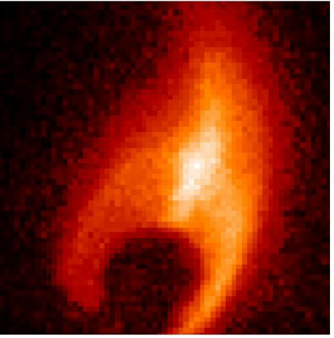
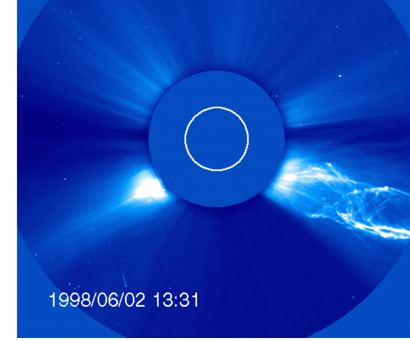


2001.6.18 at Longmont, Colorado



A Unified View of Solar Flares and Coronal Mass Ejections

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Kyoto University,

Kwasan　Observatory

Contents

1. Introduction

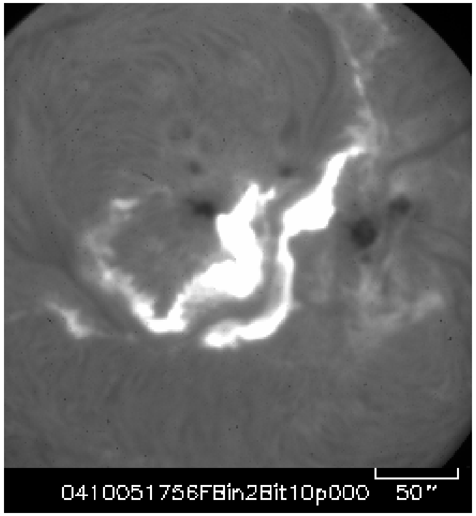
Solar flares
- discovered by Carrington and Hodgson (~1860)

Energy source = Magnetic energy

Size ～10^9 – 10^{10} cm

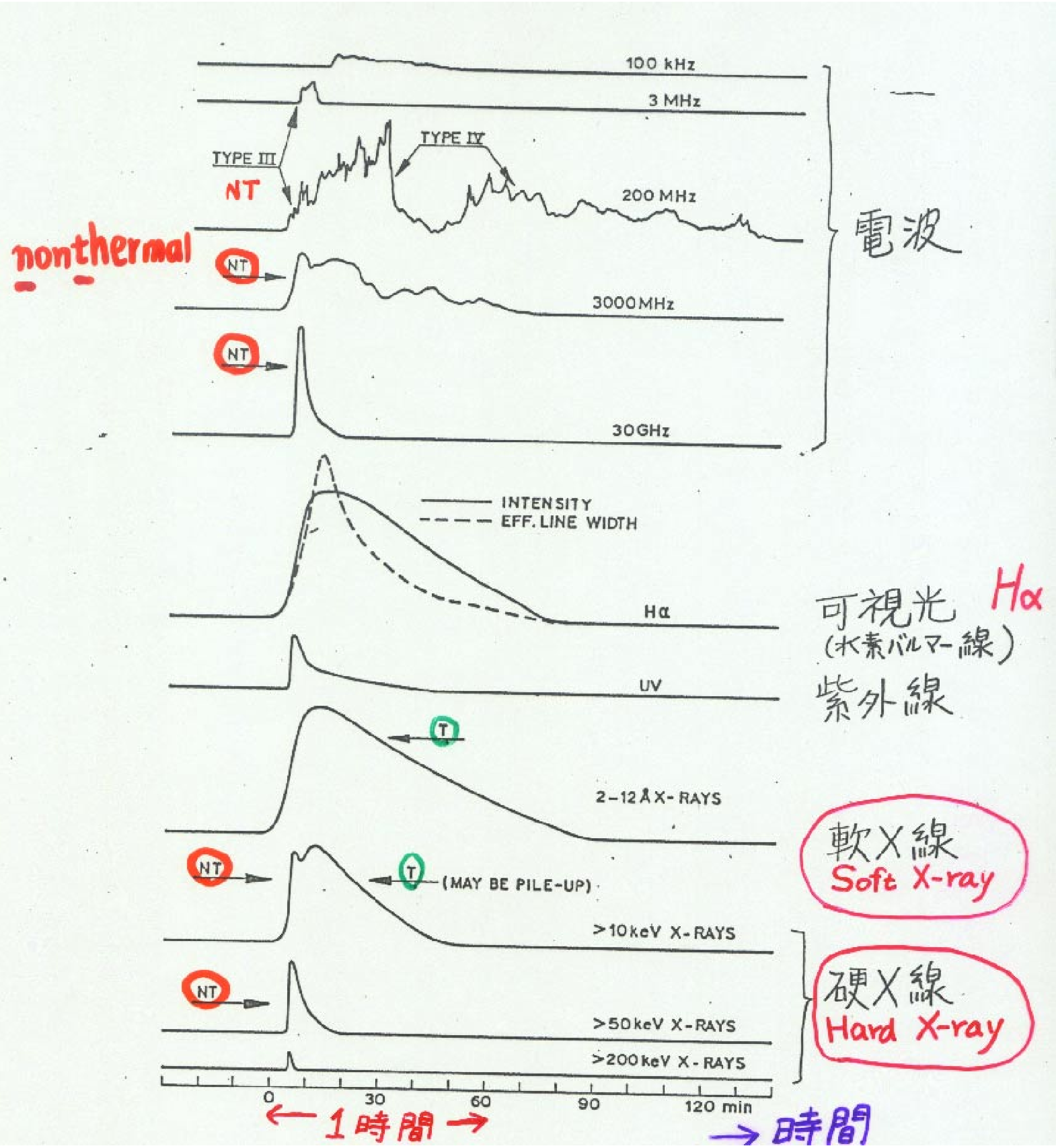
Total energy
- 10^{29} – 10^{32} erg

H alpha

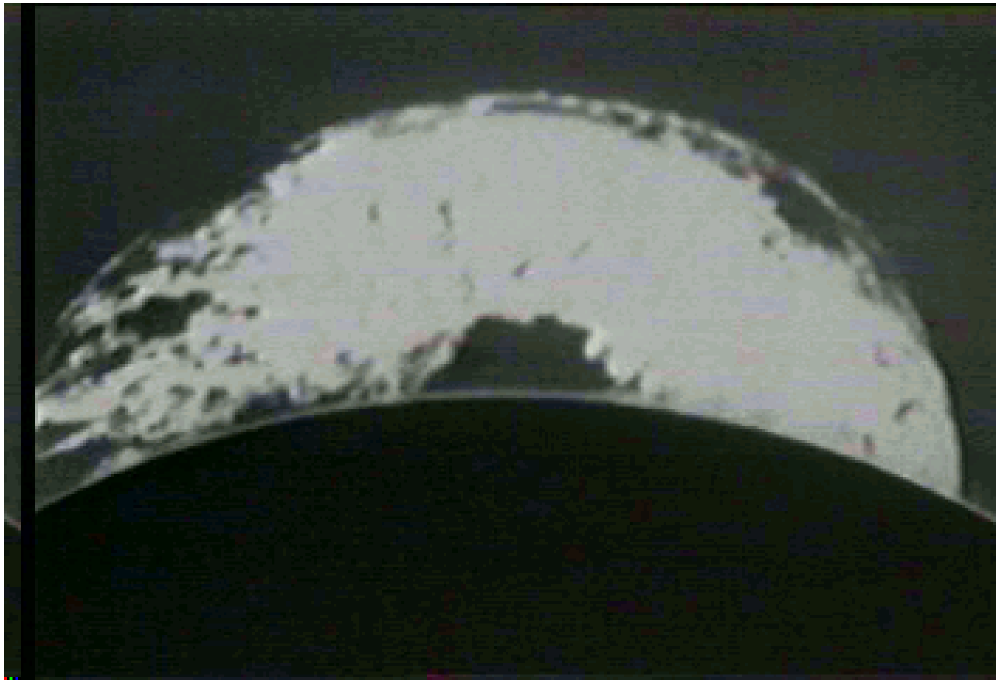


H α (Kyoto/Hida)

Electro-magnetic waves emitted from solar flares (Svestka 1976)

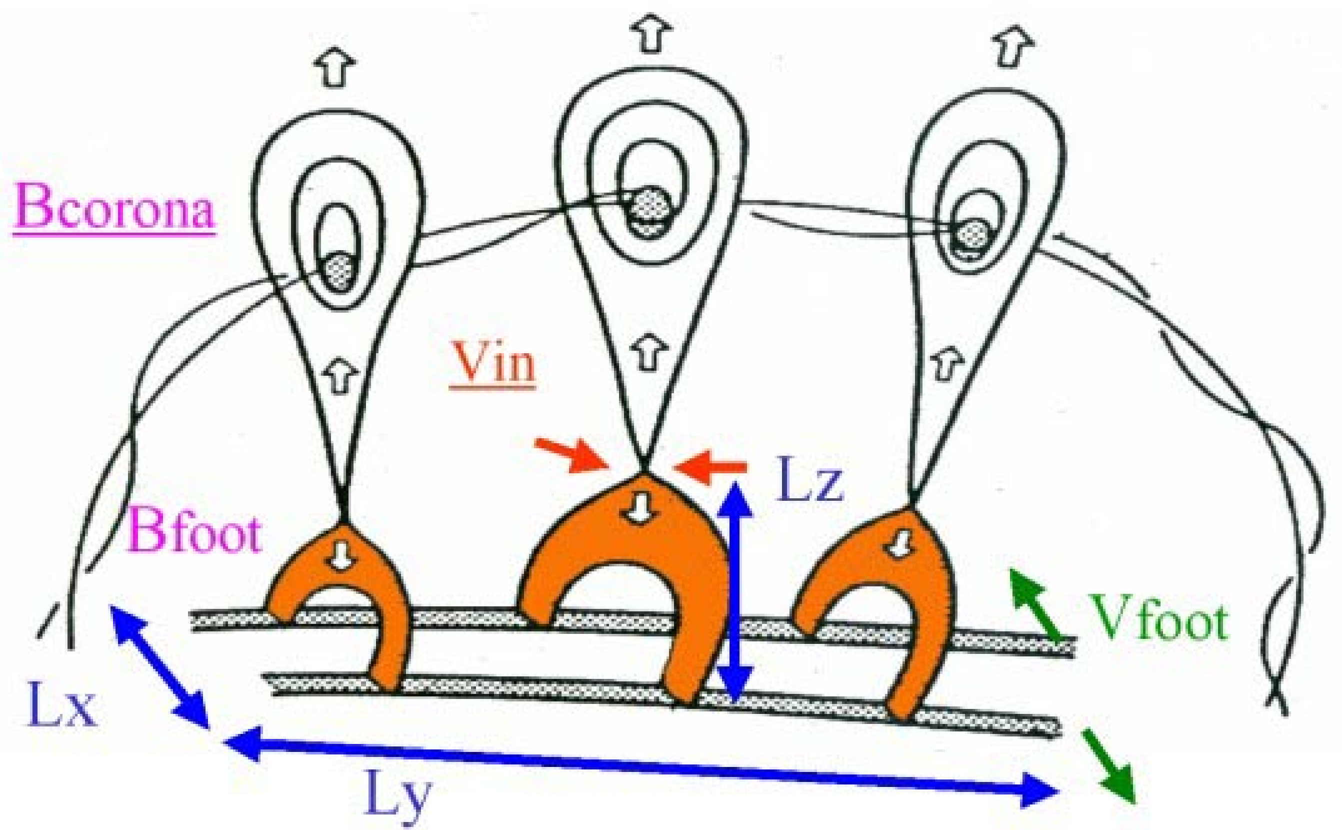


Solar flares are often associated with prominence eruptions



（１９４５年6月２８日、HAO)

Reconnection model (CSHKP model=Carmichael 1964, Sturrock 1966, Hirayama 1974, Kopp-Pneuman 1976)



Basic puzzles of solar flares before Yohkoh (1991)

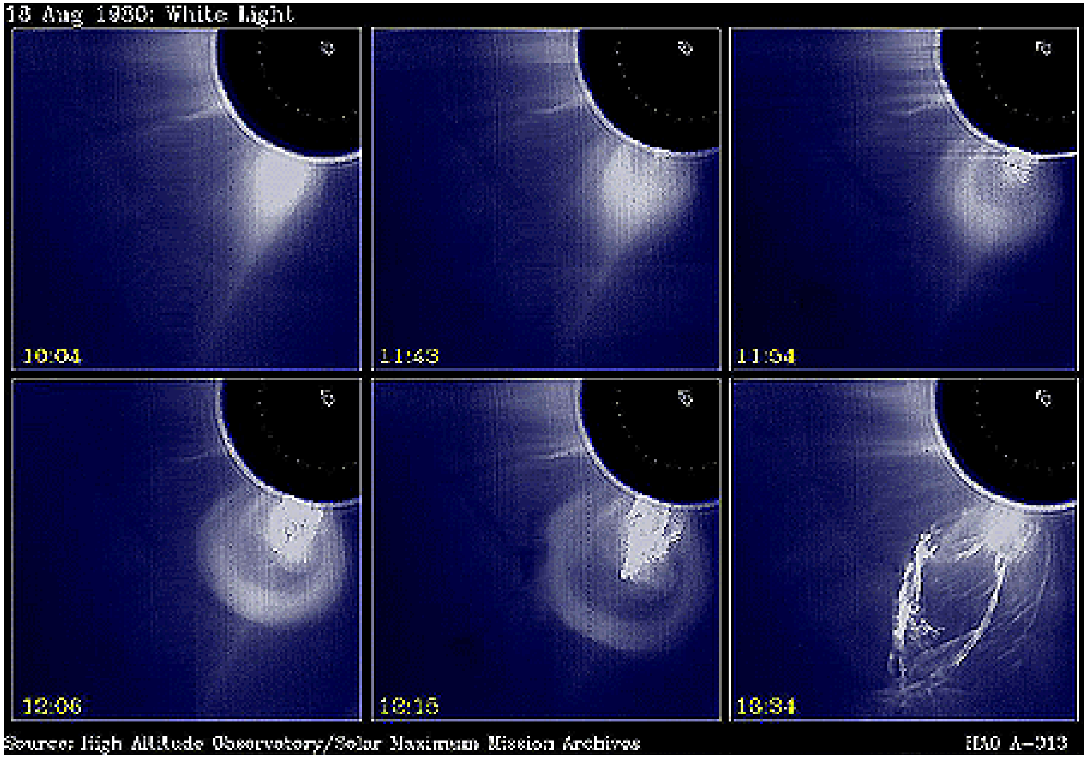
- Reconnection theory has not yet been established
- Many authorities doubted reconnection model (e.g., Alfven, Akasofu, Uchida, Melrose, ….)

  current disruption vs reconnection

- There are many flares which are NOT associated with prominence eruptions
- There was no direct observational evidence of reconnection in flares

Coronal Mass Ejections (CMEs)

- discovered in 1970s with space coronagraph
- cause geomagnetic storm
- many CMEs are not associated with flares, but with filament eruptions



Basic questions about coronal mass ejections (CMEs)

- Are CMEs more important than flares ? (Gosling 1993)
- What is the relation between CMEs and flares ? Are CMEs different from flares ?
- Is reconnection important in CMEs ?

2. Recent Space Observations of Solar Flares and CMEs

- Yohkoh (陽光)

  Aug. 30, 1991 ー present
- Japan-US-UK collaboration
- soft X-ray telescope

  (SXT~1keV)

  hard X-ray telescope

  (HXT~10-100keV)

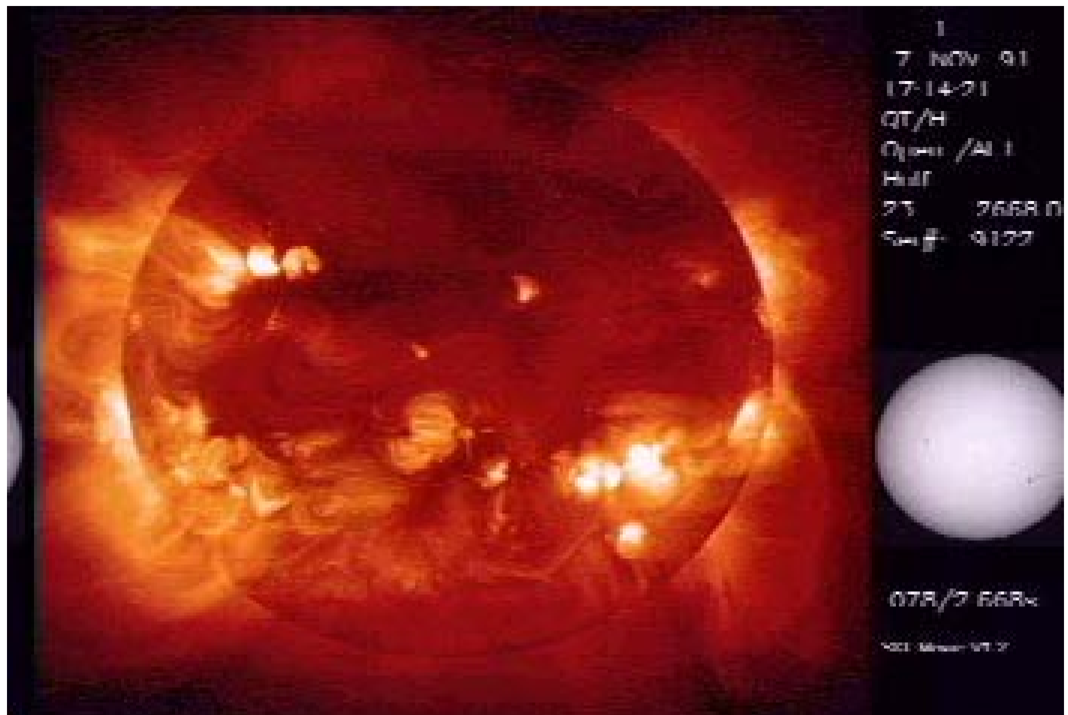
Solar corona observed with soft X-ray telescope (SXT) aboard Yohkoh

Soft X-ray

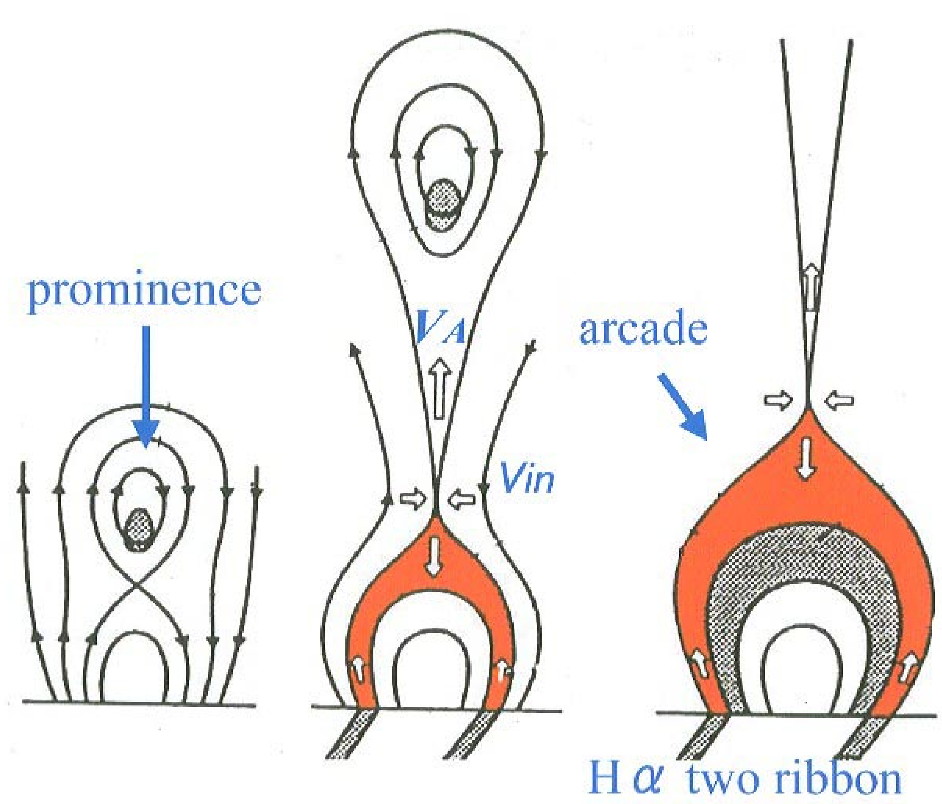
（～1 keV)

2MK－20MK

Note numerous microflares

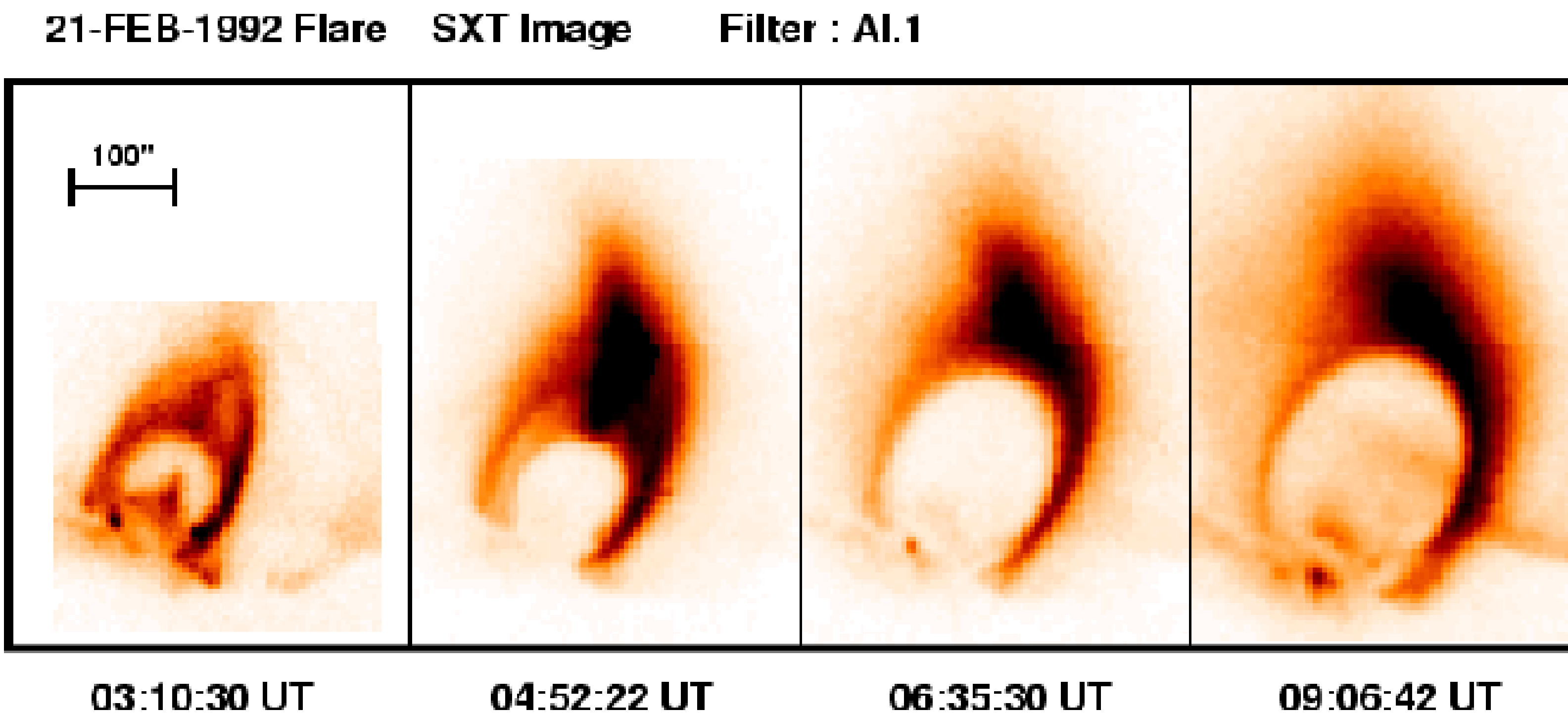


2D view of reconnection (CSHKP) model



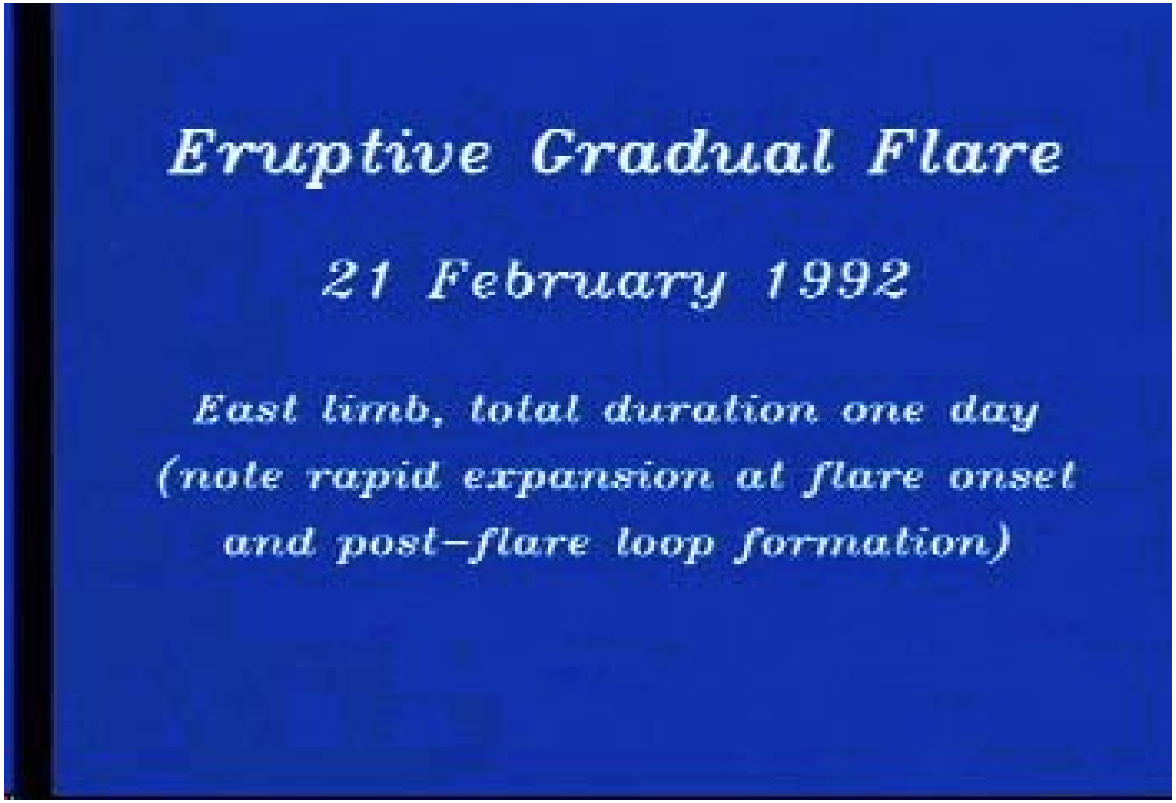
⇒should be observed in Soft-Xrays

LDE (long duration event) flare
(SXT, ～ 1 keV、 Tsuneta et al. 1992)

