Clumping in Hot Star Winds
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Tracking the Clumping in OB Stars from UV to radio

F. Najarro[1], J. Puls[2], A. Herrero[3], M.M. Hanson[4], J. Martín-Pintado[1] & D.J. Hillier[5]
[1]*DAMIR, Instituto de Estructura de la Materia, CSIC, Serrano 121, 28006-Madrid, Spain*
[2]*Universitäts-Sternwarte München, Scheinerstr. 1, D-81679 München, Germany*
[3]*Instituto de Astrofísica de Canarias, E-38200 La Laguna, Tenerife, Spain*
[4]*Department of Physics, The University of Cincinnati, Cincinnati, OH 45221, USA*
[5]*Dep. of Physics and Astronomy, Univ. of Pittsburgh, 3941 O'Hara Street, Pittsburgh, PA 15260, USA*

We review different line and continua diagnostics from the UV to radio, which can be utilized to simultaneously constrain the clumping structure throughout the stellar wind of massive OB stars.

1 Introduction

Theoretically, the intrinsic instability of radiation driven winds predicts the formation of shocks and inhomogeneities (clumps) which have been continuously studied during the last twenty years (Owocki et al. (1988), Feldmeier et al. (1997), Runacres & Owocki (2002)). Observationally, clearest evidence of clumping has been provided by Eversberg et al. (1998), by means of moving structures in the He IIλ4686 wind line profile of ζPuppis. Finally, from the modelling point of view, clumping has been invoked in stellar winds to explain inconsistencies arising between ρ (density) and ρ^2 diagnostics. For a given mass-loss, clumping causes an enhancement of ρ^2 processes while leaving unaltered those which depend linearly on ρ. Further, if mass-loss rate and clumping are scaled without changing the $\dot{\mathrm{M}}/f^{0.5}$ ratio, the ρ-dependent diagnostics vary while the recombination lines profiles ($\propto \rho^2$) remain basically unaltered. Thus, models including clumping where developed by Abbott et al. (1981) and Puls et al. (1993) to study its effects on the IR and radio continua of OB stars as well on the resonance lines, while Hillier (1991) investigated in detail the effects on the electron scattering wings of emission lines of WR-stars. Since then, clumping has increasingly gained relevance in the hot-stars business deserving its own workshop (see this proceedings).

In this paper, we make use of observations from the UV to radio of OB stars and identify key diagnostics lines to obtain the clumping structure throughtout the stellar wind. We also give a couple of guidelines to constrain the degree of clumping in stellar winds for different stellar types.

2 Models and Observations

We have used CMFGEN, the iterative, non-LTE line blanketing method which solves the radiative transfer equation in the co-moving frame and in spherical geometry for the expanding atmospheres of early-type stars. We refer to Hillier & Miller (1998) and Hillier & Miller (1999) for a detailed discussion of the code. To test our models we have used a compilation of observations from the UV to radio of the O3If$^+$ star CyOB2#7. Below we concentrate on the clumping structure utilized in our models.

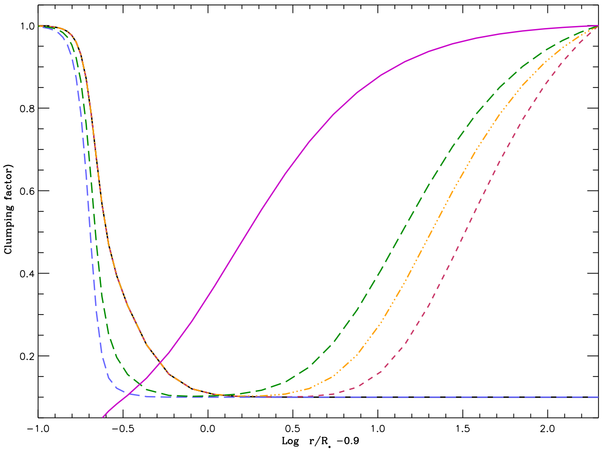

Figure 1: Radial structure of clumping factor for different values of CL$_2$ and CL$_3$ according to Eq. 1. The wind velocity structure (in units of V_∞) is also displayed to illustrate the onset of the clumping variations.

To investigate the clumping we introduce the following clumping law (see Fig. 1:

$$f = CL_1 + (1 - CL_1)e^{\frac{-V}{CL_2}} + (CL_4 - CL_1)e^{\frac{(V - V_\infty)}{CL_3}} \tag{1}$$

where CL$_1$ and CL$_4$ are volume filling factors and CL$_2$ and CL$_3$ are velocity terms defining locations

