What role does magnetic field play in heating the solar corona?

The present status of models and observations

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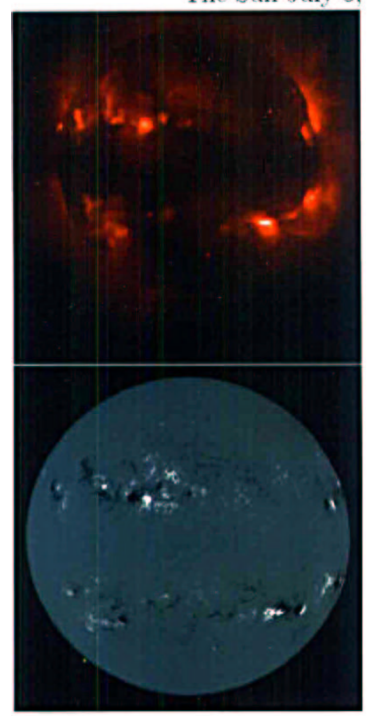
Hot corona/Magnetic corona

The Sun July 5, 1999



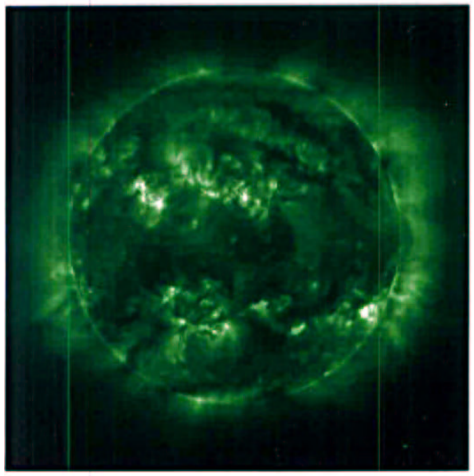
The Corona ($\sim 3\times10^6\,^\circ$K)

- Soft X-ray image — Yohkoh SXT Tsuneta *et al.* 1991
- $L_x \sim 10^{28}$ erg/sec
- Numerous bright Active Regions Vianna *et al.* 1976
- 2% plasma → 50% luminosity Acton 1996

The magnetic field

- Magnetogram — NSO/KPNO
- Maps B along line-of-sight (from circular pol'zation)
- ARs — Closed field lines

What have we learned lately?



EIT 195 Å July 7, 1999

Outline

I. Heat has magnetic origin

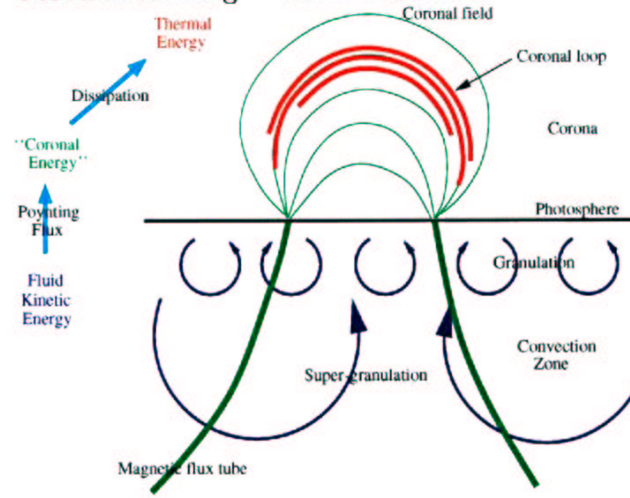
II. The importance of loops

III. Flares and the flare family

IV. X-ray bright points

V. Synthesis

Coronal Heating The overall schema



Traditional alternatives: AC *vs.* DC

	AC heating	DC heating
Picture corona as…	resonant cavity	seismic fault
Fluid motions ……	$\tau \lesssim L/v_A$	$\tau \gtrsim L/v_A$
Transport ……….	Alfvén waves	Quasi-static stressing
Coronal Energy ….	Alfvén waves	DC currents
Dissipation ……..	Wave damping	Nanoflares
Refs…………….	Ionson 1982, Hollweg 1987	Parker 1988

Energy transport to corona — Poynting flux

$$S_z = \frac{c}{4\pi}(\mathbf{E}\times\mathbf{B})_z = -\frac{1}{4\pi}(\mathbf{v}_\perp\cdot\mathbf{B}_\perp)B_z$$

