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PHYSICS OF THE X-RAY CORONA

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These are lecture notes, intended for distribution to participants.

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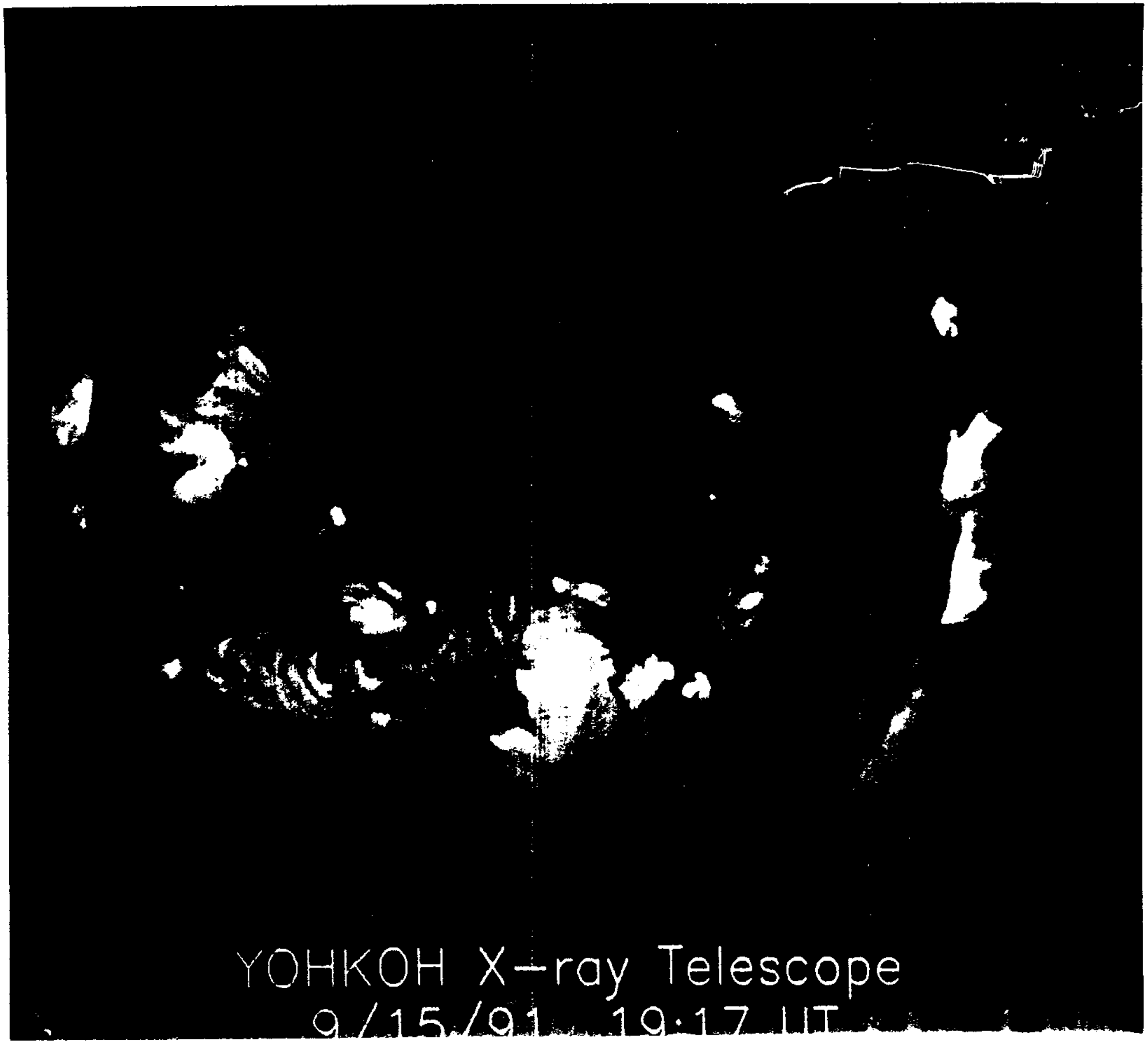
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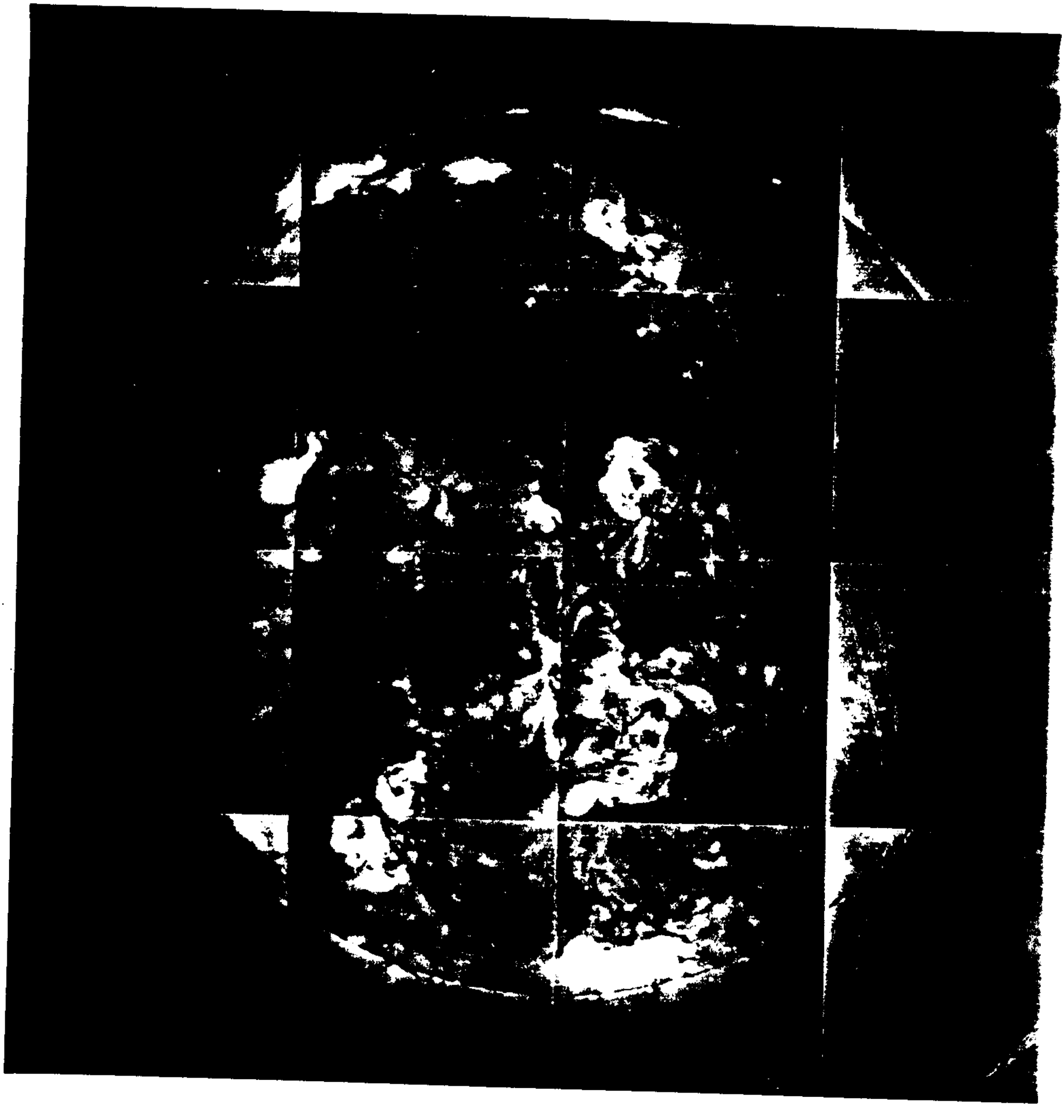


