Numerical simulations of astrophysical flows with RAMSES

Extension to relativistic hydrodynamics

Astrid Lamberts
Guillaume Dubus - Sébastien Fromang

IPAG -Sap

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Euler equations

$$
\begin{aligned}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) &= 0 \\
\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla(\rho \mathbf{v}\mathbf{v}) + \nabla P &= 0 \\
\frac{\partial E}{\partial t} + \nabla \cdot [\mathbf{v}(E + P)] &= 0
\end{aligned}
$$

Compressible flows, possibly highly supersonic
Viscous terms neglected

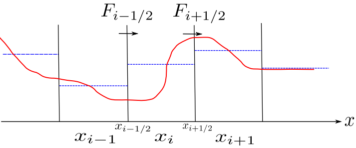
Finite volume method

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{F^i}}{\partial x^i} = 0 \Leftrightarrow \frac{\mathbf{U}_i^{n+1} - \mathbf{U}_i^n}{\Delta t} + \frac{\mathbf{F}_{i+1/2}^{n+1/2} - \mathbf{F}_{i-1/2}^{n+1/2}}{\Delta x} = 0$$

with

$$\mathbf{U}_i^n = \frac{1}{\Delta x} \int_{x_i-1/2}^{x_i+1/2} \mathbf{U}(x, t^n) dx$$

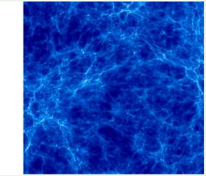
$$\mathbf{F}_{i\pm1/2}^{n+1/2} = \frac{1}{\Delta t} \int_{t^n}^{t^{n+1}} \mathbf{F}(x_{i\pm1/2}, t^{n+1/2}) dt$$



The fluxes are determined by solving a Riemann problem at the interfaces between cells.
Well adapted for shocks.

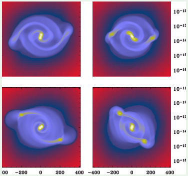
RAMSES (Teyssier, 2002)

Cosmological simulations



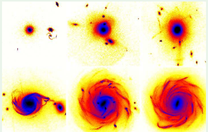
Projet Horizon, Prunet et al, 2008

Star formation



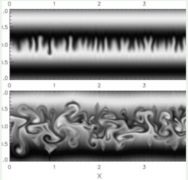
Commerçon et al, 2008

Galaxy structure



Martig et al, 2010

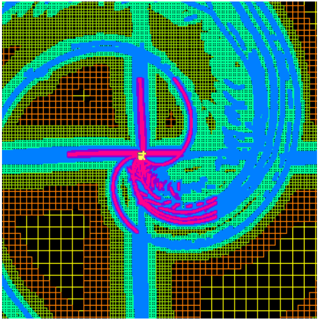
Supernova remnants

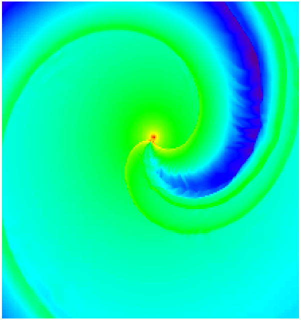


Guilet et al, 2009

Adaptive Mesh Refinement

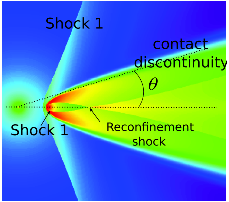
Very wide range of spatial scales ⇒ adaptive mesh refinement (AMR)



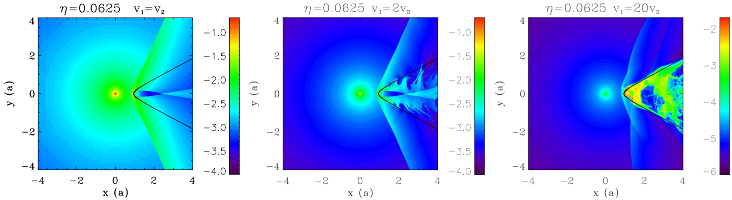


AMR and density map : refinement occurs at shocks and discontinuities

- Massive stars → supersonic winds ($\mathcal{M} \gtrsim 30$)
- Binary system → double shocked structure



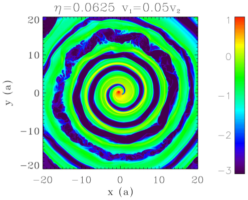
Shocked structure

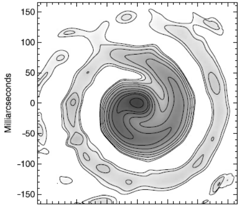


Numerical simulations with increasing velocity gradients.

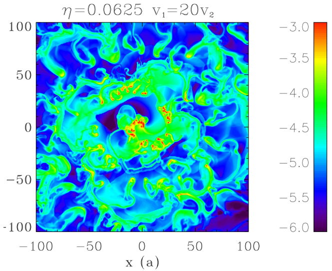
What happens at larger scales ?

Application : colliding wind binaries





Simulation and observation of large scale spiral structure



⇒ Spiral structure not maintained in all cases due to KHI

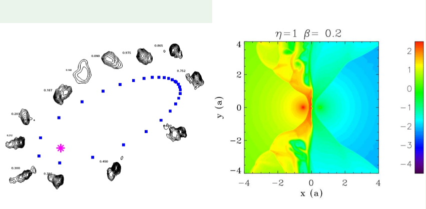
Extension to relativistic hydrodynamics

- Rest frame of the fluid $\neq$ frame of the laboratory
- v<c $\rightarrow$ relativistic summation of velocity
- Lorentz factor $\Gamma = (1 - v^2)^{-1/2}$

Equations have similar structure to HD equations but are more complex due to coupling by the Lorentz factor
Tranverse velocities impact the sctruture of the flow

Possible applications

γ-ray binaries

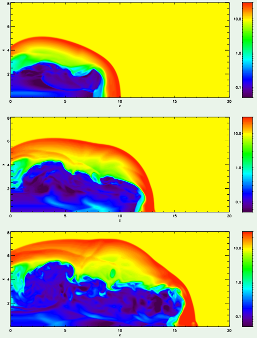


massive star + young pulsar with relativistic wind $\Rightarrow$ impact of KHI

numerical challenge

- Different timescales
- High Lorentz factors $\longrightarrow$ high resolution

Relativistic jets



Jets interacting with surroundings in microquasars, active galactic nuclei or gamma-ray bursts