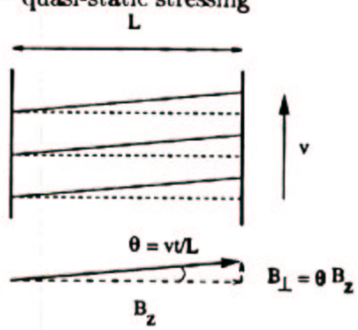
- AC — Alfvén wave propagating in $\pm B_z$ direction

$$\mathbf{B}_\perp = \mp\sqrt{4\pi\rho}\,\mathbf{v}_\perp \quad , \quad (|\mathbf{B}_\perp| \ll B_z)$$

$$\langle S_z\rangle = Q^{-1}\sqrt{4\pi\rho}\,|B_z|\,\langle v^2\rangle \sim |B_z|\,v_\perp^2 \quad \text{(AC)}$$

loop quality: $Q^{-1} \equiv \dfrac{E_\uparrow - E_\downarrow}{E_\uparrow + E_\downarrow} \simeq$ coronal absorbtion

- DC — quasi-static stressing — Parker 1983, Browning *et al.* 1986



$$|\mathbf{B}_\perp| \sim B_z\theta \quad \text{deflection by } \theta$$

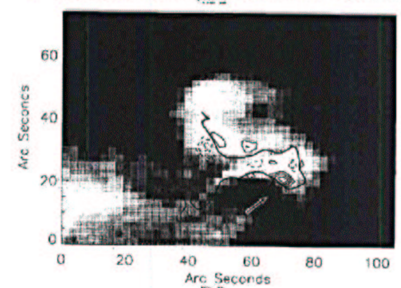
Deflection until reconnection — $\theta_{cr} = v_\perp\tau_{rx}/L$

$$S_z \sim \theta_{cr}B_z^2 v_\perp \sim B_z^2 v_\perp \qquad \text{(DC – I)}$$
$$S_z \sim B_z^2 v_\perp^2\tau_{rx}/L \sim B_z^2 v_\perp^2 \qquad \text{(DC – II)}$$

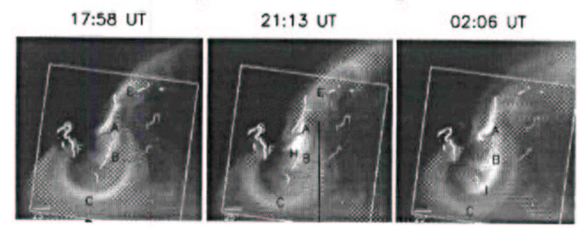
If reconnection is triggered @ $\theta = \theta_{cr}$ or $t = \tau_{rx}$.

Spatial correlations — where is the heating?

- Yohkoh SXT/Mees IVM vector m-grams — Metcalf *et al.* 1994



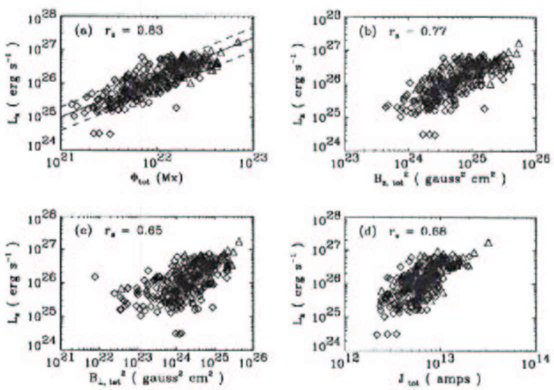
  - "There is no compelling link between currents and the SXR structures"
  - NB — observable currents $\ell \sim 10^8$ cm cannot heat corona *directly* — Parker 1972, Tucker 1973
- VLA radio/extrapolated (3d) magnetic field — Lee *et al.* 1998
  - "Modeling favors hypothesis… $T_e \sim |\mathbf{J}|$"
- Yohkoh SXT/MSFC vector m-gram — Falconer *et al.* 1997



