$\boxed{\text{Flares}}$

a complete dissipation of the sunspot in corona

$B \sim 1000\,G = 0{,}1\,T$

$V \sim (10 \times 10 \times 10)\,Mm^3 = 10^{18}\,m^3$

$\rightarrow E_m = \frac{B^2}{2\mu_0} V = \frac{0{,}01}{2\mu_0} 10^{18}\,J \sim 4 \times 10^{21}\,J$

→ many orders less than observed ⇒ a quiet dissipation can't be the source for flares

$\boxed{\text{Time scales}}$

in explosive: <u>Joule heat</u>

$$t_j = \frac{B^2/2\mu_0}{j^2/\sigma} = \left| j = \frac{1}{\mu_0} \nabla \times B \sim \frac{1}{\mu_0}\frac{B}{L} \right| =$$

$$= \frac{B^2/2\mu_0}{B^2/\mu_0^2 L \sigma^2} = \frac{\mu_0 L^2 \sigma}{2}$$

comparable

<u>field diffusion:</u>

$$\frac{\partial B}{\partial t} = \frac{1}{\mu_0 \sigma} \Delta B \Rightarrow \frac{B}{t_{diff}} \sim \frac{1}{\mu_0 \sigma} \frac{B}{L^2}$$

$$\Rightarrow t_{diff} \sim \mu_0 \sigma L^2$$

diffusivity: $\eta = \frac{1}{\mu_0 \sigma} \Rightarrow t_{dif} \sim \frac{L^2}{\eta}$

η: chromosphere $\eta \sim 10^7\,\frac{cm^2}{s}$

corona: $\eta \sim 3 \times 10^3\,cm^2/s$

slow!

<u>advection</u> – dynamical phenomenon

$t_a \sim L/v$

to compare in equilibrium steady-state

$$t_j = \frac{L^2}{\eta} = \frac{Lv}{\eta} \cdot \frac{L}{v} = R_M t_a$$

magnetic Reynolds number

⇒ advection vs. diffusion

for $R_M \gg 1$ $\quad t_j \gg t_d \Rightarrow$ diffusion plays no role

for $v \equiv c_A \sim 10^6\,m/s$

$$t_j = \frac{L^2}{\eta} = \frac{L c_A}{\eta}\,\frac{L}{c_A} = N_L\, t_A \quad \text{alfvén time}$$

Lundquist number

N_L large $\Rightarrow$ highly conducting plasma

N_L small $\Rightarrow$ resistive plasma

<u>example</u>

time it takes do dissipate dynamically with alfvén speed

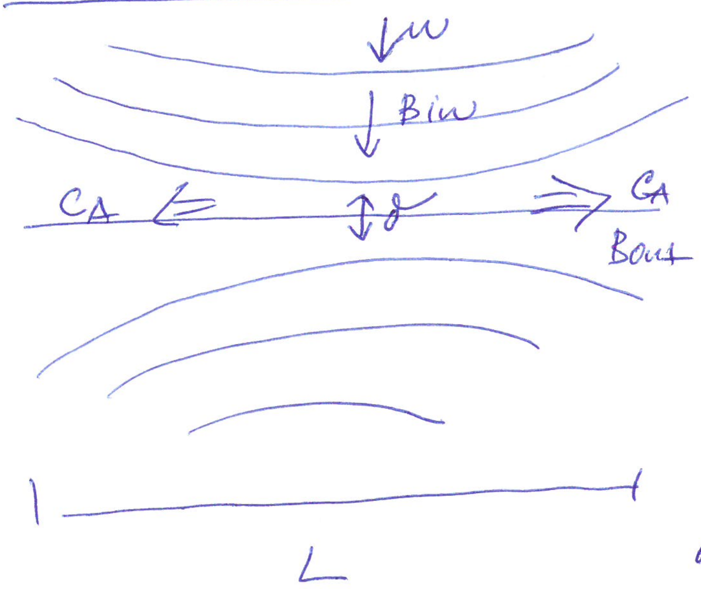
$$t_j = \frac{L N_L}{c_A}$$

corona: $L \sim 10^7\,m$, $c_A \sim 10^6\,m/s$, $\eta \sim 10^3\,cm^2/s$,

$N_L \sim 10^{14}$, $\frac{L}{c_A} \sim 10\,s$

$\Rightarrow \underline{t_j \sim 10^{15}\,s}$ $\quad \Rightarrow$ slow!

