FURTHER RESULTS ON THE LINE-PROFILE VARIABILITY OF WR 134

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Abstract. We discuss a few conclusions previously derived from the analysis of the line-profile variability of the Wolf-Rayet star WR 134; some details are made more explicit. In addition, we present a new set of data and briefly comment on recent results deduced from its analysis.

Key words: Wolf-Rayet stars: WR 134 – Line-profile variability

1. Introduction

WR 134 ≡ HD 191765 is a bright Wolf-Rayet star of type WN6 which exhibits strong line-profile variations. The first modern study of this object is due to Moffat et al. (1988) who interpret the line-profile variations as being due to blobs of wind material propagating away from the star. This interpretation has been questioned by Underhill et al. (1990) who rather favour a rotating wheel-like structure. Nearly at the same epoch, McCandliss analyzed 152 échelle spectra in the frame of his Ph.D. thesis (McCandliss, 1988). Later on, he published a further version (McCandliss, 1992) adopting the interpretation of Moffat et al. (1988). Yet another revised version will be presented at this workshop (McCandliss, 1993).

Our first analysis of the WR 134 line-profile variability is based on observations acquired in 1987: the results have been published in Vreux et al. (1992) in which a detailed introduction to the subject can also be found. A further analysis of these data is presented in section 3 whereas section 4 deals with the preliminary results obtained from a more recent dataset.

2. Observations

As soon as explorative Haute-Provence Observatory (HPO) spectra acquired in 1984 confirmed the continuous presence of strong line-profile variations in WR 134, we attempted to organize, in 1985, a coordinated campaign between Haute-Provence Observatory (HPO, J.-M. Vreux) and Kitt Peak National Observatory (KPNO, B. Bohannan), a campaign which unfortunately turned out into a disaster both for instrumental and meteorological

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reasons. In 1987, at last, successful observations were performed both at HPO (July) and at KPNO (September). The KPNO data (12 nights) cover a large part of the visible domain and constitute the basis of McCandliss' study. The HPO data are made of 74 spectra acquired over 11 nights in the wavelength range $\lambda\lambda$3940-4430 Å. These HPO data, along with the subgroup of the KPNO data corresponding to the same wavelength domain, form the basis of the Vreux et al. (1992) investigation. In 1991, new spectra, covering the region $\lambda\lambda$4230–4650 Å, were obtained at HPO: a preliminary analysis is presented in section 4.

3. Results from the 1987 data

The results we derived from the 1987 data were essentially published in Vreux et al. (1992) and we refer the reader to that paper. However, we would like to take the present opportunity to give further details or to speculate on some points.

3.1 Search for periodicities

Vreux et al. (1992) concluded that no periodicity was clearly outstanding in their data. However, they noticed that, in the pixel by pixel temporal power spectra of their HPO data, there was a tendency, around pixels sampling the line profiles, to have peaks located at frequencies such that $\nu \sim (n \times 0.5)$ d^{-1}, i.e. close to critical frequencies. Therefore, if a periodicity is present, it should be hidden close to these frequencies. The same technique applied to KPNO data led to power spectra with only a few peaks corresponding to n being odd and small. As an illustration, we show, in Fig. 1, the power spectrum of the KPNO data related to the pixels in the domain $\lambda\lambda$4203.5-4205 Å. The power spectrum is typical of the variability found in the lines just outside their very central part. It is clearly dominated by a family of aliases with the main one at $\nu \sim 0.5$ d^{-1} (the second one at $\nu \sim 1.5$ d^{-1}). A time-scale of 2 days (respectively, sixteen hours) is associated with this frequency but, strictly speaking, we cannot conclude to the existence of an actual periodicity because the peak at $\nu \sim 0.5$ d^{-1} (as well as the one at ν ~ 1.5 d^{-1}) is not really significant and, in addition, corresponds to a badly sampled frequency at which spurious peaks often occur. It is clear that a span of time of twelve days is not sufficient to firmly establish the existence of a periodicity at such a time-scale. To further study that problem, we considered the deformation pattern (i.e. the set of all the deviations from 1. exhibited by an individual mean-normalized spectrum, see Vreux et al., 1992, for further details) associated to the He II λ4200 line and we cross-correlated it from spectrum to spectrum. Concerning the KPNO data, the patterns within one night are well correlated; the patterns from one night to the next are rather anticorrelated and the patterns from one night to the

