Astronomy & Astrophysics manuscript no.
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Line-Profile Variability in the Wolf-Rayet Stars WR 135 and WR 111

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Draft version of June 26, 2001

Abstract. We have obtained time-resolved observations of line-profile variations of the two Wolf-Rayet stars WR 135 and WR 111. The spectra, taken during two consecutive nights, cover a broad range from 4470 to 6590 Å. The profile variability of the C III emission line at 5696 Å in WR 135 is shown in detail. The principal difficulties to constrain the velocity law from the frequency drift of discrete spectral features is discussed, emphasizing the crucial dependence on the adopted location of the line-emission region, and the possible necessity to distinguish between the motion of structures and the flow of the matter. – Full access to the observational data is provided via anonymous file transfer.

Key words. Stars: mass-loss – Stars: Wolf-Rayet

1. Introduction

Wolf-Rayet (WR) stars are highly evolved objects which show products of nuclear hydrogen and helium burning at the surface. Their spectra, which are formed in a dense and fast stellar wind, are dominated by broad emission lines of either helium and nitrogen (WN-type) or helium, carbon and oxygen (WC-type). In the recent years it became clear from various observations (see Brown et al. 1995 for an overview) that the winds are not homogeneous but structured, while the so-called standard model for WR stars is based on the simplifying assumptions of spherical symmetry, homogeneity and stationarity. The most obvious indications of wind structures are narrow emission features superposed on the emission lines which persist on timescales of about 10 hours and which drift generally from the center towards the edge of the lines. These features are assumed to arise from regions of enhanced emission (clumps, blobs) which are accelerated in radial direction.

In a series of papers, Lépine and co-workers have presented both, mathematical tools to investigate line profile variations (LPVs) (Lépine et al. 1996), and time-resolved observations of various WR stars (Lépine & Moffat 1999; Lépine et al. 1999, 2000). They conclude from a wavelet analysis that very many ($\approx 10^4$) discrete wind emission elements (DWEEs) contribute simultaneously to the spectral lines. In terms of the usual β-law for the velocity field they find low radial accelerations, i.e. substantially higher β values compared to the canonic value of β=1 (Lépine et al. 1999). In their most recent paper (Lépine et al. 2000) high-quality observations of WR 135 are presented and analyzed. Stochastic and structured patterns at the 2% level are found in the C III line at 5696 Å, and low radial accelerations are derived from comparison with simple clump models.

In the present paper we introduce own, time-resolved observations of the two galactic WR stars WR 135 (WC 8) and WR 111 (WC 5). The parameters of both program stars have been determined before from non-LTE spectral analyses by Koesterke & Hamann (1995). For WR 135 the result was confirmed recently by Dessart et al. (2000).

In Sect. 2 observations and data reduction are described, while only the LPVs in the C III line at 5696 Å of WR 135 are presented in detail (Sect. 3). A summary is given in Sect. 4.

2. Observation and Data Reduction

The observations were carried out by one of us (L.K.) on July 20-22, 1999, with the Calar Alto 3.5 m telescope. Using the TWIN spectrograph, two spectral regions (blue: 4470 to 5500 Å red: 5500 to 6590 Å) were covered simultaneously with a spectral resolution of about 1.1 Å. The data were reduced with IDL in the usual way. After flat and bias correction the spectra have been extracted, corrected for

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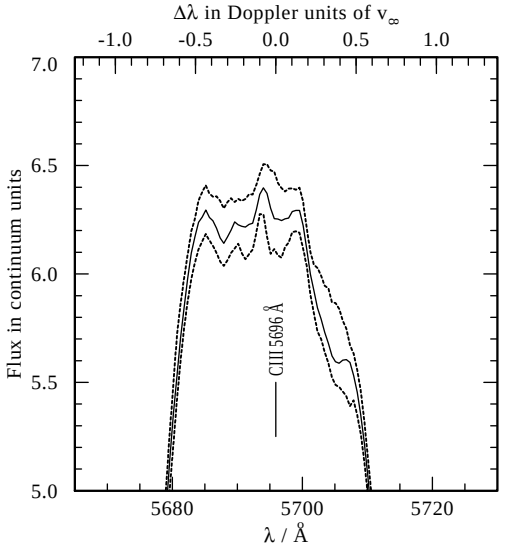

Fig. 1. Top of the C III line profile at 5696 Å from WR135 (full line), obtained as median value of all our spectra from that star (both observing nights). The dashed curves gives a minimum and a maximum profile, calculated as the 5-percentile and 95-percentile at each wavelength point.

the background, and wavelength calibrated. The S/N ratio in the continuum is 60, typically, but differs between the individual exposures due to unstable weather conditions. Note that the spectral region around 5500 Å is corrupted by the beam splitter. An overview on the observations is given in Table 1.

