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Line Profile Variability and a Possible Magnetic Field in the Spectra of Supergiant ζ Ori Aa

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Abstract. Results of spectropolarimetric observations of the supergiant ζ Ori are reported. The fast line profile variability (LPV) with a period of about 3 hours is found and a connection of LPV with a non–radial pulsation of the star is supposed. We did not find any evidence for a moderate stellar magnetic field as reported by Bouret et al., 2008.

1 Introduction

The line profiles in the spectra of OB stars are usually strongly variable (Morel et al., 1998). One can detect both the stochastic LPV, connected with formation of the small–scale structures in the stellar wind (Eversberg at al., 1998; Kholtygin et al., 2003) and the regular LPV, induced by the large–scale structures in the wind (de Jong et al., 2001; Markova et al., 2008). The regular line profile variability (LPV) is connected with the co–rotation of large–scale structures in the wind (Kaper et al., 1999).

The latter might be explained by accepting the hypothesis that hot stars possess global magnetic fields (Neiner et al., 2002; Donati et al., 2002). Magnetic field can also regularize the wind structures induced by stellar non–radial pulsations (Owocki & Cranmer, 1988). The recent measurements have shown that nine O stars and a number of B stars possibly have weak magnetic fields (e. g. Donati et al., 2001; Donati et al., 2002; Henrichs et al., 2003).

Kholtygin et al. (2004) proposed a program of searching weak magnetic fields in OB stars. Spectropolarimetric observations of 8 bright OB stars were made under this program in 2005 – 2010 and the magnetic field of the B1 Ib supergiant ρ Leo was detected (Kholtygin et al., 2007). Recently Bouret et al. (2008) reported a detection of a weak magnetic field (50 – 100 G) of O9.5 supergiant ζ Ori A. In the present paper we report the results of searching the magnetic field and LPV of this star.

2 Main Data on ζ Ori. Observations and Data Reduction

Hummel et al. (2000) discovered that the O9.5 star ζ Ori A is a binary. They found that ζ Ori A consists of two components with a mean separation of 42 mas: the primary component Aa, and the secondary is a 2 mag fainter companion star Ab. It must be a dwarf of the late O type.

The parameters of ζ Ori Aa are given in Table 1. They are adopted from the paper by Bouret et al. (2008). The mass of the primary star ζ Ori Aa is given according to Rivinius et al. (2010).

Our observations were made on February 11/12 2009. The spectra of ζ Ori A were obtained in the Special Astrophysical Observatory (SAO) on the 6–m BTA telescope and a silica echelle spectrograph in the Nasmyth focus NES (Panchuk at al., 2002) with the 2048×2048 Uppsala CCD. We used

Table 1: Parameters of ζ Ori A

spectral class	O9.7 Ib
distance (pc)	414 ± 50
rotation period (d)	7.0 ± 0.5
inclination angle (i°)	40
$T_{\rm eff}$ (K)	29500 ± 1000
lgg(cgs)	3.25 ± 0.1
$\log L(L_\odot)$	5.64 ± 0.15
$M_*(M_\odot)$	24.8 ± 5.6
$v\sin\, i$(km/s)	110 ± 10
$v_{\rm inf}$(km/s)	2100
$\dot{M}(\times 10^{-6} M_\odot {\rm yr}^{-1})$	$1.4 - 1.9$

the spectral region $\lambda\lambda\, 4020 - 5450$ Å. The observations were made with a new polarization analyzer described by Panchuk et al. (2009). The analyzer consists of an achromatic quarter–wave plate, which can be rotated and takes 2 positions (0° and 90°): 25 spectra were taken in the 0° position, other 25 spectra were taken in 90°. This technique was used in order to avoid a probable instrumental shift between the two polarized components. General information about the observations can be found in Table 2.

Table 2: General information about the observations

Parameter	Value
S/N for each spectra	300
Tot. number of spectra	50
Exposition (min)	$1-4$
Duration of observations	3 h

All the obtained spectra were processed with the REDUCE packet (e. g., Piskunov et al., 2002). For finding the positions of the spectral order we used the method of Ballester et al. (1994). For studying the line profile variability (LPV) all the spectra were normalized on the individual continuum for each spectral order using our own code to determine the continuum level.