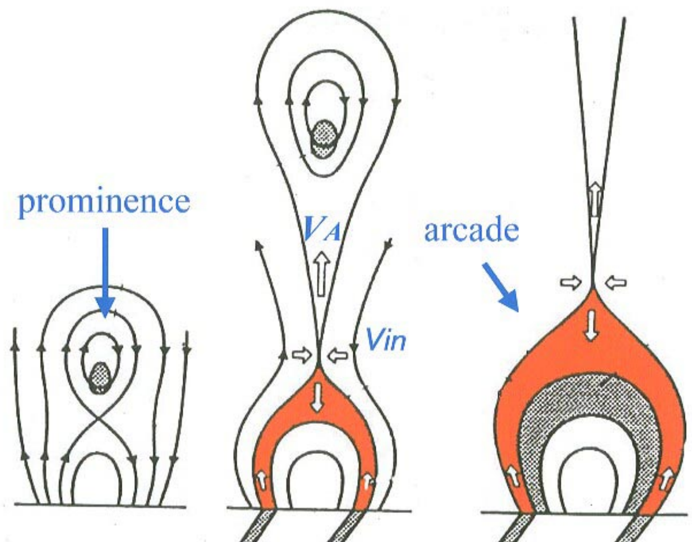


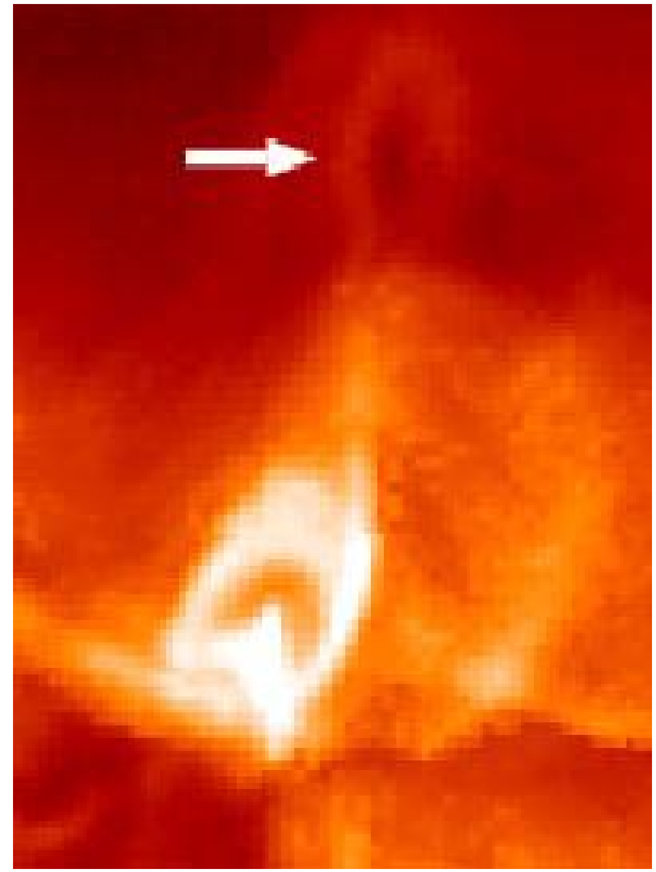
electron temperature ～１０＾７　K、
electron density～１０＾（１０）ｃｍ＾（－３）

LDE (long duration) flare
（Yohkoh/SXT: Tsuneta et al. 1992）



Plasmoid ejection associated with LDE flare (Yohkoh/SXT)

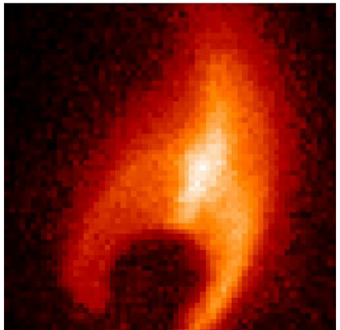


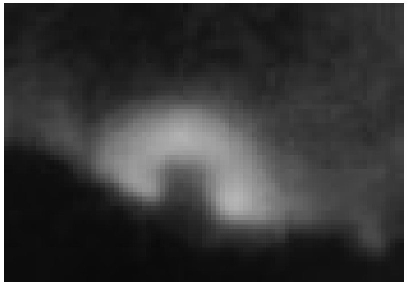


Note: there was no prominence eruption. Plasmoid speed is about ３００ｋｍ／ｓ

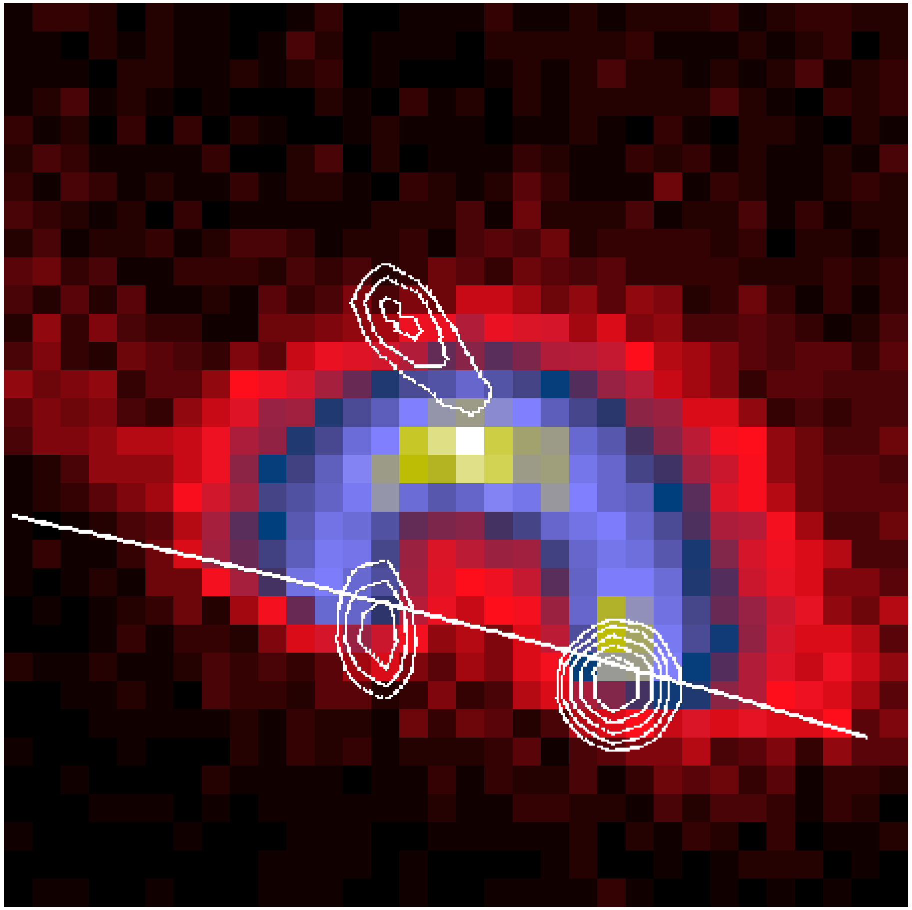
LDE flare v s impulsive flare

Life time	> 1 hour	< 1 hour
Size	large	small
Occurrence frequency	small	large
Soft Xrays	cusp	no cusp
	Reconnection	NO reconnection ?





Hard X-ray Loop Top impulsive source (Masuda et al. 1994 Nature)

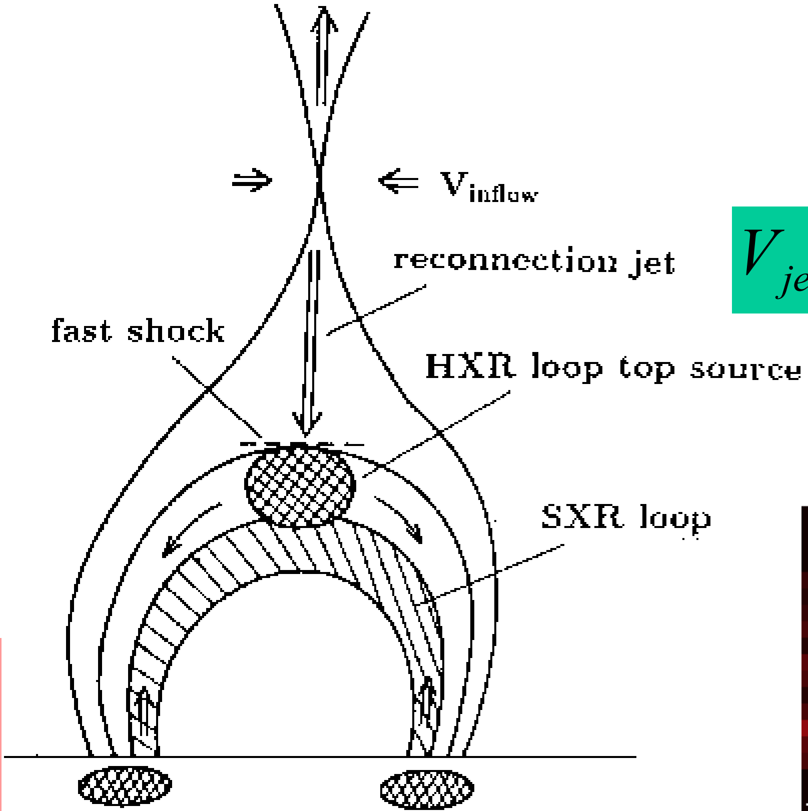


color：
soft X-ray
（1keV）

contour：Hard X-ray (30keV)

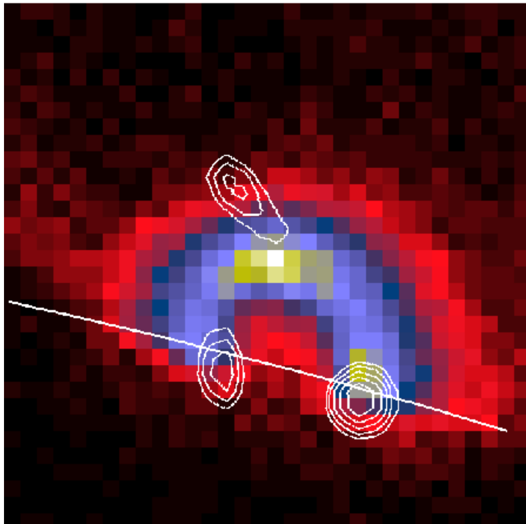
Loop top ～100MK
If thermal

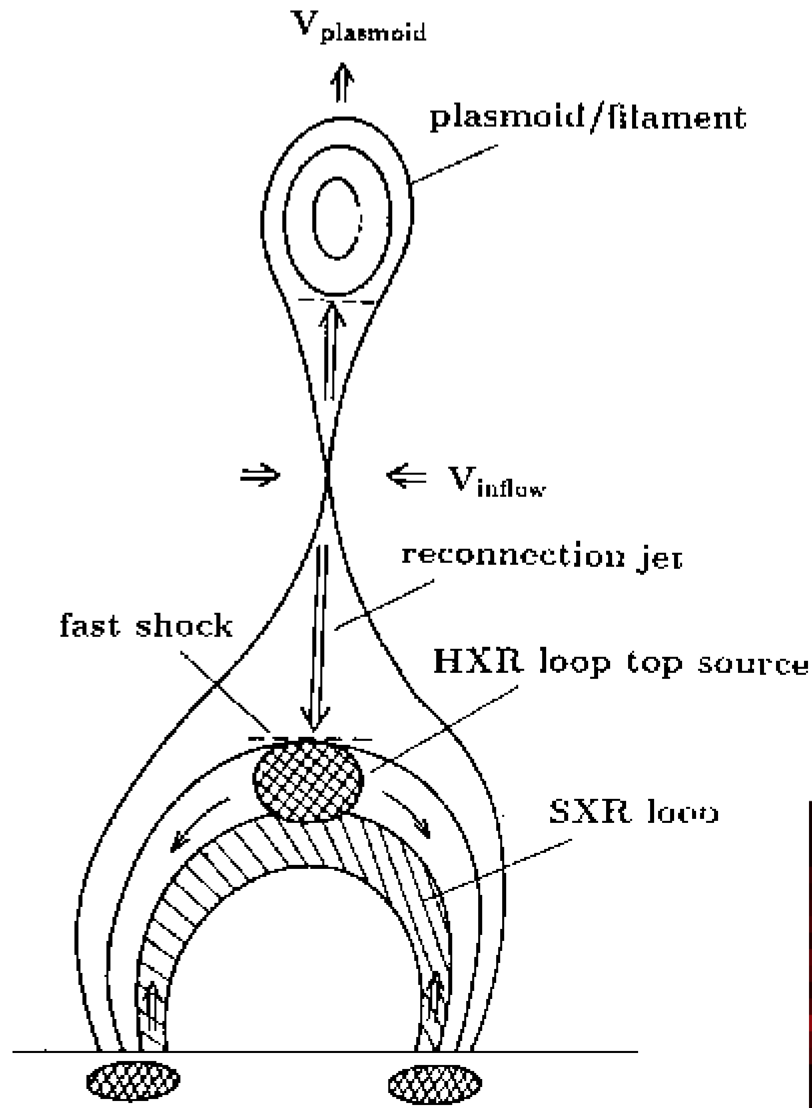
- Hard X-ray Loop top impulsive fast shock ?



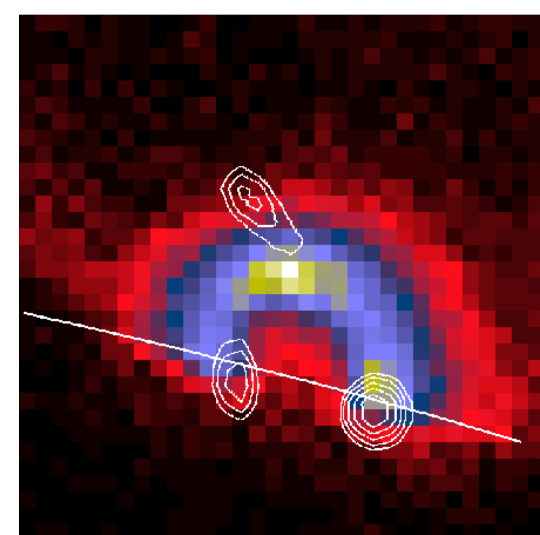
$$V_{jet} \approx V_A \approx 1000 km/s$$

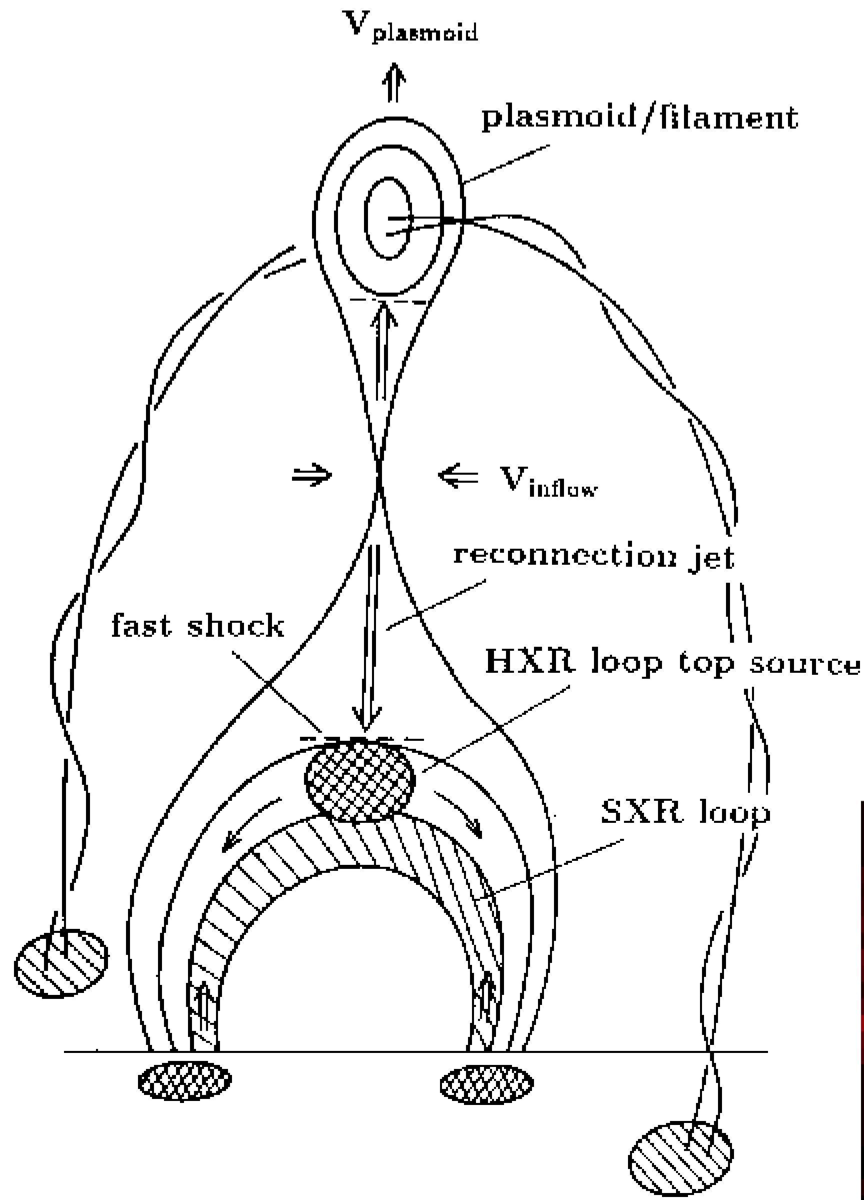
$$T \approx m V_A^{\ 2}/(6k)$$
$$\approx 10^8 K$$



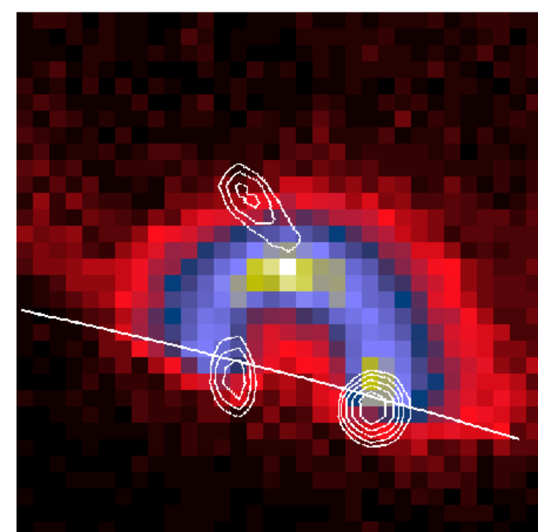


$V_{plasmoid}$
plasmoid/filament
V_{inflow}
reconnection jet
fast shock
HXR loop top source
SXR loop

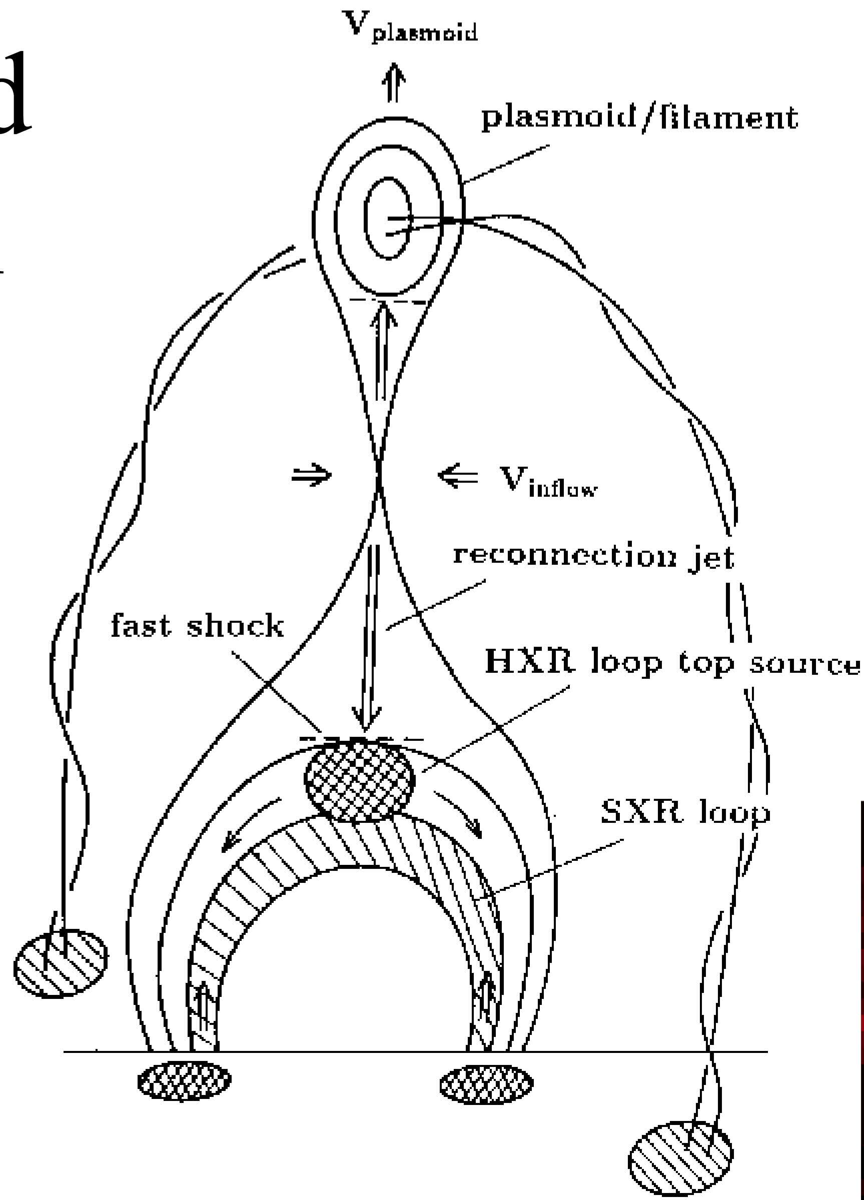




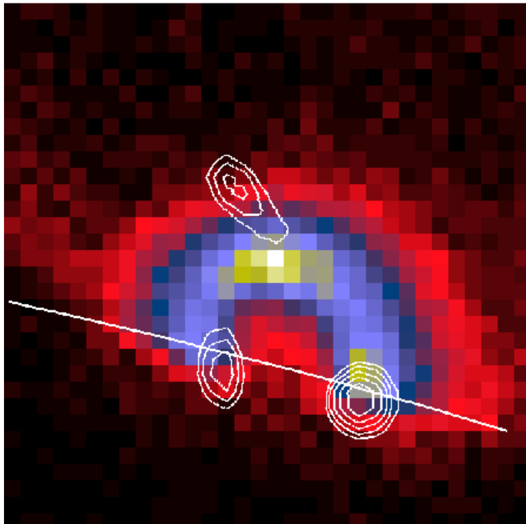
$V_{plasmoid}$
plasmoid/filament
V_{inflow}
reconnection jet
fast shock
HXR loop top source
SXR loop



Unified Model



Predict X-ray plasmoid ejections

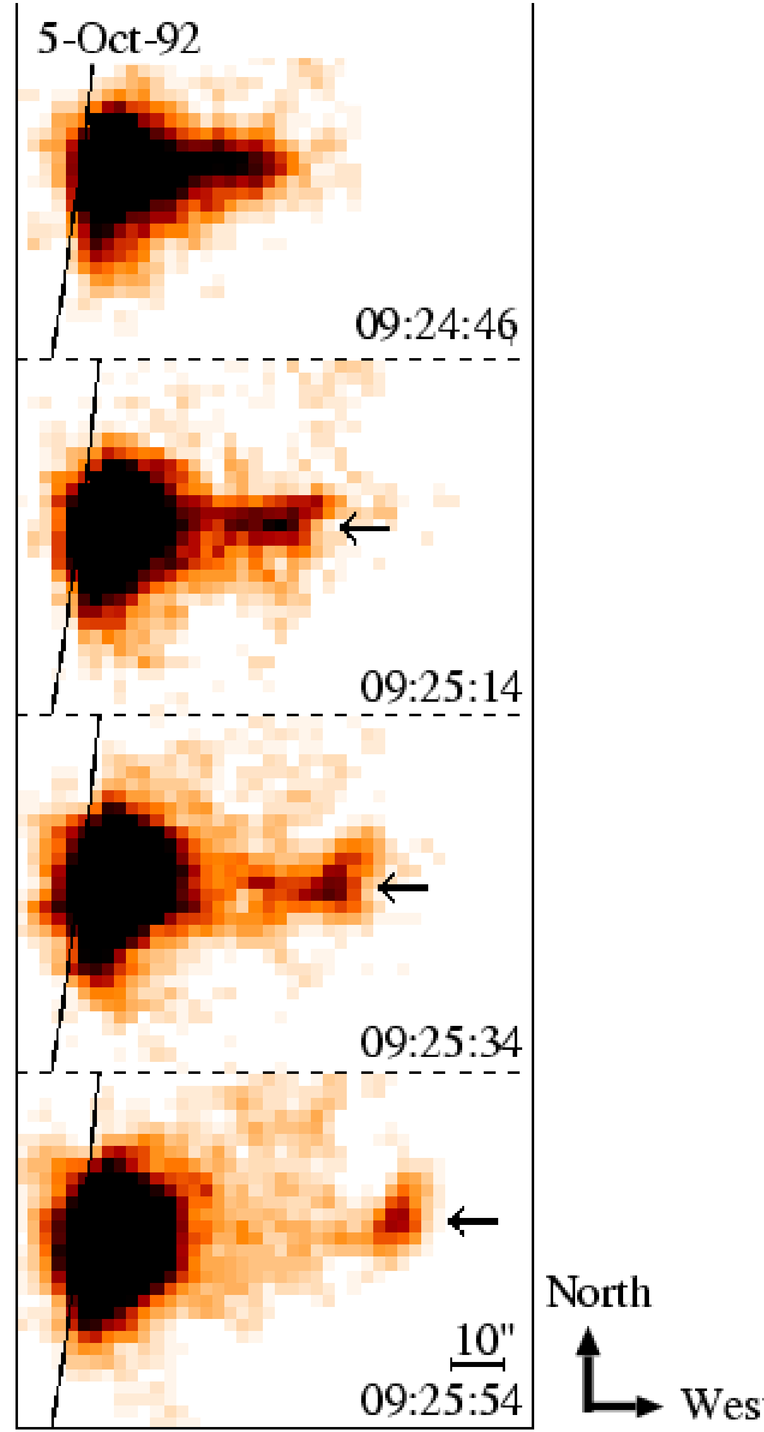


X-ray plasmoid ejections from impulsive flares

(Yohkoh/SXT:

Shibata et al. 1995,

Ohyama and Shibata 1998)

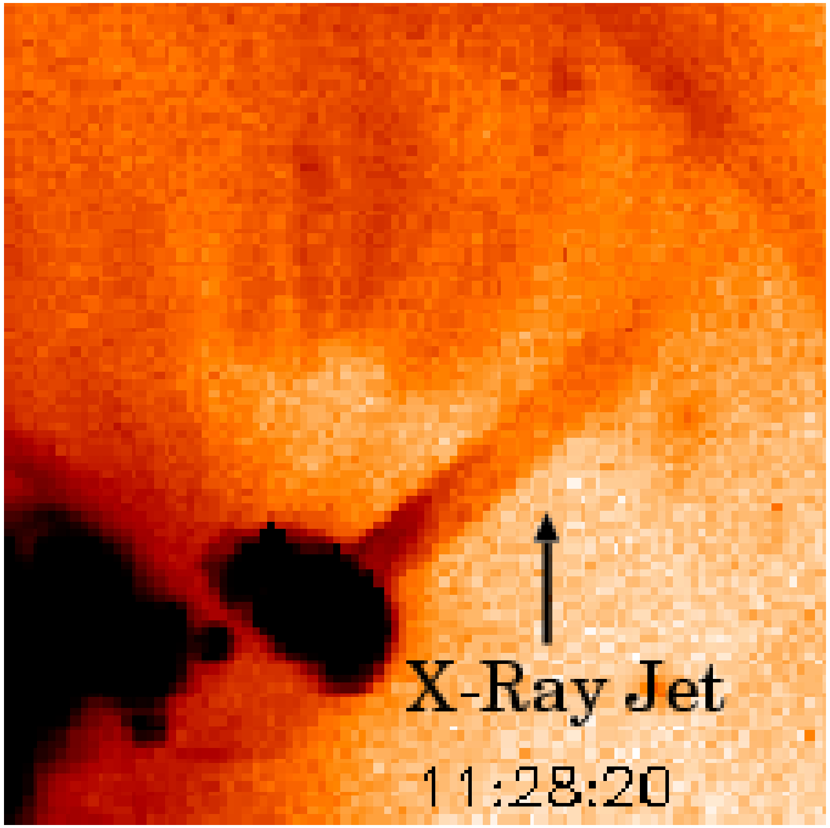


Plasmoid speed ~ 40 – 500 km/s
Size ~ 10^4 - 10^5 km
Strong acceleration during
impulsive phase of flares

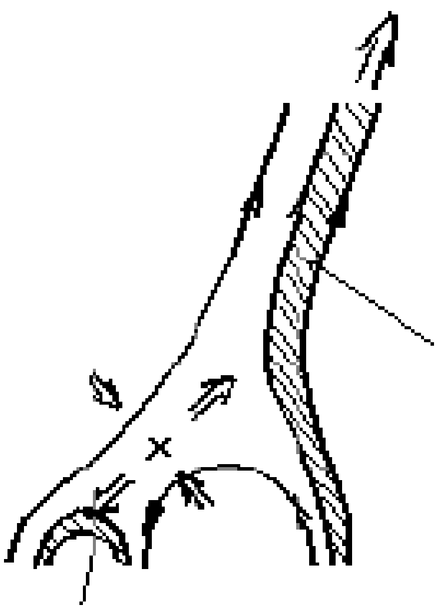
X-ray jets

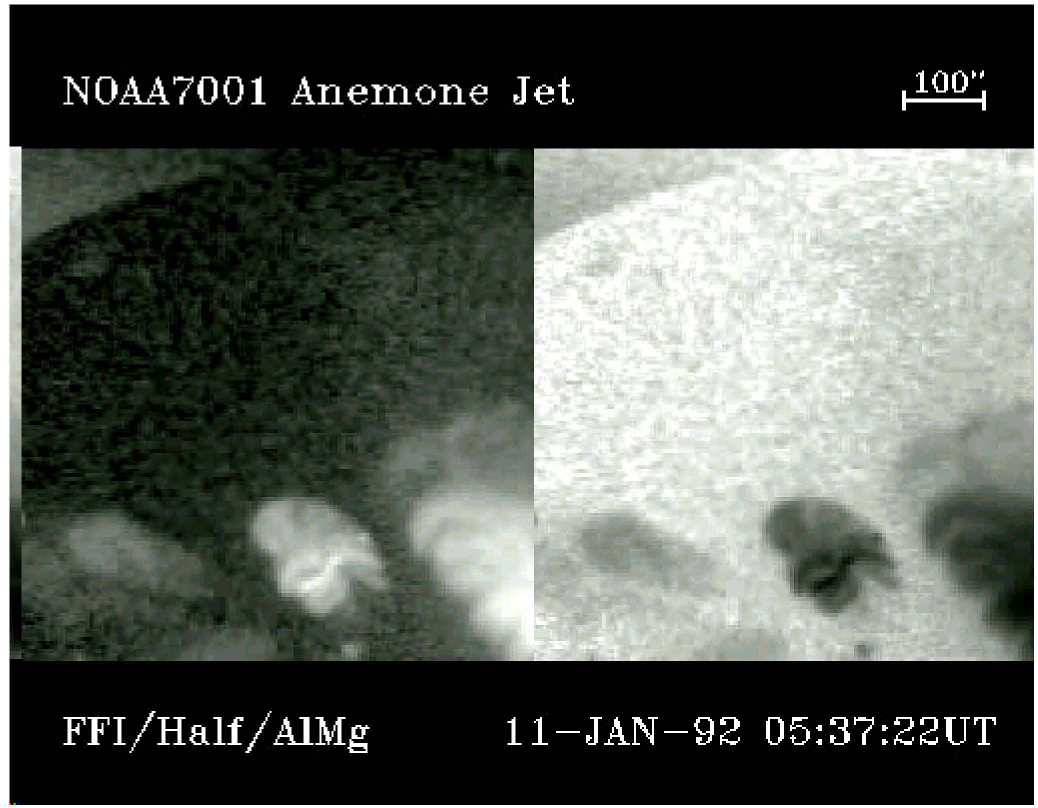
- Ejected from microflares
- Size = a few 1000 – 10^5 km
- Speed ~ 10 – 1000 km/s

（Shibata et al. 1992; Shimojo et al. 1996）



Largest X-ray jet (Shibata et al. 1994)

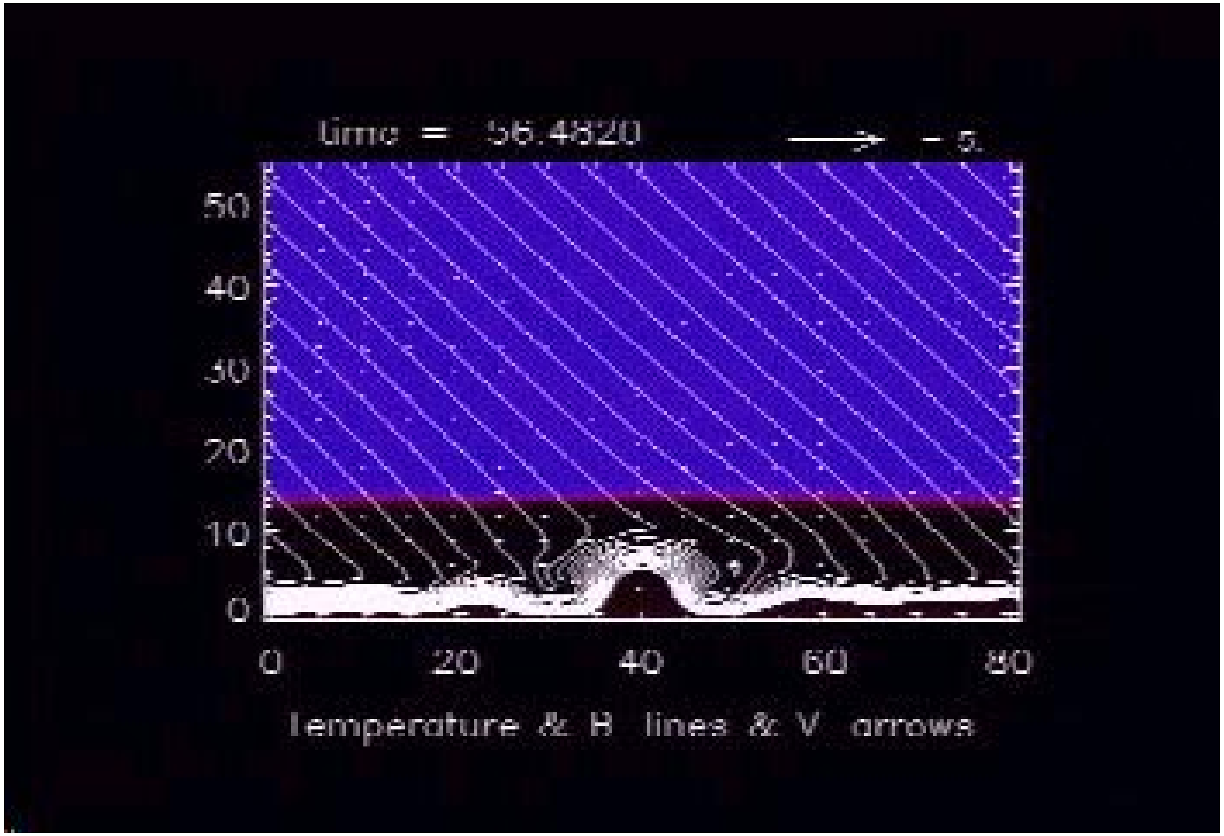




Anemone type active region

Reconnection model of X-ray jets and surges (Yokoyama and Shibata 1995 Nature 375, 42)

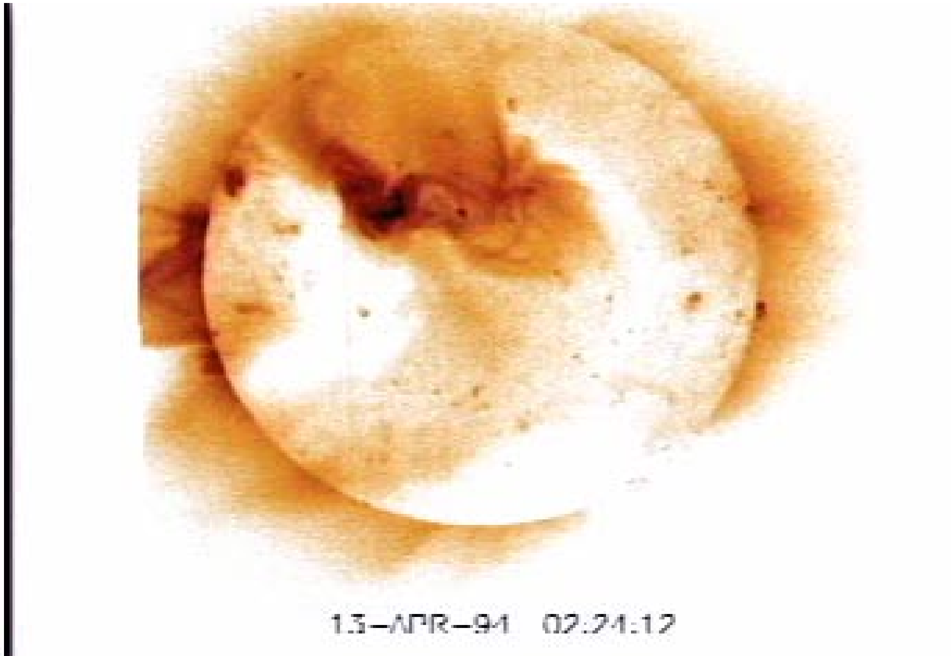
temperature



Giant Arcades

(Yohkoh/SXT: Tsuneta et al. 1992, Hanaoka et al. 1993)

- discovered with Yohkoh/SXT
- size ~ 10^5 – 10^6 km
- Many of them cannot be detected with GOES, and so were not classified as "flares". However, their properties are very similar to those of "flares".
- associated with filament eruptions (and/or CMEs).



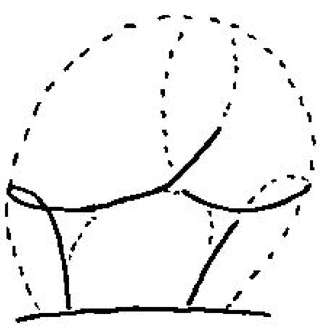
(McAllister et al. 1996)

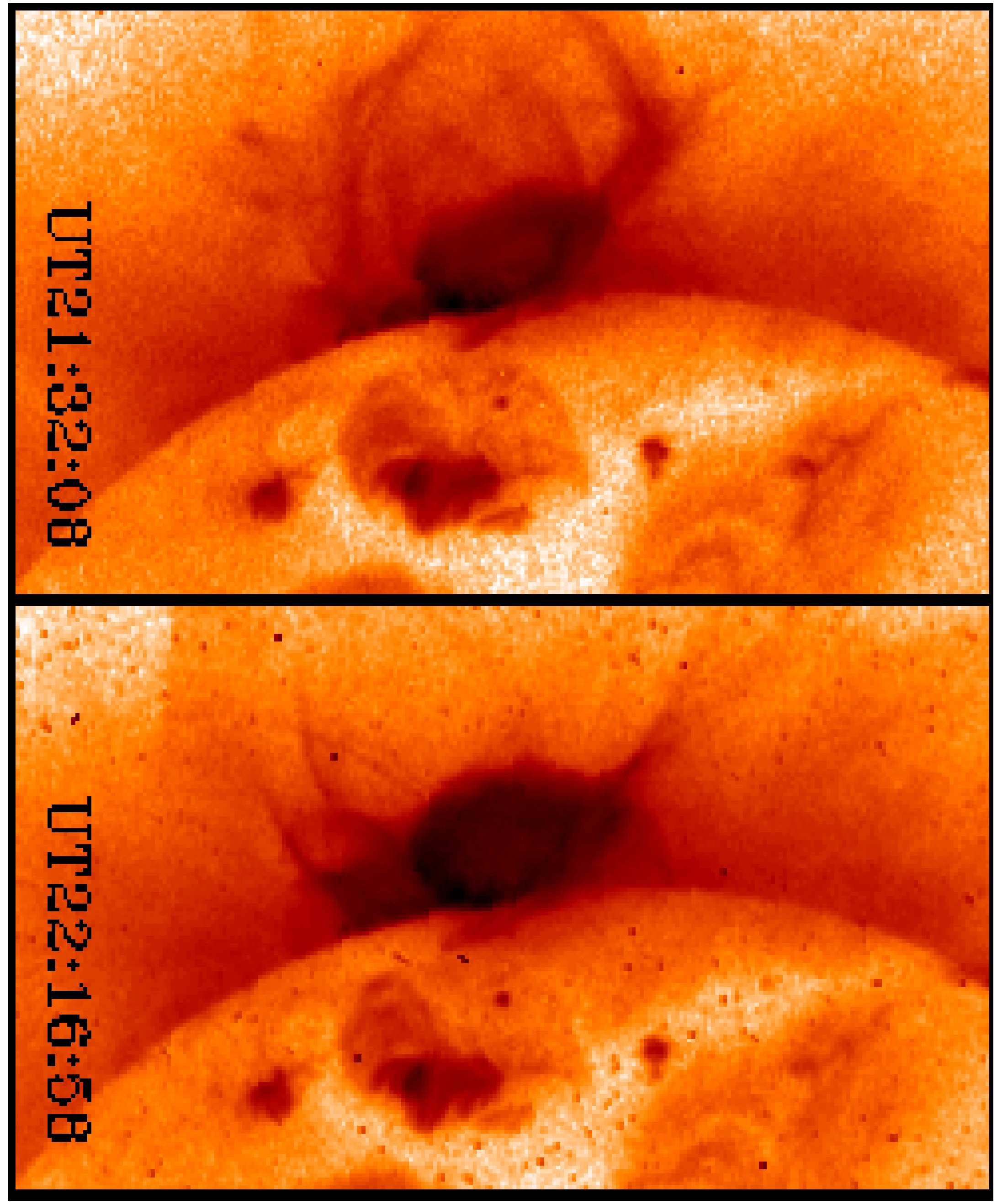
X-ray Helmet Streamer (Side View of Giant Arcades)

(Yohkoh/SXT: Hiei et al. 1994)

Helical Flux Rope of X-ray Filament (side view of Plasmoid)

obsereved with Yohkoh/SXT (Aug 28 1992)



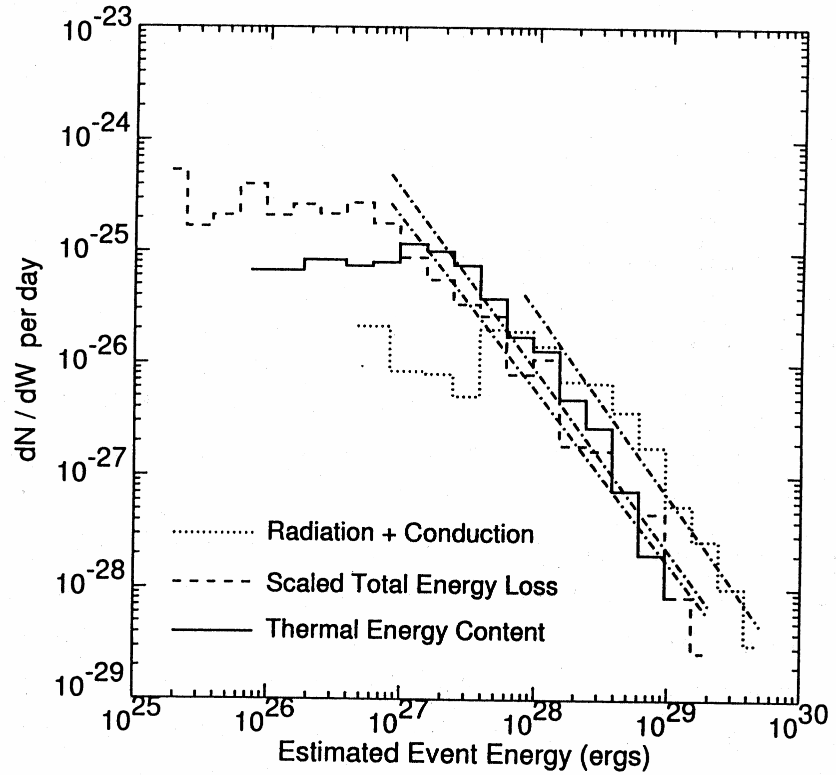


Summary of Yohkoh observations of "flares"

"flares"	Size (L)	lifetime(t)	Alfven time (t_A)	t/t_A	Mass ejection
microflares	10^3 -10^4 km	100-1000sec	1-10 sec	~100	jet/surge
Impulsive flares	(1-3) x 10^4 km	10 min – 1 hr	10-30 sec	~60-100	X-ray plasmoid/ Spray
LDE flares	(3-10)x 10^4 km	1-10 hr	30-100 sec	~100-300	X-ray plasmoid/ prom. eruption
Giant arcades	10^5 -10^6 km	10 hr – 2 days	100-1000 sec	~100-300	CME/prom. eruption

Occurrence Frequency of Microflares

(Yohkoh/SXT: Shimizu 1995)



$$\frac{dN}{dW} \propto W^{-\alpha}$$

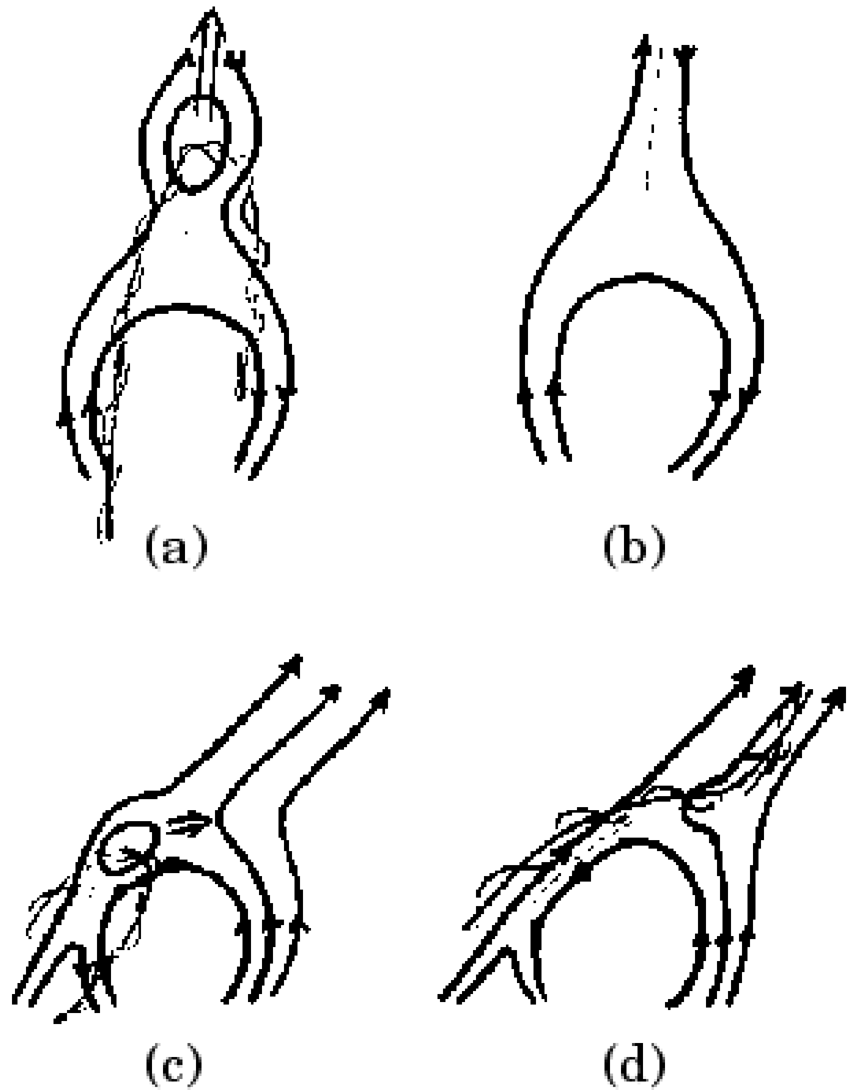
$$(\alpha \approx 1.6 \sim 1.8)$$

Same as in larger flares

Unified model
(plasmoid-induced reconnection model)

(a,b) : giant arcade, LDE/impulsive flare

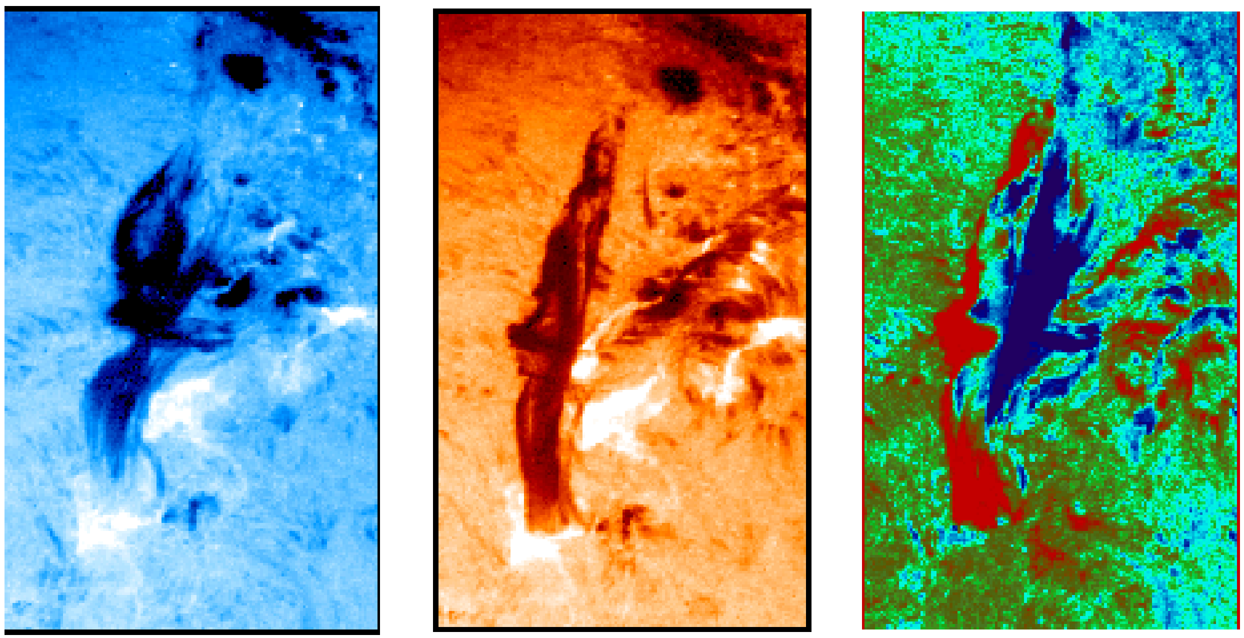
(c,d) : impulsive flares, microflares



Energy release rate = $\frac{dE}{dt} \approx \frac{B^2}{4\pi} V_{in} L^2 \approx 10^{-2} \frac{B^2}{4\pi} V_A L^2$

