Clumping in Hot Star Winds
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Wind inhomogeneities in low-Z environment: observations

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We discuss 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 $\sim 1/5 Z_{\odot}$. We were able to detect and follow numerous small-scale wind-embedded inhomogeneities in all observed stars. 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.

1 Introduction

The fast, dense winds of Wolf-Rayet (W-R) stars are driven by 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, though suggested from general principles (Lamers & Cassinelli 1999), has escaped detection until recently (see Crowther 2006, Gräfener & Hamann 2006, and references therein). Numerous spectroscopic observations of Galactic W-R and OB stars (see, e.g., Lépine et al. 2000; 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. Though wind-clumping was widely anticipated to operate also in low-Z environments (Hamann & Koesterke 1998; Crowther et al. 2002; Bouret et al. 2003), any *direct* proof was lacking.

2 Our targets and observing strategy

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 WNs: Massey et al. 2003). We tried to avoid the binaries, as, quite frequently, a large-amplitude, phase-related line-profile variability prevents detection of relatively faint details ascribed to the wind-clumping. We monitored the stars in continuous, ∼1h 40 min-long loops for two consecutive nights in August, 2006 (between HJD 2,453,974.538 and ...75.877), alternating among the 3 targets. We used the UVES spectrograph at the ESO-VLT-UT2 8-m telescope, sampling the region $\lambda 3927-6031$Å and obtaining 5-6 spectra/night/star, all with comparable signal-to-noise ratios $S/N \simeq 120-160$, and ~ 0.3Å spectral resolution (for more details see Marchenko et al. 2007). Previously a similar setup has led to robust detections of small-scale inhomogeneities in the winds of Galactic W-R stars.

3 Properties of the Clumps

Applying a widely-accepted procedure (appropriately filtered differences: individual profiles minus night averages - see, e.g., Lépine et al. 2000), we detected, as anticipated, numerous wind-embedded, stochastically appearing and gradually outmoving (notice the typical **V**-shaped structures in Fig. 1) clumps in all 3 targets and all major emission lines, namely, HeII 4686, 4859 and 5412 Å . The line-profile variability of WR1 and WR2 closely resembles the behavior of emission lines in the Galactic W-R stars. However, in WR4 one may notice the synchronized *redward* migration of weak emission features in the first half of Night 1 (Fig. 1), as well as the gradual disappearance of the broad emission feature at $\lambda \sim 4690$ during Night 2, both phenomena reminiscent of a large-scale, relatively long-lasting perturbation in the wind. These are usually linked to a co-rotating interacting. region (e.g., Massa et al. 1995). The existence of a photometric period (Foellmi et al. 2003: P=6.55 d) calls for an even closer analogy with EZ CMa, a Galactic W-R CIR proto-type (St-Louis et al. 1995). However, any direct analogy promptly ends at the inspection of the available data from FUSE (Fig. 2): where one expects to detect a coherent variability across the spectrum (St-Louis et al. 1995), we see none substantially exceeding the instrumental noise. Hence, we conclude that

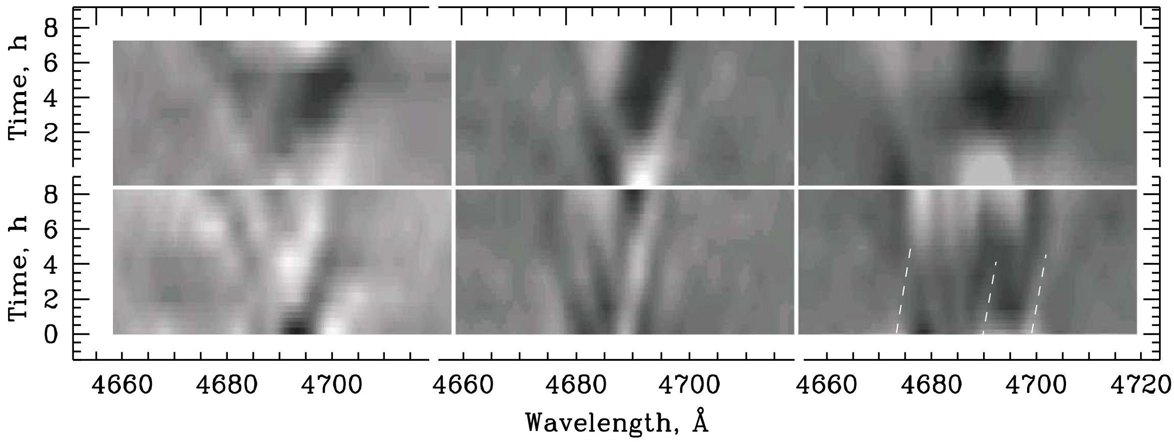

Figure 1: Grayscale plots of time-interpolated and smoothed difference (individual - night-average) spectra of WR1 (left panels), WR2 (central panels) and WR4 (right panels) for Night 1 (lower panels) and Night 2 (upper panels). The intensity ranges are -0.03 (black) to +0.03 (white) in the local continuum units ($\equiv 1$). The dashed lines in the lower-right panel for WR4 mark the features presumably related to CIRs (see text).

