Nonthermal Particle Acceleration in Magnetic Reconnection in Collisionless Relativistic Plasmas

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OUTLINE

Numerical (PIC) Studies of Nonthermal Particle Acceleration in Kinetic Relativistic Plasma Processes:

• magnetic reconnection:
  – pair plasma (2D and 3D)
  – electron-ion plasma (2D)

• kinetic turbulence:
  – pair plasma (3D)

Our main goal: chart out the resulting observable particle acceleration and radiation parameters (spectral indices, cutoffs) as functions of system’s input parameters: upstream magnetization $\sigma$, size $L$, guide magnetic field $B_g$.

(This talk will focus on non-radiative simulation results)

2D and 3D numerical kinetic studies of relativistic reconnection (lead by Greg Werner) and turbulence (lead by Vladimir Zhdankin) done with two relativistic Particle-in-Cell (PIC) codes:

• **VORPAL/VSim** (non-radiative; radiation via post-processing);
• **ZELTRON** (radiative PIC):
  • developed at Univ. Colorado by Benoit Cerutti and Greg Werner (with additional development by K. Nalewajko and V. Zhdankin);
  • includes synchrotron and inverse-Compton radiation reaction force;
  • self-consistently computes produced radiation spectra, light-curves, etc.;
  • used by us in previous years (Cerutti et al. 2013-2014) to study relativistic pair-plasma reconnection with synchrotron cooling for Crab γ-ray flares.
• publicly available.
Dissipation and emission in astrophysical plasmas

- Many astrophysical flows shine.
- Often, radiative cooling time is $\ll$ travel time from central source $\rightarrow$ in-situ dissipation and particle acceleration!
- Popular nonthermal acceleration collisionless processes: magnetic reconnection, shocks, and turbulence.
Dissipation Mechanisms

AVAILABLE FREE ENERGY

Bulk Kinetic
- longitudinal: shocks
- transverse: shear (KH) instability

Magnetic (Poynting flux)
- Magnetic reconnection
  - current sheets:

MANY OF THESE PROCESS ARE PATHS TO DEVELOPING TURBULENCE!!

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Reconnection in High-Energy Astrophysics

• Accreting black holes in XRBs and AGN

• Pulsar magnetospheres, winds, PWNe

• AGN (e.g., blazar) jets, radio-lobes

• Gamma-Ray Bursts (GRBs)

• Magnetar (SGR) flares
Relativistic Collisionless Magnetic Reconnection and Nonthermal Particle Acceleration:

1. Pair ($e^+e^-$) Plasmas

Why pair plasmas?
1) actually exist in Nature, astrophysically relevant: pulsar magnetospheres, pulsar wind nebulae (PWN);
2) conceptually and technically simpler.

Evolution of magnetic field and current density in our 2D double-periodic PIC reconnection simulations.
Collisionless Relativistic Pair Reconnection: General reconnection dynamics

Tool of choice: **Particle-in-Cell (PIC) kinetic simulations**

Key Features:
- Pair plasma reconnection is **fast**: $v_{\text{rec}} \sim 0.1—0.2 \, c$
- Reconnecting current sheets in large systems ($L > 50-100 \, \rho_L$) are unstable to **secondary instabilities** (tearing and kink) and reconnection is highly dynamic.

### Tearing (2D)

![Tearing 2D Simulation](image1.png)

### Kink (3D)

![Kink 3D Simulation](image2.png)

\begin{align*}
\text{time}=0, \quad B_z &= 0.5 \, B_0 \\
\end{align*}
Collisionless Relativistic Pair Reconnection: Nonthermal Particle Acceleration (2014-2017 view)


Recent 2D PIC studies by several groups showed: relativistic reconnection in pair plasmas indeed leads to nonthermal particle acceleration!

• Sironi & Spitkovsky et al. (2014-2016)
• Guo et al. (2014-2015) – Los Alamos
• Werner et al. (2014-2016) – Colorado

How do the power-law characteristics – power-law index $\alpha$, high-energy cutoff $\gamma_c$ – depend on system parameters?

$\gamma f(\gamma)$
The magnetization $\sigma$ parameter

- Physical parameters of ambient/upstream background plasma:
  - particle density $n_b$,
  - temperature $\theta_e = T/m_e c^2$,
  - reconnecting magnetic field $B_0$
  - guide magnetic field $B_{gz}$

- Important dimensionless parameter -- magnetization $\sigma$:
  - “Cold” sigma: $\sigma = B_0^2/(4\pi n_b m c^2)$
    (sets the scale for available magnetic energy per particle);
  - “Hot” sigma: $\sigma_h = B_0^2/(4\pi n_b h)$, where $h$ is average relativistic enthalpy per particle including rest-mass: $h = m c^2 <\gamma> + p/n$.
  - for relativistically-cold plasma ($T<<m_e c^2$): $\sigma_h \approx \sigma$.
  - for ultra-relativistically-hot plasma ($T>>m_e c^2$): $h \approx 4 \theta_e m c^2$ and $\sigma_h \approx \sigma/4 \theta_e = \sigma = B_0^2/(16\pi n_b \theta_e m c^2)$.  

