Numerical simulations of the collision of an inhomogeneous stellar wind and a relativistic pulsar wind in a binary system

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V. Bosch-Ramon, M. Perucho, M. Ribó

High-Energy Phenomena in Relativistic Outflows - V

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Outline

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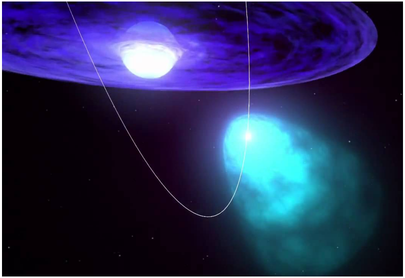
Introduction

We study the interaction of a **relativistic pulsar wind** and an **inhomogeneous stellar wind** in binary systems.



- The collision between the two winds creates a **shock structure**.
- Sources of stellar wind **inhomogeneities**:
  - **Instabilities** in the inner wind (Lucy & Solomon 1970).
  - **Rotation**, **magnetic fields**, or non-radial pulsations (Cranmer & Owocki 1996).
  - The truncation of the *Be* star equatorial **decretion disk** (Okazaki et al. 2011).
- The presence of **clumps** can **distort** the overall interaction structure (Bosch-Ramon 2013).
- This can affect the **radiative output**.

We perform numerical **Relativistic Hydrodynamical simulations**.

Outline

Clump impact on the colliding wind region I

The relativistic Euler equations can be written using the **vector of conserved variables, U,** and the **flux vector, F** as

$$\mathbf{U}_t + \mathbf{F}^{\mathrm{i}}(\mathbf{U})_{x^{\mathrm{i}}} = 0, \quad \mathrm{i} = 1, 2, 3 \tag{1}$$

$$\mathbf{U} = \begin{bmatrix} \rho\, W \\ \rho\, h\, W^2\, v^1 \\ \rho\, h\, W^2\, v^2 \\ \rho\, h\, W^2\, v^3 \\ \rho\, h\, W^2\, c^2 - p - \rho W c^2 \end{bmatrix}, \quad \mathbf{F}^1 = \begin{bmatrix} \rho\, W\, v^1 \\ \rho\, h\, W^2\, v^1 v^1 + p \\ \rho\, h\, W^2\, v^2 v^1 \\ \rho\, h\, W^2\, v^3 v^1 \\ \rho\, h\, W^2\, c^2 v^1 - \rho W c^2 v^1 \end{bmatrix}, \tag{2}$$

being the **conserved quantities** and v^{i} measured in the *laboratory frame*, and the **physical quantities** ρ and p measured in the *local rest frame* (e.g., Martí & Müller 2003).

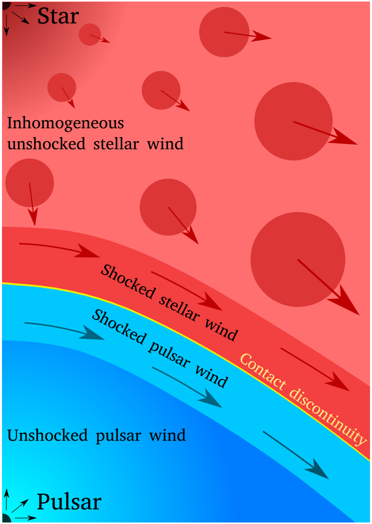
Clump impact on the colliding wind region II

The simulations were performed using a **finite-difference code** based on a high-resolution shock-capturing scheme that solves the multidimensional **equations of RHD in a conservation form** (Martí et al 1997).

- The code is parallelized using **OpenMP** (Perucho et al. 2005).
- The **intercell fluxes** are computed using Marquina's approach (see Donat & Marquina 1996).
- The **intercell physical quantities** are computed with a conservative monotonic parabolic reconstruction of the physical variables (**PPM**; see Woodward & Colella 1984; Martí & Müller 1996; and Mignone et al. 2005).
- The **time integration** is performed using a **Runge-Kutta** formula.

Clump impact on the colliding wind region III

We performed **axisymmetric RHD simulations** of the interaction of a **relativistic pulsar wind** and an **inhomogeneous stellar wind (1 clump)**.



- **Ideal gas** with single particle species and $\hat{\gamma} = 1.444$ (cold protons and relativistic electrons).
- **Grid size**: $l_r = 2.4 \times 10^{12}$ cm, $l_z = 4.0 \times 10^{12}$ cm.
- The adopted **resolution** is 150×250 cells.
- The **star** is located at $(r_0, z_0) = (0, 4.8 \times 10^{12})$ cm.
- The **pulsar** is placed at $(r_0, z_0) = (0, 0.4 \times 10^{12})$ cm.
- The star-pulsar **separation** is of $d_{\rm star-pulsar} = 4.4 \times 10^{12}$ cm.

Clump impact on the colliding wind region III

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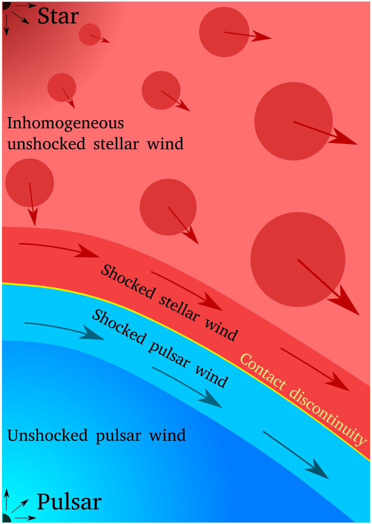

- The lower and right **boundaries** are set to outflow. The left boundary is set to reflection.
- The **stellar wind** is injected as a boundary condition at the top of the grid.
- The **pulsar wind** is injected at a radius of 2.4×10^{11} cm (15 cells).
- The **stellar mass-loss rate** is $\dot{M} = 10^{-7}\ \mathrm{M_\odot\ yr^{-1}}$.
- The **pulsar total luminosity** is $L_{\rm sd} = 10^{37}\ \mathrm{erg\ s^{-1}}$ with Lorentz factor $\Gamma = 6$.
- The pulsar-to-stellar wind **thrust ratio** of $\eta \sim 0.2$.

Clump impact on the colliding wind region III

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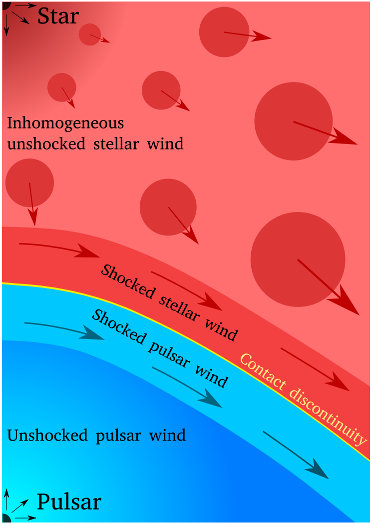
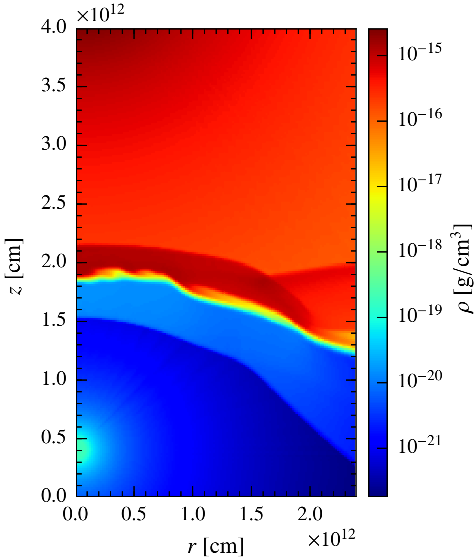


