Magnetic Reconnection in Extreme Astrophysical Environments

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Conventional Reconnection Research:

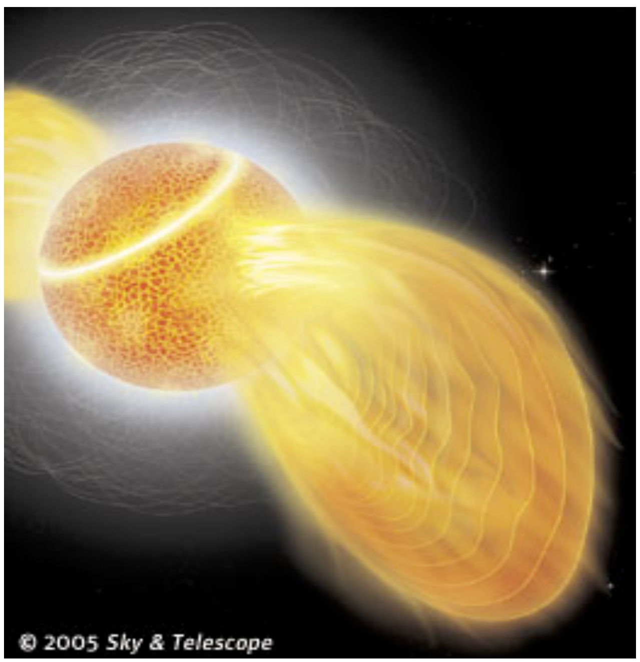
- Resistive MHD, two-fluid, or kinetic (PIC) studies of 2D or 3D reconnection in a plasma described as a collection of charged particles (electrons and ions or positrons) that are neither created or destroyed.
- Suitable for solar/stellar flares, Earth magnetosphere, laboratory plasma devices, pulsar magnetospheres at $r \approx R_{LC}$, star-disk interaction, etc.

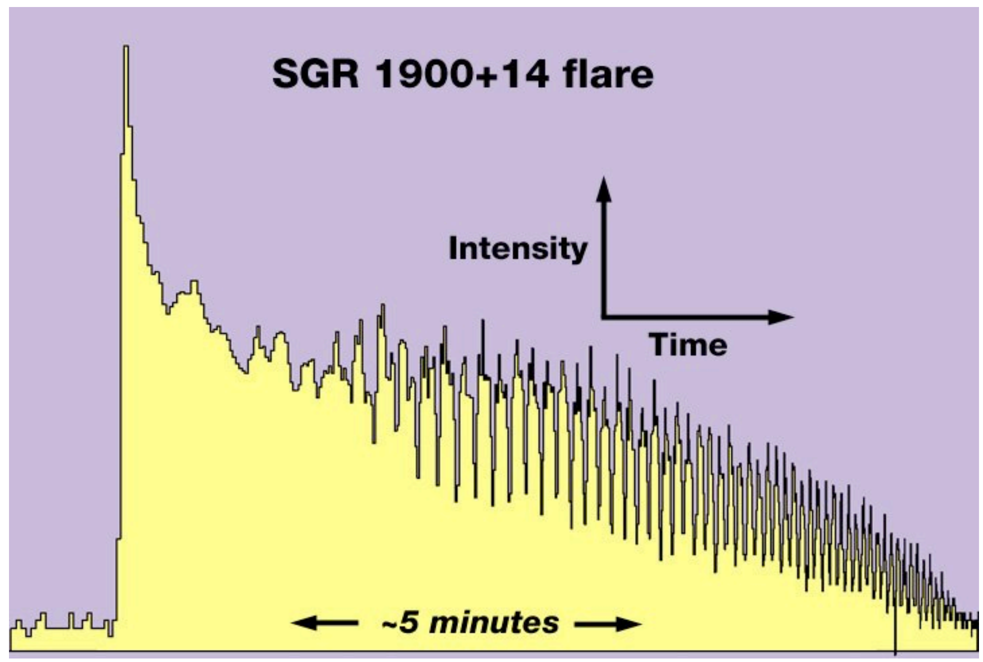
Reconnection in High-Energy Density (HED) Environments

- Particular example: reconnection of magnetar-strength ($B>10^{13}$ G) magnetic fields
- New direction of reconnection research
- Astrophysical applications: magnetar magnetospheres, GRB central engines & jets.
- Rich and exotic physics
- Example of High-Energy-Density reconnection

Motivation I: Magnetar (SGR) Flares

- Magnetars: isolated neutron stars with 10^{15} Gauss fields.
- Soft Gamma Repeaters (SGRs): magnetars exhibiting powerful (up to $10^{44} - 10^{46}$ ergs in ~ 0.3 sec) γ-ray flares.

