Astron. Astrophys. 347, 583–589 (1999)

ASTRONOMY
AND
ASTROPHYSICS

Long-term coherent variations in the WR system EZ Canis Majoris: the binary scenario revisited*

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Received 6 October 1997 / Accepted 15 April 1999

Abstract. An analysis of seven different spectroscopic and eight photometric sets of observations of the WN5 star HD 50896=EZ CMa, distributed over more than 15 years is used to refine the known 3.76 days period. The value of $P = 3.7650 \pm 0.0001d$ yields variations which have coherent phase-dependence. Although not conclusive, this coherence in the 3.7650 day periodic variations over such a long time revives scenarios in which HD 50896 consists of a binary system, a hypothesis that had been nearly completely discarded over the past few years. A binary scenario is not in contradiction with the presence of a non-spherically symmetric wind distribution or instabilities in the WR star's wind and, in fact, mechanisms such as these are probably responsible for the difficulty in having until now obtained a period which yields coherent variations. The low X-ray fluxes suggest that the possible companion may not be a collapsed object, or that the accretion process is inhibited.

Key words: stars: binaries: spectroscopic – stars: Wolf-Rayet – stars: variables: general – stars: individual: HD 50896 = EZ CMa = WR6

1. Introduction

The Wolf-Rayet (WR) star EZ CMa=HD 50896=WR6 is one of the brightest WR stars in the sky. It started to receive a great deal of attention soon after van den Heuvel (1976) proposed that the evolution of massive stars is expected to lead to the formation of binary systems in which WR stars have a closely orbiting compact companion (cc). The periodic variability discovered in this star (Firmani et al., 1980), its large distance from the galactic plane, and its surrounding ring nebula made HD 50896 an excellent candidate for such a WR+cc system. However, as further observations were made, it was discovered that the variability seemed not to be coherent over long timescales (Robert et al. 1992). In addition, analyses were performed which indicated that the observed levels of X-ray emission were not consistent with the hypothesis of an accreting compact companion (Vanbeveren et al. 1982; Stevens & Willis 1988). Furthermore, ROSAT IPCS variations reported by Willis & Stevens (1996) do not show any modulation on the 3.76 day cycle. Hence, the very binary nature of HD 50896 began to be questioned, and numerous alternative scenarios for producing the variability in the system were put forth. These alternative scenarios include wind instabilities and non-isotropic wind structures. Reviews of the different scenarios and the observations which have been accumulated over the years of this system can be found in Morel et al. (1997, 1998) and St-Louis et al. (1995).

EZ CMa is a WN5 star (van der Hucht et al. 1981) with very strong emission lines present in its spectrum. The notable emission line profile variability lead Firmani et al. (1980) to identify a period of 3.76 days for these variations, a period which was later confirmed to be present in the photometry (Cherepashchuk 1981) and polarimetric observations as well (McLean 1980). Although this basic period is maintained within most data sets, a coherent phase dependence is apparently not present from one data set to another one, when timescales are larger than a few weeks. This is the most damaging argument against the binary scenarios, since variability due to orbital motion would not be expected to present phase jumps between different observing epochs.

Recently, however, Ivanov at al. (1999) have argued that some of the features in the spectrum of HD 50896 undergo exactly the same variations at all epochs, and discuss the implications of this for the various non-binary scenarios. Also, Morel et al. (1997) confirm the persistent nature of the variations in the strength of the P Cyg absorptions of the NV 4604-20 lines. In this paper we combine different data sets, and using an improved period for the variability in HD 50896, we show the variations to be coherent over long timescales thus reopening the possibility of a binary scenario for this intriguing object.

2. An improved period: coherent variations over 15 years

There is no question that the winds of hot stars are variable in general (Howarth and Prinja 1989), and thus, non-periodic variability is expected to be present even in the most established

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* Table 3 available in electronic form only at the CDS via anonymous ftp to: cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html

Table 1. List of the photometric data.

Observatory	wavelength range	Date	HJD-2440000	number of spectra	S/N	Reciprocal Dispersion [Å/px]	reference
SIT I	4480–4800	Jan 1977	3170–3253	48	300[a]	0.7	1
SIT II	4480–4800	1977–1978	3431–3570	69	300[a]	0.7	1
SPM	4450–5000	Jan 1991	8280–8291	268	150[a]	1.0	2
BNO	3800–4800	1990–1992	7905–8667	30	25[b]	0.5[d]	3
IUE	1200–2000	Sep 1983	5581–5587	34	3[c]	0.1[e]	4
IUE	1200–2000	Dec 1988	7503–7508	107	5[c]	0.1[e]	5
IUE	1200–2000	Jan 1992	8643–9649	66	5[c]	0.1[e]	6
IUE	1200–2000	Jan 1995	9730–9746	146	10[c]	0.1[e]	6

[a] Based on photon statistics.

