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Theoretical considerations on colliding clumped winds

Rolf Walder

Institute of Astronomy, ETH Zürich, Switzerland

<http://www.astro.phys.ethz.ch/staff/walder/walder.html>

Doris Folini

Observatoire de Strasbourg, Université Louis Pasteur, Strasbourg, France

Abstract. First attempts are made to derive astrophysical implications of the collision of clumped stellar winds from order of magnitude estimates and preliminary numerical simulations. Compared to colliding smooth winds, we find that the most significant differences occur in widely separated systems like WR 140. Clumped winds de-stabilize the wind-wind interaction zone of such systems. Highly compressed, cold knots of WR-wind material can form. Hydrogen rich material is likely to be mixed into these knots by the excited turbulence. Such knots, therefore, are good candidates to form dust. We briefly discuss to what degree our results can be applied to other systems and look at different possibilities for the origin and nature of the inhomogeneities in hot star winds.

1. Introduction

It is now established that WR-winds are inherently highly structured: they carry substantial density- and velocity-inhomogeneities (see e.g. Cherepashchuk 1990; Lépine, Eversberg, & Moffat 1999, and references therein). Recently, traces of such inhomogeneities have also been found in OB-winds (Eversberg, Lépine, & Moffat 1998; Howk et al. 2000) and LBV-winds (Grosdidier et al. 1998). The results of Grosdidier et al. (1998) also indicate that the wind is structured to large distances. The question arises how the interaction of winds carrying such inhomogeneities takes place and whether – and to what degree – we have to revise the theory of colliding winds (see e.g. Folini and Walder 2000 for a review of the present theory). In this paper, we attempt to make some first steps towards answering these questions, knowing well, however, that many more have to follow. Most of our argumentation is still on the level of basic estimates and only a few quantitative results will be presented. We mainly concentrate on colliding winds in hot star binaries. Similar arguments will be valid, however, for other colliding wind binaries and for wind driven structures in general.

Some ideas on the nature of the inhomogeneities are briefly sketched in Section 2. In Section 3 we discuss the physics of the interaction of single wind-inhomogeneities with a stationary wind-wind-interaction zone, before we generalize that picture in Section 4 to the collision of structured winds. We finally draw some conclusions in Section 5.

2. The nature of the inhomogeneities in hot star winds

Presently, there is no coherent theoretical model of the formation of density- and velocity-inhomogeneities in hot star winds, of their number, size, and distribution. The best attempt in this direction so far has been presented in a series of papers by Owocki and co-workers (e.g. Owocki, Castor, & Rybicki 1988, for a review see Feldmeier & Owocki 1998). This work has shown that winds from hot massive stars (and line-driven winds in general) are inherently unstable. Within the frame of the applied approach – spherical symmetry and sampled line-opacities – small disturbances in one of the flow variables grow very rapidly. A series of high-density, shock-confined sheets is formed. The sheets move outwards in the otherwise strongly rarefied wind. However, these 1D models can neither explain the above referred observations in the optical and UV showing outmoving clumps, nor can the associated shocks account for the observed X-ray flux of hot massive stars.

The results of Owocki and co-workers can be interpreted as a form of supersonic turbulence, restricted to spherical symmetry. It is a very general feature of highly compressible turbulence that the flow is structured into high-density knots and filaments in combination with large voids. (see e.g. Walder & Folini 2000 for the density distribution function of turbulence driven by planar colliding flows). One can hope that the multidimensional generalization of the above 1D-results leads to the formation of knots and shocks within the atmosphere which better fit the observations. The radiative line forces then not only accelerate the wind but would also, in combination with compressible effects, force the turbulence to form the knots. It will be the task of future work to determine the density distribution function within such a framework.

What role in this framework would possible inhomogeneities at the wind-base play that are provided by the interior dynamics of the star? A likely scenario is that they are soon completely erased. The wind-inhomogeneities of the outer wind would then be mainly the result of the complex interplay between the stellar radiation field and the turbulent flow. The 1D results of Owocki and co-workers point in this direction. On the other hand, there seem to be cases where such excitations at the wind-base – perhaps particularly large ones – leave their fingerprints on the wind throughout the whole atmosphere, modifying the turbulence persistently. First attempts by Owocki (1998) to model DACs point in this direction.