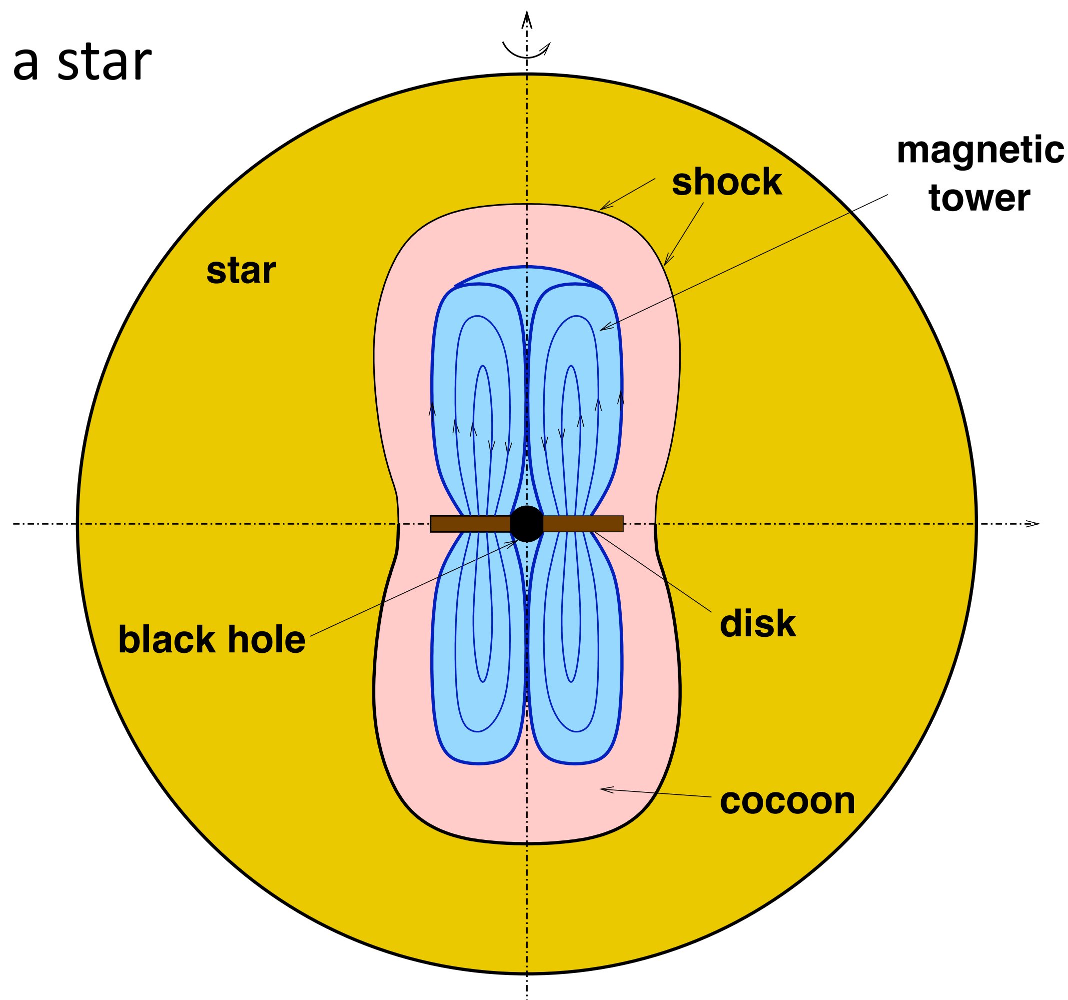




Reconnection Interpretation*: Thompson & Duncan 1995, 2001; Lyutikov 2003, 2006*

Motivation II: long Gamma-Ray Bursts

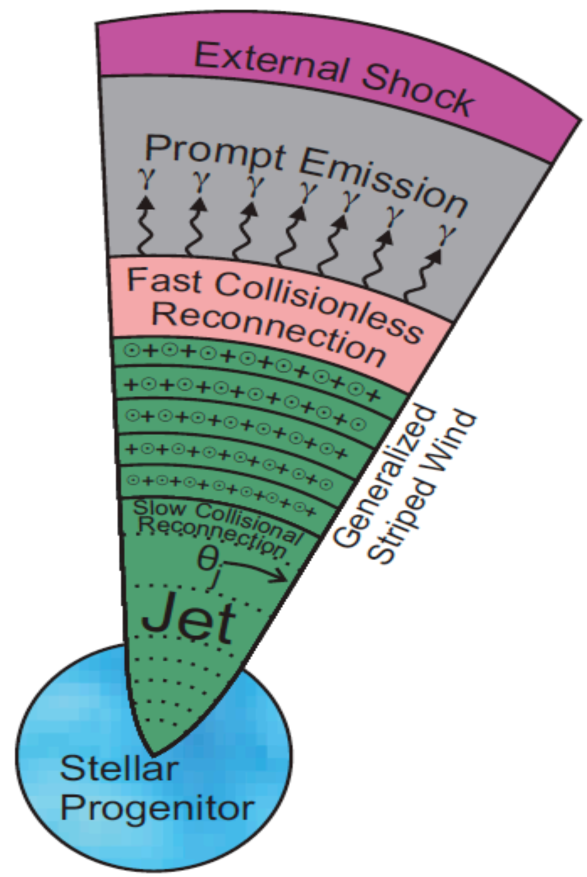
- Magnetic Tower jet inside a star



- Differential rotation→
field-line twisting→
kink instability →
current sheet formation →
reconnection?

Motivation III: dissipation in GRB jets

- Dissipation in magnetically dominated GRB jet to power prompt γ-ray emission



McKinney & Uzdensky 2010

Physics
of Extreme-field Reconnection

Critical Quantum Magnetic Field

- Critical Quantum Magnetic Field:

$$\hbar\Omega_e = m_e c^2 \;\Rightarrow\; \quad B_* \equiv \frac{m_e^2 c^3}{e\hbar} \simeq 4.4\times10^{13}\,\mathrm{G}\,.$$

- Magnetic Energy Density:

$$\frac{B_*^2}{8\pi} = \frac{1}{8\pi}\,(m_e c^2)^4\,\alpha^{-1}\,(\hbar c)^{-3} \;\simeq 8\times10^{25}\,\mathrm{erg\ cm^{-3}}\,.$$

-- High-Energy Density Physics Regime!

Critical novel physics issues
(different from conventional reconnection)

