Moving Inhomogeneous Envelopes of Stars

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Luminous hot massive stars drive strong stellar winds. New observations together with progress in model calculations reveal that these winds are highly inhomogeneous. Building on the foundations laid by V.V. Sobolev and his school, we are now developing new methods to analyze stellar spectra emerging from such winds. Among them are the new sophisticated 3D models of radiation transfer in inhomogeneous expanding media that elucidate the physics of stellar winds and improve empiric mass-loss rate diagnostics.

1 Empirical diagnostics of stellar winds using UV resonance lines

Strong ionizing radiation and stellar winds of massive stars with OB spectral types strongly influence the physical conditions in the interstellar medium and affect the formation of new generations of stars and planets.

Hot star winds are driven by their intense ultraviolet (UV) radiation [1]. Theory predicts that the winds remove the mass with a rate $\dot{M} \approx 10^{-7} - 10^{-5} M_\odot\,\mathrm{yr}^{-1}$ depending on the fundamental stellar parameters: T_eff, L_bol, and $\log g$ [2]. Hence, during the life time of a massive star (up to a few$\times 10^7$ yr), a significant fraction of its mass is removed by the wind. Thus, the mass-loss rate is a crucial factor of stellar evolution.

Empirical diagnostics of mass-loss rates largely rely on a spectroscopic analysis of resonance lines from abundant ions. When formed in a wind, these lines typically display P Cygni-type profiles. The resonance lines are produced by a photon scattering, hence the line strength and shape depend on the wind velocity and density. The latter obeys a continuity equation $\dot{M} = 4\pi v(r) r^2 \rho$. Therefore, by fitting a model line to the observed one, it is possible to estimate the wind velocity, density, and the mass-loss rate.

Line formation in a moving stellar envelope was studied by V.V. Sobolev [3]. It was shown that *if* the thermal motions in the atmosphere can be neglected compared to the macroscopic velocity, the radiative transfer problem can be significantly simplified [4]. This is now known as the *Sobolev approximation.*

Hot star winds are fast, with typical velocities of a few$\times$1000 km s^{-1}, justifying the use of Sobolev approximation for modeling their resonance lines [5, 6].

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Such models were used to estimate mass-loss rate already from the first available UV spectra of O-type stars [7, 8].

However, with time it became clear that the high turbulence in stellar winds limits the applicability of the Sobolev approximation. The error in the modeling arises mainly from the treatment of the formal integral and, to a lesser extent, from the approximated source function [9]. This is accounted for in the "Sobolev with Exact Integration" method (SEI), which treats the source function in Sobolev approximation, while finding exact integration for the transfer equation [10]. As a result, the model provides significantly better fit to the observed lines [11], and allows for more precise mass-loss rate determinations [12].

From the observational side, the problem with mass-loss determinations is that the strong resonance lines of the CNO elements are saturated in spectra of Galactic O-type stars. Therefore, these lines are not sensitive to the precise values of mass-loss rates. On the other hand, the resonance doublet of P V $\lambda\lambda 1117, 1128$ Å is never saturated because of a low phosphorus abundance ($\sim$1000 times less than the carbon one). Moreover, P V is a dominant ionization stage in O stars, hence its ionization fraction is nearly unity. This makes P V doublet very useful for the mass-loss rate measurements [13].

The Far Ultraviolet Spectroscopic Explorer (*FUSE*) measured spectra of P V for many O-type stars. The observed lines were weak, and the mass-loss rates derived from their modeling with the SEI method were found to be much smaller than expected [13]. It was concluded that either the true mass-loss rates are very small, or the traditional diagnostics of resonance lines are not suitable because of the strong stellar wind clumping.

2 Stellar wind clumping

There are clear evidences of stellar wind inhomogeneity. E.g., stochastic variability in the He II $\lambda 4686$ Å emission line in the spectrum of an O supergiant was explained by a clump propagating in its stellar wind [14]. The line-profile variability of Hα observed in a large sample of O-type supergiants was attributed to the presence of shell fragments in structured winds [15]. Using spectral diagnostics, it was shown that the winds of B supergiants are clumped [16]. The spectral lines of OB stars are variable on various time scales likely because of the wind clumping and structuring [17]. In high-mass X-ray binaries, accretion from the clumped stellar wind onto a neutron star powers strongly variable X-ray emission [18].

Stellar wind clumping is included in the modern non-LTE stellar atmosphere models [20, 21], using the usual approximation of *microclumping*, i.e. an assumption that all clumps in stellar wind are optically thin. Hence, the radiative transfer is significantly simplified in such models.

