Studying gamma-ray binaries coupling relativistic hydrodynamics and radiation

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Outline

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Introduction

Test-particle approaches: adiabatic evolution, fluid lines

(M)HD+non-thermal feedback

Some general statements (I)

- The physics of **non-thermal (NT) emission** is **tied to** the physics of **the emitting plasma**.
- A fine description of the NT emission requires accounting for the flow properties.
- A detailed account of the flow properties can only be obtained through numerical simulations.
- The NT component cannot be dynamically neglected in general.

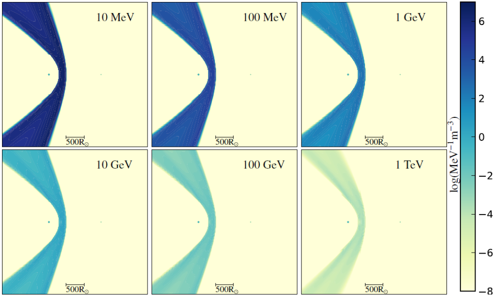
Some general statements (II)

- Studying the NT emission of powerful sources including plasma information requires:
    - **good knowledge of the sources**
    - **programming experience**
    - **(often) powerful hardware**

- Adding complexity is a never ending process: sound physical coherence plus complexity lead to dead-ends either from
    - **source understanding**
    - **computational resources**

Some previous work

- Coupling hydrodynamics and radiation has been done in the past. Traditionally, computer power and source knowledge had made this task difficult.
- Some previous work embraced **shocked clouds, massive star binaries, pulsar high-mass binaries, SNR, AGN and GRB** (Jones 1994, Downes 2002, Gracia et al. 2009, Mimica et al. 2009, Fromm et al. 2011, Takata et al. 2012, Reitberger et al. 2014, etc.).



(Reitberger et al. 2014)

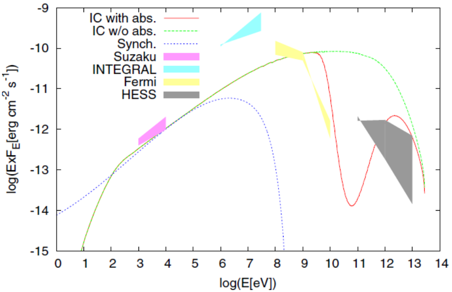
Basic models

One-zone models are useful:

- to derive basic features of the NT particles: **particle acceleration and cooling processes**
- to inform on the role of the **ambient** *B*, **photon and matter fields**,
- and can even suggest emitting **basic flow information** such as velocity or elementary structure.

Radiation reprocessing can be coupled to one-zone emission models, but only pure absorption is rather straightforward to apply.

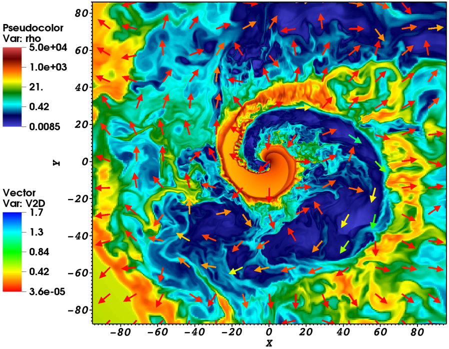
On the other hand, one-zone models are limited by an **oversimplification** of the emitting regions **to one, homogeneous zone**.



(del Palacio, B-R & Romero 2015)

Fluid dynamics (I)

- (Semi)analytical solutions of symmetric laminar flows, plus sound assumptions of shocks and turbulence generation, are a first step.
- Hydrodynamical (HD) simulations give insight on which **sites**/phenomena underlie the **NT processes**.

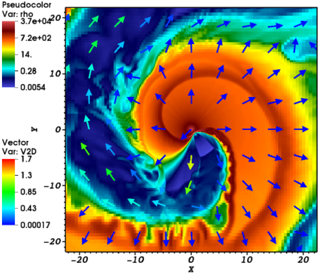


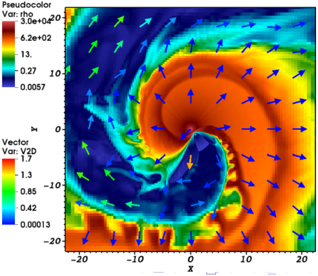
(B-R, Barkov & Perucho 2015)

- **3D numerical HD yields more realistic predictions** regarding the strength and location of shocks, instabilities, and complex sub- to super-sonic flow transitions.
- It allows for **radiation transfer** (without dynamical feedback).