[b] Improved by averaging several spectra.

[c] Calculated as average/st.dev. in the windows used for continuum normalisation.

[d] Binned onto fixed wavelengt grid of 0.5Å intervals

[e] Binned onto fixed wavelengt grid of 0.1Å intervals

(1) Firmani et al. 1980; (2) Cardona et al. 1999; (3) Ivanov et al. 1996; (4) Willis et al., 1989;
(5) St. Louis et al., 1993; (6) St. Louis et al., 1995;

of binary star systems. The variability due to non-spherically symmetric wind distributions, wind instabilities and/or other mechanisms intrinsic to the stellar winds is expected to act as noise superposed on the periodic trends in the data. The relative amplitude of the periodic vs. the non-periodic variations will determine whether the observed spectral feature predominantly displays phase-dependent effects, or non-periodic wind variations. This amplitude is related to the amount of wind material involved in each of the different processes. Clearly, a perturbation involving a small fraction of wind material cannot provide as much flux variability in the observed spectrum as a perturbation involving a significant fraction of the wind. Let us assume for a moment that the star is a binary. The variations due to binary interaction effects, by their very nature, arise in a limited portion of the stellar wind. Thus, if the companion is not comparable to the primary, its perturbing effects on the primary's stellar wind are not very prominent. Intrinsic wind variations, however, are expected to arise throughout the wind, not just in the region between the two stars nor the line-of-sight to the companion. Thus, spectral features which arise in very extended regions of a stellar wind in which intrinsic variations are present, will tend to mask the periodic variations. This is the case, for example, of the resonance lines in the UV spectra of these stars. However, for spectral lines which are formed in a smaller, more limited region, the effects due to the binary companion are more comparable to those of wind instabilities, and allow the periodic variations to be more easily detected.

In the optical spectral region, the N V 4604, 4620 doublet provides an excellent diagnostic tool because the majority of this line's emission arises very close to the stellar core in HD 50896 (Hillier 1988), and both transitions display a P Cygni-type absorption component. The P Cygni absorption components arise only in the column of wind projected onto the stellar continuum-emitting core, and thus reflect physical conditions in an even more limited region of the wind than the emission components. This absorption component for the $\lambda 4620$ line is superposed on the $\lambda 4604$ emission, making any variations in its strength easy to detect. Hence, we have started the analysis with the N V 4604-20 doublet, first in order to analyze the problem of the coherence of the variations in HD 50896, and thus to determine whether any support for the presence of a binary companion can be found. The N V 4604-20 has been shown to present persistent variations from epoch to epoch (Ivanov at al.,1996; 1999).

The observations that were used include two of the most complete optical data sets in existence for HD 50896, obtained at the Observatorio Astronomico Nacional (OAN) in Tonanzintla in 1978 and 1979 (Firmani et al. 1980) and in San Pedro Martir (SPM) in 1991 (Cardona et al. 1999). These data have been complemented with observations obtained at the Bulgarian National Observatory between 1990–1993 (Ivanov at al. 1996). We mesuared two parameters from the optical spectra: a) Window averaged flux (WAF) - the average flux in a given spectral range - is calculated for two windows $(4586, 4590)$Å for $NV4604$ and $(4603, 4609)$Å for $NV4620$ centered on their P Cyg absorption components; b) The kurtosis defined as:

$$Kurtosis = \frac{1}{N}\sum_{j=0}^{N-1}(\frac{x_j - \overline{x}}{\sqrt{variance(x)}})^4 - 3$$

is calculated for the HeII 4686, using only the line profile at level higher than 2.5 times the continuum level. In order to reduce the uncertainty, additional parameters and additional sets of data are used. We measured the skewness of the N IV 1718 line from the IUE archival data, defined as:

$$Skewness = \frac{1}{N}\sum_{j=0}^{N-1}(\frac{x_j - \overline{x}}{\sqrt{variance(x)}})^3.$$

Here we used only the line profile at level higher than 2 times the continuum level. This provides a totally independent parameter, calculated from an independent set of data, obtained over the years 1983–1995, including the IUE MEGA campaign (St-Louis et al. 1995).

In Table 1 we list the characteristics of these data sets.

