

LETTER TO THE EDITOR

Mass-loading of outflows from evolving young massive clusters

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ABSTRACT

Feedback from young massive stellar clusters (YMCs) is an important driver of galaxy evolution. In the first few Myr, mechanical feedback is dominated by the collective effects of the massive stellar winds in the YMC. The mass-loss rates (\dot{M}) and terminal wind velocities of these stars change by orders of magnitude as the massive stars evolve, and \dot{M} of red supergiant (RSG) stars in particular are uncertain by a factor ~ 20 or more. In this work we performed a first study of the time evolution of the average cluster wind velocity (\bar{V}_{cl}) as a function of the stellar metallicity (Z), assuming single star evolution. We also verified the validity of assuming Wolf-Rayet (WR) stars dominate the feedback effects of a YMC, as often done when interpreting X-ray and γ -ray observations, and tested how sensitive \bar{V}_{cl} is to current uncertainties in \dot{M} . We used PYSTARBURST99 to calculate integrated properties of YMCs for Z in the range 0.0004–0.02, which encompasses the range of environments from IZw18 to the Galactic centre. We find that \bar{V}_{cl} drops off rapidly for sub-Large Magellanic Cloud Z values, and we recommend that a value of 500–1000 km s⁻¹ be used in this regime. We show that accounting only for WR stars can overestimate \bar{V}_{cl} by 500–2000 km s⁻¹ at $Z \geq Z_{\text{LMC}}$. We also find that different RSG \dot{M} assumptions can change the inferred \bar{V}_{cl} by ~ 1000 km s⁻¹, highlighting the need for improved observational constraints for RSGs in YMCs.

Key words. circumstellar matter – stars: massive – stars: mass-loss – supergiants – stars: winds, outflows – galaxies: star clusters: general

1. Introduction

Young massive stellar clusters (YMCs) are key drivers of stellar feedback in galaxies; they host the majority of the massive stars that mediate this feedback via strong winds during both their lifetimes and their deaths as core-collapse supernovae (CCSNe; e.g. Portegies Zwart et al. 2010). They are commonly found in energetic environments such as luminous infrared and starburst galaxies, and with the advent of JWST there is a wealth of new observations for YMCs and their feedback across a range of metallicities (Z ; e.g. Linden et al. 2024; Kader et al. 2025; Correnti et al. 2025).

Feedback from CCSNe begins after only a few Myr. The start time is uncertain as ‘explodability’ depends on multiple stellar structure variables (e.g. Burrows et al. 2024; Maltsev et al. 2025), themselves strongly influenced by Z -dependent evolutionary effects. Fichtner et al. (2024) studied feedback from a large grid of stellar evolution calculations, using the SN explodability and explosion energy prescription of Schneider et al. (2021) for low- Z stellar populations. They found that CCSNe begin to dominate the initial mass function (IMF) weighted mechanical luminosity after 5 Myr in all cases; more massive stars that have shorter lifetimes than this are not predicted to explode.

Pre-SN feedback depends greatly on the individual stellar mass-loss rates (\dot{M}) and terminal wind velocities (v_{∞}), both of which vary by orders of magnitude for massive stars during post-

main-sequence evolution. The O and Wolf-Rayet (WR) stars drive a collective outflow with their hot, powerful winds, which are sensitive to Z as well (e.g. Sander et al. 2020; Hawcroft et al. 2024). Cool supergiants (CSGs) have much slower winds but similar or higher \dot{M} (e.g. Yang et al. 2023). While there is good correspondence between wind prescriptions for OB and WR stars, underpinned by detailed theory, this is not the case for CSGs. The lack of a coherent theory for CSG \dot{M} , and difficulties in direct measurements lead to large uncertainties (e.g. Beasor et al. 2020; Antoniadis et al. 2025; Bronner et al. 2025), with different assumptions having drastic consequences on both the subsequent stellar evolution and feedback (Merritt et al. 2025). Values for v_{∞} are comparatively well constrained and are only weakly dependent on Z (Hawcroft et al. 2024).

