Thermal and Ionization Aspects of Flows from Hot Stars: Observations and Theory
ASP Conference Series, Vol. 204, 2000
Henny J.G.L.M. Lamers, and Arved Sapar, eds.

The Structure of Wolf-Rayet Winds from an Observational Viewpoint

Anthony F.J. Moffat

Dépt. de physique, Univ. de Montréal, C.P. 6128, Succ. Centre-Ville, Montréal, QC, H3C 3J7, Canada, and Observatoire du mont Mégantic

Sébastien Lépine

Space Telescope Science Institute, 3700 San Martin Dr., Baltimore, MD 21218, USA

Abstract. Wolf-Rayet stars have the strongest persistent winds among hot stars. This has the advantage that one can easily observe their wind structure *globally* using Doppler spectroscopy of their strong *emission* lines (to be complemented/superseded soon by ultra-high resolution optical interferometric imaging from space!), but the disadvantage that the winds are opaque close to the star. Superposed on a general outward cooling trend, all WR winds appear to exhibit small-scale temporal fluctuations in their emission lines. The interpretation is that we are probably seeing the manifestation of some kind of all-pervasive turbulent shocks superposed on the general outflow, with essentially no background, smooth component. The flux from the variable emission subpeaks appears to follow $\sim$ the same ionization trend with radius as the global line emission. Evidence is mounting that WR winds are not alone: other, possibly all, hot-star winds may also be strongly clumped. Consequences of wind clumping, not just in WR stars, are numerous (e.g. revision downwards of mass-loss rates, trigger for dust formation, revision of the wind driving mechanism).

A small minority of WR stars also reveal large-scale, quasi-periodic line variations, reminiscent of DAC/CIR behaviour in O-star winds.

1. Introduction

Among massive stars, the most evolved tend to have the largest mass-loss rates ($\dot{M}$), leading to the presence of emission lines even in the optical. In particular, Wolf-Rayet (WR) stars are the epitome of massive, hot, stable stars with high $\dot{M}$, whether of population I (i.e. descendants of massive progenitors) or the $\sim$15 % of central stars of planetary nebulae (i.e. from low-mass stars). In the case of population I WR stars, the thrust of this article, the $\dot{M}$s are typically some 10 times that of their progenitor O stars. The reason is likely to be a combination of enhanced opacity due to increased content of heavy elements, with a shift of their continuum emitting fluxes to the UV (due to evolution to hot dense He-rich stars), where numerous, strong spectral lines prevail.

Therefore, the easiest place to start probing the properties of hot-star winds in general is where the winds are strongest, i.e. in WR stars. In particular, it is in the optical where one can easily secure high-resolution, high S/N spectra in reasonable times from the ground. The UV is certainly also well suited, although not so much with the now defunct IUE satellite and its modest S/N, or with UV spectrographs on board the Hubble Space Telescope, where it is/was difficult to obtain adequate monitoring. Once WR stars are examined, there then remains the question of applicability to other hot stars, whose winds do not necessarily follow the same trends.

Although some kind of non-spherical structure in WR winds has been surmised before (e.g. from eclipse curves of the Rosetta stone WR + O binary V444 Cygni: Cherepashchuk et al. 1984; or from the electron scattering wings: Hillier 1991), it was not until intense spectroscopic monitoring was undertaken in the last decade that the picture has become much clearer. Currently, all 12 of the bright WR stars monitored adequately so far show multi-scaled variable stochastic structures, while only two WR stars show ~periodically varying global wind structures, suggesting some kind of DAC/CIR (discrete absorption component/corotating interactive region) structures modulated by rotation.

Previous reviews of the structure and related spectroscopic variability of WR winds can be found in Moffat & Robert (1991, 1992); Robert, Moffat & Seggewiss (1991); Robert (1992, 1994); Moffat et al. (1994a,b); Moffat (1994a,b,c, 1996, 1999a,b); Lépine (1994, 1998). In this review, we will update the status of WR wind structure, proceeding from large to small scales. Emphasis will be on the observations, with a minimum of assumptions, in contrast to the sophisticated standard model of WR spectra, which has made great progress but still does not include all the known physics.

2. Global ionization structure

Lucy & Abbott (1993) made the point that radiation alone could drive the strong winds of WR stars if a strong stratification in ionization prevails, allowing multi-line momentum transfer to take place. This is in contrast to the ~ isothermal, thin winds of OB stars. Beals (1929) was the first to effectively reveal a global ionization structure in WR winds, showing that high ionization lines in WR star spectra tend to be narrower than low ionization lines. Then Kuhi (1973) demonstrated this very clearly in a plot of line width versus ionization potential in the WN6 star HD 192631 (WR136); the inner hotter wind gradually changes to a cooler outer wind. More recently, Schulte-Ladbeck et al. (1995, 1996), Rochowicz (1997), and Herald et al. (2000) repeated what Kuhi did earlier, but for a much larger sample of lines and stars. Despite the overall clear trend of width with ionization potential, the scatter for any given star is large, due to different line-formation mechanisms at play and differing line/continuum opacities even for the same line species.

