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Magnetic field related fast line profile variability in spectra of bright O supergiants

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Abstract. Results of a study of fast line profile variability (*lpv*) in spectra of selected bright O-stars are reported. A regular component of *lpv* in spectra of the star λ Ori A with estimated period $P \approx 3$ d have been detected. We suppose that the formation of long time-scale regular components of *lpv* can be explained in the framework of the magnetically confined wind-shock (MCWS) model of Babel & Montmerle (1997a). In the context of testing the MCWS model a program of searching for weak magnetic fields in bright O and early B stars is outlined. The possibility to measure weak longitudinal magnetic fields ($\overline{B}_l \approx 100$ G) is demonstrated.

1 Introduction

Hot early-type stars have fast dense stellar winds driven by the strong stellar radiation field in lines and continuum. The winds of these stars are highly structured on both small (Eversberg et al. 1998) and large (Morel et al. 1998, Kaper et al. 1999, de Jong et al. 2001) scales. Several processes are proposed to explain the formation of these structures: wind instabilities; non-radial pulsations; co-rotation of large-scale structures in the wind. The last might be explained by accepting the hypothesis that hot stars possess global dipolar magnetic fields (Babel & Montmerle 1997a,b).

Nevertheless, in spite of the numerous attempts at detecting the magnetic fields of bright O and WR stars (de Jong et al. 2001, Donati et al. 2002, Chesneau & Moffat 2002, etc.), only for one star (θ^1 Ori C) were the measurements were successful (Donati et al. 2002).

In this report we discuss recent observations of hot stars in the light of the magnetically confined wind-shock model of Babel & Montmerle (1997a). A review of attempts to detect magnetic fields of O and early B stars is given. We also propose a program of searching for weak magnetic fields in such stars using the large sequence of target stars with the Zeeman analyzer at the Northern Caucasus Special Astrophysical Observatory (SAO) 1 m telescope.

Table 1: Program stars list

HD	Name	Sp.Type	V	V_∞^1	$V_{\rm rot}\sin i^1$
3360	ζ Cas	B2IV	3.67		17
24212	ξ Per	O7.5III	4.04	2330	213
24760	ε Per	B0.5IV	2.90		134
30614	α Cam	O9.5I	4.29	1590	129
36486	δ Ori	O9.5II	2.23	2060	144
36861	λ Ori A	O8III	3.66	2175	74
37742	ζ Ori A	O8III	1.79	1860	124
47839	15 Mon	O7Ve	4.66	2110	67
91316	ρ Leo	B1Iab	3.84	1110	75
120315	η Uma	B3V	1.85		108^2
156633	68 Her	B1.5Vp+	4.80		127^2
160762	85 Her	B3IV	3.79		105^2
163472	V2052 Oph	B2IV-V	5.83	-	127^2
166182	102 Her	B2IV	4.35		84^2
180968	2 Vul	B0.5IV	5.47		84^2
203064	68 Cyg	O8e	5.04	2340	115
205021	β Cep	B1IIIevar	3.22	800	27
209975	19 Cep	O9.5I	5.11	2010	95
210839	λ Cep	O6Iab	5.09	2300	219
214680	10 Lac	O9V	4.87	1140	35

[1] from Kaper *et al.* (1997)
[1] mean values from Abt *et al.* (2002)

2 Observations and data reduction

2.1 Program of observations

Recently Kholtygin et al. (2003a) have proposed a program of spectral observations of bright O and early B stars for seeking and analysing fast line profile variations in their optical spectra with large signal to noise ratio and good time resolution (5-30^m). The list of program stars is given in Table 1.

2.2 The data and their reduction

Spectra of program stars were obtained at the 1.0 m telescope of the Special astrophysical observatory (SAO) with the CEGS spectrograph. The instrument configuration was described by Musaev (1996). Observations in 2001 were made with 1242x1152 Wright Instruments CCD detector and those in 2003 – with a 2048x2048 CCD detector.

