Clumping in Hot Star Winds
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Discussion: Spectral modeling

Moderator: Alex Fullerton

Hirschi: What is the importance of the clump size?

Townsend: We do not see individual clumps in a wind, so the clump sizes must be under some threshold, but is otherwise unconstrained. Porosity can work independently of the clump size, the key parameter is the porosity length $h \equiv L^3/l^2$, where L is the interclump distance and l is the clump size.

Moffat: But one has a distribution of sizes according to some power law, so does your lack of sensivity to unique clump size at a given radius also apply?

Fullerton: Something else we should try to keep in mind is how structure on various spatial scales merges together. Basically, what mental picture should we have of these winds? What would they look like if we could get closer to them? Evidently many or most have large-scale structures or disturbances like CIRs or whatever causes DACs. But as we zoom in, they are also comprised of physically smaller inhomogeneities, which may or may not be optically thick depending on a variety of things, including what wavelength you use as a probe. How does all this structure manage to coexist?

Cohen: I think the optically thick absorption lines in clumps (optically thick clumps) provide means of getting at clump sizes. This is because of the requirement that clumps be optically thick. If a model reproduces the absorption lines, and assumes optically thick clumps, then the line opacity and density determine a minimum clump size.

Moffat: The $\dot{M}$ correction does not depend on size but rather densities, although both are coupled.

Najarro: What is the mass loss correction the "community agrees" upon, 1, 3 or 10?

Puls: So far, we have dealt mostly with the density stratification (micro-/macroclumping), but it is similarly important to consider the velocity field. Mostly, the velocity field inside the clumps is assumed to follow the standard law, while the hydrodynamic simulations show that the velocity field inside the clump changes considerably, becoming rather flat and multiply non-monotonic. This should have a considerable effect particularly for resonance lines, since the $\bar{J}$ depends crucially on the local escape, which is controlled by $\mathrm{d}v/\mathrm{d}r$.

Townsend: As reply to Puls' comment about incorporation of velocity fields in clumped models: this is already being done in the statistical models of Stan Owocki and Wolf-Rainer Hamann and also (just last week) in my Monte Carlo code.

Najarro: Would the ionization of P V not be frozen in the interclump medium?

Cassinelli: In a paper by Brown et al. (2004, A&A, 426, 323), we addressed the role of clumps in regards to the classic wind momentum problem for Wolf-Rayet stars. It was typically found that the wind momentum rate $\dot{M}v_\infty$ exceeded the radiation momentum rate L/c by factors of order 30. This was explained away in two parts. Theorists realized that more momentum by about a factor of five to ten could be extracted from the radiation field by way of multiple scatterings (Lucy & Abbott 1993, ApJ, 405, 738; Gayley et al. 1995, ApJ, 442, 296). Observers found that mass loss rates derived from radio free-free fluxes could have been overestimated by factors of $1/(\text{filling factor})^{1/2}$ owing to clumpiness of the winds. The filling factors are very small, in the range 10^{-4} to 10^{-3}. In Brown et al., it is shown that the two effects of multiple scattering and enhanced radio flux compete rather than complement each other. This is because clumpiness of the extent needed leads to very long photon mean free paths, and this increases the escape of the radiation and eliminates the possibility of multiple scattering and thus leaves the momentum problem unsolved.

Townsend: In answer to Joe Cassinelli's point about porosity/clumping reducing radiative driving in WR stars: this will only occur if there is a significant difference in optical depth between the clumps and the interclump medium. Only if you can create channels, by which photons can easily escape the medium, you will suffer a reduction in the radiative force.

Hamann: In principle, radiation driving is hampered by macroclumping: material which hides itself in optically thick clumps experiences no radiation pressure, as you (Joe Cassinelli) have pointed out in your paper Brown et al. However, optically thick lines do not contribute much to the radiative driving anyhow. A further effect predicted by strong macroclumping is a residual intensity in the absorption minima of P Cygni lines. Here I have a question to the instrument specialists. From the good old IUE times I remember that we could never trust the background subtraction. So what we did was just to take a long ruler and draw the zero-intensity level from *assuming* that the deepest absorption minima, e.g. of the C IV or the N V resonance lines, are completely black. Could a rest intensity of a few percent therefore have escaped from detection?

Massa: New IUE data reductions and STIS suggest that there cannot be more than $1-2\,\%$ of flux there.

Gull: In reference to STIS echelle spectra and black troughs, some caution must be applied. The STIS calibration had to address a wavelength-dependent point spread function. Ideally, totally black interstellar absorption lines were used where possible, but they are inconveniently spaced across the UV. Broad "black" wind absorptions were also used to extend those studies, which were done in the initial operational phase. While there is little or no evidence for errors in calibration, e.g. no negative fluxes beyond photon statistical level, the observer should consider a 1% level as the limit without further independent tests.

Sonneborn: Independent of the calibration and spectral extraction, the strong ISM lines (Ly α, C II, etc.) will be saturated (and black) for any star beyond ~ 100 pc from the sun. Use these lines to check on any low level residual flux in the stellar wind lines.

Prinja: I think it is very important to remember that substantial variability is seen in the UV resonance lines and Balmer lines of O stars, early B supergiants and late B stars. Their fluctuations over a smaller time scale (hours to days) are not due to the (small scale) clumping that is dominating our discussions. These characteristic changes are diagnostics of the substantial role of other (large scale) structures in the wind. Small scale clumps are not going to change the equivalent width of Hα in a B supergiant by a factor of $\sim$ seven over a day or so.

