OBSERVATIONAL ASPECTS OF WOLF-RAYET ATMOSPHERES

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Abstract. Observational data suggest that WR atmospheres must be considered as highly inhomogeneous objects incorporating strong shocks induced by radiative instability and full-scale supersonic turbulence, with relatively small mean mass-loss rates.

Key words: Wolf-Rayet – spectroscopy – photometry – polarimetry – variable

1. Introduction

Great progress in modelling Wolf-Rayet atmospheres has been achieved during the past decade. Schmutz (1991) and Hamann (1994) have reviewed the results of fitting observed spectra by means of a "standard model" of a WR wind and demonstrated that generally good agreement between the theory and observations can be achieved for the continuum distribution as well as for the strengths and profiles of emission lines. At the same time, the understanding is growing that WR atmospheres are more complex objects than is assumed in the "standard model". Since observational data supporting the "standard model" are considered in detail in cited reviews of Schmutz and Hamann, here we focus on: (i) contradictions between observations and the "standard model"; and (ii) observational data, which show that the "standard model" has not been designed to account for *e.g.,* data on intrinsic variability and polarimetric data.

2. Contradictions between observations and "standard model"

Problems of the "standard model" have been mentioned by many authors (*e.g.,* Underhill 1991a; Hillier 1991a; Hamann 1994). Some contradictions, such as incorrect metal-line strengths could possibly be due to inadequate atomic data, as well as to some simplifying assumptions of the "standard model" (Hillier 1991a). Others, however, indicate real problems. These are:

(i) Calculated shortward-displaced absorption components in some lines are stronger than observed ones (Hamann *et al.* 1988; Underhill 1991a). It would appear reasonable that the real column density along the line of sight to the stellar core is smaller than the model one, thus implying $\dot{M}_{\rm real} < \dot{M}_{\rm model}$. Alternatively (Hillier 1991a) one can allow for a fluctuating velocity field. So far only one attempt has been undertaken in this direction, by Puls *et al.* (1993). Low values of $\dot{M}$ ($\leq 10^{-6} M_\odot yr^{-1}$) for WR stars have

been postulated by Underhill (1991b) (*cf.* $\dot{M} \sim (10^{-5} - 10^{-4})M_\odot yr^{-1}$ from the "standard model", with a tendency to the higher value). The problem, however, is that in the homogeneous wind model the emission part of a line profile cannot be reproduced with a small $\dot{M}$. Hillier (1991b) has shown that in a *clumped* model of the WR wind one could reproduce the emission part of line profiles reasonably well with $\dot{M}$ about 2 times smaller than $\dot{M}$ in the "standard model". However, in his 1-D model (in which clumps are represented by spherical shells) the absorption in the He I $\lambda 5876$ line remains strong (*cf.* his Fig. 16). The absorption might decrease in a more realistic model of clumps localised in space (*e.g.*, in form of "blobs") if the filling coefficient is small (Antokhin *et al.* 1992).

(ii) The electron scattering wings produced in the "standard model" are stronger than observed ones (Hillier 1991a). Hillier (1991b) has shown that significant reduction in the strength of an electron scattering wing can be achieved in a model of clumped wind for a lower mean mass-loss rate.

(iii) The double-peaked shape of the He I $\lambda 5876$ line (in WR6 and WR134) and flat-topped shape of this line in other strong lined WN and some WC stars are not fully reproduced in the "standard model" (Hamann 1994). Underhill and co-authors (see Underhill & Yang 1991 and references therein) have suggested that double-peaked line profiles could be explained in a disk-like model of the WR wind. They also claimed that systematic shifts of central wavelengths of He, N and C lines indicate *ejection* of the plasma from and its *infall* toward the star. For WR134, Vreux *et al.* (1992) have found that if *patterns on the tops of emission lines* are used to derive wavelengths of emission lines instead of usual measurements of line "centers", *any systematic shifts are absent*. Thus, the results of Underhill and co-workers may be an artifact of asymmetric line shapes and/or blends. Antokhin *et al.* (1992) have suggested that the double-peaked profile of He I $\lambda 5876$ could be explained by local asymmetry of blobs rather than global asymmetry of a wind. However, the problem with any "geometrical" explanation is that if it were true, one would expect similar line-profiles of other He I lines, which is not the case (Vreux *et al.* 1992). These authors have assumed that the shortward emission peak in He I $\lambda 5876$ is simply a blend. Considering that "standard model" tends to produce a flat–topped profile of the He I $\lambda 5876$ line, its observed shape does not convincingly indicate that WR winds are asymmetric.

(iv) The He I $\lambda 10830$ triplet shows extra emission subpeaks in the otherwise rather flat-topped profiles in many broad-line WR stars (Eenens 1991; Eenens & Williams 1994). Eenens (1991) has suggested these peaks are a signature of jets. However, the same problem as before persists: other He I lines do not show such peaks.

