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Spectroscopy of HD 4004. Search for fast spectral variability*

A. Niedzielski

Center for Astronomy, Nicholas Copernicus University, ul. Gagarina 11, 87–100 Toruń, Poland (aniedzi@astri.uni.torun.pl)

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Abstract. We present results of a detailed analysis of spectral variability observed in the optical spectrum of HD 4004 (WR1). On the basis of data obtained during monitoring of this object on 3 consecutive nights in Dec 1993, and two additional nights in Dec 1994 we show that the variability in He II λ 5411, C IV λ 5808 and He I λ 5876 may reach as much as 50% in equivalent width. This variability shows a systematic, gradual character, which justifies a search for periodicity. We show that the observed spectral-line-profile changes may mimic radial velocity variations but that any real radial velocity variations in the observed lines of HD 4004 are small. Our search for periodicity in the data was unsuccessful: the data do not show periodicities within the time covered by the observations ($\sim$ 2 days). Our data suggest, however, the existence of a longer-term variability pattern. We show that the observed pattern of the Temporal Variance Spectrum in different lines can be *qualitatively* understood in terms of stratification.

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

1. Introduction

Spectral variability among WR stars has recently been recognized as common (Moffat & Robert 1991; Robert 1994). Generally it can be divided into low-amplitude random variations, which probably reflect the non-continuous nature of winds, and larger line-profile variations (LPV) substantially altering the profiles, and sometimes showing a periodic or quasi-periodic pattern.

Due to its scale, the latter type of spectral variability of otherwise single WR objects is easier to observe even in the spectra of fainter stars and it has actually been known for a long time (Wilson 1948). In the past, it was however frequently attributed to binarity. Only very recently have these variation been studied in more detail (cf. Lépine et al. 1996; Lépine & Moffat 1999) and systematized by Lépine et al. (1999) into three groups: S (narrow and stochastic), R (broad and recursive) and P (strictly periodic) depending on the character of the modulations. The question of the nature of LPVs in WR stars remains open. Before it can be answered one needs a detailed description of the observed variability. Towards this end we present here the results of our observations of HD 4004.

The first photometric observation of HD 4004 was reported by Hiltner (1956). Later on this star was assumed to be a constant-light object until Moffat & Shara (1986) reported its weak variability. Lamontagne (1983) obtained a series of optical spectra of HD 4004 and found evidence of radial velocity variations with a possible period of $7\overset{\mathrm{d}}{.}746$ days and K=22 km s^{-1} (e=0). Line profile variations in HD 4004 were first reported by Niedzielski (1995). Later on Wessolowski & Niedzielski (1996) showed that there is no X-ray variability in the available data for this object and presented more evidence on LPVs on time scales of one night. A 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 of unique, short-lasting (3–4 days) photometric brightening of this object but found only marginal photometric variability in 11 additional days of photometric monitoring. Morel el al. (1999) were not able to find periodicity in their data.

In this paper we present the results of a complete analysis of two observing runs aimed at the detection of possible short-term periodicities in the optical spectrum of HD 4004.

2. Observations

The observations reported here were taken with the Mt. Ekar 1.82 m telescope of the Padova Astronomical Observatory (Italy) between Dec 3 and 7 1993 (first run) and on Dec 13 and 15 1994 (second run). During six nights (Dec 4–7 1993, and Dec 13, 15 1994) the telescope was equipped with a Boller & Chivens spectrograph (1200 gr mm^{-1} grating) and a CCD cryogenic detector. With this configuration we reached a 1 Å pix^{-1} reciprocal dispersion in the 5350–5950 Å range. We obtained 56 spectra in four consecutive nights of 4–7 Dec. 1993, and an additional 20 in Dec. 1994. During both runs the temporal resolution of the spectra obtained in the course of one night when more than one spectrum was taken was of the order of 15–30 min, enabling us to search for variability on both long (days) and short (hours) time-scales. In these conditions an S/N ratio of 50–100 was reached at the continuum level allowing

* Based on observations obtained with the 1.82 “Copernicus” telescope of the Padova Astronomical Observatory in Mt. Ekar (Italy).