X-Ray Astronomy of Solitary Star like the Sun.

$L_\odot = 4 \times 10^{33}$ ergs/sec, $L_* = 10^{26} - 10^{28}$ ergs/sec.

The X-rays represent thermal emission from

$$T \sim 1 - 5 \times 10^{6}\,\mathrm{K}$$

with $N \sim 10^{9} - 10^{10}$ atoms/cm^3.

Volume emissivity $\propto N^2$

Gravitational binding energy per H atom

$$\frac{GM_\odot M}{R_\odot} \sim 30 \times 10^{-10}\ \mathrm{ergs}$$

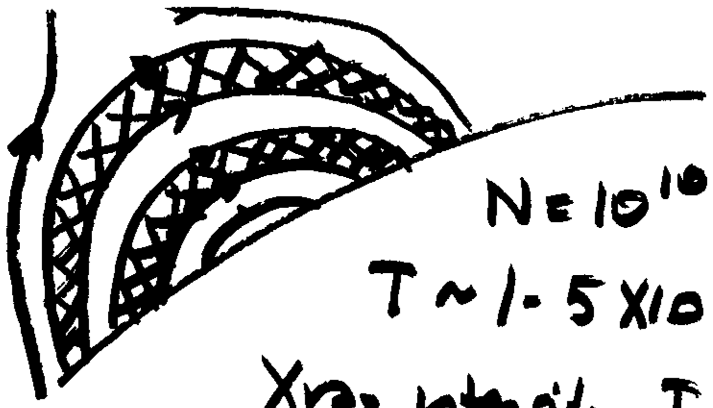
Thermal energy per H atom at 10^{6}K

$$3kT \sim 4 \times 10^{-10}\ \mathrm{ergs}$$

Strongly bound but high thermal conductivity extends T to large r.

So Emitting gas is confined in $B \gtrsim 20$ gauss.

<u>Further understanding requires detailed observation to define the context for the X-ray emission.</u>



$N = 10^{10}$ atoms/cm^3

$T \sim 1\text{-}5 \times 10^6$ K, $B \sim 100$ gauss

Xray intensity $I \sim 10^7$ ergs/cm^2 sec.

Gas pressure $2NkT \cong 6$ dynes/cm^2 $(T \sim 2 \times 10^6)$

Magnetic pressure $\frac{B^2}{8\pi} \cong 400$ dynes/cm^2

$$\beta = \frac{P}{B^2/8\pi} \sim 0.015$$

Alfven speed $$C = \frac{B}{\sqrt{4\pi\rho}} \sim 2 \times 10^8 \text{ cm/sec}.$$

The Length L of the X-ray loop ranges from about 2×10^9 cm to 2×10^{10} cm, with I essentially independent of L.

