Clumping in Hot Star Winds
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Discussion: Spectroscopy and Mass-Loss Diagnostics

Moderator: Derck Massa

Cassinelli: Planetary nebulae central stars have fast and fairly high mass loss rates. These winds collide with the surrounding slower outflow. So there should be a very large X-ray flux from the PN. However, the X-rays from the interaction are down by a factor of 100 from theoretical predictions. A solution to this is to have the winds collide with a clumpy medium and in the interaction the clumps become dispersed and "mass-load" the wind, thereby making the "wind" slower and reducing the X-ray production ability. So this is one effect of clumps. Another is that such disposal of clumps could increase the density far out in the flow and this could be the cause of the extra radio flux that several speakers mentioned.

Gull: We have heard descriptions today of clumping, and observations of clumping events that occur on a time scale of hours and days. Microclumping, macroclumping, short- and long-lasting clumps. Just what is an appropriate definition of a clump?

Cohen: Porosity, which requires optically thick clumps, implies spatially large clumps, so Alex's "macroclumping".

Ignace: I was impressed by Tony Moffat's example of using $\dot{P}$ in a binary to get a quite secure $\dot{M}$. It seems important to calibrate our different perspectives and approaches to clumping against mass loss values that are robust and independent of micro/macroclumping and porosity. How hard would it be to increase this kind of sample? Are there more such robust methods?

Moffat: V444 Cyg is unique. There is no other system to get a dynamical $\dot{M}$ with such high precision.

Leutenegger: Porosity depends on wavelength: a wind may be porous at one wavelength and "effectively smooth" at another. Furthermore, continuum opacity is only affected by geometrical clumping, while line opacity depends also on the velocity dispersion within the clumps and the velocity distribution of the clumps.

Owocki: I think it is important to distinguish between large-scale structure that might be induced by some sort of surface features and so have a certain coherence like rotational modulation, and the small-scale stochastic clumping from turbulence. This issue of scale is also relevant for distinguishing between porosity and the traditional clumping volume filling factor f (defined as the root of the ratio of the square of the mean density divided by the mean of the density squared). The latter is the factor relevant for correcting the mass loss inferred from, e.g. density-squared diagnostics.

But porosity can effect even single-density diagnostics like bound-free absorption of X-rays.The key, however, is that individual clumps become optically thick, so that some material in the clump can effectively "hide" behind other material at the front of the clump, and so effectively reduce its overall effect in absorption. But for this you require a large "porosity length" h, defined by the ratio of the clump size to the volume filling factor. In fact, among other things, this porosity length can be thought of as the mean free path between optically thick clumps, and so to make a given medium effectively more transparent, it has to be bigger than the characteristic length scale of the medium. For a wind, that would typically be the local radius of the formation of whatever diagnostic you are looking at. Note, however, that it does *not* require that the individual clumps themselves be necessarily large, and for that reason I think a term like "macroclumping" is a bit misleading. But if the clumps are small, then they must also have a very small volume filling factor to make the medium porous.

Gull: Given the different definitions of clumps we hear, can we bound the clumping definition? As an example, in the large clump limit, do clumps seen in PNs or ejecta come from clumping or major ejection events?

Smith: I would like to switch gears a bit and ask about the space in between the clumps. I mean, we talk about these clumping factors as if we have blobs at some density separated by a vacuum. Of course the densest region will tend to dominate the emission because of ρ^2 effects, but if clumping factors are only $\sim$ 4 or 5, then I wonder if the interclump medium may contribute significantly to the total mass loss even if we cannot see it. Are there observational diagnostics of the interclump medium? How much does it matter?

Cohen: From Vela X-1 ASCA (Sako et al 1999), you see spectral signatures from both the clumped and interclump medium.