Because the data in the three sets are clustered around different epochs and are not distributed uniformly in time, the standard period-searching routines are not applicable. Thus, instead we use the fact that the 3.76 day period is accurate for short time intervals. This period has been shown to exist in all data sets published by diverse autors (see the introduction) and it is unique (Antokhin et al. 1995). We searched for periods close to this value which produce a coherent phase-dependence in the different sets of data. We refined the period using the same events of the phase curve, using the fact that the curves for the NV doublet WAFs are similar in shape at different epochs. Following Massey and Niemela (1981) and Massey (1981), we first determine the time at which the ascending branch of the NV 4620 WAF reaches half its maximum intensity (at $WAF = 1.87$), which for the SIT spectra occurs at $T_1 = 2443448.77 \pm 0.01$. Then, we select the points with similar values of the WAF, again in the ascending branch of the curve for the SPM data, and thus determine the second time $T_2 = 2448286.79 \pm 0.01$. Using the first approximation to the period 3.766, we determine the possible integral number of cycles between T_1 and T_2 to be 1284 and 1285. The corresponding possible periods are 3.7679 and 3.7650 days. The same procedure was applied to the 1988 and 1992 epochs of IUE data. The times are $T_3 = 2447503.94$ and $T_4 = 2448648.41$, and with the corresponding number of cycles 303 and 304 yields the periods 3.7771 and 3.7647 days, respectively. The consistent period between the two pairs of times (T_1,T_2) and (T_3,T_4) is $P = 3.7650$ days so we adopt this as the refined period. Taking into account that the precision of T_1 and T_2 is on the order of 0.01 days and that 1285 cycles have passed between them, the formal error of the period should be better than 0.00005 days. We adopt the more conservative value of 0.0001 days.

In Figs. 1a and 1b we plot the $NV4620$ and $NV4604$ WAFs, respectively, using all optical spectral data, and with $P = 3.^{\rm d}7650$ and $T_0 = JD2443199.53$. A clear modulation of the data is evident, despite the fact that the different data sets span a timescale of 15 years (1977–1992) and were obtained with different instruments and by different observers.

Two maxima are present in these figures (near phases 0.3 and 0.6) as well as one pronounced minimum (between phases 0.6 and 1.1), and a second narrower minimum near phase 0.4. The maxima in the values of the WAFs indicate that there is a larger area contained between the flux levels in the NV 4604 line and the continuum. This occurs when the the P Cygni absorption components are weaker. On the other hand, Morel et al. (1997, 1998) have recently shown that there is a correlation between the strength of the P Cyg absorption components in this line and the intensity of the continuum, in the sense that a more intense continuum is associated with weaker P Cyg absorptions (and hence the larger WAF). It is important to note that for a line which is formed primarily by absorption processes, the strength of the P Cyg absorption component increases when the underlying continuum increases, assuming constant ionization structure. Thus, the N V variations indicate that the ionization structure does not remain stable or that there is a significant scattering contribution to the formation of this line. This could either result from an intrinsic variation at the base of the wind as proposed by Morel et al. (1998), or an interaction effect due to the presence of a very hot companion.

