Cosmic Ray Acceleration by Magnetic Reconnection

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Black Hole sources are Cosmic Ray (CR) accelerators and Very High Energy (VHE) emitters

AGNs (blazars, radio-galaxies, seyferts)

Black Hole Binaries (Microquasars)

GRBs
Particle acceleration in compact sources: new challenges

- Some Black Hole sources & jets
- Pulsar wind nebulae

If acceleration regions are magnetically dominated
  -> shocks weak

Standard particle **Fermi acceleration in shocks:**

  -> may fail to explain relativistic particles origin and associated very high energy emission (up to TeV) occurring in very compact regions

**Alternative mechanism**  ->  **Magnetic reconnection**
Observational Properties of high energy emission of these sources

- Often non-thermal power-law spectra $\rightarrow$ efficient non-thermal particle acceleration yielding high energy power law-tail

- Intense rapid gamma-ray flares (e.g. 200s TeV flares in blazars) $\rightarrow$ short time variability

PKS2155-304 (Aharonian et al. 2007)
See also Mrk501, PKS1222+21, PKS1830-211

Can magnetic reconnection explain these properties?
YES!
This key talk

MAGNETIC RECONNECTION an alternative:

- Powerful relativistic particle acceleration
- May explain gamma-ray emission
- Dissipation of magnetic energy -> conversion into kinetic energy
PLASMA in a nutshell

- Plasma quasi-neutral gas of charged particles (electrons + ions):
  \[ n_e \sim Z n_i \]
  with long range **collective interactions**.

- Over **90% of visible matter in Universe**: PLASMA
Tips - plasma parameters

- Debye length
  \[ \lambda_D \approx \frac{v_{th}}{\omega_{pe}} \approx \left( \frac{K T_e}{4 \pi n_e e^2} \right)^{1/2} = 7 \text{ cm} \left( \frac{T_e}{n_e} \right)^{1/2} \]

- Plasma frequency
  \[ \omega_{pe} = \left( \frac{4 \pi n_e e^2}{m_e} \right)^{1/2} \approx 5.6 \times 10^4 n_e^{1/2} \text{ s}^{-1} \]

- Cyclotron radius
  \[ r_L = \frac{p}{Z e B} \quad r_L = 33.36 \text{ km} \left( \frac{p}{\text{GeV/c}} \right) \left( \frac{1}{Z} \right) \left( \frac{G}{B} \right) \]

- Alfven velocity
  \[ V_A = B/(4 \pi \rho)^{1/2} \]
Intermediate - *microscopic scales*: \( l \gg \lambda_D \)

*kinetic theory* describes the collective behaviour of the many charged particles by means of particle distribution functions (*Fokker-Planck equation*):

\[ f_{e,i}(r, v, t) \]

Large – *macroscopic scales*: \( L \gg \lambda_{mfp} \sim r_L \)

effectively *collisional* - fluid description: size and time scales are large enough \( \rightarrow \) possible to apply AVERAGES over microscopic quantities: over collective plasma oscillations and collective cyclotron motions (*MHD equations*)

Applicable to most astrophysical plasma species
MHD description applicable to most astrophysical plasma species

➢ **BUT:** cosmic ray component is *collisionless*

→ need kinetic description
→ and is coupled through waves with rest of the plasma

(Tchekhovskoy’s cartoon)
Let us start ....
with Cosmic Ray Acceleration by Magnetic Reconnection
WHAT IS MAGNETIC RECONNECTION?

Approach of magnetic flux tubes of opposite polarity with finite resistivity ($\eta \sim 1$/conduction): RECONNECT

Reconnection is FAST in these environments!

$$V_{rec} \sim V_A = B/(4\pi \rho)^{1/2}$$
Reconnection beyond Solar System

- Accretion disk coronae
- Stellar X-ray Flares
- AGN & GRB Jets
- Accreting NS and SGRs
- Pulsars
- Star Formation and ISM
Magnetic Reconnection Models

- Sweet-Parker (1957) reconnection:

\[
V_{\text{rec}} \sim v_A \frac{S^{1/2}}{\Delta L} \ll 1 \quad \rightarrow \quad \text{SLOW reconnection}
\]

\[
S = L \frac{v_A}{\eta} \gg 1
\]

**But** \(\Delta/L \ll 1\)

From mass flux conservation:

\[
V_{\text{rec}} \sim v_A (\Delta/L)
\]
Magnetic Reconnection Models

Petschek (1964): X-point configuration ->

\[ \Delta \rightarrow \Delta \sim L \]

Then reconnection rate is FAST:

\[ V_{\text{rec}} \sim \pi v_A/4 \ln S \]

Where \( S = L v_A/\eta \gg 1 \)