The grating was used in 49 – 122 orders to produce spectra covering 6000 Å centered on H_α with resolution $R = 45000$ (0.08 Å/pixel near H_α). The ratio S/N from 200 to 400 per pixel in the continuum in each spectrum (depending on the weather conditions and the instrumental configuration) obtained for the target stars are presented in a Table 2, .

Reduction of data was made with standard MIDAS procedures. Flatfielding was done using as a *quasi flat field* an image of the fast rotating star α Leo ($V\sin i = 329$ km/s). It appears that the pixel inhomogeneity remaining after this procedure do not exceed 0.3% in continuum units (see Monin et al. 2002 for details). All spectra were normalized to the continuum level by means of an appropriate procedure.

Table 2: List of stars observed in 2001 and 2003

Object	$t_{exp.}$ (min.)	Number exp.	Total time of observ. (h)
September 4 - 7, 2001 .			
ξ Per	10	4	0.7
α Cam	10	11	1.8
19 Cep	15	22	6.0
10 Lac	10/15	39	10.5
November 29 - December 4, 2001			
ξ Per	5	5	0.4
α Cam	10	6	1.0
λ Ori A	10	75	12.5
ζ Ori A	2	36	1.2
10 Lac	15	27	6.7
January 22-23, 2003			
α Cam	7/10	16	2.6
ρ Leo	5	7	0.6

3 Fast line profile variations

The profiles of most lines in the spectra of studied stars seems to be variable. This set of the residual spectra (individual minus mean) of 19 Cep near H_β and CIII λ 4650 is plotted in Fig. 1 a-d. It is easy to see the variable detail of H_β line profile at the velocity $\approx$ 90 km/s from the line center. Similar details are revealed in the profiles of the H_α, and strong He lines in the spectra of the star (Kholtygin et al.2003 a,b). On the other hand, the line CIII λ 4650 (Fig.1 c-d) in the spectra of the same star shows only marginal line profile variations (*lpv*).

3.1 The cyclical components of the line profile variability

3.1.1 Period Search

To investigate temporal variations of the line profile we carried out modified CLEAN analysis (Roberts 1987 and Kholtygin & Shneiwais 2003) of the residual line profile variations $S(\lambda) = I(\lambda) - I_{\rm mean}$ for H, He and CIII lines in a spectrum of O8 star λ Ori A. For illustration we present in Fig. 2 a grey-scale plot of the Fourier power spectra for CIII λ5696 *lpv.*

The highest detected frequency $\nu_1 \approx 1.3d^{-1}$ gives a period of time variation $P \approx 18h$. This period is intermediate between those typical of non-radial pulsation (NRP) and for O star rotational periods. The nature of this Fourier component is unclear. It should be mentioned that the determined frequency is very close to the "dangerous" frequency $1.4d^{-1}$, which cannot be detected for a given set of moments of observations (see Kholtygin & Shneiwais 2003), so the reality of this component is doubtful.

The lower frequency $\nu_2 \approx 0.35d^{-1}$ ($P \approx 3d$) which is very close to one half of the period 6.1-6.3 d, suspected by Kaper er al. (1997) from analysis of the UV spectra of this star. Frequencies close to these are found from our Fourier analysis of the line profile variations of H_α, HeI λ 4713 and HeII λ 4686.

3.2 Models of cyclical components of the line profile variability

Large time scale line profile variations are often explained via a formation of large-scale structures in the stellar wind. These structures are often connected with corotating interaction regions (CIR,