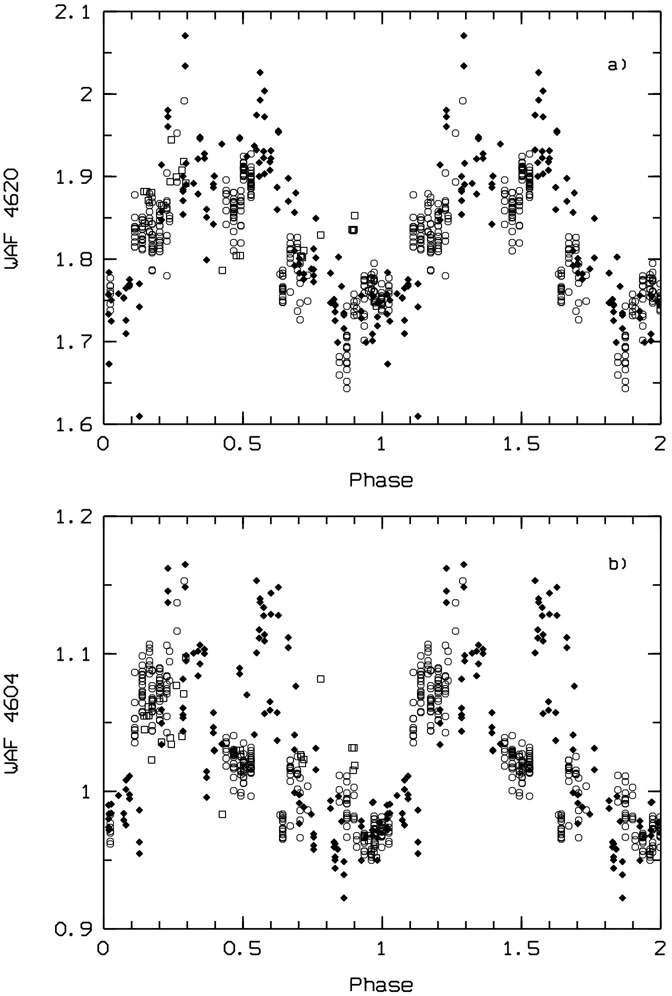

Fig. 1a and b. Window Averaged Flux of the NV 4620 **a** and NV 4604 **b** line as a function of phase using P=3.7650 days and T_0 = 2443199.53. Circles correspond to SPM data (1991), filled-in diamonds to the SIT-Tonanzintla data (1977–78), and squares to the BNAO data (1990–1993).

In Fig. 2 we present a montage of the N V 4604-20 line profiles corresponding to the two OAN data sets (SPM - left and SIT-Tonanzintla - right), side by side, plotted in order of increasing phase with the same ephemeris. One can appreciate in this figure that both sets present stronger P Cyg absorptions in the phase interval 0.8 to 1.0 and weaker P Cyg absorption components in the phase interval 0.1 to 0.3, consistent with the WAF measurements on Fig. 1.

The data of the WAF's and the kurtosis used for Figs. 1 and 3 are given in Table 3a,b,c available in electronic form only.

Coherent variations over the entire 15 year timespan are present also in other features in the optical spectra. In Figs. 3a and 3b we plot the Kurtosis of the He II 4686 and He II 4530 lines as a function of phase, with the same ephemeris as above,

