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Spectroscopy of HD 4004. Correlated profile variations?*

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Abstract. We present results of detailed analysis of spectral variability observed in the optical spectrum ($\lambda\lambda$ 4350–5700 Å) of HD 4004 (WR 1). Basing on data obtained during spectroscopic monitoring of this object in three nights in September 1994, and six nights in November 1995 we show that the variations observed in He II lines λ 4542, 4686, 4860 and 5411 are very similar and well correlated. We also show that the amount of variability in these lines is identical. We provide evidence, however, that the variations as observed in those He II show also noticeable differences. The projected velocities of perturbations exposed on He II emission line profiles do not scale with line width (FWHM). This means that the factor responsible for the observed profile variations is not coupled with the wind and its velocity law. Based on our results we argue for two-component (fast-slow) wind model of HD 4004.

Key words: stars: atmospheres – stars: mass-loss – stars: early-type – stars: individual: HD 4004 – stars: Wolf-Rayet

1. Introduction

The spectral variability or line profile variations (LPV) of otherwise single WR objects has been known for a long time (Wilson 1948) but has been the subject of detailed investigation only with the advent of linear detectors (Ebbets 1979). More recently LPVs have been recognized as very common (Moffat & Robert 1991; Robert 1994). Recently LPVs have been studied in detail for several WR stars: HD 50896 (Morel et al. 1998), HD 191765 (Morel et al. 1999) and HD 4004 (Niedzielski 2000). In spite of a long list of possible processes which may possibly result in the observed spectral variability, the question of the nature of LPVs in WR stars remains open.

The first photometric observation of HD 4004 was reported by Hiltner (1956). Moffat & Shara (1986) reported its weak photometric variability for the first time. Line profile variations in HD 4004 were first observed by Niedzielski (1995). An more extended review on HD 4004 can be found in Niedzielski (1998).

Recently Morel et al. (1999) presented an extensive photometric and spectroscopic study of HD 4004 and confirmed the spectral variability reported by Niedzielski (1995). They also presented evidence for unique, short lasting (3–4 days) photometric brightening of this object but found only marginal photometric variability in an additional 11 day photometric monitoring. Morel el al. (1999) were not able to find any periodicity in their data.

Niedzielski (2000) presented results of optical spectroscopic monitoring of HD 4004. He was able to describe the amplitude of observed variations in emission lines of different ions in terms of wind ionization stratification. Niedzielski (2000) excluded a binarity scenario both with a degenerate and non-degenerate object, as possible explanations of observed variations in the optical spectrum of HD 4004.

In this paper we present results of complete analysis of HD 4004 from two observing runs performed in lower resolution than in Niedzielski (2000) but covering much larger wavelength range, from λ 4350 to λ 5700 Å. We aim to extend the correlation of variability in He II lines reported by Niedzielski (1996) through a comparison of variability observed simultaneously in several lines.

2. Observations

The observations presented here were obtained during two runs in September 1994 and November 1995 with the 1.22 m "Galileo" telescope of the Padova University. The telescope was equipped with the Cassegrain "A" prismatic spectrograph and a CCD camera. The reciprocal dispersion of the spectra obtained in such configuration was 1.56 Å pix^{-1} at H$_\gamma$. The spectral range observed in one exposure was 4350–5700 Å. A typical exposure time of 30 min resulted in S/N ratio of 100 at the continuum level. Fe - Ar lamp spectra (Tomov & Munari 1995) were taken between the object exposures, several times during night allowing to monitor possible instrument flexure.

Complete reduction was done with standard packages of PC-IRAF. The equivalent widths and various line profile parameters were determined with the ReWiA system (Borkowski, 1992).

Details of these data are given in Table 1.

3. Results

3.1. The observed line profile variations

Due to the varying resolution of our spectra with wavelength and reported similarity of all observed He II profiles we choose the λ 4686 line as optimal for illustration of LPVs observed in the optical spectrum of HD 4004.

* Based on observations obtained with the 1.22 "Galileo" telescope of the Padova University in Asiago (Italy).

