Stellar Coronae

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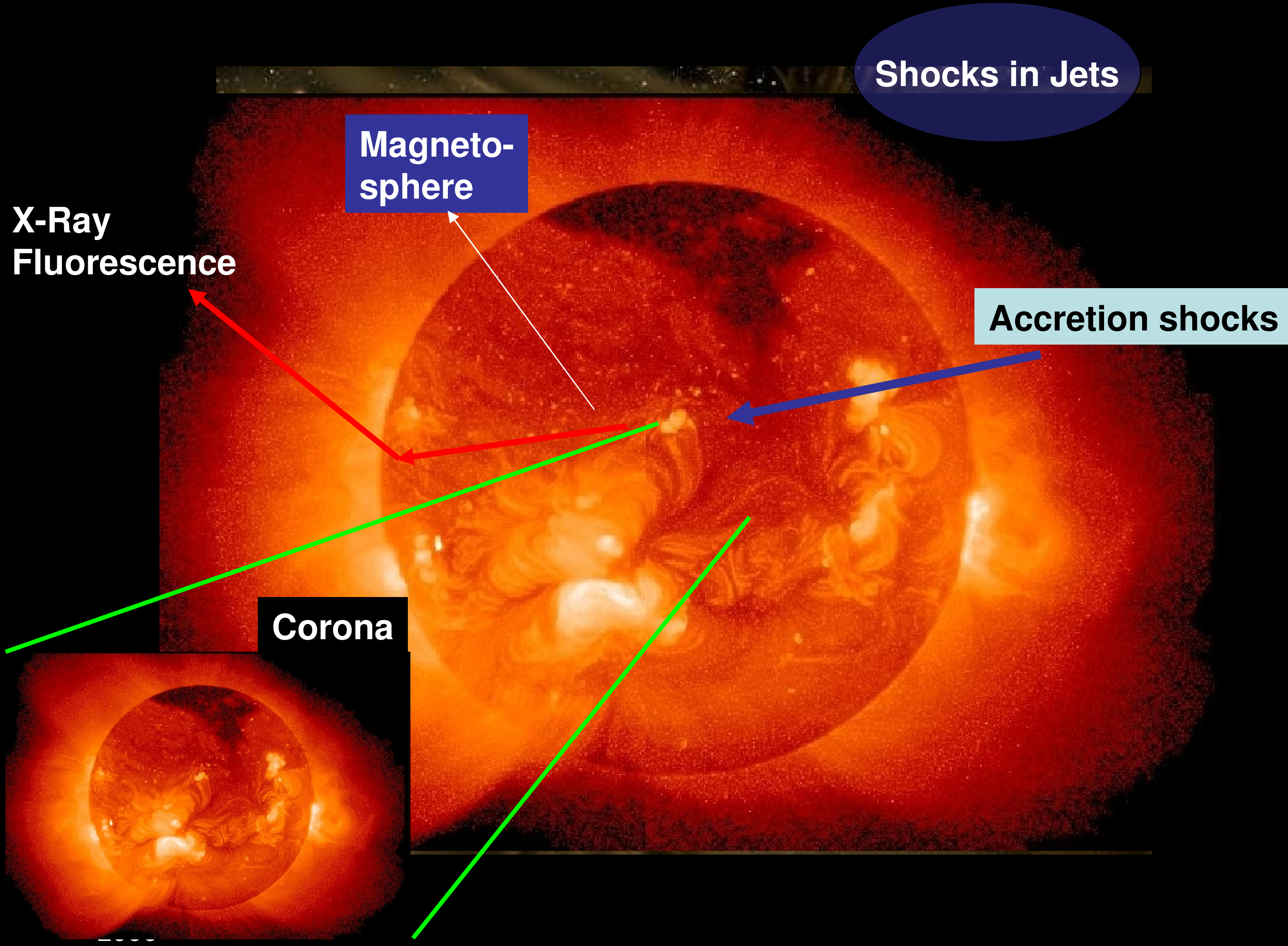
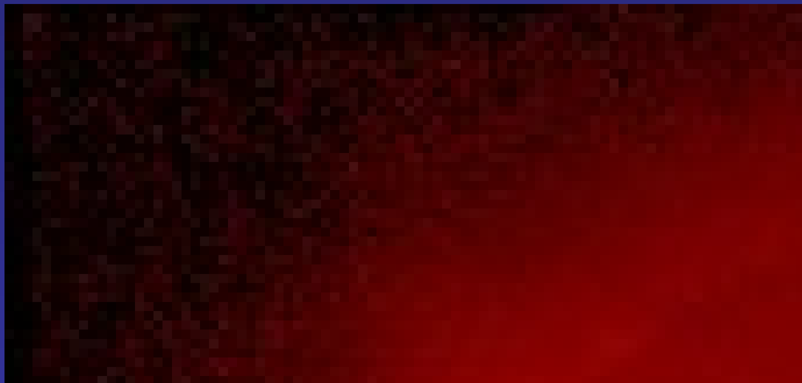
Cargese, 6 April
2006


Shocks in Jets
Magneto-
sphere
X-Ray
Fluorescence
Accretion shocks
Corona

The Sun:

$\approx 10^{27}$ erg/s in X-rays

$\approx 10^{-6}\ L_{bol}$

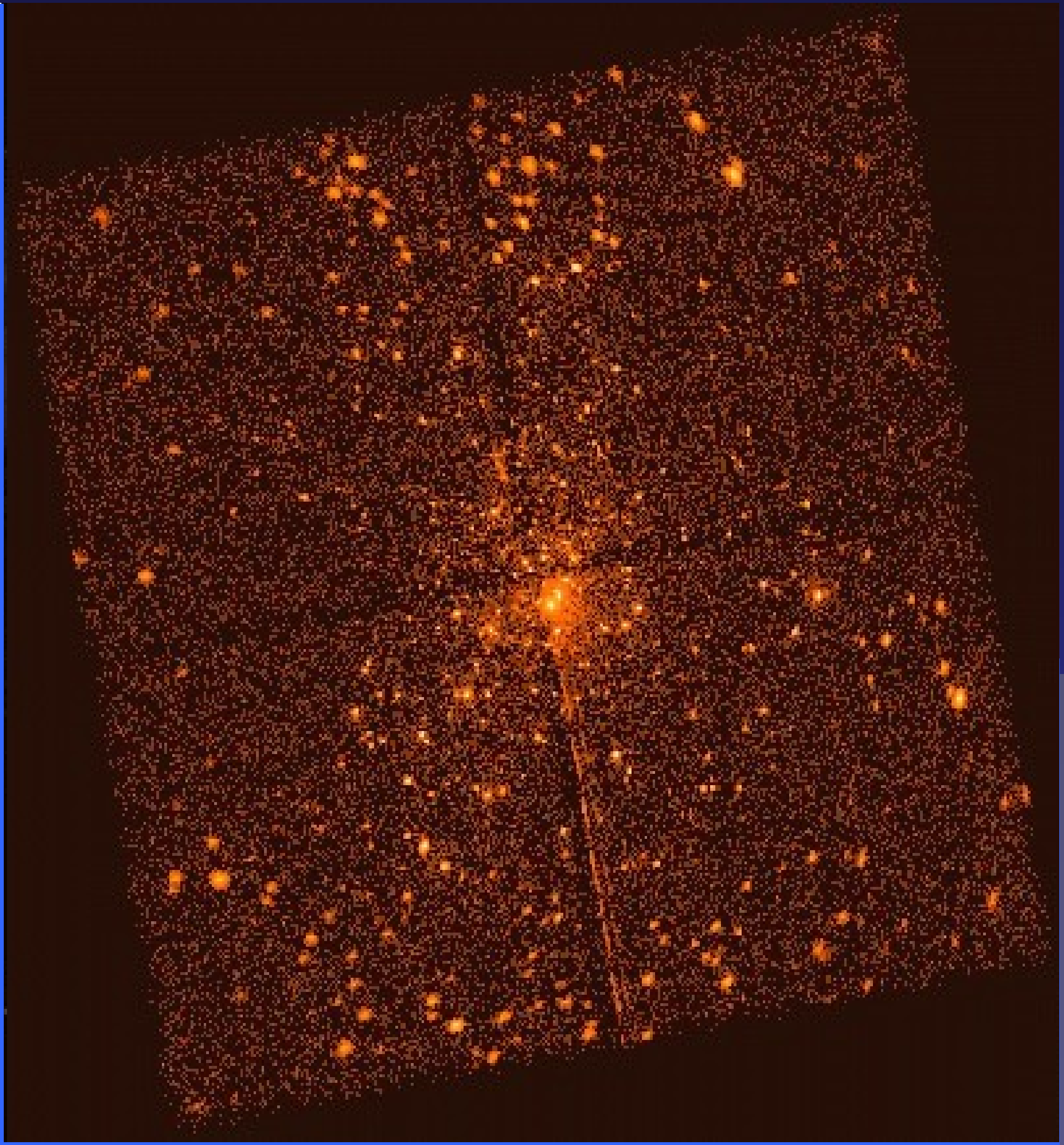


Orion Nebula Cluster

≈ 1500

luminous X-ray stars

≈ $10^{-3}\ L_{bol}$



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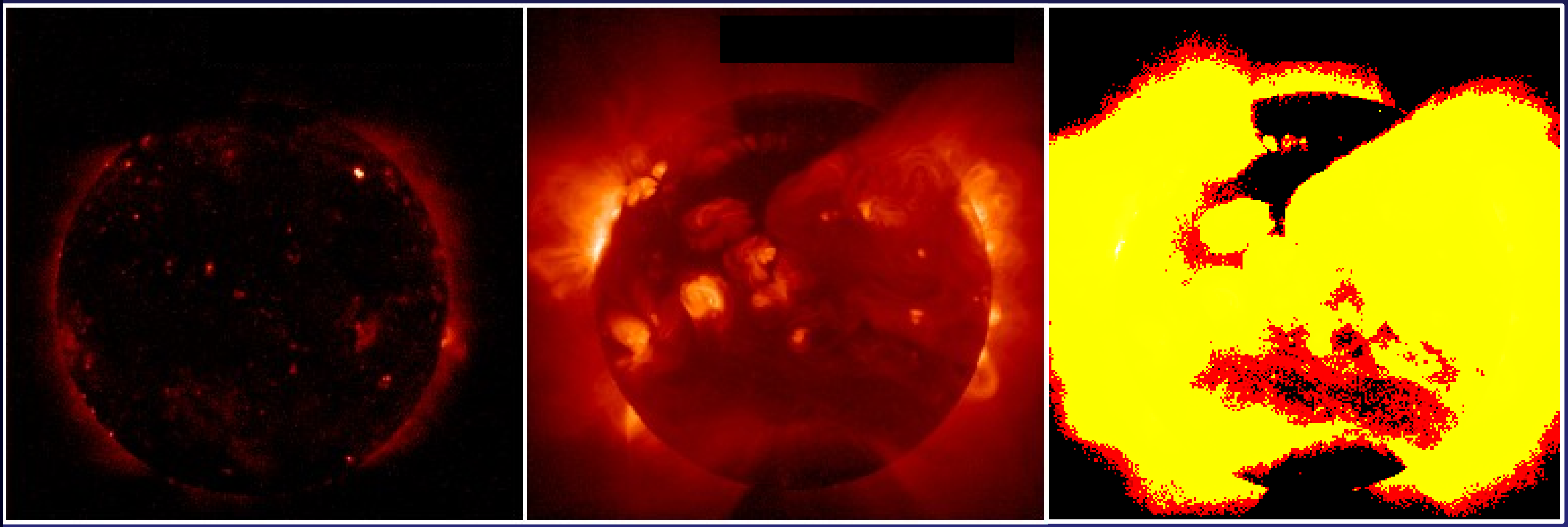
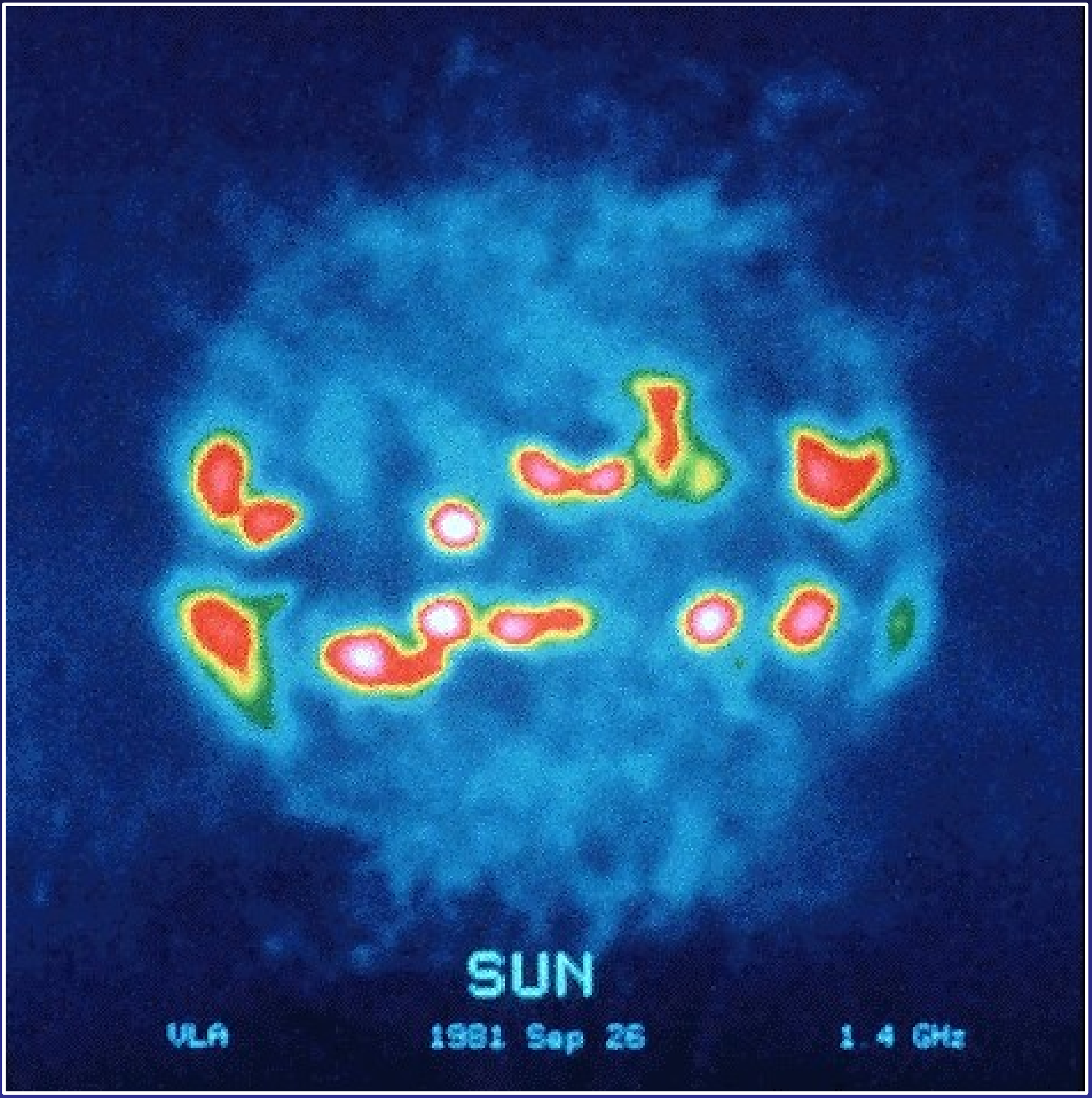
X-RAY PROBLEM: THE X-RAY LUMINOSITY



minimum Sun	maximum Sun	active star
$5x10^{26}$	**$5x10^{27}$**	**$3x10^{29}$**

(ergs/s)

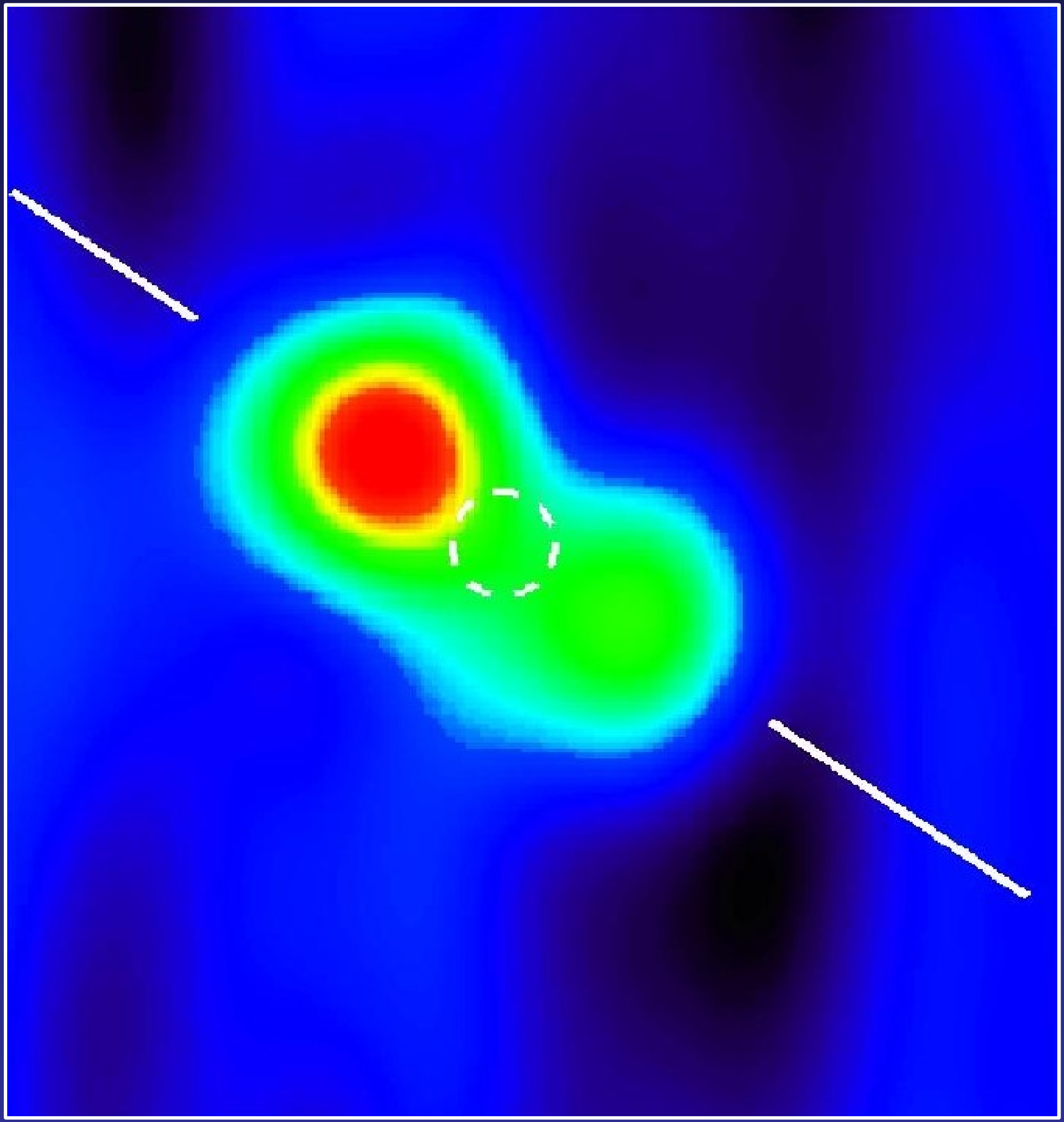
BUT: The most active solar analogs show $3x10^{30}$!



The Radio Sun:

≈ $(6\text{-}10)\times10^{10}$ erg/s/Hz

10 kK bremsstrahlung
&
1 MK cyclotron



The Radio UV Cet:

$\approx 2\text{x}10^{13}$ erg/s/Hz

large source!

(Benz et al. 1998)

Outline

Coronal Structure

Coronal Spectroscopy

Fine Structure: Coronal Magnetic Loops

Coronal Flares

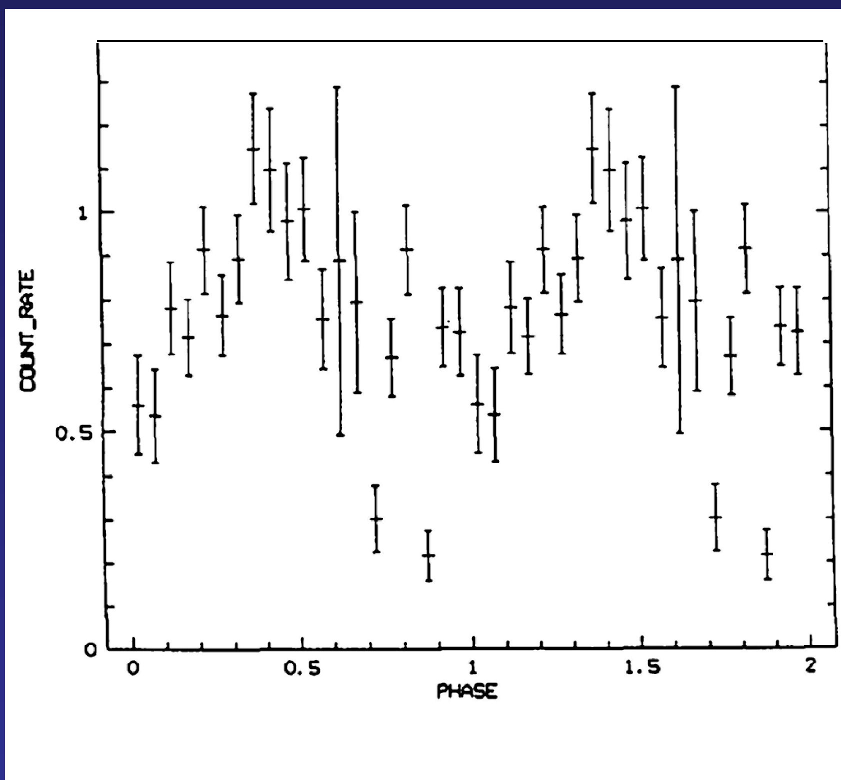
Continuous Flaring

Toward young, forming stars

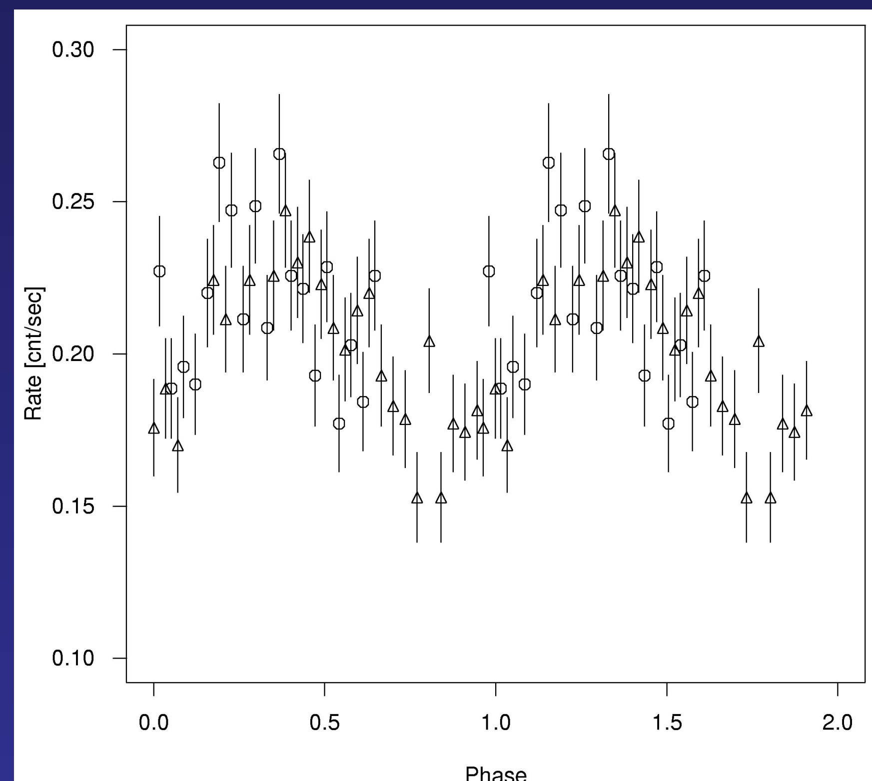
Coronal Structure

Coronal Imaging in X-rays

Principle: Use rotational self-eclipse of star or mutual eclipses in binaries to map structure



(Güdel et al. 1995)



(Marino et al. 2003)

