Clumping in Hot Star Winds
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Mid-IR observations of WC stars, and the connection to wind clumping

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We present preliminary results of a tailored atmosphere analysis of six Galactic WC stars using UV, optical, and mid-infrared Spitzer IRS data. With these data, we are able to sample regions from 10 to 10^3 stellar radii, thus to determine wind clumping in different parts of the wind. Ultimately, derived wind parameters will be used to accurately measure neon abundances, and to so test predicted nuclear-reaction rates.

1 Introduction

Classical Wolf-Rayet (WR) stars are almost bare, helium-burning cores of evolved, massive ($M_i \gtrsim 25 M_\odot$ with dense and fast, stellar winds. A star enters the WR phase as WN star, displaying CNO-processed material in its envelope (i.e. N and He). As the wind erodes the outer layers of the WN star, helium-burning products emerge in the wind, mainly carbon and, in more advanced stages, oxygen – the star is then classified as WC (or WO) star.

Theory of nuclear-reaction rates predicts that neon (Ne) abundances rise sharply when CNO-produced nitrogen is processed into Ne during helium burning (Maeder 1983). In fact, Ne becomes the fourth most abundant element after He, C, and O, and is exposed in the wind. Thus, the accurate determination of Ne abundances in WC stars becomes a powerful tool to test theoretical models.

In WC stars, Ne recombination lines are present in the ultraviolet (UV) and optical spectrum, which is formed at high densities (10^{11} to 10^{12} cm^{-3}) of the inner part (few stellar radii) of the wind. However, the Ne lines are weak and severely blended with broad lines of other elements, and thus practically unobservable. In the mid-infrared one has access to forbidden fine-structure lines, such as [NeII]$\lambda 12.8\mu$m and [NeIII]$\lambda 15.5\mu$m. These Ne emission lines are relatively strong and well-isolated, but they form only where the wind density has dropped below the critical density (10^5 to 10^6 cm^{-3}), at a few thousand stellar radii from the star.

From both theory and UV/optical observations it is well known that radiatively-driven winds are clumped, and that mass-loss rates, which are a vital quantity to derive Ne abundances, have to be modified by the related volume-filling factor f, such that $\dot{M}_{\rm clumped} = \dot{M}_{\rm smooth}/\sqrt{f}$. However, from hydrodynamical considerations it is expected that wind clumping decreases with distances from the star, and that the wind becomes smooth in the outer parts again (Runacres & Owocki 2002; see their Fig. 6). If this is true, then one cannot rely on f-values which have been obtained for the *inner* wind (e.g. from UV/optical diagnostics) to derive Ne abundances from emission lines which form in the *outer* wind.

2 Present project

We have embarked on a project to carry out tailored-atmosphere analysis of six Galactic WC stars in order to determine wind properties ranging from the inner (UV/optical) to the outer (mid-IR) parts of the wind. Our sample comprises WR4 (WC5), WR15 (WC7), WR23 (WC6), WR52 (WC4), WR135 (WC8), and WR144 (WC4), for which we have high-quality, flux-calibrated spectroscopy covering 0.4 to 1.1 (ground-based) and 5 to 35 μm (Spitzer IRS) spectroscopy; for some of the stars, IUE short/long HIRES and near-infrared data are also available.

Synthetic spectra are computed using the latest, 1D, line-blanketed CMFGEN model-atmosphere code (Hillier & Miller 1998) which assumes a spherically symmetric and stationary wind, and imposes a standard velocity law with $\beta = 1$. Clumping is treated as "shellular" (Hillier 1991). The following analytical prescription by Najarro (priv.comm.) is used to describe the radial dependence of the volume-filling factor f:

$$f(r) = f_{\max} + (1 - f_{\max}) \times \times \left[e^{-v(r)/v_1} + e^{-(v(r)-v_\infty)/v_2} \right]$$

A typical example for the run of the volume-filling factor is shown in Fig. 1, where the radius is expressed in terms of Rosseland opacity. The innermost wind (large opacities) starts smooth, but clumping quickly sets in at low wind velocities ($v_1 = 100$ kms^{-1}) to reach a predefined level (here: $f_{\max} =$

0.1) at 2 R_*. Two cases are shown, one with a constant clumping throughout the wind (black) and one where the wind increasingly becoming smooth again ($f = 0.6$ at 100 R_*, $v_2 = 100$ km s^{-1}; shown in red).

Most emission lines visible in the spectrum are recombination lines, hence their strength depends on ρ^2; on the other hand, the electron-scattering wing, which is mainly visible on the red flank of emission lines (cf. Hillier 1991), depends only on ρ. Thus, only a particular combination of $\dot{M}$ and f will reproduce correctly the strength and shape of the emission line. As an example, the C IV λ2530 lines in WR23 is shown in Fig. 2. Three models are computed using different volume-filling factors, but holding the effective mass-loss rate $\dot{M}_{\rm smooth}/\sqrt{f}$ constant, so that one can study the influence of clumping alone. The model with a volume-filling factor $f = 0.1$ clearly reproduces the line in an excellent way.