Dense clumps in the wind could, in principle, also be formed by locally strongly enhanced cooling. However, such a scenario is very unlikely in the presence of the strong stellar radiation field. Density enhancements of only a factor of ten would require to cool the wind locally to temperatures as low as 3000 K. Moreover, the formation of dense clumps by cooling would immediately disturb the wind, and turbulence would be excited also in this case.

3. Interaction of a single clump with a wind-wind interaction zone

Simulations of colliding clumped winds of entire systems are out of reach even for today's computer resources. Moreover, as discussed in the last section, the exact distribution of the clumps is not yet known. We thus follow another approach

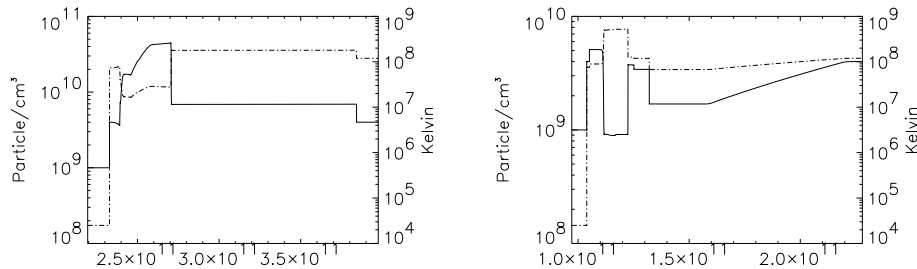


Figure 1. Wind-wind interaction zone after the interaction of a clump (left) and a void (right) with a stationary shock in a 1D test-simulation. The WR star is to the left, the O-star to the right. The original position of the undisturbed shock was at $1.31 \cdot 10^{11}$ cm (arbitrary position) and the clump or the void respectively was injected on the WR-side of the shock. Shown are density (solid) and temperature profiles (dashed). The post-shock values of the undisturbed flow are: $N = 4 \cdot 10^9$ cm $^{-3}$, $v = 715$ km/s, and $T = 1.2 \cdot 10^8$ K. The clump causes the shock to move in the direction of the O-star, the void, on the contrary, towards the WR-star. Several waves – shocks and rarefactions – are created and travel through the interaction zone, leading to a complex density- and temperature-structure.

and discuss single, different, important physical effects of clumped wind collisions before trying to unify the picture by bringing the different effects together. When being specific, we use parameters typical for WR 140 at periastron (Williams et al. 1990, 1995)¹. Most of the discussion will hold, appropriately applied, for narrow systems as well. Some differences will, however, be discussed in the next section.

Collisions of clumps and voids with a shock in the frame of 1D-Euler-equations Figure 1 shows the interaction of a clump (with a density-enhancement of a factor 10) and a void (with a density-deficit of factor 10) with a shock which is stationary with respect to the undisturbed WR-wind. In both cases, the shock immediately becomes unstationary and secondary waves start to travel in the wind-wind interaction zone (WWIZ). In 2D or 3D, these secondary waves eventually de-stabilize the interface separating the WR-star-material from the O-star-material when interacting with it.

Another important point is that already a single void or clump leads temporarily to a complex density- and temperature-structure of the WWIZ when interacting with it. In particular, as the shock is hit by a clump and thus is

¹Separation $d_p \approx 2.35$ AU, WR-wind: $\dot{M} = 5.7 \cdot 10^{-5}$ M_{\odot}/y , $v_{\infty} = 2860$ km/s, O-star-wind: $\dot{M} = 1.8 \cdot 10^{-6}$ M_{\odot}/y , $v_{\infty} = 3200$ km/s. For a smooth, stationary wind, the density of the WR-wind immediately before it gets shocked is on the order of 10^9 cm $^{-3}$. We further assume a wind temperature of 35'000 K, a value which is not crucial for the following.

pushed forward, the shock strength decreases, resulting in a significantly lower temperature and higher density of the post-shock gas as compared to the stationary value (as low as $3 \cdot 10^7$ K in the example). In the case of voids, on the other hand, the shock is strengthened, leading to a significantly higher post-shock temperature. Thus, the inhomogeneous structure of the WR-wind directly translates into a great variation of cooling times of the now patchy WWIZ. Denser regions with low temperature can cool in less than 1000 seconds, tenuous regions with high temperature need more than 0.1 years. This has to be compared to 2 days, the cooling time for the stationary value, to 9 hours, the time a sound wave (corresponding to a temperature of $1.2 \cdot 10^8$ K) needs to travel through the width of the WWIZ, and to 2.6 days, the time a sound wave needs to cross the separation between the two stars.