It has been proposed that the large ratios of wind to radiative momentum ($\dot{M}v_\infty/(L/c) > 1$) in Wolf-Rayet winds, indicative of a large tranfer of momentum from the radiation field to the wind, can be explained by multiple scattering of photons induced in a medium with a strong ionisation stratification (Lucy & Abbott 1993; Owocki & Gayley 1999). The systematic spread in the emission-

line widths of Wolf-Rayet stars suggests that strong acceleration indeed occurs over the range where a significant ionisation gradient is present. It remains to be proven, however, that the ionisation gradient is directly responsible for the wind acceleration.

3. Large-scale structure(s)

Table 1 compares large- and small-scale properties among OB and WR stars. The implication is that, while most OB stars are fast rotators, most of their descendent WR stars have lost a large part of their angular momentum via their strong winds, and therefore have more spherical winds (e.g. Fliegner & Langer 1995). When large-scale structures do prevail in the form of DACs/CIRs, their variation is basically cyclical, whereas the small-scale structures are stochastic. Among WR stars, only one WR star (HD 93131 = WR24, WN6ha) has been shown so far to exhibit DAC behavior (Prinja & Smith 1992), but even then the star only has an (extreme) Of-like spectrum.

Table 1. Comparison of large- and small-scale structures in OB and WR winds (neglecting binaries)

Descriptor	Large-scale asymmetries	Small-scale inhomogeneities
OB	~ all	(few observed)
WR	a few (WR6, 134)	~ all
Nature	DACs, CIRs (disks, shells) ~ periodic (rotation)	blobs, clumps, shocks... stochastic
Driver	local surface features (magnetic fields, NRP)	radiative instabilities (global)

Only two apparently single WR stars are known to show ~periodic spectral and other variations: HD 50896 = EZ CMa = WR6 (P = 3.76d; e.g. Morel et al. 1997, 1998) and HD191765 = WR134 (P = 2.3d; Morel et al. 1999). We illustrate this for EZ CMa in Fig.1. The complex, but periodic spectral pattern is quite coherent during several (~5 - 15) cycles but generally changes shape thereafter. Following the wind stratification, the NIV 4058 pattern is noticeably ahead of either HeII line, with HeII 6560 slightly ahead of HeII 4686. The most likely interpretation here is that we are seeing the rotation of magnetic perturbations at the stellar surface, which manifest themselves further out with increasing delays in the observable wind. Data are being analysed presently to look for magnetic signatures in circular spectropolarimetry of EZ CMa (Chesneau & Moffat 2000).

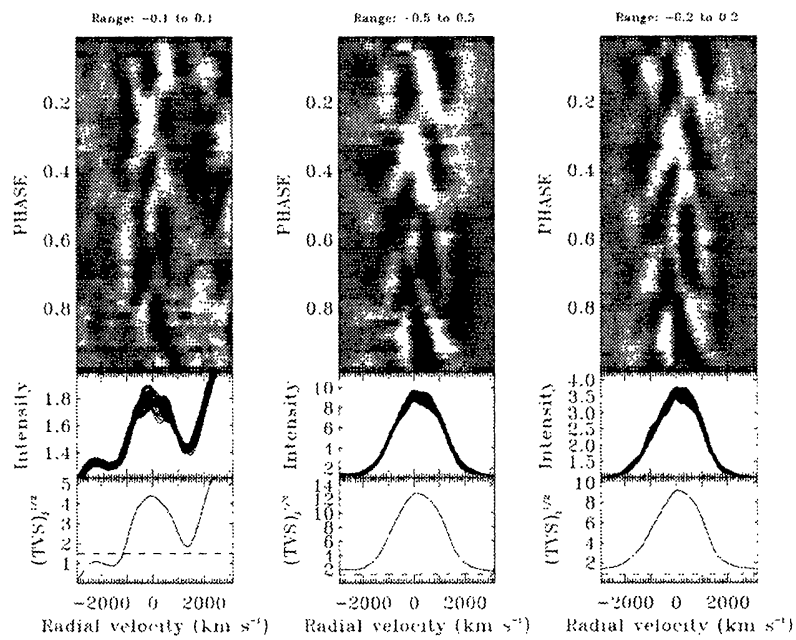

Figure 1. Grey-scale phase-plots of 3 emission lines (NIV 4058, HeII 4686, HeII 6560, from left to right) for the ~periodically variable single (?) WN5 star EZ CMa. From Morel et al. (1997).

4. Small, multi-scale structures

Most of the Universe is in the form of compressible gas, in which supersonic turbulence manifests itself virtually everywhere. The key quantitative signature of the turbulence is the presence of scaling laws as a result of energy cascading from large to small (dissipation) scales. These laws appear to vary little from one region to another and are virtually scale invariant. The driver is normally either gravity or radiation, with magnetic fields acting as a restraint. With this in mind, it should perhaps not come as a surprise that *stellar winds* are also turbulent, with stochastically varying, multi-scaled structures.

4.1. Clumping in WR winds

The first real suspicion of the stochastically clumpy nature of WR winds came from time variability, not so much from photometry (which can be ambiguous), but rather from broad-band polarimetry of single WR stars (Drissen et al. 1987; St-Louis et al. 1987). While some WR stars showed no variations above the instrumental level (σ_P ~0.015 %), others manifested random scatter in P as a function of time ranging up to 0.16 %. Since polarization is very sensitive to geometry, this suggested the presence of stochastic asymmetries forming and disappearing in the winds on timescales of less than a day.