2.1 Magnetic Field and Regular Line Profile Variations

In order to obtain the field value we used the least squares deconvolution (LSD) method (see Donati et al., 1997). All the spectra were separated into two groups, 25 spectra each (the first group of spectra corresponds to the 0° quarter–wave plate position, the second corresponds to the 90° position). The LSD method was applied to the sum of all spectra of the first and second groups.

Results are presented in Fig. 1. One can see that the Stokes V profile is flat. This means that the field is either very small or absent. We also tried to measure the magnetic field using the relative shift method: we measure the magnetic field individually for each line, after that we average the obtained values. The list of lines used for measurements is given in Table 3. This method gave us a very uncertain result. The measured value of the field is 20 ± 100 G.

Regular LPV in the spectra of ζ Ori were for the first time revealed in the UV spectra of the star by Kaper et al. (1999). The authors report a discovery of variation with the period of 1.6 days.

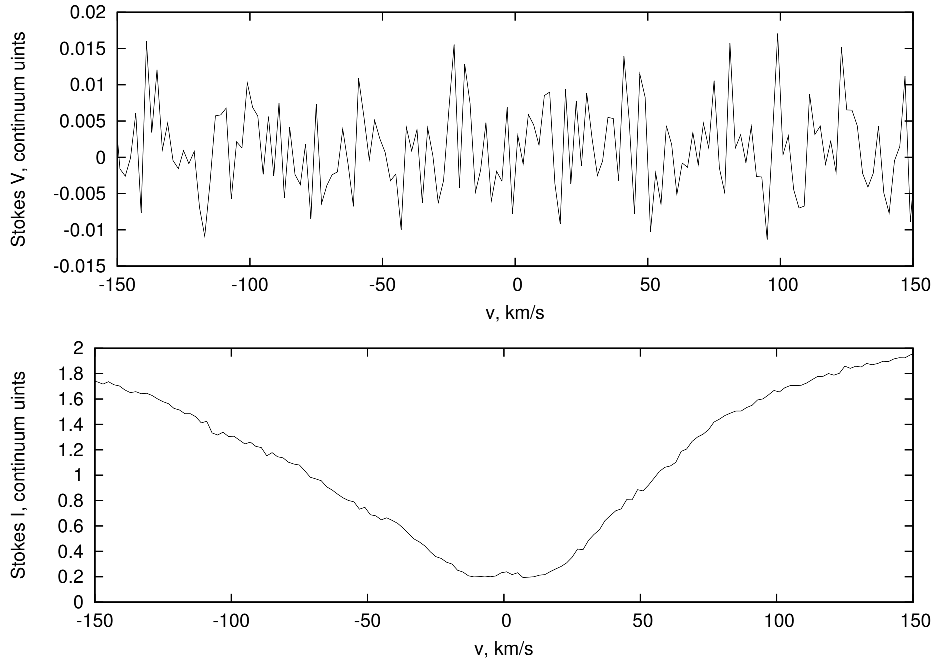

Figure 1: The Stokes V profile (upper panel) and Stokes I profile (lower panel) of LSD line profile for all the lines in the spectra of ζ Ori A listed in Table 3

Table 3: Lines used in magnetic field measurement

Element	λ, Å	Landé factor
He I	4471.473	1.100
He I	4713.139	1.250
He I	4921.931	1.000
He I	5015.678	1.000
He II	5411.520	1.000

The profiles of all the lines studied by us in the spectra of ζ Ori also appeared to be variable. For an illustration of these LPV we plotted the difference line profiles for all the 30 spectra obtained on February 11/12, 2009 in the SAO along with the night mean spectra in Fig. 2.

In order to find the contribution of a regular LPV into the total LPV we performed the Fourier–analysis of the line profiles of all the lines presented in Table 3. For all the lines we used the CLEAN algorithm (Roberts et al., 1987). In the CLEANed spectra we detected 5 regular components with frequencies ν in the interval $6-24\,\mathrm{d}^{-1}$. Two most reliable components are presented in Table 4. All the listed results correspond to the false alarm probability level $q=10^{-3}$. These regular components are probably connected with non–radial pulsations (NRP) of the primary star ζ Ori Aa.

