Magnetic dissipation in short gamma-ray burst jets

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Gamma-ray bursts (GRBs)

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- 30% of the gamma-ray bursts observed
- duration from 10 ms to 2 s
- likely generated by kilonovae

Long gamma-ray bursts

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Several open questions (long GRB from kilonovae, ultra-long GRBs, . . .)

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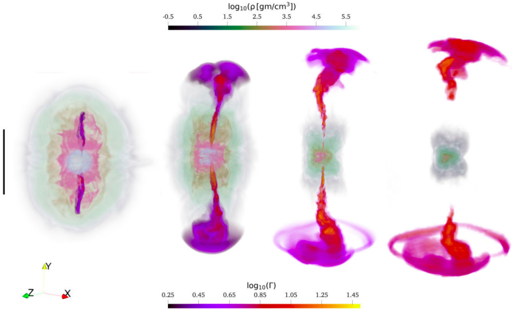
Challenges:

- resulting compact object
- consistent jet launching
- consistent propagation of jet from neutron star merging process

State-of-the-art simulations (Pavan et al 2021, 2023):

- realistic post-merger environment
- fully 3D
- analytical jet injected ad the boundary
- ideal assumption ($E = -v \times B$)



Jet-environment interplay

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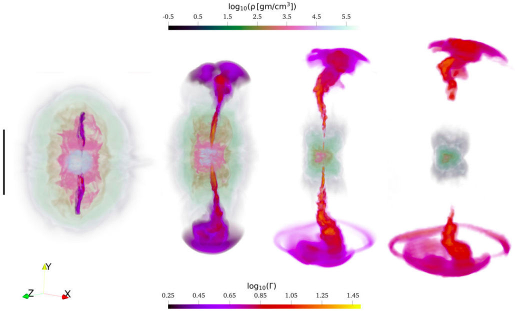

Magnetic dissipation?

Dissipative processes play a role in the formation and evolution of relativistic jets! (Vourellis et al 2020, Mattia & Fendt 2022, Mattia et al 2023)

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Open questions:

- Do GRB propagate under the assumption of finite conductivity?
- Do resistive effect propagate until the afterglow emission?
- Do resistive processes impact thejet shape and dynamics?

Need for:

- multiscale simulations
- high resolution
- consistent post-merger ambient and jet
- beyond the ideal approximation

Relativistic MHD

Set of hyperbolic partial differential equations.

Anile 1989, Del Zanna et al. 2003, Del Zanna 2007, Bucciantini & Del Zanna 2013

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Fluid conservation laws:

- mass
- momentum-energy
- Maxwell equations

Characteristic velocities:

- fluid motion v
- sound speed $\sqrt{p/\rho}$
- Alfvén speed $\sqrt{B^2/\rho}$

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Full set of relativistic MHD equations:

$$
\begin{aligned}
&\partial_t D + \nabla \cdot (\rho \gamma \mathrm{v}) = 0 \\
&\partial_t \mathrm{m} + \nabla \cdot (\rho h \gamma \mathrm{vv} - \mathrm{EE} - \mathrm{BB} + p_t \mathrm{I}) = 0 \\
&\partial_t \mathcal{E} + \nabla \cdot \mathrm{m} = 0 \\
&\partial_t \mathrm{B} + \nabla \times \mathrm{E} = 0 \\
&\partial_t \mathrm{E} - \nabla \times \mathrm{B} = -\mathrm{J}
\end{aligned}
$$

Anile 1989, Del Zanna et al. 2003, Del Zanna 2007, Bucciantini & Del Zanna 2013

From ideal to resistive

Ideal case

$$F_{\nu\mu} u^{\mu} = 0$$

$$E + v \times B = 0$$

Electric field:

- always a function of v and B
- always perpendicular to B

Resistivity:

- vanishes everywhere

Komissarov 1999, 2007, Palenzuela 2009

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Resistive case

$$F_{\nu\mu}u^{\mu} = \eta I_{\nu} + \eta I_{\mu}u^{\mu}u_{\nu}$$

$$J = \gamma\eta^{-1}[E + v \times B - (E \cdot v)v] +$$
$$+(\nabla \cdot E)v$$

Electric field:

- independent variable of the physical system
- direction is not known a priori

Resistivity:

- can change spatially and during time.

