Clumping in Hot Star Winds
W.-R. Hamann, A. Feldmeier & L.M. Oskinova, eds.
Potsdam: Univ.-Verl., 2008
URN: http://nbn-resolving.de/urn:nbn:de:kobv:517-opus-13981

On the influence of clumping on O and Wolf-Rayet spectra

D. J. Hillier
University of Pittsburgh, USA

Overwhelming observational and theoretical evidence suggests that the winds of massive stars are highly clumped. We briefly discuss the influence of clumping on model diagnostics and the difficulties of allowing for the influence of clumping on model spectra. Because of its simplicity, and because of computational ease, most spectroscopic analyses incorporate clumping using the volume filling factor. The biases introduced by this approach are uncertain. To investigate alternative clumping models, and to help determine the validity of parameters derived using the volume filling factor method, we discuss results derived using an alternative model in which we assume that the wind is composed of optically thick shells.

1 Introduction

Evidence for clumping is widespread. It is evident in images of nebulae, it manifests itself through continuum, line and polarization variability (e.g., Lépine 1999, Eversberg et al. 1998), through the relative strength of electron scattering wings to their adjacent line (Hillier 1991), in the unusual strength of certain resonance lines (e.g., P V) and subordinate lines (e.g., O V 1371Å)(Crowther et al. 2002; Hillier 2003; Hillier et al. 2003; Bouret et al. 2003; Massa et al. 2003), and in the profiles of X-ray wind lines (e.g., Kramer et al. 2003). Theoretically, clumping is expected to occur in winds produced by radiation pressure acting on bound-bound transitions (Lucy & Solomon 1970; Owocki et al. 1988).

Clumping influences spectra formation in several ways. First, it enhances (relative to a smooth spherical wind) the strength of emission lines, such as recombination lines and collisionally excited lines, that depend on the square of the density. Consequently, clumping allows a given observed emission line spectrum to be reproduced using a lower mass-loss rate. As some features depend only linearly on the density (e.g., electron scattering wings, P V in some O stars) the relative strength of features can be changed in a way that cannot be achieved by any other reasonable mechanism. Second, clumping allows for the wind to be porous, enabling photons to escape more freely. This has been invoked to explain X-ray line profiles (e.g., Oskinova et al. 2006). Third, clumping potentially allows a wider range of ionization stages to be present in the wind (see, e.g., Hillier 2003).

The incorporation of clumping into radiative transfer calculations is extremely difficult. First, clumping requires 3D radiative transfer, which is computationally expensive. Homogenous 3D models are at least three orders of magnitude more expensive than similar 1D models, while clumping introduces even more computational requirements because of the need for finer spatial and angular grids. Second, the properties of clumps in stellar winds are poorly known (but see Dessart & Owocki 2002, 2003, 2005). In general, we need to specify the size, density, and velocity of clumps (locally and as a function of radius), their internal structure, the nature of the interclump medium, and the mechanical energy deposition rate. Third, clumping introduces additional complexities into the radiative transfer. As noted by Williams (1992), for example, individual clumps can be optically thick and hence have their own ionization structure. Further, clumps can shield other clumps from the radiation field, affecting the level populations and hence the observed spectrum. Fourth, clumped winds may be inherently non-spherical, especially if rotation and/or pulsations play an important role in producing clumping. Evidence for non-sphericity is provided by the presence of "Discrete Absorption Components" (DACs) in UV resonance profiles, and other UV variability. Finally we note that clumping introduces additional free parameters potentially exacerbating degeneracies. We note, for example, that a disk causes many of the same effects as clumping. As a consequence of the difficulties outlined above, and the extreme computational effort, approximate techniques are generally used to allow for the effects of clumping.