- Set-up of the inhomogeneous stellar wind:
  1. We obtained a **quasi-steady state** of the two-wind interaction considering an **homogeneous stellar wind**.
  2. We introduced the stellar wind **inhomogeneity** characterized by a **single clump** centered at the z axis.
- We simulated 4 cases:

χ	$R_{\rm clump}$	Description
10	$8 \cdot 10^{10}$ cm	**light and small**
10	$2 \cdot 10^{11}$ cm	**light and medium**
10	$4 \cdot 10^{11}$ cm	**light and large**
30	$8 \cdot 10^{10}$ cm	**dense and small**

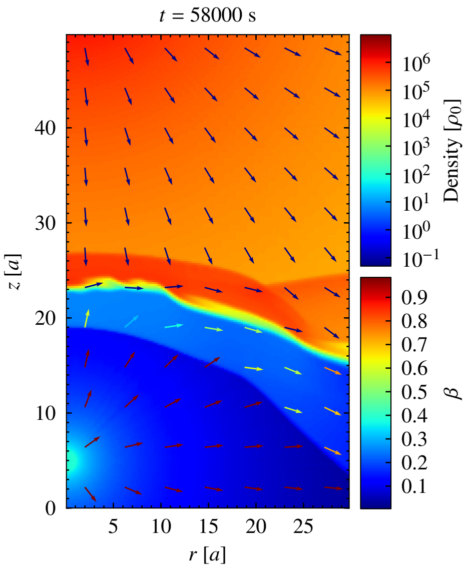
Outline

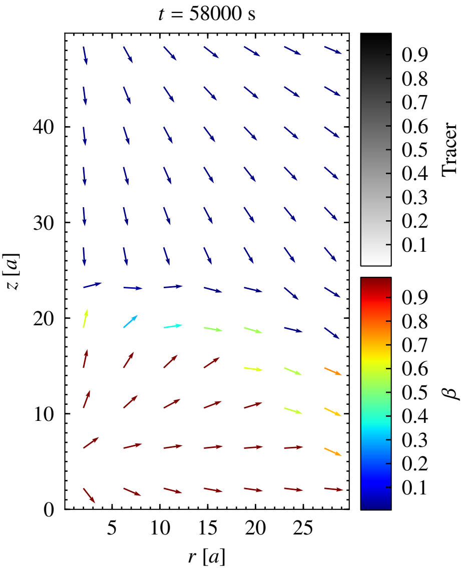
Results I



The results presented here have already been **published** in **X. Paredes-Fortuny, V. Bosch-Ramon, M. Perucho, and M. Ribó (2015)**

Results II — light and small size clump





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Code units: $\rho_0 = 22.5 \times 10^{-22}$ g cm^{-3}, $a = 8 \times 10^{10}$ cm | $d_{\text{star-pulsar}} = 4.4 \times 10^{12}$ cm.

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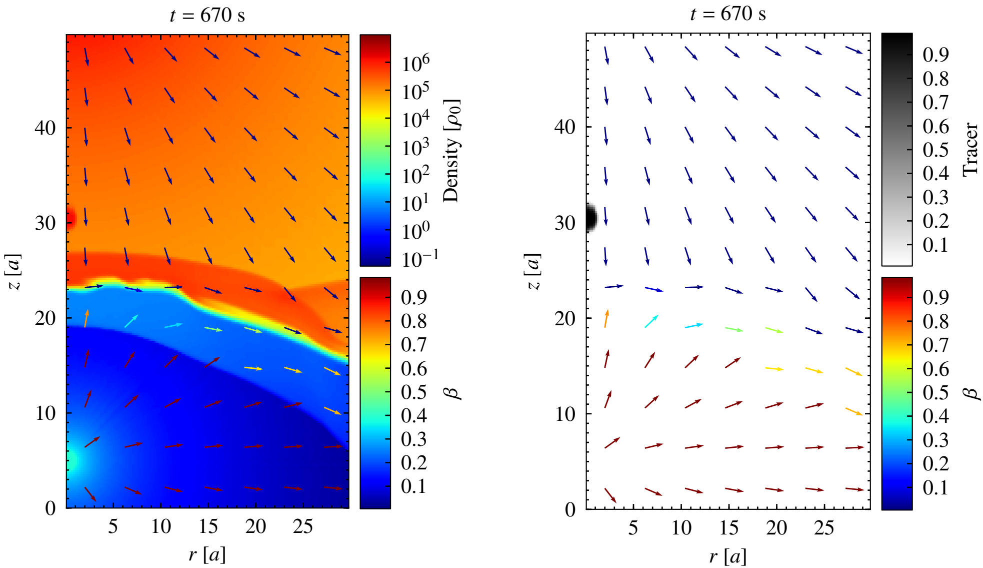

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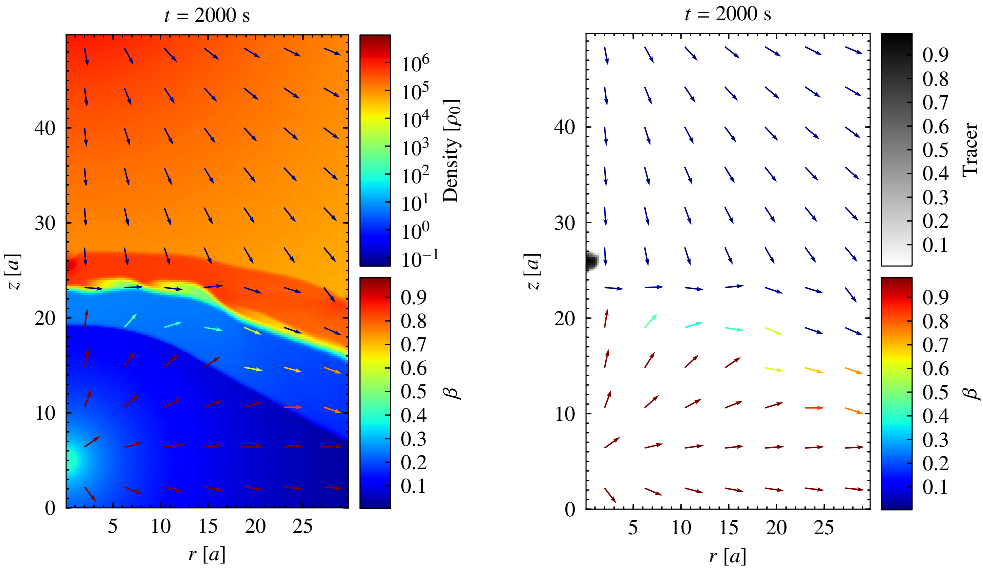

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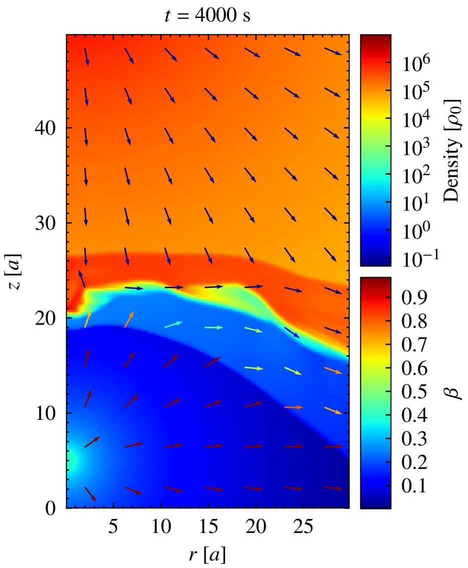

