HED Magnetic Reconnection with Strong Radiative Cooling

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Conventional Reconnection Research:

- In conventional reconnection studies (space/solar/laboratory), the plasma consists charged particles (*e*-ns & ions) --- **no photons!**

- However, in many ***astrophysical*** situations, the energy density is so high that **radiation** should strongly affect the reconnection process:
  - Radiative cooling;
  - Radiation pressure;
  - Compton-drag resistivity.

Diversity of Astrophysical Reconnection

- Reconnection is often invoked in astrophysics (beyond solar system).

- However, astrophysical environments are incredibly diverse: n_e, T_e, T_i, B, L vary greatly.

- Often, underlying microscopic physics is vastly different from traditional reconnection assumptions

Physics of High-Energy-Density Reconnection

Critical novel physics issues:
(different from conventional reconnection)

- Radiation: (quasar coronae, GRBs, magnetars)
  - Radiative cooling
  - Radiation pressure
  - Compton resistivity (due to electron-photon, rather than electron-ion, collisions)
- Pair creation (GRB engines, magnetar flares)
- Special relativity (pulsar magnetosphere/wind)

This talk: Reconnection with (optically-thin) radiative cooling: a Sweet-Parker-like analysis

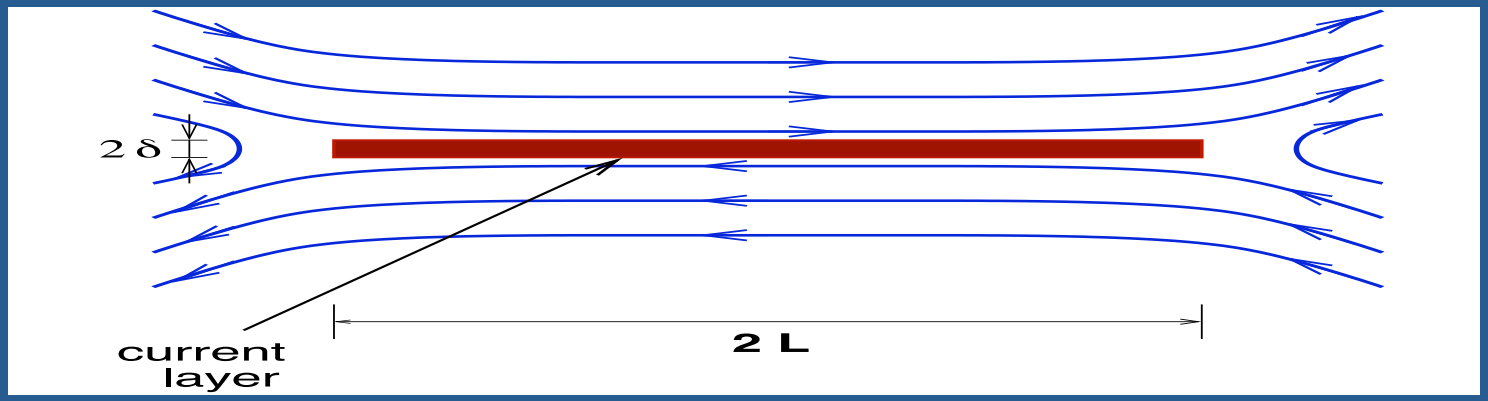
(D. Uzdensky & J. McKinney, PoP 2011)

- Radiative cooling is the first radiation effect that comes into play as energy density is increased.

- Relatively easy to include.

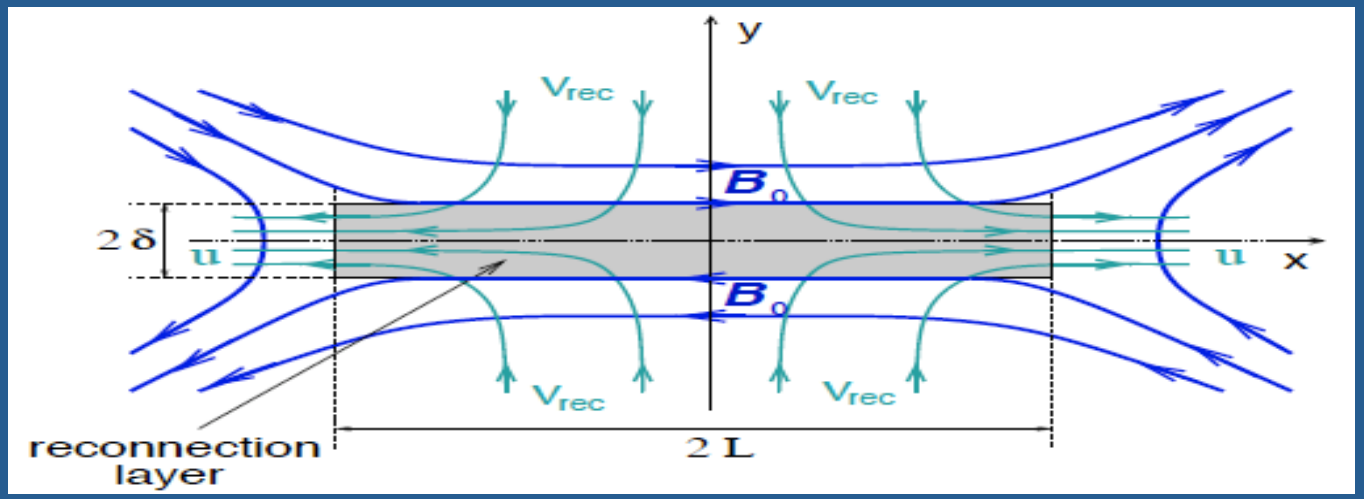
- Sweet-Parker model is a natural first step in reconnection studies.