This discovery led Moffat et al. (1988) and Robert (1992) to carry out follow-up *spectroscopic* monitoring of a complete (magnitude limited) sample of

WR stars in search of variable line profiles. Indeed, all 9 WR stars studied exhibited stochastically variable subpeaks on their emission lines, that tended to move away from line centre with time (e.g. Fig.2a). The original analysis (Robert 1992) using multiple Gaussian fits to the variable tops of the lines revealed typically 10-20 subpeaks per line. Characterizing the subpeaks by 3 simple quantities (mean velocity, width σ_v and flux f), various statistical relations were found. This "subpeak extraction" method also yielded a power law distribution in the flux of individually extracted subpeaks (Fig.2b) and between f and σ_v, suggestive of scaling laws as are typically found in supersonic compressible, turbulent media.

¿From the theory of supersonic compressible turbulence, we expect the clumps to follow specific scaling laws. Adopting l as the characteristic size of a given clump, its radiated flux will scale like $f \sim \rho^2 l^3$ for recombination emission, neglecting temperature variations from one clump to another, where ρ refers to the clump density. Furthermore, one also expects to find $\rho \sim l^{-1}$ and $\sigma_v \sim l^{1/2}$ (Larson 1981). This leads to the prediction that the flux of a clump should scale with its velocity dispersion $f \sim l \sim \sigma_v^2$, with both f and σ_v being observable quantities.

The size of clumps should also follow a power law distribution, resulting in a power law flux distribution in the form $N(f)df \sim f^{\alpha}df$. The flux frequency plot in Fig.2b shows a negative power-law slope; combined with other WR stars, a typical power index is found to be $\alpha \sim -2$. Assuming the size to be correlated with the clump mass $m \sim \rho l^3$, and using Larson's laws, one can deduce the mass power spectrum $\eta(m) = N(f)df/dm \sim m^{\gamma}$. The flux power index value $\alpha \sim -2$ corresponds to a mass power-law index $\gamma = (\alpha - 1)/2 \approx -1.5$, like that seen in giant molecular clouds (GMC) (e.g. Stutzki 1994). It was concluded therefore that WR winds do indeed exhibit the signatures of supersonic, compressible turbulence.

The analysis of the variable subpeaks was improved upon using the more objective technique of wavelet analysis (Lépine, Moffat, & Henriksen 1996). Instead of trying to extract individual features from the spectrum (subject to many pitfalls due to the general uncertainty about whether an apparent "extracted" subpeak feature has a strict correspondence to an actual clump in the wind), the subpeak patterns were analysed as a whole, from a statistical point of view (Fig.2c). Results from Lépine, Moffat, & Henriksen (1996) cast serious doubt on the previous analysis, showing that the scaling relations inferred from "subpeak extraction" ($N(f)df \sim f^{-2}$,$f \sim \sigma_v^2$) are not compatible with the observed variability patterns (Fig.2d). The existence of scaling laws could not be ruled out however, but their detection is now suspected to be significantly hampered by the presence of instrumental noise, which limits the identification of small-scale (low σ_v) features in the data. The question still remains as to whether it was a coincidence or not that the above "subpeak extraction" yielded Larson-type scaling laws. In view of the likely fractal nature of turbulent clumping, one might have expected (as in GMCs) to find similar scaling laws regardless of resolution and how one "zooms in".

A new approach to the analysis of these spectroscopic data was made by Lépine & Moffat (1999), who applied wavelets *and* a phenomenological model to perform a comparative analysis rather than trying to extract physical infor-

