LARGE-SCALE PERIODIC VARIABILITY OF THE WIND OF THE WOLF-RAYET STAR WR 1 (HD 4004)*

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ABSTRACT

We present the results of an intensive photometric and spectroscopic monitoring campaign of the WN4 Wolf–Rayet (WR) star WR 1 = HD 4004. Our broadband V photometry covering a timespan of 91 days shows variability with a period of $P = 16.9^{+0.6}_{-0.3}$ days. The same period is also found in our spectral data. The light curve is non-sinusoidal with hints of a gradual change in its shape as a function of time. The photometric variations nevertheless remain coherent over several cycles and we estimate that the coherence timescale of the light curve is of the order of 60 days. The spectroscopy shows large-scale line-profile variability which can be interpreted as excess emission peaks moving from one side of the profile to the other on a timescale of several days. Although we cannot unequivocally exclude the unlikely possibility that WR 1 is a binary, we propose that the nature of the variability we have found strongly suggests that it is due to the presence in the wind of the WR star of large-scale structures, most likely corotating interaction regions (CIRs), which are predicted to arise in inherently unstable radiatively driven winds when they are perturbed at their base. We also suggest that variability observed in WR 6, WR 134, and WR 137 is of the same nature. Finally, assuming that the period of CIRs is related to the rotational period, we estimate the rotation rate of the four stars for which sufficient monitoring has been carried out, i.e., $v_{\text{rot}} = 6.5, 40, 70,$ and $275$ km s$^{-1}$ for WR 1, WR 6, WR 134, and WR 137, respectively.

Key words: stars: individual (WR1, HD 4004) – stars: rotation – stars: winds, outflows – stars: Wolf–Rayet

Online-only material: color figures

1. INTRODUCTION

The winds of Wolf–Rayet (WR) stars are well known to be non-uniform on small physical scales. Because of the inherently unstable nature of radiatively driven hot stellar winds (Owocki et al. 1988), instabilities, which reveal themselves in the spectrum as narrow excess emission peaks superposed on the broad emission lines, appear stochastically, propagate in the wind and disappear after several hours (e.g., Moffat et al. 1988). This clumpiness leads to emission lines that are variable at a level of up to $\sim 5\%$ of the line flux (St-Louis et al. 2009). These changes are, of course, random and no periodicity is expected.

In certain cases, WR stars also display large-scale line-profile variability (lpv). For some stars this spectroscopic variability has been shown to be periodic and to originate from different physical processes. Of course, known massive WR+O binaries produce clear periodic radial-velocity (RV) variations from the orbital motion of the stars. It has also been realized in the past two decades that in such systems the winds from the stars collide, forming a shock cone that wraps around the star with the smaller momentum flux (generally the O star). This interaction induces kinematically characteristic variations in the line profiles that are also periodic.

However, large-scale lpv has also been found in WR stars that are not known to be binaries. The two most studied cases, WR 6 (WN4) and WR 134 (WN6), have been monitored intensively in photometry and spectroscopy by Morel et al. (1997, 1998, 1999b). In both cases, these authors have observed periodic large-scale lpv and a complex light curve with the same periodicity. To that list of two stars we may also add WR 137, a WC7pd star in a long-period binary system. This star shows large-scale lpv with a period of 1.2 days that is unlikely to be related to its O9 companion nor to the wind–wind collision zone (Lefèvre et al. 2005a). This behavior is most likely explained by the presence of large-scale density structures in the wind, such as corotating interaction regions (CIRs; Cranmer & Owocki 1996; Fullerton et al. 1997), but the possibility of the presence of a compact companion or of a low-mass main-sequence star cannot be completely excluded.

If the large-scale lpv and the photometric variability of single WR stars can be associated with CIRs, it may imply that the period of these variabilities corresponds directly to the rotational period of the star. Indeed, Cranmer & Owocki (1996) propose that “spots” fixed to the stellar surface, caused either by pulsations or magnetic field activity, are at the origin of the CIRs. Hence, once the radius at which the CIR originates is known, we can determine the rotational velocity of the star at that point. It follows that the rotation rate of at least some WR stars could in principle be determined by carrying out a systematic investigation of the variability of all single WR stars. As a first step, St-Louis et al. (2009) and A.-N. Chene & N. St-Louis (2010, in preparation) set out to identify new candidates for CIR-type variability by conducting a survey of all apparently single Galactic WR stars brighter than $v \sim 12.5^m$ magnitude. For each star in their sample, they obtained 4–5 spectra which allowed them to establish a list of WR stars.

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showing large-scale lpv. The next step is to observe intensively each of the candidates in order to verify and determine the periodicity.

In the above-mentioned survey, WR 1 was one of the most striking cases of large-scale lpv with changes reaching 8%−10% of the line flux and easily distinguishable large-scale subpeaks superposed on the broad wind emission profiles. Consequently, it was the first WR star on which we concentrated our efforts. Several previous studies claiming unreproducible periods for the variability of this star have been summarized in Morel et al. (1999a). Later, Niedzielski (2000a, 2000b) demonstrated that the spectrum of WR 1 varied greatly from night-to-night reaching 50% in the equivalent width of the He λ5876 line. On the other hand, they found that line-profile changes during one night are much smaller with a typical scatter of 0.5 Å in equivalent width for the He λ5411, C iv λ5808, and He λ5876 lines. The changes, however, were found to be systematic during the course of an entire night and reach a total of 3−4 Å. Moreover, the search for periods smaller than two days failed and only indications of long-term variability could be suggested. The investigation of photometric variability over more than 16 days carried out by Morel et al. (1999a) did not lead to the identification of a period. Consequently, the period search must be done using data taken over a time range of at least twice as long. More recently, Flores et al. (2007) claimed a period of \( P = 7.684 \) days in lpv of this star which they attribute to the ejecta of streams or jets from the stellar surface.

In this paper, we present the results of an intensive monitoring campaign of WR 1 extending over several weeks in photometry and spectroscopy with the aim of determining the nature of the variability and, eventually, if found to be associated with CIRs as suspected from our survey observations, the rotation period of WR 1. In Section 2, we present our photometric and spectroscopic observations and the data reduction procedures. In Sections 3 and 4 we discuss our results, and in Section 5 we discuss the possible interpretations. Finally, our conclusions are presented in Section 5.3.

2. OBSERVATIONS

2.1. Photometry

We monitored WR 1 in broadband \( V \) using CCD-imagery at the 0.81 m Tenagra Observatory Ltd. from 2003 November 20 to 2004 February 18. During this period covering 91 nights, three frames were obtained in succession every clear night with an exposure time of 60 s. Three additional frames with a 45 s integration time were obtained at an airmass of \( \sim 1.45 \) during the first 43 nights and three others with a 30 s integration time at an airmass of \( \sim 1.65 \) during the first 11 nights. Due to problems with the detector in 2003 December–2004 January, which resulted in a gap in our data set of almost 20 days, 33 frames were unusable. Also, 87 others were rejected due to bad seeing and/or low transparency of the sky, giving finally a total of 231 usable frames. In order to correct for the differential refraction of the atmosphere, we observed three frames in broadband \( B \) during two very clear nights at Tenagra Observatory Ltd., i.e., 2003 December 6 and 17, for a total of six frames.

