Wolf-Rayet Stars
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Studying Large and Small Scale Wind Asymmetries with Spectroscopy and Polarimetry

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In this paper, I review observational evidence from spectroscopy and polarimetry for the presence of small and large scale structure in the winds of Wolf-Rayet (WR) stars. Clumping is known to be ubiquitous in the winds of these stars and many of its characteristics can be deduced from spectroscopic time-series and polarisation lightcurves. Conversely, a much smaller fraction of WR stars have been shown to harbour larger scale structures in their wind ($\sim 1/5$) while they are thought to be present is the winds of most of their O-star ancestors. The reason for this difference is still unknown.

1 Introduction

Wolf-Rayet (WR) stars, which amongst hot, massive stars, have the strongest, sustained radiatively-driven outflows, were initially assumed to have smooth, spherically symmetric winds. We have since learned that these outflows are highly structured and several have been shown to harbour large-scale structures. Understanding the physical cause of these large-scale asymmetries can enlighten us about processes occurring near or on the, often hidden, stellar surface and allow us to assess how the angular momentum of the star is lost via the wind. In this paper, I review the evidence from spectroscopic and polarimetric observations of the existence of these structures in WR winds.

2 Small-Scale Variability

2.1 Spectroscopy

The earliest report of spectroscopic evidence of fast moving clumps in WR winds is from Moffat et al. (1988) in which narrow emission bumps were identified superposed on the broad He IIλ5411 emission lines of WR134 and WR136 and found to accelerate outwards with the general wind on a timescale of hours. Since then, several more WR stars have been monitored and if the quality of the data is sufficiently high, accelerating narrow emission peaks are always found. Therefore, clumping is now thought to be universal in WR outflows and probably in all radiatively driven winds. A striking example is shown in Figure 1 where Figure 10 of Chené et al. (2015, submitted) is reproduced and where clump movement in WR2 is shown. Un upper limit of 0.8% of the line flux was previously set for the line variability of this star by Chené & St-Louis (2011). The variability level is in fact ~0.5% and the features rapidly migrate toward line edges in about ~2.6 hours.

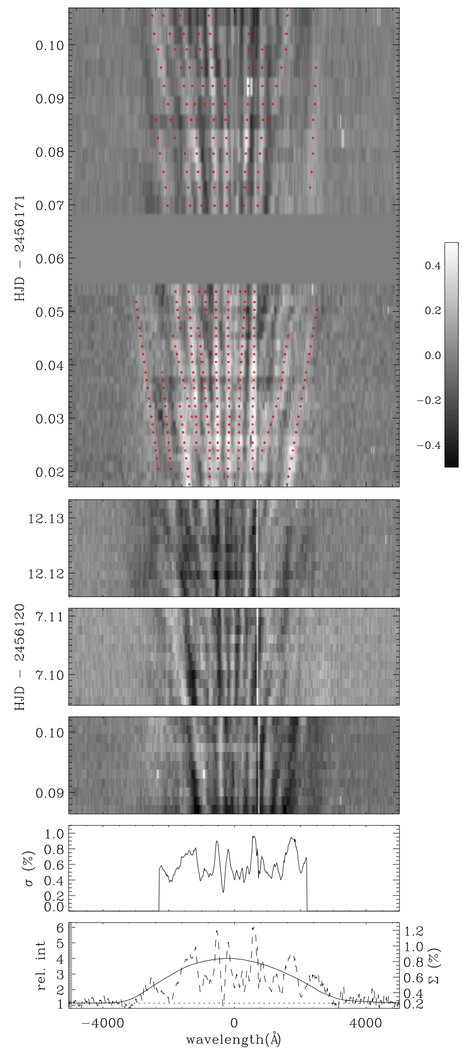

Fig. 1: Clump variability in the He IIλ4686 line of WR2, reproduced from Chené et al. (2015). The top four panels show differences from the mean as a function of time with the emission sub-peak movement indicated by red doted lines. The bottom two panels show the level of variability of the line flux (σ) and the Temporal Variance Spectrum (Σ) superposed on the mean line profile.

More quantitative analysis of this small-scale spectroscopic variability was carried out by Lépine et al. (1996) in which a wavelet power spectrum was used to characterize the variable component of optical emission lines of WR stars. A dominant scale of $\sim$100 km s^{-1} was identified for all but one star in their sample to characterize the size of the subpeaks. Later Lépine & Moffat (1999) envisioned the wind as consisting of a large number of randomly distributed Discrete Wind Emission Elements (DWEEs) of various widths and amplitudes propagating radially in the wind. They found that more than 10000 of these DWEEs must be used to account for the line variability and that the velocity dispersion within them must be four times larger in the radial than in the azimuthal direction. From the kinematics of the moving sub-peaks, Lépine & Moffat concluded that the value of the product of the β exponent of the wind velocity law and the stellar radius, $\beta R_*(R_\odot)$ was between 20–80, hinting to a lower wind acceleration at least in the region of the outflow where the clumps are accelerating.