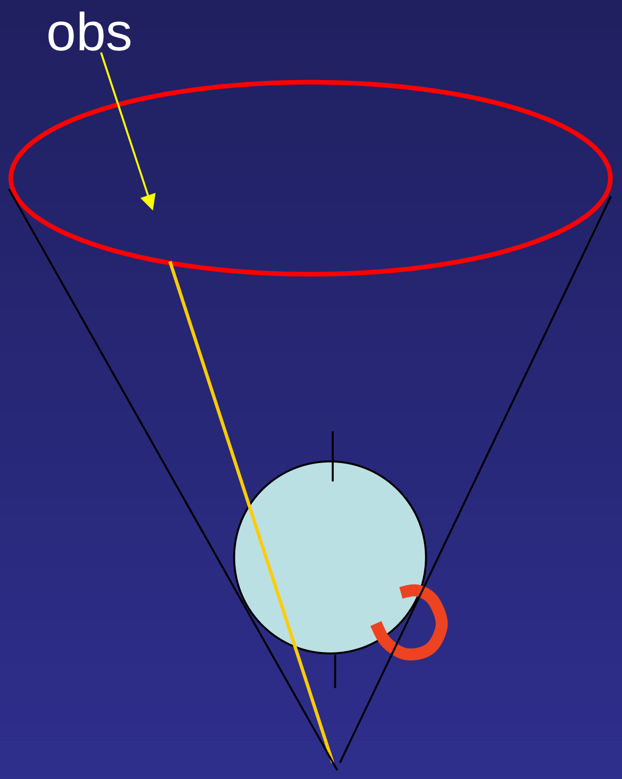
Coronal Imaging in X-rays

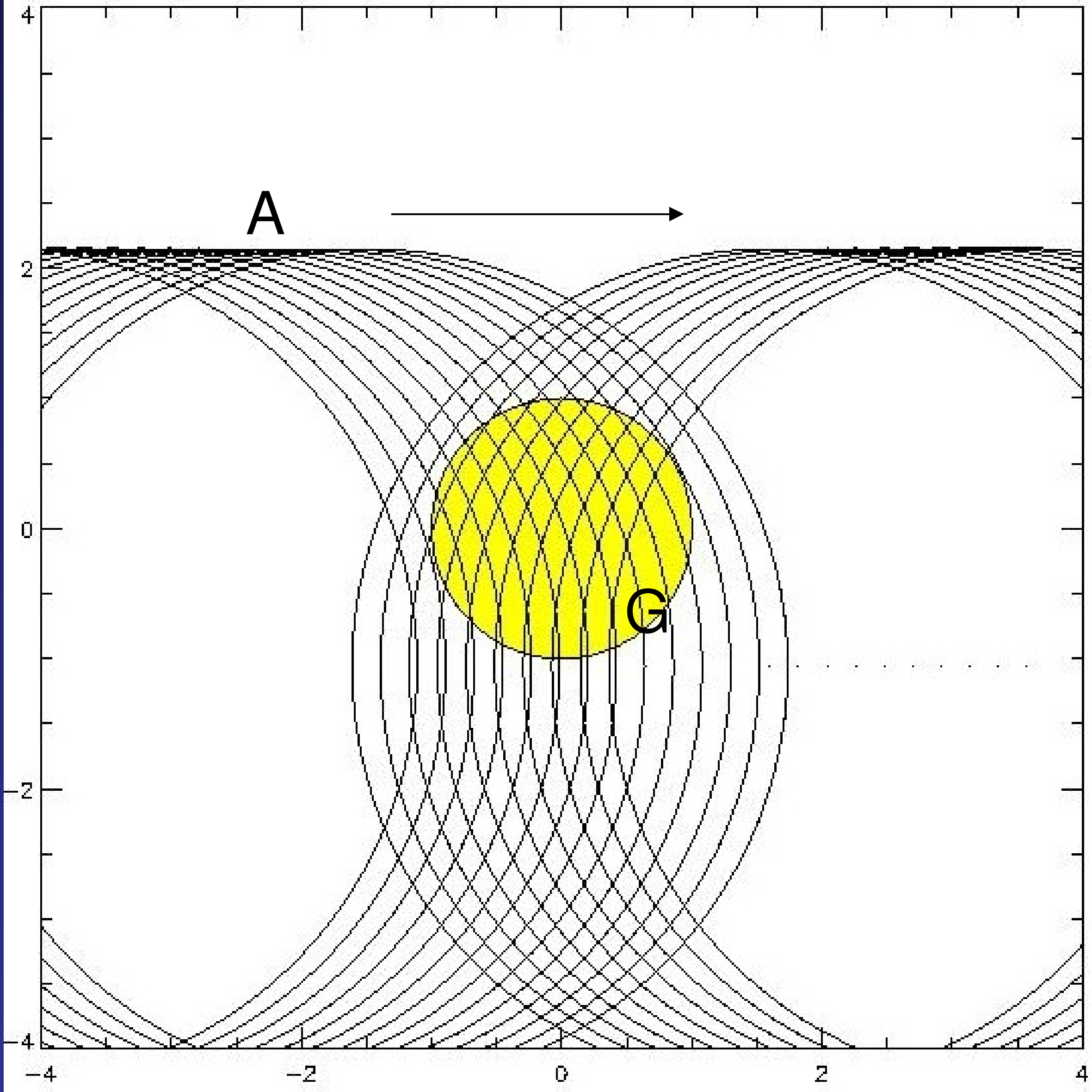
Principle: Use rotational self-eclipse of star or mutual eclipses in binaries to map structure

$$\frac{V_{\max}}{R_*^3} = \frac{\psi}{3} - \frac{(2\pi - \varphi)(1 + \sin^2 i)}{6 \sin i} + \frac{2 \cot(\chi/2)}{3 \tan i}$$

$$\tan\chi = \tan(\varphi/2)\cos i$$
$$\sin(\psi/2) = \sin(\varphi/2)\sin i$$
$$0 \leq \psi/2 \leq \pi/2$$
$$\chi, \ \varphi/2 \quad \text{in same quadrant}$$
$$0 \leq i \leq \pi/2$$

(Güdel & Schmitt 1995)



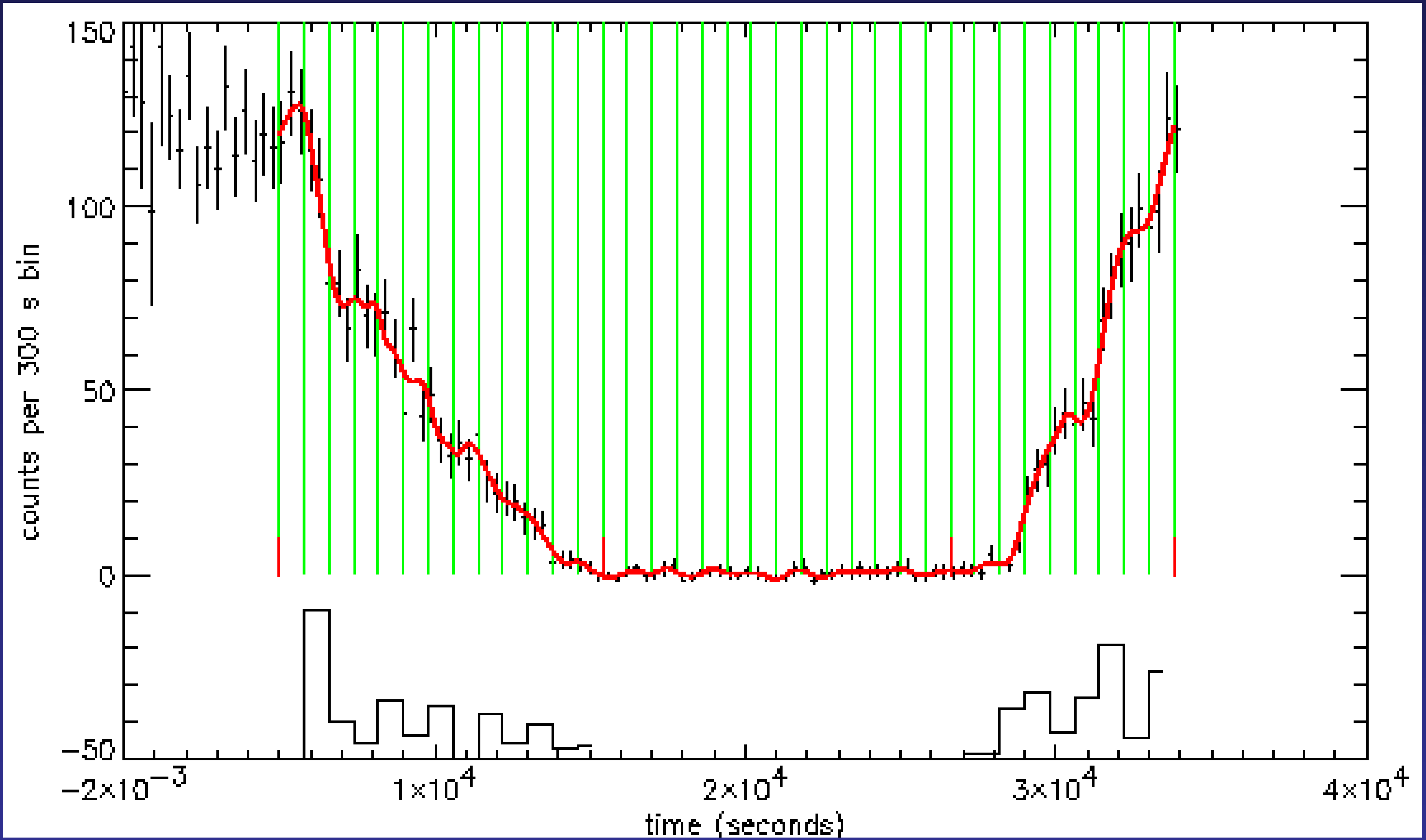


Monitor
eclipsing binary
system

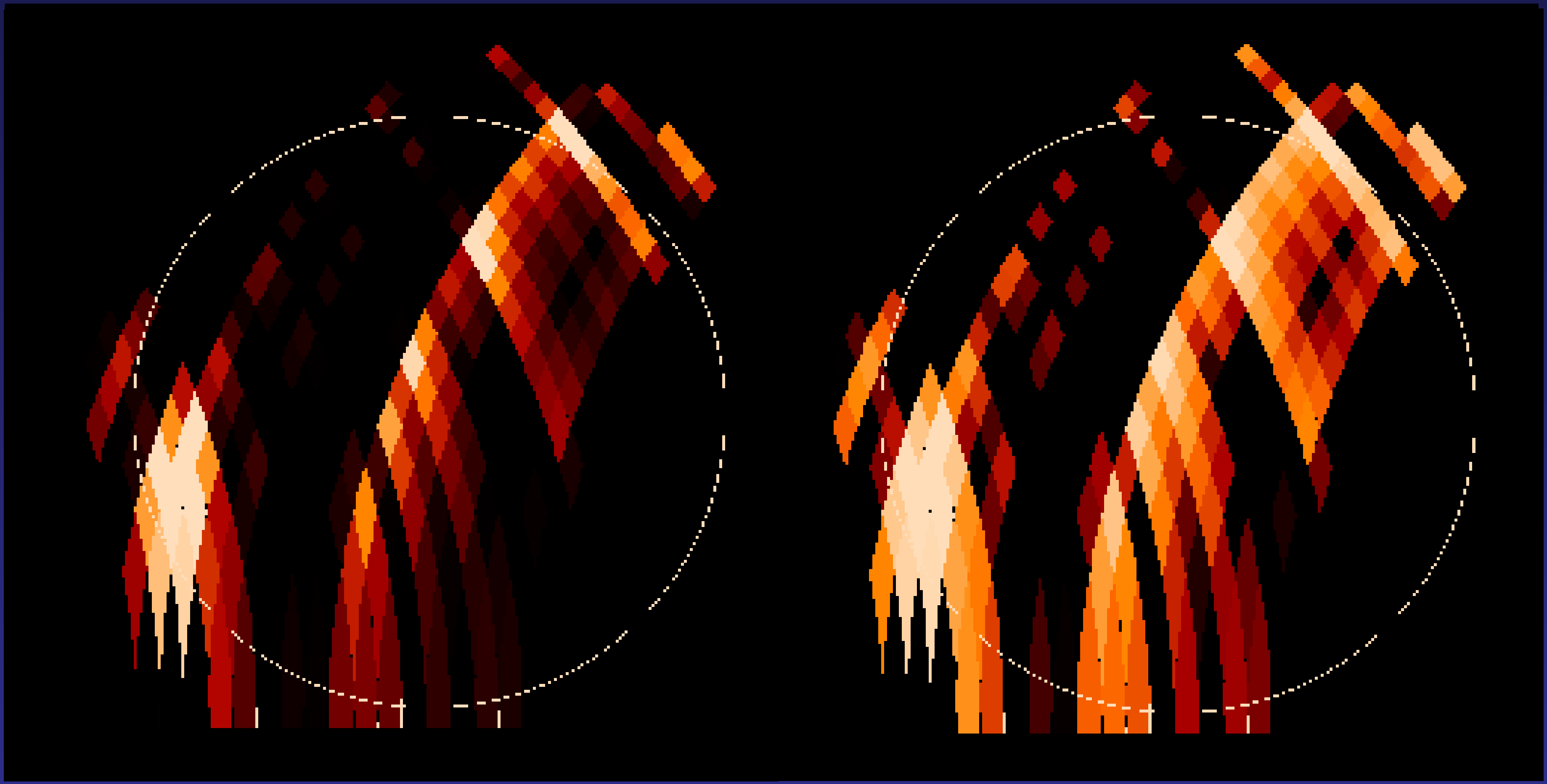
Assume coronal star
at rest, eclipsing
star moving.

Limbs cut off slices
from coronal star

(Güdel et al. 2004)

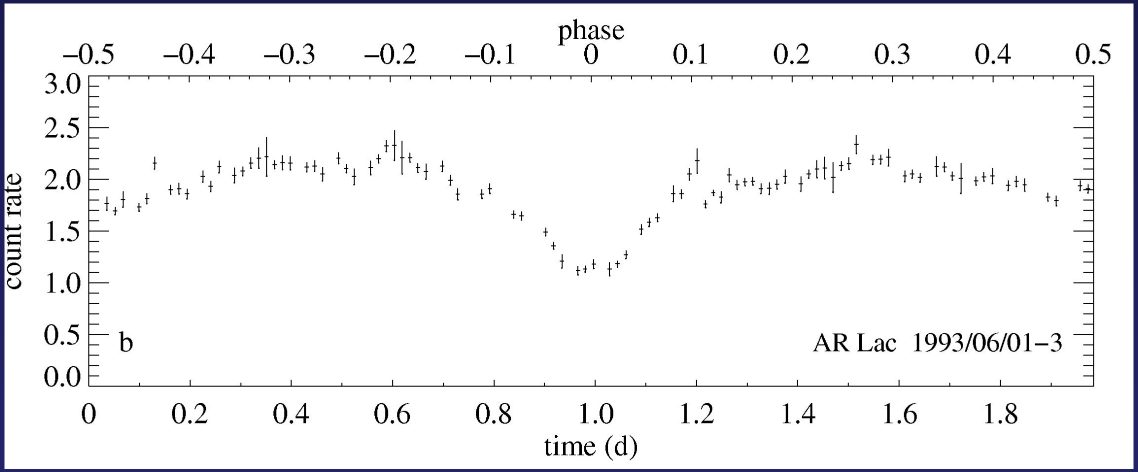


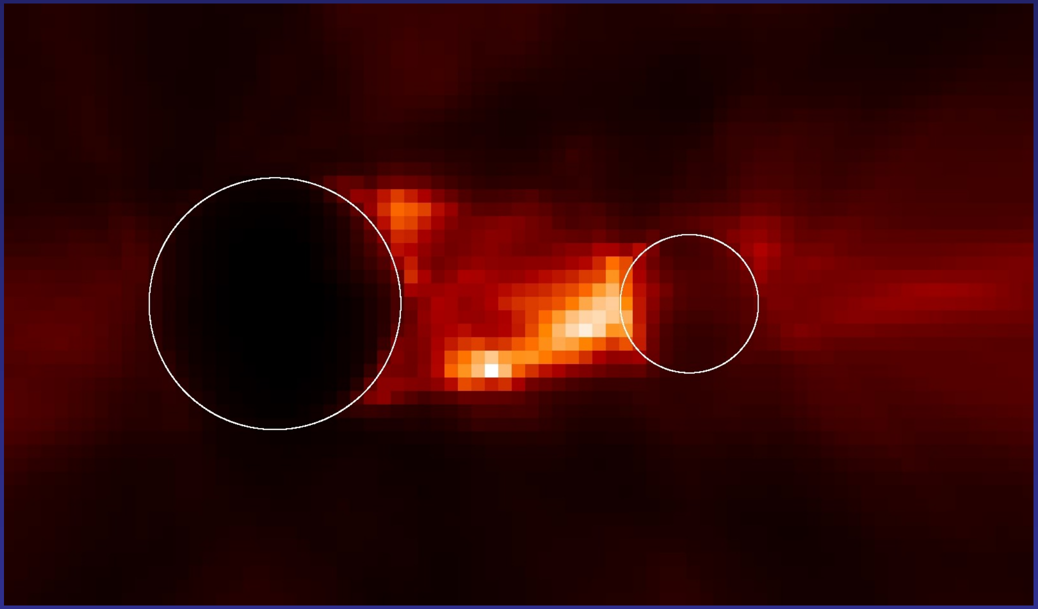
(Güdel et al. 2004)



(Güdel et al. 2004)

3-D modeling using Withbroe method (Siarkowski et al. 1993)

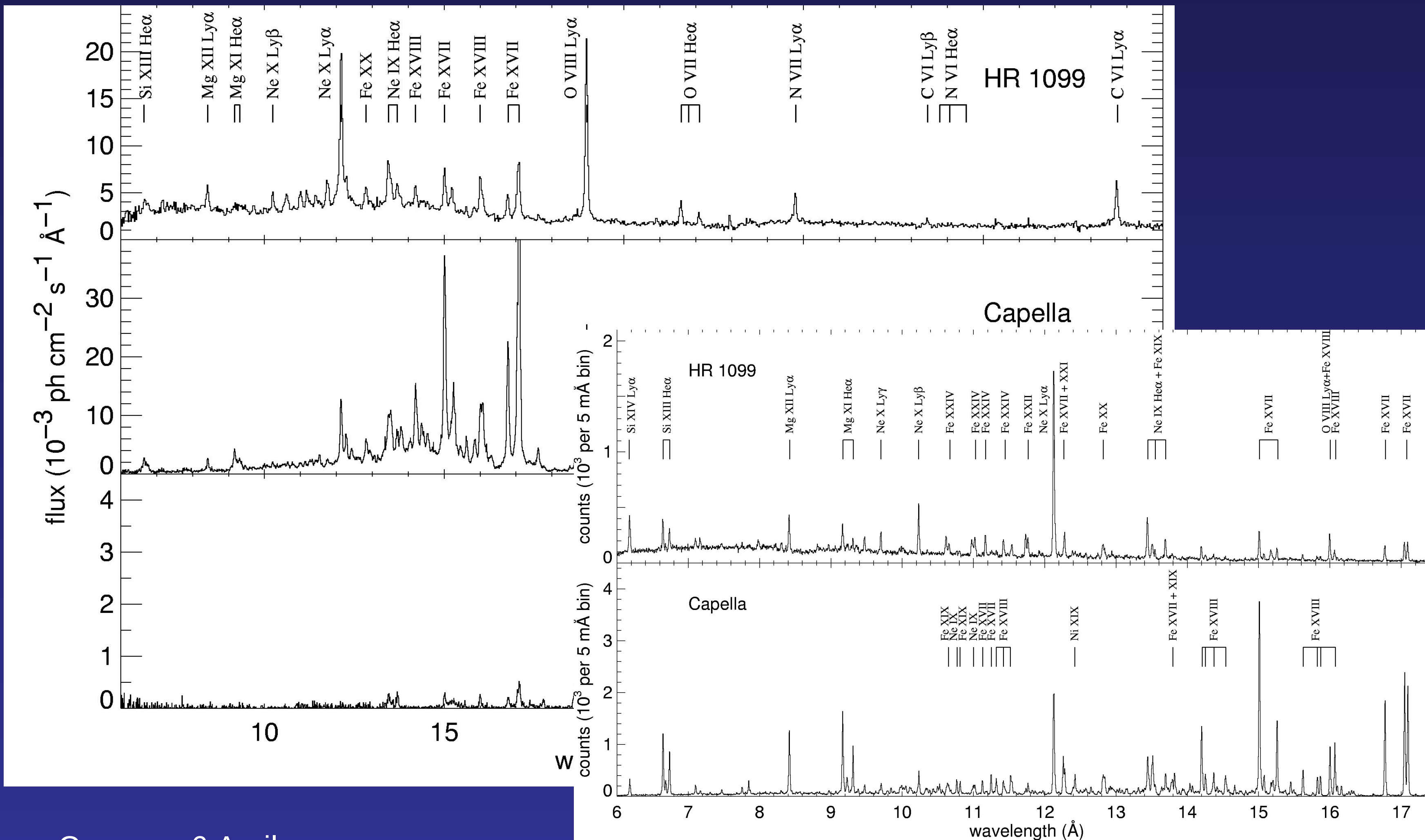




intrabinary magnetic fields?

Coronal Spectroscopy

X-rays from stellar coronae



Cargese, 6 April 2006

(Güdel 2004)

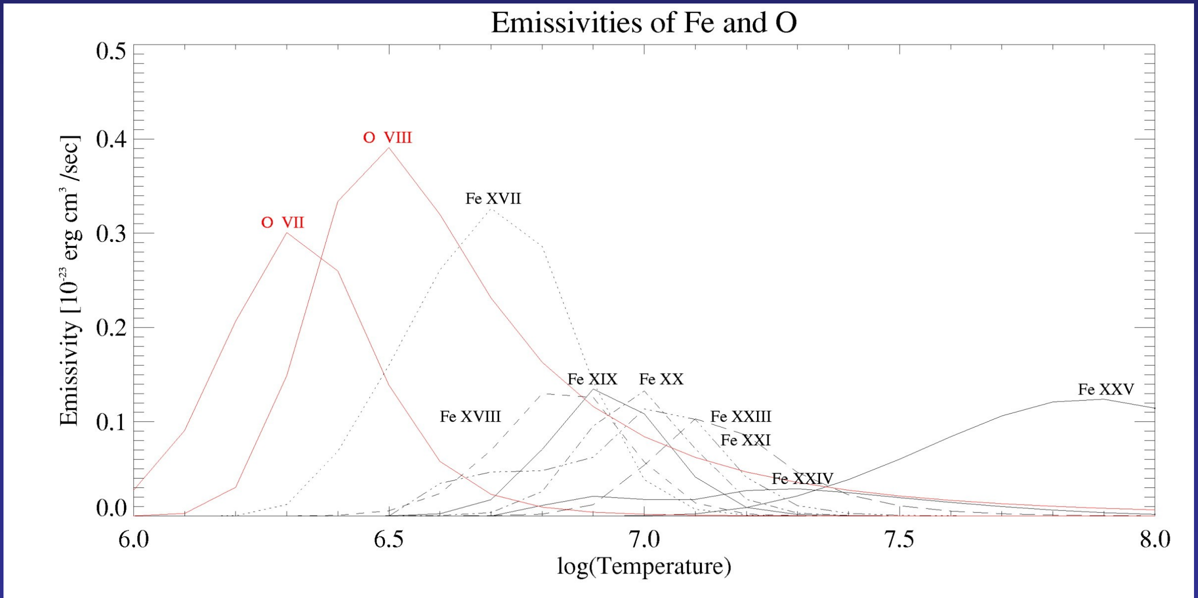
Basic definitions

Flux in a collisionally excited line:

$$\phi_j = \frac{1}{4\pi d^2} \int A G_j(T) \frac{n_e n_H dV}{d\ln T} d\ln T$$

where d = distance, A = element abundance, G = line cooling function, n_e, n_H = number densities of electrons and protons, respectively.

Each line forms typically over factor of two in T (width for a ionization stage)



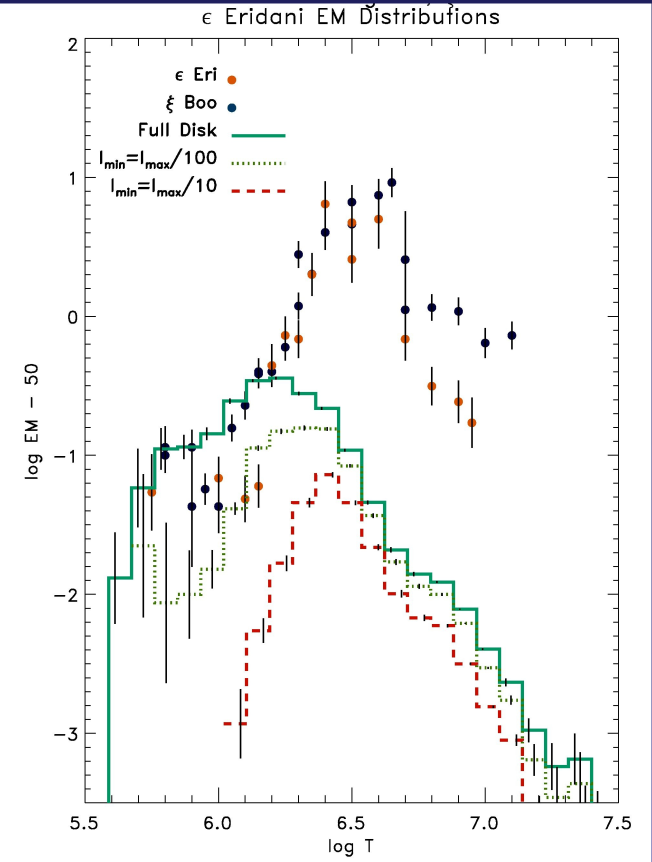
(Telleschi et al. 2005)

Basic definitions

Emission measure per dlnT

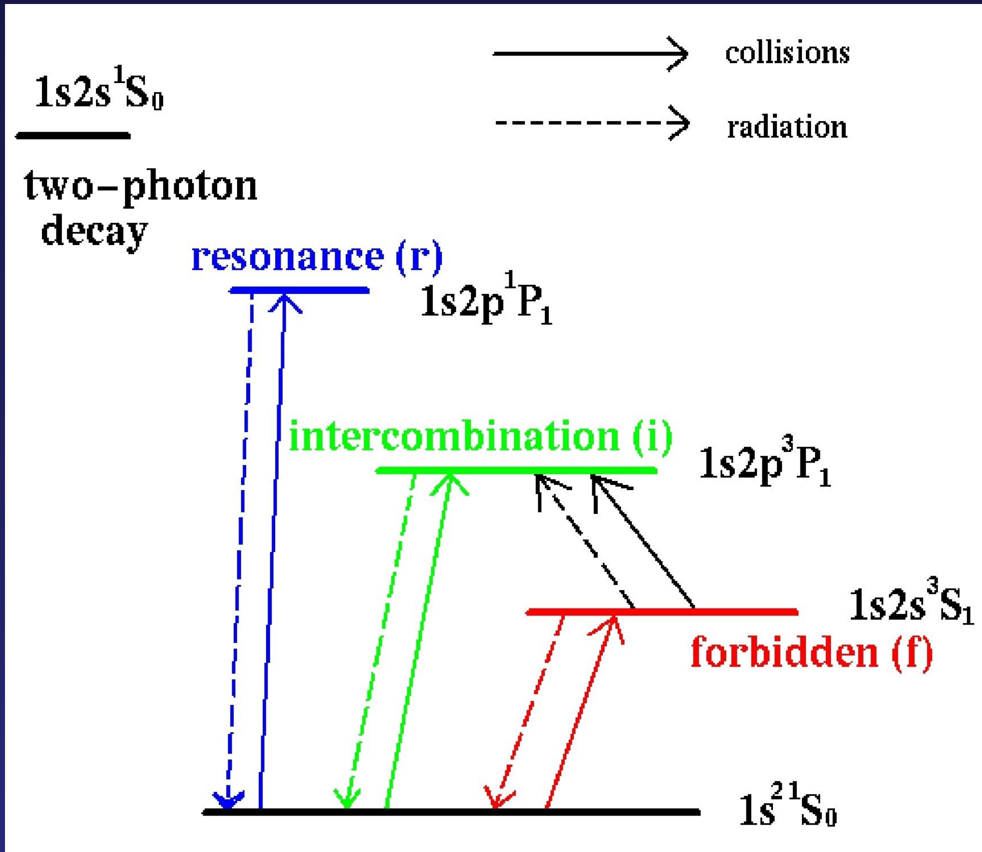
$$Q(T) = \frac{n_e n_H dV}{d\ln T}$$

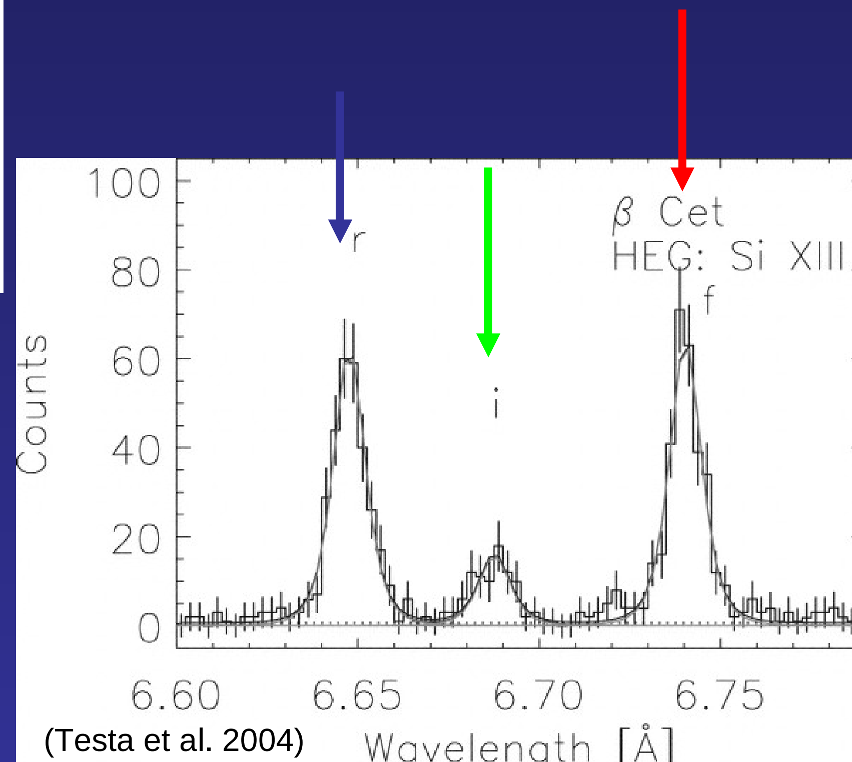
Differential emission measure distribution (DEM)



