Resistive relativistic MHD and numerical simulations of astrophysical jets

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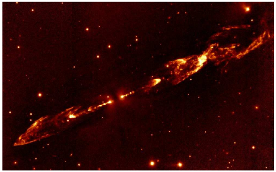
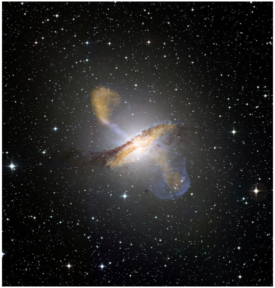
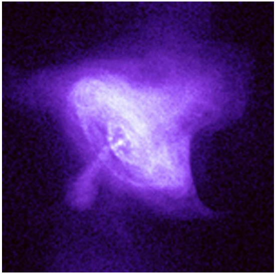
22/02/2023

Relativistic jets

Astrophysical jets: fast collimated ejection of material.
Sources: protostellar objects, active galactic nuclei, neutron star mergers, pulsars,. . . .







Credits: Nasa

Differences: order of magnitudes in space time and energy scales.
Common features: synchrotron emission from non-thermal relativistic particles.

Rybicki & Lightman 1986

Particles acceleration

Acceleration mechanisms are required! Particles in electromagnetic field:

$$\frac{d\mathrm{p}}{dt} = \frac{d(m\gamma\mathrm{v})}{dt} = e\left(\mathrm{E} + \frac{\mathrm{v}}{c} \times \mathrm{B}\right)$$

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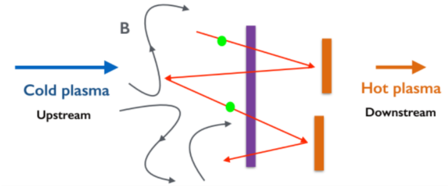
Diffusive shock acceleration:

Blandford and Eichler 1987

particles bounce through a shock front, gaining energy every time



Credits: Emanuele Beratto

Not always efficient!

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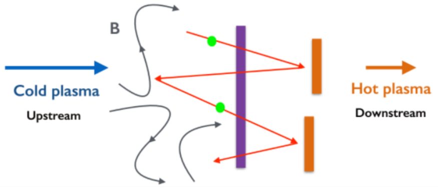

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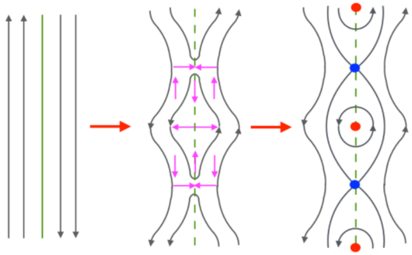
Magnetic reconnection:

Loureiro & Uzdensky 2016

rearrangement of the topological magnetic field structure



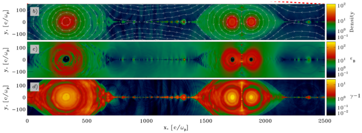
Magnetic reconnection

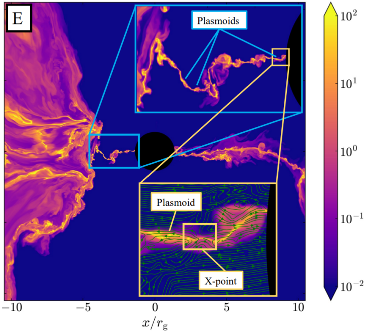
Particles acceleration in magnetic reconnection sites:

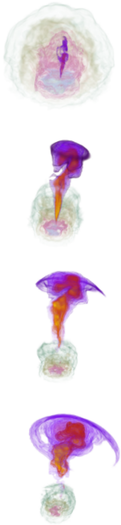
Magnetic reconnection resolved, but no large scale jet!

Connecting the scales

- Electron scale (PIC):
  - $L \approx 10^4 km$
  - $t \approx 10^2 s$
- Ion scale (Hybrid):
  - $L \approx 10^8 km$
  - $t \approx 10^4 s$
- Jet collimation(MHD):
  - $L \approx 10^{15} km$
  - $t \approx 10^9 s$
- Jet propagation (MHD):
  - $L \approx 10^{18} km$
  - $t \approx 10^{12} s$







Sironi & Spitkovsky 2014, Ripperda et al. 2022, Pavan et al. 2023

Open questions

What we do not know:

- How are particles accelerated in jets?
- Where are particles accelerated?
- Role of the large scale jet properties?
- How do we connect the particle scale with the jet propagation scale?