Dynamical Input to X-ray Loop

Characteristic dynamical time

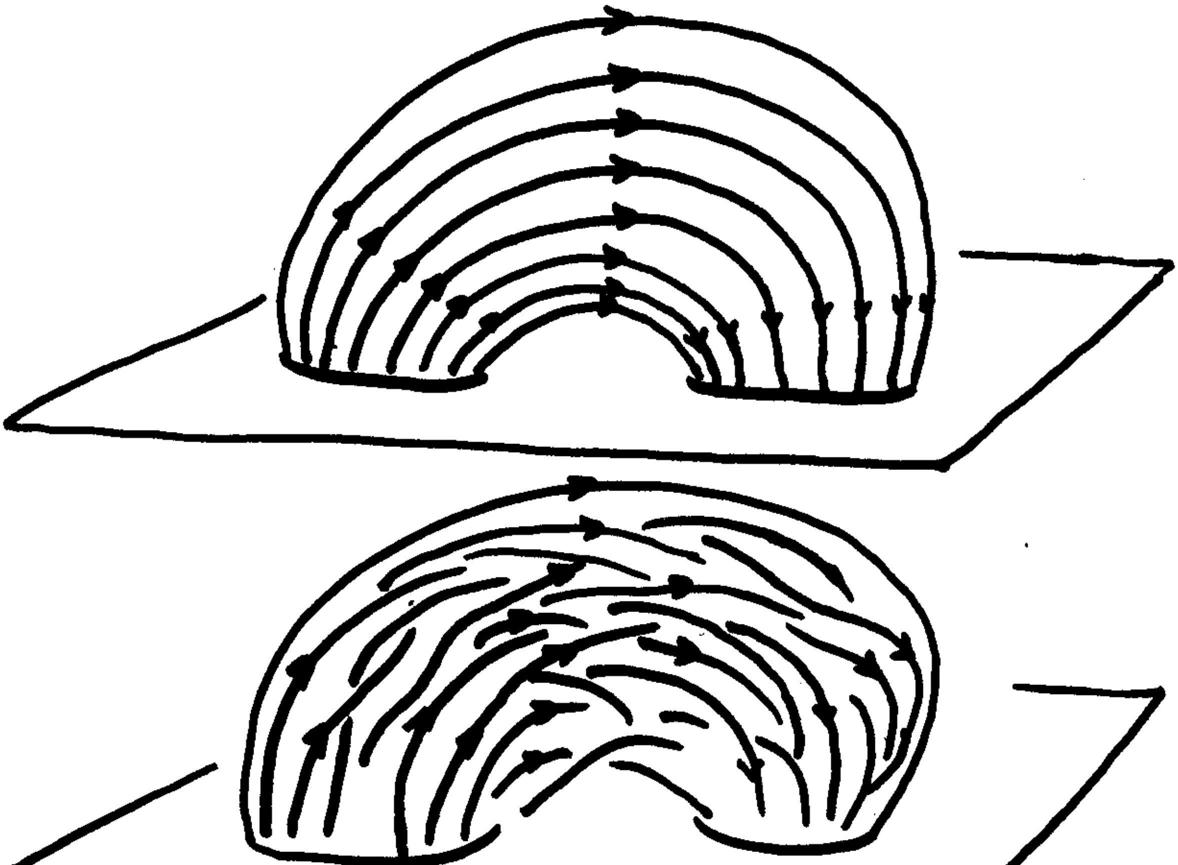
$$\tau(L) \sim L/C = 10\text{-}10^2 \text{ sec}$$

Photospheric convection time

$$\tau(\ell) \sim \frac{\ell}{v} \sim 300 \text{ sec}$$

for $\ell \sim 300$ km, $v \sim 1$ km/sec

The essential point is that the dynamical response time $\tau(L)$ is small compared to the characteristic deformation time $\tau(\ell)$. So the coronal X-ray loop is in quasi-static equilibrium while being continually deformed by the photospheric convection



Photospheric convection

$\ell \sim 300$ km, $v \sim 1$ km/sec, $\tau \sim 300$ sec.

Observations suggest a direct equation between B and heat input to the corona. Heat input is essentially independent of L. But $B^2/8\pi$ goes to heat only through the associated electric current,