A computationally expedient technique for incorporating clumping is the use of the volume filling factor (f). It provides a method for treating clumping exactly under the assumption that the medium is made of small, uniform density, optically thin clumps which occupy a fractional volume "f". While in practice these conditions are unlikely to be met, it does provide an excellent fit to spectral features insensitive to clumping in both Wolf-Rayet (W-R) and

O stars while not destroying the fit to clumping sensitive features (e.g., Hα). Another advantage of the volume filling factor approach is that one only needs to specify a single parameter ($f(r)$) at each radius — in practice one allows f to vary smoothly with radius in which case a minimum of 2 parameters are needed (Hillier & Miller 1999). Other techniques for treating clumping, with different assumptions, are also being developed (e.g., Oskinova et al. 2007).

In W-R stars the volume filling factor approach provides a means to fit the electron scattering wings on emission lines, while simultaneously allowing the strength of most emission lines and continua to be fit (e.g., Hamann & Koesterke 1998; Hillier & Miller 1999). It is still difficult to get a simultaneous fit to both high and low ionization lines, and this may be a consequence of the simplicity of the volume filling factor approach. In O stars, the volume filling factor allows models to be developed which fit most diagnostics. In particular, it provides a means of matching the strength of the P V resonance lines, the O V 1371Å subordinate lines, and strong photospheric lines simultaneously with emission lines such as Hα (Hillier et al. 2003, Bouret et al. 2003)

2 Shell model

An alternative approach to incorporate clumping is to assume that the wind is composed of dense spherical shells. While this approach has its obvious limitations it has three important strengths. First, the non-LTE problem can be solved exactly in a situation where optical depth effects in the clumps are important. Second it allows the influence of clumps on spectra to be investigated using qualitatively different assumptions. Third, it provides test results for other techniques.

We have computed shell-like models for the O star AV83 (O7 Iaf) and a W-R WN5-like star (e.g., HD 50896). In the model the shells were assumed to be equally spaced in $\log r$ and the shell size/density was adjusted to give the required volume filling factor. An illustration of a sample density structure is shown in Figure 1.

For AV83 reasonable quality fits to the spectra were obtained — a quality similar to that obtained with the volume filling factor approach. Additional calculations are being undertaken, and a more rigorous comparison will be published elsewhere.

For the WN5 star the conclusions are dramatically different. The shell model provides a very poor fit to a WN5 spectrum. In particular optically thick emission lines are much weaker than in the volume filling factor approach, while the continuum fluxes, and optically-thin line fluxes, are very similar (Fig. 2). The changes show some similarities to that seen for the optically-thick clump model of Oskinova et al (2007). The weakening of the lines can be explained by optical depth effects in the clumps. For the continuum, the clumps are effectively thin and thus their strengths remain similar. Unfortunately the correct line strengths cannot be recovered by increasing the mass-loss rate, as this would increase the continuum fluxes, destroying the agreement with observation. The distinct behavior of lines and continuua in W-R stars provides a mechanism for investigating the presence of optially-thick clumps in winds. The present modeling (albeit limited) argues that the clumps in W-R stars are better treated as optically thin. In O stars, it might be possible to use IR through radio fluxes, in combination with line measurements, to make similar inferences although in such cases it is also necessary to allow for the variation of clump properties with location in the wind.

The ionization structure of the shell model, and the equivalent volume filling factor model, are qualitatively similar. Both models show, for example, that helium is doubly ionized in the inner wind, and singly ionized in the outer wind. However, in the shell model the ionization does not vary smoothly with radius — the low density regions exhibit a higher ionization than do the denser shells. While the He II departure coefficients show a global similarity to that seen for the volume filling factor model, the variation across the shells is complicated. In the inner region, for example, the shell model tends to have large departure coefficients due to the enhanced photon trapping in optically thick lines.