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Need for:

- multiscale simulations (here focus on large scales)
- high resolution
- consistent physical processes
- cutting edge numerical algorithms

MagnetoHydroDynamics

Set of hyperbolic partial differential equations.
Fluid conservation laws:

- mass

$$\partial_\alpha \left(\rho u^\alpha\right) = 0$$

- momentum-energy

$$\partial_\alpha (T_{fl}^{\alpha\beta} + T_{em}^{\alpha\beta}) = 0$$

Maxwell equations:

$$\partial_\alpha \mathrm{F}^{\beta\alpha} = -J^\beta$$
$$\partial_\alpha^* \mathrm{F}^{\beta\alpha} = 0$$

Anile 1989, Del Zanna et al. 2003

Relativistic velocities

Characteristic velocities:

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

Plasma become relativistic when they approach the speed of light!

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. 2007

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

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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

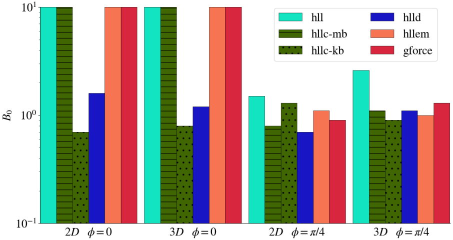
Stiff equation for the electric field:

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

Non-evolutionary equations:

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

Accuracy vs stability

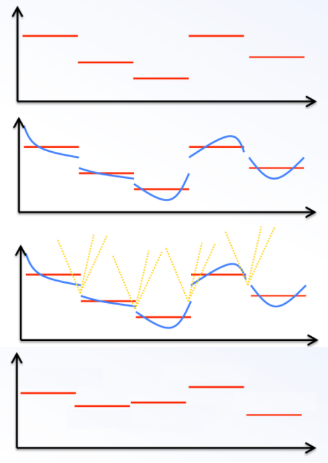


Palenzuela et al. 2009, Mignone et al. 2019, Mattia & Mignone 2022

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

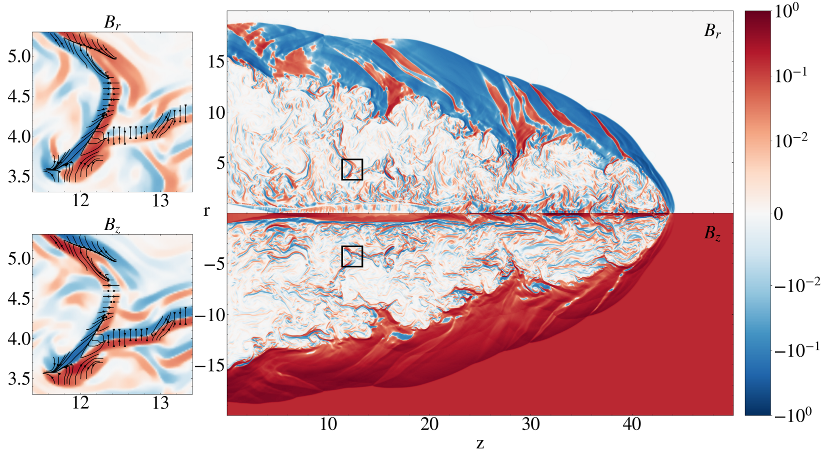


Mignone et al. 2007, 2012

Relativistic jets with finite conductivity

Formation of current sheets

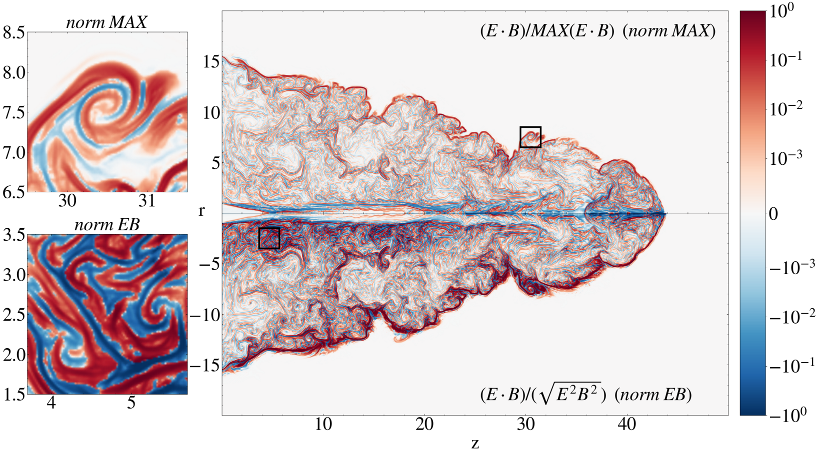
Current sheets: source of magnetic reconnection.



Consistent recipes for simulations at the smaller scales.
Resolution is too low to see the full process!

Formation of guide fields

Guide field: source of particles acceleration.



Multiple zones with strong parallel field.
Acceleration at different jet locations!

Conclusions

- We need simulations at very different scales to encompass all the relevant phenomena in astrophysical jets
- Magnetic reconnection is an efficient mechanism to accelerate particles
- Large-scale simulations can provide consistent recipes for magnetic reconnection
- Need for robust and accurate schemes and high resolution simulations
- Lots of room for improvements!

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THANK YOU