Clumping in Hot Star Winds
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Modelling the induced clumping stochastic line profile variability

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We model the line profile variability (lpv) in spectra of clumped stellar atmospheres using the Stochastic Clump Model (SCM) of the winds of early-type stars. In this model the formation of dense inhomogeneities (clumps) in the line driven winds is considered as being a stochastic process. It is supposed that the emission due to clumps mainly contributes to the intensities of emission lines in the stellar spectra. It is shown that in the framework of the SCM it is possible to reproduce both the mean line profiles and a common pattern of the lpv.

1 Introduction

In the beginning of 70th the first indications of the presence of high density regions (blobs or clumps) in the atmospheres (winds) of the early-type (hot) stars were emerged. Now the strong inhomogeneity of the winds of the early-type stars appears to be evident both from theoretical works and observations.

This inhomogeneity can be described in the *clump model*. In this model a stellar wind is proposed to be composed of the numerous dense clumps and more rarefied interclump medium. Total number of the clumps exceeds 10^3. The ions of the low and moderate ionization stages are located dominantly in the clumps while the interclump medium is strongly ionized.

2 Stochastic clump model

A random character of the clump connected lpv allows us to conclude that clumps born and dissipate randomly. A random ensemble of clumps in the atmosphere may be described in the framework of the Stochastic clump model suggested by Kostenko & Kholtyhin (1999) and Kudryashova & Kholtygin (2001) and close to that propose by Lepine & Moffat (1999). In this case one can say only about the probability for clump has a determined values of the mass, size, flux in the line and other parameters. For each cloud these values are defined through the distribution of clumps on masses, sizes and other parameters.

The total flux in the line formed by a clumped atmosphere in a frequency interval $[\nu, \nu + d\nu$ can be presented as

$$F(\nu)\nu = F^{\rm icl}(\nu)\nu + F^{\rm cl}(\nu)\nu + F^{\rm cl-icl}(\nu)\nu \,. \qquad (1)$$

Here the value of $F^{\rm icl}(\nu)$ is the part of the line flux formed by the homogeneous interclump medium only, $F^{\rm cl}(\nu)$ is the clumps contribution and $F^{\rm cl-icl}(\nu)$ refers to the contribution of the clump - interclump medium interactions to the line profile.

As it was shown by Kostenko & Kholtygin (1999) the contribution of the interclump medium into the total intensity of many lines in the hot star spectra (e.g. lines of ions CIII, HeI-II, etc.) is small. The interaction of clumps with the interclump medium give contribution mainly in the X-ray region and weakly impacts on the profiles of optical and UV lines considered. It means that the intensity of these lines are mainly determined by clumps.

Due to of the large velocity gradients in the winds the contributions of the separate clumps into the total line flux can be considered independently and a part of the total line flux formed by clumps

$$F^{\rm cl}(\nu) = \int_{(4\pi)} \int_{M_{min}}^{M_{max}} \int_{R_*}^{\infty} N_{cl}(M_{\rm cl}, R, \Omega) \times F_{\rm cl}(R,\nu)\, d\Omega\, dM_{\rm cl}\, dR \,. \qquad (2)$$

Here $M_{\rm min}$ and $M_{\rm max}$ are the minimal and maximal masses of clumps in the whole clump ensemble; a function $N_{\rm cl}(M_{\rm cl}, R, \Omega)$ describes a distribution of clumps on masses $M_{\rm cl}$, distances from the centre of a star R (R_* is a stellar radius) and directions Ω.

Studies of lpv for O and WR stars (Kaper et al. 1999, Lépine & Moffat 1999) specify that clumps are mainly formed in a narrow area of an atmosphere near the stellar core. It means that distribution of clumps on distances from the stellar core, masses and directions can be considered independently:

$$N_{\rm cl}(M_{\rm cl}, R_{\rm cl}, \Omega) = N_m(M_{\rm cl})\, N_r(R_{\rm cl}) N_\Omega(\Omega) \,. \qquad (3)$$

2.1 Modelling the clump ensemble

We present a distribution of clumps on masses in atmospheres of early-type stars as $N_m(M_{\rm cl}) \sim (M_{\rm cl})^{-\gamma}$ and adopt the values of $\gamma \approx 2.0$ (see arguments in a paper by Kudryashova & Kholtygin 2001).

For modelling the distribution $N_r(R_{\rm cl})$ we suppose that clumps are formed near the stellar core, the total clump number in the atmosphere is constant and their distribution on radius R is determined by a relation $R^2 N_r(R)(R)V_{\rm cl}(R) = const.$ For clump velocity $V_{\rm cl}(R)$ we adopt standard β-law. We use mainly the spherical-symmetric distribution $N_\Omega(\Omega)$ of directions of clumps.

