The effects of clumping on wind line variability

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We review the effects of clumping on the profiles of resonance doublets. By allowing the ratio of the doublet oscillator strenghts to be a free parameter, we demonstrate that doublet profiles contain more information than is normally utilized. In clumped (or porous) winds, this ratio can lies between unity and the ratio of the f-values, and can change as a function of velocity and time, depending on the fraction of the stellar disk that is covered by material moving at a particular velocity at a given moment. Using these insights, we present the results of SEI modeling of a sample of B supergiants, ζ Pup and a time series for a star whose terminal velocity is low enough to make the components of its Si $\mathrm{VI}\lambda\lambda1400$ independent. These results are interpreted within the framewrok of the Oskinova et al. (2007) model, and demonstrate how the doublet profiles can be used to extract infromation about wind structure.

1 Introduction

Clumping has been apparent from time series for many years (Kaper et al. 1999, Prinja et al. 2002). In this contribution we will first show how clumping affects doublet ratios and then use a time series to demonstrate the presence of clumping in winds.

2 Clumping

It is well known in the AGN community that doublet ratios are sensitive to clumping, with the ratio related to the covering factor of the clumped medium (e.g., Ganguly et al. 1999). For an extended source, the optical depth ratio determined from a doublet lies between the ratio of the blue and red f-values ($\alpha \equiv f_\mathrm{B}/f_\mathrm{R}$) and unity, depending on the covering factor of the source. Further, it is possible to interpret the observed doublet ratio within the framework of the Oskinova et al. (2007) model. In their model, the doublet components have an *observed* optical depth ratio of

$$\frac{\tau_\mathrm{rad}^\mathrm{B}}{\tau_\mathrm{rad}^\mathrm{R}} = \frac{\kappa_\mathrm{eff}^\mathrm{B}}{\kappa_\mathrm{eff}^\mathrm{R}} = \frac{1 - e^{-\tau_\mathrm{C}^\mathrm{B}}}{1 - e^{-\tau_\mathrm{C}^\mathrm{B}/\alpha}} \;, \tag{1}$$

which varies between 1 and α (see, massa:Massa, for a definition of τ_rad, and Oskinova et al. for definitions of the other symbols). Consequently, if we allow the ratio of f-values to be a free parameter,

$$\frac{\tau_\mathrm{rad}^\mathrm{B}}{\tau_\mathrm{rad}^\mathrm{R}} = \frac{f_\mathrm{B}'}{f_\mathrm{R}'} = \frac{\kappa_\mathrm{eff}^\mathrm{B}}{\kappa_\mathrm{eff}^\mathrm{R}} \;. \tag{2}$$

Thus, $f_\mathrm{B}'/f_\mathrm{R}'$ (determined by the fit) gives $\kappa_\mathrm{eff}^\mathrm{B}/\kappa_\mathrm{eff}^\mathrm{R}$ and, hence $\tau_\mathrm{C}^\mathrm{B}$. Oskinova et al. also relate the measured and smoothed opacities (or optical depths) and the clump optical depths as follows: $\kappa_\mathrm{eff}/\kappa_\mathrm{f} = (1 - e^{-\tau_\mathrm{C}})/\tau_\mathrm{C}$. Since $\dot{M}q$ (where $\dot{M}$ is the mass loss rate and q is the ionization fraction, see, e.g., Massa et al. 2003) should be derived from κ_f, the observed $\dot{M}q$ must be corrected as follows

$$\dot{M}q = (\dot{M}q)_\mathrm{obs} \left(\frac{\tau_\mathrm{C}}{1 - e^{-\tau_\mathrm{C}}} \right) \tag{3}$$