Fluid dynamics (II)

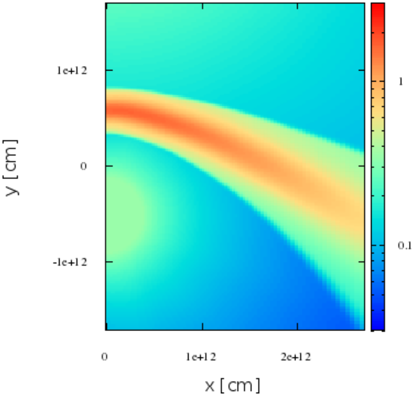
- The time and spatial ranges are limited, and numerical discretization often leads to **unphysical viscosity, heating, and magnetic field diffusion**.
- Thus, some results are **not scalable**, making extrapolation to more realistic regimes difficult.
- The bigger the efforts, the more **expensive** and hard to get the resources needed.
- **Microphysics** is often **too ideal**, as the equation of state, degree of resistivity, NT phenomena... **(↓B-R, Barkov & Perucho 2015)**

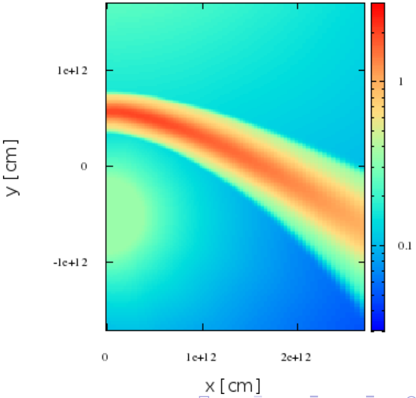




MHD improves the treatment of particle acceleration and synchrotron emission, but affects the flow evolution.

- *B* adds introduces anisotropic pressure and inertia. Non-ideal MHD adds dynamical complexity and heating (reconnection).
- even under passive *B*-fields, synchrotron **cooling thins the shocked structure**. **Left: *B* (th) / Right: *B* (nt) [cgs]**





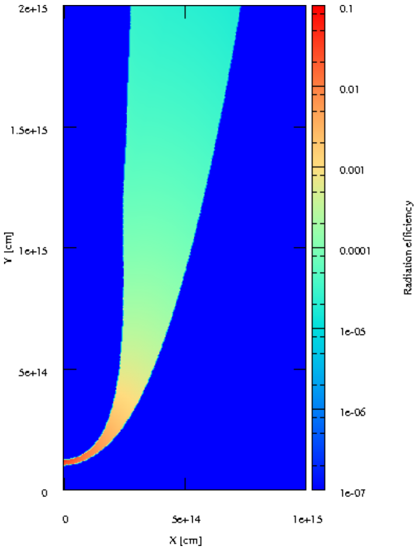
Outline

Aside

- Wind interaction structure formation on middle scales.
- 2D simulations in spherical coordinates, equatorial plane.
- A relativistic and a non-relativistic supersonic wind are injected rotating around the z-axis mimicking orbital motion.
- Wind momentum rate ratio of 0.1.

The adiabatic approximation

- (M)HD simulations with a *suitable* **equation of state**.
- The NT component is **proportional to** the generated **internal energy**.
- Assuming an injection spectrum, and a magnetic **target field prescription** ($u_B \propto u$ or ideal MHD), plus photon fields, etc., allow radiation calculations.



(B-R 2015)

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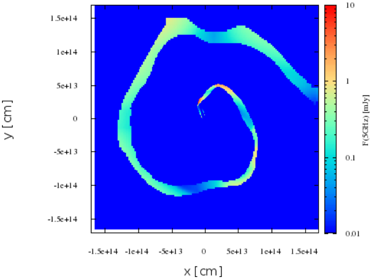
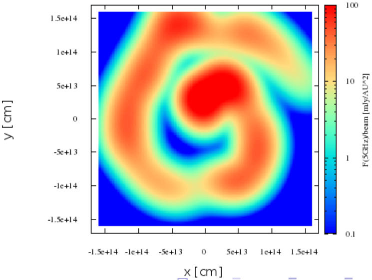
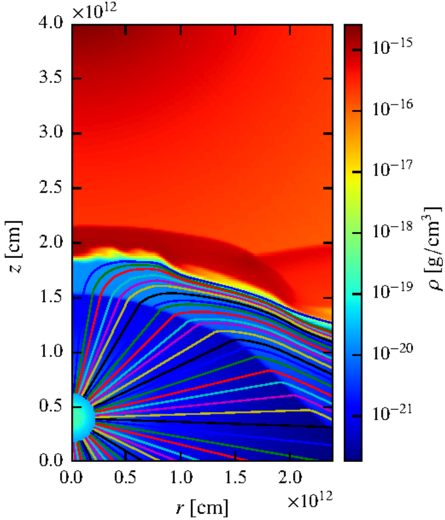




Test particle treatment: fluid lines

- Once the hydrodynamics is settled, space-time **trajectories of fluid** elements can be traced.
- At **shocks** and other dissipation regions, **particle acceleration** can be assumed.
- **NT particles will follow the fluid** trajectories (neglecting diffusion).
- If *B* and other fields are known, **radiation cooling can be included, and emission computed**.



