Plasma Astrophysics
Chapter 10: Magnetic Reconnection

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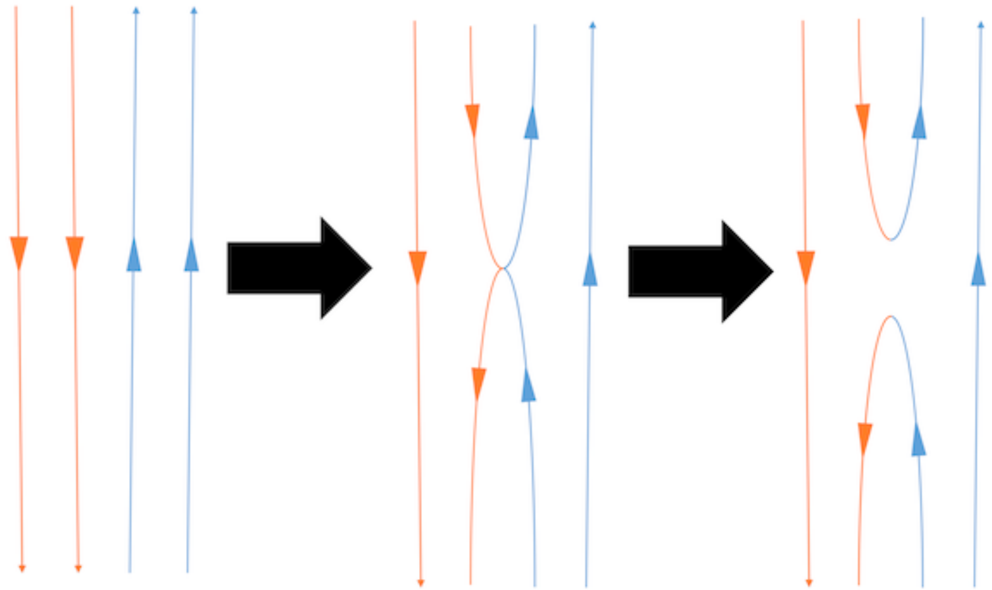
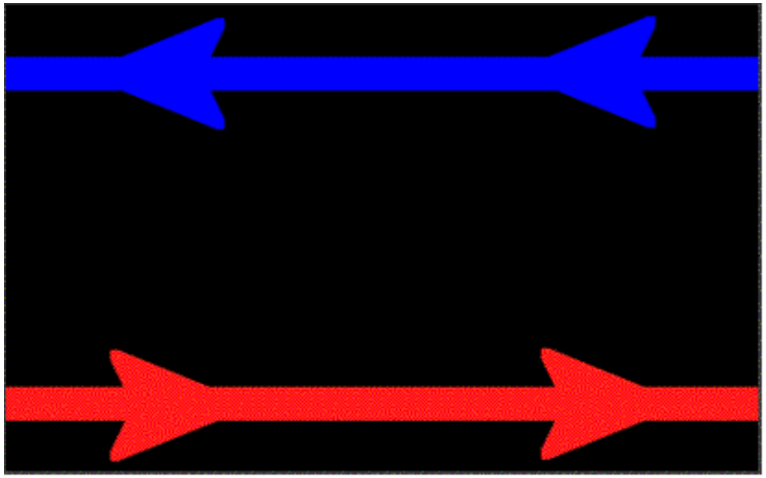
Magnetic reconnection

- Ideal MHD gives frozen in magnetic fields.
- Resistive MHD allows diffusion of fields.
- Magnetic reconnection occurs through diffusion.



- *Magnetic reconnection* is the process of a rapid rearrangement of magnetic field topology.



Magnetic reconnection (cont.)

- Magnetic reconnection is transient phenomena (flaring event).
- This process leads rapid and violent release of stored magnetic energy (to thermal and kinetic energies, particle acceleration).

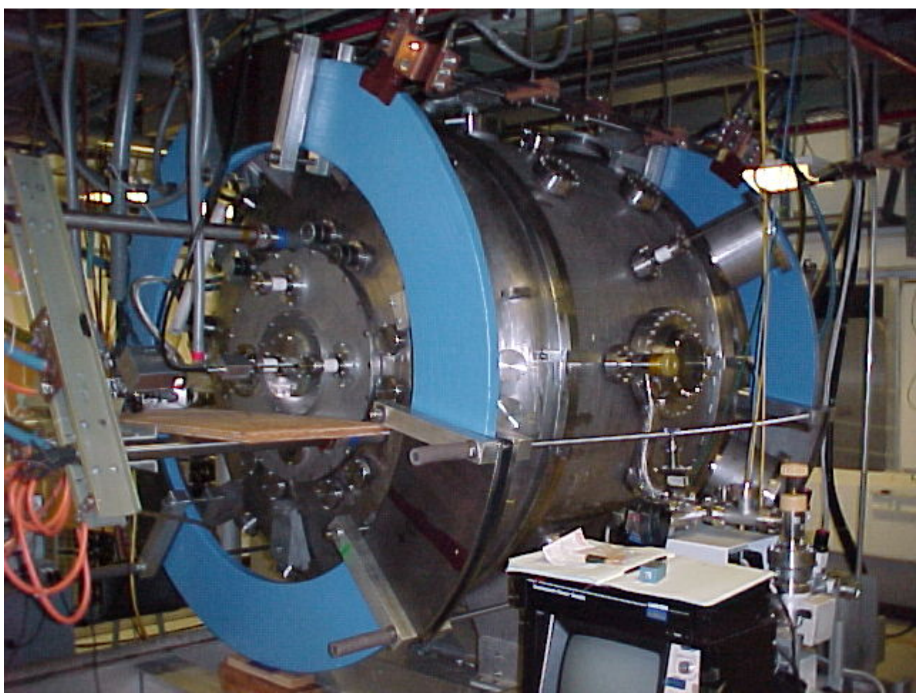
- In the universe,
- interplanetary magnetic field => aurora in planet (earth etc.)
- Sun (flare, CME)
- Pulsar wind, Pulsar wind nebula and Pulsar jets (flare)
- Magnetar flare
- Relativistic jets (flare, time variability)
- Gamma-ray bursts (time variability)

- Magnetic reconnection is observed in laboratory plasma experiment. Therefore, magnetic reconnection is real physical phenomena.

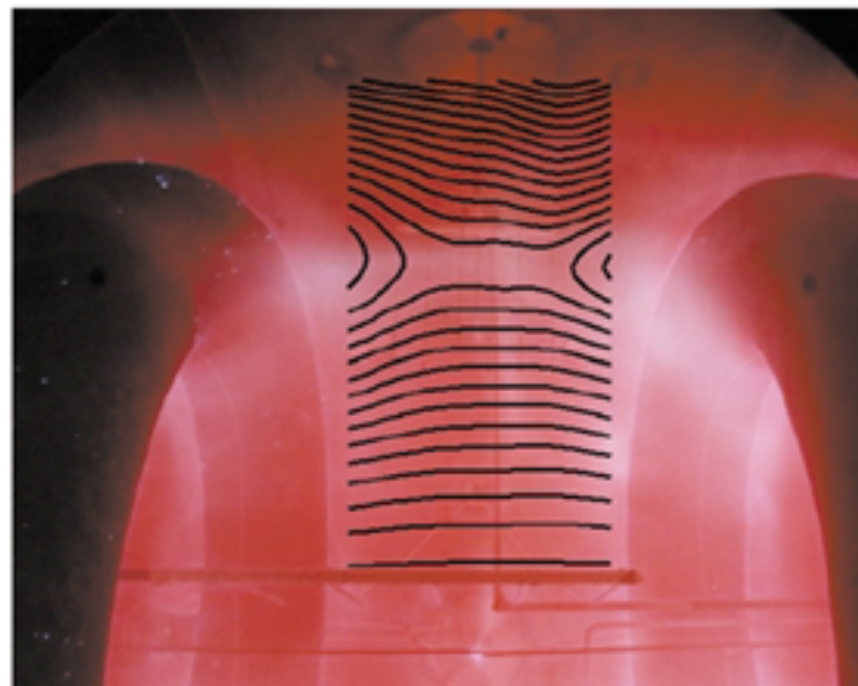
Magnetic reconnection in Laboratory

Laboratory Plasma Experiment

Magnetic Reconnection Experiment (MRX)



Magnetic reconnection seen in MRX



Magnetic reconnection in Planetary magnetosphere

Planetary (Earth) magnetosphere, aurora (substorm)

