Hard X-ray sources in the solar corona

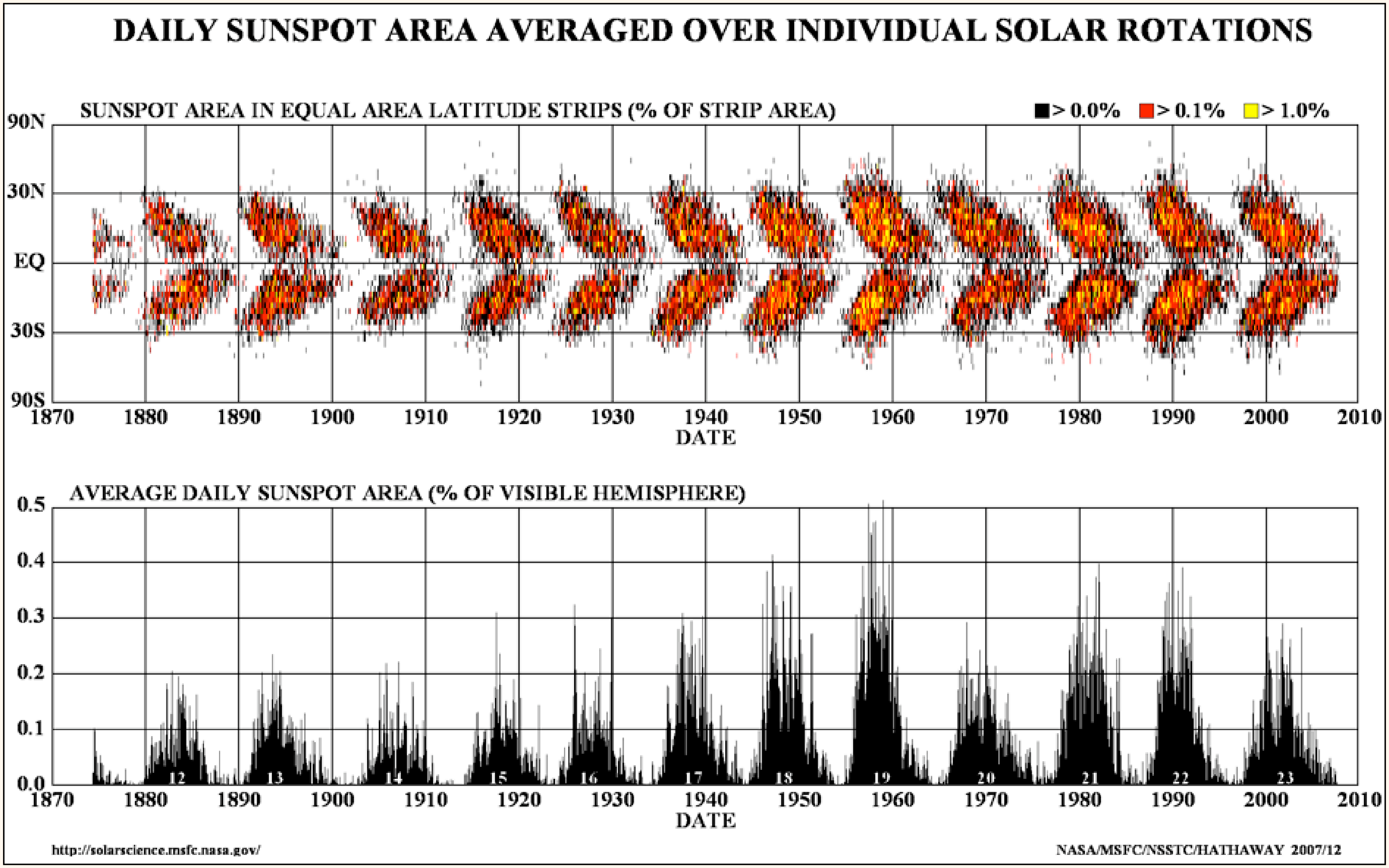
H.S. Hudson

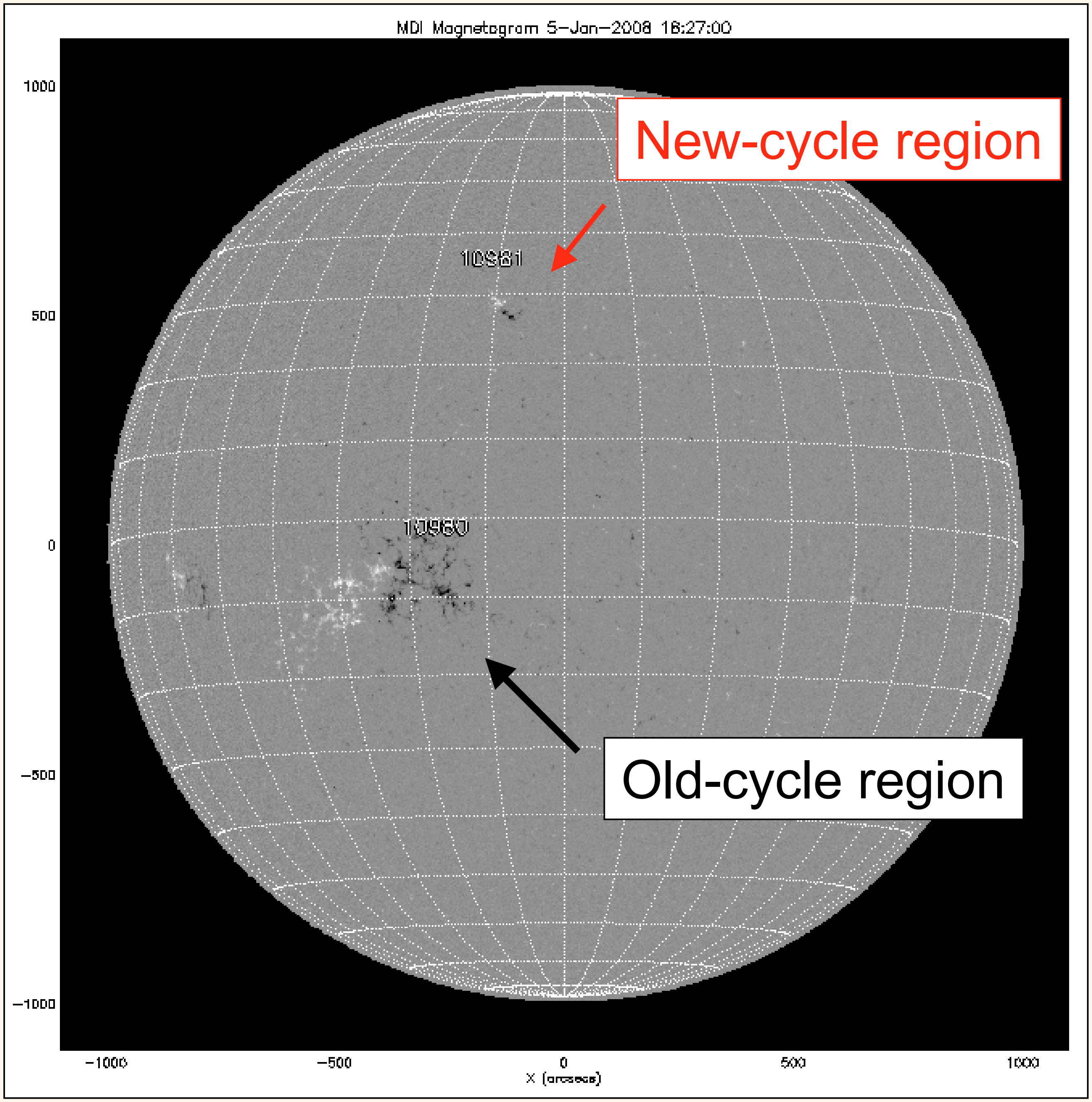
Space Sciences Lab, UC Berkeley

Contents

- Introductory material
- Flare observations
- New ideas about the impulsive phase of a solar flare
- RHESSI coronal hard X-ray sources
- New ideas about flare magnetic structure
- Conclusions