3D effects will not qualitatively alter the *conclusion* from this 1D example: Even in systems as widely separated as WR 140 parts of the shocked WR-wind can cool in the very center of the system². This is in strong contrast to the case of the collision of smooth flows investigated by Stevens, Blondin & Pollack (1992). The WWIZ is unstable and has a patchy structure. Cooled parts are highly compressed to densities of about 10^{13} cm⁻³ in the case of WR 140.

Heat conduction Heat conduction by thermal electrons and, if optically very thick, by X-ray photon diffusion, is a very efficient process. The heat conduction coefficient is a very non-linear function of temperature, $\kappa \propto T^\beta$, with $\beta = 2.5$ for thermal electrons and $\beta \approx 3$ for photon diffusion (see e.g. Spitzer 1962).

Confining shocks: Only briefly we want to note that heat conduction lowers significantly the temperature of the WWIZ by heating the stellar winds upwind of the shocks confining the WWIZ. In addition, the density of the hot parts of the WWIZ is much higher than for non-heat-conducting shocks. These two effects are enough to diminish the cooling time so much that the shocks most probably become radiative in almost all colliding wind binaries. However, even small magnetic fields, which are likely to be present, reduce this effect to potentially zero. An extended discussion can be found in Myasnikov & Zhekov (1998).

Clumps embedded in hot material: Heat conduction certainly plays an important role with regard to the dense clumps floating in the very hot environment of the patchy WWIZ. Even when a significant magnetic field threads the clumps, there always exists a direction where the ultrafast electrons of the hot phase can penetrate the clump, heating it up. However, as long as it is optically thin, the dense clump can radiate this energy again. A 1D-estimate of the heating-cooling-balance reads

$$\frac{\kappa_0}{3.5} \frac{\partial^2 T^{3.5}}{\partial x^2} = N^2 \Lambda(T). \quad (1)$$

If we apply $\Lambda = 1.5 \cdot 10^{-19} T^{-0.5}$ [erg cm⁶/s], $\kappa_0 = 6 \cdot 10^7$ [erg cm²/(s K^{7/2})], and make the approximation $\partial^2 T / \partial x^2 \approx T_{high}^2 / (\Delta x)^2$, we obtain, as on order

²At least in the short time interval near periastron. In apastron, typical wind-densities are about a factor of 10 lower. With cooling times 100 times longer even dense clumps have no chance to cool in the center and can thus also not be compressed to high densities.

of magnitude estimate, for the thickness of a cooling, heat-conducting front between the hot, shocked gas and the embedded clump,

$$\Delta x \approx 10^{10} \left(\frac{10^{10}}{N_{front}} \right) \left(\frac{T_{high}}{10^7} \right)^2 \quad [\text{cm}]. \quad (2)$$

Typical values (we consider WR140 again) for T_{high} are between 10^7 and 10^8 K. For N_{front} , a mean density in the front, typical values are between 10^{11} and 10^{13} cm^{-3} . Thus, a typical thickness of a heat-conducting, cooling front is between 10^8 and 10^{10} cm. Cool, condensed clumps embedded in hot gas must be bigger than this scale for not being evaporated by conductive heating.

We conclude that big enough clumps – clumps greater than several solar radii in the WR-wind – can also cool when heat-conduction is considered. Moreover, they will not be evaporated by heat conduction but act like a ‘catalyst’, enhancing the cooling of the hot parts of the WWIZ: energy is transported from hot parts to cold, dense parts where it can be radiated. In addition, if dense clumps of WR-material float in the shocked O-star wind, hydrogen rich material is cooled and thus becomes part of the clumps. This material eventually diffuses into the carbon rich material elsewhere in the clump. Unfortunately, diffusion is an inefficient process. However, clumps eventually collide with each other or with a shock. Then, the clump-interior becomes turbulent, the material is stirred, and the surface through which hydrogen can diffuse is much bigger. Mixing of the two materials is likely in this case.

