General relativity M-hydrodynamics code
GR-AMRVAC

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Outline

• Introduction
• Numerical tools
• Accretion disc
• Conclusions
• Projects
Numerical tools

GR-AMRVAC
Numerical tools

**GR-AMRVAC code**

**Multi-physics**
Hydrodynamic, magneto-hydrodynamic, special relativistic HD and MHD, General relativistic HD and MHD.

**Adaptive Mesh refinement**
Bloc-tree

**Parallel**
MPI parallelisation
Code structure

- MPI-AMR
  - Time evolution
    - Metric
      - Schwarzschild
    - Coordinates
      - Kerr
    - User
      - User
      - KADATH
  - User setting
    - Physic
      - Solver
      - EOS
Equations

Equation of motion + Maxwell equations
+ Equation of state

**Covariant approach**
- \( \nabla_\mu (\rho u^\mu) = 0 \)
- \( \nabla_\mu (T^{\mu\nu}) = 0 \)
- \( \nabla_\mu (F^{\ast\mu\nu}) = 0 \)
- \( p = p(\rho, \varepsilon) \)

**3+1 formulation**
- \( \frac{\partial}{\partial x^\mu} (\sqrt{-g} \rho u^\mu) = 0 \)
- \( \frac{\partial}{\partial x^\mu} (\sqrt{-g} T^{\mu\nu}) = \sqrt{-g} \Gamma_\mu^\nu T^{\mu\lambda} \)
- \( \frac{\partial}{\partial x^\mu} (\sqrt{-g} F^{\ast\mu\nu}) = 0 \)
- \( p = p(\rho, \varepsilon) \)

- Martí, Ibáñez & Miralles (1991): 1+1, general EOS
- Eulderink & Mellema (1995): covariant, perfect fluid
- Banyuls et al (1997): 3+1, general EOS

Foliate the spacetime with \( t=\text{const} \)

Finite volume
Analytical metric

Event horizon
Ergosphere

Fluid dynamics with GR-AMRVAC

$t = 20000.0$

Numerical metric with KADTAH

Image
Grid adaptation

- subdivision of blocks, not zones
- quad-tree in 2D, oct-tree in 3D
- blocks distributed among processors for load-balancing
- neighbors may never differ by more than one level
- MPI-parallelization
Refinement Criteria

• Choice of refinement criterion depends strongly on problem to be solved
• Default AMRVAC criterion is 2nd order error estimate (Löhner 1987).

\[
E = \frac{\sum (|u_{i+1/2} - u_{i-1/2}|)^2}{\sum (|u_{i+2} + u_{i-2} + u_{i-1} + u_{i+1} + u_{i+2}|)^2}
\]
Load balance

Morton space-filling curve is passed through all the blocks in the tree

Blocks consecutively assigned to processors from list

This increases chance of neighboring blocks being on same processor
Metric implementation

**Cartesian coordinate**

**Cylindrical coordinate**

**Spherical coordinate**

**Required:**

\[ g_{\mu\nu} = \begin{pmatrix} N^2 - \beta^k \beta_k & \beta_j \\ \beta_i & \gamma_{ij} \end{pmatrix} \]

- Laps
- Shift vector
- Spatial metric
Grid-Metric-Solver

- **Metric element is saved only in curved spacetime zone**
- **Numerical method is level and zone depending**
Code validations in GR (Bondi accretion)

- Second order convergence
- Treatment of numerical and analytical metric

Test with Black hole metric

Test with boson star metric
Test with boson star metric

Test with Black hole star metric

Code validations in GR (Stationary torus)

- Second order convergence
- Ability to treat inside Black Hole and boson star torus
Accretion disc

Compact objects
Recoiling black hole

Density

Image

Light curve
Accretion in the vicinity of BH/Boson star
Why study flow in the vicinity of Boson star

Boson exists

Mass of Boson star could reach Massive BHC?

Boson star can be BHC

New generation of instruments

Predict observational differences between Boson Star and BH as central object candidate
Differences Boson star/ Black Hole

- **Rotation**
  - Matter undergoes different Less-Thirring

- **Horizon**
  - Matter propagates inside/outside

- **Shape**
  - Different geodesic
Torus model

Model of thick torus

• Propose: Abramowicz et al 1978

Characteristics:

• Constant specific angular momentum
• Inner radius
• Cusp: accretion
• At center: Keplerian rotation
Shadow of Boson Stars/Kerr BH

Boson star – disk shadow

BH shadow
Accretion in BH / Boson star

Accretion in BH

Accretion – ejection in Boson star

T = 120 M

T = 74.7 M
Tidal disruption by Boson star
Tidal disruption of stars by BH

**Theory 70-80**
- Lacy et al 1982
- Luminet and Marck 1985
- ...

**Observation X-Ray**
- Komossa and Bade 1999
- Merloni et al. 2015
Tidal disruption with BS (Model)

Cloud
- Zero angular momentum
- Zero initial speed
- Uniform density
- Low pressure

External medium
- Low density
- Low pressure
Cloud near BS

First phase

• Cloud oscillates in center
• Tidal disruption increases each time cloud cross the center

Last phase

• Disc formation
Tidal disruption with BS (cloud at larger distance)

First phase
- The cloud accelerates to 0.5c
- Deflected by 120°

Last phase
- Disc formation
- Vortex within torus
Conclusions

- Development of general relativistic code
Projects

- *Time evolution of the space-time* + GRMHD
- *Particles acceleration* + *general relativistic magneto-hydrodynamic*