INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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H4-SMR 1012 - 22

AUTUMN COLLEGE ON PLASMA PHYSICS

13 October - 7 November 1997

Cosmical MHD Phenomena

1. Solar Flares

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These are lecture notes, intended for distribution to participants.

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Cosmical MHD Phenomena

I. Solar Flares

– A Laboratory for Magnetic Reconnection –

K. Shibata (NAO, Japan)

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1. Introduction

- What is a solar flare ?
- Basic difficulty
- Magnetic reconnection theory
- Fundamental questions

2. Yohkoh Observations of Solar Flares

- Observational evidence of reconnection
- numerical simulation model

3. A Unified Model of Flares

4. Summary and Remaining Questions

What is a solar flare ?

explosion in the solar atmosphere

"sudden" release of a huge amount of energy

$\sim 10^{29} - 10^{32}$ erg

time scale $\sim$ a few min – a few hours

size $\sim 10^4 - 10^5$ km

observed in all electromagnetic spectrum

white light (rare)

Hα

radio

soft X-rays → 10^7K plasma

hard X-rays → 10keV – 1MeV electrons

γ-rays → 1 – 100 Mev ions

Typical Flare Light Curve

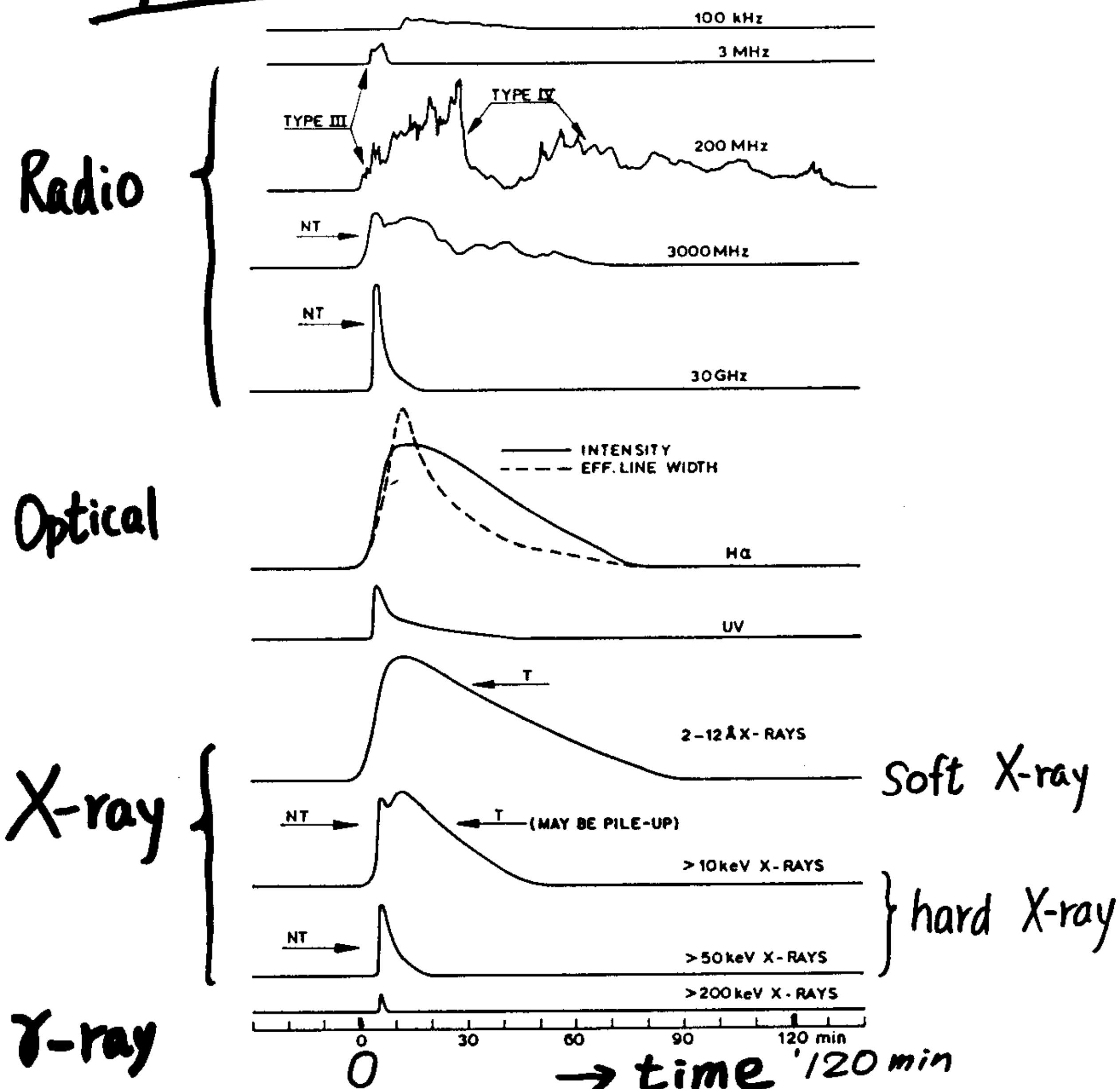


Fig. 2. Typical curves of the flare time development at different wavelengths: 3 km (100kHz) 100 m (3 MHz), 1.5 m (200 MHz), 10 cm (3000 MHz), 1 cm (30 GHz), 6563 Å (Hα), 300–1500 Å (UV), 2–12 Å, <1.2 Å (>10 keV), <0.25 Å (>50 keV), and <0.06 Å (>200 keV). *NT* indicates a non-thermal and *T* a quasi-thermal component of a burst. The lowest frequency is recorded in a radio type III, and the highest one in a hard X-ray burst. In exceptional cases, a γ-ray burst at still higher frequencies can be observed, with time development probably similar to the hard X-ray burst, but slightly delayed (cf. Figure 118).

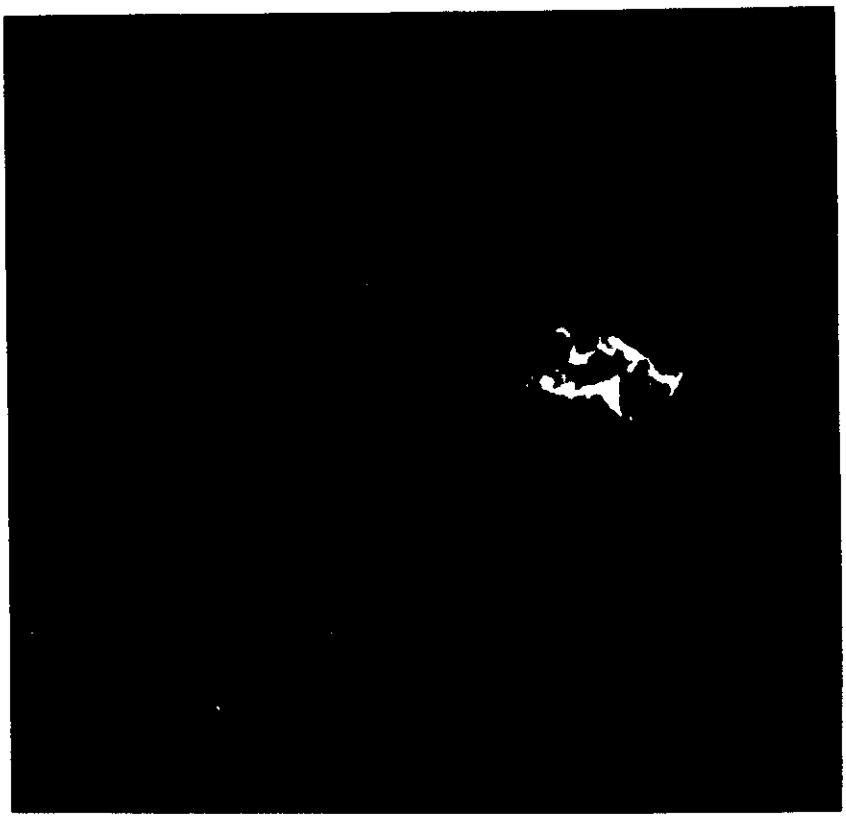
from Svestka "Solar Flares" (1976)

Figure 3 shows in a schematic way the energy range of protons and electrons that are produced in flares and either can be observed directly in space or deduced from effects they produce on the Sun. The curve shows the maxwellian distribution of thermal particles which exists in each flare at temperatures between several million degrees and more than 10^7 deg (here $T = 10^7$ K has been chosen as an example).

A Solar Flare Observed in Hα Image

Hα (水素のバルマー線) で見た 太陽フレア

1982年9月4日　乗鞍



energy source

magnetic energy stored in the solar atmosphere

$$E_{mag} = \frac{B^2}{8\pi} L^3$$

$$\approx 4 \times 10^{32} \text{ erg} \left(\frac{B}{100\text{G}}\right)^2 \left(\frac{L}{10^{10}\text{cm}}\right)^3$$

this is sufficient to explain observed total energy of flares

$10^{29} - 10^{32}$ erg

Basic difficulty to understand flares

observed time scale : $t_{flare} \approx$ a few min – a few hours

magnetic diffusion time : t_D

$$t_D = \frac{L^2}{\eta_{spitzer}}$$

$$\approx 10^{14} \left(\frac{L}{10^9 cm}\right)^2 \left(\frac{T}{10^6 K}\right)^{\frac{3}{2}} \text{ sec}$$

$$\approx 3 \times 10^6 \text{ year } ! \gg t_{flare}$$

Alfven time : t_A

$$t_A = \frac{L}{V_A}$$

$$\approx 10 \left(\frac{L}{10^9 cm}\right) \left(\frac{B}{10 G}\right)^{-1} \left(\frac{n}{10^9 cm^{-3}}\right)^{1/2} \text{ sec}$$

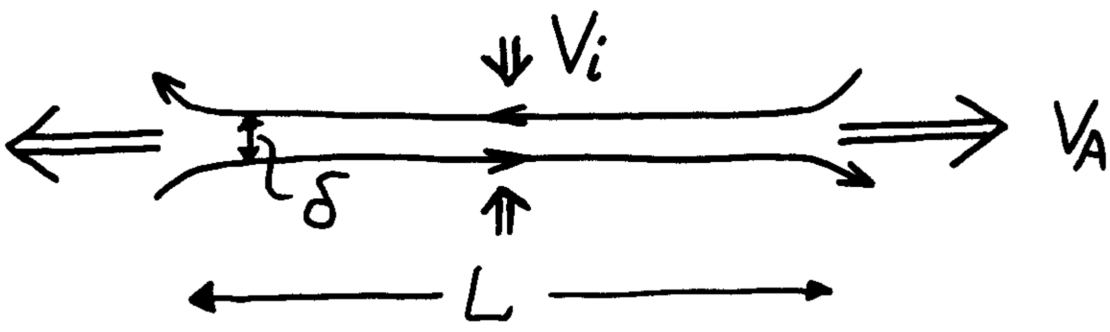
magnetic Reynolds number

$$R_m = \frac{V_A L}{\eta_{spitzer}} = \frac{t_D}{t_A} \approx 10^{13} \gg 1$$

Magnetic Reconnection Theory

Sweet – Parker model (1957)

effect of flow



$$\delta = L\, R_m^{-\frac{1}{2}}$$

$$V_i = V_A\, R_m^{-\frac{1}{2}}$$

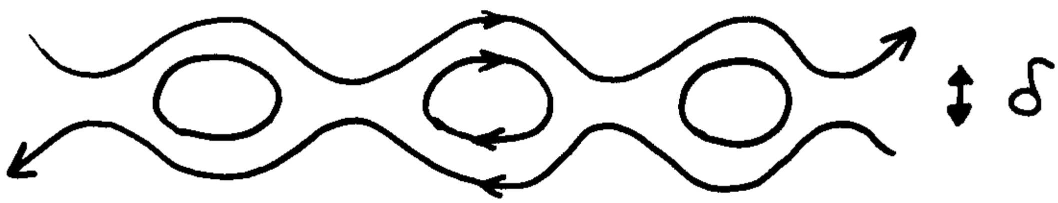
$$t_{rec} = \frac{L}{V_i} = t_A\, R_m^{\frac{1}{2}} \gg t_{flare}$$

$$\approx 10\text{-}100\, t_A$$

$$\left(\begin{array}{l} R_m = \dfrac{V_A L}{\eta_{spitzer}} \approx 10^{13} \\ t_A = L/V_A \end{array} \right)$$

much faster than simple diffusion
but still much slower than
real solar flare

Tearing Instability (Furth, Killeen, Rosenbluth 1963)



$$t_{tearing} \sim (t_D t_A)^{\frac{1}{2}}$$

$$\sim t_A R_m^{\frac{1}{2}} \gg t_{flare}$$

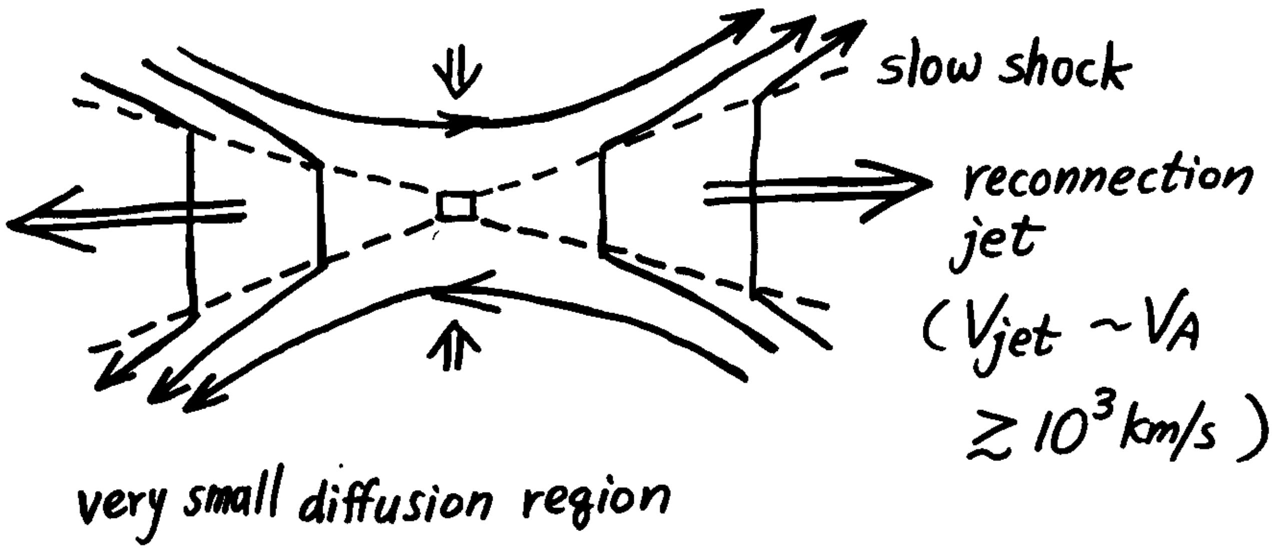
$$t_D \equiv \frac{\delta^2}{\eta}$$

$$t_A \equiv \frac{\delta}{V_A}$$

$$R_m \equiv \frac{\delta V_A}{\eta}$$

Petschek model (1964)

effect of slow shock : $\frac{B^2}{8\pi} \rightarrow \frac{1}{2}\rho v^2$



$$t_{rec} \approx 10-100\ t_A \sim t_{flare}\ !$$
$$(\propto R_m{}^0)$$

Numerical Simulation

Ugai and Tsuda (1977)