Pre-SN YMC feedback depends on individual stellar winds collectively driving a cluster wind with average velocity \bar{V}_{cl} , total mechanical velocity $L_{\text{mech,tot}}$, and total mass-loss rate \dot{M}_{cl} . Cantó et al. (2000) presented an analytic model for \bar{V}_{cl} assuming maximally efficient wind-wind interactions and mass-loading from individual stars, based on the model Chevalier & Clegg (1985) developed for starburst galaxies. Stevens & Hartwell (2003) compared expected cluster wind properties with X-ray observations using a similar approach. Following Cantó et al. (2000) and Stevens & Hartwell (2003), we can express \bar{V}_{cl} as

$$\bar{V}_{\text{cl}} = \sqrt{\frac{\sum_{i=1}^N \dot{M}_i V_i^2}{\sum_{i=1}^N \dot{M}_i}} \equiv \left(\frac{2L_{\text{mech,tot}}}{\dot{M}_{\text{cl}}} \right)^{1/2}. \quad (1)$$

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\bar{V}_{cl} is often used to approximate the cluster wind velocity field when modelling X-ray and γ -ray emission from YMCs and their immediate surroundings (e.g. Morlino et al. 2021; Albacete-Colombo et al. 2023; Härer et al. 2023; Webb et al. 2024; Haubner et al. 2025). In these cases, it is often assumed that $L_{\text{mech,tot}} \approx L_{\text{mech,WR}}$, the mechanical luminosity of the WR population, and thus the value of \bar{V}_{cl} only takes this population into account, neglecting mass-loading from other stars. Recent local-scale (magneto)hydrodynamic simulations of YMCs with individually resolved stars (e.g. Badmaev et al. 2022; Vieu et al. 2024; Härer et al. 2025) have been focussed on the dynamics on parsec scales and the ability to accelerate particles to (very) high energies, therefore largely neglecting the winds of cool, evolved stars. Mass-loading of a hot, fast cluster wind through mixing with the cool, slow wind of a single red supergiant (RSG) was studied by Larkin et al. (2025), and their results align with observations of the RSGs in Westerlund 1 (Guarcello et al. 2025).

Given the high temperatures and low densities of cluster winds, there is a lack of direct \bar{V}_{cl} observations. Only the flow speed in the core is indirectly constrained: it should not significantly exceed the adiabatic sound speed, as inferred from diffuse X-ray observations. There is some tension between these values and the \bar{V}_{cl} values predicted by theory, which tend to be a factor of ~ 2 higher (Stevens & Hartwell 2003; Härer et al. 2023; Larkin et al. 2025). More direct measurements of \bar{V}_{cl} could be done where CSG and cluster winds interact through balancing with ram pressure (e.g. Povich et al. 2008; Larkin et al. 2025).

Despite the known strong variations in both \dot{M} and v_{∞} as a function of Z , and the importance of YMC feedback in the low- Z early Universe, no studies to date have examined the variation in cluster wind properties with Z . In this work we used population synthesis to (a) compare \bar{V}_{cl} and $L_{\text{mech,tot}}$ for a range of Z , (b) compare estimates of \bar{V}_{cl} taking only WR stars into account versus taking a complete stellar population into account, and (c) test how sensitive \bar{V}_{cl} is to the choice of stellar wind prescription, with a focus on CSGs. We did not consider SNe in this work as we focussed on the earliest stages of YMC lifetimes, before SNe become dominant for YMC feedback.

Our paper is organised as follows: In Sect. 2 we describe our framework and stellar wind prescriptions. In Sect. 3 we describe Z -dependent trends in V_{cl} and $L_{\text{mech,tot}}$ for YMCs (Sect. 3.1), differences in V_{cl} for complete stellar populations compared to only WR stars (Sect. 3.2), and the influence of different stellar wind prescriptions on V_{cl} (Sect. 3.3). We discuss our findings and present our conclusions in Sect. 4.

2. Methods

2.1. pySTARBURST99

In this work we used PYSTARBURST99, hereafter PYSB (Hawcroft et al. 2025), which is an updated version of STARBURST99 (Leitherer et al. 1999, 2014), a population synthesis code intended for calculating the integrated properties of a starburst galaxy. This code calculates values such as $L_{\text{mech,tot}}$ and \dot{M}_{cl} for a single coeval stellar population of a given Z .

