The Astrophysical Journal, 656:L77–L80, 2007 February 20

SPECTROSCOPY OF SMC WOLF-RAYET STARS SUGGESTS THAT WIND CLUMPING DOES NOT DEPEND ON AMBIENT METALLICITY

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Received 2006 December 7; accepted 2007 January 12; published 2007 January 30

ABSTRACT

The mass-loss rates of hot, massive, luminous stars are considered a decisive parameter in shaping the evolutionary tracks of such stars and influencing the interstellar medium on galactic scales. The small-scale structures (clumps) that are omnipresent in such winds may reduce empirical estimates of mass-loss rates by an evolutionarily significant factor of ≥3. So far, there has been no *direct* observational evidence that wind clumping may persist at the same level in environments with a low ambient metallicity, where the wind-driving opacity is reduced. Here we report the results of time-resolved spectroscopy of three presumably single Population I Wolf-Rayet stars in the Small Magellanic Cloud, where the ambient metallicity is $\sim\frac{1}{5}\ Z_\odot$. We detect numerous small-scale emission peaks moving outward in the accelerating parts of the stellar winds. The general properties of the moving features, such as their velocity dispersions, emissivities, and average accelerations, closely match the corresponding characteristics of small-scale inhomogeneities in the winds of Galactic Wolf-Rayet stars.

Subject headings: stars: mass loss — stars: winds, outflows — stars: Wolf-Rayet

1. INTRODUCTION

Wolf-Rayet (W-R) stars, as a final evolutionary phase of hot, massive stars ($M_{\rm init} \geq 25\ M_\odot$ for a $Z \sim Z_\odot$ ambient metallicity), are especially sensitive to all phenomena that may influence their mass-loss rates. The fast, dense winds of W-R stars are driven by the radiation pressure exerted on multiple lines of mainly heavy elements. Hence, W-R mass-loss rates should be sensitive to the ambient metallicity content as well as to the locally enhanced chemical composition of the wind. The former sensitivity, although suggested from general principles (Lamers & Cassinelli 1999), has escaped detection until recently (see Crowther 2006, Gräfener & Hamann 2006, and references therein).

Line-driven winds are inherently unstable (Lucy & Solomon 1970), being constantly fragmented by numerous embedded shocks (Dessart & Owocki 2005). Such fragmentation may change the local ionization balance and create a local nonmonotonic velocity field, thus providing a strong feedback to the driving force. In the past, wind diagnostics relied on models of smooth, homogeneous winds, until numerous spectroscopic observations of Galactic W-R and OB stars (Moffat et al. 1988; Robert 1992; Lépine & Moffat 1999; Eversberg et al. 1998; Bouret et al. 2005; Fullerton et al. 2006 and references therein) demonstrated the omnipresence of wind-embedded clumps, usually taking on the form of discrete density enhancements outmoving with an accelerating wind. As an immediate and long-lasting impact, the relatively simplistic treatment of structures in the otherwise highly elaborate models of hot-star winds (Hillier & Miller 1999; Puls et al. 2006; Hamann et al. 2006) resulted in a consensual downward revision of mass-loss rates by a factor of ≥3, confirmed by numerous independent observations (e.g., Moffat & Robert 1994).

Although wind clumping was also widely anticipated to operate in low-*Z* environments (Hamann & Koesterke 1998; Crowther et al. 2002; Bouret et al. 2003), *direct* proof was lacking. Here we report the detection of outmoving spectral features in the line profiles of three SMC W-R stars. We compare the general characteristics of these clumps to those in a Galactic sample of W-R stars, finding them to be strikingly similar.

2. OBSERVATIONS

We targeted three presumably single (Foellmi et al. 2003) early-type WN stars in the SMC: SMC WR 1 (WN3ha), WR 2 (WN5ha), and WR 4 (WN6h), thus forming a representative sample of the small SMC W-R population (12 known Population I W-R stars, most of them early-type WN stars; Massey et al. 2003). We monitored the stars in continuous, ∼1 hr 40 minute long loops for two consecutive nights in 2006 August (between HJD 2,453,974.538 and HJD 2,453,975.877), alternating among the three targets: WR 4–WR 2–WR 1, etc. We used the UV-Visual Echelle Spectrograph at the ESO VLT-UT2 (Kueyen), sampling the 3927–6031 Å region. During the routine reduction, we experimented with different binning factors, finding a reasonable compromise between the desired spectral resolution, $\lesssim 0.5$ Å pixel^{-1}, and the signal-to-noise ratio, $S/N > 100$, by binning the available spectra to 0.25 Å (the region around He II 4686 Å) and 0.31 Å (He II 5412 Å) bins. With 40, 30, and 20 minute exposures, this resulted in five to six spectra per night per star, with comparable signal-to-noise ratios $S/N \simeq 120$, $\simeq 140$, and $\simeq 160$ (± 20) for WR 1, WR 2, and WR 4, respectively, estimated from the adjacent continua around measured spectral lines.