Sato and Hayashi (1979)

confirmed Petschek model

Controversies

Biskamp (1986) criticized Petschek model, and showed external driving under uniform resistivity does not lead to fast (Petschek) reconnection

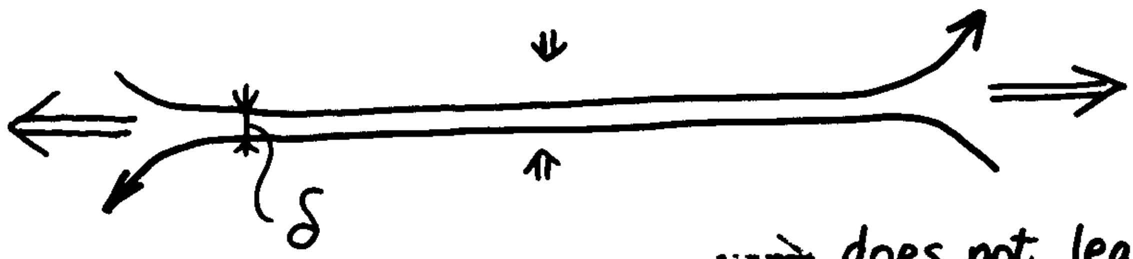
Priest and Forbes (1989)
boundary condition (external driving) is essential for fast reconnection

Tajima and Sakai (1986, 89)
localized current distribution with nonsteady effect can lead to fast (explosive) reconnection

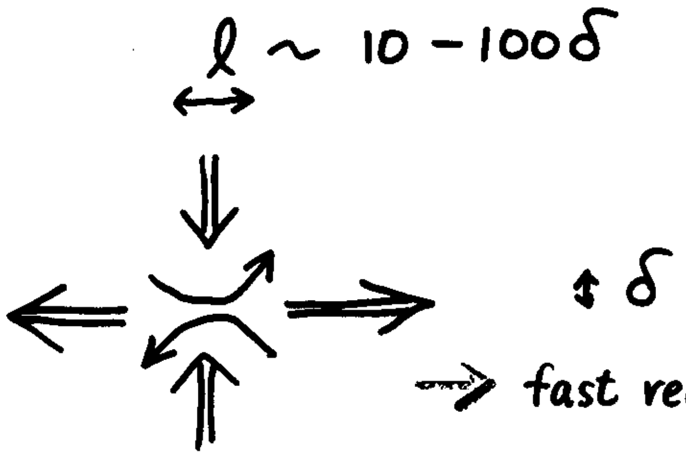
Ugai (1986-97), Scholer (1987), Jamitzky (1997), Yokoyama-Shibata (1994)
partly in agreement with Biskamp (1986), but showed that localized resistivity (such as anomalous resistivity) can lead to fast reconnection
→ needs very small scale

$$r_{\text{ion-Larmor}} \sim 10^2\,\text{cm} \ll L_{\text{flare}} \sim 10^9\,\text{cm}$$

We need not only thin current sheets
but also localized current sheets



⇢ does not lead to fast reconnection



→ fast reconnection

What is the condition for localized current sheet ?

Fundamental questions

- What is the condition for fast reconnection ?
  (localized current sheet)

- Is magnetic reconnection really occurring in solar flares ?

- If yes, is magnetic reconnection important in solar flares ?

[Note that there are many anti-reconnection models for flares
e.g., Alfven, Akasofu, ...
Feldman, ...]

2. Yohkoh Observations of Solar Flares

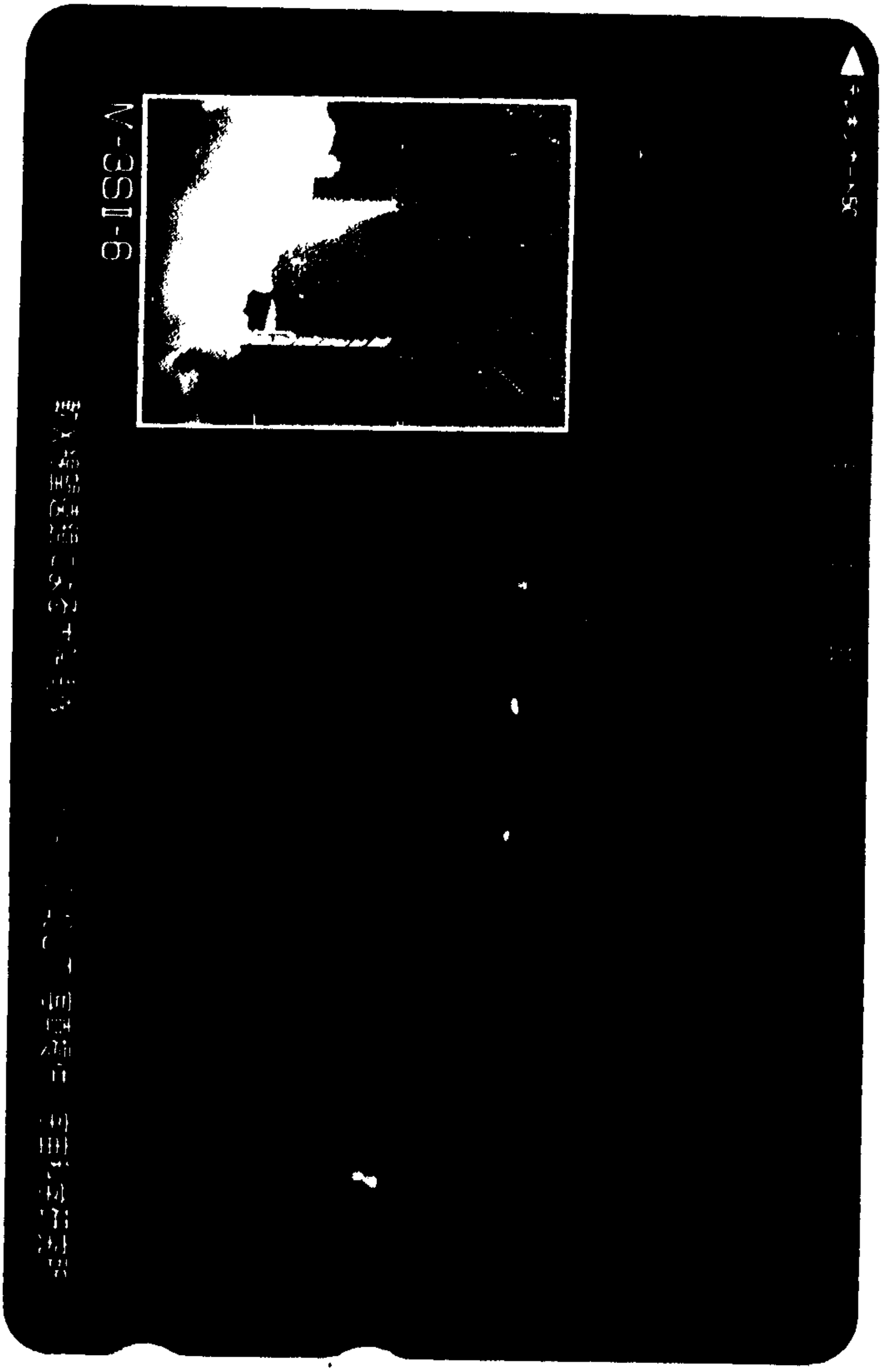
Yohkoh = 陽光 "sun beam"
ようこう

Solar X-ray observing satellite
launched on Aug. 30, 1991
(Japan – US – UK project)

- soft X-ray telescope (SXT) — ~1 keV, thermal plasma ($2-20\times10^6$ K)
- hard X-ray telescope (HXT) — 10 – 100 keV, non-thermal electron

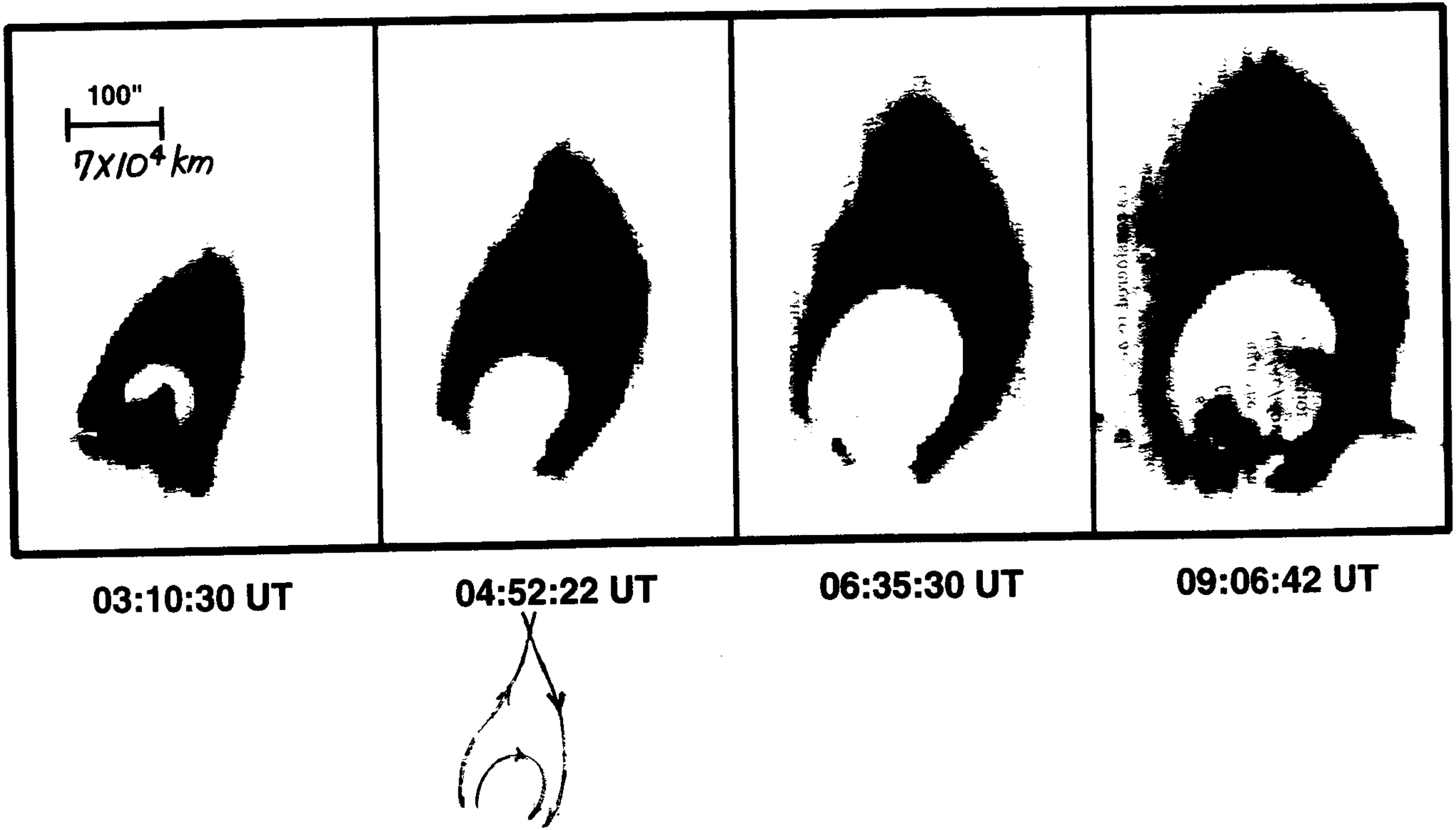
Yohkoh discovered that

- solar corona is much more dynamic than had been thought
- a lot of <u>evidence of reconnection</u> in flares (e.g., cusp, plasmoid, jets, …)



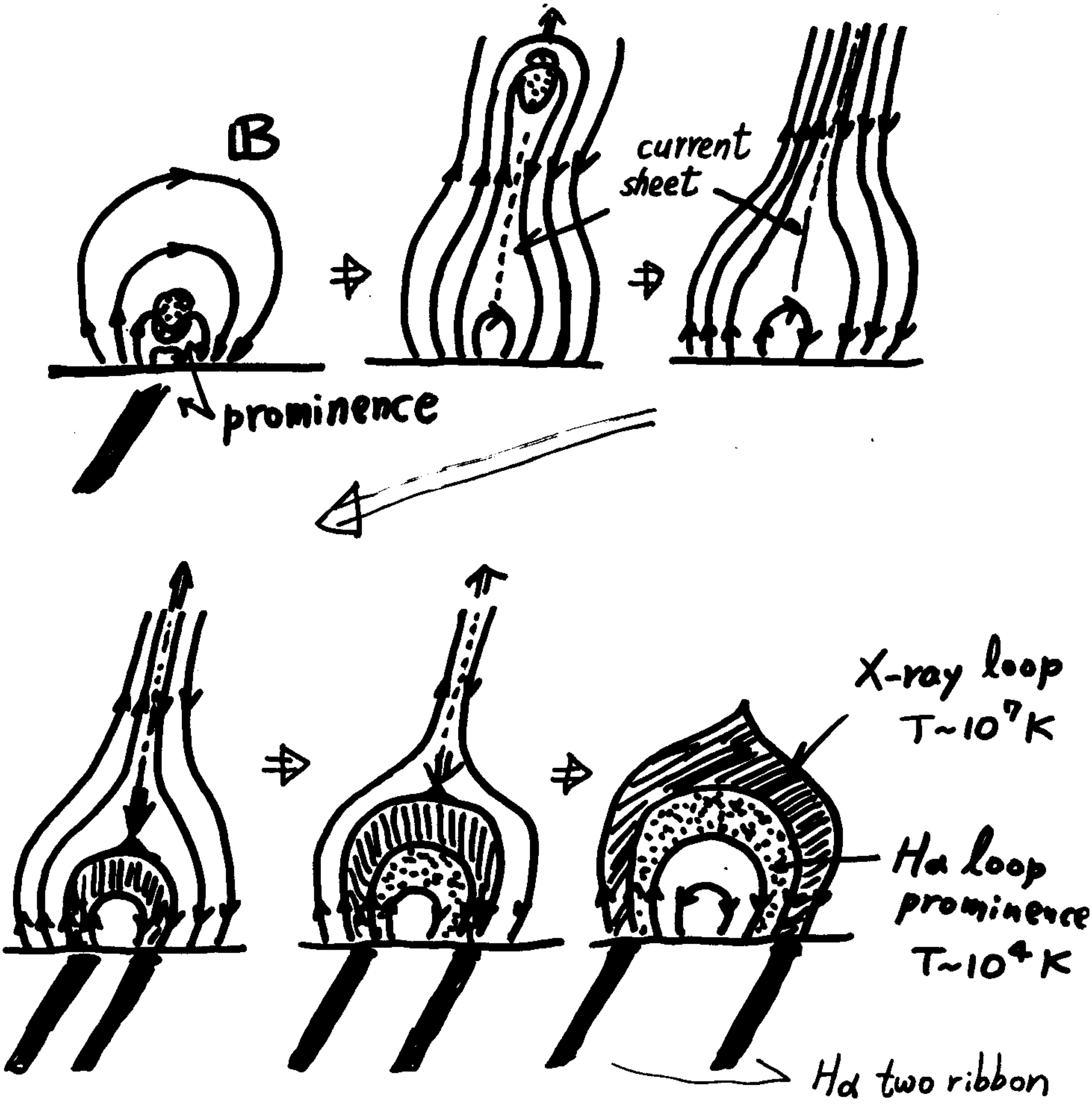
Cusp-shaped Flare

21-FEB-1992 Flare SXT Image Filter : Al.1 Tsuneta (1992, 1996)