$$4\pi \mathbf{j} = c\nabla\times\mathbf{B}.$$

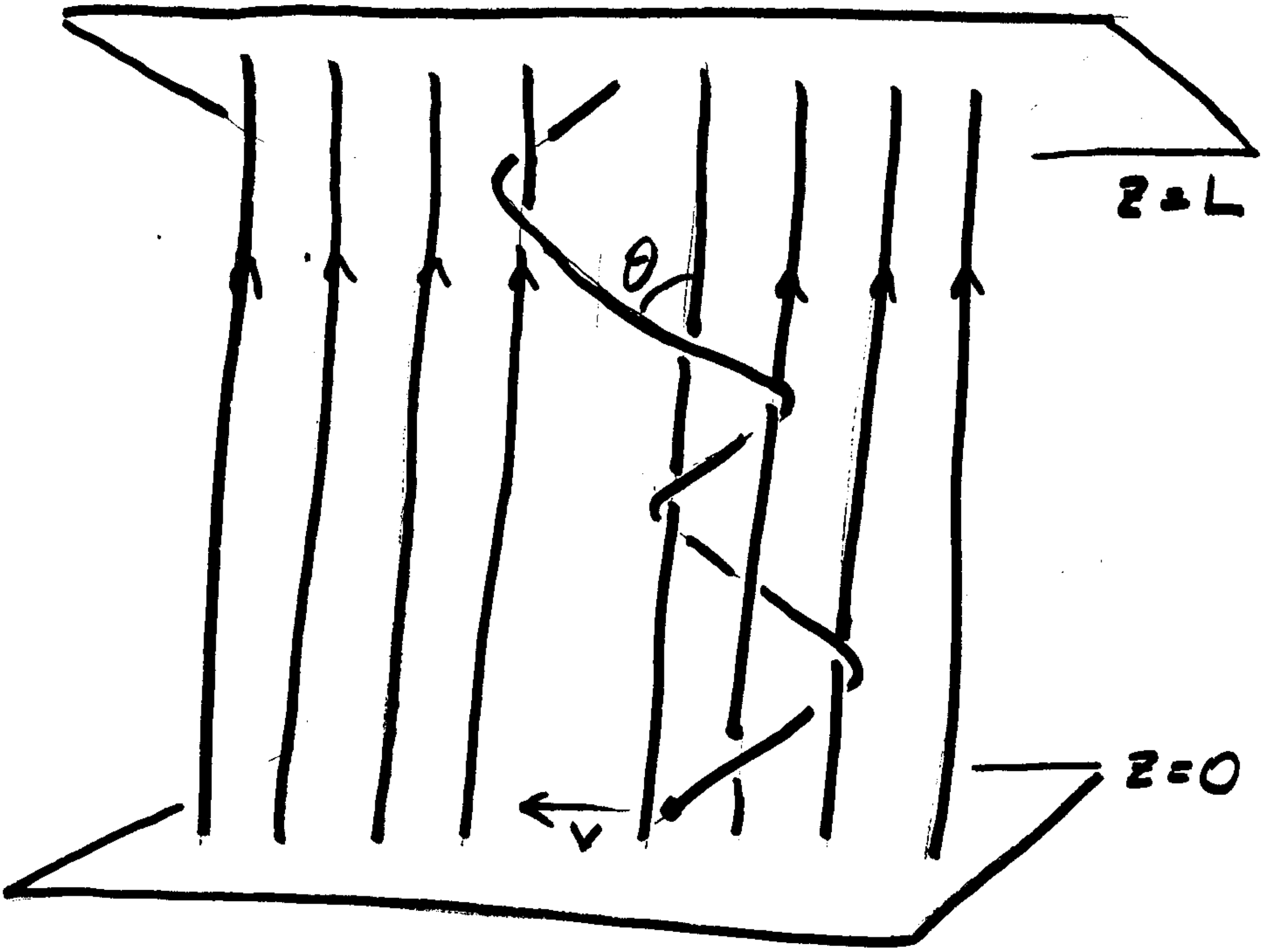
The resistive diffusion coefficient η is $\sim 10^3$ cm^2/sec at coronal T. Resistive dissipation time across scale ℓ is $\ell^2/\eta \sim 10^{12}$ sec $\sim 3\times10^4$ yrs. for $\ell \sim 300$ km.

Small eddies in the photospheric convection (scale λ, $v(\lambda) \sim v(\lambda/\ell)^{\frac{1}{3}}$) have shorter dynamical times $\tau(\lambda) = \tau(\ell)(\lambda/\ell)^{2/3}$ and correspondingly reduced kinetic energy

$$\tfrac{1}{2}\rho v(\lambda)^2 \propto \tau(\lambda)$$

If a loop were heated by $\frac{1}{2}\rho v(\lambda)^2$ for which $\tau(\lambda) = \tau(L)$, it would follow that $I \propto L$, contrary to observation.

Why does a deformed magnetic field dissipate so rapidly into Heat + Potential Field?



$$\tan\theta = \frac{vt}{L}$$

$$B_\perp = B\tan\theta$$

$$F = \frac{B B_\perp}{4\pi}$$

$$\text{Power} = Fv = \frac{B^2}{4\pi}\frac{v^2 t}{L}$$

If $B = 10^2$ gauss

$v = 0.5$ km/sec $v = 1$ km/sec.

and Power $= 10^7$ ergs/cm^2 sec

then

$\tan\theta \sim \frac{1}{4}$, $\theta \sim 14°$ $\theta \sim 7°$

The inclination θ increases with time t up to the point that $B_\perp$ is large enough that rapid reconnection across the tangential discontinuities dissipates $B_\perp$ as rapidly as the convective transport of B creates $B_\perp$.