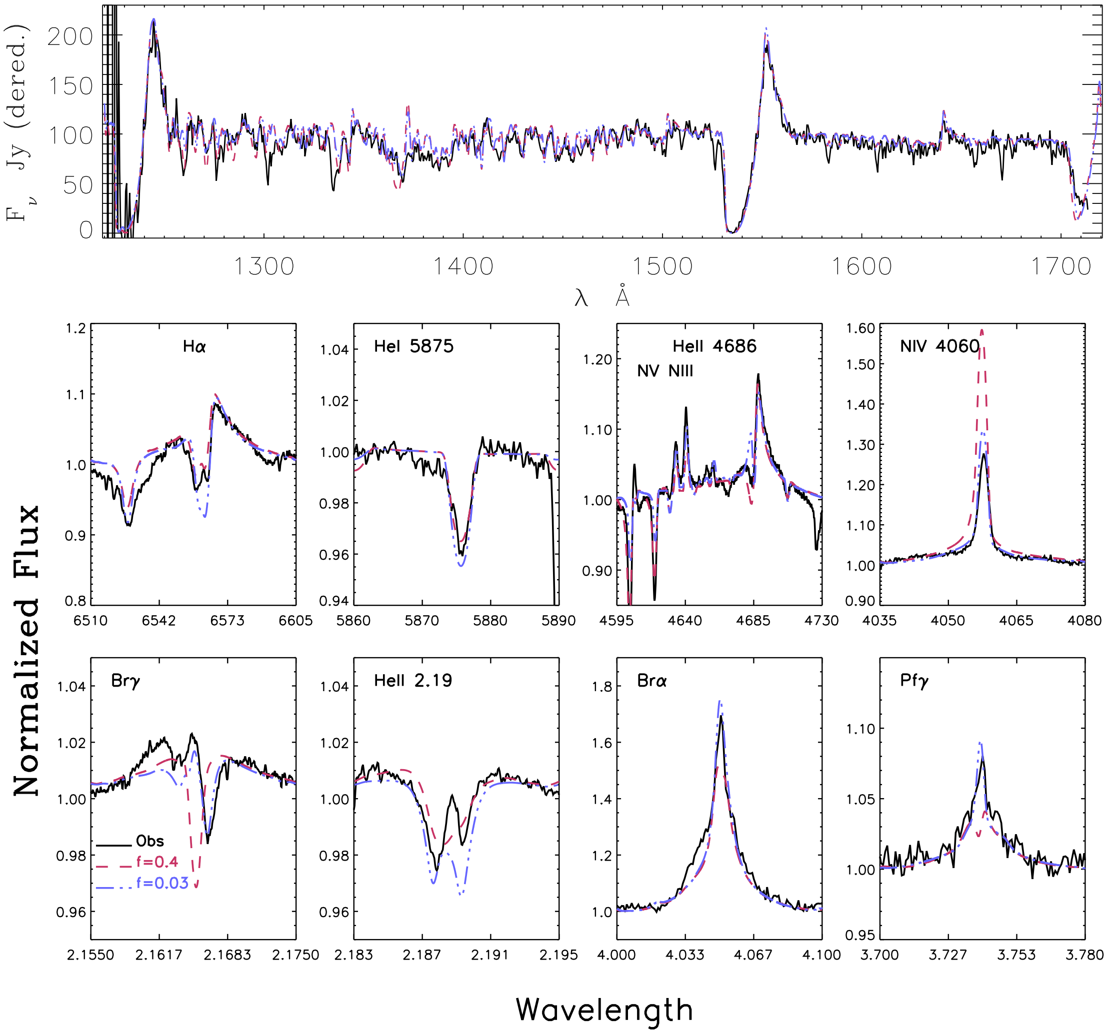

Figure 2: Model best fits to UV, optical and infrared profiles of CygOB2 #7, for two values of the main clumping value $f = \mathrm{CL}_1$.

in the stellar wind where the clumping structure changes. CL$_1$ sets the maximum degree of clumping reached in the stellar wind (provided CL$_4$ $>$ CL$_1$) while CL$_2$ determines the velocity of the onset of clumping. CL$_3$ and CL$_4$ control the clumping structure in the outer wind. This is illustrated in Fig. 1 which displays the behavior of clumping in the stellar wind for different values of CL2 and CL3. Overploted is also the velocity field in units of V_∞. From Eq.1 we note that as the wind velocity approaches V_∞, so that $(\mathrm{V}-V_\infty) \leq \mathrm{CL}_3$, clumping starts to migrate from CL$_1$ towards CL$_4$. If CL$_4$ is set to unity, the wind will be unclumped in the outermost region. Such behavior was already suggested by Nugis et al. (1998) and was utilized by Figer et al. (2002) and Najarro et al. (2004) for the analysis of the WNL stars in the Arches Cluster. Recently, Puls et al. (2006) also have found similar behavior from Hα and radio studies of OB stars with dense winds. Furthermore, our clumping parametrization seems to follow well the results from hydrodynamical calculations by Runacres & Owocki (2002). From Eq. 1 we note that if CL$_3$, and therefore CL$_4$, is not considered (CL$_3$ $\rightarrow 0$), we recover the law proposed by Hillier & Miller (1999). To avoid entering free parameters heaven we set CL$_4$ = 1 in all of our investigations, aiming to get an appropriate amount of leverage on the amount of non-constant clumping in the outer wind regions.