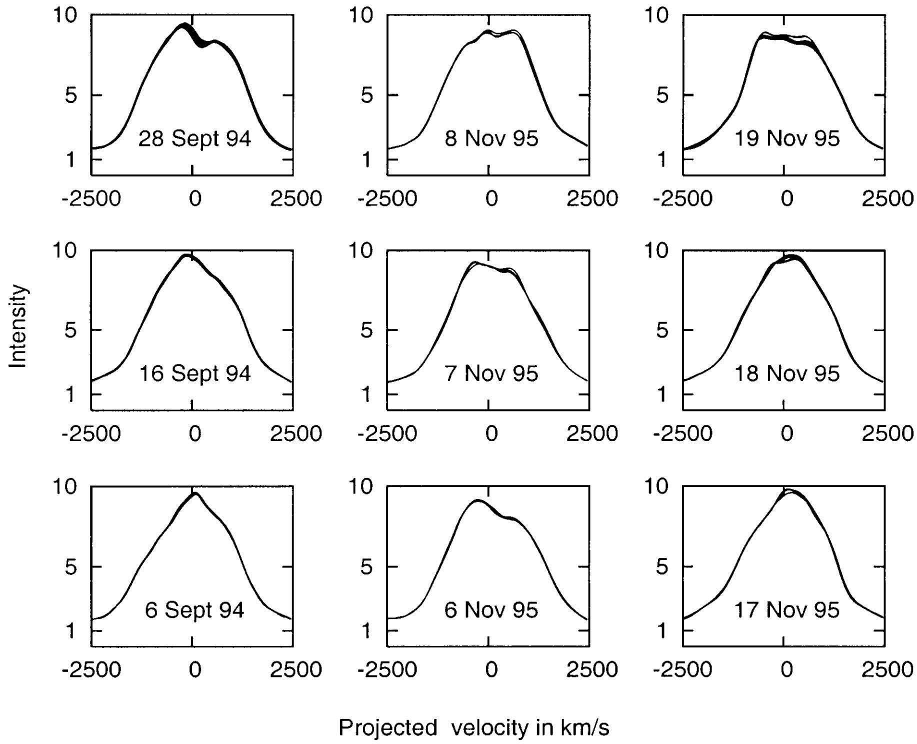

Fig. 1. The profiles of He II 4686 in HD 4004 are different every night. Some profiles appear very similar, however. The profile of Sept 28, 1994 seems to appear again on Nov 6, 1995 while the profile of Nov 7, 1995 appears again on Nov 19, 1995. All profiles obtained within a night are presented so the variability is clearly indicated. The longest runs result in most evident variability. Two 3-day sequences in November 1995 show profile development in a longer time-scale. See text for details.

Table 1. Journal of observations

Date	Mean JD-2449000	Number of spectra	Duration of run (days)
6 Sept 1994	603.480	3	0.049
16 Sept 1994	612.549	16	0.225
28 Sept 1994	624.523	21	0.307
6 Nov 1995	1028.418	4	0.139
7 Nov 1995	1029.406	3	0.301
8 Nov 1995	1030.329	3	0.059
17 Nov 1995	1039.462	7	0.436
18 Nov 1995	1040.429	8	0.429
19 Nov 1995	1041.468	8	0.392

In Fig. 1 all profiles of He II λ 4686 are presented that we obtained during both runs. All individual spectra are plotted so every night a number of profiles is given, according to Table 1. In September 1994 only three separate nights were used for observations due to weather conditions but the night of September 28, 1994 resulted in a series of 21 spectra obtained within time interval of 0.307 day. A shorter sequence was obtained on September 16–16 spectra within 0.225 day. In November 1995 two 3-day sequences of spectra were obtained: on 6–8 and 17–19. The night of November 17 resulted in longest run of observations - 0.436 day but due to changing weather conditions only 7 spectra were gathered. Similar situation took place in case of November 18 and 19 - see Table 1.