Assume that the density inside the clumps is enhanced by a factor D compared to a smooth model with the same mass-loss rate $\dot{M}$, while the interclump medium is void (i.e. the clump volume filling factor is $f_{\rm V} = D^{-1}$). Then, in the stellar atmosphere models, the rate equations have to be solved only for the clumps with the density $D\rho$ (instead of ρ as in the smooth wind case). In this case the mass-loss rates derived from fitting the lines that depend on the square of the density (such as, e.g., the recombination Hα line) will be by a factor $\sqrt{D}$ lower compared to the smooth wind models. On the other hand, mass-loss rates derived from the resonance lines (where both absorption and re-emission scales linearly grow with density) are not affected by microclumping.

3 Macroclumping

Albeit microclumping approximation is very convenient, it is too stringent for realistic stellar winds. Since optical depth in the UV resonance lines is high and the line photon mean free path is short, the wind clumps are likely to be optically thick at these wavelengths [19, 16]. To understand how such optically thick clumping ("macrocluming") affects the resonance line formation, it is useful to consider the Sobolev approximation. According to this approximation, only the matter close to the constant radial velocity surface contributes to the line optical depths. In a clumped wind, this surface will be porous (Fig. 1). Moreover,

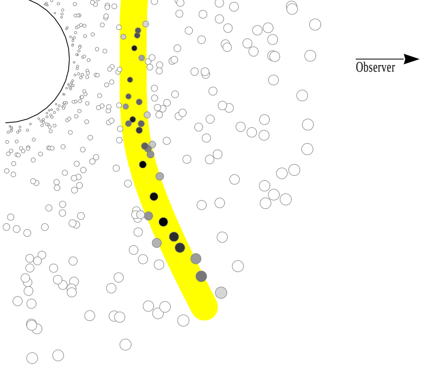

Figure 1: Sketch of a clumped stellar wind. In a smooth wind, rays of a given observer's frame frequency encounter line opacity only close to the "constant radial velocity surface" (thick shaded line). In a clumpy wind, assuming that the clumps move with the same velocity law as in the homogeneous wind, only those clumps interact with the ray that lie close to the corresponding constant radial velocity surface (dark-shaded circles). All other clumps are transparent (open circles) if the continuum opacity is small, so the wind is porous with respect to line absorption, even when the total volume is densely packed with clumps. Adopted from Oskinova et al. [19].

the opacity depends not only on geometrical matter distribution, but also on the Sobolev length $v_{\rm D}(dv/dr)^{-1}$, where $v_{\rm D}$ denotes the velocity dispersion within a clump. Correspondingly, the smaller the velocity dispersion within each clump, the narrower the constant radial velocity surface. Consequently, a smaller number of clumps can contribute to opacity, farther reducing it.

Adopting a statistical treatment of effective opacity $\kappa_{\rm eff}$, a correction factor for macroclumping that can be easily included in a sophisticated non-LTE codes was derived [19]. One can show that

$$\kappa_{\rm eff} = \kappa_{\rm f}\ \frac{1-e^{-\tau_{\rm C}}}{\tau_{\rm C}}\ \equiv\ \kappa_{\rm f}\ C_{\rm macro}. \tag{1}$$

The factor $C_{\rm macro}$ describes how macroclumping changes the opacity in the microclumping limit $\kappa_{\rm f}$. Note that for optically thin clumps ($\tau_C \ll 1$), the microclumping approximation ($\kappa_{\rm eff} \approx \kappa_{\rm f}$) is recovered. For optically thick clumps ($\tau_C \gtrsim 1$), however, the effective opacity is reduced by a factor $C_{\rm macro}$ compared to the microclumping approximation.

4 Radiative transfer using realistic 3D Monte-Carlo wind models

The statistical treatment of macroclumping provides only a first approximation for radiative transfer in clumped winds. For in-depth studies, the full 3D models of clumped winds are developed [22, 23]. In these models the density and velocity of the wind can be arbitrarily defined in a 3D space and can be non-monotonic. The photons are followed along their paths using the Monte Carlo approach. Allowing for an arbitrary optical depth, clumps can be optically thick in the cores of resonance lines, while they remain optically thin at all other frequencies. The model lines are calculated and compared to the observed ones.

Detailed study showed that strengths and shape of the resonance lines depend on the spatial distribution of clumping, density contrast, and velocity field [22]. Overall, these 3D models confirmed that macroclumping reduces effective opacity in the resonance lines, and rigorously proved that in realistic winds the P Cygni profiles of resonance lines are different from those in smooth and stationary 3D winds.