These observational results stimulated theorist to seek a more physical understanding of the origin of this type of line-profile variability. Dessart & Owocki (2002a) explored the assumption that these small-scale wind structures were caused by the line-driving instability (Owocki & Rybicki 1984, 1985). To do so, they implemented a Smooth Source function Formalism for line driving in the *Zeus*-2D hydrodynamics code, which they used in one dimension (1D) to perform hydrodynamical simulations. The 1D restriction, warranted by computational costs, produced a much higher level of variability at line edges compared to line center than was observed. To alleviate this problem, they introduced a *patch* model in which random wind velocity and density profiles which incorporate the radiative instability are used along a given radial ray and extend over a certain patch size on the surface of the star. The results were that a patch of around 3 degrees qualitatively reproduces the observed properties of the small-scale line-profile variability. Dessart & Owocki (2002b) then carried out a wavelet analysis of synthetic profiles from those models which led them to propose that there are two distinct line broadening mechanisms: (a) the lateral extension of the clumps as detected at line-centre and (b) an intrinsic radial velocity dispersion within the clump, which dominates towards line-edge. They found that their model was not capable of reproducing the observed sub-peak width at line edges, which led them to conclude that the radiative instability did not produce enough velocity dispersion in the gas. Finally, Dessart & Owocki (2003) present a two-dimensional model in which the smooth source function formalism for the line-driving is implemented independently in isolated azimuthal grid zones. The main result was that Rayleigh-Taylor instabilities break-up compressed shells, down to the adopted grid size as they are accelerated outward. An increase in the radial velocity dispersion is found, which agrees more with the observations, and the associated clumping correction factor are reduced and are now closer to the ones inferred from WR emission-line fitting using the radiative transfer code, CMFGEN. However, this breakup of the structures to very small scales does not agree with the 3-degree patches that are required to reproduce the wavelet spectrum.

2.2 Polarimetry

In the highly ionized winds of WR stars, there are copious amounts of free electrons that polarize the light from the star through Thomson scattering. If the wind is smooth and spherically symmetric, all polarized vectors cancel out an no net polarisation is observed. Conversely, any large or small asymmetry in the density distribution or in the light source will create a non-zero value of the linear polarisation. Consequently, polarimetry is a very powerful tool to study stellar wind asymmetries. Furthermore, if the phenomenon creating the asymmetry is time-dependent, secular variations will be produced in the polarisation.

St-Louis et al. (1987) first proposed that the random nature of the stochastic broadband polarimetric variability in the single-line WR star WR103 is compatible with the ejection of blobs of material in the wind on intervals of days. This can be seen in the polarized lightcurve as a sudden rise in the polarisation followed by a gradual decrease back to the initial value.

Based on data on 11 WR stars of WN and WC subtype, Drissen et al. (1987) found a correlation between the standard deviation from the mean of the randomly varying linear polarisation, σ (P), and the wind terminal velocity. This was confirmed later with observations of 26 stars by Robert et al. (1989) who noted that the correlation is fairly tight, although some scatter remains. In Figure 2 we reproduce Figure 11 of Robert et al. (1989) showing this correlation. These authors concluded that the fast-wind stars show less scatter in polarisation than the slow-wind stars, implying that the winds of earlier WC stars are more stable and those of the late WN and WC stars more subject to instabilities. A similar trend was also observed in photometry byLamontagne & Moffat (1987). The polarimetric and photometric variability was interpreted as originating from blobs of dense plasma forming as a result of some perturbation on the surface of the star (non-radial pulsations, line-driving instability, etc.) and being ejected in random directions into the wind. Somehow these blobs would be more stable in slow-moving winds with high-speed wind acting as an efficient homogenizing agent. Robert et al. also mention a possible correlation between σ (P) and log $\dot{M}$ for stars for which $\dot{M}$ can be measured from polarimetry, i.e. in binaries (which are unaffected by clumping) (see St-Louis et al. 1988) but that this correlation disappears if the $\dot{M}$ values from radio free-free emission are used instead (it was unknown at the time that those measurements were affected by clumping as this diagnostic depends on the density squared).

