Magnetic Reconnection with Optically Thin 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.

Reconnection with (optically-thin) radiative cooling:

a Sweet-Parker-like analysis

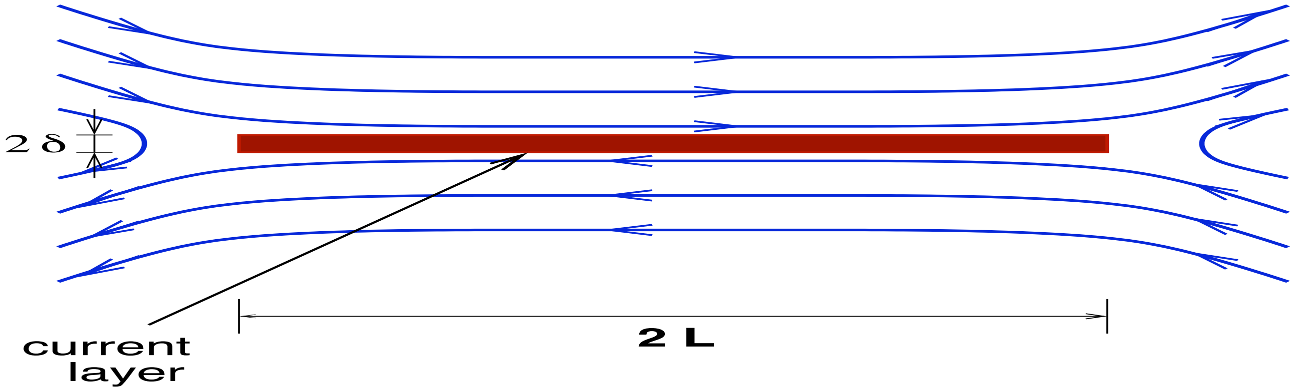
(D. Uzdensky & J. McKinney, PoP 2011)

- 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

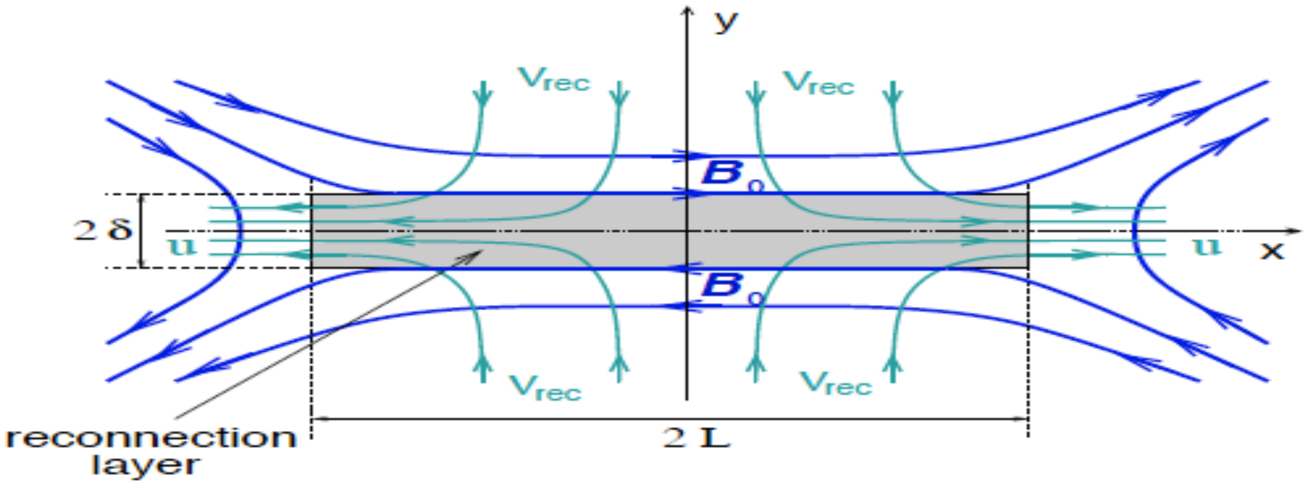


- Original SP model is incompressible -- OK even for low-$\beta^{upstream}$ plasmas.

- 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*:

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

where

$$\left\{\begin{array}{rcl} n(A) & = & n_0 A \\ k_B T(A) & = & k_B T_{\rm eq}\,A^{-1} \equiv A^{-1}\,\dfrac{B_0^2}{16\pi n_0} \end{array}\right.$$

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 $Q_{\rm rad}(A) = Q_{\rm ohm}(A) \simeq AQ_0$,

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

SUMMARY

- Radiative effects:
  - radiative cooling;
  - radiation pressure;
  - radiative (Compton) resistivity

are important in high-energy-density astrophysical environments.

- We started a program of investigating the effects of radiation on reconnection.
- First step: Sweet-Parker theory for resistive reconnection w. radiative cooling.
- Intense radiative cooling:
  - lowers layer temperature, which makes it more collisional and increases resistivity and hence reconnection rate;
  - unless there is strong B_{guide}, cooling + pressure balance → strong plasma compression, which also makes reconnection faster.
- Several astrophysically-important radiative mechanisms (bremsstrahlung, cyclo-synchrotron, and inverse-Compton) explored.