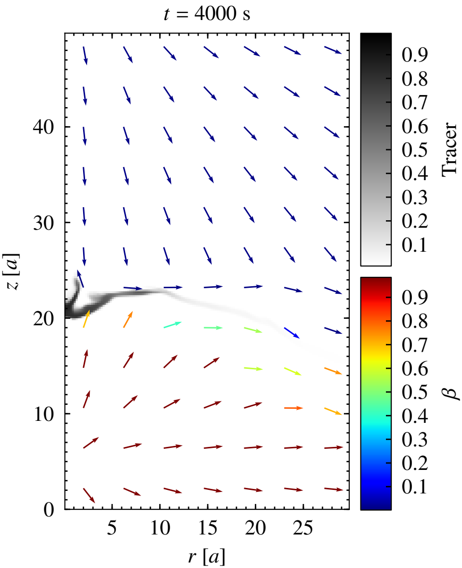

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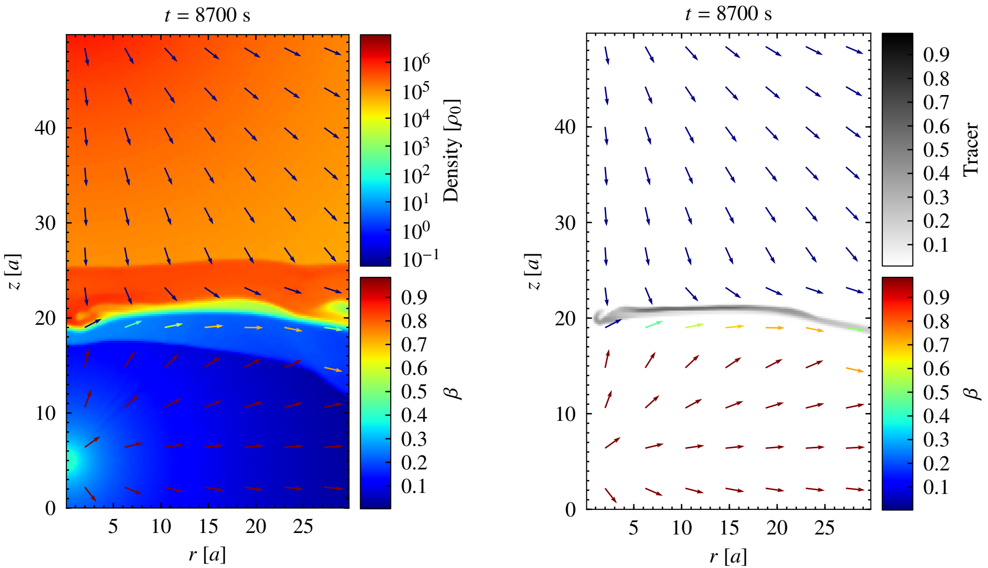

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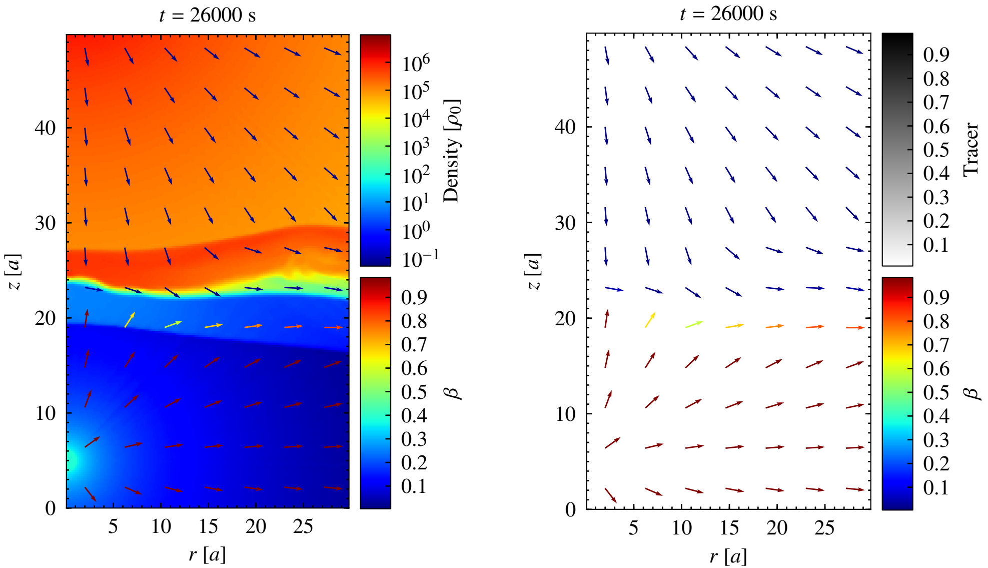

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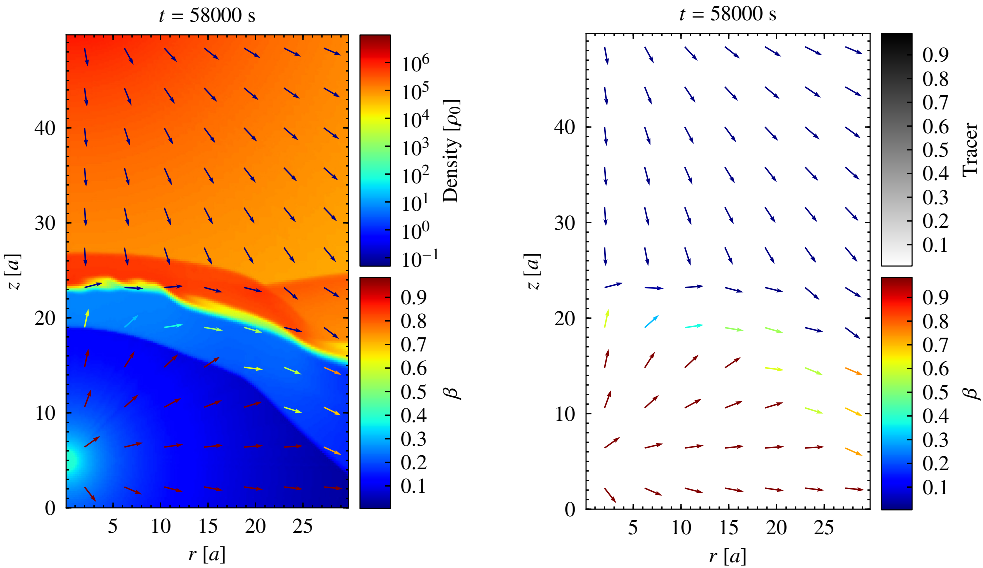

