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Stellar Winds of O-type Stars Traced by High- ionization Fine-structure Emission Lines with JWST/MIRI

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Abstract

We investigate the presence of high-ionization fine-structure emission lines across a range of 22 OB-type stars observed with JWST-MIRI as part of calibration programs and the Webb Investigation of Silicates, Carbons, and Ices and the Measuring Extinction and Abundances of Dust programs. Mid-infrared (MIR) wind emission is detected in four late O dwarfs (O8 V–O9 V), one early O dwarf (O5 V), and there are tentative detections in an additional three stars (O8.5 II, O8.5 IV, and O9 I). We measure the wind speeds and make estimates of lower limits on the mass-loss rates of five O-type stars from broad, flat-topped emission in the fine-structure line of [Ne v] 14.3 μm . We find terminal wind speeds that are generally in agreement with empirical trends, but note that in some cases the wind speeds are surprisingly low. We highlight two main takeaways from this sample, which combine to establish an exciting new window into the winds of massive stars. First, a new diagnostic ability is gained from lines formed at much higher ionization, larger spatial extent, and longer wavelengths than typical wind diagnostics. Second, there is a frequent incidence of MIR emission in O-type stars, even in the “weak-wind” regime where wind emission is often not detected in the UV and optical.

Unified Astronomy Thesaurus concepts: Massive stars (732); Stellar winds (1636); O stars (1137); O dwarf stars (1135); James Webb Space Telescope (2291)

1. Introduction

The radiation-driven winds from hot, massive stars are an effective mechanism for removing material from the stellar surface and ejecting it into the interstellar medium (ISM). The mass loss from stellar winds shapes the evolutionary pathways of massive stars, influencing their ultimate fates as supernovae and compact objects (N. Langer 2012). The magnitude of the winds directly determines the impact of stellar feedback, which is essential for regulating galaxy evolution and interpreting observational signatures (C. C. Steidel et al. 1996; F. Martins et al. 2010; R. C. Kennicutt & N. J. Evans 2012; C. Leitherer 2020). Consequently, accurate characterization of stellar winds is essential for modeling a wide range of astrophysical processes. Two crucial parameters used to quantify stellar winds are the terminal velocity and mass-loss rate, both of which are sensitive to fundamental stellar parameters such as mass, luminosity, and metallicity.

For O-type stars, the wind driving scenario through radiation pressure on metal ion transitions is well established, but complexities associated with wind structure and opacity introduce uncertainties in our ability to use spectral diagnostics

to interpret stellar wind signatures (R.-P. Kudritzki & J. Puls 2000; J. Puls et al. 2008; J. S. Vink 2022). For example, overdense clumps of wind material arising due to the inherent line-deshadowing instability result in enhanced emission from density-squared dependent recombination processes (T. Eversberg et al. 1998; A. W. Fullerton et al. 2006). This limits our ability to constrain mass-loss rates from optical hydrogen and helium lines alone. These lines are also formed close to the stellar photosphere while the wind is still accelerating, so they do not probe the maximum wind velocity. UV metal resonance lines, which scale linearly with density and form further out in the wind, are a more reliable source of wind information for massive stars (D. J. Hillier 2020). However, there are also issues with typical UV diagnostics, related to the overall wind opacity (L. M. Oskinova et al. 2007; B. Šurlan et al. 2013; C. Hawcroft et al. 2021, 2024a). Additionally, they are no longer sensitive to mass loss below a characteristic luminosity ($\log(L/L_\odot) \sim 5.2$) at the onset of the “weak-wind” regime (J. C. Bouret et al. 2003; F. Martins et al. 2004, 2005b; W. L. F. Marcolino et al. 2009; E. S. G. de Almeida et al. 2019).

A prospective new spectral window has appeared in the mid-infrared (MIR). Emission lines from fine-structure transitions of [O IV] 25.9 μm , [Ne v] 14.3 μm , and [Ne VI] 7.6 μm have been detected in MIR observations of the O9 V star 10 Lac, which provided direct wind constraints in the weak-wind regime where typical UV and optical diagnostics are limited (D. R. Law et al. 2024). These emission lines are relatively weak (flux levels a few percent of the continuum

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level, but statistically significant detections), and very broad (on the order of thousands of kilometers per second), confirming they are formed in the stellar wind. The profiles have a flat-topped morphology, suggesting they are formed in an optically thin shell of material. The high energies (55, 97, and 126 eV, respectively) and low critical densities ($\log(n_e \text{ cm}^{-3}) = 4.2, 5.2, \text{ and } 6.0$, respectively) required to reach these ionization stages also indicate the presence of a very hot, tenuous wind component. These characteristics make the MIR lines an exciting new tool for studying hot, rarefied components of stellar winds. However, concerns were raised on the broader applicability of these diagnostics as the lines could not be detected in a comparable MIR spectrum of μ Col, an O9.5 V star with very similar stellar properties to those of 10 Lac. MIR fine-structure lines are, however, a well-established feature in Wolf-Rayet stars (e.g., M. J. Barlow et al. 1988; L. Dessart et al. 2000). Generally, the lines observed are relatively low-ionization species of Ne and S, but do extend to [O IV] 25.9 μm (e.g., P. W. Morris et al. 2004). It was therefore unclear whether MIR fine-structure lines would be a new diagnostic tool for O-type stars or a rare phenomenon only arising under very specific conditions.

Fortunately, a larger sample of OB-type stars was soon observed in the MIR with JWST as part of dust extinction curve surveys (M. Decleir et al. 2025; S. T. Zeegers et al. 2025), offering the opportunity for a preliminary investigation on the incidence rate of fine-structure wind emission in massive stars. In this work, we extend the efforts of D. R. Law et al. (2024) to all OB stars observed with JWST-MIRI up to JWST Cycle 4 and discuss the viability of these lines as diagnostics for wind physics across the parameter space covered.

We describe the observations and data processing techniques in Section 2, present results on line detections and wind parameter estimates in Section 3, discuss the implications of these results in Section 4, and conclude in Section 5.

2. Observations and Data Processing

We compiled a sample of 22 massive stars drawn from a combination of JWST programs: the Webb Investigation of Silicates, Carbons, and Ices program (WISCI; 11 stars; PID: 2183, PI: Zeegers) and the Measuring Extinction and Abundances of Dust program (MEAD; nine stars; PID: 2459, PI: Decleir), augmented by calibration observations of 10 Lac (PID: 1524; PI: Law) and μ Col (PID: 4497; PI: Gordon). The WISCI and MEAD program stars were originally chosen for their location along sightlines with sufficient dust optical depth to study weak absorption features in the diffuse ISM of the Milky Way (M. Decleir et al. 2025; S. T. Zeegers et al. 2025), and therefore contain an assortment of 10 B-type stars, 11 late O-type stars, and one earlier O-type star. We omit the O8-type WISCI source LS 4992 from our sample since it has an extremely rich spectrum dominated by dust features along the line of sight that severely complicates our search for faint, broad emission features in the spectrum of the star itself.

All 22 stars were observed using the MIRI Medium Resolution Spectrometer on board JWST across the full wavelength range from 5 to 26.5 μm with a maximum resolving power $R \sim 4000$ at 5 μm that decreases to $R \sim 1500$ at 25 μm (I. Argyriou et al. 2023). For the lines discussed in this work, [Ne VI] 7.65 μm , [Ne v] 14.32 μm , [Ne v] 24.89

μm , and [O IV] 25.89 μm , the resolving power is $R = 3600, 2800, 1500, \text{ and } 1300$, respectively. Since these stars were observed as a combination of calibration programs and probes of the dusty interstellar medium, the observations span a wide range of achieved continuum signal-to-noise ratios (S/Ns), which are reported in Table 1.

We reduced the data using the JWST calibration pipeline version 1.20.2⁹ and the publicly available pipeline notebooks provided by D. Law et al. (2025). We used the default pipeline settings, except for enabling the optional correction for residual cosmic ray showers and using a smaller extraction radius of 1 FWHM (compared to the default of 2 FWHM) in order to maximize the S/N of the stellar spectra at the expense of marginally worse relative flux calibration between adjacent spectral bands. We chose to use the 1D residual fringe corrected spectra provided by the pipeline since there are no strong molecular bands in our targets. Additionally, for 10 Lac, we note residual periodic fixed-pattern noise in the vicinity of [Ne v] that was not removed by the residual fringe correction; we estimate the magnitude and phase of this noise from the continuum region and subtract it from the [Ne v] wavelengths.

3. Results

3.1. MIR Wind Detections

For each source, we fit the stellar continuum in the flux-calibrated spectrum provided by the pipeline using a third-order polynomial in the wavelength ranges $\lambda\lambda 13.6\text{--}14.1 \mu\text{m}$ and $\lambda\lambda 14.5\text{--}15.0 \mu\text{m}$ (i.e., omitting the wavelength region within 4000 km s^{-1} of [Ne v]). Figures 1 and A1 plot the resulting continuum-subtracted spectra of each of our 22 targets in the vicinity of the [Ne v] 14.3217 μm spectral feature; eight targets show evidence of broad [Ne v] emission.

In Table 1, we give the S/N of the spectral features using an empirical noise estimate based on the rms of the continuum-subtracted spectrum adjacent to the [Ne v] spectral feature and near the rest wavelengths of [Ne VI] 7.6524 μm and [O IV] 25.89 μm .

We quantify the status of the [Ne v] 14.3217 μm detections in Table 1 and show this distribution in Figure 2. For four stars (O5.5 V, O9 V, B3 II, and B3 V), the S/N is too low to comment on the presence of the emission lines. [Ne v] emission that exceeds the scatter in the local continuum by a factor of 3 or more is found in eight stars, five of which are strong detections and three of which are more tentative. Of the five strong detections, four are classified as late O dwarfs (O8 V, O8 V, O8 V, and O9 V), and one is a multiple system containing an inner O5 V + B0 V binary with a wider O9 V companion (with the MIR emission likely associated with the O5 V star, discussed in Section 3.2 and Appendix B). The three tentative detections are also late spectral types but higher luminosity classes (O8.5 IV, O8.5 II, and O9 I). Emission features are not detected in the rest of the sample, which consists of two O9.5 V stars and nine B-type stars with a wide range of spectral types and luminosity classes.

Repeating the above analysis at other wavelengths, we note that most of these eight stars also show evidence for [Ne VI] 7.6524 μm emission (Figure A2) similar to that observed in 10

⁹ This provides an updated flux calibration relative to D. R. Law et al. (2024) that fixes narrow spectral artifacts seen in their analysis of the [Ne v] emission feature, and improves the calibration in the vicinity of the [Ne VI] emission feature.