  - Enhanced SXR @ *sheared neutral lines* i.e. @ low-lying stressed loops

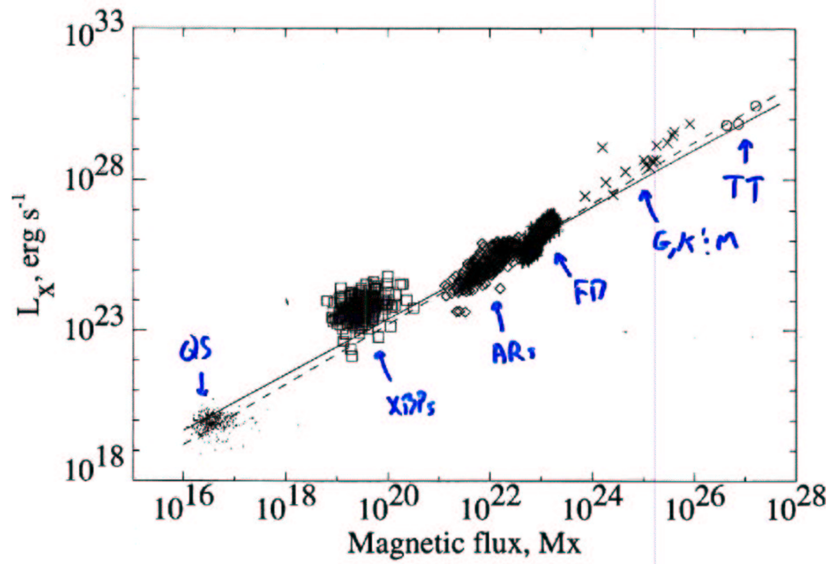
Statisical correlations — The Big Picture

- Skylab S-054 X-ray/KPNO m-grams
  Thermal energy $U_t \propto \Phi^{1.5}$ (Volume effect?) — Golub *et al.* 1980
- Yohkoh SXT/HSP vector m-grams — Fisher *et al.* 1998
  - 333 active regions



- Best correlation *
  $L_x \simeq 1.2 \times 10^{26}\,(\Phi/10^{22}\,\mathrm{Mx})^{1.19}$ ergs/sec
- No residual dependence on e.g. **J** (stress)
- $L_x \sim \Phi$ from waves — $S_z \sim B_z$ in (AC)
  $v_{\rm rms} \simeq 0.1\sqrt{Q}$ km/sec at p-sphere

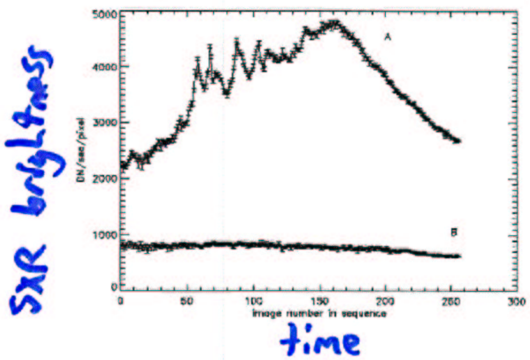
* once removed, no other correlations exist



Pevtsov et al. In prep.

Evidence for waves...

- Brightness oscillation in Yohkoh loops — McKenzie & Mullan 1997



  - 16 loops w/ oscillations (of 544 examined)
  - $Q \gtrsim 10$ (based on width of frequency peak)

- Observed "vibration" of loop following flare TRACE 171 Å — Ofman *et al.* 1999
- Spectroscopic evidence for compressive waves — Judge *et al.* 1998

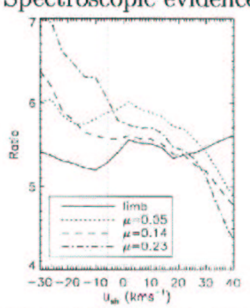
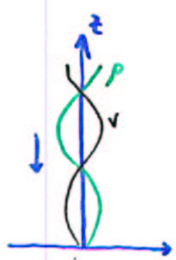
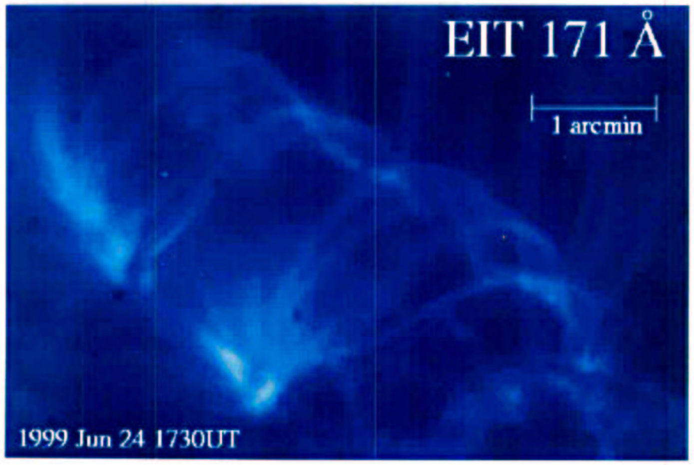


FIG. 5.—Line ratio of the O IV 1399 and 1401 Å lines as a function of wavelength for four locations along the slit: above the limb (*solid line*), at μ = 0.05 (*dotted line*), at μ = 0.14 (*dashed line*), and at μ = 0.23 (*dash-dotted line*). The data plotted belong to the data set acquired on 1996 October 26.