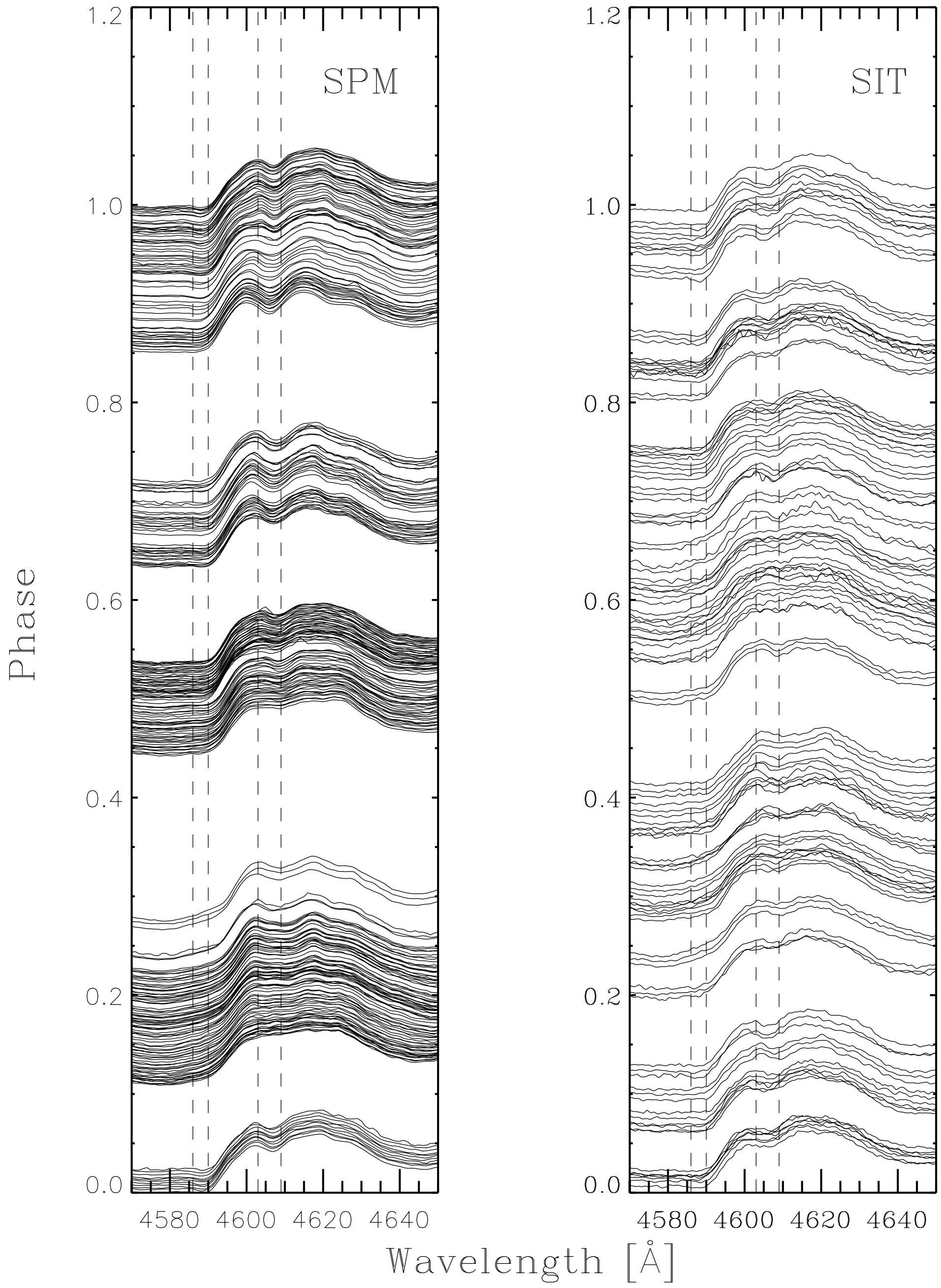

Fig. 2. Plots of the N V 4604, 4620 doublet stacked in order of increasing phase computed as in Fig. 1. Phase increases from bottom to top; SPM data are on the right and the SIT-Tonanzintla data are on the left. The vertical dashed lines mark the wavelength regions within which the WAFs plotted in Fig. 1 are computed.

and for the same data sets as in Fig. 1, illustrating a fairly stable pattern of variability with one maximum near phase 0.5 and a minimum near phase 0.9.

Thus, the spectral variations in the optical lines present in data obtained over a 15 year timespan can be plotted to yield coherent phase curves adopting the revised period of $P = 3.^{\rm d}7650$.

3. Several variabililty states?

Fig. 4 presents the skewness calculated for the line NIV 1718 Å present in the IUE wavelength range, plotted as a function of phase computed with the new ephemeris. Fig. 4a contains data obtained in 1983 and 1995, while Fig. 4b contains data obtained in 1988 and 1992, and although each panel of this figure displays a regular behavior of the skewness with phase, there is a clear difference in the number of maxima present. The top panel (Fig. 4a), which contains the data obtained in the IUE MEGA Campaign, display 3 maxima per cycle, while the bottom panel (Fig. 4b) displays only one. Thus, we conclude that there are at least two variability states in the system which are recurrent, one "active" state in which more variability is present per cycle, and a second, more "passive" state. The remarkable aspect of this shift from one state to another is that each state retains coherence in the variability, despite being separated by many cycles from a previous, similar state.

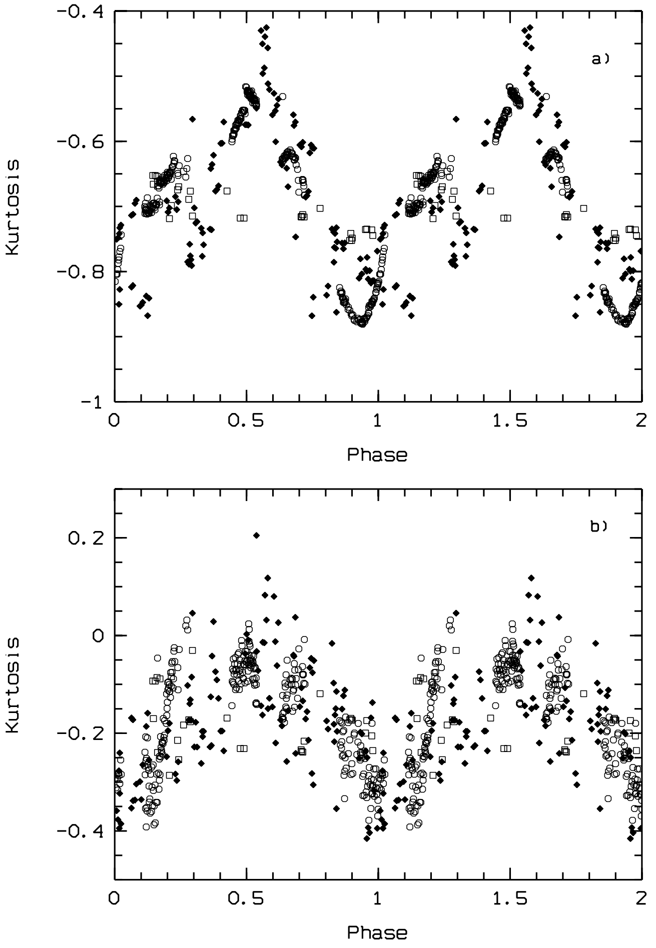

Fig. 3a and b. Kurtosis measurements of the two He II optical lines, plotted with the same ephemeris and symbols as in Fig. 1. **a** He II 4686 and **b** He II 4540.