For all populations modelled here, we used $M_{\text{tot}} = 1 \times 10^5 M_{\odot}$ and a maximum initial stellar mass (M_{init}) of $120 M_{\odot}$. We calculated models for all Z values in PYSB except zero. These represent Z typical of the Galactic centre ($Z_{\text{MWC}} = 0.02$), the Galaxy ($Z_{\text{MW}} = 0.014$), and the Large and Small Magellanic Clouds ($Z_{\text{L/SMC}} = 0.006, 0.002$) and IZw18 ($Z_{\text{IZw18}} = 0.0004$). For each Z , we adopted the non-rotating evolutionary tracks. Using model

parameters from these tracks, at each timestep we assigned each star to a stellar class, following those used in PYSB:

1. Luminous blue variable (LBV): $3.75 < \log_{10} T_{\text{eff}} < 4.4$ & $\log_{10} \dot{M} > -3.5$.
2. CSG: $\log_{10} T_{\text{eff}} < 3.9$ and not an LBV.
3. WR: $\log_{10} T_{\text{eff}} > 4.4$ and surface H abundance < 0.4 .
4. OB: Remaining stars with $\log_{10} T_{\text{eff}} > 3.9$.

New RSG \dot{M} prescriptions were applied to CSGs where $\log_{10} T_{\text{eff}} < 3.7$ and $M_{\text{init}} > 8 M_{\odot}$, with the remaining CSG \dot{M} left at default values. This matches where RSG \dot{M} is used in the evolutionary models. Stars with a M_{init} less than $7 M_{\odot}$ do not lose mass on the main sequence in these evolutionary tracks, so these filters cover all stars that are relevant for this work.

2.2. Stellar wind prescriptions

PYSB includes a default wind prescription (referred to here as ‘base’) and options for using \dot{M} rates from Vink & Sander (2021) or Björklund et al. (2021), or the v_{∞} relation from Hawcroft et al. (2024) for the main-sequence OB stars, referred to as Vink, Leuven and XShootU respectively as in Hawcroft et al. (2025). We also added the \dot{M} prescriptions from Sander & Vink (2020) and Sander et al. (2023, hereafter, the Sander prescription) for WRs. Given the large number of possible RSG wind prescriptions (see Yang et al. 2023; Decin et al. 2024, and references therein), we implemented recent examples of a low (Beasor et al. 2020, 2023) and a high (Yang et al. 2023) \dot{M} rate. We did not include the theoretically motivated prescription from Kee et al. (2021) given the range of possible \dot{M} values for reasonable turbulent velocity choices (Merritt et al. 2025). The effects of the alternative \dot{M} prescriptions on the stellar evolution were not accounted for, and so the positions on the Hertzsprung-Russell diagram may not be consistent at all times.

3. Results

3.1. Metallicity trends for $L_{\text{mech,tot}}$ and V_{cl}

In Fig. 1 we show $L_{\text{mech,tot}}$ and \bar{V}_{cl} for different Z . The upper panel shows a consistent $L_{\text{mech,tot}}$ trend. The variation is smooth during the pre-WR phase until ~ 2.5 Myr. At this time, $L_{\text{mech,tot}}$ increases for the Milky Way (MW) centre, MW, and Large Magellanic Cloud (LMC) populations due to the effects of WR stars. These effects are weaker at Z_{SMC} and lower, as the stellar evolution tracks (which are themselves Z -dependent) produce few or no WR stars as defined in PYSB. We discuss this effect in Appendix A. Peak $L_{\text{mech,tot}}$ occurs at ~ 3 Myr in all cases except the Small Magellanic Cloud (SMC), and decreases rapidly as WR stars die off, as shown in Hawcroft et al. (2024).

The lower panel shows a qualitatively consistent trend of a slowly decreasing \bar{V}_{cl} until ~ 2.5 Myr. This is where evolved massive stars begin to affect the population, and there is a clear separation from this time forwards. For the higher- Z populations, the \bar{V}_{cl} increases due to WR stars, whereas at lower Z , the \bar{V}_{cl} falls off rapidly due to increased mass-loading from cool evolved stars, which is not offset by powerful WR winds.

3.2. Effects of complete stellar populations

In Fig. 2 we show $L_{\text{mech,tot}}$ and \bar{V}_{cl} for Z_{LMC} and higher, where single WR stars are relevant. The upper panel validates the canonical assumption that $L_{\text{mech,tot}} \approx L_{\text{mech,WR}}$. This is generally true for the time when WR stars are active, with a gradual divergence at later times for the LMC population in particular.

