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SUPERFAST LINE PROFILE VARIATIONS IN STELLAR SPECTRA

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The regular line profiles variations (LPVs) with periods ranging from a few hours to days in spectra of stars are well investigated. At the same time the LPVs at minute time scale are badly known. In order to study the spectral variability on such short timescales, we launched Large Project to search for the superfast line profile variations (sfLPVs) in spectra of bright stars. By the end of 2022 year we have obtained over 20000 spectra of selected OBAFGKM stars at the 6-m and 1-m telescopes of the Special Astrophysical Observatory (Northern Caucasus, Russia) and at the 1.25-m telescope of Crimean Astronomical Station of the Sternberg Astronomical Institute (Moscow State University, Russia). Both regular LPVs with periods from 2 to 140 minutes and non-regular LPVs with amplitudes of 1-3% of the continuum level were detected for all studied stars. Such short-term spectral variability was not studied systematically in the past, while it can be crucial for the future theoretical understanding of the stellar physics and for modeling the stellar evolution. We plan to use additional telescopes for spectral observations with an ultra-high temporal resolution and in particular the Shamakhy Astrophysical Observatory (SHAO) 2-m telescope. In future we are also going to study the sfLPVs for bright stars at the pre-main stage of stellar evolution.

Keywords: Stars – Spectra – Line Profiles variations

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1. INTRODUCTION

Houtgast [1] first argued that line profiles in the solar spectra are variable and depend on the location of the studied region of the solar disks. Later, nearly 50 years ago line profile variations in the stellar spectra were detected [2]. 50 years of LPVs investigations showed that the main causes of them are the rotational modulations and non-radial pulsations (NRPs). The typical time scales of LPVs in spectra of OBA stars vary from days to hours [3,4].

For example, for bright A0 supergiant HD 92207 Kaufer et al. [5] detected the NRPs with a period of 27 days, and no shorter periods were revealed. Searching for fast and super-fast LPVs appeared to be far from the main scientific interest. Surprisingly, the short time-scale line profile changes in the spectra of HD 92207 were recently discovered by Hubrig et al. [6].

These authors detected clearly visible LPVs for different elements in individual subexposures up to 3% in intensities (in continuum units) and up to 30 km/s in radial velocities. Such short-term LPVs were not previously known for non-radially pulsating supergiants. These observations gave an impetus to our research of the superfast line profile variations in spectra of early-type stars at minute and even seconds time scales. Such line profile variations remain practically uninvestigated until now. In order to guess whether the short-term LPVs are typical for all OBA and stars of later spectral type, we launched in 2015 the Large Observational Program to analyze the LPVs with high temporal resolution.

In the present paper we describe our Large Program and review the main results of our fast LPVs investigations at the moment. The program and the observations are reviewed in section 2. In section 3 the selected results of analysing our new observational data are discussed. Some conclusions are given in section 4.

2. OBSERVATIONS

The main goal of our program is to study the super-fast variations of the line profiles in the spectra of OBA stars at time scales of second and minute and to develop the models explaining such variations. We also plan to investigate the dependence of the super-fast LPVs parameters on the spectral type, rotation velocity, chemical abundances, and other stellar parameters.

The list of program stars includes all bright stars for which it is possible to get high temporal resolution and to obtain the signal to noise ratio $S/N > 300$. The list of the proposed targets contains all bright stars with V$\leq 4^m$. The catalog of bright stars[1] was used as a source to choose the targets. It means that the

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[1] http://tdc-www.harvard.edu/catalogs/bsc5.html

sample of the program stars will be complete up to V$\leq 4^m$. Among the more weak targets with V$> 4^m$ the massive OB stars will be predominantly included in the list.

Our experiences show that the sfLPVs in spectra of bright stars at minute or second time scales can be detected for $\Delta T < 30$ s and $S/N \geq 300$. Here ΔT is the time interval between successive observations. That is a sum of exposure and CCD matrix readout time. The selection of telescopes and spectrographs has to be made to provide such parameters of observations as given above.