Fig. 1 shows how the "observed ratio" defines a point on the y-axis which gives $\tau_\mathrm{C}^\mathrm{B}$. $\tau_\mathrm{C}^\mathrm{B}$ then gives the ratio of the effective to actual opacity, $\kappa_\mathrm{eff}^\mathrm{B}/\kappa_\mathrm{f}^\mathrm{B}$. Note: *to obtain $\kappa_\mathrm{eff}^\mathrm{B} \ll \kappa_\mathrm{f}^\mathrm{B}$ and $\dot{M}$'s near expected values*, requires $\tau_\mathrm{C}^\mathrm{B} \gtrsim 5$, which implies $\kappa_\mathrm{eff}^\mathrm{B}/\kappa_\mathrm{eff}^\mathrm{R} \lesssim 1.1$.
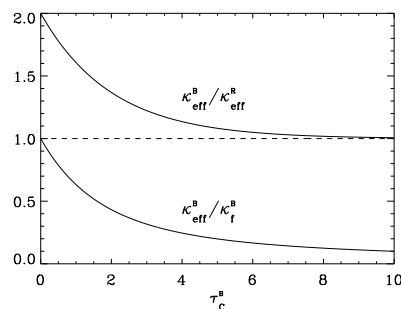
Figure 1: Ratio of effective opacities, $\kappa_\mathrm{eff}^\mathrm{B}/\kappa_\mathrm{eff}^\mathrm{R}$, (top) and effective to smooth opacities, $\kappa_\mathrm{eff}^\mathrm{B}/\kappa_\mathrm{f}^\mathrm{B}$, (bottom) versus clump optical depth, τ_C^B, for a doublet with $\alpha = 2$.
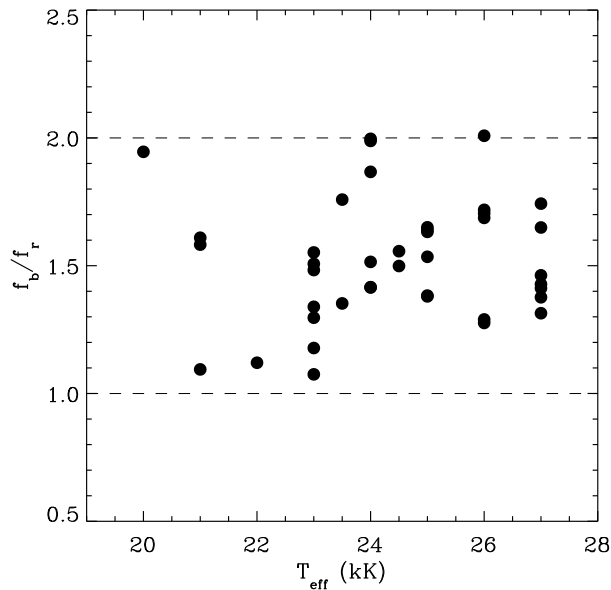
Figure 2: Derived ratios of oscillator strengths versus T_{eff} for Si IV $\lambda\lambda1400$ in B supergiants with wind lines $0.3 \leq \tau_{rad} \leq 5$ (weaker have inadequate optical depth information and stronger are too saturated).
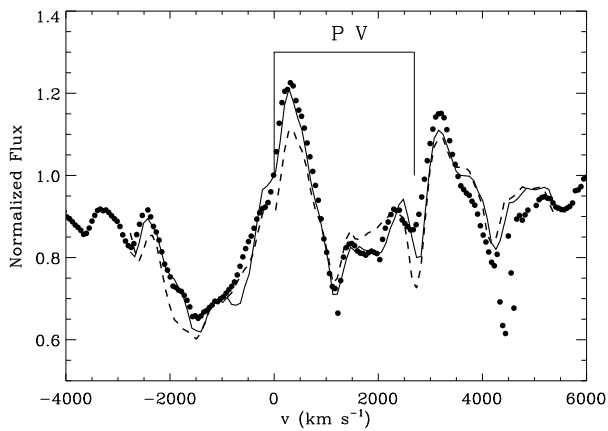

Figure 3: P V in ζ Pup. Points are data, dashed curve is SEI fit with fixed f-values, solid curve allowed the ratio of f-values to vary.

It must now be determined whether this additional information is present in the observed profiles. As a first test, we fit the Si IV$\lambda\lambda1400$ doublet in the sample of B supergiants given in Prinja et al. (2005) using a variable f-value. The results are shown in Figure 2. Notice that all of the f-value ratios lie between 1 and 2, as expected for a clumped wind.

