SF2A 2010
S. Boissier, M. Heydari-Malayeri, R. Samadi and D. Valls-Gabaud (eds)

HYDRODYNAMICAL SIMULATIONS OF PINWHEEL NEBULA WR 104

A. Lamberts[1], S. Fromang[2] and G. Dubus[1]

Abstract. The interaction of stellar winds from two companion stars leads to the formation of a shocked structure. Several analytic solutions have been developped to model this phenomenon. We compare our 2D and 3D hydrodynamical simulations to these results and highlight their shortcomings. Analytic solutions do not take orbital motion into account although this drastically changes the structure at large distances, turning it into a spiral. This is observed in Pinwheel Nebulae, binaries composed of a Wolf-Rayet star and an early-type star. Their infrared emission is due to dust whose origin is stil poorly constrained. We perform large scale 2D simulations of one particular system, WR 104. Including the orbital motion, we follow the flow up to a few steps of the spiral. This is made possible using adaptive mesh refinement. We determine the properties of the gas in the winds and confirm the flow in the spiral has a ballistic motion.

Keywords: stars: individual (WR104), stars: binaries, winds, circumstellar matter, hydrodynamics, methods: numerical

1 Introduction

Massive stars possess line-driven radiative winds. These winds are highly supersonic, with terminal velocities reaching more than 1000 km.s^{-1}. Their mass loss rates range from $10^{-8} M_{\odot}\mathrm{yr}^{-1}$ for O stars to $10^{-5} M_{\odot}\ \mathrm{yr}^{-1}$ for Wolf-Rayet (WR) stars. Many massive stars belong to binary systems (Van der Hucht 2001) and form colliding wind binaries (CWB). The interaction of two winds from companion stars creates a double-shocked structure. For each wind there is a free unshocked component upstream of the shock and a dense, hot shocked wind downstream (Stevens et al. 1992). The shocked winds of both stars are separated by a contact discontinuity, where the normal velocity components equalize while pressure is continuous. If the two winds are identical, this surface is equidistant to both stars. If the winds have different momenta the shocks are bent towards the star with the weaker wind. The momentum ratio is given by

$$\eta = \frac{\dot{M}_1 v_{\infty 1}}{\dot{M}_2 v_{\infty 2}} \tag{1.1}$$

where the subscript 1 stands for the stronger wind, the subscript 2 for the weaker one. For $\eta \gg 1$ the weaker wind is very collimated and the whole structure looks like a cometary tail.

As a prototype of CWB, we consider WR 104, a system composed of an O-B star and a WC9 star. The WR wind is 500 times denser than the OB wind, which is very collimated. The resulting structure is a narrow, spiral structure (Harries et al. 2004). The system has a 245 days period, the separation a =2.34 AU, the orbit is very close to circular and the system is viewed almost pole-on. This system shows a beautiful example of Pinwheel Nebula in infrared (Tuthill et al. 2008). The step of the spiral is determined by the properties of the strong WR wind. Up to now large scale models have assumed ballistic motion of the shocked winds along an Archimedian spiral.

The infrared emission is due to the presence of dust in the WR wind, whose origin is still poorly constrained. The CWB certainly plays a role since dust emission is seen to occur preferentially at periastron in other systems. This suggests dust production (Marchenko & Moffat 2006) seems to be possible only in dense regions. As the

[1] Laboratoire d'Astrophysique de Grenoble, UMR 5571 CNRS, Université Joseph Fourier, BP 53, 38041 Grenoble, France
[2] Laboratoire AIM, CEA/DSM-CNRS-Université Paris Diderot, IRFU/Service dAstrophysique, CEA-Saclay F-91191 Gif-sur-Yvette, France

WR wind is very poor in hydrogen and dust is composed of carbon and hydrogen some mixing of the O-B star wind with the WR star wind probably occurs. Radiative aspects also seem to play a role, as the second step of the spiral seems to be in the shadow of the first one, shielding dust from UV radiation from the star. In this proceeding we report on hydrodynamical simulations of WR 104. We first compare our code to analytic solutions without orbital motions and highlight their limitations. Then we perform large scale 2D simulations of the Pinwheel nebula. This gives us quantitative estimates of the density and velocity structures of the winds.