Table 1
[Ne v] 14.3 μm Detections with Continuum S/N for Target Stars

Source	Spectral Type	Detection	Flux	EW	S/N at 14 μm	S/N at 7 μm	S/N at 26 μm	PID	Obs
HD 206267 ^a	O5 V	yes	28.0 ± 0.6	114 ± 3	118	183	4	2459	14
ALS 15134	O8 Vz	yes	0.78 ± 0.03	40 ± 1	151	188	6	2183	10
[CPR2002] A38	O8 V	yes	0.62 ± 0.02	48 ± 1	143	184	5	2183	4
Schulte 1	O8 V + B	yes	2.74 ± 0.05	72 ± 1	162	205	8	2183	1
10 Lac	O9 V	yes	3.75 ± 0.06	25.0 ± 0.4	479	391	95	1524	16
HD 207198	O8.5 II	?	9.7 ± 0.6	42 ± 3	108	207	4	2459	16
HD 73882	O8.5 IV	?	6.6 ± 0.6	64 ± 6	64	120	0	2459	6
HD 152249	OC 9 Iab	?	4.7 ± 0.5	27 ± 3	81	137	3	2459	10
μ Col	O9.5 V	no	...	...	236	218	26	4497	4
ALS 15181	B0 V	no	...	...	90	172	5	2183	7
TYC 7380-1046-1	B0 Ia	no	...	...	159	166	14	2183	19
TYC 8989-436-1	B0.5 II	no	...	...	173	191	10	2183	35
HD 203938	B0.5 IV	no	...	...	73	156	2	2459	12
GSC 08152-02121	B2 IV	no	...	...	113	170	6	2183	32
2MASS J20452110+4223513	B2 V	no	...	...	149	195	7	2183	13
TYC 6272-339-1	B3 II	no	...	...	153	207	7	2183	22
CPD-59 5831	B5 Ia	no	...	...	139	221	13	2183	38
CD-40 11169	B8 Ia	no	...	...	170	217	10	2183	16
HD 14434	O5.5 V	...	...	...	23	42	0	2459	2
HD 216898	O9 V	...	...	...	31	96	0	2459	18
HD 38087	B3 II	...	...	...	14	69	0	2459	4
HD 147888	B3 V	...	...	...	32	199	3	2459	8

Notes. Spectral types are taken from S. T. Zeegers et al. (2025) and M. Declair et al. (2025).

S/N columns refer to continuum S/N at the respective wavelengths.

^a O5V(fc) + B0:V + O9V (J. Maíz Apellániz & R. H. Barbá (2020), O6V + O9V (M. Declair et al. 2025).

Lac (D. R. Law et al. 2024), while [Ne V] 24.31 μm and [O IV] 25.89 μm emission is more difficult to confirm (e.g., Figure A3 for [O IV]). Generally, the [Ne VI] spectral width is consistent with the observed [Ne V] width. However, given the low S/N of the WISCI and MEAD observations at these wavelengths, it is difficult to characterize these fainter line features in detail, and we therefore focus our attention in the present contribution exclusively on the [Ne V] 14.32 μm emission feature.

The MIRI wavelength range also covers fine-structure transitions of [Ne II] 12.81 μm and [Ne III] 10.86, 15.56 μm . These features are not seen in any of our samples, with the exception of HD 206267, where [Ne III] 15.56 μm is detected. As discussed in the Appendix, this object is complex with at least two components. It is not clear which component produces the [Ne V] and [Ne III] emission, but the widths of the features suggest it is the O5 V star component.

3.2. Wind Speeds

As the [Ne V] 14.3 μm line is formed in an optically thin shell of expanding material, as evidenced by the flat-topped profile morphology, the terminal wind velocity (v_∞) can be estimated by measuring the half-width of the profile at zero intensity in continuum-subtracted spectra. We compare the measured wind speeds to empirical predictions from C. Hawcroft et al. (2024b). The relation provided in C. Hawcroft et al. (2024b) is based on the R. K. Prinja et al. (1990) sample for Galactic OB stars, shown in Figure 3. Of the five stars with visibly flat-topped profiles, the two stars with stronger winds tend to agree more closely with the general empirical trend: Schulte 1 lies well within the predicted wind speed region, along with HD 206267, assuming the [Ne V] emission is coming from the O5 V component (as opposed to the O9 V binary companion). The

stars with relatively weaker emission (A38 and ALS 15134) lie significantly below the empirical prediction, by $\sim 700 \text{ km s}^{-1}$. 10 Lac has the largest discrepancy compared to the empirical prediction, by $\sim 1000 \text{ km s}^{-1}$.

The three stars with more tentative detections do not have clear flat-topped morphologies, and so any estimates of v_∞ are less robust. HD 207198 sits well above the empirical prediction when estimating the width of the statistically significant emission, but given the significance of the detection is already low, it would not be surprising if this is an overestimate. From a visual inspection of the spectrum, as shown in Figure 1, it would be reasonable to estimate a v_∞ of $\sim 2000 \text{ km s}^{-1}$ which is closer to the empirical prediction. HD 73882 and HD 152249 do, however, lie along the observed trend.

3.3. Mass-loss Rates

Using the techniques described in D. R. Law et al. (2024), and defined in M. J. Barlow et al. (1988), L. Dessart et al. (2000), and P. A. Crowther et al. (2024), we estimate the mass-loss rates required to drive the observed line flux in [Ne v]14.3 μm (shown in Figure 4). Using these relations, specifically Equation (A3) from D. R. Law et al. (2024), we inherit the assumption that the upper levels are populated only through collisional excitation; however, contributions from UV continuum fluorescence or nonradiative processes could be significant. We also adopt assumptions from D. R. Law et al. (2024) on the mean ionic mass and mean number of electrons per ion, commonly ~ 1.5 and ~ 0.8 , respectively, for O-type stars. We assume a solar neon abundance of $\log(\text{Ne}/\text{H})+12 = 8.09$ for all stars apart from 10 Lac, for which we use the photospheric abundance measured in P. Aschenbrenner et al. (2023) of $\log(\text{Ne}/\text{H})+12 = 8.24$. An increase in Ne abundance would lower the mass-loss rate,

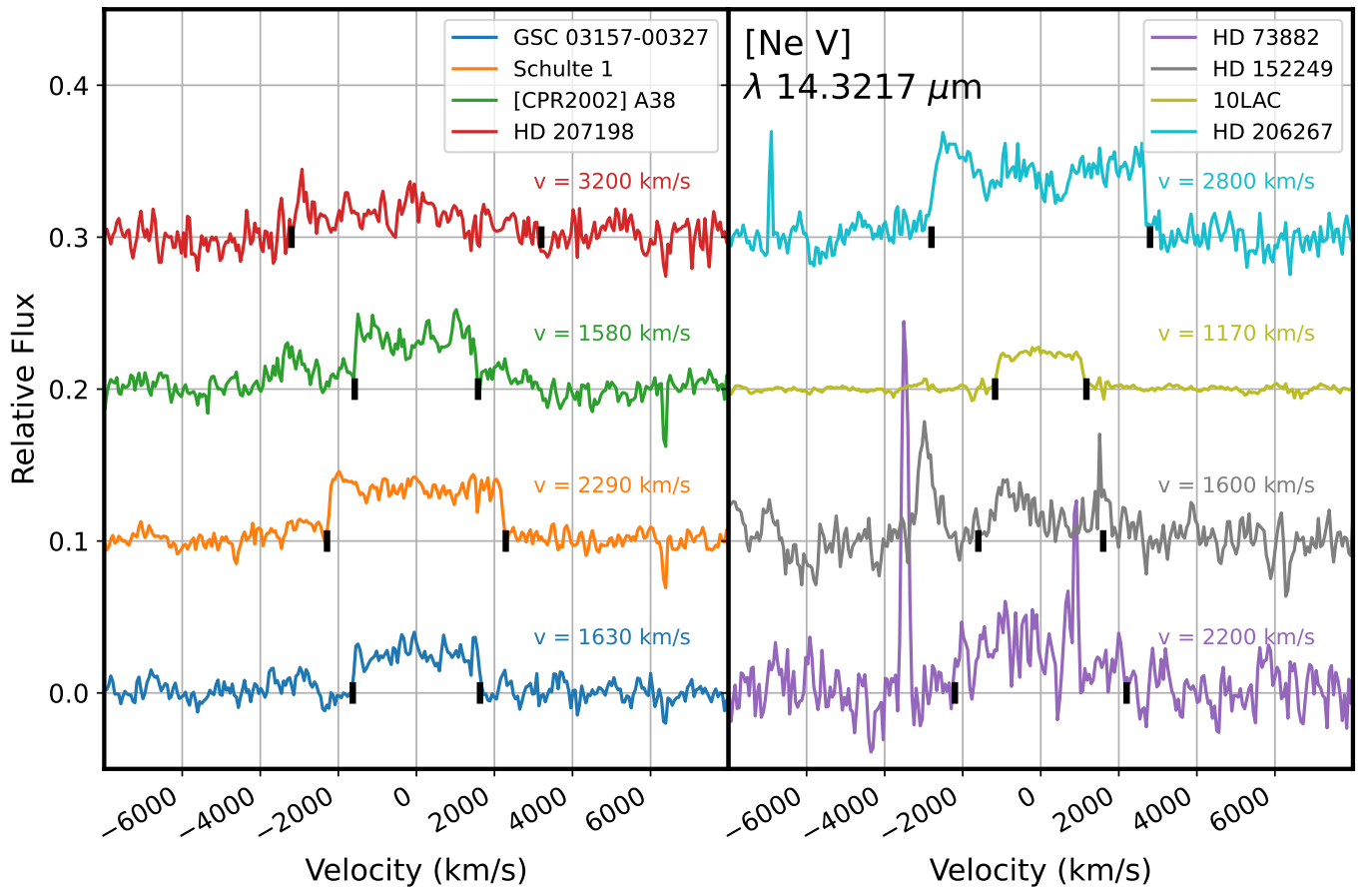


Figure 1. Continuum-subtracted spectra for all stars in which statistically significant [Ne V] emission is detected. Each spectrum has been continuum-subtracted and normalized by the median continuum value at $14.3 \mu\text{m}$; a value of 0.1 thus represents a strength 10% of the stellar continuum. Note that each spectrum has been offset by 0.1 for clarity; the typical [Ne V] line strength peaks at about 2%–5% of the continuum. Wavelengths are given in velocity units relative to the $14.3217 \mu\text{m}$ rest wavelength of the [Ne V] emission feature; vertical black lines atop each spectrum denote the maximal wind velocities derived in Section 3.2 and denote the integration limits to measure equivalent widths (EWs). The feature at -2900 km s^{-1} is H I $14.183 \mu\text{m}$ (13–9). Note that GSC 03157-00327 is referred to as ALS 15134 throughout the text.

further reducing the lower limits estimated here; however, the shift is relatively small. For example, in the case of 10 Lac, an increase of 0.2 dex in Ne would result in a downward shift of 0.1 dex in $\log \dot{M}$. Finally, we assume a smooth wind for the emission region, in line with the L. B. Lucy (2012) scenario where high-ionization emission arises from the hot, rarefied interclump wind, meaning the emission lines measured here should not be affected by enhanced emission arising from cooler, overdense clumps of material. The ionization fraction (q , the fraction of atoms in a given ionization state, in this case Ne v) as a function of mass-loss rate is shown for the stars with strong [Ne v] $14.3 \mu\text{m}$ detections in Figure 5. The estimates of limits on mass-loss rates should be considered with the caveat of only collisional excitation in mind, until these results can be tested with more detailed stellar atmosphere models, the development of which is beyond the scope of this work. Additionally, we assume [Ne v] contributes the full ionization fraction and use an electron temperature of $T_e = 35 \text{ kK}$ to provide lower limits on the observed mass-loss rate. Any reduction to the ionization fraction of [Ne V] or increase in electron temperature would increase the required mass-loss rate. An example of the increased mass-loss rate with the q relation as a result of increasing electron temperature to $T_e = 200 \text{ kK}$ for 10 Lac is shown in Figure 4 of D. R. Law et al. (2024).