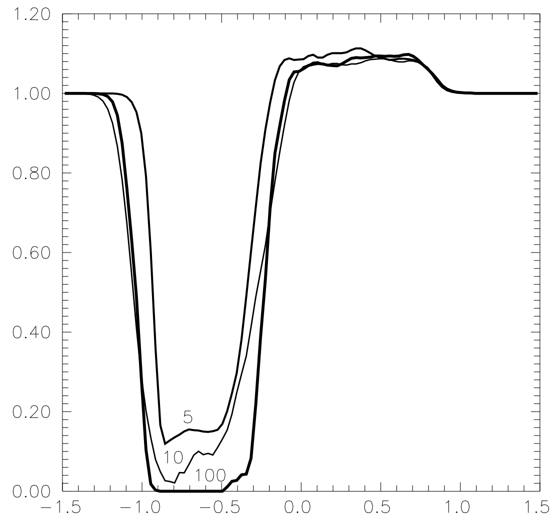

Figure 1: Mean line profile in the SCM in a dependence on a parameter $\tau_{\rm cl}^{\rm max}$.

We assume that each clump forms a detail of the line profile (subpeak) with gauss distribution of intensity. Dependencies of a total flux in the different lines formed by separate clump at the distance R to star were calculated by Kostenko & Kholtygin (1999). Follow Lépine (1994) we suppose that the full fluxes of subpeaks $F_i \propto \sigma_i^2$, where σ_i^2 is a velocity dispersion inside a clump with number i.

Follow Kudryashova & Kholtygin (2001) we suppose that mean clump *lifetime* is determined by a relation $T^{\rm cl} = T_{\rm cl}^{\rm max}\,(F_{\rm cl}^{\rm max}/F_{\rm cl})^\gamma$, where $T_{\rm cl}^{\rm max}$ is a *lifetime* of a clump with the maximal flux $F_{\rm cl}^{\rm max}$ and $\gamma \approx 1$ (see Lépine (1994 for details). We suppose that after its *lifetime* a clump can exists by does not emit in the considered line. It means that *lifetime* of clump depends of the line considered.

The resonance lines of the most of ions in the atmospheres of hot stars have the strong absorption components. Assume the next procedure taking into account the absorption in the violet wing of the line. Suppose that clumps which are located on a line of sight can absorb the radiation of the stellar photosphere and the total optical depth for absorption of the continuum radiation can be presented as a sum of all optical depths of the clumps on a line of sight. To calculate an optical depth $\tau_i(\nu)$ of a clump with a number i in the central frequency of the considered line we use the scaled relations $\tau_i(0) = \tau_{\rm cl}^{\rm max}(F_i/F_{\rm max})^{\mu_\tau}$, where $\tau_{\rm cl}^{\rm max}$ is an optical depth of a clump with a maximal line flux $F_{\rm max}$. From the calculations of the ionization structure of the hot stars (Kostenko & Kholtygin 1999) we can conclude that parameter $\mu_\tau \approx 2$.

2.2 Results of the line profile calculations

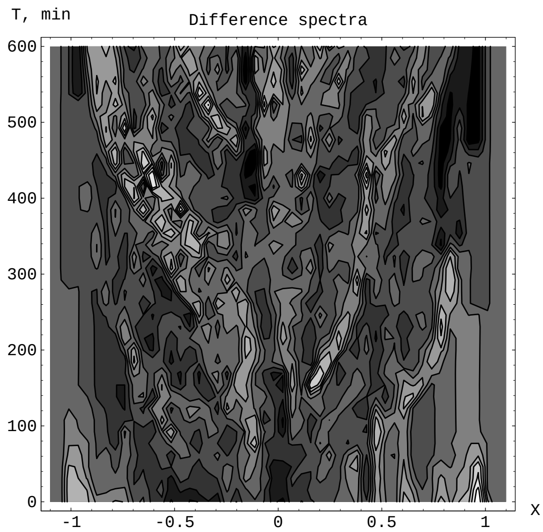

Figure 2: Dynamical spectra in the SCM for parameters $\sigma_{max} = 0.20$, $\varepsilon = 10^{-3}$ and $\tau_{cl}^{max} = 0$ and for 10^h of total time of "quasi-observations".

The relation (2) gives us the *instantaneous* line profile only, whereas the observed line profiles are the mean of all instantaneous profiles over the whole interval of the observations. For evaluating the *quasi-observed* line profile we average all *instantaneous* line profiles on the typical time of observations of one line profile – ΔT.

For obtaining the difference spectra we calculate the averaged *quasi-observed* line profiles over the whole period of observation $T_{\rm obs}$. The difference spectra are an individual quasi-observed profile minus this average profile.

