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Smooth time variation spectra as a tool to study line profile variability in spectra of hot stars

*N. P. Sudnik**

Saint-Petersburg State University, 28 Universitetskiy ave., 198504, Saint-Petersburg, Russia

Line profiles in spectra of almost all OB stars are variable. In many cases the line profile variations are extremely weak (not more than 1% of the continuum level). For detection of such micro line profile variations of various nature we used a smooth Time Variation Spectra method (smTVS). This method appeared to be very sensitive and can be used to detect ultra weak line profile variations which can not be detected by other methods. We applied the smTVS method to detect the micro LPV in spectra of bright O stars λ Cep, λ Ori A and ζ Ori A. Spectra of these stars were obtained by using the 6-m and 1-m telescopes of the Northern Caucasus Special Astrophysical Observatory (Russia) and the 1.8-m telescope of Bohyunsan Astronomical Observatory (Korea).

Key words: stars: early-type, stars: massive, stars: individual: λ Cep, λ Ori A, ζ Ori A; line: profile variations; methods: data analysis, methods: statistical

INTRODUCTION

An investigation of the line profile variations (LPV) in spectra of hot stars started in 70th of the XX century. To detect variability researchers usually overplotted individual or residual (individual profile minus the mean one) profiles of line or computed dynamical spectrum. It was easy to recognize the LPV by using these procedures if spectral deviations are large compared with noise and data are well sampled in time. With improvement of observational and computational facilities for LPF study different methods, intended to obtain periods, scales and other characteristics of LPV and their changes in time, have come to use. At present the most widely used methods are Temporal Variance Spectrum (TVS) analysis, Fourier analysis, wavelet analysis, Doppler imaging technique. Here we describe a smoothing Time Variation Spectrum (smTVS) method proposed by Kholtygin et al. [5] and its application for detection of micro LPV in spectra of O stars.

OBSERVATIONS

We analysed the observations that were made in 1997–2009 at the Special Astrophysical Observatory (SAO) of the Russian Academy of Science and at Bohyunsan Optical Astronomy Observatory (BOAO), Korea. The stars were observed in SAO with the 6-m telescope and LYNX spectrograph[1] with spectral resolution 60,000 and CCD 512×512 pixels and with the 1-m telescope and CEGS spectrograph [9] with spectral resolution 45,000 and CCD 1242×1152 pixels. The reduction of SAO spectra was made with the help of the `MIDAS` software package. The stars were also observed at BOAO with the 1.8-m telescope and the BOES spectrograph [6] with spectral resolution 45,000 and large CCD (2048×4096 pixels). All spectra in BOAO were obtained within the $3830-8260$ Å region. Preliminary reduction of CCD frames was made with the help of `IRAF` software package. A log of observations is given in Table 1. All spectra were normalized to the continuum level by the same way. The procedure of finding the continuum level is described in [5].

SMOOTHING TIME VARIATION SPECTRUM (SMTVS) ANALYSIS

For detection of micro LPV of various nature we used the smooth Time Variation Spectra (smTVS) technique. That is substantially modified version of Temporal Variance Spectrum (TVS) analysis introduced by Fullerton et al. [2]. In this method the standard deviations of variations in both lines and continuum are compared. If the amplitude of deviations within a line is larger than in the continuum then detection at a selected significance level

*snata.astro@gmail.com

[1] `http://www.sao.ru/hq/ssl/LYNX.html`

can be claimed. If the observed standard deviations are smaller than expected for the noise contribution into LPV at the selected significance level, then only an upper limit of the amplitude of the LPV can be estimated.

In the case of line profile variability with a sufficiently high amplitude the value of $TVS(\lambda)$ in the vicinity of the corresponding line substantially exceeds its value in the adjacent continuum. But in many cases the LPV are extremely weak (not more than 1% of the continuum level for many of O stars). In the absence of any visible variations we can determine whether a line profile was indeed variable using a following procedure.

Before the standard deviation spectrum was obtained, 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 peak in the standard deviation spectrum that corresponds to the variable component can be detected.

This procedure, called smoothing Time Variation Spectra (smTVS), was introduced by Kholtygin et al. [5]. The smTVS is described by the following equation:

$$smTVS(\lambda, S) = \frac{\sum\limits_{i=1}^{n} g_i \left[F_i(\lambda, S) - \overline{F(\lambda, S)}\right]^2}{(N-1)\sum\limits_{i=1}^{n} g_i}, \quad (1)$$

where N is a number of spectra, $F_i(\lambda, S)$ is a flux in the spectrum with number i at wavelength λ smoothed with Gauss filter (S is a filter width) and normalized to the continuum level, $\overline{F(\lambda, S)}$ is a flux at wavelength λ averaged over all smoothed fluxes, g_i is a relative weight of the i^{th} observation.