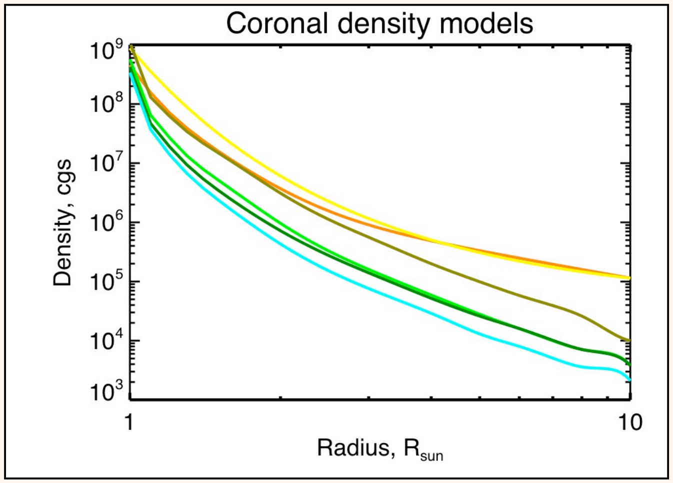
Maunder's (Carrington's?) "butterfly diagram"

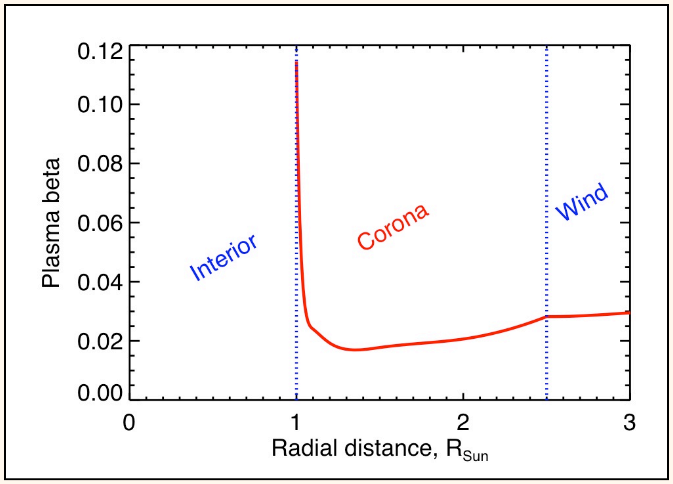



MDI Magnetogram 5-Jan-2008 16:27:00
New-cycle region
10981
10980
Old-cycle region
1000
500
0
-500
-1000
-1000
-500
0
500
1000
X (arcsecs)

Background information (corona)

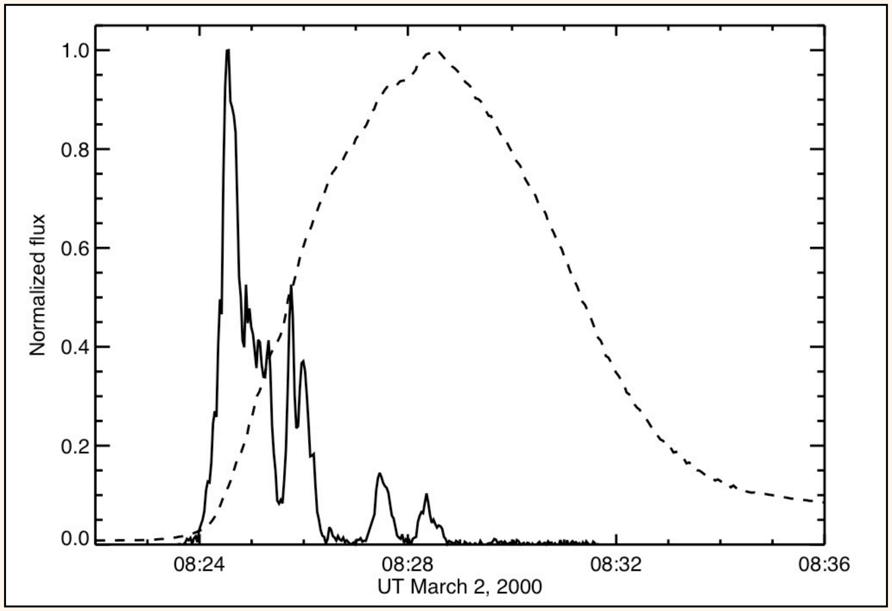
- "Hard" for solar purposes means $h\nu >> kT$ (few keV)
- The emission mechanism is bremsstrahlung (and maybe some free-bound)
- Bremsstrahlung is very inefficient and the corona has low density, hence it should not be a strong hard X-ray source



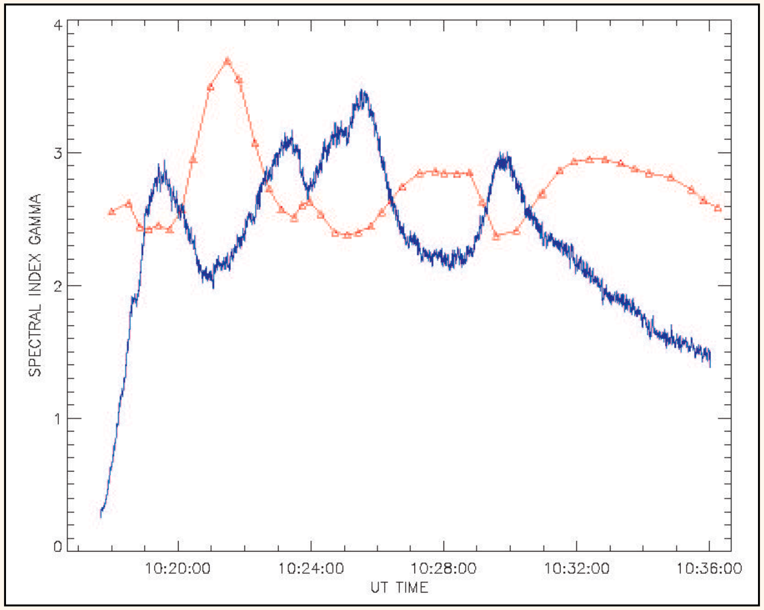


Background information (flares)

- A flare is the sudden conversion of magnetic energy into other forms
- This happens *impulsively*

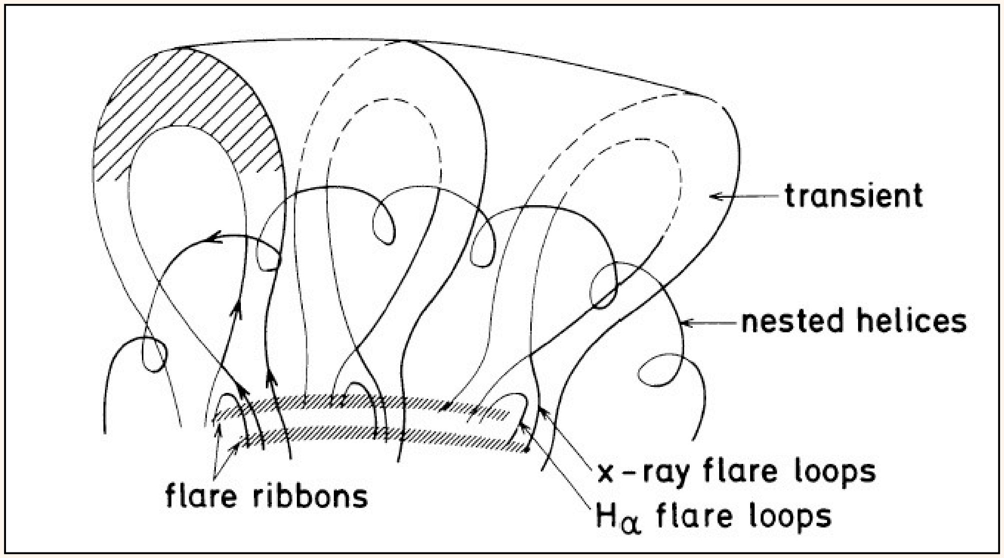


The Neupert effect

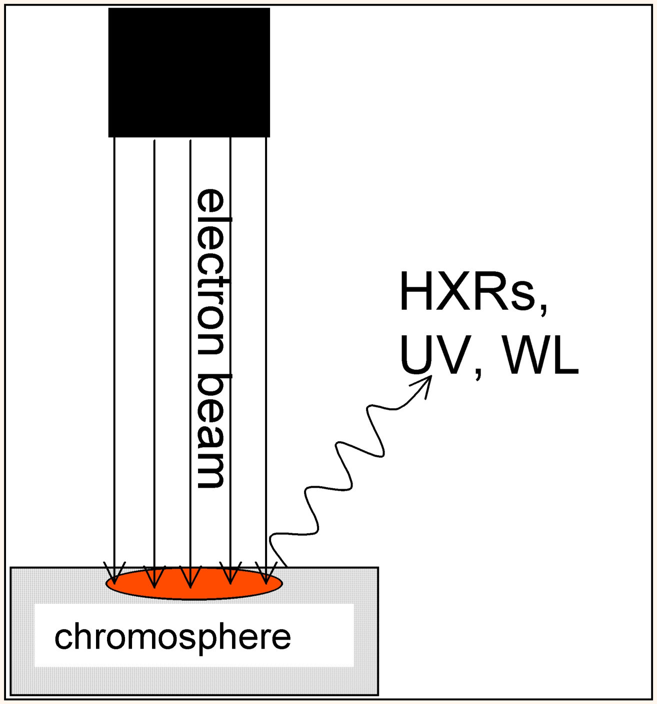


Soft-hard-soft

Background information (flare models)