(Drake et al. 2000)

Density-sensitive
He-like triplets in X-rays:





(Testa et al. 2004)

EM = $n_e^2 V$ measured from spectrum

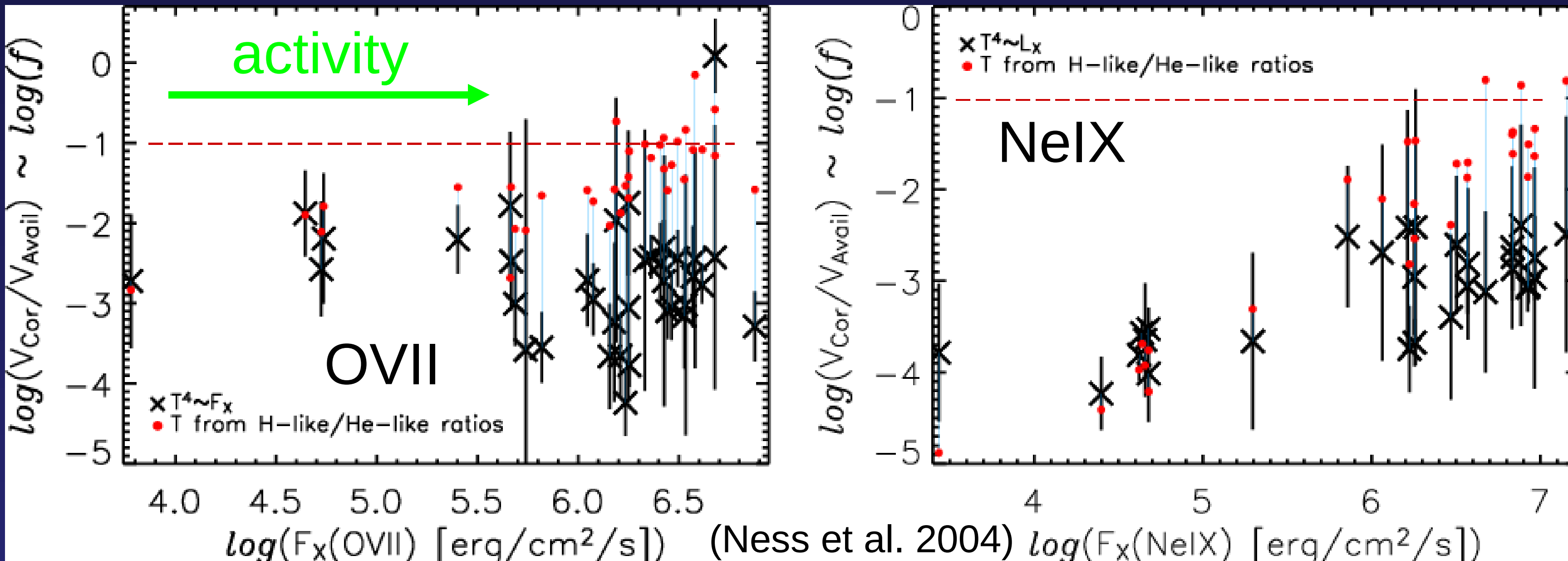
n_e measured spectroscopically

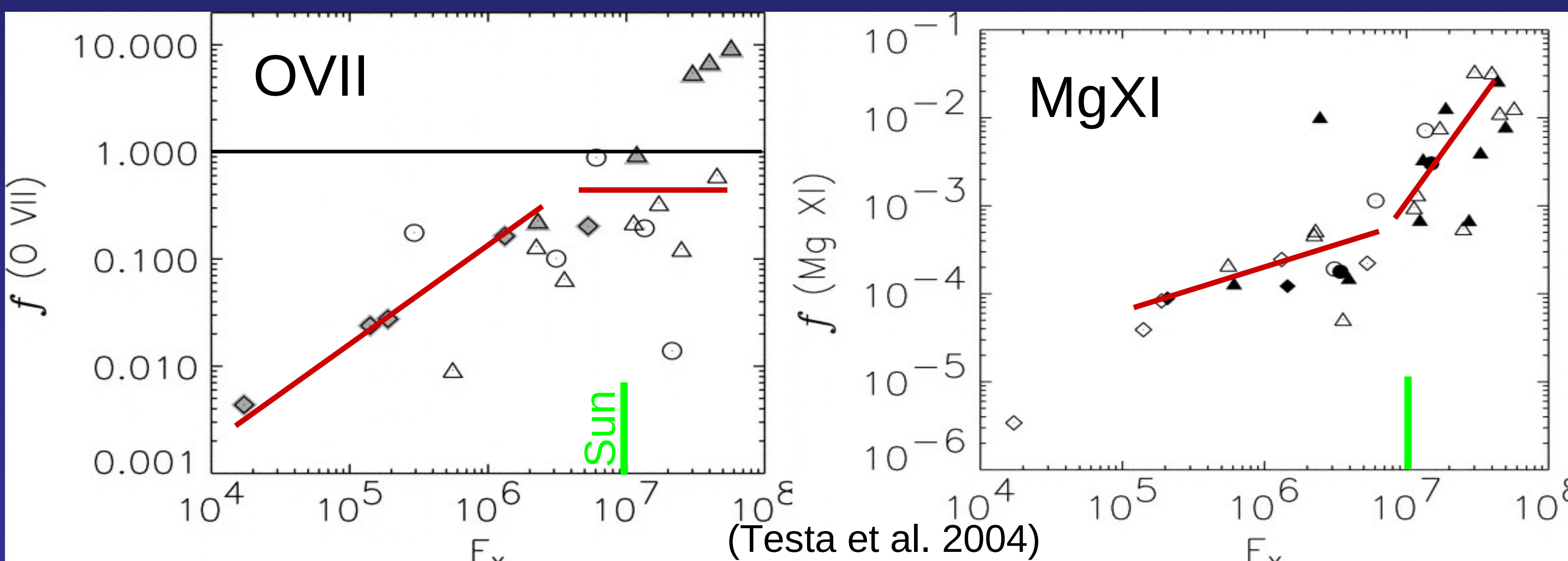
$V = EM/n_e^2$

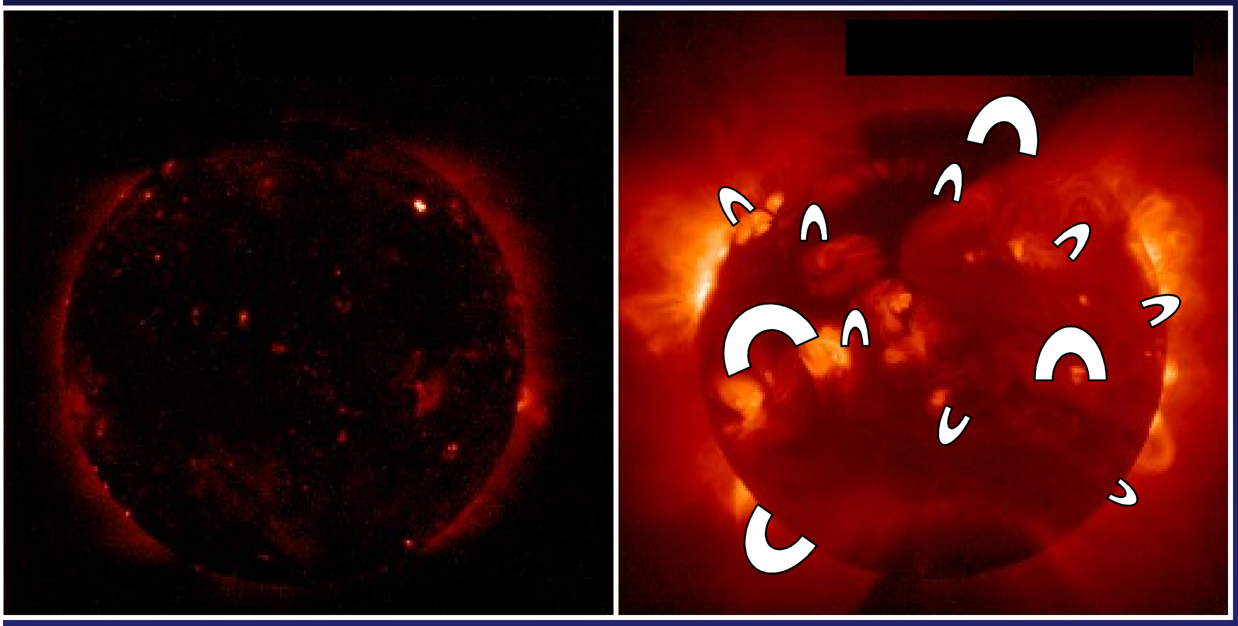
assume reasonable scale height of corona
(or coronal loop height)

$\rightarrow$ surface filling factor of X-ray bright loops

Conclusions from density surveys: plasma filling factors







Stronger dynamo → Cool (2 MK) active regions increase filling factor (but << 1)

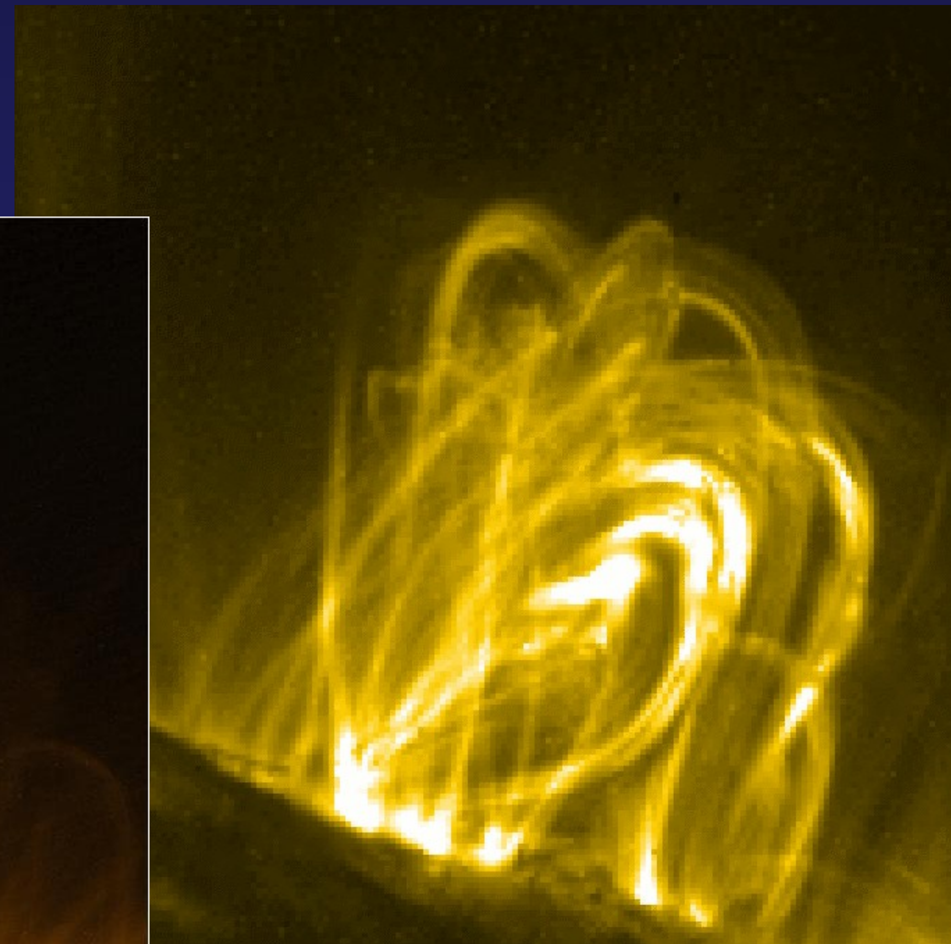
More magnetic interaction → flaring:

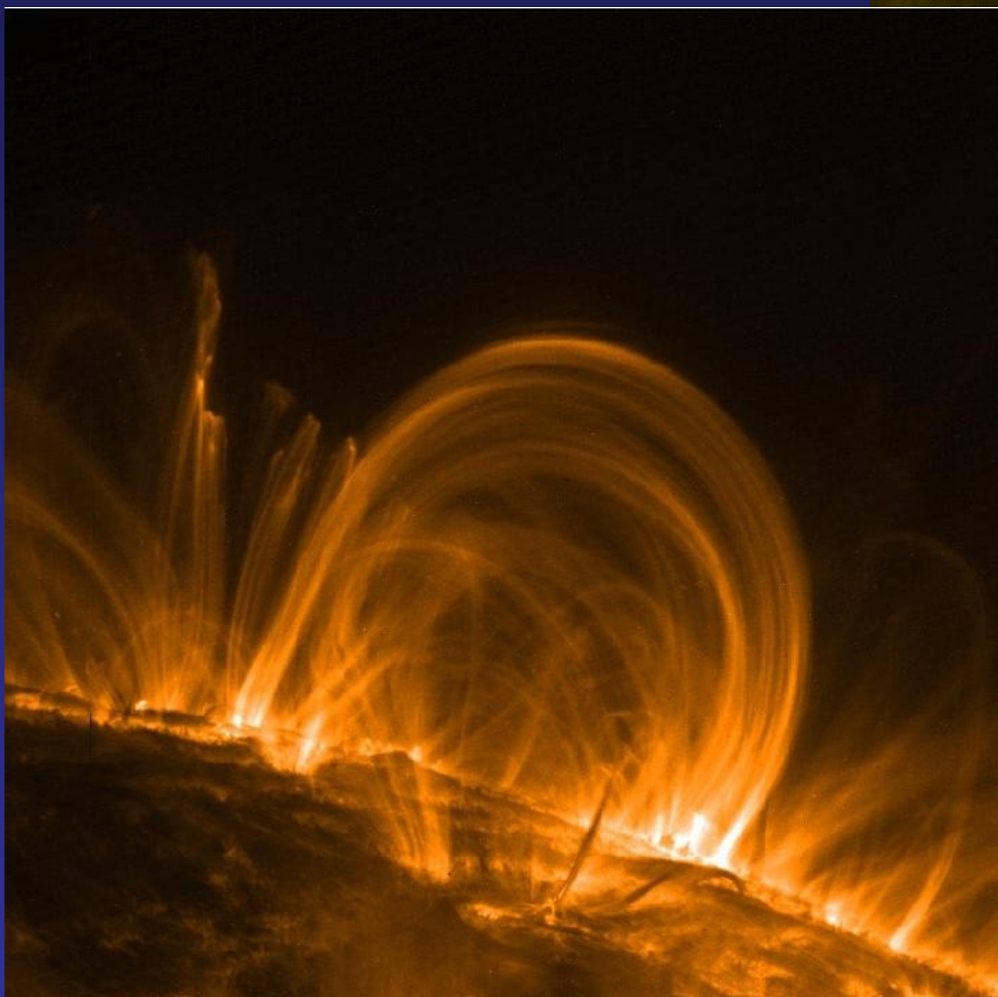
Emergence of growing hot, high-density (→ high-luminosity) component between cooler regions.

(Güdel et al. 1997, Drake et al. 2000, Ness et al. 2004, Testa et al. 2004)

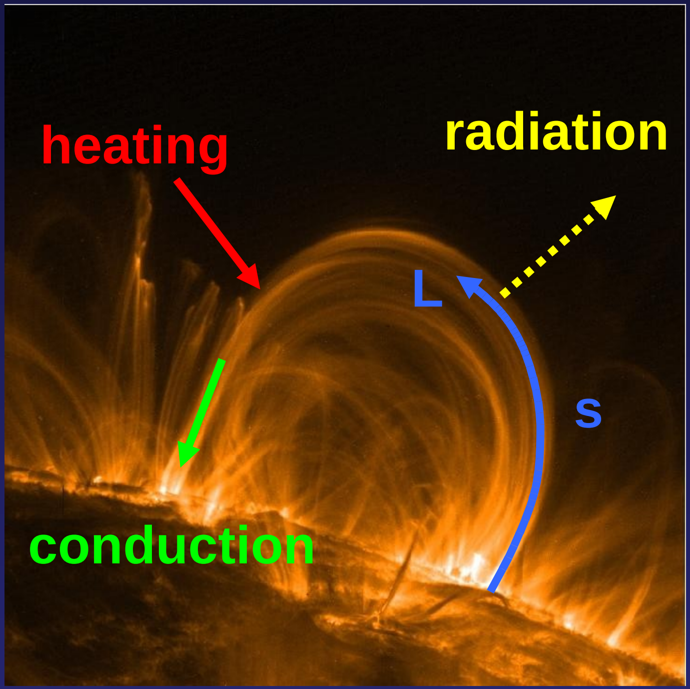
- ***Fine Structure: Magnetic Loops***

Determining coronal structure with X-rays





Magnetic loops as building blocks



Simplifying assumptions:

energy balance
no flows
constant pressure along B
("no gravity" or "height << scale height")

Energy balance: $\mathbf{E_H - E_R - \nabla F_c = 0}$

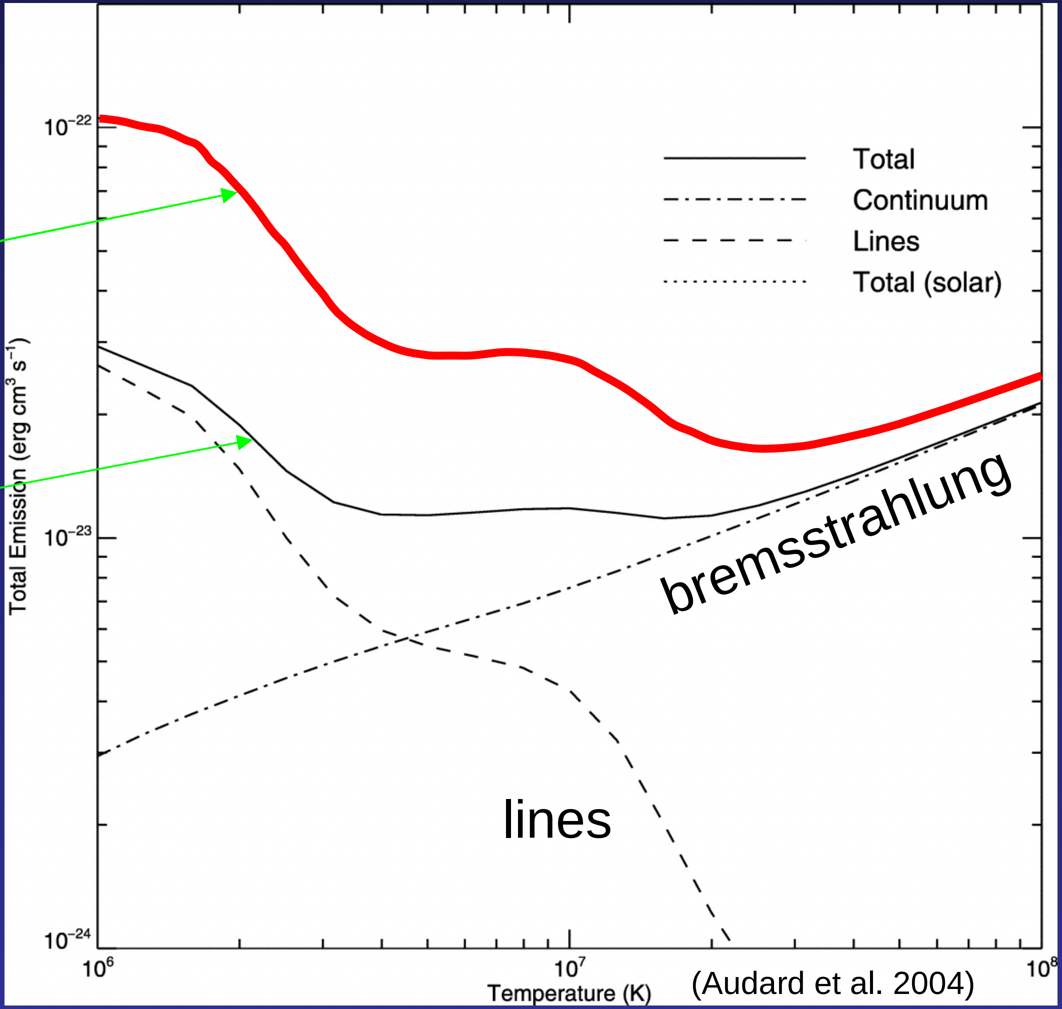
$F_c(s)$	$= -\kappa T^{5/2}\, dT/ds$	conductive heat flux
E_R	$= n^2\Lambda(T)$	emissivity
E_H	$=$???	heating term

Here, E_H being unknown, one usually assumes **uniform heating**, or some geometric distribution (footpoint heating, apex heating, etc)

X-ray cooling function: Radiative power for unit EM

solar abundances

active-stellar abundances



order of magnitude: 2×10^{-23} erg/s per unit EM

System of coupled nonlinear differential equations

$dT/ds = - F_c / kT^{5/2}$ heat conduction law

$dF_c/ds = E_H - n^2\Lambda(T)$ heat balance

conduction heating radiation

$F_c = 0$ at apex

solve for T(s) and n(s) (Rosner et al. 1978, Vesecky et al. 1979, van den Oord et al. 1997)

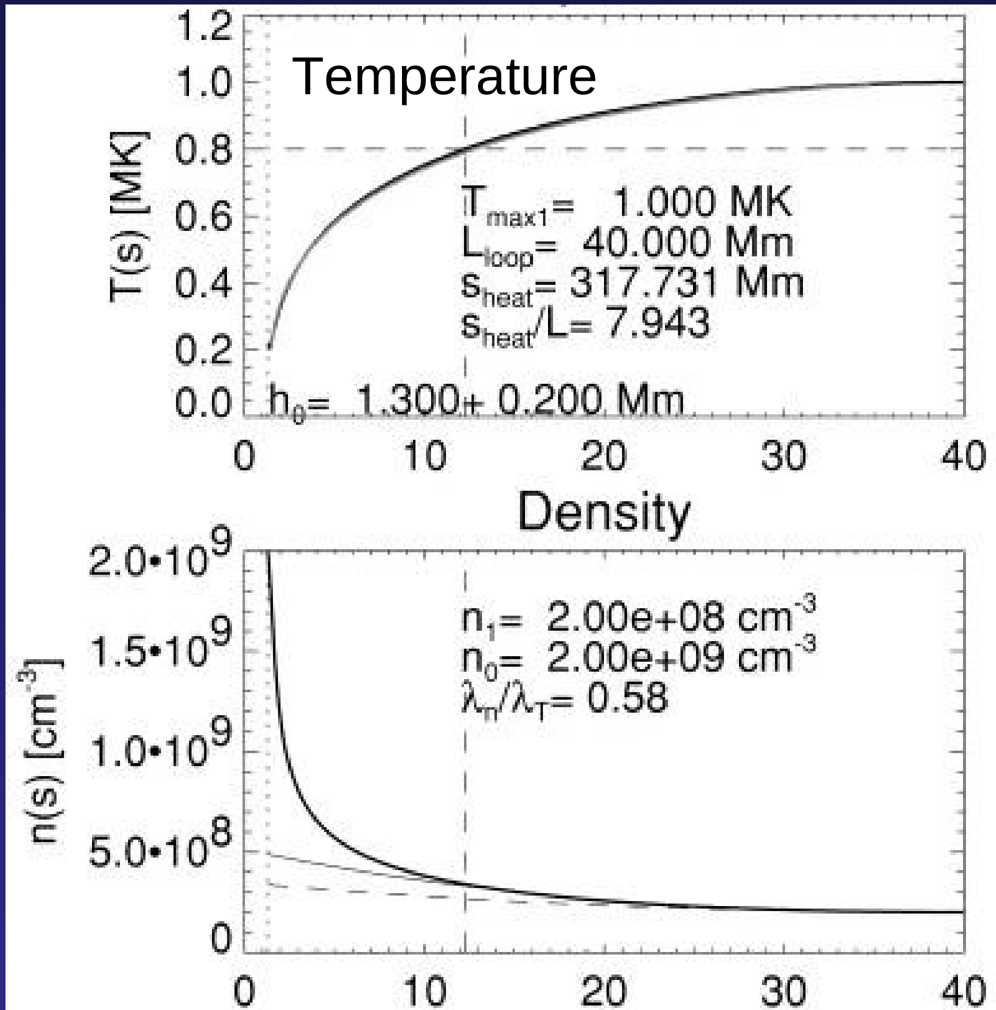
$DEM(T) \propto pT^{3/2}$ if significant conductive flux through footpoint