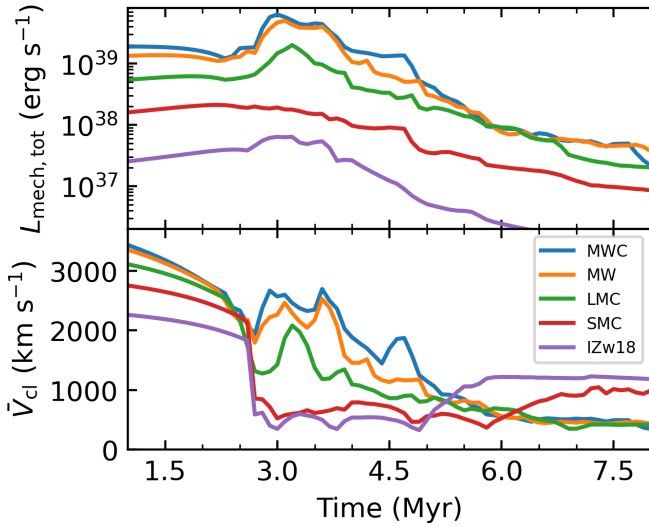


Fig. 1. Time evolution of $L_{\text{mech,tot}}$ (upper panel) and \bar{V}_{cl} (lower panel) for different Z .

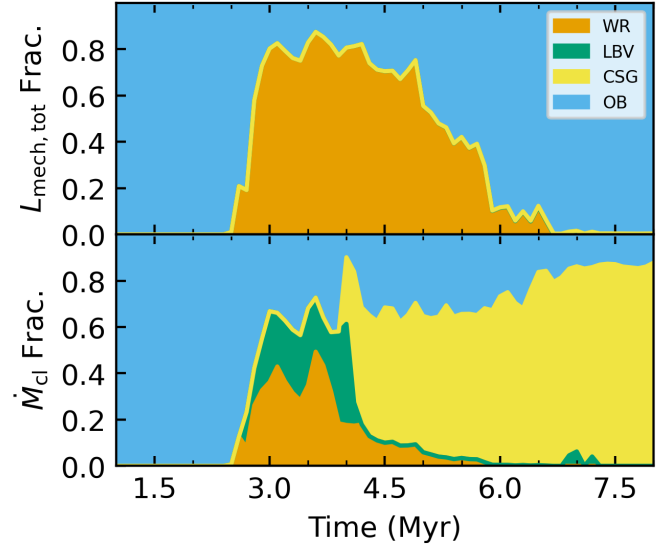


Fig. 3. Time evolution of the relative contribution of each stellar class to the total $L_{\text{mech,tot}}$ (upper panel) and \dot{M}_{cl} (lower panel) for Z_{MW} .

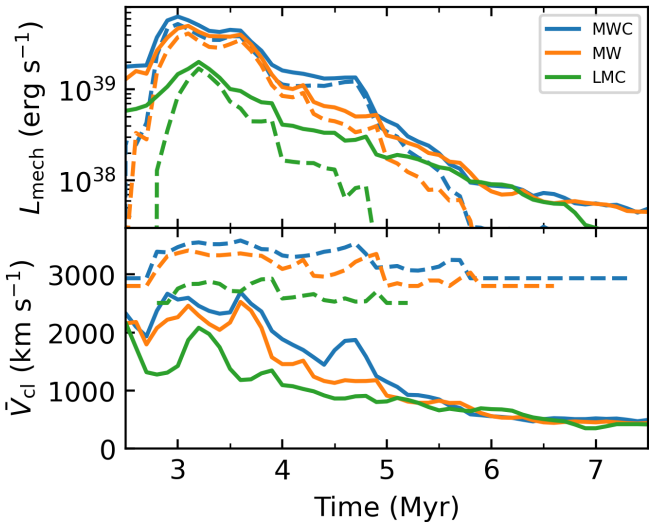


Fig. 2. Time evolution of L_{mech} (upper panel) and \bar{V}_{cl} (lower panel) for different Z , for all stars (solid line) and only WR stars (dashed line).

When active, WR stars account for $\sim 80\%$ of $L_{\text{mech,tot}}$, with the OB stars contributing almost the entirety of the remainder.

