The "Photosphere-Wind Connection" in Wolf-Rayet Stars: Simultaneous Photometry and Spectroscopy of EZ CMa*

T. Morel, N. St-Louis and S. V. Marchenko

Département de Physique, Université de Montréal, Québec, Canada
and Observatoire du Mont Mégantic.
e-mail: morel, stlouis, sergey@astro.umontreal.ca

Abstract: In an attempt to reveal the driving mechanism for the 3.77-day periodicity associated with the Wolf-Rayet star EZ CMa (compact companion or rotational modulation of a structured wind), we have monitored this object in optical spectroscopy and narrow-band photometry for 20 consecutive nights in January 1995, simultaneously with the *IUE* Mega project. Arguments are presented against a compact companion as the origin of the observed periodic variability. Instead, we propose that the atypical level of variability intrinsic to this object results from the rotation of its structured wind. The existence of large-scale structures in the wind of EZ CMa is most likely triggered by a spatial (azimuthal) dependence in the physical conditions at the base of the outflow. A local or large-scale magnetic field could cause this inhomogeneity.

1 Introduction

A long series of papers devoted to the single-lined Wolf-Rayet (WR) star EZ CMa (HD 50896; WR 6) began when, nearly fifty years ago, Wilson (1948) reported spectacular night-to-night variations in the line profiles of this object. Later, Ross (1961) observed large-amplitude photometric variations but it was the almost-simultaneous discovery by Firmani et al. (1979) and Mc Lean (1980) of a 3.77-day modulation in the spectroscopic, photometric and polarimetric data which drew attention to this object. This led many authors to propose that the regular and unique "clock" associated with this star is either revealing the binary revolution of an invisible companion (e.g., Firmani et al. 1980) or the rotational modulation of a structured wind (e.g., St Louis et al. 1995). In this paper, we present the results of a campaign devoted to reveal the nature of this peculiar object.

*Based on data collected at the Cerro Tololo Inter-American Observatory and University of Toronto Southern Observatory, Chile.

2 Observations

EZ CMa was simultaneously monitored during a 20-night run in narrow-band photometry at the 60-cm Lowell telescope at CTIO and in spectroscopy at the 60-cm Helen Sawyer telescope at UTSO, Chile. This campaign was planned as ground-based support observations for the *IUE* Mega-project (see Massa et al. 1995).

In the photometric mode, two filters were chosen: (1) Central wavelength λ_0 = 3650 Å, and full-width at half-maximum, FWHM = 100 Å (u-filter); and (2) λ_0 = 5140 Å and FWHM = 90 Å (v-filter). Both filters sample the continuum of EZ CMa.

The spectra cover the spectral domain 3700-6750 Å with a 2.2 Å pixel^{-1} resolution and a typical S/N of 100 in the continuum. They were subsequently rectified and corrected for the variable continuum flux.

3 Results

As shown in Fig.1, the optical continuum light curve is very similar to the UV continuum flux variations (St Louis et al. 1995). Both have an amplitude of ~ 0.1 mag. Note the lack of *significant* $(u - v)$ colour variations (bottom panel), as well as the increased amplitude of the variations in the far ultraviolet (central panel) compared to the optical. This strongly suggests that the temperature at the base of the wind of EZ CMa increases during maximum light.