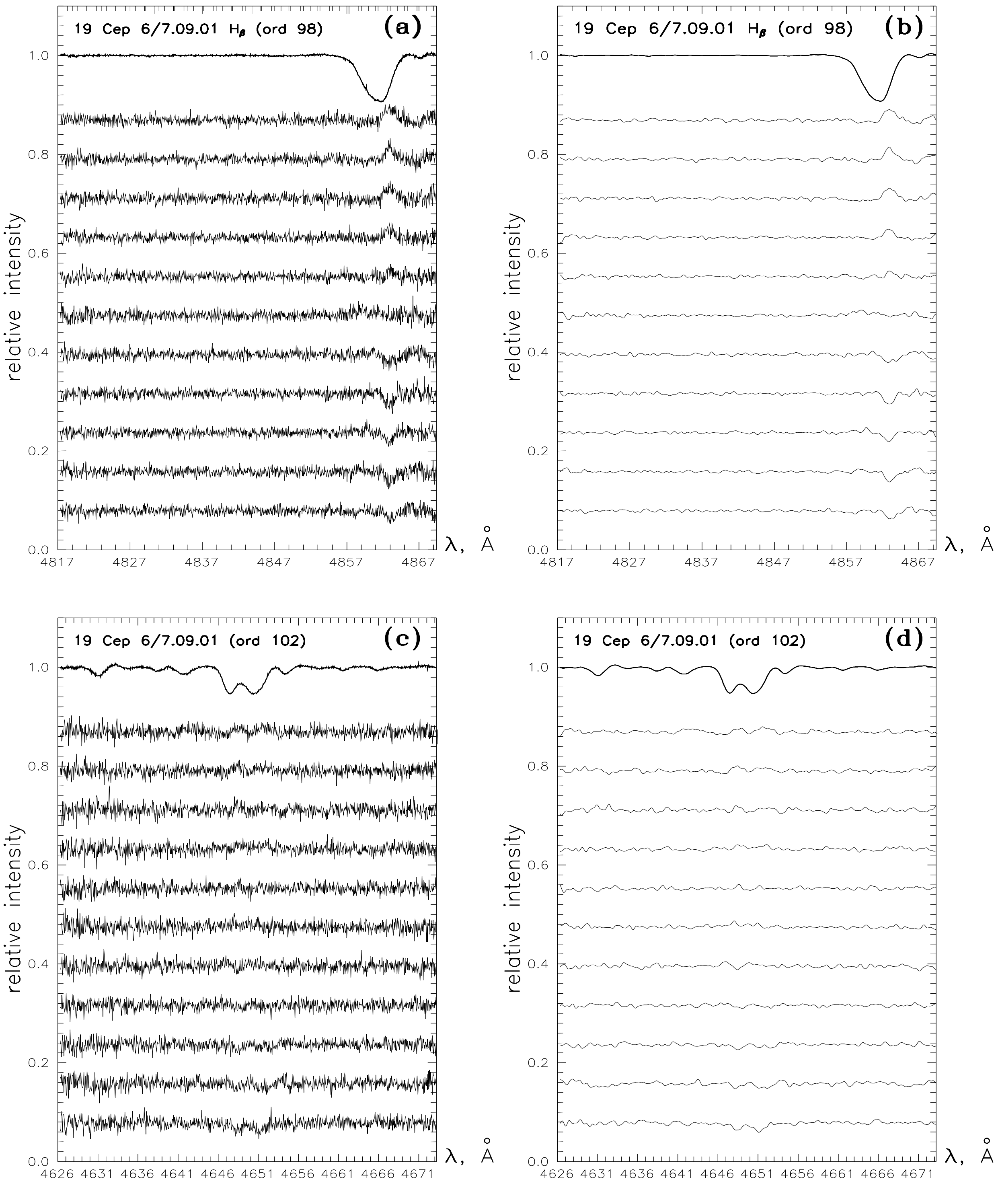

Figure 1: **a:** Residual spectra near H_β for 19 Cep (order 98). **b:** the same as in **a**, but with all spectra smoothed with a gaussian filter ($W = 0.2$Å), **c, d:** - the same as in **a, b**, but for order 102 (including CIII λ4650 line). The time interval between the successive spectra is about of 30 min. Time increases upward.