Equilibrium time-scales In a pure, completely ionized hydrogen gas, the electron self-collision time (the time electrons need to thermalize after a significant disturbance like a shock-passage) can be estimated by (Spitzer 1962)

$$t_c(e-e) \approx 0.2664 \times \frac{T^{3/2}}{N_e \ln \Lambda} [\text{s}]. \quad (3)$$

For the self-collision time $t_c(p-p)$ of the protons and the equilibration time $t_c(p-e)$ between electrons and protons the relations

$$t_c(e-e) : t_c(p-p) : t_c(p-e) \approx 1 : \left(\frac{m_p}{m_e} \right)^{1/2} : \frac{m_p}{m_e} = 1 : 43 : 1836 \quad (4)$$

hold. For typical values of the shocked gas of WR 140 in periastron, $N_e = 10^{10} \text{ cm}^{-3}$, $T = 10^8$ K, one obtains $t_c(e-e) \approx 1$ s, and $t_c(e-p) \approx 2000$ s. For a pure, completely ionized helium gas, the equipartition time is of the same order of magnitude. The equipartition time is thus comparable with the estimates for the fastest cooling time-scale and even of the same order of magnitude as sound crossing times of the high temperature regions of the WWIZ.

We conclude that for quantitative predictions two-temperature models are required, i.e. models which distinguish between the electron temperature, T_e , and the ion temperature, T_{ion} . We add two notes: 1) In a patchy interaction zone, electron temperatures higher than $5 \cdot 10^8$ K (see Figure 1) are likely in some parts of the WWIZ, at least if they have time to thermalize. Then, a

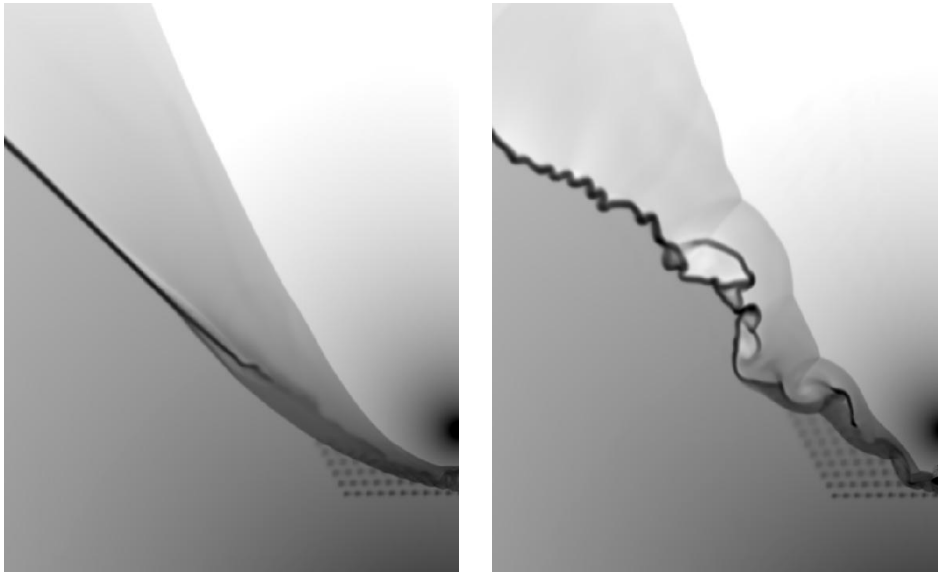


Figure 2. Axisymmetric simulation of colliding clumped winds in WR 140 shown in density on a logarithmic scale (white: 10^5 cm^{-3} , black: 10^{11} cm^{-3} and higher). The scale in the horizontal direction is approximately 3 AU. Left panel: The first clumps have hit the previously stationary interaction zone. Right panel: fully developed turbulent interaction zone. Cold, high-density clumps are embedded in the hot gas.

considerable amount of relativistic electrons is present. Such electrons may contribute to non-thermal emission in the WWIZ. 2) In situations where the ion-electron equipartition time is comparable to typical transport times, shock-preheating by heat conducting thermal electrons will be significantly suppressed.