All images were uniformly reduced using standard procedures carried out with routines written in Interactive Data Language (IDL). After the bias, dark and flat-field treatments, we performed aperture photometry using the APER Astrolib routine in IDL on all stars present in the field of WR 1. We adopted an aperture size equal to twice the FWHM of the point-spread function (PSF) and an annulus of sky was selected with inner and outer radii of, respectively, 4 and 8 times the FWHM of the PSF.

Once the photometry was obtained for all frames, we then applied a correction for the differential refraction of the atmosphere. To do so, we needed to know how the flux of a star varies with airmass and according to the slope of its spectrum. For each star in our field of view (FOV), a relative \((B−V)\) color was obtained by subtracting the average fluxes measured in the \( B \)- and \( V \)-band frames observed at the same airmass. We then obtained the slope \( M \) of the linear relation describing the variability of the flux as a function of airmass for each star during the best clear nights. Although a certain number of stars can present intrinsic flux variations within a single night, we can assume that it is not the case for most of them. Using a robust least absolute deviation method, we fitted \( M_{B−V} \), the slope of the flux–airmass relation appropriate for a given \((B−V)\) color, and obtained a linear expression for the correction that must be applied to the flux as a function of airmass. The final corrections are contained in a range of 0.1%−1%.

The final light curves were obtained by subtracting the magnitude of WR 1 to that of two comparison stars (see Figure 1). Since no star with a magnitude similar to that of WR 1 was available in the FOV, we decided to average the brightest stars showing small light deviations. Ten stars were selected and divided in two groups to create two comparison stars of similar magnitudes. The accuracy of the final light curve of WR 1 varied during our observing period. We have thus estimated a typical error for each day as follows: for a time interval of 10 days centered on a given day of observation, we have calculated the standard deviation \((\sigma)\) of the \( c1−c2 \) light curve. All values are shown in the bottom panel of Figure 1. For the entire observing period, the standard deviation is \( \sigma = 0.012 \) mag.

2.2. Spectroscopy

We collected a total of 326 spectra of WR 1 during five dedicated runs distributed in 2003 July–August and 2004 August–October with the 1.52 m telescope of the Observatoire de Haute-Provence (OHP), the 3.6 m Canada–France–Hawaii Telescope (CFHT), the 1.6 m telescope of the Observatoire du Mont Méjantique (OMM), and the 1.85 m telescope of the Dominion Astronomical Observatory (DAO). The details of these observing runs are summarized in Table 1. We list the run number, the telescope used, the dates of the observations, the wavelength coverage, the spectral resolution, the number of spectra obtained, and the average signal-to-noise ratio \((S/N)\). Unfortunately, no spectra were obtained simultaneously with our photometry described in the previous section.

The bias subtraction, flat fielding, spectrum extraction, sky subtraction, and wavelength calibration of all spectra were executed in the usual way using the IRAF4 software. Calibration-lamp spectra were taken every 30–40 minutes depending on the run. The accuracy of the wavelength calibration estimated by measuring the wavelength of 10 lamp emission lines is variable depending on the instrument used. It is 0.005 Å for OHP, 0.2 Å for \( \lambda < 5200 \) Å and 0.02 Å for \( \lambda > 5200 \) Å for CFHT, 0.01 Å for OMM, and 0.04 Å for DAO. Special care was taken for the normalization of the spectra. First, a mean was made for each run. Then, each spectrum of a run was divided by the run mean and the ratio fitted with a low-order Legendre

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4 IRAF is distributed by the National Optical Astronomy Observatories (NOAO), which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation (NSF).
Figure 1. Light curve of WR 1. The top and middle panels show the difference between the magnitude of WR 1 and that of the “artificial” comparison stars c1 and c2, respectively, as a function of time. Both c1 and c2 were constructed from the average of five bright stars. The six cycles of the 16.9 day period covered by the photometric data set are delimited. The bottom panel shows the difference between the magnitude of c1 and c2 as a function of time. A series of vertical lines show the typical error as a function of time (see the text for details).

Table 1

| Run | Telescope  | Dates (UT) | λ Coverage (Å) | Δλ (3 pixels) | No. of Spectra | S/N |
|-----|------------|------------|----------------|---------------|----------------|-----|
| 1   | OHP 1.52 m | 2003 Jul 7–14 | 5230–6140 | 1.4 Å | 30 | 135 |
| 2   | CFHT       | 2003 Aug 8–13 | 4380–6240 | 1.5 Å | 33 | 185 |
| 3   | OMM        | 2003 Aug 22–24 | 4900–6020 | 1.6 Å | 9 | 130 |
| 4   | OMM        | 2004 Aug 21–2004 Sep 6 | 4310–6440 | 1.6 Å | 170 | 145 |
| 5   | DAO 1.85 m | 2004 Sep 18–2004 Oct 13 | 5140–5980 | 1.4 Å | 84 | 90 |

polynomial (between fourth and eighth order). The original individual spectrum was divided by this fit, and was therefore at the same level as the run mean. When this procedure was done for each run, the run means were then put at the same level by using the same procedure as described above. This allowed us to put all individual spectra at the same level. Then, we combined all run means into a global, high-quality mean, which was then fitted in selected pseudo-continuum regions, i.e., wavelength regions where large emission lines do not dominate. More specifically, these regions are 4376.0–4381.0 Å, 4473.0–4477.0 Å, 4798.0–4816.0 Å, 5002.0–5147.0 Å, 5349.0–5362.0 Å, 5558.0–5663.0 Å, 5956.0–5992.0 Å, and 6295.0–6321.0 Å. These regions are shown in Figure 4, which we will discuss later in Section 4. Finally, the fitted continuum function is applied to each individual spectrum. The error on the continuum normalization measured as the standard deviation of individual spectra around the continuum function is typically of 0.5%.

3. PHOTOMETRIC VARIATIONS

The light curve of WR 1 is plotted as a function of the Heliocentric Julian Date (HJD) in Figure 1. The flux from the star alternatively increases and decreases with an amplitude that varies between $\Delta V = 0.06–0.12$ mag within 5–7 days ($\sigma(c1–c2) \sim 0.012$ mag), suggesting that the changes are periodic with a period of at least five days. The variability within a single night is small and typically reaches an amplitude not higher than $2\sigma$. Since only slow variability is observed in photometry and spectroscopy within a single night (Morel et al. 1999a; Niedzielski 2000a), we binned all the data obtained during a given night to increase the S/N.

