MFUIII, 2011 Aug 22-25, Zakopane, Poland
Magnetic Field in the Universe, III.
Invited talk (25min)

Solar and Stellar Flares - nanoflares to superflares -

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thanks to H. Maehara, T. Shibayama et al.

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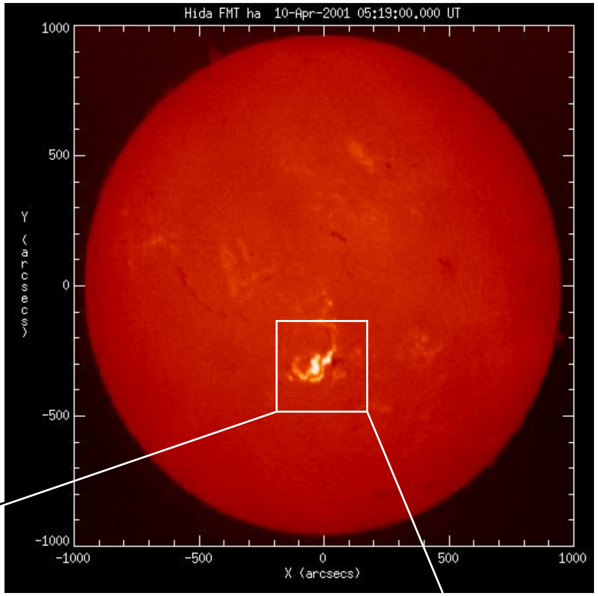
- Solar flares
  - Recent observations
  - Unified model
- Stellar flares
- Superflares on Solar type stars

Solar flares

Solar flare



Hα

Discovered in 19c

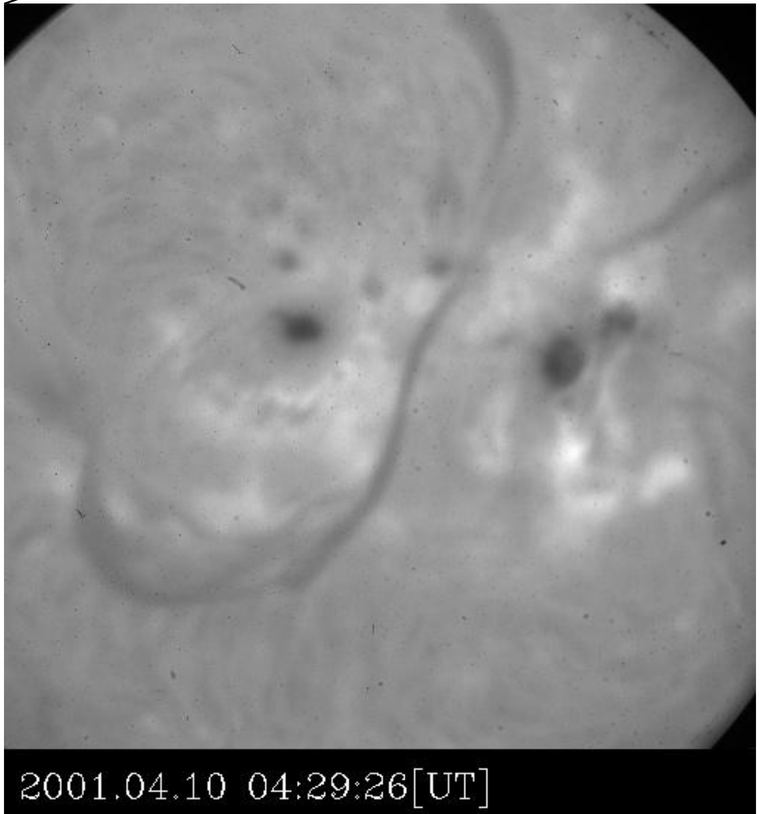
Explosive energy release

That occur near sunspot
magnetic energy is the source of energy

Size ~ $10^9 - 10^{10}$ cm

Time scale ~ 1min – 1hour

Total energy ~
10^{29} - 10^{32}erg



Mechanism has been puzzling since 19c until recently

Hida Obs/Kyoto U.

