Simulating gamma-ray binaries with a relativistic extension to the RAMSES code

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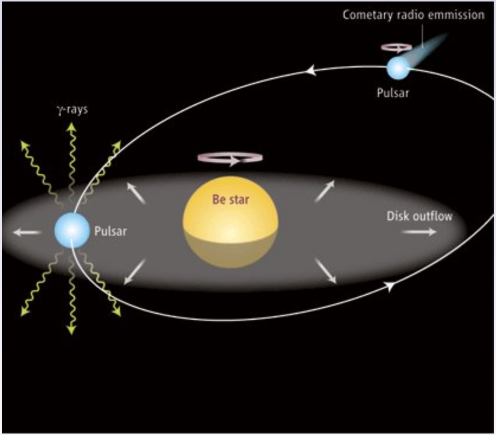
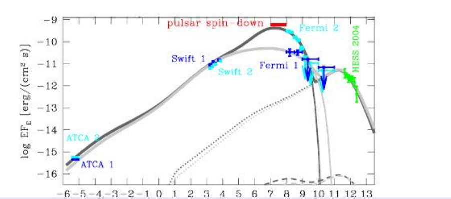
Gamma-ray binaries : pulsar + massive star



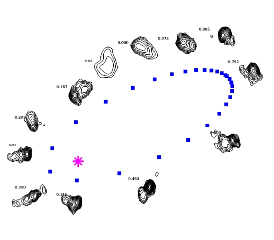
PSR B1259-63 (taken from Mirabel et al, 2006)

- → colliding wind region similar to massive stars (Dubus, 2006)
- Particle acceleration at relativistic shock → very high energy emission
- A handful of systems discovered so far (e.g. LS 5039/PSR B1259-63/ LSI 61+303)

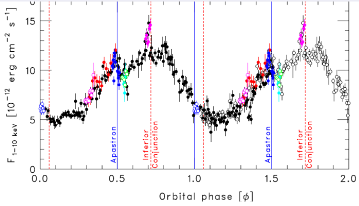
Puzzling observations



SED of PSR B1259-63 (Fermi Collab, 2011)



LSI 61 303 radio map (Dhawan et al., 2006)

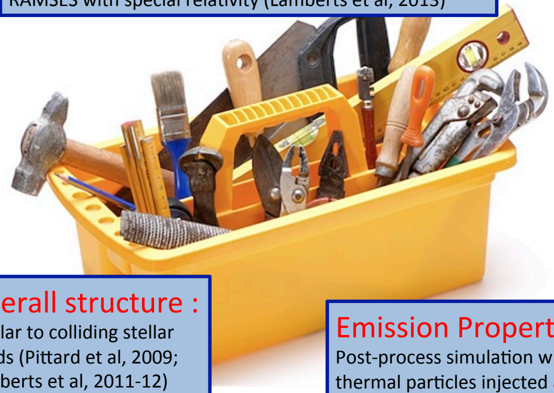


γ lightcurve (Kishishita et al, 2009)

- Which are the emitting regions?
- Where do modulations come from?
- Time-variable, relativistic, magnetised, 3D flow with non-thermal particles $\rightarrow$ Complex to model

Our toolbox

Hydrodynamical evolution :
RAMSES with special relativity (Lamberts et al, 2013)



Overall structure :
Similar to colliding stellar winds (Pittard et al, 2009; Lamberts et al, 2011-12)

Emission Properties :
Post-process simulation with non-thermal particles injected at shock

The only equations of this talk

HD

$$\frac{\partial \mathbf{U}}{\partial t} + \sum_{i=1}^{3} \frac{\partial \mathbf{F_i}}{\partial x_i} = 0 \quad \mathbf{U} = \begin{pmatrix} \rho \\ \rho v_i \\ \frac{1}{2}\rho v^2 + \frac{P}{\gamma-1} \end{pmatrix} \quad \mathbf{F_i} = \begin{pmatrix} \rho v_i \\ \rho v_i v_j + P\delta^{ij} \\ v_i(E+P) \end{pmatrix}$$

(special)RHD (c≡1)

$$\mathbf{U} = \begin{pmatrix} D \\ M_i \\ E \end{pmatrix} = \begin{pmatrix} \Gamma\rho \\ \Gamma^2\rho h v_i \\ \Gamma^2\rho h - P \end{pmatrix} \quad , \quad \mathbf{F_i} = \begin{pmatrix} \rho\Gamma v_i \\ \rho h\Gamma^2 v_i v_j + P\delta^{ij} \\ \rho h\Gamma^2 v_i \end{pmatrix}$$

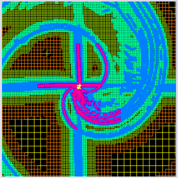
RHD vs HD

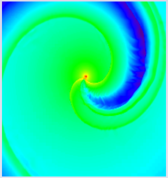
Similar structure but coupling through Lorentz factor $\Gamma = \frac{1}{\sqrt{1-v^2}}$