We performed a period search using two independent methods. The first is a phase-dispersion minimization (PDM) algorithm (Stellingwerf 1978) which is well suited to cases in which only a small number of observations are available over a limited period of time, especially if the signal is highly non-sinusoidal. The method consists in folding the data points in phase using different trial periods and dividing the resulting curves in a predetermined number of phase bins. For each trial period we can define $S_j^2$, the variance of bin $j$, $S^2$, the variance of all $S_j^2$, and finally $\Theta = S^2/\sigma^2$, where $\sigma^2$ is the variance of all data points. The other method used is the clean algorithm (Scargle 1982; Roberts et al. 1987) which has the advantage of taking into account the unevenness of the data sampling, since it “cleans” the discrete Fourier spectrum with a window function. Both the $\Theta$ spectra from the PDM method and the power spectra from the clean method are shown in Figure 2 for WR1–c1, WR1–c2, and c1–c2.

The total time elapsed between the first and last point of the light curve is 91 days and, as mentioned above, we combined the
data to obtain one measurement per night. Therefore, the search was performed over a range of frequencies from 2/91 to 0.5 day$^{-1}$ with a step of 0.00111 day$^{-1}$, respecting the Nyquist criterion. When using the PDM method for (WR1-c1) and (WR1-c2), one frequency ($v_{1,\text{PDM}}$) is found to be predominant over all others. Interestingly, when only the first 60 nights are included in the period search, $v_{1,\text{PDM}}$ becomes even more significant, and three other frequencies can be distinguished from the noise in the periodogram. The strongest detection is at $v_{1,\text{PDM}} = 0.059^{+0.001}_{-0.002}$ day$^{-1}$ and the three others are at $v_{2,\text{PDM}} = 0.028^{+0.001}_{-0.002}$, $v_{3,\text{PDM}} = 0.118^{+0.001}_{-0.002}$, and $v_{4,\text{PDM}} = 0.236^{+0.001}_{-0.002}$ day$^{-1}$.

Note that the peaks at $v_{2,\text{PDM}}$, $v_{3,\text{PDM}}$, and $v_{4,\text{PDM}}$ reach comparable levels and are much smaller than the peak at $v_{1,\text{PDM}}$. The periodogram of (c1–c2) shows no signal at all, indicating that there is no periodic variability present in the light curve of either of the comparison stars. The power spectra obtained using the CLEAN algorithm for both the (WR1-c1) and (WR1-c2) light curves show only three peaks that reach values higher than the 99% confidence level threshold and that are absent in the comparison light curve (c1–c2). These peaks are at $v_{1,\text{CLEAN}} = 0.119 \pm 0.007$ (≈ $v_{3,\text{PDM}}$), $v_{2,\text{CLEAN}} = 0.057 \pm 0.007$ (≈ $v_{1,\text{PDM}}$), and $v_{3,\text{CLEAN}} = 0.240 \pm 0.007$ day$^{-1}$ (≈ $v_{4,\text{PDM}}$).

The two main frequencies identified using the two different methods ($v = 0.059, 0.119$ day$^{-1}$) can be linked by an integer number. It is therefore clear that one is a harmonic of the other. According to the PDM analysis, the frequency with the strongest signal is $v_{1,\text{PDM}} = 0.059^{+0.001}_{-0.000}$ day$^{-1}$ (period of 16.9 ± 0.6 days), but according to the CLEANed spectrum, it is $v_{1,\text{CLEAN}} = 0.119 \pm 0.007$ day$^{-1}$ (period of 8.4 ± 0.5 days). In an attempt to settle which among these two possible periods for WR 1 is the correct one, we folded the light curve in phase using the two different frequencies. The frequency that produced the smallest dispersion and the clearest curve is $v_{1,\text{PDM}}$. This result is presented in Figure 3 where each 16.9 day cycle of (WR1-c2) is plotted using a different symbol. The six cycles of 16.9 days covered by our photometric data set are delimited in Figure 1. The 16.9 day folded light curve for cycles 1 to 4 shown in the top panel of Figure 3 shows basically three bumps: one broad and small centered at $\phi \sim 0.6$ and two stronger ones spaced closer in phase at $\phi \sim 0.95$ and 0.15. The bottom panel shows the same data folded with a 8.4 day period. Clearly the scatter is much larger than when folded with the shorter period. A careful examination of Figure 1 also shows that there is no clear pattern repeating in any successive 8.4 days, which supports this result. The fifth and sixth cycles demonstrate the epoch dependency of the light curve. Indeed, the curve shown in the middle panel of Figure 3 shows the disappearance of the second bump near phase 0.95. Indeed, the third bump seems significantly higher and wider than during the previous cycles and starts from a lower level, but the star seems to have skipped the previous increase and decrease in flux, as if the two nearby peaks had merged.

We have no data at phase 0.6 for these cycles, so we cannot tell if the bump at that location is still present. To show the difference between the shapes of the light curves, we overlaid in the middle panel showing cycles 5 and 6, the cycle 1 to 4 light curve as a thick gray curve which roughly encompasses all data points. This epoch dependency of the light curve of WR 1 shows that a period can only be found when observations are taken consecutively, during a period of time for which the physical conditions of the region where the continuum flux originates do not change. This means that no data taken after a certain coherence timescale can be added to the sequence in order for a period search to be successful. Indeed, even if the period remains the same, the amplitude and the shape of the light curve will change. We cannot determine with accuracy the time of

![Figure 2. Periodograms: (a) Φ-spectrum obtained from the PDM analysis of the WR 1-c1 curve. The four frequencies $v_{1,\text{PDM}}, v_{2,\text{PDM}}, v_{3,\text{PDM}},$ and $v_{4,\text{PDM}}$ are indicated with an arrow. (b) Same as (a) for WR1-c2. (c) Same as (a) for c1–c2. (d) CLEANed power spectrum of WR1-c1 (green), WR1-c2 (blue), and c1–c2 (red). Three levels of confidence at 99%, 95%, and 90% are plotted in black. The three frequencies $v_{1,\text{CLEAN}}, v_{2,\text{CLEAN}},$ and $v_{3,\text{CLEAN}}$ are indicated with an arrow. (A color version of this figure is available in the online journal.]

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coherence for WR 1, but according to our data, it seems to be at least four cycles, i.e., ∼60 days.

A light curve was obtained by Morel et al. (1999a). During their observations extending over a period of 16 days, the authors found only one bump lasting five days in width, followed by a period of 11 days during which the curve was flat. In the context of an epoch-dependent light-curve shape, it is interesting to note that their curve is not inconsistent with our choice of adopting a period of 11 days during which the curve was flat. In the middle panel of Figure 3 where we have arbitrary shifted their observations extending over a period of 16 days, the authors found only one bump lasting five days in width, followed by a second period of 16.9 days as the single bump observed by Morel et al. (1999a) is also plotted with `*` signs. Bottom panel: the same data folded with a 8.4 day period. The symbols represent the nine different cycles of the 8.4 day period.