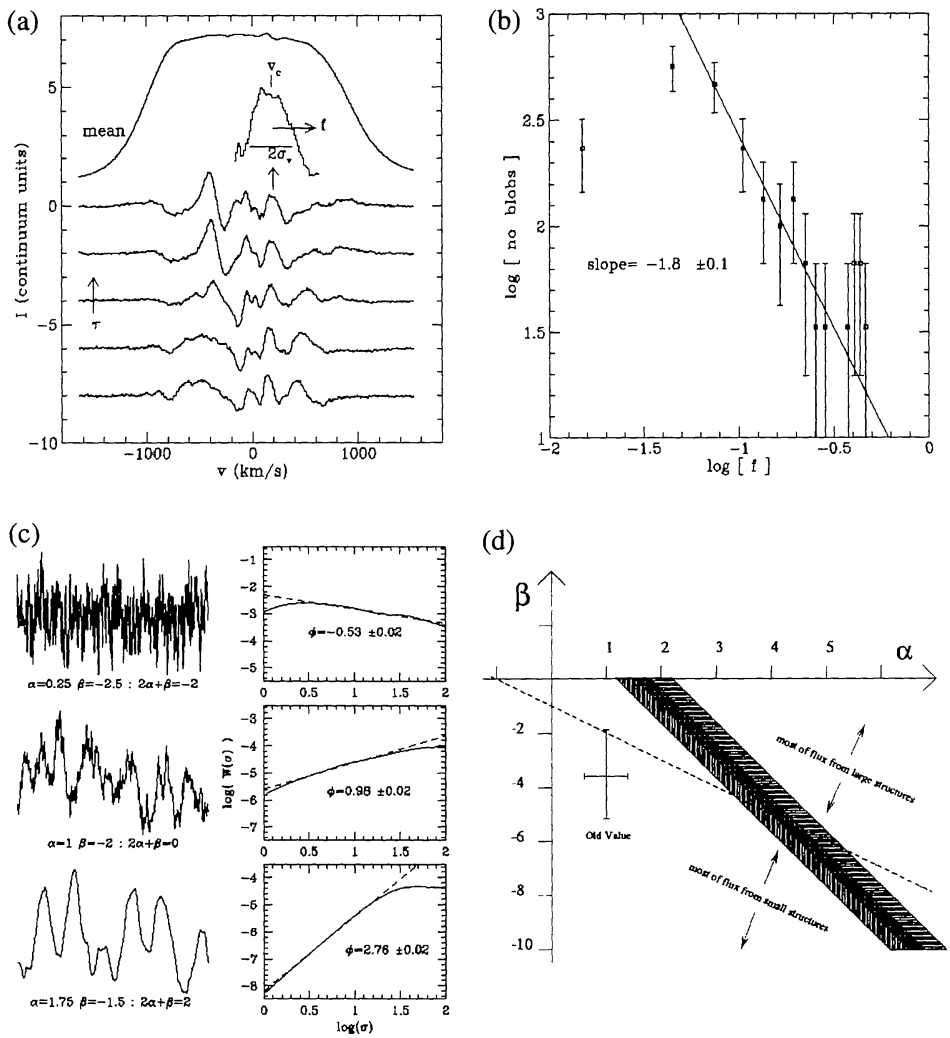

Figure 2. Analytical methods for the analysis of variability in the CIII 5696 line of the WC8 star HD192103 (=WR135). (a) A montage showing the mean profile for 4 consecutive nights, and a series of 5 residual spectra (difference from the mean) from one night of observation. (b) Flux distribution of "individually extracted" subpeaks, fitting a power law $N(f)df \sim f^{-1.8}df$. Extracted subpeaks also followed a $f \sim \sigma_v^2$ relation between the flux f and width σ_v. (c) Simulations of power-law distributions of emission subpeaks following general scaling laws $f \sim \sigma_v^{\alpha+1}$ and $N(\sigma_v)d\sigma_v \sim \sigma_v^{\beta}d\sigma_v$ (left). The value of the combined index $\alpha+\beta$ can be quantitatively deduced from the slope Φ of the wavelet power spectrum (right). (d) Range of possible values for α and β inferred from wavelet analysis of the WR135 data. The cross ("old value") marks the range for α and β inferred from the "subpeak extraction" method, whose results are clearly inconsistent with the more rigorous wavelet analysis. (a) and (b) from Moffat et al. (1994a), (c) and (d) from Lépine et al. (1996).

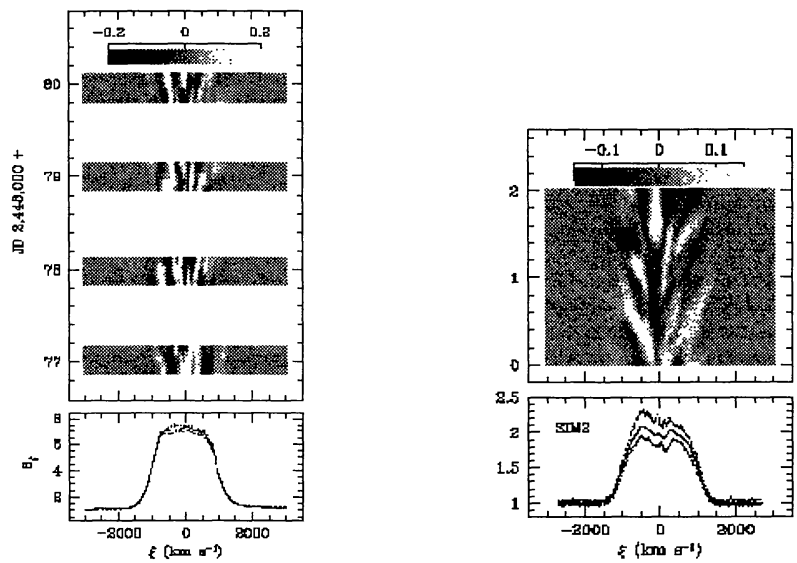

Figure 3. Left: mean profile from 4 nights of observation and greyscale time-series of the residuals for the CIII 5696 emission line in WR135. Right: mean profile and greyscale time series of the residuals for a simulation of the line emission from a clumped wind with $\approx 10,000$ distinct emission elements (see Lépine & Moffat 1999).

mation directly from the data (Fig.3). This study clearly shows that superposition effects are important, i.e. each observed apparent subpeak on a spectral line generally arises in numerous elementary, independent clumps in the wind. Compared to line-profile simulations (Lépine & Moffat 1999), analysis of the 9 variable WR star spectra leads to the following highlights (see also Moffat 1999a):

• Each observed subpeak generally is the sum of a large number of independent, discrete wind-emitting elements (DWEEs).

• The relatively *low* degree of line variability implies (according to Poisson statistics) that the number of DWEES is very large, $> 10^4$ typically. This means that DWEEs must be spatially small (typically $< R_\odot$) in order to fit in the line-forming zone.