As a second test, we fit *Copernicus* data of the

P V$\lambda\lambda1117,1128$ doublet in ζ Pup. Two least squares SEI (Lamers et al. 1987) fits are shown in Fig. 3. Both use a $T_{eff} = 40$kK, $\log g = 3.5$ TLUSTY model photosphere. The dashed fit uses the actual ratio of f-values, 2.02. The solid fit varied the ratio, giving a best fit value of 1.84. This 10% change clearly improves the fit, making the blue absorption weaker relative to the red. The fit gives $\tau_C^B \simeq 0.5$ and $\kappa_{eff}^B/\kappa_f^B \simeq 0.5$. Thus, the correction to $\dot{M}q$ is only 1.3, increasing ratio of P V to radio mass loss rates given by Fullerton et al. (2006) from 0.11 to 0.14 – *still far smaller than expected*, even if $q(P V) \sim 0.5$. Thus the mass loss rate in this case is truly smaller than expected.
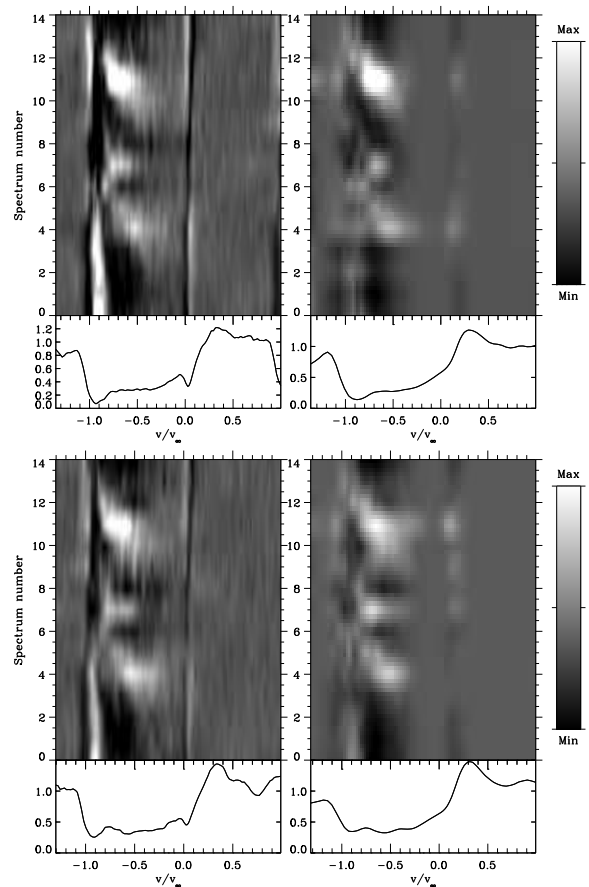

Figure 4: Dynamic spectra of the observed (left) and modeled (right) spectra of the blue (top) and red (bottom) components of Si IV$\lambda\lambda1400$ in HD 47240. The spectra are normalized by their means.

3 Clumping and time series

Time series for stars with $v_\infty \geq 2c\Delta\lambda/\lambda$, where $\Delta\lambda$ is the doublet separation, present a valuable test for the effects of clumping on wind lines. The B1 Ib,
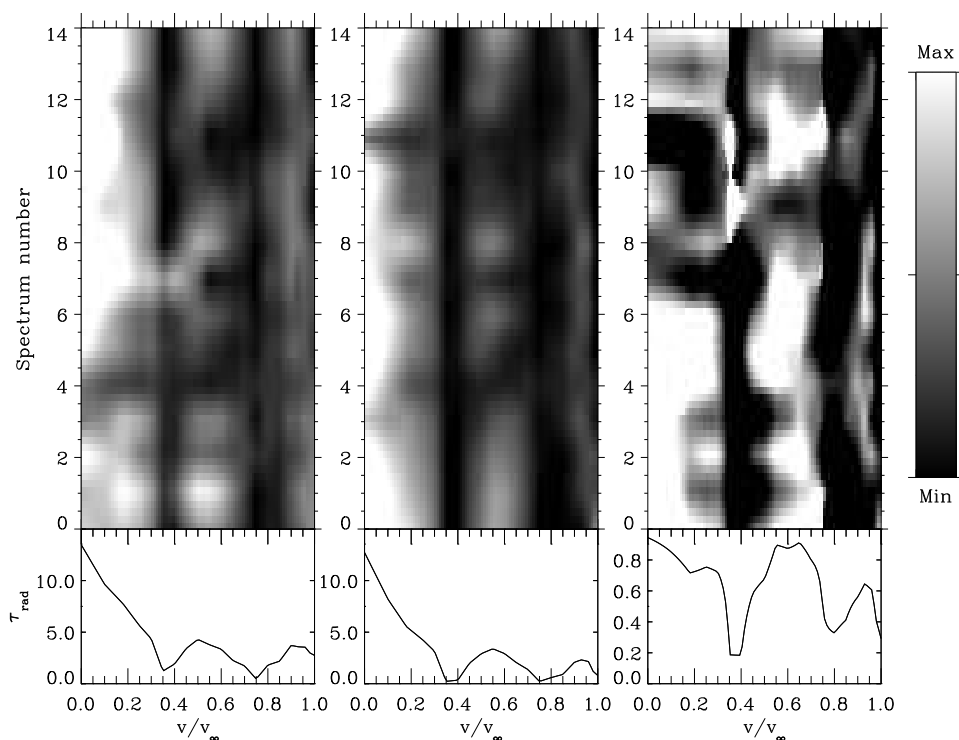
Figure 5: Dynamic spectra for $\tau_{\mathrm{rad}}^{\mathrm{B}}$ (left), $\tau_{\mathrm{rad}}^{\mathrm{R}}$ (middle) and $\tau_{\mathrm{rad}}^{\mathrm{R}}/\tau_{\mathrm{rad}}^{\mathrm{B}}$ (right) in HD 47240.