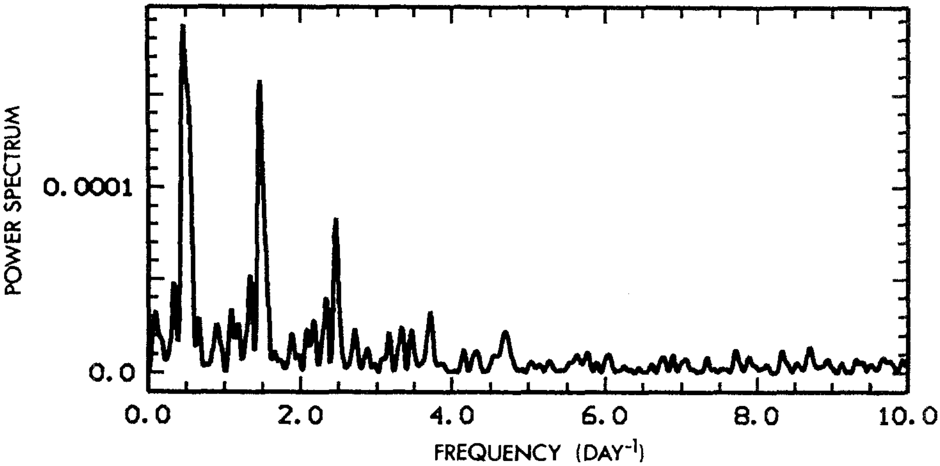

Fig. 1. Power spectrum of the KPNO time series of values adopted by the mean-normalized spectra in the wavelength domain $\lambda\lambda$4203.5-4205 Å. The ordinate is in arbitrary units.

next but one are rather correlated again. The phenomenon seems to extend over the entire run, odd nights being anticorrelated with even nights. This gives further support to the possible existence of a typical time-scale around two days but the regularity is not so well-marked on our higher quality HPO data. It certainly does not extend over the whole run. In addition, in the HPO data, variability within one night sometimes implies that the last spectrum is rather anticorrelated with the first one of the same night. However, this remains compatible with the sixteen hour time-scale, although the pattern analysis of KPNO data hardly supports it. Similar results are obtained with the N IV λ4058 line. Therefore, we conclude that the existence of a periodicity is definitely not firmly established.

3.2 Characteristics of the variability

The lack of observable periodicity does not necessarily imply that the variations are purely stochastic. Indeed, a few other characteristics can be outlined. For example, Vreux et al. (1992) stressed that the deformation patterns are very similar from line to line, particularly among the observed He II lines but also between the He II lines and the N IV λ4058 one. They illustrated their conclusions in their Figs. 2 and 5. We present here (Fig. 2) another example of the great similarity between the individual deformations of He II λ4200 and N IV λ4058.

This figure also illustrates another characteristic noticed by Vreux et al. (1992): the tendency for the deformation pattern to display an alternation