• The dominant scale of velocity dispersion, independent of WR subclass, geometry, terminal wind speed, etc..., is $\sigma_v \sim 100$ km s^{-1} in most cases. The peculiar star WR134 is an exception with $\sigma_v \sim 350$ km s^{-1}.

• A strong anisotropy prevails, typically with $\sigma_{v_r} \sim 4\sigma_{v_t}$, (r and t are the radial and tangential directions, respectively) compatible with radiative driving (Rybicki et al. 1990). WR134 is the exception again, with $\sigma_{v_r} \sim \sigma_{v_t} \approx 350$ km s^{-1}, implying significant rotational motion and thus compatible with its detected short (rotation?) period.

• The optical thickness of DWEEs is only marginally greater in the transverse compared to the radial direction. This is compatible with "pancakes" rather than "cigars" (axis of symmetry in the radial direction in both cases).

• The subpeak motion allows one to trace the kinematics of the wind, assuming the clumps on average to act as tracers of the wind flow. Adopting a β wind velocity law, acceleration/mean-velocity statistics lead to constraints only in the product $\beta R_* \sim 20....80 R_\odot$. This differs dramatically from assumptions often made within the standard model of Wolf-Rayet spectra: $\beta = 1; R_* \approx$ several $R_\odot$. (Larger β values are now emerging in the more recent models: Schmutz 1997; Hillier & Miller 1999.)

• The average duration of subpeak events agrees with the overall spectral line shape, i.e. a relatively thin line-emitting region in velocity space.

• The stochastic behaviour of DWEEs agrees with model simulations of O-star winds (Gayley & Owocki 1995), with rapid growth of random fluctuations near the wind base out into the observed part of the wind.

The above study is being extended (Lépine et al. 2000) to the analysis of an intensive, nearly continuous 3-day run with multi-wavelength coverage at two 4m-class telescopes (CFHT & WHT) on one WR star (WR135). These data show that the subpeak patterns change according to the ionization potential, compatible with an ionizationally stratified wind. This is somewhat in contrast to the slow-wind WC9 star HD 164270 = WR103, which shows little difference of its line-profile variations from line to line, and hence little if any ionization stratification (Lépine 1996). It is also compatible with slower-wind WNL stars (Schulte-Ladbeck et al. 1996). The simultaneous presence in the spectrum of WR103 of lines of different ionization might therefore be explained by DWEEs with varying degrees of ionised "skins", rather than a strong global ionization gradient with radius. In reality, both may prevail. As a byproduct of the WR103 study, cross-correlation of various lines in the spectra allows a "sharpening" of the spectrum to ~ 2 Å, i.e. the scale of the subpeaks, instead of the ~ 20 Å in the original spectrum. This allows identification of many new lines that could only be intimated in the original spectrum.

4.2. Universality

So far, all ~ 12 WR stars observed appropriately show clumping effects in their winds. Since these WR stars were not chosen for any other reason than that they are apparently bright in the sky, it is thus very likely that in fact *all* WR winds show the same kind of behaviour in general. We are checking this currently among a much larger sample of WR stars.

But what about other types of hot stars with winds? So far, only one O-star has been observed adequately to test for this: ζ Puppis, O4Inf (Eversberg et al. 1998). Even this star, with its strong wind (for an O star), has relatively weak emission lines compared to WR stars. The strongest line in the visual spectrum of ζ Pup, HeII 4686, is $\sim$ten times weaker than in most WN stars, making it necessary to observe ζ Pup with $\sim$ten times higher S/N but at similar (high) spectral and time resolution. As illustrated in Fig.4, ζ Pup shows a similar relative level of spectral line variation in HeII 4686 as does HeII 5411 in a typical WN star. Detailed analysis shows that the subpeak trajectories in ζ Pup's spectrum also exhibit similar behaviour as in WR spectra, except that they

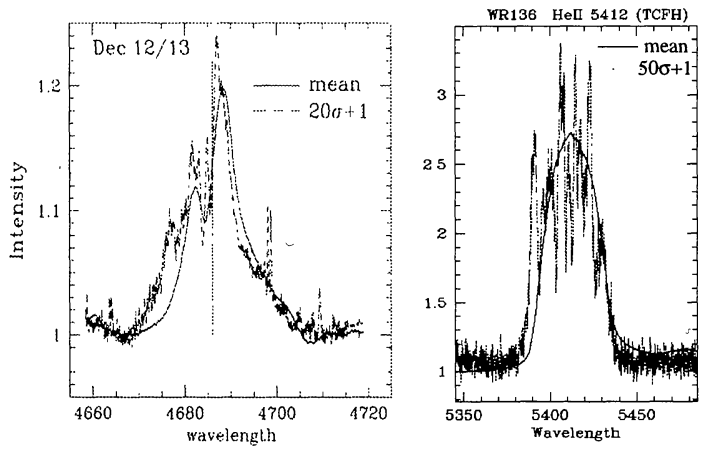

Figure 4. Mean line profile along with its superposed standard deviation spectrum (different vertical scale) of HeII 4686 in the O-star ζ Pup (left, one night of data, from Eversberg et al. 1998), and of HeII 5411 in the WN6 star WR136 (right, four nights of data, from Moffat & Robert 1992). Note how I(λ) and $\sigma(\lambda)$ both follow the same general shape in each respective star, implying that the clumping is distributed throughout the whole wind, and that both stars show similar *relative* variation (~2-5 %) in their respective lines.

yield a "normal" value of $\beta \simeq 1.2$ in ζ Pup, compared to much larger β values in WR winds. This gives us confidence that the analysis and interpretation is reasonable in *both* O and WR stars. We are currently following up by monitoring the spectra of other O stars with observable wind emission lines.