As shown in Figure 4, we observe a trend of increasing mass-loss rate with luminosity. The lower limits on mass-loss rates for the sample all lie within the boundaries of theoretical mass-loss rate predictions. We find lower limits slightly above the R. Björklund et al. (2021) and J. Krtićka & J. Kubát (2017) predictions but below the J. S. Vink et al. (2000) rates. This is in good agreement with generally observed trends between empirical and theoretical mass-loss rates, which come from studies based on UV/optical spectroscopy of typical O-type stars that take into account the effects of clumping on the observed line profiles (e.g., C. Hawcroft et al. 2021; S. A. Brands et al. 2022; F. Backs et al. 2024; C. Hawcroft et al. 2024a). If the limits found here are good representations of the true mass-loss rates, the best agreement would be with the J. Krtićka & J. Kubát (2017) rates, which underpredict the observed mass-loss rate lower limit by a factor of 1.7 on average, while J. S. Vink et al. (2000) and R. Björklund et al. (2021) over- and underpredict the observed values by factors of 3.5 and 2.6, respectively.

3.4. Profiles of Fine-structure Lines

Figure 1 indicates that the shape of the [Ne v] $14.32 \mu\text{m}$ line is usually consistent at the 2σ level with the square, flat-topped profile expected for optically thin emission in a spherically

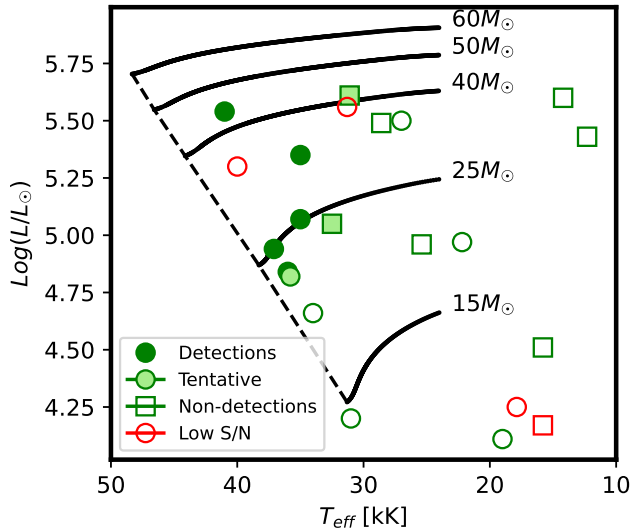


Figure 2. Hertzsprung–Russell diagram showing the full sample discussed in this work. Symbols in green have sufficient S/N to allow us to make some comment on the nature of the line detection; those in red have very poor S/N. Filled symbols indicate a detection in [Ne V] 14.3 μm , those filled with a lighter color are the tentative detections, and open symbols are nondetections. Shapes indicate the luminosity class, circles for dwarf stars and squares for (super)giants. Black lines are main sequence evolutionary tracks for nonrotating Galactic massive stars from I. Brott et al. (2011), labeled with their respective initial masses. The dashed line indicates the ZAMS.

symmetric outflow (e.g., R. Ignace & A. Brimeyer 2006). However, significant deviations from a flat-top profile also occur, in particular for HD 206267, which exhibits double-peaked “horns” at its wavelength extrema. The profile of [O IV] 24.89 μm in the spectrum of 10 Lac has a similar morphology (D. R. Law et al. 2024).

We explored possible origins for the double-horned morphology by computing line profiles for distributions of outflowing material that deviate from spherical symmetry in stellar colatitude while maintaining axisymmetry. Our simplified approach and its limitations are described in Appendix C. Figure 6 shows a selection of profiles for distributions of material that are not based on specific physical models, but are only intended to illustrate the effects of nonspherical distributions of density and the aspect of the viewer. As expected, a purely radial distribution of density produces a flat-topped line profile at all viewing angles. However, as previously shown by R. Ignace & A. Brimeyer (2006), distributions that are enhanced at the stellar pole or equator produce line profiles that range from double-horned to rounded and centrally peaked. For example, double-peaked profiles are produced both by strongly polar emission seen pole-on and by strongly equatorial emission seen edge-on. For a given distribution of material, the profile depends strongly on the inclination angle of the observer.

Although the double-horn morphology appears to be a clear signature of an aspherical distribution of material, a more detailed interpretation requires additional information. In the case of HD 206267, Figure 6 suggests that the double-horn profile results from a modest enhancement of material at the stellar equator viewed by an observer inclined to the rotation axis by 60° – 90° . In this connection, it is interesting to note that F. Raucq et al. (2018) estimated the inclination of the orbital plane of HD 206267 to be $i = 76^\circ$ by comparing spectroscopic and dynamical masses. If the normal to the orbital plane is

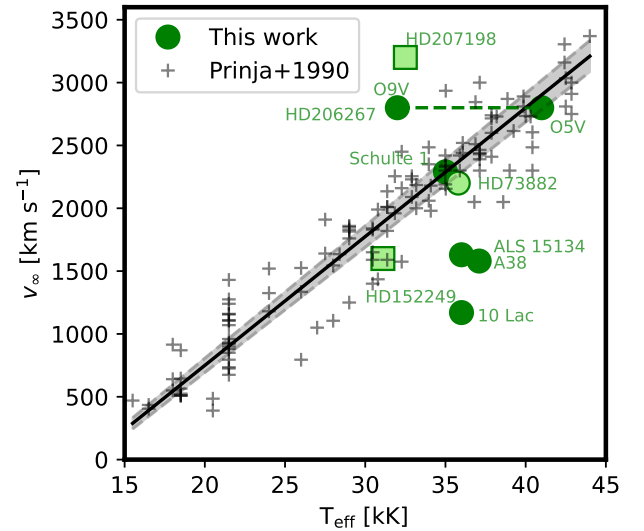


Figure 3. Terminal wind speeds as a function of effective temperature for the five stars with strong [Ne V] detections (filled dark green circles) and three stars with tentative detections (filled light green circles and squares, as in Figure 2). Green points correspond to measurements from the [Ne V] 14.3 μm line from this work; the gray sample is terminal wind speeds measured for Galactic OB stars from UV spectroscopy in R. K. Prinja et al. (1990). Note the wind speed of HD 206267 is shown for two temperatures, to illustrate the positions if the emission is arising from the O5 V or O9 V components of the multiple system.

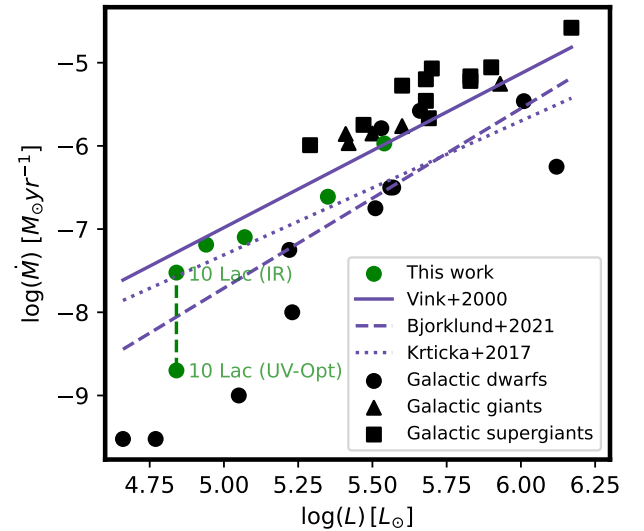


Figure 4. Mass-loss rates as a function of luminosity for the five stars with strong [Ne V] detections, shown as green circles. Black markers show a sample of Galactic O-type stars from T. Repolust et al. (2004), F. Martins et al. (2005b), and P. A. Crowther et al. (2006) for comparison. Circles, triangles, and squares correspond to luminosity classes V, III, and I, respectively. Solid and dashed lines show theoretical mass-loss rate predictions from J. S. Vink et al. (2000) and R. Björklund et al. (2021), respectively.

aligned with the rotation axis, the similarity in viewer aspect suggests the existence of enhanced density in the vicinity of the orbital plane of this complex system.

4. Discussion

4.1. Wind Speeds

To first attempt to verify whether the outliers in wind speed measurements are related only to the MIR measurements, or whether UV diagnostics also often result in outliers from the

general trend, we compare with empirical calibrations drawn from a large sample of Galactic OB stars (R. K. Prinja et al. 1990). UV diagnostics do not seem to result in outliers in wind speed, as the R. K. Prinja et al. (1990) sample does not contain a subsample of stars with $T_{\text{eff}} > 30$ kK that show saturated UV P Cygni profiles and have significant outlier measurements of v_{∞} (especially after updating the stellar parameters with the latest literature, see Appendix B for the details).

The temperatures for the three stars in this sample with discrepant v_{∞} measurements (A38, ALS 15134, and 10 Lac), have all been measured with fitting of synthetic spectra from tailored stellar atmosphere models (for A38 and ALS 15134 see S. R. Berlanas et al. 2020 and for 10 Lac see P. Aschenbrenner et al. 2023), making them robust to within a few kK, and ruling out the possibility that they could each be >5 kK cooler, which would be required to agree with the empirical predictions. This supports the notion that the wind speeds measured from the MIR for these three stars are genuine outliers from the general trend. It is unclear whether the wind speeds, in that case, would be underestimated due to the MIR lines not tracing the true terminal wind speed of the global outflow, or whether the wind speeds are indeed significantly lower than predicted. Similarly, these three stars have low wind speed to escape speed ratios ($v_{\infty}/v_{\text{esc}} = 1.1, 1.8,$ and 1.6 for 10 Lac, ALS 15134, and A38, respectively), while the other stars sit close to the $v_{\infty}/v_{\text{esc}}$ relation measured in C. Hawcroft et al. (2024b) (see Figure A4).