Solar corona observed in soft X-rays (Yohkoh)

Soft X-ray telescope （1keV)

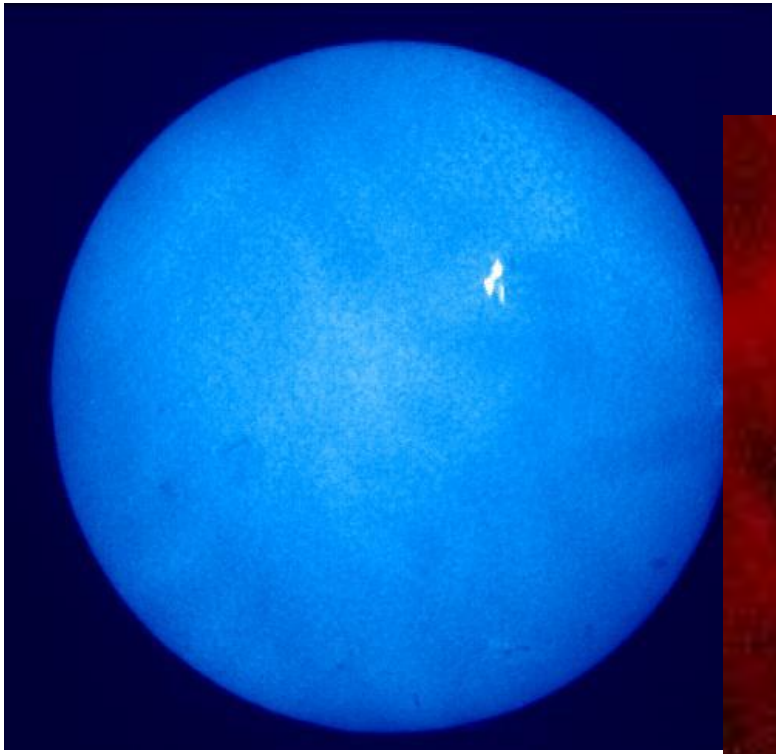
Coronal plasma

2MK-10MK

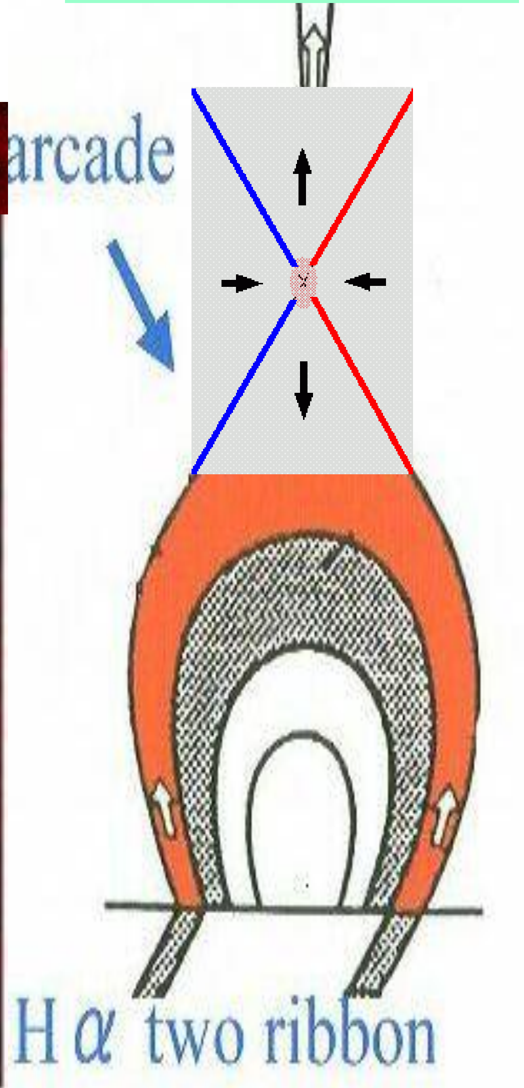
Simultaneous Halpha and X-ray view of a flare