Table 1. O stars

Star	Sp.type	V	$N_{\rm sp}$	Exp (s)	Tele-scope	Spectro-graph	Dates
ξ Per	O7.5III	4.06	1249	15	1.25-m	A-Sp	07.10.2021
α Cam	O9Ia	4.29	434	15	Z-1000	UAGS	29-30.10.2021
19 Cep	O9Ib	5.11	390	2	BTA	SCORPIO	17-18.08.2021
			225	10	1.25-m	A-Sp	21.09.2020
ζ Ori A	O9.2I	1.88	76	90	BTA	MSS	19.02.2019
HD 93521	O9.5III	7.03	529	3	BTA	SCORPIO	19-20.01.2015
			28	900	BTA	MSS	30.12.2021-2.2.2021
HD 34078	O9.5V	5.96	27	300	BTA	MSS	5-8.1.2020
HD 45314	O9:npe	6.64	209	600	BTA	MSS	5-8.1.2020

This means that the diameters of the telescopes used for observations must be in any case greater than 1 meter. To provide the ratio $S/N \geq 300$ for 1-2 meter telescopes it is necessary to use spectrographs with low resolving power $R \sim 1000/2000$. Higher spectral resolution can be only reached with very large telescopes with a diameter $D > 5$ meters. For making the polarization observations and measuring the magnetic field strength one needs to use telescopes with a diameter of at least 5 meters.

Our observations of the program stars were made with the 6-m telescope BTA (Big Azimuthal Telescope), the 1-meter telescope Zeiss-1000 (Z-1000) of Special Astrophysical Observatory, and the 1.25-m telescope of the Crimean Astronomical Station (CAS) of the Sternberg Astronomical Institute (SAI) of the Moscow State University.

For our observations at the BTA telescope we used both low resolution spectrograph SCORPIO [7] and the medium resolution Main Stellar Spectrograph (MSS) [8]. The observations at the 1.25-m telescope were made with a low-resolution A-spectrograph (A-Sp) [9]. Up to the present day more than 20 000 spectra of OBAFGM stars have been obtained.

Table 2. B stars

Star	Sp.type	V	$N_{\rm sp}$	Exp (s)	Telescope	Spectrograph	Dates
β Cep	B0.5IIIs	3.21	74	60	BTA	MSS	30.12.2020-2.2.2021
			1576	2	1.25-m	A-Sp	13-14.9.2020
γ Cas	B0.5IVpe	2.39	138	60	BTA	MSS	1-2.2.2021
			2460	1.5	1.25-m	A-Sp	7-8. 9.2021
SAO 49725	B0.5III/IVe	9.27	432	5	BTA	SCORPIO	17-18.08.2021
			1271	1	BTA	SCORPIO	19-21.01.2015
ρ Leo	B1Iab	3.87	80	90	BTA	MSS	19.02.2019
			263	10	1.25-m	A-sp	26.10-2.11.2019
π Aqr	B1III-IVe	4.64	1250	5	1.25-m	A-sp	10.10.2021
HD 45995	B1.5Vne	6.14	208	30	BTA	A-sp	10.10.2021
V2156 Cyg	B1.5Ve	8.91	7	20	BTA	SCORPIO	18.08.2021
α And	B8IV	2.06	2611	2	1.25-m	A-sp	13-14.9.2020
	-VHgMn		709	10	Z-1000	UAGS	28-30.10.2020

Table 3. AFGM stars

Star	Sp.type	V	$N_{\rm sp}$	Exp (s)	Telescope	Spectrograph	Dates
α^2 CVn	A0spe	2.90	866	1	BTA	SCORPIO	21-22.01.2015
			71	90	BTA	MSS	5.1.2020
HD 21389	A0Ia	4.54	330	11	BTA	SCORPIO	25-26.09.2016
γ UMi	A2III	3.00	249	20	BTA	SCORPIO	25-26.09.2016
β Cep	A8Vn	2.46	641	10	Z-1000	UAGS	28-30.10.2020
V388 Cep	F0IV	5.55	505	20	1.25-m	A-sp	13.09.2021
π,Peg	F5III	4.29	1302	5	1.25-m	A-sp	7+9.09.2021
β Cam	G1Ib	4.02	1159	4	1.25-m	A-sp	12.09.2021
51 Peg	G2IV	5.46	400	20	1.25-m	A-sp	7.10.2021
4 Cas	M1III	4.96	488	10	1.25-m	A-sp	13.09.2021