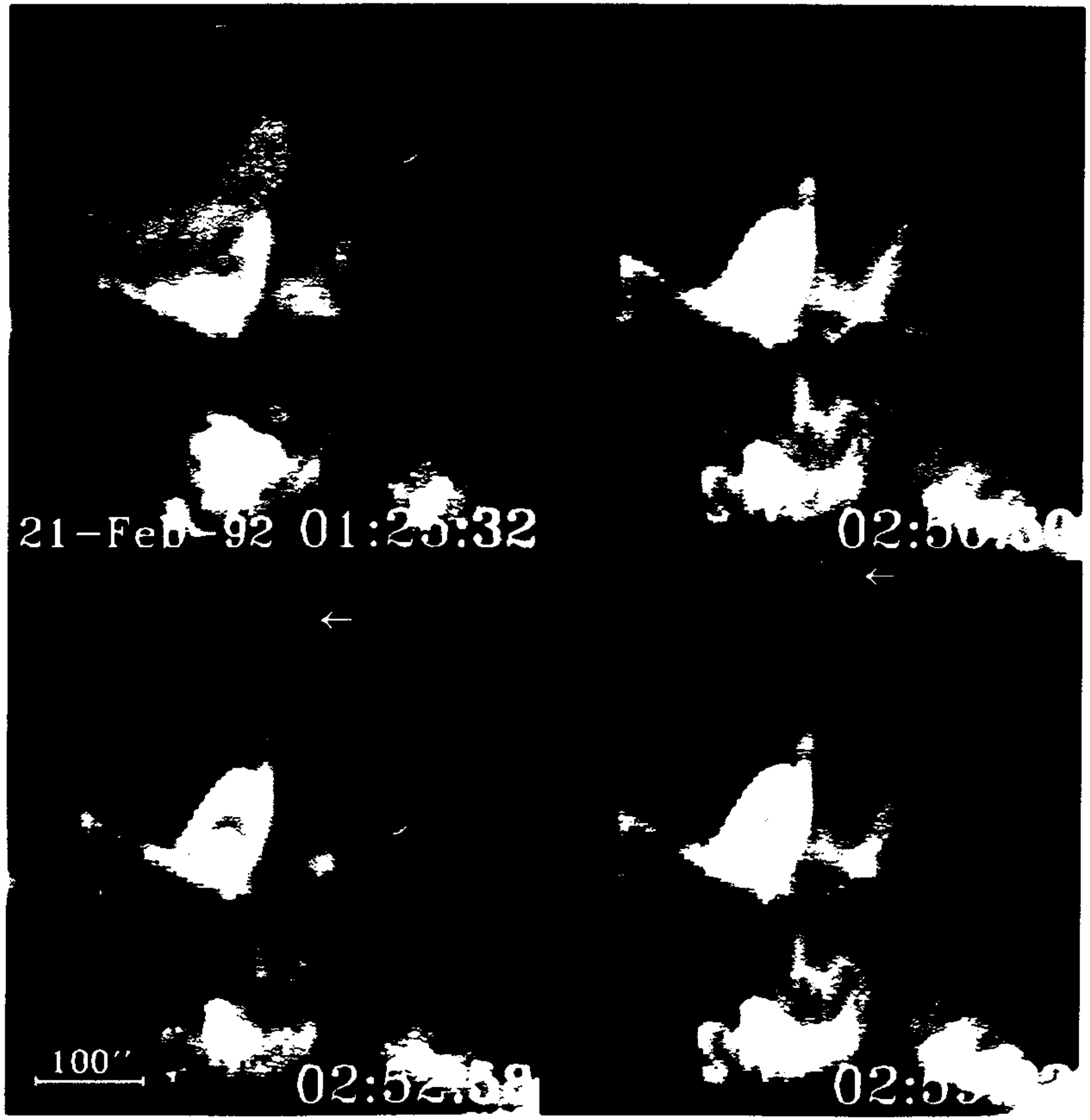
CSHKP model

Carmichel (1964), Sturrock (1966)
Hirayama (1974), Kopp-Pneuman (1976)



plasmoid ejection in LDE flare

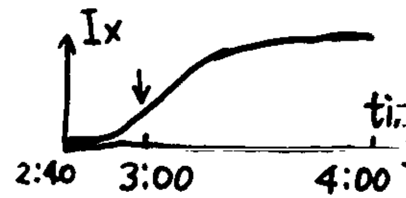
preflare



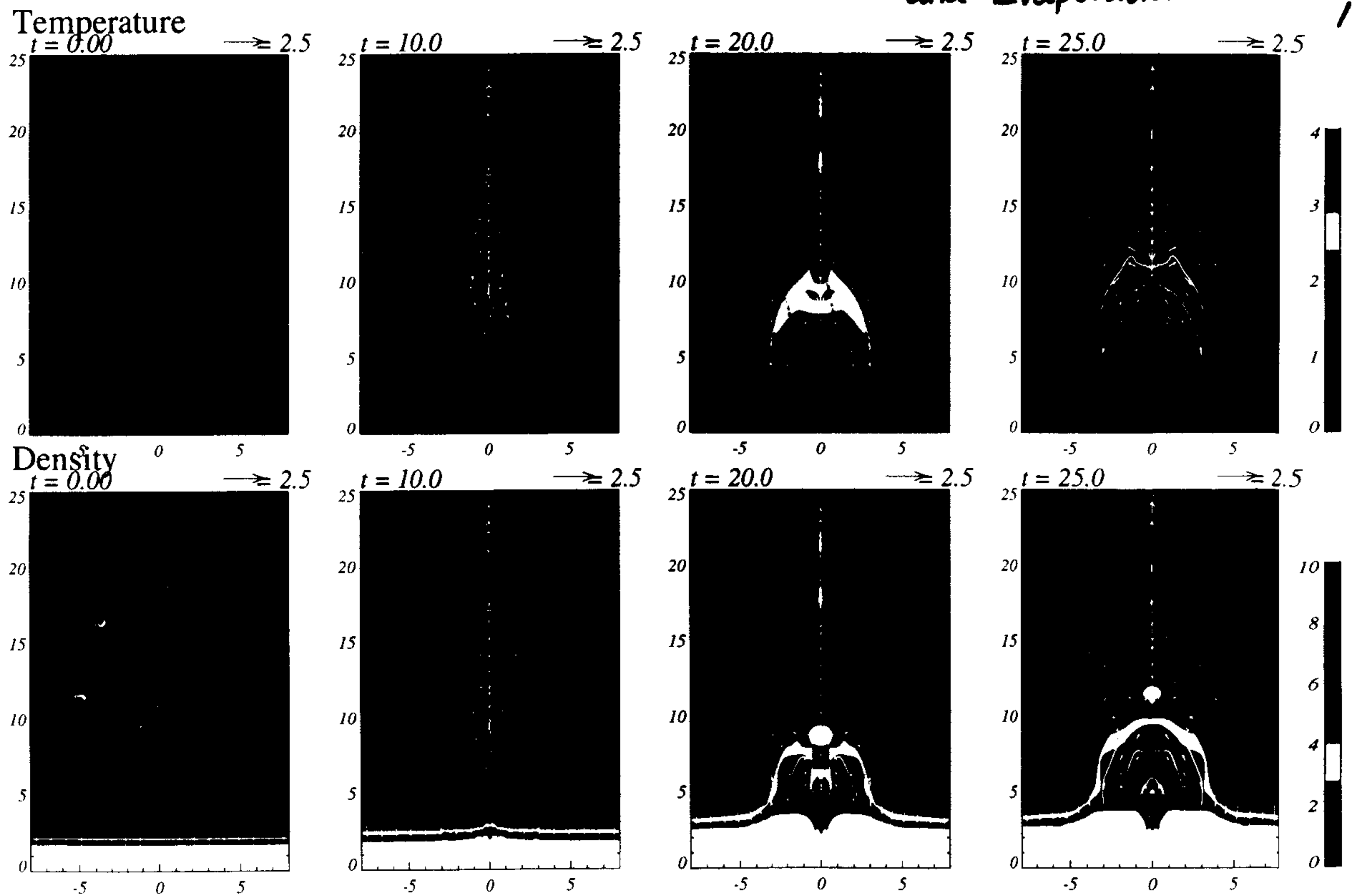
21 Feb 92
(Hudson 1994)

V~100 km/s

rise phase



Magnetic Reconnection Coupled with Heat Conduction and Evaporation (Yokoyama, Shibata 1997)



$\beta = 0.2$, $T_0 = 2 \times 10^6$ K, $L = 3 \times 10^8$ cm, $\tau = 18$ s, $n_0 = 10^9\ cm^{-3}$

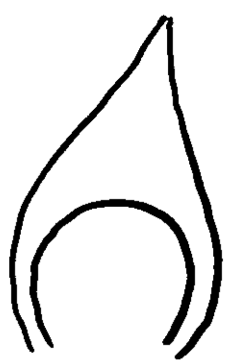
LDE flares vs. Impulsive flares
(long duration event)

arcade flares vs. loop flares

CME related flares vs. compact flares

ejective flares vs. confined flares

cusp



reconnection

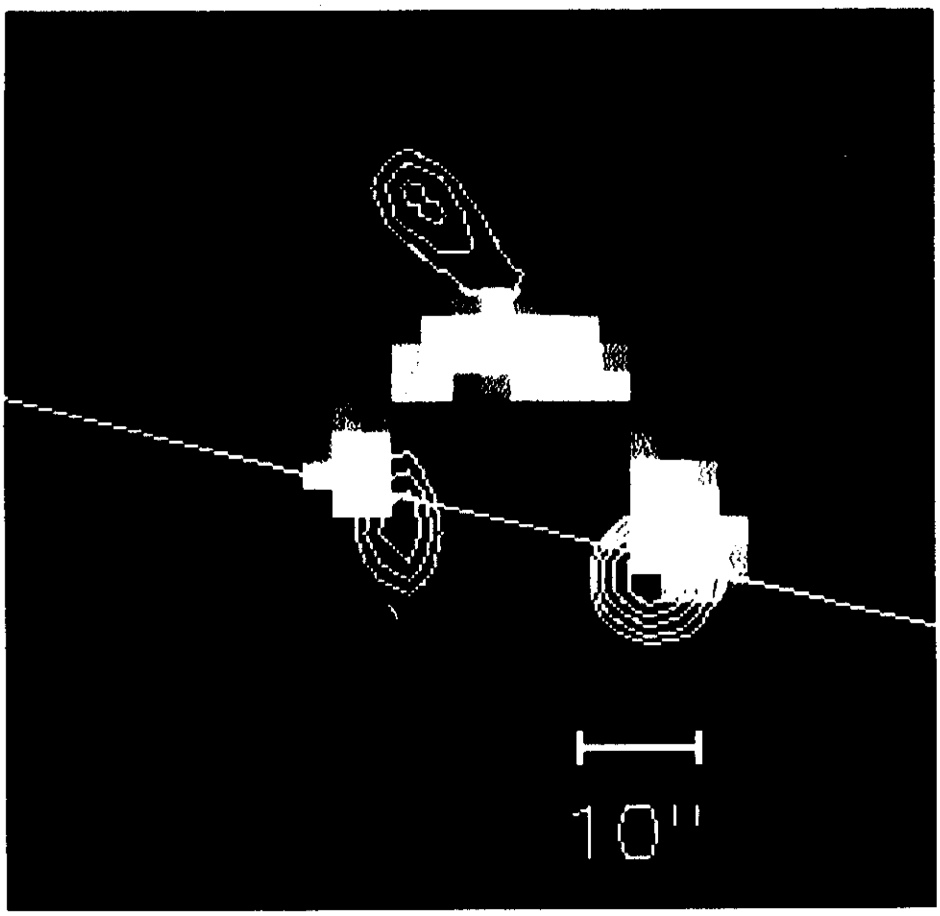
non-cusp

non-reconnection ?