3. PROPERTIES OF THE CLUMPS

The high quality of the spectra allowed us to apply a rather straightforward procedure to detect the line-profile variability. We rectified the profiles of all relatively prominent He II lines (the only lines strong enough to provide sufficient precision,

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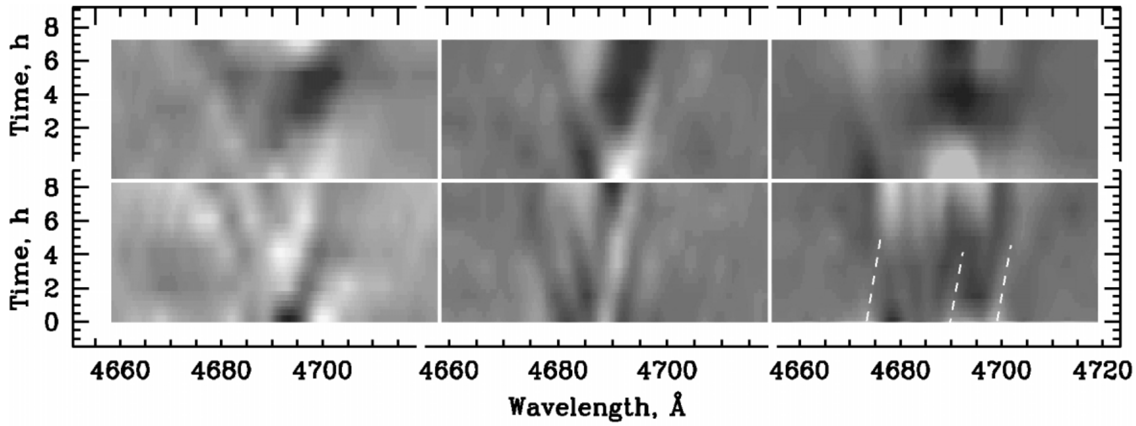

FIG. 1.—Gray-scale plots of time-interpolated and smoothed difference (individual minus average) spectra of WR 1 (*left panels*), WR 2 (*middle panels*), and WR 4 (*right panels*) for night 1 (*lower panels*) and night 2 (*upper panels*). The intensity ranges are from −0.03 (*black*) to +0.03 (*white*) in the local continuum units (≡1). The dashed lines in the lower right panel mark the features presumably related to CIRs (see text).

namely, He II λ4686, λ4859, and λ5412) by linearly interpolating between the line-free regions located in the immediate vicinity of a given line. Then we created unweighted average profiles of each line for each night of observation and subtracted these averages from the individual profiles. We found that all the major emission lines in all three stars can be considered as variable at a level substantially exceeding the predicted instrumental noise level.

For a proper comparison of the new results with previous studies of inhomogeneities in the winds of Galactic W-R stars, we closely follow the already developed approaches specifically designed to reveal basic properties of clumps:

1. First of all, we attempt to detect similarities in the variability patterns of major emission lines by cross-correlating the difference (individual minus average) spectra of different line transitions. We use the average cross-correlation functions (see Lépine et al. 2000, eqs. [7] and [8]); namely, we produce an unweighted average of the individual (transition-to-transition) cross-correlation functions for a given star and a given spectral window (usually $\pm v_\infty$, centered on the transition's $\lambda_0 + \Delta\lambda$, where $\Delta\lambda$ corresponds to the SMC's systemic velocity). The maxima of the average cross-correlation functions reach 0.2–0.4, which is comparable to $I_{\rm max} = 0.2$–0.8 measured in the C III and C IV profiles of the Galactic star WR 135. Taking into account that (*a*) the considered transitions arise from different, although overlapping, line-forming regions, (*b*) there is some hydrogen present in the λ4860 blend, and (*c*) there might be some transition-dependent optical-depth effects (see below), we did not anticipate a very high degree of correlation. Nevertheless, for general consistency, plus a slight gain in S/N, we combine the appropriately shifted (to the rest frame of the He II λ4686 transition) difference spectra of the three lines, smooth them with a Gaussian filter (FWHM = 7 pixels), linearly time-interpolate the neighboring spectra in order to fill the unavoidable gaps, and plot the results in Figure 1. The continuous, V-shaped structures present in the difference spectra of the SMC W-R stars are remarkably similar to the variations seen in *all* appropriately studied Galactic W-R stars (Lépine & Moffat 1999), with the latter firmly linked to the presence of numerous small-scale inhomogeneities moving outward in the accelerating parts of the stellar winds.