The general impact of clumping on line profiles that was described in the introduction of this paper will occur provided the ionization equilibrium is on the "safe" side. We consider the "safe" region to be where the population of the next ionization stage clearly dominates over the one the line belongs to (i.e., H II $\gg$ H I for the hydrogen lines). Noting, however, that ionization depends linearly on density whereas recombination is proportional to ρ^2, a "changing" ionization situation may occur, where two adjacent ionization stages have similar populations. In such a case clumping, which enhances recombination, will cause a net reduction of the mean ionization. This will result in weaker lines.

Finally, in the infrared, via bound-free and free-free processes ($\propto \rho^2$), not only the lines but also the continuum will depend on clumping, resulting in high sensitivity of the continuum-rectified line profiles to CL$_1$ and CL$_2$.

One may, therefore, distinguish between lines formed on the "safe" region and those arising from the "changing" region. Figure 2 shows that the N IV λ4058 and N V λ4600 lines in CygOB2 #7 are clearly formed on a "changing" region, as confirmed in our models, while the rest of optical lines are less affected by the large change on clumping and seem to follow the "safe" region behavior. On the other hand, Fig. 2 shows that, contrary to the optical, most of the infrared lines react strongly to changes on clumping. This is because, as discussed above, both line and continua are affected by clumping. Interestingly, our best current models for CygOB2 #7 (Najarro et al. in prep.), which favor a large clumping starting relatively close to the photosphere, provide *consistent* simultaneous fits to the UV, optical and IR observations of this object (see Fig. 2).

We note that while the optical and IR spectra of CygOB2 #7 provide strong constraints on CL$_1$ and CL$_2$, the UV spectra and submillimeter and radio observations constitute crucial diagnostics to determine CL$_1$ and CL$_3$. Indeed, our UV and submillimeter data (see Fig.3) support the presence of constant clumping, at least, up to mid-outer wind regions where the millimeter continua of CygOB2 #7 are formed. However, recent radio observations by Puls et al. (2006), which continua form at much larger radii, show that clumping may start to vanish at the outermost regions of the stellar wind. The expected emission of our models with constant clumping severely overestimate the upper limits provided by the observations by Puls et al. (2006) of CygOB2 #7. This demonstrates the need of multi-wavelength observations to constrain the run of the clumping structure.

Finally, we tentatively provide some diagnostic optical lines that, depending on the stellar type of the object, could be used to constrain the absolute degree of wind clumping. These are intimately related to the "changing" region situation presented in this paper. No strong UV lines are included as they may strongly be affected by X-rays. For early O supergiants, the N IV λ4058 and N V λ4600 lines. For late O supergiants the He II, N III and C III lines turn into important clumping diagnostic lines. Valuable clumping information may be obtained from cool LBVs for which the He I and Fe II] lines will arise from "changing" regions.

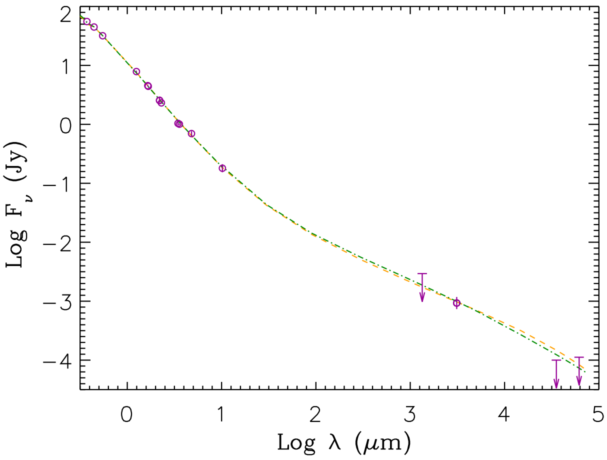

Figure 3: Potential of the submillimeter and radio observations to track the behavior of clumping in the outer wind (see text).

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Smith: If you are using IR/sub-mm/radio fluxes to derive the clumping at various radii, do you not need to worry about variability, if the observations are not obtained simultaneously? Rather, do you have a sense yet for how much variability there is in the sub-mm/radio?

Najarro: Of course variability plays an important role. The problem is that, appart from optical spectra which do show variability, we just have single measurements.

Hamann: You have shown an excess of emission at about 10 μm in the spectrum of Cyg OB2 no. 11. Can this be due to warm circumstellar dust? While hot stars usually do not show such dust emission in the mid-IR, we found unexpectedly warm dust around two WN stars in the dense environment of the Galaxy.

Najarro: The excess was consistent with bound-free and free-free emission. Unfortunately we are missing the wavelength gap $10\,\mu\mathrm{m} - 30\,\mu\mathrm{m}$, where we could see traces of warm circumstellar dust.