SUMER OIV
anti-correlation n_e vs. v
DOWNWARD propagation
(launched in corona?)



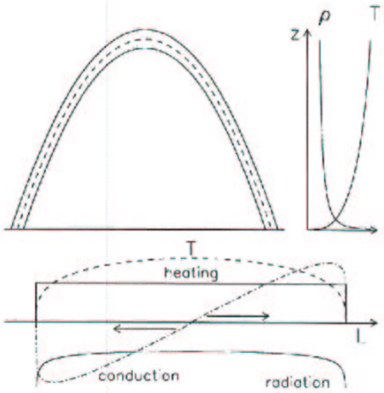
Learning from loops



- There are loops...
  "[T]he loop is the basic building block..." — Rosner *et al.* 1978 (RTV)
- ...and space in between —
  localized, intermittent heating? — Litwin & Rosner 1993
- Loops brighten suddenly —
  impulsive heating — Shimizu *et al.* 1992
- Cross section — circular
  Otherwise, expect apparent width variations
- Cross section filled or hollow? — Beliën *et al.* 1996

A steady coronal loop

Rosner *et al.* 1978, Vesecky *et al.* 1979



- Volumetric heating ϵ determines e.g. $T_{\max}$

$$T_{\max} \sim \epsilon^{2/7} L^{4/7}$$

- Measurements (MSSTA) from XBPs* : Kankelborg *et al.* 1997

$$\langle\epsilon\rangle \sim 3\times10^{-3}\,\mathrm{erg\,sec^{-1}\,cm^{-3}}$$
$$\langle\epsilon\rangle L \sim S_z \sim 3\times10^{6}\,\mathrm{erg\,sec^{-1}\,cm^{-3}}$$

- $\epsilon(\ell)$ determines $T(\ell)$
  Yohkoh SXT observations of $T(\ell)$ — consistent w/ uniform $\epsilon(\ell) = \langle\epsilon\rangle$ (Priest *et al.* 1998)
  NB — standing wave: $\epsilon(\ell) \propto \sin^2(\pi\ell/L)$

∗ XBP = X-ray bright point — isolated, quiet sun loop

Using loops to constrain heating

Porter & Klimchuk 1995, Mandrini *et al.* 1999

- Assume field strength scaling: $B \sim L^{\delta}$
- Models lead to inferred scalings

$$\langle\epsilon\rangle \sim \frac{S_z}{L} \sim \begin{cases} B_z\,L^{-1}\langle v^2\rangle\big|_{\omega=\pi v_A/L} \sim L^0 & \mathrm{AC}^{\dagger} \\ B_z^2/L \sim L^{2\delta-1} & \mathrm{DC\text{-}I} \end{cases}$$

- Golub *et al.* 1980 + Porter & Klimchuk 1995: $\delta \simeq -0.7$
  Mandrini *et al.* 1999: $\delta \simeq -0.9$

$$\Longrightarrow \quad \langle\epsilon\rangle \sim \begin{cases} L^0 & \mathrm{AC} \\ L^{-2.6} & \mathrm{DC\text{-}I} \\ L^{-3.6} & \mathrm{DC\text{-}II} \end{cases}$$

Loop Observations

- 47 AR loops (Yohkoh SXT) $\langle\epsilon\rangle \sim L^{-2}$ — Porter & Klimchuk 1995
- 23 XBP loops (MSSTA) $\langle\epsilon\rangle \sim L^{-2}$ — Kankelborg *et al.* 1997
- 32 loops in AR7150 (Yohkoh SXT) — Kano & Tsuneta 1995

$$T \sim L^{0.36} \Longrightarrow \langle\epsilon\rangle \sim L^{-3/4}$$

- Transient brightenings* $\langle\epsilon\rangle \sim L^{+0.6}$ — Shimizu1995, Ofman *et al.* 1996