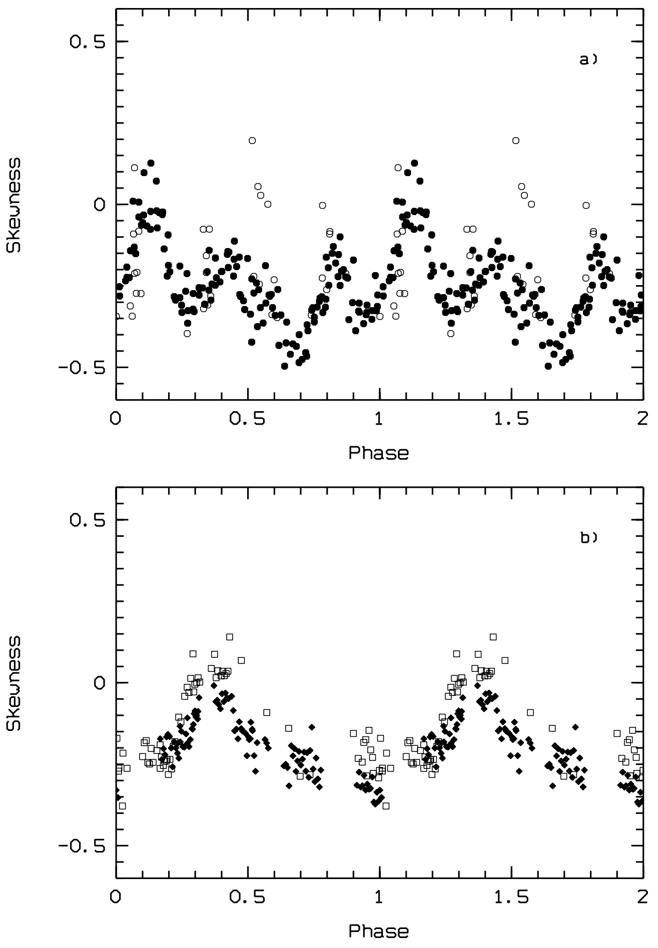

Fig. 4a and b. Skewness of the N IV 1718 line as a function of phase with the same ephemeris as in Fig. 1. **a** "Active" state illustrated by data obtained in 1983 (open circles) and in 1995 (filled circles, IUE MEGA campaign). **b** "Passive" state illustrated by data obtained in 1988 (filled-in diamonds) and in 1992 (open squares).

The photometric variability of EZ CMa has a behavior similar to that of the skewness in that the light curve is variable in shape and amplitude (Duijsens et al., 1996). However, here also one can identify patterns in the shape of the light curves which recur, and one can thus extend the concept of different variability "states" to the photometric behavior. For example, the data of Cherepashchuk (1981) and Robert et al. (1992), obtained respectively in 1980 and 1990 have almost identical phase-dependent behaviors, as can be seen in Fig. 5a. These light curves have a maximum near phase 0.5 and a trend towards a maximum at phase 0.0 which is broken by a minimum. The other two light curves plotted in Fig. 5b and 5c (data obtained in 1988 (Robert et al., 1992) and 1987 (Drissen et al., 1989), respectively) have maxima near phase 0.0, with only a hint of a maximum near phase 0.5 A similar story is illustrated in Fig. 6: the data of Balona et al. (1989a), obtained in 1986, and Lamontagne et al. (1986), obtained in 1985, have almost identical shapes as illustrated in Fig. 6c, with a prominent maximum near phase 0.65 and a hint of a maximum near phase 0.2. The other light curves in this figure, corresponding to data obtained in 1993 (Antokhin et al., 1995) (Fig. 6a) and 1990/91 (Duijsens et al., 1996) (Fig. 6b) also have maxima near these same phases, although the maximum near phase 0.2 is much more pronounced. We emphasize that the phases computed for the data plotted in Figs. 5 and 6 have the *same* initial epoch and period as all the rest of the data in this paper, and no artificial phase shift has been introduced to match up the data. Hence, once again, it is remarkable that when the light curves are very similar, they display coherent variations (as in Figs. 5a and 6c), despite being separated by numerous cycles. Furthermore, it is interesting to note that there are two sets of phase intervals within which a maximum can occur: (0.2, 0.65), "state" A; and (0.0, 0.5), "state" B. The photometric data used are described in Table 2.