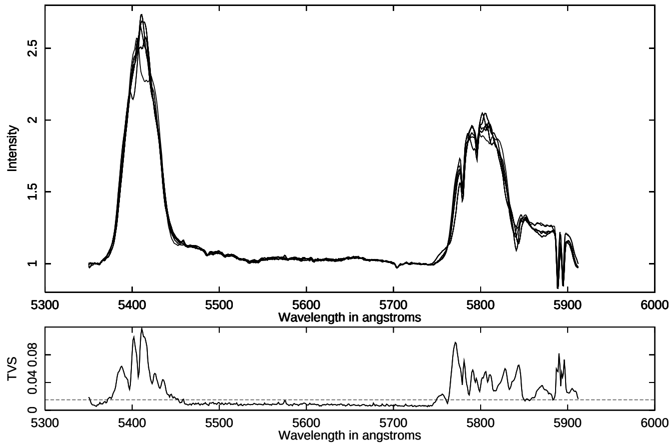

Fig. 1. Temporal variance spectra computed from all 75 spectra collected during two runs: on 4–6 December 1993 and 13,15 December 1994. The contour corresponding to a statistical significance of p=1% is included (dashed line). The variability in the wavelength range occupied by the emission lines is evident. See text for details.

Table 1. Journal of observations

Date	Mean JD-2449000	Number of spectra	Reciprocal Dispersion Å pix^{-1}
3 Dec 1993	325.5631	2	1.9
4 Dec 1993	326.3558	23	1.0
5 Dec 1993	327.5190	21	1.0
6 Dec 1993	328.3784	11	1.0
7 Dec 1993	329.5082	1	1.0
13 Dec 1994	700.4277	15	1.0
15 Dec 1994	702.3472	5	1.0

us to trace details in the observed emission lines. Comparison lamp (Fe - Ar) spectra were taken between the object exposures, several times during each night, allowing us to reduce possible instrument flexure. On Dec 3, 1993, additional spectra were obtained within another project, in a different instrumental setup, with the 600 gr mm^{-1} grating, resulting in two times lower resolution. For more details, including mean Julian day of observations see Table 1. The spectra were reduced with the standard procedures of IRAF. Based on the identification of well exposed IS lines (Na I 5890, 5896) small shifts in wavelength scale were calibrated. The equivalent widths (EW) and various line profile parameters were determined using the ReWiA system (Borkowski 1992).

3. Results

3.1. Observed variability

In the upper panel of Fig. 1 we present mean spectra of the 5 nights obtained with the same instrumental settings, three in December 1993 and two in December 1994. The variability is most evident in the central part of the He II line at λ 5411 which shows a different shape each night. This line can be approximated by a Gaussian round-topped profile with a central intensity of 2.64 in continuum level units, a FWHM of 38.8 Å and an EW of 67.6 Å, on average. The peak intensity of this line varies in both position and intensity. The strongest variations[1] occur between -890 km s^{-1} and +780 km s^{-1}. They appear mainly in the wavelength range where the intensity of the line is more than 65–80% of the central value. The center of the profile of He II is located on average at approximately its rest wavelength, with only a slight red-shift: RV=+28 $\pm$2 km s^{-1} (average from all our spectra). The red, electron scattering wing of the line does not vary significantly We studied the central intensity, the mean position determined from a Gaussian fit and the position of the peak of the profile, the EW and the skewness for this line. The EW was determined by integration of the observed profile over $\lambda\lambda$ 5362–5462 Å.