Our large program was started in 2015-2017 from the observations of fast rotating O9.5III star HD 93521, BIa supergiant ρ Leo, A0I supergiant HD 21389, A0V magnetic standard α^2 CVn, and A2III giant γ UMi with the 6-m BTA telescope.

Firstly, we investigated the LPVs in spectra of HD 93521. We reveal the fast profile variations with periods of 4-5 and 32-36 minutes [10]. The possible origin of short time-scale spectral variations was discussed.

The fast variations in spectra of a slow-rotating [11] star $\rho\,$Leo were reported by Kholtygin et al. [12]. They detected short-period transient regular variations of the H and He lines with periods from 2 to 90 minutes. These results were later confirmed by Kholtygin et al. [13]. The authors explain the presence of these transient components assuming that the high modes of non-radial pulsations (NRPs) are unstable and can either dissappear or be generated on short time scales ranging within 10-100 minutes.

An analysis of the spectra of the $\gamma\,$UMi in January 2017 with the BTA telescope equipped with the SCORPIO spectrograph showed the presence of the LPVs' harmonic components with periods within the $10-65$ minute interval [14].

In a recent paper by Kholtygin et al. [15] the authors analyze $\alpha^2\,$CVn observations carried out on January $20-21$, 2015 using the BTA telescope with the SCORPIO spectrograph. Short-term regular variations in the Balmer H lines and HeI lines with periods ranging from about 30 to 135 minutes were detected.

LPVs in spectra of this star were additionally investigated using the observations carried out with the 6-meter BTA telescope on January 6, 2020 using the MSS spectrograph. Regular short-term periodic variations of the H_β, FeII, and CrII lines with periods ranging from 4 to 140 minutes were registered [16].

Spectra of the chemically peculiar (mercury-manganese overabundant) B8IV-V star $\alpha\,$And, characterized by its spot activity [17] and belonging to the group of $\alpha^2\,$CVn type star, were also obtained at the 1.25-m telescope on 13/14.9.2020. Our CLEAN analysis shows the presence of regular LPVs in the $\alpha\,$And spectra with periods of 4.93 ± 0.60, 18.38 ± 8.36 and 20.74 ± 10.64 minutes at a False Alarm Probability (FAP) level of 10^{-3} [18]. These periods are close to those for $\alpha^2\,$CVn mentioned above.

Our observations of the B0.5IVpe star $\gamma\,$Cas at the 1.25-m telescope on the Crimean station of SAI are analysed by Kholtygin et al. [19]. The regular components of LPVs with periods from 4 to 37 minutes are registered. This telescope was also used to observe another $\gamma\,$Cas type star $\pi\,$Aqr [20] on October 10/11, 2021. The regular LPVs at the short-time scale with periods from 4 to 136 minutes in spectra of $\pi\,$Aqr are revealed.

Analysing the X-ray spectra of the stars opens an opportunity to study their fast variability. A comparison of periods of the X-ray flux variations for selected $\gamma\,$Cas type stars shows that these periods correspond to those obtained from an analysis of the optical spectra of such stars [18]. This means that the regions where the optical and X-ray spectra are formed close to the stellar surface.

3. LINE PROFILE VARIATIONS

Line profiles in spectra of all observed by us stars appeared to be variable. The typical amplitude of LPVs is about 1-3% in the continuum units as it is shown in the Fig. 1 for normalized H_β and H_α line profiles in spectra of δ Scuti type variable star V388 Cep.