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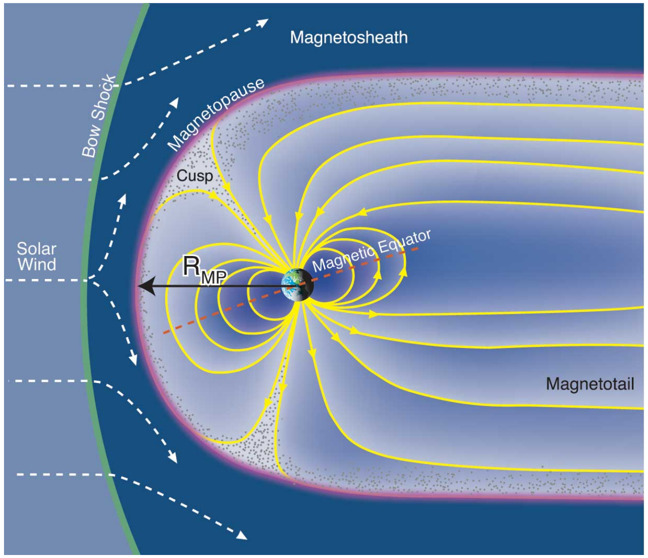

Magnetic reconnection in the Sun

Two ribbon flare (top of view of solar flare)

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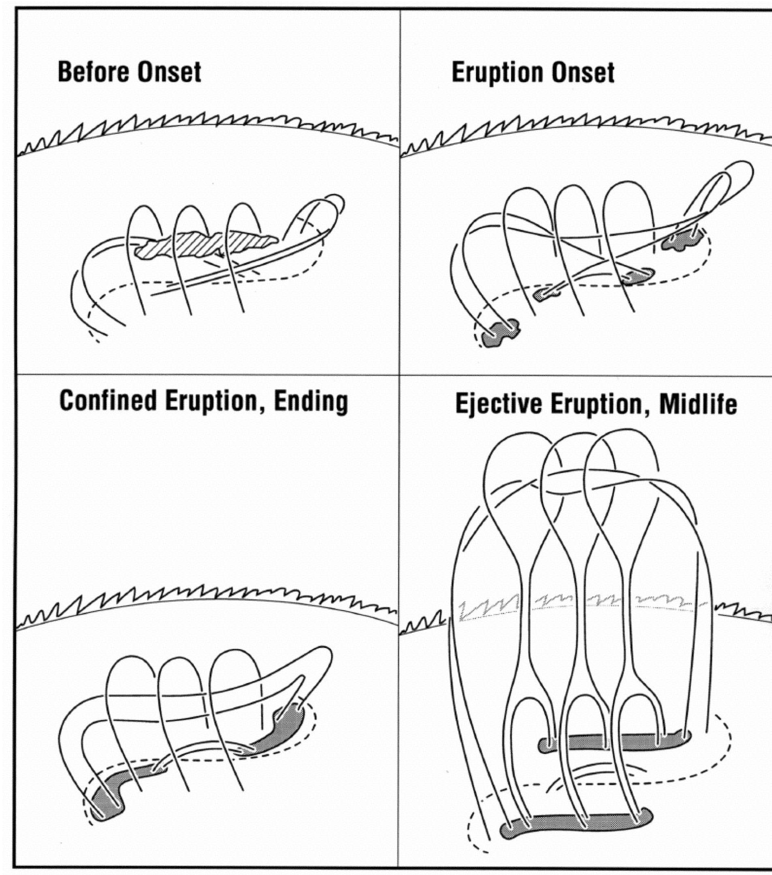
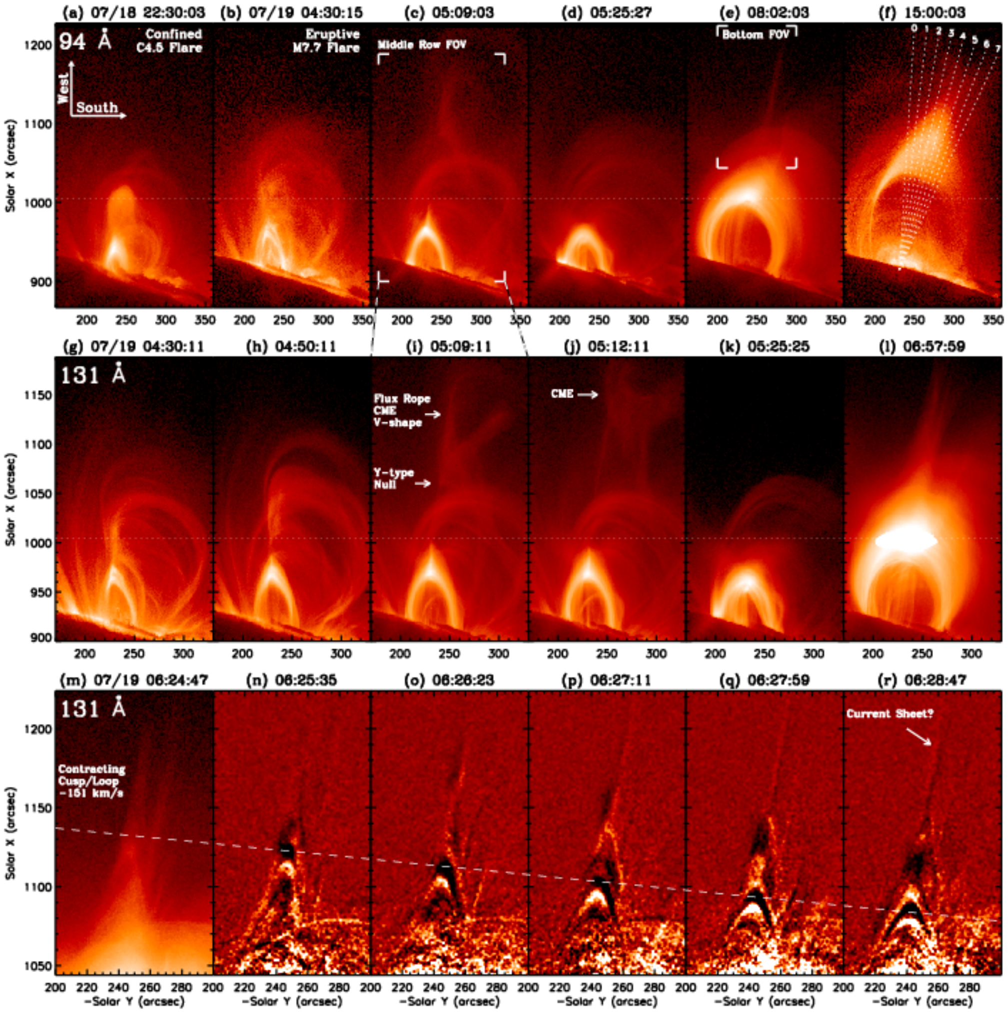
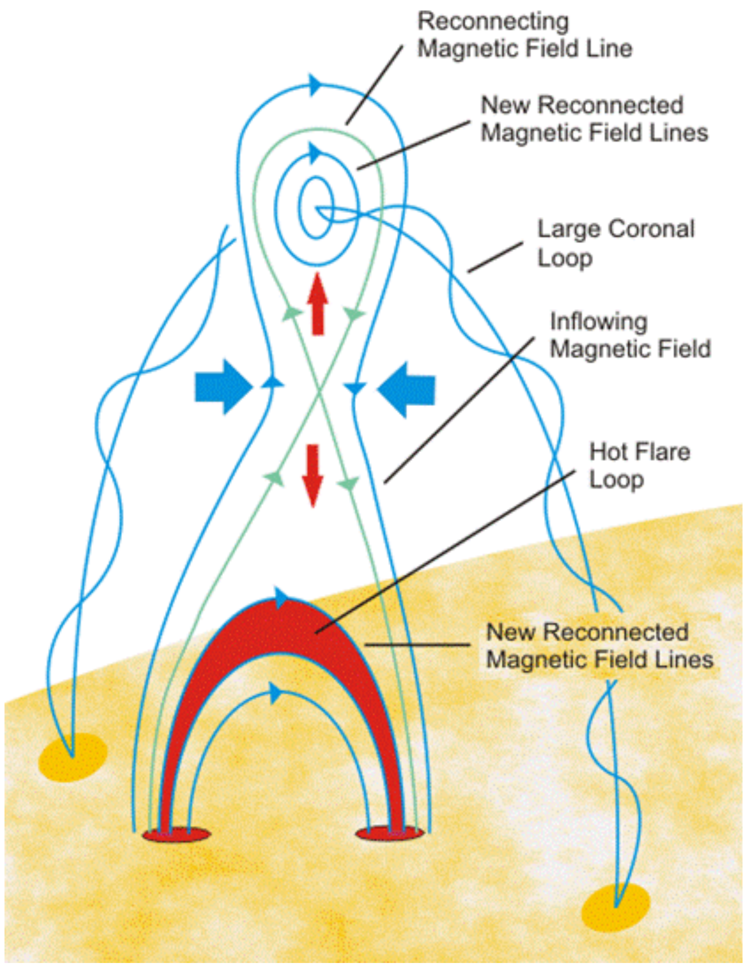


