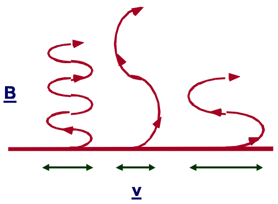
HOW TO CREATE A CORONA

- need to heat the coronal plasma to several million degrees…
- and then prevent this plasma from escaping

  i.e. need closed magnetic loops
- solar corona requires a heat input of 10^7 ergs cm^{-2} s^{-1} (=10^4 Wm^{-2}) to maintain its X-ray surface brightness
- solar bipolar magnetic regions have scales ranging from 2 x10^5 km down to less than 10^4 km (X-ray bright points), but all have roughly the same surface brightness

- hence the heating mechanism must heat all bipoles
- the source of energy for this is the convective motions at the surface coupled with the magnetic field
- the energy is transmitted up into the corona by the magnetic field
- two possible mechanisms for releasing this energy are wave dissipation and current sheet dissipation

Wave Dissipation



- Surface convective motions jiggle the magnetic field lines.
- This sends magnetoacoustic waves (such as slow and fast waves and Alfven waves) up into the corona.
- If these waves can dissipate in the corona, they can deposit their energy there.

Problems:

- only Alfven waves survive as far as the corona
- this is a non-dissipative mode and these waves cause no compression of the gas (unlike slow and fast waves) so they do not give up their energy
- hence not very good for heating the corona
- BUT: this mechanism may heat open field lines

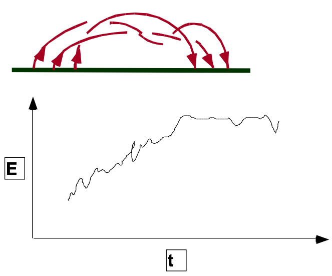
  since wave mode can change to a dissipative mode if the field lines are not straight

- characteristic photospheric motions have timescales of 50-300s, giving Alfven wavelengths of 1 - 6 x 10^5 km in the corona
- hence in general the wavelengths generated are greater than the size of the magnetic structures
- hence the magnetic loops evolve through a series of equilibria

Current sheet dissipation

Magnetic field lines are tangled and twisted by surface convective motions. This stores energy in the magnetic field.

The energy contained in the loop first rises, then reaches a plateau as energy is released from the loop as fast as it is deposited.



How is this energy released?

From the induction equation

$$\frac{\partial \underline{B}}{\partial t} = \underbrace{\underline{\nabla} \times (\underline{v} \times \underline{B})}_{\text{advection}} + \underbrace{\eta \nabla^2 \underline{B}}_{\text{diffusion}}$$

The ratio of the advective and diffusive terms gives the magnetic Reynolds number

$$R_m = \frac{v L}{\eta}$$

For the solar corona, $R_m \approx 10^{10}$

and so diffusion is negligible. The magnetic field is *frozen in* to the plasma and there is no dissipation.

At each of the knots in the twisted coronal loop, however, the length-scale of the field is very small and R_m may become small enough for diffusion to be important.

For simple diffusion, we have $\frac{\partial \underline{B}}{\partial t} = \eta \nabla^2 \underline{B}$

giving a diffusion timescale of $\tau_D \approx l^2 / \eta$

which for $l = 10^4 m$ gives $\tau_D = 10^8 secs$

($\eta \approx 10^9 T^{-3/2} m^2 s^{-1}$ for the corona so $\eta \approx 1$)

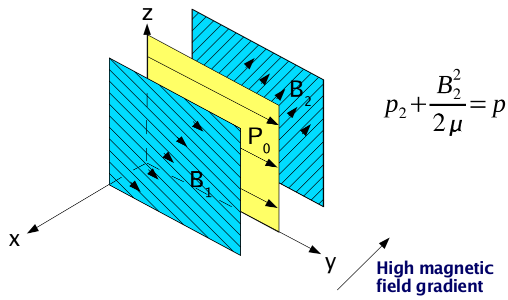
This is still too long to explain the very rapid energy release in flares (fractions of a second).

