Massive Stars Near and Far
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New empirical mass-loss rates and clumping properties of massive stars

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Abstract. Hot, massive stars are known to host unstable, radiation-driven outflowing winds, giving rise to dense clumps of material which severely affect the diagnostic techniques used to derive wind properties of massive stars. Most of the current diagnostic models account for wind inhomogeneities by assuming a one-component medium consisting of optically thin clumps, and maintaining a smooth velocity-field. However, this neglects important light-leakage effects through porous channels in-between the clumps. These light-leakage effects have recently been incorporated in the stellar atmosphere modelling code FASTWIND, and here we will present quantitative mass-loss results from a combined Ultraviolet-Optical wind analysis of O-supergiants in the Galaxy. Using a genetic-algorithm fitting-approach, we systematically investigate the impact the wind physics has on derived stellar and wind parameters, and how this depends on metallicity and spectral type. We compare our findings with earlier results (which do not take into account such light-leakage effects), to standard mass-loss rates usually included in evolution model studies of massive stars, and with theoretical predictions of clumping properties. We will also present the first systematic empirical constraints on the new wind parameters, associated with light-leakage, and compare these with theoretical predictions.

Keywords. stars: mass loss, stars: early-type, stars: atmospheres

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1. Introduction

Massive stars ($M_{\rm ini} > 8M_\odot$) are important objects in the context of the evolution of their host environments and galaxies at large Bresolin et al. (2008). Through strong, radiation-driven outflows these stars enrich the interstellar medium with heavy elements, as well as imparting significant amounts of ionising radiation and kinetic energy (Chiosi & Maeder (1986), Matteucci (2008), Geen et al. (2020)). These stellar winds are also one of the most critical factors in understanding the evolution of massive stars as the magnitude of the mass lost through the stellar lifetime affects the evolutionary pathway Langer (2012). Typical uncertainties on observed mass-loss rates are a around a factor of three in the evolutionary stages near the main sequence Puls, Vink, & Najarro (2008). This uncertainty is a result of a wind structure composed of slow, dense clumps of material and fast, tenuous flows developing in the winds (see e.g. Owocki, Castor, & Rybicki

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(1988); Feldmeier (1995); Dessart & Owocki (2003); Sundqvist & Owocki (2013); Sundqvist, Owocki, & Puls (2018); Driessen, Sundqvist, & Kee (2019)) due to the inherent instability of radiation line driving (MacGregor, Hartmann, & Raymond (1979), Carlberg (1980), Owocki & Rybicki (1984)), which affects observational diagnostics of mass-loss rates (e.g. Oskinova, Hamann, & Feldmeier (2007), Sundqvist, Puls, & Feldmeier (2010), Šurlan et al. (2013)). This level of uncertainty in mass loss is also important for understanding the supernova explosion and resulting chemical yields Renzo et al. (2017), as well as the angular momentum transport in the stellar interior Keszthelyi, Puls, & Wade (2017).

In order to reduce the uncertainties on empirical mass-loss rates we must consider the wind structure in simultaneous fitting of UV and optical wind diagnostics. In this work we achieve this by performing a combined UV and optical fit of a sample of well-studied O-supergiant stars in the Milky Way, using the NLTE stellar atmosphere and wind modelling software FASTWIND which has recently incorporated the effects of optically thick clumping through a statistical approach.

2. Observations

The sample of eight Galactic O-supergiants analysed in this study is the same as the full sample of Bouret et al. (2012). We utilise the spectra as presented in Bouret et al. (2012), without adjusting the normalisation. For each star there is FUV, UV and optical coverage, the details of which are presented in Bouret et al. (2012) and Hawcroft et al. (2021). The spectra include a multitude of diagnostic lines, of which we focus on a subset of hydrogen, helium, carbon, nitrogen, oxygen, silicon and phosphorus features.