In the lower panel, we see the effects of mass-loading from non-WR stars in these populations. When we consider only WR stars, the V_{cl} is $\sim 2500\text{--}3500\text{ km s}^{-1}$ over the time period they are present. When we include all stars, there is an initial peak in V_{cl} from WR winds of $\sim 2500\text{--}3000\text{ km s}^{-1}$, which rapidly falls off. From $\sim 4\text{ Myr}$, WR stars begin to die off and cool evolved stars become active. This leads to $L_{\text{mech,tot}}$ decreasing and \dot{M}_{cl} increasing simultaneously, and thus \bar{V}_{cl} falls off. Even for early times, the WR-only \bar{V}_{cl} exceeds that of the full population by $>500\text{ km s}^{-1}$. By $\sim 4\text{--}5\text{ Myr}$, the age typically assumed for the prototypical Galactic YMC Westerlund 1, the difference increases to $\sim 1500\text{ km s}^{-1}$. This is because WR stars do not dominate \dot{M}_{cl} as they do $L_{\text{mech,tot}}$ for the time they are active – the WR \dot{M} is typically 30% of the total \dot{M} and never exceeds 60% of it. We show how different stellar classes contribute to $L_{\text{mech,tot}}$ and \dot{M}_{cl} over time for Galactic Z in Fig. 3.

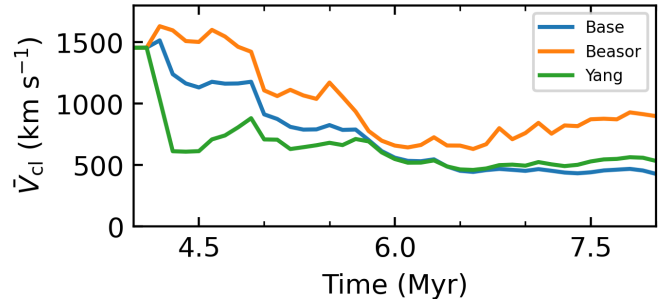


Fig. 4. Time evolution of \bar{V}_{cl} for different RSG \dot{M} prescriptions at Z_{MW} .

3.3. Cluster wind sensitivities to different prescriptions

We next studied the effects of different stellar wind prescriptions all at Z_{MW} . For the OB regime we used the PYSB default options of Vink & Sander (2021), Björklund et al. (2021), and Hawcroft et al. (2024). For WRs we added the Sander prescription, and for RSGs the Beasor et al. (2020) and Yang et al. (2023) prescriptions. The \bar{V}_{cl} is relatively insensitive to most changes among the considered OB and WR prescriptions, and we show these effects in Appendix A. In Fig. 4 we show the effects of using the \dot{M} prescriptions of Beasor et al. (2020) and Yang et al. (2023) on \bar{V}_{cl} for Z_{MW} .

Between ~ 4 and 5.5 Myr the difference in V_{cl} from changes in assumptions regarding the RSG \dot{M} is of the order of $500\text{--}1000\text{ km s}^{-1}$. These prescriptions are independent of Z , and in general the RSG \dot{M} does not strongly depend on Z (e.g. Beasor et al. 2020; Antoniadis et al. 2025). Thus, CSG mass-loading is likely consequential for YMCs in general.

4. Discussion and conclusions

In this work we present a first estimate of the effects of stellar evolution on the \bar{V}_{cl} of a YMC wind. There are some effects we have not considered that are believed to also play a role. We used the formalism from Cantó et al. (2000) – which assumes the stellar winds interact with maximum efficiency, producing a uniform cluster wind – and we did not account for IMF stochastic effects either. Some parts of the cluster wind can move faster, and the velocity profile is expected to deviate from spherical symmetry

(Härer et al. 2023; Vieu et al. 2024). YMCs are embedded in their parent molecular cloud until around 1 Myr and expel the leftover natal gas in this time frame (Portegies Zwart et al. 2010); we did not account for this either. This leftover material will mass-load the cluster wind at early times, reducing the \bar{V}_{cl} .

We also assumed only single star evolution. Most massive stars will experience some binary interaction over their lifetime (e.g. Sana et al. 2012), leading to effects that would both increase $L_{mech,tot}$ (binary stripped WR-like stars) and increase mass-loading (e.g. ejection of common envelopes and luminous red novae). The net result of these competing effects is unclear. We adopted $M_{init} = 120 M_{\odot}$. Very massive stars (VMS) above this limit are likely important for 1–2 Myr but will have died off by the time the winds of WRs and CSGs become important (Sabhahit et al. 2022). We also did not consider the effects of SNe. It is not clear whether stars above $\sim 30 M_{\odot}$ explode or what dependence this maximum SN mass may have on Z and \dot{M} prescriptions. We only considered single stellar populations (SSPs). Given the expected sensitivity to the number, initial masses, and ages of sub-populations, we defer this to future work, where we will also include binarity, VMSs, and SNe.

