Magnetic stars, 2004, 250-258

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

Kholtygin A.[1], **Brown J.**[2], **Fabrika S.**[3] **and Surkov A.**[3]

[1] Astronomical Institute of St.Petersburg University
[2] Glasgow University, UK
[3] Special Astrophysical Observatory of the Russian AS, Nizhnij Arkhyz 369167, Russia

Abstract. Results of study of fast line profile variability (*lpv*) in the spectra of selected bright O-stars are reported. A regular component of *lpv* in the spectra of the star λ Ori A with estimated period $P \approx 3\,\mathrm{d}$ 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 the program of searching for weak magnetic fields in bright O and early B stars is outlined. The possibility of measuring weak longitudinal magnetic fields ($\overline{B}_l \approx 100\,\mathrm{G}$) is demonstrated.

Key words: stars: early type – stars: magnetic fields – line: profiles

1 Introduction

Hot early-type stars have fast dense stellar winds driven by strong stellar radiation field in the lines and in the 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 attracted to explain the formation of these structures: wind instabilities, non-radial pulsations and co-rotation of large-scale structures in the wind. The last can be explained with accepting a hypothesis that hot stars possess global dipolar magnetic fields (Babel & Montmerle 1997a,b).

Nevertheless, in spite of the numerous attempts of 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) the measurements were successful (Donati et al. 2002).

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

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 searching and analysing the fast line profile variations in their optical spectra with large signal-to-noise ratio and a high time resolution (5–30^m). The list of program stars is given in Table 1.

Table 1: Program stars list

HD	Name	Sp.Type	V	V^1_∞	$V_{\rm rot}\sin i^2$
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*
156633	68 Her	B1.5Vp+	4.80		127*
160762	85 Her	B3IV	3.79		105*
163472	V2052 Oph	B2IV-V	5.83	-	127*
166182	102 Her	B2IV	4.35		84*
180968	2 Vul	B0.5IV	5.47		84*
203064	68 Cyg	O8e	5.04	2340	115
205021	β Cep	B2IIIevar	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)
[2] data are taken from SIMBAD database (http://simbad.u-strasbg.fr/Simbad/) along with mean values from Abt et al. 2002 (marked with asterisks)

2.2 The data and their reduction

Spectra of program stars were obtained at the SAO 1.0 m telescope with CEGS spectrograph. The instrument configuration was described by Musaev (1996). Observations in 2001 were made with a 1242 × 1152 Wright Instruments CCD detector and those in 2003 — with a 2048 × 2048 CCD detector.

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

Reduction of data was made with standard MIDAS procedures. Flatfielding was done with using an image of the fast rotating star α Leo ($V\sin i$ = 329 km/s) as a *quasi-flat field*. It appeared that the pixel inhomogeneity remaining after this procedure does 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.

3 Fast line profile variations

The profiles of most lines in the spectra of studied stars seem to be variable. This illustrates the set of the residual spectra (individual minus mean) of 19 Cep near H_β and CIII λ 4650 plotted in Fig. 1 a-d. It is easy to see the variable detail of the H_β line profile at the velocity ≈ 90 km/s from the line center. The similar details are revealed in the profiles of the lines 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 the marginal line profile variations (*lpv*).