What is responsible for the maxima in the light curves? What physical process can switch the system from one state to another one, and yet retain coherent variability within each of the two different states? It is beyond the scope of this paper to even attempt providing aswers to these questions. All we are able to conclude at this time is that the phase coherence of the data, separated by many years, points to a common underlying periodic process with a *stable* ephemeris.

Table 2. List of the photometric data.

JD-2440000.0	Dates	No. of obs.	Amplitude	State[a]	Filter	reference
4321–4392	Mar 80–Jun 80	23	0.083	B	Jonson V	1[b]
6149–6166	Mar 85–Apr 85	42	0.083	A	Jonson V	2
6761–6774	Nov 86–Dec 86	177	0.060	A	Strömgren b	3[c]
6865–6897	Mar 87–Apr 87	54	0.092	B	Jonson V	4
7437–7455	Oct 88–Oct 88	19	0.090	B	Jonson V	5
7930–7971	Feb 90–Mar 90	32	0.066	B	5388 Å	5
8150–8294	Sep 90–Mar 91	286	0.110	A	Strömgren y	6
9038–9089	Feb 93–Apr 93	154	0.110	A	5140 Å	7

[a] See text for details

[b] Shifted by 0.015 mag to fit the data of Robert et al. (1992)

[c] Shifted by 0.820 mag to fit the rest of the data

(1) Cherepashchuk 1981; (2) Lamontagne et al. 1986; (3) Balona et al. 1989b; (4) Drissen et al. 1989; (5) Robert et al. 1992; (6) Duijsens et al. 1996; (7) Antokhin et al. 1994;

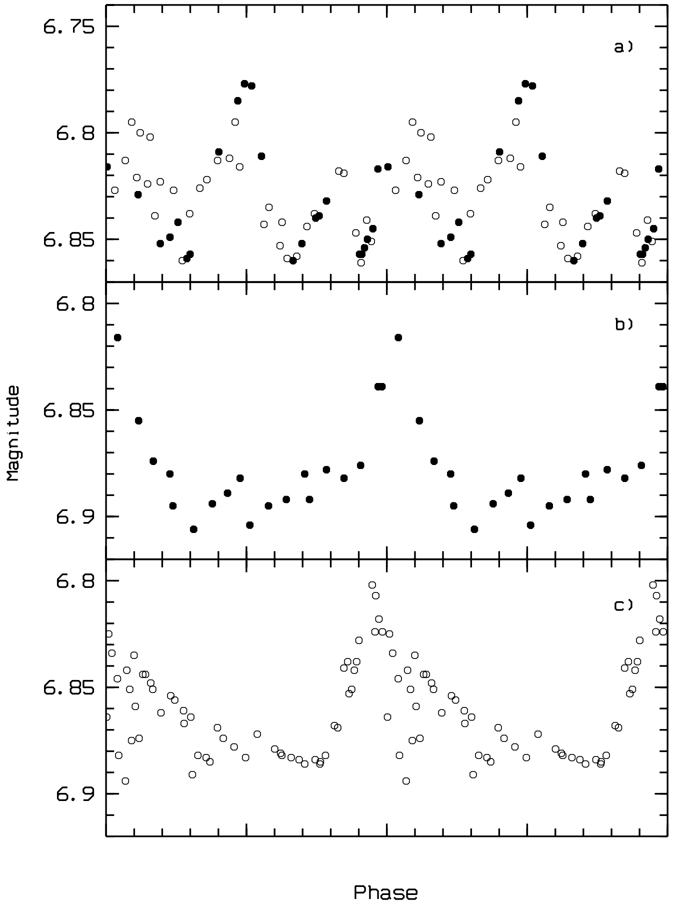

Fig. 5a–c. Light curves plotted with the same ephemeris as in Fig. 1 for the sets of data summarized in Table 2. The plotted data were obtained in the years: **a** 1980 (filled-in circles) and 1990 (open circles); **b** 1988; **c** 1987. These light curves all display maxima near phases 0.0 and/or 0.5.