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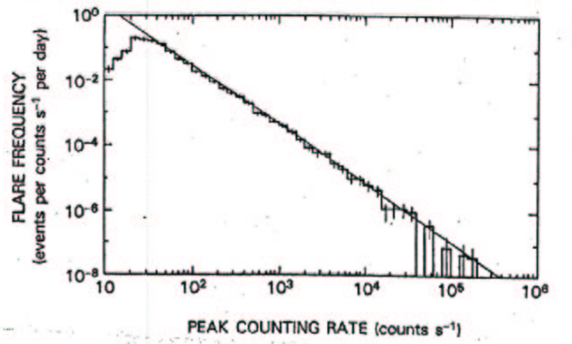
† with Kolmogorov spectrum of footpoint velocity
*May not be steady loops

The Nanoflare — recluse of the "Flare Family"



X-ray bursts from HXRBS (Dennis 1985)

- Flare "converts" stored mag. E to thermal E
- "Conversion" emits HXRs as $2^{\rm ndary}$ biproduct
- Flare of energy E occur w/ frequency

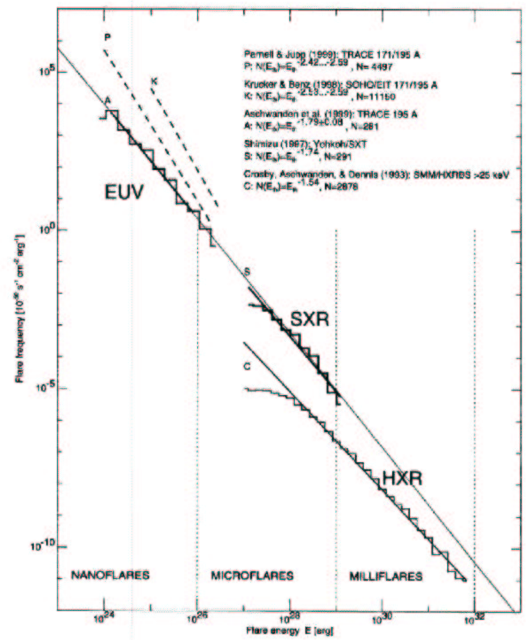
$$\frac{dN}{dE} \sim E^{-\alpha}$$

- Heat deposited by all flares (Hudson 1991)

$$F \sim \int \frac{dN}{dE} E\, dE \sim E^{2-\alpha}\Big|_{\rm small}^{\rm large}$$

- Possibilities:
  - $\cdot\ \alpha < 2$ — large (observed) flares dominate $F \sim 10^3\,{\rm erg\,sec^{-1}\,cm^{-2}} \ll$ observed heating
  - $\cdot\ \alpha > 2$ — small (unobserved) flares dominate "The nanoflare hypothesis" (Parker 1988)

Surveying the data (Aschwanden *et al.* 1999)



E	in	instrument	ref	α
$e^- \geq 25$ keV	flares	HXRBS	Crosby *et al.* 1993	1.5
$e^- \geq 30$ keV	flares	ISEE-3	Bromund *et al.* 1995	1.6
U_t	EUV loop brightenings	TRACE	Aschwanden *et al.* 1999	1.8
U_t	EUV fluctuations	EIT	Krucker & Benz 1998	2.6

Nanoflares — other consequences...

1. "Episodic heating"
   — different time average from steady state (Sturrock *et al.* 1990, Cargill 1994)

   - Differential emission measure (DEM)

$$\mathrm{DEM}(T_0) \equiv \int n_e^2(z)\,\delta[T(z)-T_0]\,dz$$

   - Measured (Skylab) vs. Steady RTV Loop (Raymond & Doyle 1981)

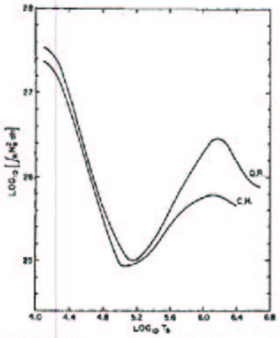
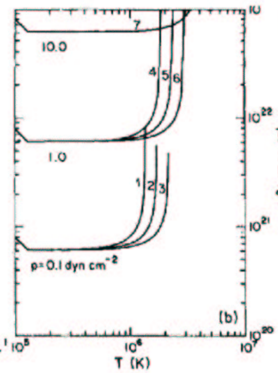
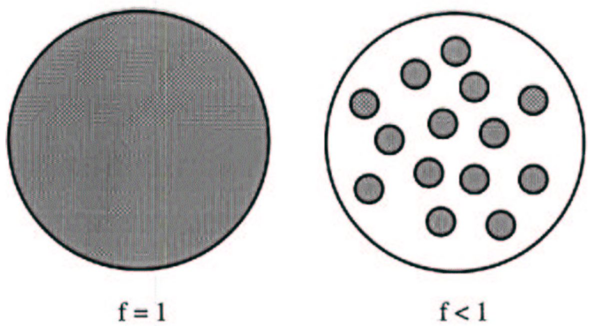


FIG. 3.—Emission measure distributions for the average quiet-Sun and average coronal hole.