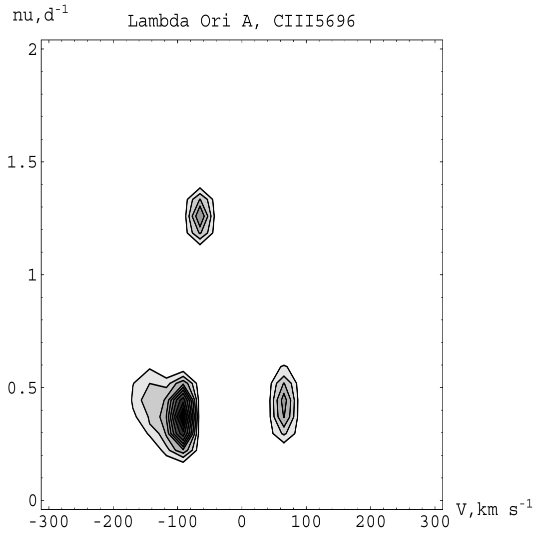

Figure 2: The CLEAN Fourier spectrum for CIII λ 5696 line profile variations in spectra of λ Ori A. The points above the significance level $\alpha = 0.999$ are only plotted.

Cranmer & Owocki 1996) resulting from a localized "bright spot" on the stellar surface. These CIRs are thought to produce the cyclical modulation of the P-Cygni absorptions in optical and UV lines (e.g. Kaper et al. 1999, de Jong et al. 2001).

Alternative explanation of the cyclical line profile variations can be obtained in the framework of "confined corotating wind" model. In this model a star is an oblique magnetic rotator (see, for example, Fig. 15 in Rauw et al. 2001) . Such a model has been proposed to explain the *lpv* observed in the spectra of ζPup (Moffat & Michaud 1981) and θ^1 Ori C (Stahl et al. 1996).

4 Magnetic fields in O stars

4.1 Magnetically confined wind-shock model

The "confined corotating wind" model described in the previous section was developed by Babel & Montmerle (1997a) as magnetically confined wind-shock (MCWS) model. In this model the wind streams from both magnetic hemispheres collide with each other and produce a strong shock, an extended X-Ray-emitting post-shock region and a thin dense cooling disc in the magnetic equatorial plane. (Note that, while interesting, the material in this model may be unstable against fall back, in contrast to the Cassinelli et al. (2002) magnetically torqued disk model where centrifugal support stability it - (cf. U'Doula and Owocki 2002)

This model can explain the rotational modulation of the X-Ray luminosity due to partial eclipse of the magnetosphere effect by the cooling disc. In support of this X-Ray flux modulation we can mention a correlation between X-ray fluxes and optical line profile variability (see discussion in Kholtygin et al. 2003b).

The crucial point for explanation of the line profile variations in the framework of the "confined corotating wind" or MCWS models is the presence a magnetic field at the surface of the star. The necessary values of the field are not very large. Babel & Montmerle (1997b) found that a magnetic field ($B_* \approx 270-370\,G$) can confine a significant fraction of the wind of θ^1 Ori C into a "circumstellar cooling disk" located in the plane of the magnetic equator (cf Cassinelli et al 2000).

Waldron & Cassinelli (2000), based on their own X-Ray observations of 09.7 star ζ Ori, have estimated that at a value of $n_{\rm e} = 10^{12}{\rm cm}^{-3}$ typical for this star and an X-Ray line temperature in the hot stellar wind $T_X \approx 5 \times 10^7$K, a surface magnetic field strength ≈ 180 G results assuming a balance between gas and magnetic pressure.

Parameters of this hot dense plasma revealed by Waldron & Cassinelli (2000) in the wind of ζ Ori are comparable with those of solar flares . This is a very different interpretation from the MCWS model for this star though Schulz et al. (2001) proposed that the very high wind temperature of θ^1 Ori C (up to 6×10^7K) obtained by them from the X-Ray line intensity ratios can also be explained in the MCWS model.

4.2 Searching for the magnetic fields of O and early B stars

There exist various methods to determine a stellar magnetic field. One of the most popular is measurement of line shift between left and right circular components of spectral lines (detecting the first moment of the Stokes V parameter) (e.g. Brown & Landstreet 1981, Monin 1999, Monin et al. 2002). This method is sensitive only to the line-of-sight component of the disc-integrated vector field. This technique can measure magnetic fields in the range 10^2 to 10^2 G. The so-called *Robinson technique* (Robinson 1980) is based on measuring the differential Zeeman broadening between magnetically sensitive and intensity sensitive spectral lines. Nevertheless this technique has large systematic errors. A very effective method of determining the field structure is the Zeeman-Doppler imaging (e.g. Donati et al. 1997).