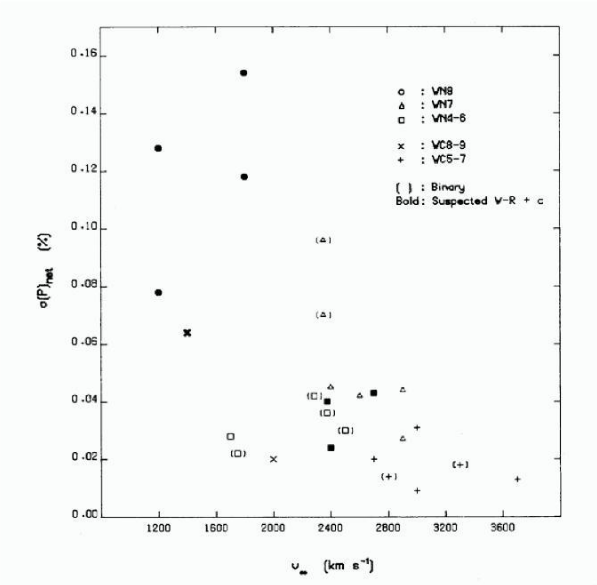

Fig. 2: Standard deviation of the linear polarisation from the mean value as a function of wind terminal velocity for 26 WN and WC stars. Reproduced from Robert et al. (1989).

Almost 20 years later, Davies et al. (2007) explored models of linear polarisation induced by light scattering off clumps in hot-star winds. They present a description of how the polarisation from clumps evolves as a function of their position in the wind and by using a standard beta velocity law as a function of time for different values of the β exponent. In their model, they used the results of Rodrigues & Magalhães (2000) who found that the polarisation increases linearly with the optical depth of the clump but then remains constant for values of τ higher than unity. The main conclusion of the work of Davies et al. was that the observed levels of random polarimetric variability is compatible with two regimes: either a small number of massive, optically-thick clumps or a large number of low-mass clumps. They favoured the regime with a high number of clumps, based mainly on arguments related to the timescale of the observed polarimetric variability. This conclusion is consistent with the observed levels of X-ray fluxes from hot-star winds which, as first suggested by Lucy & White (1980), likely arise from shocks caused by the movement of $\sim 10^9$ blobs in the wind.

Another interesting result these authors found is that the resulting level of polarisation from a population of clumps is proportional to the mass-loss rate; stars with higher $\dot{M}$s have higher levels of polarisation. The fact that the *large number of blobs* regime implies that the inner wind consists of thousands of low mass clumps means that the observed polarisation results in the random statistical deviation from spherical symmetry of a fragmented wind. This leads to night-to-night variations, as observed, and to the result that stars with higher mass-loss rates such as Luminous Blue Variables (LBVs) are more likely to show high levels of polarimetric variability, as hinted by Robert et al. (1989). This is consistent with the data of Davies et al. (2005) who find that polarisation levels and variability is higher in LBVs with stronger Hα lines, i.e. higher $\dot{M}$.

3 Large-Scale Structure

WR stars have also been shown to display variability that has different characteristics and seems to originate in larger scale structures in the wind. Cranmer & Owocki (1996) presented two-dimensional hydrodynamical simulations of the reaction of an optically thin stellar outflow to the presence on the surface of the star of bright or dark spots. They found that Corotating Interaction Regions (CIRs) form when fast-moving material collides with slow-moving material in the wind of a rotating star. Bright spots produce high-density, low-velocity material while dark spots produce low density, high-speed gaz. The presence of large-scale structure in the winds of WR stars has been demonstrated using spectroscopy and polarimetry. This will be discussed in the following sections.