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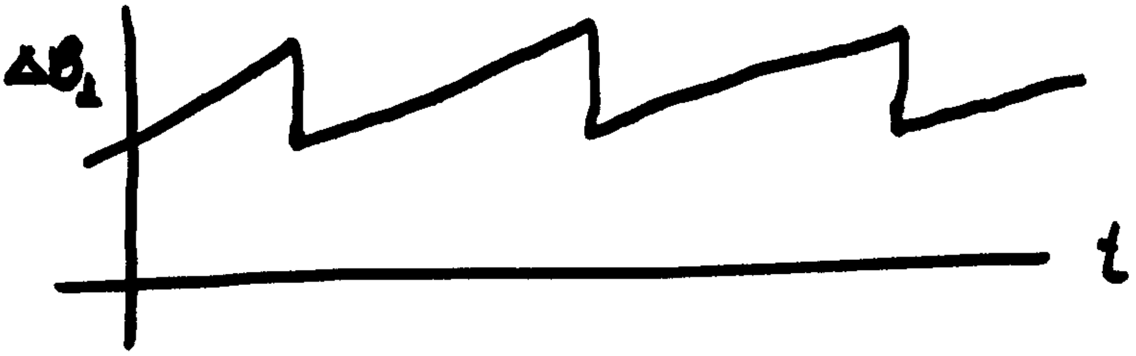
Recent observations by Alan Title show the vigorous intermixing of the magnetic fibrils (filigree) at the photospheric level, at speeds of 0.5-2 km/sec. It is that mixing, then, that is the cause of the X-ray emission from solitary stars like the Sun. That is the basis for the X-ray astronomy of solitary late main sequence stars.

Reconnection across transverse field components $\Delta B_\perp \sim \theta B$, with rms inclination θ to mean field B, proceeds slowly until $\Delta B_\perp$ exceeds some threshold. Then it proceeds with a burst of energy release. So continuing field deformation provides a sawtooth ΔB



The energy $\mathcal{E}$ of the individual reconnection event may be estimated as

$$\mathcal{E} = 0.1\, \ell^2 \frac{\ell}{\theta} \frac{(\Delta B_\perp)^2}{8\pi}$$

$$= 0.1\, \theta \ell^3 B^2/8\pi$$

For $\ell \sim 3 \times 10^7$ cm, $\theta = 0.1$, $B = 10^2$ gauss,

$\mathcal{E} \sim 10^{23}$ ergs nanoflare

$N_L = \frac{l C}{\eta}$ $l \sim 3\times10^7$ cm

$C = \frac{\Delta B}{\sqrt{4\pi\rho}}$, $\Delta B \sim 10$ gauss

$u = \frac{C}{N_L^{1/2}}$, $h = \frac{l}{N_L^{1/2}}$ $\rho \sim 2\times10^{-14}$ gm/cm^3

10^{10} atoms/cm^3

$N_L \sim 0.6\times10^{12}$, $C \sim 2\times10^7$ cm/sec

$u \sim 30$ cm/sec $h \sim 30$ cm

$l/u \sim 10^6$ sec

Electron conduction velocity w

$j = -New$ $New = \frac{c}{4\pi}\frac{\Delta B}{h}$

$w \sim 2\times10^8$ cm/sec

ion thermal velocity ~ 2×10^7 cm/sec.

This suggests the onset of small-scale plasma turbulence and anomalous resistivity

Petschek mode?

THE XRAY CORONA IS A SEA OF NANOFLARES

$10^{22}-10^{25}$ ergs per nanoflare

The early work of Lin et al showed a spectrum of X-ray bursts down to the instrumental threshold at 10^{24} ergs.

The NRL group has studied the intense fast jets from reconnection at transition region levels ($T \sim 10^5$ K).