2 Comparison to analytic models

Several authors have developed analytic solutions for CWB (see *e.g.* Gayley (2009) and references therein.). Almost all are based on the 'thin shell' hypothesis : thermal pressure can be neglected in the shocked winds so both shocks and the contact discontinuity are merged in one single layer. We compared our 2D and 3D adiabatic ($\gamma = 1.67$) simulations to the solution of Canto et al. (1996) assuming conservation of mass, momentum and angular momentum through the shell. We also compared to the solutions of Antokhin et al. (2004), assuming equality of momentum perpendicular to the shell . The results are shown in figure 1 for both the 2D and 3D case. We show the density map and overplot the two analytic solutions. In these simulations $\eta = 8$, the velocity from the stronger wind is 8 times higher than for the weaker wind, both mass loss rates are identical.

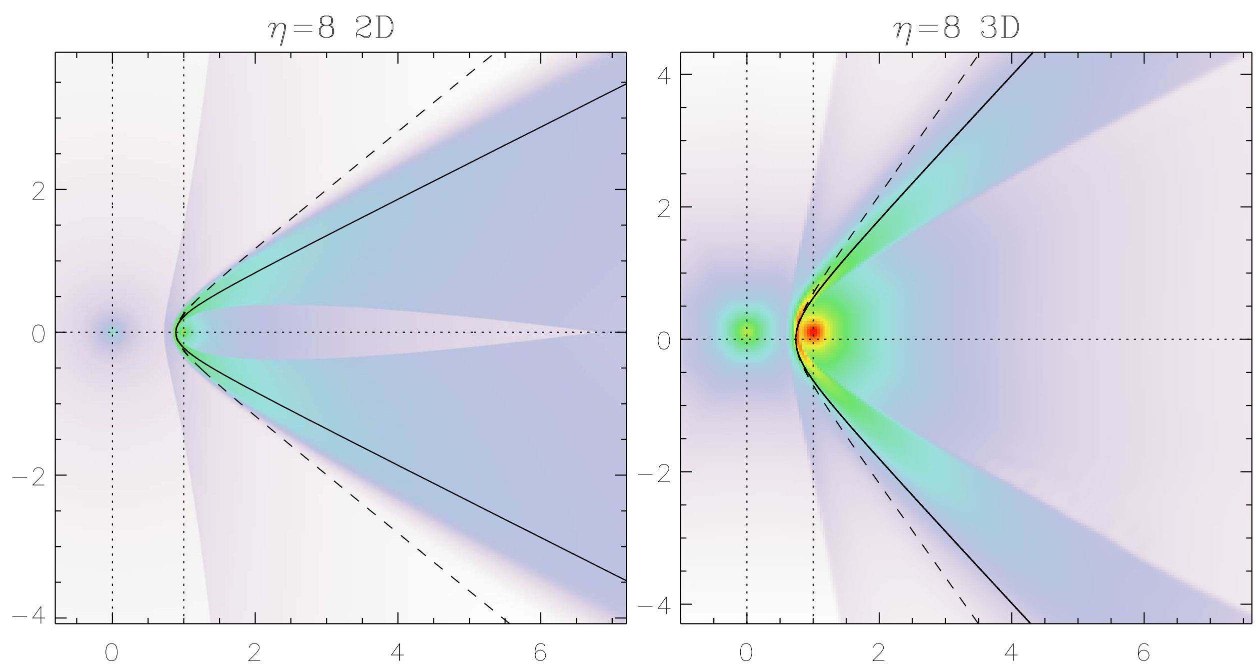

Fig. 1. Density in 2D (left panel) and 3D (right panel) for $\eta = 8$. The stars are located at the intersections of the dotted lines. The dashed line represents the solution from Canto et al. (1996), the solid line the solution from Antokhin et al. (2004). The length scale is the binary separation a.