Spinning Hα jet

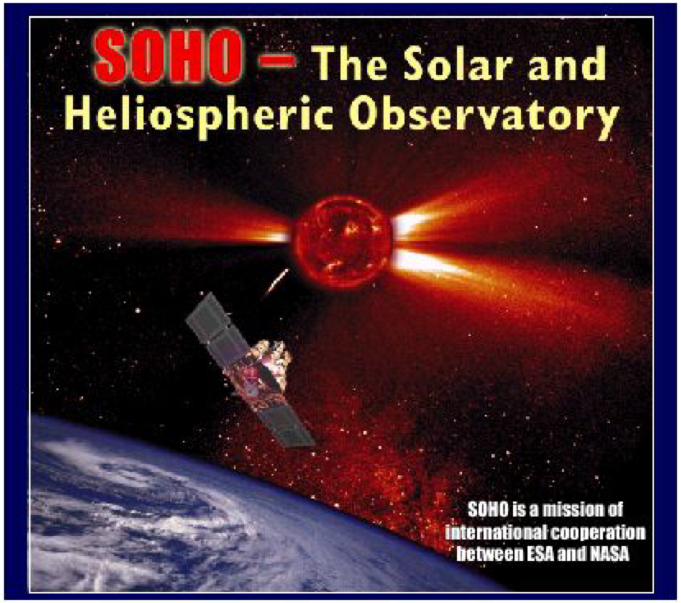
（Kurokawa et al. １９８８）



blue-shift　　red-shift

SOHO and TRACE

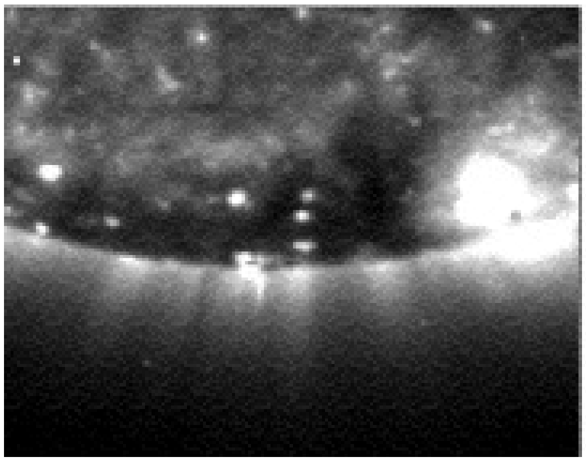
- 「SOHO」 launched 1995 Dec
  - Extreme Ultravilet Imaging Telescope (EIT)
  - Space coronagraph (LASCO)
  - SUMER, CDS, MDI, etc.
- 「TRACE」 launched 1998 Apr
  - EUV telescope

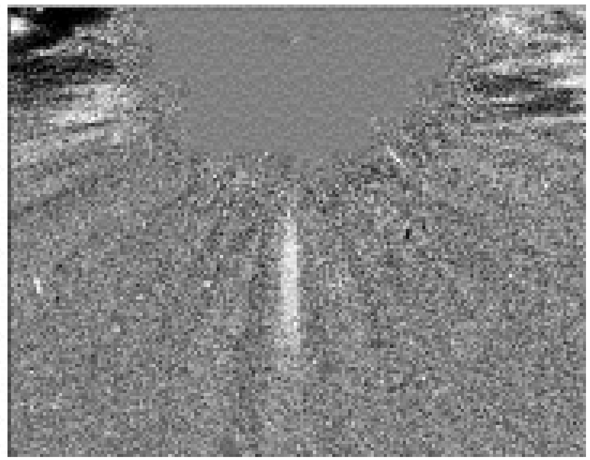


SOHO/TRACE results

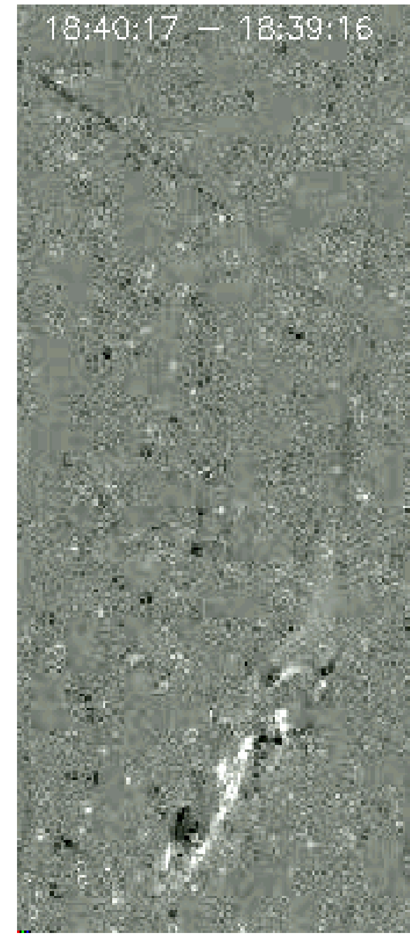
- Basically confirm Yohkoh results with higher spatial and temporal resolutions
- Solar atmosphere is filled with nanoflares and smaller jets
- Even quiet Sun is not quiet !
- More and more evidence of reconnection

more and more spinning helical jets have been discovered (SOHO,TRACE)

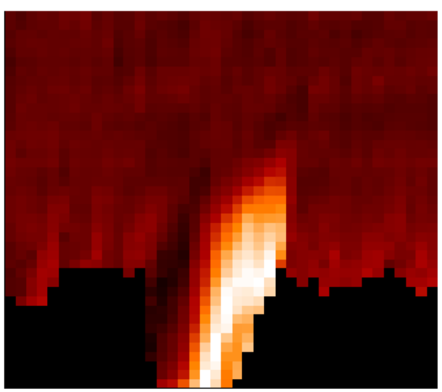




SOHO/EIT-LASCO jet (Wang, Y.M.)

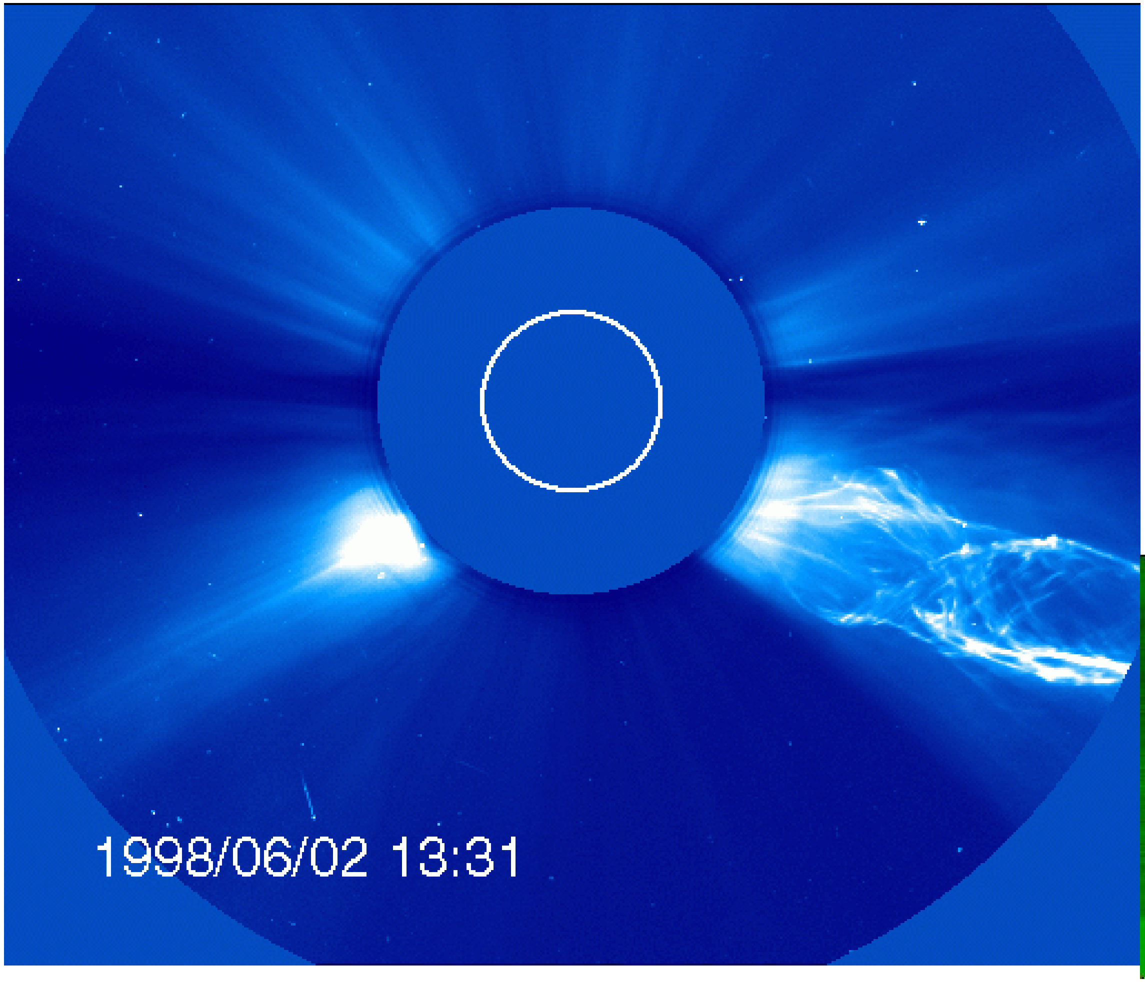


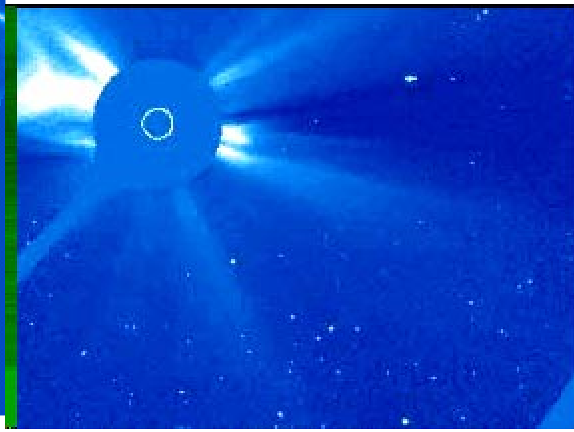
TRACE (Alexander and Fletcher)



spinning jet (Pike&Mason)

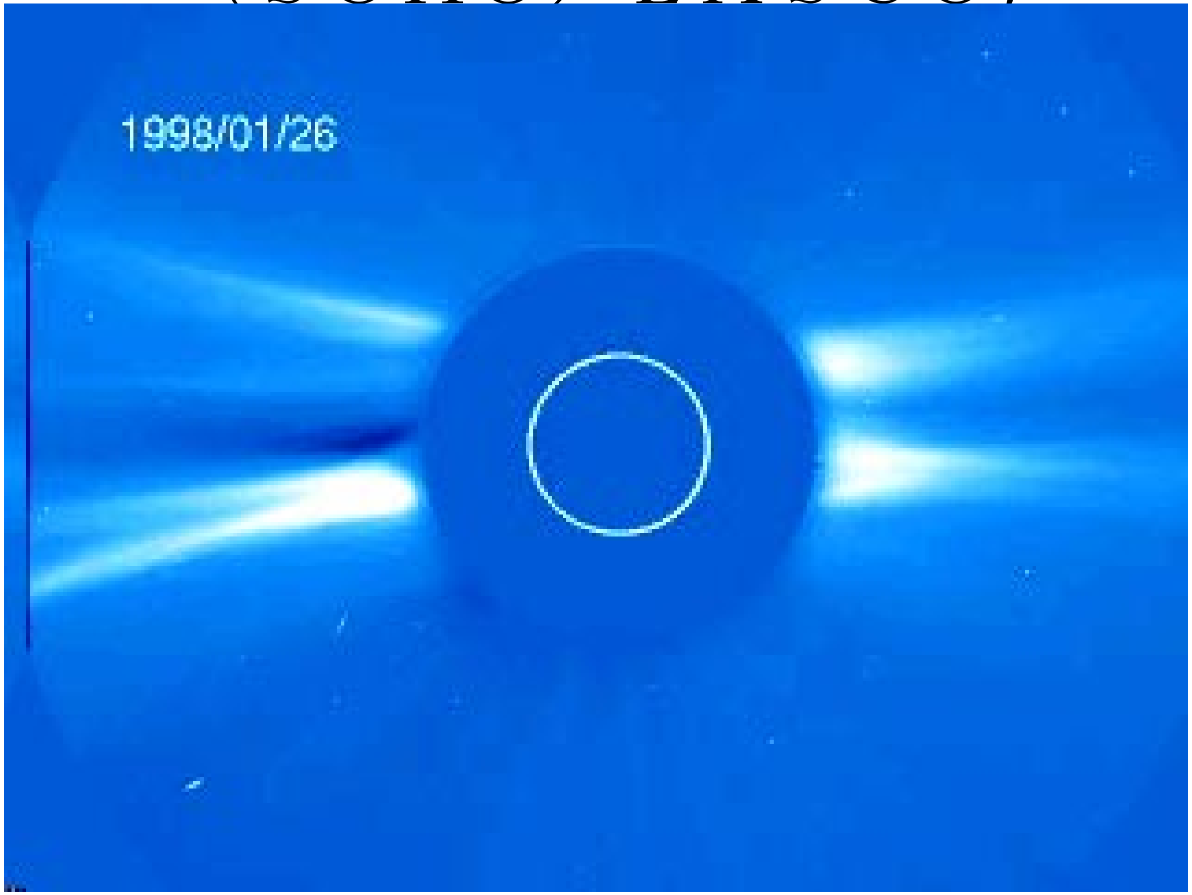
CME: Helical Jet
(SOHO/LASCO)





Coronal mass ejections　（ＣＭＥ）

（ＳＯＨＯ／ＬＡＳＣＯ）



Velocity～１０－１０００ｋｍ／ｓ、mass～１０＾（１５）－

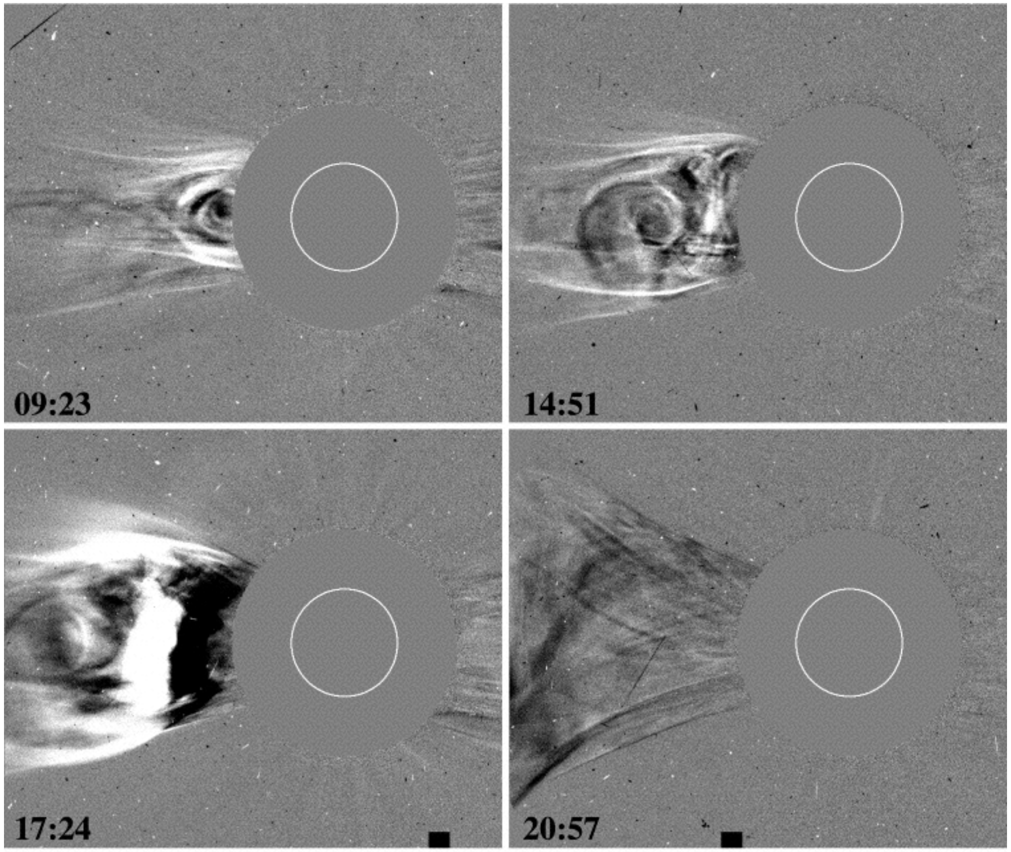
Flux Rope/Disconnection Event in CMEs

- **SOHO/LASCO has also revealed that flux rope or disconnection event (i.e. plasmoid) are much more common in CMEs than had been thought**

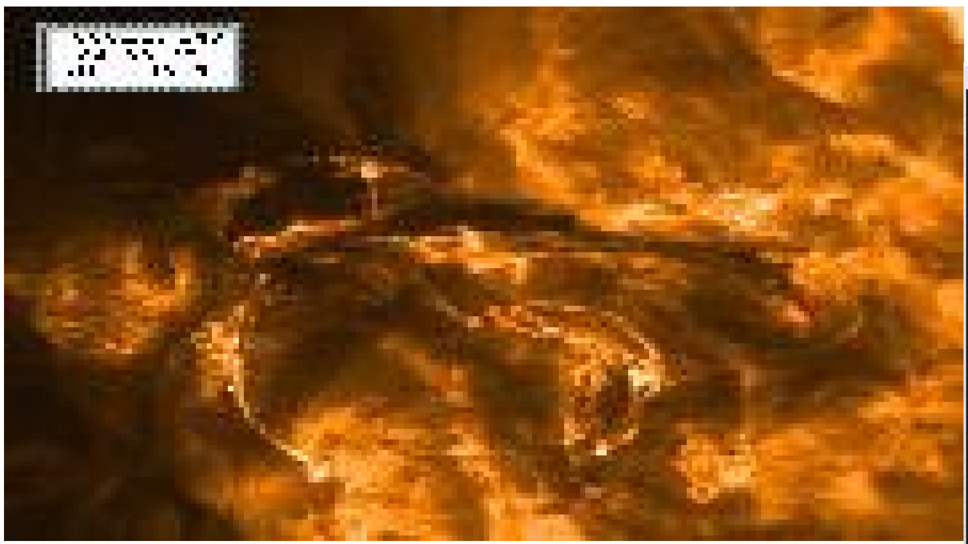
(Dere et al. 1999, Simnett et al. 1997)

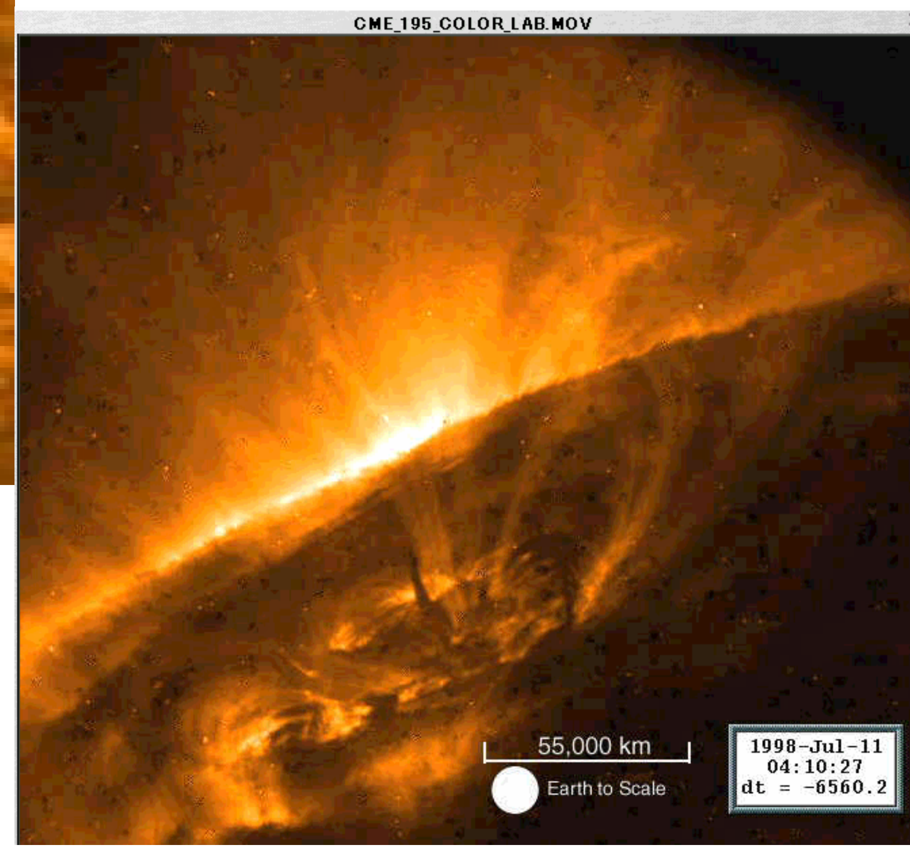
Flux Rope (Plasmoid) in CME

observed with SOHO/LASCO
(Dere et al. 1999)



TRACE observations of flares and ejections

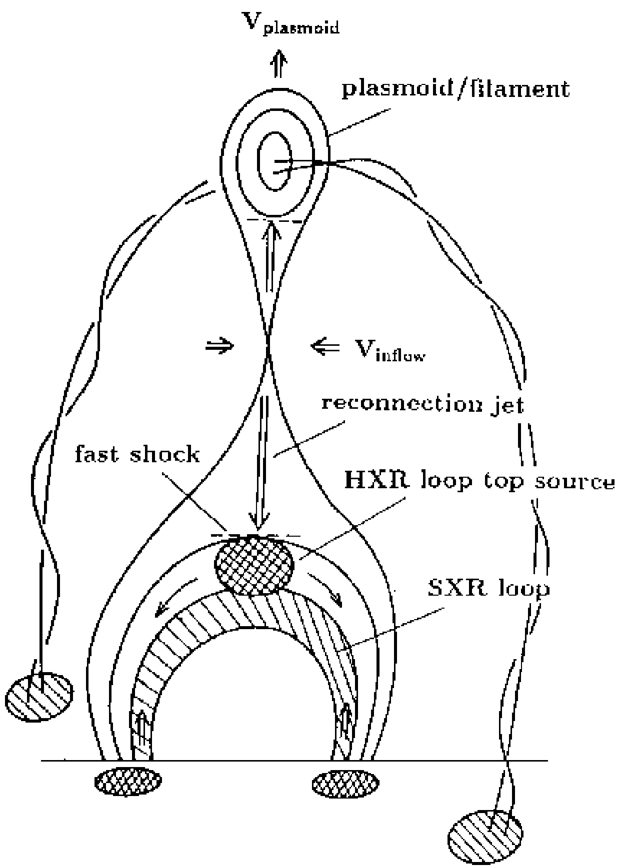


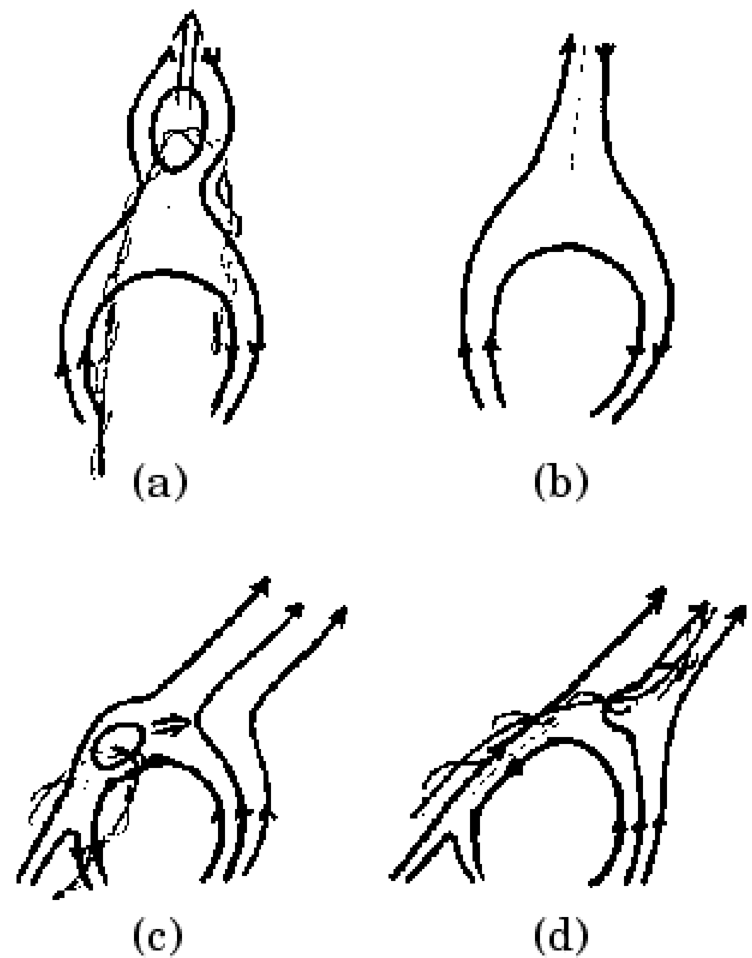


3. A Unified Model

= Plasmoid-Induced-Reconnection model

(extension of CSHKP model)