Similar effects can be found in the winds of low-mass [WC] stars (Balick et al. 1996; Grosdidier et al. 1998a, 2000) and in outflows from recurrent novae (Lépine et al. 1999). As far as LBVs and other supergiants as well as supernovae are concerned, there are simply not sufficient data yet to judge, although Gäng (1999) does find relatively long-lived inhomogeneities in the emission-line spectrum of the LBV P Cygni.

4.3. Evidence beyond the emission-line forming zone

Evidence for clumping in hot-star winds goes well beyond the relatively nearby optical/UV line-forming regions in the winds. Although there has been no systematic survey done to prove this, one can note several clear examples:

• Dust formation occurs in the winds of many WC9 stars on scales out to several 100 stellar radii, requiring strong clumping if the stars are single (Williams et al. 1987). Direct photometric evidence for dust clumps has been found in several WC9 stars by Veen et al. (1998). If binary, the colliding winds can provide the compression (Tuthill et al. 1999; Monnier et al. 1999)

• A high-resolution radio continuum image of the thermal emission from the wind of the nearby WN8 star WR147 reveals remarkable temporally variable clumpy structure on scales of >0.06" (the instrumental resolution) throughout

the observed wind out to a radius of ~0.2" (2500 R_* for $R_* \sim 10R_\odot$) (Williams et al. 1997; Watson et al. 1999). Propagation occurs outwards with the known terminal wind speed (Contreras & Rodríguez 1999).

• H-α/[NII] emitting bullets/knots have been seen in the ring nebula RCW 104 around the WR star WR75 by Goudis et al. (1988) and in M1-67 around the runaway WN8 star WR124 by Grosdidier et al. (1998b). Both of these occur at a distance of the order of a parsec from the central star. They are reminiscent of N-rich clumps seen around some planetary nebulae and supernova remnants (Goudis et al. 1988).

• Finger-like gaseous streaks are seen in the bipolar flow around the O6.5f?p star HD148937 (Scowen et al. 1995).

Simulations of clumps in WR winds by Grosdidier et al. (1999) show that they can survive out to at least 10's of stellar radii. If further calculations show that the clumps cannot survive out to *parsec* scales, then they will have to be continuously formed at those distances.

5. Impact of structured winds

Due to the density-squared dependence of the most common mass-loss rate estimators (e.g. radio/IR free-free emission, recombination lines), assuming a smooth wind instead of a clumpy one will overestimate the mass-loss rates. The best empirical evidence for this is for the WR component in the Rosetta stone WN5 + O6 binary V444 Cygni (St-Louis et al. 1993). Polarization modulation and dynamical period changes are impervious to this problem and both lead to consistent $\dot{M}$s that are a factor 3 or more lower than those based on radio/IR f-f or line emission. This is supported by theoretical models of WR stars with simple clumping algorithms that require reductions of a factor 3-5 in $\dot{M}$ compared to smooth-wind models in order to best match the small electron-scattering line-profile wings (Hillier & Miller 1999; Hillier 2000). Such reductions in $\dot{M}$ for WR stars will have an important impact on their evolution, in particular with respect to the question whether WR stars reach their present subtypes with or without a progression from cooler subtypes first.

Does the same correction factor also apply to other hot-star winds? Our best guess is that it is similar for O-star winds, since the observed clumping variability is similar in WR and O stars (with the caveat that this is based on 12 WR stars and only 1 O star so far). On the other hand, it is possible that some of the variability is drowned out in dense WR winds due to saturation or superposition effects, so that the correction factor may be higher for WR-star than for O-star winds. In any case, even if it is "only" a factor of 2 for O stars, the result can be dramatic for O-star evolutionary tracks of massive stars in the H-R diagram (Maeder & Meynet 1994). Furthermore, a reduction in $\dot{M}$-estimates for O stars may also require a corresponding decrease in mass, if one accepts the fundamental coupling between (1) $\dot{M}$ and luminosity (Castor et al. 1975; Lamers & Casinelli 1999; with some additional dependence on radius and mass) for radiatively driven winds and (2) luminosity and mass for main-sequence stars. The resulting relation between $\dot{M}$ and mass is not linear however, so that a reduction in $\dot{M}$ by a factor 3 will imply a reduction of only several 10% in the masses (Moffat et al. 2000). This would help solve the problem of

the mass discrepancy for massive stars (Herrero et al. 1992) in favour of the lower spectroscopic masses over evolution based masses, the latter tending to be larger by as much as a factor of 2. Some very recent theoretical support comes for this, based on massive star models that now include rotation (Maeder 1999; Langer & Heger 1999). These models lead to higher luminosity for a given mass (or equivalently lower mass for a given (observed) luminosity). Whether this quantitatively gives consistency overall remains to be seen.

Other points of impact include:

• Aid in dust formation in WC-star winds (see section 4.3).

• Allow one to study supersonic, compressible turbulence in action with timescales of hours, compared to 10^5 years and more in the ISM.