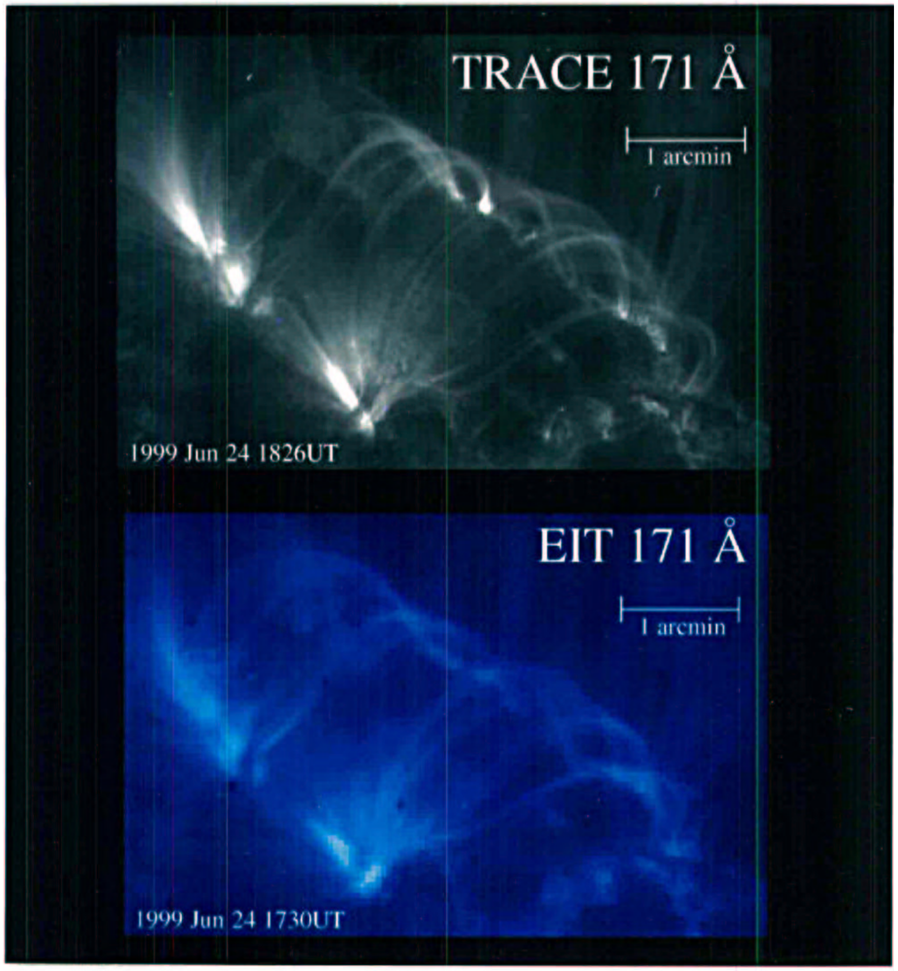
   - Episodic heating contributes cool material
     — material in process of cooling

2. Loop filling factor f —
   Observed steady state "loop" *actually* comprised of multiple sub-loops (nanoflares) living $\sim \tau_R$

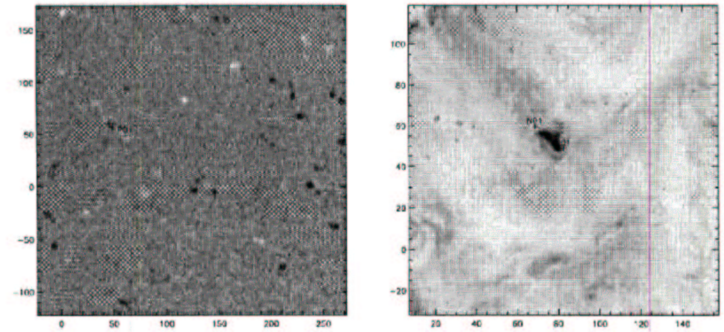


   - Model Yohkoh SXT loops w/ $f \lesssim 0.1$ (Cargill & Klimchuk 1997)
   - High resolution (TRACE) reveals sub-loops (Nightingale *et al.* 1999)
     $\Longrightarrow$ impulsive heat — radiative cool