The shell models reveal some interesting computational aspects. First, the Sobolev approximation is no longer valid. This occurs because photon escape is affected by the finite size of the clumps — photons can escape from the clump surface much easier than from the center of the clump. If the lateral size of the clumps is comparable to their radial size (as suggested by the studies of Dessart & Owocki (2002, 2003, 2005) fragmenting the shells might potentially have a significant effect, since it would increase the surface area from which photons could escape. Second (and as noted by Hamann during the meeting), the shell model has velocity porosity (a term introduced by Owocki, this meeting) because the shells are located at distinct radii, and hence at distinct velocities. Since the shells are complete, there is limited "volume" porosity; there is some porosity due to the finite number of shells. Third, it is necessary to treat a large number of rays in order to fully resolve the radiation field. In the non-LTE calculation we used a fine spatial grid across the shells, and a much coarser grid for the inter-shell medium. This is probably an adequate approach as the moment equations are used to solve for the mean intensity; the angular dependance of the radiation field only enters through the Eddington factors, and the denser material generally dominates spectral formation. For the calculation of the formal spectrum we initially adopted the usual approach, and chose the impact parameters according to the radius grid. This approach is inadequate, and produced "spiked profiles", an effect

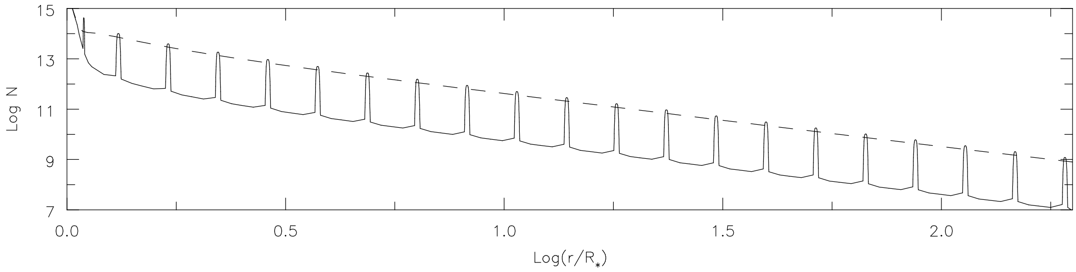

Figure 1: Illustration of the density (atoms/cm^3) structure of a WN5 shell model as a function of radius. Also shown (solid line) is the density of the model which uses the volume filling factor approach.

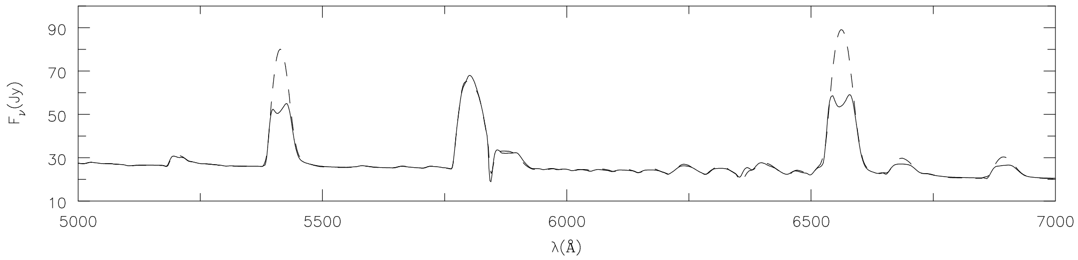

Figure 2: Spectral comparison between the WN5 shell model (solid) and volume filling factor model (dashed). The later model was scaled by a factor of 0.945 to facilitate line comparison. Notice that optically thick lines (e.g, He II 5411Å) are significantly reduced in intensity while other lines (e.g., C IV/He I complex at 5800 to 5900Å) are unchanged.

related to velocity porosity (along a given sight-line only some velocities are represented). To solve this problem additional rays, with impact parameters located in the inter-clump medium, had to be inserted.

3 Conclusion

The volume filling factor approach has proved a worthwhile tool, and has allowed simultaneous excellent fits to be obtained to multiple features, both clumping-sensitive and clumping-insensitive, in W-R and O stars. However the approach is simplistic, and its basis and adequacy needs to be tested via very detailed spectroscopic studies, through theoretical studies of clump generation, and through the use of alternative methods for treating clumping. For W-R stars, an alternative approach using optically thick shells appears to be less able to quantitatively match observed spectra.