As comparison points for consistency in wind speeds, we list wind speeds measured from the UV and MIR in Table 2. Unfortunately, HD 206267 (O5 V) is the only object with strong wind lines in the UV and MIR. We can also consider HD 207198, HD 152249, and HD 73882, which have strong UV lines and tentative detections in the MIR. HD 207198 and HD 152249 have visually very weak MIR detections and estimates of v_{∞} from the MIR, which do not agree with those measured in the UV. HD 73882 has a slightly more visible signature in the MIR, and the estimate of v_{∞} is in agreement with that measured from the UV. It is therefore difficult to say from these three stars whether the UV and MIR give consistent wind parameters. For HD 206267, the wind speed can be robustly measured from the C IV $\lambda 1548$ Å and N V $\lambda 1240$ lines as well as the [Ne V] $14.3 \mu\text{m}$ line. The estimates on v_{∞} from the UV are consistent (within 110 km s^{-1}) with those measured from the [Ne V] line and are discussed further in Appendix B. HD 206267 gives the preliminary impression that wind speeds from the hot component visible in the MIR are consistent with the cooler wind component traced by UV resonance lines, at least for a relatively early (O5 V) O-type star. However, given the limitations on the scope of the current sample, and a lack of options for multiwavelength follow-up on targets with high visual extinction, it is difficult to draw further conclusions on the wind speeds of these objects.

Nonetheless, with confirmation of the MIR lines across a wider sample, we have a new window to measure wind speeds for the first time at longer wavelengths. Such information was only previously available in the UV. These MIR lines are also viable wind diagnostics for stars with either no strong UV wind signatures or high extinction. Since they probe different density regions, the simultaneous presence of UV and MIR wind diagnostics may provide additional constraints on the velocity structure of the wind.

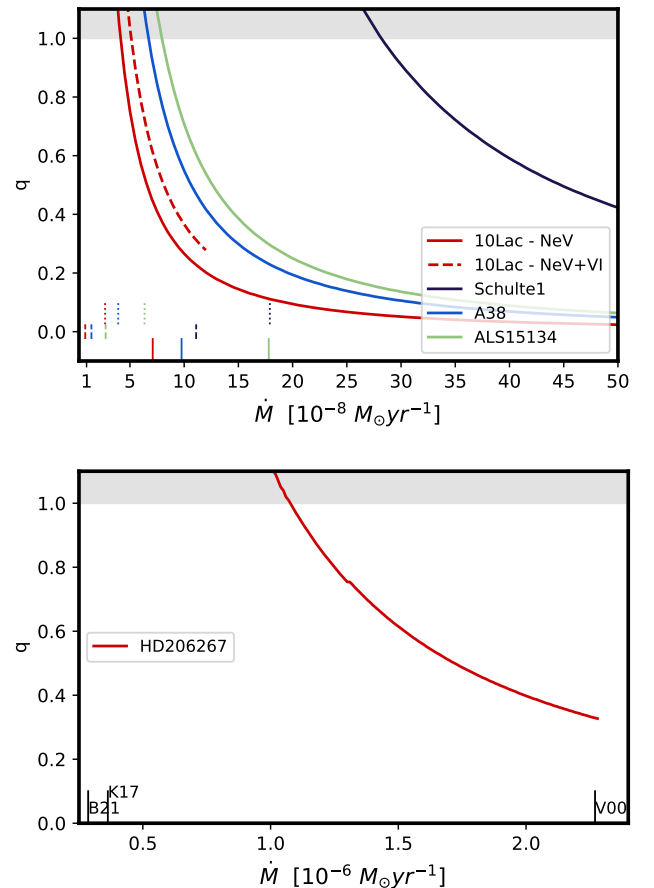


Figure 5. Ionization fraction q as a function of mass-loss rate for Ne^{4+} . All curves represent an electron temperature of $T_e = 35$ kK. Vertical ticks show theoretical mass-loss rate predictions from R. Björklund et al. (2021), dashed, J. Krtićka & J. Kubát (2017), dotted, and J. S. Vink et al. (2000), solid.

4.2. Mass-loss Rates

The long-standing weak-wind problem is one of the most pressing open questions related to stellar winds, and may be the largest source of uncertainty in wind strengths for O-type stars on the main sequence (e.g., J. Puls et al. 2008; J. S. Vink 2022). Recent efforts exploring mass-loss rate relations with key parameters like structure and metallicity have greatly reduced uncertainties on wind strengths over the majority of the main sequence. However, even for typical O-type stars at extreme ends of the luminosity range $5.2 < \log(L/L_{\odot}) < 6.0$, the magnitude and nature of the wind remain unclear. Focusing on the low-luminosity weak-wind stars, the issue refers to a sudden reduction in the strength of typical wind diagnostics in the UV-optical regime in stars with $\log(L/L_{\odot}) < 5.2$, resulting in a drop in inferred mass-loss rates by around 2 orders of magnitude (J. C. Bouret et al. 2003). This reduction is a strong discontinuity from the general observed trend and has been shown to be at odds with established theoretical predictions across a range of environments with varying metallicities (F. Martins et al. 2004, 2005a; W. L. F. Marcolino et al. 2009; E. S. G. de Almeida et al. 2019; C. Hawcroft et al. 2024a).

There are two main avenues toward a solution: either a true reduction in wind strength or maintaining wind strength but shifting away from typical diagnostics, both of which highlight missing physics in our current wind models. Multiple theoretical solutions have been proposed in both cases. For

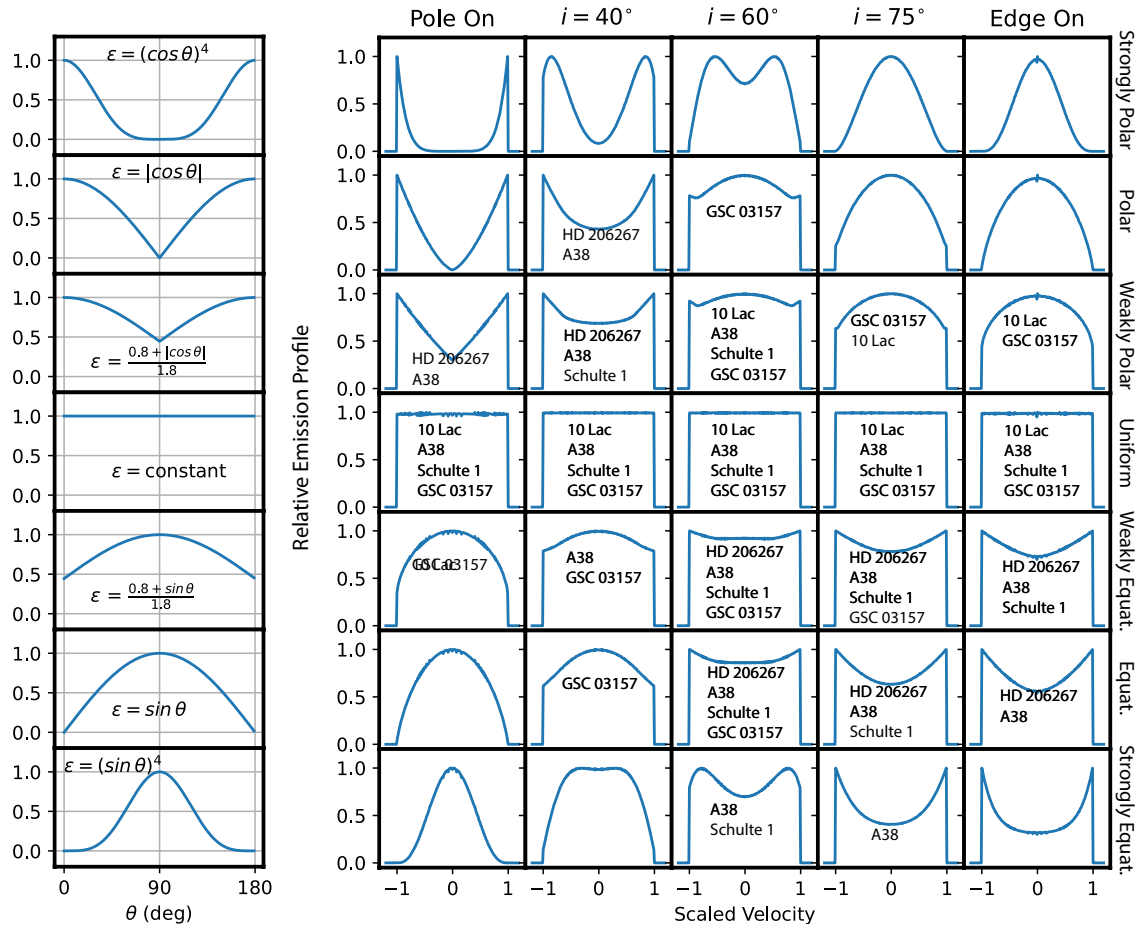


Figure 6. Left panel: density profiles $G(\theta)$ as a function of the polar angle θ . Right panel: continuum-subtracted profiles of fine-structure lines that would be seen by a distant observer as a function of the viewing inclination i . Labels within each panel list the stars whose spectra are statistically consistent with the computed profile.

the latter, L. B. Lucy (2012) envisioned a scenario where the low density of the winds in late O-type stars results in inefficient cooling relative to the much denser winds in early O-type stars. In combination with shock heating due to the inherent line-deshadowing instability, this suggests that the ionization state would be too high to form wind line profiles in the typical UV diagnostics and would shift to higher ionization transitions. This scenario has been further explored in hydrodynamic simulations of O-type star atmospheres by C. Lagae et al. (2021). In the alternate case, that winds truly are weaker, J. S. Vink (2022) suggests a reduction in line-driving force could arise from the recombination of iron to a lower state with fewer transitions. A. S. Lattimer & S. R. Cramer (2021) provide an updated formalism for radiative line driving and predict a sharp decrease in wind strength below 15 kK. While this threshold temperature is too low to fully account for the O-type star weak-wind problem, it identifies a mechanism that could partially contribute and highlights that line-driving formalisms could be revised. S. P. Owocki & J. Puls (2002) discuss that a reduction in line force could arise from the decoupling of minor ions from the bulk wind.