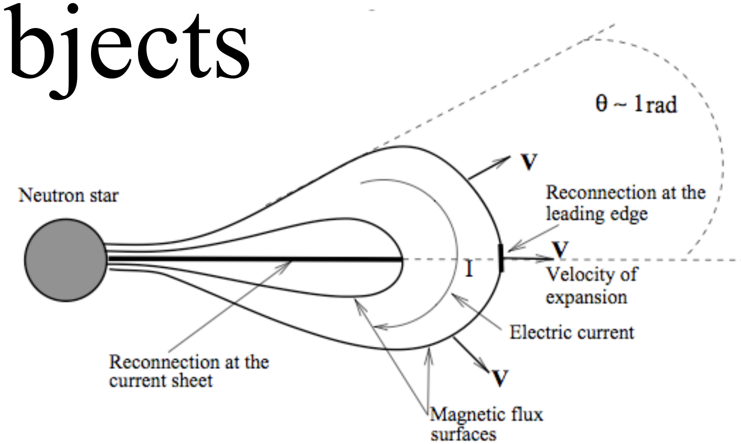
Magnetic reconnection in the Sun (cont.)

Cusp flare (side view of Solar Flare}





Magnetic Reconnection in Relativistic Astrophysical Objects



Pulsar Magnetosphere & Striped pulsar wind

• obliquely rotating magnetosphere forms stripes of opposite magnetic polarity in equatorial belt

• magnetic dissipation via magnetic reconnection would be main energy conversion mechanism

Magnetar Flares

• May be triggered by magnetic reconnection at equatorial current sheet

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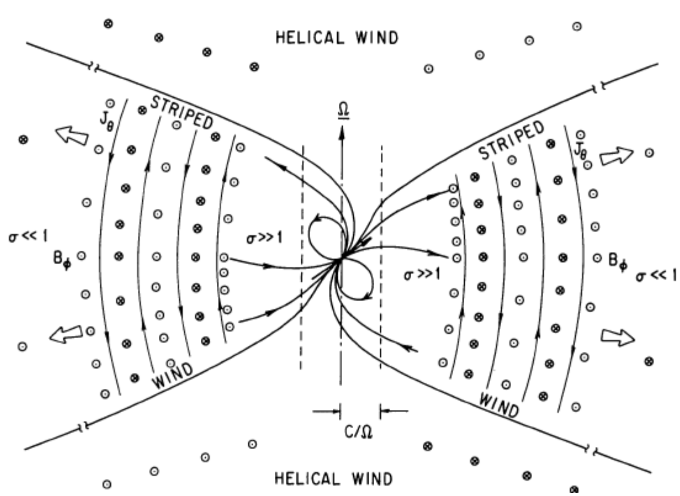


Magnetic diffusion

- Consider the simplest case in which magnetic field (or current) dissipates only by resistivity (= diffusivity)
- In this case, diffusion time for solar flare case becomes

$$\tau_D = L^2/\eta \simeq 10^{14}(L/10^9\mathrm{cm})^2(T/10^6\mathrm{K})^{3/2}\mathrm{sec}$$

- Where L is typical size of solar flare, η is magnetic diffusivity (= $c^2/4\pi\sigma$) and becomes

$$\eta \simeq 10^{13}T^{-3/2} \simeq 10^4(T/10^6\mathrm{K})^{-3/2}\mathrm{cm}^2\mathrm{s}^{-1}$$

for coulomb collision. This is called *classical resistivity* or *Spitzer resistivity.*

- The diffusion time becomes 10^{14} sec ~ 3 million year. It is difficult to explain solar flare time scale (10-100 sec ~ 10-100 τ_A).

Spitzer resistivity

- Classical model of electrical resistivity based on electron ion collisions
- Collision term: $P_{ei} = \nu_{ei} n_e m_e (v_e - v_i)$ (see ch 3.5)
- Collisions are Coulomb collisions, P_{ei} is proportional to Coulomb force (e^2) and densities, so we can write

  $P_{ei} = \eta e^2 n^2 (v_e - v_i)$ (see ch 4, here $q = e$)
- So collision frequency is written as $\nu_{ei} = (ne^2/m_e)\eta$

- Collision cross section: $\sigma = \pi r_c^2 = e^4/16\pi\epsilon_0^2 m_e^2 v_e^4$ (see ch 1, here $mv^2 \sim 3/2\, k_B T$)
- Collision frequency: $\nu_{ei} = n\sigma v_e = ne^4/16\pi\epsilon_0^2 m_e^2 v_e^3$
- Resistivity is ($mv^2 \sim 3/2\, k_B T$)

$$\eta \approx \frac{\pi e^2 m_e^{1/2}}{(4\pi\epsilon_0)^2 (k_B T)^{3/2}}$$

Spitzer resistivity (cont.)

- This resistivity is considered large-angle collision alone. Therefore we also need to consider small-angle collision
- Spitzer is shown as

$$\eta \approx \frac{\pi e^2 m_e^{1/2}}{(4\pi\epsilon_0)^2 (k_B T)^{3/2}} \ln \Lambda$$

Spitzer resistivity

- Λ is plasma parameter (see ch.1)

Magnetic diffusion (cont.)

- Dynamical time scale is defined as the Alfven transit time, $\boldsymbol{\tau_A}$

$$\tau_A = L/v_A \simeq 1(L/10^9\mathrm{cm})(B/100\mathrm{G})^{-1}(n/10^9\mathrm{cm}^{-3})^{1/2}\mathrm{sec}$$
$$v_A = B/(\mu_0\rho)^{1/2} \simeq 10^4(B/100\mathrm{G})(n/10^9\mathrm{cm}^{-3})^{-1/2}\mathrm{km/s}$$

- The magnetic Reynolds number (Lundquist number) R_m (S) is defined by

$R_m \equiv \mu_0 v L/\eta$ (see ch 4) $S \equiv \mu_0 v_A L/\eta$ (*Lundquist number*)

$$S \simeq \tau_D/\tau_A = v_A L/\eta$$
$$\simeq 10^{14}(L/10^9\mathrm{cm})(T/10^6\mathrm{K})^{3/2}(B/100\mathrm{G})(n/10^9\mathrm{cm}^{-3})^{-1/2} \quad (10.1)$$

- Explosive magnetic energy release occurs even though S ($\sim R_\mathrm{m}$) >> 1 in every kind of hot plasma. This puzzle is considered to be one of the most difficult and fundamental problem in nature.

Magnetic Reynolds / Lundquist number

- The magnetic Reynolds number: $R_m \equiv \mu_0 v L / \eta$
- Lundquist number: $S \equiv \mu_0 v_A L / \eta$

- If the typical velocity of motion is Alfven speed, $v=v_A$, magnetic Reynolds number = Lundquist number
- The magnetic reconnection is treated the dynamics of magnetic field. So the typical velocity of motion is Alfven speed.
- Therefore in the study of magnetic reconnection

$$R_m = S = \mu_0 v_A L / \eta$$

Magnetic diffusion (cont.)