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2D PIC studies with cold upstream plasma, so $\sigma_h \approx \sigma = B_0^2/(4\pi n_b mc^2)$

$$f(\gamma) \sim \gamma^{-\alpha} \quad (\gamma = \varepsilon/mc^2)$$

- $\alpha = \alpha(\sigma_h, L)$
- $\alpha$ depends on $L$ for small $L$, but asymptotes to a finite value $\alpha_*(\sigma_h)$ as $L \to \infty$.
- $\alpha_*(\sigma_h)$ is $> 2$ for $\sigma_h \sim 1$ but decreases with $\sigma_h$ and approaches a finite asymptotic value $\alpha \approx 1.12$ as $\sigma_h \to \infty$.

(consistent with studies by Sironi & Spitkovsky 2014, Zenitani & Hoshino, Lyubarsky & Liverts 2008)
**High-Energy Power-Law Cutoff**

(Werner, Uzdensky, Cerutti, Nalewajko, Begelman 2016)

\[
f(\gamma) = \frac{dN}{d\gamma} \propto \gamma^{-\alpha} \exp\left(-\frac{\gamma}{\gamma_{c1}} - \frac{\gamma^2}{\gamma_{c2}^2}\right)
\]

**Two** high-energy cutoffs:

- \(\exp\left(-\frac{\gamma}{\gamma_{c1}}\right)\); \(\gamma_{c1} \sim 4\sigma\),
  - independent of \(L\);

- \(\exp\left[-\left(\frac{\gamma}{\gamma_{c2}}\right)^2\right]\); \(\gamma_{c2} \sim 0.1 \frac{L}{\rho_0}\)
  - available voltage drop \(\varepsilon_{\text{max}} \sim e E_{\text{rec}} L \sim 0.1 e B_0 L\) ("extreme acceleration")

\(\gamma_{c1} \sim 10 < \varepsilon >\)

Large-system regime:

\((\gamma_{c1} < \gamma_{c2})\):

\[L/\rho_0 > 40 \sigma\]
Why is there a $\gamma_c \approx 4\sigma$ cutoff?

- Cutoff comes from small laminar *elementary interplasmoid layers* at the bottom of the plasmoid hierarchy (marginally stable to plasmoid instability).
- Modest-energy particles are accelerated in these layers but then become trapped inside plasmoids.
- Rel. particle acceleration in a laminar single-X-point elementary layer:

\[
\frac{dn}{d\gamma} \propto \frac{1}{\gamma} \exp\left(-\frac{\gamma}{\gamma_0}\right).
\]  

(Larrabee et al. ‘03; Lyubarsky & Liverts ‘08)

- Cutoff: $\gamma_0 = e E_{\text{rec}} l / m_e c^2 \approx 0.1 e B_0 l / m_e c^2 = 0.1 l / \rho_0$.
- Layers are marginally stable to tearing $\rightarrow l \sim 100 \delta$.
- Layer thickness: $\delta \approx \rho \langle\gamma\rangle = \langle\gamma\rangle \rho_0 \approx (\sigma / 3) \rho_0$.
- Thus, $l / \rho_0 \approx 100 \delta / \rho_0 \approx 30 \sigma \Rightarrow \gamma_0 = 3 \sigma$.

\[\begin{align*}
\rho_0 &= m_e c^2 / e B_0 \\
\sigma &= B_0^2 / (4\pi n m c^2)
\end{align*}\]
Relativistic Pair Plasma Reconnection in 3D

• Most PIC reconnection simulations are 2D, but real world is 3D. Should we be concerned?

• Reason for concern: \textit{Relativistic Drift-Kink Instability (RDKI)}:
  • develops rapidly along the layer in ignorable $z$-direction, absent in 2D;
  • corrugates the layer and dramatically changes its structure;
  • suppressed by a strong guide magnetic field $B_z$.

• \textit{Zenitani & Hoshino}'s (2007-2008) 3D PIC simulations: nonlinear development of \textbf{RDKI} without strong guide field leads to efficient heating but \textit{suppresses nonthermal particle acceleration}.

• More recent work (e.g., Sironi & Spitkovsky ’14, Guo et al.’15): particles are still accelerated efficiently on longer timescales.
Relativistic Pair Plasma Reconnection in 3D


We have recently completed a thorough 2D/3D comparison for ultra-relativistic pair reconnection, for varying:

- layer’s aspect ratio $L_z/L_x$ – proxy for 3D;
- guide magnetic field ($B_{gz}/B_0$).

[keeping fixed upstream temperature $T_b \gg m_e c^2$ and magnetization: $\sigma_{hot} = B_0^2/(4\pi n \theta_e mc^2) = 25$]
Relativistic Pair Reconnection: 2D vs. 3D vs. guide field $B_{gz}$

Starting from a Harris configuration, with a small magnetic field perturbation (uniform in z), the initial current layer rapidly tears (in x-y) and, in 3D, kinks (in y-z).