3 Discussion

ζ Ori A is a well known bright X–Ray source with $\log L_X/L_{\mathrm{bol}}=-6.74$ (Berghofer at al., 1997). The shape of its X–ray spectra is determined by the magnetically confined X–ray plasma in the binary systems (Pollock, 2007). Unfortunately, our attempts to detect the magnetic field of ζ Ori A have

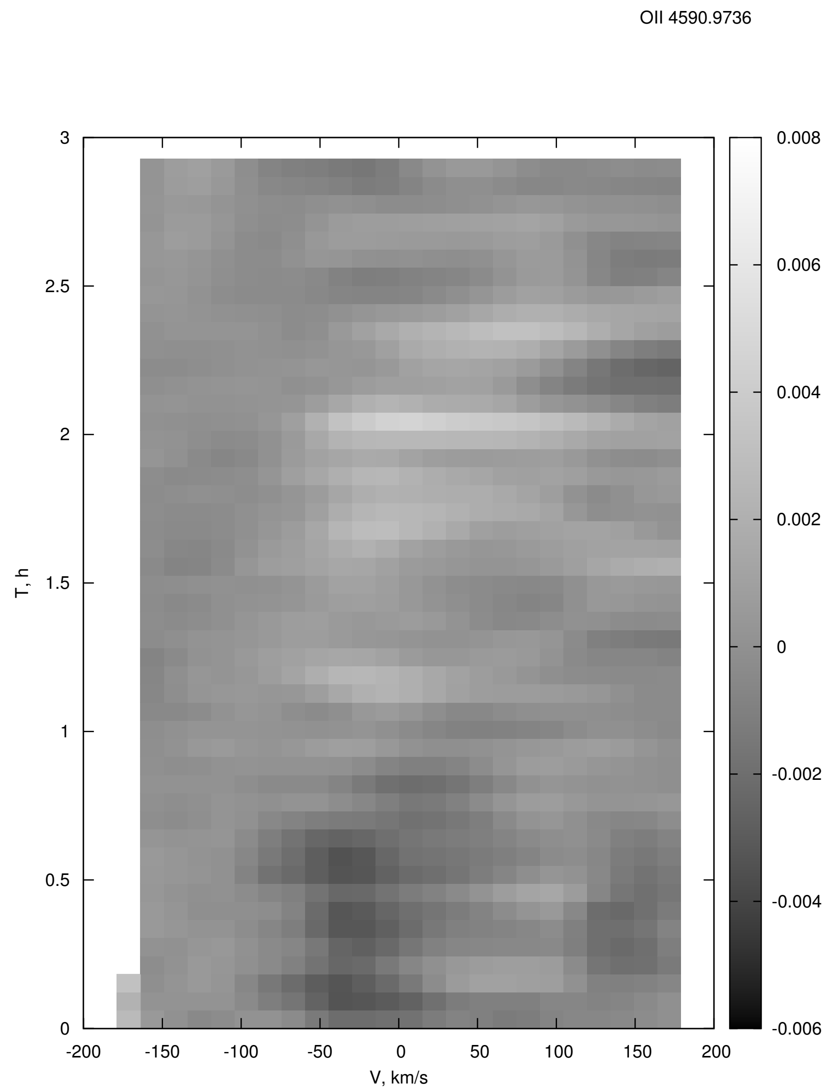

Figure 2: LPV in the spectra of ζ Ori A in the region $\lambda\lambda\,4588-4595$ Å in dependence of the Doppler shift from the centre of the lines (the stellar rest frame). The residual fluxes with respect to the mean one are converted into the levels of grey. Time T is expressed in hours from the beginning of observations.

yielded no results. It can be connected with the fact that the observations were made near the rotation phase, when the effective field value B_l is close to zero. The low accuracy of the rotation period (see Table 1) and short period of our observations (0.125 day) does not let us to test this hypothesis.

Our analysis of LPV indicates a possible presence of regular line–profile variations of ζ Ori Aa with $P \approx 3$ h (see Table 4). These short–term variations are common for profile variations associated with non–radial pulsations (NRP) of OB–stars (de Jong et al., 1999).