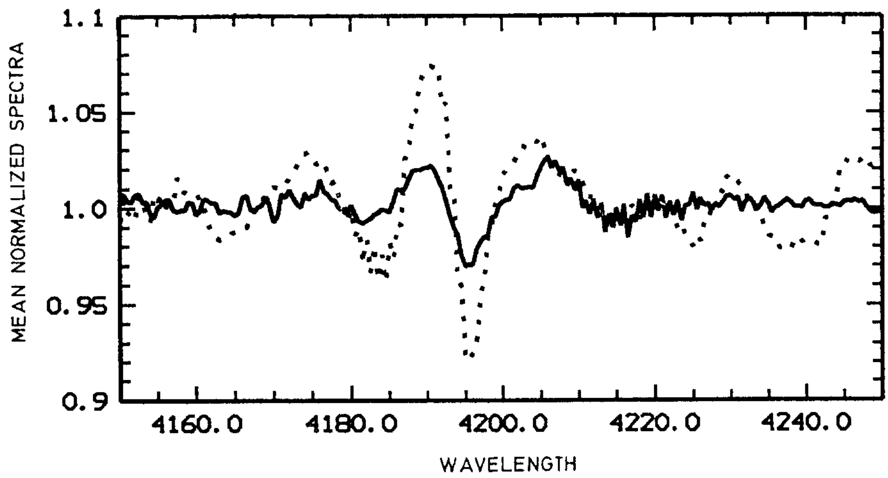

Fig. 2. An example of deformation patterns: the mean-normalized spectrum acquired on August 5, 1987 at U.T. 20^h 31^m, in the region of the He II λ4200 line (full line); superimposed is the region of the N IV λ4058 line (dotted line) shifted to the same laboratory wavelength.

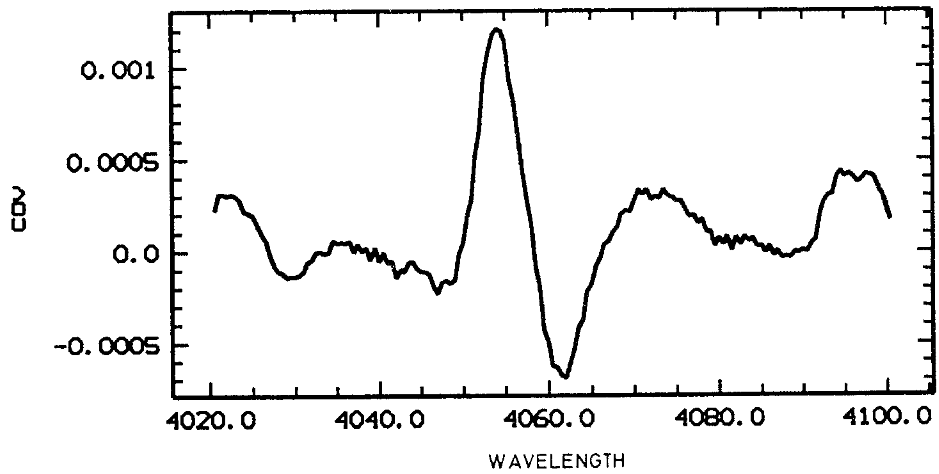

Fig. 3. Covariance, over all the HPO spectra, between the reference deviation defined by an average on the domain λλ4049.5-4056.5 Å (in the blue wing of N IV λ4058) and the actual deviation observed at various wavelengths.

of positive and negative deviations from the mean, in rather well defined wavelength intervals, separated by some kind of nodes where the variability is lower. A consequence of this is the corresponding tendency for the deviations on both sides of the central minimum of variation to be anticorrelated. This effect appears in Fig. 3 where we have plotted, for the N IV λ4058 line, the mean covariance over all the HPO spectra between the deviation observed on the blue side of the central minimum of variation (as averaged over a 7 Å domain between λ4049.5 and λ4056.5) and the deviation of the individual pixels at various wavelengths. The covariance is, of course, maximum around λ4054.0. The interesting point is that it becomes equal to zero around λ4058.5 (near the minimum of variability, the central node) and is minimum around λ4061.7. The covariance is again positive beyond λ4066.2. On the blue side, it is negative around λ4047.0. The same result can be extracted from the He II lines. Although it is hard to associate any statistically sound confidence level to these oscillations of the covariance, they are nevertheless a nice illustration of our previous conclusions.