As shown in Fig. 1 sequences of profiles of He II λ 4686 obtained within one night show slow but noticeable variability. This is best illustrated by the September 28, 1994 plots. The development of different shapes of the He II profile is seen through November spectra, where the intensity of the red wing of the profile is rising during following nights from November 6 to 8. At the same time the blue wing shows less variability. Another, slightly less evident sequence is seen in November 17–19. There we see how the blue wing is getting stronger starting from an almost symmetric round topped profile on November 17 to a flat topped one two days later. The red wing in that period seems to be constant.

Interesting enough the profile variations we observe are not completely random. Some of them appear again even in our limited sample. For example the profile of November 6 looks very much like that of September 28, 1994. Also the profiles of November 8 and 19 are similar and show a mirror reflection of each other. Both sequences of profile changes of November 1995 suggest that there is some recurrence in profile variations of He II λ 4686 but the possible period is certainly longer than 3 days.

We find that similar profiles variations of He II were observed by Morel et al. (1999). Similar behavior of emission line profiles of helium and nitrogen in HD 50896 was also reported by Smith & Willis (1994).

More detailed information on hourly profile variations of He II λ 4686 is provided in Figs. 2 and 3. Top panel of Fig. 2 presents all 16 profiles of that line observed during 5.5 hours of monitoring on September 16, 1994. The middle panel shows a montage of deviations present in individual profiles obtained by subtracting from every spectrum the first one taken that night (the spectra are artificially shifted upwards in the intensity scale by 0.1, as indicated by the arrow). A slow development of profile variations in time is clearly visible. In the bottom panel of Fig. 2

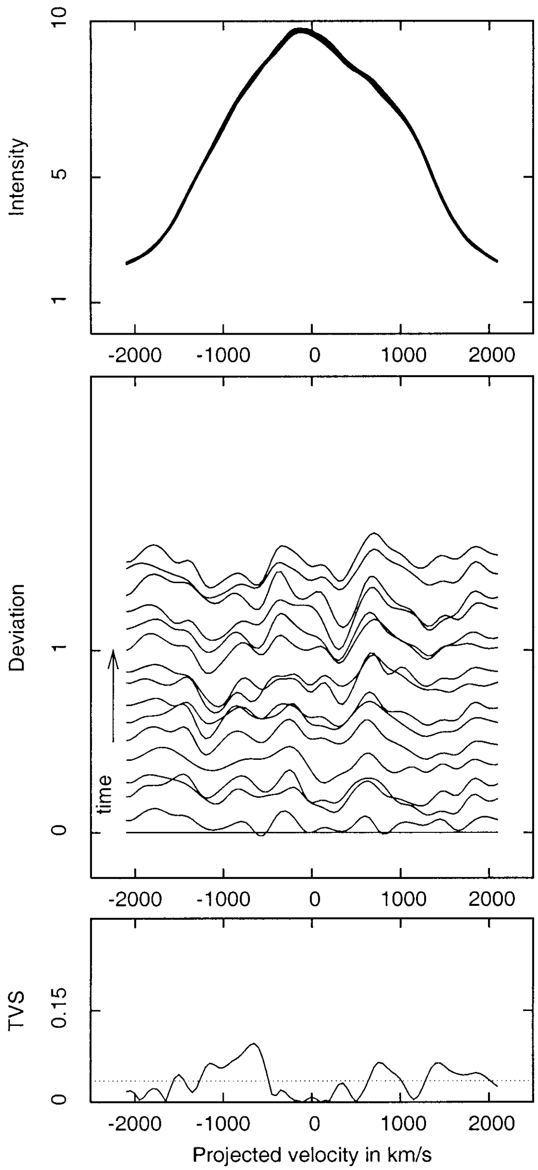

Fig. 2. The profile of He II 4686 as observed on Sept 16, 1994. The upper panel presents all 16 spectra of this line while the middle one shows development of the profile in time. In this panel all spectra are shown as deviations from the first one obtained that night. During 5.5 hours of continuous observations the growing difference in profile is easily noticeable. Interesting enough the deviation seems to appear and develop at the same projected velocity. In the lower panel the Temporal Variance Spectrum of this profile is presented for the same period indicating the amplitude of observed variations at different projected velocities. The contour of statistical significance of p=1% is presented by dotted line.