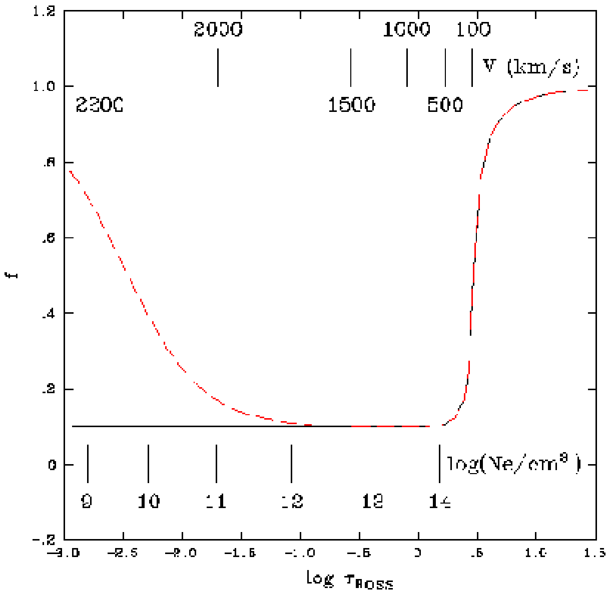

Figure 1: Parametrization of the volume-filling factor (i.e. inverse clumping factor), f, as a function of Rosseland optical depth (as measure of radius). This "clumping law" is used in the models.

Due to their ionized winds, massive stars display continuum free-free (i.e. *bremsstrahlung*) excess emission at longer wavelengths (infrared and beyond) whose strength depends on ρ^2. Radio fluxes therefore can be (and already have been) used to derive mass-loss rates of O and WR stars. However, such measures cannot provide information on wind clumping because radio observations are monochromatic; also the radio emission originates from the outer part of the wind (at thousands of R_*) that has already reached its terminal velocity. The mid-IR spectrum, in contrast, is formed only at few hundreds of R_*, where the wind is still accelerating, and because WR stars have such high mass-loss rates, their free-free excees is readily observable in the mid-IR.

In Fig. 3, we show the Spitzer data for WR23. The model with constant clumping ($f = 0.1$) throughout the wind is able to reproduce the continuum slope, whereas the model with decreasing clumping ($f = 0.6$ at 100 R_*) does not generate enough free-free emission. Note that both models reproduce the UV/optical emission spectrum equally well, as the inner-wind clumping factors are identical. Given that models have to successfully reproduce both the emission-line spectrum and the SED over a very large spectral range, resulting wind parameters and, by consequence, Ne abundances, are very reliable.

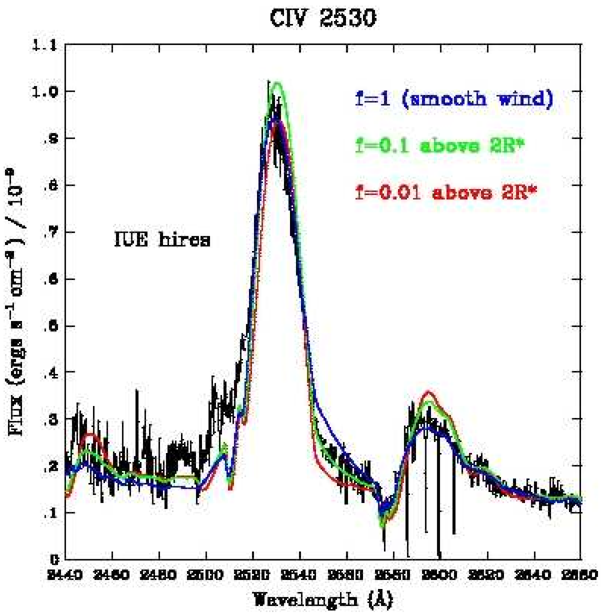

Figure 2: C IV λ2530 lines in WR23. Overplotted are model spectra with three different voluefilling factors: $f = 1$ (i.e. unclumped wind; blue), $f = 0.1$ (green), and $f = 0.01$ (red). Note the strong differences of the electron-scattering wing on the red flank of the emission line.