• Allow one to trace the wind kinematics empirically (Lépine & Moffat 1999).

• Soften wind-wind and wind-ISM collisions and interactions. In particular, theory using smooth winds predicts not only inflated $\dot{M}$s, but also X-ray fluxes from colliding winds in WR + O binaries that are orders of magnitude higher than observed.

6. Future

Several urgent tests need to be undertaken regarding the importance of inhomogeneous structures in hot-star winds:

• All hot-star winds produce X-rays that are thought to arise via shock formation in the winds. The fact that no-one has yet detected significant stochastic temporal fluctuations in X-ray flux from single luminous hot stars implies that either this is false, or that there are so many shocks that their time variability is drowned in Poisson noise (almost like clumps that were only found through patient spectroscopic monitoring with sufficiently high quality data). Perhaps the current larger X-ray telescopes (especially XMM) will be able finally to detect X-ray variability among hot luminous stars.

• Realistic hydrodynamic modeling of winds are urgently needed, that fully include the radiation field of the central star and the wind itself.

• Clumps should be resolved interferometrically. This has already been partly done at modest (60 mas) resolution in the radio. The advent of NASA's Space Interferometer Mission (SIM) in ~2007 with the capability to make microarcsec resolution optical images will undoubtedly revolutionize the clumping problem. For example, 1 $R_\odot$, the estimated maximum clump size, at the distance of the closest WR star (γ Vel), ~250 pc, corresponds to an angle of 20 microarcsec. A narrow-band on-line image of this star with SIM should do the trick.

• More probing of the behaviour of lines of different ionization potential should be undertaken on WR stars over longer time intervals.

• Deep searches for magnetic fields using spectropolarimetry among hot stars. Even better: spectro-interfero-polarimetry, i.e. high spatial resolution will ease the tolerances in measuring the Zeeman signatures, since localized fields are expected to be stronger than a globally diluted field in spatially unresolved data (e.g. Rousselet-Perraut et al. 2000).

Acknowledgments. AFJM acknowledges financial support from NSERC (Canada), FCAR (Québec) and the Canada Council for the Arts for a Kil-

lam Fellowship. SL is supported by a post-doctoral fellowship from NSERC (Canada).

References

Balick, B., et al. 1996, AJ, 111, 834

Beals, C.S. 1929, MNRAS, 90, 202

Castor, J.I., Abbott, D.C., Klein, R.I. 1975, ApJ, 195, 157

Cherepashchuk, A.M., Khaliullin, K.F., Eaton, J.A. 1984, ApJ, 281, 774

Chesneau, O., Moffat, A.F.J. 2000, in prep.

Contreras, M.E., Rodríguez, L.F. 1999, ApJ, 515, 762

Drissen, L., St-Louis, N., Moffat, A.F.J., Bastein, P. 1987, ApJ, 322, 888

Eversberg, T., Lépine, S., Moffat, A.F.J. 1998, ApJ, 494, 799

Fliegner, J., Langer, N. 1995, IAU Symp. 163, p.326

Gäng, T. 1999, preprint

Goudis, C.D., Meaburn, J., Whitehead, M.J. 1988, A&A, 191, 341

Grosdidier, Y., et al. 1998a, IAU Symp. 180, p.108

Grosdidier, Y., Moffat, A.F.J., Joncas, G., Acker, A. 1998b, ApJ, 506, L127

Grosdidier, Y., Acker, A., Garcia-Segura, C., Moffat, A.F.J. 1999, GRETA meeting, Obs. de la Côte d'Azur, in press

Grosdidier, Y., et al. 2000, submitted

Gayley, K.K., Owocki, S.P. 1995, ApJ, 446, 296

Herald, J.E., Schulte-Ladbeck, R.E., Eenens, P.R.J., & Morris, P. 2000, ApJS, *in press*

Herrero, A., et al. 1992, A&A, 261, 209

Hillier, D.J. 1991, A&A, 247, 455

Hillier, D.J. 2000, these proceedings

Hillier, D.J., Miller, D.L. 1999, ApJ, 519, 354

Kuhi, L.V. 1973, IAU Symp. 49, p.205

Lamers, H.J.G.L.M., Cassinelli, J.P. 1999, Introduction to Stellar Winds, Cambridge UP: Cambridge

Langer, N., Heger, A. 1999, IAU Symp. 193, p.187

Larson, R.B. 1981, MNRAS, 194, 809

Lépine, S. 1994, Ap.Sp.Sc., 221, 371

Lépine, S. 1996, 33rd Liège Int'l. Ap. Coll., 253

Lépine, S. 1998, Ph.D. thesis, Univ. de Montréal

Lépine, S., Moffat, A.F.J., Henriksen, R.N. 1996, ApJ, 466, 392

Lépine, S., Moffat, A.F.J. 1999, ApJ, 514, 909

Lépine, S., Shara, M.M., Livio, M., Zurek, D. 1999, ApJ, 522, L121

Lépine, S., et al. 2000, in prep.