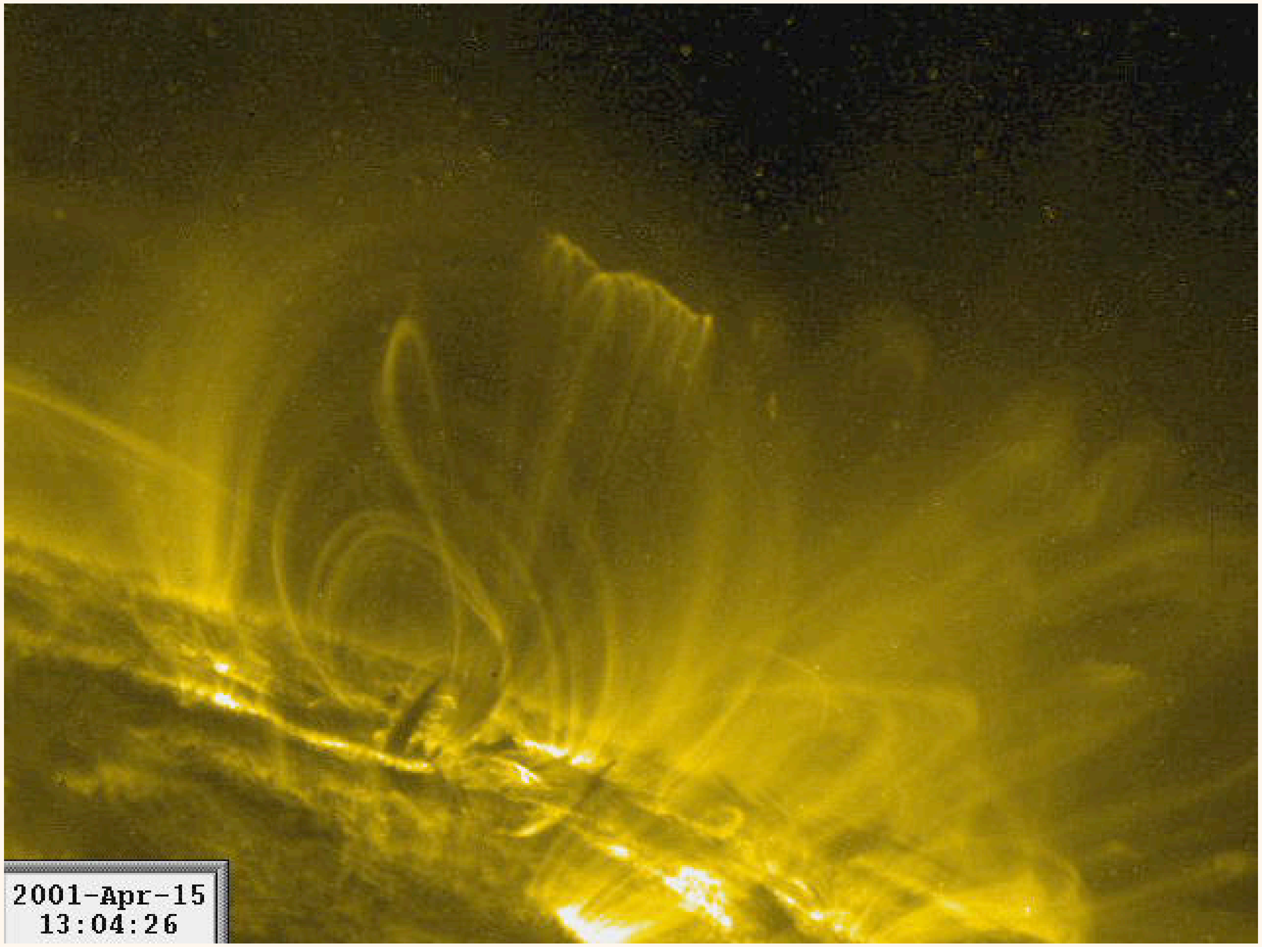
The "CSHKP" model
(Anzer & Pneuman 1982)



The thick-target model
(L. Fletcher)

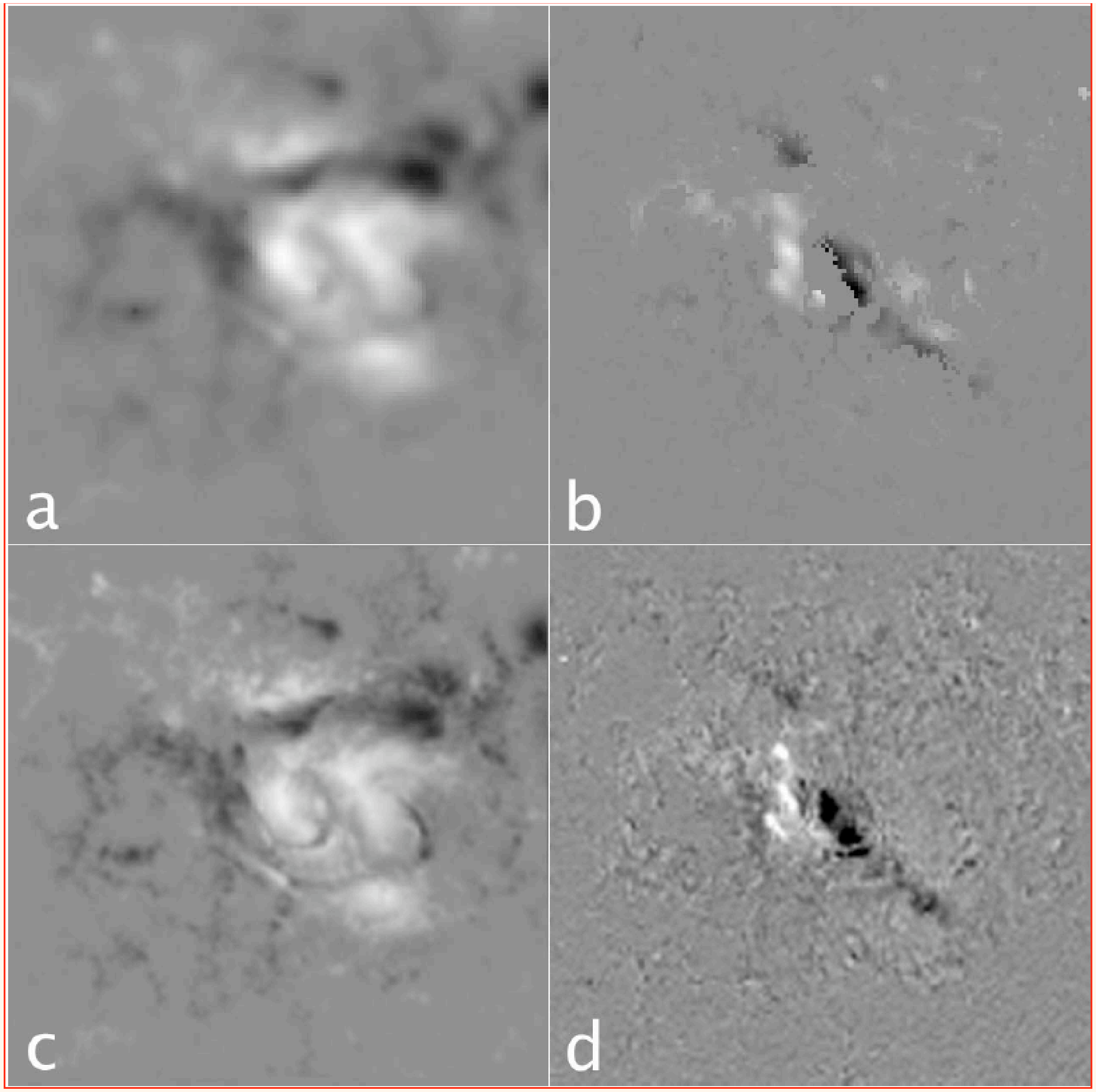
Background information (flare movies)