3 Preliminary results

Very preliminary results indicate that for all our sample stars, models with constant clumping (typically $f \sim 0.1$ above 2 R_*) throughout the entire wind are able to reproduce both the UV/optical and the mid-IR spectrum. However, models with identically clumped inner wind but with an increasingly smooth outer wind fail to generate enough free-free excess

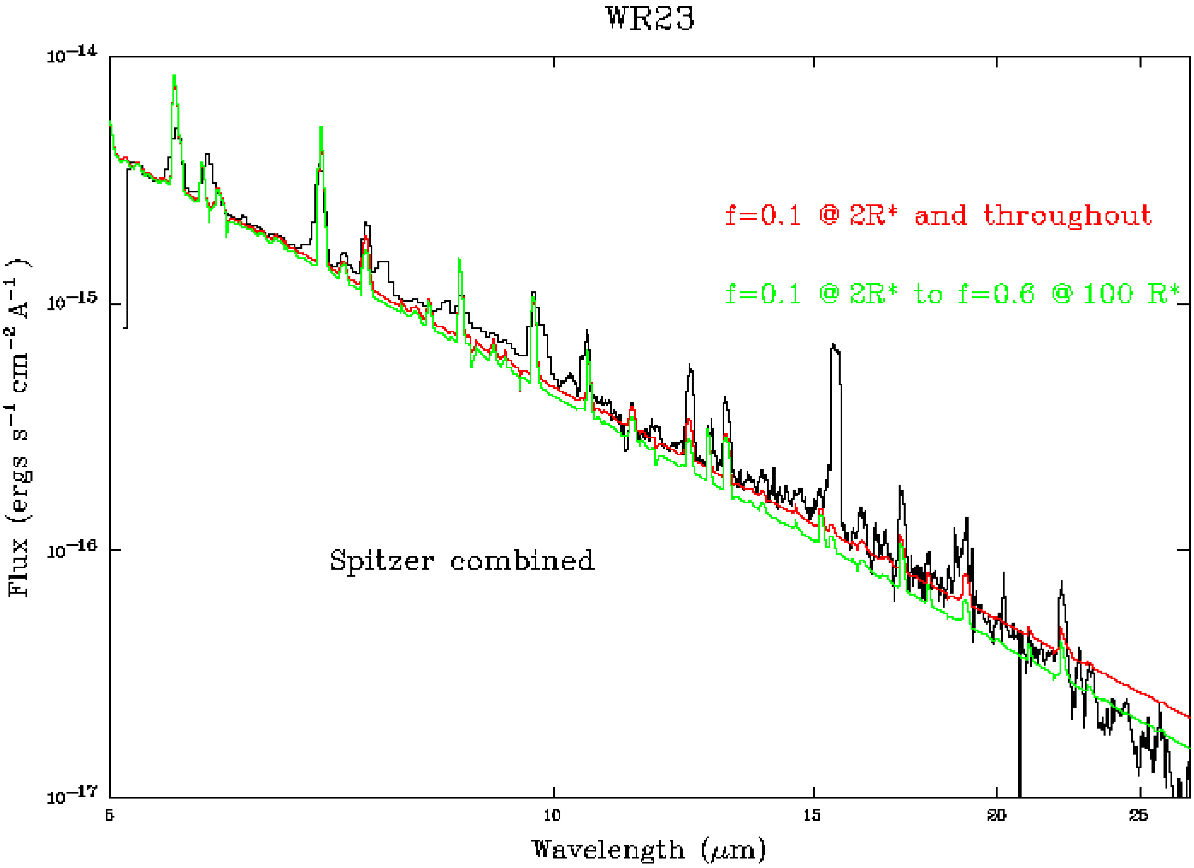

Figure 3: Spitzer data (5 to 35μm) of WR23. Overplotted are two model atmospheres, one with constant ($f = 0.1$ above 2 R_*; red) and one with a clumping that decreases outwards again (green). The constant-clumping model repreduces the observed continuum slope much better. Neon has not yet been included in the model, so that e.g. the strong [NeIII]λ15.5μm line is not reproduced.

in the mid-IR. Due to the broad spectral coverage of our mid-IR data and the rather pronounced effect clumping has on the mid-IR continuum, even slight changes in the clumping of the outer wind can be easily noticed. However, a more thorough analysis is required. Major points are the robustness of the clumping law in terms of the onset of the clumping roll-off, and its slope.

Provisionally using constant volume-filling factors throughout the wind and mass-loss rates, and Dessart et al.'s (2000) approach to derive Ne abundances, we find that the Ne fraction in our sample stars is $\sim$ 1% by mass. These results are in line with what is expected from model calculations of reaction rates and new solar abundances.

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Ignace: How do errors for the absolute flux calibration affect your slope fitting?

Schnurr: Certainly, the quality of the flux calibration is an issue that will have to be discussed, but while we are aware of it, we have not yet looked into it.

Barniske: Do you see signs of dust present in the mid-IR spectra?

Schnurr: Presently, we think that non of our program stars shows a dust excess (after all, we have chosen WC4 to WC8 types for this reason), but yes, we will have to be careful.

Oskinova: Did you study the shape of forbidden [Ne] emission lines?

Schnurr: So far, we have not even included neon into our model atmosphere, but in principle, [Ne] lines give some information about the velocity structure. These lines form in the outer wind and therefore should be flat-topped. Unfortunately, the Spitzer-irs spectral resolution does not allow for a more sophisticated analysis of the line profiles.

Najarro: Are the neon lines sensitive to the radial structure of clumping compared to the constant clumping models?

Schnurr: Yes, they are.