**BUT:** unstable and evolves to Sweet-Parker (Biskamp’96) unless:

**pair plasma at kinetic scales** with localized resistivity \( \eta \)
Magnetic Reconnection Models

Petschek X-point configuration $\rightarrow$ arises naturally in kinetic (collisionless) ion-$e^-$ or $e^+e^-$ pair plasma with localized $\eta$

- **Kinetic simulations**: 2-dimensional (2D) Particle In Cell (PIC) simulations of $e^+e^-$ pair plasma:

  few plasma inertial length $\sim$ 100-1000 $c/\omega_p$

(Sironi & Spitkovsky 14)

Current sheet: unstable to **tearing mode** and break up into chain of **plasmoids** (or islands)
Magnetic Reconnection Models

➢ **Kinetic simulations**: 2D PIC simulations of ion-e⁻ pair plasma (up to $3000 \Lambda_D$):

(Werner, Uzdenszky et al. 2017)
Fast Reconnection in MHD flows

Turbulence drives FAST RECONNECTION!
(Lazarian & Vishniac 1999; Eyink et al. 2011)

Magnetic lines wandering: many simultaneous reconnection events

Tested in 3D numerical simulations (Kowal et al. 2009, 2012; Takamoto et al. 2015)

\[ V_{\text{rec}} = V_A \left( \frac{l}{L} \right)^{1/2} \left( \frac{v_f}{V_A} \right)^2 \]

(Alternative descriptions: Shibata & Tanuma01; Loureiro+07; Bhattacharjee+09)
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Particle Acceleration by Reconnection

- **Released magnetic energy by reconnection** -> into heating and particle motion (kinetic energy)

- **30%–40%** of magnetic energy converted into particle kinetic energy (PIC simulations, e.g. Werner et al. 2017)

- **Laboratory plasmas:** ~**50%** goes into kinetic particle acceleration (Yamada+ 2015)
How particles are accelerated in reconnection sites?

Shock Acceleration

1st-order Fermi (e.g. Bell+1978; Begelman & Eichler 1997)

\[ \langle \Delta E/E \rangle \sim \frac{v_{sh}}{c} \]

\[ \langle \Delta E/E \rangle \sim \frac{v_{rec}}{c} \]
How particles are accelerated in reconnection sites?


1st-order Fermi (e.g. Bell+1978; Begelman & Eichler 1997)

\[
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\[
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\]
How particles are accelerated in reconnection sites?

1st-order Fermi (e.g. Bell+1978; Begelman & Eichler 1997):

\[ <\Delta E/E> \sim v_{sh}/c \]

Reconnection Acceleration


particles bounce back and forth between 2 converging magnetic flows

\[ <\Delta E/E> \sim v_{rec}/c \]
Most simulations of particle acceleration by magnetic reconnection: **2D kinetic plasmas (PIC)** (e.g. Drake+ 06; Zenitani & Hoshino 01; 07; 08; Cerutti, Uzdensky+ 13; Li+ 15) and **3D** (Sironi & Spitkovsky 2014; Guo+2015; 16; Werner+ 17)

@ scales: **few plasma inertial length ~ 100-1000 c/ωₚ**

**Larger-scale astrophysical systems (BHBs, AGNs, GRBs):**

→ **MHD description → collisional reconnection**
Isothermal MHD equations to build reconnection domain:
second-order Godunov scheme and HLLD Riemann solver (Kowal et al 2009)

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \quad (5)
\]

\[
\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot \left[ \rho \mathbf{v} \mathbf{v} + \left( \alpha^2 \rho + \frac{B^2}{8\pi} \right) \mathbf{I} - \frac{1}{4\pi} \mathbf{B} \mathbf{B} \right] = \mathbf{f}, \quad (6)
\]

\[
\frac{\partial \mathbf{A}}{\partial t} + \mathbf{E} = 0, \quad (7)
\]

Particle Acceleration by Reconnection using MHD Simulations with test particles

- **Isothermal MHD equations to build reconnection domain:** second-order Godunov scheme and HLLD Riemann solver (Kowal et al 2009)

  ![Diagram of MHD simulation](image)

- **Inject test particles** in the MHD domain of reconnection and follow their trajectories (6th order Runge-Kutta-Gauss):

  \[
  \frac{d}{dt} (\gamma m \mathbf{u}) = q (\mathbf{E} + \mathbf{u} \times \mathbf{B}) \quad \rightarrow \quad \frac{d}{dt} (\gamma m \mathbf{u}) = q [(\mathbf{u} - \mathbf{v}) \times \mathbf{B}]
  \]

Particle Acceleration in 2D MHD Reconnection

2D Multiple current sheets to compare with PIC simulations

Kinetic energy increase

$1^{\text{st}}$ order Fermi Reconnection Acceleration: successful numerical testing in 3D MHD