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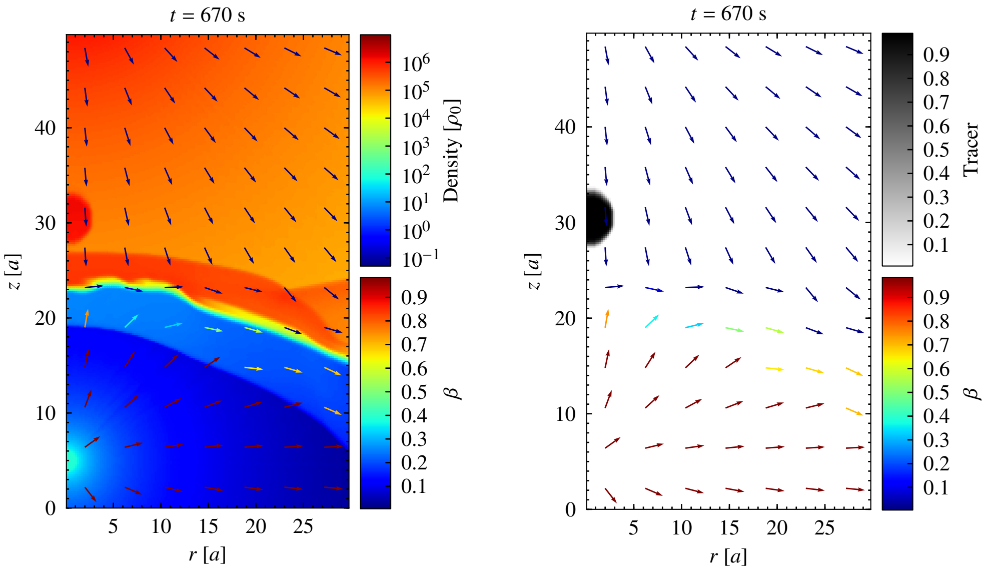

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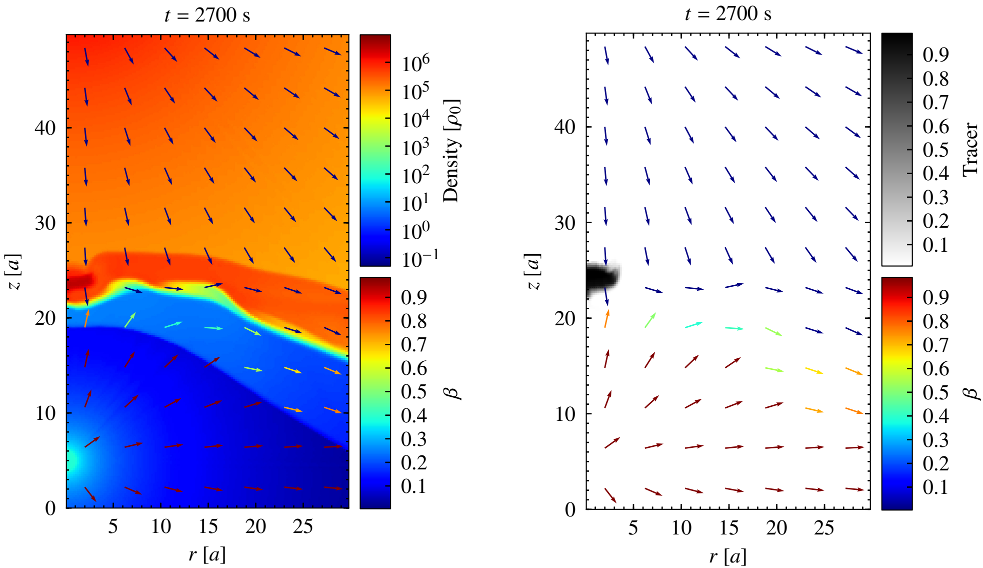

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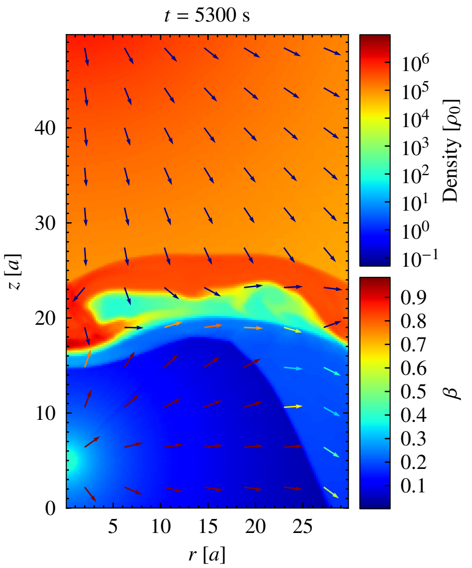

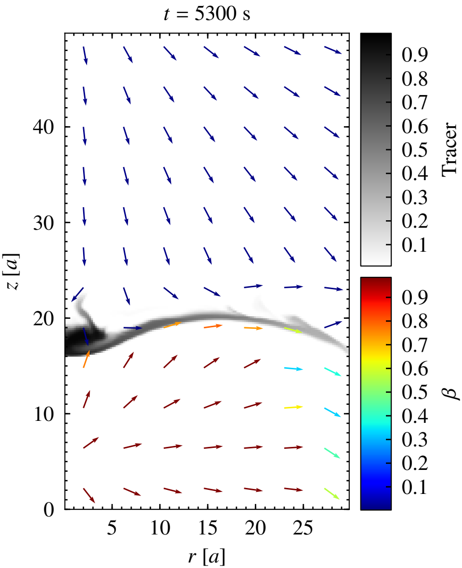

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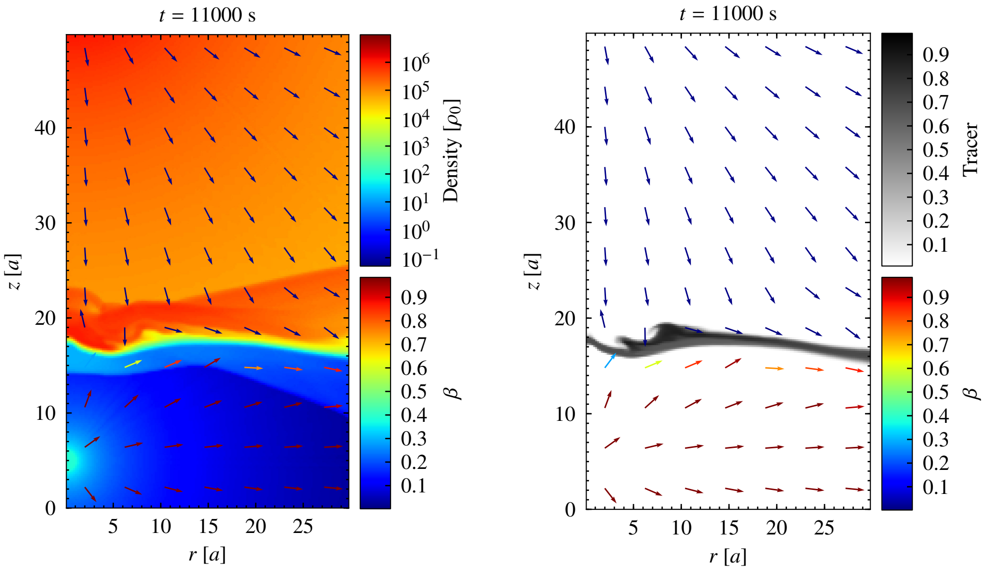