Impulsive Flare
インパルシブ・フレア

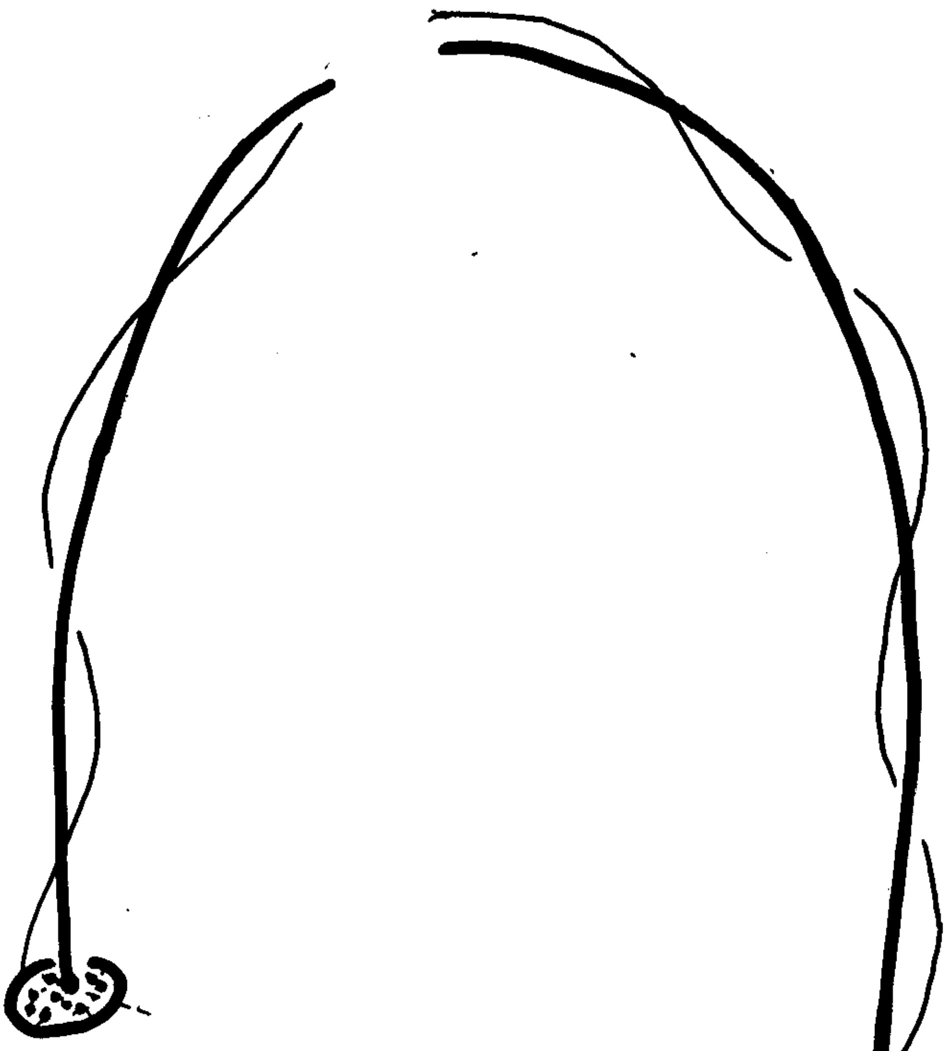
Hard X-ray→
Loop Top
Source

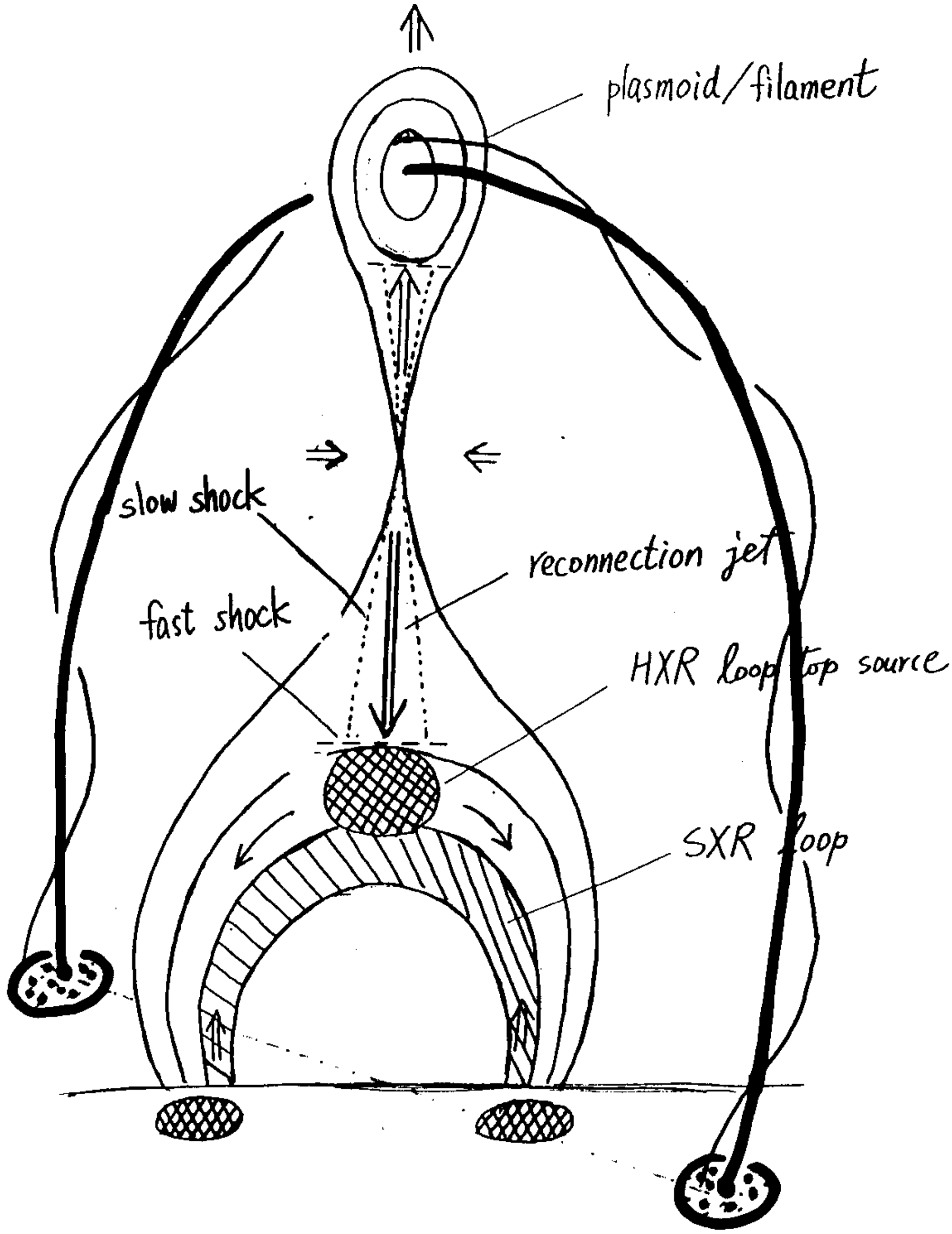
hard X-rays
(contour)
+
soft X-rays
(color)



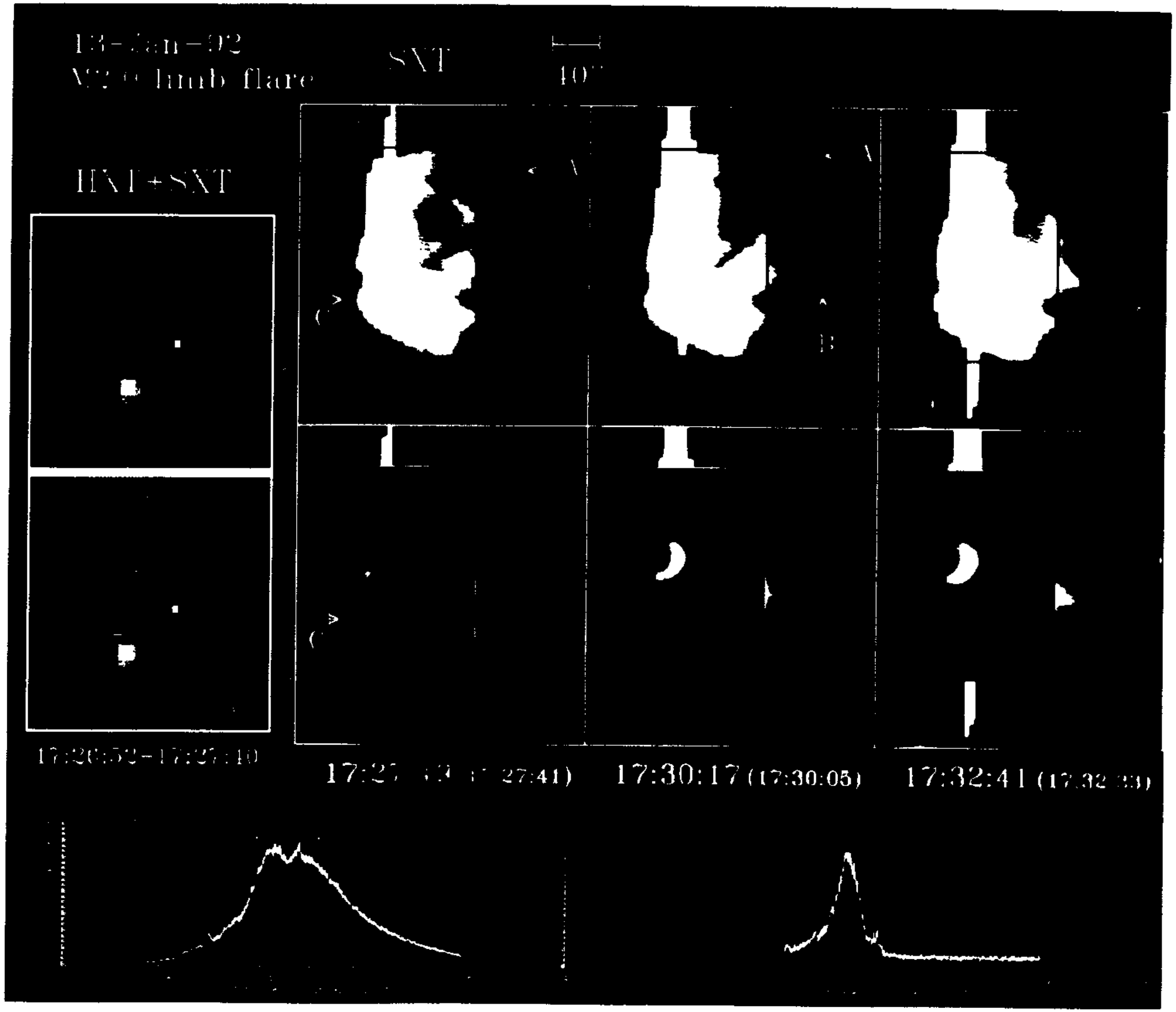
硬X線像
(等高線)
+
軟X線像
(偽似カラー)

Masuda et al. (1994)
Nature 371, 495



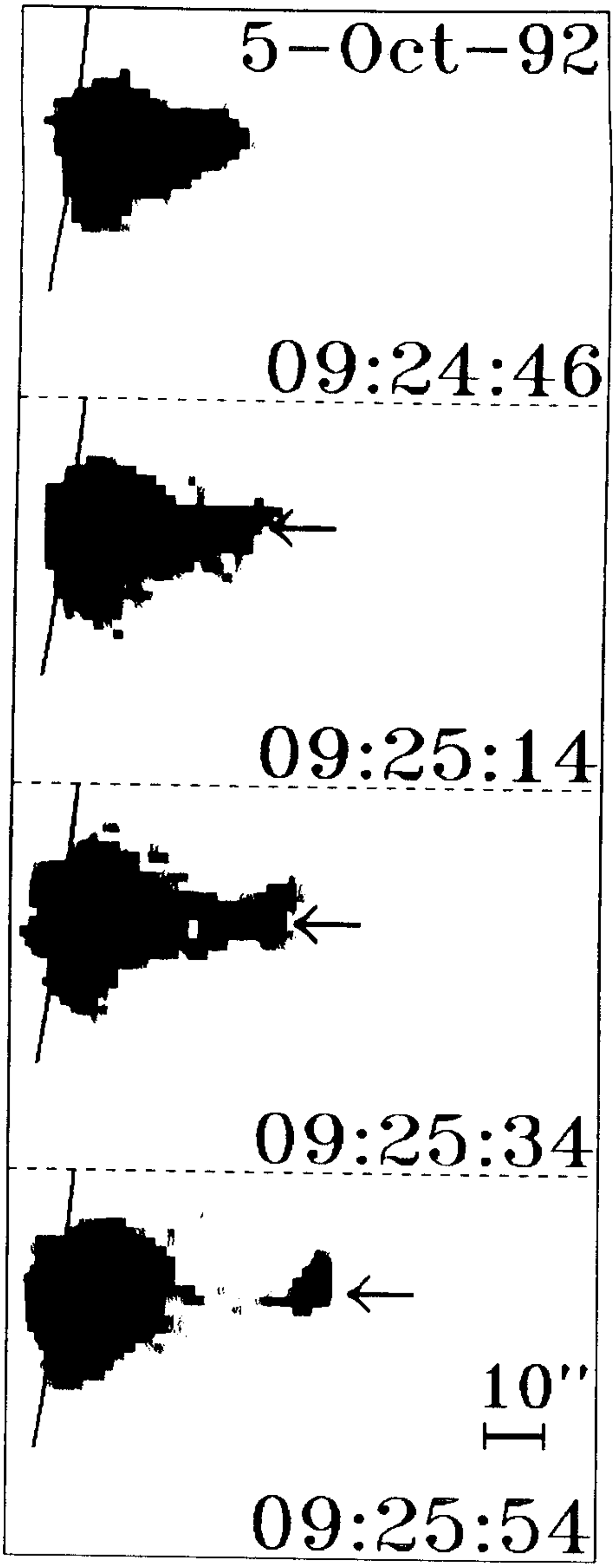

plasmoid/filament
slow shock
reconnection jet
fast shock
HXR loop top source
SXR loop

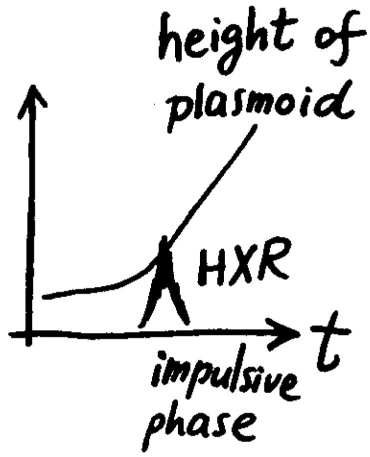
X-ray filament/plasmoid eruption in impulsive flare 13-Jan-9



Shibata et al. (1995) Ap. J. Lett. 451

X-ray Plasmoid Ejections from Impulsive Flare on 5 Oct 1992
(Ohyama & Shibata 1997)