For example we plot a dependence of mean line profile versus $T_{\rm cl}^{\rm max}$ in Fig. 1 for a resonance doublet CIV λ 1548,1550. For the sake of simplicity we use a dimensionless frequencies in a line $x = (\nu - \nu_{ik})/\Delta\nu_\infty$, where $\Delta\nu_\infty = \nu_{ik}(V_\infty/c)$ is a full width of a line, ν_{ik} is the central frequency of the line, and V_∞ is a wind terminal velocity.

Main parameters of the model are σ_{max}, ε and τ_{cl}^{max}, where σ_{max} is a velocity dispersion in a clump with a maximal flux, ε is a ratio of a minimal and a maximal fluxes of line formed by an ensemble of clumps. For an illustration we plot the typical dynamical spectra for line CIII λ 5696 for the typical parameters of a clump ensemble at a total duration $T^{\rm full} = 10^h$ of *quasi-observations*.

2.3 Using wavelets for testing clumps

For OB stars the clump contribution in the total line profile is not so significant as for WR ones. Because of this we need to use the more elaborate methods for testing a clump contribution in the line profile. The most convenient tool for solving such problem is a wavelet analysis. Kholtygin et al. (2006) described a procedure of construction the *dynamical wavelet spectra* for lines in spectra of OB stars. Those are the wavelet transform of the difference spectra for studied line in the velocity V space in a dependence of the time of observation t for the fixed scale S. For scales in an interval $S = 1 - 5$ km/s the dynamical wavelet spectra is determined by the noise contribution mainly, whereas for large scales $S > 25$ km/s mainly regular variations in the *dynamical wavelet spectra* can be detected (see Kholtygin et al. 2006) for details.

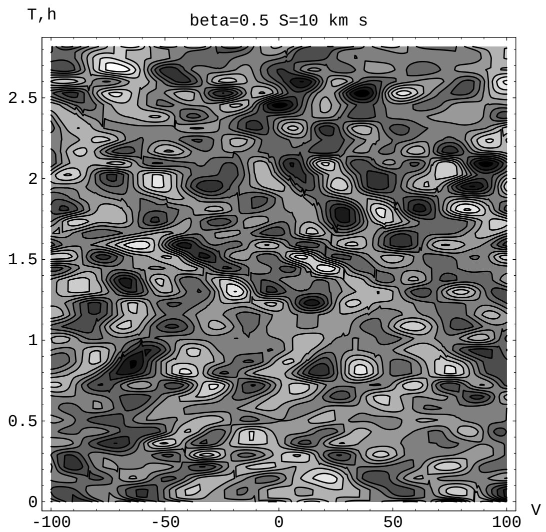

Figure 3: Dynamical wavelet spectra for the Hα line in the spectrum of δ Ori A

At the same time for intermediate scales ($S \in [5 - 25]$ km/s) the contribution of the stochastic lpv, connected with the clumps contribution can be seen. Figure 3 illustrate the stochastic variations in the dynamical wavelet spectra of line H_α in a spectra of a bright triple system δ Ori A (O9.5II) for scale $S = 10$ km/s with using the Mexican Hat as a Mother wavelet.

3 3-phase model of winds of early-type stars

Early-type stars are the powerful sources of X-Ray emission (e.g., Oskinova et al. 2006). For explanation both the UV optical an X-Ray spectra of these stars we postulate the *3-phase model* of winds. In this model we suppose that wind consist of 3 phase: homogeneous warm wind with a mean temperature $\approx 10^5\,K$, cold clumps with $T \approx 10^4\,K$ and hot clumps (hot zones with T up to 10^8 K. Warm wind and cold clumps emit in an optical and UV range, whereas a radiation of hot zones are mainly in a X-Ray region.

For WR stars clumps give the *main contribution* in the line emission, but for OB stars clumps give the smaller one. There exist a phase transitions between hot and cold phases. Cold clumps can be heated by shocks up to 10^8 K (Bychkov & Aleksandrova 2000), whereas hot zones cool very fast with cooling time is less than 1 min and convert to cold clumps. In a support of our model we can mention a connection between optical and X-Ray variability (see Oskinova et al. 2001 and reference therein).

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Moffat: In the time-series spectra of the few O stars that have been observed so far (e. g. ζ Pup, HD93129A), the sub-peaks seem to have similar velocity compared to those seen in WR stars. Is this compatible with your statement that clumps in O star winds have spatially smaller clumps compared to these in WR stars?

Kholtygin: As far as I remember, direct evidence for clumps in the atmosphere of an O star is only found for ζ Pup. But this star is untypical for O stars and the properties of its clump ensemble can be very different from that of other O stars. We have estimated the clump sizes for α Cam and found that these clumps are really smaller than in WR stars. For other O stars this conclusion must be checked.