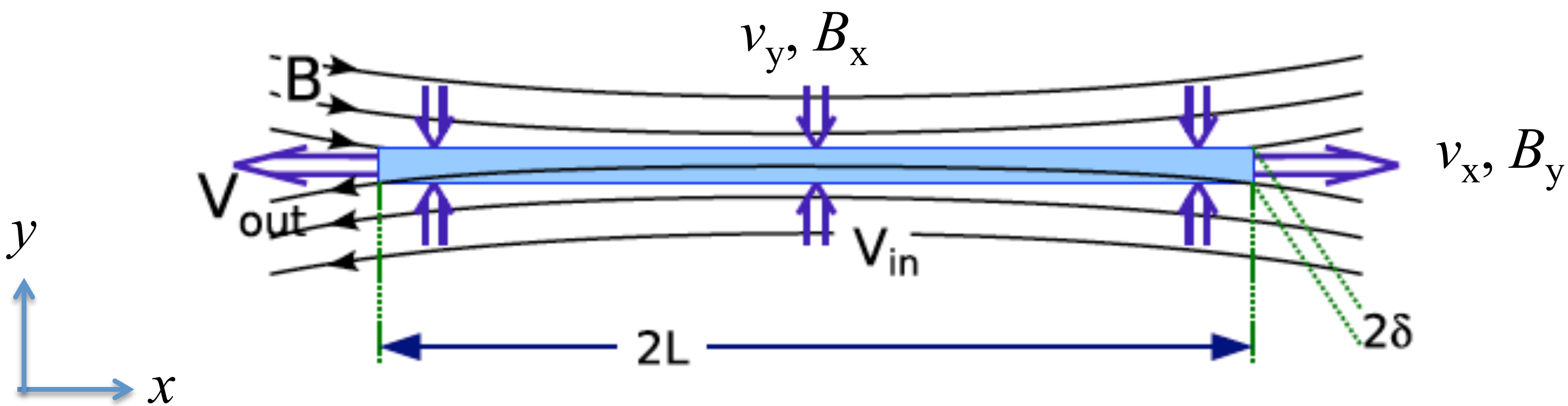
	Magnetopause	Magnetotail	Solar corona (flares)
n_0 [cm^{-3}]	4	0.5	$6 \cdot 10^8$
B_0 [nT]	40	20	$3 \cdot 10^7$
L_0 [m]	10^6	10^7	10^7
v_A [m/s]	$4.4 \cdot 10^5$	$6.2 \cdot 10^5$	$2.7 \cdot 10^7$
τ_A $[s]$	2.3	1.6	0.37
T_i $[K]$	10^6	$5 \cdot 10^7$	10^6
T_e $[K]$	10^5	$5 \cdot 10^6$	10^6
ω_{pe} [s^{-1}]	$1.1 \cdot 10^5$	$4.0 \cdot 10^4$	$1.4 \cdot 10^9$
Λ	$1.3 \cdot 10^{11}$	$1.3 \cdot 10^{13}$	$7 \cdot 10^7$
Collision frequency ν_c [s^{-1}]	$2 \cdot 10^{-7}$	10^{-9}	10
λ_e [m]	$2.7 \cdot 10^3$	$8.0 \cdot 10^3$	0.2
τ_{diff} $[s]$	$7 \cdot 10^{11}$	$1.5 \cdot 10^{15}$	$2.5 \cdot 10^{14}$
R	$3 \cdot 10^{11}$	10^{15}	10^{15}

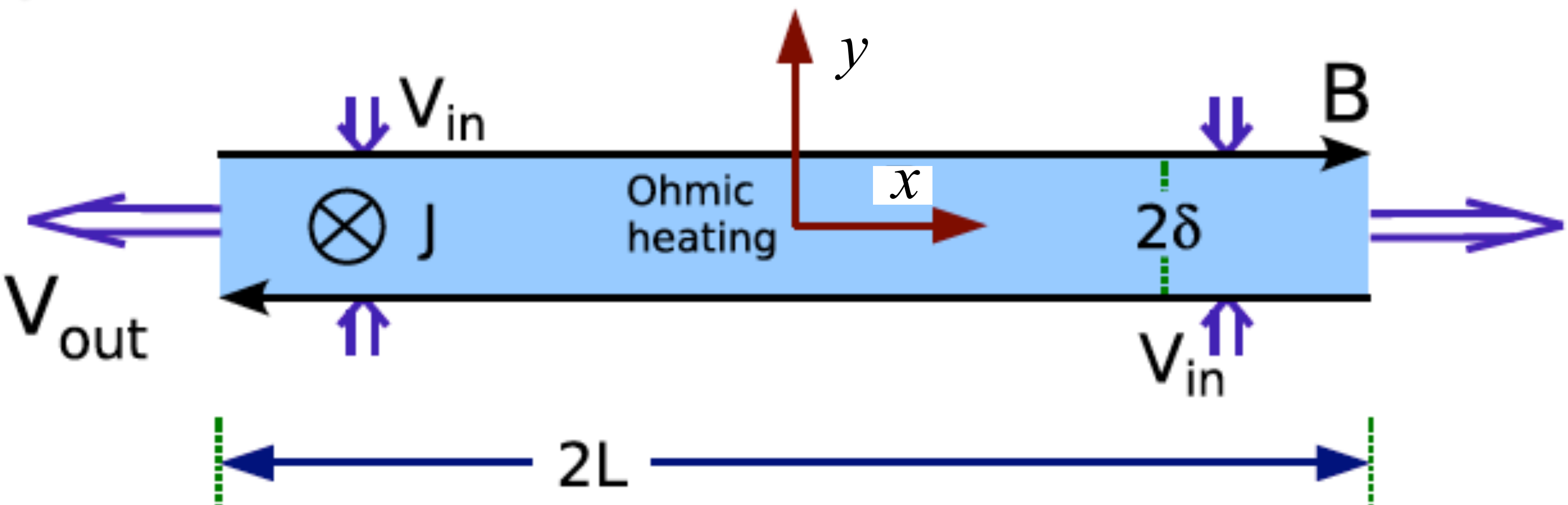
Lundquist number (R)

Sweet-Parker Model

- Sweet (1958) and Parker (1957) have developed a simple theory of steadily driven reconnection, taking into account the effect of plasma flow (2D model).
- Consider current sheet (or diffusion region) has a total length of $2L$ and total thickness of 2δ (aspect ratio of the diffusion region is fixed).
- At the inflow region, a magnetic field B_0 that is strongly tangential to the inflow boundary. The inflow velocity is approximately constant with $v_{\rm in}$.
- At the outflow boundary the magnetic field is $B_{\rm out}$ and the outflow velocity is $v_{\rm out}$
- The the region inside the diffusion region is assumed to be dominated by diffusion and the outside region is assumed to be ideal.

Sweet-Parker Model (cont.)





Diffusion region (current sheet)

$$v_{in} = v_y, \; B_{in} = B_x \quad v_{out} = v_x, \; B_{out} = B_y$$

Sweet-Parker Model (cont.)

- First we estimate the inflow velocity to diffusion region.
- From the assumption, there is no current in inflow region. Therefore, from Ohm's law,

$$E = -v_{in} B_{in}$$

$$\boldsymbol{E} = -(\boldsymbol{v} \times \boldsymbol{B}) + \eta \boldsymbol{j}$$

- At the center (diffusion region), there is no magnetic field. Hence from induction equation

$$E = \eta j$$

- From Ampere's law, The current at the center is roughly estimated as

$$j = \frac{B_{in}}{\mu_0 \delta}$$

$$\boldsymbol{j} = \nabla \times \boldsymbol{B} / \mu_0$$

- From them, the inflow velocity is

$$v_{in} = \frac{\eta}{\mu_0 \delta} \qquad (10.2)$$

Sweet-Parker Model (cont.)

- From mass conservation, inflowing mass and outflowing mass is conserved:

$$L v_{in} \rho = \delta v_{out} \rho$$

$$v_{in} = v_y, \; B_{in} = B_x$$

$$v_{out} = v_x, \; B_{out} = B_y$$

- This gives velocity ratio:

$$\frac{\delta}{L} = \frac{v_{in}}{v_{out}} \qquad (10.3)$$

- The same relation is hold for magnetic field

$$\frac{B_{in}}{B_{out}} = \frac{v_{in}}{v_{out}} = \frac{\delta}{L} \qquad (10.4)$$

Sweet-Parker Model (cont.)

- We calculate the outflow velocity. Consider the equation of motion (assuming steady and ignore pressure) in x-direction (parallel to outflow),

$$\rho(\boldsymbol{v} \cdot \nabla) v_x = (\boldsymbol{j} \times \boldsymbol{B})_x$$

$$\rho v_x \frac{\partial v_x}{\partial x} = \frac{1}{\mu_0}\left(-\frac{\partial}{\partial x}\frac{B^2}{2} + (\boldsymbol{B} \cdot \nabla) B_x\right)$$

- Along center of diffusion region, $\partial B_x/\partial x = 0, \ \partial B_y/\partial x \approx 0$
- Therefore the equation of motion is

$$\rho v_x \frac{\partial v_x}{\partial x} \approx \frac{B_y}{\mu_0}\left(\frac{\partial B_x}{\partial y}\right)$$

$$v_{in} = v_y, \ B_{in} = B_x$$
$$v_{out} = v_x, \ B_{out} = B_y$$

- This gives the result:

$$\rho \frac{v_{out}^2}{L} \approx \frac{B_{out} B_{in}}{\mu_0 \delta} \quad (10.5)$$

Sweet-Parker Model (cont.)

- We put the relation $B_{out}/\delta = B_{in}/L$ (10.4) into this equation,

$$\rho \frac{v_{out}^2}{L} \approx \frac{B_{out} B_{in}}{\mu_0 \delta}$$

- This gives

$$v_{out}^2 \approx \frac{B_{in}^2}{\mu_0 \rho} = v_{A,in}^2 \qquad (10.6)$$

- That is, the outflow velocity (reconnection jet(outflow)) is of the order of the Alfven speed in inflow region.