The brightest O star ζ Puppis (O4I(n)f) is the most attractive target for searching for the magnetic field. Barker (1981) tried to measure the longitudinal Zeeman effect in the wings of the Hβ line with a photoelectric Pockel cell polarimeter. The mean value of $B_l = -44 \pm 105$ G obtained means that the field is too small to be detected in this experiment.

Recently Chessneau & Moffat (2002) have reported a new attempt to detect the magnetic field in ζ Puppis . The disc-averaged value of the longitudinal component field was estimated using a line profile integration of continuum normalized Stokes V parameter for four lines HeII and NIV. For four observational nights values of $\overline{B}_l = -220 \pm 225, 88 \pm 359, -236 \pm 201$ and 143 ± 215 G, were obtained respectively. This means no magnetic field detection. Moreover, no short time-scale variability of the Stokes V parameter in the investigated line profile were detected within 0.1% level of noise per resolution element.

De Jong et al. (2001) have reported an attempt to measure the longitudinal component of the field for bright O7.5 star ξ Persei. The average value of all measurements is 27 ± 70G so the error bars of these measurements are too large to detect a field.

Recently Donati et al. (2002) have obtained accurate longitudinal field ($\overline{B}_l$) estimations for the very young O star (θ^1 Ori C) by measuring the first moment of the Stokes V profile, normalized by the line equivalent width, using a least-squares deconvolution technique (Donati et al. 1997). The derived $\overline{B}_l$ values are equal to 357 ± 46 G, 37 ± 35 G, 257 ± 49 G, 191 ± 63 G and 257 ± 73 G for rotational phases of 0.033, 0.621, 0.789, 0.920 and 0.177, respectively. The phase dependence of $\overline{B}_l$ can be cosine fitted with a mean value $B_0 = 172 \pm 30$ G. Modeling the Stokes V parameter variations indicates that the obtained $\overline{B}_l$ values are consisted with the assumption that the magnetic field can be represented as a dipole with polar field strength $B_p = 1.1 \pm 1.1$ kG inclined at $42 \pm 6°$ to the rotational axis, in turn assumed to be inclined at 45° to the line of sight.

Attempts to determine magnetic fields for selected early B stars had no positive results (Monin et al. 2002). Recently Donati et al.(2001) detected a moderate variable magnetic field of $|B_l| < 100$ G and with a polar strength $B_p \approx 360 \pm 30$ G on bright B1 star β Cephei. A weak varying longitudinal magnetic field with a strength between 10 G and -46 G, corresponding to $B_p \approx 335\,G$ was detected in B2IV star ζ Cas (Neiner at al. 2003).

MacGregor & Cassinelli (2003) have discussed the possibility of generation of magnetic fields on hot stars. They found that fields in hot main-sequence stars generated by a dynamo mechanism at the interface between the radiative core and convective envelope of the star could rise to the surface and reach the necessary level for the wind confining values.

4.3 Program of detection of magnetic fields

It is clear from the previous section that moderate values of $\overline{B}_l \approx 100-200\,\mathrm{G}$ and even smaller for O and early B stars may be expected. We propose a program for searching for the magnetic fields of bright O and early B stars, presented in Table 1. The mean longitudinal magnetic fields $\overline{B}_l$ of the star can be determined via the wavelength shift $\Delta\lambda$ between right and left circular polarization components of the line (e.g. Monin 1999):

$$\Delta\lambda = \lambda_R - \lambda_L = 2\,k_0\,\overline{g}\,\overline{B}_l\,\lambda_0^2 \tag{1}$$

where λ_R and λ_L are the wavelengths of the centre of gravity of the right and left circular polarized components of the line respectively, $\overline{g}$ is the effective Landé factor of the line, λ_0 is the rest wavelength of the line and constant $k_0 = 4.67\times10^{-13}\mathrm{\AA}^{-1}\mathrm{G}^{-1}$.