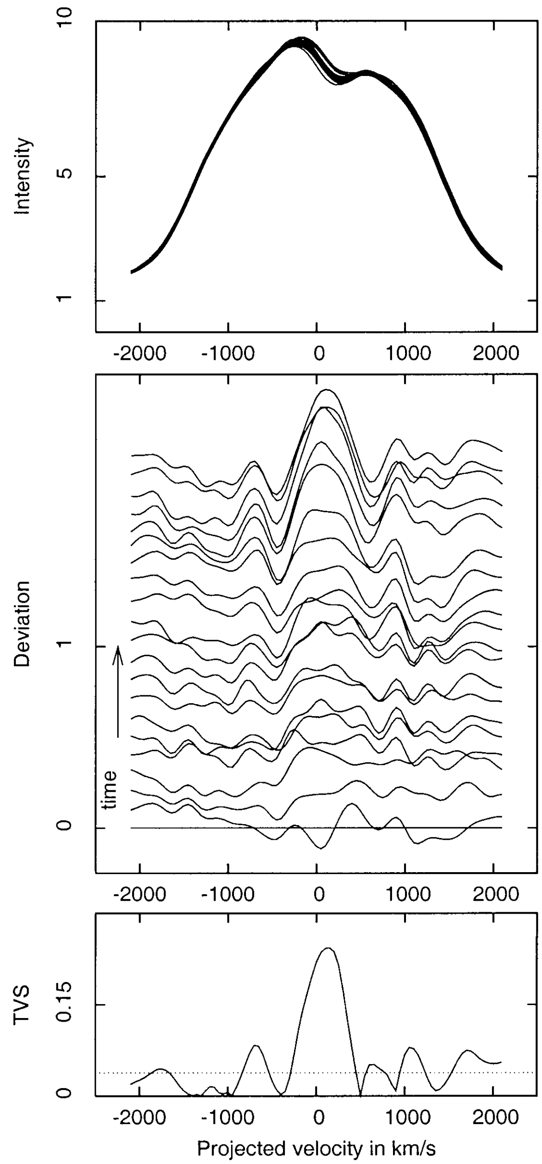

Fig. 3. Same as Fig. 2 but for the 21 spectra gathered in 8 hours of monitoring on Sept 28, 1994.

the Temporal Variance Spectrum, calculated for the September 16 spectra is presented. The dotted line is the contour of statistical significance of p=1%.

In Fig. 3 the same data for the night of September 28, 1994 are shown. Due to longer monitoring (21 spectra in 8 hours) the development of profile variations is more evident. The TVS (bottom panel) confirms that the amplitude of variations is much larger in these data. Interesting enough our data resolve the observed profile variations into smaller components that appear and develop at fixed projected velocity. Our data show no migration of a profile deviation (change of projected velocity in time). The profile variations of He II λ 4686 as observed on September 28, 1994 appear to be a result of varying intensity of 3 narrow components (300–700 km s^{-1}) located at fixed positions relative to line center.

3.2. The observed spectrum and Temporal Variance Spectrum (TVS) analysis – general view

The mean spectra obtained within both observing runs as well as temporal variance spectra - TVS (Fullerton, Gies and Bolton 1996) are presented in Fig. 4. We can see a well developed emis-