3.1 Spectroscopy

The ubiquitous presence of Narrow Absorption Components (NACs) in the ultraviolet (UV) P Cygni absorption components was demonstrated by Howarth & Prinja (1989) in their study, using the IUE satellite, of 203 galactic O stars. These components are thought to be snapshots of Discrete Absorption Components (DACs), which are broad low-velocity absorptions that evolve into narrow high-velocity absorptions and which are found in time series of UV spectra of selected O stars (e.g. Prinja & Howarth 1988). Cranmer & Owocki (1996) showed that CIRs would have a kinematic signature in P Cygni absorption components in agreement with that observed for DACs. A related observational signature of CIRs is blue-edge variability, which are changes occurring in the P Cygni absorption components at velocities above the terminal velocity of the wind. Such variations are observed in O stars but also in WR stars for which it is impossible to observe DACs, as in most cases (except for WR24 – see Prinja & Smith 1992), the P Cygni absorption components of strong UV lines are saturated. The presence of blue-edge variability in WR stars therefore constitutes indirect evidence of the presence of CIRs in the winds of these stars. Dessart & Chesneau (2002) used the hydrodynamical simulation of Cranmer & Owocki (1996) to carry out a theoretical study of optical and near-infrared theoretical line variability caused by CIRs in a radiatively driven wind. They simulated changes produced by two diametrically opposed CIRs for different inclination angles with respect to the line-of-sight and for different line formation regions (distance and width). They predict an unambiguous S-shape pattern in the frequency-time space which are extremely reminiscent of those observed for 3 WR stars by Morel et al. (1997, 1999) and Chené & St-Louis (2010) for WR6, WR134 and WR1 respectively. Figure 3 shows an example of such observations for the WN4b star, WR6. St-Louis et al. (2009) and Chené & St-Louis (2011) carried out a survey to identify new candidates for CIR-type spectroscopic variability and concluded that only $\sim 20\%$ of WR stars potentially harbour such structures in their winds. These, however, need to be confirmed by intense and uninterrupted time series of spectra. The reason for the striking contrast between the fraction of O stars showing DACs (most likely 100%) and the number of WR stars showing spectroscopic evidence of CIRs is not known. Possibilities include a rotation rate of WR stars that is too low for a CIR to develop, a CIR lifetime in some WR winds that is too small to make it possible to observed them and the absence of perturbations at the base of the wind.

3.2 Polarimetry

In the literature, one can find some periodic broad-band polarisation lightcurves for WR stars that are presumed single. See for example Drissen et al. (1989) or Robert et al. (1992) for WR6. Most of these stars have been shown through spectroscopic observations to have CIRs in their wind. The presence of such large-scale structures within a radiatively driven wind certainly constitutes an asymmetry and should therefore produce a net level of polarisation. Furthermore, as the star rotates, our viewing angle of the asymmetry will change and in consequence the observed polarisation will vary with time. Rotation will render the changes periodic although perhaps not *strictly* periodic as if the CIR dissipates and reforms due to a changing perturbation at the base of the wind, the characteristic of the variability might change, either in phase, amplitude or shape of the curve.

Modelling these polarisation light curves should allow us to determine the physical characteristics of the density asymmetries such as their density contrast with the unperturbed wind, their location in the wind and their originating position on the star, their opening angle, their winding radius, etc. Ignace et al. (2009) published a first model of a spiral-shape asymmetry in the equatorial plane of a hot-star wind. An improved model was presented by Ignace et al. (2015). Although still considering the optically thin case, the latter authors studied the effects of varying the curvature, latitude of the CIR but also the number of CIRs present in the wind. An important conclusion is that the net polarisation produced by these structures is weighted more towards the inner radius of the wind. In consequence, as the outflows have quite high velocities, the CIRs can be considered as mostly conical in shape when modelling the polarisation. It is only after a few stellar radii that the CIR transition towards a more spiral shape. As expected, one CIR or two diametrically located CIRs produce symmetrical polarisation lightcurves with two peaks separated by 0.5 in phase. Changing the winding radius has the effect of changing the amplitude of the curve; a smaller winding radius produces lower polarisation levels and amplitudes of variability due to cancelling effects. Two CIRs that are not diametrically located still produce a lightcurve with two peaks per cycle but the separation between the peaks is no longer 0.5 in phase. The smallest distance between peaks is reached when the two structures are perpendicular to each other. The amplitude of the curve is then smaller as well when all the other parameters are kept the same. Another important result is obtained when considering CIRs at different latitudes. Changing the latitude, all else being equal, has consequences for whether the light curve is single or double peaked. As the polarisation is sensitive to the full 3D structure of the asymmetric distribution of density, a far more diverse range of polarimetric lightcurves is produced. Finally, including more that two CIRs renders the behaviour of the lightcurves even more diverse. In the latter two cases, the potential-added complexity could become a strength when used in conjunction with other diagnostics, such as spectroscopic variability. The optically thick case as well as the modelling of particular lightcurves will be presented in an upcoming publication (St-Louis et al. in prep.).

4 Conclusion

Much has been revealed in the past 25 years about large and small scale structures in WR-star winds using spectroscopy and polarimetry. Stellar wind models now include somewhat arbitrary correction factors to take clumping into account and work is ongoing to incorporate the small-scale asymmetries in a more self-consistent way and to understand all their observational signatures. For large-scale structure, much remains to be understood, as the source of the perturbation at the base of the wind has not yet been clearly identified. Whatever it might be (small or large scale magnetic field, non-radial pulsations, etc), we are sure to learn more, by studying their observational signature, about physical processes taking place below the dense stellar wind and for which we presently know very little.