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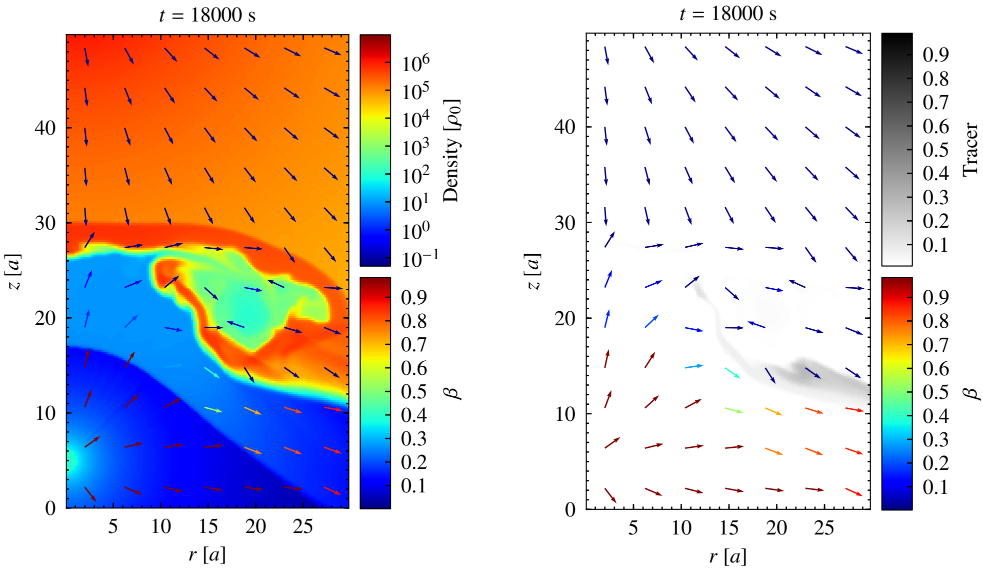

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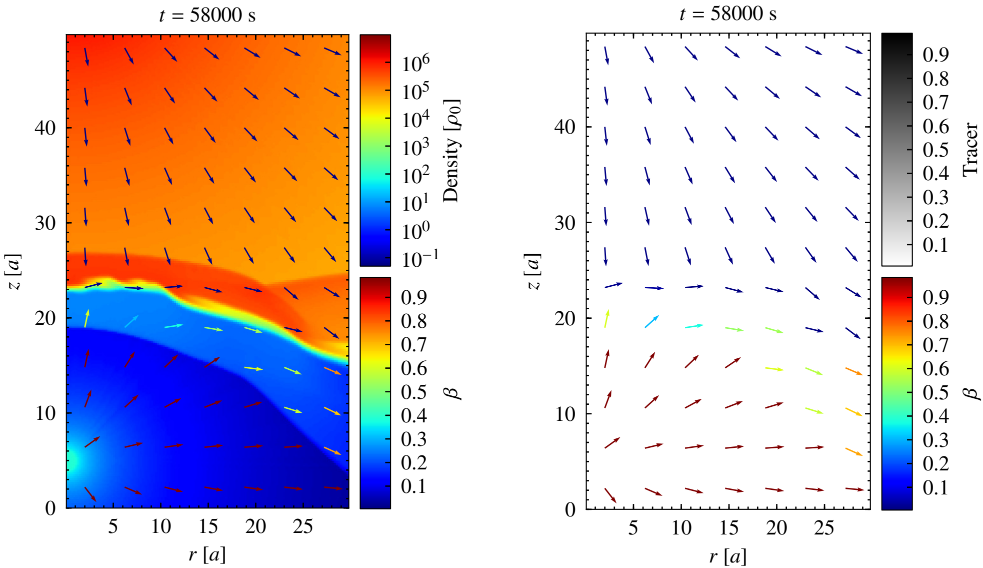
Results IV — light and large size clump



Clump: $\chi = 10$, $R_{clump} = 5\,a = 4 \cdot 10^{11}$ cm

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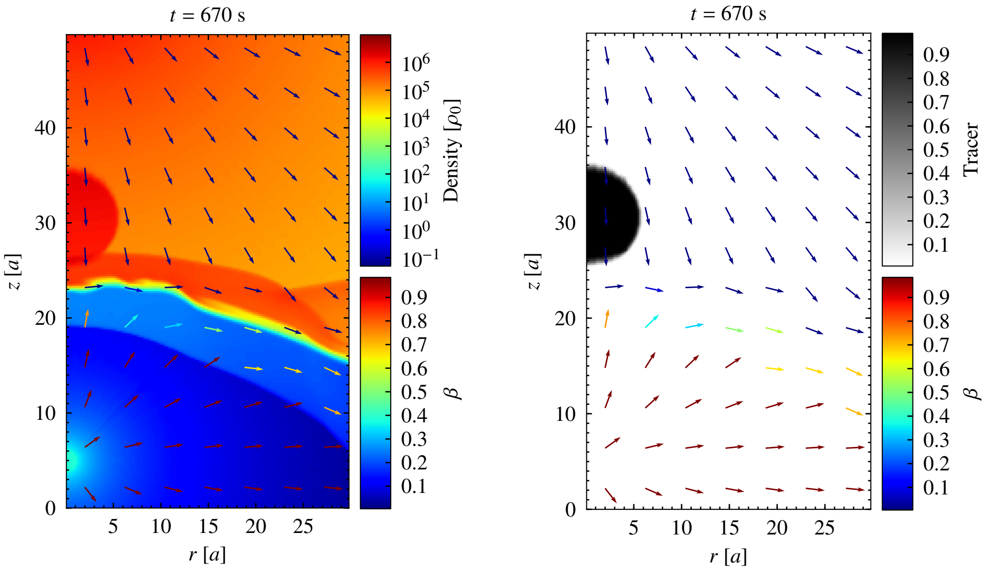

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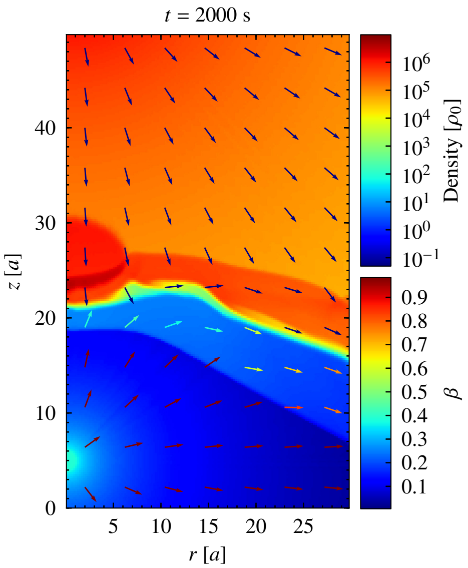

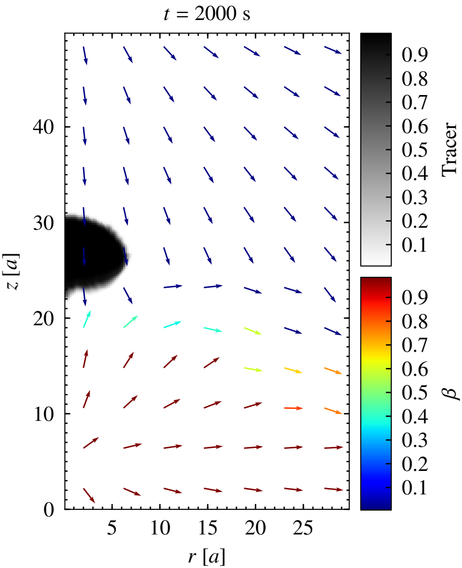

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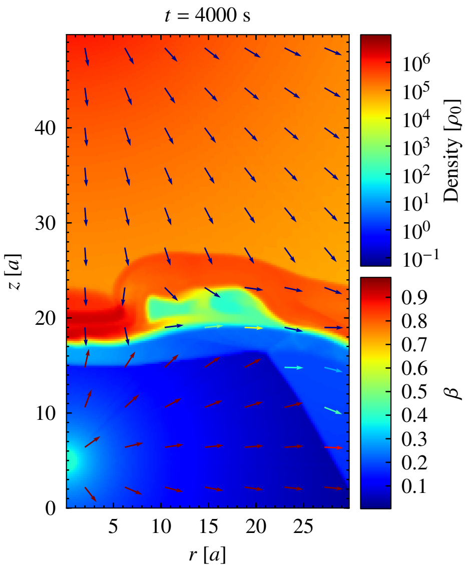