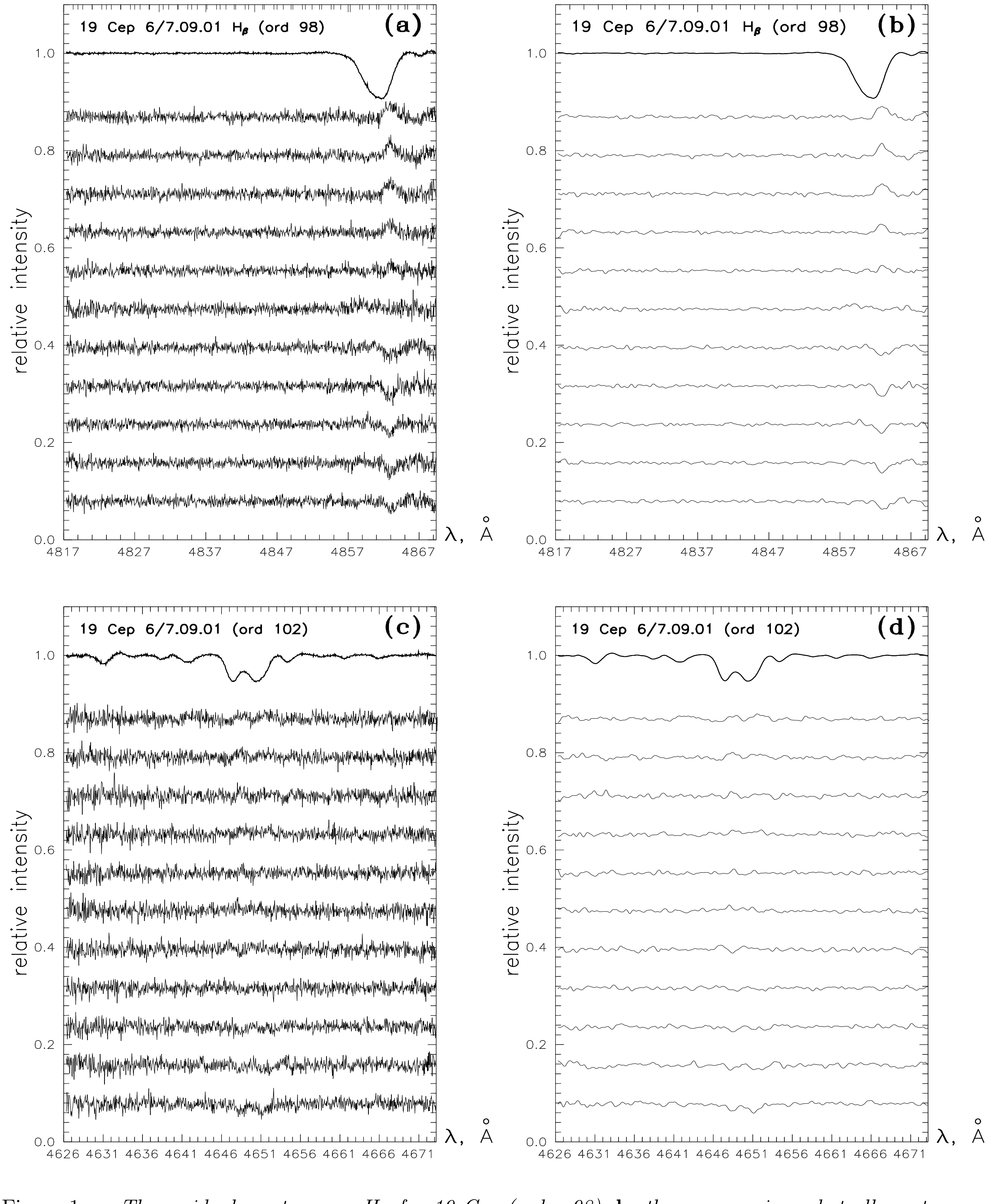

Figure 1: **a:** *The residual spectra near H_β for 19 Cep (order 98).* **b:** *the same as in* **a**, *but all spectra were smoothed with gauss filter ($W = 0.2\AA$),* **c, d:** *— the same as in* **a, b**, *but for order 102 (including CIII λ4650 line). The time interval between the successive spectra is about 30 min. Time grows upward.*

Table 2: List of stars observed in 2001 and 2003

Object	$t_{\rm exp.}$ (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

3.1 The cyclical components of the line profile variability

3.1.1 Period Search

To investigate the time variations of the line profile, we make the modified CLEAN (see Roberts 1987 and Kholtygin & Shneiwais 2003) analysis of the residual line profile variations $S(\lambda) = I(\lambda) - I_{\rm mean}$ for H, He and CIII lines in spectra 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 higher detected frequency $\nu_1 \approx 1.3d^{-1}$ gives the period of time variation $P \approx 18h$. This period is intermediate between the typical one of non-radial pulsation (NRP) and the typical of O stars rotational periods. The nature of this Fourier component is unclear. It should be mention that the determined frequency is very close to the "dangerous" frequency $1.4d^{-1}$, which can not be detected for a given set of moments of observations (see Kholtygin & Shneiwais 2003), so the reality of this component is not evident.