Table 2. Daily means and standard deviations of displacements (RV) of He II 5411

JD-244900	RV in km s^{-1} 5411 center	5411 peak	IS 5797
325.5631	(1)	(151)	(25)
326.3558	14±5	278±41	2±11
327.5190	28±8	78±68	11±9
328.3784	31±15	33±26	0±8
329.5082	(24)	(-54)	(-4)
700.4277	45±12	-22±24	0±10
702.3472	49±5	-238±30	15±11

Another line studied here in detail is C IV λ 5808. This line also shows an approximately round-topped profile, with intensity of ~2.0 (in units of the continuum), and an equivalent width of 53.3 Å on average. From the top panel of Fig. 1 it is clear that this line undergoes substantial variability as well. However, it behaves in a different way compared to He II λ 5411. Here the variability shows up practically from the continuum level on the blue side up to the blue border of He I λ 5876 Å. The EW of C IV is measured by integration of the observed profile between λ 5740 and λ 5840 Å. The position of the center of the C IV λ 5808 line is stable but blue-shifted, as noted already in Niedzielski (1998). Here however, after calibration of the wavelength scale using interstellar features the shift is found to be somewhat smaller: -137 $\pm$ 2 km s^{-1} (averaged over all data). We did not try to trace the position of the peak intensity of this line since it is badly defined - two diffuse interstellar bands (DIBs) at $\lambda\lambda$ 5780 and 5797 influence it strongly.

At λ 5840 Å a minimum between C IV λ 5808 and He I λ 5876 is reached. This may be the P Cygni component of the He I line, as expected from models of WR envelopes (Schmutz 1997).

The third line we observe is He I λ 5876. Allowing for the influence of the red tail of CIV 5808, it shows a typical flat-topped profile (sometimes even depressed in the center) which follows the (possible) P Cygni absorption and is assumed here to extend from λ 5840 up to λ 5910 Å - Fig. 1 (top panel). This

[1] All radial velocity data are referred to the laboratory wavelengths of observed interstellar lines.

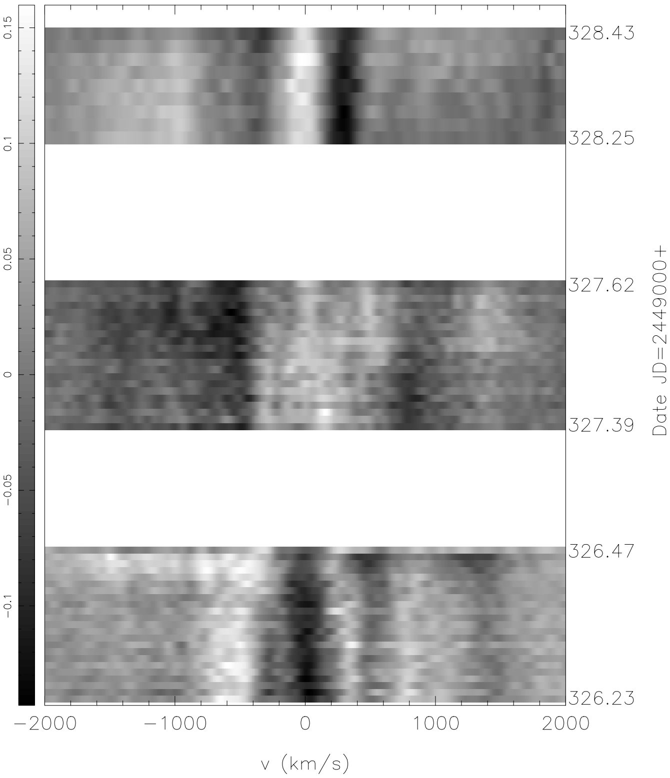

Fig. 2. Gray-scale montage of the He II λ 5411 variations as observed in December 1993. The mean spectrum of this run is used as a template. Nightly changes of the profile are slow but noticeable. The difference between profiles of different nights is evident. For every night the mid-time of first and last exposure is given.

line seems to vary much less than C IV λ 5808 and He II λ 5411; however, it is much weaker. We observe mainly variations of the central part of the profile which we locate at λ 5871 Å. Due to its complicated shape no wavelength shifts were measured for this line. The EW was obtained via integration of the profile over its total extent as given above.