4. Interaction of inhomogeneous winds

From the estimates presented above and from test examples it becomes clear that a quantitatively correct, consistent model of colliding inhomogeneous winds is out of reach even with present day computer resources. In this section we will try to develop a qualitative picture of those effects which are important in an astrophysical sense. Moreover, we try to draw some observational consequences.

In a multidimensional context, the size of clumps will be small compared to the shock surface. Thus, not the entire shock will be pushed forward when colliding with a clump, but only a little section of it. At the same time, parts of the shock are colliding with clumps of different sizes, but also with voids. Moreover, the same part of the shock will collide subsequently with clumps and with voids. In a certain moment of time, the shape of the WWIZ thus looks very chaotic and its patchy interior is governed by turbulence. On longer terms and in a statistical sense, however, the dynamics of the WWIZ of colliding clumped flows will not necessarily differ much from the case of colliding smooth flows.

Wide systems We present a 2D simulation of WR140 in the frame of Euler equations and optically thin radiative cooling. Heat conduction is not explicitly taken into account. However, the numerical diffusion inherently present in each numerical simulation mimics also heat conduction. It is not possible to estimate this effect in detail. It is, however, likely that around clumps the numerical heat conduction is stronger than the physically correct one. Figure 2 shows (in density) the WWIZ of a clumped WR-wind with a smooth O-star-wind. Again, parameters of the system WR 140 are applied. The stars are assumed to be in periastron and the orbital movement of the stars is neglected. The clumps of the WR-wind have a size of $2 R_{\odot}$ in diameter and are injected in the neighborhood of the WWIZ. Their density is enhanced by a factor of 3.333... compared to the density of the stationary wind. The volume occupied by the clumps is 1/8 of the total volume.

We found that the interaction zone is immediately de-stabilized. Tinny, high-density knots (hardly visible in the graph) float in the hot material even in the center of the structure. Mixing does occur in this simulation. However, the mixing in the simulation is driven by numerical diffusion which is not controllable. But physical mixing is likely in the presence of turbulence. Strong compression and mixing are two ingredients which favor the formation of dust (see e.g. Cherchneff et al. 2000). For the real formation of dust, temperatures below typical temperatures of the WWIZ are necessary. Whether this is possible remains uncertain. However, the reduced strength of the stellar radiation fields in wide systems, together with occultation effects described in Walder, Folini & Motamen (1999) and Folini & Walder (this volume) perhaps allow for such cooling. If the system is too wide, however, even dense clumps may not be able to cool when shocked. Compression will not take place and thus one ingredient of dust production is not present.

A note on narrow systems Narrow systems have a radiative WWIZ even if smooth flows collide (Stevens et al. 1992). Such a WWIZ is inherently unstable. In such systems, the situation is further complicated by the dynamical importance of the stellar radiation fields (Gayley, Owocki, & Cranmer 1997).

Clumped winds will not generally alter this picture. Minor changes include probably a more pronounced division between hot and cold parts: many of the cooled clumps are likely to be denser and some of the hot gas will have higher temperature and lower density than predicted by the theory of smooth wind collision. The new generation of X-ray telescope will allow to test this prediction.

5. Summary and conclusions

We have discussed some properties of colliding clumped winds in hot massive star binaries. We found that in this case the interaction zone is inherently unstable and turbulent. It is possible, however, that in a statistical sense, and averaged over typical turbulent time-scales (not yet known), the interaction zone may again be quasi-stationary.

In wide systems like WR 140, clumped winds result in a partly radiative interaction zone even in the very center of the system. This allows the formation

of highly condensed knots floating in the elsewhere hot WWIZ. Such knots can escape evaporation if their size is on the order of 10^9 cm. Partial mixing between O-wind and WR-wind-material is likely due to the turbulence in the dense knots. The production of dust is favoured by dense, well-mixed carbon-hydrogen knots.

In narrow systems the overall picture of the WWIZ will not be altered by clumped wind.

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