HD 47240, is such a star with $v_\infty = 980$ km s^{-1}. Consequently, each of its Si IV components are effectively independent. Thus, they were fit independently. The result is equivalent to allowing $f_{\mathrm{B}}/f_{\mathrm{R}}$ to be a function of velocity. The results are shown in Fig. 4, which shows the observed and modeled normalized dynamic spectra versus spectrum number for each component, and Fig. 5, which shows the unnormalized optical depths and their ratio. Several points are noteworthy. First, *both* components show similar, persistent velocity dependent structure. The fits of many B supergiants given by Prinja et al. (2005) had similar structure appearing in different ions in the same star. Thus, this structure may be real. Whether it results from density inhomogeneties or velocity plateaus, cannot be determined. Second, when τ_{rad} is greater than a few tenths and well-defined, the ratio of optical depths varies between 1 (clumped) and 0.5 (unclumped). Third, it appears that the ratio (clumping) decreases at velocities where the density decreases. Fourth, there seems to be a general decrease in the clumping at larger velocity, similar that seen in O stars by Puls et al. (2006).

4 Discussion

It has been demonstrated that resonance doublets contain more information than is usually exploited, that this information is related to clumping, and that it can be interpreted by the Oskinova et al. (2007) model. Our ultimate goal is to apply these techniques to a large number of stars with a range of stellar and wind parameters. This will allow us to examine how these relate to the empirically determined clumping parameters and provide clues to the physical agents responsible for wind clumping.

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Moffat: Why do you not see the small scale clumping directly via variable sub-peaks on the emission lines in the UV, as we see in the optical? Is it a question of signal-to-noise?

Massa: In a way, yes. In OB stars, we only see the wind in resonance lines. In which case, we can only see emission on the red part of the profile. As a consequence, any excess emission is seen against the average emission of a huge constant velocity surface. This makes it hard to detect sub-peaks compared to the absorption which is seen along a column to the stellar disk. Nevertheless, we do see faint, migrating emission features in a few cases like the MEGA data for HD 64760.

Moffat: 1. For your plot of mean radial optical depth that has two minima, is the radial optical depth essentially always low near the minima? 2. How does the assumption of spherical SEI affect your interpretation of the "banana" features?

Massa: 1. Yes, the radial optical depth is always low near the minima. 2. I am sure that SEI has some effect on the results but, unfortunately, there is currently nothing better. Nevertheless, it seems to produce reasonable results, so it cannot be mucking things up too badly. Furthermore, deJong et al. showed the presence of "bananas" by comparing dynamic spectra of the Si IV 1400 doublet at high velocity and the N IV 1718 excited state line at low velocity.

Oskinova: Thank you for showing us your very interesting results. Do your results imply that porosity effects are important also for clump optical depths less than one?

Massa: Thank you. Yes, they do make a detectable difference for small optical depths.