To test and distinguish between the proposed scenarios, a few alternate observational diagnostics have been highlighted in the literature, such as near-infrared hydrogen lines, which are known to be more sensitive to changes in mass-loss rates at low values (F. Najarro et al. 2011). Although estimates of mass-loss rates using $\text{Br}\alpha$ in M. Garcia et al. (2025) agree with values found from UV and optical diagnostics. Individual

Table 2
Wind Speeds for Stars with [Ne v] Detections

ID	v_∞ (UV) (km s ⁻¹)	v_∞ (MIR) (km s ⁻¹)
HD 206267	2815 ^a	2800
ALS 15134	...	1630
[CPR2002] A38	...	1580
Schulte 1	...	2290
10 Lac	1070 ^b	1170
HD 207198	2090 ^c	3200 ^d
HD 73882	2315 ^c	2200
HD 152249	2100 ^c	1600

Notes.

^a Measured directly from STIS spectra.

^b From F. Martins et al. (2005b).

^c From R. K. Prinja et al. (1990).

^d Measurement from statistically significant emission, likely an overestimate from visual inspection.

cases of higher mass-loss rates have been observed through extreme X-ray flux in μ Col (D. P. Huenemoerder et al. 2012), a star with very weak UV and optical wind lines, which supports the L. B. Lucy (2012) scenario. Further evidence in this direction comes from the detection of high-ionization fine-structure line emission in the MIR in 10 Lac (D. R. Law et al. 2024). Although curiously μ Col shows no trace of wind emission in the MIR.

The detections of high-ionization emission in the MIR in four additional stars presented here build on the 10 Lac finding. The preliminary agreement between the observed and predicted mass-loss rates for these stars in the weak-wind regime using the [Ne V]14.3 μm line is enticing, and there is clearly an avenue to measure mass-loss rates from this line (and other high-ionization fine-structure emission lines in the MIR). However, we cannot yet place strong constraints on the mass-loss rates, given the caveats surrounding our assumption of collisional excitation built into the relation used to make our estimates. As a result, we delay further discussion to future work, which can be informed by more detailed, tailored stellar atmosphere models.

A comparison between multiwavelength mass-loss diagnostics for this sample would also be informative. Unfortunately, we cannot make such comparisons for any stars aside from 10 Lac, as there is no mass-loss information available in the literature from studies at short wavelengths. There are no archival UV spectra for ALS 15134 or A38, and there are flux gaps in the STIS UV spectra of Schulte 1 over the C IV λ 1548 Å line. There are existing STIS optical spectra, although with insufficient S/N and resolution for detailed stellar atmosphere modeling. The large visual extinction for these targets ($A_V > 5$) limits the possibility for follow-up spectroscopic observations and analysis at shorter wavelengths. For HD 207198, HD 73882, and HD 152249, there are extensive UV observations with strong wind lines; however, the only tentative detections of emission in [Ne V] again limit a multiwavelength comparison. For HD 206267, the extinction is less extreme, and there are archival UV and optical spectra. In this case, we can make a comparison with the terminal wind speeds as the UV P Cygni profiles are saturated, but the UV spectra have not been modeled in detail with stellar atmosphere codes in the literature, likely due to the additional complications of this being a multiple system including a close binary. While it may be possible to disentangle the components to obtain a clean spectrum of each component using existing observations/tools (discussed further in Appendix B), such efforts are beyond the scope of this work.

5. Conclusions

D. R. Law et al. (2024) presented the first detection of wind emission in high-ionization fine-structure lines ([Ne v], [Ne VI], and [O IV]) in an O-type star in 10 Lac, but found no trace of the lines in μ Col. Given the similar spectral types (O9 V and O8.5 V, respectively), this raised the question of whether such wind emission diagnostics would be common among O-type stars or if 10 Lac was a special case.

In this work we have established that high-ionization wind signatures in the mid-infrared are not unique to 10 Lac (O9 V) and may be present in O stars across a wider range of spectral types, with confirmed detections of [Ne V] wind emission in four additional stars (O8.5 V, O8 IV, and O5 V), and tentative detections in another three (O8.5 II, O8.5 IV, and OC 9 Iab). The full sample of 22 stars comprises two early O stars (<O5 V, one confirmed and one tentative detection), 10 late O stars (>O8, with a mix of luminosity classes, three confirmed and three tentative detections), and 10 B stars. We find no evidence for the [Ne V] line in any B-type stars.

Using the line strength of [Ne v]14.3 μm in the stars with clear detections, we estimate lower limits on mass-loss rates,

with the caveats that we assume a two-level atom when three levels are involved in the formation of [Ne v] 14.32 μm , and that the contribution of only collisional excitation populates the upper level. The mass-loss rate lower limit estimates are in good agreement with theoretical predictions. The relative agreement to theoretical predictions is similar to that found in recent literature studies on early O-type stars, which use UV and optical diagnostics and include the effects of clumping. Using the line widths, we measure terminal wind speeds in good agreement with empirical calibrations (R. K. Prinja et al. 1990; C. Hawcroft et al. 2024b) for four stars, while the same calibrations overpredict the wind speeds of three stars by at least 700 km s^{-1} . Using simple geometric models, we assess the profile morphology and find that all but one of the profiles are statistically consistent with the flat-topped profile expected from spherical emission. The line morphology in HD 206267, however, shows significant deviation from the flat-topped profile, suggestive of enhanced emission in the equatorial plane.

The presence of wind signatures in this sample is particularly notable for two reasons:

(i) A subset of the sample is obscured by high levels of extinction, prohibiting high-quality spectroscopic observations of wind signatures in the UV and optical. These MIR diagnostics, therefore, allow us to study the winds of previously inaccessible objects.

(ii) A subset of the detections is for stars in the “weak-wind” regime, offering new insight into the nature of stellar winds for these puzzling objects, which have no diagnostic information at UV and optical wavelengths.

Unfortunately, the limited composition and nonuniformity of S/N of the current sample of massive stars observed with JWST-MIRI prevent us from making any stronger comment on the presence of additional MIR wind emission lines, or the likelihood of their presence in OB-type stars in general. We are also unable to make a comparison of wind features in MIR with typical diagnostics at shorter wavelengths due to the limited feasibility of follow-up observations, hampered by the high extinction ($A_V > 5$) across the WISCI sample, although there is a viable path toward multiwavelength modeling of HD 206267 (from MEAD, $A_V < 2.5$) if the binary components can be disentangled.

From the current sample, we can conclude that the [Ne v] 14.3 μm line has a diverse range of strengths, widths, and morphologies across the sample of now five stars with confirmed detections (with an additional three tentative), establishing a viable new diagnostic to measure the wind properties of late O-type stars and a new window to investigate wind driving from the MIR. It will soon be possible to study these new MIR diagnostics further with a series of upcoming observations across a variety of late O-type stars that will be obtained as part of a JWST Cycle 4 program (PID: 8683).

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contract NAS 5-03127 for JWST. These observations are associated with programs #1524, #2183, #2459, and #4497 and can be accessed via doi:[10.17909/7qhs-8s19](https://doi.org/10.17909/7qhs-8s19). M.D. and S.Z. acknowledge support from the Research Fellowship Program of the European Space Agency (ESA). D.J.H. gratefully acknowledges support from grant JWST-GO-07169.003.

Appendix A Additional Figures

Here, we show nondetections of Ne V in the full sample in Figure A1. We show the regions around [Ne VI] $7.65 \mu\text{m}$ and [O IV] $25.89 \mu\text{m}$ in Figures A2 and A3, respectively.

We show trends between terminal wind speed v_∞ and escape speed v_{esc} in Figure A4.

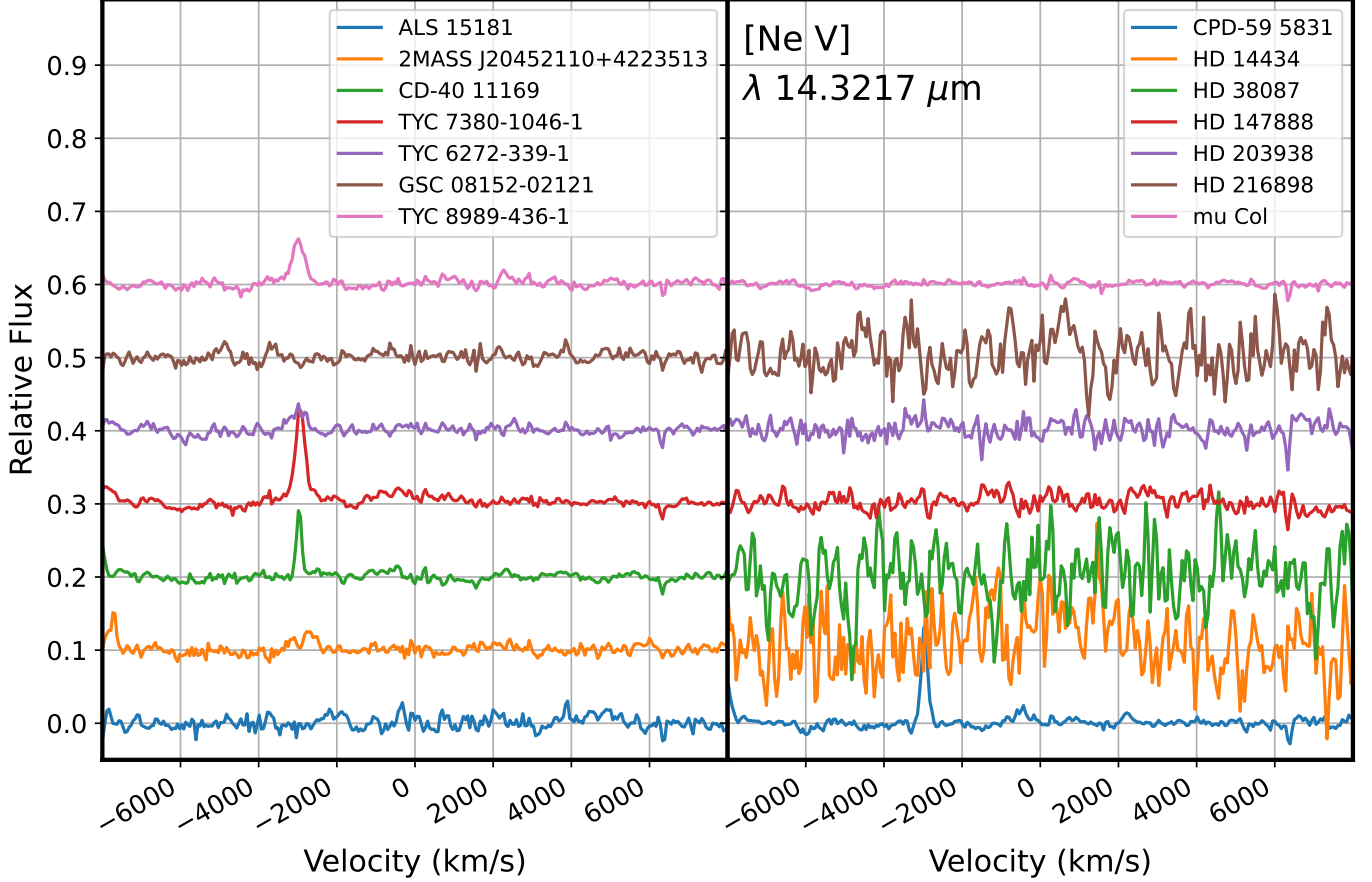


Figure A1. As Figure 1, but for the 14 stars in which no statistically significant [Ne v] emission was detected.