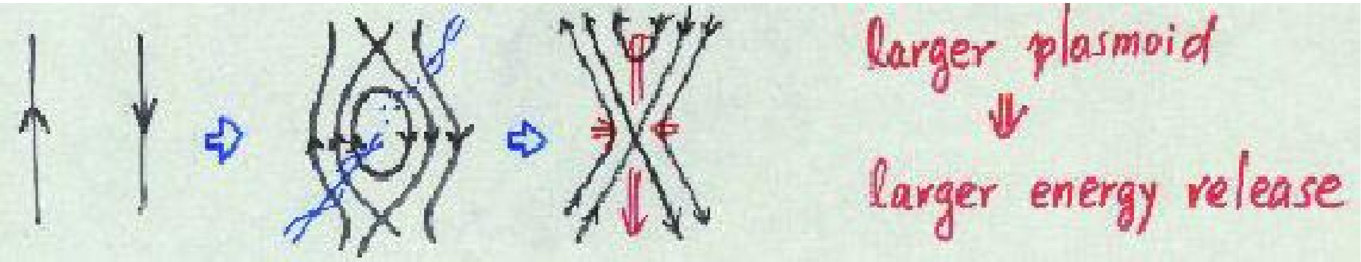




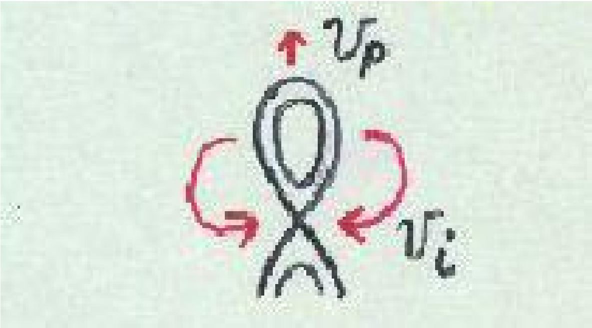
- Large flare
- Small flare

Role of Plasmoid

1. To store energy by inhibiting reconnection



2. To induce strong inflow into reconnection region

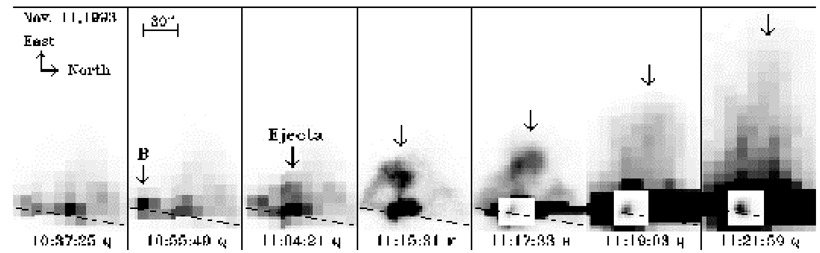


Key Observations on Plasmoid Ejections

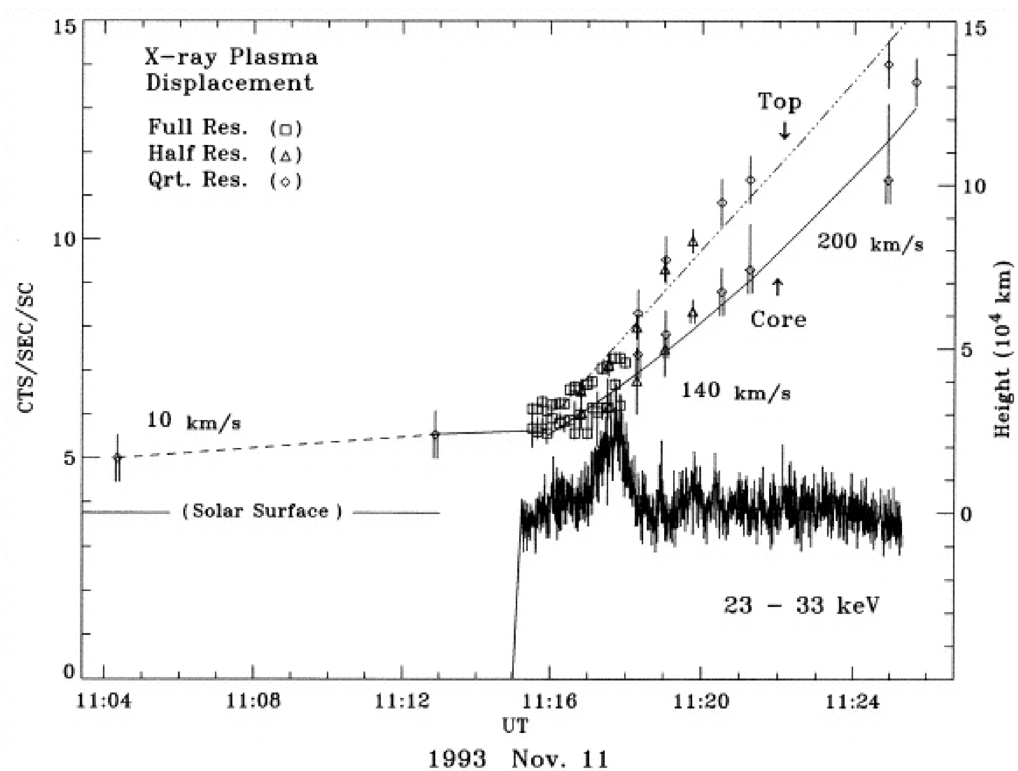
1) Plasmoids are accelerated during impulsive phase of flares

2) There is a positive correlation between plasmoid velocity and reconnection inflow velocity

Plasmoid Acceleration during impulsive phase (Ohyama and Shibata 1997) observed with Yohkoh/SXT



Ohyama & Shibata (1997)



CME height vs. SXR light curve (Hundhausen 1999)

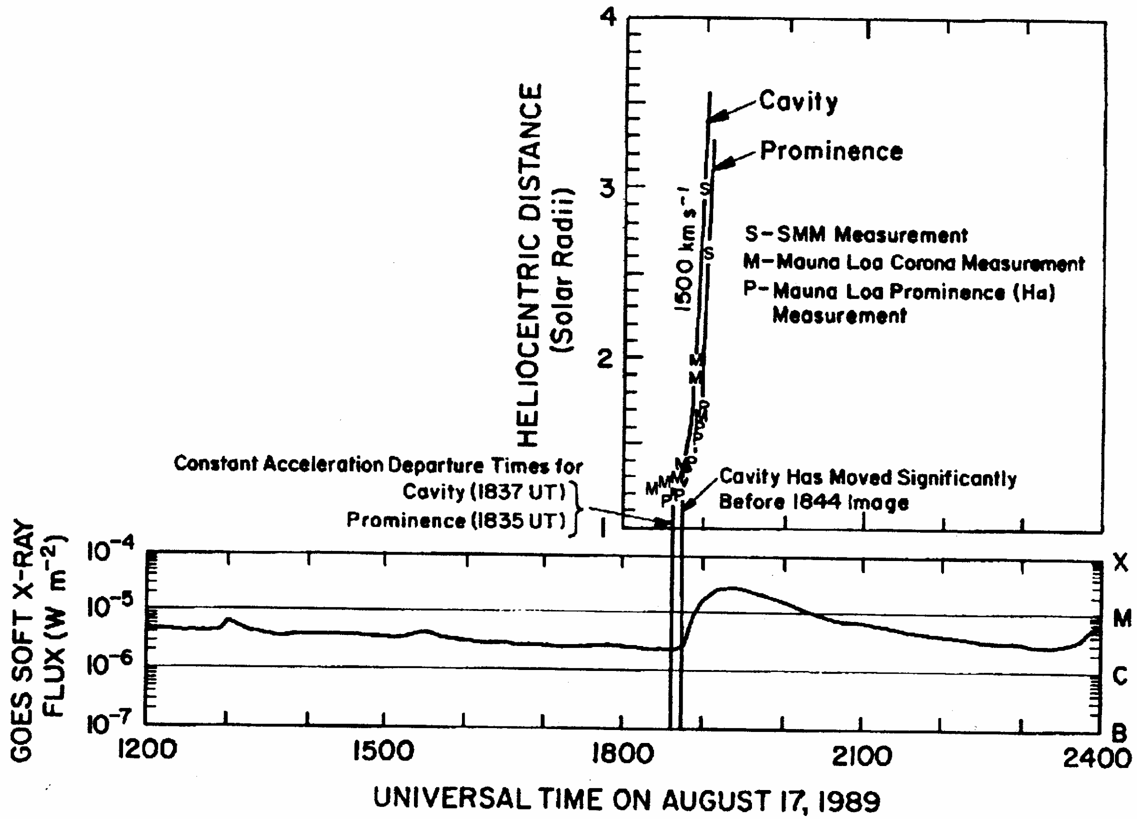


Figure 5.30 Heliocentric positions of the top of the cavity and toe GOES plot showing the timing of the 1989 August 17 ejection.

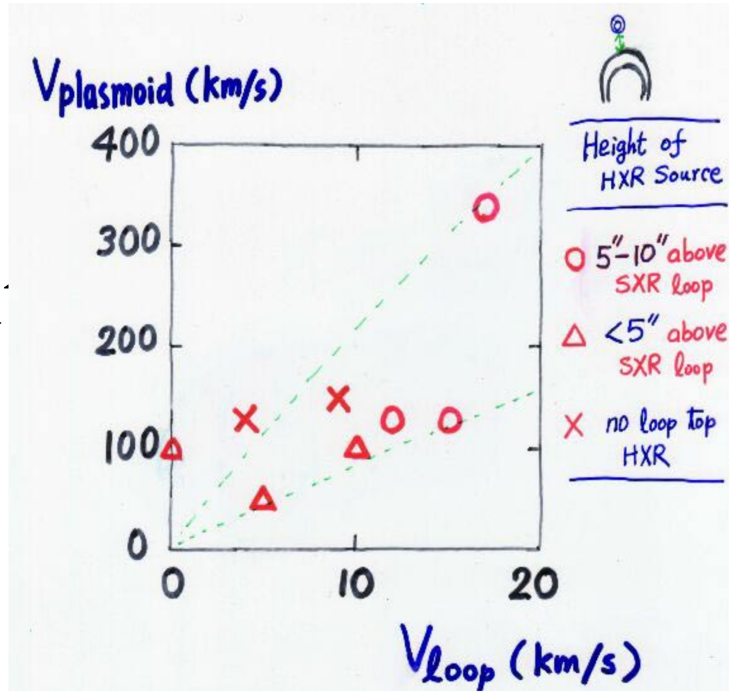
Plasmoid Velocity vs. Reconnection Inflow Velocity

- Yohkoh/SXT observations (Shibata et al 1995) show

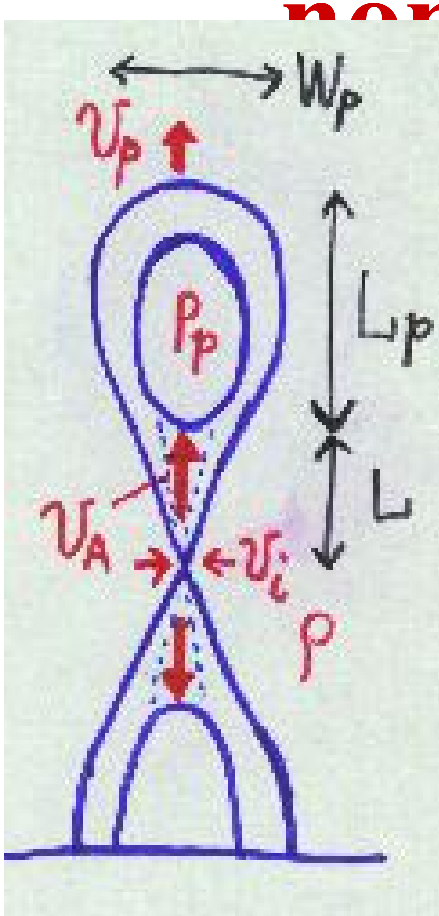
$$V_{plasmoid} = (6-20) \times V_{loop}$$

V_{loop} = apparent rise veloci[ty] of flare loop

$$V_{loop} = (B_{in} / B_{loop}) \times V_{in}$$



Analytical model of plasmoid-induced-reconnection: nonlinear instability



$$\rho_p L_p W_p \frac{dv_p}{dt} = \rho v_i L v_A$$

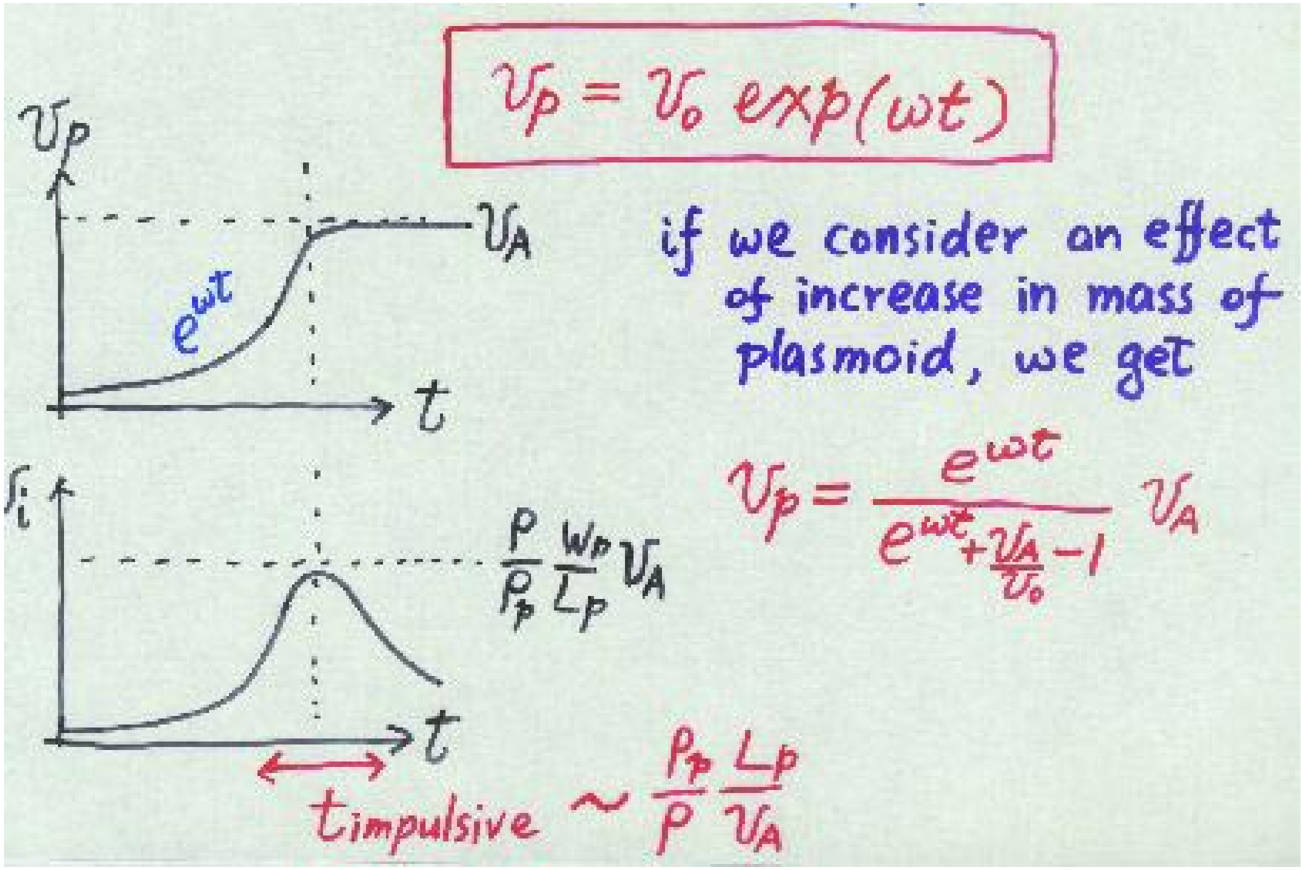
$$= \rho v_p W_p v_A$$

$$\left(\because v_i = \frac{W_p}{L} v_p\right)$$

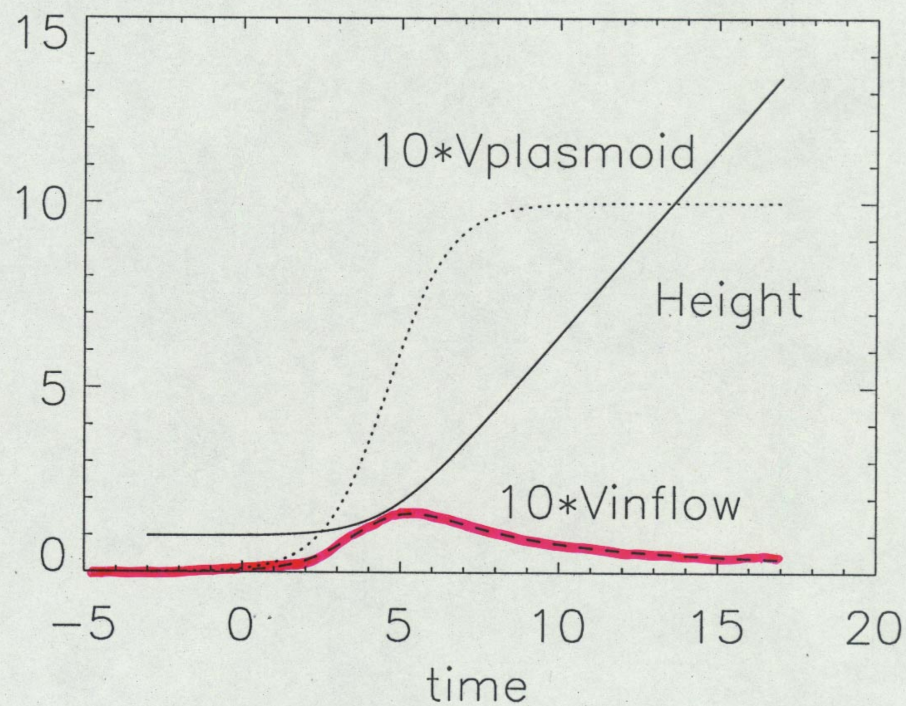
$$\frac{1}{v_p}\frac{dv_p}{dt} = \omega \equiv \frac{\rho v_A}{\rho_p L_p}$$

$$\boxed{v_p = v_0 \exp(\omega t)}$$

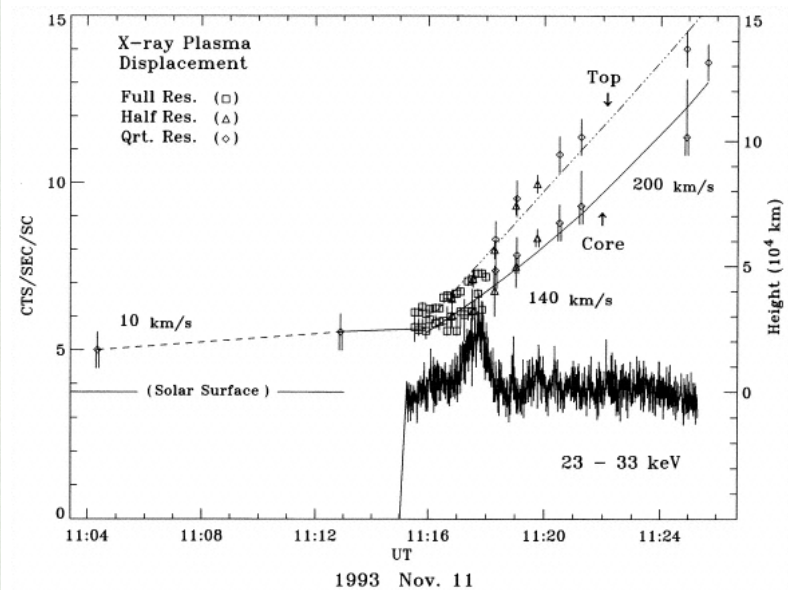
Analytical model of pasmoid-induced-reconnection : saturation of nonlinear instability



Typical analytical solution



$$\left(\frac{v_i}{v_A}\right)_{max} = \frac{\rho}{\rho_p}\frac{W_p}{L_p}$$



Yohkoh/SXT Obs.
(Ohyama and Shibata 1997)

MHD simulations of Flares and Coronal Mass Ejections

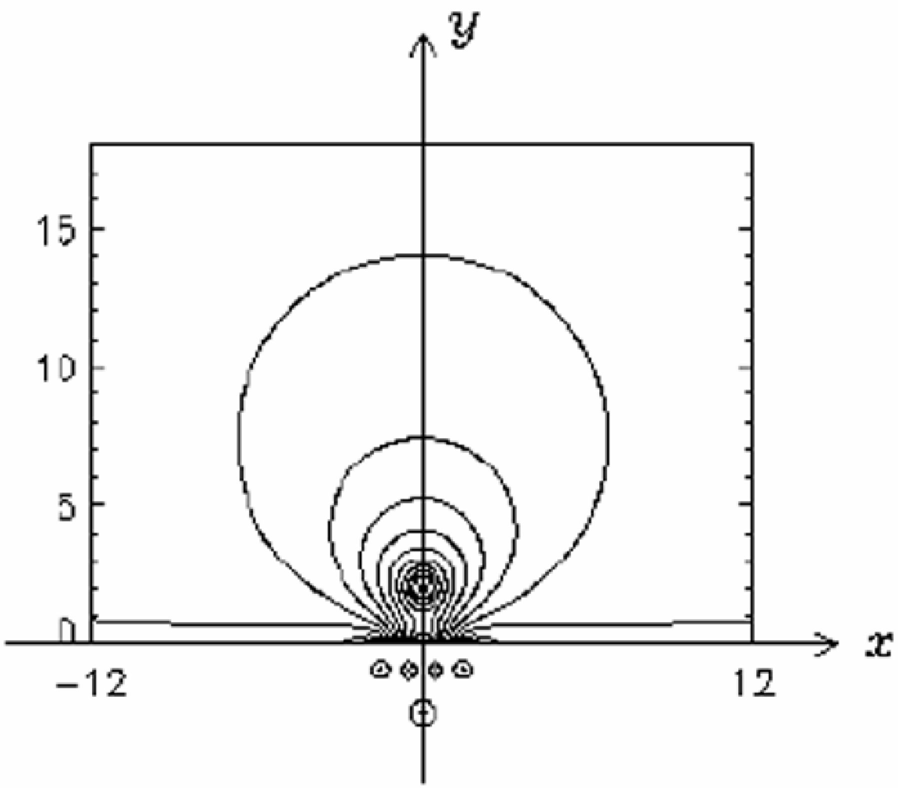
- Wu et al.
- Mikic and Linker
- Forbes
- Antiochos
- Choe and Cheng
- Kusano
- Magara, Yokoyama, Shibata
- Chen and Shibata

and so on

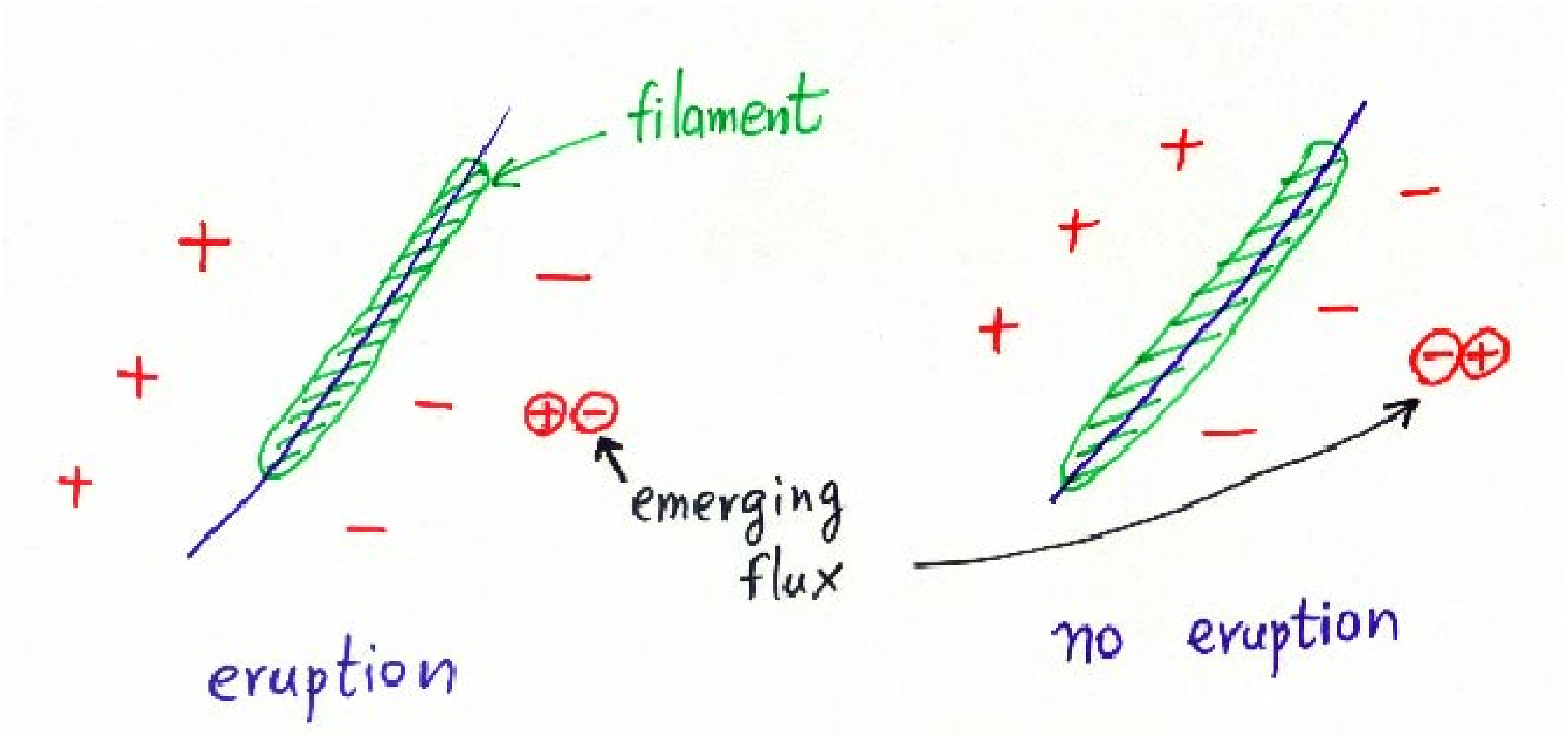
MHD simulation of flares/CMEs

(Chen and Shibata 2000)

- Initial condition
- (extension of Forbes model)



Motivation: Observations of emerging flux triggering filament eruption (Feynman and Martin 1994)