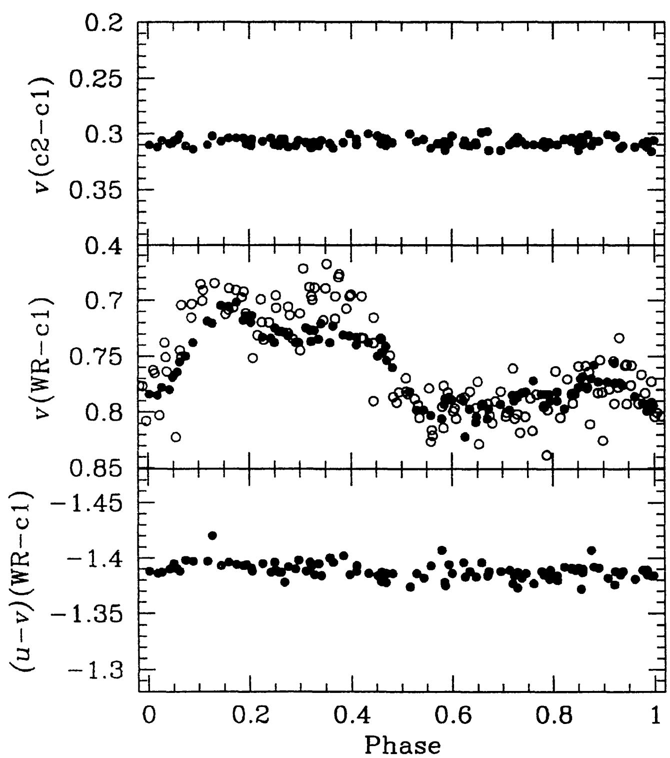

Figure 1: The light-curve of EZ CMa folded with the 3.77-day period (Lamontagne, Moffat & Lamarre 1986). Upper panel: differential v magnitudes for the c1 and c2 comparison stars. Central panel: v-filter continuum light-curve (filled dots); combined *IUE* continuum (2.5 × log $[F(1689\text{Å}) + F(1860\text{Å})]$; open symbols).

The main results from the spectroscopic analysis are as follows:

- The same pattern of variability consisting of extra emission components travelling across the line profile is seen for *all* transitions with only small apparent time-delays (Fig.2). Furthermore: (i) *All* the variations are coherent with the 3.77-day periodicity; (ii) The *bluest* excursions of these sub-structures coincide with the occurence of the brightness light-curve maxima at $\phi \sim 0.15$ and 0.40; (iii) Each part of the profiles displays a statistically significant level of variability, with additional enhancement of the variability at some specific velocities (lower panels). Note in particular the remarkable variability of the lines at high-negative and high-positive velocities.

