Relativistic Reconnection heating and IC cooling

Magnetic reconnection energizes particles;
Energetic particles radiate;
Radiation excites astronomers...

Featuring PIC codes (in omegapsical order)
Zeltron and Vorpal and Tristan-MP

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Background: reconnection yields NTPA

Since about 2014 a new generation of PIC simulations has shown really convincing power-law particle distributions from reconnection in:

- 2D
- pair plasma
- zero guide field
- high $\sigma_h$
- high $\sigma$
- low $T_e$ (cold/nonrel.)
- $T_i = T_e$

But astrophysical sources have:

- 3D
- pair and/or electron-proton
- some small/large guide field
- maybe $\sigma_h \sim 1$ or 10
- high $\sigma$ is fine
- etc.

(see also Guo et al 2014, Werner et al 2016...)
The goal of the game

Connect the parameters of reconnection to the corresponding radiation signatures.

dimensionality: (e.g., 2D or 3D)
mass ratio: \( m_i/m_e \) (e.g., 1 or 1836)
guide field: \( B_{gz}/B_0 = 0, 0.25, 0.5, 1, 2 \)

\[
\sigma_h = \frac{B_0^2}{4\pi h} \approx \frac{B_0^2}{4\pi (4n_b T_b)}
\]

(ultrarelativistic limit)

\[
\sigma = \frac{B_0^2}{4\pi n_b m_e c^2}
\]

Radiative cooling, e.g., IC or synchrotron: \( \gamma_{\text{rad}} \)

Background temperature: \( T_b/m_e c^2 \)

Temperature ratio: \( T_i/T_e \)

etc.
Reconnection simulation setup

Upstream Parameters:
• plasma $n_b, T_b$
• reversing magnetic field $\pm B_0 x$
• guide field $B_{gz}$
• density to balance upstream $B_0$ pressure
• current $J_z$ to balance $dB_x/dy$

Plus a Harris layer

nominal length scale:

$\rho_0 = \frac{m_e c^2}{eB_0}, \rho_c = \sigma \rho_0$

System size: Lx, Ly, and (in 3D) Lz
Formal outline

How do particle (and radiation) spectra vary as we change:
• dimensionality: 2D vs 3D
• guide magnetic field: zero, weak, strong
  • effective magnetization
• mass ratio: positrons vs. protons
  • magnetization
• IC radiaction: weak -> moderately strong
  • radiaction = radiaction reaction (force)
Brief Conclusions

- From 2D, pair, zero guide field, negligible radiaction, we have now explored:
  - 3D pair reconnection (pretty much the same as 2D pair)
  - 2D and 3D with guide field (guide field slows reconnection, steepens NTPA power law)
  - 2D electron-ion (slower ions slow reconnection, steepen electron power law)
  - 2D pair with radiaction (doesn’t slow reconnection, steepens high-energy part of power law)
Why 3D? Isn’t 2D good enough? Maybe it is!

Does the 3D-only relativistic drift-kink instability (RDKI) inhibit particle acceleration? Guide magnetic field may be important: it inhibits RDKI.

from Zenitani & Hoshino, 2008:

However, more recent simulations (e.g., Sironi & Spitkovsky 2014, Guo et al 2015, Werner & Uzdensky 2017) have suggested that particle acceleration is robust to 3D effects.
Despite significant RDKI, 2D and 3D reconnection have similar reconnection rates and NTPA.

3D, $L_z = L_x$, $B_z = 0$
3D current sheet evolution
Energetics of 2D and 3D reconnection are similar regardless of guide field (for later: guide field has a significant effect)
Here $L_z$ is the length in the 3\textsuperscript{rd} dimension.

Energy in in-plane $B$

\[ \frac{t c/L_x}{B_{gz}/B_0} \]

\[ \frac{U_{mag,xy}(t)}{U_{mag,xy}(0)} \]

$B_{gz}/B_0 = 0, 0.25, 1, 2$

2D-3D
$m_i/m_e = 1$
$B_{gz}/B_0 = 0-1$
$\sigma_n = 25$
$\sigma >> 1$
$T_e/m_e c^2 >> 1$
$T_i = T_e$
$\nu_{rad} = \infty$
And 2D and 3D particle spectra are similar

Nonthermal acceleration remains robust from 2D to 3D!
Also, a little guide field $B_{gz}$ hardly disturbs acceleration.