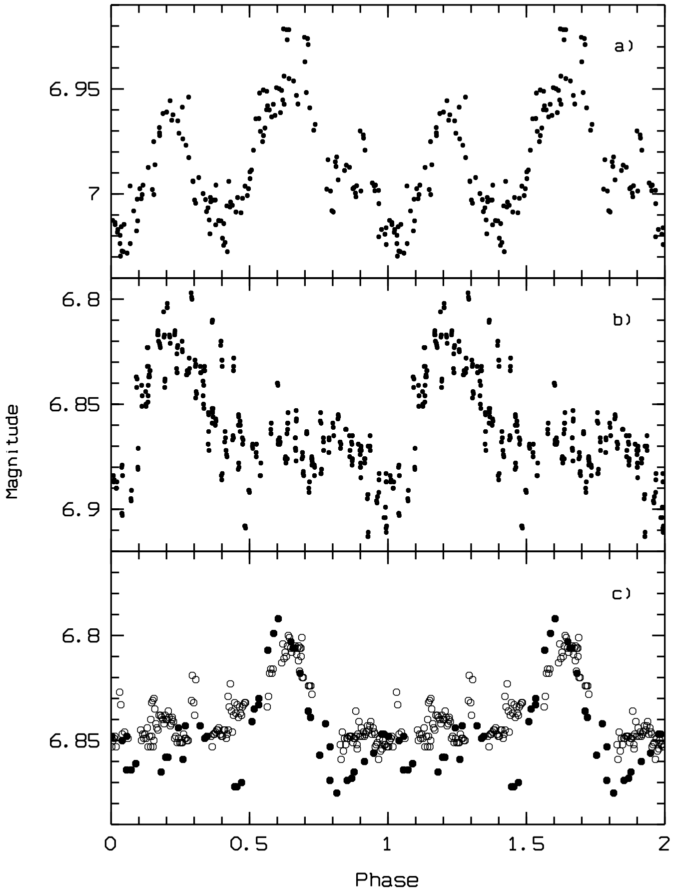

Fig. 6a–c. Same as Fig. 5 but for different sets of data, obtained in the years: **a** 1993; **b** 1990/91; and **c** 1986 (open circles) and 1985 (filled-in circles). These light curves all display maxima near phases 0.2 and/or 0.65.

4. Conclusions

We have refined the period for the variability in HD 50896, P=3.7650 days, which produces a phase-dependent modulation of three different spectral quantities and the photometric light curves which have coherent properties over a timespan of 15 years. This shows that the underlying process responsible for the periodic variations has a high degree of repeatability, and thus cannot be associated with wind instabilities or any other such mechanism which would not yield coherent variations over such long timescales. This does not mean that wind instabilities are absent, nor does it mean that other potential phenomena such as magnetic structures and non-spherically symmetric outflows cannot be present. In fact, some of these mechanisms must be present, as is evident from the secular variations observed, but the coherence over such a long timescale can only be compatible with a binary scenario or one of a rotating star with a fixed, non-spherically symmetric wind distribution. The rotation scenario requires a spatially stable structure displaced from the rotational axis in order to produce the variations (cf. the jets proposed by Mattews et al. 1992). To be stable, these structures would be expected to be symmetric with respect to the rotational axis, which would produce a double wave in the phase-dependent variations. There is, indeed, evidence for two maxima and minima, at least in the N V 4620 WAF and the He II 4686 kurtosis phase curves, but they are not equally spaced. Two maxima are at times present in the photometric light curves as well. A discussion of mechanisms which could give rise to non-spherically symmetric outflows from a star such as HD 50896 is given in Morel et al. (1998), although it is yet to be shown that such mechanisms can remain stable over such long timescales as the ones we now have shown to persist.

The coherent variations allow us to revisit the binary hypothesis for HD 50896. According to this scenario, the periodic changes in the N V 4604,4620 lines can be explained as the result of the perturbation of a portion of the WR wind by X-ray emission from the companion and/or a shock cone associated with the companion. This phenomenon is known as the Hatchett - McCray effect (Hatchett and McCray, 1977) who first predicted its existence. Because these N V lines arise deep in the WR star's wind, the companion's perturbing effect has to be very far reaching, unless its orbit is very close. Since the X-ray flux levels are not very high (cf. Stevens & Willis 1988), the former seems very unlikely. Rather, if HD 50896 contains a companion, its orbit must lie close to the base of the stellar wind, near the region where the N V 4604,4620 lines are formed. If the companion is a collapsed object, a mechanism to inhibit accretion and thus limit the X-ray flux could be invoked (Lipunov 1982). If the companion is not collapsed, it remains to be explained how its interaction with the WR primary produces such significant variability.

Acknowledgements. We would like to thank the referee Dr. Niemela for the very useful suggestions and comments which have helped us to improve the paper significantly. This work has been supported by UNAM/DGAPA grants IN 107094 and 109496, and CONACYT grant 3677P-A9607, ESO C&EE program grant A-05-95 and Bulgarian Science Fundation grant F704/97.

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