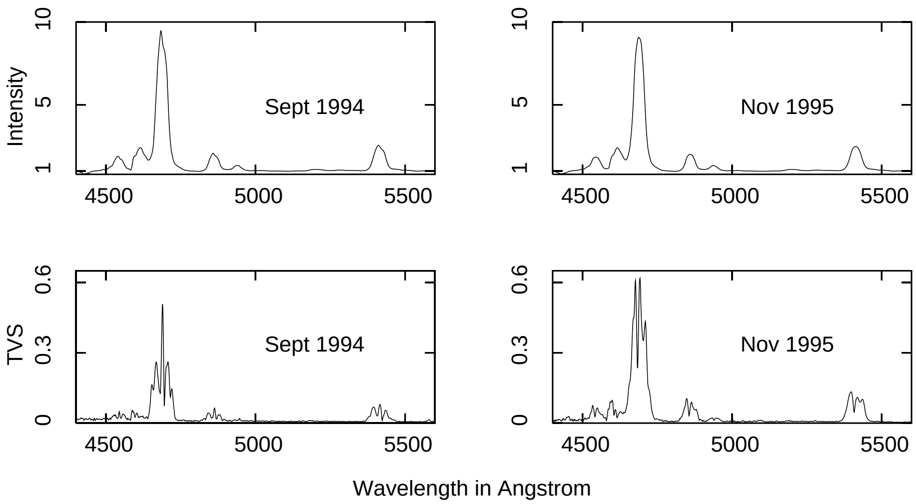

Fig. 4. The mean spectra (top) and TVS (bottom) for the two runs in September 1994 (left) and November 1995 (right). The mean profiles of HeII lines differ between runs but are identical for all He II lines within a run. The same concerns TVS in all observed He II profiles. All He II lines within one run show exactly the same variability pattern (TVS). The variability during the Nov 1995 run is stronger than in Sept 1994 data.

Table 2. Measurements (mean values within an observing run) for the observed He II lines.

Line	FWHM mean of September 1994	EW	FWHM mean of November 1995	EW
4542	31.3	22.0	32.0	22.9
4686	39.1	348.4	40.1	361.5
4860	33.8	37.6	34.8	39.1
5411	41.9	68.1	42.1	69.5

Table 3. Central intensities (Ic) and the amplitude of TVS for the observed emission lines in both runs.

Date		He II 4542	He II 4860	He II 5411	He II 4686	N V 4945	N III-V 4615
Sept	Ic	1.89	2.07	2.55	9.47	1.33	2.41
1994	TVS	0.049	0.064	0.079	0.507	0.019	0.042
	$\frac{TVS}{Ic-1}$	0.055	0.060	0.051	0.060	0.058	0.029
Nov	Ic	1.84	2.00	2.48	9.07	1.33	2.40
1995	TVS	0.0075	0.104	0.130	0.608	0.022	0.053
	$\frac{TVS}{Ic-1}$	0.089	0.104	0.088	0.075	0.067	0.038

sion line spectrum in the upper panels and TVS[1] (lower panels), which in case of all observed helium lines are very similar to that described by Niedzielski (2000) for He II 5411. It shows that the variability in the case of He II lines takes place mainly in the central part of observed profiles. Detectable profile variations are observed however already at projected velocities of over $\pm$ 1500 km s^{-1}. The equivalent widths and line widths (FWHM) for both runs (mean values) are presented in Table 2.

It appears also that although the general shape of the spectrum is similar, all observed profiles of emission lines (averaged over a run) are different in both runs. However, all observed He II lines show identical (on average) profiles within one run. This surprising finding was first reported by Niedzielski (1996). Morel et al. (1999) confirmed such correlation in the optical spectrum of HD 4004 through construction of Spearman rank-order correlation matrices for He II 5411 with He II 4686 and 4860. Morel et al. (1999a) found also the same behavior in the optical spectra of HD 191765. This property of helium lines is confirmed by the TVS plotted in lower panel of Fig. 4 where we can see that also the TVS for all He II lines appear similar within one run.

In Table 3 we present our measurements of central intensities Ic (in continuum level units), amplitude of TVS and the ratio of $\frac{TVS}{Ic-1}$. This ratio shows some scatter but it's value for all observed here He II lines is very similar and contrary to McCandliss (1992) we report that all He II vary with the same relative amplitude in HD 4004. Since according to models of WR envelopes (Hillier 1987) the helium lines observed here are effectively formed in distant layers of the envelope (see also Niedzielski 1994) we can also state that we do not see any development of the amplitude of the line profile disturbing agent outward in the envelope. On contrary our observations suggest that it is constant, at least in the zone of the envelope where the He II lines are formed. It is true, however, that the amount of variability, or the amplitude of TVS is different during different observing runs. In our case the data of November 1995 show much larger ($\sim$50%) variations.