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 et al. (1997) from analysis of the UV spectra of this star. The close frequencies 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

The large time scale line profile variations are often explained via formation of the large-scale structures in the stellar wind. These structures are connected with corotating interaction regions (CIR, 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). Nevertheless, the formation of many variable lines occurs close to the stellar surface so that azimuthal extension of the line formation region due to bending of the CIRs structure must remain small. Moreover, the occultation effect for CIRs must be observed in the case of the multiple CIRs in the wind. The detected by us cyclical variability of the emission line CIII λ 5696 (see Fig. 2) hardly agrees with the CIR model.

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), the wind is confined in latitude and its symmetry axis is the tilted magnetic axis of the star. 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).

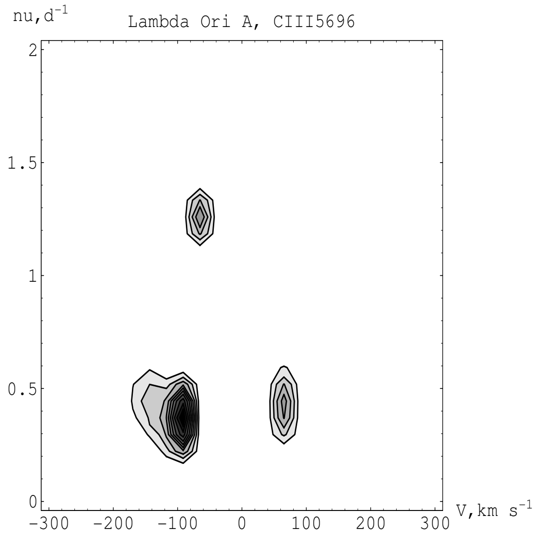

Figure 2: *The CLEAN Fourier spectrum for CIII λ 5696 line profile variations in the spectra of λ Ori A. Only the points above the significance level $\alpha = 0.999$ for a hypothesis on a presence of the periodical components in the lpv are plotted.*

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 a 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.

This model can explain the rotational modulation of the X-ray luminosity due to a 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 "confined corotating wind" or MCWS model is the presence of 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.

Waldron & Cassinelli (2000), based on their own X-ray observations of O9.7 star ζ Ori, have estimated that at the value $n_e = 10^{12}\mathrm{cm}^{-3}$, typical of this star, and the temperature of the hot gas emitting in the X-ray lines in stellar wind, $T_X \approx 5 \times 10^7$K, obtained by them, the surface magnetic field strength can be estimated to be ≈ 180 G assuming a balance between gas and magnetic pressures.

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

4.2 Searching for magnetic fields of O and early B stars

There exist some different techniques to determine the stellar magnetic field. One of the most popular methods is measurement of the line shift between the left and right circular components of spectral lines (detecting the first moment of 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 obey to measure the magnetic fields from 10^2 G. The so-called *Robinson technique* (Robinson 1980) is based on measurements of the differential Zeeman broadening between magnetically sensitive and intensive spectral lines. Nevertheless, this technique has large systematic errors. A very effective methods of determination of 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 in 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 obtained mean value of $B_l = -44 \pm 105\,\mathrm{G}$ 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 field component was estimated using line profile integration of continuum normalized Stokes V parameter for four lines HeII and NIV. During four observational nights the following values were obtained: $\overline{B}_l = -220 \pm 225, 88 \pm 359, -236 \pm 201$ and $143 \pm 215\,\mathrm{G}$, respectively. It means no detection of the magnetic field. Moreover, no short-time scale variability of the Stokes V parameter in the investigated line profile were detected within a 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 the bright O7.5 star ξ Persei. The average value of all measurements is 27 ± 70G. The error bars of these measurements appeared to be too large to detect a field.