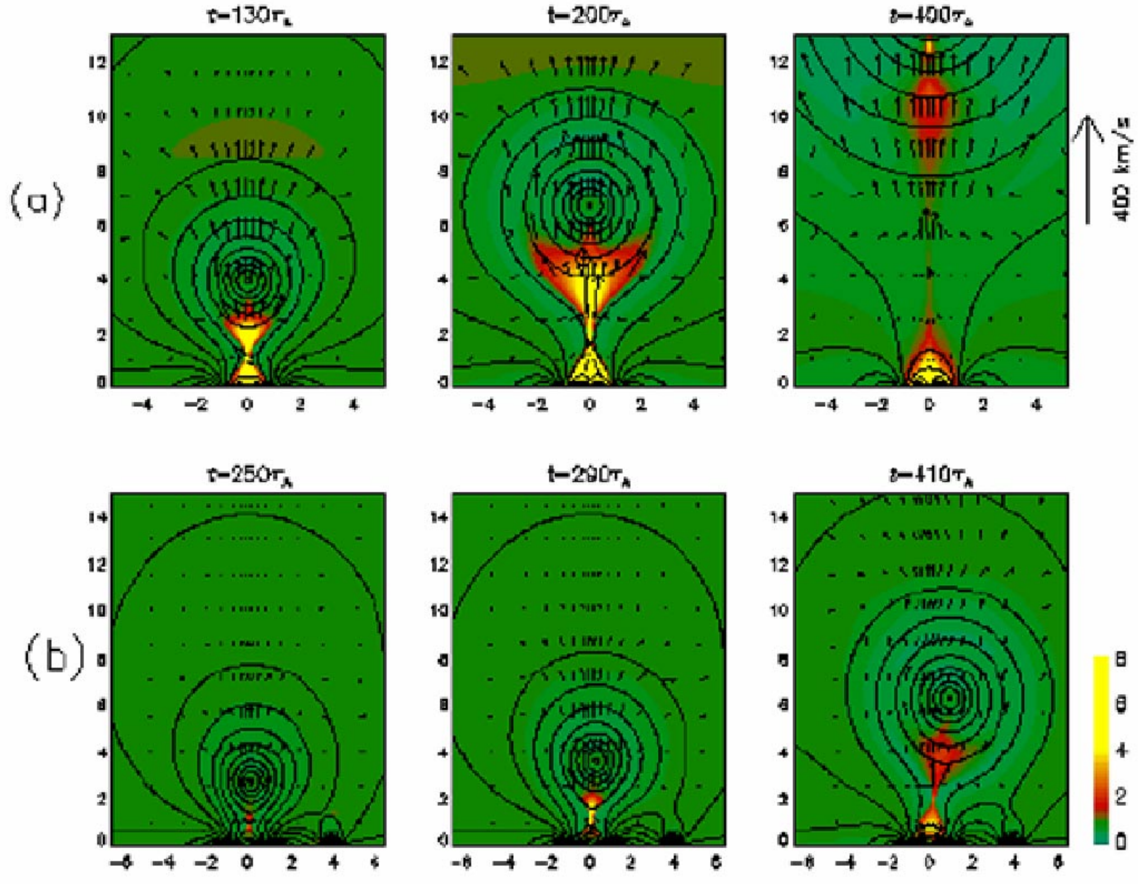
2D-MHD simulation of emerging flux triggering filament eruption

Case A

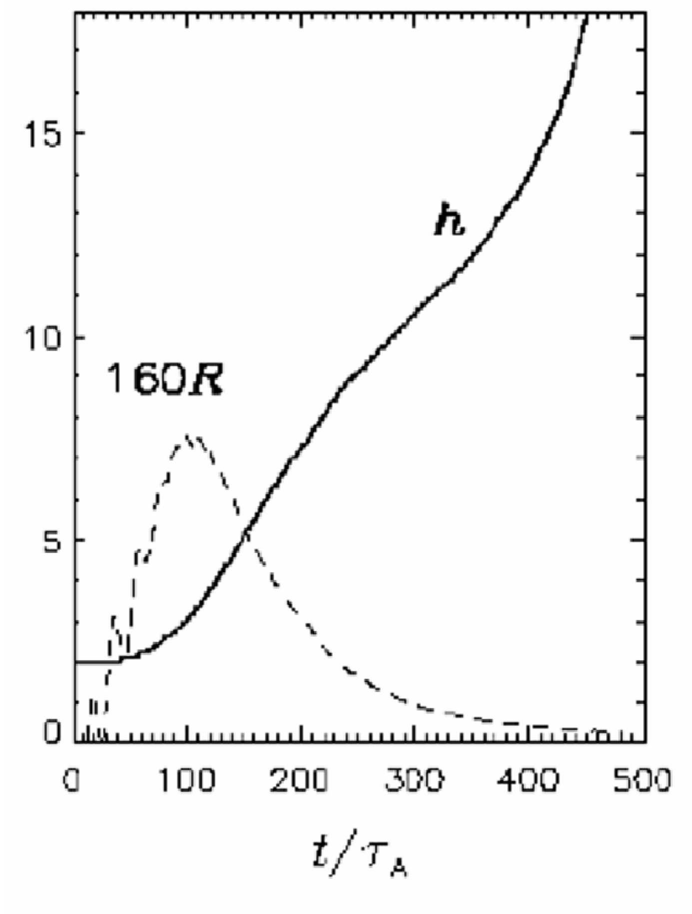
movie

Case B

movie



Plasmoid height vs. reconnection rate



- If we inhibit reconnection, fast mass ejection can not occur

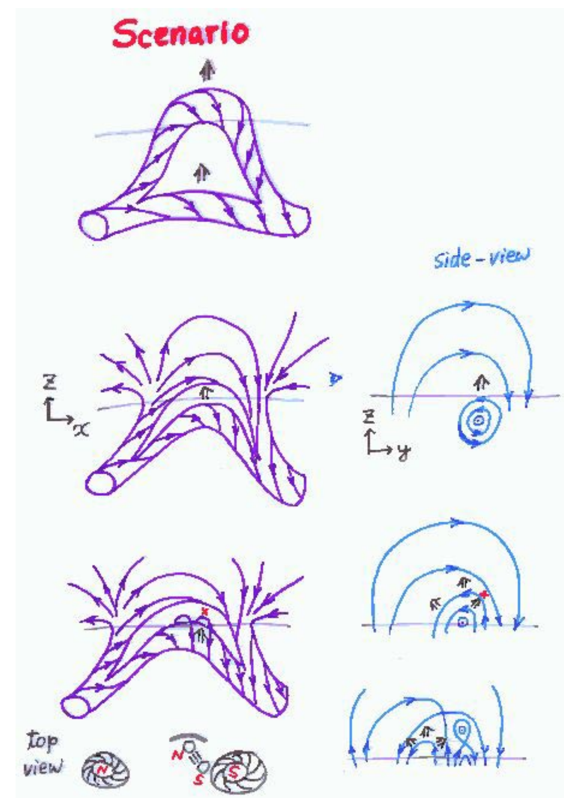
4. Summary

- It has been revealed that magnetic reconnection play essential role in solar flares
- Coronal mass ejections (CMEs) are physically similar to flares, so (I think) magnetic reconnection play essential role also in CMEs (though still controversial) => SHINE meeting
- Even smaller scale flare-like events such as microflares and nanoflares show common properties with flares and CMEs, which led us to propose a unified model called plasmoid-induced-reconnection model.

Remaining Questions

- Energy storage mechanism, trigger mechanism ? (=> emerging flux ?)
- Coronal heating mechanism ?
- Detection of reconnection jet, inflow, and MHD shocks

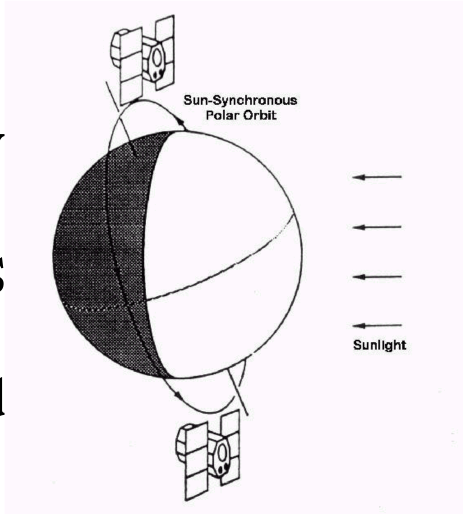
＝＞Solar B (2005)



Solar-B Mission

- Solar Optical Telescope (SOT)
- X-Ray Telescope (XRT)
- EUV Imaging Spectrometer (EIS)

- Launch Date: 2005 J-fiscal y
- Mission Lifetime: > 3 years
- Orbit: Polar, Sun Synchronou



Science Objectives of Solar-B Mission

- coronal heating
- coronal dynamics and structure
  - jet, CME, solar wind
- reconnection dynamics
  - reconnection jet, inflow, slow/fast shocks,…
- emerging flux and dynamo

Discovery of Reconnection Inflow (SOHO/EIT :Yokoyama et al. 2001)

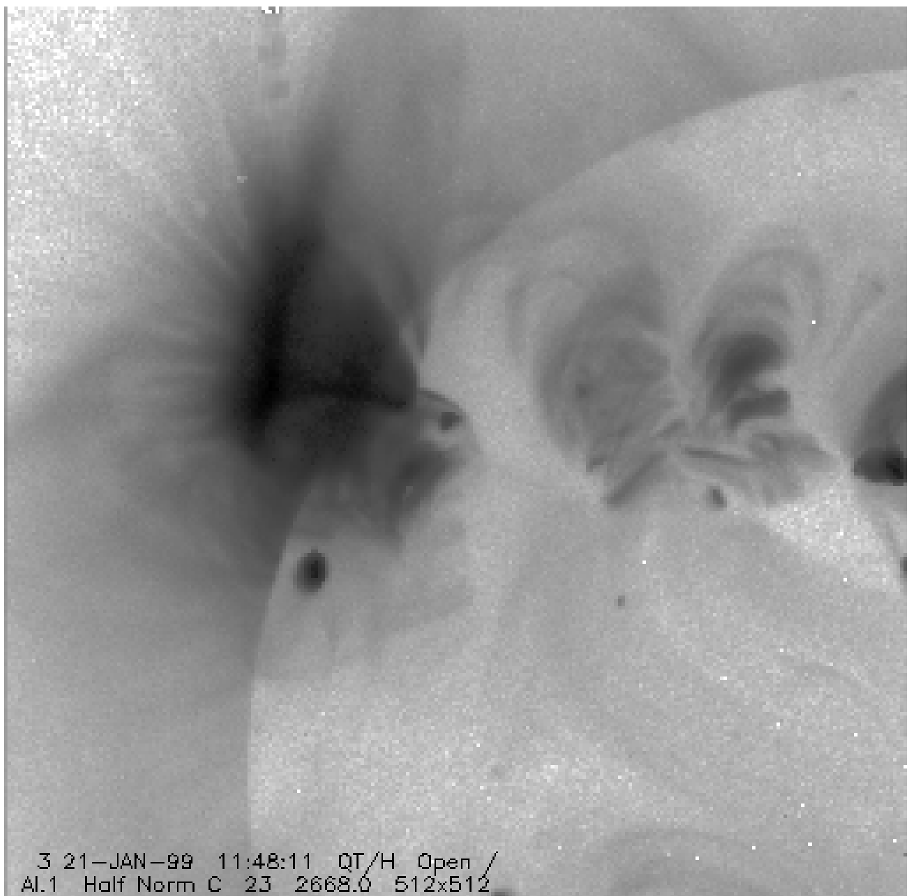
Inflow

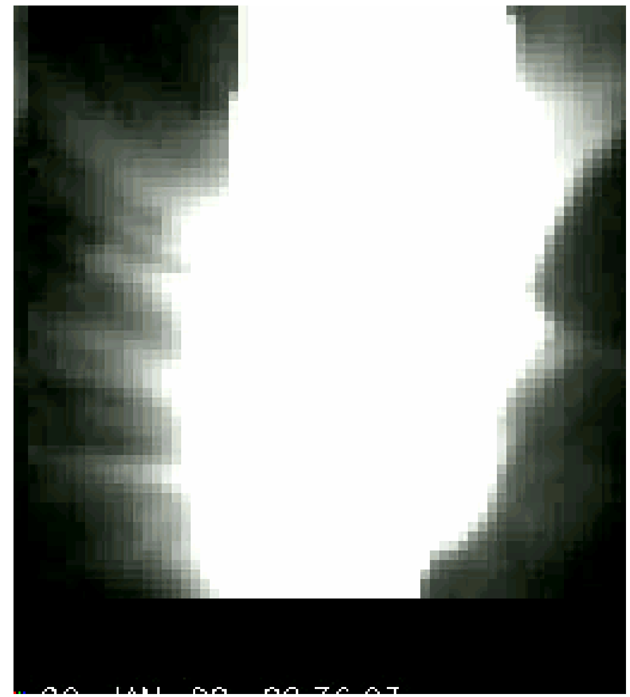
Speed ~

5 km/s

Discovery of Reconnection Downflow

(Yohkoh/SXT: McKenzie and Hudson 1999)



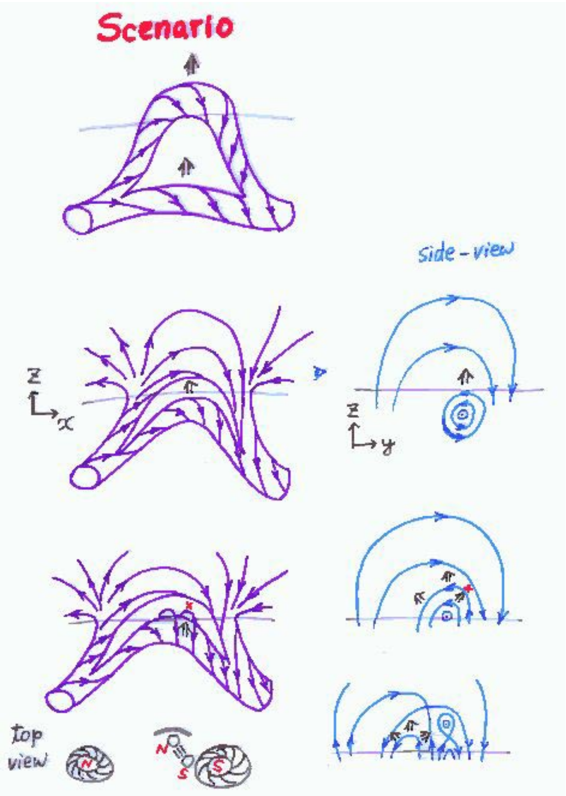


Downflow speed
~ 30-500 km/s

Remaining Questions

- Energy storage mechanism, trigger mechanism ? (=> emerging flux ?)
- Coronal heating mechanism ?
- Detection of reconnection jet, inflow, and MHD shocks

＝＞Solar B (2005)



4. Stellar flare

- X-ray intensity time variation of stellar flare is very similar to that of solar flares

- Proxima Centari
- (Einstein : Haisch et al. 1983, Reale et al. 1988)

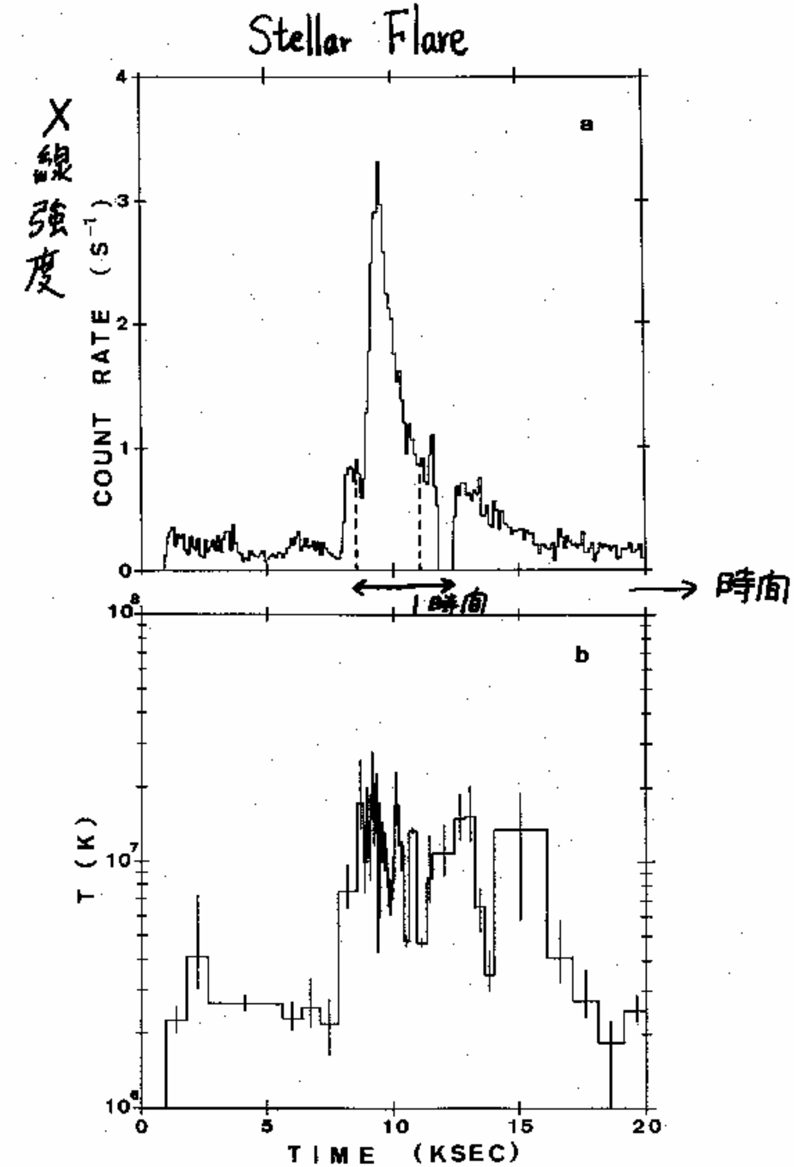
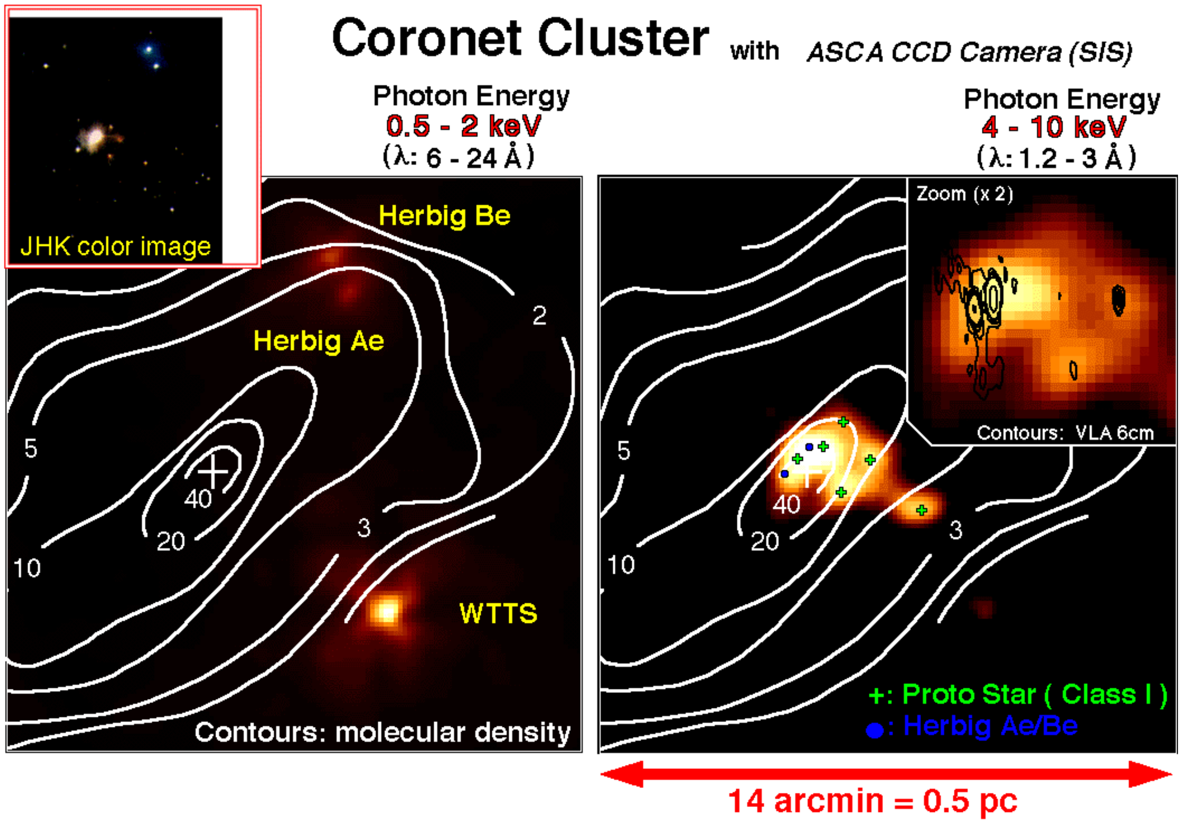


Fig. 4. (a) Observed light curve of the flare on Proxima Centauri detected in the IPC X-ray band with the Einstein satellite telescope (from Haisch *et al.*, 1983). The dashed vertical lines bound the time range covered by the hydrodynamic calculations. (b) Evolution of the single-component temperature, derived from the data. (From Reale *et al.*, 1988.)

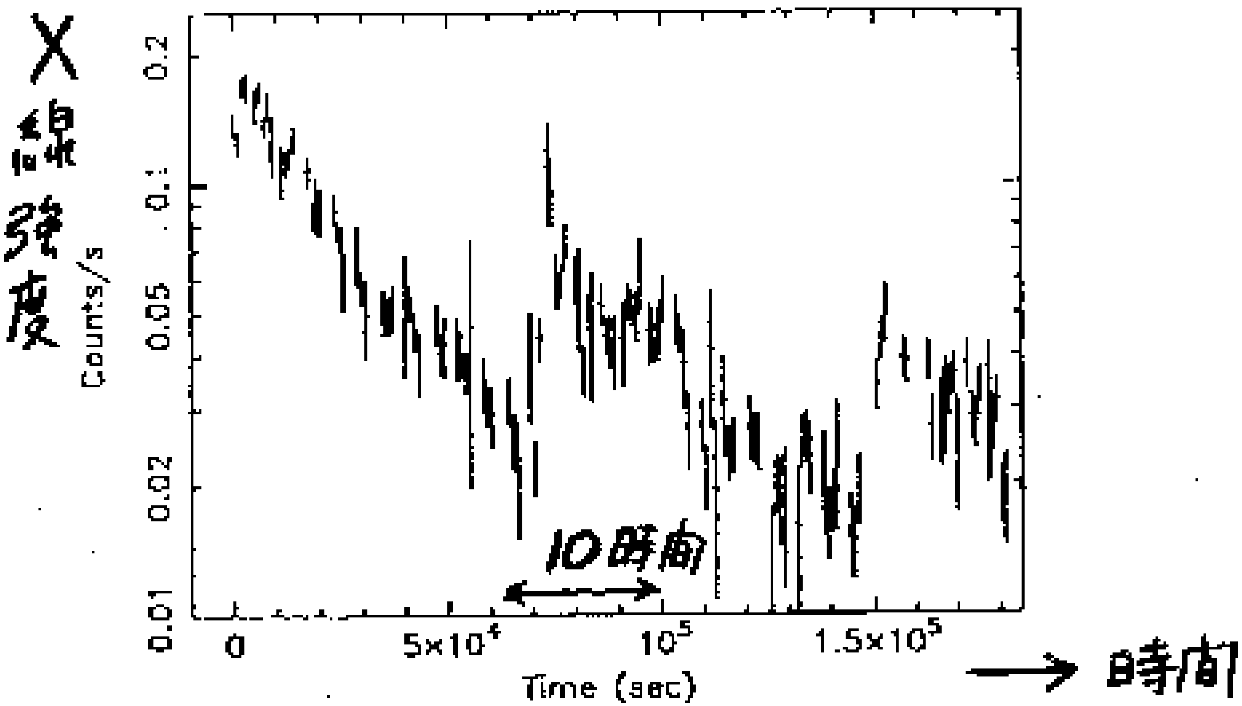
Protostellar Flare
（ASCA ：Koyama et al. １９９５）



Temperature
~ 100MK

cf) solar flare
temperature
~ 10-20 MK

Protostellar flare (ASCA: Tsuboi et al. 2000)



Quasi-periodic

Total energy
$10^{36} \sim 10^{37}$ erg

cf) solar flare
total energy
$\sim 10^{29} \sim 10^{32}$ erg

Characteristics of Protostellar Flares

Flares occur much more frequently in protostars than in solar flares

- Lifetime of protostellar flares (a few – 10 hours) is comparable to that of long duration (LDE) solar flares
- Temperature (~50-100 MK) is much higher than that of solar flares (~10-20 MK)
- Total energy is 10^4 times more than that of solar flares

Can protostellar flares be explained by magnetic reconnection mechanism ?