Table 4: The frequencies (ν) and periods (P) of regular harmonics of LPV in the spectra of ζ Ori A. The presence of a given frequency component in the periodogram of LPV for the considered lines is marked with a plus sign.

P (h)	ν (d^{-1})	He I λ 4349.42	O II λ 4552.62	He I λ 4590.97	O II λ 4921.93	Si III λ 5015.68
2.44	9.84	–	–	+	+	–
3.05	7.87	+	+	+	+	–

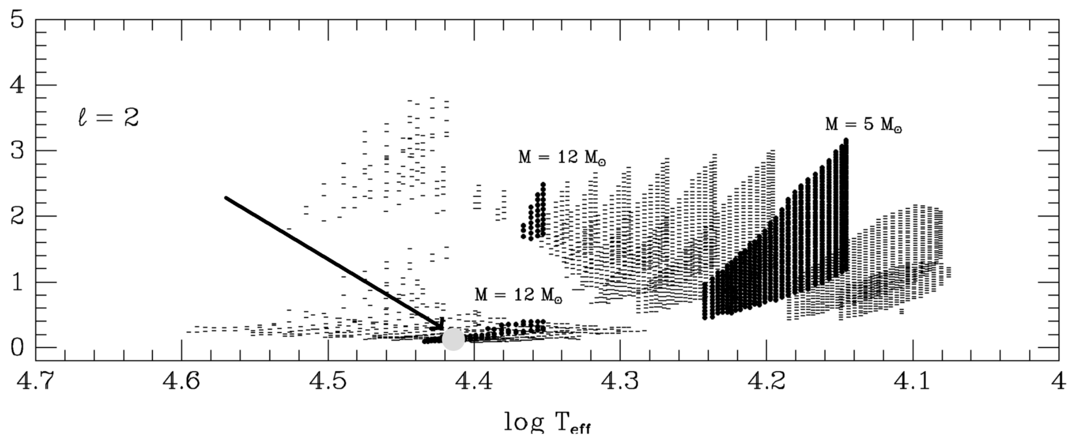

Figure 3: Pulsation periods (axe y, in days) of β Cep stars and slowly pulsating B (SPB) stars in the region of effective temperatures (axe x) $T = 10^4$–$5 \cdot 10^4$ K (points), according to the calculations of Pamyatnykh et al. (1999). A large grey circle marks the location of ζ Ori on this diagram.

The (l, m) NPR modes can be found from relations $l \approx 0.1 + 1.09|\Delta\phi_0|\pi$, and $m \approx 1.33 + 0.54|\Delta\phi_1|/2\pi$, where $\Delta\phi_0 = \phi_{\mathrm{red}} - \phi_{\mathrm{blue}}$ is the phase difference of the Fourier components of the profile variations in the red (ϕ_{red}) and blue (ϕ_{blue}) wings of the lines of the NRP component ν_0. $\Delta\phi_1$ is determined in a similar manner, but for the first harmonic of the line–profile variations $\nu_1 = 2\nu_0$ (Telting & Schrijvers, 1997). Due to the short duration of observations, $\Delta\phi_0$ and $\Delta\phi_1$ can not be determined very well. The best results can be obtained from the analysis of He I λ 4590.97 Åline. We can determine $|\Delta\phi_0|$ in the interval -170 to 30 km/s. An extrapolation of phase difference in these intervals to the total range of velocities $\pm V \sin i$ gives us $l \geq 2$.

To find out if these profile variation frequencies correspond to the possible NRP of OB stars, we plotted in Fig. 3 the frequencies of LPV components on the $T_{\mathrm{eff}} - P$ diagram. We see that the frequencies (filled circles) are located in the region of pulsation instability for the quadrupole mode ($l = 2$).

4 Conclusion

We report the results of study of fast LPV in the spectra of a bright O supergiant ζ Ori, and search for its magnetic field. The regular short time-scale components of LPV in the spectra of the star with periods of $P \approx 2.4 - 3$h have been detected. These components are probably connected with non-radial pulsations of the primary component Aa of the binary system ζ Ori A. The presence of a magnetic field reported by Bouret et al., 2008 is not confirmed.

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