Background information (flare movies)

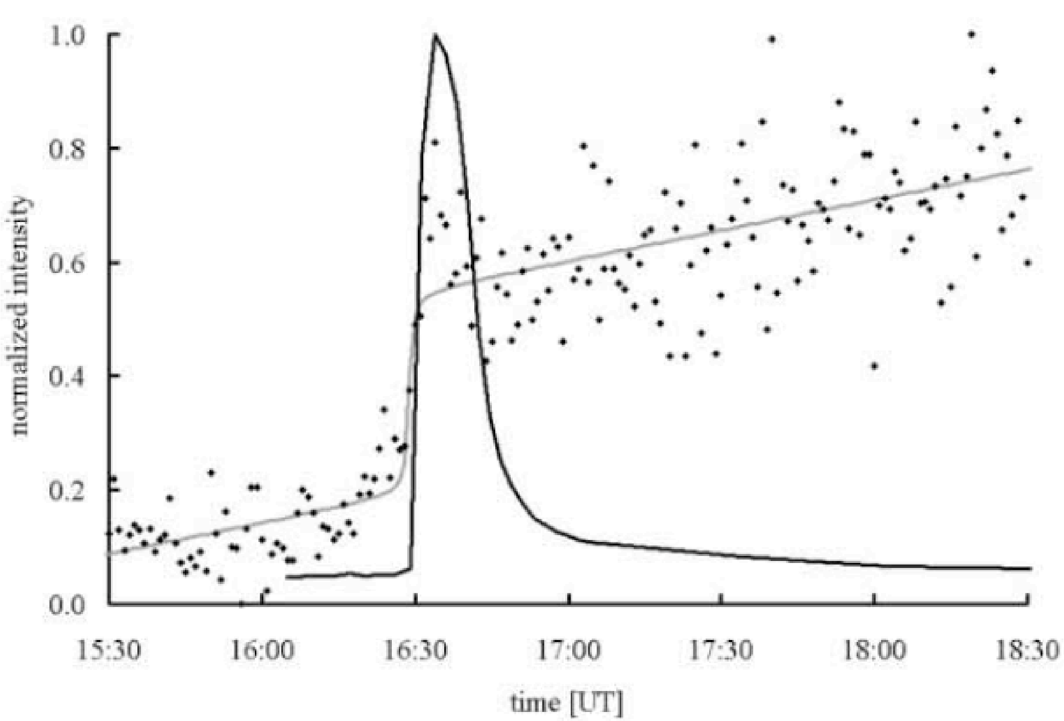


New observational wrinkles

- Very high Alfvén speeds in the active-region corona: B = 1000 g at n = 10^9 => $\mathbf{v_A = 0.2c}$
- Photospheric field changes (next graphic)
- Implosive motions at flare onset



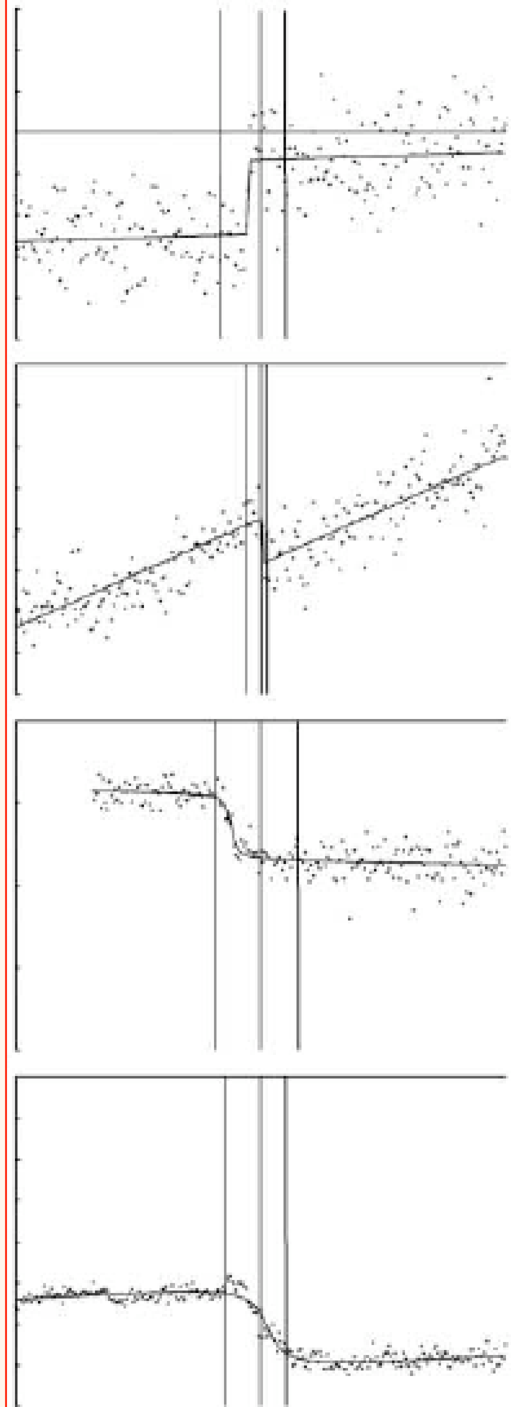
Sudol & Harvey (2005), flare of 2003 Oct. 29, line-of-sight field differences



Flare of 2001 Aug. 25:
GONG + GOES

The changes are stepwise, of order 10% of the line-of-sight field, and primarily occur at the impulsive phase of the flare

Other examples with GOES times

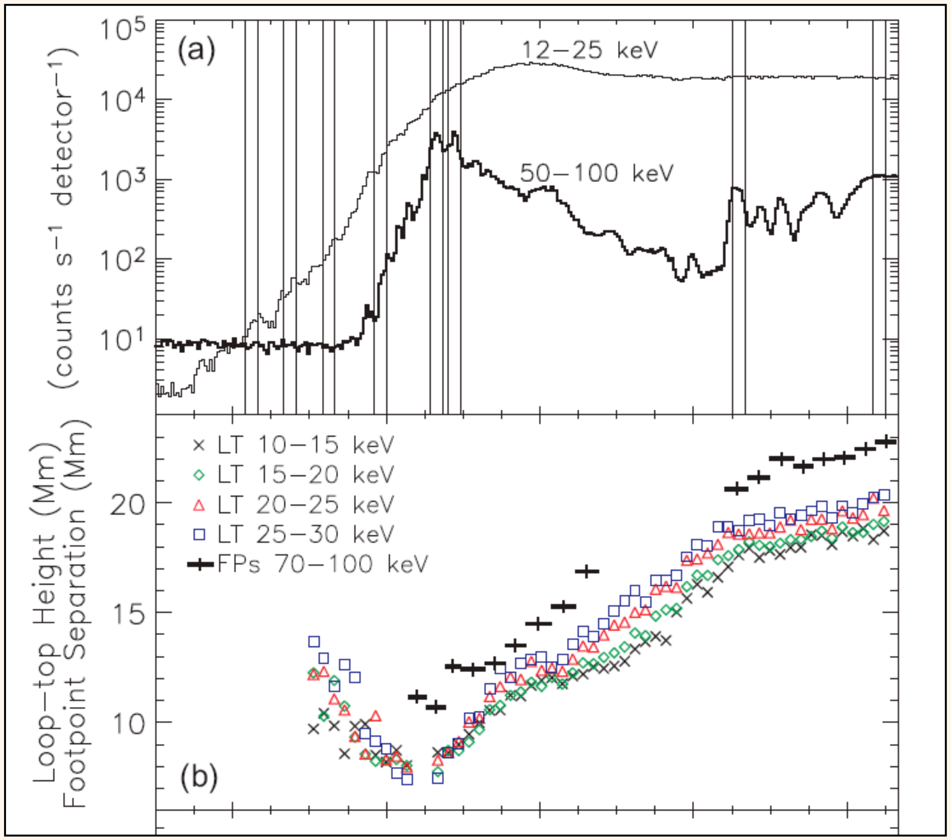


Anticipation of vector measurement: a conjecture

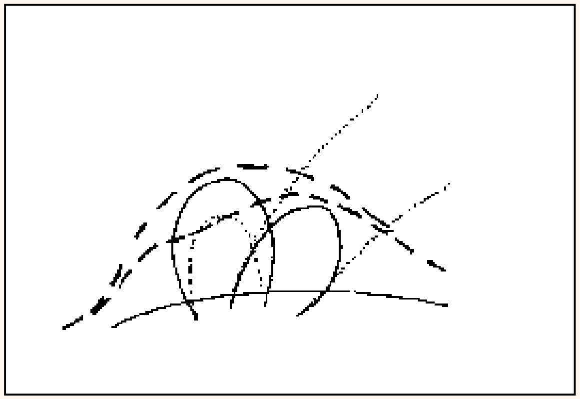
- J_z = constant during a flare (Melrose)
- $\mathrm{Curl}(\mathbf{B})_z = \mathrm{Curl}(\mathbf{B} + \mathbf{B}_1)_z$ = constant
- Difference $\mathbf{B}_1$ must be a **potential field**