Sweet-Parker Model (cont.)

- We calculate the reconnection rate. Using eq(10.2) and (10.3), the inflow velocity is written as

$$v_{in}^2 = \eta v_{A,in}/\mu_0 L$$

$$S = \mu_0 v_A L/\eta$$

$$v_{in} = v_{A,in}\frac{\delta}{L} = \frac{v_{A,in}}{\sqrt{S}} \qquad (10.7)$$

- The resulting *reconnection rate* for the Sweet-Parker model is

$$E = \eta j = \frac{\eta B_{in}}{\mu_0 \delta} = \frac{B_{in} v_{A,in}}{\sqrt{S}}$$

- Thus the *reconnection rate* normalized to the typical electric field $E = B_{in} v_{A,in}$ is

$$r = \frac{v_{in}}{v_{A,in}} = \frac{\delta}{L} = \frac{1}{\sqrt{S}}$$

Normalized reconnection rate

Sweet-Parker Model (cont.)

- Since Lundquist (magnetic Reynolds) number is typically very large number, the resulting reconnection rate is very small.
- This implies also a very large aspect ratio L/δ (see normalized reconnection rate).

- In solar flare case, the time scale of Sweet-Parker reconnection is

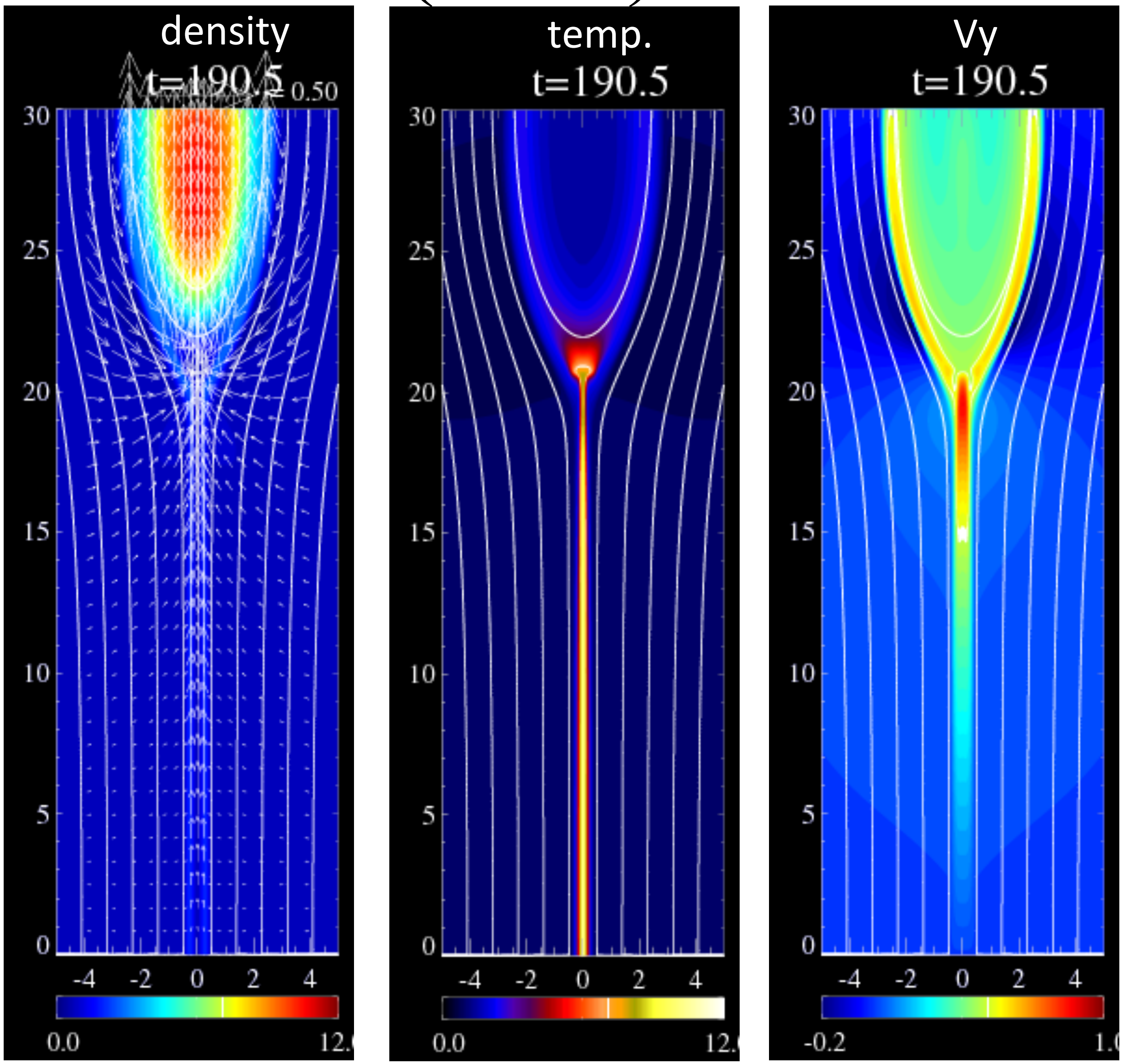
$$\tau_{SP} = L/v_{in} = L\sqrt{S}/v_{A,in} \approx 10^7 \mathrm{sec}$$

- This is not fast enough to explain the solar flare (10-100 sec).
- Sweet-Parker reconnection is *slow reconnection*
- Using classical resistivity, the thickness of diffusion region for solar flare is

$$\delta \simeq L/\sqrt{S} \sim 1 \text{ m}$$

Sweet-Parker Model (cont.)

density



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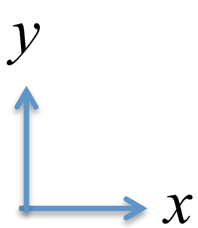
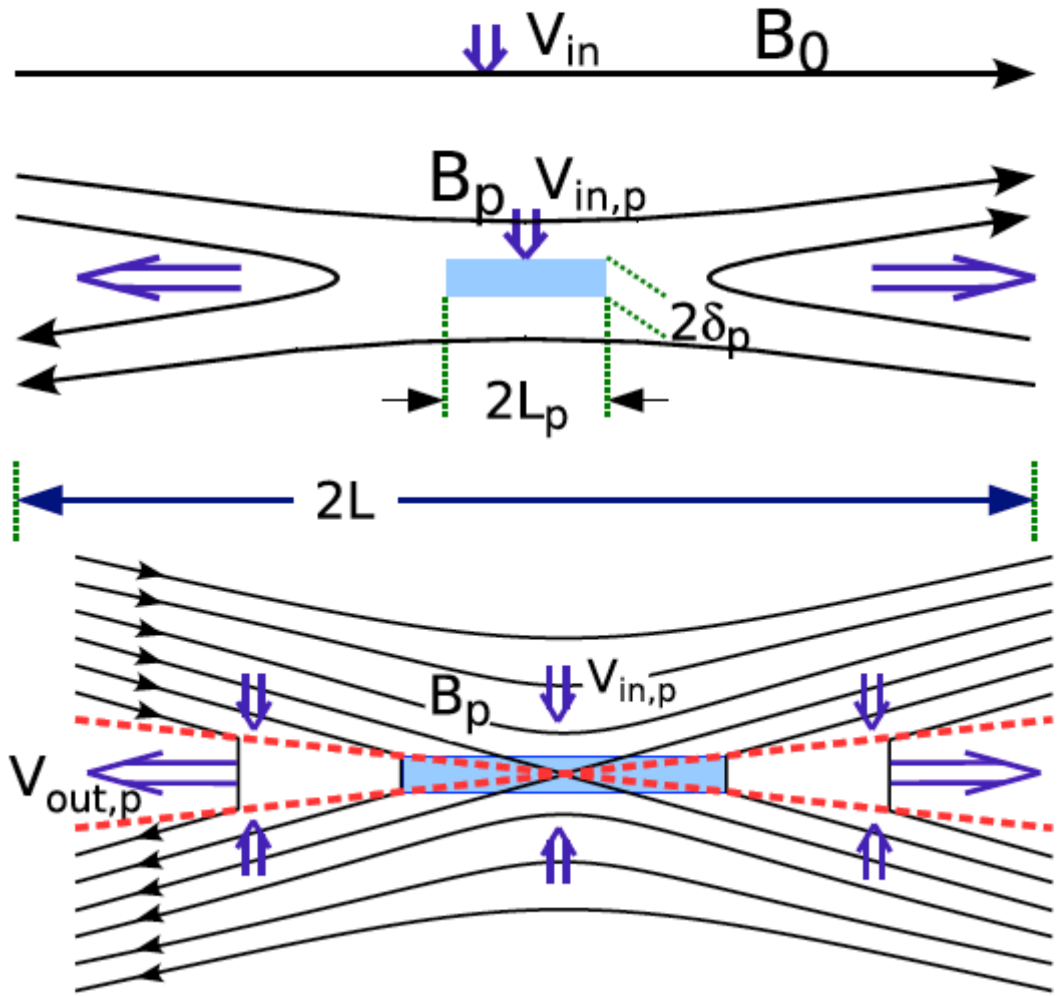
Petschek Model

- The large aspect ratio limits the possible reconnection rate in the Sweet-Parker model
- Petschek (1964) realized that a much larger reconnection rate would be possible if the diffusion region were much shorter.
- The main point in Petschek's model is that the length of the diffusion region should be much shorter $L_p \ll L$ in order to realize a higher reconnection rate.
- A much shorter diffusion region also implies a thinner diffusion region, i.e., $\delta_p \ll \delta$, because faster reconnection implies a larger electric field and a higher current density at the x-line.
- The fast transport out of this diffusion region over the scale from L_p to L occurs through a flow layer which is bounded by slow shocks.