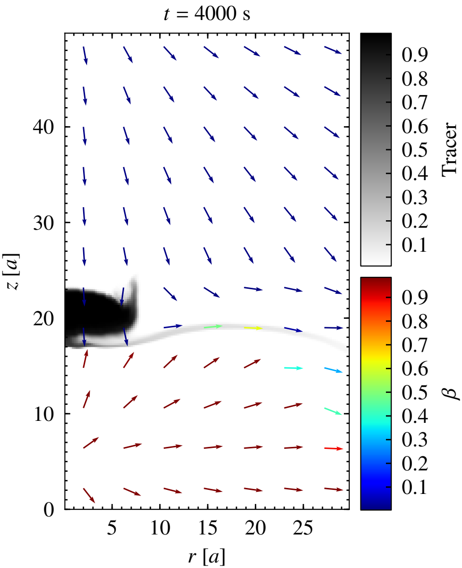

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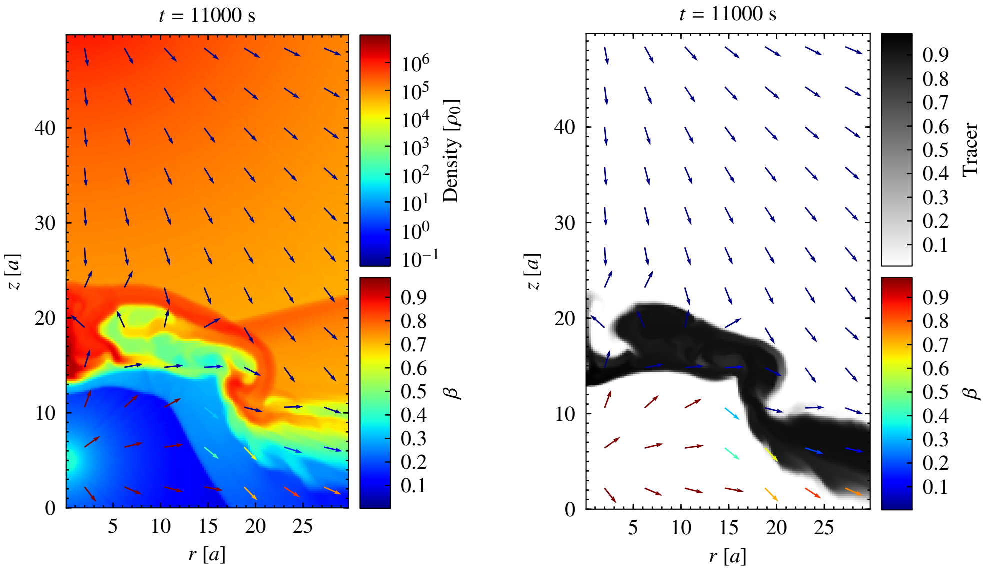

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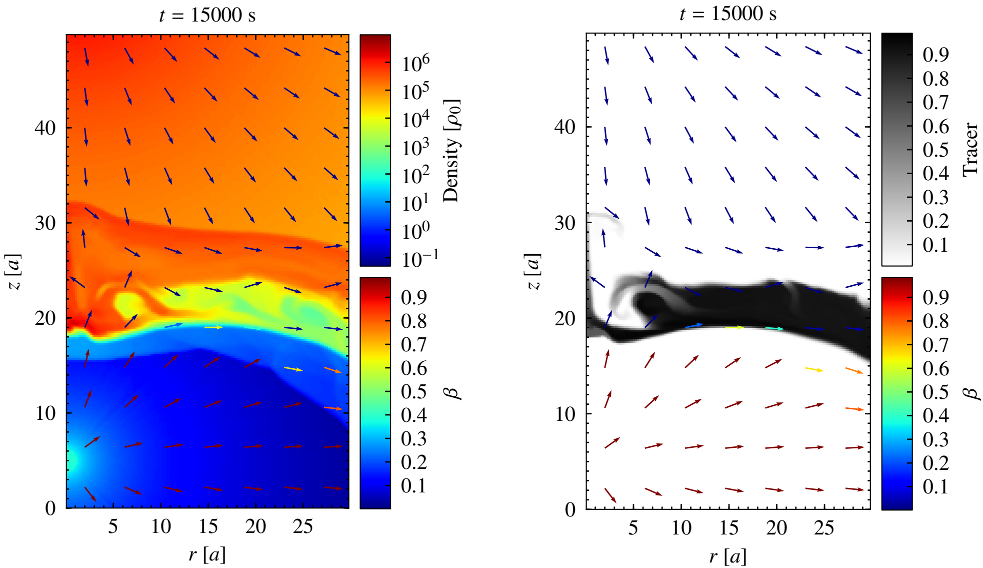

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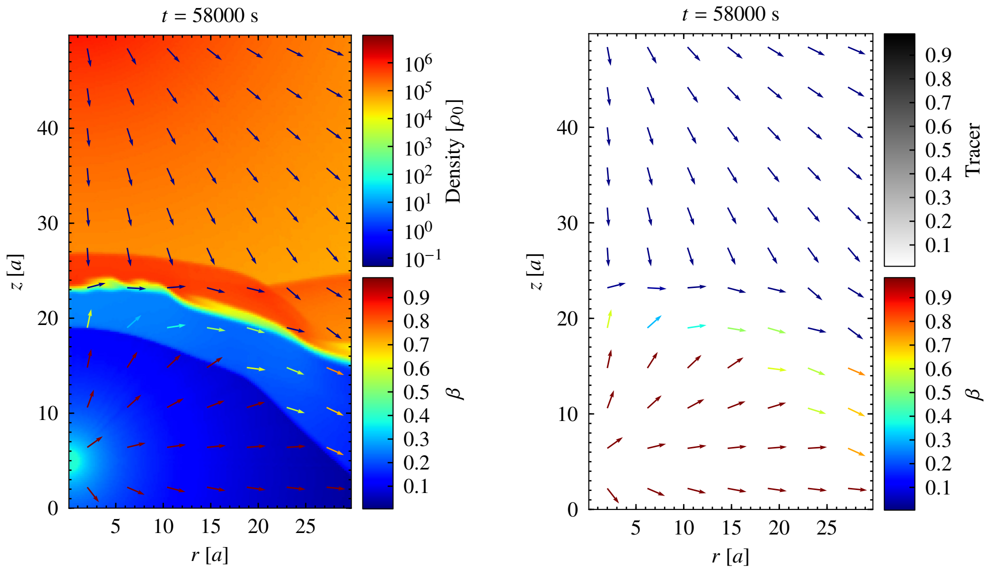

