9, 4417.0	O II 4416
He I	4471.5	He I 4471
N II	4613.9, 4621.4, 4630.5 4601.5, 4607.2, 4643.1	N II 4601
N III	4534.6	He II 4541
He II	4541.4	He II 4541