Reconnection in Magnetically-Dominated Plasmas: Jets and Disks

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Cosmic Accelerators, November 6\textsuperscript{th} 2017

Magnetic reconnection

\[ E = v \wedge B \]

reconnecting field

\[ \sigma = \frac{B_0^2}{4\pi n_0 m_p c^2} \]

\( \sigma \ll 1 \)

\( \sigma \gg 1 \)

Relativistic Reconnection

\[ \sigma = \frac{B_0^2}{4\pi n_0 m_p c^2} \gg 1 \quad v_A \sim c \]

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AGN jets

Lab

MMS

Crab Nebula
Outline

1. Blazar jets (also microquasars, GRB jets, pulsar winds). Ultra-relativistic reconnection ($\sigma \gtrsim \text{a few}$).

2. Collisionless accretion flows (like Sgr A* in our Galactic Center). Trans-relativistic reconnection ($\sigma \sim 1$).
No approximations, full plasma physics of ions and electrons

Tiny length-scales ($c/\omega_p$) and time-scales ($\omega_p^{-1}$) need to be resolved: $\omega_p = \sqrt{\frac{4\pi ne^2}{m}}$

⇒ huge simulations, limited time coverage

• Relativistic 3D e.m. PIC code TRISTAN-MP (Buneman 93, Spitkovsky 05, LS+ 13)
Dynamics and particle spectrum
• Inflow into the layer is non-relativistic, at  \( v_{in} \sim 0.1 \, c \) (Lyutikov & Uzdensky 03, Lyubarsky 05).

• Outflow from the X-points is ultra-relativistic, reaching the Alfvén speed  \( v_A = c \sqrt{\frac{\sigma}{1 + \sigma}} \)
• In 3D, the in-plane tearing mode and the out-of-plane drift-kink mode coexist.
• The drift-kink mode is the fastest to grow, but the physics at late times is governed by the tearing mode, as in 2D.

(LS & Spitkovsky 14)
The particle energy spectrum

- At late times, the particle spectrum approaches a power law $\frac{dn}{d\gamma} \propto \gamma^{-p}$.

- The max energy grows linearly with time, if the evolution is not artificially inhibited by the boundaries.

(LS & Spitkovsky 14)
1. Reconnection in blazar jets
(A) Extended non-thermal distributions

Blazar phenomenology:

- extended power-law distributions of the emitting particles, with hard slope
  \[ \frac{dn}{d\gamma} \propto \gamma^{-p} \quad p \lesssim 2 \]

Relativistic reconnection:

✓ it produces extended non-thermal tails of accelerated particles, whose power-law slope is harder than \( p=2 \) for high magnetizations (\( \sigma > 10 \))
For stronger guide fields, the normalization and the maximum energy are smaller, because the reconnection electric field (and so, the reconnection rate) are smaller.
(B) Fast time variability

Blazar phenomenology:

- at TeV and GeV energies, fast (~10 minutes) flares

Relativistic reconnection:

✓ the fast islands/plasmoids can be a promising source of short-time variability

PKS 2155-304

10 mins

(Aharonian et al. 07)

3C 279

(Ackermann+16)

“jets in a jet”

(Giannios 09,13)

[Giannios’s talk]
Plasmoids in reconnection layers

- Density
- Magnetic energy
- Kinetic energy
- Outflow 4-velocity

\( \sigma = 10 \quad c t_{lab} / L = 0.0 \quad L \sim 1600 \, c / \omega_p \)

\( B_0 \)

(LS, Giannios & Petropoulou 16)
We can follow individual plasmoids in space and time.

First they grow, then they go:

- First, they grow in the center at non-relativistic speeds.
- Then, they accelerate outwards approaching the Alfven speed $\sim c$.

\[ \sigma = 10 \quad L \sim 1600 \, c/\omega_p \quad \text{electron-positron} \]

(LS, Giannios & Petropoulou 16)
The plasmoid width $w$ grows in the plasmoid rest-frame at a constant rate of $\sim 0.1 \, c$ ($\sim$ reconnection inflow speed), weakly dependent on the magnetization.