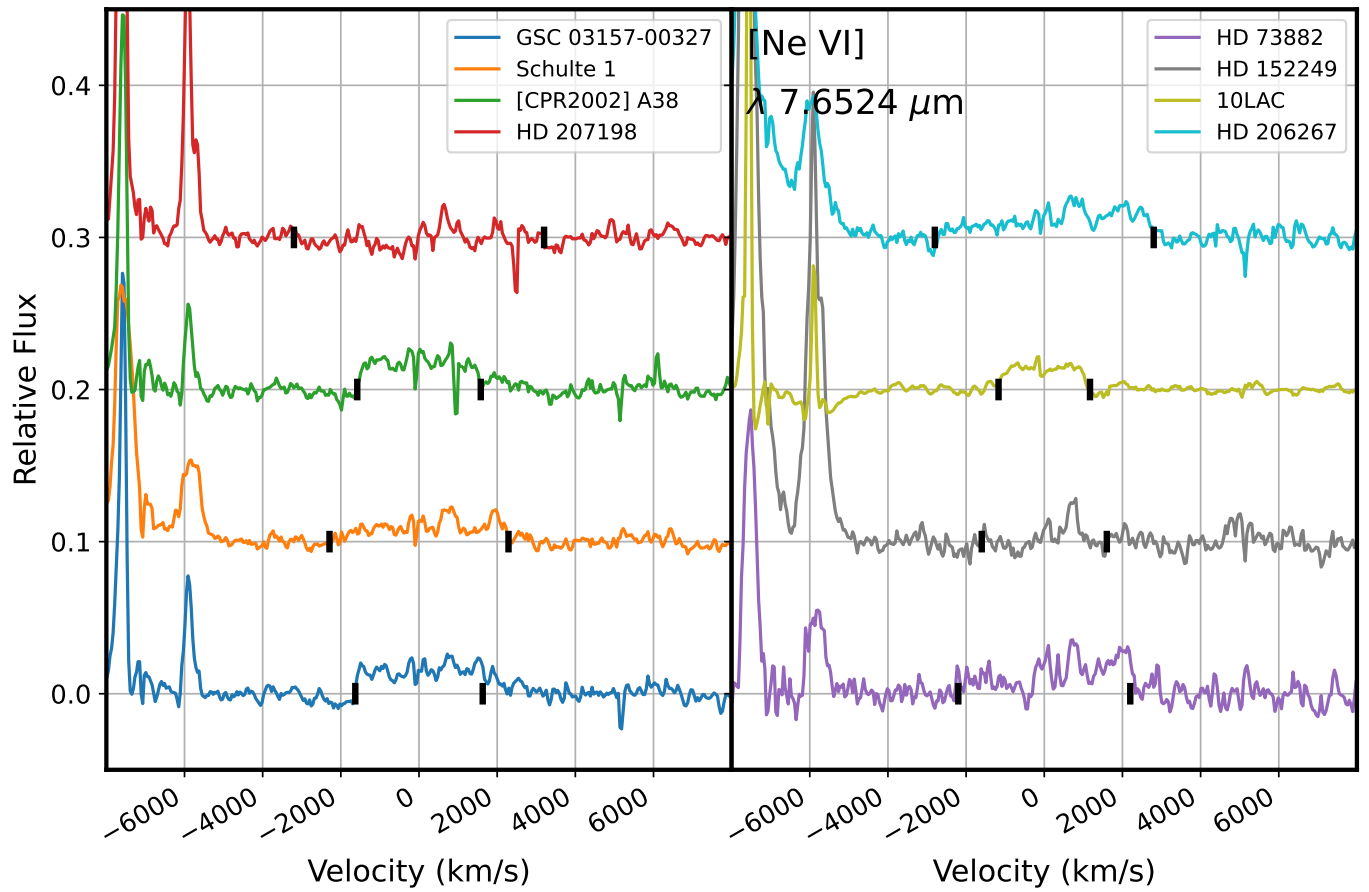


Figure A2. As Figure 1, but for [Ne VI] emission at $\lambda = 7.6524 \mu\text{m}$. The black vertical lines show the maximal wind velocities derived from the [Ne V] emission, which is a good match to [Ne VI] where such emission can be seen. The strong emission features at -6000 and -7500 km s^{-1} are H I 8–6 and 6–5, respectively.

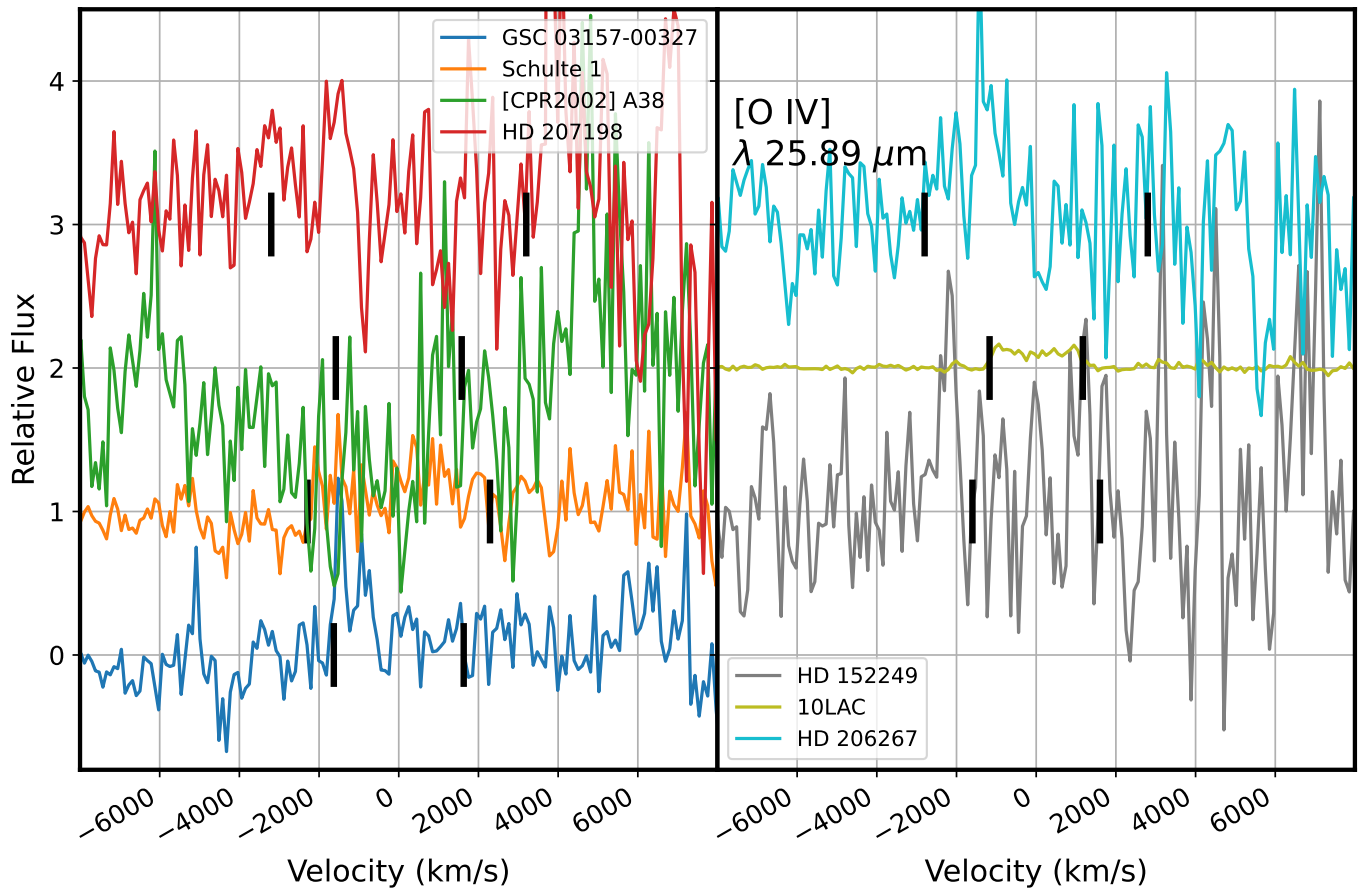


Figure A3. As Figure 1, but for [O IV] emission at $\lambda = 25.89 \mu\text{m}$. The black vertical lines show the maximal wind velocities derived from the [Ne v] emission, which is a good match to [O IV], where such emission can be seen.

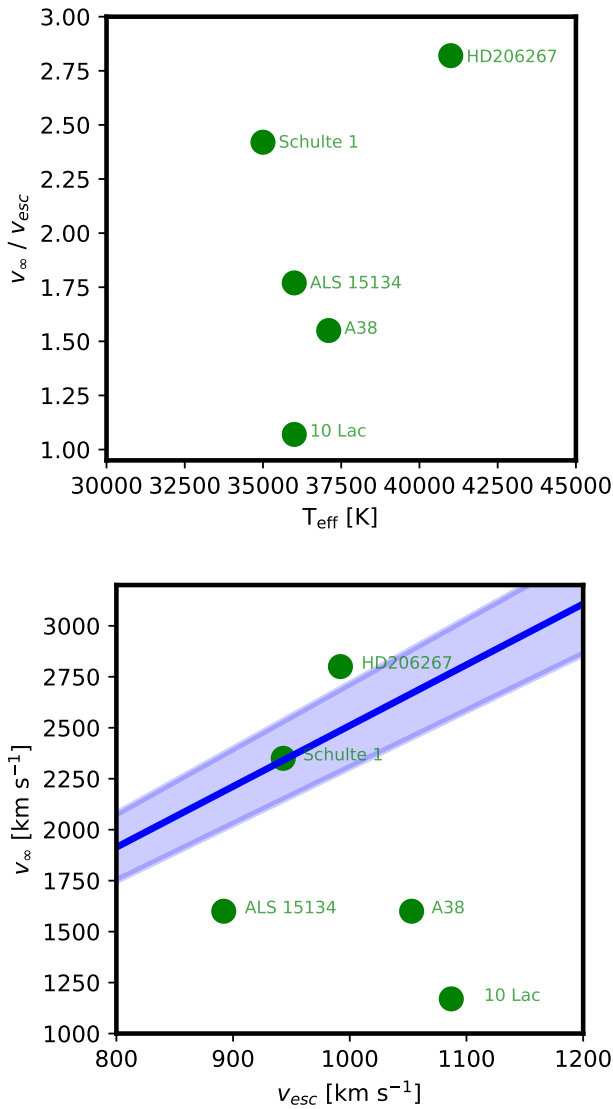


Figure A4. Upper panel: terminal wind speed to escape speed ratio as a function of effective temperature for the five stars with strong [Ne v] detections. Green points correspond to measurements from the [Ne v] 14.3 μm line from this work compared to escape speeds and temperatures taken from the literature. Lower panel: terminal wind speed as a function of escape speed, points as described for the upper panel. Additionally, the terminal wind speed to escape speed ratio from C. Hawcroft et al. (2024b) is overplotted in blue (with uncertainties included as the shaded region).