Petschek Model (cont.)

$$v_{in} = v_y, \; B_{in} = B_x$$
$$v_{out} = v_x, \; B_{out} = B_y$$





Petschek Model (cont.)

- First look at the scaling in the vicinity of diffusion region.
- The magnetic field in the inflow of the Petschek region is denoted $B_{\text{in,p}}$ which is smaller than B_{in}

- However, from magnetic flux conservation

  $v_{\text{in}}B_{\text{in}}=v_{\text{in,p}}B_{\text{in,p}}$ (and assuming constant mass density)

  using $v_{A,p} = B_{in,p}/\sqrt{\mu_0\rho} = v_A B_{in,p}/B_{in}$
- the inflow Alfven Mach number is ($\mathcal{M}_{in} = v_{in}/v_A$)

$$\frac{\mathcal{M}_{in}}{\mathcal{M}_{in,p}} = \frac{v_{in}}{v_{in,p}}\frac{v_{A,p}}{v_A} = \frac{B_{in,p}^2}{B_{in}^2} \qquad (10.8)$$

Petschek Model (cont.)

- Using $S = \mu_0 L v_A/\eta, \quad S_p = \mu_0 L_p v_{A,p}/\eta$
  and the relation $S_p = v_{A,p}^2/v_{in,p}^2 = 1/\mathcal{M}_{in,p}^2$
  for length scale we obtain

$$\frac{L_p}{L} = \frac{S_p}{S}\frac{v_A}{v_{A,p}} = \frac{1}{S}\frac{v_A}{v_{A,p}}\frac{v_{A,p}^2}{v_{in,p}^2} = \frac{1}{S}\frac{v_{A,p}^2}{v_{in,p}^2}\frac{B_{in}}{B_{in,p}} \qquad (10.9)$$

- Using $B_{in}/B_{in,p} = \mathcal{M}_{in,p}^{1/2}/\mathcal{M}_{in}^{1/2}$ (from eq(10.8)) , we obtain

$$\frac{L_p}{L} = \frac{1}{S}\frac{1}{\mathcal{M}_{in,p}^{3/2}}\frac{1}{\mathcal{M}_{in}^{1/2}} \qquad (10.10)$$

- or

$$\frac{\delta_p}{L} = \frac{L_p}{L}\frac{1}{\sqrt{S_p}} = \frac{1}{S}\frac{1}{\mathcal{M}_{in,p}^{1/2}}\frac{1}{\mathcal{M}_{in}^{1/2}} \qquad (10.11)$$

Petschek Model (cont.)

- Thus, once we have determined $B_{in,p}$/ B_{in}, we can obtain the ratio of the inflow Mach numbers as well as the scale of the Petschek diffusion region.
- This is just a re-scaling of the diffusion region in size and is applicable to any smaller scale diffusion region.
- Note that similar to the Sweet-Parker model, Petschek reconnection model also does not treat the diffusion region self-consistently.
- The main insight from Petschek model is that the the transport from L_p to L does not require the thin outflow layer.
- Petschek suggested that the outflow region is bounded by two slow switch-off shocks.
- This is strictly only true if the shocks are horizontal, i.e., aligned with the x-direction.
- But, since the shocks are only very slightly inclined, the error in the assumption of switch-off shocks is small

Petschek Model (cont.)

- From the discussion of switch-off slow shocks, away from diffusion region, to satisfy the switch-off shock condition, the plasma in outflow region is jetting with at the speed of

$$v_{out,p} = v_{At,p} \approx B_{in,p}/\sqrt{\mu_0 \rho} \qquad (10.12)$$

- Noted that the actual normal velocity in the downstream (outflow) region is 0.
- This means that the slow shock is moving with a velocity

$$v_{nu} = v_{An} = B_n/\sqrt{\mu_0 \rho}$$

toward the upstream (inflow) region.

Petschek Model (cont.)

- The prior discussion assumes that the density is constant, which is incorrect for a slow shock.
- We can compute the outflow density from the switch-off shock properties.
- To do so, one has to determine the angle of the upstream magnetic field with the shock normal.
- The tangential and normal components are $B_{\mathrm{in,p}}$ and B_{n}
- Magnetic flux conservation implies $v_{nu} B_{in,p} = v_{At,p} B_n$
- The angle the upstream magnetic field is

$$\tan\theta = \frac{B_n}{B_{in,p}} = \frac{v_{nu}}{v_{At,p}} = r_p \qquad (10.12)$$

- where r_{p} is the reconnection rate for the Petschek diffusion region

Petschek Model (cont.)

$$\tan\theta = \frac{B_n}{B_{in,p}} = \frac{v_{nu}}{v_{At,p}} = r_p$$

- This indicates that $\theta \approx r_p \ll 1.$
- In this case, inflow velocity is $v_{in} \approx \theta v_{A,p}$

Petschek Model (cont.)

- Determine the magnetic field at the diffusion region $B_{\mathrm{in,p}}$
- This field is modified because the field in the vicinity of the diffusion region is curved and different from the field B_{in} at large distance from the diffusion region

- From long calculations, the magnetic field at the diffusion region is obtained as

$$B_{in,p} = B_{in} - \frac{4B_n}{\pi} \ln \frac{L}{L_p} = B_{in} \left(1 - \frac{4\mathcal{M}_{in}}{\pi} \ln \frac{L}{L_p} \right) \quad (10.13)$$

Petschek Model (cont.)

- For $\frac{4\mathcal{M}_{in}}{\pi} \ln \frac{L}{L_p} \leq \frac{1}{2}$, eq(10.13) implies roughly $B_{in,p} \approx B_{in}$ such that $\mathcal{M}_{in,p} \approx \mathcal{M}_{in}$ (modification is small)
- From eq (10.10), the relations for the diffusion region scales become

$$\frac{L_p}{L} = \frac{1}{S}\frac{1}{\mathcal{M}_{in}^2}, \quad \frac{\delta_p}{L} = \frac{1}{S}\frac{1}{\mathcal{M}_{in}}$$

- Petschek suggested that the process becomes inefficient if $B_{in,p}$ becomes too small

Petschek Model (cont.)

- Assuming that a reasonable value for the minimum $B_{in,p}$ is $B_{in,p} \sim B_{in}/2$ yields for the approximate maximum inflow Mach number (or reconnection rate)

$$\mathcal{M}_{in} = r_p \approx \frac{\pi}{8\ln(L/L_p)} = \frac{\pi}{8\ln(\mathcal{M}_{in}^2 S)} \sim \frac{\pi}{8\ln S}$$

- This reconnection rate is much larger than the Sweet-Parker rate (*fast reconnection*).
- For instance, the case of $R_m = 10^8$,
  - the Petschek reconnection rate is $r_p \sim 2 \times 10^{-2}$
  - The Sweet-Parker reconnection rate is $r_{sp} \sim 10^4$

Petschek Model (cont.)

- The reason is that the aspect ratio δ_p/L_p is much larger than δ/L for the Sweet-Parker diffusion region.
- This is accomplished by a much smaller length of the diffusion region

$$L_p \approx 64L \ln^2 S/(\pi^2 S)$$

- However, the thickness of diffusion region is also much smaller

$$\delta_p \approx 8\delta \ln S/(\pi\sqrt{S})$$

- In solar corona case, using classical resistivity ($S \sim 10^{14}$), the diffusion length of Petscheck reconnection becomes smaller than ion gyro-radius (~10 cm) (*MHD is acceptable?*).
- Although Petscheck model is a very attractive idea, the question arises whether the single Petscheck reconnection controls the entire flare process or not (large scale difference).