Additional constraint v<c, more complex equation of state

(Very) brief introduction to RAMSES (Teyssier 2002)

- Based on finite volume method $\rightarrow$ ideal for discontinuities
- Allows Adaptive Mesh Refinement (AMR) Local increase of resolution according to gradients



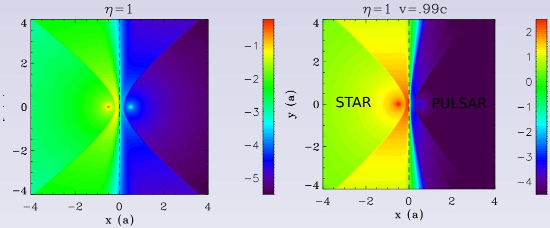


AMR map and density map

3D RHD implementation (Lamberts et al, 2013)

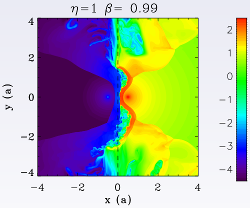
- HLL and HLLC Riemann solver
- AMR with refinement on Lorentz factor
- relativistic equation of state (Mignone et al, 2005)
- U-MUSCL and PLM second order interpolations

colliding wind region (2D, no orbital motion)



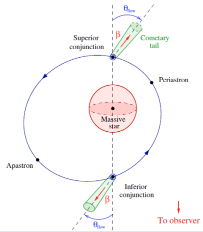
Density for and $v = 0.99c$ non relativistic/relativistic (Lamberts et al, 2013)

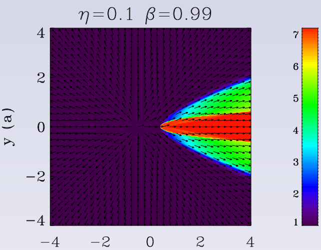
- Positions of discontinuities change due to relativistic jump conditions across shocks → pulsar wind could be more collimated than expected
- Kelvin-Helmholtz instability : large scale impact?



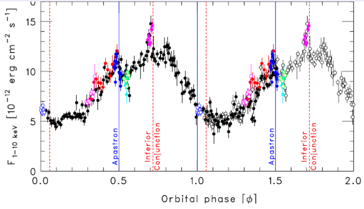
Density when KHI is enabled (Lamberts et al, 2013)

RHD→ Lorentz factor→ boosted emission





Geometry (Dubus, et al, 2010)/Lorentz factor map



γ lightcurve (Kishishita et al, 2009)

Modulated emission in LS 5039

- X-ray/TeV are correlated
- Peak at conjunction → geometrical effects dominate
- Absorption cannot explain X-ray modulation (Szostek et al, 2011)
- → Could be Doppler boost

Modeling the non-thermal emission

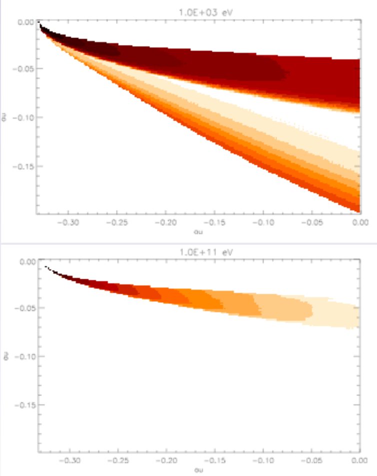
Model cooling of distribution of non-thermal particles

- For each pixel in shocked pulsar wind, follow streamline backwards to shock
- Inject particles at shock and follow then allong the streamlines
- Take into account adiabatic losses (from simulation), synchrotron and anisotropic inverse Compton (with KN effect)
- Relativistic effects : time delay and change of photon density

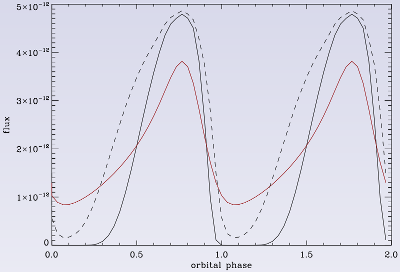
Determine their high energy emission

- In each pixel, determine the resulting synchrotron and IC emission
- Determine absorption because of pair creation
- Take into account orbital effects and Doppler boosting

Preliminary results with 2D simulation for LS 5039



Kev-100GeV emission maps



high-energy lightcurves

- Relativistic Doppler boosting dominates in LS5039
- TeV and KeV emission comes from same electrons

Conclusions

Gamma-ray binaries with RAMSES

- RAMSES-RHD works : 3D AMR code (Lamberts et al, 2013) : suited for relativistic jets, GRB, pulsar wind nebulae...
- Close to the binary, γ-ray binaries show similar structure to stellar binaries with small relativistic effects
- Coupling between RHD simulations and non-thermal particle emission works well
- We reproduce lightcurves and different populations of particles
- 3D model of LS 5039 $\rightarrow$ lightcurves, spectra $\rightarrow$ constraints on orbital parameters and companion