Numerical issues and challenges

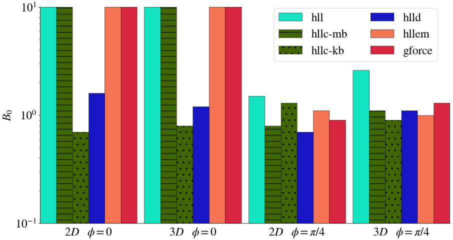
Stiff equation for the electric field:

$$\partial_t \mathrm{E} - \nabla \times \mathrm{B} + \frac{\gamma}{\eta}[\mathrm{E} + \mathrm{v} \times \mathrm{B} - (\mathrm{E} \cdot \mathrm{v})\mathrm{v}] + q\mathrm{v} = 0$$

Non-evolutionary equations (+ charge conservation):

$$\nabla \cdot \mathrm{B} = 0$$
$$\nabla \cdot \mathrm{E} = q$$

Accuracy vs stability

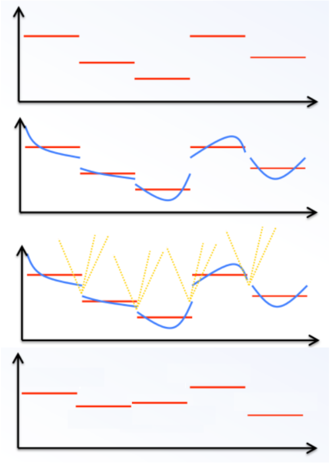


Bucciantini & Del Zanna 2013, Mignone et al. 2019, Tomei et al. 2020, Mattia & Mignone 2022, Mattia et al. 2023

The PLUTO code

PLUTO is a finite-volume code designed to integrate and solve a set of conservation laws in the following steps (Mignone et al. 2007, Mignone et al. 2012):

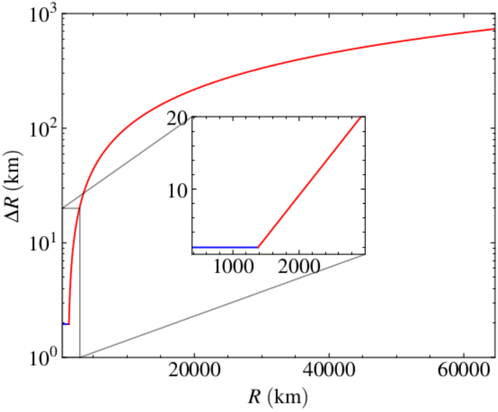
- Starts from volume averages
- Reconstruct interface values from zone averages
- Solve Riemann problems between adjacent, discontinuous states to compute the interface flux
- Update conserved variables with time stepping algorithm



Mignone et al. 2007, 2012

Numerical setup

- 2D spherical axisymmetric simulation (R,θ)
- jet launched close to the axis
- resolution $N_R \times N_\theta = 1024 \times 256$
- uniform $+$ stretched grid
- radial extension: $[380, 65000]$ km



Initial and boundary conditions

- analytical environment + analytical jet
- breakout radius (post-merger wind / atmosphere) at 5000 km
- density and pressure $\rightarrow$ power law
- expanding post-merger wind, static atmosphere
- magnetic dipole from the compact object, unmagnetized atmosphere
- jet luminosity: $L_{0,tot} = 1.079059 \times 10^{52} \mathrm{erg/s}$
- radial + toroidal jet speed/magnetic field
- jet injected at the inner radial boundary
- jet angular structure (not uniform in θ)

Resistivity prescription

Non-dimensional parameter: Lundquist number (radio between Alfvèn timescale and diffusive timescale)

$$S = \frac{L v_a}{\eta} \rightarrow \eta = \frac{L v_a}{S}$$

$L = 380.0 = R_{min}$.