Owocki: Well, one point here is that a simple picture of a medium with clumps of just a single size separated by a completely empty medium is surely too simple. More likely the clumped structure contains a range of scales and compression factors, with perhaps also a floor level for the density even between the denser clumps. Such structure can be modeled phenomenologically using for example a "power-law porosity" approach, but ultimately one needs a dynamical model to predict the true nature of such structure.

Hamann: Sure, $\langle\rho^2\rangle/\langle\rho\rangle^2$ is a clear definition of the clumping density contrast. However, for the spectrum formation the actual distribution of density also matters, because high density enhances recombination. In the process of fitting WR spectra, we often encounter stars which show three subsequent ionization stages, e.g. N III, N IV and N V. With our models, it is sometimes impossible to produce all three stages with the observed line strength. I would attribute this to the scatter or stratification of densities in the clumps, which is neglected when assuming a fixed density contrast.

Cohen: Can we use the ISM as an analogy? The thermal pressure keeps clouds and intercloud medium separate. Maybe there is a magnetic field at cloud surfaces. If we could fly into an O star wind, what would the boundaries of clumps look like? Would they be sharp?

Smith: I think the clumps and cometary structures that you see in planetary nebulae like the Helix or the Ring Nebula are very different from the clumps in O star winds. Instead of forming directly out of an instability in the driven wind, they probably form as a result of the strong interaction of two winds, i.e. Rayleigh-Taylor-like instabilities as a hot fast wind overtakes a slow wind.

Gull: The ejecta around η Car show very well-defined clumps, bullets and diffuse structures. However, they all appear to have come from the same nitrogen-enriched source. Indeed the 513 km/s Homunculus contains molecules mixed at the same velocity. What feedback mechanism makes these single shells and otherwise clumps?

Sonneborn: The observed structure in supernova remnants is the result of Rayleigh-Taylor instabilities in the expanding SN ejecta (blast wave) with circumstellar and/or interstellar media. This is primarily a ballistic process, not a radiatively driven one as in O stars.

Smith: With respect to the velocity-dependent radiative driving leading to clumping in O stars, it may (or may not) be worth mentioning that we know from observations (like OH, H_2O and SiO masers) that cool supergiants have winds that are highly clumped, yet in those objects the driving force is not velocity-dependent (radiation pressure on dust). It may be interesting to consider if there is anything to be learned from (or applied to) those winds.

Vink: The central question is whether the mass loss rates are down and by what factor. But before we "vote" on this, we should probably first define what we compare it to: the ρ^2 diagnostics (Hα and radio) or the smooth radiation-driven wind models, as these two values are discrepant by a factor of two (with the theory underpredicting the unclumped ρ^2 data).

Runacres: Even though the radiative acceleration is negligible beyond $30\,R_*$, the wind can remain clumped out to very large distances ($\gtrsim 1000\,R_*$). The main reason is that the clumps have different speeds and therefore collide. The collision produces a dense clump and enhances the clumping factor. This partly counteracts the pressure-expansion of the clumps.

Feldmeier: One should also keep in mind that the extent of clumping may depend on the photospheric seed perturbations for the line-driven instability. Since the line-drag effect of Lucy causes the flow to be marginally stable directly above the photosphere, stochastic perturbations with quite a substantial velocity dispersion of, say, one third of the sound speed are required in the photosphere, in order to produce cloud-cloud collisions in the wind that can account for the observed X-ray emission, and that can counteract the pressure expansion at large radii, as Marc (Runacres) just noted.

Moffat: We should not be loath to make analogies of clumping in winds with the ISM, where we resolve the matter and can describe its nature. In winds you do have the inconvenience of having to deal with spherical geometry, but in Moffat & Robert (1994) we calculated the filling factor for a hypothetical wind with similar scaling laws as in the ISM. We found f values giving $\dot{M}$ corrections of $3-4$ for very reasonable ratios of the largest and smallest scales.

Feldmeier: We must clearly distinguish between micro- and macroturbulence, i.e. whether the photon mean free path is longer or shorter than the length-scale of the clumps.