Moffat: It is time for observers to become more innovative. Some ideas come to mind: e.g. in eclipsing binaries perhaps one can constrain clump sizes during eclipses, or in massive X-ray binaries looking at X-ray flares.

Feldmeier: It is not just the clump size that matters, but also the clump shape. Since the outflow is strongly radial, spherical clumps, and therefore isotropic turbulence, may not be expected. Instead, the clumps should be rather "flat", and oriented perpendicular to the outflow direction. If the X-ray emission really originates from small, fast clumps crashing into big, slow clumps, then this clump shape (spherical vs. flat) has a large influence on the X-ray line shape.

Puls: It has to be stressed that multiple non-monotonic v-fields do create a black trough, but can modify the red emission part considerably with respect to its shape. I guess that the precise shape should depend on the distribution and shape of the clumps, and might be used as a diagnostic tool. Would it be possible to use interferometry to obtain information on the structure at least in the outer regions of not too thin winds (as was done earlier for P Cygni)?

Feldmeier: In our time-dependent hydrodynamic simulations, we have recently (2006, A&A) began to include this multiple scattering in non-monotonic velocity fields in the calculation of the radiative line force, using the source function iteration procedure of Rybicki & Hummer (1978, ApJ). At each of some 20,000 time steps of the simulation, the source function is calculated by standard lambda iteration (which converges quickly due to the small number of discrete coupling points) over the full spatial mesh.

Townsend: In answer to Alex Fullerton's question about "what is the key issue?" I would like to understand what the clumps actually look like. Are they pancakes? Spheres? The small scale structure seen in the 2D line-driven instability calculations by Stan Owocki and Luc Dessart? And to answer this question, we really need to get a handle on what causes the clumping.

Cohen: Can the line-driven instability make structures at arbitrarily small radii?

Feldmeier: It does not seem so. Even if you apply large photospheric perturbations, say Langevin turbulence with a velocity dispersion on the order of the sound speed, a pronounced wind structure develops only when the wind reaches about one third of the terminal speed. But there are also delicate issues about growth rates when applying the EISF force instead of the SSF force, so it is really difficult to know if there is pronounced structure close to the star.

Ignace: What does MOST tell us about hot stars? I am specifically thinking of producing structure in the deep wind.

Moffat: MOST has observed several WR and OB stars. The variation in OB stars (m-magnitude) comes mostly from non-radial pulsations due to p-mode and g-mode. In WR, a WN8 star is highly variable at the 10% level, which must be due to pulsations at multiple frequencies, not due to clumping, since the variation amplitude is large.

Massa: Doublets contain additional information that has not been tapped. I will be talking about that tomorrow. This will give a way to determine parameters for simple models that may help guide us to the next level.

Cassinelli: I see a problem in your assumption that the ion stage is P V inside the clumps, and which allows you to get the total column density of P V. If shock fronts at the face of the clumps are the sites for the formation of the X-rays, then the X-ray mean intensity inside the clumps can be very high, and in this case the dominant ionization stage can be changed owing to the Auger effect. In the case of elements with fewer than ten electrons, K shell absorption by the dominant ion leads to the ejection of two electrons, and for heavier elements, like Phosphorus, an even larger number of electrons can be ejected by the Auger process (Odegard & Cassinelli 1982, ApJ, 256, 568). The net effect would be that the mass loss rates might not be reduced by anywhere near as much as you have calculated under the assumption that P V is the dominant stage everywhere in the wind.

Hamann: With present interferometry facilities, there is no chance to resolve clumps in hot-star winds. Given the relatively large distance to the OB and WR stars, one would need a resolution of about 10^{-5} arcsec, while e.g. ESO-VLTI can resolve only milli-arcseconds.

Prinja: The impressive upgrades to radio facilities such as e-MERLIN and EVLA will provide greater sensivity that permits us to conduct deeper surveys of clumping as a function of stellar parameters ($T_{\rm eff}$, $v_{\rm rot}$, $\dot{M}$). A survey that includes not only O supergiants, but also (weak wind) O main-sequence and B giants is now going to be possible.

Massa: I would just like to add that as we detect stars with weaker winds we will be sampling deeper into the wind. This will make interpreting the observations more difficult, but also provide more information.

Owocki: It is perhaps important to distinguish between multi-D radiation hydrodynamic models for small vs. large-scale structure. The latter can be done using a generalized CAK/Sobolev approach for the line force, which is purely local and thus quite tractable in even a 3D model.But small-scale structure arising from the line-driven instability can have a size near and below the mean Sobolev length, making a Sobolev treatment useless. Instead, this requires a fuller *non-local* treatment of the time-dependent transport, using various approximations based on integral escape probabilities (such as the "Smooth Source Function" (SSF) or "Escape Integral Source Function" (EISF) methods). It is now relatively routine to carry out instability simulations in simple 1D models. But 2D or 3D models are still a real challenge, and have only been done in approximations that ignore the lateral components of the radiation force, e.g. the 2D hydrodynamic and 1D radiation models computed by Luc Dessart. My basic point is that there are still great challenges if we want to model such small-scale clumping in multi-D. But at least these initial efforts give some clues that we should pay attention to as we develop more phenomenological descriptions involving the clumping factor and porosity.

Cohen: Even at the national labs the full 3D radiative transfer is not being done. And they have quasi-infinite resources.