The most probable interpretation is that the period of 16.9±0.3 days, obtained using both methods, is the real period and that the other detections are simple harmonics or a consequence of the fact that the light curve is not a simple sinusoid. Note that the 7.684 day period claimed by Flores et al. (2007) has been obtained from spectra taken during two different runs of five and eight nights separated by ∼6 years. Due to an insufficient time coverage and to the complexity of the variability pattern, they have detected only a fraction of the real period.

4. SPECTROSCOPY

The photometry discussed in the previous section provides information on the variability of the continuum of the star since for this star only 10% of the flux in broadband V comes from emission lines. This continuum originates in deep regions of the stellar wind. In order to probe the wind at different radii, we must study spectral variability, because the different WR emission lines are formed in regions of different velocity regimes (i.e., different radii), depending on the ionization potential of the given elements (e.g., Kuhl 1973; Hillier 1987). From spectral variability, we hope to obtain clues as to the origin of the period found in photometry.

4.1. Level of Variability

In Figure 4(a), we present the mean spectrum for each of our spectroscopic data runs listed in Table 1 (thick black lines). Line identification is provided in the panel for run 1.

To illustrate which parts of our spectra are variable, we have calculated the temporal variance spectrum (TVS) according to the method introduced by Fullerton et al. (1996). Then, assuming that our data are governed by a reduced \( \chi^2 \) distribution with \( N - 1 \) degrees of freedom, we calculated the \( \Sigma \) spectrum as follows:

\[
\Sigma_j(99%) = \sqrt{\frac{(TVS)_j}{\sigma_j^2 (99%)}},
\]

where \( N \) is the total number of spectra and \( \sigma_j \) a standardized dispersion. The \( \Sigma \) spectrum for each run is overplotted (thin blue line) on the mean spectra in Figure 4(a). A \( \Sigma(99%) \) value of 3, for example, means that we are 99% confident that the corresponding part of the spectrum is variable at a 3σ level (see St-Louis et al. 2009, for more details). It can easily be seen that all lines show variability at high sigma levels with a high degree of confidence for each run. Note that since the TVS compares the variability level at each pixel with the variability calculated in the continuum regions, no changes can be identified in the continuum with this method.

In Figure 4(b), we present the \( \sigma \) spectrum which we defined in St-Louis et al. (2009). This spectrum gives the fraction of the line flux that is variable (and therefore is only defined within spectral lines). We present four regions of our wavelength range which include spectral lines. Note that each region is not covered by the same number of spectra. Hence, some are more noisy, such as He \( \lambda 4686 \) for which we only have ∼20 spectra as opposed to He \( \lambda 5411 \) for which we have ∼320. The reason we have so little spectra for the He \( \lambda 4686 \) line is that we decided to allow this line to saturate in run 4, the run with the largest number of spectra, in order to increase the total number of spectra we obtained. Indeed, the alternative would have been to divide the exposure time by a factor of 3 and observe three times as often, which would have led to tripling the amount of...
time spent reading the detector. It can be seen that all lines vary typically at a ∼7% level. This is exactly the same result found by St-Louis et al. (2009) for this star, but based only on five spectra.

4.2. Variability Pattern of Different Spectral Lines

In order to compare the variability pattern of different emission lines, we have calculated correlation coefficients between each velocity bin of the different emission profiles, using the Spearman rank-order correlation. This procedure yields a matrix of correlation that assesses how well the variability pattern of two lines correlate. For lines with overlapping formation regions (which is often the case), a correlation should be found if an overdensity is present in the wind. In the case of line formation zones far-removed from the acceleration region, large sections of the wind are associated with a narrow velocity interval. In such a case, a correlation would support “solid” rotating CIRs. In the case of perfectly correlated variations, a matrix unity is obtained. In Figure 5, we present the correlation matrices of He\(\text{II}\)\(\lambda5411\) with He\(\text{II}\)\(\lambda4860\), N\(\nu\lambda4945\), and C\(\text{IV}\)\(\lambda5808\). The lowest level represents a significant correlation at the 99.5% confidence level. The correlation matrix of He\(\text{II}\)\(\lambda5411\) with He\(\text{II}\)\(\lambda4686\) is not shown here, but has already been published by Morel et al. (1999a). The variability pattern of He\(\text{II}\)\(\lambda5411\) is clearly correlated with that of all other emission lines, except for He\(\text{II}\)\(\lambda5876\) and for N\(\nu\lambda4603/20\), which is blended with the highly variable absorption part of the P Cygni profile of He\(\text{II}\)\(\lambda4686\). One can note that, contrary to Morel et al. (1999a), we were able to detect a clear correlation between the variability pattern of the He\(\text{II}\)\(\lambda5411\) and N\(\nu\lambda4945\) lines. This is most likely due to the higher S/N and the greater number of spectra in our data set.

In view of the above results, we only show here the variability pattern of the He\(\text{II}\)\(\lambda5411\) line which is a strong and isolated line...
Figure 5. Contour maps of the correlation matrices of He\(\text{ii}\)\(\lambda\)5411 with He\(\text{ii}\)\(\lambda\)4860, N\(\text{v}\)\(\lambda\)4945, and C\(\text{iv}\)\(\lambda\)5808. The line contours indicate a correlation (in black) or an anti-correlation (in red) in the variability pattern of the lines. The lowest contour level represents a correlation at the 99.5% confidence level.

(A color version of this figure is available in the online journal.)

Figure 6. Top panel: gray scale of residuals for the He\(\text{ii}\)\(\lambda\)5411 line obtained by subtracting the mean spectrum of all runs from the rectified spectra taken during runs 4 and 5. Bottom panel: superposition of all spectra taken during the two runs. Note that for clarity the time corresponding to daylight has been filled by the duplicate of the spectra obtained during the previous night.

and is common to all our observing runs. The variability of that line when observed during individual nights is typical of what has already been reported by Niedzielski (2000a) for WR 1, i.e., low-level variations occurring slowly and systematically during the night. However, the changes are more interesting when displayed in the form of a gray-scale plot covering a time period of more than a week, as shown in Figure 6, where we plot the complete data set of our runs 4 and 5. For clarity, the spectra obtained during each night have been repeated once to fill the space in the gray-scale plot corresponding to daylight, when no observations were possible. This way, no free space has been left between two consecutive nights, which makes it easier to see the structures moving on a timescale of several days. Although our time coverage is not ideal, one can begin to distinguish the typical “S-type” pattern characteristic of CIR-type variability.