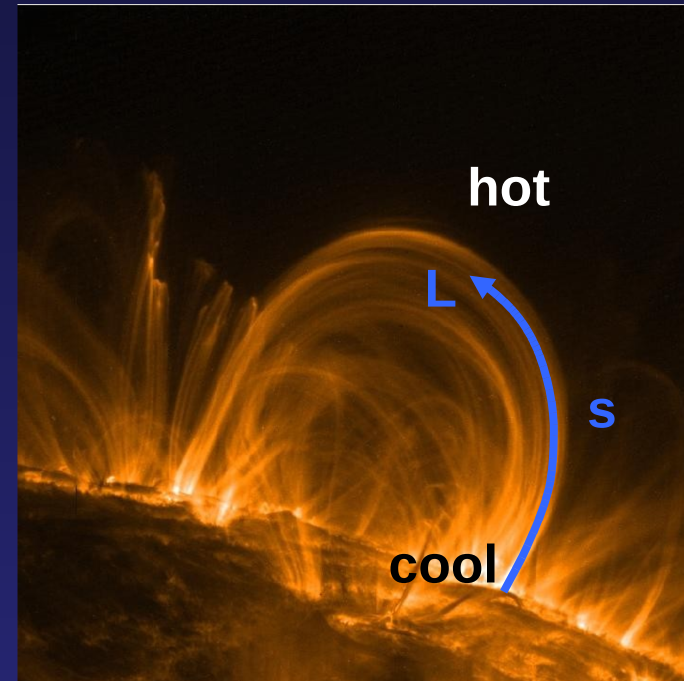
$\propto pT$ if *no* conductive flux through footpoint

$T_{apex} = 1400\ (pL)^{1/3}$

$E_H = 98000\ p^{7/6}\ L^{-5/6}$

"Scaling laws" for "RTV loops"





footpoint loop top

Cargese, 6 April 2006

Verification for the solar corona:

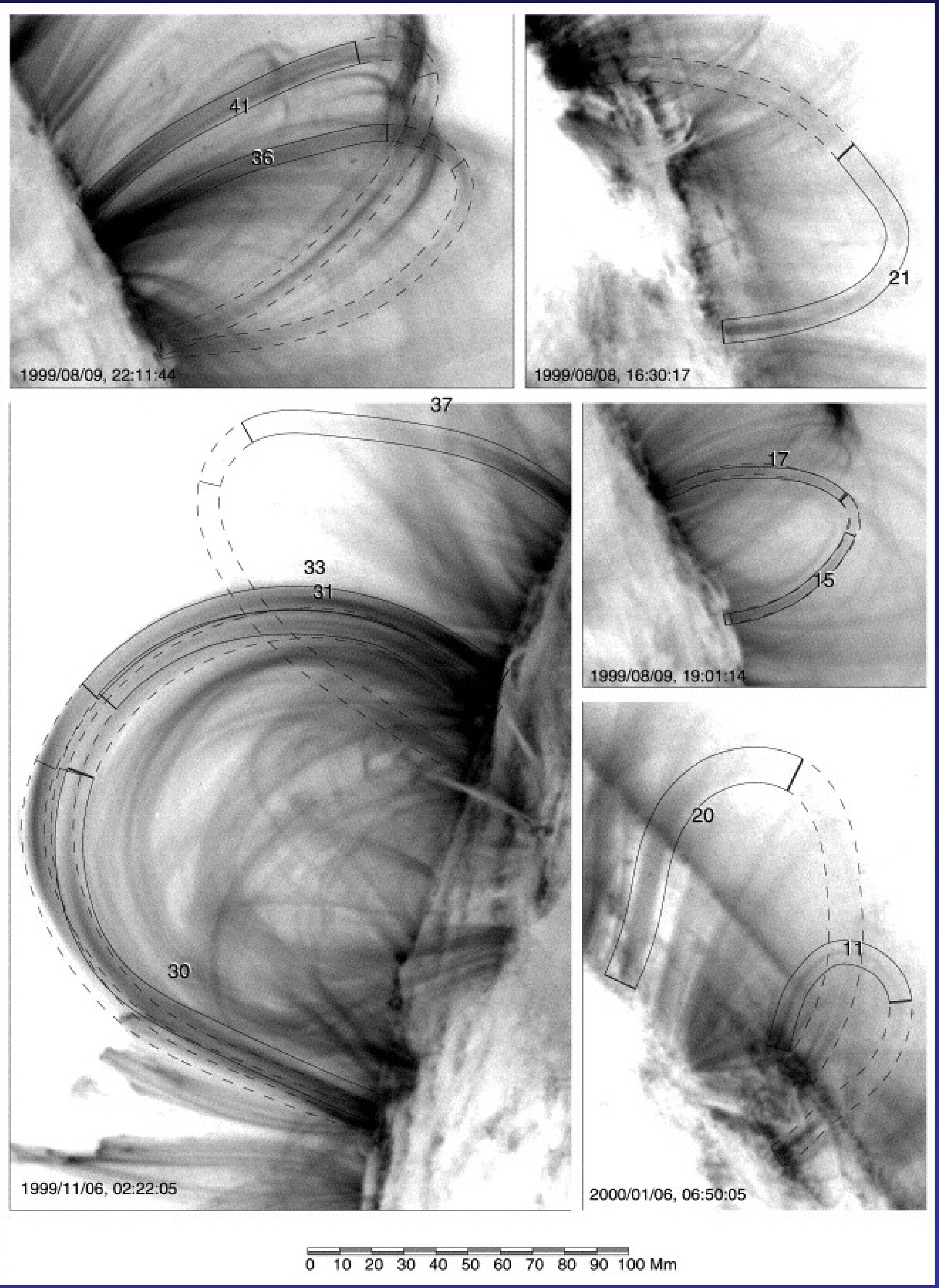
(Aschwanden et al. 2000, 2001)

* determine T(s), n(s) from TRACE data (flux, filter ratios)

* reconstruct p(s), DEM(T)

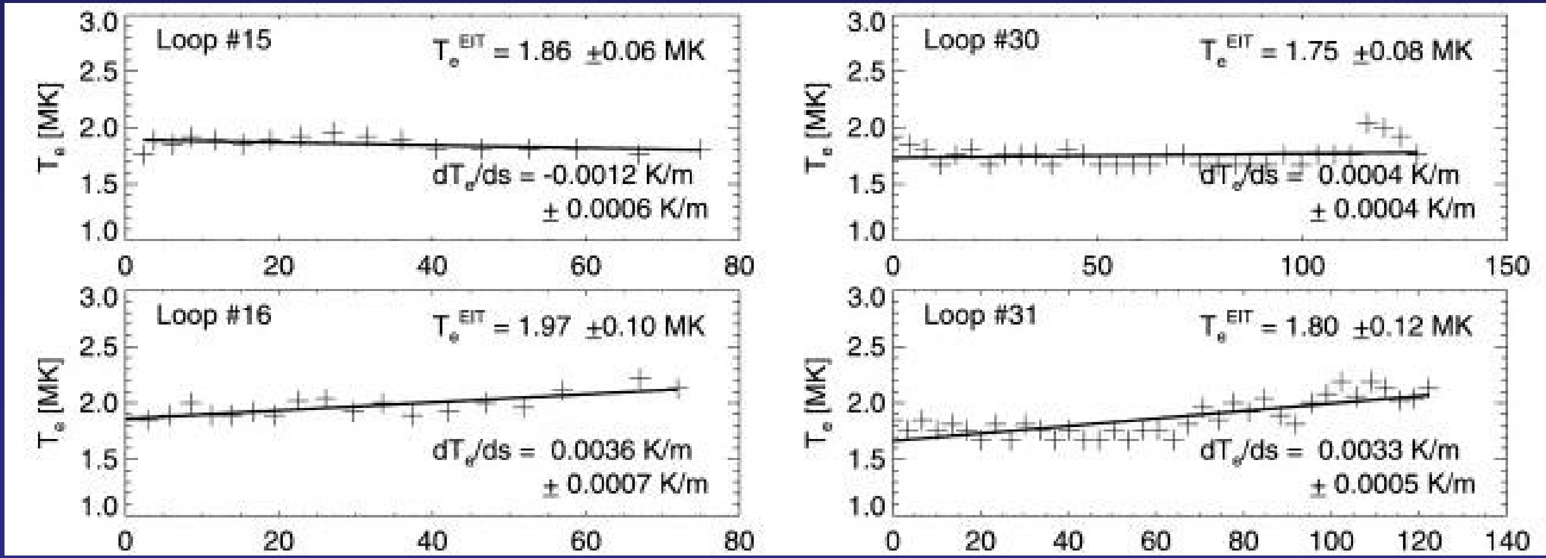
* compare with theory

Tests predominantly cool loops (T < 2 MK).



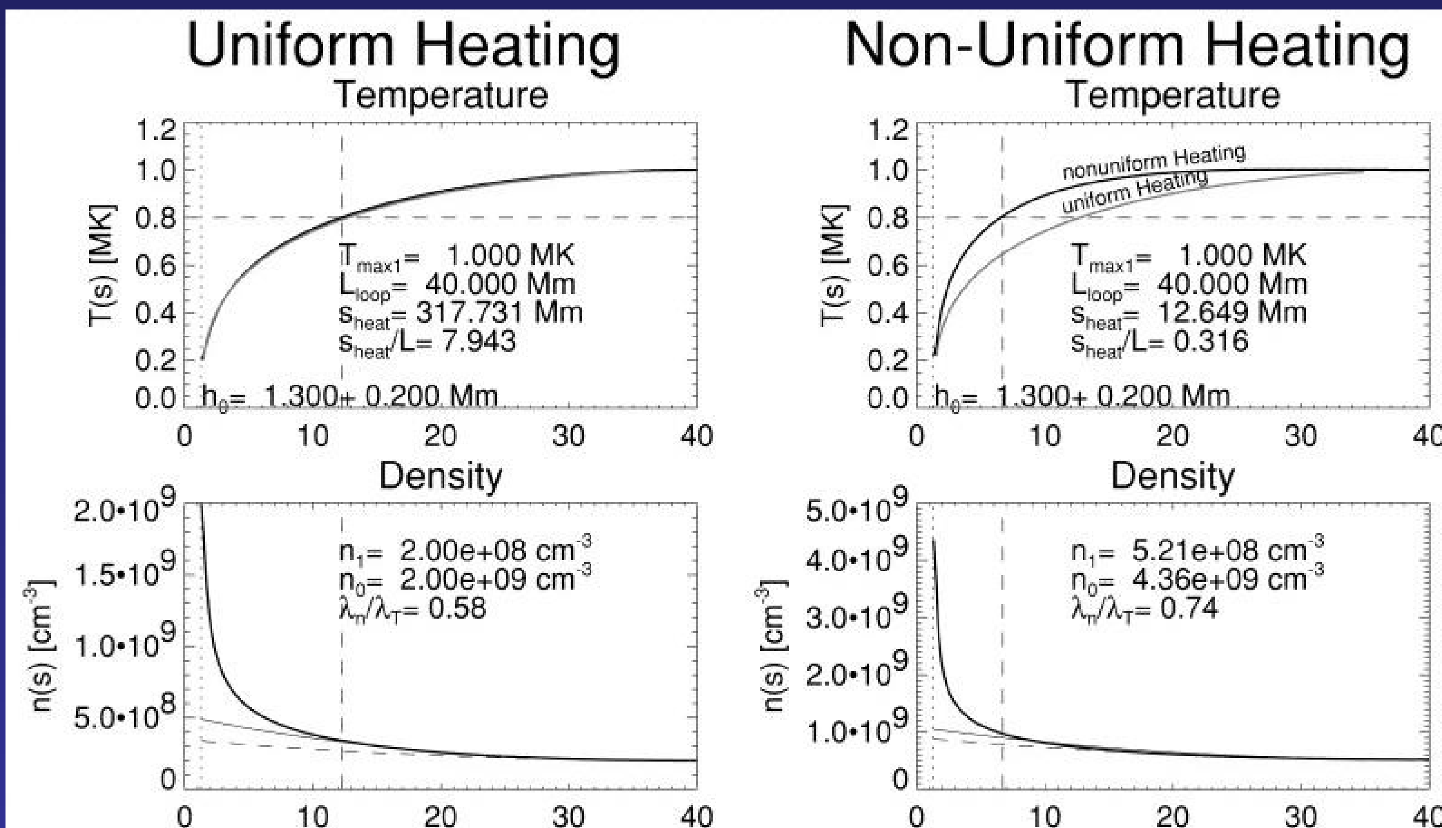
Verification for the solar corona (Aschwanden et al. 2000, 2001):

- Solar coronal loops nearly isothermal: RTV uniform heating not applicable



Verification for the solar corona (Aschwanden et al. 2000, 2001):

- Non-uniform heating near loop footpoints yields flatter T profile
- Flatter T profile provides steeper DEM
- Heating scale height above footpoint: (1.7 +/- 0.6) x 10^9 cm = 0.024 R_o



2006

Verification for the solar corona:
(Aschwanden et al. 2000, 2001)

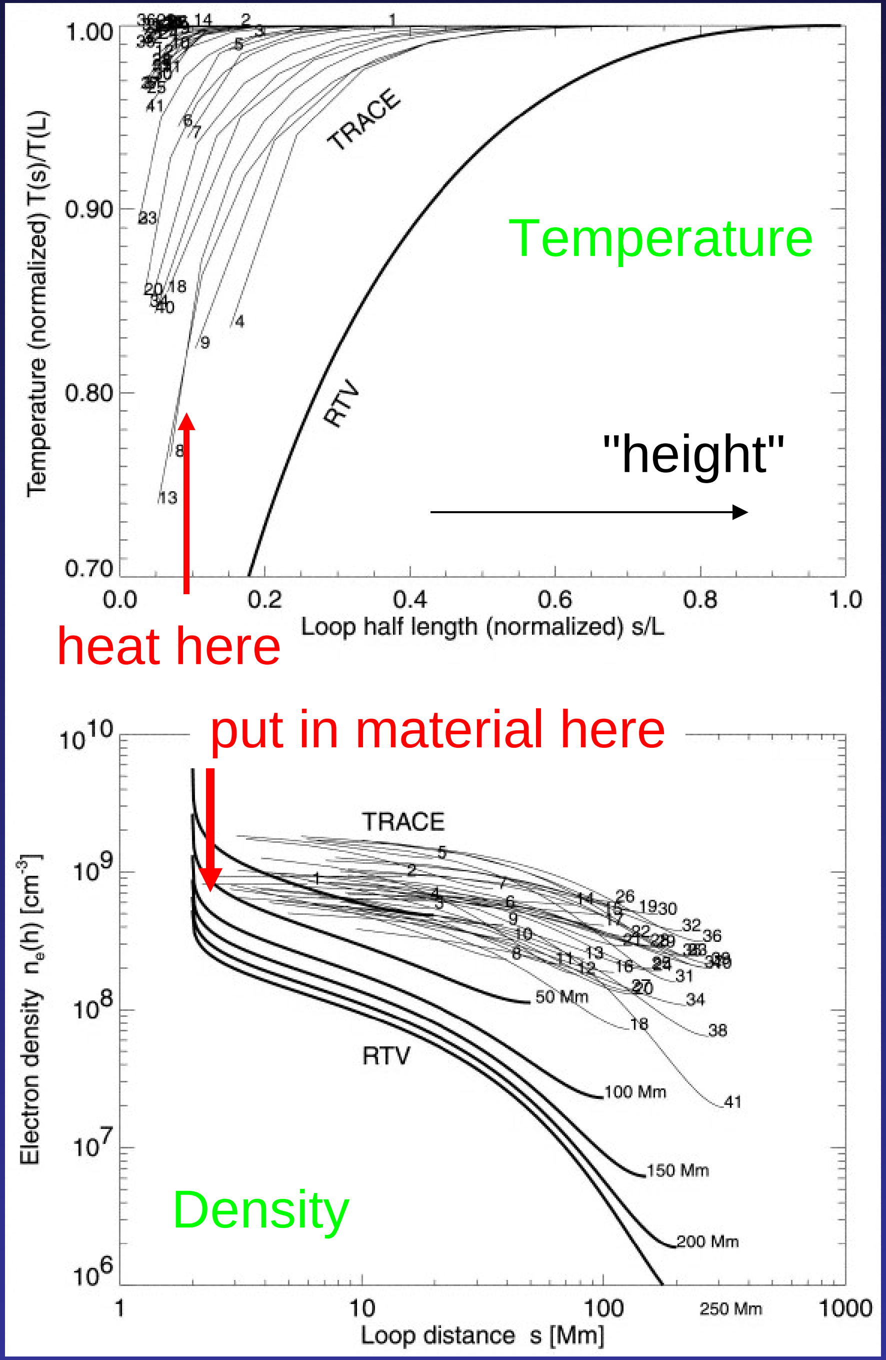
In 60%, density too high for whatever static loop model (uniform or non-uniform heating)

Flat T and high pressure:
Conduction unimportant

Energy balance:

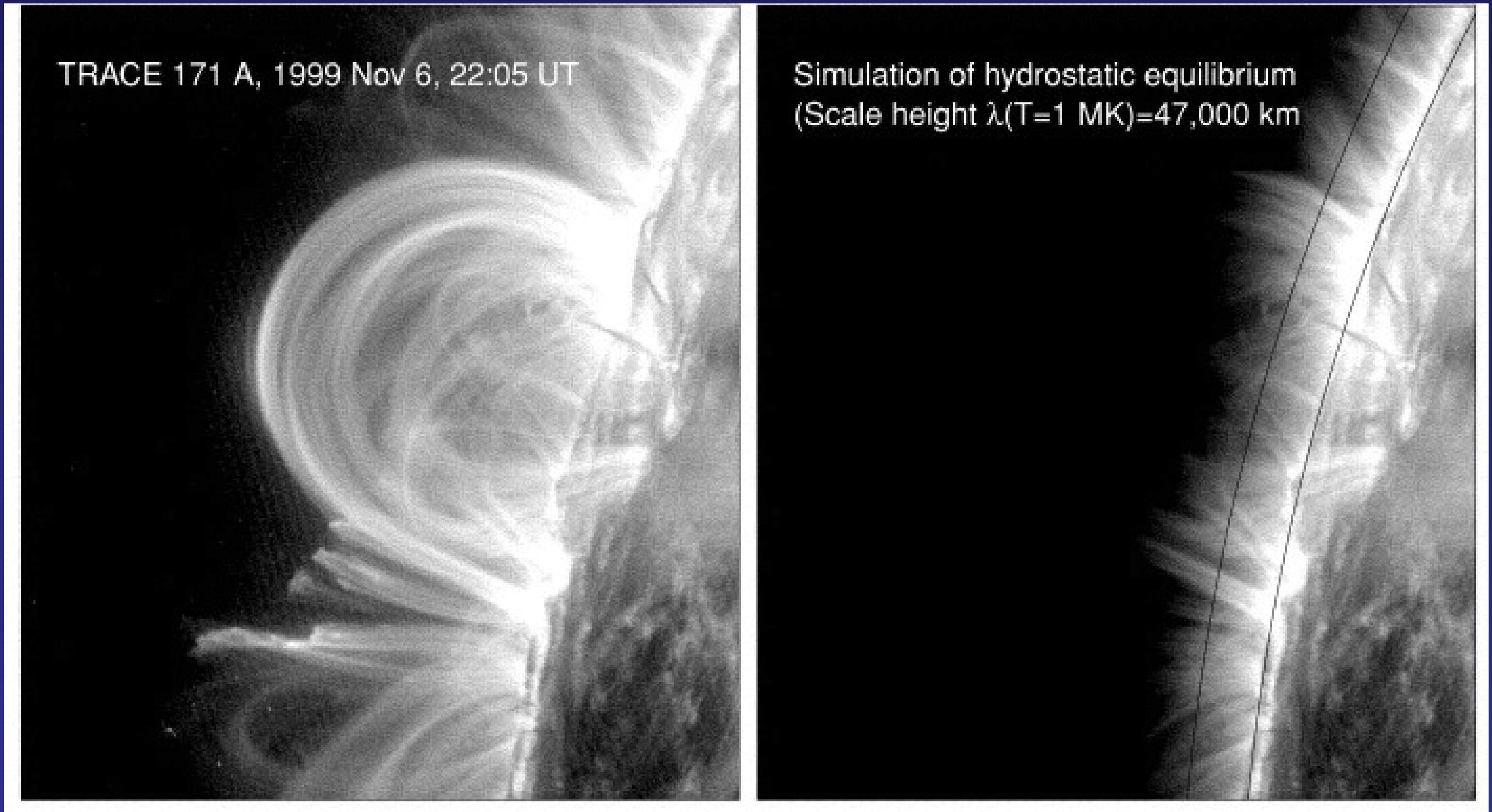
$$E_H + E_R = 0$$

Energy and mass flow through footpoints into loops?
Dynamic loops; stochastic energy release?



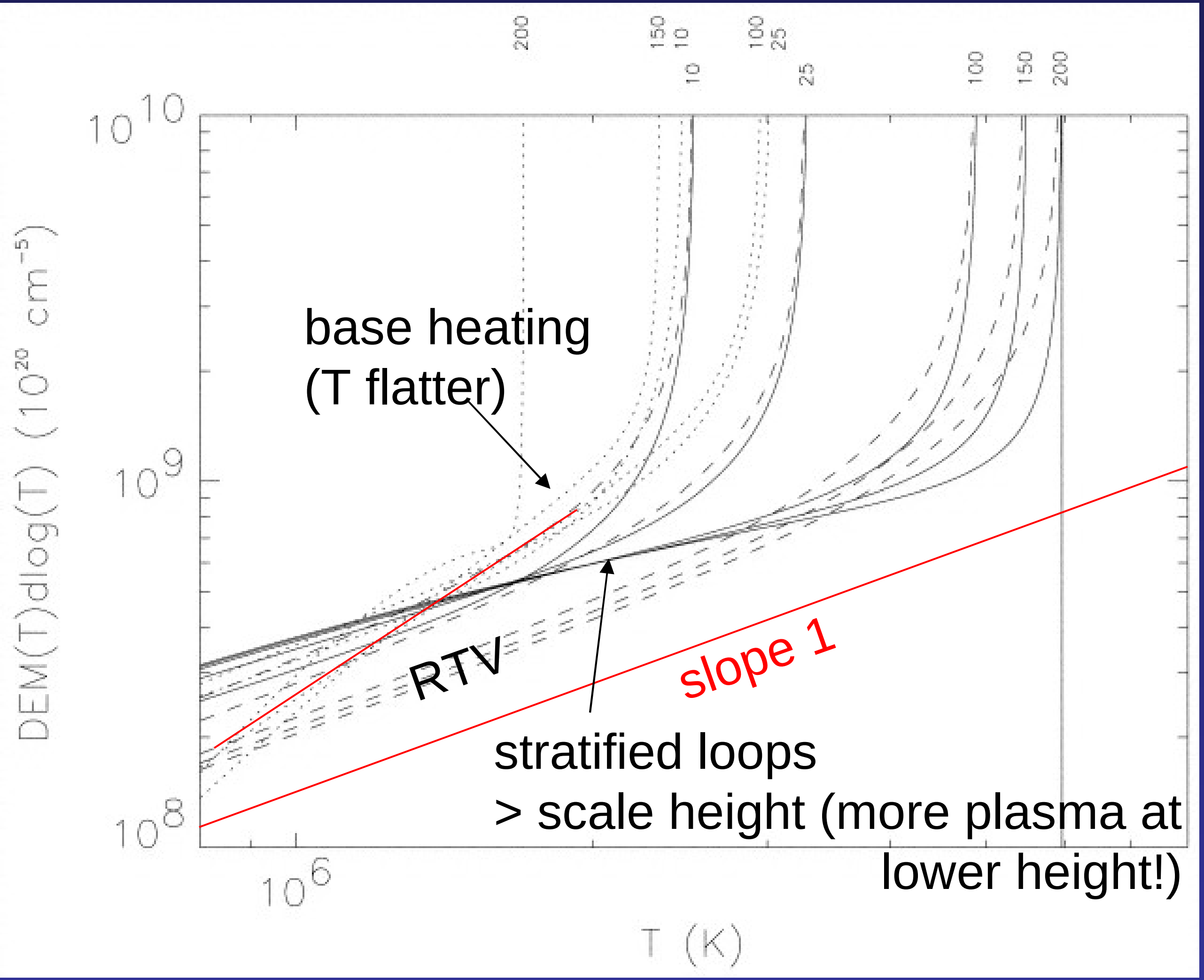
Verification for the solar corona: (Aschwanden et al. 2000, 2001)

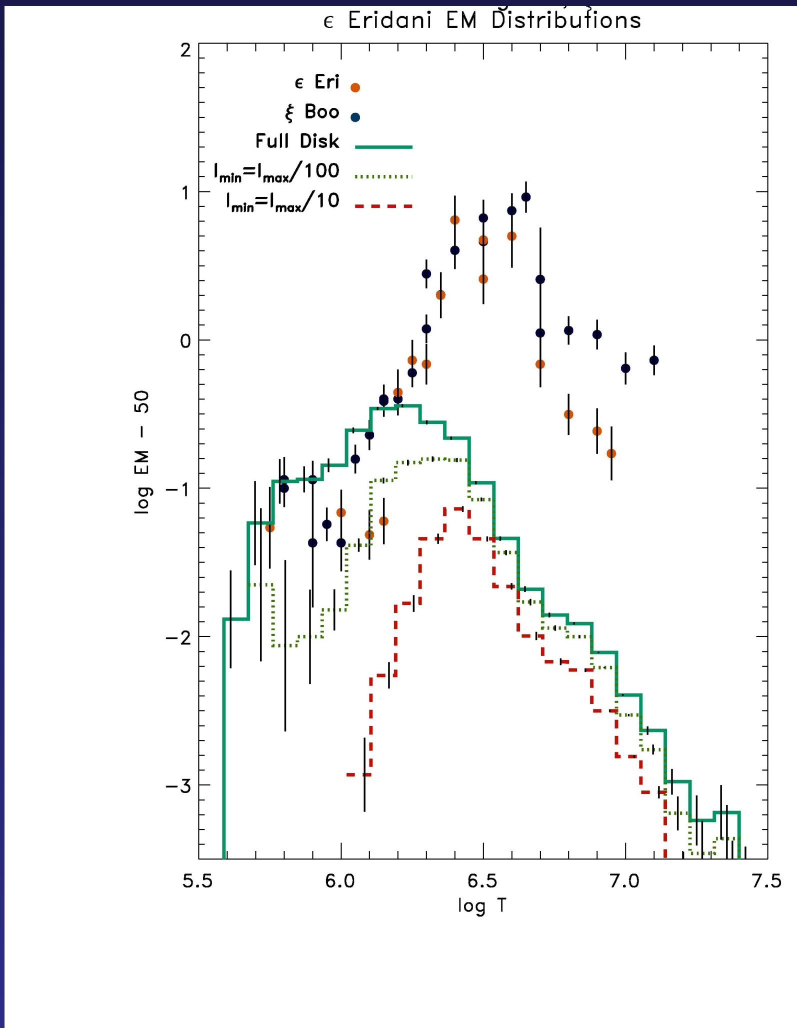
Many large loops show scale heights that are much larger than predicted by theoretical static models: *Mass inflow at footpoints?*