- Ampere's law integral is an easy test

Implosive motion

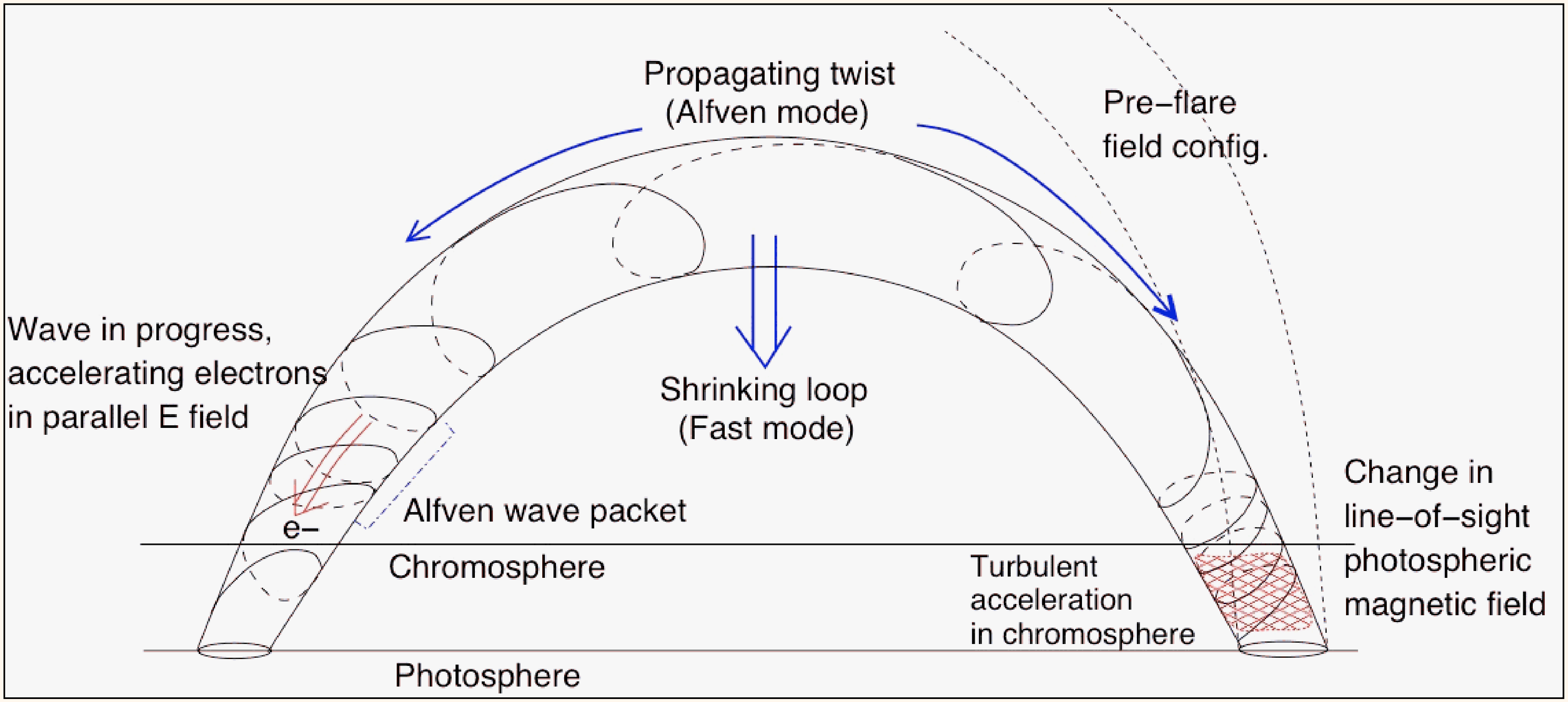


Veronig et al. 2005



Hudson 2000

New description of the impulsive phase



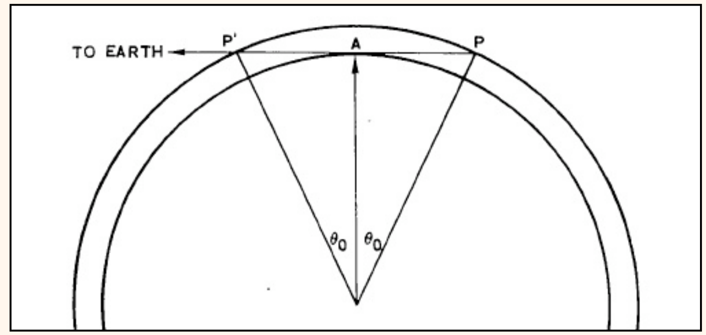
Fletcher & Hudson 2008

http://solarmuri.ssl.berkeley.edu/~hhudson/cartoons/

How does this cartoon help?

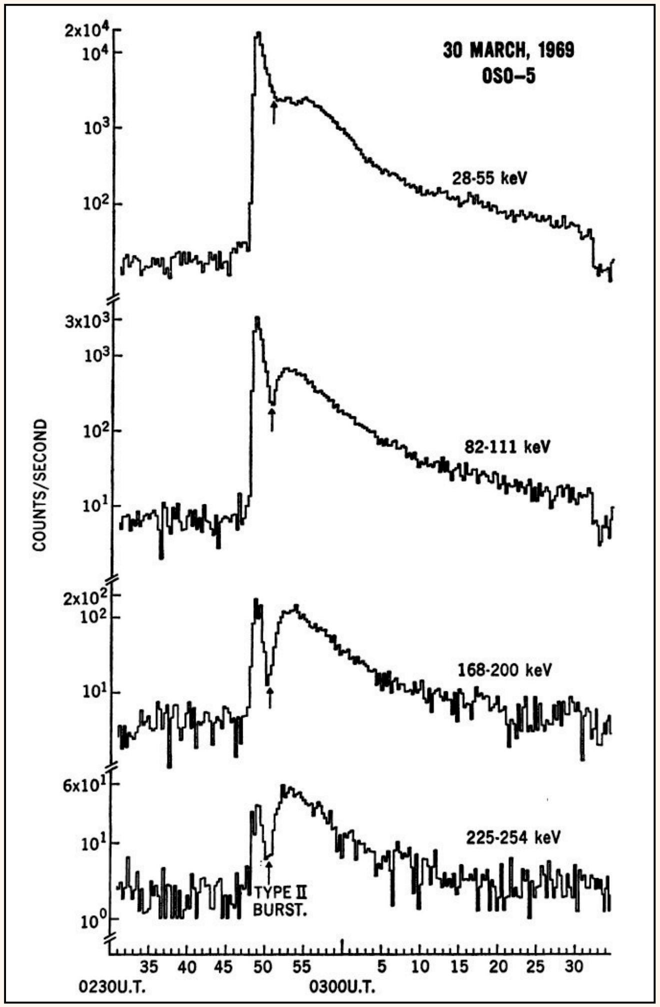
- It is a useful application to astrophysics of lessons learned in space plasmas
- It takes a different and healthy approach to the major flare problem of electron beam stability
- It acknowledges a recent solar observational breakthrough - the stepwise changes in B_{LOS} observed in the photosphere below a flare
- It suggests the need for further stereoscopic observation after STEREO, e.g. Solar Orbiter and the Sentinels