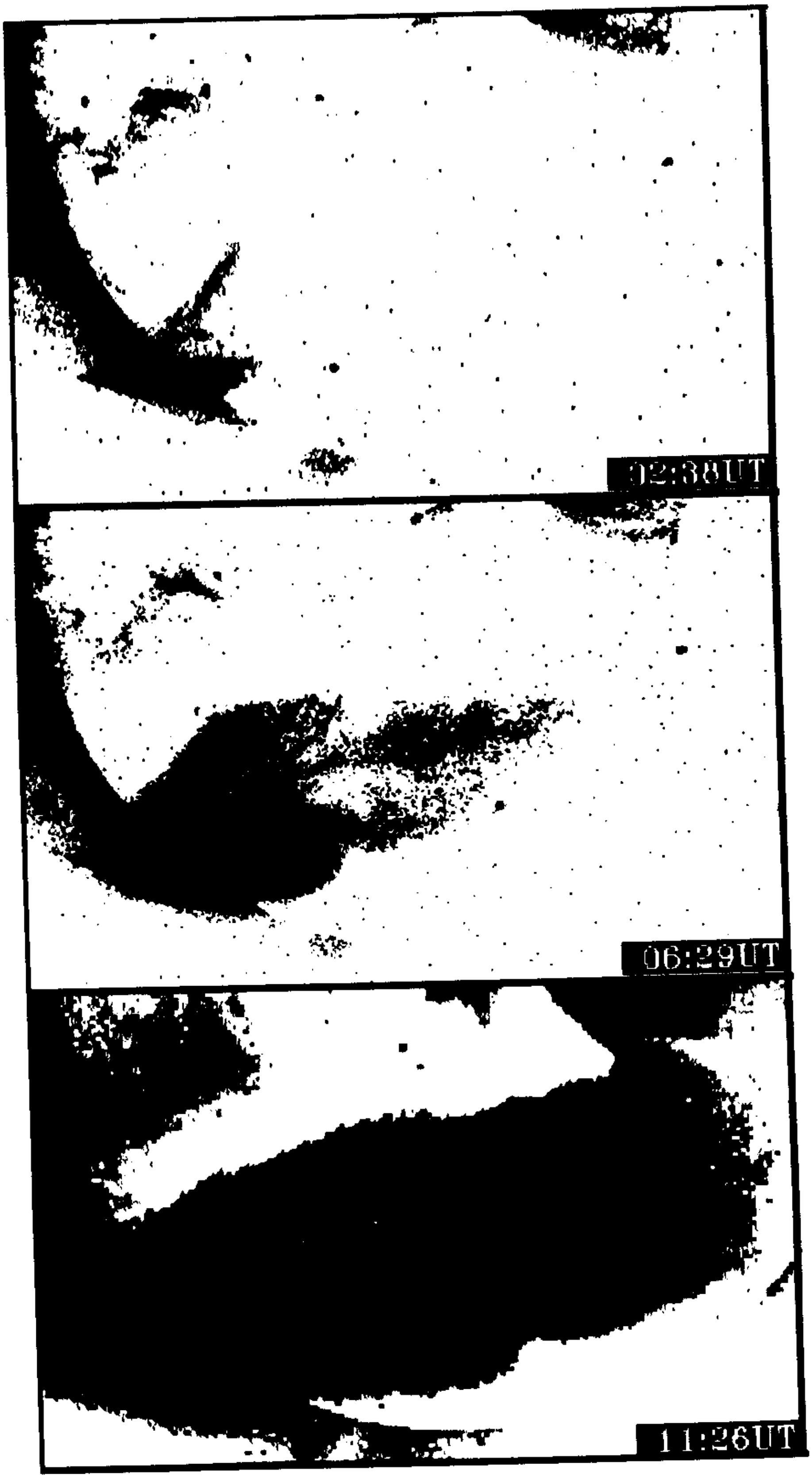
⇓

strong accel. of plasmoid before impulsive HXR peak

N
W

Large Scale Arcade Formation

(global restructuring) on 14 Apr 1994 (McAllister et al. 1995)



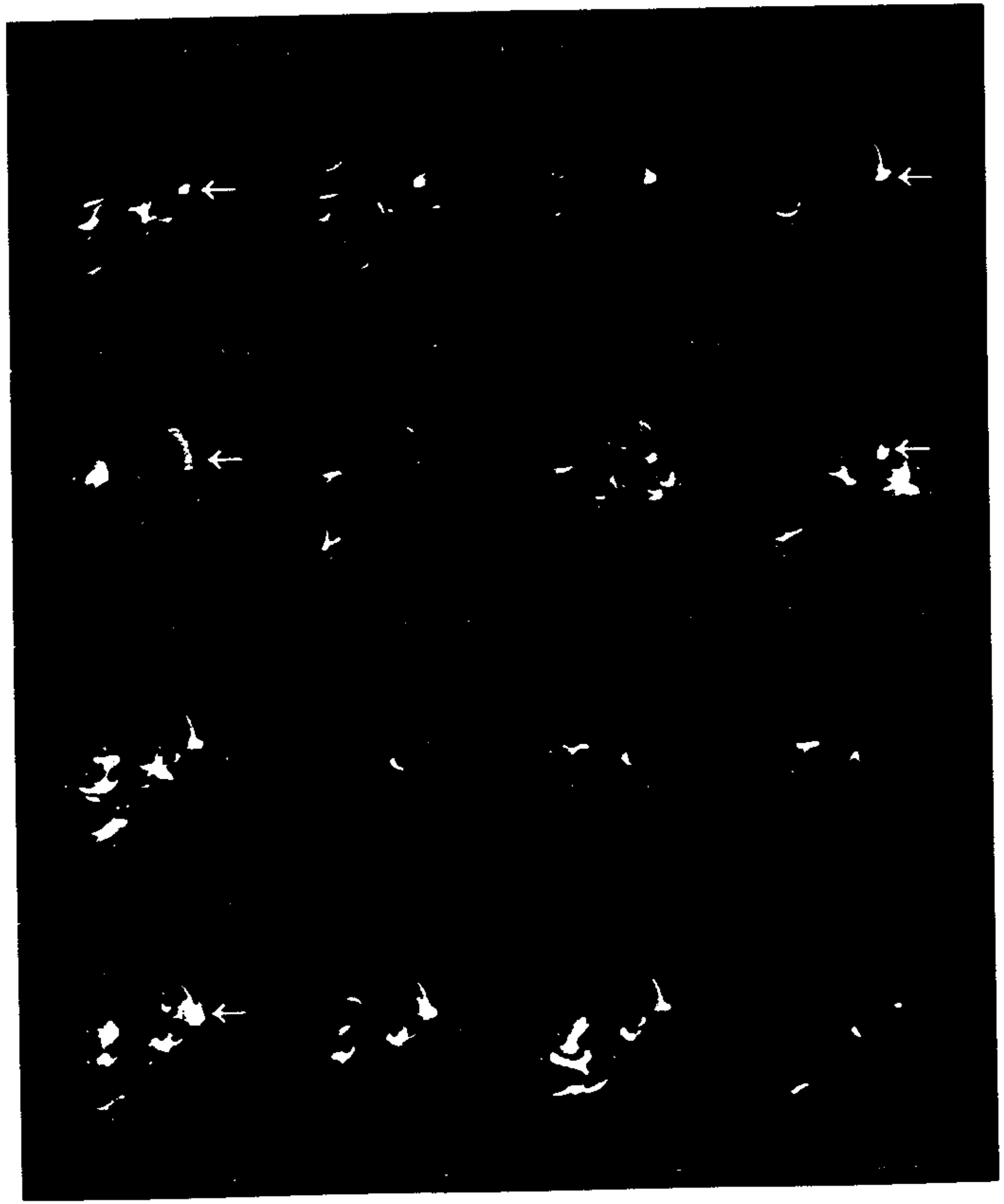
コロナ質量放出

Coronal
Mass
Ejection
(CME)

10-1000 km/s

Fig. 1.35. A coronal transient associated with a prominence eruption (10 June 1973), observed High Altitude Observatory coronagraph on board Skylab (courtesy R. MacQueen).

Active Region Transient Brightenings = microflares



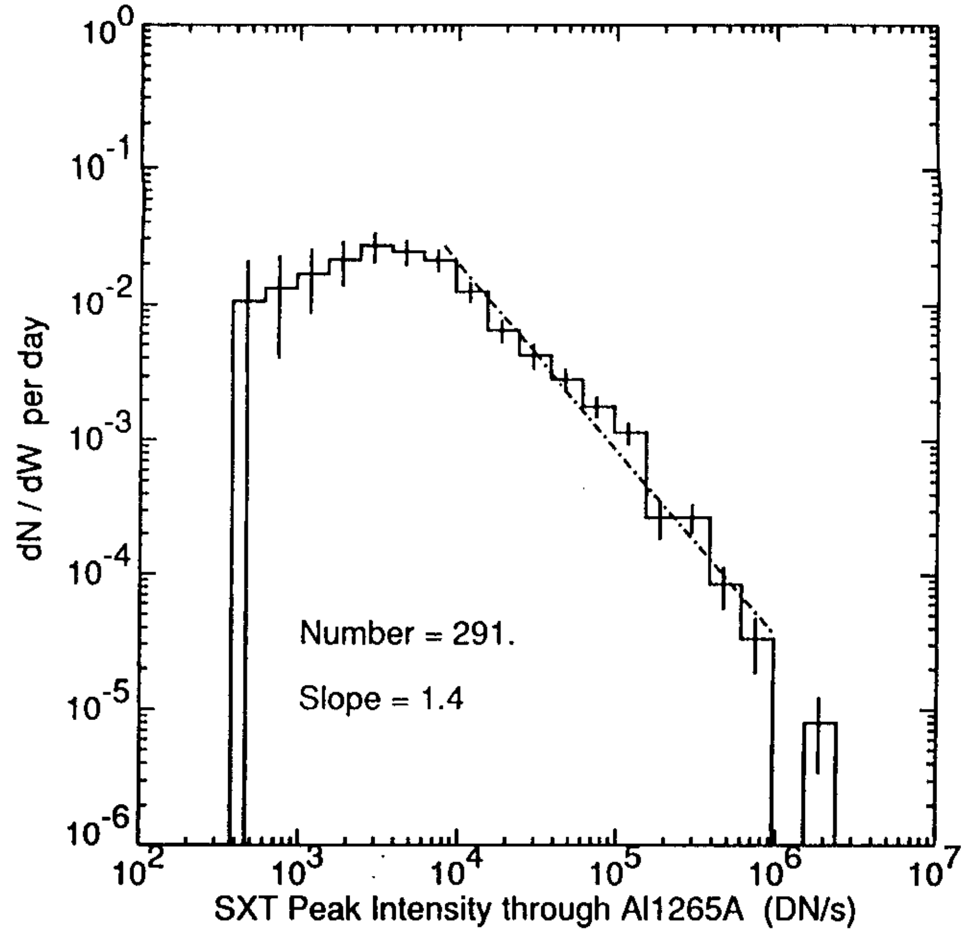
Shimizu et al.
(1992) PASJ **44**,
L147

$E \sim 10^{25} - 10^{29}$ erg

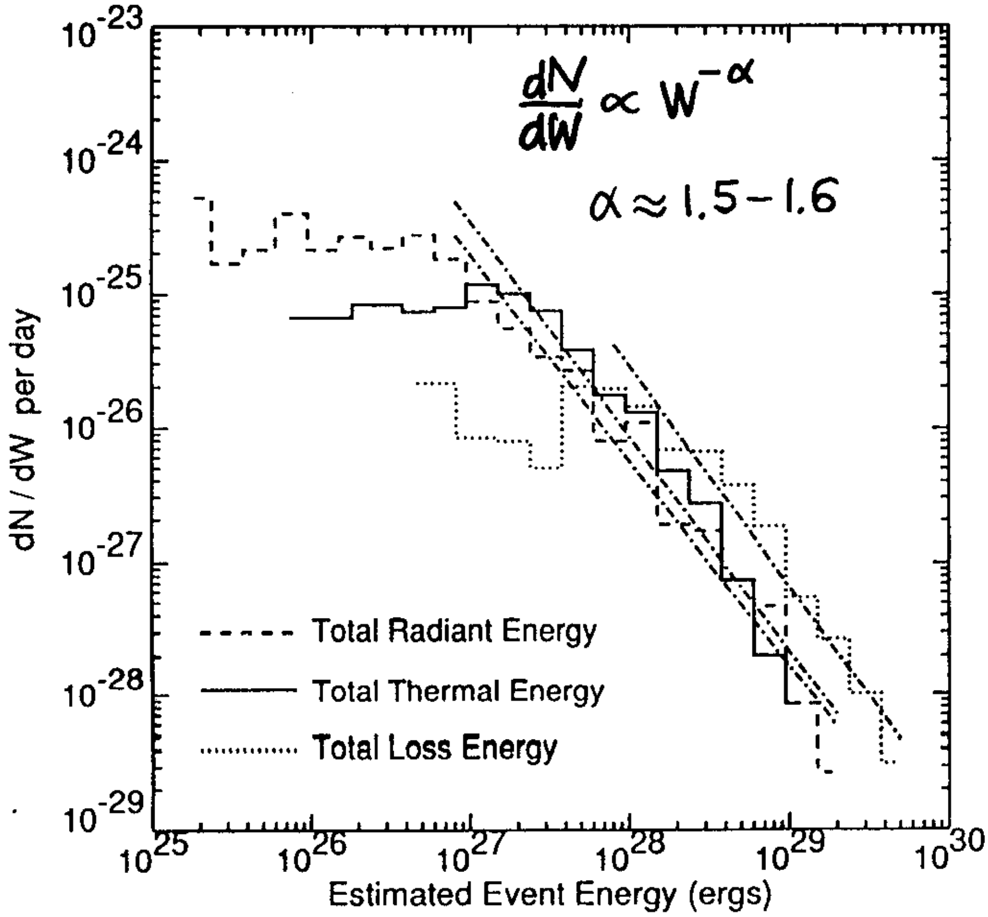
$t \sim 1 - 10$ min.