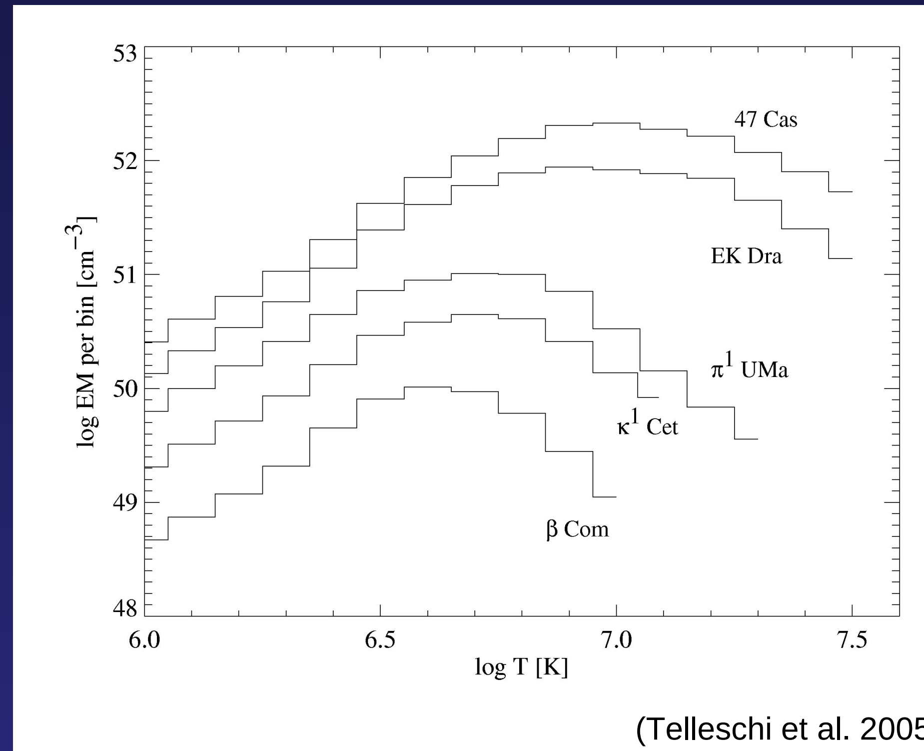
observed simulated for static conditions

DEMs of loops for uniform (RTV) and non-uniform heating , small (RTV) and large stratified loops (Schrijver & Aschwanden 2002)





(Drake et al. 2000)



(Telleschi et al. 2005)

Power-laws on each side of peak
Very steep on cool side

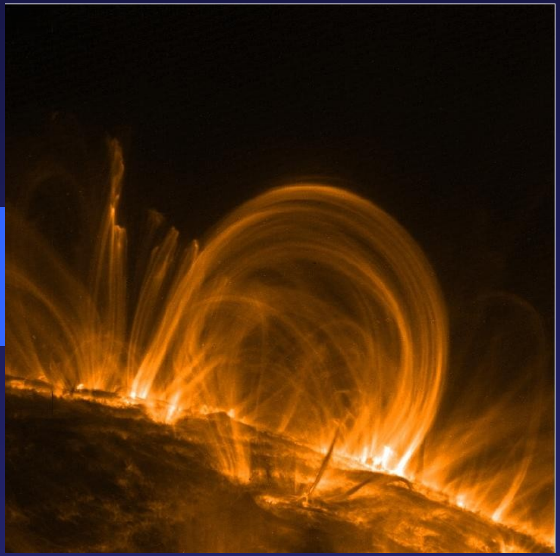
More active (luminous)
→ higher peak (average) temperature

Conclusions for the stellar astronomer:

- **Static loop** models to be used with **caution**
- In magnetically **active stars**, risk that static approach is inappropriate is even larger
- Need to consider **dynamic** heating models: stochastic (quasi-continuous) reconnection between adjacent fields? Microflaring?

More on this from the perspective of stellar coronal astronomy later

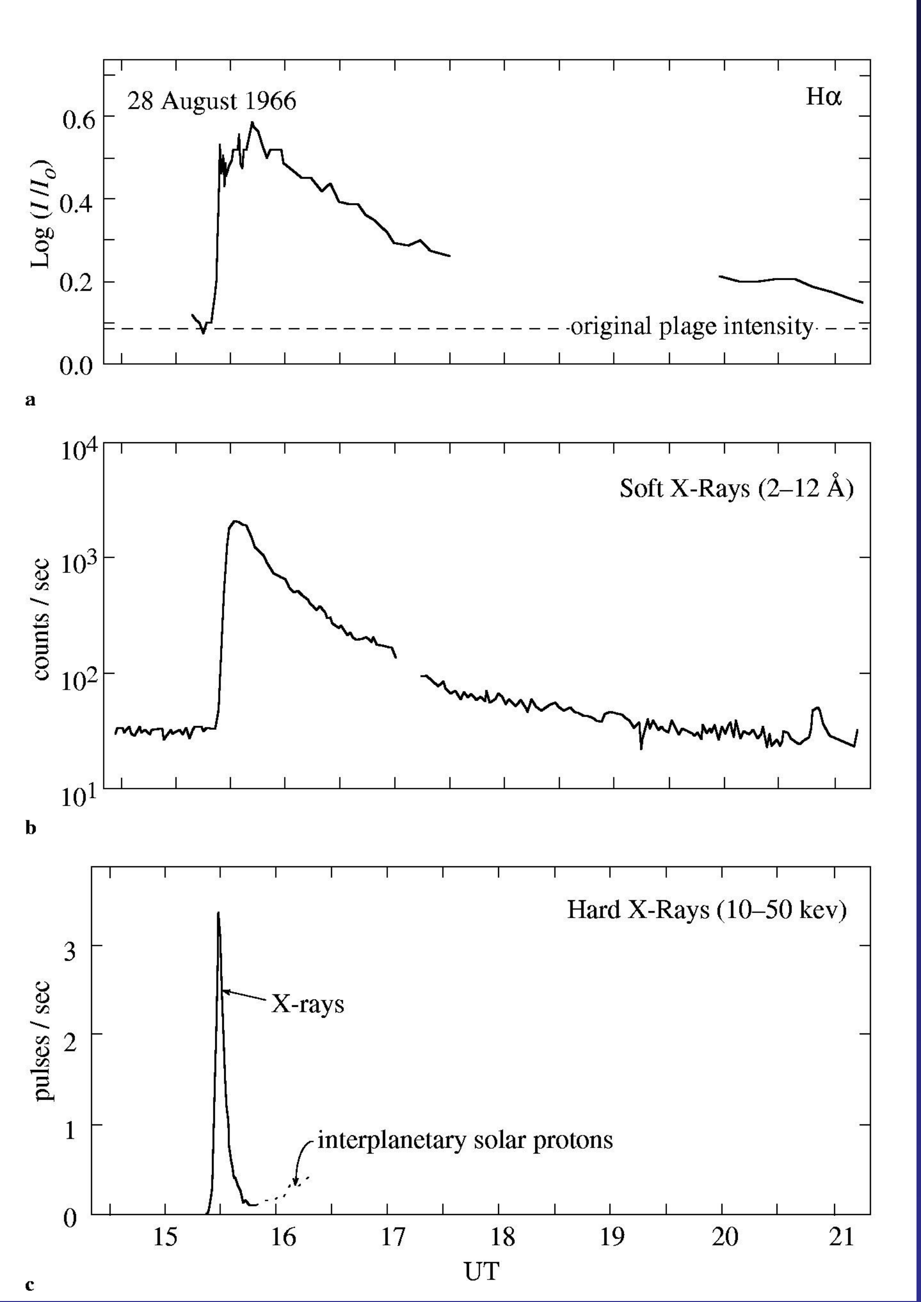
Coronal Flares



Explosive release of energy in a solar/stellar magnetic atmosphere,

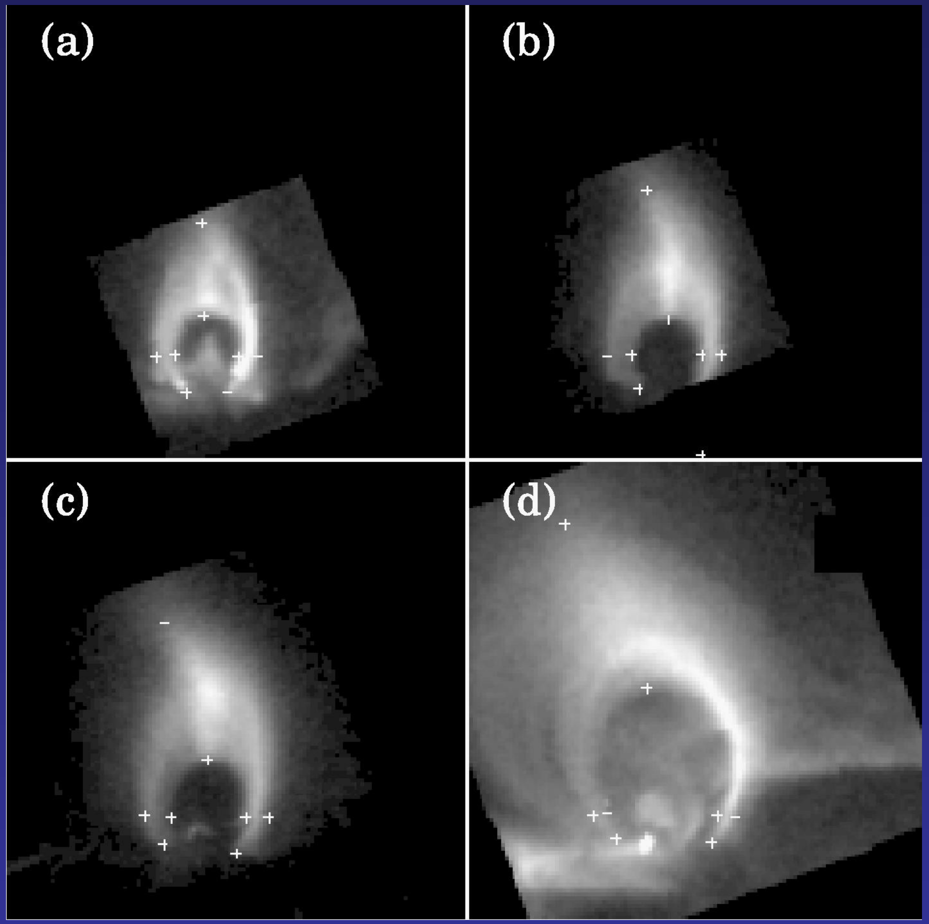
- seen at many wavelengths (radio, optical, UV, X-rays, gamma rays)
- affecting many layers of the atmosphere (photosph., chromosph., corona)
- accelerating and ejecting particles and mass packets into space

10^{32} erg on Sun, up to 10^{36} erg on stars
lasting from minutes to hours

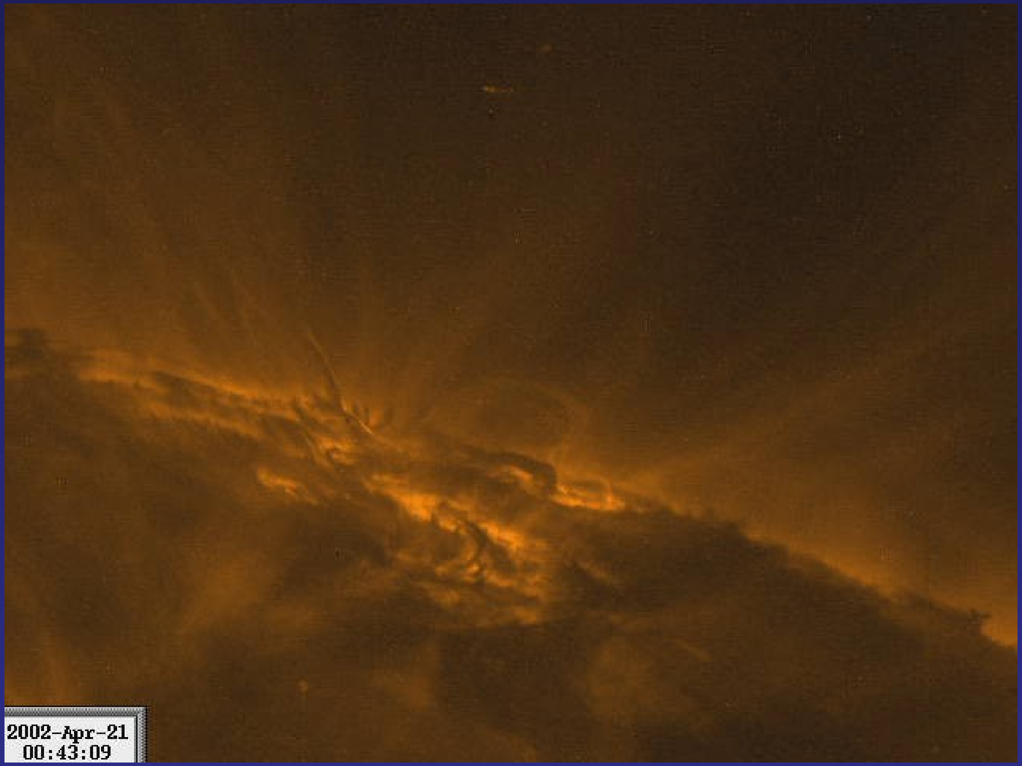


(Priest & Forbes 2000)

In X-rays, flares occur in closed magnetic systems that contain heated plasma.



(Forbes & Acton 1996)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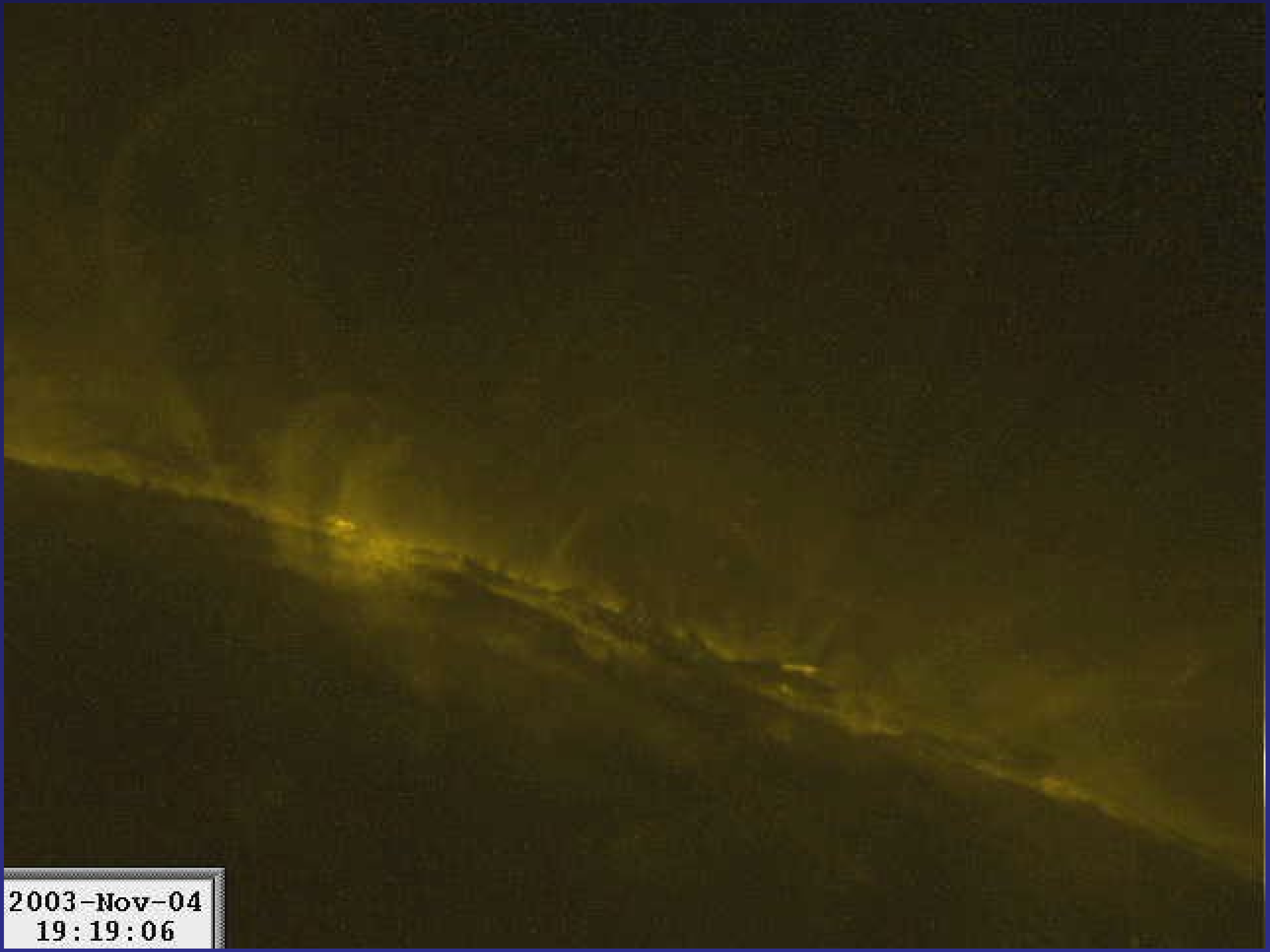
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Two major questions:

Why do flares occur?	Triggered release of stored energy
How do flares operate?	Heating of plasma, acceleration of particles

Magnetic Fields as Carriers of Energy: Reconnection

Maxwell's equations:

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

$$\nabla \times E = -\frac{1}{c}\frac{\partial B}{\partial t}$$

Ohm's law:

$$j = \sigma(E + \frac{1}{c} v \times B)$$

solve for B:

$$\frac{\partial B}{\partial t} = -c\nabla \times E$$

$$E = \frac{j}{\sigma} - \frac{1}{c} v \times B$$

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

$$\nabla \times (\nabla \times B) = \nabla(\nabla B) - \nabla^2 B$$

(see presentation by M. Tagger)

Magnetic Fields as Carriers of Energy: Reconnection

$$\frac{\partial B}{\partial t} = \nabla \times (v \times B) + \frac{c^2}{4\pi\sigma}\nabla^2 B$$

Induction equation

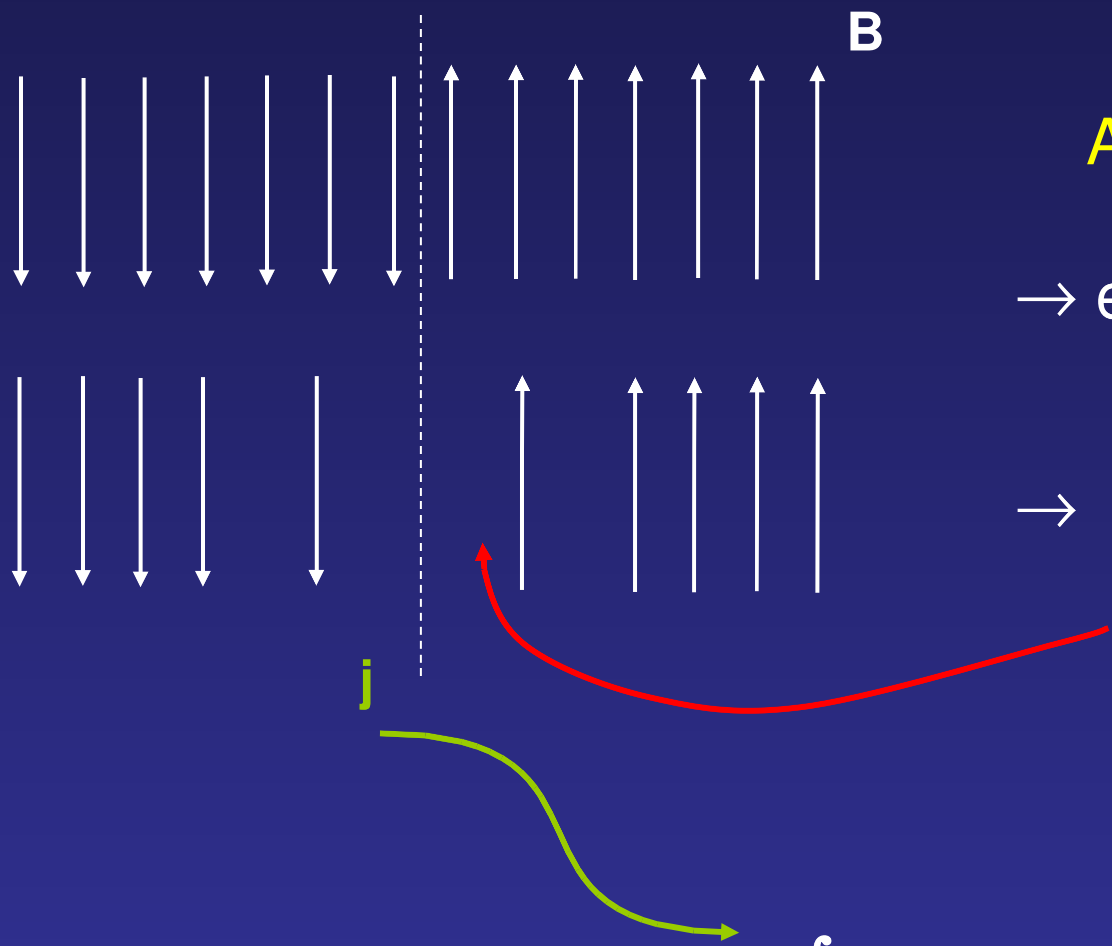
(1) Flow of matter (B frozen in plasma)

(2) Diffusion (finite σ)

Ratio (1)/(2): mag. Reynolds number (on large scales: 10^8 in solar flares)

Diffusion is mostly negligible across the Universe.
Exception: On short length scales!

Magnetic reconnection



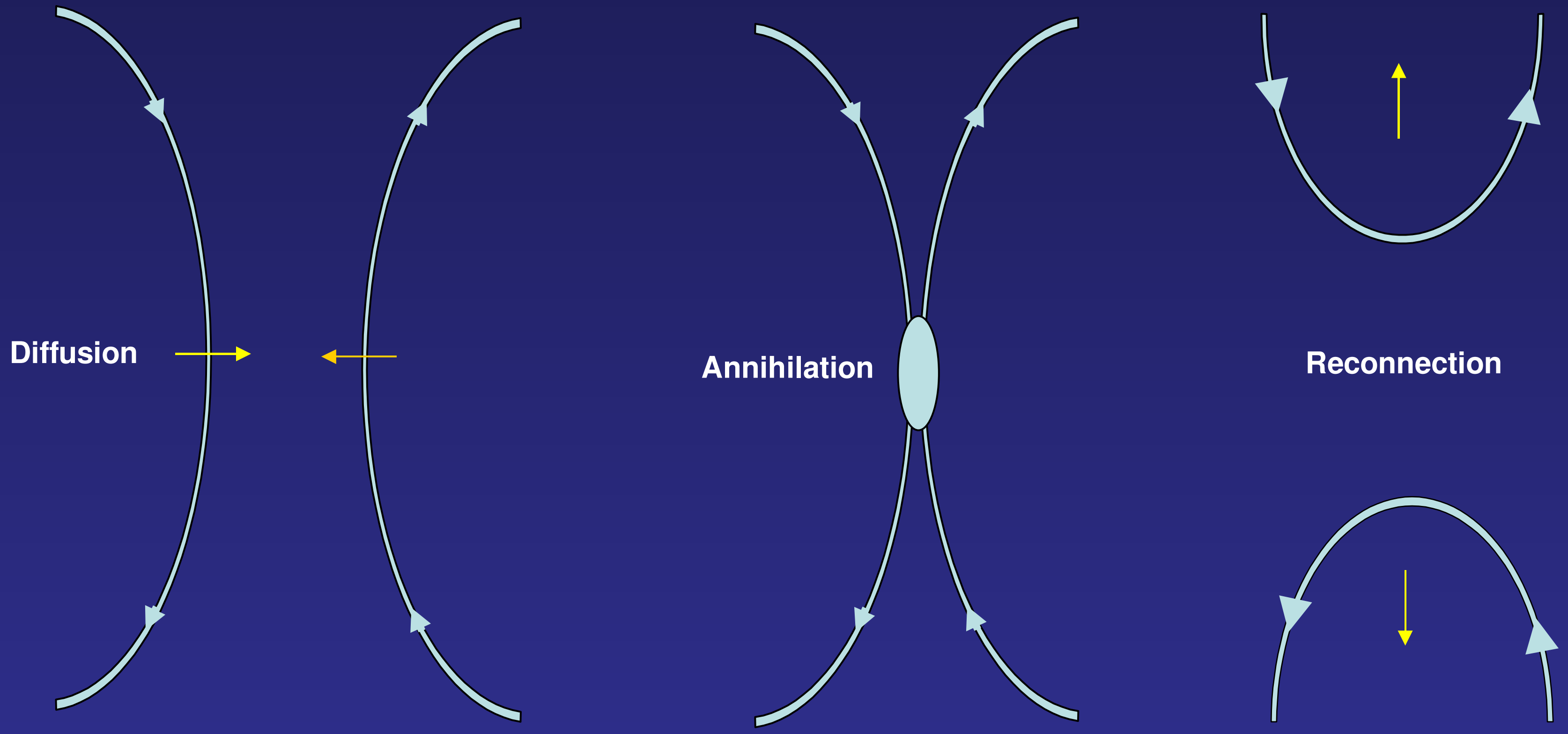
Annihilation of B

→ energy dissipation

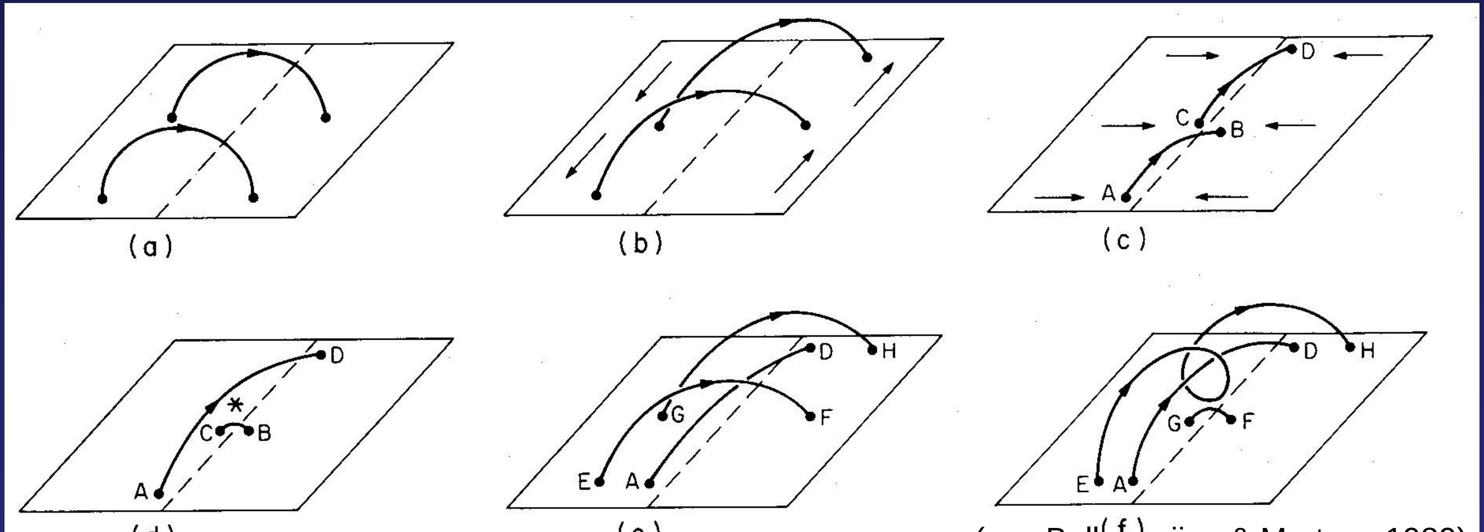
→ $\int B^2/8\pi \, dV$ drops

$\int j^2/\sigma \, dV$ Ohmic heating

Reconnection of Magnetic Fields

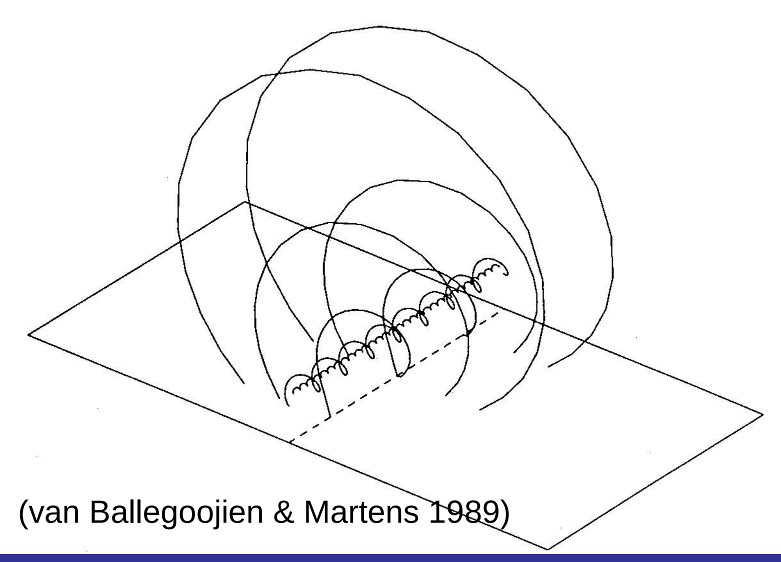


Active photosphere is in motion. Assume shear motion between two regions of opposite polarities:

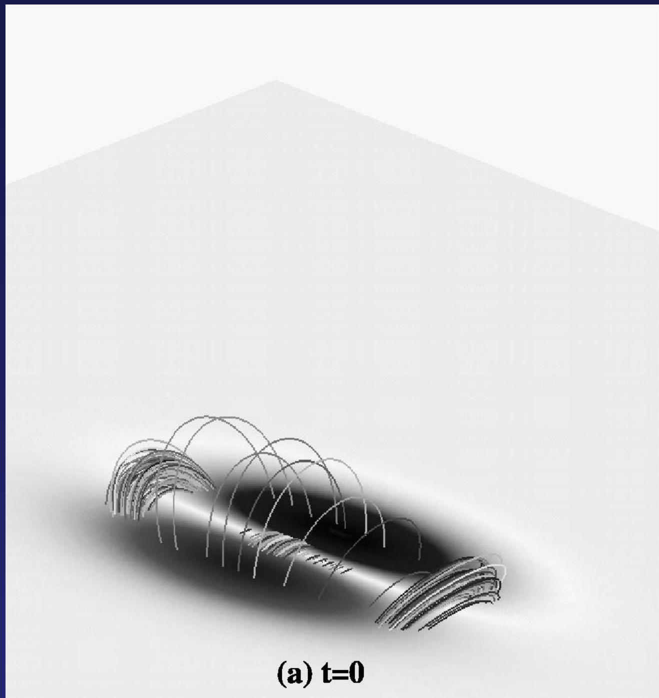


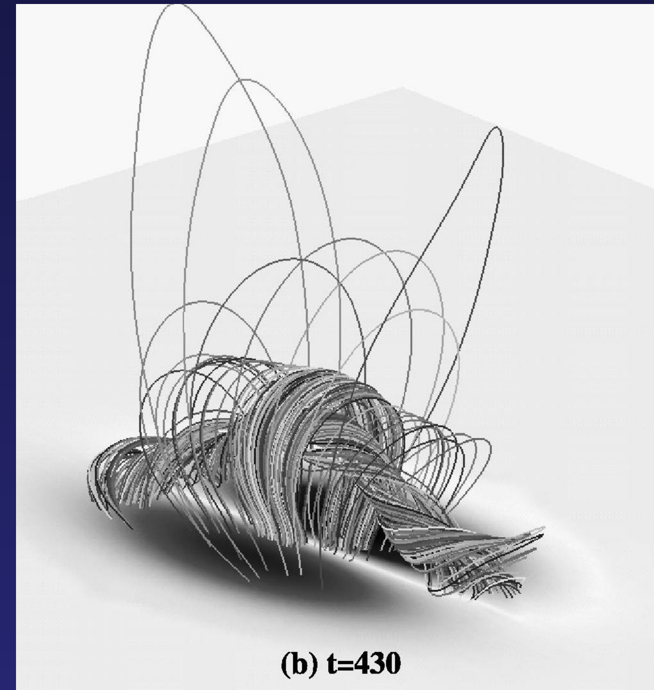
(van Ballegoojien & Martens 1989)

Sheared archade reconnects to form twisted flux rope within an overlying archade



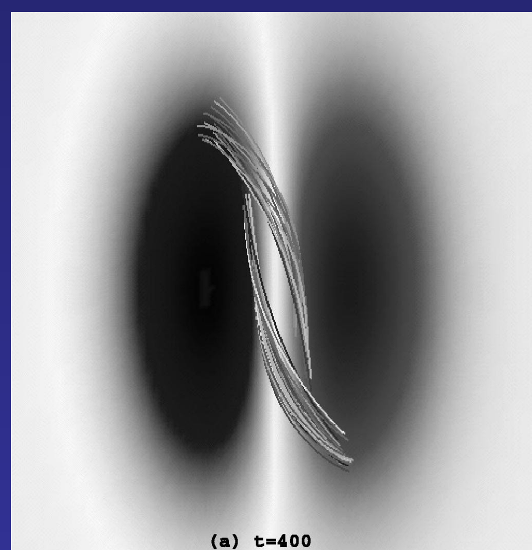
(van Ballegoojien & Martens 1989)

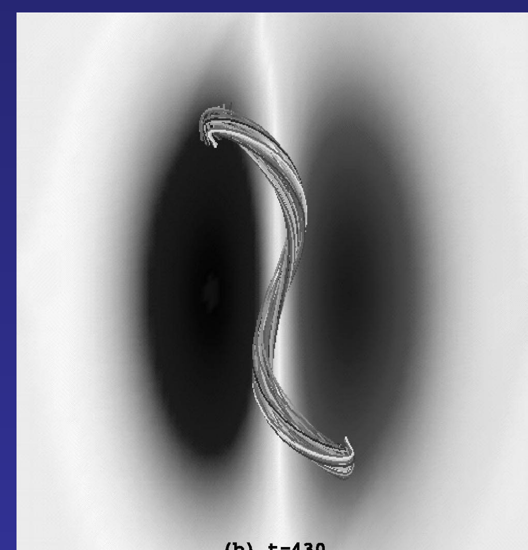


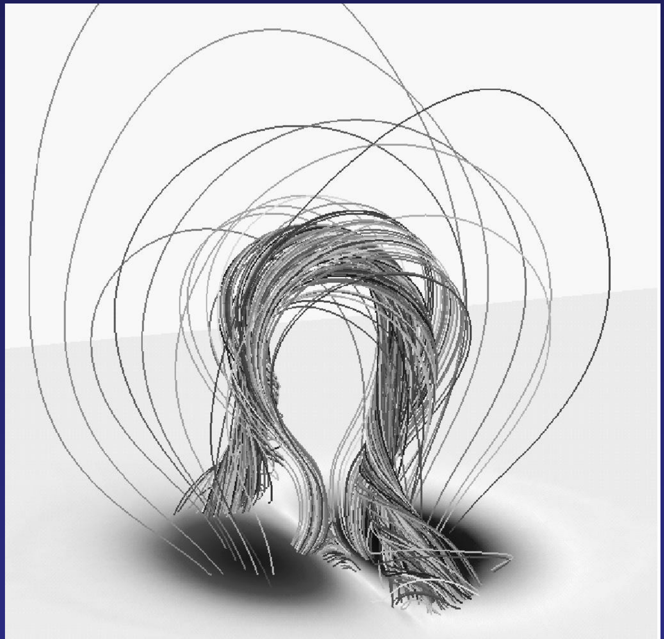


Sheared archade
$\rightarrow$ twisted rope

(Amari et al. 2000)







(a) t=450

(b) t=490

(Amari et al. 2000)

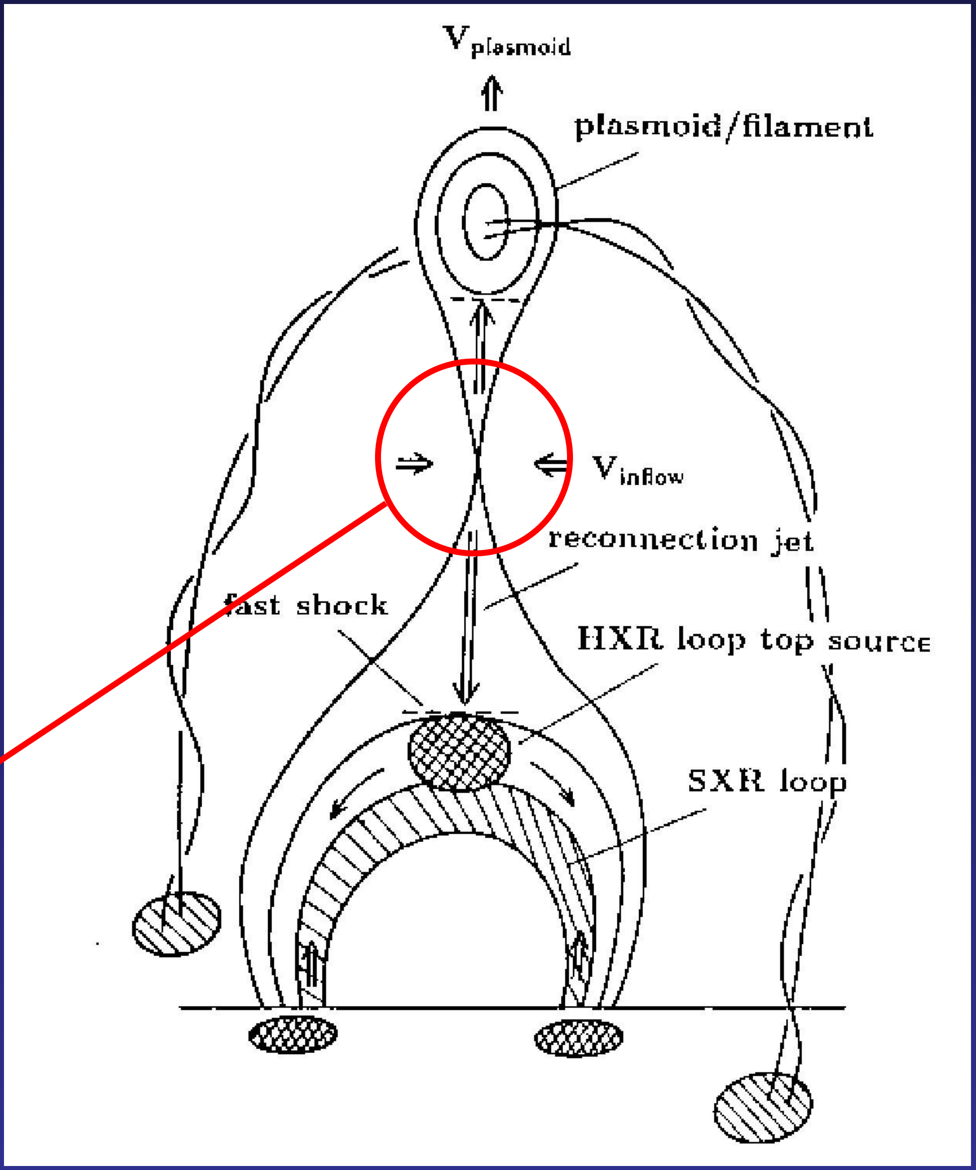
Unified flare model:

explains

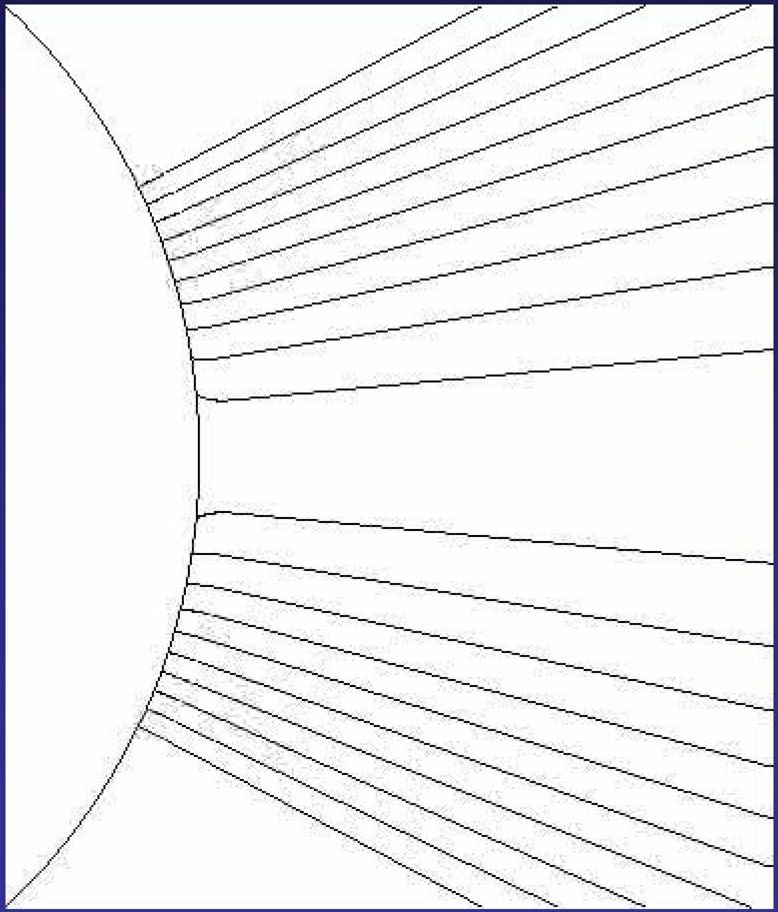
- filament eruption
- mass ejection
- flare proper

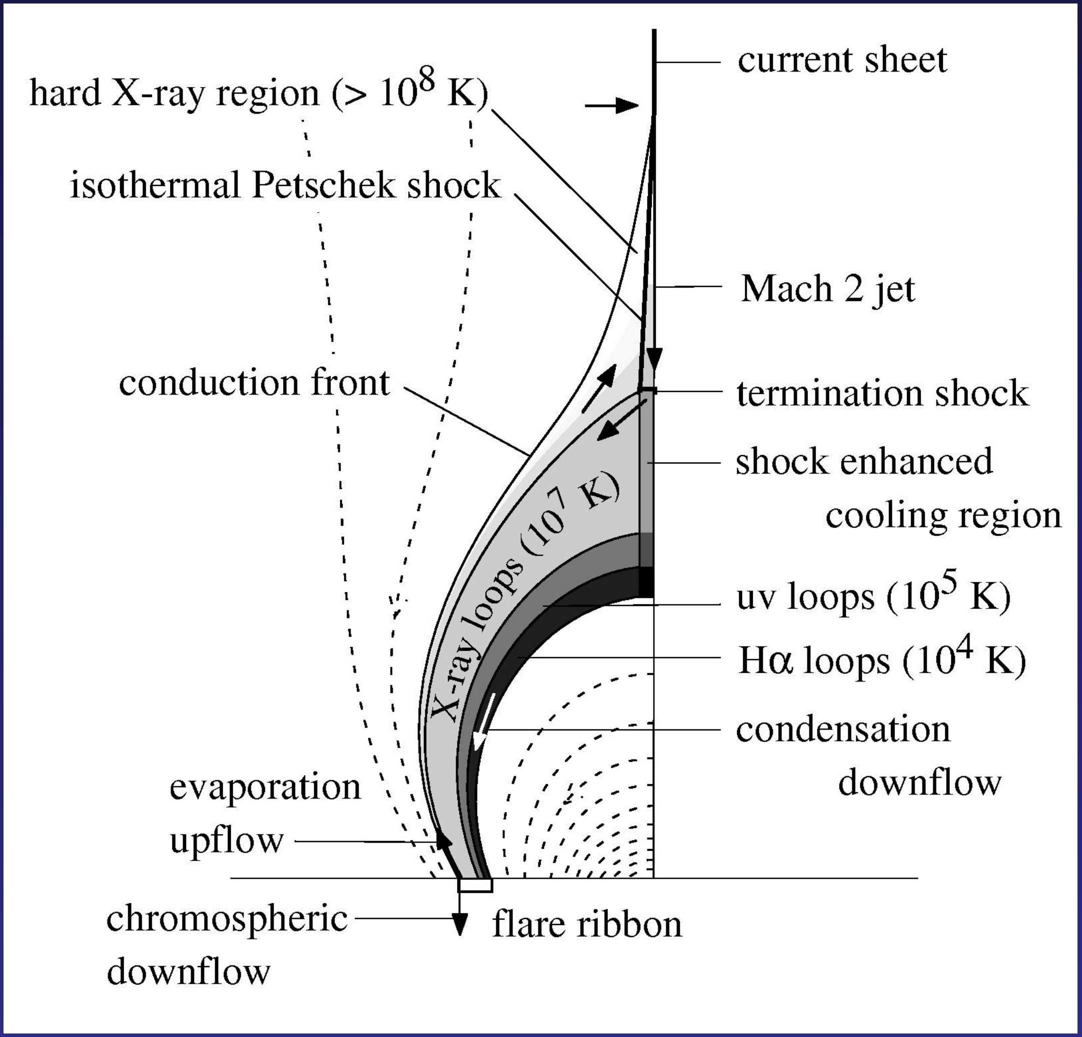
at once

place of action:
- *heating*
- *shock formation*
- *particle acceleration*



(Shibata 1999)





(Priest & Forbes 2002)

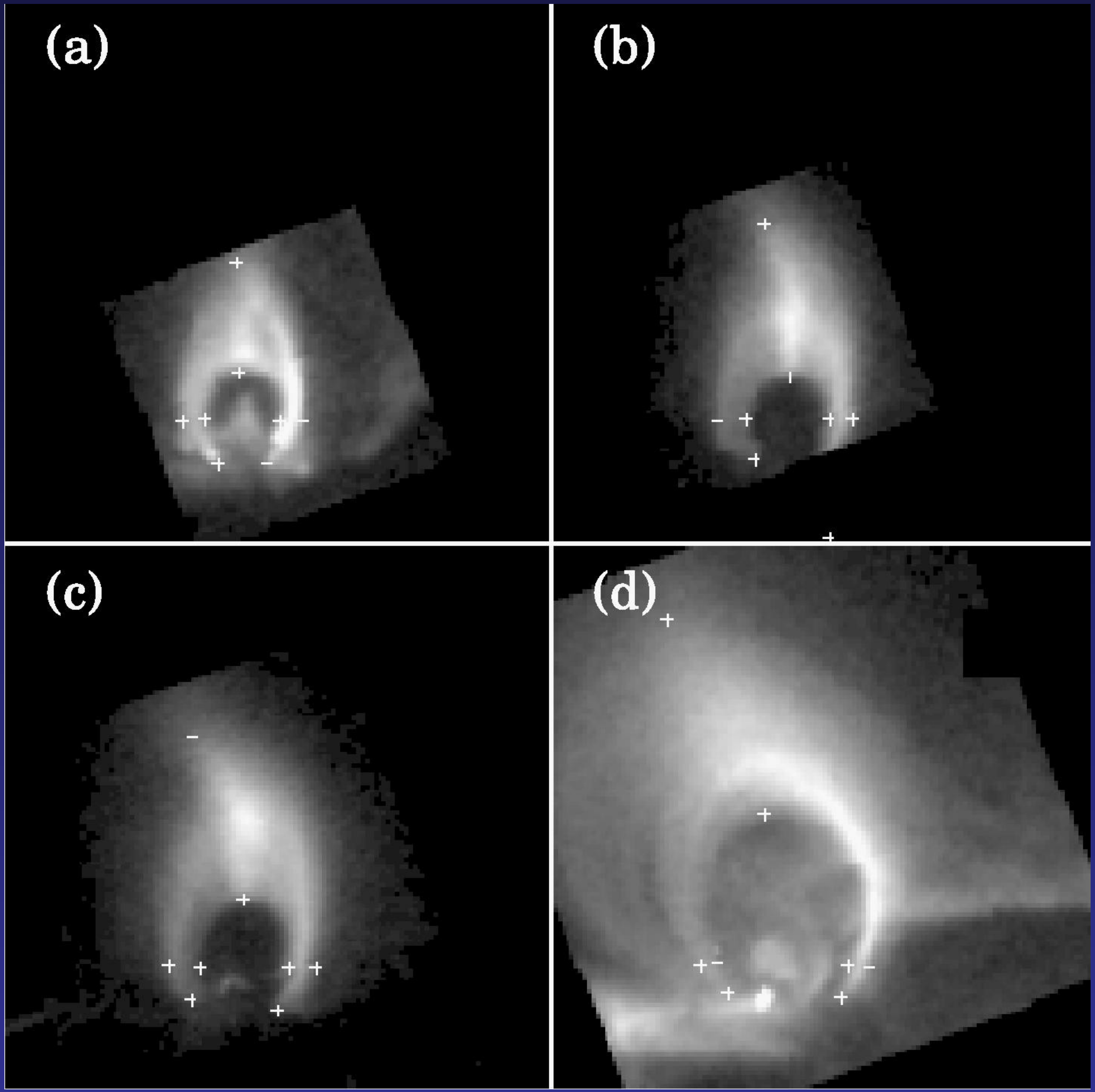
For the X-ray observer: closed magnetic loops heat up and evaporate chromospheric material:

X-ray bright loops

Uppermost, new loops:
X-rays

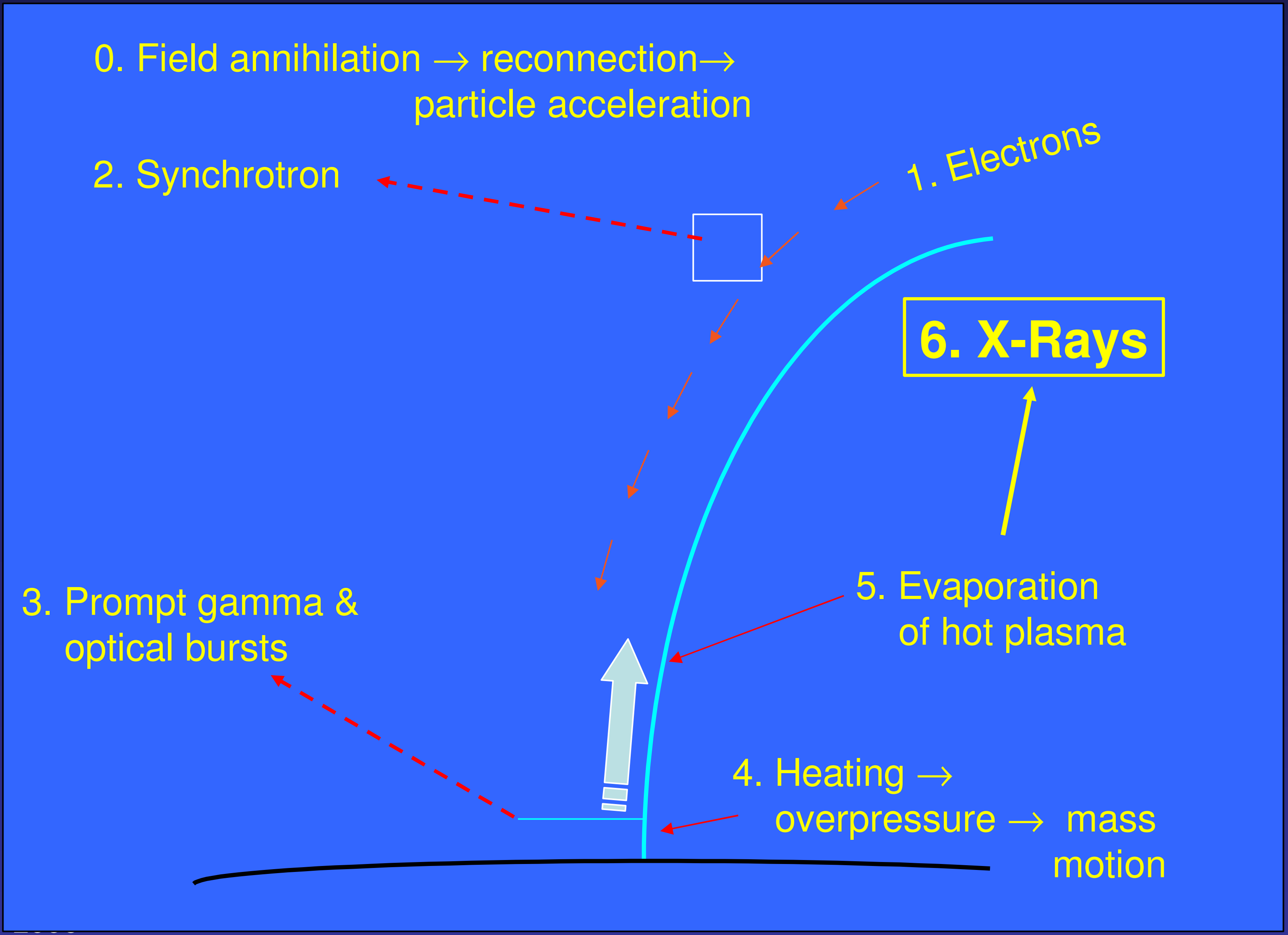
lower loops:
cooling, Hα

Growing X-ray arcade (Yohkoh)