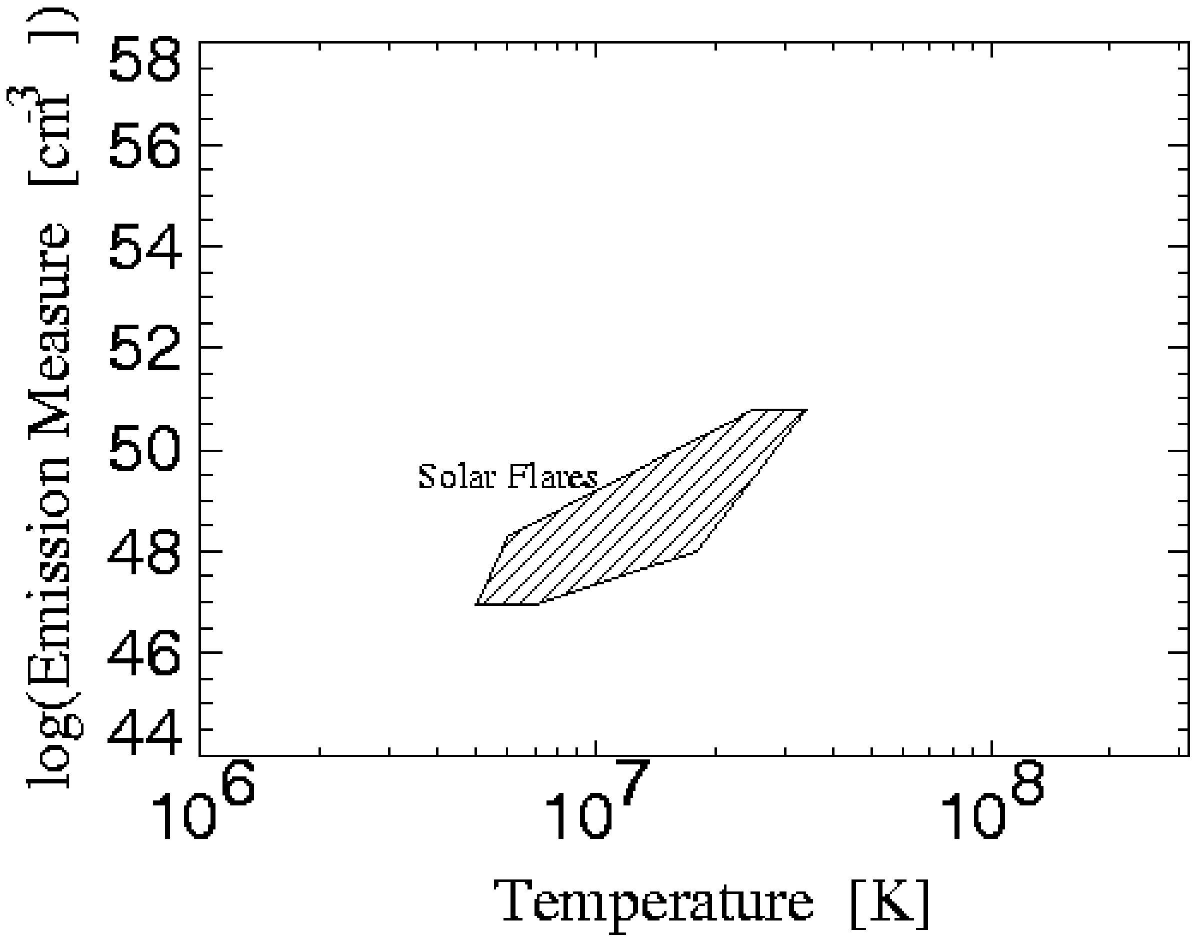
- Yes !
- Indirect evidence has been found in empirical correlation between

  Emission Measure $EM = n^2 L^3$)

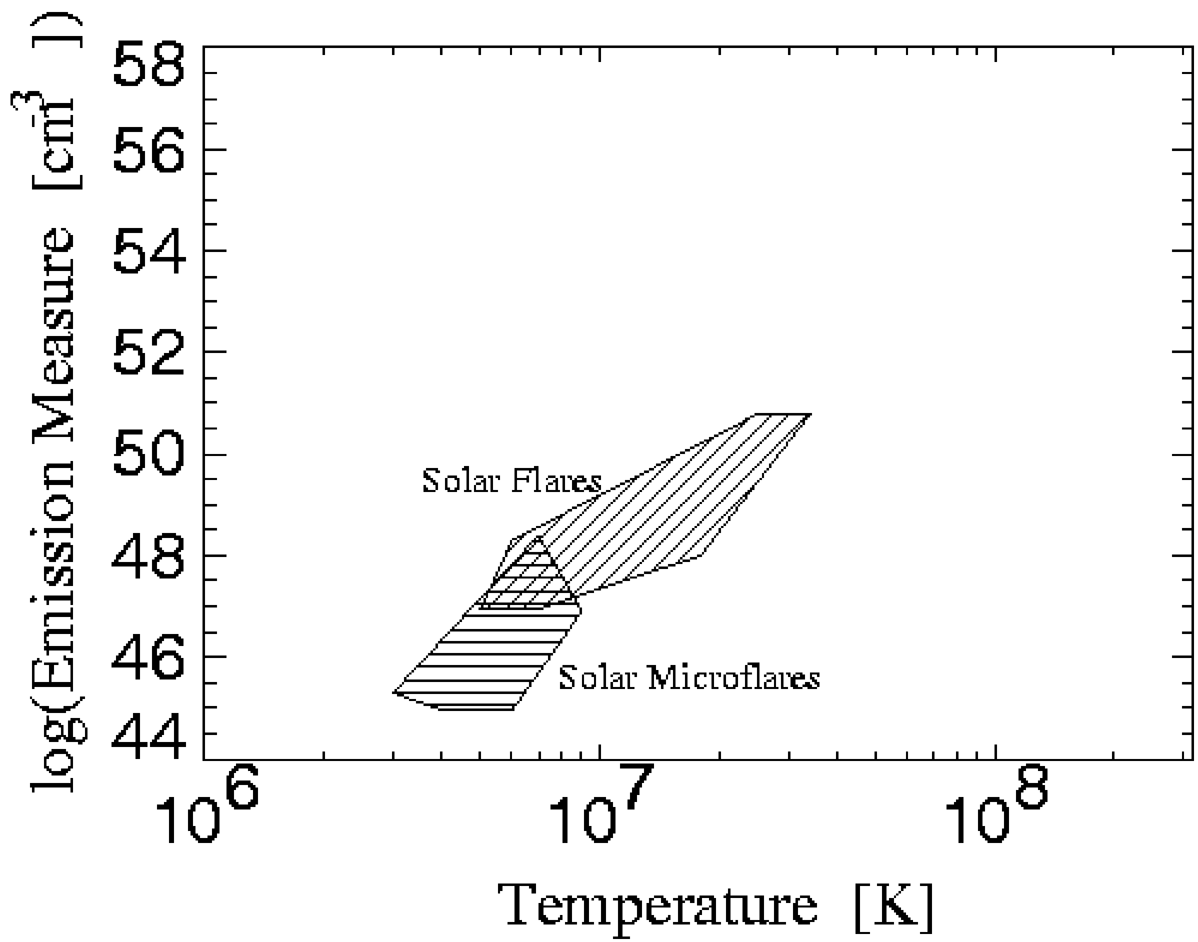
  and Temperature

  (Shibata and Yokoyama 1999)

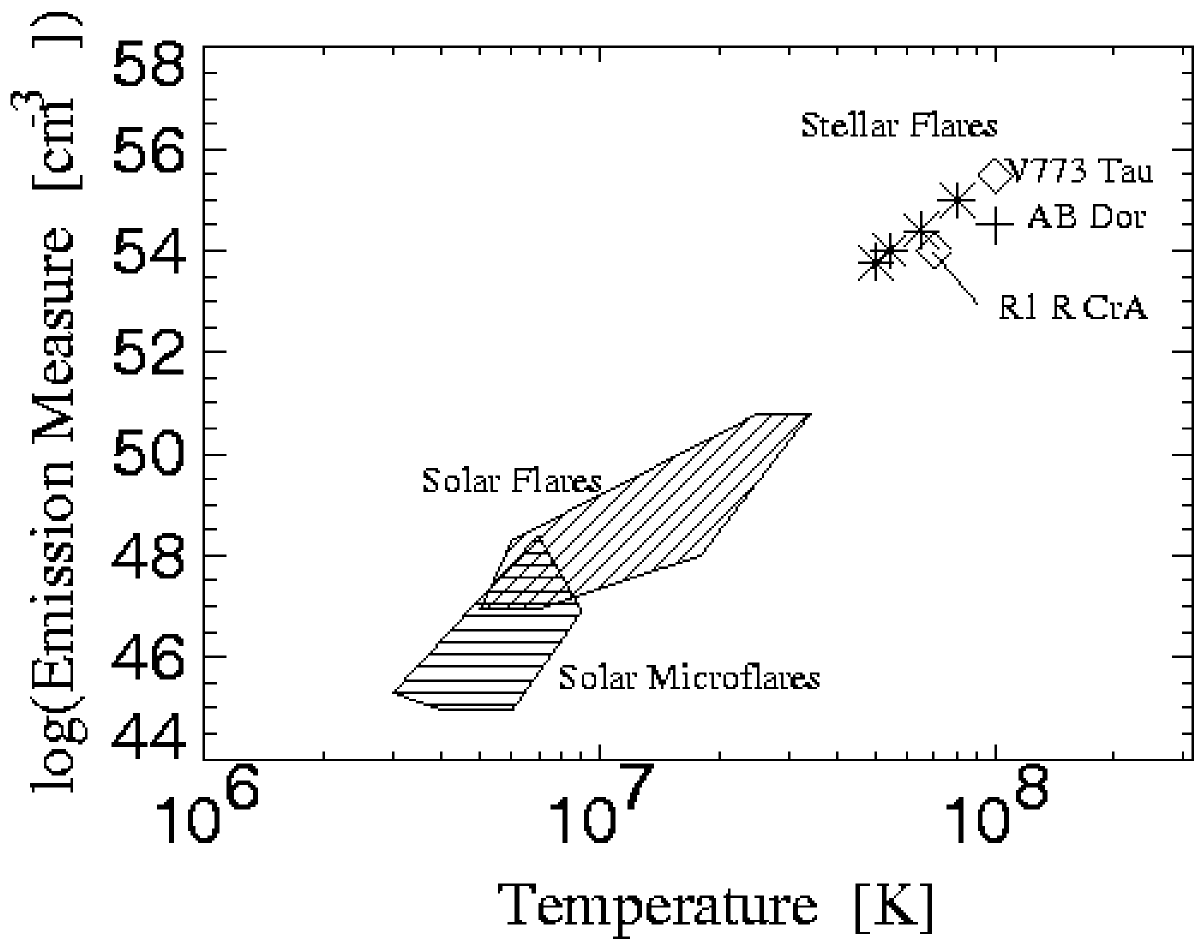
Emission Measure vs Temperature in solar flares (Feldman)



Emission Measure vs Temperature



Emission Measure-T correlation holds also for proto-stellar flares and jets



What determines flare temperatures ？

Reconnection heating＝conduction cooling

（Yokoyama and Shibata 1998)

$$B^2 V_A / 4\pi = \kappa T^{7/2} / 2L$$

$$T \propto B^{6/7} L^{2/7}$$

Flare Emission Measure

(Shibata and Yokoyama 1999)

- Emission Measure

$$EM = n^2 L^3$$

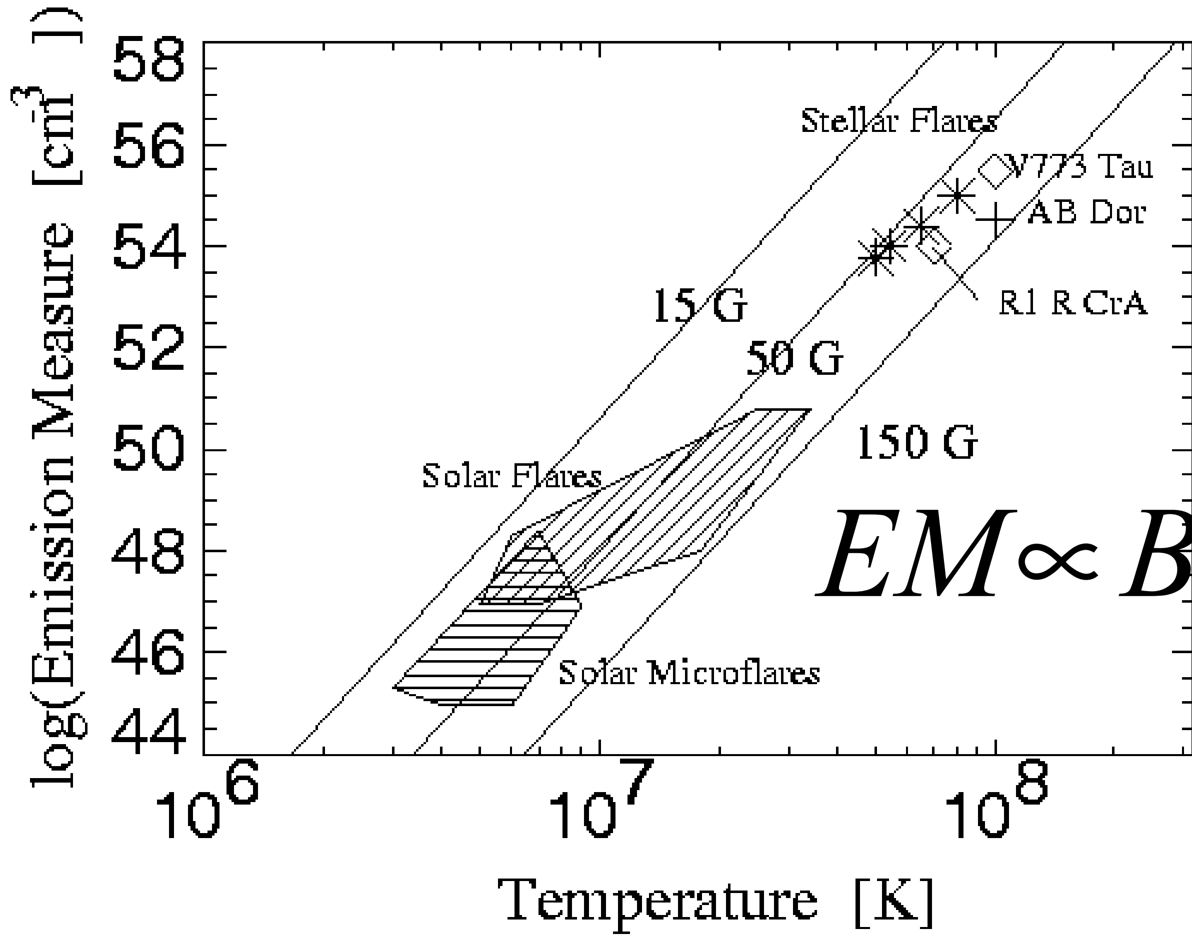
- Dynamical equilibrium

$$2nkT = B^2 / 8\pi$$

- Using Temperature scaling law, we have

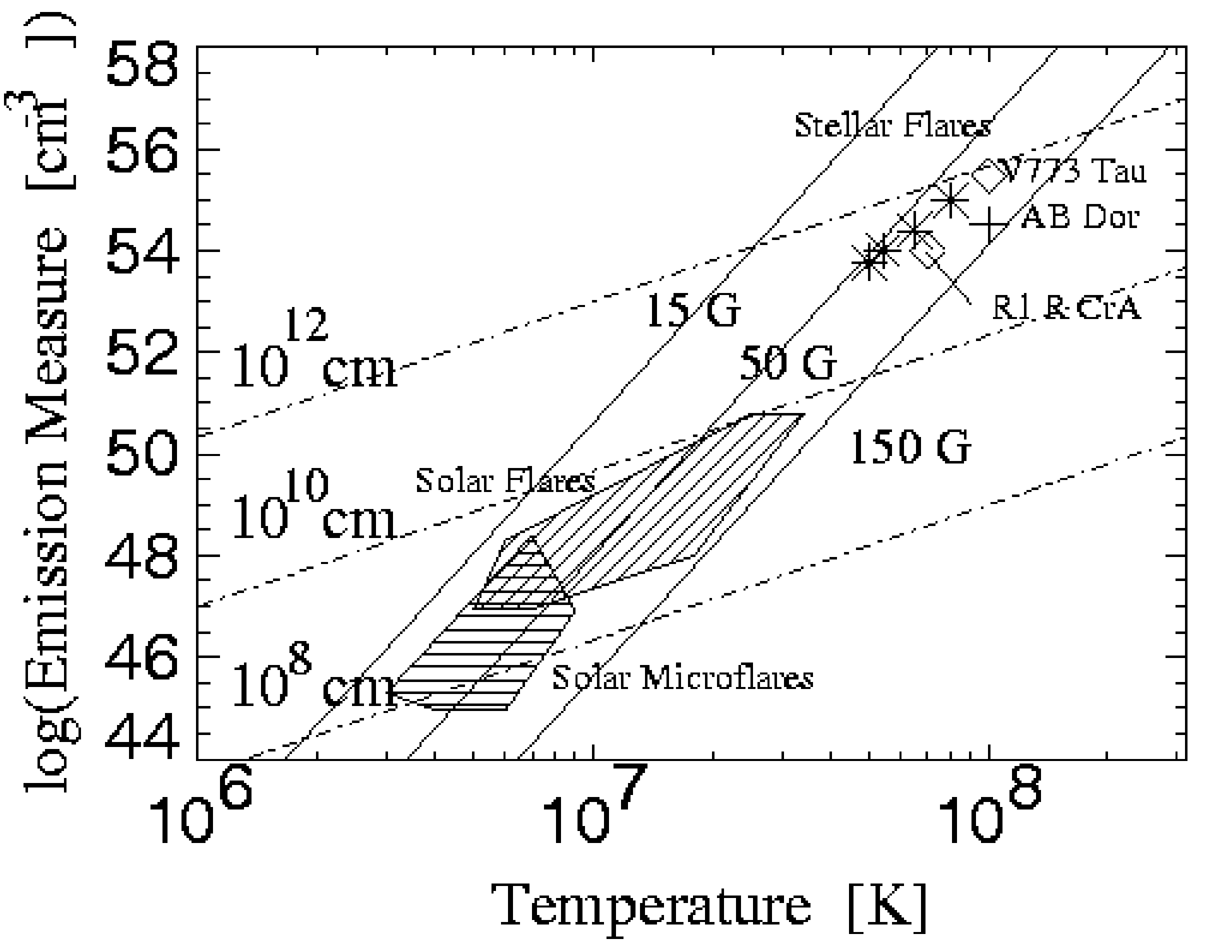
$$EM \propto B^{-5} T^{17/2}$$

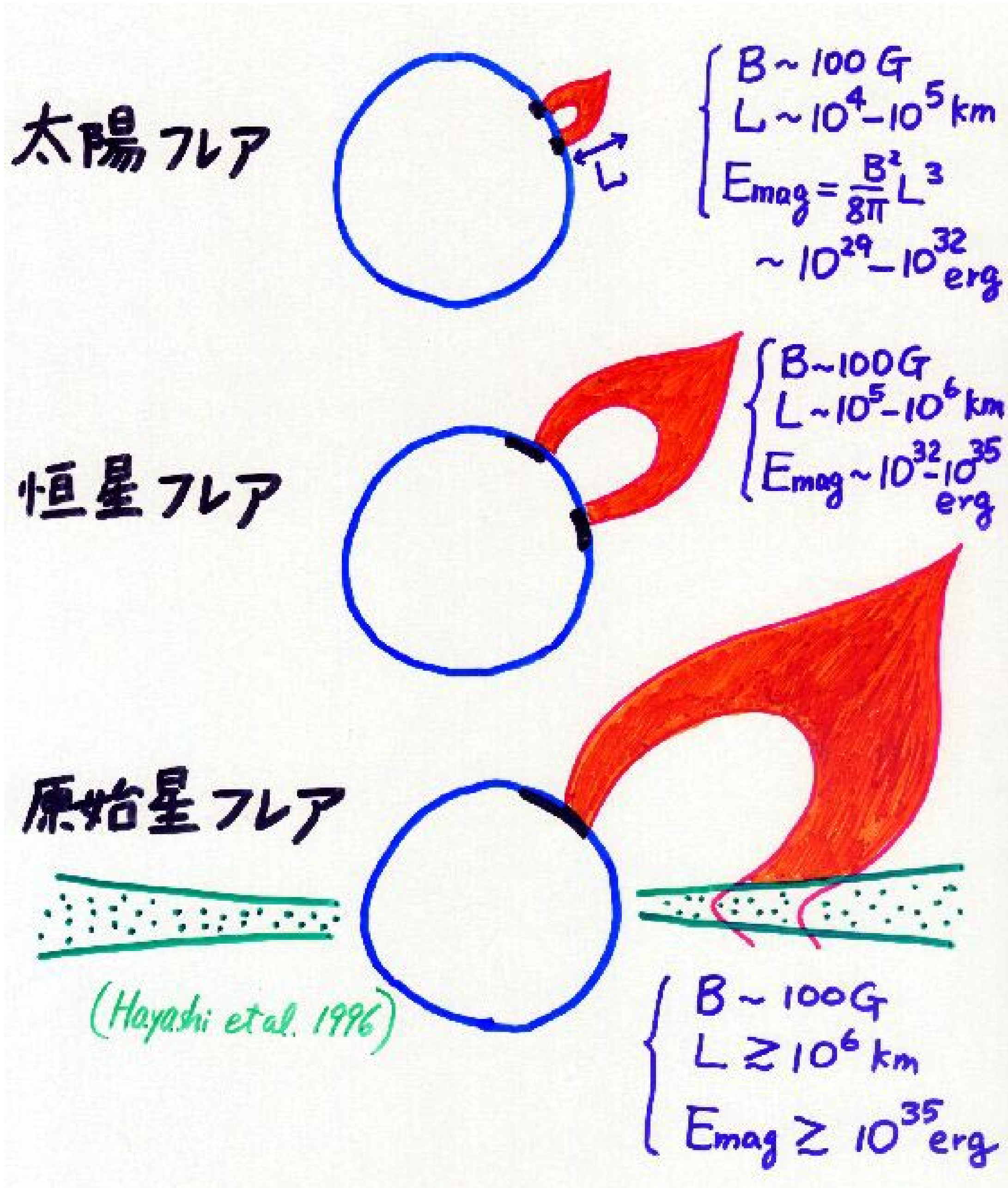
Theoretical EM-T scaling law



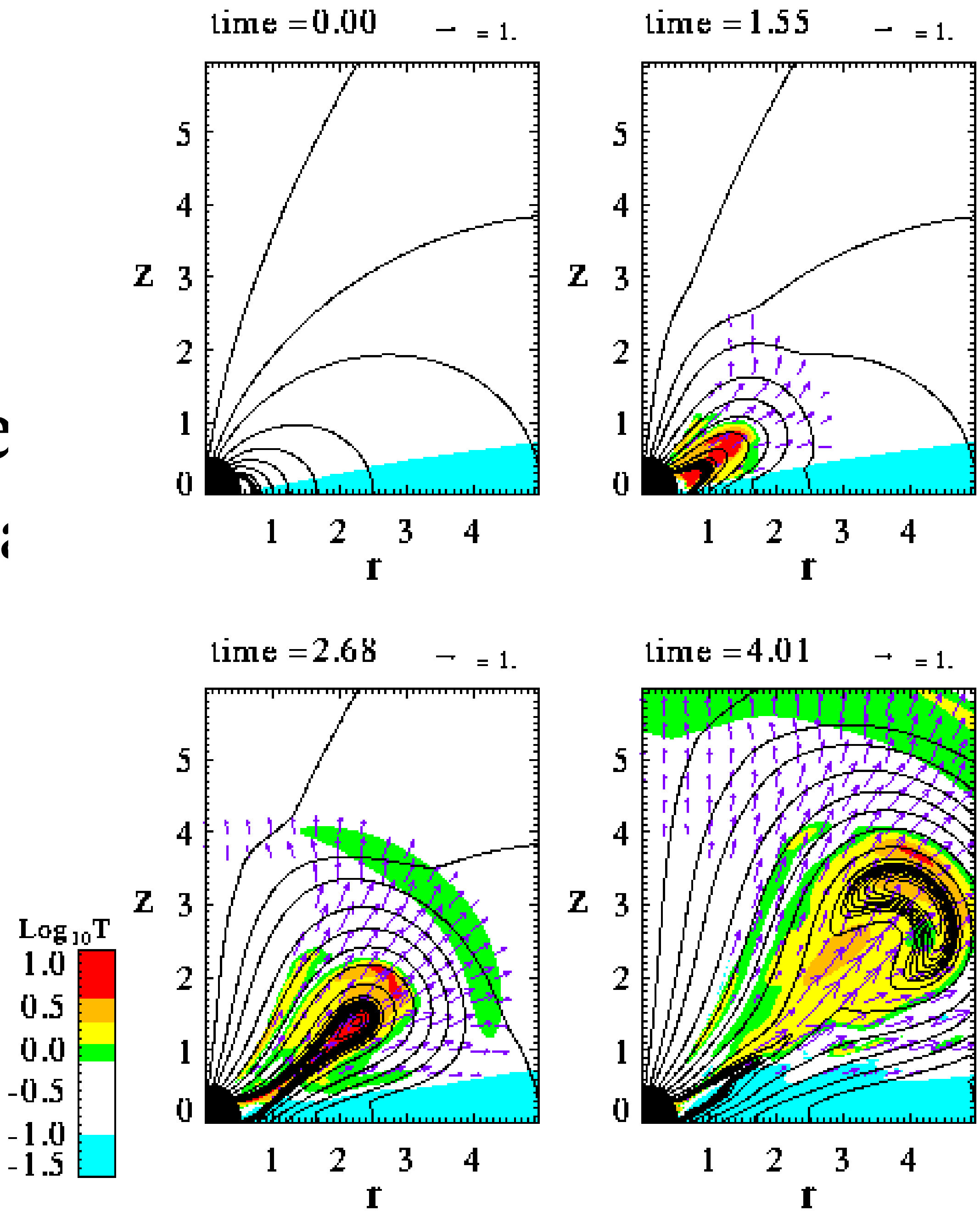
$$EM \propto B^{-5} T^{17/2}$$

What is the length of flare loops ?

