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Theoretical predictions for the cold part of the colliding wind interaction zone

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Abstract.

We present 2D and 3D hydrodynamical simulations of the colliding wind interaction zone in WR+O binaries. It is shown that 3D effects can basically explain certain observed, orbit dependent flux variations. Possible connections between the interior structure of the interaction zone and dust formation are outlined and its stability is re-investigated.

1. Introduction

A sufficient theoretical understanding of the wind-wind collision zone in WR+O binaries is essential to achieve a physically correct interpretation of the observational data. The task is difficult as many physical processes and scales are involved and as, at least for some phenomena, 3D studies are unavoidable.

The presented results are based on numerical simulations. Bearing in mind the character of the workshop, we try to bring them together with thoughts and contributions of other participants. We address the global shape of the interaction zone in Section 2. Its interior is the topic in Section 3, and Section 4 deals with stability. Conclusions follow in Section 5.

2. A spiral in 3D

As the two stars orbit around each other, the O-star carves a spirally shaped 'tunnel' out of the WR-material. The O-star wind material is separated from the WR-wind material by the wind-wind interaction zone. In the more central part of the system, this zone is confined by shocks. There, wind material gets heated and compressed as it enters the interaction zone. Far enough away from the center, such shocks confining the interaction zone are essentially absent. There, no further heating or compression occurs. Instead, all matter moves outwards at approximately the same speed and the high density interaction zone disperses.

In the observers frame, the spiral just described can be regarded as a wave pattern as it is not linked to any spirally shaped particle paths. In this frame, particles essentially proceed radially outwards with respect to the system center. In circular systems the spiral pattern is stationary in the frame co-rotating with

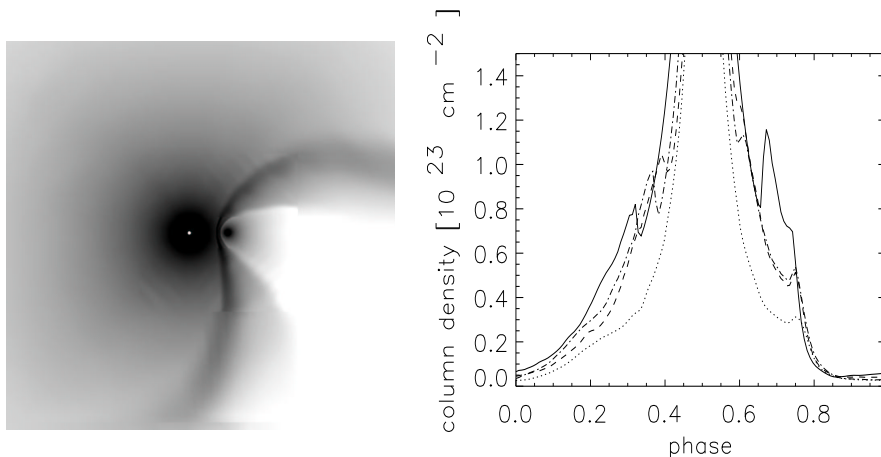


Figure 1. Spirally shaped colliding wind interaction zone and resulting column density. **Left:** Density distribution in the orbital plane at periastron in an adiabatic 3D simulation of γ Velorum (logarithmic scale, high density is black, WR-star (white) to the left, O-star (black) to the right). The x- and y-extension of the slice shown are 10^{14} cm. **Right:** Variation of the column density, measured along $1.9 \cdot 10^{14}$ cm long rays towards the O-star. Each individual curve denotes the column density an observer would see if, at one fixed time, he were to move around the system within the orbital plane. The four different curves denote four different times. *Solid line:* periastron. *Dashed line:* quadrature following periastron. *Dotted line:* apastron. *Dash-dotted line:* quadrature following apastron. X-axis: location of the observer (0: observer on the line connecting WR- and O-star, on the side of the O-star). Increasing x: observer proceeds in direction of orbital motion (counter clockwise in the left picture). Y-axis: column density in units 10^{23}cm^{-2} . Note the asymmetry with respect to $x=0.5$. The chopped, central peak corresponds to the undisturbed WR-wind.

the system. In highly eccentric systems, on the other hand, the spiral pattern (e.g. opening angle of the spiral) undergoes slight changes as a function of orbit (for details see Walder, Folini & Motamen 1999, WFM in the following).

This spirally shaped matter distribution has observable consequences. For the case of γ Velorum it was shown in WFM that with such a spirally shaped interaction zone the observed asymmetric X-ray light curve (Willis, Schild, & Stevens 1995) can basically be understood. We predict that such a matter distribution can also account for orbit dependent line flux variations as observed in GP Cep (see Demers, this volume) and other systems.