3. Methods

We determine stellar and wind parameters we compare the observed spectra with synthetic spectra, produced using the code FASTWIND (v10.3, Santolaya-Rey, Puls, & Herrero (1997), Puls et al. (2005), Rivero González, Puls, & Najarro (2011), Carneiro et al. (2016), Sundqvist & Puls (2018)). We employ a genetic-algorithm (GA) fitting technique to simultaneously optimise all the input parameters of the FASTWIND models, including the effective temperature $T_{\rm eff}$, surface gravity $\log g$, rotational and macroturbulent velocities ($v \sin i$, $v_{\rm macro}$), the wind β acceleration parameter, terminal wind speed v_∞, mass-loss rate $\dot{M}$, clumping factor $f_{\rm cl}$, surface abudances of helium, carbon, nitrogen and oxygen. We also include parameters associated with optically thick clumping, the velocity filling factor $f_{\rm vel}$, the interclump density factor $f_{\rm ic}$ and the clumping onset velocity $v_{\rm cl}$. The GA is based on the principles of genetic evolution and built upon the framework of Charbonneau (1995) and Mokiem et al. (2005). GA fitting has been shown to be effective in producing statisically unique solutions in fits of massive early-type stars in a number of studies (Mokiem et al. (2006); Mokiem et al. (2007); Tramper et al. (2011); Tramper et al. (2014); Ramírez-Agudelo et al. (2017); Abdul-Masih et al. (2019); Abdul-Masih et al. (2021), Hawcroft et al. (2021), Brands et al. (2022)). Figure 1 shows a spectral fit for the star HD14947, and Fig. 2 the reduced χ^2 distributions of models with respect to various parameters.

4. Results

We determine new mass-loss rates while including the effects of optically thick clumping. Figure 3 shows that the best-fit mass-loss rates are, on average, a factor of 3.6 below the predictions of Vink, de Koter, & Lamers (2000), and within a factor of 1.4 of the

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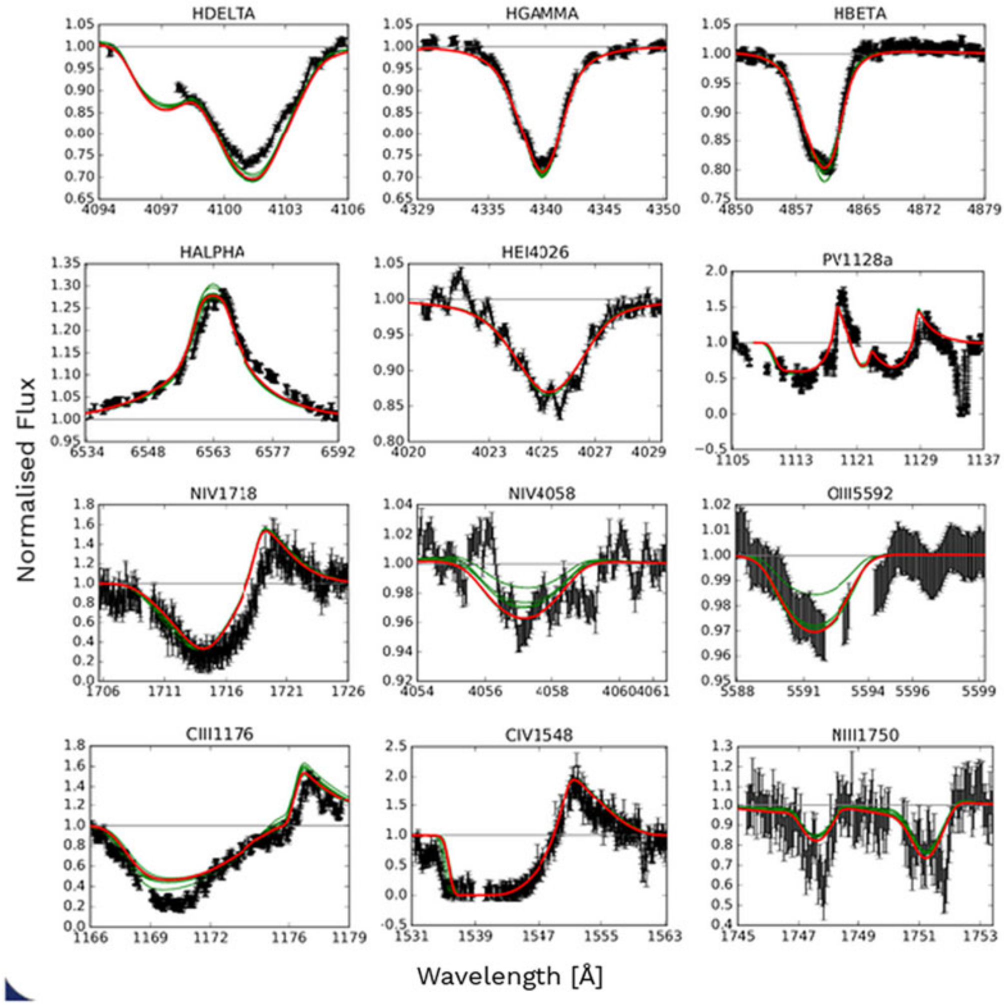