Recently Donati et al. (2002) have informed on the longitudinal field ($\overline{B}_l$) estimations for O6 star θ^1 Ori C obtained by measuring the first moment of the Stokes V profile, normalized by the line equivalent width, with using the least-squares deconvolution technique (Donati et al. 1997). The derived $\overline{B}_l$ values are equal to $357 \pm 46\,\mathrm{G}$, $37 \pm 35\,\mathrm{G}$, $257 \pm 49\,\mathrm{G}$, $191 \pm 63\,\mathrm{G}$ and $257 \pm 73\,\mathrm{G}$ for rotational phases 0.033, 0.621, 0.789, 0.920 and 0.177, respectively. The phase dependence of $\overline{B}_l$ can be cosine fitted with the mean value $B_0 = 172 \pm 30\,\mathrm{G}$. The modeling of the Stokes V parameter variations indicate that the obtained $\overline{B}_l$ values are consistent with the assumption that the magnetic field can be presented as a tilted dipole with the polar field strength $B_p = 1.1 \pm 1.1\,\mathrm{kG}$ inclined at $42 \pm 6°$ with respect to the rotation axis, which, in turn, is assumed to be inclined at 45° to the line of sight.

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

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

4.3 Program of detection of magnetic fields

It is clear from the previous section that the moderate values of $\overline{B}_l \approx 100 - 200\,\mathrm{G}$ and even smaller for O and early B stars are expected. This means a necessity for the procedure of measuring the fields of this value for O and B stars. For this purpose, we propose a program of searching for the magnetic fields of bright O and early B stars, presented in Table 1. As the main method of determination of the magnetic field, we plan to use the simple "photographic technique" (see subsection 4.2) as a procedure most suitable for numerical targets.

Using this procedure, the mean longitudinal magnetic field $\overline{B}_l$ of the star is determined via the wavelength shift $\Delta\lambda$ between the 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 circularly polarized components of the line, respectively, $\overline{g}$ is the effective Landé factor of the line, λ_0 is the rest wavelengths of the line, and constant $k_0 = 4.67 \times 10^{-13}\mathrm{Å}^{-1}\mathrm{G}^{-1}$.

The value of

$$\lambda_R = \frac{1}{W_\lambda} \int \lambda r_\lambda d\lambda\,, \tag{2}$$

where W_λ is the line equivalent width, r_λ is the residual intensity of the line at wavelength λ. A similar expression can be written for the value of λ_L.