4.3. Radial Velocity, EW, Skewness, and Kurtosis Variations

We next investigate the variability of the RV of spectral lines as well as the changes in the global intensity of the line profile by measuring the equivalent width (EW), the skewness, and the kurtosis of the He\(\text{ii}\)\(\lambda\)5411 line. The RVs were obtained by cross-correlating individual spectra in the wavelength interval \(\Delta \lambda = 5140–5980 \text{ Å}\) with the mean spectra. The RVs of the different campaigns were obtained separately. We corrected the systematic shifts between runs by cross-correlating the mean spectra of the runs. The typical values for the applied corrections ranged between \(-20 \text{ km s}^{-1}\) and \(-40 \text{ km s}^{-1}\). The EWs of emission lines were calculated by integrating the function \((1 - F_{\lambda})\), where \(F_{\lambda}\) is the rectified line flux between \(\Delta \lambda = 5348\) and \(5460 \text{ Å}\). In order to highlight the variability, we prefer to use \(\Delta\text{EWs}\) obtained by dividing the EWs by the mean value of all EWs. In order to verify that the \(\Delta\text{EW}\) of the He\(\text{ii}\)\(\lambda\)5411 line is representative of the curve for any other emission line in the wavelength range of our observations, we compared its \(\Delta\text{EW}\) to the one of the N\(\text{v}\)\(\lambda\)\(\lambda\)4603/20, He\(\text{ii}\)\(\lambda\)4686, He\(\text{ii}\)\(\lambda\)4860, C\(\text{iv}\)\(\lambda\)5808, and He\(\text{i}\)\(\lambda\)5876 lines. We present in Figure 7 the \(\Delta\text{EW}\) of the He\(\text{ii}\)\(\lambda\)4686 and He\(\text{ii}\)\(\lambda\)5411 lines observed in run 2. The changes clearly follow the same pattern. In general, except for the blended N\(\text{v}\)\(\lambda\)\(\lambda\)4603/20 and the weakly varying He\(\text{i}\)\(\lambda\)5876

Figure 7. \(\Delta\text{EW}\) of the He\(\text{ii}\)\(\lambda\)4686 (diamonds) and He\(\text{ii}\)\(\lambda\)5411 (triangles) lines observed in run 2. The error bars are 3\(\sigma\) long. Note that due to problems with the first spectrum of that run at \(\lambda < 5200 \text{ Å}\), \(\Delta\text{EW}\) could not be computed for He\(\text{ii}\)\(\lambda\)4686 on the first night.
lines, with the quality of the data in hand, there is no significant
difference that can be seen in the 
lines, with the quality of the data in hand, there is no significant
difference that can be seen in the 
lines, with the quality of the data in hand, there is no significant

\[ \text{skewness} = \frac{\mu_3}{\mu_2^{3/2}}, \]

where \[ \tilde{\lambda} = \frac{\sum I_j \lambda_j}{\sum I_j \lambda_j^2} \]

with \( I_j \) being the intensity of the line and \( \lambda_j \) the wavelength.

\[ \mu_n = \frac{\sum (\lambda_j - \bar{\lambda})^n I_j}{\sum I_j}, \]

The skewness is \( \mu_3/\mu_2^{3/2} \) and the kurtosis is \( \mu_4/\mu_2^2 \). All these quantities are plotted as a function of time in Figure 8.

On average, the EW of the He \( \uplambda 5411 \) line increased by

\[ \sim 15\% \]
during the first three runs (left panel) and by \( \sim 5\% \)
during the last two (right panel). The RVs show long-term

changes with a full amplitude \( K \sim 70 \text{ km s}^{-1} \) as well as shorter
timescale changes which are particularly apparent during run 4.

However, the skewness, which characterizes the asymmetry of
the line profile, is strongly anti-correlated with the RVs. Indeed,
these values are anti-correlated with a 90% confidence level
when we remove run 5, which seems to have abnormally high
dispersion. This strong anti-correlation indicates that the RV
changes that we measure essentially come from changes in the
degree of asymmetry of the line profile of He \( \uplambda 5411 \), which
dominate the spectrum in the wavelength interval in which the
cross-correlation was carried out. Consequently, if WR 1 shows
intrinsic RV variability in He \( \uplambda 5411 \), it must be at a very small
level and therefore is difficult to detect in view of the line-
profile variability. Both EW and RV of the He \( \uplambda 5411 \) line vary
with an amplitude of at most \( \sim 5\% \) in a single night. This can
be compared with the observations of Niedzielski (2000a) who
found EW variations of He \( \uplambda 5411 \) of \( \sim 15\% \) for their first run
with a structured variability pattern over a \( \Delta t = 5 \text{ day period, but only} \sim 5\% \) for their second run on a timescale of \( \sim 2 \text{ days.} \)
Unfortunately, Flores et al. (2007) did not observe this line. The
variations in EW are clearly epoch dependant.

4.4. Search for Periods

A period search was performed using the PDM method on the
EWs, skewness, and kurtosis variations (but not on the RVs, due
to this similarity with the skewness). No clear period could be
found in the EW curves. However, the periodograms calculated
for both the skewness and the kurtosis curves have a significant
peak at \( 0.059 \text{ day}^{-1} \), i.e., the photometric frequency \( v_{1,\text{PDM}} \)
discussed in the previous section (see Figure 9). The curves
folded with that frequency are shown in Figure 10. Each point is
the mean value for a single night. Run 1 is represented by circles,
run 2 by squares, run 3 by triangles, run 4 by diamonds, and
run 5 by stars. The folded curves for the EW and the skewness
have quite a large scatter and poorly confirm the detected period.
However, the folded curve for the kurtosis is more promising.
The largest scatter is found between phases 0.55 and 1.0, but it
can be greatly reduced if one considers separately runs 1, 2, and
3 observed in 2003 (\( \Delta t \sim 55 \text{ days} \)) and runs 4 and 5 observed in
2004 (\( \sim 55 \text{ days} \)). Interestingly, this is also the time interval after
which a change in the shape of our light curve was observed.
One maximum, centered at phase \( \sim 0.1 \) is common to all runs.

The variations between phases 0.55 and 1.0 can be described as
one additional maximum for runs 1, 2, and 3 and a minimum
(around phase 0.6) followed by a maximum (around phase 0.9)
for runs 4 and 5.