Nevertheless, we derived important insights from our study. It is clear that assuming only WR stars contribute to \dot{M}_{cl} can lead to overestimations of \bar{V}_{cl} , and that significant quantities of material expelled in cooler stages will be present for all times that WR stars are active. In a sufficiently populated cluster, \dot{M}_{cl} will never be dominated only by WR stars (unlike $L_{mech,tot}$), so our general trend should hold even when assuming different wind prescriptions. Morlino et al. (2021) assumed a \bar{V}_{cl} of 3000 km s^{-1} when studying the acceleration of PeV energy cosmic rays by YMC cluster winds, which is likely an overestimate for Galactic YMCs older than ~ 2 Myr. Alternatively, CCSNe could accelerate up to these energies (e.g. Vieu & Reville 2023; Härer et al. 2025).

The qualitative difference in \bar{V}_{cl} between Z_{LMC} and Z_{SMC} is important for interpreting feedback from observations. At high Z , when we considered all contributors, our findings are in broad agreement with currently used values (e.g. Kader et al. 2025). However, for Z_{SMC} and below, it is clear that a \bar{V}_{cl} of $\sim 500\text{--}1000 \text{ km s}^{-1}$ is more appropriate in the pre-SN feedback regime before $\sim 5\text{--}10$ Myr (Schneider et al. 2021). The sensitivity of our results to CSG \dot{M} assumptions underlines the need for empirical measurements not affected by dust-to-gas ratio assumptions in a range of environments (Beasor et al. 2020; Decin et al. 2024), for example via ram-pressure balancing as proposed by Larkin et al. (2025). CSG mass-loading likely impedes YMC outflows across all Z . Yet, current galaxy evolution simulations struggle to resolve individual stellar feedback as the typical cell resolutions are a few M_{\odot} (e.g. Lahén et al. 2025). We conclude:

- The average cluster wind velocity (\bar{V}_{cl}) is strongly dependent on Z , with the biggest difference obtained between Z_{LMC} and Z_{SMC} . We advise assuming a \bar{V}_{cl} of $\sim 500\text{--}1000 \text{ km s}^{-1}$ for clusters at Z_{SMC} and lower.
- By the time SNe start dominating the energetics of stellar feedback from clusters ($\sim 5\text{--}10$ Myr), the stellar wind L_{mech} cannot drive a cluster wind with a $\bar{V}_{cl} > 500 \text{ km s}^{-1}$, at least for the SSPs studied here and for $Z \geq Z_{LMC}$.
- Our findings support the canonical assumption that $L_{mech,tot}$ can be well approximated by assuming only the WR stars of a cluster contribute, but we find that the \dot{M} from CSGs mass-load the cluster wind and can slow \bar{V}_{cl} by $500\text{--}2000 \text{ km s}^{-1}$.
- \bar{V}_{cl} is particularly sensitive to current uncertainties in CSG \dot{M} prescriptions. We find that changes in RSG prescriptions produce differences of the order of 1000 km s^{-1} in \bar{V}_{cl} , highlighting the impact of uncertainties in RSG \dot{M} rates on understanding feedback from YMCs for all Z .

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Appendix A: Sensitivity to OB and WR wind prescriptions

A.1. OB winds

In Fig. A.1 we show the effects of using the wind prescriptions of Vink & Sander (2021), Björklund et al. (2021), and Hawcroft et al. (2024) on $L_{\text{mech,tot}}$ and \bar{V}_{cl} for Z_{MW} .

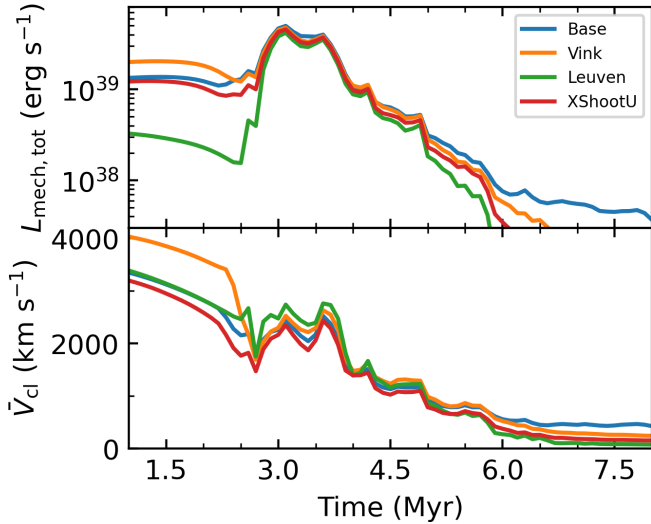


Fig. A.1. Time evolution of $L_{\text{mech,tot}}$ (upper panel) and \bar{V}_{cl} (lower panel) for different OB wind parameter prescriptions at Z_{MW} .