Limb occultation

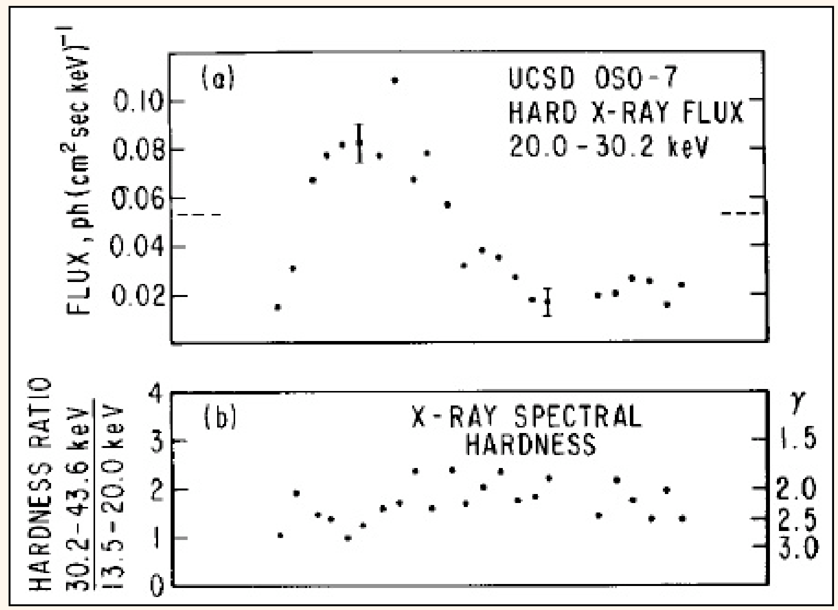


$$\cos\theta = \left[\left(\frac{R}{R+h}\right)^2 \times \sec^2\psi - \tan^2\psi\right]^{1/2}$$