(Hot magnetization) $\sigma_{\text{hot}} = 25$

EM-PIC simulation code: Zeltron (double periodic box)

Spoiler Alert: 2D and 3D reconnection are very similar, even without guide field. Guide field, on the other hand, has a large effect.

(Zoomed in on current layer)
Particle spectra for different $L_x$: box-size dependence

Conclusion: power-law index converges with $L_x$
Relativistic Pair Plasma Reconnection in 3D

Particle spectra for different $L_z/L_x$: no guide field

$B_{gz} = 0 \quad B_z = 0$

$\gamma f(\gamma)$

$\gamma f(\gamma)$

$\gamma$

$\gamma$

$\gamma$

$L_z/L_x = 0.001$

$L_z/L_x = 0.0042$

$L_z/L_x = 0.25$

$L_z/L_x = 0.5$

$L_z/L_x = 1$

$L_z/L_x = 2$

$L_z/L_x = 4, \ t\omega_c = 107$

Conclusion: 2D and 3D are fairly similar!
Relativistic Pair Plasma Reconnection in 3D

Does this conclusion depend on guide field?

**Conclusion:** nonthermal particle acceleration in relativistic pair-plasma reconnection is similar in 2D and 3D for any given guide field.

**Implication:** 2D simulations are sufficient, adequate for studies of NTPA in relativistic pair reconnection.
Conclusion: particle acceleration is negatively affected by strong guide field.

Proposal: Enthalpy of the guide magnetic field, \( B_{gz}^2/4\pi \), modifies the effective hot sigma: \( \sigma_{h,\text{eff}} = B_0^2/(B_{gz}^2 + 4\pi nh) \)
Relativistic Collisionless Magnetic Reconnection and Nonthermal Particle Acceleration:

2. Semi-Relativistic and Relativistic Reconnection in Electron-Ion Plasmas

[Black hole accretion flows, accretion disk coronae, jets]

Werner et al. (arXiv:1612.04493)
Electron-Ion Reconnection in Semi-relativistic and ultra-relativistic regimes

- PIC studies of *electron-ion* rel. reconnection have just begun (Werner et al. 2013, 2015, Melzani et al. ’14, Guo et al. ‘15, Sironi et al. ‘15).

- When both electrons and ions are *ultra-relativistic*, they behave the same → reconnection is similar to pair-plasma case.

- **Semi-relativistic reconnection regime**: ultra-relativistic electrons but non-relativistic ions – relevant to many astro systems (BH ADC).

- We conducted a *systematic 2D PIC study* (no guide field, real mass ratio $m_i/m_e=1836$) of reconnection in *ei* plasmas in semi- and trans-relativistic regimes (Werner et al. 2016b).

- **Main question**: how do key reconnection characteristics – rec. rate, energy partitioning, particle acceleration – change as one transitions from semi-relativistic ($\sigma_i << 1$) to full-relativistic regime ($\sigma_i >> 1$)?
Relativistic e-i reconnection: Key PIC Sims Results I

Reconnection rate: \( v_{\text{in}}/c = E/B_0 \)

Energy partitioning between electrons and ions

\[ \frac{E}{B_0} \]

\[ \frac{cE}{V_AB_0} \]

\[ V_A = c \frac{B_0}{\sqrt{4\pi n_i m_i c^2 + B_0^2}} = c \frac{\sqrt{\sigma_i}}{\sqrt{1 + \sigma_i}} \]

In semi-relativistic case ions gain 3 times more energy than electrons.

Werner et al. 2016
Particle Acceleration:

- electrons: ✔️
- ions: ?

Electron power-law index $p$ and cutoff $\gamma_c$:

$\frac{p_e}{\sigma_i}$

$\frac{\gamma_c}{\sigma_i}$

Werner et al. 2016
• Relativistic reconnection in *pair* plasmas produces robust nonthermal particle spectra in both 2D and 3D with a power-law index $\alpha$ that:
  – becomes independent of $L$ as $L \to \infty$.
  – decreases with magnetization $\sigma$: $\alpha \to 1$ as $\sigma \to \infty$.
  – increases with $B_{gz}$: $\alpha \approx C_1 + C_2 (\sigma_{h,\text{eff}})^{-1/2}$, $\sigma_{h,\text{eff}} = B_0^2/(B_{gz}^2 + 4\pi h)$

• Semi-Relativistic (ultra-rel. electrons, non-rel. ions) and relativistic reconnection in *electron-ion* plasma (2D; $B_g=0$):
  – *electron energy fraction* grows from $\sim \frac{1}{4}$ to $\frac{1}{2}$ as $\sigma_i$ increases.
  – power-law *electron* spectra, with index $\alpha \sim C_1 + C_2/\sigma_i^{1/2}$
  – nonthermal *ion* acceleration is not clear.