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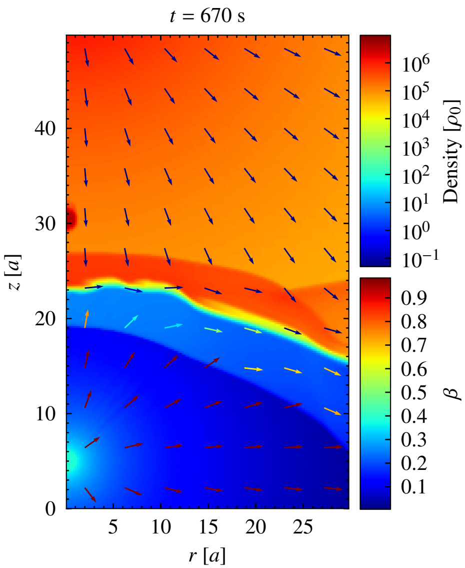
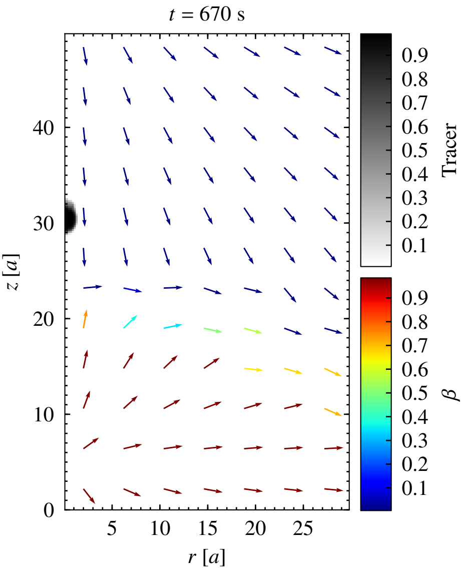
Results V — dense and small size clump





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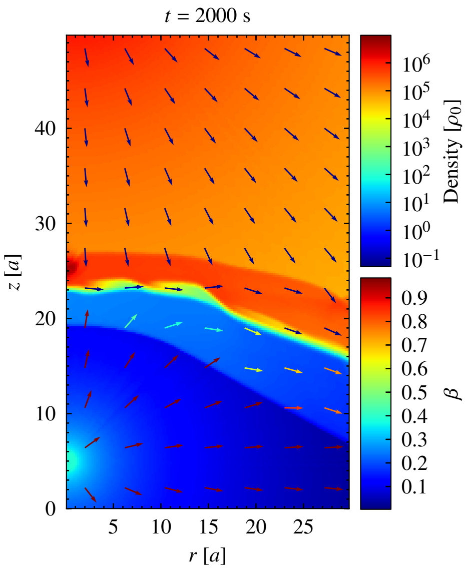

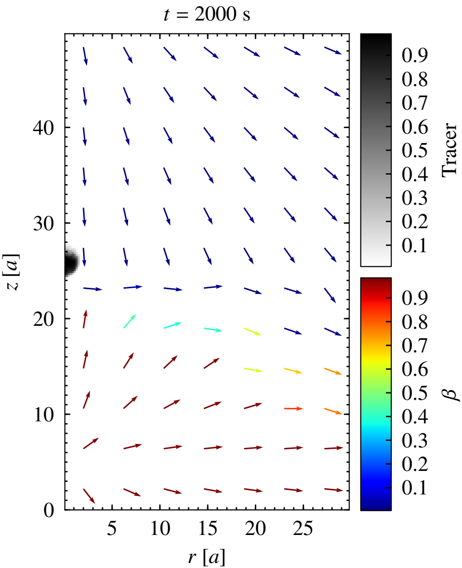

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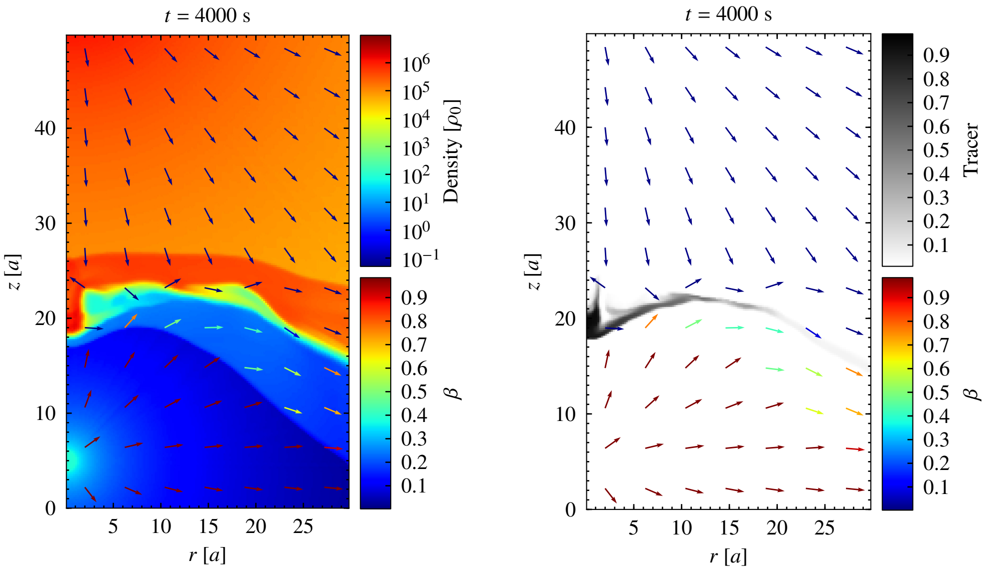

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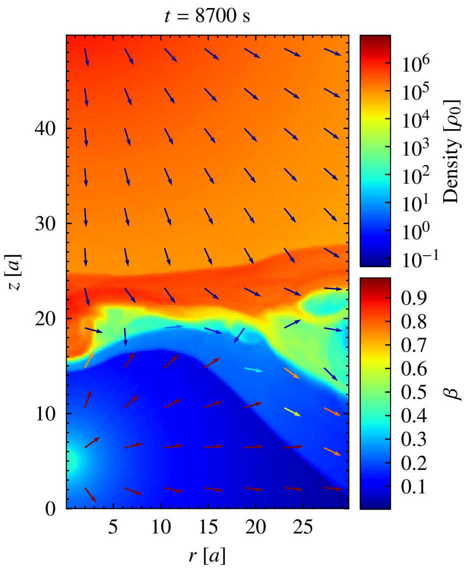

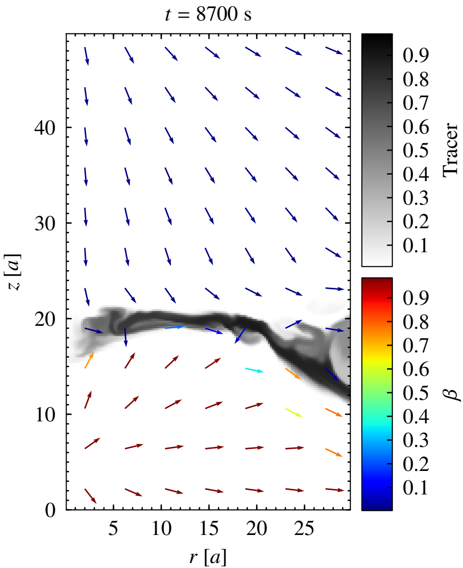

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Outline

Discussion I

General remarks:

- The **steady state** is very **sensitive** to the initial set-up parameters (grid size and density contrast / pulsar wind Lorentz Factor).
- The arrival of **clumps** can have very **strong impact** on the whole interaction structure (overcoming any possible numerical perturbation).
- The **clumps** trigger **Rayleigh-Taylor/Richtmyer-Meshkov and Kelvin-Helmholtz** instabilities leading to **quick changes** of the shocked pulsar-wind region (see also Bosch-Ramon et al. 2015).

