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MODELLING OF RESONANCE LINES IN INHOMOGENEOUS HOT STAR WINDS

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Abstract. The instability of wind radiative driving may cause the occurrence of wind shocks and spatial wind density and velocity structures. Observational evidence suggests that clumpy structures are a common property and a universal phenomenon of all massive, hot star winds. The structured stellar winds are essentially three-dimensional (3-D), and the full description requires the 3-D radiative transfer. Calculations using our own full 3-D Monte Carlo radiative transfer code for inhomogeneous expanding stellar winds are presented. We show how different model parameters influence resonance line formation. By modelling ultraviolet resonance lines, we demonstrate how wind inhomogeneities influence line profiles.

1. INTRODUCTION

In the course of past few decades, there has been growing evidence that the stellar winds are not smooth, as opposed to what has been assumed by most models of spherically symmetric line driven winds (see proceedings Hamann et al. 2008). Detailed theoretical studies showed that the line-driven winds are intrinsically unstable (Lucy & White 1980). Theoretical evidence of clumping is based on numerical simulations of radiatively line driven stellar winds. It is known that the instability of wind radiative driving may cause the occurrence of wind shocks and spatial wind density structures called clumps. Theoretical predictions are supported by direct observational evidence of clumping (e.g. Eversberg et al. 1998).

2. WIND MODEL

Our wind model (see Fig. 1) consists of a smooth region (i.e. without clumps) $r_{\rm min} < r < r_{\rm cl}$ (the inner wind radius is taken to be the stellar radius, $r_{\rm min} = R_*$) and a clumped region $r_{\rm cl} < r < r_{\rm max}$. The latter region has two components, namely the clumps and the inter-clump medium (ICM). The underlying wind velocity field is assumed to obey the β-law,

$$v_\beta(r) = v_\infty \left(1 - \frac{b}{r}\right)^\beta , \tag{1}$$

and the wind line opacity $\chi(r)$ is taken into account in a parametric way following Hamann (1980),

$$\chi(r) = \frac{\chi_0}{r^2 v_\beta(r)/v_D}\, q(r)\, \phi_x \tag{2}$$

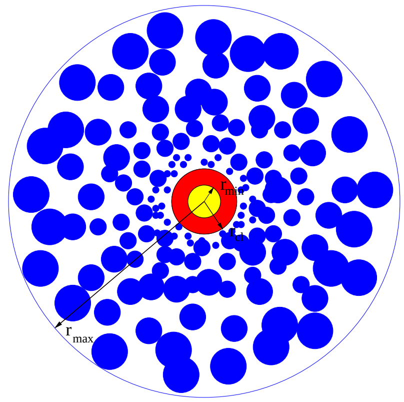

Figure 1: A schematic view on a wind model. The circle in a center represents the star, the annulus around it is a smooth wind region, and the circles around it represent clumps.

where $\phi_x = (1/\sqrt{\pi})\, e^{-x^2}$ is the Doppler line profile, χ_0 is the opacity parameter, x is the dimensionless frequency, and $q(r)$ is the ionization fraction, usually taken to be equal to 1 (constant ionization condition).

Our model can account for macroclumping, i.e. clumps in the wind can be optically thick. Optically thin clumps can be treated as well. This differs from usual treatment of clumping in NLTE wind codes, which can handle only optically thin clumps. Clumps are statistically distributed with average separation $L(r)$ and are assumed to be spherical with the radius $l(r)$. The density inside clumps $\rho_{\rm cl}(r) = D\,\rho_{\rm sw}(r)$, where $\rho_{\rm sw}(r)$ is the density of a smooth wind, and $D \geq 1$ is the clumping factor. Number density of clumps $n_{\rm cl} \propto \left(r^2 v_r\right)^{-1}$, which means that the average clump separation $L = n_{\rm cl}^{-1/3}$. Both clump distribution and clump radius are characterized by the clump separation parameter L_0,

$$L(r) = L_0 \sqrt[3]{r^2\,\frac{v_r}{v_\infty}}, \qquad l(r) = L_0 \sqrt[3]{\frac{3}{4\pi D}\, r^2\, \frac{v_r}{v_\infty}}. \tag{3}$$

The density of ICM, $\rho_{\rm ic} = d\rho_{\rm sw}$, where $0 \leq d < 1$ is the ICM density factor.

Using these free parameters (D, L_0, and d) we create a clump distribution. The distance of the i-th clump ($i = 1, \ldots, N_{\rm cl}$, $N_{\rm cl}$ is the total number of clumps) from the stellar center $r_i = (r_{\rm max} - r_{\rm cl})\xi_i + r_{\rm cl}$, where $0 < \xi_i \leq 1$ is a random number, which is chosen to obey the probability density distribution function $1/v_\beta(r)$. For the case of "vorosity" (inhomogeneities in the velocity field), velocity inside clumps is expressed as

$$v(r) = v_\beta(r) + v_{\rm dis}\,\frac{r - r_i^{\rm c}}{l_i}, \tag{4}$$

where $v_{\rm dis} = m\, v_\beta(r)$, $0 < m \leq 1$, and $r_i^{\rm c}$ is the position of the i-th clump's center.