(Forbes & Acton 1996)

Standard flare scenario after reconnection

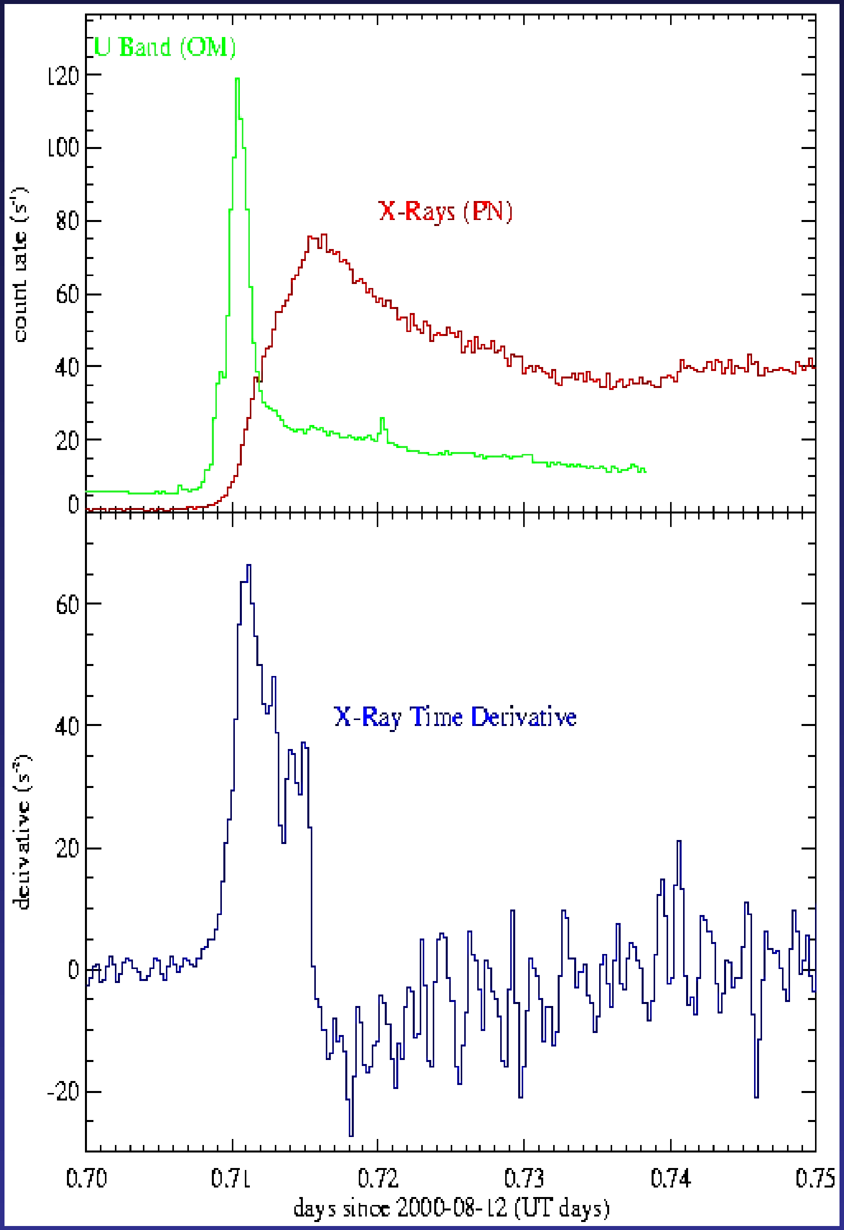


approximation: radiative loss time >> energy release time

$$\frac{d}{dt}(3n_e kTV) \quad \propto \quad \text{electron flux} \quad \propto \quad L_R$$

$$\frac{d}{dt}L_X \quad \propto \quad L_R$$

(the proportionality between thermal energy content and radiative loss is a crude approximation)



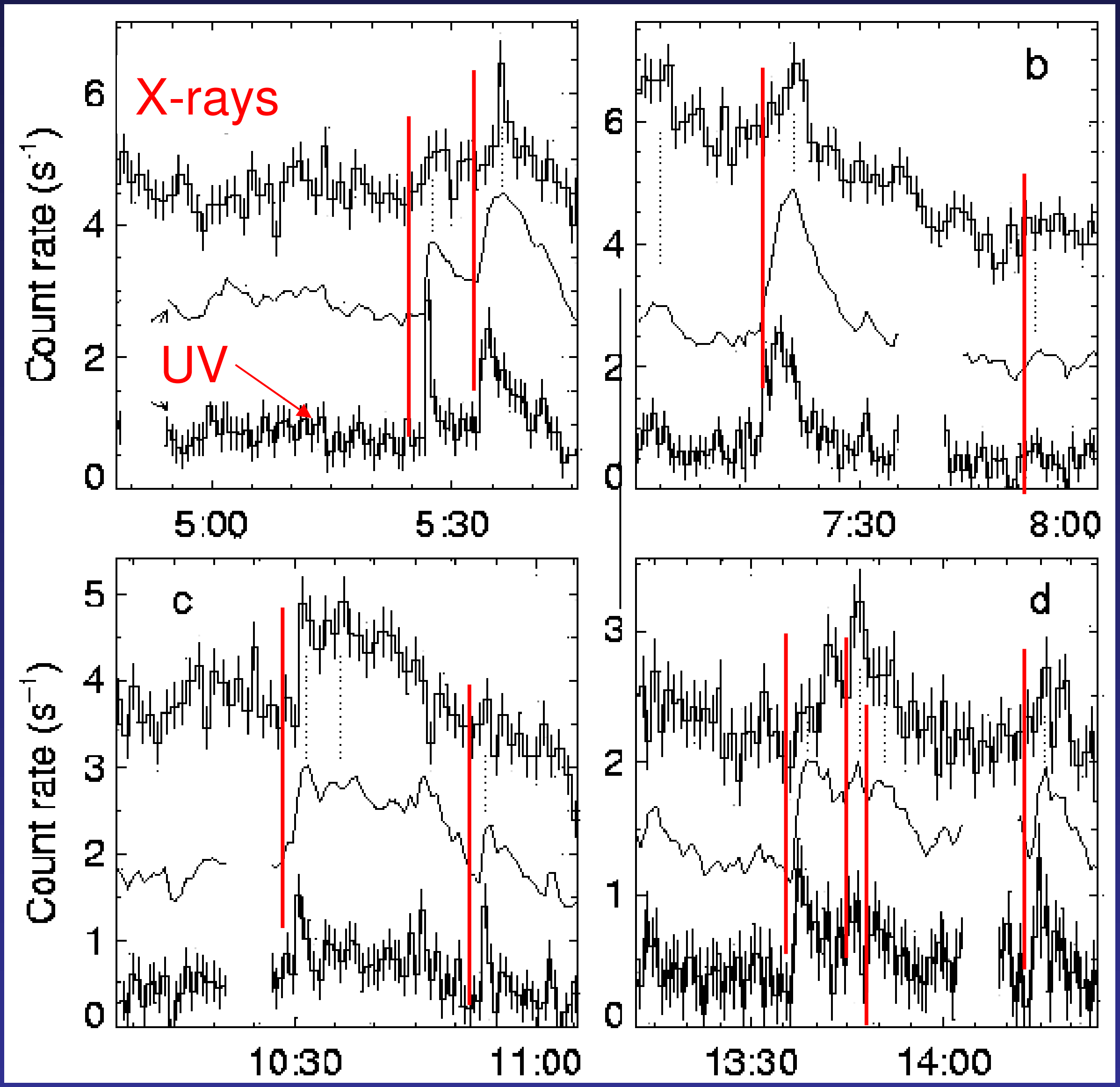
(Güdel et al. 2002)

Same for optical bursts:

"Neupert Effect"

Continuous Flaring

Smallest stellar flares seen in X-rays



(Güdel et al. 2002)

Stochastic Heating

Tangential discontinuities owing to footpoint motion

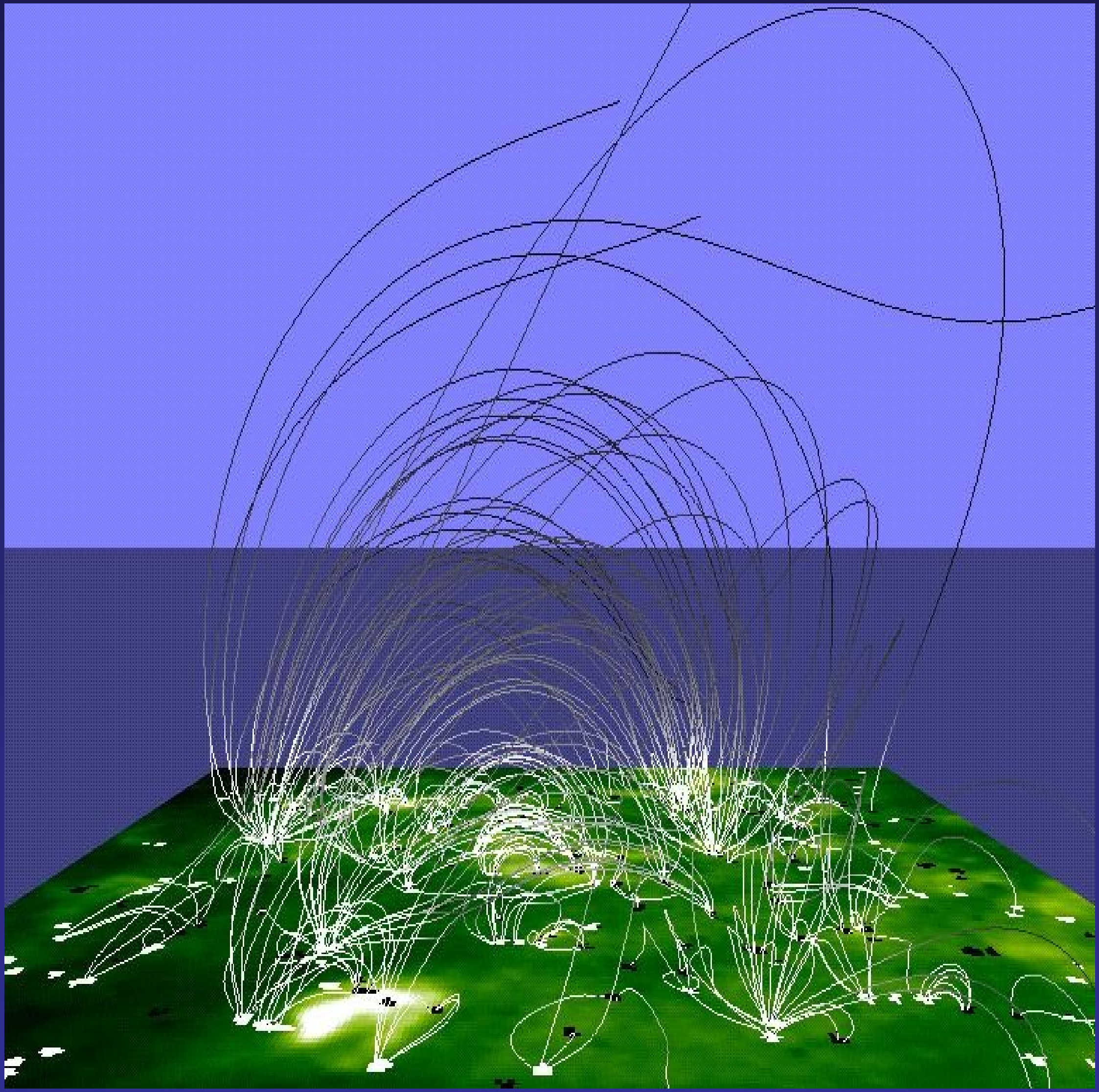
↓

current sheets, reconnection

↓

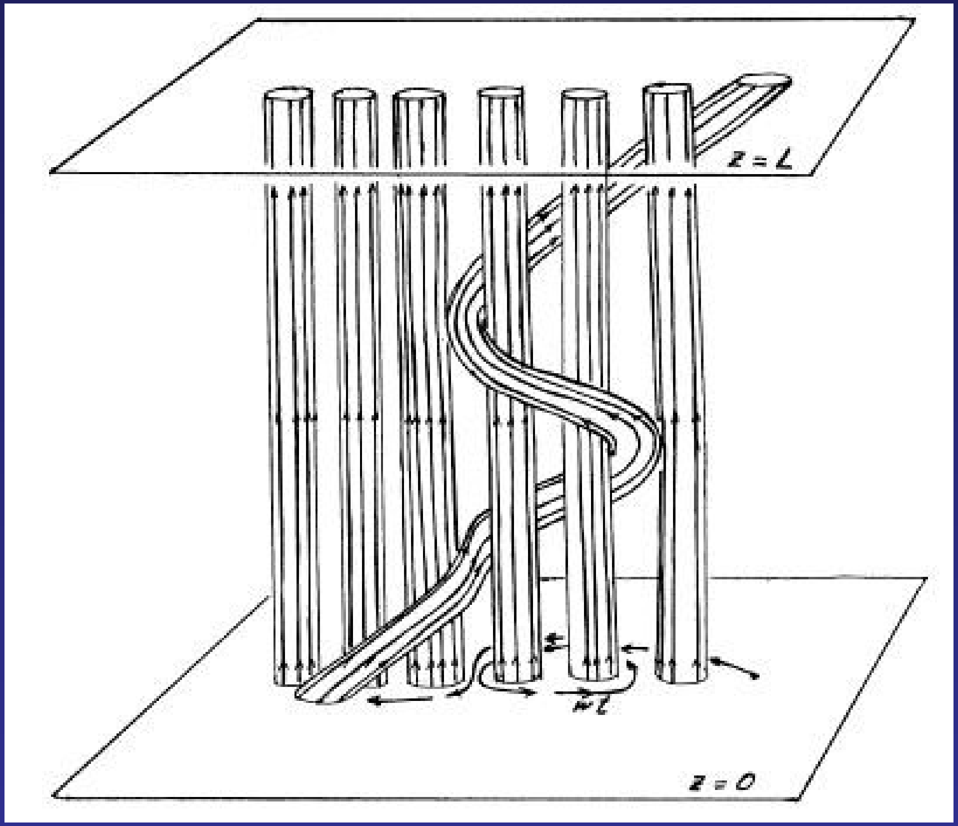
Stochastic energy release

(Parker 1988)



Conclusions for heating:

Tangled magnetic fields in random walk driven by footpoint motion produce current sheets in which magnetic fields reconnect:



Energy release of order $10^{24} – 10^{27}$ erg over 100 sec

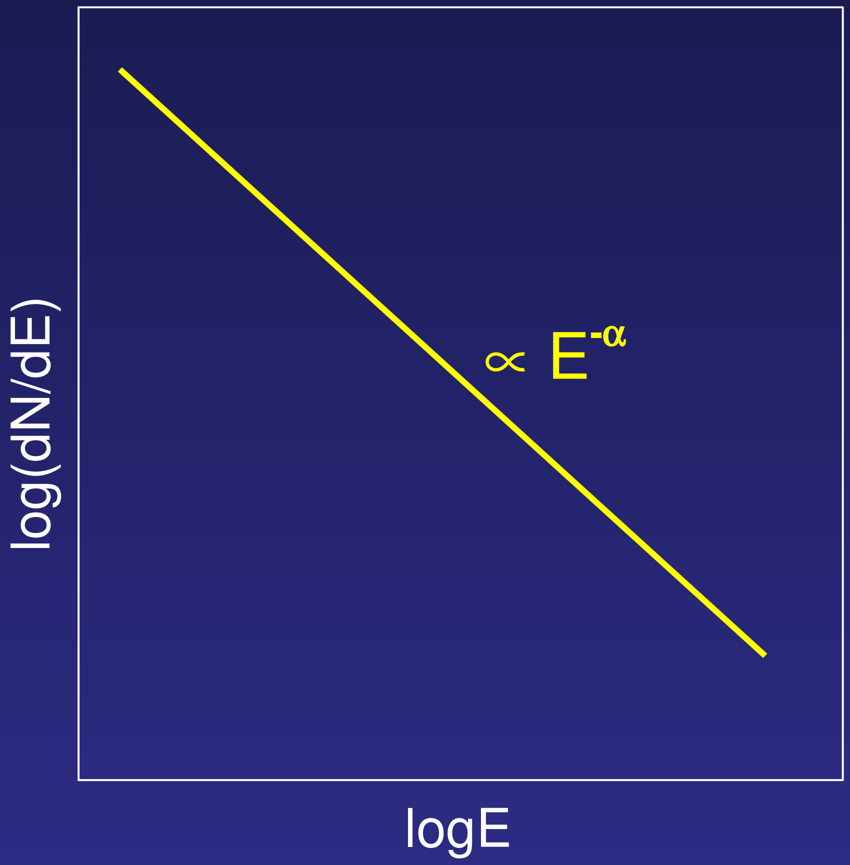
(Parker 1983)

FLARE ENERY DISTRIBUTIONS

$dN/dE \propto E^{-\alpha}$

$L_X \propto \int_{E1}^{E2} E \, dN/dE \, dE$

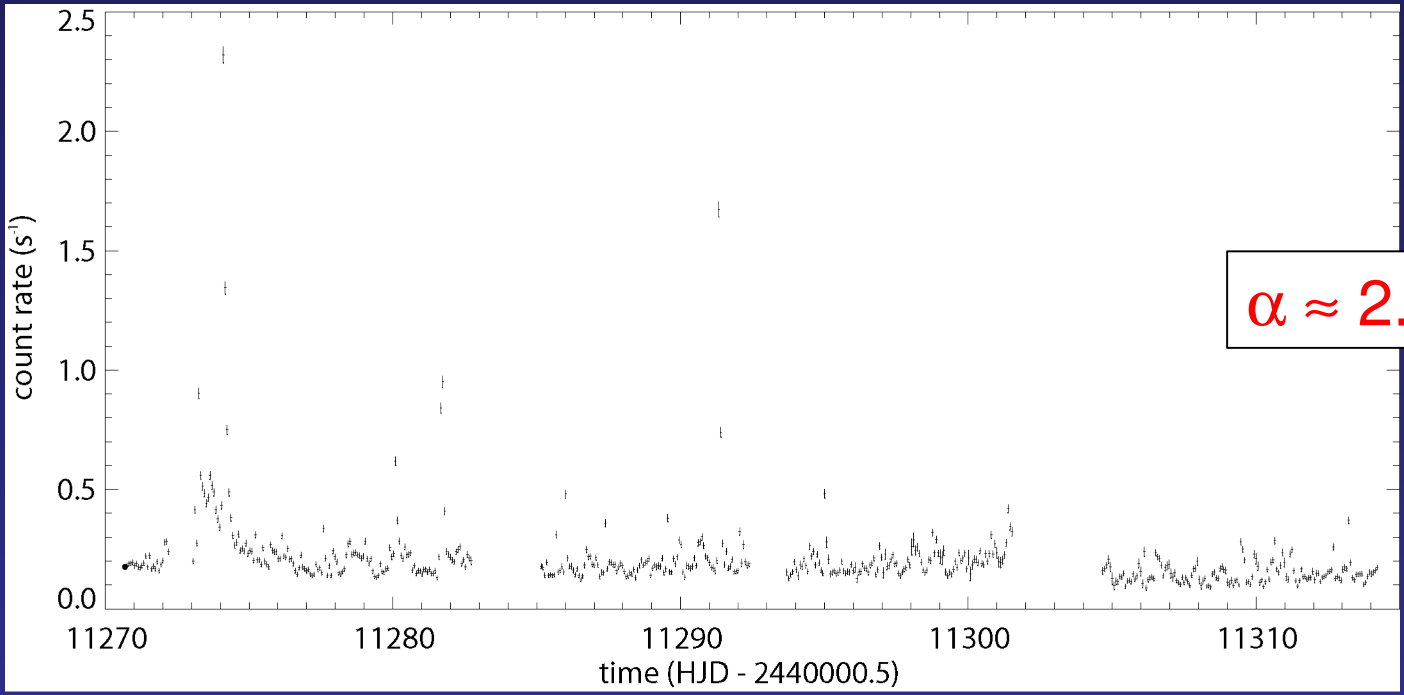
$\alpha \geq 2$: divergence for
$E1 \rightarrow 0$
("microflares")



In that case, all of the observed (quasi-steady) emission may be due to the superposition of small flares

Statistical tests of light curves show that
$dN/dE \propto E^{-\alpha}$ implies $\alpha > 2$

(Audard et al. 1999, 2000, Güdel et al. 2003, Kashyap et al. 2002, Arzner & Güdel 2004)



$\alpha \approx 2.1\text{-}2.3$

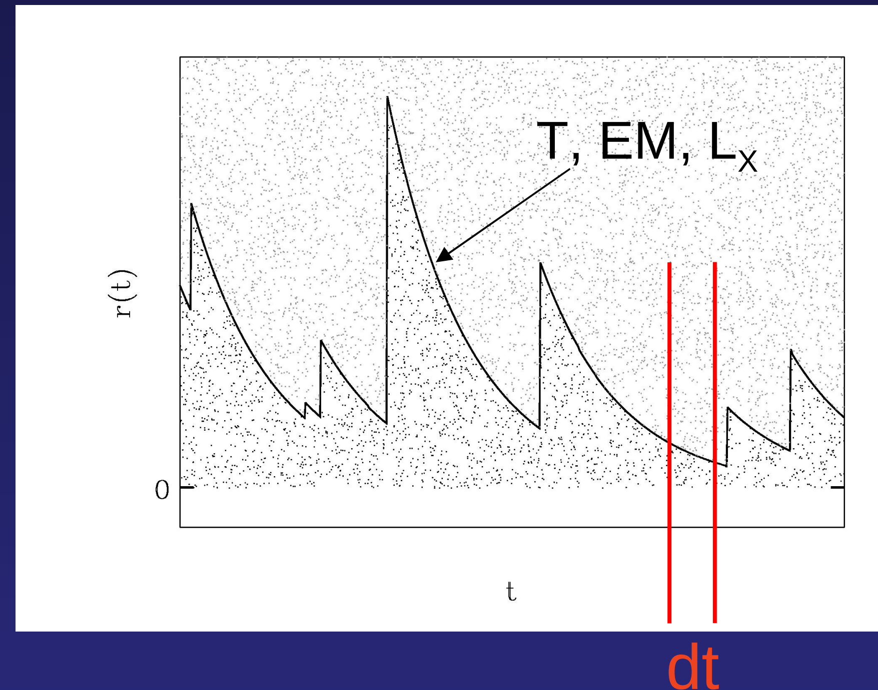
44 days

(Güdel et al. 2003)

Flares distributed in energy:

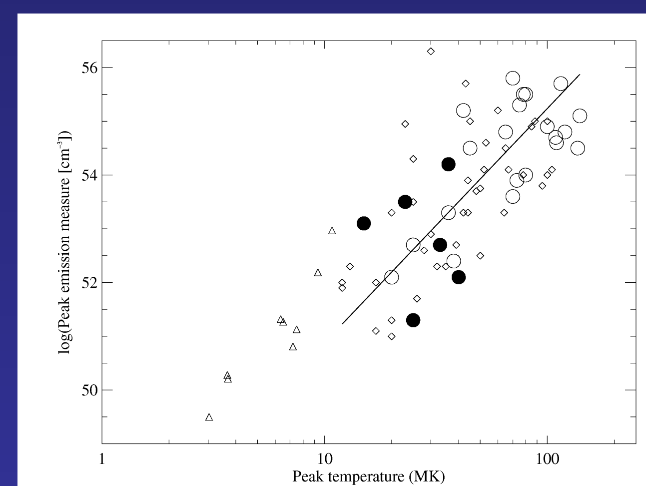
$$dN/dE = E^{-\alpha}$$

Each flare decays <u>exponentially</u> in T, EM, L_X:



The peak T and EMs correlate:

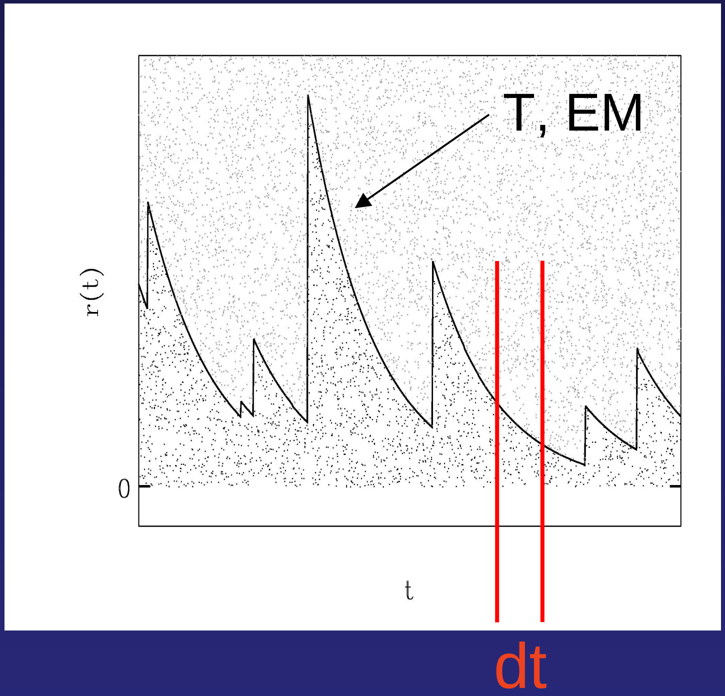
$$\mathrm{EM}_0 = aT_0^b \quad [\mathrm{cm}^{-3}]$$ (b = 4.3)