Lucy, L.B., Abbott, D.C. 1993, ApJ, 405, 783

Maeder, A. 1999, IAU Symp. 193, p.177

Maeder, A., Meynet, G. 1994, A&A, 287, 803
Moffat, A.F.J. 1994a, Rev. Mod. Astron., 7, 51
Moffat, A.F.J. 1994b, NATO ASI Series C, 436, 117
Moffat, A.F.J. 1994c, Ap.Sp.Sc. 221, 467
Moffat, A.F.J. 1996, 33rd Liège Int'l Ap. Coll., 199
Moffat, A.F.J. 1999a, IAU Coll. 169, p.230
Moffat, A.F.J. 1999b, ASPC, 168, 449
Moffat, A.F.J., Robert, C. 1991, IAU Symp. 143, p.109
Moffat, A.F.J., Robert, C. 1992, ASPC, 22, 203
Moffat, A.F.J., Drissen, L., Lamontagne, R., Robert, C. 1988, ApJ, 334, 1038
Moffat, A.F.J., Lépine, S., Henriksen, R.N., Robert, C. 1994a, Ap.Sp.Sc., 216, 55
Moffat, A.F.J., Lépine, S., Robert, C., Henriksen, R.N. 1994b, Bull. CFHT no.31, 14
Moffat, A.F.J., et al. 2000, in prep.
Monnier, J.D., Tuthill, P.G., Danchi, W.C. 1999, in press
Morel, T., St-Louis, N., Marchenko, S.V. 1997, ApJ, 482, 470
Morel, T., et al. 1998, ApJ, 498, 413
Morel, T., et al. 1999, ApJ, 518, 428
Owocki, S.P., & Gayley, K.G. 1999, IAU Symp. 193, p.157
Prinja, R.K., Smith, L.J. 1992, A&A, 266, 377
Robert, C. 1992, Ph.D. thesis, Univ. de Montréal
Robert, C. 1994, Ap.Sp.Sc., 221, 137
Robert, C., Moffat, A.F.J., Seggewiss, W. 1991, IAU Symp. 143, p.147
Rochowicz, K. 1997, Acta Astronomica, 47, 381
Rousselet-Perraut, K., Chesneau, O., Vakili, F. 2000, A&A, in press
Rybicki, G.B., Owocki, S.P., Castor, J.I. 1990, ApJ, 349, 274
Schmutz, W. 1997, A&A, 321, 268
Schulte-Ladbeck, R.E., Eenens, P.R.J., Davis, K. 1995, ApJ, 454, 917
Schulte-Ladbeck, R.E., Herald, J.E., Eenens, P.R.J., Morris, P. 1996, 33rd Liège Int'l Ap. Coll., 321
Scowen, P., et al. 1995, ApJ, 450, 196
St-Louis, N., et al. 1987, ApJ, 322, 870
St-Louis, N., et al. 1993, ApJ, 410, 342
Stutzki, J. 1994, Rev. Mod. Astron., 6, 209
Tuthill, P.G., Monnier, J.D., Danchi, W.C. 1999, Nature, 398, 487
Veen, P., et al. 1998, A&A, 329, 199
Watson, S.K., Davis, R.J., Williams, P.M. 1999, IAU Symp. 193, p.396
Williams, P.M., van der Hucht, K.A., Thé, P.S. 1987, A&A, 182, 91
Williams, P.M., et al. 1997, MNRAS, 289, 10

Discussion

J. Hillier: Comment: CIII λ 5696 is a classification line and varies considerably in strength with WC spectral type. Most of the other CIII emission lines do not show the same variation. Thus observationally CIII λ 5696 might be expected to vary more than other lines. Also due to atomic physics, and because it is optically thin, CIII λ 5696 is expected to vary due to clumping more than other lines. On the other hand CIV λ 5802; 5812 is optically thick. Optical depth effects could reduce the variation in line profile resulting from clumping.

A. Moffat: Optical depth effects reduce the variations, but not necessarily make them disappear. What I showed in the campaign on WR 135 (WC8) is that the form of the variations in CIV 5802/12 is different from the simultaneous variations in CIII 5696, so they must be formed at different places (on average) in the wind.

S. Fabrika: In your line-profile simulation did you take into account the relativistic boosting effect? It has to be about a few percent in line profile wings intensity at the expansion velocities of about a few thousands km/s.

A. Moffat: No, we didn't even think of it; thanks! However, now I suspect that this effect will be washed by other line-formation effects at this level.

L. Kaper: One of the arguments to propose the clumpy structure of WR winds is that dust should be formed in areas shielded from the intense radiation field. I thought that it has been suggested that dust formation only occurs in binary systems. Is there observational evidence for this suggestion?

A. Moffat: According to Williams et al. there are two classes of WR dust emitters: 1) WC + O binaries of any WC subclass in which the wind collision zone periodically (mainly at periastron) compresses the WR wind ultimately to form dust and 2) late-type (cool) single WC stars (WCL) which, if actually single, must have very high compression to persistently form and shield the dust in their winds. However, one of the most spectacular persistent dust producers,WR 104 (WC9) was shown (Tuthill et al. 1999), using high-resolution IR imagery at Keck I, to be a binary in which the dust is formed mainly by wind-wind collision. Unlike the other known episodic dust-producing binaries, the orbit of WR 104 is nearly circular and seen nearly face-on. Even more recently, WR 98a was shown to behave much like WR 104 (Minnier et al. 1999). It would seem unlikely that all the (dozen) known persistent WCL dust-producers are face-on binaries with circular orbits, although the final jury is still out!