The value of λ_R is

$$\lambda_R = \frac{1}{W_\lambda}\int \lambda r(\lambda)d\lambda\,, \tag{2}$$

where W_λ is the line equivalent width, r_λ is the residual intensity of the line at wavelength λ with a similar expression for λ_L.

The required mean longitudinal magnetic fields $\overline{B}_l$ is the line intensity weighted mean over the visible stellar disk (Eversberg 1997):

$$\overline{B}_l = \frac{1}{W_\lambda}\int_0^{2\pi} d\varphi \int_0^{\pi/2} B_l\cos(\theta)\sin(\varphi)d\theta \times \int r_\lambda(\theta,\varphi)d\lambda\,. \tag{3}$$

Here $B_l = B_l(\theta,\varphi)$ is the line of sight component of the magnetic field, θ and φ are the coordinates of the point at the stellar disk and $r_\lambda(\theta,\varphi)$ is the residual intensity of the line at this point.

For a tilted dipole magnetic field and a linear law of limb darkening $r\lambda(\theta,\varphi) = 1-u+u\cos(\theta)$ (u is the parameter of limb darkening for the wavelength considered) the variation of $\overline{B}_l$ with rotational phase ϕ can be obtained by integration of Eq.3. Finally (see, e.g. Preston 1967 for details):

$$\overline{B}_l = B_p\,\frac{15+u}{20(3-u)}[\cos\beta\cos i + \sin\beta\sin i\cos 2\pi(\phi-\phi_0)]\,, \tag{4}$$

where B_p is the polar magnetic field strength, β is the angle between the magnetic and rotational axes, i is the rotational axis inclination angle and ϕ_0 is the phase of the maximal longitudinal field.

The possible dependence of mean longitudinal magnetic field strength B_l on the rotation phase is plotted in Fig. 3 (left panel). We take the values $B_p = 1100\,\mathrm{G}$ for polar field strength and $i = 45^\circ$ for the inclination angle as obtained by Donati et al. (2002) for θ^1 Ori C. From this figure we see that the maximal B_l value never exceeds 1/3 of the B_p value.

The phase average values of $\overline{B}_l^{\mathrm{mean}}$ are plotted in fig 3 (right panel). For almost all values of an angle β and rotational axis inclinations i the phase averaged field $\overline{B}_l^{\mathrm{mean}}$ do not exceed 100 G.

By this means, for detecting magnetic fields in O stars, we should measure very small lambda differences $\Delta\lambda$ between right and left circular polarized components of the lines. For example, for strong HeI $\lambda\,7065$ line (effective gaunt factor $\overline{g} = 2$) the value of $\Delta\lambda \approx 0.01$ Å. With the parameters of the instrument planned to search for the magnetic field (see subsection 2.2) we are not able to determine the value of $\Delta\lambda$ with the necessary accuracy from a single line.