To ensure that LPV are real we defined a small significance level $\alpha \ll 1$ for the hypothesis that the line profile variations are due to a random variations of the noise component of the profiles only. The smTVS obeys a χ^2/d.o.f. statistics with $N-1$ degrees of freedom. Let χ^2_α be specified so that the probability $P\left(\chi^2/\text{d.o.f.} > \chi^2_\alpha\right) = \alpha$. If the calculated $smTVS(\lambda)$ value exceeds χ^2_α, the hypothesis that the line profile is variable can be accepted.

It was shown empirically that the best results correspond to smoothing with a Gaussian filter with width $S = 0.7 - 1.3$ Å (it means usually 15–30 pixels). For $S = 0$ the value of smTVS(λ,0) corresponds to the TVS value introduced by Fullerton et al. [2].

Note that the efficiency of the method is sensitive to the number of obtained spectra, and it enhances substantially as this number increases.

Here we present an application of smTVS analysis to the spectra of bright massive O stars λ Cep, λ Ori A and ζ Ori A. Parameters of these stars are presented in Table 2.

The Figure 1 presents a density plot of the smTVS for the HeII λ 4200 Å line profiles. Darker areas correspond to higher amplitudes of the smTVS. The density plot shows that the variability of the HeII λ 4200 Å line is clearly present at all filter widths. The smTVS with the filter width more then 1 Å also indicates variability of the weak CIII λ 4187 Å and SiII λ 4212 Å lines profiles, which cannot be detected using ordinary methods.

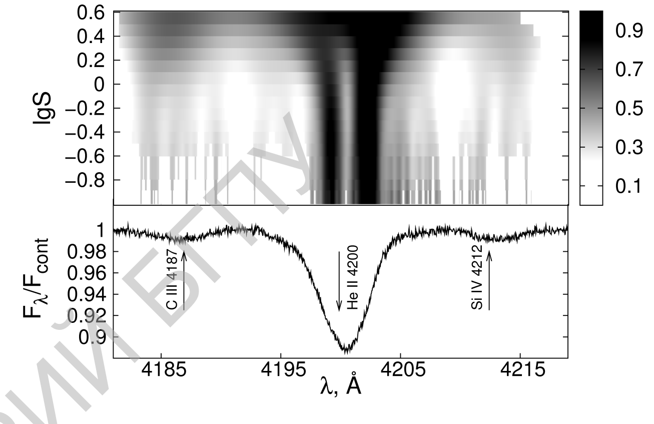

Fig. 1: Density diagram for smTVS (top) and mean line profile of HeII λ 4200 Å line (bottom) in spectra of λ Cep. Darker areas correspond to higher amplitudes of the smTVS. The maximum smTVS value is taken as 1.

In Figure 2 TVS (top panel) and smTVS (bottom panel) functions are shown for comparison. The variability of CIII and SiIV line undetected by simple TVS analysis is clearly seen.

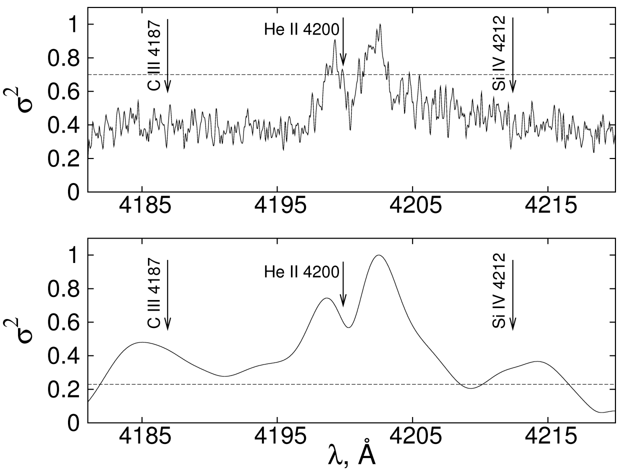

Fig. 2: TVS (top) and smTVS (bottom) of the HeII λ 4200 Å line in spectra of λ Cep. Filter width is 1.5 Å. The horizontal line corresponds to the significance level 0.001.

The smTVS of the line profiles in spectra of ζ Ori A presented in Figure 3 is obtained for observations made in BOAO. The total duration of observation is 2 hours. In spite of this the variability of the line H_γ and weak lines in its wings can be seen.

In spectra of λ Ori A a weak variability (no more than 1% of the continuum level) is also detected. In Figure 4 one can see that the variability of lines H_γ, and lines of Si, O, N ions occurs at all filter width although it can not be found by simple TVS analysis.