Sweet-Parker vs Petschek

		Magnetopause	Magnetotail	Solar corona (flares)
	n_0 [cm^{-3}]	4	0.5	$6 \cdot 10^8$
	B_0 [nT]	40	20	$3 \cdot 10^7$
	L [m]	10^6	10^7	10^7
	v_A [m/s]	$4.4 \cdot 10^5$	$6.2 \cdot 10^5$	$2.7 \cdot 10^7$
	$E_0 = v_A B_0$ [V]	$1.8 \cdot 10^{-2}$	$1.3 \cdot 10^{-2}$	$8 \cdot 10^5$
	τ_A [s]	2.3	1.6	0.37
	v_{thi} [K]	10^5	$7 \cdot 10^5$	10^5
	v_{the} [K]	$1.3 \cdot 10^6$	10^7	$4.3 \cdot 10^6$
	λ_e [m]	$2.7 \cdot 10^3$	$8.0 \cdot 10^3$	0.2
	τ_{diff} [s]	$7 \cdot 10^{11}$	$1.5 \cdot 10^{15}$	$2.5 \cdot 10^{14}$
Lundquist number →	R	$3 \cdot 10^{11}$	10^{15}	10^{15}
Reconnection rate	r_{sp}	$1.8 \cdot 10^{-6}$	$3 \cdot 10^{-8}$	$3 \cdot 10^{-8}$
	r_p	$1.5 \cdot 10^{-2}$	$1.1 \cdot 10^{-2}$	$1.1 \cdot 10^{-2}$
	r_{obs}	$3 \cdot 10^{-2}$	$3 \cdot 10^{-2}$	10^{-4} to 10^{-2}
Thickness of diffusion region	δ_{sp} [m]	1.8	0.3	0.3
	δ_p [m]	$2 \cdot 10^{-4}$	10^{-6}	10^{-6}
	L_p [m]	$1.4 \cdot 10^{-2}$	10^{-4}	10^{-4}

Sweet-Parker vs Petschek (cont.)

		Magnetopause	Magnetotail	Solar corona (flares)
	L [m]	10^6	10^7	10^7
	v_A [m/s]	$4.4 \cdot 10^5$	$6.2 \cdot 10^5$	$2.7 \cdot 10^7$
	τ_A [s]	2.3	1.6	0.37
	R	$3 \cdot 10^{11}$	10^{15}	10^{15}
	τ_{diff} [s]	$7 \cdot 10^{11}$	$1.5 \cdot 10^{15}$	$2.5 \cdot 10^{14}$
Reconnection time	τ_{sp} [s]	10^6	$5 \cdot 10^7$	10^7
	τ_p [s]	150	150	35
	v_{diff} [m/s]	$1.5 \cdot 10^{-6}$	$6 \cdot 10^{-10}$	$2.7 \cdot 10^{-8}$
Outflow velocity	v_{sp} [m/s]	0.8	0.02	0.1
	v_p [m/s]	$3 \cdot 10^3$	$5.5 \cdot 10^3$	$2.5 \cdot 10^5$

Petschek Model (cont.)

- The numerical simulations show that the Petschek model for fast reconnection does not arise under uniform resistivity in the limit of large *S*. (Biskamp 1986)
- In order to develop Petschek-type reconnection, we need to use non-uniform resistivity (spatially-localized resistivity), so-called *anomalous resistivity*

- What is the anomalous resistivity?
- Until now, it is still unknown. But it may be related microscopic (kinetic) process.

Petschek Model (cont.)

Movie here

Tearing instability

- Sweet-Parker model is slow reconnection process. It can not be explained solar flare.
- Petschek model is fast reconnection process. It may be explained solar flare time scale but physically not-perfect.

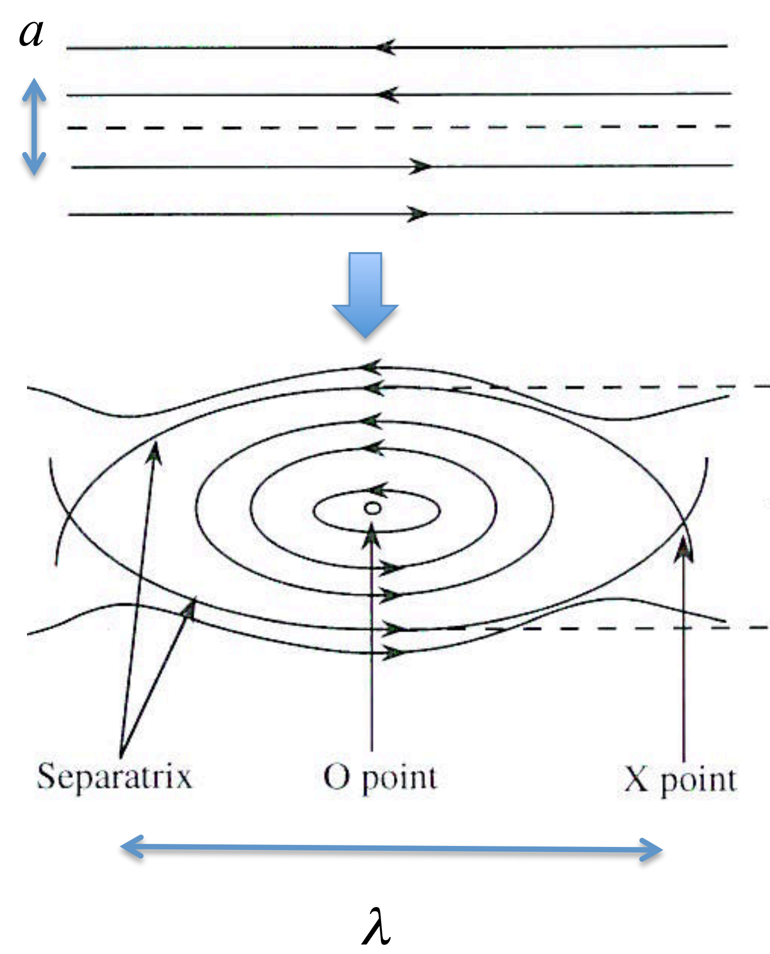
- Here we again focus on *Sweet-Parker model*.
- The problem for slow reconnection is the large aspect ratio.
- Question is can we make small aspect ratio?

- In the evolution of Sweet-Parker reconnection, the diffusion region (current-sheet) is expanded.
- Such long current-sheet is unstable against *tearing instability*

Tearing instability

- Tearing mode is resistive instability that occurs in presence of current sheet
- The tearing mode forms magnetic islands
- The magnetic island grow unsteadily.

- We follow Furth, Killeen & Rosenblth (1963) (FKR) study



Tearing instability (cont.)

- According to their analysis, the growth rate of the tearing instability is of the order of

$$\gamma \sim \alpha^{-2/5} \tau_{D,*}^{-3/5} \tau_{A,*}^{-2/5} \sim \alpha^{-2/5} \tau_{A,*}^{-1} S_*^{-3/5}$$

- For large S_* and long wavelength $\lambda > 2\pi a$ in parallel to current sheet, where

$$\begin{aligned} \tau_{D,*} &= a^2/\eta, \\ \tau_{A,*} &= a/v_A, \\ S_* &\simeq \tau_{D,*}/\tau_{A,*} = a v_A/\eta, \\ \alpha &= ka = 2\pi a/\lambda \end{aligned}$$

- a is the thickness of current sheet and k is transverse wavenumber of the tearing mode

Tearing instability (cont.)

- From FKR, the instability only exists for

$$S_*^{-1/4} < \alpha < 1$$

- Using the fastest growing mode, the maximum growth rate is

$$\gamma_{max} \sim \tau_{A,*}^{-1} S_*^{-1/2}$$

- From numerical analysis of the linear tearing instability without using the so-called constant ψ approximation (Steinolfson & van Hoven 1984), the maximum growth rate is

$$\begin{aligned} \gamma_{max} &\sim \tau_{A,*}^{-1} \alpha^{2/3} S_*^{-1/3} \\ \alpha_{max} &\sim S_*^{-1/4} \end{aligned}$$

- This growth rate is faster than that found by FKR.

Tearing instability (cont.)