(see de la Cita's talk; de la Cita, B-R, Paredes-Fortuny, et al.)

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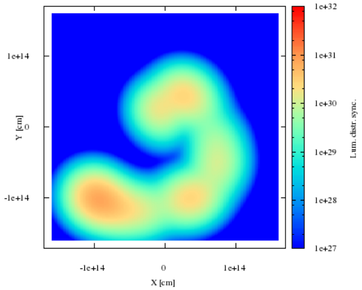
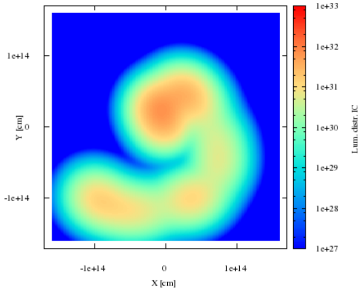
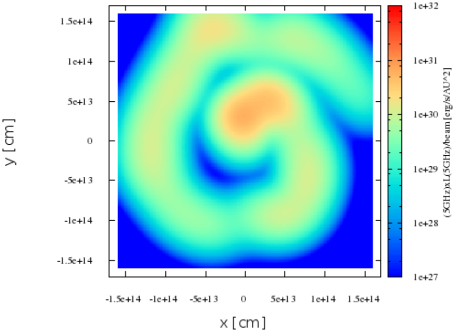


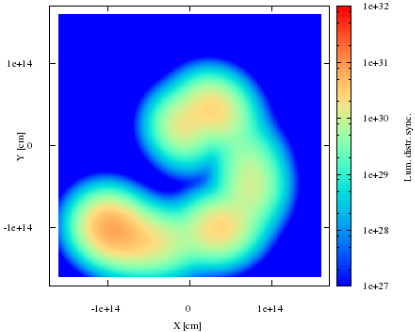


Adiabatic vs fluid lines (I)

Radio flux in mJy/beam computed from the pulsar wind internal energy distribution.

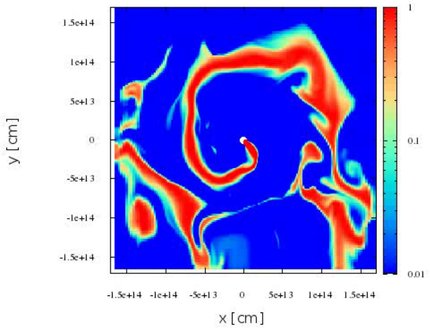
Radio bolometric luminosity per beam around $\sim 2 - 20$ **GHz.**



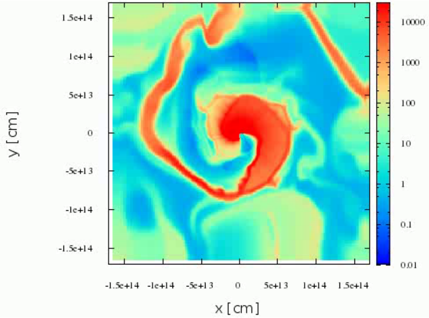


Adiabatic vs fluid lines (II)

Pulsar wind distribution of the interaction region.



Density map of the interaction region.



The two-wind structure suffers of strong mixing from numerics but also instabilities.

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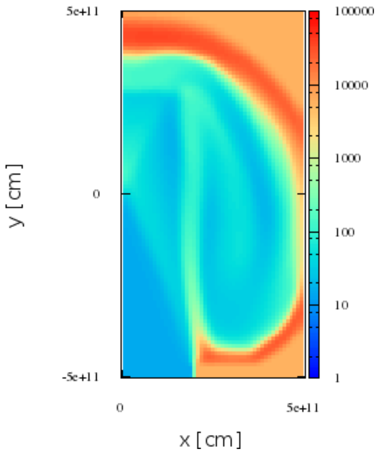
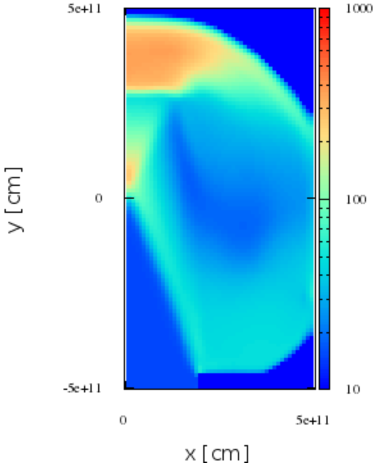
Test simulation