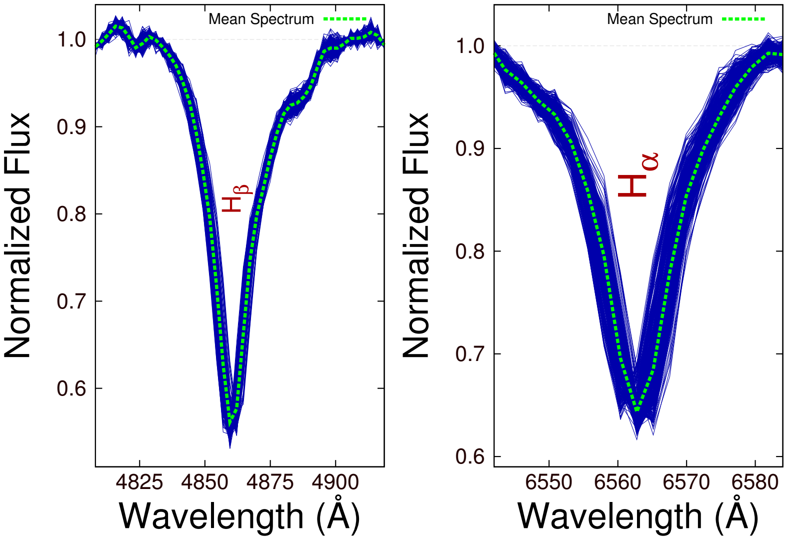

Fig. 1. Line profiles in spectra of V388 Cep, obtained on 13.09.2021 at the 1.25-m telescope.

In order to look for regular components of profile variations, we determine the difference line profiles. Let one have N observed spectra of the studied object. Denote by $F_i(\lambda)$, $i = 1, \ldots, N$ the continuum-normalized flux in the $i-$th stellar spectrum at wavelength λ. Let $\overline{F}(\lambda)$ be the line flux at the wavelength λ averaged over all observations. Then the difference line profile

$$d(\lambda) = F_i(\lambda) - \overline{F}(\lambda) \qquad (1)$$

To analyze the difference line profiles, it is more convenient to use the Doppler shifts V with respect to the laboratory wavelength λ_0 of the line:

$$V = c(\lambda/\lambda_0 - 1),$$

where c is the speed of light.

For spectra of different quality, one could use different profile weights g_i, which are proportional to the square of S/N ratio in the continuum region near the line, when calculating the average and difference line profiles.

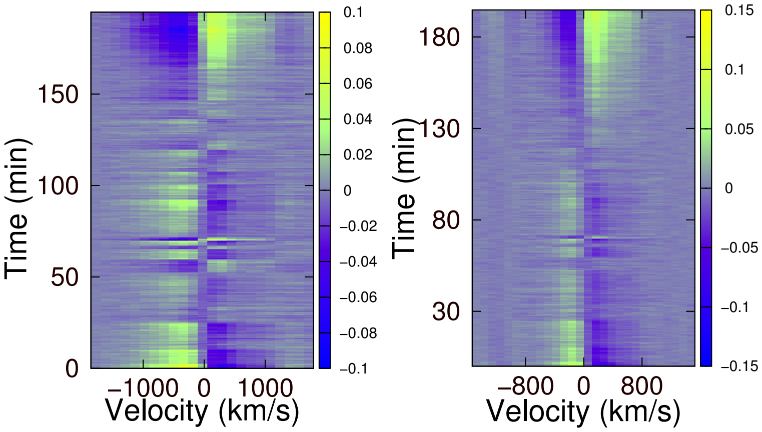

Fig. 2. Dynamical spectra of the H_β (left panel) and H_α (right panel) LPVs in spectra of V388 Cep.