Kowal, de Gouveia Dal Pino, Lazarian, PRL 2012

$E_{\text{max}} \sim e l_{\text{acc}} B$

- Acceleration more efficient in 3D than in 2D
1st order Fermi Reconnection Acceleration: successful numerical testing in 3D MHD

Kowal, de Gouveia Dal Pino, Lazarian, PRL 2012

N(E) \sim E^{-1,-2}

(\sim\text{PIC simulations})

Valle, de Gouveia Dal Pino, Kowal MNRAS 201
3D MHD Reconnection Acceleration tested for different values of reconnection velocity

$\nu_A/c = 1/10 - 1/1000$

Power-law index of Acceleration time

Reconnection acceleration time (nearly independent of turbulent parameters that drive fast reconnection):

$\tau_{\text{acc}} \sim E^{0.45 \pm 0.15} \quad (\tau_{\text{min}} \sim e/lB)$

Kowal, de Gouveia Dal Pino, Lazarian, PRL 2012

Valle, de Gouveia Dal Pino, Kowal, 2016 MNRAS
Particle Acceleration in 3D MHD Pure Turbulence

Kowal, de Gouveia Dal Pino, Lazarian, PRL 2012

scattering by approaching and receding magnetic irregularities
Implication to BHs and relativistic jets
VHE emission much more common in Blazars

High Luminous AGNs

✓ Jet ~ along our line of sight
✓ VHE Emission (poor resolution): attributed to particle acceleration along the relativistic jet
✓ with apparent high flux due to strong Doppler boosting ($\gamma \sim 5-10$)
✓ shock acceleration in kinetic-dominated flux
...But

a few Non-Blazars Low Luminous AGNs

✓ Also Gamma Ray emitters
✓ Jet does not point to the line of sight
✓ no significant Doppler boosting!
But... a few Non-Blazars Low Luminous AGNs

- Also Gamma Ray emitters
- Jet does not point to the line of sight
- No significant Doppler boosting!

- Does it come from core or jet?
- Rapid variability emission: size $\sim c t_{\text{var}} \sim 100 r_s$
  - Compact emission (core)?

- Where are particles accelerated?
- Is acceleration magnetically dominated?

Reconnection Acceleration?
Reconnection acceleration in the surrounds of BHs?

Accretion disk/jet systems (AGNs & galactic BHs)

AGNs and microquasars

de Gouveia Dal Pino & Lazarian 2005; de Gouveia Dal Pino+2010
Evidence of Reconnection in MHD Simulations

Kadowaki, Master thesis 2011 (also Zani & Ferreira 2013; Romanova+)
Evidence of Reconnection in MHD Simulations

Kadowaki, Master thesis 2011 (also Zani & Ferreira 2013; Romanova+)
Evidence of Reconnection in MHD Simulations

Kadowaki, de Gouveia Dal Pino, Stone (in prep.)

M87

AGNs and microquasars

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Kadowaki, de Gouveia Dal Pino, Stone 2016

M87

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Evidence of Reconnection in MHD Simulations

Reconnection acceleration in the surrounds of BHs

Magnetic Power released by fast reconnection

\[ \dot{W}_B \approx 1.66 \times 10^{35} \Gamma^{-\frac{1}{2}} r_x^{-\frac{5}{8}} l_x^{-\frac{1}{4}} q^{-2} \dot{m}^{\frac{3}{4}} m \text{ erg/s} \]

Magnetic Reconnection Power around BHs

![Graph showing magnetic reconnection power versus source mass. The graph includes data points for BHBs and non-Blazars, with annotations for IC 310, Per A, M87, Cen A, and Sy+L.]


0.0005 ≤ \( \dot{m} \) ≤ 1
1 ≤ \( l_x \) ≤ 18
\( r_x = 6 \)
\( \Gamma \sim 1 \)
Magnetic Reconnection Power around BHs

Magnetic Reconnection around BHs works for different Accretion Disk Models

Applying the reconnection acceleration model in the core to build the full SPECTRUM of Non-Blazars: CenA, M87, PerA, 3C110 (Khiali, de Gouveia Dal Pino, Sol, arXiv:1504.07592)

Reconnection Acceleration & Radiative Losses

Cooling of the particles -> emission:

\[ t_{\text{acc}} \sim t_{\text{loss}}(\text{Synchrotron, SSC, pp, } p_\gamma) \]

Ex.: Galactic Black Hole Cyg X3

Spectral Energy Distribution (SED)

Neutrino emission from cores of low luminous AGNs (z ~ 0 – 5.2) due to reconnection acceleration

\[ p + \text{photons} \rightarrow \pi + p \]

\[ \pi^0 \rightarrow \gamma\gamma \]

\[ \pi^\pm \rightarrow \mu^\pm \nu \]