McKenzie 1975

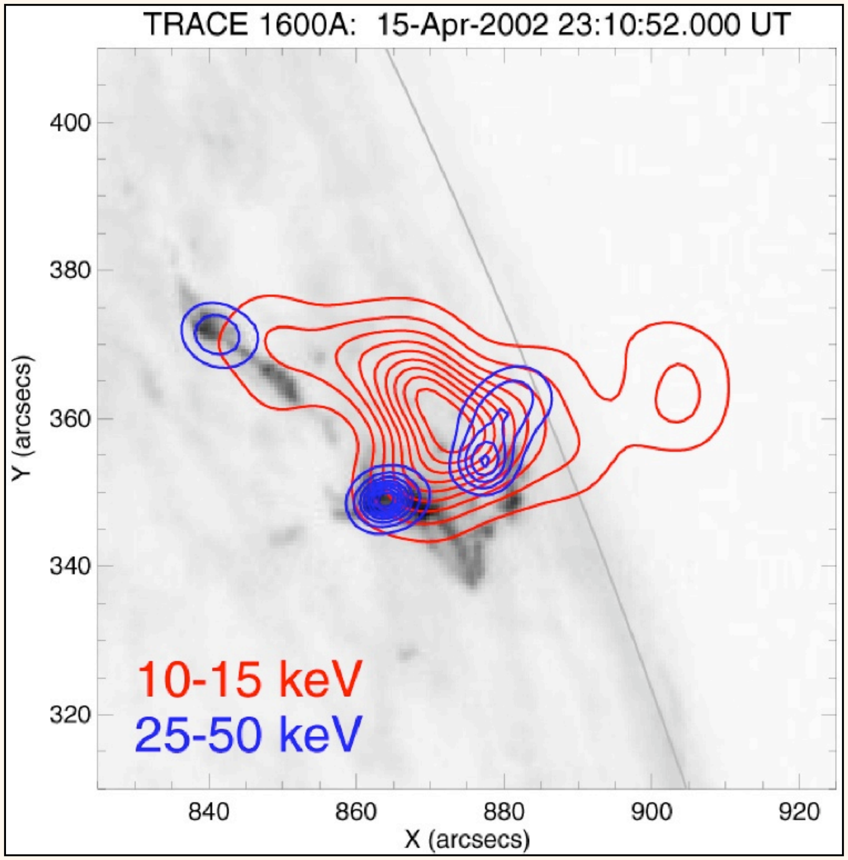


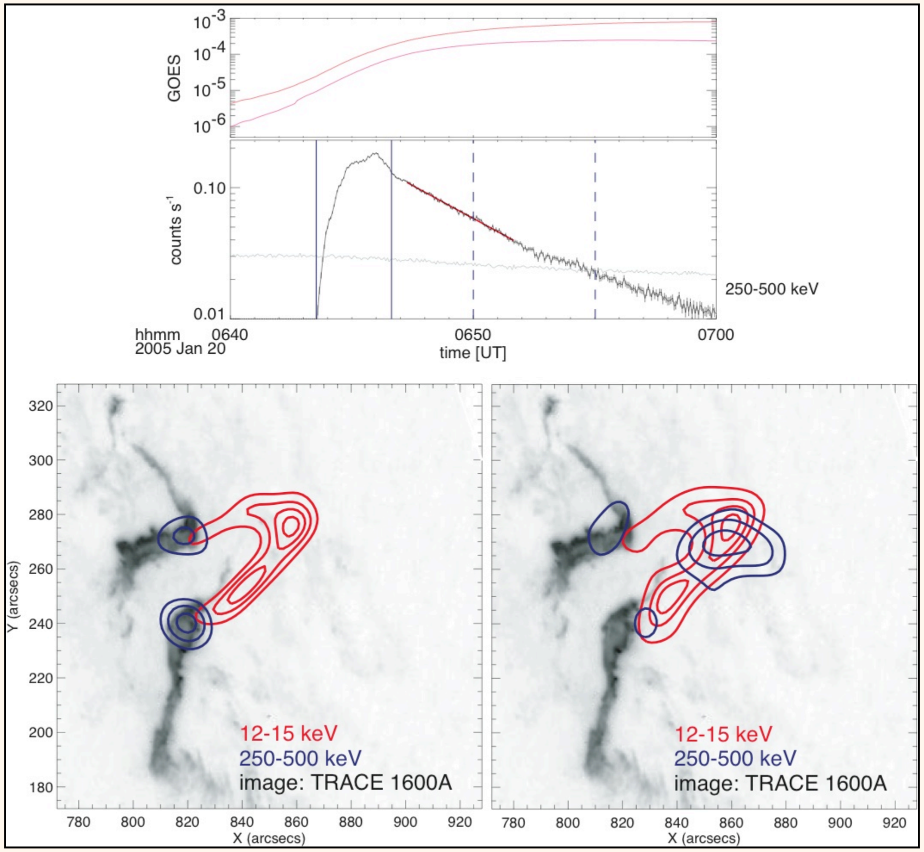
Frost & Dennis 1971



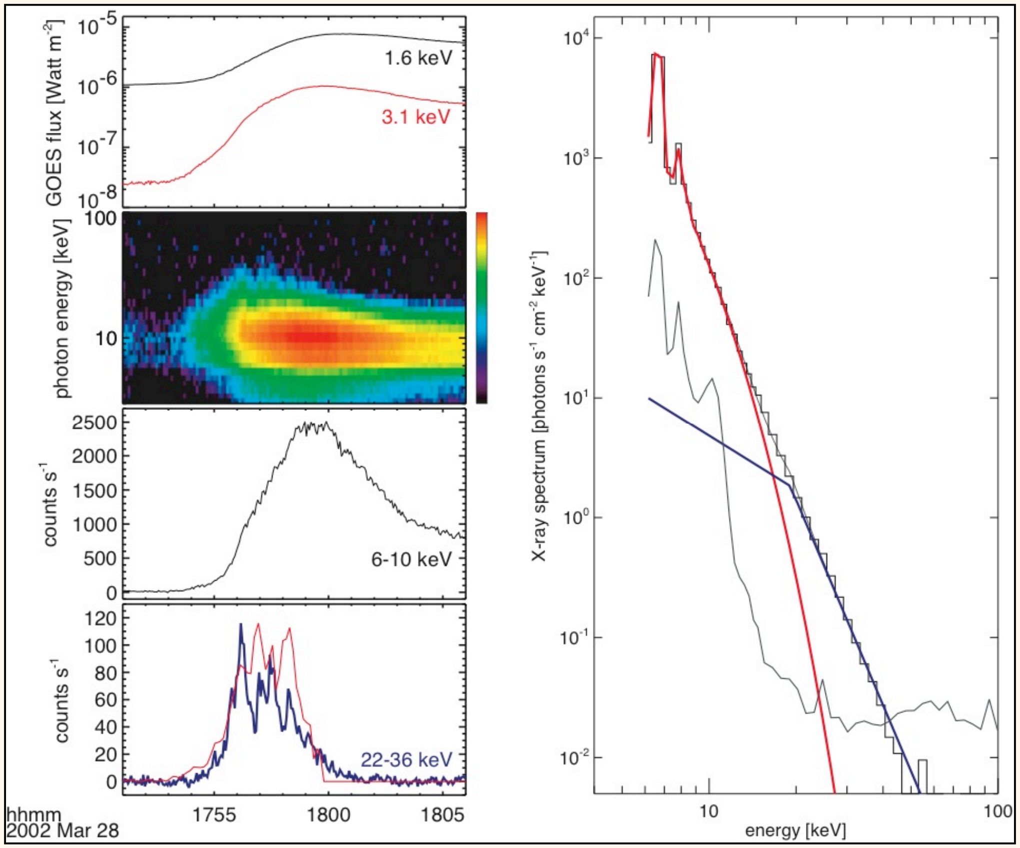
Hudson 1978

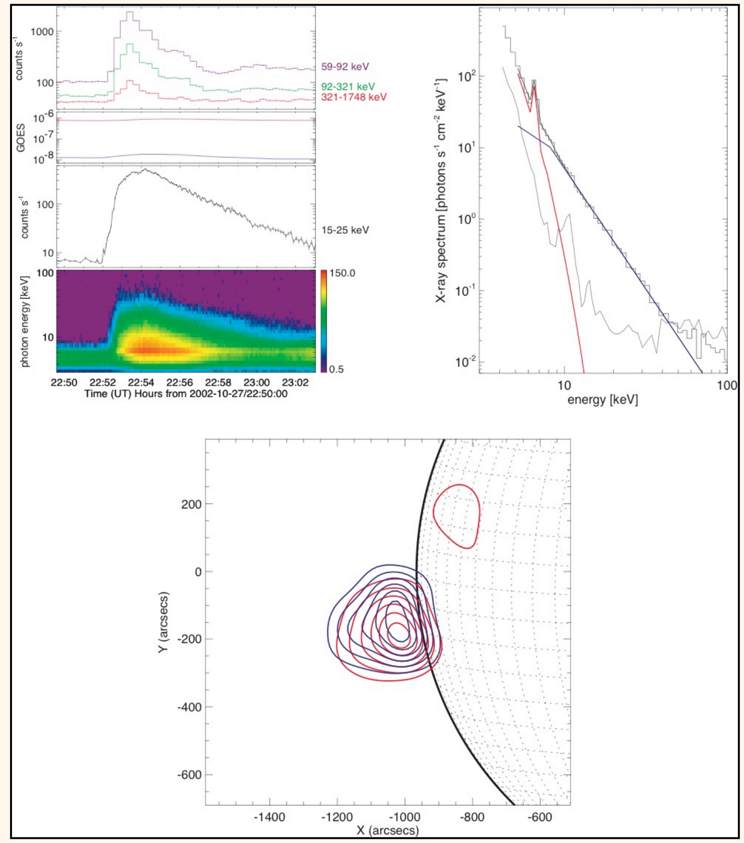
Splendid RHESSI observations, courtesy Säm Krucker I



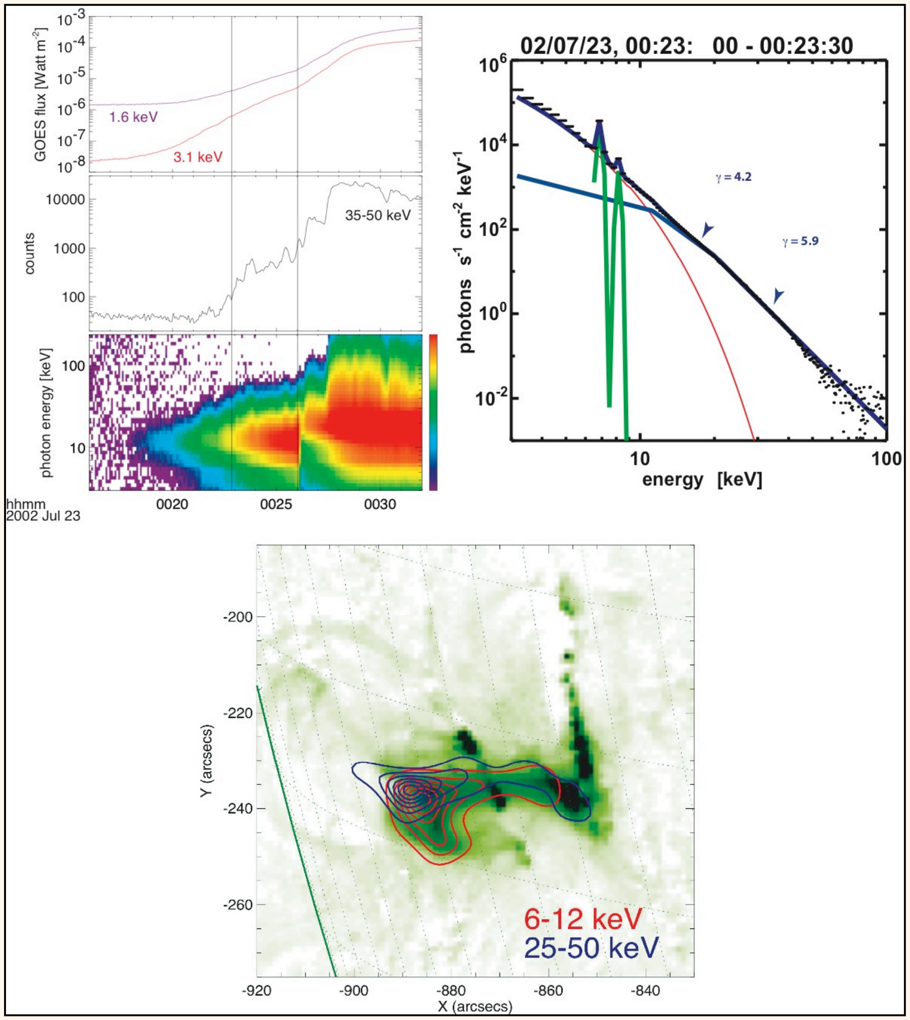


Splendid RHESSI observations, courtesy Säm Krucker II





Splendid RHESSI observations, courtesy Säm Krucker III



Lin et al. 2002

Obligatory table

Table 1 Coronal hard X-ray sources: representative parameters

Type[a]	Phase[b]	Archetype event (d/m/y)	Number studied	Height Mm	E_{obs} keV	F_{30}[c]	γ[d]	Density cm^{-3}	Δt Min	Scale Mm	Velocity[e] $km\ s^{-1}$
Early	(1)	23/07/2002 [1]	3	20	<100	10	5	$\sim 10^{10}$	5	5	small
Masuda	(2)	13/01/1992 [2]	<10	20	25-50	0.2	3-4.5	$<10^{9}$	2	5	small
Coronal thick	(2)	14/04/2002 [3]	~5	20	<50	1	6-7	$\sim 10^{11}$	15	10	small
Fast ejecta	(2)	18/04/2001 [4]	10	>100	<100	0.1	4	$\sim 4 \cdot 10^{9}$	5	>20	$\sim 10^{3}$
High coronal	(2-3)	16/02/1984 [5]	10	>100	<100	0.1	3-5	$<10^{9}$	5	>20	$\sim 10^{3}$
Superhot	(3)	27/06/1980 [6]	many	20	<40	100	Th	–	5-30	–	–
Double	(2)	15/04/2002 [7]	3	30	15-25	–	Th	$\sim 10^{10}$	~3	10	complex
Occulted	(2-3)	2/12/1967 [8]	many	20	10-50	0.5	4-7	$\sim 10^{10}$	1-30	10	small
Late phase	(3)	30/03/1969 [9]	10	40	30-250	2	2	–	10-100	–	–
MeV	(3)	20/01/2005 [10]	3	20	$200\text{-}10^{3}$	2^{f}	2	$\sim 10^{10}$	10	<20	–
Footpoints	(1-3)	21/05/1980 [11]	many	–	$5\text{-}10^{3}$	100	2-5	$>10^{12}$	0.1-30	<3	–

[a] Not intended as a classification scheme
[b] Event phase: (1) pre-impulsive; (2) impulsive; (3) late
[c] Maximum reported, in ph/(cm^2 sec keV) at 30 keV
[d] Th = Thermal
[e] Apparent radial velocity
[f] Extrapolation