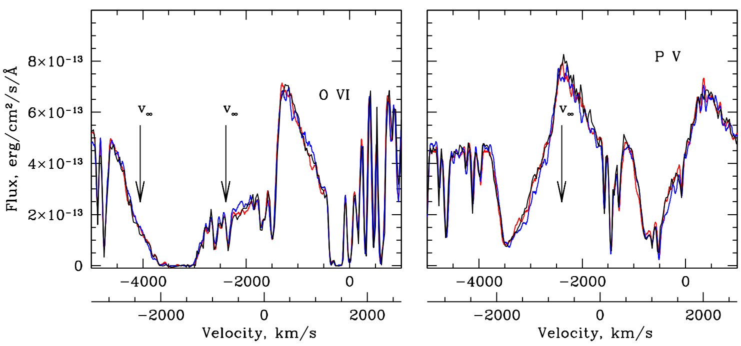

Figure 2: The line-profile variability (or, rather, a lack of variability) in WR4 observed with FUSE. Black lines: data from 14 June, 2001 (Willis et al. 2004); red lines - 06 August, 2006; blue lines - 01 October, 2006. The double X-axis shows velocity scales for the two components of the OVI and P V doublets. Their v_∞ edges are marked by vertical arrows.

practically all the variability patterns seen in Fig. 1 are caused by stochastical appearance of small-scale overdensities in the winds of the SMC W-R stars.

Evaluating the characteristics of wind-clumps, we apply the well-developed suite of techniques, such as time-averaged cross-correlation functions, the degradation functions, etc. (see Lépine et al. 2000) and find that the basic properties of the Galactic wind-clumps are indistinguishable from those in the SMC sample (Fig. 3).

Two unveiled characteristics deserve special attention:

(i) the simultaneous appearance of some clumps in all studied HeII lines allows to address the important question of the optical depth of the detected clumps. The limited amount of spectra, as well as insufficiently high (for this particular purpose) S/N do not provide a single answer. However, we are left with only two potentially viable alternatives: (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;

(ii) even more interesting is the the lack of any dependence of clump FWHMs on spectral class or terminal velocity of the W-R winds (Fig. 3, left section). Such 'insensitivity' may signify that the clumps are direct products of supersonic turbulence operating in compressible outflows. Indeed, evaluating the expected velocity dispersions in a shock-bound cold dense layer (Folini & Walder 2006), we find a reasonably close match with the observed FWHMs of

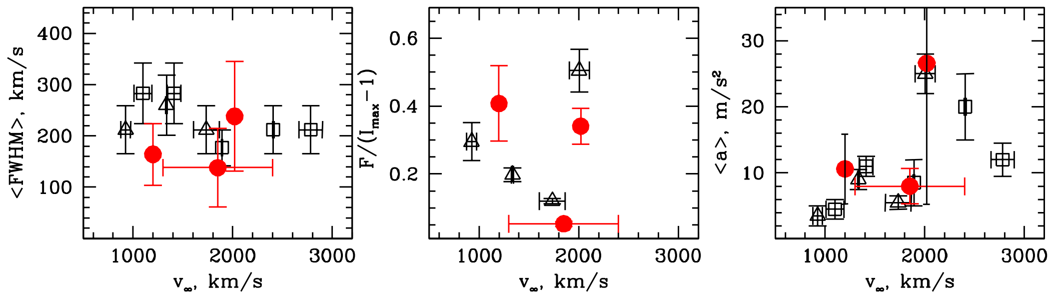

Figure 3: The left panel shows the average FWHMs of the clumps observed in the HeII 5412Å profile in the SMC stars (red circles), as well as Galactic WC (open squares) and WN (open triangles) stars (see Lépine & Moffat 1999). The data are arranged by the corresponding terminal velocities of the WR winds. The middle panel shows the average fluxes (F) of the clumps detected in the HeII 5412Å line and normalized by the maximum intensity of this emission profile ($I_{max} - 1$), in order to be compared with the measurements of Robert (1992). The right panel shows the average accelerations of outmoving clumps.

wind-clumps.

4 Conclusions

The general properties of wind-clumps are the same in the Galactic and SMC stars.

The clumps should be considered as direct products of supersonic turbulence operating in a compressible outflow. The observed FWHMs of the wind-clumps (Fig. 3) point to the filling factor $f \sim 0.1$, in line with the widely accepted value (e.g, Hamann & Koesterke 1998).

Presently, we are not able to choose between the two possibilities: (a) either the clumps are optically thin or (b) the filling factor f is very low.

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