Two roles of radiative cooling



- Original SP model is incompressible -- OK even for low-$\beta^{upstream}$ plasmas.
- In radiative reconnection, incompressibility gets replaced by heating/ cooling balance, which then control layer temperature.
- Consequences of strong radiative cooling:
  - Strong plasma **compression** (if no guide field): $A = n/n_0 >> 1$.
  - Lower T_e → **higher resistivity** → faster reconnection.

Key parameters



- Upstream Alfven velocity:

$$V_{A0} \equiv \frac{B_0}{\sqrt{4\pi n_0 m_p}}.$$

- Global Alfven transit time:

$$\tau_{A,0} \equiv \frac{L}{V_{A,0}}$$

- Lundquist number:

$$S_0 \equiv \frac{L V_{A,0}}{\eta} \gg 1$$

Equations I:

- Mass Conservation:

$$n_0 v_{\rm rec} L = n u \delta \quad \Rightarrow \quad v_{\rm rec} L = A\, u \delta\,.$$

- Faraday's law:

$$\partial_t B = 0 \Rightarrow \nabla \times E = 0 \Rightarrow E_z = const$$

- Ohm's law:

$$cE_z^{upstream} = -v_{rec} B_0 = cE_z(0,0) = \eta' j_z(0,0)$$

- Ampere's law:

$$j_z(0,0) \approx c\,\frac{B_0}{4\pi\delta}$$

- Ohm + Ampere:

$$\eta = v_{\rm rec}\delta$$

Equations II: equations of motion

- Pressure balance across layer:

$$\frac{B_0^2}{8\pi} = P = 2nk_BT$$

- Equation of motion along layer:

$$\rho v_x \partial_x v_x = -\partial_x p + j_z B_y/c$$

- Reconnected magnetic field:
  (from $cE_z = v_{\rm rec} B_0 = u\, B_1$)

$$B_1 = B_0 \frac{v_{\rm rec}}{u} \simeq B_0 \frac{\delta}{L} A$$

- Magnetic tension >> pressure gradient:

$$j_z B_y/c \sim A\, B_0^2/4\pi L \quad >> \quad \partial P/\partial x \sim B_0^2/8\pi L$$

- Outflow velocity:

$$u \sim \frac{B_0}{\sqrt{4\pi n_0 m_p}} = V_{A0}$$

Solution in terms of *A*:

- Compression ratio:

$$A \equiv \frac{n}{n_0}$$

(n_0 – upstream density; n -- density in the layer)

- Reconnection velocity:

$$v_{\rm rec} = V_{A0}\, S_0^{-1/2}\, A^{1/2}$$

- Layer thickness:

$$\delta \sim \frac{\eta}{v_{\rm rec}} \sim L\, S_0^{-1/2}\, A^{-1/2} = \delta_{\rm SP}\, A^{-1/2}$$

Equations III: Heating/cooling balance determines compression ratio *A*

- Ohmic heating rate:

$$Q_{\rm ohm} = \eta' j^2 \sim A\,\frac{B_0^2}{4\pi\tau_{A,0}} \equiv A\,Q_0$$

where $Q_0 \equiv B_0^2/(4\pi\tau_{A,0})$

- Advective cooling rate:

$$Q_{\rm adv} \sim \frac{nkT}{L/u} \sim \frac{B_0^2}{4\pi\tau_{A,0}} \simeq Q_0$$

- Radiative heating/cooling balance:

$$Q_{\rm rad}(n,T) = Q_{\rm ohm} \sim A\,Q_0$$

- Equation for *A*:

$$Q_{\rm rad}[n(A),T(A)] = \frac{B_0^2}{8\pi\tau_{A,0}}\,A = A\,Q_0$$

where

$$\begin{cases} n(A) = n_0 A \\ k_B T(A) = k_B T_{\rm eq}\,A^{-1} \equiv A^{-1}\,\dfrac{B_0^2}{16\pi n_0} \end{cases}$$