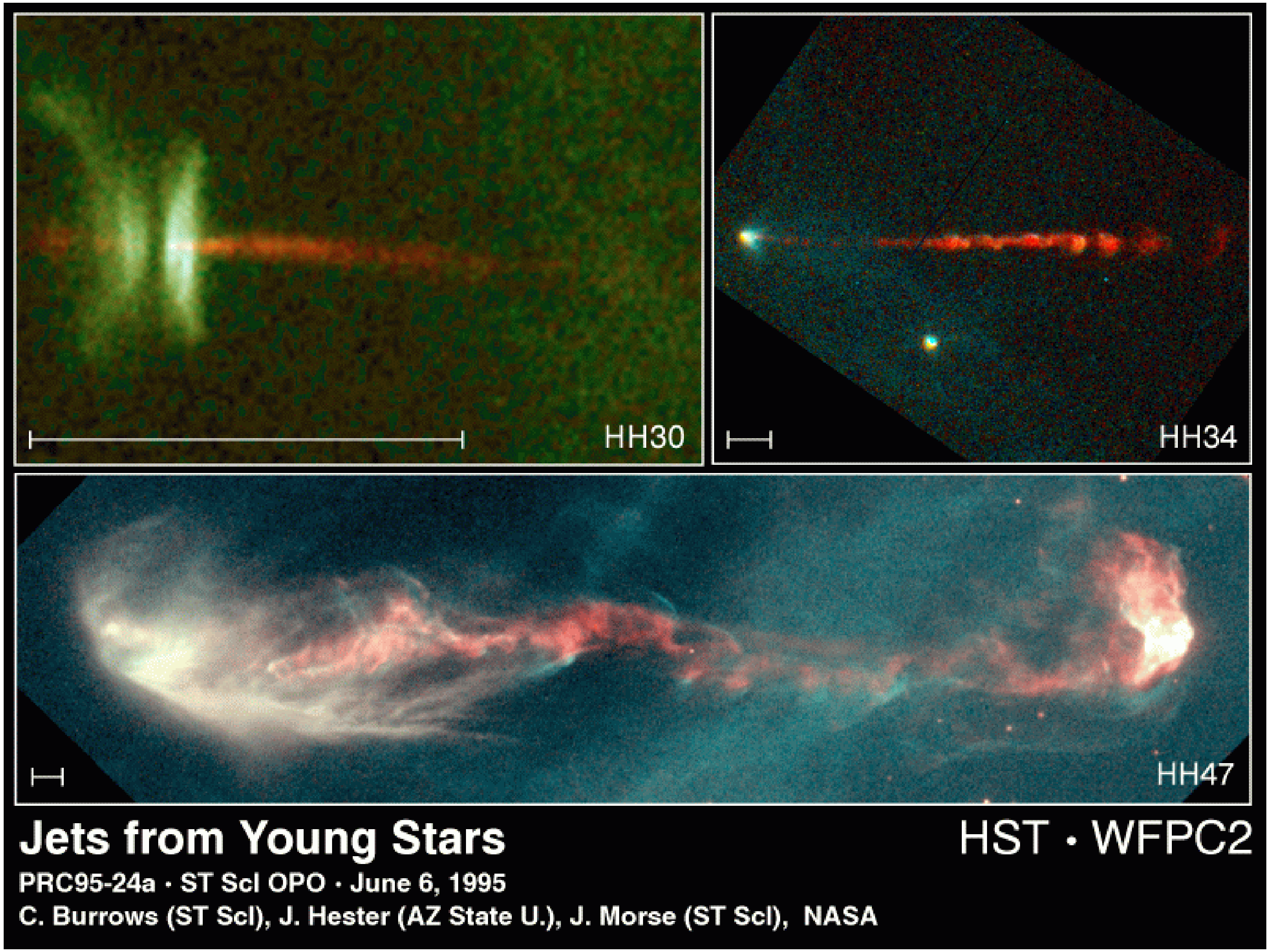



太陽フレア
L
B ~ 100 G
L ~ 10^4 – 10^5 km
Emag = B²/8π L³
~ 10^29 – 10^32 erg
恒星フレア
B ~ 100 G
L ~ 10^5 – 10^6 km
Emag ~ 10^32 – 10^35 erg
原始星フレア
(Hayashi et al. 1996)
B ~ 100 G
L ≳ 10^6 km
Emag ≳ 10^35 erg

Reconnection model of protostellar flare (Hayashi, Shibata Matsumoto 1996)



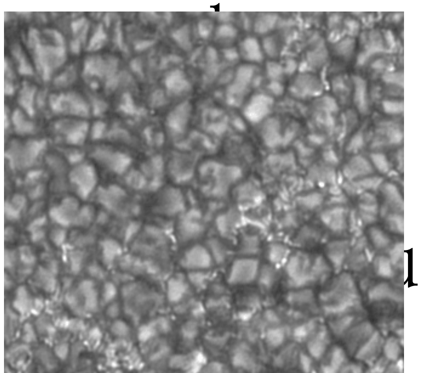
宇宙ジェット
(原始星ジェット)



Solar Optical Telescope (SOT)

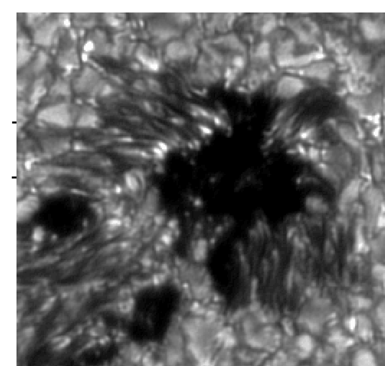
- 50 cm Aplanatic Gregorian – Japan
- Focal Plane Package – US(LMATC)

  (Filtergram+Spectro-polarimeter)
- => 0.2 arsec resolution; 380-700



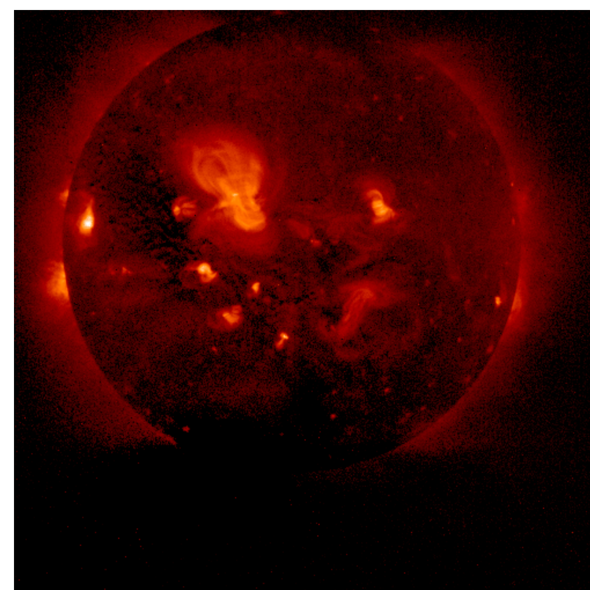
vector magnetic fiel

urements



X-Ray Telescope (XRT)

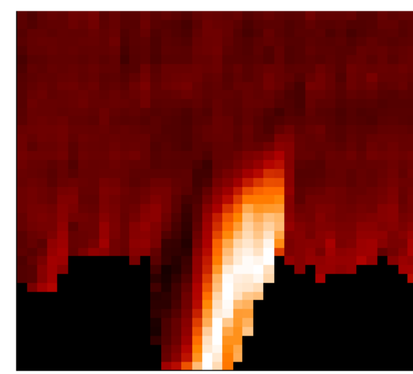
- Grazing-Incidence Optics – US(SAO)
- CCD Camera – Japan
- => 1 arcsec resolution; 1 – 30 MK

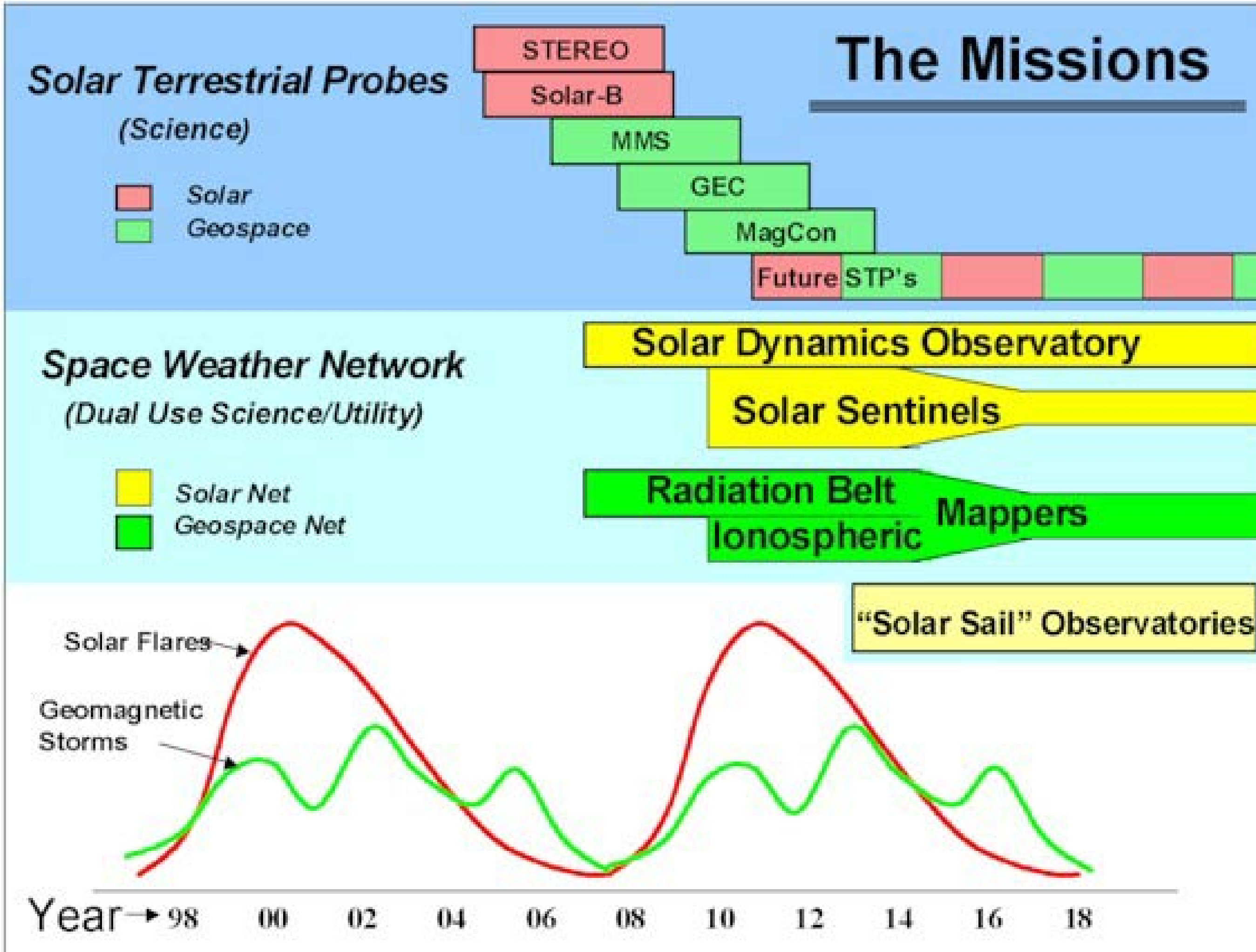


EUV Imaging Spectrometer (EIS)

- 15 cm Offset Parabolic Mirror, Slit/Slot & Multilayer Grating – US (NRL, GSFC)
- Camera – UK(MSSL, RAL, Birmingham)
- Controller – Japan
- 20 km/s nonthermal motio
- 2 arcsec spatial resolut
- Temperature coverage

  0.1 – 20 MK




The Missions
Solar Terrestrial Probes
(Science)
Solar
Geospace
STEREO
Solar-B
MMS
GEC
MagCon
Future STP's
Space Weather Network
(Dual Use Science/Utility)
Solar Net
Geospace Net
Solar Dynamics Observatory
Solar Sentinels
Radiation Belt
Ionospheric
Mappers
"Solar Sail" Observatories
Solar Flares
Geomagnetic Storms
Year
98
00
02
04
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08
10
12
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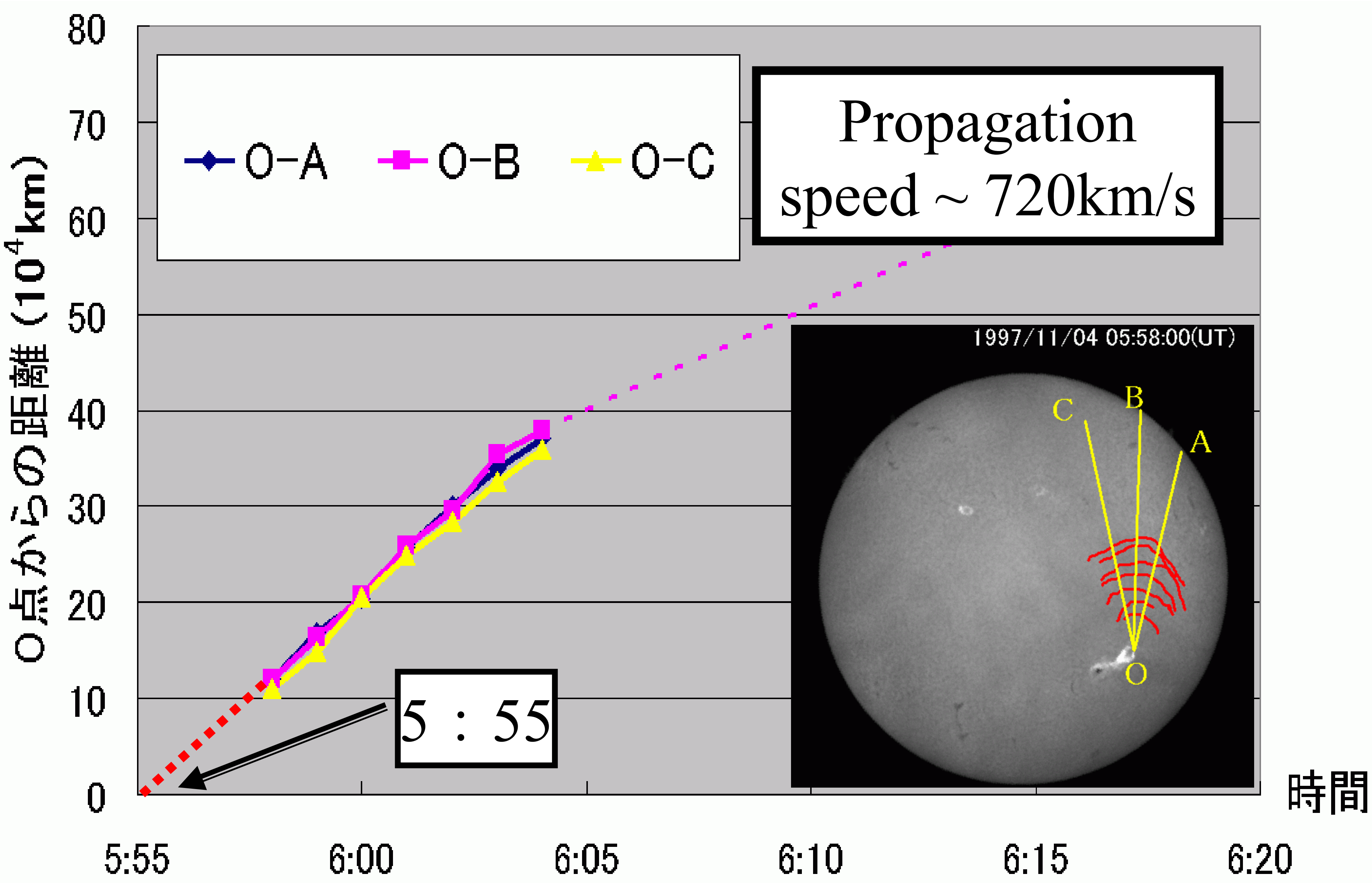
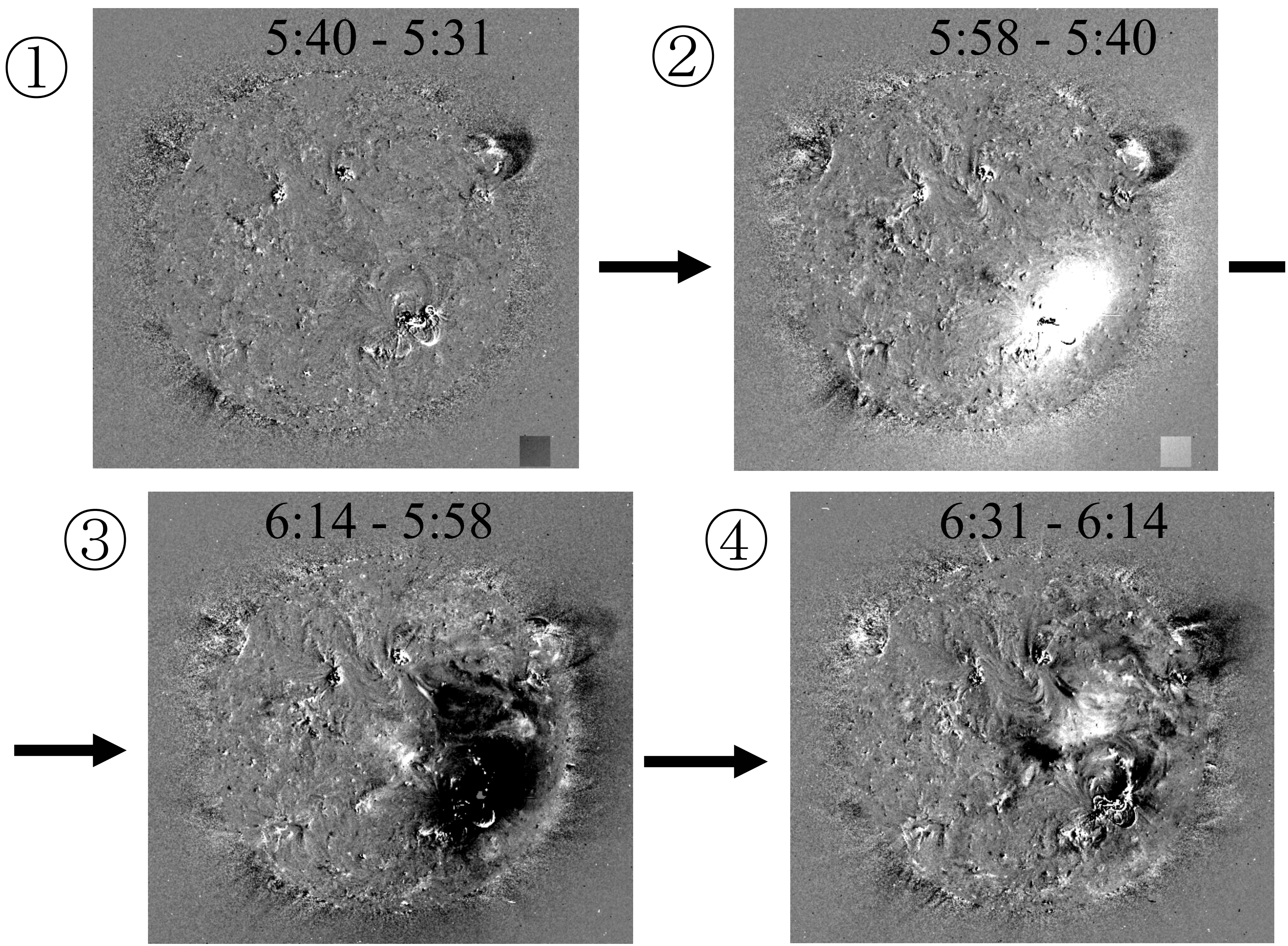
16
18

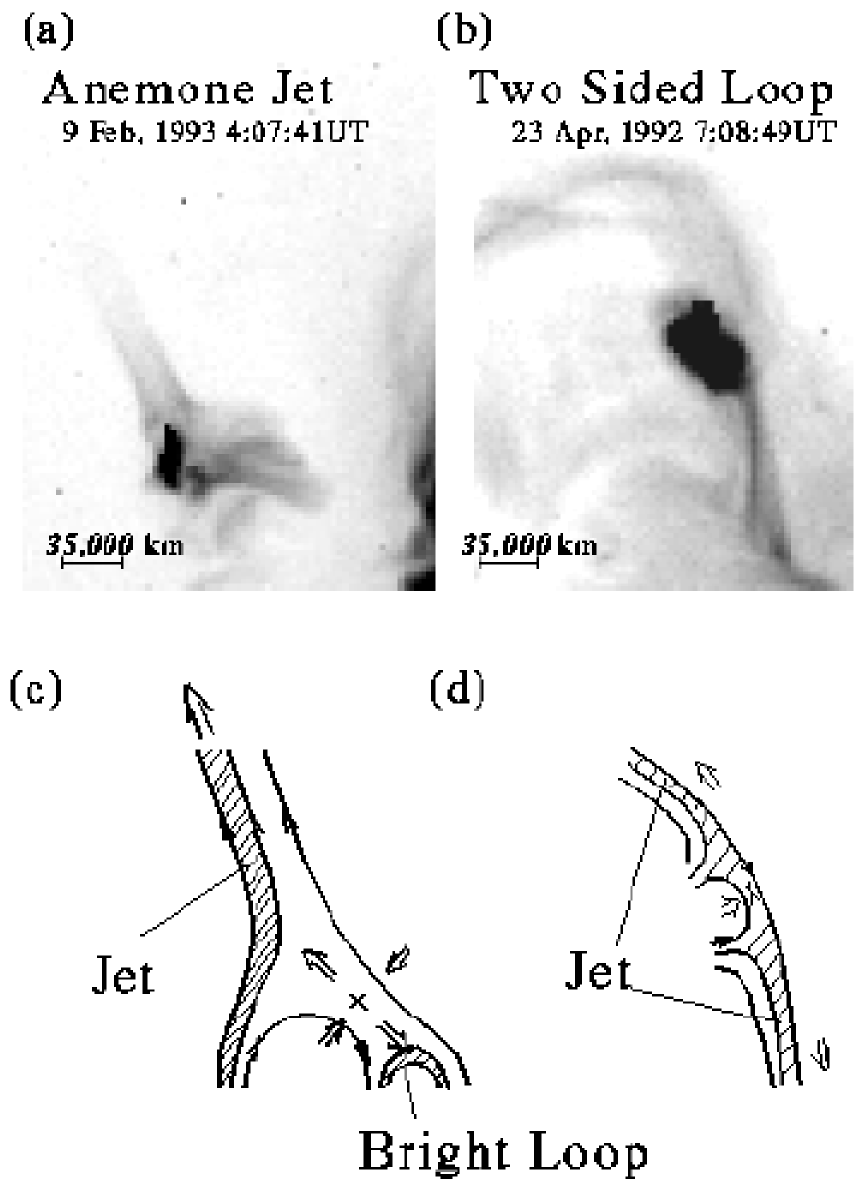
Wave front of Moreton wave




①
5:40 - 5:31
②
5:58 - 5:40
③
6:14 - 5:58
④
6:31 - 6:14

Emerging flux is important: Different coronal field gemetry leads to different morphology in X-rays

(Yokoyama and Shibata 1995)



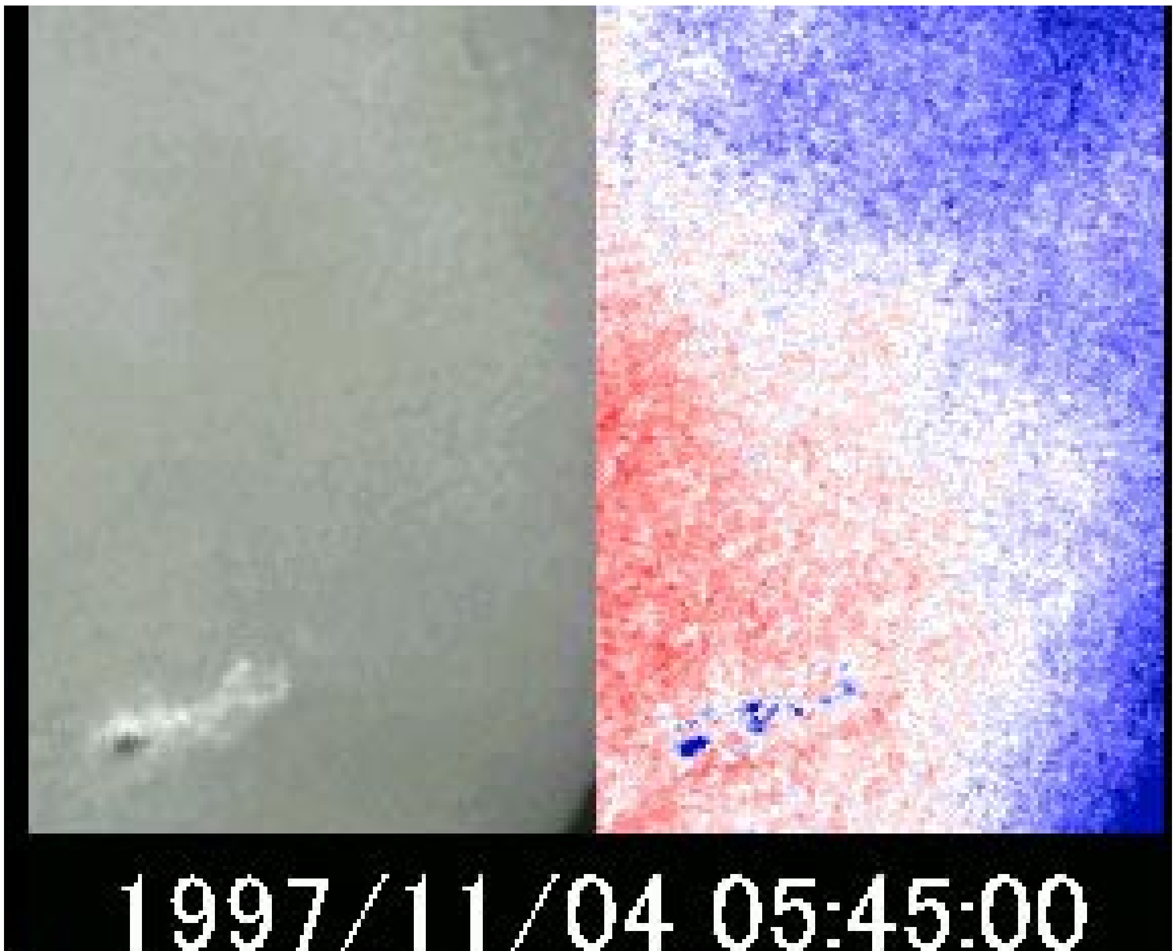
EIT waves

Discovered by SOHO/EIT (Thompson et al.)

Often associated with CMEs

What is the relation to Moreton wave ?

Moreton Wave
(Hα : Hida FMT, Eto et al. 2001)



Moreton wave
= Fast mode
MHD shock
(Uchida 1968)

Its origin is
still
puzzling.