4. New results from the 1991 data

The 1991 data have the advantage to cover both He II λ4542 and He II λ4339, the latter allowing direct comparison with the 1987 data. In addition, the 1991 data include two new species: He I through its line at λ4471 and N V through the $\lambda\lambda$4603-4619 doublet. The variability in He I λ4471 is only present in the absorption part of the P Cygni profile whereas the variations of the N V lines are present both in the emission and the absorption parts of the P Cygni profiles, with a power similar or slightly inferior to the one associated to the He II lines. It should be mentioned that, due to blending, the interaction between the two lines of the N V doublet can be quite strong, somewhat vitiating the individual observed variability.

As far as the He II lines are concerned, the amplitude of the variations on the mean-normalized spectra is of the same order among all the members of the Pickering series, only slightly increasing for the very lower members (as deduced from the KPNO data). As a matter of fact, if the slope of the Wolf-Rayet energy distribution is taken into account, we come to the conclusion that the observed variability is not stronger for the lines whose bulk of the emitting region is located, according to current theoretical models, in the external part of the wind. This is in good agreement with the strong variability observed for N IV λ4058 (which is known to form deep in the wind), but disagrees with McCandliss' conclusions (McCandliss, 1992). However, nothing indicates that the variable features are formed in the same part of the wind than the main and stable part of the line profile. In particular, it is crucial to notice how similar are the deformation patterns. The instantaneous patterns of deformation are, in the first order approximation, quite similar for all the He II lines of the Pickering series, but also for the He II λ4686 and N IV λ4058 lines. The only marked discrepancy concerns N V, although, in a few cases, we observe the same pattern for them too: this, however, is not systematic.

On the basis of our 1991 data, we also notice that, in the very few cases where the deformation pattern is strong at a negative velocity large enough to reach the velocity of the He I absorption, the He I absorption line exhibits deviations similar to the ones of the He II emission lines.

We measured the equivalent width of the He I absorption. A power spectrum of this time series clearly exhibits (again) peaks at $\nu \sim 0.5\ \mathrm{d}^{-1}$ and at the corresponding one-day aliases. However, both the related phase diagram and the simple plot versus time of the measured equivalent widths are not conclusive and they rather cast doubt on the existence of a periodicity although a typical time-scale related to $\nu \sim 0.5\ \mathrm{d}^{-1}$ is probably present.

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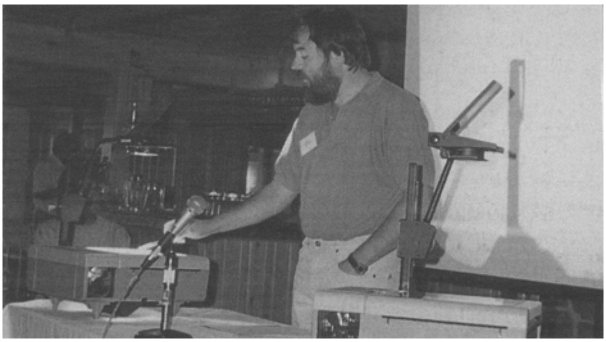

Eric Gosset

DISCUSSION

Marchenko: I would like to make a short comment concerning the wrong direction of the blobs. We are talking about blobs where supposedly we are seeing only features that are moving outward, but we are forgetting about the effective gravity. If we have a dense enough blob, with a contrast of density up to 30 and higher, the effective gravity may dominate and it should go inward. If the density is low enough, the material goes in the other direction, so we can see both accelerating and decelerating stuff; it goes both ways.

Gosset: The only thing I could say is: we don't see strong features accelerating downward, but I wouldn't even dare to interpret that as moving blobs, because I don't want to overinterpret these systematic patterns that we recognize 6 or 7 days apart.

Cherepashchuk: Could you explain the physical nature of this process?

Owocki: Gravity is independent of mass, right? I mean the acceleration of gravity is the same on a heavy object as a light one. I cite a man named Galileo. [Laughter].

Marchenko: If you account for the acceleration of the absorption.

Owocki: Oh, you mean the radiation force. Sure, I can show you simulations in which the density is too high, and the material reaches a certain height and then falls back down on the star, because it can't be driven away from the star. But that's different from saying the gravity changes.