$\ell \sim 0.5 - 4 \times 10^{4}$ k

$T \sim 6 - 8$ MK

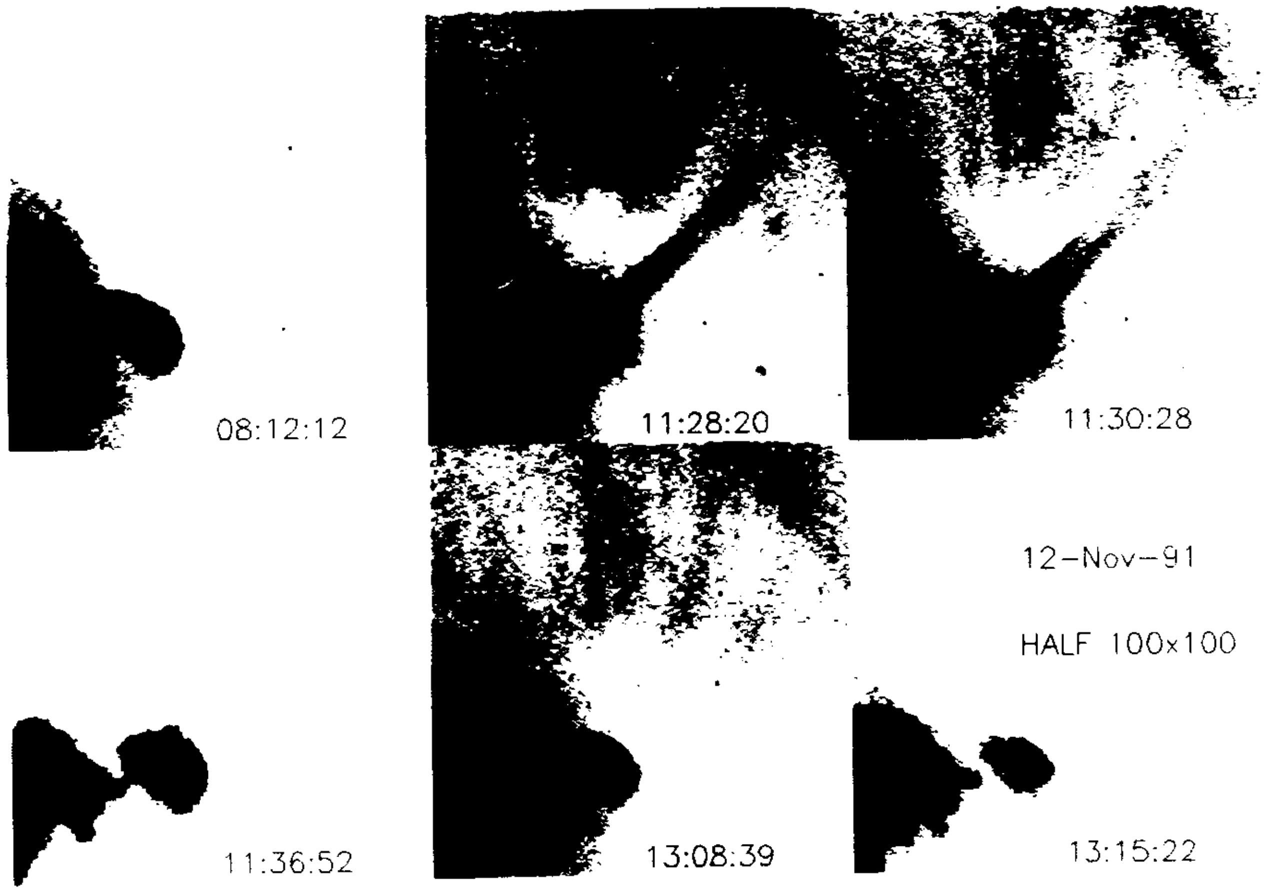


Kofu-symp fig 1



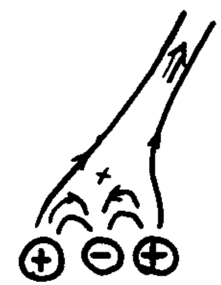
Shimizu (1995) PASJ 47, 251

Coronal X-ray Jet



length ~ 2×10^5 km

velocity ≳ 100 km/s

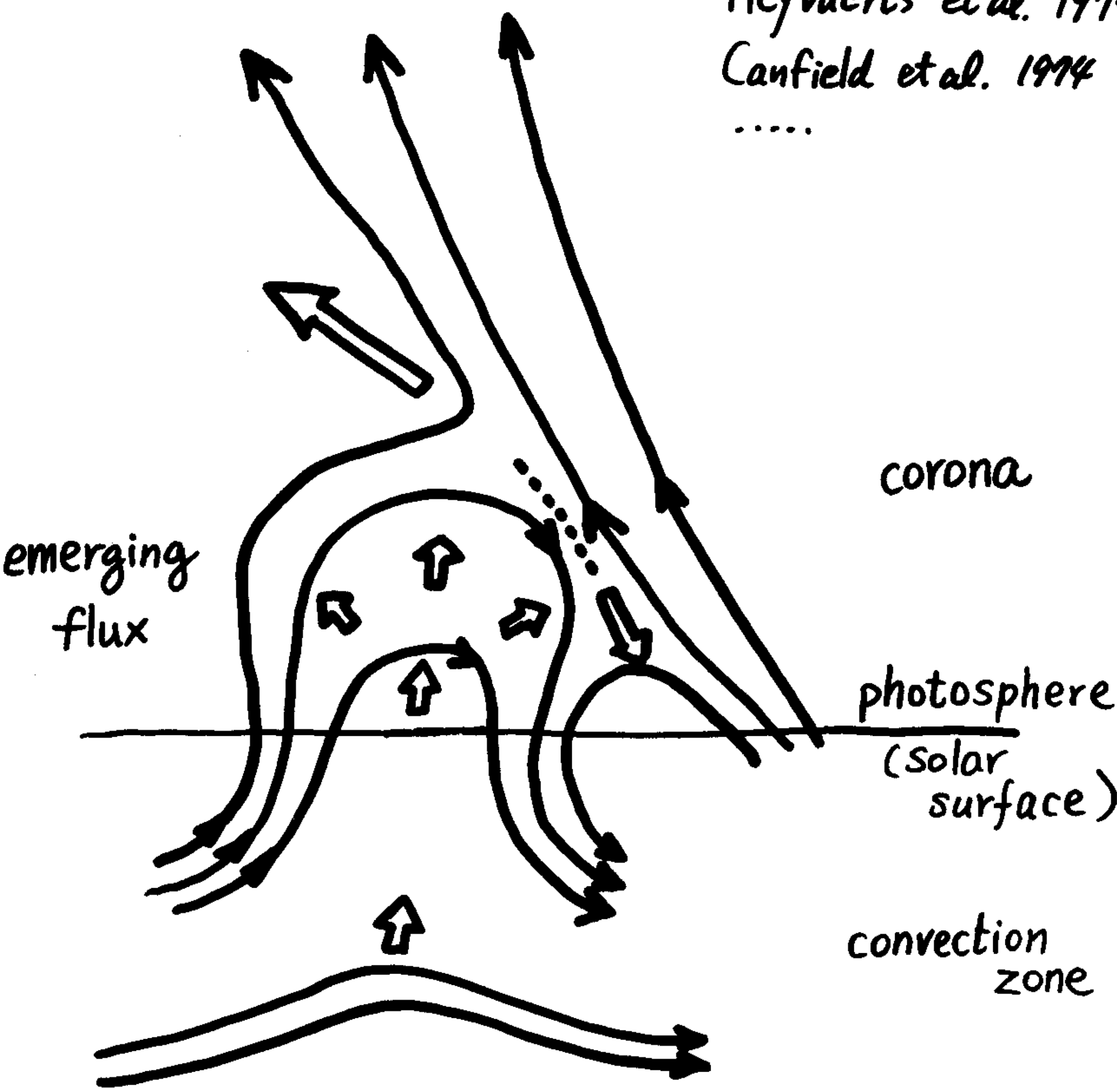


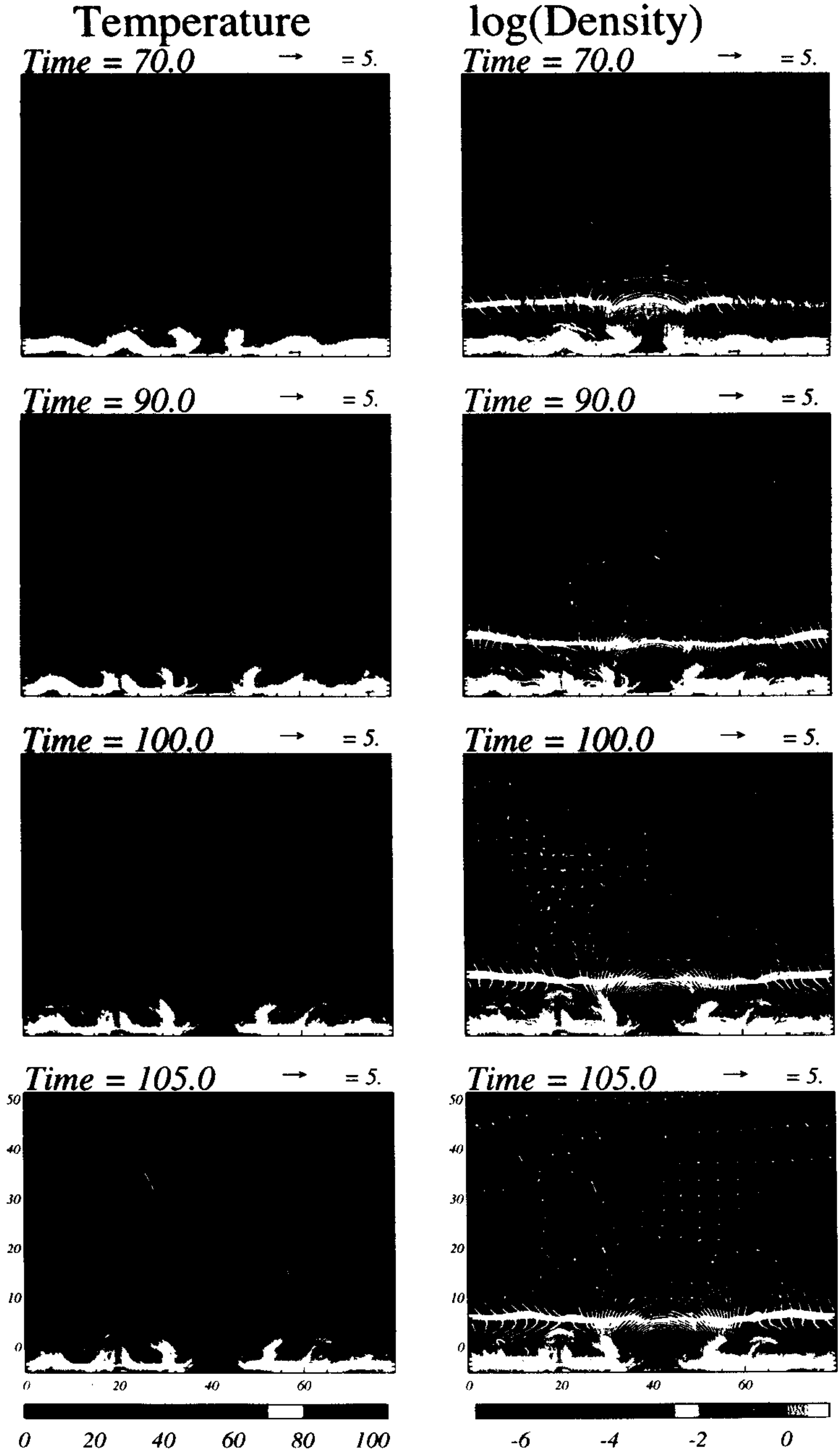
Shimojo et al. (1997)

Shibata et al. (1992)
PASJ 44, L173

Emerging Flux Model

Heyvaerts et al. 1974
Canfield et al. 1974
.....





$V_{jet} \sim V_A$

Yokoyama and Shibata (1995) Nature 375, 42
(1996) PASJ 48

Summary 1

flares	size $=l$ (km)	B (G)	E_{mag} (erg) (available energy)	t_A (sec)	t_{ob} (sec)
transient brightening (microflare)	10^3-10^4	10^2	4×10^{26} -4×10^{29}	0.1–1	10 -100(
impulsive flare	10^4-10^5	10^2	4×10^{29} -4×10^{32}	1–10	100 -100(
LDE flare	$\sim10^5$	30	$\sim4\times10^{31}$	~30	10^3 -10^4
global restructuring	$10^5\sim10^6$	10	4×10^{30} -4×10^{33}	50–500	10^4 -10

$$E_{mag} = \frac{B^2}{8\pi} l^3 \qquad t_A = l / V_A$$

$$V_A = \frac{B}{\sqrt{4\pi\rho}} = 10^4 \left(\frac{B}{100G}\right)\left(\frac{n_e}{10^9 cm^{-3}}\right)^{-\frac{1}{2}} \text{ km/s}$$

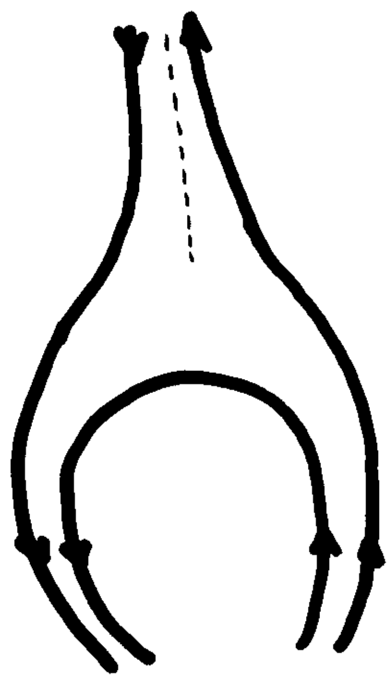
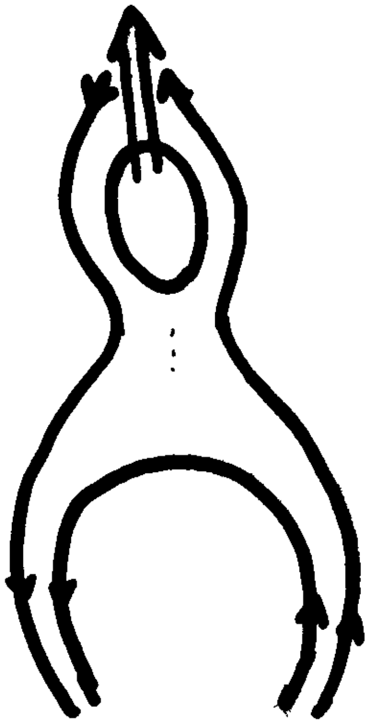
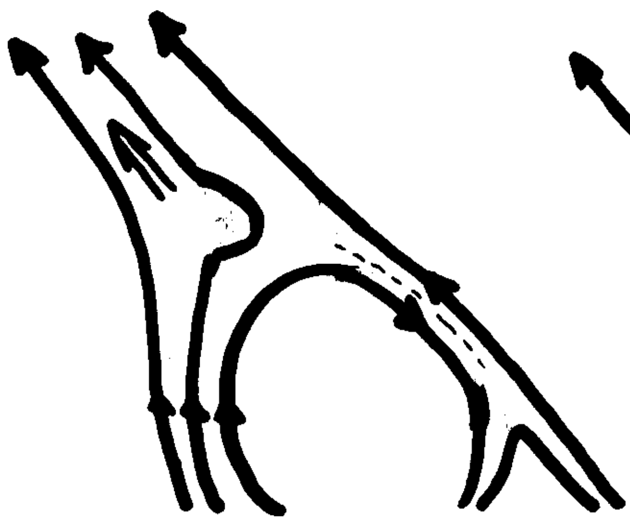
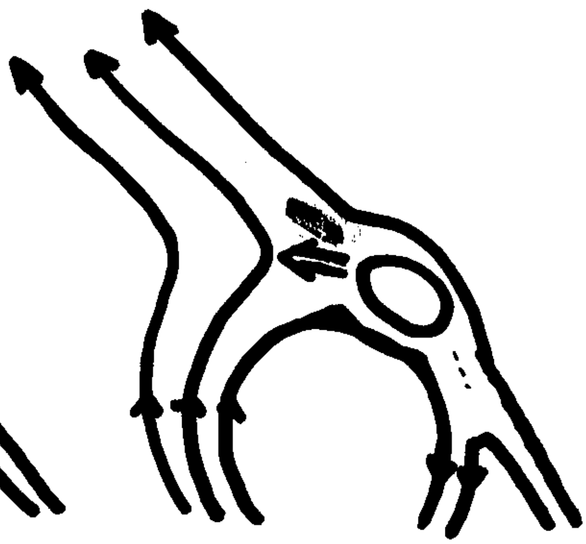
$$\frac{t_{obs}}{t_A} \approx 10-100$$