Discussion II

Clump effects on the global structure and radiation:

- **Modest inhomogeneity degree**: non-negligible variations of the interaction structure and enhance the instability growth.
- **High inhomogeneity degree**: strong variations in the size of the two-wind interaction structure.
- **Both** generate quick and global variations in the **shocked pulsar wind**:
    - This affects the **location** of the pulsar wind **termination shock**, and therefore **reducing the emitter size** and increasing the magnetic field density (Bosch-Ramon 2013).
    - The relativistic **flow variations** on small spatial and temporal scales downstream of the pulsar wind shock **would lead to a complex radiative pattern in time and direction** caused by **Doppler boosting** (Khangulyan at al. 2014).

Discussion III

For the **PSR B1259−63 flare** observed by Fermi $\sim$ 30 days after periaston passage (Abdo et al. 2011):

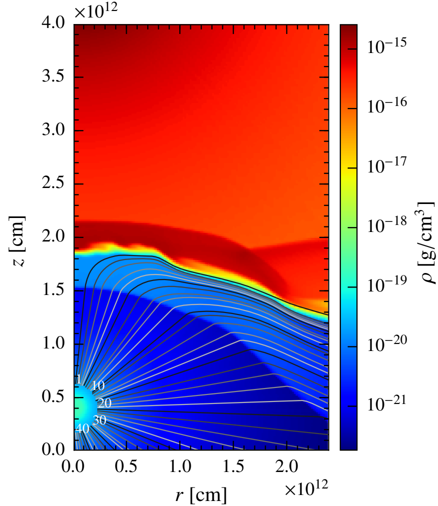
- The impact of **a piece of disk** on the two-wind interaction structure might have led to **efficient Compton scattering** by GeV electrons on local X-ray photons (Dubus & Cerutti 2013; Khangulyan et al. 2012 for IR photons), as a result of the strong **enhancement of the synchrotron photon density**.

For the **short flares of scales** of second to hours found in **X-ray** lightcurves of **LS 5039 and LS I +61 303** (e.g., Bosch-Ramon et al. 2005; Paredes et al. 2007; Smith et al. 2009; Li et al. 2011):

- The impact of **clumps** might explain this short X-ray variability (Bosch-Ramon 2013).

Outline

Work in progress — Radiative output



- V.M. de la Cita, V. Bosch-Ramon, X. Paredes-Fortuny, D. Khangulyan, M. Perucho, and M. Ribó in **prep.**
- **Tomorrow's talk by Moreno de la Cita, Víctor at 9:50** on the same radiative code but applied to star-jet interactions in AGN.

Backup slides

Backup slides

Stellar and pulsar parameters

Table 1: Wind velocity v, specific interal energy ϵ, and density ρ at a distance $r = 8 \times 10^{10}$ cm with respect to the star and pulsar centres located at (r_0, z_0).

Parameter	Stellar wind	Pulsar wind
v	3×10^8 cm s^{-1}	2.94×10^{10} cm s^{-1}
ϵ	1.8×10^{15} erg g^{-1}	9×10^{19} erg g^{-1}
ρ	2.68×10^{-13} g cm^{-3}	1.99×10^{-19} g cm^{-3}
(r_0, z_0)	$(0, 4.8 \times 10^{12}$ cm$)$	$(0, 4 \times 10^{11}$ cm$)$

- Typical physical values in gamma-ray binaries:

  $R_* \sim 10\, R_\odot$,

  $d_{\rm star-pulsar} \sim 10^{13}$ cm,

  $R_{\rm clump} =\sim 0.2 d_{\rm star-pulsar}$

High resolution simulations

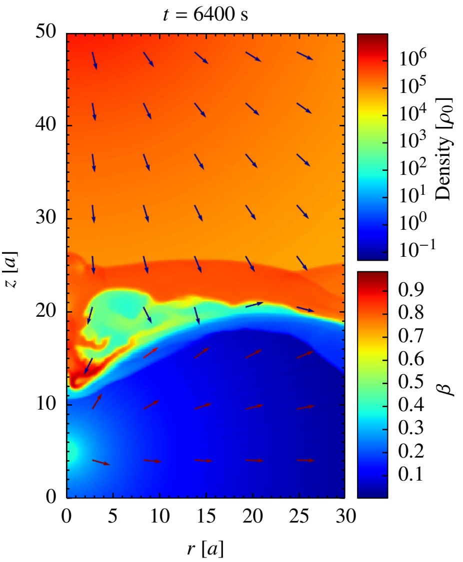


Figure 1: Resolution 1.5 times higher. Clump: $\chi = 10$, $R_{\mathrm{clump}} = 2.5\,a = 2 \cdot 10^{11}$ cm.

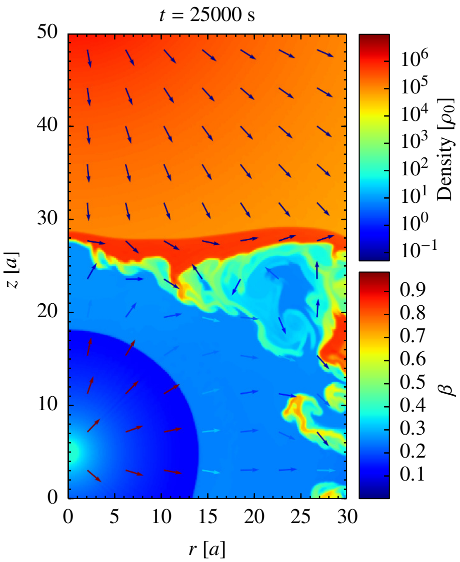
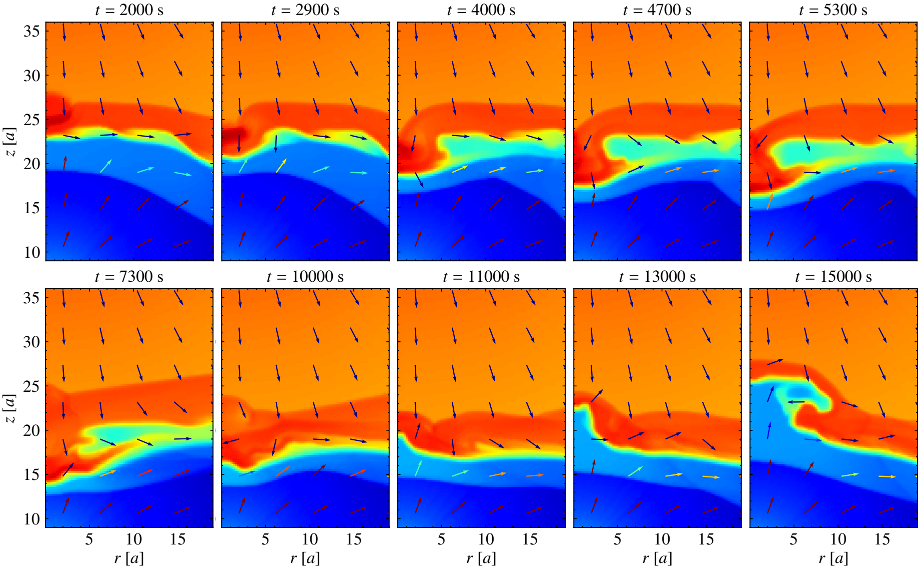


Figure 2: Resolution 2 times higher. Steady state not reached.

Results — light and medium size clump



Clump: $\chi = 10$, $R_{clump} = 2.5\,a = 2 \cdot 10^{11}$ **cm**

Code units: $\rho_0 = 22.5 \times 10^{-22}\ \mathrm{g\ cm^{-3}}$, $a = 8 \times 10^{10}\ \mathrm{cm}$ | $d_{star-pulsar} = 4.4 \times 10^{12}$ cm.