Table 1. Overview on the observations

Date 1999	Star	Start JD -2451380	Duration [min]	No. of spectra
Jul20/21	WR 135	0.39167	30	6
Jul20/21	WR 111	0.41736	13	5
Jul20/21	WR 111	0.45556	7	4
Jul20/21	WR 135	0.46250	6	4
Jul20/21	WR 135	0.56111	87	52
Jul21/22	WR 111	1.38659	124	70
Jul21/22	WR 135	1.47292	254*	145

*Bad weather from $130^{\rm th}$ to $150^{\rm th}$ min

3. Variation of the C III line profile in WR 135

The C III line at 5696 Å is known to show the most pronounced profile variations. We focus on our observations of WR 135 in the night July 21/22, 1999, because this is the longest of our time series. In order to uncover the variations we proceed in the following way: (a) all spectra are normalized with respect to a straight continuum which is fixed at two points, bluewards (5640 Å) and redwards (5750 Å) of the C III line; (b) a template profile is subtracted from each individual observation.

For the template we take the 95-percentile of all our spectra from that star over both observing nights. (The n-percentile at each wavelength point has by definition a value which is higher than n% of the individual measurements, but lower than the rest.) In Fig. 1 we show this template spectrum together with a median and a minimum profile which are obtained as 50-percentile and 5-percentile, respectively. With the 95-percentile template the LPVs become visible best, but our discussion does not depend on this particular choice. As can be seen, the flux in the top of the line profile varies by about ±0.14, in units of the continuum flux (which is ±2% relative to the line top flux).

In Fig. 2 the variation of the C III line profile is shown in a grey-scale representation. Note that the time at the right-hand ordinate is converted at the left-hand axis in units of flight times $t_{\rm flight} = R_*/v_\infty$. With a stellar radius of $R_* = 2.6\,R_\odot$ and the terminal velocity $v_\infty = 1300\,{\rm km\,s^{-1}}$ (from Koesterke & Hamann 1995, in fair agreement with Dessart et al. 2000) one obtains $t_{\rm flight} = 23.2\,{\rm min}$. The wavelength scale (top abscissa) is translated into Doppler shift velocities relative to the line center (bottom abscissa). The difference to the mean template shows a couple of features which are drifting away from the line center. It is not clear if one should consider the bright features as *excess of emission*, or the dark structures as *lack of emission* (compare Figs. 2 and 4). Only, because of the emission process of that line are fed by recombination processes, one should not expect the dark features being due to absorption – in contrast to the "discrete absorption components" observed in the UV resonance lines of O stars.

The drift in wavelength contains information about the wind dynamics. Lépine & Moffat (1999) applied sophisticated methods on similar (and better) data, concluding that the velocity law in WR 135 and other WR stars is less steep than commonly assumed.

We will not repeat this detailed analysis, but use our present data and some simple kinematic modeling to discuss some general aspects of the information which is contained in those spectra.

In a straight-forward interpretation, one might assume that the drifting features are originating from some density structures (clumps or voids). If these features are fully advected with the stellar wind, their wavelength drift reflects the velocity law $v(r)$. The time to reach an outflow velocity v is obtained by integrating

$$t = \int \frac{{\rm d}r}{v(r)}\,. \qquad (1)$$

An integration constant t_0 is a free parameter for each individual feature and reflects the different time when the corresponding structure is passing some reference radius. The observed wavelength shift is $\Delta\lambda = \mu\, v(t)/c$. Therefore, a second free parameter is the projection factor μ, i.e. the cosine of the angle between the direction to the observer and the direction in which the structure is flying off from the star. In contrast to the "discrete absorption components" in UV resonance lines, which are formed be-

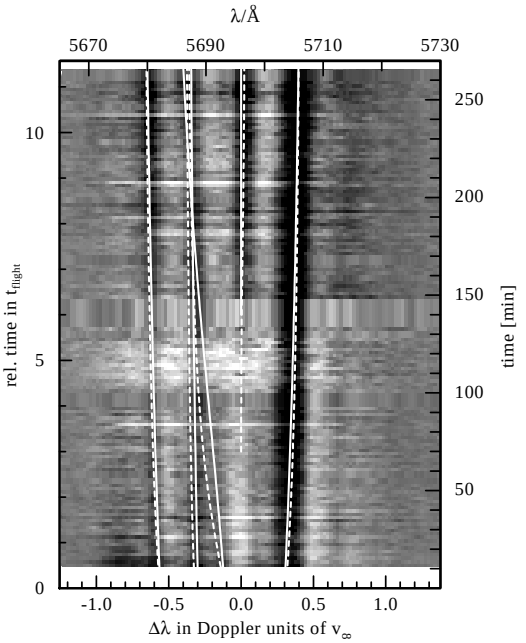

Fig. 2. LPVs in the C III line at 5696 Å of WR 135 on July 21/22, 1999. A mean template has been subtracted. The y-axis is given in units of $t_{\rm flight} = R_*/v_\infty$. Slowly outwards moving patterns darker or brighter than the template (black and white, respectively) are visible. Superimposed are kinematic curves fitted tentatively to dark features, assuming the usual β-law with $\beta = 4$ (solid) and $\beta = 1$ (dashed), without restricting the line-emitting region.