By subtracting the mean profile from a single spectrum we can follow the nightly variations of the line profiles in detail. This is shown in Fig. 2 for the He II line as observed during the first (longest) run in December 1993. One can see that the variations during one night are slow (cf. Wessolowski & Niedzielski 1996; Morel et al. 1999). Differences between profiles observed during following nights are substantial, however (cf. Fig. 1).

3.2. Temporal Variance Spectrum (TVS) analysis

Our qualitative description of the variability is supported by the Temporal Variance Spectrum (TVS) analysis (Fullerton et al. 1996). In the lower panel of Fig. 1 we plotted the TVS^2 spectrum calculated from the 75 spectra taken in the course of the two runs. The ordinate gives the amplitude of the deviations as a percentage of the normalized continuum. The contour corresponding to a the statistical significance for p=1% is shown as well (dashed line).

It is evident from the TVS analysis that all three line profiles described above are variable. In the case of He II λ 5411 the TVS confirms that the variability takes place mainly in the central part of the profile. Some variability, with TVS above the p=1% level appears however in a larger range from -1885 km s^{-1} to +1774 km s^{-1}. The discrete character of the TVS in the range of the helium line is interesting but may reflect the limited temporal resolution of our data. The positions of the individual peaks are more or less symmetric; the five most prominent ones are located approximately at -1275, -500, 0, +830, +1330 km s^{-1}.

The TVS for the spectral region occupied by the C IV line λ 5808 has a different shape. Here we see variability of practically the whole profile. Again one can see several peaks in the TVS curve. They appear at different wavelengths than those in He II λ 5411 and even with a possible radial velocity shift of the C IV line, and allowing for its doublet nature, we can find no correspondence between them. The last strong peak of TVS close to the C IV line at $\lambda \sim 5840$ represents the variability of the (possible) P Cygni absorption.

The TVS for He I λ 5876 confirms significant variability in the central part of the profile only. This variable region of the profile extends from -1000 km s^{-1} to +360 km s^{-1}. Maximum variability is seen at λ 5871 (-255 km s^{-1}).

The close double peak of the TVS curve seen in Fig. 1 (lower panel) is due to the interstellar lines of Na I at λ 5890 and 5896. However, the reason for it is not variability. This rise of TVS is connected with a fall of S/N at the bottom of these strong absorption features and with the fact that these narrow lines are not completely resolved in our spectra.

The profile variations described by TVS when compared to the line central intensity (Ic-1) are largest in He I λ 5876, TVS/(Ic-1)=0.16. In C IV λ 5808 line this ratio reaches 0.06 and in He II λ 5411 - 0.07.

3.3. Radial velocity variations

As we have shown the most striking variations of the He II line λ 5411 are present in its center - Fig. 1. Both intensity and wavelength of the peak of this line vary. The variations of the position of the peak intensity of λ 5411 and of its mean position (the latter determined from a Gaussian fit), are presented in Fig. 3 and in Table 2. The abscissa is given in Julian Days since JD=2449000.0 (arbitrary).

The position of the peak (nightly mean) changes linearly from +278 km s^{-1} on Dec 4, 1993 to -238 km s^{-1} in Dec 15, 1994. On Dec 4, 5 and 6 1993 we can see a systematic decrease of the shift of the peak of the He II line. On Dec 13 and 15 the peak of the observed profile moves in the same direction, towards the blue. The additional lower-resolution spectra taken on Dec 3 and the only spectrum of Dec 7 (1993) seem to fit the trend. The middle panel of Fig. 3 presents the variations of the position of the center of He II λ 5411. The amplitude of these variations is much lower and the line seems to be always red-shifted by 14–49 km s^{-1}. The observed amplitude of these