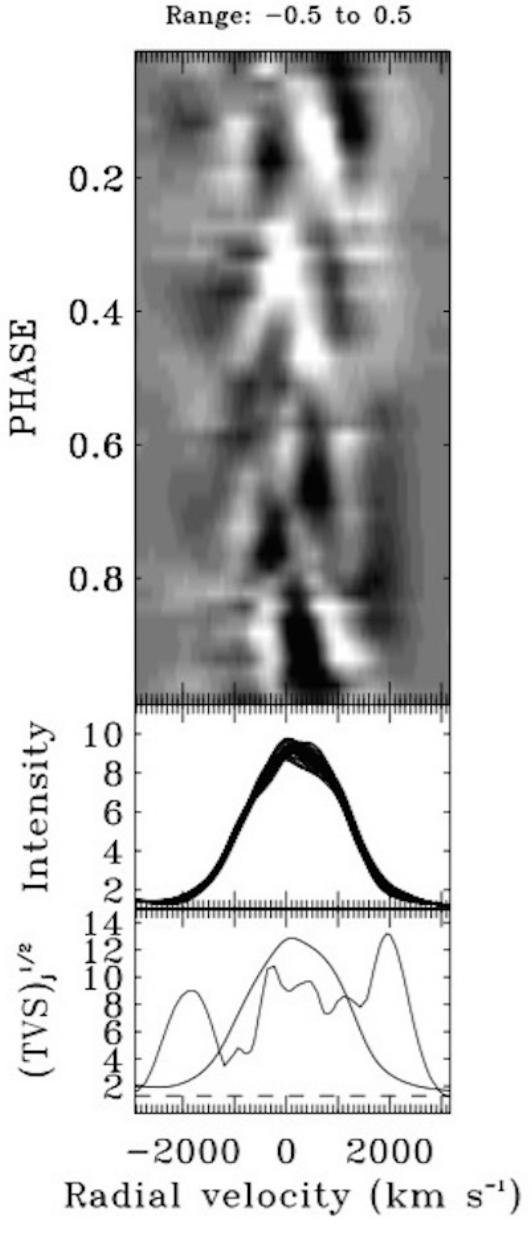

Fig. 3: Top: Differences from the mean as a function of phase using a period of 3.766 days for WR6 reproduced (from Morel et al. 1997). The HeII λ4686 emission line is shown. All superposed spectra are displayed in the middle panel while the mean and TVS spectra are presented in the bottom panel.

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Tomer Shenar: Are there any observational constraints on the "evolution" of clumping with radius ($D(r)$ or $f_V(r)$)?

Nicole St-Louis: To answer your question we need to analyse blob numbers/density and their movement in spectral lines formed at sufficiently different radial distances in the wind. To my knowledge, this has not been done properly yet. Most of the strong emission lines in the optical that have been looked at are formed in similar regions of the wind and the lines that are formed closer to the surface are of low flux and we would need higher S/N data to detect the clumps.

Jesús A. Toalá: Can you tell the difference in the velocity between the CIR and the terminal wind velocity in WR 6?

Nicole St-Louis: In the ultraviolet P Cygni absorption components, we see variations in the edge velocity ($v_{\rm max}$) from -1900 km/s to -2900 km/s. However, it is not totally clear how this is related to the velocity structure of the CIR.

Peredur Williams: What is the density ratio to ambient wind in CIRs?

Nicole St-Louis: In our (Ignace et al. 2014) model of the broadband polarization light-curve of WR 6, we obtained a density contrast of about 2. However, this model is preliminary for a Wolf-Rayet star because it does not include multiple scattering in the inner regions of the wind, which will decrease the overall value of the net polarization.

Gloria Koenigsberger: Do clumps and CIRs coexist and/or interact?

Nicole St-Louis: Yes. CIRs and clumps do coexists. However, so far there has not been a dataset sufficiently long and/or dense enough in sampling to be able to show how exactly this happens and if there is a link between both phenomena.

Andy Pollock: Do clumps flow across CIR boundaries?

Nicole St-Louis: I presume they do but I would not be able to tell what the effect is.

Andy Pollock: Does the small amplitude of variability in the weirdo star WR 2 tell you anything about the global structure of the wind?

Nicole St-Louis: Well, first it shows that the wind of WR 2 is clumped albeit at a very small level of 0.5% of the line flux that is variable. Also, as you can read in Chené et al. (2015), if you believe the acceleration versus projected velocity plots, the product of the beta of the wind's velocity law and radius of the star is $6.2\,R_\odot\,{\rm km\,s^{-1}}$. If you adopt a radius for WR 2 of 0.89 (Shenar et al. 2014), you obtain a beta value of 7 in the line formation region of He II $\lambda4686$.