(v) Black troughs in saturated P-Cygni profiles of resonance lines and accompanying "blue edges" are not reproduced by means of the "standard
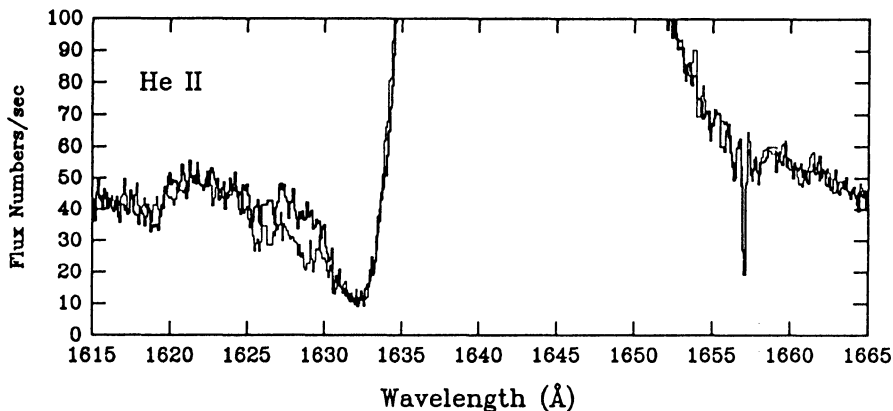
Fig. 1. *IUE* spectra of WR6 illustrating the variations in some P- Cygni profiles (from St-Louis *et al.* 1993a)

model" (*cf.* Hillier 1988). Large turbulent velocities ($\Delta V > 200 \mathrm{kms}^{-1}$) or acceleration of the wind to velocities higher than v_∞ at low electron densities have been mentioned as possible solutions of the problem. Observations of "blue edge" variability (see below) and pilot modelling of Puls *et al.* (1994) indicate that the latter mechanism is workable through the development of strong shocks in the outer wind.

(vi) The "standard model" is unable to explain an increase of the effective radius of the WR component of the binary WN5+O6 star V444 Cygni in the infrared (Hamann & Schwarz 1992; Cherepashchuk *et al.* 1994). Again, a clumpy structure of the WR wind appears to be a reasonable explanation.

3. Intrinsic variability

Intrinsic variability itself does not influence the model parameters, because "the deviations from the mean profile are generally not larger than the deviations of the synthetic profiles from the observed (mean) profile" (Schmutz 1991). The conclusion is true, however, only *if we believe the assumptions central to the "standard model"*, *i.e.*, spherical symmetry and homogeneity. The importance of the intrinsic variability lies in the fact that it indicates that these assumptions are *not valid*. A model based on different assumptions (*e.g.*, clumped wind) might be able to produce a theoretical spectrum similar to the one obtained with the "standard model" but at different values of stellar parameters, as has been indeed demonstrated by the pilot calculations of Hillier (1991b) and Antokhin *et al.* (1992).

In a previous review of intrinsic variability of WR stars (Moffat & Robert 1991) the conclusion was reached that the general pattern of variability "can

be explained by one common phenomenon: stochastic formation, propagation and decay of density enhancements in the winds". New observations complicate this picture.

3.1   "Blue edges" and discrete absorption features

Time resolved UV spectroscopy of WR6 (Willis *et al.* 1989) and WR136 (WN6) (St-Louis *et al.* 1989) has lead to the conclusion that existence of "soft blue absorption edges" in P-Cygni profiles and their variability are qualitatively consistent with the propagating shock models (Owocki *et al.* 1988; Puls *et al.* 1994). The "blob" hypothesis (Moffat & Robert 1991) seems to be unlikely to account for these data, because an unknown mechanism to accelerate the blobs to super-terminal velocity must be postulated.

Later, an extensive data set consisting of 130 high-resolution *IUE* spectra over a period of six days for WR6 has been published by St-Louis *et al.* (1993a) (Fig. 1). The previous conclusion was generally confirmed. No discrete absorption features have been seen during these observations, unlike in O-type stars, due possibly to saturation effects.

In 1992, Prinja and Smith (1992) reported the discovery of blueward migrating discrete absorption features in the unsaturated He II $\lambda 1640$ P-Cygni profile of WR24 (WN7+abs). Their properties resemble of those in O-type stars, providing additional support for a common physical mechanism (radiative instabilities) for wind variability in O and WR stars.

3.2   Optical emission line variability

Systematic micro-variability in optical emission lines of some WR stars showing evidence for "bumps" moving away from the center of line, has been reported in the late 1980s (Moffat & Robert 1991) and interpreted as a signature of blobs moving away from the star. That interpretation has been criticized by Underhill *et al.* (1990) and Underhill & Yang (1991).

