Non-radial pulsation and magnetic fields of OB stars

Natallia Sudnik and Alexander Kholtygin

Abstract We report the results of our studying the fast line-profile variability (LPV) in spectra of bright OB stars. Spectral and spectropolarimetric observations of 15 OB stars were made during the last ten years in the framework of the program of searching for the regular and stochastic LPV in spectra of OB stars and their magnetic fields. The spectra were obtained using the 6-m telescope of the Special Astronomical Observatory (SAO, Russia) and the 1.8-m telescope of the Bohyunsan Optical Astronomy Observatory (BOAO, Korea). For all studied stars we detected regular LPV connected with non-radial pulsation (NRP) and induced by the rotation of the large-scale structures in the stellar wind. We propose that the NRP are a trigger of the formation of the large-scale structures in the stellar wind. Results of searching for the polarimetric line profile variability (pLPV) in the spectra of OB stars are also reported. We find that the pattern of LPV can differ for the left and right polarized components of stellar radiation.

1 Observations

The observations analyzed were made in 1997–2010 at the SAO and BOAO. More than 1000 spectra of 15 OB stars (ξ Per, ε Per, α Cam, HD 35502, δ Ori, λ Ori A, θ^1 Ori C, ζ Ori A, 15 Mon, ρ Leo, HD 93521, 85 Her, 19 Cep, λ Cep and 10 Lac) were obtained. The 6-m telescope observations were made with the Lynx spectrograph (spectral resolution $R = 60000$) and a CCD with 512×512 pixels, with the NES spectrograph ($R = 60000$) and a $1\text{k} \times 1\text{k}$ CCD and with the MSS spectrograph

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($R = 15000$) and a 2k $\times$ 2k CCD, while the 1-m telescope observations were made with the CEGS spectrograph ($R = 45000$) and a 1242 $\times$ 1152 CCD. Most of these stars were also observed in BOAO by using the 1.8-m telescope equipped with the BOES spectrograph ($R = 45000$) and large 2k $\times$ 4k CCD. The reduction of SAO spectra was made with MIDAS while the BOAO spectra were processed with IRAF.

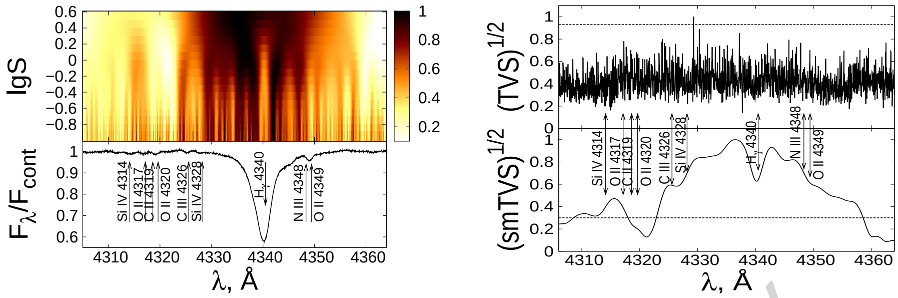

Fig. 1 Left panel: smTVS map (top) and mean line profile (bottom) in the region $\lambda\lambda\,4308-4362$ Å in spectra of λ Ori. **Right panel:** TVS (top) and smTVS (bottom) for lines in the same interval as in the left panel. Filter width is 1.26 Å. The dashed line marks the significance level $\alpha = 0.001$.

2 Line Profile Variability

The amplitudes of the line profile variations in the spectra of O and early B stars are small, so we call this line profile variability as microvariability (microLPV). To detect microLPV we use smoothing Time Variation Spectrum (smTVS) analysis introduced by Kholtygin et al. [1]. In this method before the standard deviation spectrum was obtained, the differential spectra were smoothed using a wide Gauss filter (S). After smoothing the amplitude of a noise component of the differential profiles decreases by a factor of $\approx \sqrt{S/\delta\lambda}$, where $\delta\lambda$ is a pixel width. If the width of the variable component is not smaller than that of the filter, then smoothing will not significantly change the amplitude of the variable component, and a peak in the standard deviation spectrum that corresponds to the variable component can be detected. The smTVS is described by

$$smTVS(\lambda,S) = \frac{1}{N-1}\left(\sum_{i=1}^{n} g_i \left[I_i(\lambda,S) - \overline{I(\lambda,S)}\right]^2 \Big/ \sum_{i=1}^{n} g_i\right), \qquad (1)$$

where N is the number of spectra, $I_i(\lambda,S)$ is the line intensity in the spectrum number i at wavelength λ smoothed with Gaussian filter (S is a filter width) and normalized to the continuum level, $\overline{I(\lambda,S)}$ is the mean intensity at wavelength λ averaged over all smoothed line profiles, g_i is a relative weight of the i^{th} observation. The smTVS analysis is a very sensitive tool to detect micro-variations of line profiles. It can be used when the amplitude of variations is small and do not exceed the noise level, when the number of spectra is small and the time grid is uneven.