Due to relatively low resolution of presented data we are not in position to discuss in detail (as in Niedzielski 2000) possible similarities or differences in the TVS shape of lines of other ions covered by our spectra. We are able to identify TVS variations above the p=1% level only for the N III-V blend at around λ 4615 and the N V line at λ 4945. In case of the former one the amplitude of the TVS variations as presented in Table 3 is low, factor of 2 lower than that of He II lines. It is however difficult to interpret because of problems with identification of the most important component of the blend and possible influence of the P Cygni absorption of N V at λ 4606. The former one, N V λ 4945 varies by approximately the same amount as He II lines in September 1994 and a bit less in November 1995. The shape of the TVS for that line appears similar to helium lines in both

[1] Following the notation of Fullerton et al. 1996 we use the name TVS for(TVS)$^{1/2}$

Table 4. Projected velocities (in km s^{-1}) of five strongest individual distinguished extrema (peaks or valley) in TVS over observed He II lines. Their similarity within a run is noticeable. The peaks are not the same in both runs so any comparison between runs is not possible.

Line	v1	v2	v3	v4	v5
September 1994					
4686	-1216	-384	+128	+512	+1280
5411	-1130	-410	+89	+532	+1141
4860	-1110	-555	+123	+555	+1234
4542	-911	-251	+145	+541	+1070
November 1995					
4686	-748	-300	+211	+914	+1362
5411	-875	-321	+232	+787	+1230
4860	-771	-277	+216	+894	+1203
4542	-739	-277	+25	+580	—

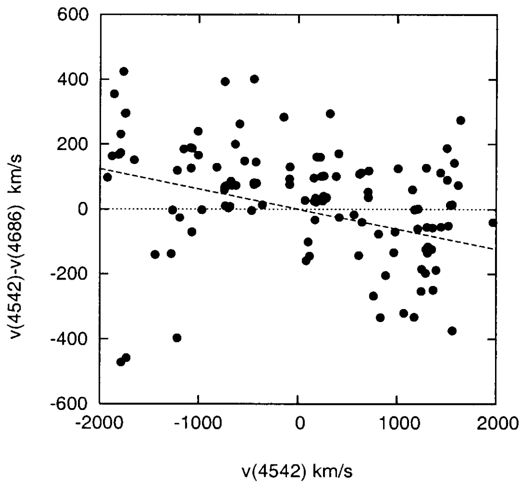

Fig. 5. Projected velocities of four individual peaks measured in "deformation patterns" of Nov 1995 data for two helium lines are compared. The velocity of a peak as seen in He II λ 4542 profile is presented as abscissa. The ordinate is the difference between projected velocity of the same peaks as observed in λ 4542 and λ 4686. The projected velocity (absolute value) is always larger in the wider line - λ 4686. The best linear fit is presented which shows that the difference in projected velocities reaches on average 6.2% of the velocity of a peak observed in he II λ 4542.

runs but again, due to low resolution we are not able to compare them in detail.

3.3. The sub-peaks evolution

We have mentioned already that not only the mean emission line profiles but also the shape of TVS within a run is identical for all He II lines. As presented in Fig. 4 the TVS for He II lines reproduces exactly the same features what is best seen in case of λ 4686 and 5411 which are the strongest (when comparing details displayed on TVS of different lines one has to remember that in our prismatic spectra the resolution is decreasing with wavelength).

The measurements of projected velocities of individual subpeaks (or valleys) present in TVS of lines under consideration are are presented in Table 4. We note an interesting property of those features, most clearly present in case of larger projected velocities. The projected velocity of a given, well identified sub-peak, present in all studied lines is usually highest in the strongest and widest lines and is decreasing in less intense, narrower or higher members of given series, lines. This is most readily seen when comparing λ 4686 and λ 4542, both recorded on our spectra with similar resolution but very different in widths.

To study this effect in more detail we have measured the projected velocities of individual, well identified features which were present in "deformation patterns" of all He II lines on the same spectrum. Such "deformation patterns," similar to that described in case of HD 191765 by Vreux et al. (1992) are obtained by subtracting the mean spectrum over a run from every spectrum (see also Figs. 2 and 3, middle panels). This way we have explored the fact that all He II lines have very similar shape at the same time (on one spectrum) and therefore an individual sub-peak in deformation pattern can easily be identified in all profiles.