Universal relation for the plasmoid acceleration:

$$\Gamma \frac{v_{\text{out}}}{c} \approx \sqrt{\sigma} \tanh \left( \frac{0.1 \, x}{\sqrt{\sigma} \, w} \right)$$

(LS, Giannios & Petropoulou 16)
Let us measure the system length $L$ in units of the post-reconnection Larmor radius:

$$r_{0,\text{hot}} = \sigma \frac{mc^2}{eB_0}$$

Relativistic reconnection is a self-similar process, in the limit $L \gg r_{0,\text{hot}}$:

- The width of the biggest (“monster”) islands is a fixed fraction (~0.1-0.2) of the system length $L$.

- The Larmor radius of the highest energy particles is a fixed fraction (~0.03-0.05) of the system length $L$: Hillas criterion of relativistic reconnection.

$\rightarrow$ the scalings can be used to extrapolate up to the scales of blazar emission!

[Petropoulou’s talk]

(LS, Giannios & Petropoulou 16)
Rise: based on PIC simulations.

Decay: parameterized (cooling / photon diffusion / drop in particle injection).

(Petropoulou, Giannios & LS 16)

\[ w_f = 0.2 \text{ L (large & slow)} \]

\[ w_f = 0.04 \text{ (small & fast)} \]

\[ \sigma = 10 \quad \theta_{\text{obs}} = 0.5 / \Gamma_j \]

(Petropoulou's talk)
2. Reconnection in accretion disks
Magnetic reconnection in Sgr A*

\[ \nu = 2.2 \times 10^{11} \text{Hz} \]
\[ \lambda = 1.3 \times 10^{0} \text{mm} \]

\[ \beta = \frac{8\pi n_0 k_B T}{B_0^2} \quad \sigma = \frac{B_0^2}{4\pi n_0 m_p c^2} \]

- The plasma around reconnection layers spans a range of beta and sigma.

[Log[\beta] vs. Log[\sigma]]

(Ball+ 17)
Electron heating in Sgr A*

Sgr A* : spectrum

• Thermal trans-relativistic electrons (with $T_e/T_p \sim 0.3$) are invoked to explain the peak of Sgr A* spectrum.

• Non-thermal electrons are invoked to explain the spectrum and time variability of X-ray flares from Sgr A* (Ponti+ 17).

Electron-to-total heating ratio

• Electrons are always heated less than protons (for $\sigma \ll 1$, the ratio is $\sim 0.2$).

• Comparable heating efficiencies if:
  - high beta, when both species already start relativistically hot.
  - in relativistic ($\sigma \gg 1$) reconnection.

[Rowan’s poster]
Particle acceleration mechanism
The highest energy electrons

2D $\sigma=0.3$ electron-proton

Two acceleration phases: (a) at the X-point; (b) in between merging islands

(Ball, LS & Ozel, in prep)
The highest energy particles

Two acceleration phases: (a) at the X-point; (b) in between merging islands
The particles are accelerated by a Fermi-like process in between merging islands (Guo+14, Nalewajko+15).

Island merging is essential to shift up the spectral cutoff energy.

In the Fermi process, the rich get richer. But how do they get rich in the first place?
In cold plasmas, the particles are tied to field lines and they go through X-points. The particles are accelerated by the reconnection electric field at the X-points (Zenitani & Hoshino 01). The energy gain can vary, depending on where the particles interact with the sheet. The same physics operates at the main X-point and in secondary X-points.
Dependence on beta

$\sigma = 0.1 \quad \beta = 0.01$

$\sigma = 0.1 \quad \beta = 2$

[Rowan’s poster] (Rowan, LS & Narayan 2017)
Summary

- Ultra-relativistic magnetic reconnection ($\sigma \gtrsim 1$) is an efficient particle accelerator, in 2D and 3D, with and without a guide field. The power-law slope is harder for higher magnetizations and weaker guide fields.

- Plasmoids generated in the reconnection layer are in rough energy equipartition between particle and magnetic energy. The largest plasmoids contain the highest energy particles, with Larmor radius $\sim 0.04 \, L$ (Hillas criterion). Fast plasmoids can explain the extreme time variability of blazar flares.

- In trans-relativistic reconnection ($\sigma \sim 1$), the power-law slope is a function of both the magnetization sigma and the plasma beta. The slope is harder for higher sigma and/or lower beta. Electron injection happens at X-points, which are more frequent for higher sigma and lower beta.

- Open questions:
  - What determines the power-law slope, from the non-relativistic to the ultra-relativistic regime, accounting for the dependence on sigma and beta?
  - How do current sheets arise, in a global model?