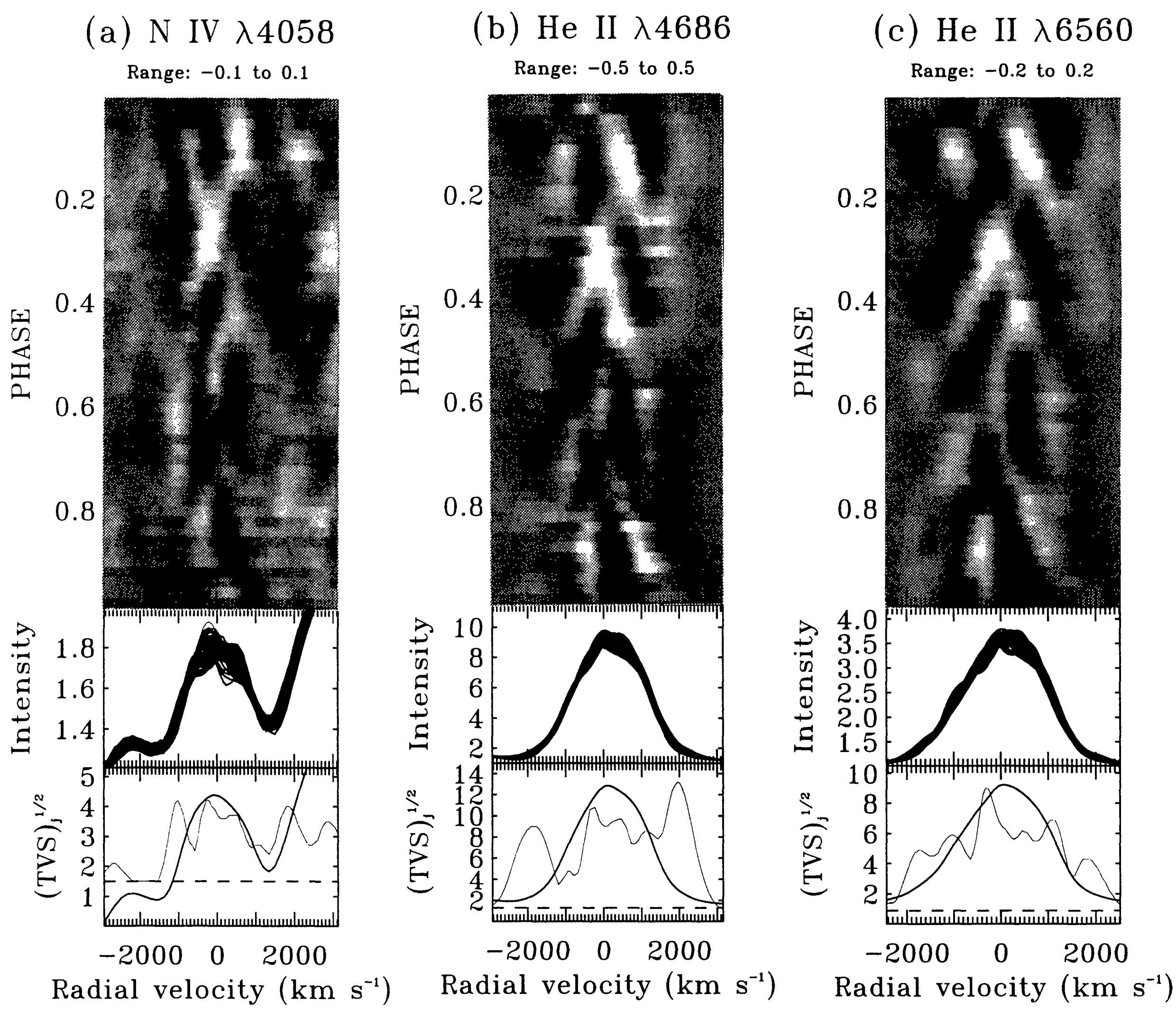

Figure 2: Grey-scale plots of the residuals (the individual spectra minus the mean spectrum) of (a) N IV λ4058, (b) He II λ4686 and (c) He II λ6560 folded with the 3.77-day period. These residuals were binned to a 0.02 phase interval. The middle panel presents the superposition of the individual profiles. The values of $(\mathrm{TVS})^{1/2}$ (Fullerton 1990) and the mean profile (in arbitrary units) are presented in the lower panel. The dashed line indicates the 1 % variability detection threshold.

- Although the amplitude of the variability is significantly different from line to line, a causal relationship is found between the continuum light variations and the line equivalent widths: as the continuum flux and UV to optical color increase (and thus the star becomes hotter and brighter), the EWs become higher (Fig.3a).
- A daily recurrence timescale appears in the full-width at half-maximum and skewness variations (Figs.3b, c).

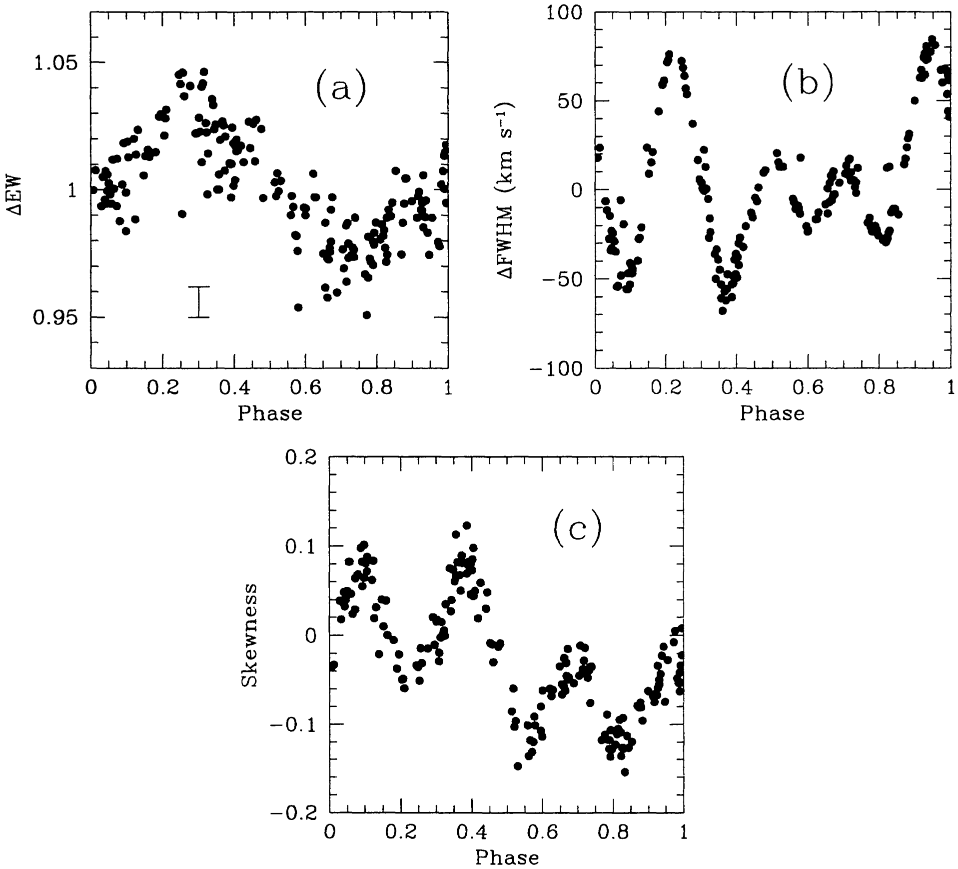

Figure 3: (a) Equivalent width (normalized to the mean value) of He II λ4686 as a function of phase. The effect of the continuum variations has been removed from this curve; (b) Variations from the mean value of the full-width at half-maximum; (c) Skewness of the He II λ4686 profile.