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

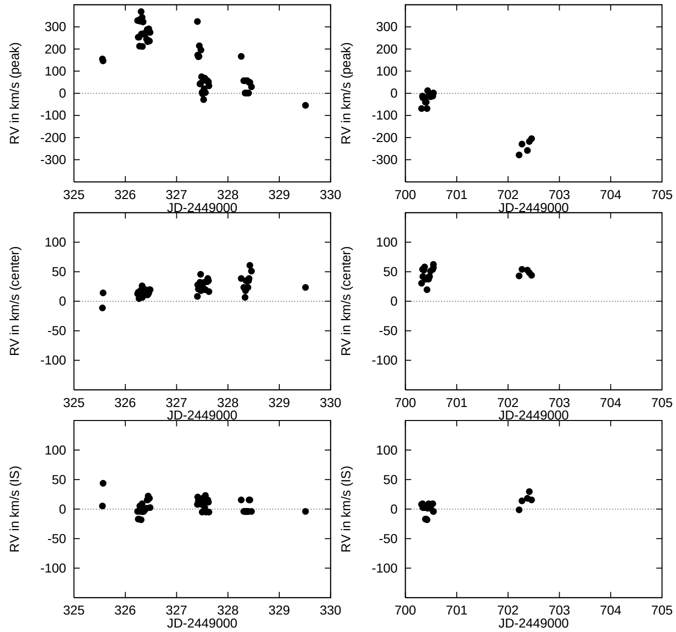

Fig. 3. Variations of the peak (top) and mean position as determined from a Gaussian fit (middle) of He II λ 5411 expressed in km s^{-1} vs Julian Day after 2449000.0 (arbitrary). The shifts of the IS 5797 template (bottom) used as indication of RV accuracy are shown for comparison. The data from the two runs are presented, viz. Dec 93 (left) and Dec 94 (right). Additional points obtained one night before the first run and the only spectrum of Dec 7 1993 are shown as well.

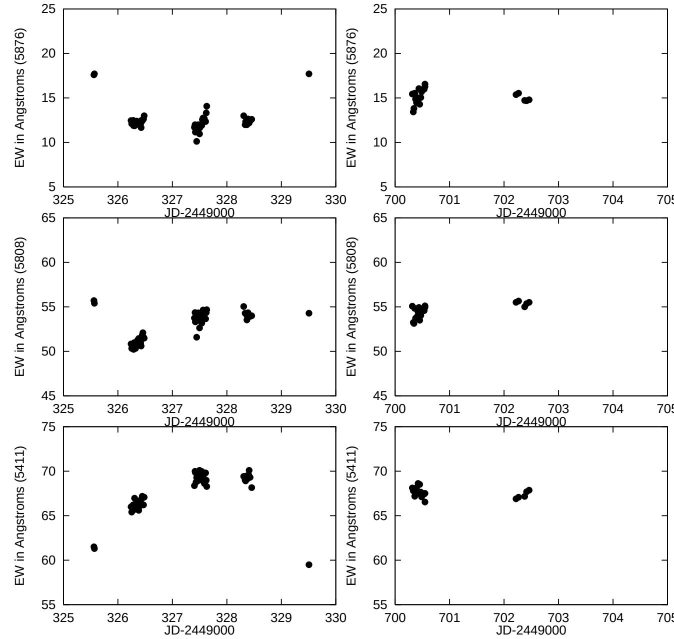

Fig. 4. Equivalent widths of He II λ 5411 (bottom), C IV λ 5808 (middle) and He I λ 5876 (top) are plotted vs Julian Day after 2449000.0 (arbitrary). The data from two runs are presented, viz. Dec. 93 (left) and Dec. 94 (right). Additional points obtained one night before the first run and the only spectrum of Dec 7 1993 are shown as well.

displacements is 35 km s^{-1}. Maximum redshift of the He II λ 5411 line center is reached on Dec 15, 1994 (+49 km s^{-1}). Only these variations may be interpreted as radial velocity variations of HD 4004.