- Let us now apply to solar corona, If we assume a =10^4 km (typical length of solar flare), the Lundquist (magnetic Reynolds) number becomes S_*~10^{14}. Then we find

$$\alpha_{max} \sim 10^{-3.5}, \text{i.e.,}\ \lambda_{max} \sim 2 \times 10^4 a \sim 2 \times 10^8 \text{km} > R_\odot$$

- Hence the (most unstable) tearing mode cannot be applied to the solar corona.
- But if we assume a =1km (10^3 times larger thickness estimated from SP model), we have $S_* = 10^{10}$, and

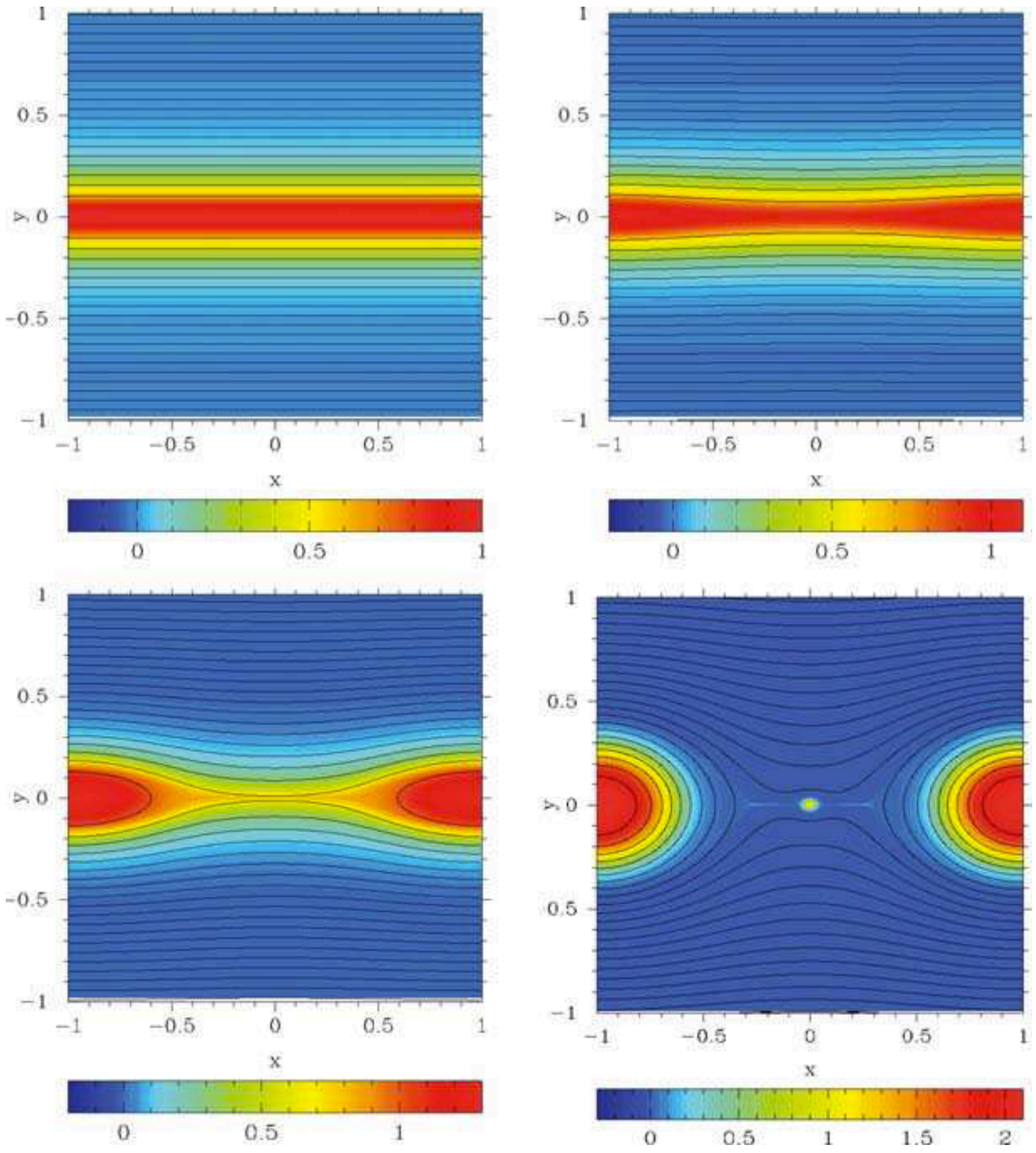
$$\alpha_{max} \sim 10^{-2.5}, \text{i.e.,}\ \lambda_{max} \sim 2 \times 10^3 a \sim 2 \times 10^3 \text{km}$$

- And the growth time becomes $\tau_{tearing} \sim 10$ sec
- So in this case, the tearing instability can occur in the solar corona and will form multiple magnetic islands with a size 2 x 10^3 km in the coronal current sheet

Tearing instability (cont.)

Current density

Force-free simulation



Tearing instability (cont.)

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Current trend of magnetic reconnection

- *Instability (turbulence) in collisional reconnection*
  - Trigger of fast reconnection from Sweet-Parker type condition
  - Time-dependent, non-stationary reconnection in very large systems (Sweet-Parker type situation) show the development of multiple magnetic islands via tearing instability
  - Growing instability leads to turbulence in reconnection.
  - Turbulence makes small aspect ratio of diffusion region and leads to fast reconnection.
  - Now we consider interaction between two fundamental plasma processes: reconnection and turbulence

- *Collisional reconnection to collision-less reconnection.*
  - Development of Physically correct Petschek type reconnection
  - Spatially-localized anomalous resistivity due to plasma micro-instabilities
  - Hall-term effect (two fluid effect) enables Petschek-like structure ($v_{rec} < 0.1\ v_A$)

3D Magnetic reconnection

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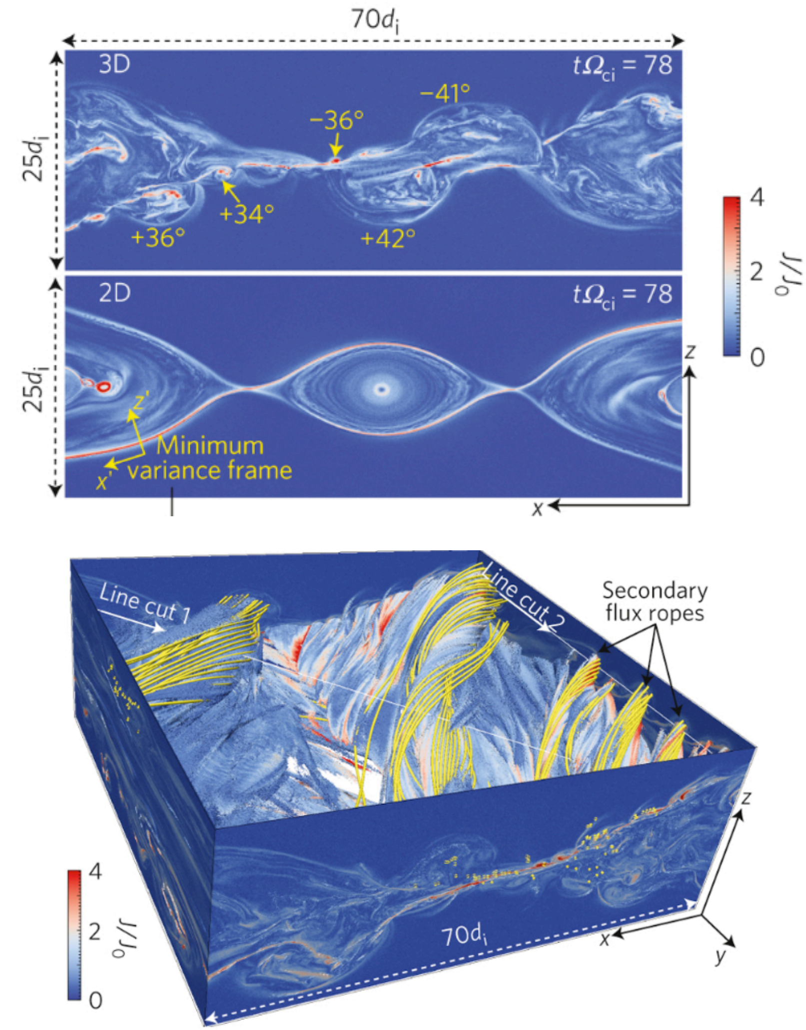

Summary

- Magnetic reconnection is the process of a rapid rearrangement of magnetic field topology which leads to rapidly and violent release of magnetic energy.
- Flaring event (rapid energy release) in the universe may be related magnetic reconnection process.
- In basic theory of magnetic reconnection, there are two physical models, Sweet-Parker model and Petscheck model.
- Both models have some advantage and disadvantage.
- Until now, we have not developed perfect magnetic reconnection theory
- Magnetic reconnection is one of the most important fundamental questions in physics.