2. We proceed with measurements of the clump properties, closely following the approaches developed in Lépine & Moffat (1999) and in Lépine et al. (2000). Namely, we use the degradation function to estimate the average acceleration of the outmoving emission features (Fig. 2) and the net intrinsic variability levels, $\sigma_{\rm intr}$, in different transitions (Fig. 3). We remind the reader that the degradation function (Lépine et al. 2000, eq. [2]) measures the mean standard deviation between spectra separated by a (variable) interval Δt. In addition, this function

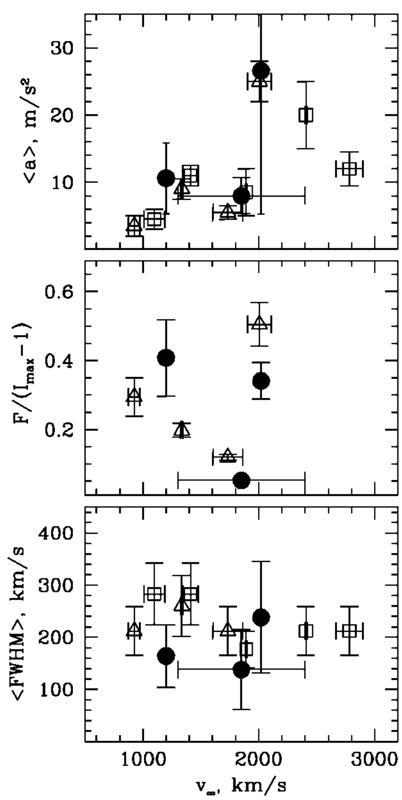

FIG. 2.—*Upper panel*: Average accelerations of outmoving clumps in the winds for SMC stars (*filled circles*) as well as the measured ranges for Galactic WC (*open squares*) and WN (*open triangles*) stars (see Lépine & Moffat 1999). The data are arranged by the corresponding terminal velocities of the WR winds. *Middle panel*: Average fluxes (*F*) of the clumps detected in He II λ5412 and normalized by the maximum intensity of this emission profile ($I_{\rm max} - 1$), in order to be compared with the measurements of Robert (1992). *Lower panel*: Average FWHMs of the clumps observed in the He II λ5412 profile. Note that WR 134 was omitted from the lower panel due to the very high FWHM, ~800 km s^{-1} (see explanations in Lépine & Moffat 1999). The v_∞ estimates are rather uncertain for WR 1 and WR 2 (P. Crowther 2006, private communication); for WR 4 they come from Crowther (2000) and Willis et al. (2004).

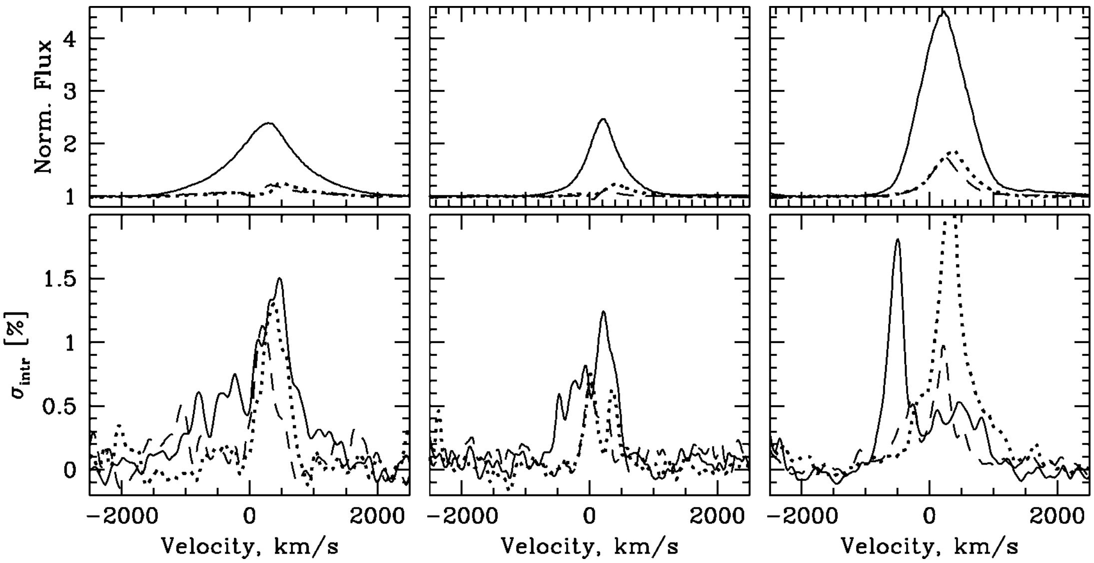

FIG. 3.—Intrinsic variability across the line profiles in WR 1, WR 2, and WR 4 (*lower panels, left to right*); the solid lines correspond to He II λ4686, the dotted lines correspond to He II + H λ4860, and the dashed lines trace He II λ5412. The upper panels show average rectified profiles of the transitions.