Hα

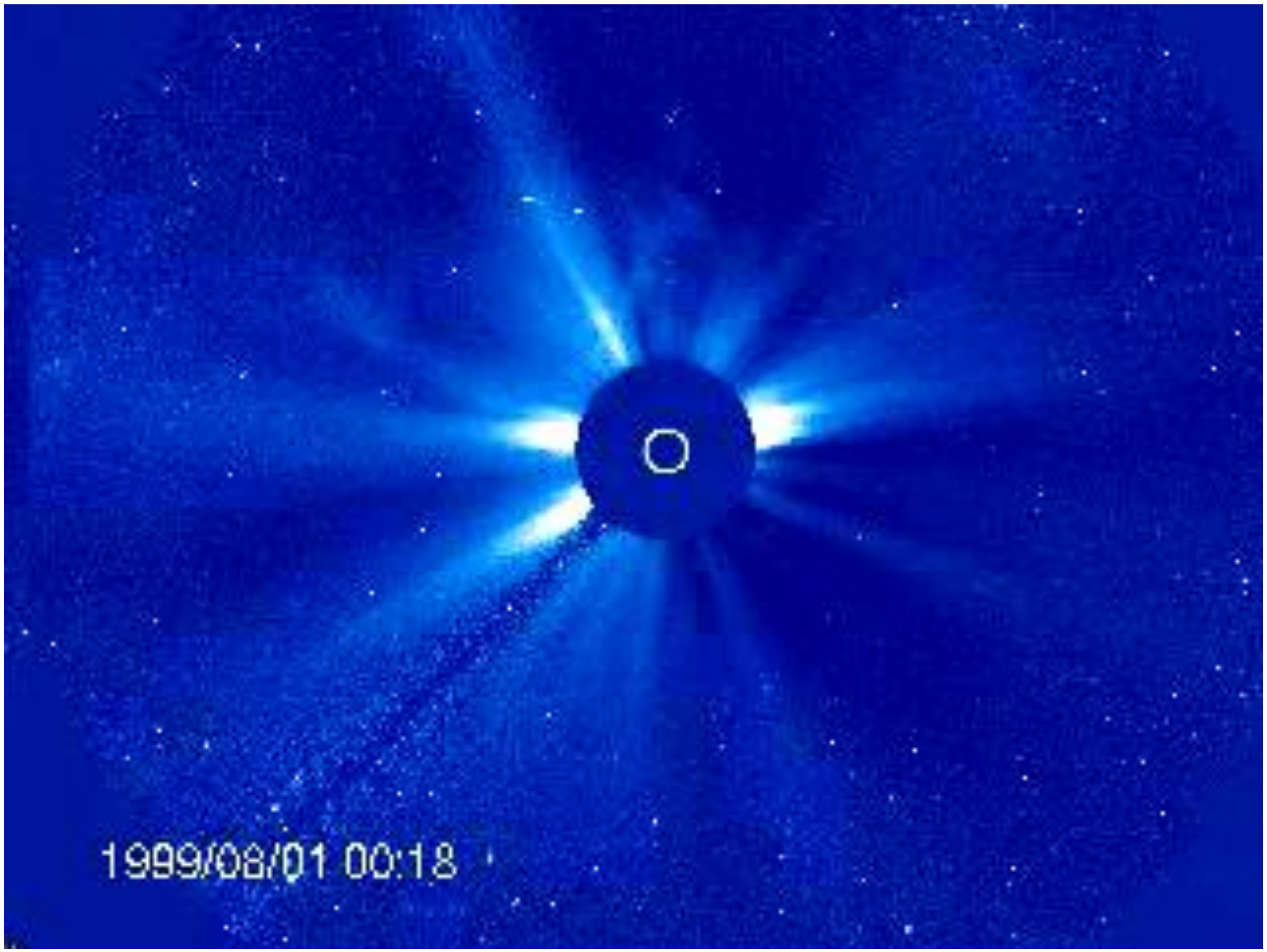
X-ray



Magnetic reconneciton

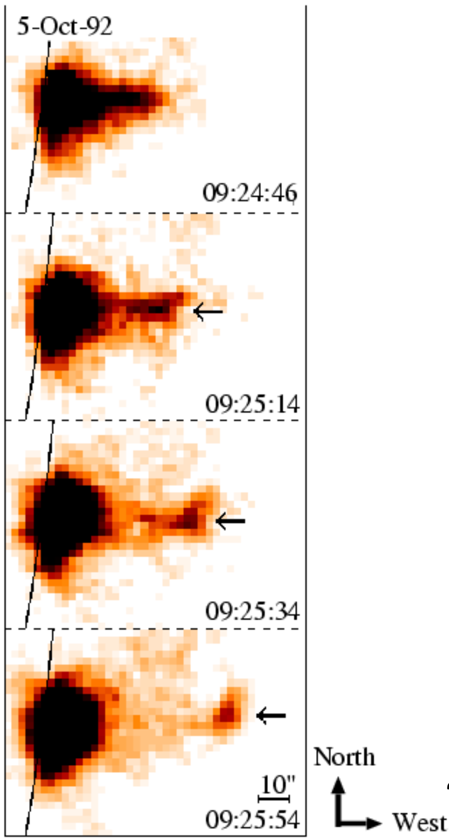


Coronal mass ejections (CME) and Solar Wind (SOHO/LASCO)