T and n_e decay like $$T \propto n^{\zeta} \qquad \zeta \approx 0.5 - 2$$

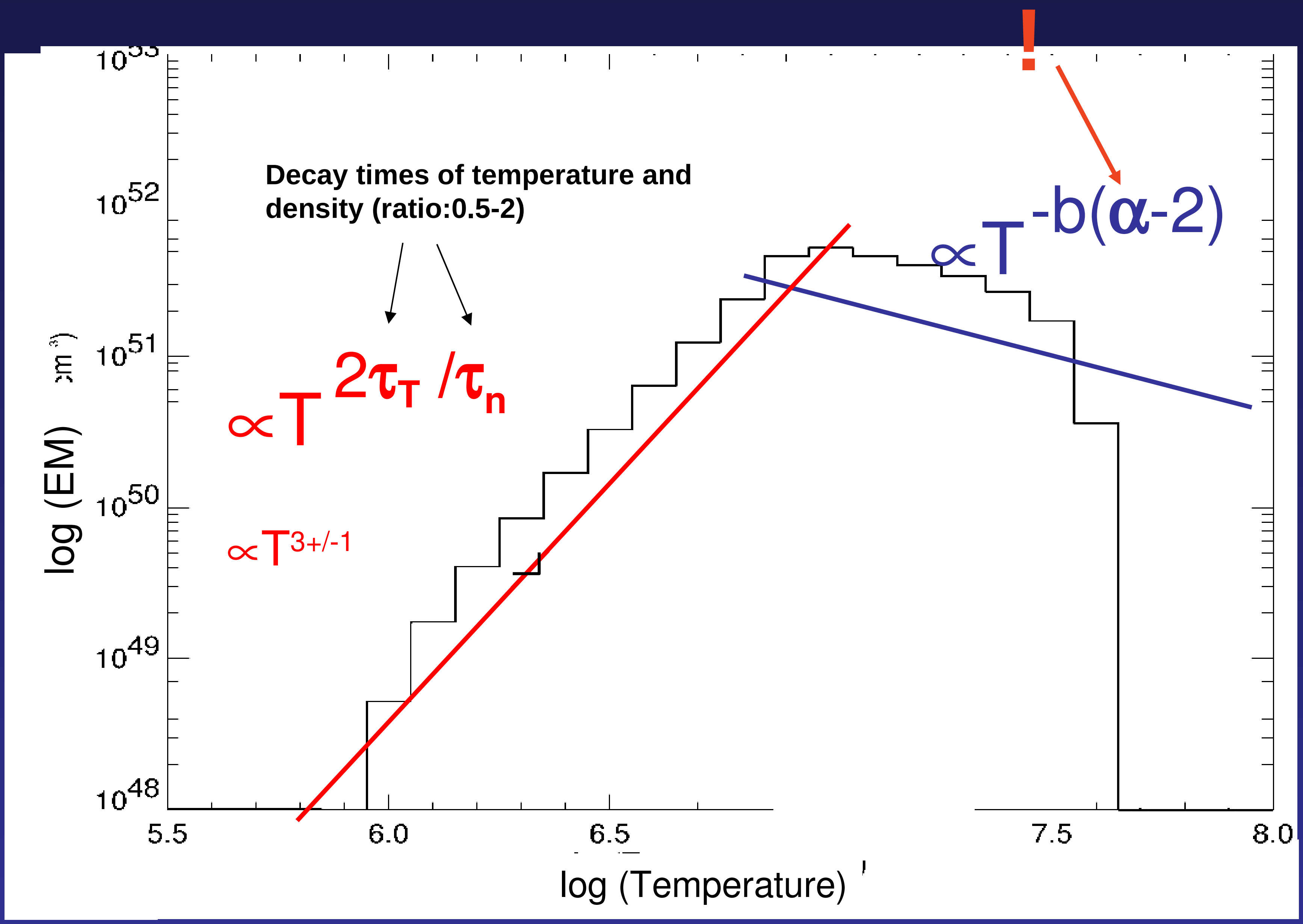
Radiation $$L_X \approx \mathrm{EM}\,\Lambda(T) = f\ \mathrm{EM}\ T^{-\phi}$$

and integrate over flare evolution and the distribution of flares

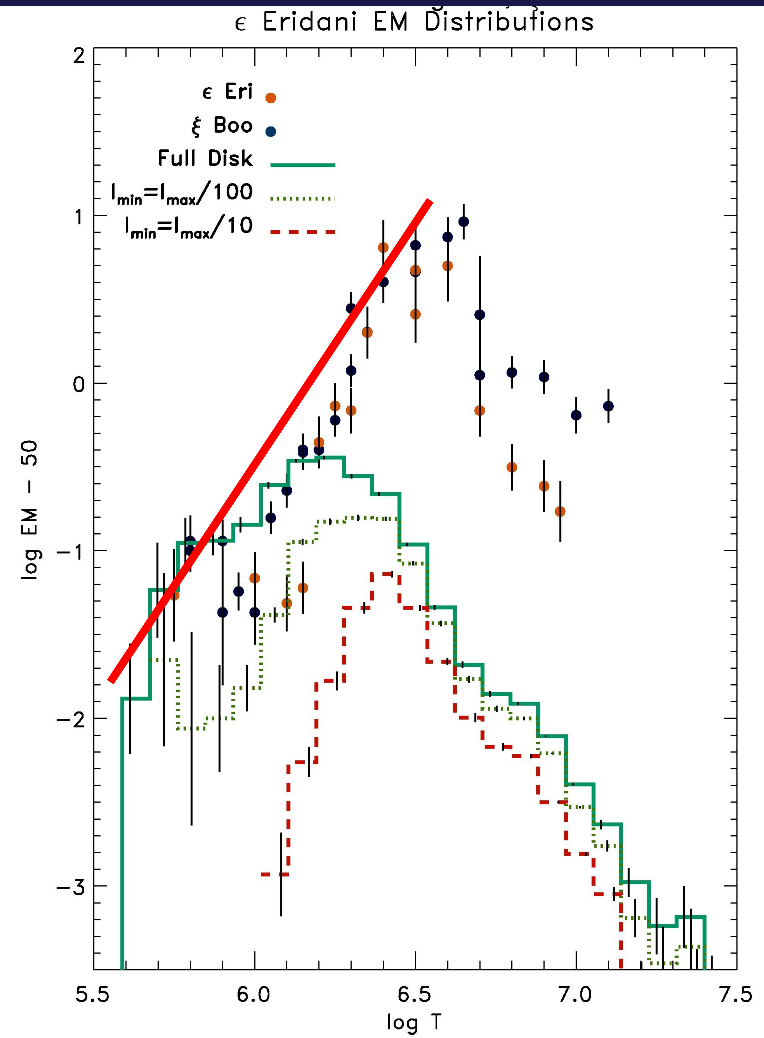


$$Q(T) \propto \begin{cases} T^{2/\zeta} & \text{for} \quad T < T_m \\ T^{-(b-\phi)(\alpha-2\beta)/(1-\beta)+2b-\phi} & \text{for} \quad T > T_m \end{cases}$$

(Güdel et al. 2003)



!
Decay times of temperature and
density (ratio:0.5-2)
$\propto T^{2\tau_T / \tau_n}$
$\propto T^{-b(\alpha-2)}$
$\propto T^{3+/-1}$
log (EM)
log (Temperature)
10^53
10^52
10^51
10^50
10^49
10^48
5.5
6.0
6.5
7.5
8.0



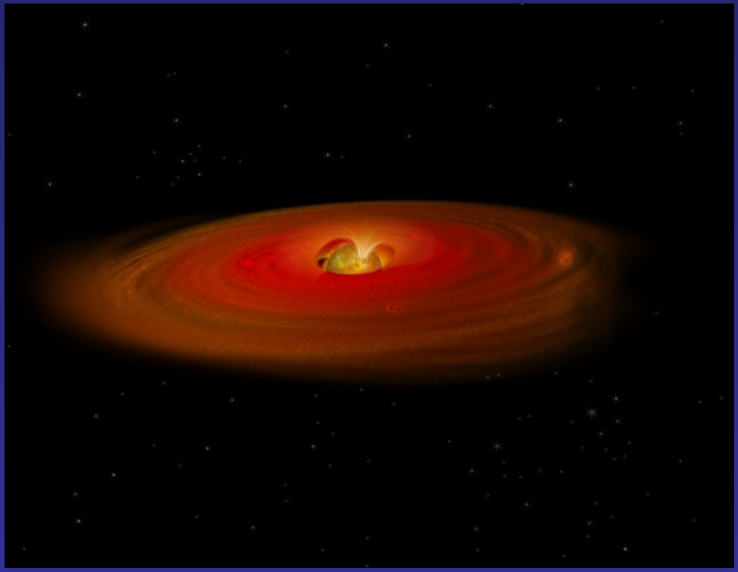
(Drake et al. 2000)

Power-law DEMs measured in stellar coronae are steep on low-T side (slopes of 2-4)

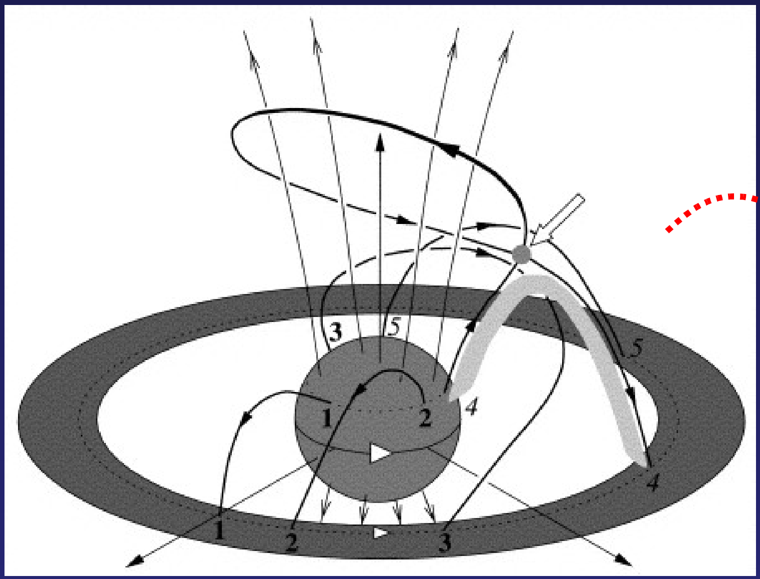
Toward Pre-Main Sequence Stars

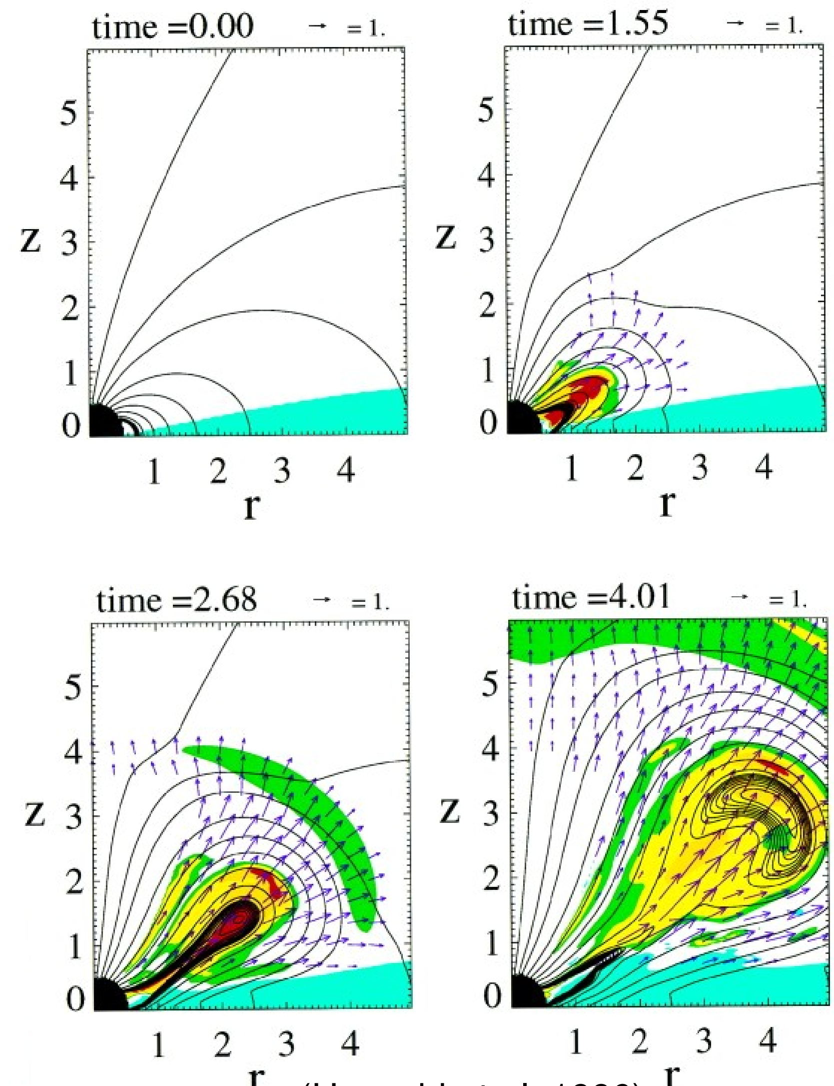
Low-mass stars < 10 Myr:
Accretion disks/flows, winds, jets, outflows, molecular clouds may matter

Classical T Tau stars: active accretion from disk, microjets



Reconnection, Heating, and Jet Formation





(Hayashi et al. 1996)

Wind-up of magnetic field lines (Montmerle et al. 2000):

→ Antiparallel magnetic fields
→ Heating and reconnection
→ Ejection of hot plasma clouds
→ Jets? Outflow due to accretion

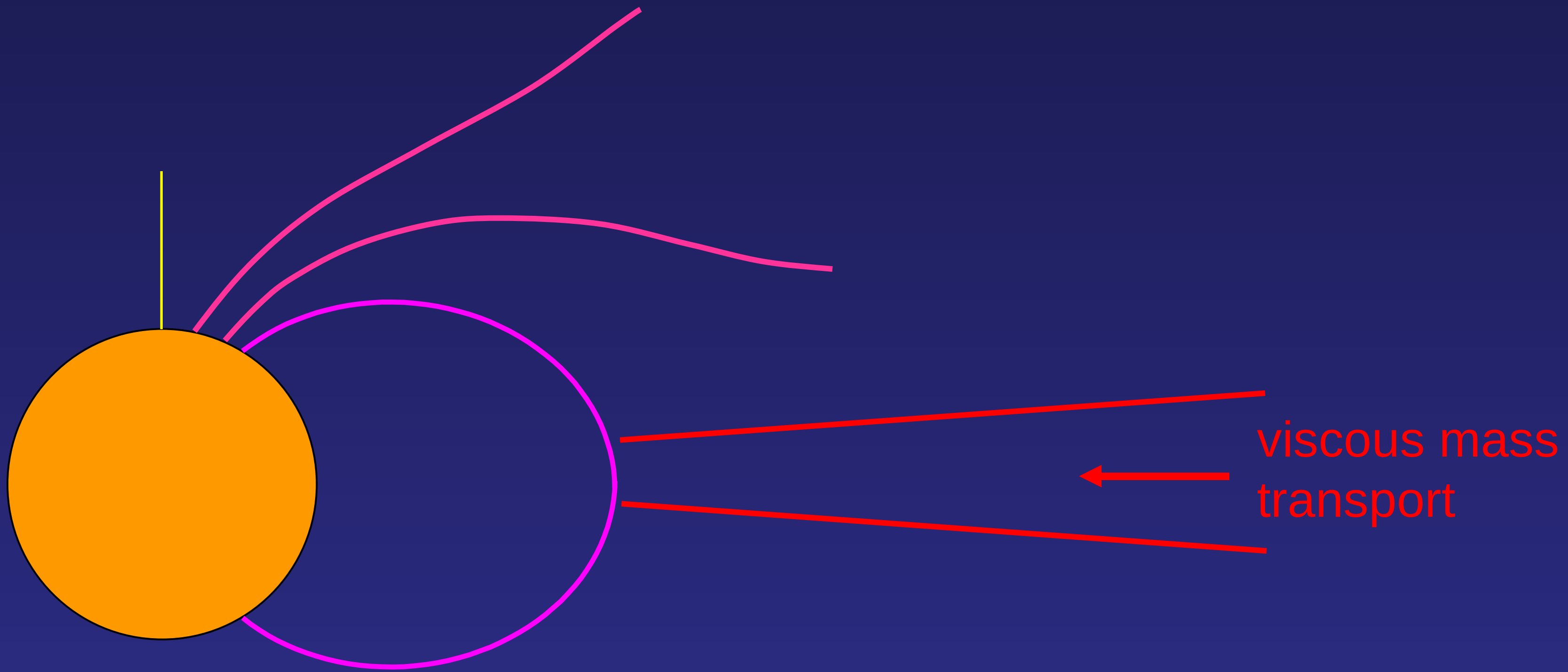
Plasmoid ejection may be the origin of jets:

typical outflow velocities

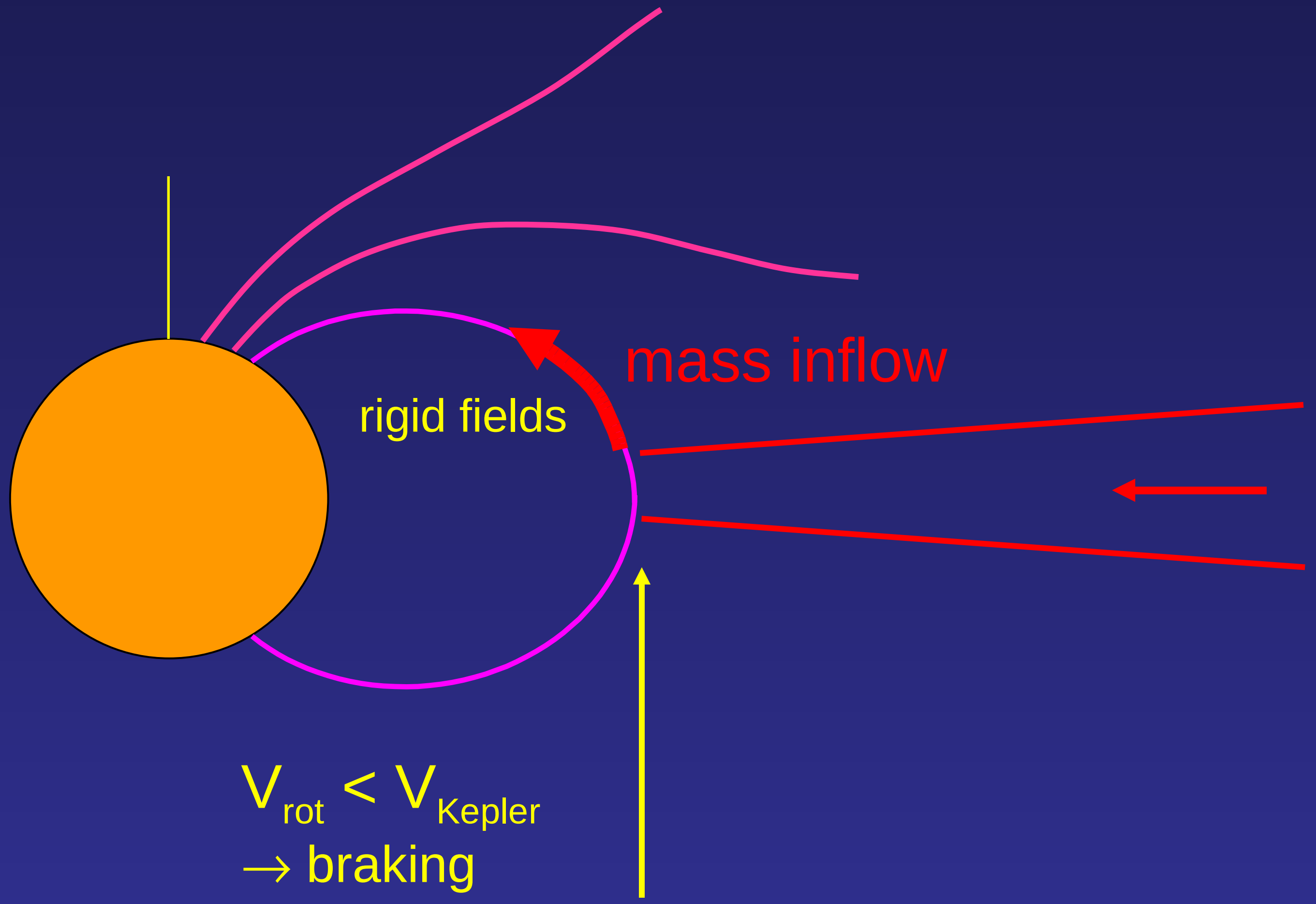
≈ 300 km/s

(NASA/A. Watson)

Magnetic fields and accretion onto the star



Magnetic fields and accretion onto the star: Magnetic funneling



$V_{rot} < V_{Kepler}$
$\rightarrow$ braking

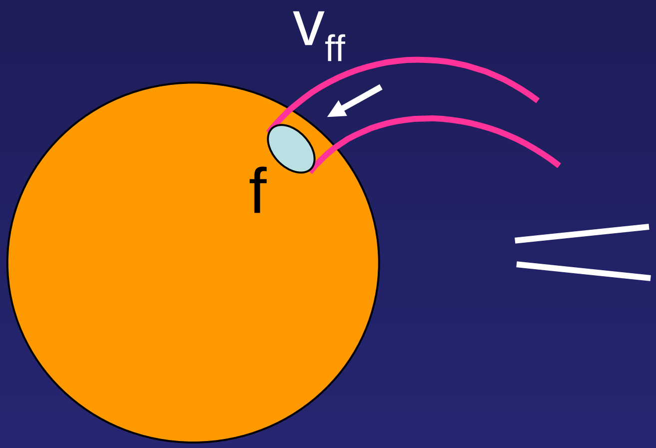
co-rotation radius (few R_*)

Magnetic accretion onto stars:

$$T_s = \frac{3}{16k}\mu m_p v^2$$

$$v \approx v_{\rm ff} = \left(\frac{2GM}{R}\right)^{1/2}$$

$$\dot{M} = 4\pi R^2 f \cdot m_p n \cdot v_{\rm ff}$$

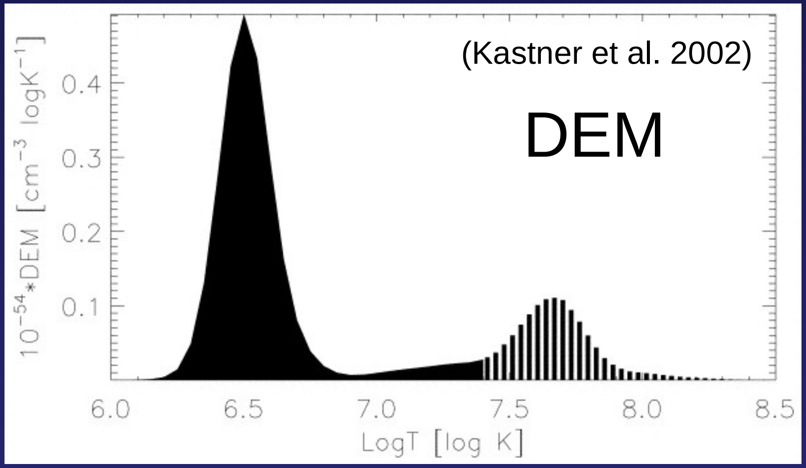


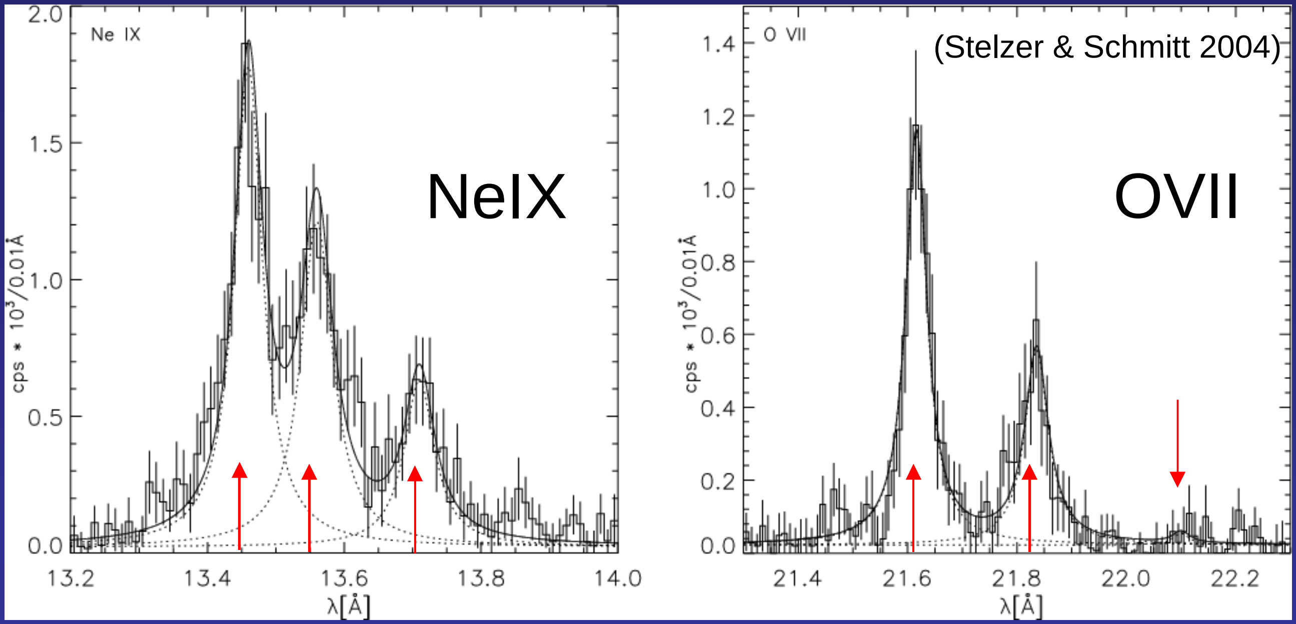
→ T a few MK

→ $n_e \approx 10^{12}$-10^{14} cm^{-3}

X-ray spectroscopy of CTTS: TW Hya

- DEM peaks at 3 x 10^6 K
- high densities: 10^{13} cm^{-3}





Summary

Magnetically active stars as ideal sources to test coronal heating models, in particular flare-related models. Much of the "basic physics" is really studied in the solar corona.

- Basic building blocks of a stellar corona are closed magnetic "loops" filled with 1-100 MK plasma

- Principal energy release at large heights due to reconnecting fields, inducing particle acceleration and heating

- Magnetic structures may not be static: time-dependent heating + flows

- Emission measure distributions are compatible with stochastic flaring

- Flare statistics support flare-heating models

- Alternative X-ray mechanisms in accretion and jets being studied

END