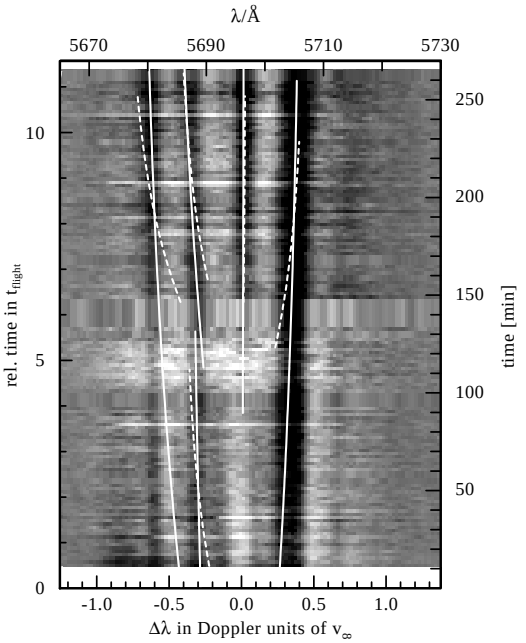

Fig. 3. Same as Fig. 2, but now restricting the kinematic curves to the velocity range of the line-emission region ($890 \pm 240\,{\rm km\,s^{-1}}$ following Lépine & Moffat 1999). As can be seen, the $\beta = 1$ curves (dashed) now cannot be fitted to the observation, as their velocity drift is much too fast.

tween the stellar disk and the observer, μ can have any values between -1 and +1 for wind emission elements.

In Fig. 2 we have roughly fitted some $\Delta\lambda(t)$ to the dark structures in the dynamical spectrum by adjusting t_0 and μ "by eye". For the velocity law we adopt the usual "β-law" of the form $v(r) = v_\infty(1 - R_*/r)^\beta$, testing $\beta = 1$ (dashed) and $\beta = 4$ (solid line). The whole velocity range from (almost) zero to v_∞ is plotted, i.e. no restriction is assumed yet for the line-emitting region. As the figure shall demonstrate, the features can be fitted equally well by both, dashed and solid curves, i.e. the velocity law exponent cannot be constrained this way.

An essential conclusion of Lépine & Moffat (1999) was that the acceleration in WR winds is *slow*. Their result for WR 135 is $\beta R_* > 20\,R_\odot$, which means $\beta > 7$ for a plausible stellar radius. Why the above kinematic fits do not exclude a β as low as 1? The reason is, that we did not restrict yet the region of line formation. The acceleration is decreasing towards large radii, and hence arbitrarily slow wavelength drifts can be reproduced by adjusting the two available free parameters. The essential information needed is thus the range (in velocity or radius) of line formation.

Lépine & Moffat (1999) derived that range by an inverse method from the (average) line profile, performing a "spherical deprojection" under some simplifying assumptions. For the formation of the C III line in WR 135 they obtain a velocity range of $890 \pm 240\,{\rm km\,s^{-1}}$ (corresponding to a fraction of 0.46 ... 0.80 of their $v_\infty = 1405\,{\rm km\,s^{-1}}$). In Fig. 3 we have restricted the kinematical curves to that range in velocity, and re-adjusted the fit parameters as good as possible. Now it is obvious that the $\beta = 1$ curves (dashed) predict much faster wavelength drifts than observed. Moreover, the structures are crossing the line emission region faster than their observed lifetime.

This example demonstrates the crucial role of the adopted location of the line-emission region for deriving velocity-law parameters. Alternatively, we can extract the location of the line-emission region from our line-blanketed non-LTE models for WC atmospheres (cf. Gräfener et al. in prep.). Selecting a model which reproduces the whole WR 135 spectrum reasonably well, the C III line is found to be formed between 0.78 and 0.95 v_∞, i.e. further out than stated by Lépine & Moffat (1999). Adopting this range, even a β value as small as unity becomes compatible with the dynamical spectra because the acceleration decreases towards large radii in any β law. (Implicitly, this can also be seen from Fig. 14 in Lépine & Moffat 1999.) However, we are not yet fully confident in our models with respect to the C III line, because its formation is corrupted by complicated details of the radiative transfer (dielectronic recombination, stimulated emission).