Electron/Positron energy spectra

2D-3D
$m_i/m_e=1$
$B_{gz}/B_0=0 - 0.25$
$\sigma_h=25$
$\sigma>>1$
$T_e/m_e c^2 >>1$
$T_i=T_e$
$\gamma_{rad}=\infty$
During reconnection, the in-plane magnetic field compresses plasmoids.

When there’s a guide field, that guide field resists compression and slows reconnection (reduced $v_A$, reduced $E/B_0 \sim 0.1 \, v_A/c$).
Guide field not only slows reconnection rate, but steepens the NTPA power law.

Including the guide field enthalpy into an effective $\sigma_h$ accounts for compression of guide field.

$$\sigma_{h,\text{eff}} = \frac{B_0^2 / 4\pi}{h_{\text{particle}} + B_z^2 / 4\pi}$$

2D-3D
$m_i/m_e=1$
$B_{gz}/B_0=0 - 2$
$\sigma_h=25$
$\sigma>>1$
$T_e/m_e c^2 >> 1$
$T_i=T_e$
$\gamma_{\text{rad}}=\infty$
3D aside: spatial fluctuations -> turbulence?

Power spectrum of magnetic field (3D, L_z=L_x, B_z=0)

half-way upstream

in the reconnection midplane

x is the direction of B_0 reconnecting magnetic field;
z is the initial current direction
3D aside: Effect of initial perturbation in 3D (and 2D)

Density of initial Harris layer particles in the middle of the current sheet.

If you add a little guide field, perturbation doesn’t matter.
Electron – Proton: \( m_i/m_e = 1836 \)
(We use the real mass ratio!)

(Why is this possible? In the ultrarelativistic [but nonradiative] limit, ions and positrons have the identical motion. As ions become less relativistic, the scale separation between electrons and ions increases, and simulation becomes more difficult.)

\[
\sigma_i = \frac{B_0^2}{4\pi n_b m_i c^2} = (\text{roughly}) \text{ average magnetic energy per ion, normalized by ion rest mass energy.}
\]

\( \sigma_i \gg 1 \) -> ultrarelativistic
\( 1/1836 < \sigma_i < 1 \) -> \text{semirelativistic} (electrons are relativistic, ions are sub-rel.)
\( \sigma_i << 1/1836 \) -> nonrelativistic
Semirelativistic electron/ion reconnection energetics: ions are slow energy hogs

The absolute reconnection rate slows as ions become more iony, but so does $v_A$;

the normalized reconnection rate stays around 0.1 (within 20 or 30%).

Ions gain more energy than electrons....

$$2D \quad m_i/m_e=1836 \quad B_{gz}/B_0=0 \quad \sigma_i=0.03 - 10000 \quad T_e/m_ec^2 = 1836\sigma_i/200 \quad T_i=T_e \quad \gamma_{rad}=\infty$$
Our most important semirelativistic electron/ion NPTA results
(blue lines = electron energy spectra)

\[ \sigma_i = 0.1 \]

\[ \sigma_i = 1 \]

\[ \sigma_i = 10 \]

\[ \sigma_i \]

\[ e^- : \; t\omega_e = 1800 \]
\[ i^+ : \; t\omega_e = 1800 \]

\[ e^- : \; t\omega_e = 840 \]
\[ i^+ : \; t\omega_e = 840 \]

\[ e^- : \; t\omega_e = 770 \]
\[ i^+ : \; t\omega_e = 770 \]

\[ 2D \]
\[ m_i/m_e = 1836 \]
\[ B_{gz}/B_0 = 0 \]
\[ \sigma_i = 0.03 - 10000 \]
\[ T_e/m_e c^2 = 1836 \sigma_i / 200 \]
\[ T_i = T_e \]
\[ \gamma_{rad} = \infty \]

\[ \sigma_i = B_0^2 / 4\pi n_b m_i c^2 \]

\[ p \text{ (for electrons)} \]

\[ 1.9 + 0.7/\sqrt{\sigma_i} \]

resembles guide-field dependence
Finally, (ultrarelativistic pair) reconnection with IC radiaction

High energy electrons (or positrons) scatter of photons, emitting high energy photons, and experiences radiation reaction (radiaction) force.