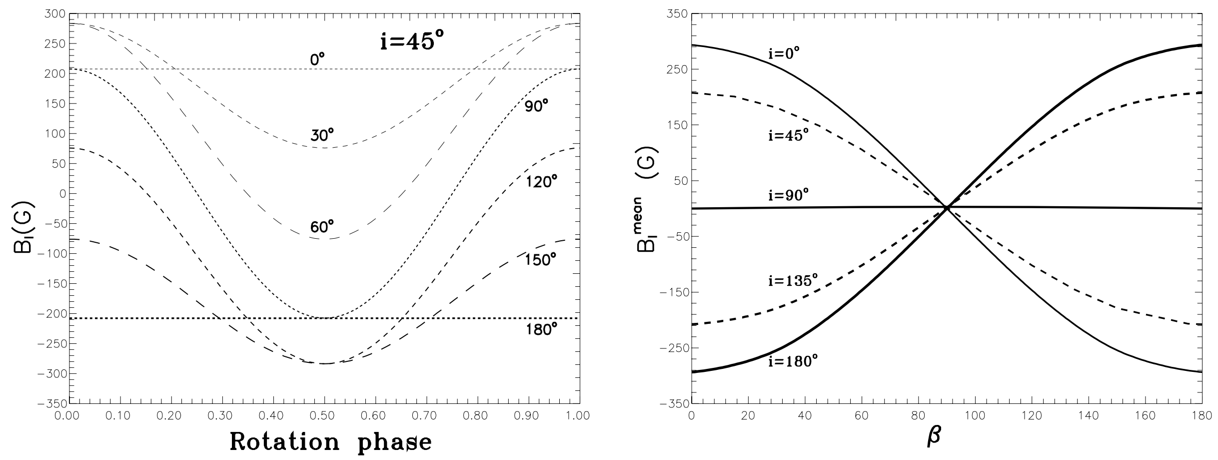

Figure 3: **Left panel:** Mean longitude magnetic field strength B_l as a function of rotational phase for values $B_p = 1100$ and $i = 45°$. **Right panel:** Phase averaged longitude magnetic field strength $B_l^{\rm mean}$ versus the angle β between rotational and magnetic axis.

The accuracy of $\Delta\lambda$ determination can be strongly enhanced when a large number of lines is used. In this case we have to use for each line λ_i its weight $\omega_i \sim (r_{\lambda_L} + r_{\lambda_R})/2$, where r_{λ_L} and r_{λ_R} are residual intensities of left and right circular polarized components of the line at their centers of gravity (Monin 1999).

Then the effective number of lines used for $\Delta\lambda$ determinations can be estimated as

$$N_{\rm line} = n \times \frac{\sum_{i=1}^{n} w_i}{\omega_o}\,,$$

where ω_o is the weight for some *reference* line (e.g. HeI λ 7065).

However, the number of suitable lines in spectra of O stars is not very large (about 30 - 50) and to enhance a gain in the line displacement measurements we can use a number of successive spectra N_{sp}, obtained during the observing run. Looking to Fig. 3 we can see that it is possible effectively to use not more then 1/4 of the total rotational period, when changes of the value of B_l are not too large.

From the above reasoning, it is clear that stars with the maximal rotational periods are the most suitable targets. In our list of program stars (Table 1) only two stars (19 Cep and λ Ori A) have rather large rotational periods (≥ 6 d). For this star we can use spectra for 2 observational nights. It gives a total number $N_{\rm sp} \approx 2 * \times 30 \approx 60$ spectra. Thus, the effective number of lines can be used for $\Delta\lambda$ measurement is $N_{\bf eff} = N_{\rm line} \times N_{\rm sp}$. Substituting in this expression the typical values $N_{\rm line} \approx 50$ and $N_{\rm sp} \approx 60$ we have a total $N_{\bf eff} \approx 3000$.

To estimate the possibility of measuring weak fields using the above described method we have conducted a numerical experiment to reproduce the parameters of real observational runs (see subsection. 2.2). For a better determination of line center of gravity we have used the gaussian fit of the line profile. We also suppose that all instrumental correction to the λ values are made.

Supposing that for a given line i and for observational run j the value of $\Delta\lambda = \Delta\lambda_{ij}$ is measured, we can estimate the value of mean longitudinal magnetic field via the relation:

$$\overline{B}_l^{(ij)} = 0.5 \times \Delta\lambda (k_0\, \overline{g} \lambda_0^2)^{-1}\,. \qquad (5)$$

Averaging the obtained $\overline{B}_l^{(ij)}$ values over all possible values of i and j we can determine the *effective* longitudinal magnetic field $\boldsymbol{B}_{\bf eff}$ and its standard deviation σ.