Figure 1. Subset of diagnostic lines with best-fit for HD14947 from the GA fit with optically thick clumping. Observed spectrum is shown in the dashed line, solid lines are statistically equivalent best-fit models within the confidence interval. Figure adapted from Hawcroft et al. (2021).

predictions of Björklund et al. (2021). To compute these predictions, best-fit parameter values from Hawcroft et al. (2021) are used as inputs for the recipes provided by the respective theoretical works. The empirical mass-loss rates we find are, on average, within 0.3 dex of the mass-loss rates found by Bouret et al. (2012), without the need to change the phosphorus abundance from solar, as the additional light leakage offered by the reduced effective opacity due to the inclusion of optically thick clumping allows us to reproduce the UV P-Cygni PV profiles. Bouret et al. (2012) do not include optically thick clumping and so must reduce the phosphorus abudance to reproduce the PV profiles. We find empirical constraints on parameters associated with optically thick clumping of: $f_{\rm cl} \sim 25$, $f_{\rm vel} \sim 0.5$ and $f_{\rm ic} \sim 0.1 - 0.3$.

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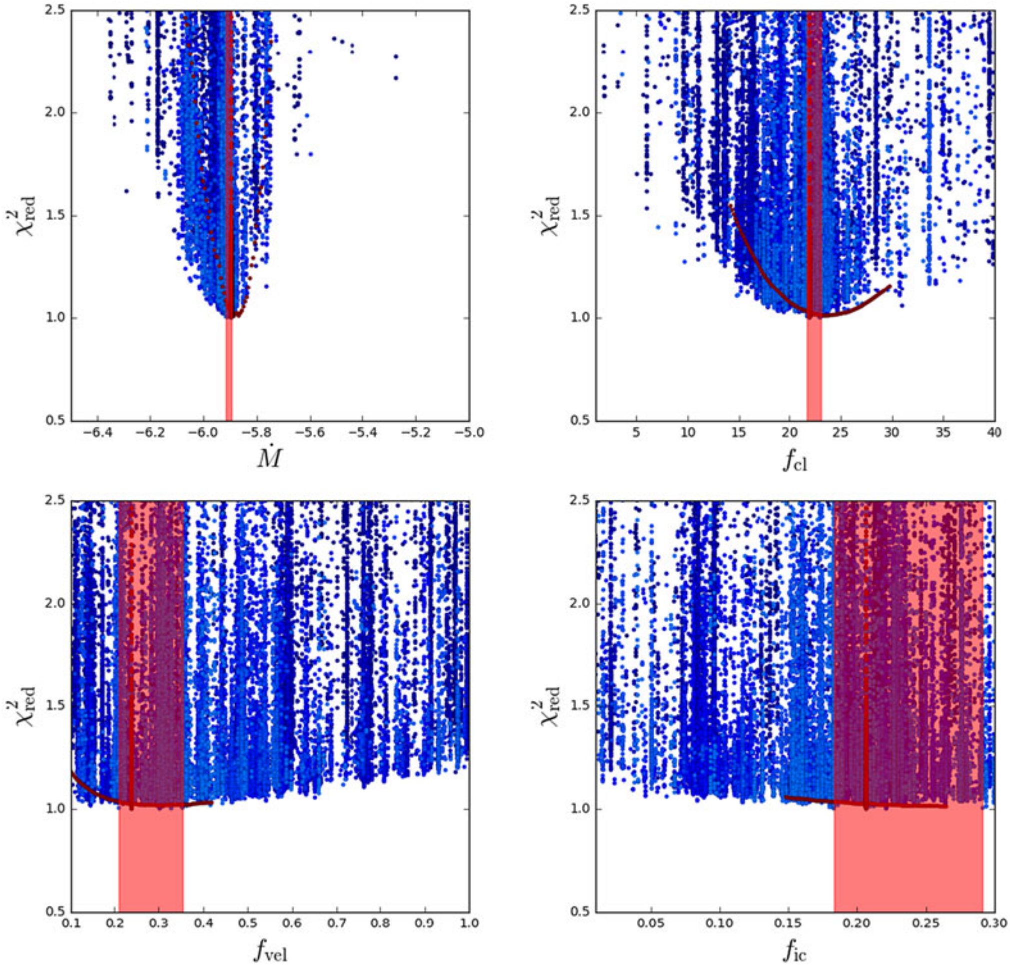

Figure 2. Subset of χ^2 distribution per parameter for HD14947 including mass-loss rate $\dot{M}$ (upper left), clumping factor $f_{\rm cl}$ (upper right), velocity filling factor $f_{\rm vel}$ (lower left) and interclump density factor $f_{\rm ic}$ (lower right). Models in blue are those produced by the GA, red points are models created to define the confidence interval around the GA best-fit. Region marked in red is the confidence interval.

