Clumping in Hot Star Winds
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Potsdam: Univ.-Verl., 2008
URN: http://nbn-resolving.de/urn:nbn:de:kobv:517-opus-13981

Discussion: Hydrodynamic modeling

Moderator: Jorick Vink

Hirschi: From the stellar evolution point of view, a mass loss reduction of three is possible, but ten would imply many critically rotating stars and a low WR/O ratio, and models would not fit observations as well.

Townsend: In answer to Jorik's question (are diagnostics indicating clumping very close to the star incompatible with the result that the line-driven instability does not kick in until a little bit away from the star?) – there are of course photospheric processes that could seed the instability at the wind base. I do not know, however, whether the Lucy drag effect would quench any perturbations introduced at the base.

Hamann: I want to ask those of you who are calculating the hydrodynamic models to consider critically your inherent approximations and assumptions: which of your predictions are robust against the approximations, and which might be actually artifacts? I must say that I am still not fully convinced that Abbott waves are real, and not only an artifact of the Sobolev approximation. My opinion very much depends on the day of the week. On Monday I am skeptical, but till Friday Achim (Feldmeier) has convinced me of their existence. Over the weekend I recover, and next Monday I am doubtful again. For example, is the radiation transfer treated sufficiently correct in the time-dependent hydrodynamic simulations? When the wind encounters a shock, the velocity makes a huge jump downwards. Hence, for optically thick lines the opacity is shifted back into its own shadow, and will hardly intercept any pressure from the stellar radiation. Are such effects properly taken into account in the time-dependent wind models?

Feldmeier: Most of the material in the shock jump is highly rarefied and not optically thick. What is really relevant for these issues of non-monotonic velocity laws, of multiple resonances, and of self-shadowing is the material in the dense shells. The velocity coverage of these shells is, as Stan pointed out in his venetian-blind model for velocity porosity, at most 10%, and clearly not 100%. Furthermore, the effect of multiple resonances on the optical depth is actually included in the simulations. And we have recently started to also include the effect of multiple resonances on the source function, using the iteration method developed by Rybicki & Hummer (1978).

Townsend: To add to what Joe said: 1. Massive stars do have convection zones below the surface, as any stellar structure model made since the early 1990s will show. Around 200,000 K, where the iron opacity bump is located, the blocking effect of the opacity leads to the onset of convection. 2. Even without convection, there are processes, such as the Tayler-Spruit dynamo mechanism, that can generate magnetic fields in radiative envelopes.

Pollock: It is certain that there are magnetic fields in some WR binary systems, those that are non-thermal radio sources. It remains to be seen if the fields are in some way connected to the stellar surfaces or whether the colliding plasmas make up their own fields in order to satisfy the boundary conditions.

Moffat: In the case of magnetic fields in WR stars, we still only have few real empirical constraints from Zeeman data. Nicole (St-Louis), a PhD student and myself have only found modest upper limits to B of 20-40 G in two stars looked at so far (EZ CMa and γ Vel). We still cannot exclude much higher fields at the hydrostatic core ($\sim 10^{3-4}$ G) if they scale as a global dipole. So, we cannot a priori exclude magnetic driving of WR winds.

Feldmeier: I would like to ask Stan whether Alfvén waves could propagate outward through the wind and lead to a large magnetic pressure at large radii, so that the magnetic field would actually have a strong influence at large distances from the star, like e.g. in the afterburner effect in the solar wind.

Owocki: In principle, yes. But as transverse waves, Alfvén waves along a more or less radially oriented magnetic field line would be expected to be strongly damped by the lateral line-drag effect in a radiatively driven flow. But to be honest, there has not been any very extensive modeling or detailed analysis published on the potential role of Alfvén waves in a line-driven wind, so I guess the mechanisms you mentioned might still be relevant. But I would note that the non-radial divergence of field lines in MHD simulations, e.g. by Asif ud-Doula, do show a clear effect in increasing the wind speed in regions of open field in a line-driven wind.

Townsend: One remark – perhaps the final one – about magnetic fields. Jirí Krtička made a good point earlier today, that if you play around with a wind below the critical point, you can change the overall mass loss rate. So, even small-scale, high-order fields that do not really extend into the wind, and have no detectable signature, can lead to a very inhomogeneous mass loss across the stellar surface. This could serve as seed for the line-driven instability to amplify into clumping.