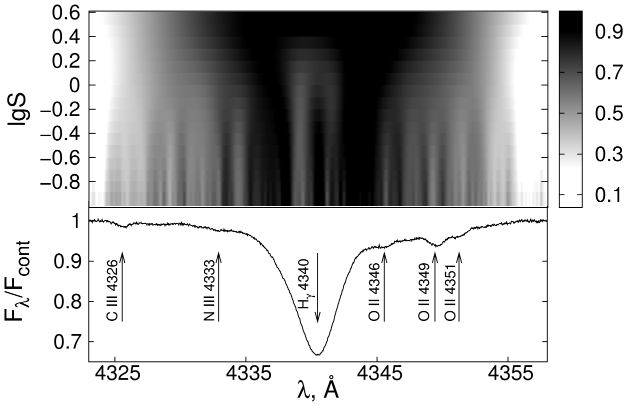

Fig. 3: The same as Fig. 1 but for the H_γ line in spectra of ζ Ori A.

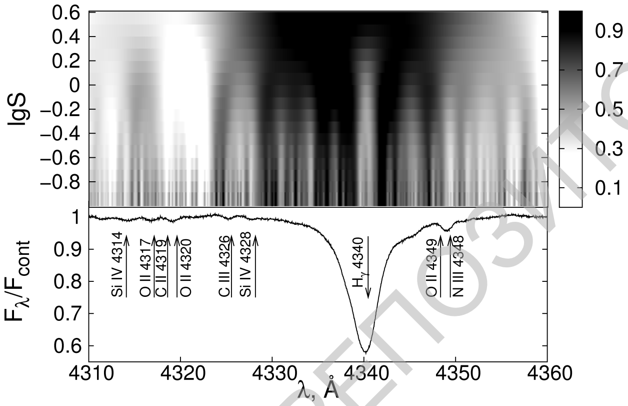

Fig. 4: The same as Fig. 1 but for the H_γ line in spectra of λ Ori A.

Note that, in spite of the fact that a lot of lines are extremely weak and their residual intensities do not exceed the noise level of the adjacent continuum their variability is clearly detected.

Unfortunately, our technique cannot be used for accurate localization of weak lines with variable profiles for large filter widths.

The procedure of searching the LPV described above can only answer a question whether the profile of a specific line is variable or not. At the same time, to determine a mechanism of LPV we need to know whether the profile variations are regular (cyclical), irregular (stochastic) or both. To define this and also to reveal characteristic features of variability and its changes in time we have to use the Fourier or wavelet analysis.

RESULTS AND CONCLUSIONS

We can see that the smTVS analysis is a very sensitive method to detect micro LPV that can not be found in a usual way. It can be used when amplitude of variation is small (less then 1% in continuum units) and do not exceed the noise level, a number of spectra is small, time grid is uneven.

Weak variability of the lines of the Si, C, O, N ions in spectra of O stars λ Cep, λ Ori A and ζ Ori A was revealed by smTVS only.

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Table 1: Log of observations. Δ T is duration of observations, t_{exp} is exposition time.

object	date	number of spectra	t_{exp}, min	Δ T, h	telescope	spectrograph, CCD
λ Cep	14.08–16.08 1997	70	2–5	7.8	SAO, BTA	Lynx, 512 x 512
HD 210839	20.11–16.12 2007	30	3–5	7.2	BOAO, 1.8 m	BOES, 2048 x 4096
λ Ori A	29.11–04.11 2001	75	10	12.5	SAO, 1 m	CEGS, 1242 x 1152
HD 37742	20.11–22.11 2007	18	1–3	2.4	BOAO, 1.8 m	BOES, 2048 x 4096
ζ Ori A	29.11–04.11 2001	36	2	1.2	SAO, 1 m	CEGS, 1242 x 1152
HD 36861	17.12 2007	34	7	2.9	BOAO, 1.8 m	BOES, 2048 x 4096

Table 2: Parameters of program stars

	λ Cep (O6 I (n)fp)		λ Ori A (O8 III ((f)))		ζ Ori A (O9.7 Ib)	
parameter	value	reference	value	reference	value	reference
m_V	5.04	[8]	3.41	[8]	3.78	[8]
$\lg L/L_\odot$	5.83	[10]	5.38	[7]	5.64	[1]
T_{eff}, K	36 000	[3]	33 600	[3]	29 500	[1]
$M/M_\odot$	62	[10]	31	[7]	40	[1]
$R/R_\odot$	21	[3]	15	[3]	25	[1]
$\lg g$	3.58	[10]	3.61	[7]	3.25	[1]
$\dot{M}/M_\odot \cdot 10^{-6}$	2.7	[3]	≤ 1.4	[3]	1.4–1.9	[1]
$V \sin i$, km/s	200	[10]	74	[4]	110	[1]
V_∞, km/s	2250	[3]	2400	[3]	2100	[1]