One can clearly distinguish the two shocks and the contact discontinuity. The location of the contact discontinuity is approximately matched by the analytic solutions. Simulations with an isothermal equation of state ($\gamma = 1$) should yield solutions closer to the 'thin shell approximation'. As the shocked gas is allowed to cool, the two shocks are much closer to each other. In the left panel from figure 2 we can see both shocks and the contact discontinuity have merged in one single layer. The right panel shows the same simulation once the steady state is reached. The structure is dominated by the 'thin shell instability' and the shocks cannot clearly be distinguished anymore (Pittard 2009). High spatial resolution is required to allow its growth. This cannot be modelled with the analytic solutions. Moreover the analytic solutions do not account for the orbital motion and for effect of thermal pressure which pushes away the shocks. These effects can be properly modelled using hydrodynamical simulations.

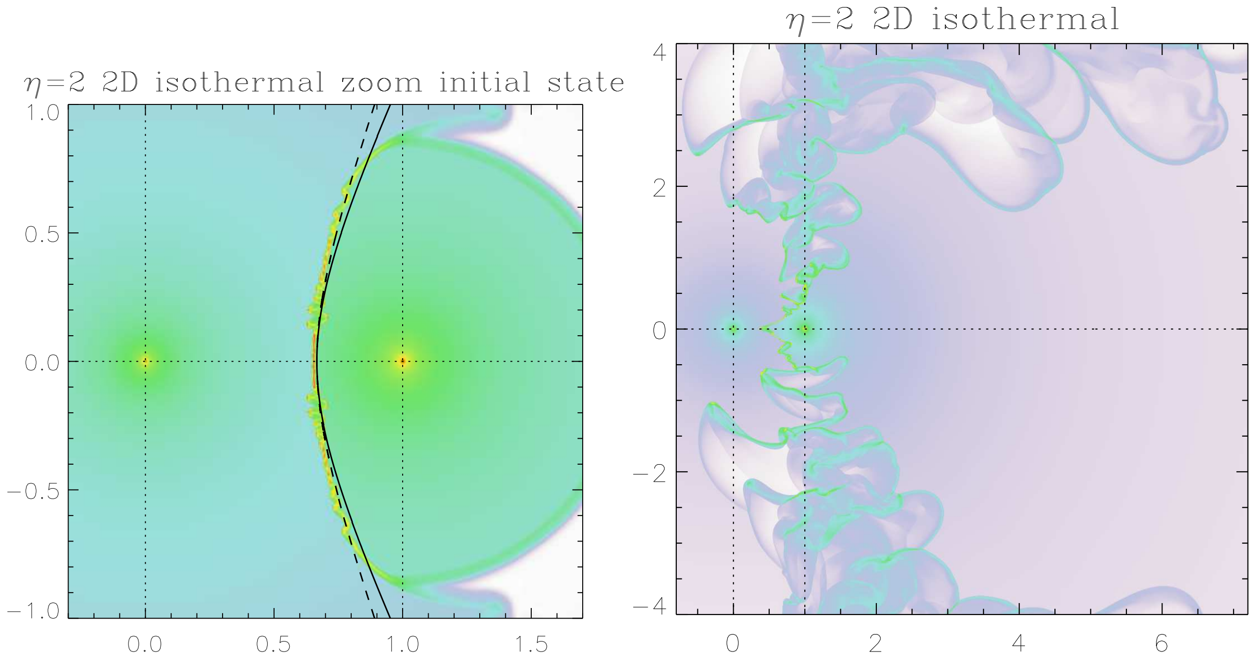

Fig. 2. Density for $\eta = 2$ in the isothermal case. Left panel : zoom on binary at the initial state. The analytic solutions are overplotted. Right panel : Density in the whole box in the steady state

3 The case of WR 104

3.1 Method

We use the code RAMSES (Teyssier 2002; Fromang et al. 2006), to solve the equations of hydrodynamics using a finite volume method. The Adattive Mesh Refinement (AMR) enables us to locally increase the spatial resolution according to the properties of the flow. We can properly resolve the shock formation and determine the large scale structure at reasonable computational cost. Indeed $\eta = 305$ in WR 104 so the shocks are very close to the O-B star. A proper modelling is thus very demanding. We use a method developed by Lemaster et al. (2007) to implement the winds.