DJH wishes to thank Stan Owocki for supplying a clumped model of Zeta Pup.

References

Bouret, J.-C., Lanz, T., Hillier, D. J., et al. 2003, ApJ, 595, 1182
Crowther, P. A., Hillier, D. J., Evans, C. J., et al. 2002, ApJ, 579, 774
Dessart, L., Owocki, S. P. 2002, A&A, 383, 1113
Dessart, L., Owocki, S. P. 2003, A&A, 406, L1
Dessart, L., Owocki, S. P. 2005, A&A, 437, 657
Eversberg, T., Lépine, S., Moffat, A. F. J. 1998, ApJ, 494, 799
Hamann, W.-R., Koesterke, L. 1998, A&A, 335, 1003
Hillier, D. J. 1991, A&A, 247, 455
Hillier, D. J., Miller, D. L. 1999, ApJ, 519, 354
Hillier, D. J., 2003, in *A Massive Star Odyssey: From Main Sequence to Supernova*, IAU Symp. 212, eds, K. van der Hucht, A. Herrero, C. Esteban, p .70
Hillier, D. J., Lanz, T., Heap, S. R., et al. 2003, ApJ, 588, 1039
Kramer, R. H., Cohen, D. H., Owocki, S. P. 2003, ApJ, 592, 532
Lépine, S., Moffat, A. F. J. 1999, ApJ, 514, 909
Lucy, L. B., Solomon, P. M. 1970, ApJ, 159, 879
Massa, D., Fullerton, A. W., Sonneborn, G., Hutchings, J. B. 2003, ApJ, 586, 996
Oskinova, L. M., Feldmeier, A., Hamann, W.-R. 2006, MNRAS, 372, 313
Oskinova, L. M., Hamann, W.-R., Feldmeier, A. 2007, A&A, 476, 1331
Owocki, S. P., Castor, J. I., & Rybicki, G. B. 1988, ApJ, 335, 914
Williams, R.E. 1992, ApJ, 392, 99

Najarro: Have you checked the parameterized shell model for ζ Pup in the UV? Would you see stronger effects in the optical in this star if the clumping would start at smaller radii?

Hillier: The current models have only been run for two cases, an AV83 like model, and a WN5 like model. Any effect on optical lines for ζ Pup will crucially depend on the exact mass loss rate, and where the clumping starts. As yet I have not had a chance to study the influence on lines in detail, and more test calculations need to be run.

Hamann: I agree that we are (almost) perfectly happy with the agreement between models and observations of WR spectra. Macroclumping can only spoil this happiness. However, for O stars we need to solve the P V discrepancy, that is why macroclumping is so interesting. Maybe WR clumps are smaller than O star clumps?

Hillier: Whether WR clumps are smaller than O star clumps remains to be seen, obviously one difference between O and WN5 stars is that the former contain H and the latter (generally) do not. As for the O stars I think it is important not to concentrate on P V and Hα only; there are other lines which also show sensitivity to lower mass loss rates and/or clumping. Furthermore, to understand the P V problem it is important to do detailed modelling in order to get the correct ionization structure. As I understand it to date, detailed modelling of O stars using the approximate volume filling factor approach has led to at most a factor of ten reduction (usually less, see Bouret's talk). Porosity may decrease this reduction by a factor of two, but it is clear that mass loss rates are lower than values derived from Hα.

Ignace: For lines from discrete spherical shells, some had a double-horned appearance. Are those the effect of escape from a thick shell dominating that line?

Hillier: The lines showing the horns are indeed optically thick. However the models are still rather preliminary, and there are some issues that I still need to resolve for computing accurate line profiles from these clumped media. It is also possible that the horns will disappear in models where the shells are broken up into detached pancakes.