Particle Acceleration II: by Magnetic Reconnection

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CR acceleration: new challenges

- **UHECRs** - extragalactic astrophysical sources origin: birth of compact objects, GRBs, AGNs, ICM medium? mechanism?

- **Very high energy observations of pulsars, AGNs and GRBs** (Fermi, Swift, HESS, VERITAS, MAGIC):

  → compact magnetized emission regions: sometimes shocks absent
MAGNETIC RECONNECTION?

Approach of magnetic flux tubes of opposite polarity:

Solar corona

magnetotail

Reconnection is FAST!
Magnetic Reconnection Models

• Standard Sweet-Parker (57-58) reconnection: SLOW

\[ V_{\text{rec}} \sim v_A (\Delta/L) \]
\[ S = L \frac{v_A}{\eta} \]
\[ V_{\text{rec}} \sim v_A S^{-1/2} \ll 1 \]

• Petschek (1964): X-point configuration -> FAST

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

Unstable and collapse to S-P (Biskamp’96) unless collisionless pair plasma with localized \( \eta \) (Sturrock 1966; Birn+01, Yamada+10).
• Petschek-X-point configuration in collisionless pair plasmas \((L \sim \lambda_{e,mfp})\):

\[ \delta_{ion} = \frac{v_A}{\omega} > S-P \text{ diffusion scale } \Delta_{SP} = (L\eta/v_A)^{1/2} \]

At these scales Hall effect important:

\[ \vec{v}_e = \vec{v}_i - (\vec{v}_i - \vec{v}_e) \approx \vec{v} - \frac{\vec{J}}{n_e e} \]

\[ \rightarrow v_e \times B \text{ term in Ohm’s law:} \]

\[ \vec{E} = -\frac{\vec{v}_e}{c} \times \vec{B} + \frac{m_e}{e} \vec{g} - \frac{1}{n_e e} \nabla p_e + \eta \vec{J} \]

\[ \rightarrow \text{sustains X-point } \rightarrow \text{ FAST reconnection} \]

(Shay et al. 1998, 2004, Yamada et al. 2006)
Ubiquitous Fast Magnetic Reconnection

TURBULENT RECONNECTION (Lazarian & Vishniac 1999):

- \( V_{\text{rec}} \sim V_A \)

- **FAST**

- **Reconnection layer**: THICKER
- **THREE-DIMENSIONAL**

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

B dissipates on a small scale \( \lambda_\parallel \): many simultaneous reconnection events

Successfully tested in numerical simulations (Kowal et al. 2009, 2012)

(Similar description: Loureiro+07; Shibata & Tanuma01; Uzdensky+10)
Reconnection beyond Solar System

Accretion disk coronae

Stellar Xray Flares

AGN & GRB Jets

Accreting NS and SGRs

Star Formation and ISM

Pulsars
Reconnection Beyond the Solar System

Stellar X-ray flares (Cassak+08; Shibata+05)

Young stellar objects (van Ballegooijen94; Hayashi+1996; Goodson+1997; Feigelson & Montmerle’99; Uzdensky+’02; 04; de Gouveia Dal Pino+’10; D’Angelo & Spruit’10)

Interstellar medium and star formation (Zweibel89; Lesch & Reich92; Brandenburg & Zweibel95; Lazarian & Vishniac99; Heitsch & Zweibel03; Lazarian05; Santos-Lima+10, 12, 13; Leao+13)

Accreting neutron stars & white dwarfs (Aly & Kuijpers90; van Ballegooijen 1994; Warner & Woudt02)

Accretion disk coronae (Galeev+79; Haardt & Maraschi91; Tout & Pringle96; Romanova+98; Di Matteo+99; de Gouveia Dal Pino & Lazarian01, 05; Liu+03; Schopper et al. 1998; Uzdensky & Goodman08; Goodman & Uzdensky08; de Gouveia Dal Pino+10)

Pulsar magnetospheres and winds (Coroniti90; Michel94; de Gouveia Dal Pino & Lazarian01; Blasi+01; Lyubarsky & Kirk01; Lyubarsky03; Kirk & Skjæraasen03; Contopoulos07; Arons07; P’etri & Lyubarsky07; Spitkovsky08; Lyutikov10; Cerutti+13)