In the lower panel of Fig. 3 the variations of the position of DIB at λ 5797 Å are plotted. They illustrate errors present in our data which affect the RV determinations. We can see that the scatter in the average nightly values of position determinations is usually below 15 km s^{-1}.

3.4. Equivalent widths

Not only the positions and the shapes of spectral lines are variable in HD 4004, we can see in its spectrum EW variations as well. The most precise EW data are expected for the He II line since the continuum level is obvious and the line is unblended. However, in the EW of this line some influence of its red (electron scattering) wing is certainly present due to the measurement procedure applied. The red end of the C IV line is not clearly seen so the spectral range used is a bit arbitrary. This should be kept in mind when comparing our EW data for this line with other results. The measurements for the He I lines have the largest uncertainties.

The resulting EWs (in Å) are plotted versus time in Fig. 4. The data collected during the 3 nights of contiguous monitoring in Dec 1993 (left panel) show a variability of the order of 5–10% in EW of the He II and C IV lines and some 25 % in He I. Less variability seems to be present in the data from the second run (right panel).

When the supplementary data of December 1993 are also considered, the amount of variability in this run reaches some 15% in the case of He II and almost 50% in the case of He I. The mean values of the measured equivalent widths are given in Table 3.

Table 3. Daily means and standard deviations of equivalent widths

JD-244900	EW in Å		
	He II λ 5411	C IV λ 5808	He I λ 5876
325.5631	(61.4)	(55.6)	(17.7)
326.3558	66.2±0.5	51.0±0.5	12.3±0.3
327.5190	69.3±0.6	53.8±0.7	12.0±0.8
328.3784	69.2±0.5	54.2±0.4	12.4±0.3
329.5082	(59.5)	(54.3)	(17.7)
700.4277	67.7±0.5	54.3±0.7	15.2±0.9
702.3472	67.3±0.4	55.4±0.3	15.0±0.4

3.5. Period search

The data presented were obtained in a mode suitable for analysis of short period variations. Actually during the first run, in December 1993, we obtained 55 observations within three nights. The length of monitoring during a night depended on local weather conditions. The largest number of observations was obtained during the night of Dec 4 (δt=0$^{\rm d}_{.}$0104). This night, the longest night of this run, lasted ΔT=0$^{\rm d}_{.}$2402 (almost 6 hours). During the following run, in December 1994 we also obtained

ΔT=0$^{\rm d}_{.}$2418 of monitoring (Dec 15) but with a much lower frequency of observations (δt=0$^{\rm d}_{.}$0484).

The period search was performed using the Lomb periodogram method as presented in Numerical Recipes in C (Press et al. 1992) with the number of independent frequencies found using a Monte Carlo technique according to Horne & Baliunas (1986).

We started the period search with datasets obtained from single nights separately and then combining those from the three nights of December 1993 and the two nights of December 1994 respectively. The data from the individual nights of both runs contain no detectable signals with periods between 4 and 45 cycles per day (P=30 min – 6 hours).

The combined data for the December 1993 run do show peaks in periodograms at $\nu \approx$ 0.7, 1.2 and 2.2 cycles per day (P $\approx$ 1$^{\rm d}_{.}$4, 0$^{\rm d}_{.}$83 and 0$^{\rm d}_{.}$45 respectively). These frequencies appear in the EWs of He II 5411 and C IV 5808, the central intensity of He II 5411, the intensity of the P Cygni component of the He I line at λ 5840, in skewness of He II 5411 and in peak intensity of He II 5411. No significant periodicities are present in the December 1994 data. Unfortunately all of the above mentioned signals appear also in randomly interchanged data as well as in random data placed at the same time points as our observations. We are therefore not able to interpret the periodicities found as real. We conclude that they represent the observational window.

Our set of the December 1993 data used for searching periodicities can be extended by adding the two spectra taken on Dec 3, 1993 and the sole spectrum of Dec 7, 1993. A sine fit to these (non-uniform) data shows a period of 5$^{\rm d}_{.}$2–5$^{\rm d}_{.}$5. This period is however longer than our longest run in December 1993 (ΔT=3$^{\rm d}_{.}$95 including all data).