- **2D axi-symmetric RHD: MQ jet leaving its birth environment.**



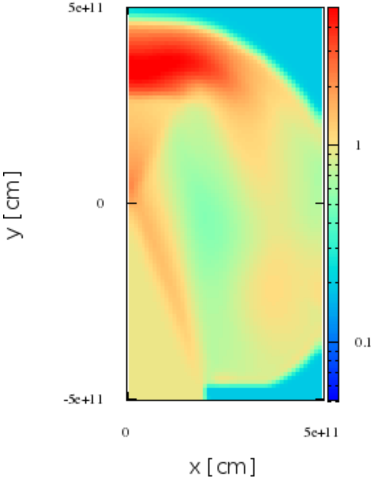
Density map [cgs]



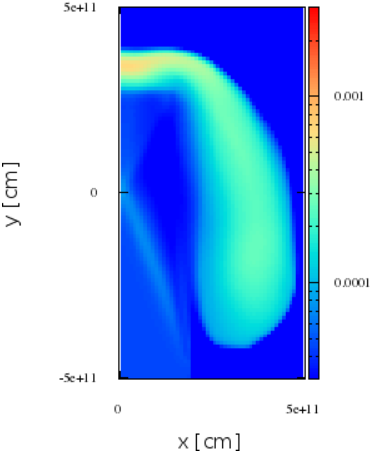
Pressure map

Magnetic field

- **Magnetic lines are advected in the plasma but (here) HD is respected.**



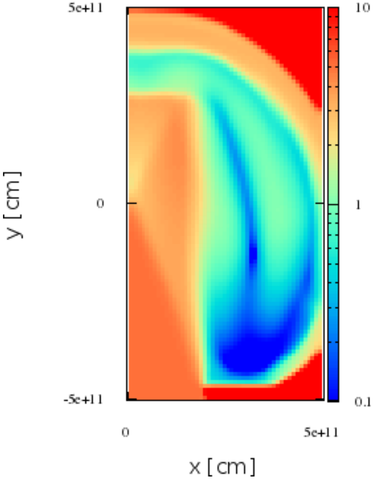
B **strength**



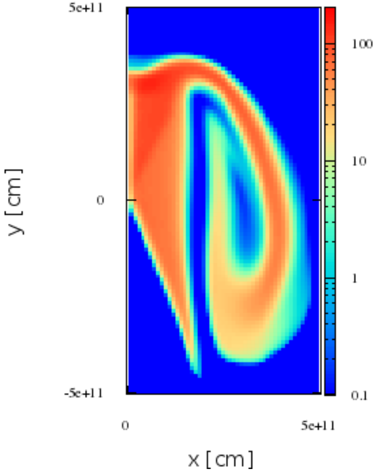
u_B/u **distribution**

Non-thermal particles

- **Shocks *produce* NT particles that are advected and release energy.**



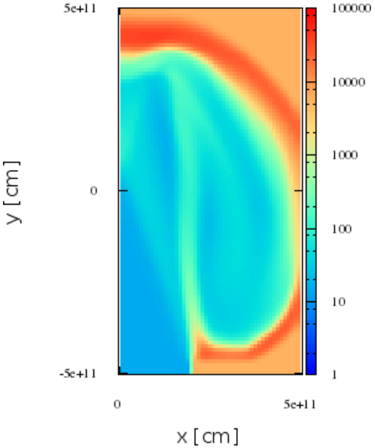
Mach number



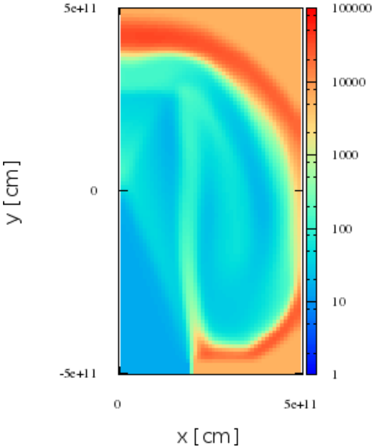
NT energy density

Dynamical feedback

- **Particle cooling depletes the flow of internal energy $\rightarrow \rho$, v and B change**



Fast NT cooling: density



No NT cooling: density