- Radiation:
  - Radiation pressure
  - Radiative cooling
  - Compton resistivity
- Pair creation
- (special relativity)

Radiation and Pair Production

- Pressure balance across layer or energy conservation determine central temperature, T_0:

$$P_{\mathrm{magn}} = \frac{B_0^2}{8\pi} = P_{\mathrm{rad}} = \frac{a}{3} T_0^4 \quad \Rightarrow \; \theta_e \equiv \frac{T}{m_e c^2} \simeq 2.2\, b^{1/2}$$

$\rightarrow$ **relativistically-hot plasma:** $T \sim m_e c^2$ **!**

$(b \equiv B_0/B_*.)$

Pair Production

- Copious pair production (Saha equilibrium):

$$n(\theta_e \ll 1) \simeq 2 \times 10^{30}\, \theta_e^{3/2}\, e^{-1/\theta_e}\, \mathrm{cm}^{-3}\,,$$

$$n(\theta_e \gg 1) \;\simeq\; 3.2 \times 10^{30}\, \theta_e^{3}\, \mathrm{cm}^{-3}\,.$$

- Current layer is dressed in optically-thick pair coat

Key Effects of Pair Production:

1. Reconnection is layer **optically thick**: $\tau = n\,\sigma\,\delta >> 1$

Yet, photon diffusion time across layer may be << global advection time along layer:

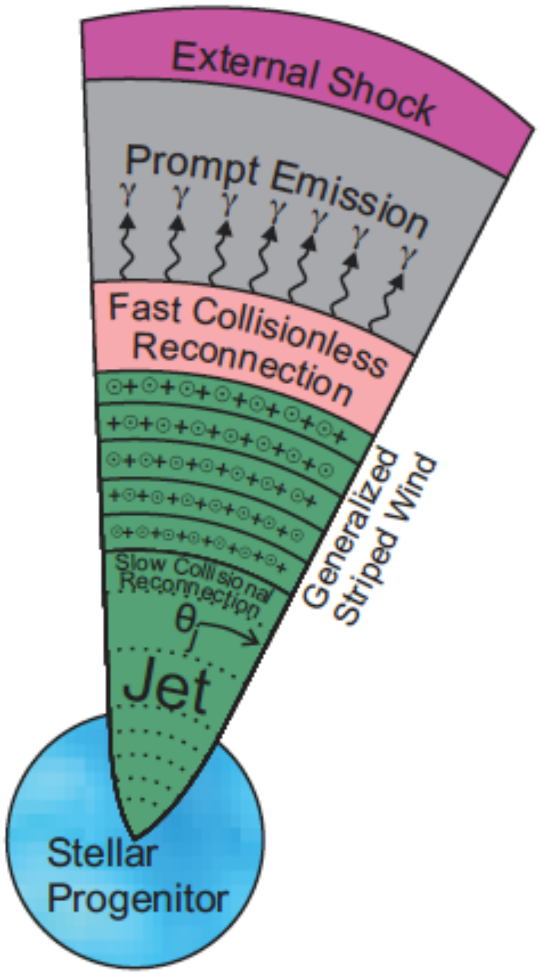
- **radiative cooling** dominates over advection.
- reconnection problem = **radiative transfer** problem!

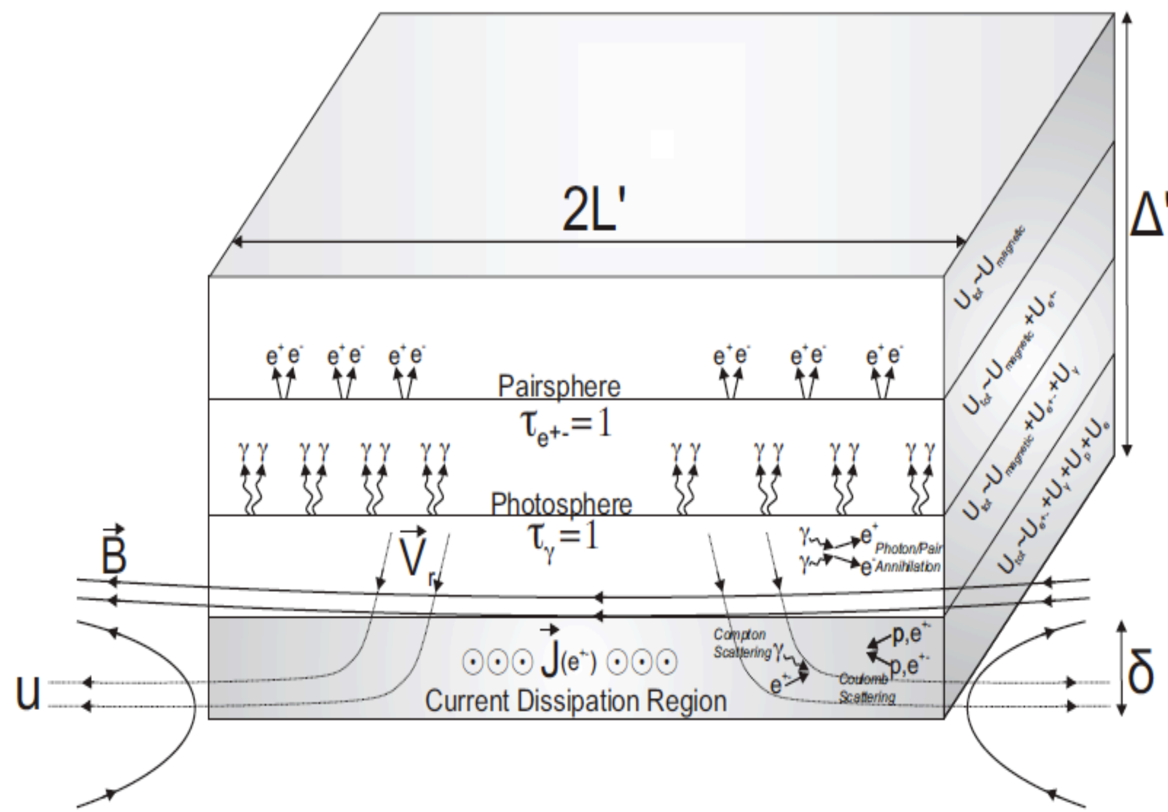
2. Reconnection layer is highly **collisional**:

$\delta_{SP} \gg d_e\,,\ \rho_e \sim 10^{-10}\,\mathrm{cm},\ \ \lambda_{e,mfp} \sim 10^{-6}\,\mathrm{cm}.$

- radiative resistive MHD should apply!
- resistive-MHD reconnection is still important!

Reconnection Switch to Trigger GRB Jet Dissipation (*McKinney & Uzdensky 2010*)





SUMMARY

- Reconnection of B ~ B_* ~ 4 x 10^{13} G fields is a new frontier in reconnection research --- example of High-Energy Density reconnection.
- High-Energy Astrophysics applications:
  - – Magnetar flares (SGR giant flares);
  - – GRB central engines and jets.
- Key physics issues:
  - – pair production
  - – radiation (and pair) pressure
  - – Layer is optically thick
  - – Radiative cooling across layer dominates over advection along layer
  - – Reconnection becomes radiative transfer problem
  - – Layer is highly collisional: $\delta_{SP} \gg d_e, d_i$, $\Rightarrow$ resistive radiation-MHD
- Caveats and open questions abound!

Pairs trap radiation:

- High pair density $\Rightarrow$ layer is optically thick:

$$\tau = n\,\sigma\,\delta >> 1$$

– in sharp contrast with conventional reconnection.

- Yet, photon diffusion time across layer may be << global advection time along layer:

$$\tau_{\rm rad,diff} \sim \frac{\delta}{c}\tau \ll \tau_A \equiv \frac{L}{c},$$

if $\tau << L/\delta$

- **Radiative cooling** dominates over advection.

- Fundamentally, the reconnection problem becomes

a **radiative transfer** problem!

Collisionality of Reconnection Layer

- EXAMPLE (Uzdensky & MacFadyen 2006):
- $B_0 = 0.5\ B_* = 2 \times 10^{13}$ G, T ~ 300 keV, $n_e \sim 2 \times 10^{29}\ \mathrm{cm}^{-3}$.
- Spitzer resistivity: $\eta_S = 0.1\ \mathrm{cm}^2/\mathrm{sec}$

(photon drag gives comparable contribution)

- Typical global scale: L = 10 km
- Lundquist number: $S = Lc/\eta_S \sim 10^{18}$
- Sweet-Parker layer thickness: $\delta_{SP} = L\ S^{-1/2} \simeq 10^{-3}$ cm.
- $\delta_{SP} \ll L$, but $\delta_{SP} \gg d_e \sim 10^{-9}$ cm, $\rho_e \sim 10^{-10}$ cm, $\lambda_{e,mfp} \sim 10^{-6}$ cm.
- Thus, reconnection layer is highly collisional, resistive MHD (with Compton drag) should apply!

Additional Possible Complications:

- **Quantum effects** of the super-strong magnetic field on microphysics
  – discrete, quantized electron gyro-orbits (Landau levels);
  – effects on radiation propagation (e.g., photon splitting, suppression of Compton scattering).

- **Relativistic motions:** v ~ c ⇒special-relativistic effects: Lorentz contraction, time dilation, etc.

- Optically-thin **neutrino cooling**: $ee^+ \rightarrow \nu\bar{\nu}$

$$Q_\nu^- \sim 10^{25}\, T^9_{MeV}\ \text{erg cm}^{-3}\,\text{s}^{-1}$$