4. Summary and conclusions

The EWs of the emission lines observed here varied by 5–50 % during the period covered by our observations. Although the scatter within one night is of the order of 0.5 Å we observe *systematic* changes of some 3–4 Å during a night, and larger during several nights, which we assume to be real.

In HD 4004 the line profile of the He II λ 5411 shows variability which also affects the position of this emission line, inducing variations similar to radial velocity variations due to binarity. The position of the peak of He II λ 5411 line may vary by over $\pm$ 500 km s^{-1}, well above the resolution of a single observation. At the same time the position of the line center varies by no more than 35 km s^{-1}, actually below the resolution of our data. Taking into account that the estimated accuracy of RV determination is 15 km s^{-1} we interpret these minor variations as a reflection of profile variability.

The period search in the combined data shows no real periods between 30 min and $\sim$2 days. The 0$^{\rm d}_{.}$775 day period proposed in Niedzielski (1996) is probably not real but reflects the observational window. The smooth variation of observed quantities suggests however the existence of some periodicity longer than the time covered by the observations. A similar conclusion is also reached by Morel et al. (1999).

Following the discussion of possible binarity of WR1 presented by Morel et al. (1999) we can state that the lack of periodicity less than $\sim$ one day reported here excludes binarity with a degenerate, low-mass object as a possible explanation of the observed variability. Since binarity with a non-degenerate component was excluded by Morel et al. (1999) we can state that WR1 is most probably a single object.

The described spectral variations are not of the same character in all lines observed here. One may try to interpret this behavior *qualitatively* in terms of the production of line profiles in an extended wind with monotonic velocity law. The central part of an emission line profile is created in the slowest, most inner, part of the wind acting over the area of line creation (cf. Bowen et al. 1997). If such an idealized model can be *qualitatively* accepted for HD 4004 we can state that the variability seen in the center of He II λ 5411 reflects some kind of activity at the base of the area of the envelope, where this line arises. The behavior of the two other lines observed here can be further interpreted by recalling the ionization stratification picture of Kuhi (1973). The C IV line which, according to the stratification scheme, should be created in a deeper part of the envelope than He II, shows variability in the whole profile. It seems to be wholly created in the violent wind base zone. In contrast, the He I line, created in the outermost part of the envelope (wind), shows variability only in the most central part of its profile.

The base of the line-forming region can be identified with the thick/thin border of the wind. According to Marchenko & Moffat (1999), in the most active (variable) WR star winds substantial speeds are reached already at the inner base of the thin wind. This is the case for the stars WR 6, WR 134 and those of type WN8. For HD 4004 we estimate from the spectra presented in Niedzielski (1998) that $v_{\rm phot}/v_{\infty}$ = 0.57 (using N V λ 4603), very close to the values for WR6 and WR134 (Marchenko & Moffat 1999).

If the thick wind zone has such a high velocity on its outer border it must be very extended. Any fluctuation of this part of the wind (which may appear due to rapid acceleration of matter) when reaching the thin wind base may give rise to spectral variability observed in lines at least partly created at the base of the thin wind. A possible rotation of the WR core may additionally influence the variability by adding a recurrent (periodic) pattern. With such a fluctuation spiraling outwards, the wind may further influence other lines when passing zones where they are formed.

HD 4004 certainly deserves more systematic observations aiming at a more detailed TVS analysis (higher time and spectral resolution, longer observing runs) and determination of possible periodicity (longer observing runs). With a possible time scale of recurrence of several days it is an ideal target for a multi-site or space program. The different character of variability in different lines may help us to understand the nature of the observed variations; therefore, also multi-wavelength observations are highly necessary. The non-uniformity of the WR winds may appear, paradoxically, to be the key to understanding their internal structure.

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