3.1. Regular LPVs

We detect the regular components of LPVs with periods from 3-4 to 90 minutes for bright OBA stars. Periods of the regular LPVs depend on the spectral type of stars. The shortest periods down to 3-4 minutes are detected for O and early B stars [14]. Such short-time periods of regular line profile variations can be connected with the high modes of the non-radial pulsations (NRP). We supposed that detected LPVs are connected with p modes of NRP with values of $l \sim 50 - 200$. Such high NRP modes are well known in the solar 5-minutes oscillations [21].

For late B and A stars the shortest periods of LPVs seem to be larger than for O and early B stars [13]. In order to understand the tendency for the line profile variation period to increase from the early to late spectral type stars, we analyzed the LPVs in spectra of the F0IV star V388 Cep. We obtained 505 spectra of this star (see Table 3). The dependence of the values of $d(V,t)$ on the time of observations (dynamical spectra) for H_β and H_α lines in spectra of this star is plotted in Fig. 2. One can see the similarity of the LPV pattern for both lines.

We tried to detect regular components in the LPVs in spectra of V388 Cep using the CLEAN Fourier analysis method by Roberts et al. [22]. In Table 4 we present the frequencies and periods detected from the analysis of the LPVs (2nd and 3rd columns). In the last column the False Alarm Probability (FAP) level is given.

The standard top estimate of the frequency error $\Delta\nu = 1/T$, where $T = 194.8$ minutes is the total observation time [23], is too big. Our numerical experiment shows that the value of $1/3T$ is more realistic.

Table 4. Frequencies and periods of regular components for LPVs in spectra of V388 Cep

No.	ν, min^{-1}	P, min	FAP
1	0.005335 ± 0.00171	187.4 ± 60.1	10^{-6}
2	0.006669 ± 0.00171	149.9 ± 38.5	10^{-2}
3	0.011070 ± 0.00171	90.3 ± 14.0	10^{-4}
4	0.074026 ± 0.00171	13.5 ± 1.0	10^{-2}

The components 2 and 4 correspond to the value FAP= 10^{-2} and should be confirmed by future observations. The components 1 and 3 are larger than 1 hour. That is, the minimum periods of LPVs in the spectrum of F stars are significantly longer than those of OBA stars. This confirms our conclusion that the periods of LPVs are to increase from early to late spectral types.

One can compare our data with those obtained by other authors. A detailed analysis of the photometric variability of V388 Cep in the B and V bands has been done by Hao et al. [24]. A total of 156 hr of data in the U, B, and V bands were obtained in the 17 days campaign in 1994 September-October using the 60 cm reflector at the Xinglong Station, Beijing Astronomical Observatory (China) and the 48 cm Cassegrain telescope of Ege University Observatory (Turkey).

As a result of their frequency analysis five frequencies $f_1 = 3.617$, $f_2 = 3.655$, $f_3 = 4.286$, $f_4 = 2.385$, and $f_5 = 5.847$ c/d were detected. Mode identification showed the first four frequencies to be interpreted as the $l = 2$ mode of the non-radial pulsation (NRP) with the rotational frequency splitting identified with $m = -2, 1, -1, 2$, and 2 respectively.

A comparison of these frequencies with ones obtained by us and given in Table 4 shows that the frequency 2 could be the 4-th harmonic of the frequency $f_4 = 3.617$. The frequency 1 can be (taking into account errors of its determination) the 2nd harmonic of the frequencies f_1 or f_2. This confirms the reality of detecting regular components of LPVs in spectra of V388 Cep.

4. CONCLUSIONS

The present study allowed us to make the following conclusions:

1. Our observations with the SCORPIO spectrograph on the 6-m BTA telescope and 1.25-m SAI telescope show the presence of short-period LPVs for all studied stars never known previously for OBA stars.

2. Fast variations of the line profiles in the spectra of studied stars are probably associated with the high modes of NRP.

3. The periods of LPVs increase from early to late spectral types.

In future we suppose to use the additional telescopes for the spectral observations with the ultra-high temporal resolution and in particular the SHAO 2-m telescopes. We are also going to study the sfLPVs for bright Ae/Be Herbig stars and T Tauri stars to study super-fast spectral variability for the pre-main sequence stars.

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