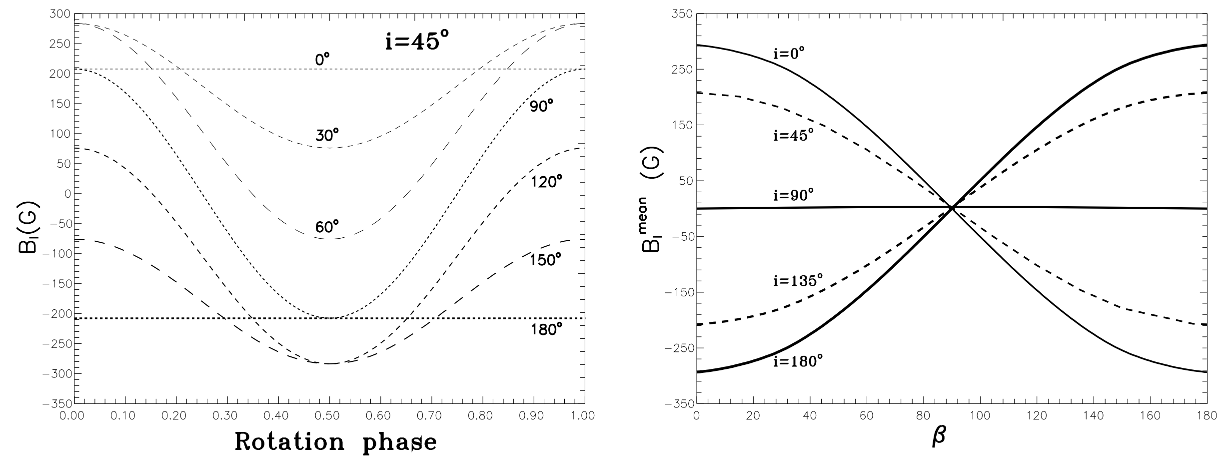

Figure 3: **Left panel:** *Mean longitudinal magnetic field strength* B_l *as a function of rotational phase for values* $B_p = 1100\,G$ *and* $i = 45°$. **Right panel:** *Phase averaged longitudinal magnetic field strength* B_l^{mean} *versus the angle* β *between rotational and magnetic axes.*

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

$$\overline{B}_l = \frac{1}{W_\lambda} \int\limits_0^{2\pi} d\varphi \int\limits_0^{\pi/2} B_l \cos(\theta) \sin(\varphi) d\theta \times \int r_\lambda(\theta, \varphi) d\lambda \,. \tag{3}$$

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 on the stellar disk and $r_\lambda(\theta, \varphi)$ is the residual intensity of the line in this point.

For a tilted dipole magnetic field and the 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 Eq.3. Finally (e.g., see 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 magnetic and rotational axes, i is the rotational axis inclination angle and ϕ_0 is the phase of the maximal longitudinal field.

The mean longitudinal magnetic field strength B_l versus the rotation phase is plotted in Fig. 3 (left panel). We accept the values $B_p = 1100\,$G for the polar field strength and $i = 45°$ for the inclination angle which have been obtained by Donati et al. (2002) for θ^1 Ori C. From this figure we see that the maximal B_l value never exceed 1/3 of the B_p value.

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

By this means, for detecting the magnetic fields in O stars we have to measure very small lambda differences $\Delta\lambda$ between the right and left circularly polarized components of the lines. For example, for the strong HeI λ 7065 line (effective Gaunt factor $\overline{g} = 2$) the value of $\Delta\lambda \approx 0.01$ Å. With the parameter of the instrument intended to be used in searching for the magnetic field (see subsection 2.2) we are unable to determine the value of $\Delta\lambda$ with the necessary accuracy from a single line.

The accuracy of $\Delta\lambda$ determination can be largely improved when a large number of lines are 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 circularly polarized components of line at their center 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).