If $U_{ph}$ is the photon energy density, then the power loss, for an electron with $\gamma m_e c^2$ is:

$$P_{rad} = \frac{4}{3} \sigma_T c U_{ph} \gamma^2$$

Power gain (accel.) in the reconnection electric field $E=0.1B_0$:

$$P_{acc} = (0.1)eB_0c$$

These 2 forces (powers) balance for $\gamma=\gamma_{rad}$:

$$\gamma_{rad} = \sqrt{\frac{3(0.1)eB_0}{4\sigma_T U_{ph}}}$$

Particles can’t gain much more energy than this.
IC scattering doesn’t affect basic reconnection dynamics very much

\[ \gamma_{\text{rad}} = \infty \] (no cooling)

\[ \gamma_{\text{rad}} = 2\sigma \] (strong cooling)

Color=plasma density (normalized to \( n_b \))
IC cooling has little effect on magnetic energy dissipation, reconnection rate

Magnetic energy vs time

Strong cooling doesn’t alter the amount of magnetic energy transferred to particles...but strong cooling means particles promptly radiate that energy.

2D
$m_i/m_e=1$
$B_{gz}/B_0=0.25$
$\sigma_n=100$
$\sigma>>1$
$T_e/m_e c^2 >>1$
$T_i=T_e$
$\gamma_{rad}/\sigma=1 \text{ to } \infty$

$\beta_{rec}$

$\gamma_{rad}/\sigma$ 

$\infty$
IC cooling changes particle spectra significantly: noisy, steeper

2D
$m_i/m_e=1$
$B_{gz}/B_0=0.25$
$\sigma_n=100$
$\sigma>>1$
$T_e/m_e c^2 >>1$
$T_i=T_e$
$\nu_{rad}/\sigma=2$
IC cooling changes particle spectra significantly

- **Weak cooling:** usual hard power law
- **Strong cooling:** variable steep power law
- **Intermediate:** both power laws

\[
\frac{2D}{m_i/m_e} = 1, \quad \frac{B_{gz}/B_0}{0.25}, \quad \sigma_h = 100, \quad \sigma >> 1, \quad \frac{T_e/m_ec^2}{>>1}, \quad T_i = T_e, \quad \gamma_{\text{rad}}/\sigma = 2, 8, \infty
\]
Time-integrated IC photon spectra

Photon power law index alpha = (p-1)/2.  
Hard slope $p_h=1.9 \rightarrow \alpha = 0.45$ (measured 0.5)  
Steep slope $p_s=3-5 \rightarrow \alpha = 1-3$  
however: a harder slope means more IC emission,  
so alpha should be dominated by the hardest $p_{s,min}=3 \rightarrow \alpha= 1$ (measured 1.1)

In this particular case (ultrarelativistic pair plasma, sigma_h=100, B_gz=B_0/4),  
adding a soft photon bath changes index from alpha=0.5 to alpha=1.1.
Moving on: 3D electron-proton reconnection differs slightly from 2D.

8 simulations with the same setup were run for 2D and 3D.

For electron-proton with small system size, there is considerably fluctuation from run to run.

2-3D
\( \frac{m_i}{m_e} = 1836 \)

\( \frac{B_{gz}}{B_0} = 0 \)

\( \sigma_i = 0.1 \)

\( \frac{T_e}{m_e c^2} = 1836 \sigma_i / 200 \)

\( T_i = T_e \)

\( \gamma_{rad} / \sigma = \infty \)
But: for electron-proton reconnection, the perturbation may be significant

Unlike the 2D ultrarelativistic (pair) case, where a small guide field has a small effect and the initial perturbation has no effect, in semirelativistic electron-proton reconnection, the perturbation has a significant effect (e.g., on electron power-law slope).
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