We used several additional simplifying assumptions in our model. We assumed that radiation entering the wind at the lower boundary is free of lines and that there is no limb darkening. The lines are assumed to be pure scattering ones with a Doppler profile, and with complete redistribution.

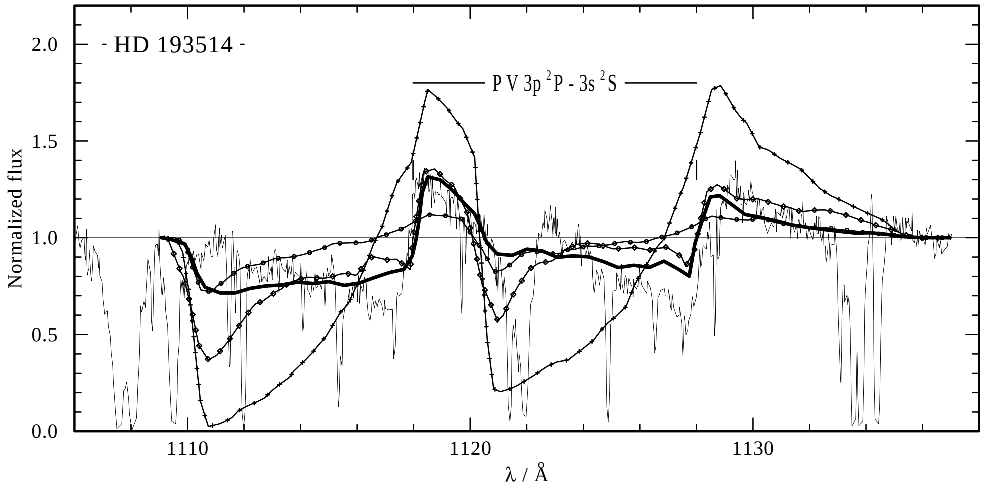

Figure 2: Comparison of line profiles calculated using different wind models with the observed spectrum of HD 193514 observed by `FUSE` (the thin full line). Models were calculated for $v_\infty = 2200\,\mathrm{km\,s^{-1}}$, $\chi_0 = 462.58$, and $v_D = 20\,\mathrm{km\,s^{-1}}$. The smooth (unclumped) wind model is shown by the full line with crosses. Clumped models are calculated for $L_0 = 0.5$. The full line with circles corresponds to the clumped wind model with the clumping factor $D = 10$, void ICM, and monotonic velocity. The full line with squares is the clumped wind with $D = 10$, non-void ICM ($d = 0.05$), and $v_{\mathrm{dis}}/v_\beta = 0.1$. The thick full line is the best fit with $D = 400$, $d = 0.05$ and $v_{\mathrm{dis}}/v_\beta = 0.1$.

3. MONTE CARLO RADIATIVE TRANSFER

The radiative transfer is solved using the Monte Carlo method by following the path of individual photon packets (hereafter photons). Each photon is sent from the surface of the star, both its frequency and initial direction are randomly determined. Then the optical path, which it is allowed to travel is determined also randomly. Then the photon starts its travel and the passed optical distance is accumulated by integrating the opacity along its path. Once the integrated optical path reaches the randomly preselected optical depth, it defines the place of interaction and scattering happens there. After scattering, new photon direction is randomly determined and the process is repeated. After the photon leaves the star, its frequency is stored into a predefined frequency bin and a new photon is sent from the surface. After all photons are sent, emergent flux is determined for all bins. Our method was described in detail in Šurlan (2012).

4. COMPARISON WITH OBSERVATION

Here we applied our code to fit the P V resonance doublet of HD 193514 observed by `FUSE` (thin line in Fig. 2). As the terminal velocity of HD 193514 we adopt $v_\infty = 2200\,\mathrm{km\,s^{-1}}$, and the value of $\beta = 0.7$. The synthetic spectra of the smooth and clumped wind models are calculated. The model parameters are chosen to fit the observed spectrum best. It can be seen that the predicted unclumped (smooth) P-Cygni profile (full line with crosses) of P V is much stronger than the observed one (thin full line). However, the synthetic spectrum for the clumped model with appropriate clumping parameters (thick full line) fits the strength of the observed line very well. Therefore, using the unclumped model can lead to underestimating the empirical mass-loss rates. These results are consistent with Oskinova et al. (2007), Sundqvist et al. (2010, 2011), and Šurlan et al. (2012a,b).

5. CONCLUSIONS

The influence of macroclumping on line profiles is striking. When macroclumping is taken into account line strength becomes significantly weaker. For a given clumping factor D, the key model parameter L_0 further affects the effective opacity and, consequently, the mass-loss rate $\dot{M}$. The line saturation is strongly affected by the inter-clump medium. Our 3-D model confirms that any mass-loss diagnostics which do not account for wind clumping must underestimate the actual mass-loss rate $\dot{M}$.

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