Marchenko: That's what I am saying now.

Owocki: OK, it's clear.

Cassinelli: What was the significance of the blue-red anti-correlation? Does that mean the material is in a ring or something?

Gosset: It's hard to estimate the degree of freedom. It's not easy to say. I would say on the basis of the data that we have this significance level around 0.5% or so. But it's an estimation because we really must admit that all the information necessary for determining the statistical significance is not available.

Cassinelli: It probably rules out blobs coming from the star, certainly.

Gosset: I don't speak of blobs. I see things moving in my data, but I don't want to interpret them as blobs.

Cassinelli: So if you want to make a physical picture, you want rings.

Gosset: No, not really. The only thing we did is to propose a bipolar model, just as an alternative, and I think it's a good proposal. I mean, it's not only blobs, that's for sure.

McCandliss: Concerning Joe Cassinelli's remark about what could be in the N IV line: if you look at the peaks of the blue-red asymmetry in the cross correlation, you'll find that the separation is $\pm$ 500 km/s. This 500 km/s is indicative of the snaky feature going back and forth in the cores of all the lines. A couple of more comments about frequency and sampling to find the period: The implementation of my periodograms - it's the Scargle periodogram described by Press and Teukolsky - demands that the frequency be sampled linearly, which of course means the period is sampled inversely, and so you may not be sampling well enough to pull out the 2.2 day period. And I would ask you to look there. You do have a very strong peak at 0.5 in frequency, and so I would ask you to sample that a little better. You seem to be sampling more at high frequencies; I suggest that you sample the lower frequencies a little more completely.

Gosset: We did sample correctly: I just showed the periodogram. From the statistical point of view, if you use standard methods, you should not go beyond the Nyquist frequency; this is known to be statistically wrong. But even then, you were already statistically wrong before, because of aliasing, and so on.

McCandliss: You have a huge dataset right now, at least the largest that I know of, and so you can sample very effectively at lower frequencies. And, finally, I'd like to know if the 6.8 day recurrence in the symmetry is really exactly 3 times the 2.2 day period.

Gosset: Be careful! The 6.8 day "recurrence" occurred only once.

Robert: Just a short comment: maybe you missed the periodicity because there is a combination of two processes. One is periodic but it gets confused by the general blob phenomenon, that we see in all stars, depending on the relative amplitude.

Massa: I don't know very much about this Wolf-Rayet business, and I may be a little confused. Are there "wiggly" Wolf-Rayets and "blobby" Wolf-Rayets?

Gosset: I would say so. What Carmelle Robert showed is typical of a WC star, a vertical advancing of the blobs. In WR 134, I have difficulties to believe it because systematically we don't see one blob, we see several blobs strangely distributed, in my opinion.

Robert: In the case of WR 134 (like for WR 6), the overall variations look different from the general variations due to blobs observed in most WR stars.

Gosset: Yes, what you showed looks quite convincing, that you have moving blobs for a WC star. Whereas, for WR134, we have a different case.

Robert: Maybe there is a difference between WN stars and WC stars? Not really. I showed WR 135 because it has a flat-top line where the blobs are easy to point out. Other WN stars than WR 134 have similar blob behavior like the WC stars, when we look at the difference spectra (difference between individual profiles and their mean).

Gosset: Yes, I agree that this is a way to see the problem. But in WR 134, I don't see moving blobs. I won't say that this is perfectly clear. From time to time, there is a feature or pattern, and we have a tendency to see the pattern showing systematic motion; but then the pattern changes completely. And I see no way to go from one pattern to another.

Robert: In your mind you should associate one type of variation with something that affects the global shape of the line. On top of this you then superpose little structures, i.e. blobs, moving outward. Depending on the relative amplitude of the two types of variations, I believe it can become very complicated to isolate one phenomenon.

Oral discussion of blobs among Henriksen, Robert, and Vreux; in the case of Carmelle, they seem to be *very* oral