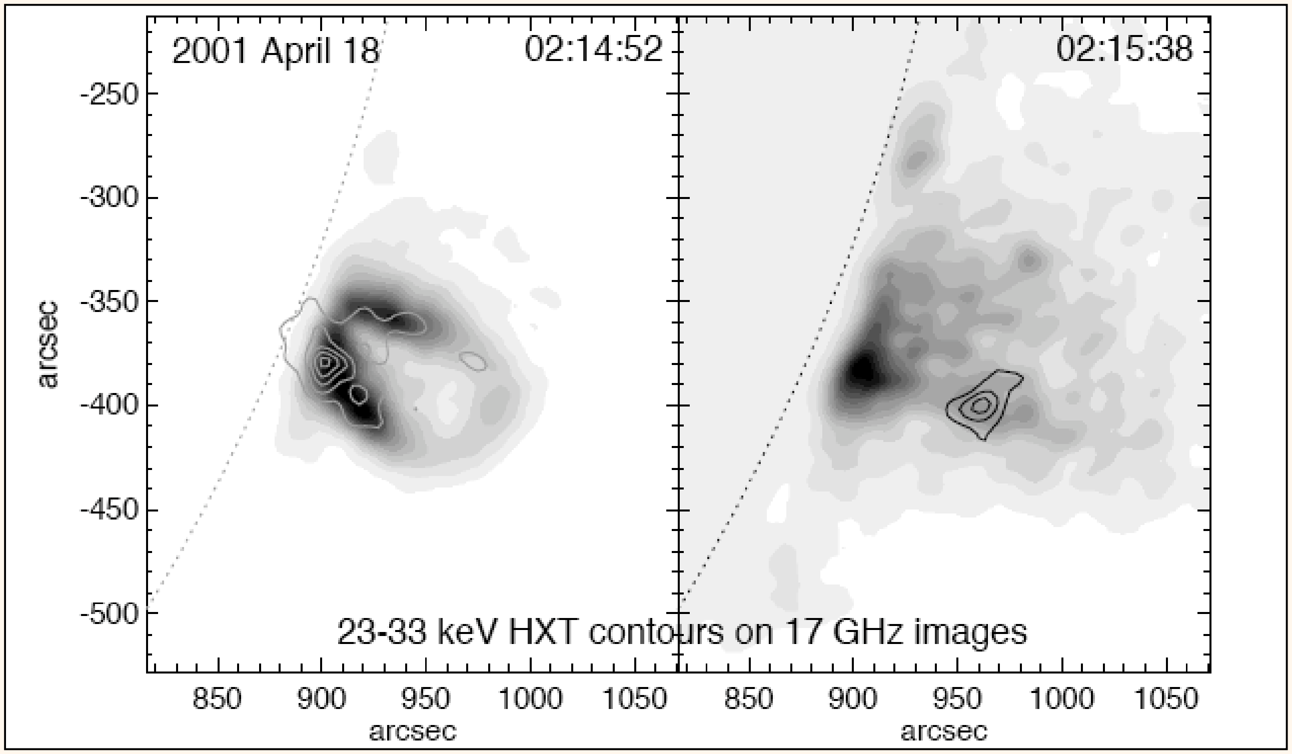
[1] Lin et al (2003)
[2] Masuda et al (1994)
[3] Veronig and Brown (2004)
[4] Hudson et al (2001)
[5] Kane et al (1992)
[6] Lin et al (1981)
[7] Sui and Holman (2003)
[8] Zirin et al (1969)
[9] Frost and Dennis (1971)
[10] Krucker et al (2008b)
[11] Hoyng et al (1981)

Krucker et al. 2008

What are the coronal sources?

- Large numbers of fast electrons trapped stably in coronal mirror geometries
- Early-phase sources (cf. Masuda event) are mysterious and probably really important
- Possibility that the tail of the electron distribution is the dominant pressure
- Moving sources may wind up being identified with the filament region of the CME

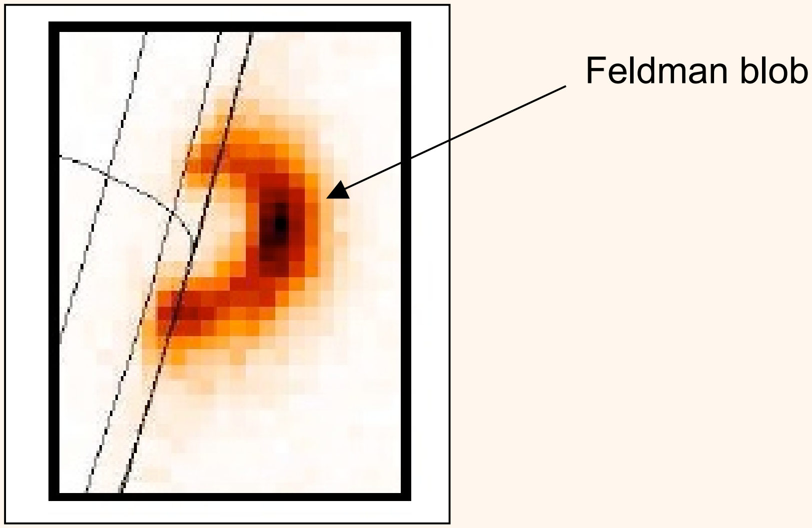
Prototype moving source



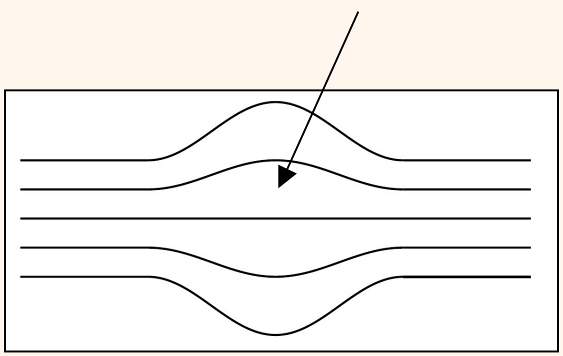
Hudson et al. 2001

Loop-top brightenings and diamagnetism

- Flare soft X-ray sources have mysterious bright "Feldman blobs" at their tops
- We propose to explain these by "non-thermal pressure" or diamagnetism of trapped collisionless particles

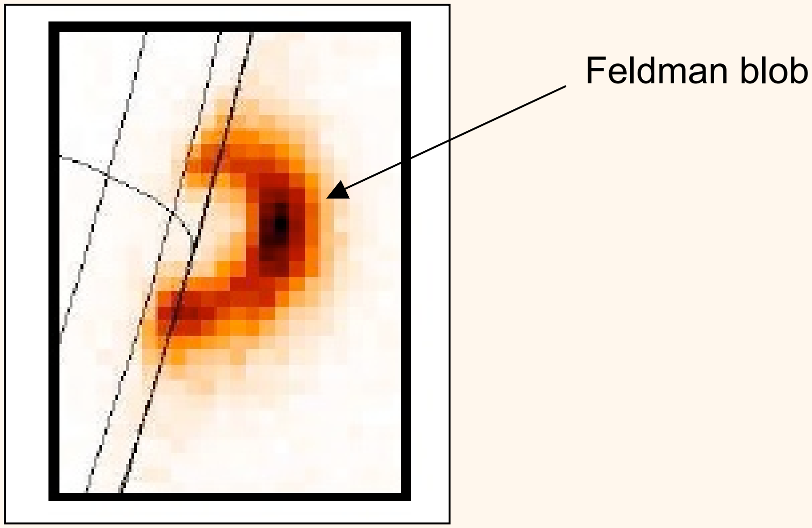


"Masuda flare" soft X-rays

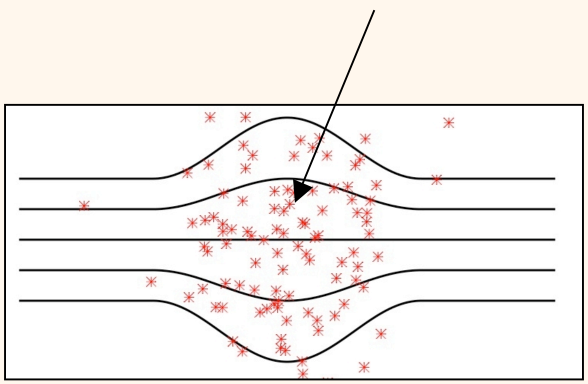


Loop-top brightenings and diamagnetism

- Flare soft X-ray sources have mysterious bright "Feldman blobs" at their tops
- We propose to explain these by "non-thermal pressure" or diamagnetism of trapped collisionless particles



"Masuda flare" soft X-rays



Conclusions

- RHESSI (and Yohkoh) have substantially changed our view of flare physics
- The new observations are just being assimilated theoretically and there are many opportunities
- The coronal sources are surprisingly detectable
- We wish we had large-area focusing optics for solar hard X-ray observations (and FASR)