Our measurements confirm similarity in observed line profiles. The correlation between positions of individual features in different He II lines is very high. For example in the case of λ 4686 and λ 4542 as observed in November 1995 this correlation reaches r=0.991. Similar situation is present in case of other line-pairs. However, projected velocities observed in different He II lines are not identical. In Fig. 5 we plot the difference of the projected velocities of the same four sub-peaks identified in two helium lines λ 4542 and λ 4686 in November 1995 run as function of the projected velocity of the same sub-peak in λ 4542. One can easily note that a shift is present in the projected velocity, rising rapidly on both sides of the profile center (zero velocity). The projected velocity of sub-peak present in profile of λ 4686 (its absolute value) is always larger than in λ 4542.

The projected velocities do not scale in different He II lines as the line widths (FWHM). The projected velocities measured in sub-peaks of λ 4542 are only 6% lower than in λ 4686 (best fit to data presented in Fig. 5) while the difference in FWHM suggest much larger difference of 20–25%. This difference suggest that general line profiles and small profile deviations are not formed in the same conditions: the general wind law is different from that governing motion of the disturbing factor seen exposed on emission lines. This further suggests presence of a two-component wind in HD 4004.

4. Towards a model of the variable wind of HD 4004

Of many models invoked in the literature so far to explain variability in similar objects the two-component wind with magnetic, equatorial disc of rotating star (Bjorkman & Cassinelli 1993, Ignace, Cassinelli, Bjorkman 1998) seems to be most adequate for HD 4004. However, to consider this model seriously one should address rotation, magnetic field and polarization of this object.

The role of rotation for stars evolving with mass-loss has recently been discussed by Maeder (1999), who finds the possibility of a strong enhancement of rotation velocity in stellar evolution towards the Wolf-Rayet stars through strong wind asymmetry (polar wind enhancement causing small momentum losses via stellar wind). The rotation velocity of any WR stars including WR 1 is not available but since the rotation velocity of WR progenitors, O stars is of the order of Vsin(i) 100–300 km s^{-1} and it may rise during evolution it is likely that WR stars are rotating with velocities which may be important for the shape of their winds. In the case of WR 1 the observed LPVs recurrence period is probably of the order of several days and may appear as reflection of rotation on non-uniform disc formed at the distance of several stellar radii.

The strengths of magnetic fields in case of WR stars are not known at all. The only indication of them might be the non-thermal character of radio emission. In the particular case of WR 1 the non-thermal character of radio emission was found by Altenhoff et al. (1994). This makes our considerations more likely.

Another factor supporting the two-component wind in case of HD 4004 would be any indication of non-spherical wind. That is very difficult since no polarization studies are available for WR 1 at all. The only support for such supposition may come form the IR excess reported by Hackwell (1974) which according to Coté & Waters (1987) can suggest optical polarization.

In such a two-component wind the source of LPV is located in the base of the slow wind, where probably a minor part of observed profiles is created. This is in agreement with an observational fact that only a small amount of a line profile varies. Most of line emissions comes from a more stable area. In the base of the slow wind a non-stable disk structure may temporally appear (Bjorkmann & Cassinelli 1993). Irregularities connected with the slow wind might travel outwards the envelope with velocity law different from that of fast wind where most of emission is created. The sudden appearance or disappearance of the unstable inner disc may result in photometric brightening as observed by Morel el al. (1999). Between large wind instabilities connected with violent disc creation/destruction the general brightness of WR 1 is relatively constant and only minor variations are observed as LPVs. The interactions of two wind components may however result in the observed, random X-ray variability (Wessolowski & Niedzielski 1996) of WR 1.

Two-component winds may change our understanding of the WR stars. Already Ignace, Cassinelli and Bjorkman (1998) noted that in such a case the momentum problem becomes much less severe. Another interesting consequence of the two-component winds may be a geometric differentiation of WR stars depending on which (fast or slow) wind we mostly observe.

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