We want to see at least one step of the spiral structure. The step S is determined by the velocity of the stronger WR wind and the orbital motion. One has $S/a \simeq 70$ (Harries et al. 2004) so we choose to take a box length of 200 a. We stress this involves a very high resolution close to the binary because we want to properly capture shock formation. Less resolution is needed to compute the large scale structure, so we gradually decrease it towards the edges of the computational domain.

3.2 Results

Here we present some initial investigations of the CWB structure in WR 104. We first made a 2D simulation with adiabatic winds. The density map and profiles are shown in figure 3. The different components of the wind can clearly be seen. Most of the gas is composed of the unshocked WR wind. We can see on the left panel its density decreases $\propto r^{-1}$ as one expects in 2D. The densest zone is the shocked WR wind at both edges of the spiral. It also has a $\propto r^{-1}$ profile. The low density unshocked O-B wind is very collimated and cannot be distinguished ont the density map. The density in the shocked O-B wind at the center of the spiral is constant, confirming the hypothesis of ballistic motion. We overplot the analytic solution for the Archimedian spiral using a black solid line, it perfectly matches the results of the simulation.

While the present simulation uses an adiabatic equation of state, in reality the cooling timescale in the WR wind is much smaller than the dynamical timescale. This suggests an isothermal equation of state is more appropriate. We thus expect the presence of the thin shell instability. Mixing between both winds might be more efficient in this case. This could explain the chemical composition of the dust. To show this instability, high resolution is required throughout the whole simulation zone. The density map is shown on figure 4. The

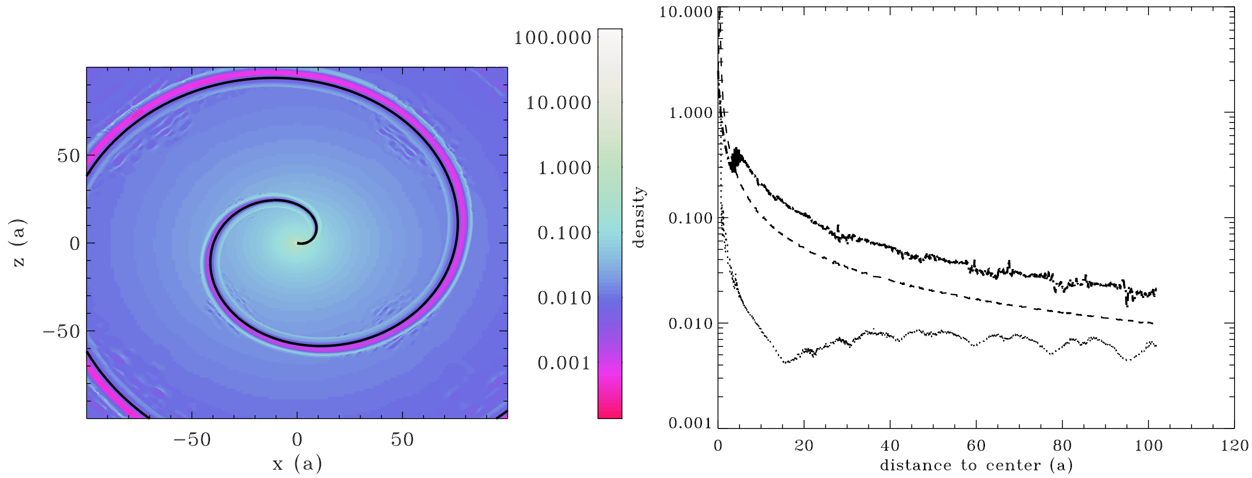

Fig. 3. Left panel: Density map of WR 104. The theoretical Archimedian spiral is overplotted. Left panel : Density profile of WR 104. The dashed line represents the density in the unshocked WR wind, the solid line represents the density in the shocked WR wind and the dotted line represents the density in the shocked O-B wind

structure is similar to the adiabatic case. No instabilities can be seen in the spiral, which is confirmed in the zoomed image on the right panel. This can have a physical or numerical reason. The extreme confinement of the O-B star wind could prevent the developpement of the instability. Orbital motion could also have a stabilizing effect. It also adds more numerical diffusion and an even higher resolution might be needed to correctly model the instability.