To (i) quantify the information about subpeak parameters in a more objective way and to (ii) move to small features which could not be recognized "by eyes", Robert (1992), Moffat & Robert (1992) and Moffat *et al.* (1993) have applied multi-Gaussian and wavelet analysis technique. The main result is that scaling laws between subpeaks parameters (flux, velocity dispersion, lifetime, position on the line, *cf.* Fig.2) strongly support the hypothesis of *anisotropic supersonic compressible turbulence* in the wind. Moffat & Robert (1994) have shown that a turbulent wind with observed properties could lead to a decrease in the derived value of $\dot{M}$ by a factor of ≥ 3 compared to homogeneous wind of the same free-free or subordinate line flux.

Another conclusion of Robert (1992) is that, at least in some WR stars, acceleration of blobs is very slow ($\beta > 10$). Thus, *assuming that blobs are good tracers of the flow velocity* the usually adopted value of $\beta \simeq 1$ seems
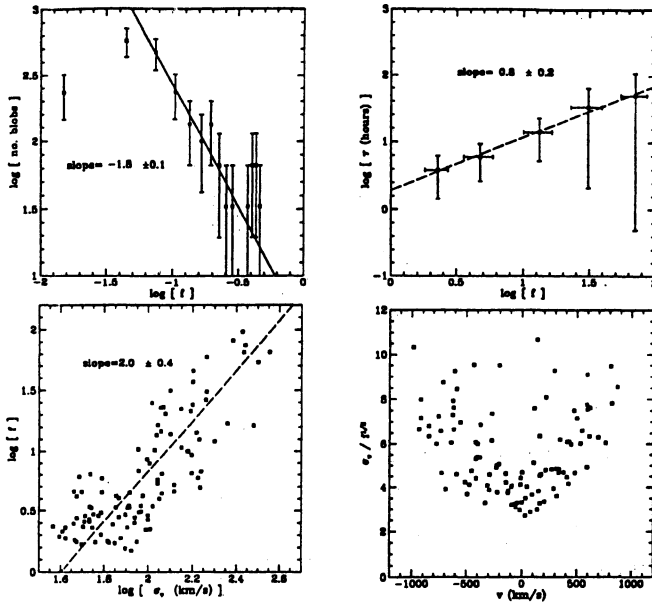
Fig. 2. Results of wavelet analysis for C III λ5696 profile of WR135 (WC8) (from Moffat *et al.* 1993): (a) flux spectrum; (b)flux vs. velocity dispersion; (c)life-time vs. flux; (d)normalized velocity dispersion vs. position on the line.

inadequate. This result is compatible with the conclusion of Koenigsberger (1990) obtained from an analysis of phase-dependent Fe V/Fe VI pseudo-continuum in binary WR+O stars.

A further complication of the overall picture comes from observations of WR134 performed by Vreux *et al.* (1992). The authors have shown that while the pattern of micro-variations of emission line profiles in several nights was similar to that found by Moffat *et al.*, there were also many events which differ remarkably from a picture of "gently moving" blobs. In particularly, there are preferable points (nodes) in the line profiles, where the variations are much smaller than in between. Two typical examples of variability are illustrated in Fig.3: (i) a given pattern repeats itself after some time; (ii) two patterns are nearly *the mirror image* of one another. To explain all observational facts, the authors suggest a tentative model of a wind resembling the *Luminous Magnetic Rotator* model (Cassinelli 1991).

3.3 PHOTOMETRIC VARIABILITY

A number of photometric investigations of apparently single WR stars have been undertaken since the review of Moffat & Robert (1991). The results are:

(i) Several stars (WR24 (WN7+abs), WR25 (WN7+abs), WR78 (WN7), WR108 (WN9-Ofpe) (Gosset *et al.* 1994), WR82 (WN8) (Antokhin *et al.*
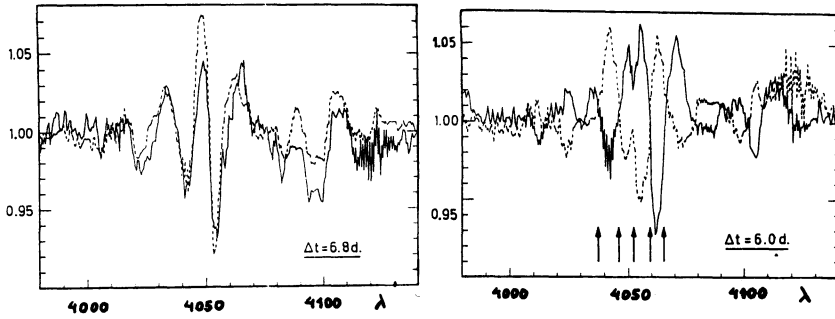
Fig. 3. Examples of the (a) repeatability and (b)"mirror" situation in the N IV λ4058 profile of WR134 (from Vreux *et al.* 1992).