Owocki: If the pulsations are relatively low-order in l and m, then in principle one can model their effects on a stellar wind using the multi-D CAK/Sobolev hydrodynamic approach, ignoring the small-scale instability. I think this should be one focus for future research.

Kellermann: Is there an influence of the rotation (uniformly versus differential rotation) on the pulsation of the star? There are some influences on the oscillation in neutron star models.

Townsend: In massive stars, neither p modes nor g modes probe the convective core, they are both reflected, due to the variation in the Lamb and Brunt-Väisälä frequencies. There is some evidence claimed in one β Cep star of differential rotation, revealed by p mode frequency splitting, but the evidence is rather marginal.

Owocki: Regarding critical points, these in my opinion are really a somewhat artificial consequence of assuming a steady-state solution. A time-dependent model has no such critical points, but nonetheless a time-dependent simulation will generally relax quite quickly to something quite close the steady, critical solution derived by a CAK analysis. In such CAK models, the sonic point represents the transition between the nearly hydrostatic atmosphere where gas pressure balances gravity, and the wind where the radiative force is able to overcome gravity and accelerate a net outflow. The CAK critical point is where it is the most difficult for the line-driving to sustain the mass flux. But since at the sonic point the flow inertia is effectively canceled by the gas pressure term, the line force there can drive an arbitrarily large mass flux simply through an increased velocity gradient. The CAK critical point thus occurs *above* the sonic point, when gas pressure becomes negligible and the line force must balance both the gravity and wind inertial acceleration.

Feldmeier: To emphasize Stan's answer: the critical point lies very close to the star not because it coincides with the sonic point, but because photons are predominantly lateral close to the star, and therefore cannot carry $\dot{M}$ away from the star in radial direction. The critical point has his name for good reasons: it is the point where the radiation field has the hardest time to lift the wind mass against stellar gravity. This is in complete analogy with the Laval nozzle, where the critical point coincides with the location of minimum nozzle area, i.e. with the nozzle constriction. The critical point in an O star wind has to do with the radiative force, and hence the flow becomes super-Abbottic there, not supersonic.

Moffat: One should look at the ISM, even if detailed conditions are different (e.g. no radial fall-off of driving).

Massa: The evidence for clumping starting near the stellar surface comes from O stars. Could it be that clumping does not begin close to the surface in WRs but it does in O stars?

seems to be surprisingly similar between different object classes. For WN stars, we (Liermann & Hamann, these proceedings) found that clumping in the line-forming region is about three times stronger than in the radio region – i.e. similar in tendency but less pronounced than what Puls et al. (2006) obtained for O-type supergiants. Moreover, all studies show evidence that clumping is already strong at velocities of the order of the sound speed. These properties are puzzling and not quantitatively explained by the hydrodynamic models of the line-driven instability.

Gräfener: In our optically thick wind models it happens that the dependence on ρ and T dominates over the CAK-α effect. Close to the Fe-opacity peaks, the radiative force increases due to the outward decrease of ρ and T and *not* due to the α-effect. In such a case the sonic point becomes the critical point. Other effects that strongly deviate from the CAK asssumptions are extreme line-overlaps due to a pronounced ionization structure and an "active" line transfer. In extreme cases (e.g. outwardly increasing line source functions) the latter can even cause negative fluxes in the line core. So, as far as I see, there are many effects not taken into account in the CAK approach which may significantly alter the wind physics.

Hirschi: How does metallicity affect clumping and the different mass loss diagnostics?

Fullerton: I think that Raphael (Hirschi) is correct to raise the issue of abundances. Certainly, the current controversy about the solar oxygen abundance is a reminder that determining absolute abundances is a very tricky business. In the case of phosphorus, I think we are on reasonably solid ground. As I mentioned yesterday, the abundance really does appear to be solar along eight sightlines recently studied with FUSE spectra (Lebouteiller et al. 2005, A&A). This is the material from which Galactic O stars formed "the day before yesterday", so it is hard to see how it could be lower by factors of three or ten. Furthermore, the mass loss discrepancy between P V and Hα persists in both the LMC and SMC; so it is also hard for me to see how abundance can play a key role in resolving the problem. Of course, for his work Raphael is primarily concerned with the abundances of the elements that actually drive the wind. Phosphorus is completely unimportant in this regard.

Weis: Is there a difference between the phosphorus lines comparing LMC and galactic objects?