As we have not modeled any of these systems in great detail so far, we build our argumentation on a related, however adiabatic model instead. The presented results, therefore, have qualitative value only. Figure 1 shows the spirally shaped density distribution in the orbital plane of an adiabatic 3D simulation of the system γ Velorum, along with derived column densities towards the O-star. For details of the 3D simulation see WFM. As can be taken from this figure,

considerably enhanced column densities, associated with the spirally shaped interaction zone, do occur in this case. The enhancement is more pronounced for the trailing edge of the spiral than for its leading edge. And the enhancement does not occur all the time. While being rather pronounced at periastron, hardly any enhancement is present at apastron. This difference is due to the highly eccentric orbit of γ Velorum. For another system than γ Velorum, with other wind parameters, the quantitative values will be different.

We predict that these adiabatic results essentially carry over to the case where the interaction zone efficiently cools close to the center, i.e. to narrow binaries. Compared to the adiabatic case, the density increases while the zone becomes geometrically thinner. The resulting high density interaction zone is located close to where the contact discontinuity resides in the adiabatic case. If efficient cooling occurs already in the system center the interaction zone most likely is unstable. This again increases its apparent geometrical thickness somewhat while it decreases the column density. In summary, we make on this basis the following predictions for the column density in the radiative case. The enhancement is going to be larger but it is going to cover a shorter phase. The spiral carved by the O-star is going to be more narrow. Compared to the adiabatic case, the highest column densities are going to occur at phases further away from $x=0.5$ in the notation of Figure 1, when the trailing edge of the spiral is in the line of sight towards the observer.

One may speculate that such high column densities in principle can shield a portion of matter from the intense stellar radiation, thus promoting dust formation (episodically, as e.g. in WR 137, Marchenko, Moffat, & Grosdidier 1999, or permanently, as e.g. in WR 104, Tuthill, Monnier, & Danchi 1999). However, more detailed studies are necessary to decide whether such shielding is efficient enough and can last long enough to really promote dust formation.

3. Interior structure

The structure within the cold, high density interior of a radiatively cooling interaction zone, its density, velocity, temperature, and chemical composition, are probably of importance with regard to dust formation and observed large line widths (e.g. Lépine, Eversberg, & Moffat 1999).

The density and velocity in a *radiatively cooling interaction zone* most probably are inhomogeneous for two reasons. First, it seems clear today that at least the WR-wind is clumped already (Owocki, Castor, & Rybicki 1988; Cherepashchuk 1990; Lépine, Eversberg, & Moffat 1999). The interaction zone then is probably clumped at least as much (see also Walder & Folini, this volume). Second, even for the collision of homogeneous flows, 2D plane parallel simulations including radiative cooling show a highly non-homogeneous, turbulent density- and velocity-distribution within the interaction zone (e.g. Blondin & Marks 1996; Folini & Walder 2001).

The prediction of the temperature within the high density interaction zone is a more difficult case (see Folini & Walder 2000), but low temperatures must be reachable as dust is observed in some WR+O binaries.

The chemical composition is particularly important with regard to dust formation (Le Teuff, this volume; Cherchneff et al. 2000). A central question

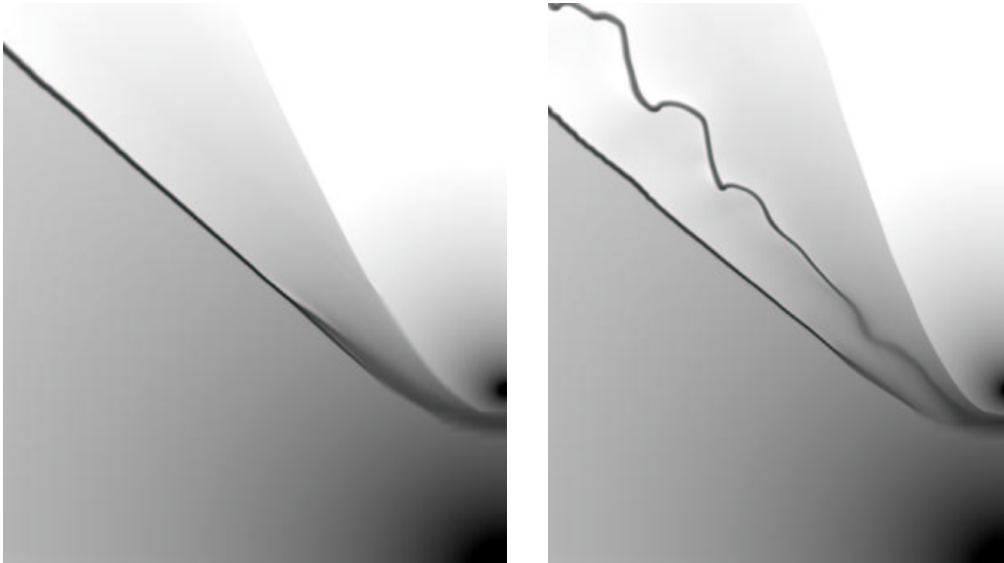


Figure 2. 2D radiatively cooling simulation of WR 140, shown in density (logarithmic scale, high density is black, WR-star at bottom, O-star further up, the x-dimension shown is about $7 \cdot 10^{13}$ cm). For the parameters see Walder & Folini (this volume). **Left:** No disturbances except for numerical noise are present. The shocked WR wind cools roughly one separation away from the system center (dark line). The situation is stationary. **Right:** Starting from the left figure, a high density knot (3.333... times higher density than ambient wind medium, about $2 R_{\odot}$ big) was injected into the interaction zone, about $1/6$ separation away from the stagnation line. A cold, high density ribbon forms which flutters in the hot, shocked O-star wind.