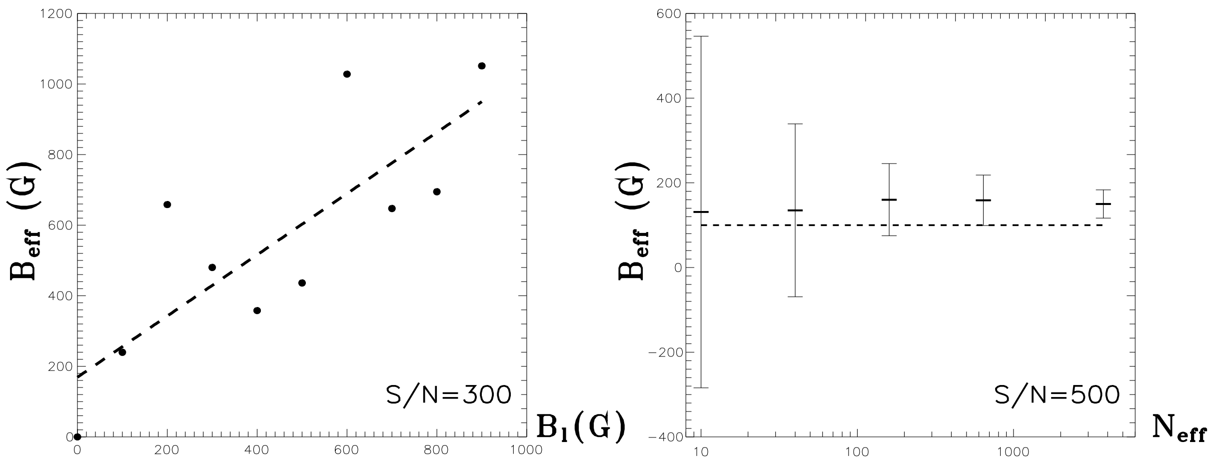

Figure 4: **Left panel:** *Mean effective magnetic field* $\boldsymbol{B_{\rm eff}}$ *as a function of input mean longitudinal field* B_l *for signal-to-noise ratio S/N=300 and* $N_{\rm eff}$*=200.* **Right panel:** *Dependence of mean effective magnetic field* $\boldsymbol{B_{\rm eff}}$ *versus the effective number of observations* N_{eff} *for S/N=500. The input value of* $\overline{B}_l = 100\,$*G. The error bars (at 3σ level) and mean values of* $\boldsymbol{B_{\rm eff}}$ *are plotted.*

However, the number of the suitable lines in the spectra of O stars is not very large (about 30–50) and to increase the gain in the line displacement measurements, we can use a number of successive spectra N_{sp}, obtained during the observational run. Looking at Fig. 3 we can see that it is possible to effectively 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 the 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 ($\geq 6\,$d). For these stars we can use spectra of 2 observational nights. This gives a total of $N_{\rm sp} \approx 2 \times 30 \approx 60$ spectra. Thus, the effective number of lines which can be used for $\Delta\lambda$ measurement is $N_{\rm eff} = N_{\rm line} \times N_{\rm sp}$. Substituting in this expression the typical values $N_{\rm line} \approx 50$ and $N_{\rm sp} \approx 60$ we have a total of $N_{\rm eff} \approx 3000$.

To estimate the possibility of measuring weak fields using the above described procedure, we have made a numerical experiment to reproduce the parameters of real observational runs (see subsection 2.2). For a better determination of the line center of gravity we have used the Gauss 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 an observational run j the value of $\Delta\lambda = \Delta\lambda_{ij}$ is measured, we can estimate the mean longitudinal magnetic field via the following 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 $\boldsymbol{B_{\rm eff}}$ and its standard deviation σ by usual way.

The resulting dependence of $\boldsymbol{B_{\rm eff}}$ on the input value of $\overline{B}_l$ is presented in Fig. 4 (left panel). We can see that for a not very large number of $N_{\rm eff}$ values the scattering of $\boldsymbol{B_{\rm eff}}$ is too large, and for the low values of $\overline{B}_l$ the mean effective magnetic field appeared to be 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). In this work it is shown that in this case the measured line fluxes have not normal, but log.–normal distribution with displacement to the 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 this measurement in the total set of line profile measurements. In our case we measure the line shifts rather than fluxes, but the nature of measurements seems to be very close.

Fig. 4 (right panel) demonstrates the possibility of improving the accuracy of determination of the $B_{\rm eff}$ value with increasing the effective number of observations N_{eff}. For the large values of N_{eff} the weak input field $\overline{B}_l = 100\,$G can be detected at $3\,\sigma$ level.

5 Conclusion

We report the results of a study of the fast *lpv* in spectra of selected bright O stars. The regular long time-scale components of *lpv* in the spectra of the star λ Ori A with the estimated period $P \approx 3$ 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 of detection of the weak magnetic fields in bright O and early B stars with the Zeeman analyzer at the North Caucasus Special Astrophysical Observatory (SAO) 1 m telescope is proposed. We demonstrate a principal possibility of measuring weak magnetic fields ($\overline{B}_l = 100 - 200$ G) for the program stars.

Acknowledgements. The work was supported by grants of NATO CLG 6978036 and RFBR 01-02-16858.