SGRs (Thompson & Duncan95, 01; Lyutikov 03, 06; Uzdensky08; Masada+10)

Relativistic jets (microquasars/AGNs/GRBs) (Romanova & Lovelace92; Larrabee+03; Lyutikov+03; Jaroschek+04; Giannios10; Giannios+09, 10; de Gouveia Dal Pino+10; Nalewajko et al. 2010); Spruit et al. 2001; Lyutikov & Blackman01; Lyutikov & Blandford02; Drenkhahn & Spruit02; Giannios & Spruit05, 06, 07; Rees & M´esz´aros 2005; Uzdensky & MacFadyen06; McKinney & Uzdensky10; 12; Uzdensky11; Zhang & Yan09).
Reconnection & Particle Acceleration

Reconnection breaks the magnetic field topology -> releases magnetic energy into plasma in short time -> explains bursty emission

✓ Solar/stellar flares produced by fast \textit{reconnection}
✓ Particle acceleration connected with flares

→ Can reconnection lead to direct particle acceleration?
Particle acceleration in reconnection site:
due to advective electric field directed along $z$-axis (linear)

\[ e_z = v_{\text{rec}} \frac{B}{c} \rightarrow \text{reconnection electric field} \]
1st-order FERMI ACCELERATION @ RECONNECTION SITE

Shock Acceleration

1st-order Fermi (Bell+1978):

\[ \langle \Delta E/E \rangle \sim v/c \]

Reconnection Acceleration

1st-order Fermi (de Gouveia Dal Pino & Lazarian 2005):

particles bounce back and forth between 2 converging flows

\[ \langle \Delta E/E \rangle \sim 8v_{\text{rec}}/3c \]
1st-order Fermi (de Gouveia Dal Pino & Lazarian 2005):

\[ \langle \Delta E/E \rangle \sim 8v_{\text{rec}}/3c \]

✓ Particle and Synchrotron Spectrum? (see also de Gouveia Dal Pino & Kowal 2013)

\[ N(E) \sim E^{-5/2} \rightarrow S_\nu \sim \nu^{-0.75} \]

✓ Relax the assumption considered above that particle escapes rate \( \sim \) shock (Drury 2012) \( \rightarrow \)

\[ N(E) \sim E^{-(r+2)/(r-1)} \quad r = \rho_2/\rho_1 \rightarrow N(E) \sim E^{-2.1} \]
Reconnection a powerful mechanism to accelerate particles?

To probe analytical results → numerical simulations:

- Most 2D simulations of particle acceleration by magnetic reconnection: **collisionless plasmas (PIC)** @ scales (e.g. Drake+; Zenitani & Hoshino):
  
  few plasma inertial length $\sim 100 \, c/\omega_p$

- Larger-scale astrophysical systems (pulsar, AGNs, GRBs):
  
  → MHD description → collisional resistive reconnection
MHD Simulations of Reconnection Particle Acceleration

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \]

\[ \rho \left( \frac{\partial}{\partial t} + u \cdot \nabla \right) u = -c_s^2 \nabla \rho + (\nabla \times B) \times B - \rho \nabla \Psi + f \]

\[ \frac{\partial B}{\partial t} = \nabla \times (u \times B) + \eta_{\text{Ohm}} \nabla^2 B \]

- 2nd order shock capturing Godunov scheme with HLLD solver (Kowal et al. 2007, 2009)

- f: isotropic, non-helical, solenoidal, delta correlated in time random force term (responsible for injection of turbulence)
Probing Particle Acceleration by Reconnection with Numerical MHD Simulations

- **Isothermal MHD equations solved**: second-order Godunov scheme and HLLD Riemann solver (Kowal et al. 2007, Kowal et al 2009)

- **Test particles injected** in the MHD domain of reconnection and their trajectories followed:

\[
\frac{d}{dt} (\gamma mu) = q [(u - v) \times B]
\]

Kowal, de Gouveia Dal Pino, Lazarian 2011; 2012
Particle Acceleration in MHD Reconnection

Resistive Sweet-Parker Current Sheet:

particles confined
→ 1st order Fermi:
\[ \frac{\Delta E}{E} \sim \frac{v_{\text{rec}}}{v} \]