It is not necessarily trivial to link the variability of the global
moments of the lines and the wind variability of the star. Here,
we present an investigation that aims to reveal the periodicity of
the movement of the extra bumps observed superposed on the
emission line profiles. These can be seen moving from one side

![Figure 8](image-url)

**Figure 8.** Top panel: \( \Delta \text{EW} \) of the He \( \uplambda 5411 \) line, obtained by integrating the line flux and dividing the result by the mean value of all the EWs. Second panel from top: RVs obtained by cross-correlating the spectra in the 5140–5980 Å range. Second panel from bottom: skewness of the He \( \uplambda 5411 \) line calculated as skewness = \( \mu_3/\mu_2^{3/2} \), where \( \mu_n \) is the central moment of order \( n \) of the line. Bottom panel: kurtosis of the He \( \uplambda 5411 \) line calculated as kurtosis = \( \mu_4/\mu_2^2 \).
Figure 9. Θ-spectrum obtained from the PDM analysis of the skewness curve (black, dashed line) and the kurtosis curve (red, solid line) of He ii λ5411, presented in Figure 8. The photometric frequency ν_{1,PDM} discussed in Section 3 is indicated with an arrow.

(A color version of this figure is available in the online journal.)

Figure 10. ΔEW, skewness, and kurtosis curves for He ii λ5411 folded with the frequency ν_{1,PDM} = 0.059 days^{-1}. Each point is the mean value for a single night. Run 1 is represented by circles, run 2 by squares, run 3 by triangles, run 4 by diamonds, and run 5 by stars.

(A color version of this figure is available in the online journal.)

of the profile to the other for runs 4 and 5 in Figure 6. We define the scalar value σ_{res}, i.e., the standard deviation of the residuals obtained from the subtraction of two spectra observed separately with a time interval of Δt. Theoretically, when two spectra are obtained at the same point of a given variability pattern and therefore should be most similar, σ_{res} reaches a minimum and takes the value of the quadratic sum of the noise levels of both spectra. Also, any significant difference between the two spectra will increase the value of σ_{res} proportionally to the magnitude of that difference. The great advantage of σ_{res} is that its value depends weakly on the epoch dependency of the signal. Indeed, even if the signal changes after 4 or 5 cycles (see Section 3), all spectra from any cycle can be used at a given Δt, since only the spectra separated by the time interval Δt are used. The effect of the epoch dependency becomes significant for Δt greater than the coherence time, i.e., in this case, when two spectra separated by more than (at least) ~4 cycles (~67 days) are compared.

In Figure 11 we plot the values of σ_{res} measured within a wavelength interval of 65 Å centered on λ = 5411 Å for Δt < 55 days, using all the spectra from our five observing runs. The wavelength interval has been chosen to include the part of the He iiλ5411 line where most of the lpv occurs, without
adding too much of the less intense parts that do not contain much information and have a much lower S/N. For clarity, we have organized the values of $\sigma_{\text{res}}$ as a function of $\Delta t$ in a gray scale. In black are plotted the regions with the higher number of data points and, in white, the regions with no data point. Since the spectrum of WR 1 does not vary very much within a single night (see above), we assume that the mean value of $\sigma_{\text{res}}$ measured for all $\Delta t < 1$ day can be used to determine the minimum value for $\sigma_{\text{res}}$ (plotted with a dotted line). Also, the spectra have been normalized in amplitude to avoid any change coming from the line dilution caused by the variation in the continuum that we observe in photometry.

The periodogram calculated for the $\sigma_{\text{res}}$ versus $\Delta t$ curve using the PDM method is shown in Figure 12. The four frequencies $v_1, v_2, v_3,$ and $v_4$ are indicated by arrows. In Figure 11, a vertical dashed line is plotted at a constant interval of 16.9 days. Interestingly, $\sigma_{\text{res}}$ reaches a minimum value near $\Delta t = n \times 16.9$ days, where $n = 1, 2,$ and 3. These minima are significant when compared with $\sigma_{\text{res}}$, but they do not reach the minimum value corresponding to the noise level. This may indicate that even after one cycle, the variability pattern has changed slightly (but not drastically). Two other small minima can be seen at $\Delta t \approx 4.5$ and 11.8 days, but they do not repeat at greater $\Delta t$. This can be caused by line-profile variability that shows a similar pattern occurring more than once within the period for at least one cycle (as seen in the photometry).

Finally, in order to illustrate the line-profile variability pattern, we display in Figure 13 the residuals obtained by subtracting the mean spectrum of all runs from the mean spectra of each night of runs 4 and 5 for the N $\lambda 4945$ and He $\lambda 5411$ lines (note that the N $\lambda 4945$ line was not observed during run 5). The location on the y-axis of the residual spectra is determined by the phase ($P = 16.9$ days) at which the spectrum was taken. Different colors are assigned to residuals from different cycles.

One can see from Figure 13 that the residuals at nearby phases are not always strictly identical (as expected from the above analysis). However, some features seem to survive for several cycles. The clearest case is that of the bump that appears at $v \sim \pm 250$ km s$^{-1}$ at phase $\phi = 0.40$ of the first cycle (HJD–HJD(2000) = 1702.54), that moves toward negative velocities during phases $\phi = 0.44-0.61$ of the third cycle (HJD–HJD(2000) = 1736.85–1739.83), and continues its blueward motion during phases $\phi = 0.65-0.70$ of the first cycle (HJD–HJD(2000) = 1706.70–1707.70) before disappearing. More moving structures can be followed on Figure 13 and are shown by dashed (for bumps) and dotted lines (for dips). One can note that the motion of the bumps explains the changes we have observed in the central moments of the He $\lambda 5411$ line presented above. Indeed, the two biggest bumps trace a sinusoidal trajectory on the line, both in opposite directions. Hence, it is expected that the skewness, which measures the asymmetry of the line, would not vary too much due to the motion of the bumps, and that the kurtosis, which measures the degree of “peakedness” of the line, would be more sensitive to it.

5. DISCUSSION

St-Louis et al. (2009) have already shown that WR 1’s spectrum shows large-scale lpv with a similar amplitude to what is observed for WR 6 and WR 134, two presumably single WR stars showing periodic photometric and spectroscopic variability (Morel et al. 1997, 1998, 1999a, 1999b). With the intensive monitoring campaign presented here, we are now able to conclude that, as for those two stars, WR 1 presents a unique period in its epoch-dependent light curve and spectral variability. The changes consist in large-scale bumps moving periodically from one side of the emission lines to the other. The origin of this type of variability is debated in several papers and the two main interpretations put forward are a binary system (with a compact or low-mass companion) and a rotating non-spherically symmetric wind. In what follows, we discuss these two possible interpretations in the context of the variability of WR 1 as characterized in this work, as well as that of WR 6 and WR 134 as detailed in the literature. We also discuss the
variability of the WR star member of the binary WR 137, which shows large-scale lpv with a 1.2 day period that cannot be caused by the O9 companion nor the wind–wind collision zone, since the orbital period is $\sim$13 years and the average distance between the two components is high.