For $S = 0$ the value of smTVS(λ,0) corresponds to the TVS (Temporal Variance Spectrum) value introduced by Fullerton et al. [2]. The best results are obtained for smoothing with a Gaussian filter with $S = 0.7 - 1.3$ Å (15–30 pixels).

In Fig. 1 (left panel) we present the density plot of the smTVS for the region of the H_γ line in spectra of λ Ori. Darker areas correspond to higher amplitudes of smTVS. Clearly the variations of the H_γ line profiles can be seen at all filter widths. The smTVS with the filter width more than 1 Å also indicates variability of the weak C II-III N II, O II and Si IV line profiles. In a Fig. 1 (right panel) TVS and smTVS functions are shown for comparison. The variations of weak lines can be easily detected using the smTVS analysis.

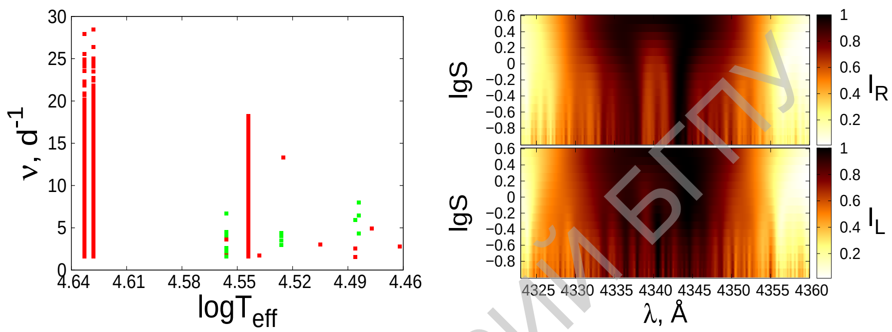

Fig. 2 Left panel: detected NRP frequencies for O stars as function of the effective temperature of the stars. **Right panel:** Density plot diagram of smTVS for I_R (top) and I_L (bottom) components of line profiles in spectra of ζ Ori.

To search for the regular LPV we carried out Fourier analysis using the CLEAN procedure [3] modified in [4]. LPV periods detected by us for the program stars are given in Table 1. Both long periods of LPV connected with rotational modulation ($\approx 0.6 - 3.5^{\mathrm{d}}$), and short periods attributed to NRP ($\approx 3 - 8^{\mathrm{h}}$) were found. We plot in Fig. 2 (left panel) the frequencies of NRP for O stars taken from the literature and including our own data. More than 10 well-studied O stars seem to be non-radial pulsators. We suppose that NRP is the common feature of all hot massive stars.

Table 1 Period detected in the program stars LPVs

Name	Spectral type ^{a}	Period	Name	Spectral type ^{a}	Period
λ Cep	O6.5 I f(n)p	3–11$^{\mathrm{h}}$, 0.6–3.4$^{\mathrm{d}}$	ζ Ori A	O9 Ib	3–6$^{\mathrm{h}}$
λ Ori A	O8 III ((f))	3–16$^{\mathrm{h}}$, 1.3–1.8$^{\mathrm{d}}$	ι Her	B3 IV	7–13$^{\mathrm{h}}$, 0.9–2.9$^{\mathrm{d}}$
δ Ori A	O9.5 II	4.1$^{\mathrm{h}}$	ρ Leo	B1 Iab	3–6$^{\mathrm{h}}$, 0.6–1.8$^{\mathrm{d}}$

^{a} from [5] and from SIMBAD data base for ι Her and ρ Leo

3 Polarimetric Line Profile Variability

We study LPV in integral (Stokes parameter I), left (I_L) and right (I_R) polarized components of the line profile in spectra of stars λ Cep, ζ Ori A and λ Ori A. We find that pattern of LPV for I_L and I_R can differ.

Applying Eq. (1) to the left-polarized components I_L^i of the line we obtain the smTVS$_L$ spectra and the smTVS$_R$ spectra in the case of components I_R^i. The density plot of the smTVS$_L$ and smTVS$_R$ spectra for the region near H$_\gamma$ line in spectra of the star ζ Ori is shown in the Fig. 2. Darker areas correspond to higher amplitudes of the smTVS. The differences between smTVS$_L$ and smTVS$_R$ spectra are clearly seen and can be indirect evidence that the stars possess a magnetic field.

We also compare the Fourier spectra of the I_L and I_R components of the lines in the spectra of the program stars. We find that there are regular components which can be detected in the Fourier spectrum for the I_L component of line and cannot be detected for the I_R component and vice versa. We do not know the cause of this difference. Possibly it is connected with the clumps in the stellar wind and the rugged structure of the magnetic field above the photosphere.

4 Conclusions

All studied stars show microLPV with the amplitude about 0.5–3%. Regular short and long timescale components of LPV have been detected. These components are probably connected with non-radial pulsations and rotation modulation. NRP seems to be common for all massive OB stars.

Weak variability of lines of the ions Si, C, O, N in spectra of the stars λ Cep, λ Ori A, δ Ori A and ζ Ori A was revealed by smTVS. It is possible that the LPV for the left and right-polarized components of the line profiles can differ.

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