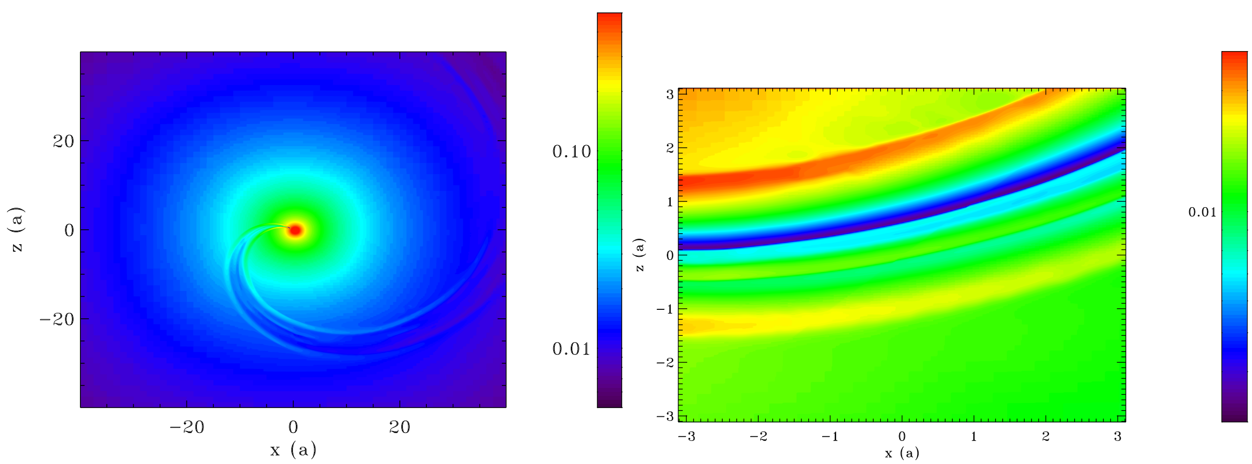

Fig. 4. Density map (left panel)in the isothermal case. Zoom on the spiral (right panel).

4 Summary and conclusions

Properly modelling colliding wind binaries requires numerical simulations. Although analytic solutions are good approximations, only simulations can properly take into account the effects of thermal pressure and orbital motion. They might also capture possible dynamical instabilities in the flow. We presented a preliminary study of WR 104, a dust-producing binary. We performed 2D large scale simulations of the system, completely modeling one step of the spiral structure. This work confirms that motion along the spiral is ballistic. More analysis is necessary to put stronger constrains on dust formation. We will also make a deeper study of the thin shell instability. We want to understand what physical or numerical aspects prevent its developpement in the simulation of WR 104.

This work is supported by the European Community via contract ERC-StG-200911. This work was performed using HPC resources from GENCI- [CINES] (Grant 2010046891)

References

Antokhin, I. I., Owocki, S. P., & Brown, J. C. 2004, ApJ, 611, 434

Canto, J., Raga, A. C., & Wilkin, F. P. 1996, ApJ, 469, 729

Fromang, S., Hennebelle, P., & Teyssier, R. 2006, A&A, 457, 371

Gayley, K. G. 2009, ApJ, 703, 89

Harries, T. J., Monnier, J. D., Symington, N. H., & Kurosawa, R. 2004, MNRAS, 350, 565

Lemaster, M. N., Stone, J. M., & Gardiner, T. A. 2007, ApJ, 662, 582

Marchenko, S. V. & Moffat, A. F. J. 2006, arXiv0610531

Pittard, J. M. 2009, MNRAS, 396, 1743

Stevens, I. R., Blondin, J. M., & Pollock, A. M. T. 1992, ApJ, 386, 265

Teyssier, R. 2002, A&A, 385, 337

Tuthill, P. G., Monnier, J. D., Lawrance, N., et al. 2008, ApJ, 675, 698

Van der Hucht, K. A. 2001, VizieR Online Data Catalog, 3215