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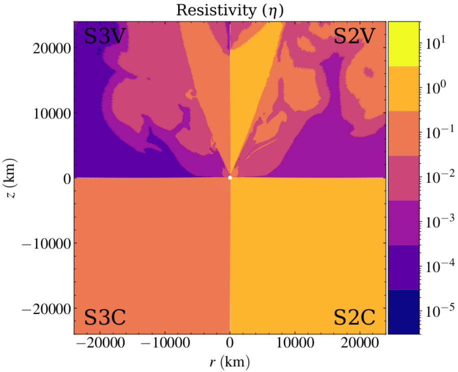
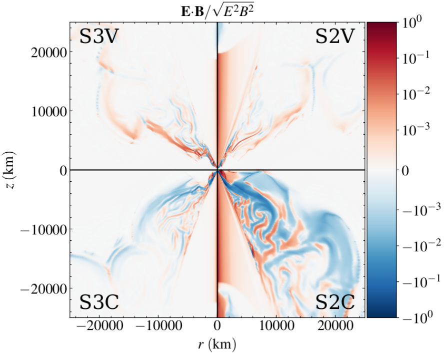
Different cases:

- $S = 10^2$, $v_a = 1$ (S2C)
- $S = 10^2$, $v_a = v_a$ (S2V)
- $S = 10^3$, $v_a = 1$ (S3C)
- $S = 10^3$, $v_a = v_a$ (S3V)



Results: jet electromagnetic fields



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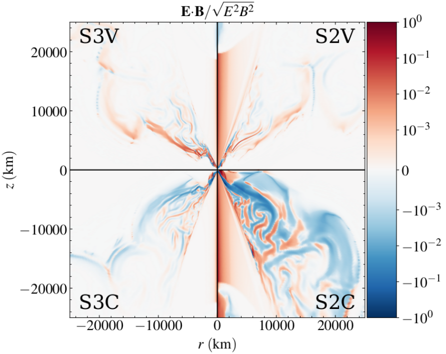
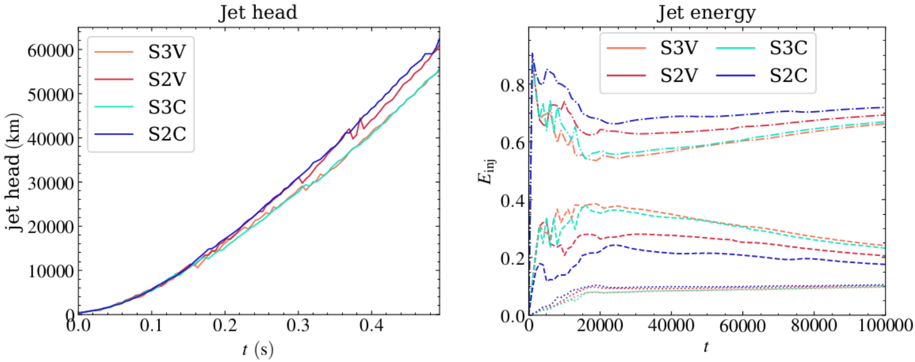


Different resistivity prescription affect the evolution of the jet and its interaction with the post-merger medium

Results: jet shape and energy



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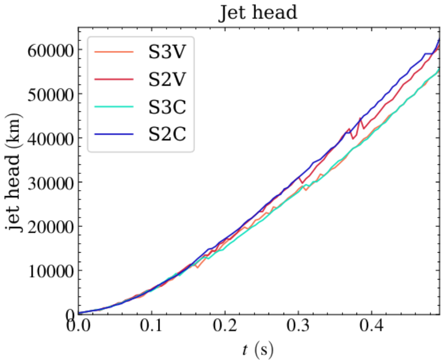

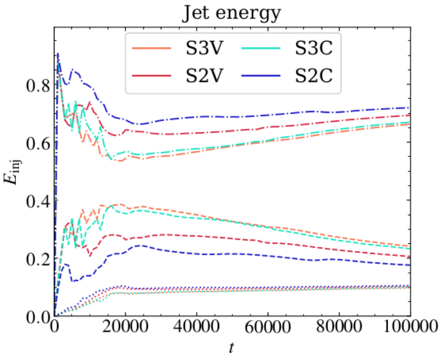

Diffusion processes impact the jet energy balance and dynamics!

Conclusions

In summary:

- non-ideal processes may play a strong role on short GRB-jets evolution
- the dynamics and the energetics of the jet is related to the magnetic resistivity
- non-ideal processes occur within $\sim 1000\ \mathrm{km}$ but their impact extends much further
- resistivity impacts also the interaction with jet and the post-merger medium

Next steps:

- 3D resistive simulation with analytical environment
- 3D resistive simulation with realistic environment

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THANK YOU