Conditions of validity

- Strong cooling/strong compression: $A >> 1$

- Evolutionary condition:

plasma should be able to cool down to this state

$$Q_{\rm rad}[n_0, T_{\rm eq}(n_0)] > Q_{\rm Ohm}[n_0, T_{\rm eq}(n_0)] \simeq Q_0$$

- Combining with $Q_{\rm rad}(A) = Q_{\rm ohm}(A) \simeq A Q_0$,

we get a condition on the cooling function:

$$Q_{\rm rad}[n(A), T(A)] < A\, Q_{\rm rad}[n_0, T_{\rm eq}(n_0)]$$

Which radiative processes allowed?

- Evolutionary condition:

$$Q_{\rm rad}[n(A), T(A)] < A\, Q_{\rm rad}[n_0, T_{\rm eq}(n_0)]$$

- Consider general form:

$$Q_{\rm rad} \sim n^{\alpha}\, T^{\beta}$$

- Then, strong radiation regime requires:

$$\alpha < 1 + \beta$$

- Important special cases:
  - Bremsstrahlung (α=2,β=1/2) ☒
  - Cyclotron (α=1,β=1) ☑
  - Inverse Compton (α=1,β=1) ☑

Inverse Compton (IC) Cooling

- Important for accreting black hole coronae/jets, etc.
- IC cooling rate per electron: $$Q_{\rm rad}/n = \frac{4}{3}\,\sigma_T\,c\,U\,\beta^2\gamma^2$$

where $U=U_{\rm rad,ext}$

- Non-relativistic limit: $$Q_{\rm rad} \sim \sigma_T\,c\,U\,\frac{nT_e}{m_e c^2} \sim \sigma_T\,c\,U\,\frac{P}{m_e c^2}$$
- Compression ratio: $$A = \frac{Q_{\rm rad}}{Q_0} \sim \sigma_T\,c\,\frac{U\tau_{A,0}}{m_e c^2}$$

Cyclotron/Synchrotron Cooling

- Cyclo/synchrotron cooling rate per electron:

$$Q_{\rm rad}/n = \frac{4}{3}\,\sigma_T\,c\,U\,\beta^2\gamma^2$$

where $U = U_{\rm magn} = B^2/8\pi$

- Nonrelativistic limit:

$$Q_{\rm rad} \sim \sigma_T\,c\,U\,\frac{nT_e}{m_e c^2} \sim \sigma_T\,c\,U\,\frac{P}{m_e c^2}$$

- Compression ratio:

$$A = \frac{Q_{\rm rad}}{Q_0} \sim \sigma_T\,c\,\frac{U\tau_{A,0}}{m_e c^2} \sim \frac{m_i}{m_e}\,\frac{V_{A,0}}{c}\,\tau_T$$

where

$$\tau_T = \sigma_T\,n_0\,L$$

Work in Progress/Open Questions:

- Generalization to finite optical depth
- Synchrotron cooling for relativistic plasmas
- Resistive-MHD validity (collisionality): $\delta > d_i, \rho_i$
- Electron-ion thermal equilibration: $T_e = T_i$?
- Radiation pressure, Compton resistivity
- Astrophysical applications
- Connection to HED Laser-Plasma laboratory experiments *(Nilson et al. 2006; C.K. Li et al. PRL 2007)*

SUMMARY

- *High-Energy Density (HED)* reconnection is a new exciting frontier in magnetic reconnection research!
- Radiative effects (radiative cooling; radiation pressure; Compton resistivity) are important in HED astrophysical reconnection.
- We started a program of systematic investigation of the effects of radiation on reconnection. First step: Sweet-Parker theory for resistive reconnection with radiative cooling.
- Strong radiative cooling greatly affects reconnection dynamics and energetics:
  - lower layer temperature → higher resistivity → faster reconnection;
  - strong plasma compression (without strong B_{guide}), also leading to faster reconnection.
- Several astrophysically-important radiative mechanisms (bremsstrahlung, cyclotron, and inverse-Compton) explored.

SUMMARY

- *High-Energy Density* reconnection is a new frontier in magnetic reconnection research!
- *High-Energy Astrophysics applications:*
  – Magnetar flares (SGR giant flares);
  – GRB central engines and jets.
- *Key new physics issues:*
  – reconnection probem = radiative transfer problem
  – radiative cooling, radiation pressure
  – pair production
  – relativistic effects, etc., etc.

- *Radiative cooling* (with no guide field) leads to dramatic changes in reconnection dynamics and energetics: strong plasma compression, faster reconnection, etc.