IceCube flux of Neutrinos

\[
\begin{array}{c|c|c|c}
\text{Parameters} & \text{Model 1} & \text{Model 2} & \text{Model 3} \\
\hline
m & 10^7 & 10^8 & 10^9 \\
p & 1.9 & 1.7 & 2.2 \\
\end{array}
\]

Reconnection Acceleration along Relativistic Jets

If jet emission produced near the core and jet is magnetic, then reconnection acceleration may prevail.
Jets possibly born magnetically dominated

Magneto-centrifugal acceleration by helical field arising from the accretion disk (Blandford & Payne)

Or powered by BH spin (Blandford-Znajek)

**Major Problem:**
Most energy in magnetic field

► Need rapid conversion (dissipation) to kinetic:

Requires RECONNECTION?

GRMHD simulations (e.g. McKinney 06; Tchekhovskoy 2015)
Very-rapid TeV Flares in *Blazar Jets* hard to explain with standard acceleration

- **Variation timescale:**
  \[ t_v \sim 200 \text{ s} < \frac{r_s}{c} \sim 3M_9 \text{ hour} \]

- For TeV emission to avoid pair creation \( \gamma_{em} > 50 \) (Begelman, Fabian & Rees 2008)

- But bulk jet \( \gamma \sim 5-10 \)

- **Emitter:** compact and/or extremely fast

- A proposed Model: **Reconnection** inside the jet

PKS2155-304 (Aharonian et al. 2007)
See also Mrk501, PKS1222+21, PKS1830-211

Giannios et al. (2009)
GRB jet prompt gamma-ray emission may require reconnection acceleration too.

Internal collision-induced magnetic reconnection turbulent model (ICMART) (Zhang & Yan 2011):

- GRB prompt emission: turbulence, magnetic reconnection, and particle acceleration via internal collisions of multiple launched parcels.

(See also Giannios 2008; McKinney & Uzdensky 2012)
Regions of AGN & GRB Jet Propagation

$\sim 10 - 10^{2.5 \pm 0.5} r_S$

Alfven Point

Modified Fast Point

Magnetically Dominated

Collimation Shock

Kinetic Energy Flux Dominated

Current Driven Kink Instability (Mizuno et al. 2012)

Sheath

Modified from D. Meier & Y. Mizuno (courtesy)
**CD Kink Instability**

- Well-known instability in laboratory plasma (TOKAMAK) and astrophysical plasmas (Sun, jets, pulsars)

- In configurations with strong **toroidal magnetic fields**, current-driven (CD) kink mode \((m=1)\) is unstable

- This instability excites **large-scale helical motions** that can strongly distort or even disrupt the system

- Distorted magnetic field structure may trigger **magnetic reconnection**

\[
t_{kink} \simeq \frac{2\pi R_j}{c} \frac{B_p}{B_\phi}
\]

Kink instability in lab plasma (Moser & Bellan 2012)
MHD Simulations of Reconnection driven by Kink in Magnetically Dominated Relativistic Jets (GRBs & AGNs)

MHD Simulations of Reconnection driven by Kink in Magnetically Dominated Relativistic Jets (GRBs & AGNs)

- Precession perturbation allows growth of CD kink instability with helical density distortion.
- Helical kink advected with the flow with continuous growth of kink amplitude in non-linear phase.
- Helical structure is disrupted
- Magnetic energy converted into kinetic energy density

Reconnection driven by Kink in Magnetically Dominated Relativistic Jets (GRBs & AGNs)

\[ \sigma = \frac{B^2}{\gamma^2 \rho h} \]

\[ v_{\text{rec}} \sim 0.05 \, v_A \]

\[ \text{curl } B = \text{max} \]

Sites for magnetic reconnection, dissipation, particle acceleration (and gamma-rays)!

In situ 1st-order Fermi Relativistic MHD Reconnection x shock acceleration in Jets

Competing mechanisms

de Gouveia Dal Pino & Kowal, ASSL 2015
Summary

- Reconnection can be important around BHs for particle acceleration, dissipation of magnetic energy and conversion Magnetic -> Kinetic

- Particles trapped in current sheets with fast reconnection (e.g. driven by turbulence): exponential increase of energy in a 1st order Fermi acceleration: $N(E) \sim E^{-1}$

- Fermi particle acceleration by turbulent magnetic reconnection (numerically tested): can explain gamma-ray of BH binaries and non-blazar AGNs as coming from the core

- The magnetic reconnection power matches well with the observed correlation of radio/gamma-ray luminosity versus BH mass of BH binaries and non-blazar AGNs over 10 orders of magnitude in BH mass

- Reconnection acceleration can be also important in magnetically dominated regions of relativistic blazars and GRBs jets
postdoc & phd positions in my group

@ IAG-USP (FAPESP):

http://www.iag.usp.br/astri/en/opportunities