5.1. The Binarity Scenario

Like WR 6, WR 134, and WR 137, WR 1 shows very small RV amplitude, consistent with null, and its soft X-ray luminosity is within the normal range for single WR stars (see Morel et al. 1999a). Hence, it is completely excluded that its companion is an OB star. The presence of a compact companion, such as a neutron star or a black hole, in WR 1, WR 6, and WR 134 was not seen as a viable interpretation by Ignace et al. (2003), Morel et al. (1997), Skinner et al. (2002), and Morel et al. (1999b). Indeed, the strong correlation between the lpv of He II lines with that of a highly ionized line such as N V $\lambda$4945 indicates that the ionizing shell around the compact companion would have to be extremely large and would emit a high X-ray flux, which is not observed (Morel et al. 1997, 1999b; Pollock et al. 1995).

Therefore, the only remaining possibility for the binary scenario for WR 1, WR 6, and WR 134 is that of a low-mass, non-compact companion. Indeed, assuming circular orbits and taking the published RV variation amplitudes measured for the three stars (Morel et al. 1997, 1998, and this work) as the maximum possible value (recall that RV variations are highly dominated by lpv), the periods lead to an upper limit for the mass of such a companion of $8 M_\odot$ in all cases, if the inclination of the orbital plane is higher than 20°. As for WR 137, the scatter in RV on a timescale of a few days is $\sim$10 km s$^{-1}$ (Lefèvre et al. 2005a) and its measured $M \sin^3 i = 3.4 \pm 1.0 M_\odot$. Hence, if the inclination of the orbital plane is higher than 20°, the mass of the companion would have to be as small as 0.8 $M_\odot$ in an orbit of 7.6 $R_\odot$, which is very unlikely. But, can a low-mass companion be responsible for such a complex and epoch-dependant pattern of photometric and spectroscopic variability? Moreno & Koenigsberger (1999) and Moreno et al. (2005) have shown that tidal interactions involving a relatively low-mass companion in a binary system can produce very small-scale surface oscillations leading to lpv in photospheric absorption features. However, it is unclear how such a process can affect the massive wind of a WR star and lead to large-scale variability of the strong emission lines. It is possible that it could serve as a seed mechanism for CIRs. However, in such a case, it is likely that the period that would be detected would be the rotation period of the WR star rather than the orbital period.
than the orbital period of the binary, if not a combination of both.

Therefore, although very unlikely, it is not yet possible from the observations to definitively exclude the possibility that WR 1, WR 6, and WR 134 are binaries, and that WR 137 has a third low-mass companion. However, the only viable binary scenario involves the formation of massive binaries with a high initial mass ratio (up to 10), which seems to be extremely unlikely both observationally and theoretically (e.g., Garmany et al. 1980; Kobulnicky et al. 2007; Bonnell 2007).

5.2. The Non-spherically Symmetric Wind Scenario

If WR 1, WR 6, WR 134, and the WR star in the WR 137 binary system are single stars, the periodic variability very likely originates in an asymmetry in their wind modulated by the stellar rotation. Spectropolarimetric observations of WR 6, WR 134, and WR 137 (Schulte-Ladbeck et al. 1991; Robert et al. 1992; Harries et al. 1998) have shown the presence of an intrinsic continuum polarization component due to electron scattering, indicating that the winds of these stars are not spherically symmetric. This is revealed by the depolarization of emission lines compared to the neighboring continuum. It was also found that the degree of depolarization of spectral lines increases with decreasing ionization state. This is interpreted to be a consequence of the ionization stratification of hot stellar winds; as scattering lines with a higher degree of ionization are formed deeper in the wind, their polarization level is closer to that of the continuum because of the higher density close to the core and therefore their level of depolarization is lower. If a line has a strong recombination component, which is not polarized, its polarization level will be even lower and the depolarization with respect to the continuum stronger. Finally, the level of linear polarization of the continuum as measured in broadband light of WR 6, WR 134, and WR 137 is extremely variable and periodic (Drissen et al. 1989; Moffat et al. 1993). This suggests that the wind density has a varying asymmetric distribution, such as density structures that extend rather far in the wind. Unfortunately, there is no published high signal-to-noise spectropolarimetric nor continuum polarization observation of WR 1. The only observation so far was carried out by Schmidt (1988) and does not show a depolarization in its emission lines compared to the underlying continuum. The latter, however, shows a significantly high level of polarization, although it remains to be demonstrated that this is intrinsic to the star rather than interstellar in origin. If the polarization is proved to be interstellar, this would explain why no depolarization is observed in the lines since the continuum is not polarized to start with. If, on the other hand, the light from the star is confirmed to be highly polarized, a possible explanation for the lack of depolarization in the lines is that for some yet unknown reason, the region in which the lines arise shows a degree of polarization as high as that in which the continuum arises. Also, the epoch-dependent nature of the changes could mean that relatively quiet periods can exist. Therefore, more spectropolarimetric observations are needed to verify whether the polarization of the emission lines of WR 1 varies with time.

The possible existence of large-scale density structures, such as CIRs, was first proposed by Mullan (1984). Following this idea, Cranmer & Owocki (1996) modeled the propagation of CIRs in a hot, radiatively, line-driven stellar wind. In that context, CIRs are caused by perturbations at the base of the wind which in turn could be caused, for example, by a magnetic field or pulsations. These perturbations propagate through the wind while being carried around by rotation. This generates spiral-like structures in the density distribution that can lead to a characteristic, large-scale, periodic variability pattern in WR-wind emission lines, extremely similar to what is observed in the WR stars we discuss here (Dessart & Chesneau 2002). Thus, taking into account the photometric and spectropolarimetric periodic variability, the spectropolarimetric observations and the low soft and hard X-ray fluxes, we conclude that CIRs constitute an extremely likely interpretation. As for the epoch dependency, it can easily be explained by the variable behavior of perturbations that generate CIRs together with a finite lifetime of the structures in the wind. Indeed, even if the period of the variability caused by the motion of CIRs is always the same, the number and position of the CIRs may change depending on conditions at the surface. The origin of CIRs is still debated and no clear theoretical predictions of the typical lifetime of a CIR have been made yet. However, one can speculate that it will depend on the lifetime of the perturbation at the base of the wind and, to a lesser extent, on the flow speed in the wind. Observationally, it could be determined from continuous observations during a great number of rotational periods, (e.g., several weeks for WR 6 and WR 134).

5.3. Remarks on the Putative CIRs in the Wind of WR 1

We believe that the best scenario to explain the photometric and spectroscopic variability we have detected in WR 1 is the presence in its wind of large-scale structures, most likely CIRs. In that case, each CIR would translate into a bump in the light curve and a bump over the spectral emission lines.