5. Conclusions

We carried out a simultaneous UV and optical spectroscopic analysis of 8 early O-supergiant stars. By including a description of the span of the outflowing clumps in velocity space and allowing the clumps to become optically thick we have constrained two new parameters associated with wind structure for the first time. These are the fractional filling of velocity space by clumps and the density of interclump material. We are also able to constrain the degree of the overdensity in the clumps and the conditions for the onset of clumping. We estimate that, on average, 50% of the velocity field must be covered by clumps and the interclump material is 10-30% less dense than the mean outflow. We find that the clumps are, on average, 20 times more dense than the average wind. With these considerations we are able to fit UV and optical wind features with consistent mass-loss rates and abundances. The new empirical mass-loss rates are roughly three times lower than those commonly implemented in stellar evolution calculations.

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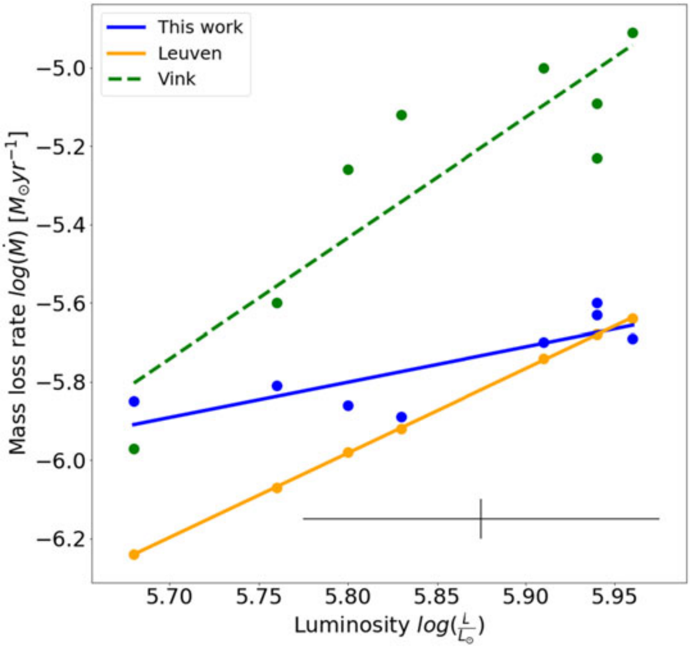

Figure 3. Mass-loss rates from the GA best-fits of Hawcroft et al. (2021), compared to the pre- dictions made by Leuven (Björklund et al. 2021) and Vink (Vink, de Koter, & Lamers 2000) for each star in our sample. The GA mass-loss rates are those found from the best-fit with optically thick clumping. Black cross in bottom right shows minimum error on mass-loss from this analysis and error on luminosity ±0.1 from Bouret et al. (2012). Figure adapted from Hawcroft et al. (2021).

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Discussion

J. Vink: The luminosity of the stars in your sample approach $10^6 L_\odot$ which is close to the transition mass-loss where the Björklund et al. (2021) mass-loss rates are a factor of three too low and the Vink, de Koter, & Lamers (2000) rates agree better with the observations, and this doesn't depend on clumping or porosity. Could it be that the clumping prescription in the models is incorrect which is affecting the mass-loss rates, for example the onset of clumping?

C. Hawcroft: Indeed, there could be issues with the clumping prescriptions as they are currently implemented. For example, we find that the clumping onset, which currently has a variable onset velocity and increases linearly to the maximum, is degenerate with the wind acceleration parameter β, so the shape of the wind and clumping acceleration profile is uncertain. To try to get a better understanding of this we have tried to compared to theoretical predictions, specifically the LDI simulations of Driessen, Sundqvist, & Kee (2019), these authors find onset velocities of clumping which are consistent with the velocities determined through the GA fits. However, these are 1D prescriptions and we may see changes in the clumping parameters and prescriptions as the simulations are computed in higher dimensions.

M. Williamson or M. Gagne: In which wavelength ranges are the twenty times denser clumps optically thick?

C. Hawcroft: It is difficult to give an exact answer to this across the full spectrum from this work as we mainly focus on UV and optical diagnostics, but in this parameter regime the clumps are mainly optically thick at UV wavelengths and less so at optical wavelengths.

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