The models were compared with the observed spectra of five O-type stars to measure their mass-loss rates and other wind parameters [23]. This was done using a combination of the non-LTE Potsdam Wolf-Rayet (PoWR) stellar atmospheres (Fig. 2) and the Monte Carlo routine for the transfer of radiation in resonance lines. It was shown that the strength of model P V lines is reduced in realistic 3D models compared to the smooth wind models. Therefore, the observed lines could be fitted with high mass-loss rates similar to those theoretically expected (Fig. 3).

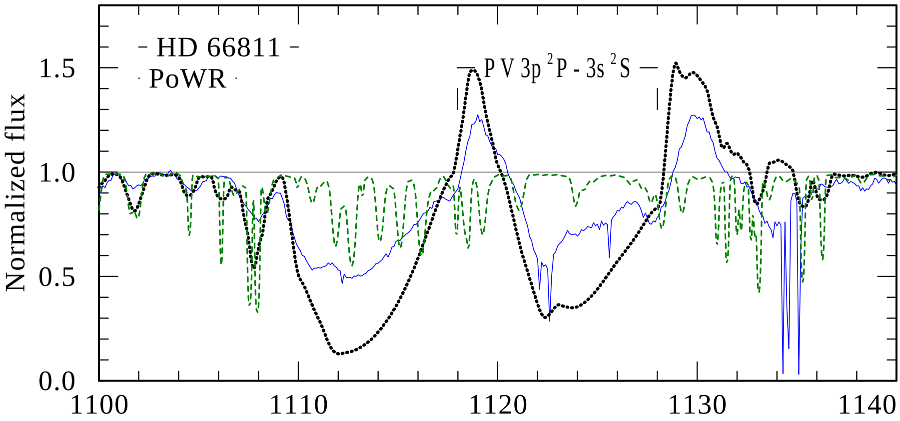

Figure 2: Comparison of observed and model spectra of P v in the O4I star HD 66811 (ζ Pup). Thin solid-blue lines is the observed spectrum. Dotted black line is the PoWR model spectrum adopting $\dot{M} = 2.5 \times 10^{-6}\,M_\odot\,\mathrm{yr}^{-1}$. The dashed-green lines are from the same model, but only accounting for the photospheric lines while wind contribution is suppressed.

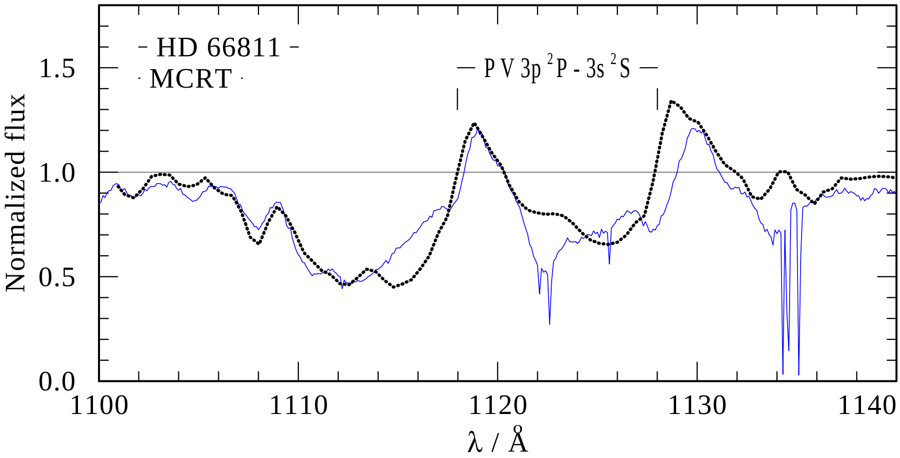

Figure 3: The same as in Fig. 2, but now the dotted black line is computed with the 3D Monte Carlo wind model, using the PoWR photospheric spectrum as input. The adopted mass-loss rate is $\dot{M} = 2.5 \times 10^{-6}\,M_\odot\,\mathrm{yr}^{-1}$. The line strength is significantly reduced compared to Fig. 2 despite the same adopted $\dot{M}$. See model details in Surlan et al. [23].

To summarize, the advances of macrocluming approach and 3D wind modeling improved empiric mass-loss rate diagnostics and showed that the mass-loss rates of OB supergiants are in good agreement with the theoretical predictions. Depending on the adopted clumping parameters, the observed spectra can be well reproduced with only a factor of 1–3 reduction compared to the predicted ones.

Thus, macroclumping is a new step in our quest for realistic descriptions of stellar wind, which would have been not possible without deep insights of V.V. Sobolev and his school into the physics of moving stellar envelopes.

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* The color figures are available online in the Proceedings at *http://www.astro.spbu.ru/sobolev100/*.