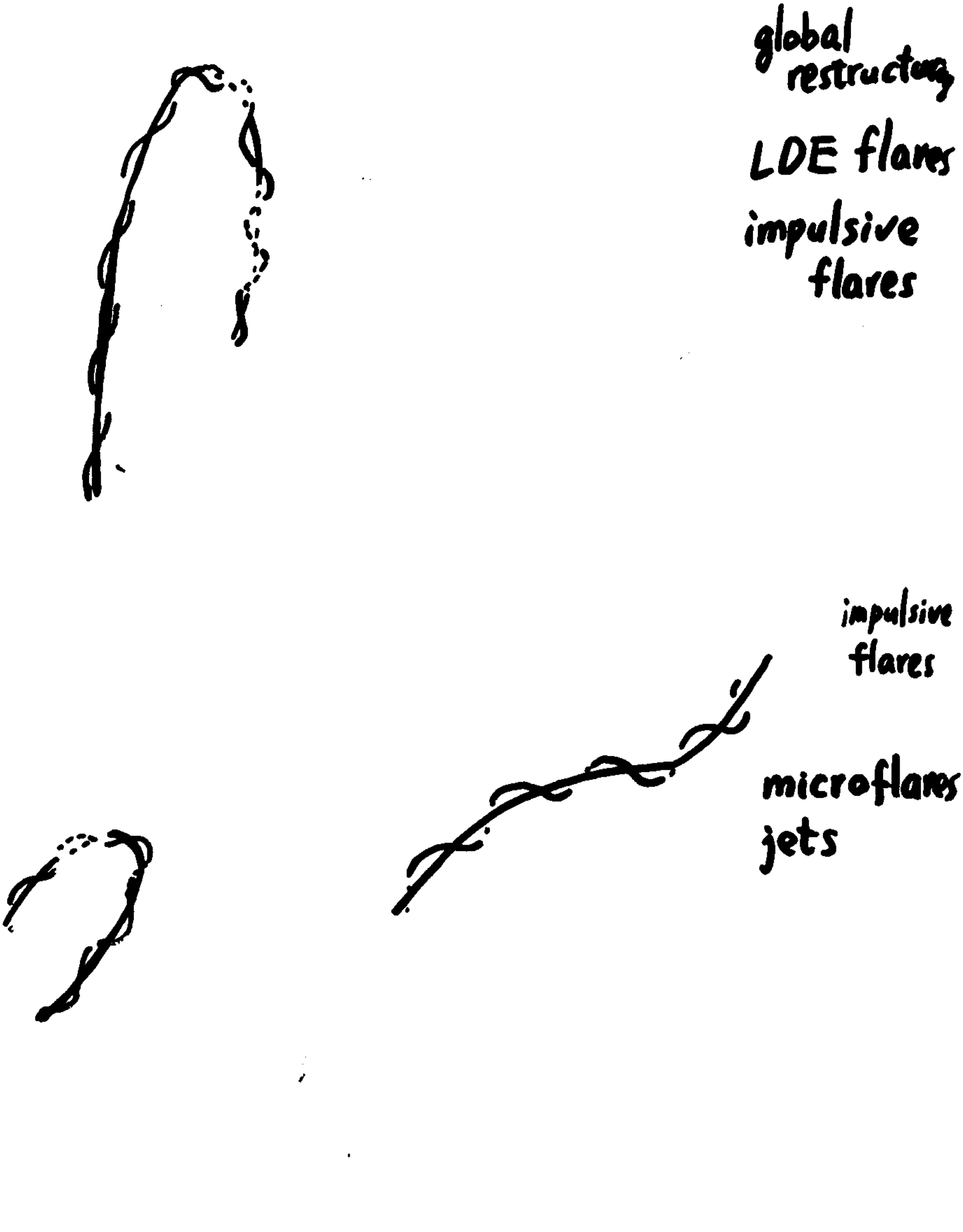
Summary ②

[Unified View of Flare – Mass Ejection Relation]

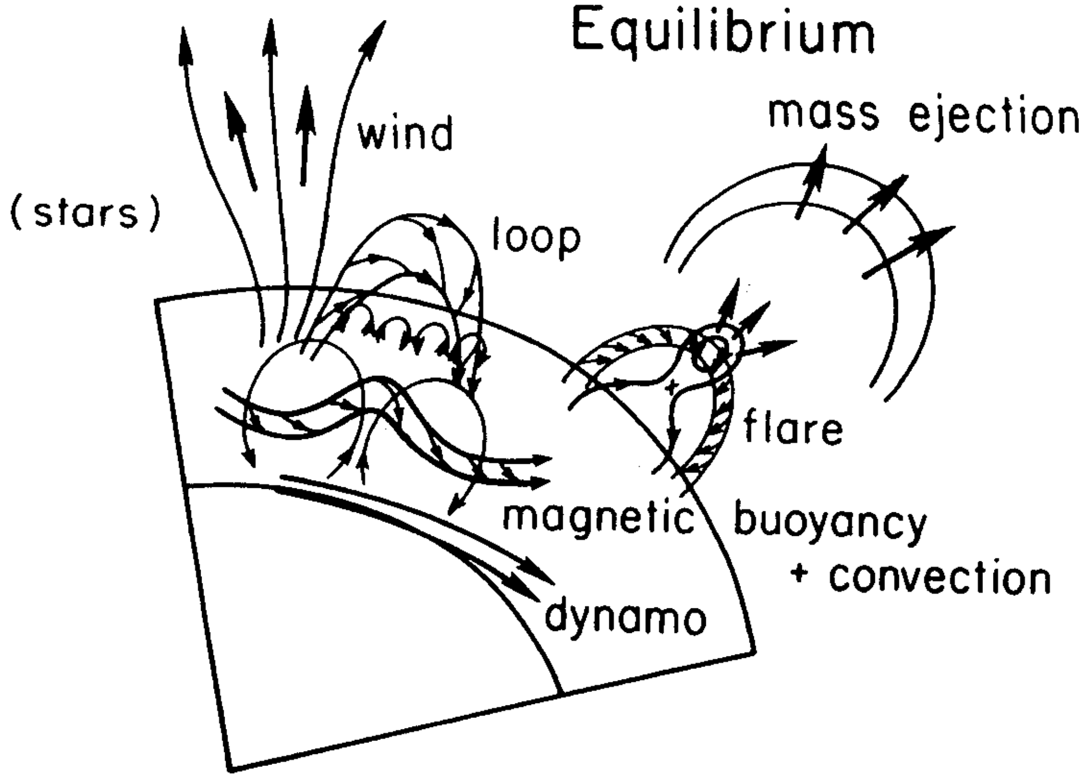
Flare	Mass Ejection: cool	Mass Ejection: hot
global restructuring	Hα filament eruption	CME
LDE flare	Hα filament eruption	X-ray plasmoid ejection / CME
impulsive flare	Hα spray	X-ray plasmoid ejection
transient brightening (microflare)	Hα surges	X-ray jet

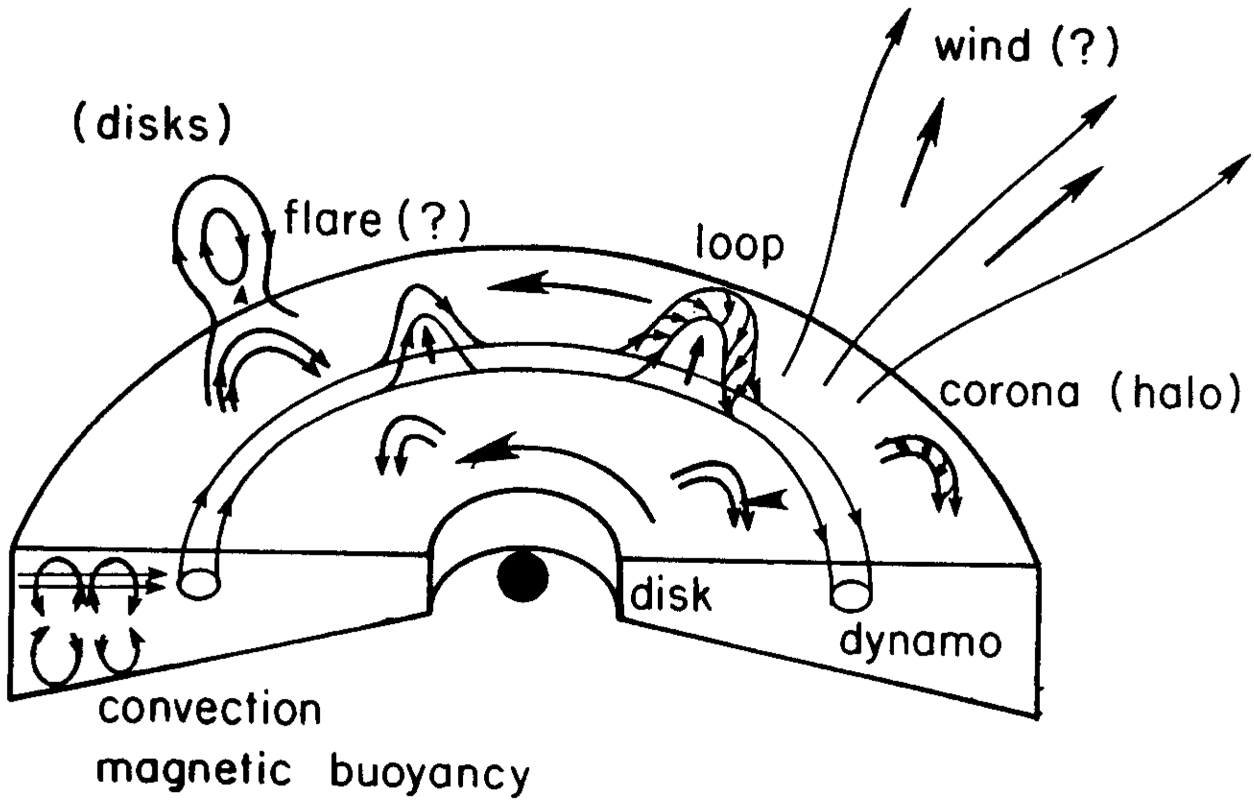
YOHKOH

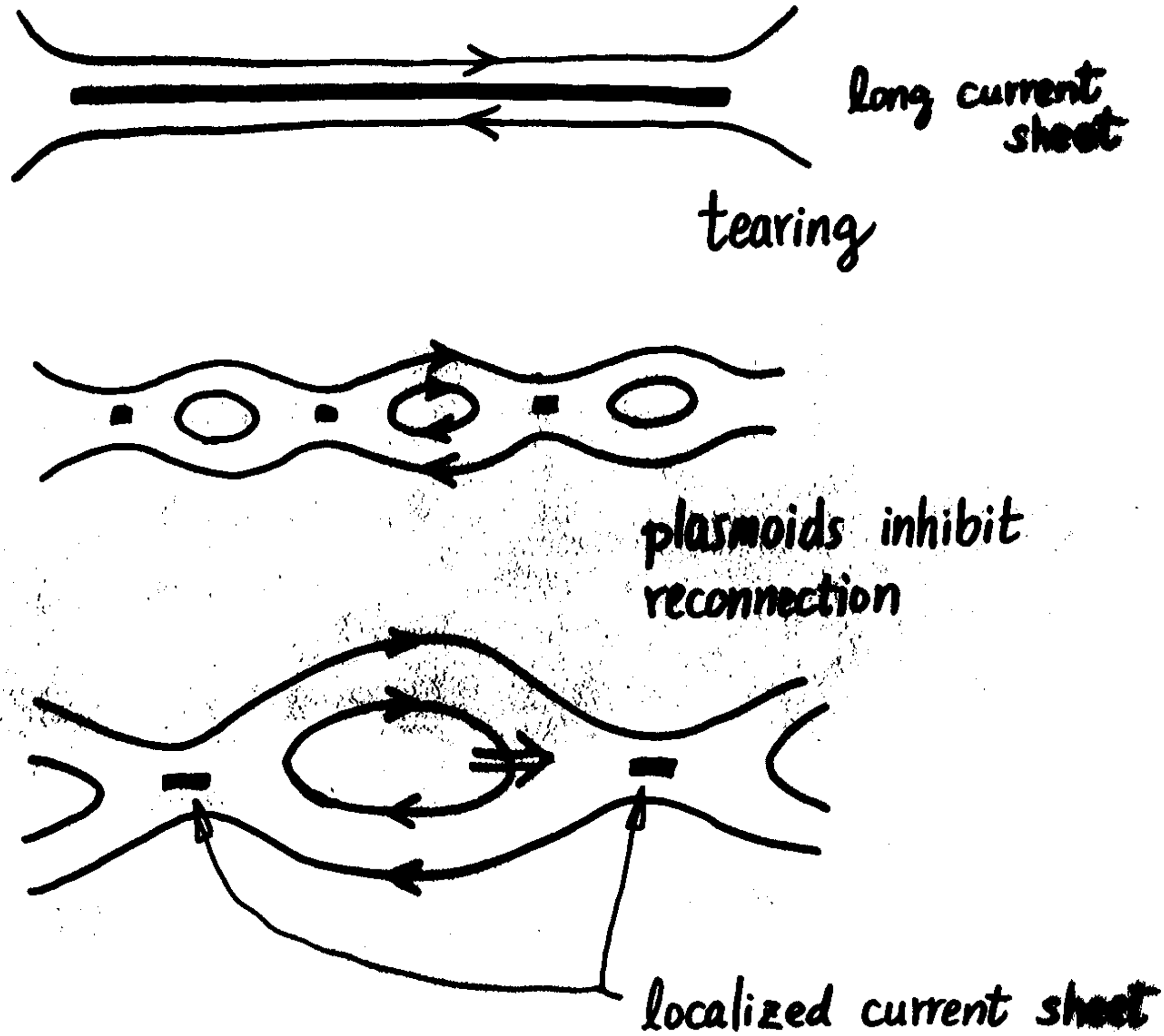

global restructuring
LDE flares
impulsive flares
impulsive flares
microflares
jets