Lépine et al. (2000) emphasized that each moving feature in the observed LPV represents many individual "wind emission elements", which only by random superposition sometimes form an outstanding signal. However, in optically thin emission as given in the considered C III line, any superposition should also reflect the wind dy-

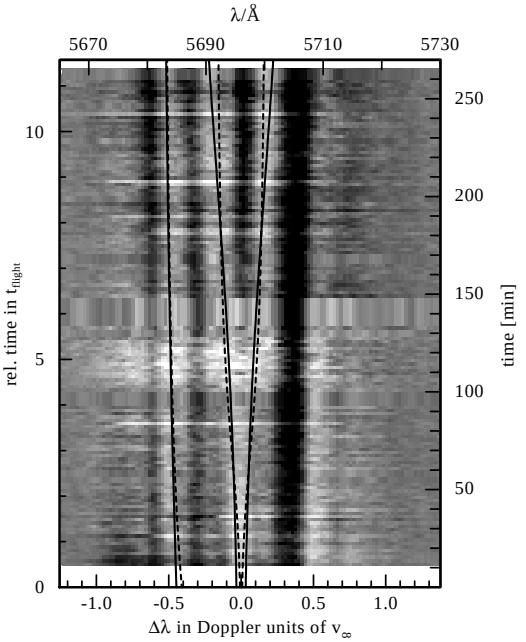

Fig. 4. Same as in Fig.2 but with tentative fits to bright features (solid: $\beta = 4$; dashed: $\beta = 1$).

namics in the same way as a single event, despite of a possible broadening or narrowing of the feature's shape, so that the above kinematic considerations remain valid at least in first approximation.

As another caveat, we want to emphasize that the interpretation of the LPVs as reflecting directly the matter velocity might be not adequate. The drifting features are formed in local structures of the wind, which cause some excess absorption or emission in the line profile. These structures might be enhancements or rarefactions of the density, which enters quadratically the recombination rates. Disturbances in the velocity gradient can also affect the C III line emission via the complicated coupling between the non-LTE population numbers.

The frequency drift observed in the LPV reflects the velocity of the matter (via Doppler effect) *at the place of the local structure*. But only if that structure is fully advected with the flow of matter, the interpretation is as straightforward as adopted above. However, in a radiation-driven wind, structures might actually propagate relatively to the matter flow.

Two corresponding effects are known in line-radiation driven winds. Abbott (1980) discovered a new type of radiative-acoustic waves, and Owocki et al. (1988) reported on reverse shocks due to the so-called de-shadowing instability. Due to these mechanisms, structures can propagate *upstream* with high velocity. As a result, the structures still move outwards, but slower than the matter flow which is passing through the structures.

Hamann et al. (in prep.) show that e.g. a structure propagating upstream with $0.4\,v_\infty$ relative to the matter, while the matter itself streams according to a $\beta = 1$ law, leads to a frequency drift very similar to the case of a fully advected pattern moving according to a $\beta = 4$ law. The idea of upstreaming patterns is very attractive since it brings the low β of about 1 from the theory of radiation driven winds (Pauldrach et al. 1986, Friend & Abbot 1986) in accordance with the higher β values derived by Lépine and coworkers (e.g. Lépine et al. 1999).

4. Summary

New time-series observations have been obtained for the two Wolf-Rayet stars WR 135 and WR 111. The profile variability of the C III emission line at 5696 Å in WR 135 is shown in detail. Discrete features, drifting away from the line center, contain information about the wind velocity field. By means of simple kinematic modeling we discuss the possibilities to restrict the velocity-law exponent β. Adopting the location of the line-emission region as derived by Lépine & Moffat (1999), β must be much larger than unity; otherwise, the variable spectral features should show a faster drift in wavelength. However, this conclusion depends sensitively on the location of the line-emission region. If assuming that the line is formed further out in the wind, low values of β cannot be ruled out.

Moreover, one must possibly distinguish between the motion of the structures in the wind which cause the drifting spectral features, and the velocity of the matter flow, as the former may propagate relatively to the latter and thus mimic a flatter velocity law.

An advantage of the presented observations is their broad wavelength coverage from 4500 Å to 6500 Å. In principle this allows the simultaneous investigation of several spectral lines, e.g. from different ions. According to Lépine et al. (2000) such work could improve our knowledge concerning (1) the size and location of the line-emitting region, (2) the ionization structure, (3) the wind dynamics, and (4) the radial trend of the clumpiness. However, the S/N ratio of our data is possibly not sufficient for studying lines with a low level of variability. Anyhow, such thorough-out study is beyond the scope of our present paper.

Full access to the observational data is provided via anonymous file transfer:
ftp: `ftp.astro.physik.uni-potsdam.de`
user: `anonymous`
password: `your email address`
files: `pub/lkoesterke/lpvdata/*`

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