here is whether hydrogen rich O-star material and, in dust forming binaries, carbon rich WR-material can mix efficiently enough. Mixing itself is a diffusive process and thus not described by the models presented here. These models do not contain any explicit physical diffusion. On the other hand, the presented models do contain numerical diffusion, but this diffusion is not controllable. Other studies are required to investigate whether physical mixing does occur fast and efficiently enough to be of importance with regard to dust formation. What we can say is that the conditions for mixing are improved in such interaction zones by efficient stirring, due to turbulence and instabilities (see below).

4. Stability

As a great number of publications already exists on this topic (see e.g. Walder & Folini 1998 for a recent review) we address here only a few selected issues.

Let us look at the colliding wind interaction zone in a relatively wide WR+O binary, assuming that the stellar winds are homogeneous. In this case, radia-

tive cooling becomes efficient only some distance away from the system center. Figure 2 (left) shows that in this case the interaction zone can be stationary, provided that there are no disturbances or at least that disturbances are dispersed by sound waves before they reach regions of strong radiative cooling. In particular, the numerical noise, which is always present, is insufficient to cause instability under these conditions.

But also a single, high density clump injected into such an interaction zone is probably not enough to cause the interaction zone as a whole to become unstable. Figure 2 (right) shows a first attempt to investigate such a scenario. Although we do not yet fully understand the numerical results we obtain, and not controllable numerical effects, in particular numerical diffusion, certainly influence the results, we decided to publish them here to allow others to think and discuss about them. What we basically observe is that the injection of such a clump first causes some shaking of the interface confining the interaction zone, which later on dies away again. Meanwhile, an additional, cold, high density ribbon forms, which flutters in the ambient, hot, shocked O-star material. The starting point of this ribbon stays more or less fixed in space, close to the system center. The ribbon persists for at least 10^8 s, much longer than a typical advection time scale in this system.

Several questions arise in connection with this result. With regard to the limited space, we address only two of them here. First, why does the ribbon with its starting point close to the system center persist? An explanation may be numerical diffusion and associated conduction effects (we have no physical heat conduction included in the presented models), in combination with radiative cooling. Conduction and cooling time scales could be such that their effect exactly compensates the outward transport, leaving the starting point of the ribbon stationary. Also compression or ablation effects, as the 'normal' post shock flow hits the existing ribbon, and subsequent enhanced cooling could contribute to the persistency of the ribbon. Second, is the fluttering of the ribbon real? This question is of importance as it is probably related to the more general question of the stability of a radiatively cooling wind-wind interaction zone. Kelvin-Helmholtz instabilities could be an explanation for the fluttering. If so, the fluttering would depend on the cooling cut-off used in the radiative cooling model, which determines the density ratio between the high density sheet and the surrounding medium. The higher this density contrast, the smaller the wavelength of the Kelvin-Helmholtz instability and its growth rate. This seems in agreement with the findings of Myasnikov, Zhekov, & Belov (1998), who report a similar dependence of the stability of the cold, high density interaction zone in colliding wind binaries on the applied cooling cut-off.

To obtain an unstable, high density interaction zone numerical simulations suggest that it is necessary to have either a narrow WR+O binary or to inject a large number of clumps into an otherwise stationary interaction zone (see Walder & Folini, this volume). As these results can be qualitatively corroborated by physical arguments we consider them to be *qualitatively* reliable. This despite the fact that there are a number of difficulties associated with *quantitative* numerical results. We only want to mention here one of the more prominent problems that occur, namely the pile up of mass along the stagnation line. This carbuncle

phenomenon (Quirk 1994) can be remedied by introducing sufficient artificial viscosity, but other features may be 'drowned' in this way as well.

5. Conclusions

3D numerical simulations show that the global, spirally shaped matter distribution in colliding wind binaries can basically account for observed, orbit dependent flux variations. We suggest that such shielding effects can also promote the formation of dust. The interior structure of a cold, high density interaction zone most likely is inhomogeneous in density and velocity. Efficient stirring of the WR-star and O-star material is most likely. How much mixing — important with regard to dust formation and in contrast to stirring a diffusive process — is induced in this way remains to be investigated. However, 2D simulations show that the cold, high density interaction zone can be stationary, provided that efficient cooling is present only some distance away from the system center, i.e. in wide binaries, and that there are no significant disturbances, like e.g. clumped winds. These preliminary results also suggest that the stability of the interaction zone as a whole is not affected by the injection of one single, high density clump, but that only a cold, high density ribbon forms within the hot, shocked O-star material.

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