Celestial Objects in Quasi-Hydrostatic Equilibrium





Hypothesis ...... Plasmoid-Induced-Reconnection model



impulsive phase of solar flares

= ejection of large plasmoids

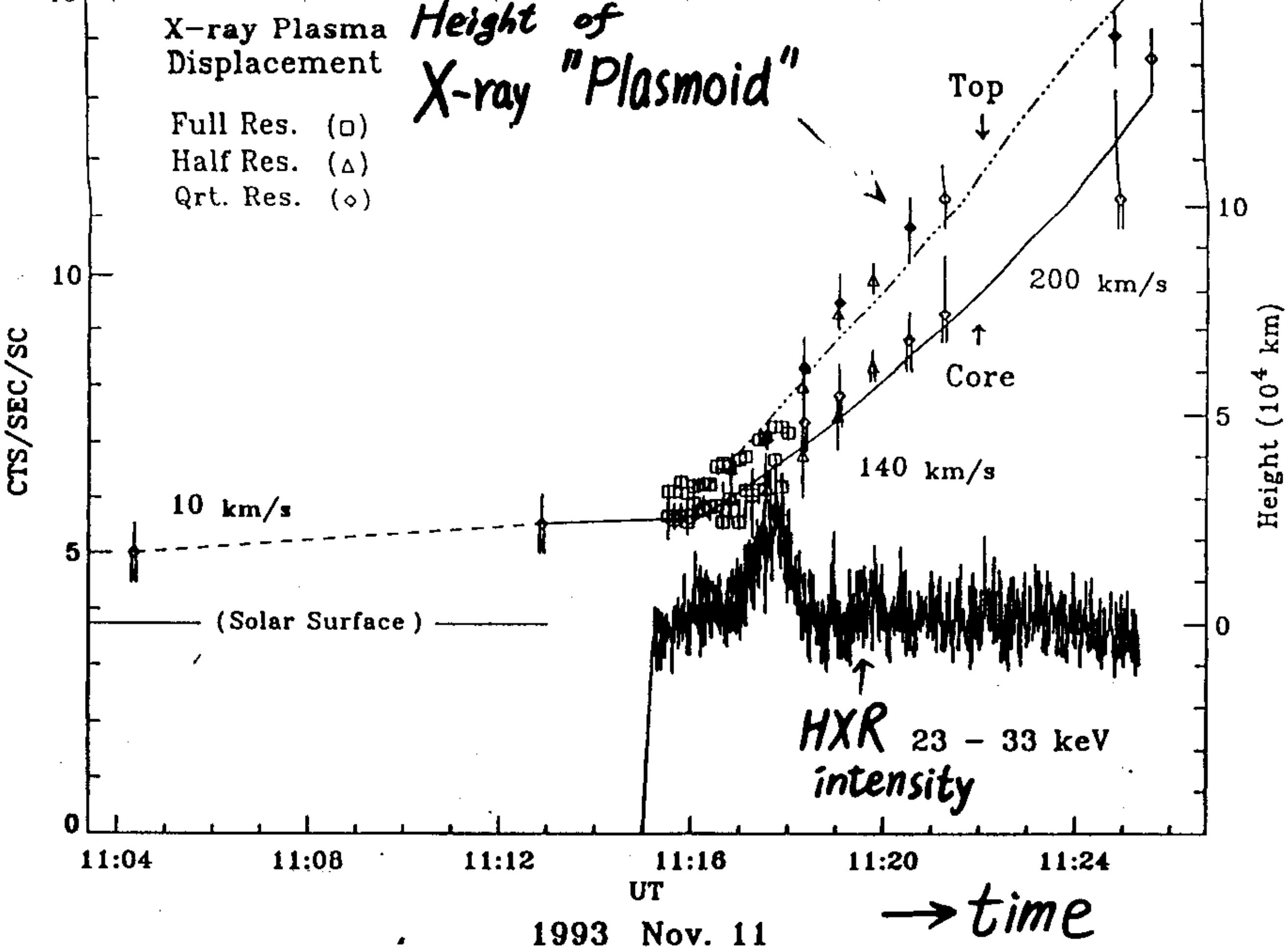


Figure 6. Plasma displacements in AlMg filter images and the hard X-ray (23 – 33 keV) counting rates.

Ohyama and Shibata (1996)

Plasmoid-induced reconnection model

(Shibata, 1997)

$E_{kin,\,plasmoid} \approx 10^{28}-10^{29}\,\mathrm{erg}$

$\ll E_{flare} \approx 10^{30}-10^{31}\,\mathrm{erg}$

strong acceleration of plasmoid

⇕

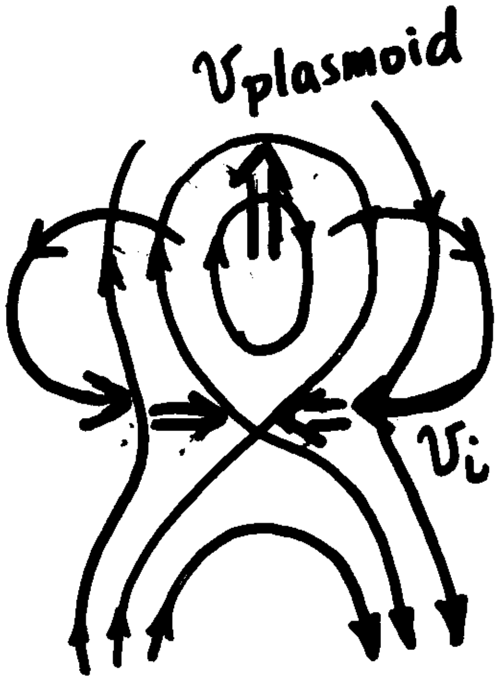
large v_i

⇓

large electric field $E \sim v_i B$

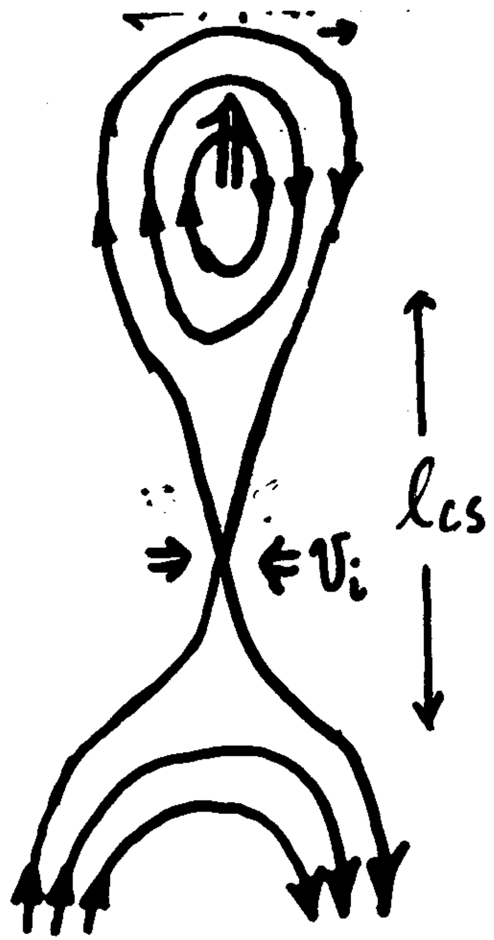
⇓

HXR impulsive phase



$v_i \sim v_{plasmoid}$

impulsive phase



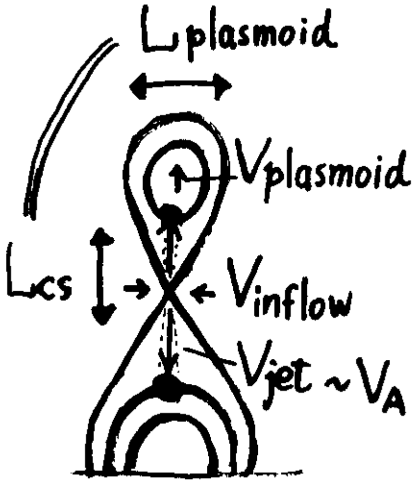
$v_i \sim \frac{l_{plasmoid}}{l_{cs}} v_{plasmoid} < v_{plas}$

gradual / decay phase

Order-of-magnitude estimate of physical quantities in *impulsive* phase

our hypothesis :

impulsive phase = initial phase of plasmoid ejection



← Obs.

$V_{inflow} \sim V_{plasmoid} \sim 50\text{–}400$ km/s

$\sim 0.02 - 0.1\, V_A$

$V_A = 3000 \text{ km/s} \left(\frac{B}{100G}\right)\left(\frac{n_e}{10^{10}\text{cm}^{-3}}\right)^{-1/2}$

$M_A = \frac{V_{inflow}}{V_A} \simeq 0.02 - 0.1$

$\frac{1}{2}\rho V_{jet}^2 \sim 3\rho R_g T \rightarrow T_{loop\text{-}top} \sim 2\times10^8 K \left(\frac{B}{100G}\right)^2 \left(\frac{n_e}{10^{10}\text{cm}^{-3}}\right.$

$\tau_{impulsive} \sim L_{plasmoid} / V_{plasm}$

$\sim 3\text{min} \left(\frac{M_A}{0.03}\right)^{-1}\left(\frac{B}{100G}\right)^{-1}\left(\frac{n_e}{10^{10}\text{cm}^{-3}}\right)^{1/2}\left(\frac{L_{pl}}{2\times10^9 \text{cm}}\right.$

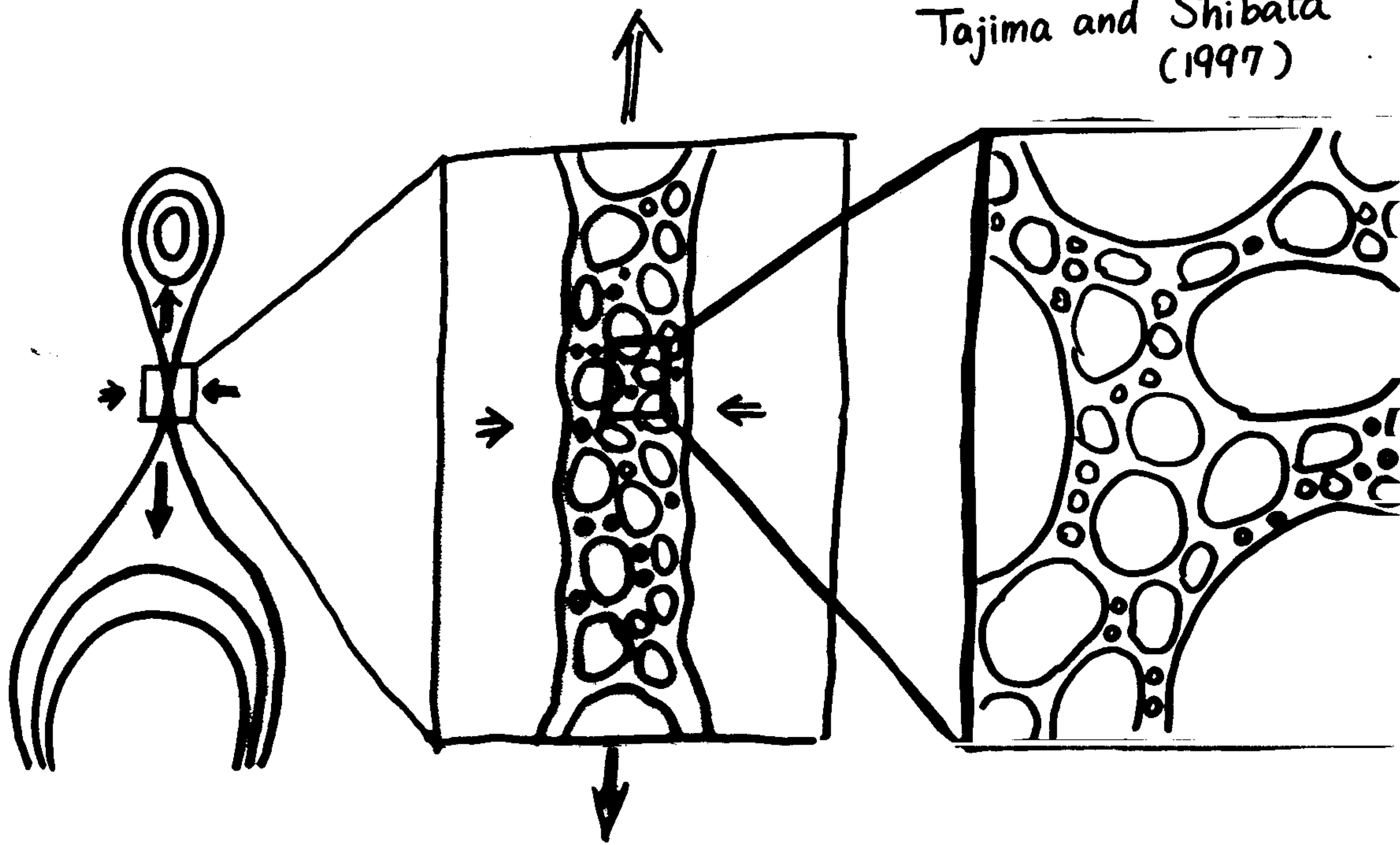
$\frac{dE}{dt} \sim 2L_{plasmoid}^2 B^2 V_{inflow}/4\pi$

$\sim 4\times10^{28} \text{ erg/s} \left(\frac{B}{100G}\right)^3\left(\frac{n_e}{10^{10}\text{cm}^{-3}}\right)^{-1/2}\left(\frac{L_{plasmo}}{2\times10^9\text{cm}}\right)^2 \left(\frac{M_A}{0.03}\right)$

in agreement with Masuda (1994)'s observation

Fractal Current Sheet

Tajima and Shibata (1997)



$l_{max} \approx 10^3 - 10^4$ km

$l_{min} \approx r_i = \frac{m_i c v_{th,i}}{eB}$

$\approx 10 \left(\frac{T}{\cdots}\right)^{\frac{1}{2}} \left(\frac{B}{\cdots}\right)^{-1}$

$E \approx V_{inflow} B \sim 10^3 \text{ volt/m} \left(\frac{V_{inflow}}{100\text{ km/s}}\right) \times \left(\frac{B}{\cdots}\right)$

4. Summary and Remaining Questions

Summary

- Yohkoh discovered a lot of evidence of reconnection in solar flares
  - cusp shaped loops / arcades
  - loop top hard X-ray source (fast shock ?)
  - plasmoids and jets
- Yohkoh observations revealed a common nature of various flares, leading to unified view of flares and mass ejections
- A unified model (plasmoid-induced-reconnection model) is presented
  - plasmoids limit the length of current sheet
  - nonsteady ejection of large plasmoids is the direct origin of impulsive phase of flares
  - current sheet has a fractal structure consisting of many plasmoids

Remaining Questions

- What is the condition for fast reconnection ?
- What is the origin of resistivity ?

  $r_{ion\text{-}Larmor} \approx 10\ \mathrm{cm} \ll L_{flare} \approx 10^{9}\ \mathrm{cm}$

- What is the mechanism of particle acceleration ?
- What is the pre-flare energy build-up process ?