- Similarly to the P Cygni absorption components of the UV profiles, the optical He I lines strengthen in response to the increased continuum flux (Fig.4a). Conversely, the absorption trough of N V λ4604 gradually disappears as the star brightens (Fig.4b).

4 Discussion

4.1 A Compact companion?

In order to derive the location of the hypothetical companion as a function of phase, we have compared the representative profiles of N IV λ1718 for the "low-" and "high-velocity" states as were observed by *IUE* in January 1995 (referring to the blueward extension of the P Cygni absorption components; St Louis et al. 1995), with the relatively quiescent profiles taken in September 1983 (Willis et al. 1989). The 1983 profile morphology is quite similar to the 1995 "low-velocity" profile: the part of the envelope which is seen projected on the stellar disk between $\phi \sim 0.5$ and $\phi \sim 0.8$ is thus *relatively* unperturbed. The companion (if any) must be in front at $\phi \sim 0.15$, i.e., at maximum light (cf. Fig.1).

In this context, there are multiple contradictions which challenge the binary hypothesis. The most serious are: (i) The impossibility to account for the variability in terms of the "Hatchett-Mc-Cray effect" (Hatchett & Mc-Cray 1977); (ii) The need for a large photoionized cavity and/or photoionization wake (Fransson & Fabian 1980) to account for the observed spectral changes (Fig.4), which are both unlikely because of the low X-ray flux from this object; (iii) The basic properties of EZ CMa which are difficult to reconcile with those of other well-known wind-fed high-mass X-ray binaries.