Appendix B Notes on Individual Stars

ALS 15134

ALS 15134 is a late-type dwarf (O8.5 Vz or O8.5 V) with a relatively high extinction ($A_V \sim 6$), so there are no existing UV spectra, meaning the wind parameters for this object were previously unconstrained. It is part of the Cygnus OB2 association, and optical spectra are available (e.g., from the Isaac Newton Telescope, covering key line profiles from 4000 to 5000 $\text{\AA}$, and including coverage of HeII4686 and $\text{H}\alpha$, S. R. Berlanas et al. 2020). It was classified in the GOSSS catalog as an O8.5 Vz star, suggesting it could be close to the zero-age main sequence (ZAMS; J. Maíz Apellániz et al. 2016). As discussed further in J. I. Arias et al. (2016), the star crossed the threshold for the z classification due to its relatively strong

He II 4686 absorption compared to He I 4471 (ratio of 1.15 with threshold of 1.1). The optical spectrum was then analyzed using stellar atmosphere models in S. R. Berlanas et al. (2020), so robust constraints on the fundamental stellar photospheric parameters are available (and listed in Table 3). These authors note that ALS 15134 does not have a peculiar proper motion and is not identified as a spectroscopic binary. The rotation rate is moderate ($v \sin i \sim 95 \text{ km s}^{-1}$) and there is no sign of surface helium enrichment, although no metal abundances have been estimated so far. There are no previous spectroscopic studies at longer wavelengths than the optical, but ALS 15134 has been observed in X-rays with XMM-Newton. The X-ray luminosity is relatively low for a typical O-type star at $\log L_X / L_{\text{bol}} = -7.1$ (A. Nebot Gómez-Morán & L. M. Oskina 2018). From the current information available from previous studies, this appears to be a normal single O-type star, which would presumably sit within the weak-wind regime based on its late spectral type and luminosity ($\log(\frac{L}{L_\odot}) \sim 5.07$).

[CPR2002] A38

A38 is a late-type dwarf (O8 V) with a similar extinction and archival spectra scenario as for ALS 15134. It is also a member of Cygnus OB2 and was previously analyzed by S. R. Berlanas et al. (2020). There is little to add beyond the discussion for ALS 15134 as these are very similar stars, with A38 having a lower luminosity by 0.13 dex, a higher temperature by $\sim 1 \text{ kK}$, and faster rotation by $\sim 120 \text{ km s}^{-1}$. One difference is that the X-ray properties for A38 are derived from Chandra observations; both A38 and ALS 15134 are included in G. Rauw et al. (2015). These authors note that A38 has an X-ray flux around a factor of 3 lower than ALS 15134.

Schulte 1

Schulte 1 is another late-type dwarf (O8 V) but is notably a spectroscopic binary (SB 1) comprised of the O8 V primary and likely a B-type companion (implied by a companion mass of 4–6 $M_\odot$) (S. R. Berlanas et al. 2020), but it does not have reliable astrometry, so quantities such as distance and luminosity are not included in that work. The primary mass is around 18–21 $M_\odot$ (E. Trigueros Páez et al. 2021). It is also a short-period (4 days; H. A. Kobulnicky et al. 2014), eccentric eclipsing binary (A. Prša et al. 2022), suggested to also show the heartbeat phenomenon (dynamical tidal distortions and tidally induced pulsations). S. C. Wolff et al. (2006) estimate a luminosity of $\log(\frac{L}{L_\odot}) \sim 5.35$ with a temperature of $\sim 33 \text{ kK}$ estimated from the spectral type calibrations and bolometric corrections from P. Massey et al. (2005). Using the 35 kK temperature from S. R. Berlanas et al. (2020), along with fluxes and extinction values from S. T. Zeegers et al. (2025) and the bolometric corrections of F. Martins & B. Plez (2006) gives $\log(\frac{L}{L_\odot}) \sim 5.25$. In either case, it is unclear whether the observed flux magnitudes are corrected for the contribution of the companion. Therefore, it is difficult to tell whether Schulte 1 should be a weak-wind star based on its luminosity, and unfortunately, the existing STIS spectra are missing coverage of the key wind features. Schulte 1 has an X-ray flux halfway between ALS 15134 and A38 (G. Rauw et al. 2015).

Table 3
Stellar Parameters for Stars with Strong [Ne v] Detections

ID	SpT	v_∞ (km s ⁻¹)	$\log(\dot{M})$ (dex)	$\log(\frac{L}{L_\odot})$ (dex)	T_{eff} (kK)	$\log g$ (dex)	R ($R_\odot$)	v_∞ [pred] (km s ⁻¹)	$v \sin i$ (km s ⁻¹)	$N_{\text{He}}/N_{\text{H}}$	$\log(\dot{M})$ [lit] ($M_\odot \text{ yr}^{-1}$)	$\log L_X/L_{\text{bol}}$ (dex)
ALS 15134	O8 Vz	1630	-7.1	5.07 ^a	36	3.8	8.8	2270	95	0.099	-8.5 ^b	-7.1 ^b
[CPR2002] A38	O8 V	1580	-7.2	4.94 ^{a,c}	37.1	4.03	7.2	2370	120	0.105	...	
Schulte 1	O8 V + B	2290	-6.6	5.35 ⁱ	35	3.69	12.8	2180	185	<0.066	...	...
HD 206267	O5 V	2800	-6.0	5.49 ^d	40.9	3.9	11.2	2730	?	?	?	-6.47 ^j
10 Lac	O9 V	1170	-7.5	4.84 ^h	36	4.1	6.7	2270	14	0.09	-8.7	-7

Notes.

^a Stellar parameters from S. R. Berlanas et al. (2020).

^b Stellar parameters from A. Nebot Gómez-Morán & L. M. Oskoinova (2018).

^c Stellar parameters from G. Rauw et al. (2015).

^d [O5 V((fc)) + B0:V] + O9V - Spectral type calibration for an O5 V star F. Martins et al. (2005a).

^e Stellar parameters from W. L. F. Marcolino et al. (2017).

^f Stellar parameters from L. P. Carneiro et al. (2019).

^h Stellar parameters from T. W. Berghoefer et al. (1997); F. Martins et al. (2005b); P. Aschenbrenner et al. (2023).

ⁱ Stellar parameters from S. C. Wolff et al. (2006).

^j Stellar parameters from P. Pradhan et al. (2023).

HD 206267

HD 206267 is a complex spectroscopic and visual binary system at the center of the Trumpler 37 cluster, detailed in J. Maíz Apellániz & R. H. Barbá (2020). This object is comprised of a central system Aa (a short period—3.71 days—SB 2 O5 V((fc)) + B0:V binary, designated Aa1 and Aa2) with an Ab component ~ 100 mas away (an O9 V star), a B component 1.8'' away (which is too faint to contribute significantly to the spectrum), as well as two further away C and D components which are B0 and B0.2 stars.

Given the complicated nature of this stellar system, it is difficult to assess the properties of the stars based on previous analyses, which have been unable to disentangle the many components, especially as the O9 V Ab star was first classified by J. Maíz Apellániz & R. H. Barbá (2020).

The most pertinent issue for this analysis is to identify which component of the system produces the forbidden line emission. Excluding the widest companions, the remaining options are the Aa and Ab components. This cannot be resolved with the MIRI observations alone, as the 100 mas separation is less than half of the FWHM at the shortest wavelengths. There are, however, a number of archival UV spectra (from IUE and STIS) showing strong P Cygni wind profiles in N v $\lambda 1240$ and C IV $\lambda 1550$, which are formed in the wind of the O5 V (Aa) star. Estimating the wind speed directly and using Sobolev with exact integration (SEI) models through the techniques described in C. Hawcroft et al. (2024b) gives $v_\infty = 2815 \text{ km s}^{-1}$ from C IV 1550 and 2690 km s^{-1} from N v $\lambda 1240$, which is consistent with 2800 km s^{-1} measured from the [Ne v] line. The STIS spectrum was taken through the 0.1×0.03 "Jenkins" slit, which was oriented to exclude any possible contamination from the Ab component.

This comparison provides some confidence that the O5 V Aa1 star is the primary source of wind emission at all wavelengths in this system. This somewhat complicates the weak-wind driving notion that a sufficiently shock-heated wind would be low enough density so as to be inefficient at cooling and remain hot enough into the outer wind that the higher ionization diagnostics appear, but the typical diagnostics disappear. However, the shock-heated wind simulations of C. Lagae et al. (2021) only tested an early O supergiant and a

late O dwarf, so the existence of both sets of lines in an early dwarf O star has not been assessed by current simulations. It is also unclear what contribution the O9 V star and/or an interaction between the O5 V and B0 V inner binary has to the wind emission line profiles; a wind-wind collision zone could be another viable mechanism to drive these emission lines. P. Pradhan et al. (2023) estimate the system is very X-ray bright ($\log L_X/L_{\text{bol}} = -6.47$).