$\boxed{\text{Explosive dissipation}}$



$\boxed{\text{Sweet-Parker}}$

antiparallel fields pushed together at length L, plasma pushed away in between of the antiparallel field by alfvén speed

∇B grows up until the steady state (*) $\rightarrow$

δ – thickness of the current sheet

current sheet: $j = \frac{1}{\mu}\nabla\times B \sim \frac{B}{\mu\delta}$

energy: $\dot{U} = \eta j^2 = \eta \frac{B^2}{\mu^2\delta^2}$

=II=

(*) a the axis – overpressure (thermal scale of $t_{HW} = L/c_A$), which is ballanced by the mg. field pressure (the thermal energy is removed from the mg. field)

$$U \sim \dot{U} t_{HW} \Rightarrow \frac{B^2}{2\mu} = \eta \frac{B^2}{\mu \delta^2} \frac{L}{c_A}$$

$$\Rightarrow \delta = \sqrt{\frac{2\eta L}{\mu c_A}} \propto \sqrt{\frac{\eta L}{c_A}}$$

continuity equation:

$$\rho w L = \rho \delta c_A \Rightarrow w = \frac{\delta}{L} c_A = \frac{\sqrt{\frac{\eta L}{c_A}}}{L} c_A = \sqrt{\frac{\frac{\eta L c_A^2}{c_A}}{L^2}} =$$

$$= \sqrt{\frac{\eta c_A}{L}}$$

using $N_L = \frac{L c_A}{\eta}$

$$w = \sqrt{\frac{\eta c_A}{L}} = \sqrt{\frac{\eta}{L c_A} c_A^2} = \frac{c_A}{\sqrt{N_L}}$$

↑ reconnection speed

→ characteristic time:

$$t_{sp} = \frac{L}{w} = \frac{L\sqrt{N_L}}{c_A}$$

for the coronal conditions $t_s \sim 10^8 s$

slow

Energetics

$\delta \ll L \Rightarrow w \ll c_A$

inflow speed (rate) of elmag. energy → Poynting flux

$$(E \times H) L \sim EHL = \left| \begin{array}{l} E_{\text{induced}} \\ \Rightarrow E = u \times B \end{array} \right| =$$

$$= E \frac{B_{in}}{\mu} L = w \frac{B_{in}^2}{\mu} L$$

ratio of kinetic & magnetic fluxes:

$$\frac{E_{k,in}}{E_{m,in}} = \frac{w \frac{1}{2}\rho w^2 L}{w \frac{B_{in}^2}{\mu} L} = \frac{w^2}{2\frac{B_{in}^2}{\mu \rho}} = \frac{w^2}{2 c_A^2} \ll 1$$

⇒ most of the energy influx is magnetic

outflow:

mg. flux conservation: $c_A B_0 = w B_{in}$

$$\nabla \cdot B = 0 \Rightarrow \frac{B_{out}}{\delta} \sim \frac{B_{in}}{L} \Rightarrow B_{out} \ll B_{in}$$

elmag energy outflow:

$E B_{out}\, \delta / \mu_0 << E_{m,in}$, Because $B_{out} << B_{in}$ and $\delta << L$

where is the rest of the energy?

$$\frac{E_{k,out}}{E_{m,in}} = \frac{c_A \frac{1}{2} \rho c_A^2 \delta}{\approx B_i^2 L/\mu_0} = \frac{\frac{1}{2} c_A^2}{c_A^2} = 1/2$$

$\Rightarrow$ 1/2 of the inflowing energy converted to the kinetic energy of particles, the second 1/2 to heat. The mg. field energy is negligible

$\boxed{\text{Petschek model}}$

$t_s \sim L$ $\Rightarrow$ shorten the L and the speed increases

after "some algebra"

$$t_p \sim \frac{L \ln N_L}{c_A}$$

for the corona: $t_p \sim 300\,s$

$\Rightarrow$ explosive dissipation in thin current sheets

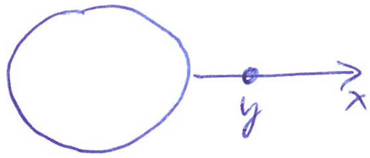
Deformation of mg. fields brings free energy $\Rightarrow \Delta B \rightarrow$ current sheets

anomalous resistivity – speed of electron (drift speed) comparable to the speed of plasma waves $\Rightarrow$ increase of the resistivity $\Rightarrow$ shortening the time

$$N_L \propto \frac{1}{\eta}$$

Corona

→ how to estimate the density from the observations



$y \perp x$; $y \parallel$ l.o.s.

→ spherically symmetric corona

E_k ... emission in the local volume for the l.o.s.

$$\rho^2 = \left(\frac{r}{R_\odot}\right)^2 = x^2+y^2 \Rightarrow \rho\, d\rho = y\, dy = \sqrt{\rho^2-x^2}\, dy$$

observed intensity:

$$I(x) = \int_{-\infty}^{\infty} E_k(\rho)\, dy = 2\int_0^{\infty} E_k(\rho)\, dy =$$

$$= 2\int_0^{\infty} \frac{\rho\, E_k(\rho)}{\sqrt{\rho^2-x^2}}\, d\rho$$

E_k unknown, $I(x)$ measured ⇒ we invert

inverse Abel tranform:

$$\Rightarrow E_k(\rho) = -\frac{1}{\pi}\int_{\rho}^{\infty} \frac{dI/dx}{\sqrt{x^2-y^2}}\, dx$$

ansatz: intensity of the K-corona is due to the Thomson scattering ~~of~~ on free electrons

$$\Rightarrow E_k(\rho) = \sigma_T\, n_e\, \frac{1}{4\pi}\int I_\odot(\vartheta)\, d\Omega^*$$