For $L_{\text{mech,tot}}$, the prescriptions introduce variations of 0.1 dex or less, with the exception of the Björklund rates which reduce $L_{\text{mech,tot}}$ by ~ 0.8 dex, as discussed in Hawcroft et al. (2025). The variations are only prominent before evolved stars begin to contribute at ~ 2.5 Myr.

For \bar{V}_{cl} , variations until this time are present but of order 100 km s^{-1} , with the exception of the the Vink & Sander (2021) rates. The increased v_{∞} in this prescription increases \bar{V}_{cl} by $\sim 500 \text{ km s}^{-1}$ before evolved stars begin to contribute. In both cases, the changes in OB wind prescriptions are negligible after this time.

A.2. WR winds

In Fig. A.2 we show the effects of using the WR wind prescription of Sander & Vink (2020), including the temperature dependence recommended in Sander et al. (2023), on $L_{\text{mech,tot}}$ and \bar{V}_{cl} for Z_{MW} , assuming only WR stars contribute as for Fig. 2.

We test this prescription for two cases, firstly applying only the Sander & Vink (2020) prescription to all WR stars as defined earlier, and secondly applying the Sander & Vink (2020) prescription with temperature dependence (Sander et al. 2023) to WR stars with $T_{\text{eff}} > 90 \text{ kK}$, which is the regime they were derived for, and using the Base prescription for cooler WR stars. We use the default v_{∞} prescriptions in PYSB for all cases.

In the upper panel, there is a moderate change in L_{mech} of order 0.1–0.2 dex until ~ 3 Myr. At this point the hot WR stars become active and L_{mech} increases by up to an order of magnitude for the temperature-dependent case compared to the Base scenario until ~ 4.5 Myr. The effects of the WR prescriptions on \bar{V}_{cl} are comparatively small, changing by $\sim 100 \text{ km s}^{-1}$ at most.

There is a tiny contribution from winds classified as WR in the code for $Z_{\text{I}Z\text{W}18}$ due to a ‘sweet spot’ of low Z and high T_{eff} . We assess the impact of this by comparing the Base prescrip-

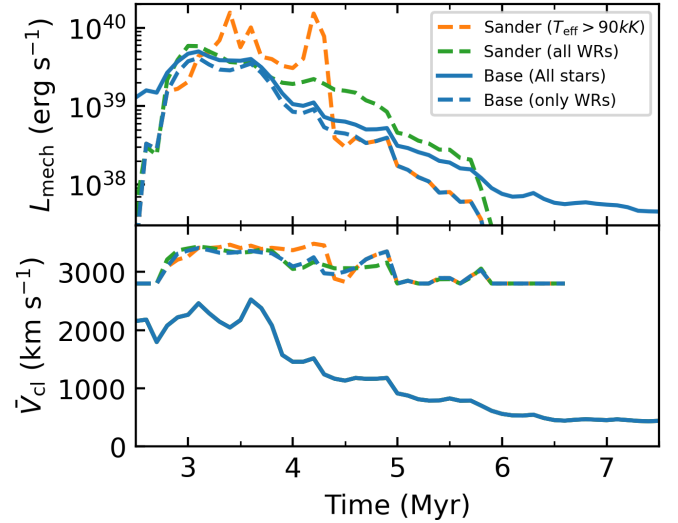


Fig. A.2. Time evolution of L_{mech} (upper panel) and \bar{V}_{cl} (lower panel) for Z_{MW} , assuming the base prescription for all stars (solid blue), the base prescription for only WR stars (dashed blue), the Sander prescription with a T_{eff} dependence for WR stars with $T_{\text{eff}} > 90 \text{ kK}$ (dashed orange), and the Sander prescription without a T_{eff} dependence for all WR stars (dashed green).

tion with increasing the WR T_{eff} criterion to $\log_{10} T_{\text{eff}} > 4.44$ (i.e. from $\sim 25 \text{ kK}$ to 27.5 kK), thus making the WR assignment negligible. This makes a difference of order a few percent for $L_{\text{mech,tot}}$ and less than 1% for \bar{V}_{cl} .