We may describe each of these knots as current sheets, since they are regions where the magnetic field has steep gradients.

$$\mu \underline{j} = \underline{\nabla} \times \underline{B}$$

Current sheets

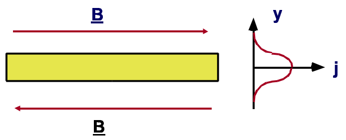
A current sheet can be defined as a non-proagating boundary between two plasmas, with the magnetic field tangential to the boundary



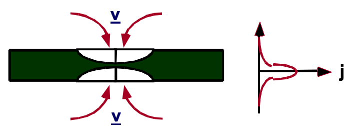
$$p_2 + \frac{B_2^2}{2\mu} = p_1 + \frac{B_1^2}{2\mu}$$

If we have a magnetic field $\underline{B} = (B_x(y), 0)$ then the current associated with this field is in the z-direction

$$\mu \underline{j} = \underline{\nabla} \times \underline{B} = \begin{vmatrix} i & j & k \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ B_x & 0 & 0 \end{vmatrix} = \frac{-\partial B_x}{\partial y} \hat{\underline{z}}$$



This current sheet may be unstable to the tearing mode which is a resistive instability



If the current sheet is compressed (perturbed) locally, the current density rises and so the rate of dissipation rises.

The magnetic pressure drops and plasma rushes in to re-establish pressure balance. This carries in more field which feeds the instability.

This instability occurs for perturbations with wavelength greater than the width of the current sheet.

Long current sheets are the most likely to be unstable as the fastest-growing mode is the one with the longest wavelength. Its growth time is

$$\tau_{TM} \approx \sqrt{\tau_A \tau_D}$$

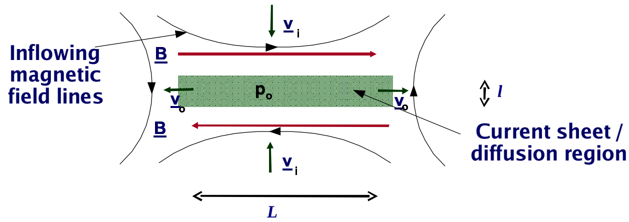
where $\tau_A = l / v_A$ is the Alfven crossing time for the sheet

and $v_A = \frac{B}{\sqrt{\mu \rho}}$ is the Alfven speed.

for our very thin current sheet, $\tau_A \approx 10^{-3} s$

and so $\tau_{TM} \approx 10^{2} s$

Magnetic Reconnection



Force balance transverse to sheet:

$$p_o = p_i + \frac{B_i^2}{2\mu}$$

Force balance along the sheet: $p_o = p_i + \frac{1}{2}\rho_0 v_0^2$

hence: $v_0^2 = \frac{B_i^2}{\mu \rho} = v_{Ai}^2$

v_{Ai} is the inflow Alfven speed

Steady state: rate of inflow of new field balanced by rate of diffusion

$$v_i = \frac{\eta}{l}$$

Mass conservation (incompressible fluid):

$$L v_i = l v_{Ai}$$

Hence the reconnection rate:

$$M_i = \frac{v_i}{v_{Ai}} = R_{mi}^{-1/2} \approx 10^{-3} - 10^{-6}$$

where

$$R_{mi} = \frac{L v_{Ai}}{\eta}$$

This is still too slow to explain flares.

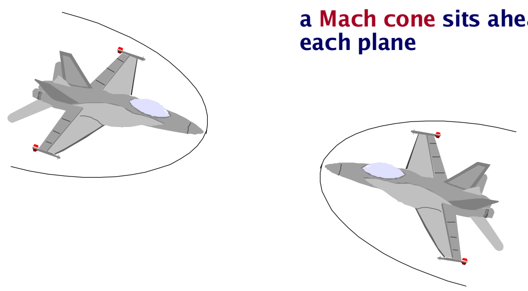
Note that for sub-Alfvenic inflow, i.e. $M_i \ll 1$, the outflow field strength

$$B_0 = \frac{v_i}{v_{Ai}} B_i = M_i B_i$$

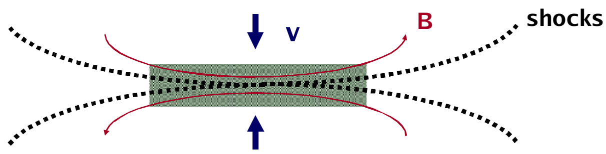
is smaller than the inflow field strength

→ Current sheets convert magnetic energy into heat and flow energy

Imagine two supersonic planes....



a Mach cone sits ahead of each plane



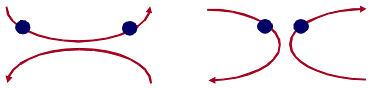
Petschek (1964) realised that MHD shocks would be generated at the reconnection site.

By allowing for the energy transfer in these he obtained a maximum reconnection rate of:

$$M_e = \frac{\pi}{8 \ln R_{me}} \approx 0.1$$

Finally! This is fast enough for flare timescales.

Reconnection is also important as it changes the connectivity of field lines:



This allows knots in flux tubes to unravel, leading to a cascade effect as small reconnection events are triggered throughout a loop.