also accounts for a possible motion of the clumps (predominantly away from the line's center), by including the average acceleration as a free parameter. The levels of net intrinsic variability are estimated across emission-line profiles (Lépine et al. 2000, eqs. [4] and [5]) by using the variability in line-free continuum regions adjacent to emission lines and treating it as a source of instrumental noise, then adjusting this noise level by allowing for the difference in count statistics across the profile of a prominent emission line.

3. In order to compare our measurements of the individual fluxes and full widths at half-maxima of the detected clumps with corresponding values for Galactic W-R stars, we follow the general approach and published measurements from Robert (1992), thus using only the line He II λ5412. Namely, we measure the fluxes, maximum intensities, and FWHMs from the least-squares fits of Gaussian profiles to the recognizable features in the difference spectra (individual spectrum minus night average). Figure 2 shows that, within the statistical uncertainties, which are larger for the SMC stars mainly due to the relatively lower S/N, the properties of the Galactic clumps are indistinguishable from those in the SMC sample. Note that for the estimates of the clump properties, we use the unsmoothed difference spectra.

The broad spectral coverage of the data allows us to address the question of the optical depth of the clumps by comparing the intrinsic variability patterns in different transitions. One should note (Fig. 3) the most instructive contrast between He II λ4686 (transitions 3–4) and He II λ5412 (transitions 4–7). In order to make quantitative intercomparisons of the intrinsic variability levels, we normalise $\sigma_{\rm intr}$ by the line-profile intensity of the corresponding transition. Both SMC WR 1 and WR 2 show a reasonably consistent behavior in both transitions (Fig. 3; compare to Fig. 6 from Lépine et al. 2000), if one takes into account the pronounced difference in the extensions of the line-forming regions; compare the velocity extensions of the average profiles of He II 4686 to their He II λ4859 and λ5412 counterparts. Surprisingly, the variability patterns of WR 4 come as a sharp contrast to the predictably congruent behavior of the patterns in WR 1 and WR 2.

4. DISCUSSION AND CONCLUSIONS

First of all, we concentrate on the intrinsic line variability as related to optical-depth effects introduced by the clumps. Relying on the differences in the total optical depths of the studied transitions and assuming that these are also applicable to the population of discrete density enhancements, one expects to detect different $\sigma_{\rm intr}$ dependencies across the profiles. Most notably, the significant optical depth of He II λ4686 may result in a blueshifted peak of $\sigma_{\rm intr}$ relative to He II λ4859 and He II λ5412. Quite predictably, SMC WR 1 and WR 2 show little, if any, line-opacity effects; note the pronounced (Fig. 3) absorption components in the profiles of He II λ4859 and He II λ5412, which are generally linked to low optical depths of the winds. Concurrently, Lépine & Moffat (1999) find only mild clump-related optical-depth effects in the (optically thin) C III λ5696 line formed in the winds of Galactic WC stars, along with the possible presence of opacity-related effects in He II λ5412 seen in the Galactic WN stars. Hence, for WR 1 and WR 2, one may conclude that either (*a*) the clumps are optically thick in all transitions, *and* the winds have rather low volume filling factors (e.g., Owocki & Cohen 2006), or (*b*) all clumps are optically thin. Unfortunately, our present limited data set does not allow one to choose between these two alternatives. The only noticeable difference between WR 1 and WR 2 is the secondary maximum in $\sigma_{\rm intr}$ of He II λ4859 for WR 2, which may be caused by the presence of relatively high quantities of hydrogen in the wind.