10 Lac

10 Lac is a very well-studied late-type dwarf (O9 V). A recent compilation of estimates for its effective temperature (T_{eff}) and logarithmic gravity ($\log g$) was given in Table 6 in P. Aschenbrenner et al. (2023), with those authors finding $T_{\text{eff}} = 34.55 \pm 0.3 \text{ kK}$, and $\log g = 4.04 \pm 0.05$. This is in agreement with the stellar parameters found using a wide range of techniques at different wavelength regimes, as discussed in P. Aschenbrenner et al. (2023). The most extreme range of parameters found through all these studies gives $T_{\text{eff}} = 34.6^* - 36.0 \text{ kK}$ and $\log g = 3.90 - 4.05$, with differences in the approaches and assumptions accounting for discrepancies in best-fit parameters. 10 Lac is moderately nitrogen-enriched, radial velocity constant, and there is no evidence for line profile variability. There has been some uncertainty in the distance to 10 Lac, which is discussed extensively in K. D. Gordon et al. (2018) and P. Aschenbrenner et al. (2023), with their final estimates now converging to 566 ± 59 and $542 \pm 60 \text{ pc}$, respectively. It is found to be nonmagnetic (A. David-Uraz et al. 2014) and to have an X-ray luminosity typical for O-type stars ($\log L_X/L_{\text{bol}} = -7$, T. W. Berghoefer et al. 1997).

Notes on the R. K. Prinja et al. (1990) Sample

From the parameters published in R. K. Prinja et al. (1990), it appears as though there are multiple other objects with similar discrepancies in wind speed as seen in A38, ALS 15143, and 10 Lac, but measured from the UV. However, upon revisiting archival UV spectra and recent literature, the majority of these stars have received updates to their stellar parameters. For example, for HD 14947, R. K. Prinja et al. (1990) quote v_∞ as 1885 km s^{-1} , while C. Hawcroft et al.

(2021) measured 2300 km s^{-1} . HD 190429A has a very similar correction. HD 14434, on the other hand, has a revised temperature in G. Holgado et al. (2020), which is 2 kK lower than used in R. K. Prinja et al. (1990). The same temperature correction is applied to HD 15180 (P. A. Crowther & C. J. Evans 2009). HD 57060 is a contact binary which introduces significant uncertainties on the temperature estimate and may result in a large correction on v_∞ if radial velocity variations are not accounted for (M. Abdul-Masih et al. 2022). It is therefore likely that all other outliers in the R. K. Prinja et al. (1990) sample (at least above 30 kK) should be revised to much closer agreement with the general trend. We have corrected these outliers in Figure 3, but they are visible, e.g., C. Hawcroft et al. (2024b).

Appendix C Computing the Line Profiles

The power from an optically thin emission line received by an external observer in a frequency interval $d\nu$ centered at frequency ν is given in a spherical coordinate system by

$$L_\nu d\nu = \int_0^{2\pi} \int_0^\pi \int_0^\infty \eta r^2 \sin \theta dr d\theta d\phi d\nu \quad (\text{C1})$$

where $\eta \equiv \eta(r, \theta, \phi, \nu)$ is the volume emissivity in $\text{erg s}^{-1} \text{cm}^{-3} \text{sr}^{-1} \text{Hz}^{-1}$. For a line transition between upper level u and lower level l with frequency ν_{ul} , the emissivity can be separated into position- and frequency-dependent parts:

$$\eta(r, \theta, \phi, \nu) = \eta_{ul}(r, \theta, \phi) \times \varphi(\nu - \nu_{ul}) \quad (\text{C2})$$

$$= n_u A_{ul} \left(\frac{h\nu_{ul}}{4\pi} \right) \varphi(\nu - \nu_{ul}) \quad (\text{C3})$$

where $n_u(r, \theta, \phi)$ is the number density in the upper level, A_{ul} is the Einstein coefficient for spontaneous emission, h is Planck's constant, and where the integral of the intrinsic profile $\varphi(\nu - \nu_{ul})$ over all frequencies is 1. In the simplified case of a two-level atom in which a collisional excitation from the ground state $l = 1$ to the excited state $u = 2$ at a rate C_{12} is followed either by a spontaneous radiative decay or a collisional de-excitation at a rate C_{21} , manipulation of the rate equation gives

$$\eta_{21}(r, \theta, \phi) = n_2 A_{21} \left(\frac{h\nu_{21}}{4\pi} \right) \quad (\text{C4})$$

$$= n_e n_1 C_{12} \left(\frac{1}{1 + n_e/n_{\text{crit}}} \right) \left(\frac{h\nu_{21}}{4\pi} \right) \quad (\text{C5})$$

where $n_1(r, \theta, \phi)$ is the number density of ions in the ground state, $n_e(r, \theta, \phi)$ is the electron number density, and the critical density is defined by $n_{\text{crit}} = A_{21}/C_{21}$.

To explore the effects of aspherical but axisymmetric density distributions on the morphology of fine-structure line profiles, we allowed the density of a wind to vary as a function of stellar colatitude by an arbitrary, dimensionless function $G(\theta)$ and assumed that these changes do not affect the temperature or ionization structure, which are taken to be constant throughout the wind. None of these assumptions is likely to be valid, in particular because the ionization balance is certainly altered by changes in density. Nevertheless, these simplifications allow the electron number density to be specified as $n_e(r, \theta) = k_e G(\theta)/r^2$, where k_e is the mean number of electrons per ion in the wind; the number density in

the ground state of the ion of interest to be approximated by $n_1(r, \theta) \approx n_i(r, \theta) = k_i G(\theta)/r^2$, where n_i is the number density of the ion and k_i is the fraction of wind material in that ion.

Finally, we assume that the intrinsic line profile can be replaced by a δ function: $\varphi(\nu - \nu_0) \equiv \delta(\nu - \nu_0)$, which is valid in the Sobolev approximation. To account for the shift in line center as seen by an external observer, the profile in a moving medium becomes $\delta(\nu - \nu_0(1 + v_{\text{LoS}}/c)) \equiv \delta(\Delta\nu_{v_{\text{LoS}}})$, where v_{LoS} is the velocity of the wind projected along the line of sight to the observer. Since the fine-structure lines are expected to form preferentially in low-density environments at large radii, we assume that the velocity is constant, independent of θ , and equal to v_∞ , even though in practice the velocity will vary with the local mass flux. The large emission radius also implies that occultation by the star can be neglected, as already indicated by the integration limits in Equation (C1).

With these assumptions, the profile of a fine-structure line is given by

$$L_\nu = \int_0^{2\pi} \int_0^\pi \int_0^\infty \eta_{21}(r, \theta) \delta(\Delta\nu_{v_{\text{LoS}}}) r^2 \sin \theta dr d\theta d\phi. \quad (\text{C6})$$

The integral over r assumes a standard analytic form with the substitution $u = \sqrt{n_{\text{crit}}/G(\theta)} k_e r$:

$$\int_0^\infty \eta_{21}(r, \theta) r^2 dr = C G^{\frac{3}{2}}(\theta) \int_0^\infty \frac{1}{u^2 + 1} du \quad (\text{C7})$$

$$= C G^{\frac{3}{2}}(\theta) \left(\frac{\pi}{2} \right) \quad (\text{C8})$$

where the constant

$$C = (k_e n_{\text{crit}})^{\frac{1}{2}} k_i C_{12} (h\nu_{21}/4\pi). \quad (\text{C9})$$

Consequently, Equation (C6) simplifies to

$$L_\nu = C \left(\frac{\pi}{2} \right) \int_0^{2\pi} \int_0^\pi G^{\frac{3}{2}}(\theta) \delta(\Delta\nu_{v_{\text{LoS}}}) \sin \theta d\theta d\phi. \quad (\text{C10})$$

Note that the integrand in Equation (C10) is 0 except when $\Delta\nu_{v_{\text{LoS}}} = 0$; i.e., when $\nu = \nu_{21}(1 + v_{\text{LoS}}/c)$, which simplifies the integration. Also note that L_ν can be compared directly to the observed flux F_ν , since conservation of energy requires

$$L_\nu = 4\pi D^2 F_\nu, \quad (\text{C11})$$

where D is the distance to the star and the units of flux are $\text{erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1}$.

Figure C1 illustrates the geometry needed to determine v_{LoS} . For an axisymmetric configuration, the observer can be placed in the x - z plane without loss of generality. By aligning the rotational axis of the star with the $\theta = 0$ direction, the observer's line of sight in Cartesian ($\hat{i}, \hat{j}, \hat{k}$) coordinates is

$$\hat{n}_{\text{obs}} = \sin i \hat{i} + \cos i \hat{k}$$

and the direction of a patch of the radial outflow is given by

$$\hat{r} = \sin \theta \cos \phi \hat{i} + \sin \theta \sin \phi \hat{j} + \cos \theta \hat{k}.$$

Consequently,

$$v_{\text{LoS}} = v_\infty (\hat{n}_{\text{obs}} \cdot \hat{r}) \quad (\text{C12})$$

$$= v_\infty (\sin i \sin \theta \cos \phi + \cos i \cos \theta). \quad (\text{C13})$$

Flux profiles were constructed by numerically integrating Equation (C10) on a discrete mesh of (θ, ϕ) points spaced at

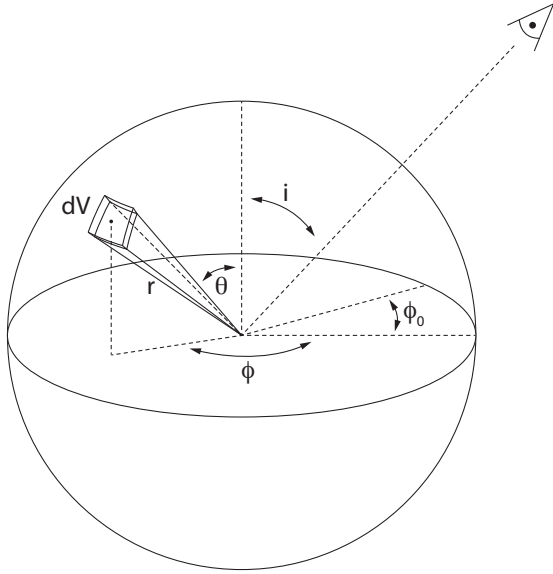


Figure C1. Schematic illustration of the spherical coordinate system adopted for the wind model. The rotational axis of the star is aligned with the direction $\theta = 0$, and the wind is viewed from an angle of $(\theta_0, \phi_0) = (i, 0)$.

intervals of $(\Delta\theta, \Delta\phi) = (0.2, 0.2)$. For a specified inclination angle i , each patch at (θ_j, ϕ_k) contributes its surface area weighted by $G(\theta_j)$ to the flux profile at the value of v_{LoS} given by Equation (C13). The fluxes were accumulated in bins with widths of 10 km s^{-1} to produce the profiles illustrated in Figure 6.

As a final caveat, we note that this approach assumes a two-level atom and that collisions dominate the population of the upper level. The two-level atom approach is valid for [Ne VI] $7.65 \mu\text{m}$ and [O IV] $24.89 \mu\text{m}$ lines, but three levels are involved in the formation of the [Ne V] 14.32 and $24.89 \mu\text{m}$ features. Pumping by UV continuum radiation may also play a role in populating the upper level of these transitions.

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