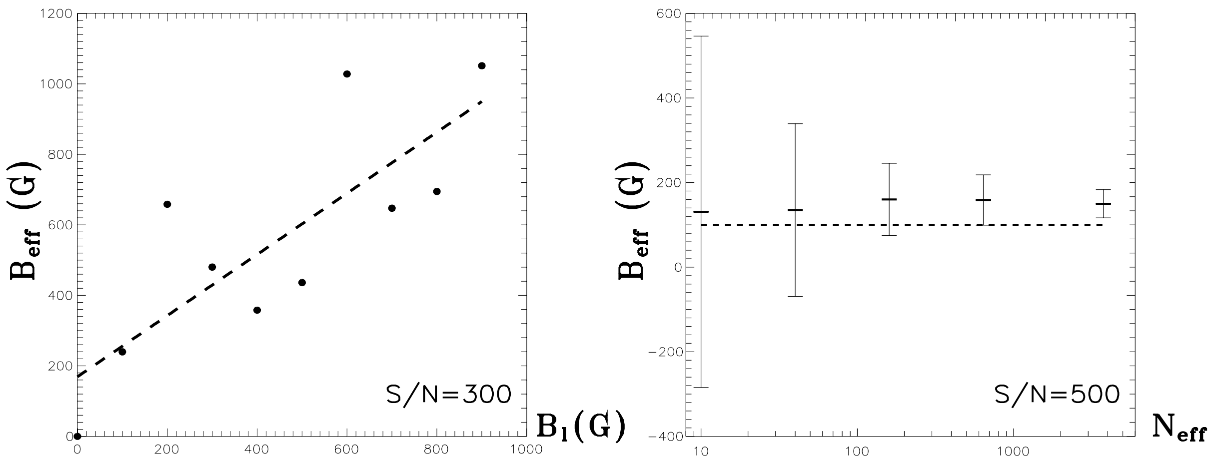

Figure 4: **Left panel:** Mean effective magnetic field $\boldsymbol{B}_{\mathbf{eff}}$ as a function of input mean longitudinal field B_l for signal to noise ratio S/N=300 and $N_{\mathbf{eff}}$=200. **Right panel:** Dependence of mean effective magnetic field $\boldsymbol{B}_{\mathbf{eff}}$ versus the effective number of observations $N_{\mathbf{eff}}$ for S/N=500. The input value of $\overline{B}_l = 100\,\mathrm{G}$ The error bars and mean values of $\boldsymbol{B}_{\mathbf{eff}}$ are plotted.

The resulting dependence of $\boldsymbol{B}_{\mathbf{eff}}$ on the input value of $\overline{B}_l$ is presented in Fig. 4 (left panel). We can see that for a rather small number $N_{\mathbf{eff}}$ of values the scattering of $\boldsymbol{B}_{\mathbf{eff}}$ is too large and for low values of $\overline{B}_l$ the mean effective magnetic field is overestimated. A similar effect also exists for weak line intensity determination with $A/N < 6$, where A is the maximal line intensity (see Rola & Pelat 1994 for details). This work shows that in this case the measured line fluxes do not have a normal, but log.-normal distribution with a displacement to larger fluxes.

The nature of this effect is very simple: if the observed line flux (real flux plus noise) appears to be smaller than the noise level we do not detect it and do not include it in the total set of line flux measurements. In our case we measure not fluxes but the line shifts. Nevertheless, a nature of the effect seems to be very close.

Fig. 4 (right panel) demonstrates the possibility of enhancing the precision of determination of the $\boldsymbol{B}_{\mathbf{eff}}$ value by increasing the effective number of observations $N_{\mathbf{eff}}$. For large values of $N_{\mathbf{eff}}$ the weak input field $\overline{B}_l = 100\,\mathrm{G}$ can be detected at $3\,\sigma$ level.

5 Conclusion

We report the results of a study of fast *lpv* in spectra of selected bright O-stars. The regular long time-scale components of *lpv* in spectra of star λ Ori A with estimated period $P \approx 3\,\mathrm{d}$ have been detected. The formation of such components of *lpv* can be explained in the framework of the MCWS model of Babel & Montmerle (1997a).

A program for detection of weak magnetic fields in bright O and early B stars with the Zeeman analyzer at the Northern Caucasus Special Astrophysical Observatory (SAO) 1 m telescope is proposed. We demonstrate the possibility of measuring weak magnetic fields ($\overline{B}_l = 100 - 200\,\mathrm{G}$) for program stars.

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