In theory, CIRs do not suffer from differential rotation and if the recurrence of the changes is caused solely by their rotation, they provide a direct measurement of the rotation period of the underlying star at the position in which they originate, most likely close to the stellar surface. Thus, assuming a value for the radius of WR 1 of 2.2 $R_\odot$ (a radius that corresponds to a Rosseland optical depth of 20; Hamann et al. 2006), we obtain an equatorial rotational velocity of 6.5 km s$^{-1}$. This is an order of magnitude lower than the values obtained for WR 6 (40 km s$^{-1}$) and WR 134 (70 km s$^{-1}$) when assuming a radius of $R_\star \sim 3 R_\odot$ (Hamann et al. 2006). However, all these rotational velocities are in agreement with the very small values predicted for WR stars by massive-star evolutionary models at solar metallicity (Meynet & Maeder 2003). The order of magnitude difference between the rotation velocity of WR 1 and that of WR 6 and WR 134 is not completely surprising since the observed rotational velocity of a massive star at the WR evolutionary stage depends on several parameters such as the initial stellar mass, the mass-loss rate and the age of the star (time spent as a WR star). Interestingly, adopting a radius of 4.5 $R_\odot$ (corresponding to the radius of the hydrostatic core; Nugis & Lamers 2000) for WR 137, we deduce an equatorial rotational velocity of 275 km s$^{-1}$, i.e., more than half the breakup velocity. If confirmed, such a fast rotation for a WC star would render WR 137 an interesting candidate for an eventual long-term gamma-ray burst.

Inspired by the analysis of Dessart & Chesneau (2002), we can estimate the inclination of the CIRs in the wind of WR 1. Indeed, the maximum Doppler velocity that a bump associated with a CIR reaches during its motion on an emission line is $v_{\text{max}} = \pm v_{\text{fr}} \cos(\theta)$, where $v_{\text{fr}}$ is the velocity of the wind at the radii corresponding to the formation region of the observed emission line over which the bump is observed, and $\theta$ is the
inclination angle of the CIR with the line of sight (LOS). In Figure 13, we track two bumps that reach $v_{\text{max}} \sim \sim 1300$ km s$^{-1}$ and $v_{\text{max}} \sim +700$ km s$^{-1}$ on the He $\lambda 5411$ line. Assuming that the velocity law of the wind can be described by a $\beta$-law for which the velocity as a function of radius can be written as follows (Castor & Lamers 1979):

$$v(r) = v_\infty \left(1 - \frac{R}{r}\right)^\beta,$$

where $v_\infty$ is the terminal velocity of the wind, the value of $v_{\text{fit}}$ for He $\lambda 5411$ can be estimated using the emissivity function described by Lépine & Moffat (1999). However, that function depends on the value of $\beta$. Unfortunately, $\beta$ cannot be estimated observationally for WR 1, since no clumps are observed in the spectra. We can, however, give estimates of $\theta$ as a function of $\beta$. If $\beta = 1, 2, 3$ the first CIR has an inclination angle of $\theta_1 = \pm 40^\circ$, $\pm 38^\circ$, or $\pm 30^\circ$, respectively, and the second bump has $\theta_2 = \pm 65^\circ$, $\pm 64^\circ$, or $\pm 62^\circ$, respectively. When $\beta$ is greater than 3, the velocity of the He $\lambda 5411$ line formation region is lower than 1300 km s$^{-1}$. Hence, under our first assumptions, we deduce that the $\beta$ value for the wind of WR 1 should be lower than 3.

Of course, the association of the period of the CIRs with the rotation period of the underlying star remains to be confirmed. In the wind of OB stars, the presence of CIRs is thought to be at the origin of periodically recurring Discrete Absorption Components (DACs) in P Cygni profile of UV resonance lines (e.g., Fullerton et al. 1997). In many cases, the period of the outward moving DACs is found to correspond to $v_{\text{eq}} \sin i$, where $v_{\text{eq}}$ is the rotational velocity at the equator and $i$ the inclination of the rotational axis with the LOS (Henrichs et al. 1988; Prinja 1988). But in the case of HD 64760, a B0.5 Ib star, the CIRs rotate more slowly than the stellar surface. Lobel & Blomme (2008) carried out a hydrodynamical simulation of the CIRs for that star, following Cranmer & Owocki (1996), with the difference that they allowed the “spots” at the origin of the CIRs to move on the stellar surface. They were able to obtain a fairly good fit to the pvp of the Si IV $\lambda 1394,1403$ and concluded that, for that star, the origin of the CIRs must be the interference pattern of a number of non-radial pulsations at the surface of the star.

So far, there is no model for the “spots” that are at the origin of the creation of the CIRs and there are only a limited number of data sets available that could potentially be used to confirm either the pulsational or the magnetic origin of CIRs. The range of frequency expected for pulsations in WR stars is not well determined. Up to date, only one detection of a relatively stable 9.8 hr period that can be attributed either to g-modes (Townsend & MacDonald 2006) or strange-mode pulsations (Dorfi et al. 2006) has been claimed in WR 123 (Lefèvre et al. 2005b). No pulsational period of a few days is currently known or predicted. Also, no detection of a magnetic field has been achieved in a WR star so far; only an upper limit of $\sim 25$ G for WR 6 has been claimed (St-Louis et al. 2008).

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REFERENCES

Bonelli, I. A. 2007, in ASP Conf. Ser. 367, Massive Stars in Interactive Binaries, ed. N. St.-Louis & A. F. J. Moffat (San Francisco, CA: ASP), 303
Cranmer, S. R., & Owocki, S. P. 1999, ApJ, 520, 469
Castor, J. I., & Lamers, H. G. J. M. 1979, ApJS, 39, 481
Dorfi, E. A., Gautschy, A., & Saio, H. 2006, A&A, 453, L35
Drissen, L., Robert, C., Lamontagne, R., Moffat, A. F. J., St-Louis, N., van Weeren, N., & van Gendemer, A. M. 1989, ApJ, 343, 426
Flores, A., Koenigseberger, G., Cardona, O., & de la Cruz, L. 2007, AJ, 133, 2859
Fullerton, A. W., Gies, D. R., & Bolton, C. T. 1996, ApJS, 103, 475
Harries, T. J., Hillier, D. J., & Howarth, I. D. 1998, MNRAS, 296, 1072
Dorfi, E. A., Gautschy, A., & Saio, H. 2006, A&A, 453, L35
Drissen, L., Robert, C., Lamontagne, R., Moffat, A. F. J., St-Louis, N., van Weeren, N., & van Genderner, A. M. 1989, ApJ, 343, 426
Flores, A., Koenigseberger, G., Cardona, O., & de la Cruz, L. 2007, AJ, 133, 2859
Garmany, C. D., Conti, P. S., & Massey, P. 1980, ApJ, 242, 968
Garmany, C. D., Conti, P. S., & Massey, P. 1980, ApJ, 242, 968
Garmany, C. D., Conti, P. S., & Massey, P. 1980, ApJ, 242, 968
Garmany, C. D., Conti, P. S., & Massey, P. 1980, ApJ, 242, 968