1994b)) show random low-amplitude variability in the continuum, exceeding observational noise.

(ii) The WN8 stars WR16 and WR40 show along with random light-variations some degree of periodicity (Gosset *et al.* 1994; Antokhin *et al.* 1994b). Matthews & Moffat (1994) have suggested that photometric variations of WR40 may be understood as a signature of orbital and rotational periods in a WR binary system.

(iii) Blecha *et al.* (1992) have reported the discovery of radial pulsations in WR40 with a period of $\simeq$ 10 minutes. This kind of pulsations had been predicted theoretically (Maeder & Schaller 1991). The result, however, has not been confirmed by subsequent observations (Gosset *et al.* 1994, Marchenko *et al.* 1994).

(iv) No periods $\leq$ 1d which could indicate non-radial pulsations (NRP) have been found in all mentioned stars as well as in WR6 (WN5) (Gosset *et al.* 1994; Antokhin *et al.* 1994a). However, Antokhin *et al.* (1994b, see also these proceedings) discovered a 3.5h periodicity in WR66 (WN8). This may be the first clear example of NRP among WR stars. Another tentative interpretation is that we observe the NS-companion at spiral-in stage.

4.   Polarimetry

Great progress in polarimetric investigations of WR stars, both single and binary, has been achieved in recent years. Since detailed reviews on polarimetric data can be found in Schulte-Ladbeck (1994), only the main results will be summarized here:

(i) $\sim$ 80% of the investigated WR stars show intrinsic polarimetric variability, indicating that their winds are both temporally and spatially variable.

(ii) Line effects (depolarization across a line) are present in about 25% of the investigated WR stars. Of those only WR6 and WR134 appear to have

axisymmetric winds.

(iii) Polarimetric estimates of mass-loss rates in binary WR+O stars tend to be smaller than those from radio data and from modelling emission-line spectra of WR stars (St-Louis *et al.* 1993b).

5.   Conclusions

The observations considered strongly suggest that mass-loss rates in WR atmospheres are smaller than those predicted by the "standard model" (possibly $< 10^{-5} M_\odot yr^{-1}$). If a star's $\dot{M}$ is small, its wind must contain density enhancements, to produce the observed flux in emission lines. There is also direct observational evidence for the inhomogeneity of WR winds.

The qualitative observational picture of WR winds has become more complicated than suggested in Moffat & Robert (1991). Instead of randomly ejected blobs, gently moving in an otherwise smooth wind we come to an empirical model which incorporates strong shocks induced by the radiative instability of the wind and full-scale supersonic (anisotropic) turbulence. In some cases, there is evidence for global asymmetry of a WR atmosphere. The usual β law is possibly not adequate. The question is how the observational data could be used in future models of WR atmospheres. Most of them could serve as constraints. Scaling laws from recent papers of Robert (1992) and Moffat *et al.* (1993) could hopefully be directly incorporated into existing models. New time-resolved simultaneous observations in different modes will hopefully reveal new empirical correlations and provide new insights into the physics of WR atmospheres.

6.   Acknowledgements

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DISCUSSION:

Moffat: While recent quantitative analyses have advanced our understanding of substructures in WR winds greatly, we are still a long way from understanding their nature, let alone their origin. For example, we only are seeing the tip of the iceberg; we have no (direct) idea of what happens at small scales.

Antokhin: Yes, this is correct. Still, I think it is worth trying to incorporate your (extrapolated to small scales) empirical correlations into existing atmosphere models.

Hillier: The spectrum of 10830 in WR 134 is an excellent example of a blend between Pγ and HeI 10830. Other profiles in the Eenens paper probably provide a better example of unusual profiles.

Williams: I have examined the contribution of Pγ and its helium analgues to the 10830 profile in WR 134 and they cannot account for the emission peak.

Pollock: What is the relation between supersonic turbulence and the strong shocks? Does the radiative instability thought responsible for the shocks also provide the driving mechanism for the turbulence?

Owocki: I believe what you refer to as "shocks" and "supersonic turbulence" should be thought of as the same thing. The line-driven instability is a good potential mechanism for generating this turbulence and maintaining it against the strong dissipation arising from its compressive nature. Recent calculations suggest that WR winds may indeed be subject to a moderately strong line-driven instability.

Vreux: Concerning the profile of HeI λ10830 in WR 134, I would like to point out the following. It is true that most of the time P. Eenens and myself have observed the profile you have shown i.e. there is a small emission peak on the red side of the top of the HeI λ10830 line. Nevertheless, I have one night, with a fair S/N, showing a double peaked profile, i.e. a small peak is also present on the blue side of the top of the HeI line. Then, this profile is reminiscent of some of the ones predicted by A. Underhill when she assumes that there is a ring around a star. But P. Eenens's suggestion most probably is also still possible.