WR 4 tells a different story. The intensity of the He II λ4686 transition, as well as the lack of developed P Cygni absorptions, calls for a denser wind. If the global properties of the wind are related to the properties of clumps, then one may detect different wavelength dependencies of $\sigma_{\rm intr}$. This clearly pertains to WR 4, where the blueward displacement of the He II 4686 Å peak may point to a high optical density of clumps. However, the disparity of the He II 4859 and 5412 Å distributions prompts an alternative explanation; the spectral variability could be, in part, related to the presence of corotating interacting regions (CIRs; Massa et al. 1995; Morel et al. 1999 and references therein), as seen in several Galactic W-R stars. One may notice the synchronized *redward* migration of weak emission features in the first half of night 1

(Fig. 1, *dashed lines*: λ ~ 4673 Å shifting to ~4676, ~4689 gradually moving to ~4693, and ~4698 moving to ~4702) as well as the gradual disappearance of the broad emission feature at λ ~ 4690 Å during night 2, both phenomena reminiscent of a CIR. In addition, along with general expectations, WR 4 is a periodic photometric variable (Foellmi et al. 2003; $P = 6.55$ days) and not an obvious binary. This period is then likely related to rotation. However, this does not mean that WR 4 lacks clumps.

One should also notice the lack of any dependence of clump FWHMs on spectral class or terminal velocity of the W-R winds (Fig. 2, *lower panel*). The recent comprehensive analysis of turbulence in colliding supersonic flows (Folini & Walder 2006) shows that the velocity dispersions in the shock-bound cold dense layers (the clumps?) depend only on the upwind Mach numbers, M_u. We consider a "generic" W-R wind with $v_\infty = 2000$ km s^{-1}, estimating the dispersion of turbulent velocities as $\sigma(v_{\rm turb}) \sim (0.1\text{–}0.2)v_\infty$ (Prinja et al. 1990; Marchenko & Moffat 1999). We assume an "asymptotic" wind temperature $T = 2 \times 10^4$ K. This provides an estimate for the sound speed in the clump-formation zone, ~(5–100)$R_\star$ (see the models in Lépine et al. 2000). Using $M_{\rm rms} \sim \eta^{-1/2} M_u$ with density contrast $\eta \sim 30$ (Folini & Walder 2006), one may estimate the typical width of a clump as FWHM ~ 1.4–2.7 Å, or 90–170 km s^{-1} at λ = 4686 Å. This rough estimate falls tantalizingly close to the measurements from Figure 3, which give FWHM = 100–300 km s^{-1}. One may match these figures even more closely under the assumption that the hydrodynamically modeled density contrasts fall below the pre-specified value of $\eta = 30$, by adopting $\eta \sim 10$ as frequently used in models of W-R spectra (Hamann & Koesterke 1998).

Hence, quite justifiably, we favor the notion in which the clumps have the approximately same internal velocity dispersion defined by compressible turbulence in a supersonic flow but different emissivity volumes (cf. Lépine & Moffat 1999).

Concluding our study, we can state that:

1. Despite the differences in ambient metallicity, the winds of Galactic and SMC W-R stars show a clear presence of small-scale structures.

2. The general properties of these structures (namely, average acceleration rate, average individual flux, and average velocity dispersion inside the clump) are similar for both populations of W-R stars.

3. The second point comes as a big surprise, considering that the wind-driving force (and thus the radiatively driven instability) sensitively depends on the presence of heavy elements (Vink & de Koter 2005).

4. A wind-clumping factor must be included in the models of massive-star winds in low-Z environments, just as in high-Z environments. Our understanding of the first population of stars in the early universe, mostly all very massive, as well as processes of enrichment of the interstellar medium, will depend on reliable estimates of mass-loss rates, i.e., the assumed wind-clumping factors. Indeed, wind clumping could be rather extreme in a low-Z environment; one may recall $f = 0.01$ used in the models of NGC 346 MPG 324 [O4 V((f)) star in the SMC; Bouret et al. 2003] and $f = 0.06$ for Br 43 (WC4 star in the LMC; Hamann & Koesterke 1998), to be contrasted with the more modest $f \sim 0.1\text{–}0.3$ values for Galactic W-R stars. However, note that the recent data on Galactic OB stars also provide $f \ll 0.1$ (Bouret et al. 2005; Fullerton et al. 2006). This may signify that either the filling factors depend on the evolutionary status of massive stars or the invoked wind-clumping factors are biased by the model approach and the choice of diagnostic lines. The latter, in turn, may be related to a (strong) radial dependence of the wind-clumping factor. This obviously calls for a thorough investigation, which is far beyond the scope of this Letter.

The extreme clumping may dramatically decrease estimates of the mass-loss rates, thus helping to retain the expected high rotational velocities for the progenitors of the long/soft γ-ray bursts, as well as affect the appearance of their immediate environments, thus the observable reaction (echo) on the incoming burst.

This Letter is based on observations made with ESO telescopes at the Paranal Observatory under program ID 077.D-0029. C. F. thanks C. Esparza for his efficient and friendly technical support during observations. A. F. J. M. is grateful to NSERC (Canada) and FQRNT (Québec) for financial assistance. F. M. acknowledges support from the Alexander von Humboldt Foundation.

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