Confirming de Gouveia Dal Pino & Lazarian (2005)
Particle Acceleration in 2D MHD Reconnection

Merging islands: particles confined → 1st order Fermi

2D Multiple current sheets

v fluctuations: to allow reconnection and islands formation

Kowal, de Gouveia Dal Pino, Lazarian 2011 (see also Drake)
Particle Acceleration in 3D MHD Fast reconnection

Current sheet with turbulence fast reconnection

Exponential growth of energy

$N(E) \sim E^{-1}$

Kowal, de Gouveia Dal Pino, Lazarian 2012
Particle Maximum Energy in Fast Reconnection

- Particle can no longer be confined within the reconnection region when:
  \[ r_g = \frac{E}{B} e c > l_{\text{rec}} \rightarrow E_{\text{max}} \sim l_{\text{rec}} c e B = 9 \times 10^{12} \text{ eV} \ l_{\text{rec,cm}} B_G \]

- Cooling of the particle is fast enough to inhibit further acceleration:
  \[ t_{\text{acc}} \sim t_{\text{loss}}(\text{Synchrotron, SSC, pp, } p_\gamma) \]

AGN M87:
- if \( B \sim 10^5 \text{ G} \), \( v_{\text{rec}} \sim 0.1v_A \)
- \( E_{\text{max}} \sim 10^{15} \text{ eV} \)

Khiali, de Gouveia Dal Pino, del Valle, Sol (20130
Particle Acceleration in pure turbulence

Perseus cluster

scattering by approaching and receding magnetic irregularities

2nd order Fermi

Kowal, de Gouveia Dal Pino, Lazarian, 2012
Turbulent reconnection versus Turbulence

1st order Fermi

2nd order Fermi

Kowal, de Gouveia Dal Pino, Lazarian, 2012
APPLICATIONS
Reconnection Acceleration of UHECRs in GRB & AGN jets?

Assuming multiple field reversals along jet (separated by $\sim c \ t_{\text{rot}}$) → 1st-order Fermi acceleration (Giannios 2010):

$$E_{\text{conf}} = 6 \times 10^{19} \frac{\epsilon_{-1} L_{52}^{1/2}}{\Gamma_{2.5}} \text{ eV}$$

UHECRs

Multiple reconnection layers

![Image of GRB jet and particle distribution](image-url)
Reconnection acceleration in accretion disk corona?

Accretion disk/Jet systems (AGNs & galactic BHs)

AGNs and microquasars

degouveia Dal Pino & Lazarian 2005, de Gouveia Dal Pino+2010
Power Released by Fast Reconnection

\[ \dot{W}_B \approx 1.6 \times 10^{35} \alpha_{0.5}^{-19/16} \beta_{0.8}^{-9/16} M_{14}^{19/32} R_{X,7}^{-25/32} l_{100}^{11/16} \text{ erg/s} \]

Radio + Gamma Emission

Explains fundamental plane of Merloni+2003)
Relativistic Reconnection

Fast reconnection in relativistic environments: $v_{\text{rec}} \sim v_A \rightarrow c$


- **Sweet–Parker relativistic reconnection** (Lyubarsky 05): SLOW
  
  $\rightarrow v_{\text{rec}} \ll c$

- **X-point (Petschek) relativistic reconnection**: FAST
  
  $\rightarrow v_{\text{rec}} \approx \pi/4 \ln S$, $S \equiv Lc/\eta$

- **Numerical advances**: in relativistic collisionless Petschek’s reconnection only:
  
  $\rightarrow$ confirmed analytical theory
In situ 1\textsuperscript{st}-order Fermi Relativistic MHD
Reconnection x shock acceleration

Competing mechanisms

de Gouveia Dal Pino & Kowal 2013
What is Next?

Particle acceleration in:

- **Relativistic MHD fast reconnection with turbulence** (e.g. de Gouveia Dal Pino & Kowal 2013)

- **Relativistic reconnection electron-ion, high energy density, radiative plasmas** (e.g. Uzdenski 2011):

  → **open fundamental issues** → SGRs, GRBs, AGNs,...?
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