i.e. $\tau_{life} = \tau_{cool}$



X-ray bright points — quiet heat

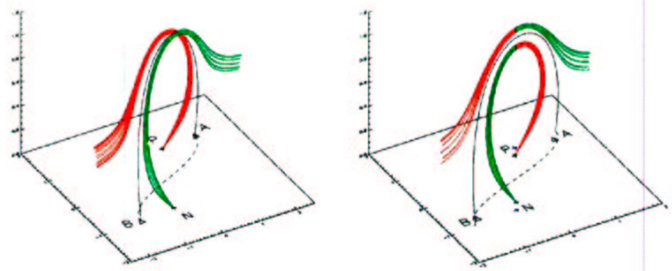


SOI/MDI m-gram & TRACE 171 Å image

- XBPs isolated loops in quiet sun — Golub *et al.* 1974
- Occur above magnetic bipoles + & −
- Most often when poles are converging — Webb *et al.* 1993
  (Would AC heating lead to asymmetry?)
- Loops powered by heating — Kankelborg *et al.* 1997
  $\langle\epsilon\rangle \sim 3 \times 10^{-3}\,\mathrm{erg\,sec^{-1}\,cm^{-3}}$
- ΣXBPs cannot account for quiet sun heating — Habbal & Grace 1991

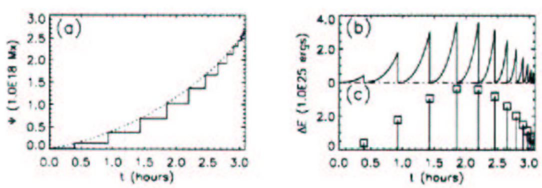
The stress/reconnect cycle (MCC)

Longcope 1998



- Poles (flux $\Phi_\pm$) initially join field B_0
- Approach @ v & become interconnected
- Corona prevents flux x-fer ($E = d\Phi/dt \simeq 0$)
- Currents build — released by reconnection

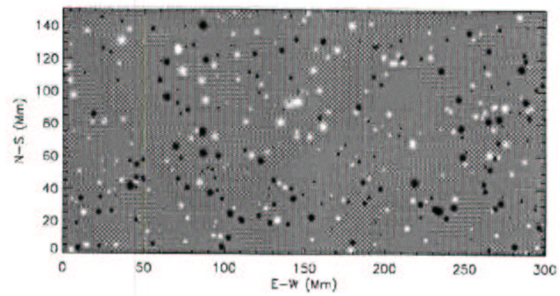
Longcope & Kankelborg 1999



$$P \;\simeq\; vB_0 \min(\Phi_+, \Phi_-)$$

The magnetic carpet

Schrijver *et al.* 1998



Estimating heating from elements

- Flux recycling rate

  Schrijver *et al.* 1998

  $S_z \sim B_z^2 v^2 \tau / L$, (DC-II)

  · 40 hour flux replacement enhances diffusion

  · $v^2\tau \;\sim\; 2{,}000\,\mathrm{km}^2/\mathrm{sec} \gg$ turbulent value $v_{\rm gran}^2 \tau_{\rm gran} \simeq 300\,\mathrm{km}^2/\mathrm{sec}$

  $\Longrightarrow$ explains coronal heating

- Reconnection @ pairwise collisions

  Longcope & Kankelborg 1999

  · Pos./Neg. elements w/ densities $\bar{B}_+ \simeq \bar{B}_- \simeq 1.6$ G

  NB — these are *not* field strengths

  $$S_z \;=\; 0.1\,\bar{B}_+ \bar{B}_-\, v_{\rm rms}$$

  c.f. DC-I

  $\Longrightarrow$ S_z too small to heat quiet sun corona

Synthesis (a personal view)

- Loops are heated by impulsive events (nanoflares?) AR loops, XBPs
- Alfvén waves exist — perhaps launched by same impulsive events
- **Not** adequate for all hot plasma
- Possibly also a diffuse hotter corona, outside loops (TRACE 284 Å) Tsuneta 1997, Schrijver *et al.* 1999