$$d\Omega = r\, d\vartheta\, d\varphi$$

we compare the two solution e.g. in a form of the series:

$$n_e(\rho) = n_{e0}\left(\frac{1.55}{\rho^6} + \frac{2.99}{y^{16}}\right); \quad n_{e0} = 10^{14}\, m^{-3}$$

rough estimate at $1 R_\odot$ distance:

$$E_k \sim \sigma_T\, n_e\, R_\odot I_\odot; \quad E_k(R_\odot) \sim 10^{-6} I_\odot$$

$$\Rightarrow n_e \sim \frac{E_k(R_\odot)}{\sigma_T R_\odot I_\odot} \sim \underline{4\times 10^{13}\, m^{-3}}$$

Emission lines

→ X-rays and EUV regions

emission line of the $(m-1)$-times ionized element X (X^{+m}), there in transition $j \to i$ electron levels.

$$X_j^{+m} \to X_i^{+m} + h\nu_{ij}$$

emissivity: $$P_\nu = \underbrace{N_j(X^{+m})}_{\text{density}} \underbrace{A_{ji}}_{\text{Einstein coefficient}} h\nu_{ij} \underbrace{\psi_\nu}_{\text{emission profile}}$$

$$\int \psi_\nu \, d\nu = 1$$

<u>coronal approximation</u> — j-level populated from the ground state g by collisions with electrons.
Depopulation radiatively

then: $$P_{gj} = \underbrace{A_X}_{[X/H] \text{ abundance}} \underbrace{G(T, \lambda_{gj})}_{\text{contribution function}} \frac{hc}{\lambda_{gj}} \underbrace{N_e^2}_{\text{electron density}}$$

$A_X N_e \sim [X]$

radiative flux at distance R

$$F(\lambda_{gj}) = \frac{1}{4\pi R^2} \int_V P_{gj} \, dV =$$

$$= \frac{1}{4\pi R^2} A_X \int G(T, \lambda_{gj}) \frac{hc}{\lambda_{gj}} N_e^2 dV =$$

$$= \frac{1}{4\pi R^2} A_X \int G(T, \lambda_{gj}) \frac{hc}{\lambda_{gj}} Q(T) dT$$

where: $N_e^2 dV = \underbrace{Q(T)}_{\text{differential emission measure (DEM)}} dT$

DEM – measure of the amount of radiating plasma as a function of temperature from the other side:

for 1-D: $EM = \int N_e^2 dz$ emission measure

$$EM = \int N_e^2 dz = \int N_e^2 \frac{dz}{dT} dT = \int \underbrace{N_e^2 \left(\frac{dT}{dz}\right)^{-1}}_{DEM = Q(T)} dT$$

$N_e^2 dV = \underbrace{N_e dV}$ N_e ← electron density

$\underbrace{\text{number of free electrons}}$

excitation of the electrons to higher levels by collisions ⇒ intensity of the ~~emitting~~ emitted radiation depends on it

for the region:

$$L = 4\pi R^2 \; F(\lambda_{gj}) = \int N_e^2 P(T) dV = \int Q(T) P(T) dT$$

$$P(T) = A_x \, G(T, \lambda_{gj}) \frac{hc}{\lambda_{gj}}$$

↳ radiative losses → only function of T (weak)

⇒ $L \sim N_e^2$ ⇒ coronal brightness above active regions is mostly due to larger N_e

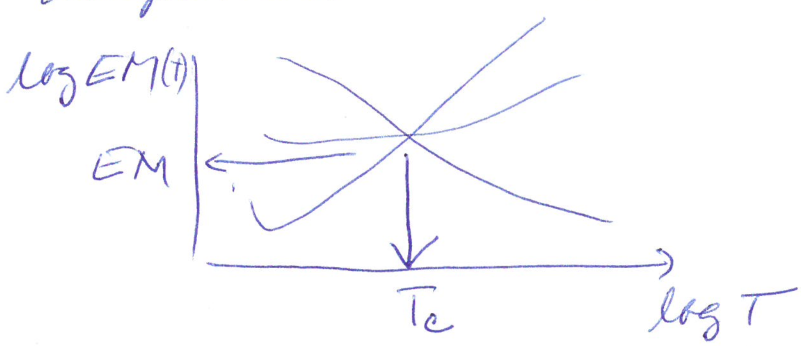
Diagnostics

for isothermal plasma: $F = \frac{1}{4\pi R^2} G(T_e) EM(T)$

$$\Rightarrow \underbrace{EM(T)}_{EM\ low} = 4\pi R^2 \frac{F}{G(T)}$$

→ strong dependence on T

diagnostics: $EM(T)$ for several ions:



isothermal plasma – all $EM(T)$ curves cross in one point

↳ (EM, T_e)

if not ⇒ plasma multithermal

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more ions EM(T) for different transitions of the same ion indistinguishable

the best → various ions of the same species (lesser inaccuracies from atomic physics)

a large number of line → vertical shift of crosssections can be used to derive the abundances