References

Abt H.A., Levato H., Gross M., 2002, Astrophys. J., **573**, 359
Brown D.N., Landstreet J.D., 1981, Astrophys. J., **246**, 899
Brown J.C., 1994, In: Moffat A.F.J., St-Lois N. (eds.) Quebec Workshop in Instability and Variability in Hot Star Winds. Ap&SS, **221**, 357
Babel J., Montmerle T., 1997a, Astron. Astrophys., **323**, 121
Babel J., Montmerle T., 1997b, Astrophys. J., **485**, L29
Chessneau O., Moffat A.F.J., 2002, Publ. Astr. Soc. Pacific, **114**, 112
Cranmer S.R., Owocki S.P., 1996, Astrophys. J., **462**, 469
Donati J.-F., Semel M., Carter B.D., Rees D.E., Cameron A.V., 1997, Mon. Not. R. Astron. Soc., **291**, 658
Donati J.-F., Wade G.A., Babel. J., Henrichs H.F., de Jong J.A., Harries T.J., 2001, Mon. Not. R. Astron. Soc., **326**, 1265
Donati J.-F., Babel J., Harries T.J., Howarth I.D., Petit P., Semel M., 2002, Mon. Not. R. Astron. Soc., **333**, 55
Eversberg T., 1997, Université de Montréal, Thesis
de Jong J.A., Henrichs H.F., Schrijvers S., Gies D.R., Telting J.H., Kaper L. and Zwarthoed G.A.A., 1999, Astron. Astrophys., **345**, 172
de Jong J.A., Henrichs H.F., Kaper L., Nichols J.S., Bjorkman K. et al., 2001, Astron. Astrophys., **368**, 601
Kaper L., Henrichs H.F., Fullerton A.W., Ando H. et al., 1997, Astron. Astrophys., **327**, 281
Kaper L., Henrichs H.F., Nichols J.S., Telting J.H. et al., 1999, Astron. Astrophys., **344**, 231
Kholtygin A.F., Monin D.N., Surkov A.E., Fabrika S.N., 2003b, Astron. Lett., **29**, 177
Kholtygin A.F, Brown J.C. , Cassinelli J.P., Fabrika S.N., Monin D.N., Surkov A.E., 2003a, Astron.& Astrophys. Transact., **22**, 499
Kholtygin A.F., Shneiwais A.B., 2003, Astrophysics, in press
Eversberg T., Lépine S., Moffat A.F.J., 1998, Astron. Astrophys., **494**, 799
MacGregor K.B., Cassinelly J.P., 2003, Astrophys. J., **586**, 480
Mathys G., 1991, Astron. Astrophys. Suppl. Ser., **89**, 121
Morel et al., 1998, Astrophys. J., **498**, 413
Monin D.N., 1999, Bull. Spec. Astrophys. Obs., **48**, 121
Monin D.N., Fabrika S.N., Valyavin G.G., 2002, Astron. Astrophys., **396**, 131
Moffat A.F.J., Michaud G., 1981, Astrophys. J., **251**, 133
Neiner C., Geers V.C., Henrichs H. F., Floquet M., Fremat Y., Hubert A.-M., Preuss O., Wiersema K., 2003, Astron. Astrophys., **406**, 1019
Preston G.W., 1967, Astrophys. J., **150**, 547
Rauw G., Morrison D.M., Vreux E.G., Gosset E., Mullis C.L., 2001, Astron. Astrophys., **366**, 585
Rola C., Pelat D., 1994, Astron. Astrophys., **287**, 677
Roberts D.H., Lehar J., Dreher J.W., 1987, Astron. J, **93**, 968
Robinson R.D., 1980, Astrophys. J., **239**, 961
Schulz N.S., Canizares C.P., Huenemoerder D., Kastner J.H., Taylor S.C., Bergstrom E.J., 2001, Astrophys. J., **549**, 441
Stahl O., Kaufer A., Rivinius T. et al., 2000, Astron. Astrophys., **312**, 539
Waldron W.L., Cassinelli J.P., 2000, Astrophys. J., **548**, L45