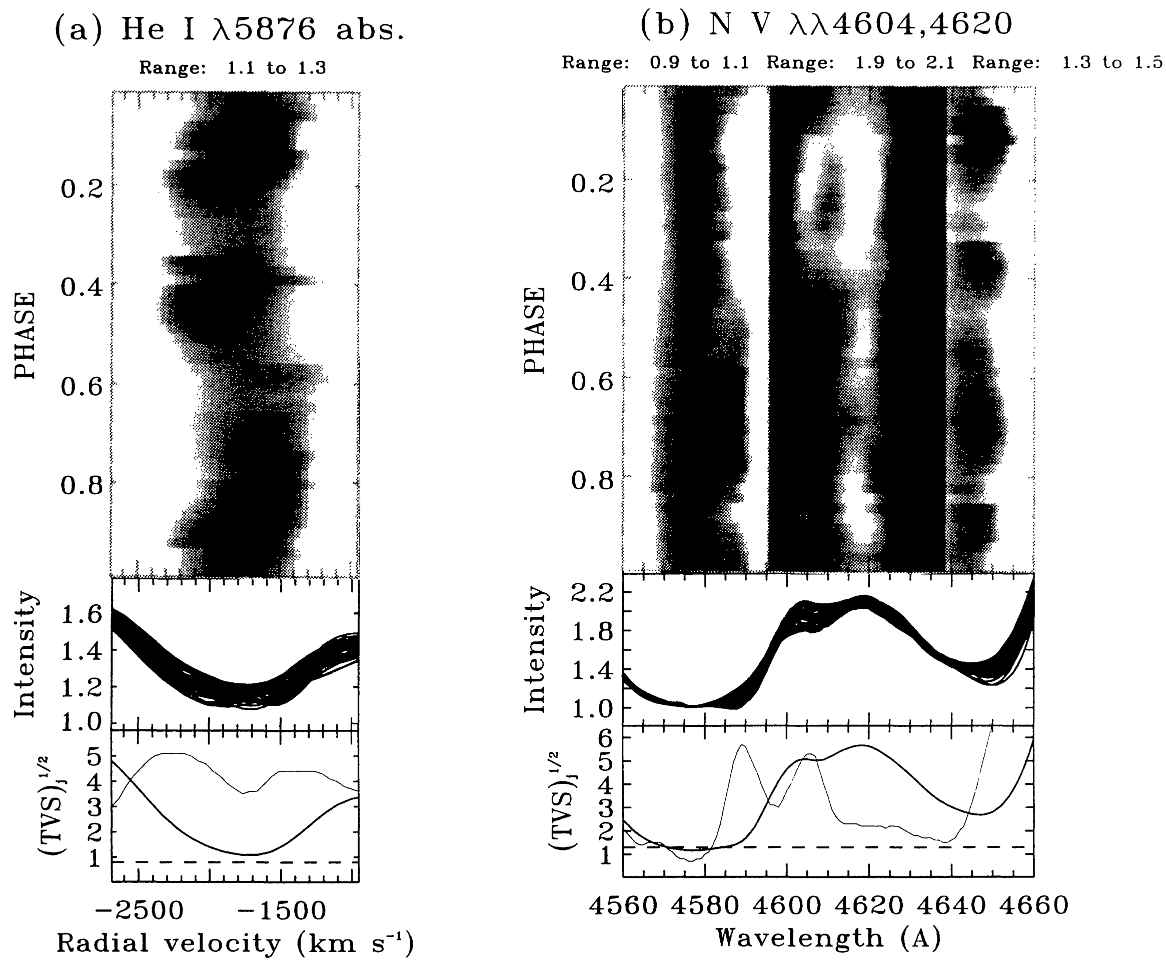

Figure 4: Grey-scale plots of the P Cygni absorption components of (a) He I λ5876 and (b) N V λλ4604,4620 folded with the 3.77-day period. Note the blue wing variability of He II λ4686 (extreme right of Fig.4b). The helium lines present an enhanced absorption component at high velocity at maximum light. Conversely, the nitrogen transition develops a violet absorption edge when the star fades (cf. Fig.1).

4.2 A structured wind?

We propose that *the periodicity of the wind variability results from the rotation of a structured wind.* The formation of these large-scale structures (somewhat similar to the "co-rotating interacting regions"; Cranmer & Owocki 1996), which differ by their physical and kinematical properties, is subject to the conditions prevailing at the base of the outflow, as revealed by the tight correlation between the continuum light and line-profile variability. From this point of view, these observations tend to support the existence of a "photosphere-wind connection" for this WR star similarly to what is now commonly observed for O stars.

What triggers the formation of these structures?

- (Non-)radial pulsations? These seem unlikely because the 3.77-day period is much too long compared to theoretical expectations (Glatzel, Kiriakidis & Fricke 1993).
- Localized/large-scale magnetic fields? Although they remain to be detected, magnetic fields are serious candidates for controlling the morphology of EZ CMa's wind.

Acknowledgements

We wish to thank the Natural Sciences and Engineering Research Concil (NSERC) of Canada and the Fonds pour la Formation de Chercheurs et l'Aide à la Recherche (FCAR) of Québec for financial support.

References

Cranmer, S. R., & Owocki, S. P. 1996, ApJ, 462, 469
Firmani, C., Koenigsberger, G., Bisiacchi, G. F., Ruíz, E., & Solar, A. 1979, in IAU Symp.83, Mass Loss and Evolution of O-Type Stars, ed. P. S. Conti and C. W. H. de Loore, 421
Firmani, C., Koenigsberger, G., Bisiacchi, G. F., Moffat, A. F. J., & Isserstedt, J. 1980, ApJ, 239, 607
Fransson, C., & Fabian, A. C. 1980, A&A, 87, 102
Fullerton, A. W. 1990, Ph. D. thesis, University of Toronto
Glatzel, W., Kiriakidis, M., & Fricke, K. J. 1993, MNRAS, 262, L7
Hatchett, S., & Mc-Cray, R. 1977, ApJ, 211, 552
Lamontagne, R., Moffat, A. F. J., & Lamarre, A. 1986, AJ, 91, 925
Mc Lean, I. S. 1980, ApJ, 236, L149
Massa et al. 1995, ApJ, 452, L53
Ross, L. W. 1961, PASP, 73, 354
St-Louis, N., Dalton, M. J., Marchenko, S. V., Moffat, A. F. J., & Willis, A. J. 1995, ApJ, 452, L57
Willis, A. J., Howarth, I. D., Smith, L. J., Garmany, C. D., & Conti, P. S. 1989, A&AS, 77, 269
Wilson, O. C. 1948, PASP, 60, 383