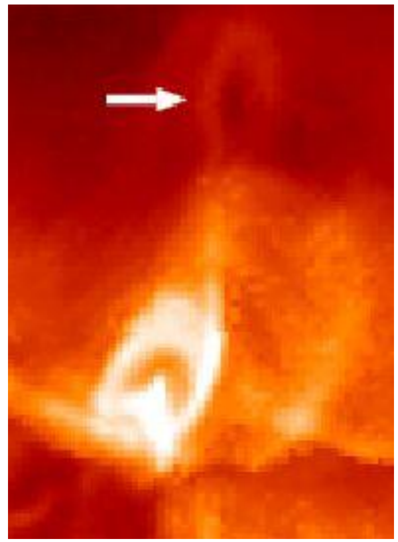


Velocity ~ 10 – 1000 km/s, mass ~ $10^{15} - 10^{16}$ g

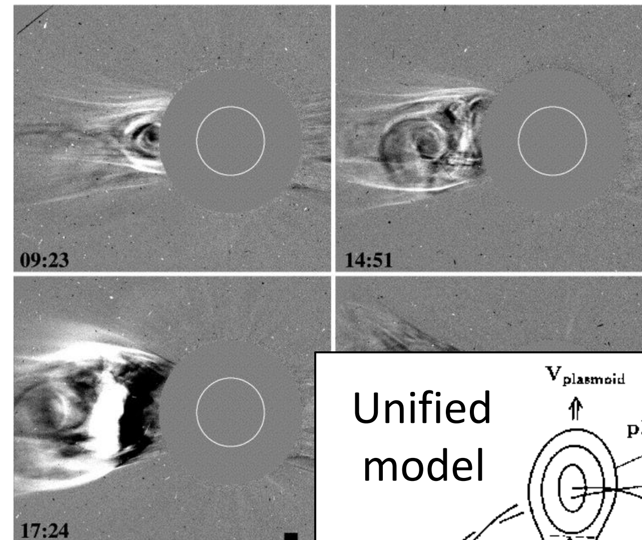
Plasmoid (flux rope) ejections



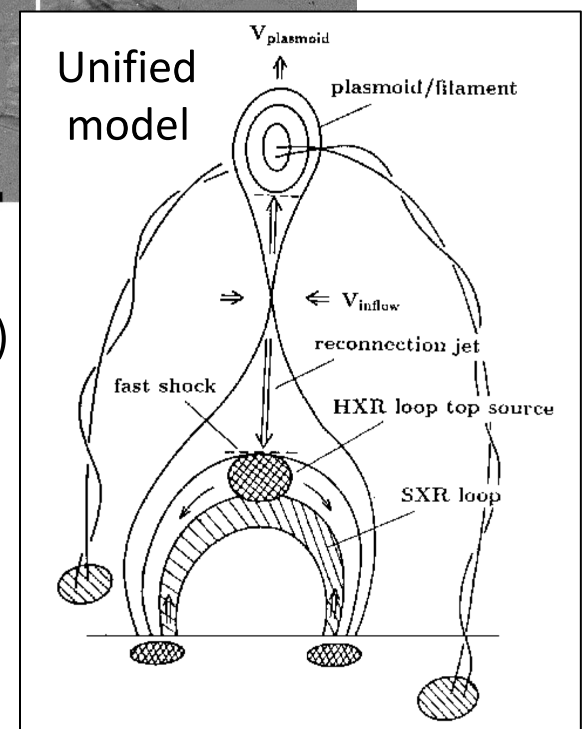
impulsive flares
~ 10^9 cm



LDE(Long Duration Event) flares
~ 10^10 cm



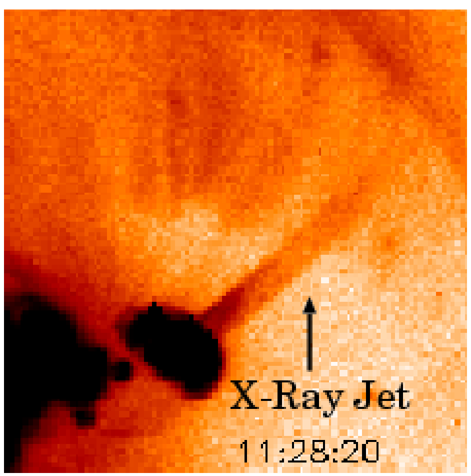
CMEs
(Giant arcades)
~ 10^11 cm

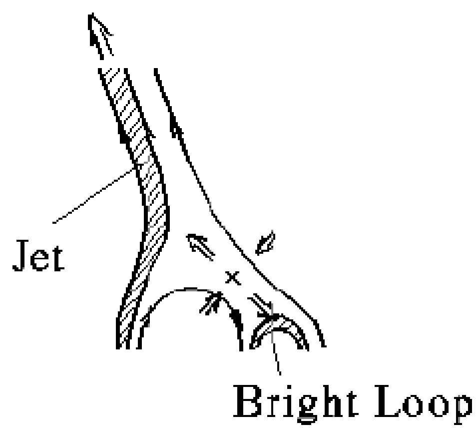


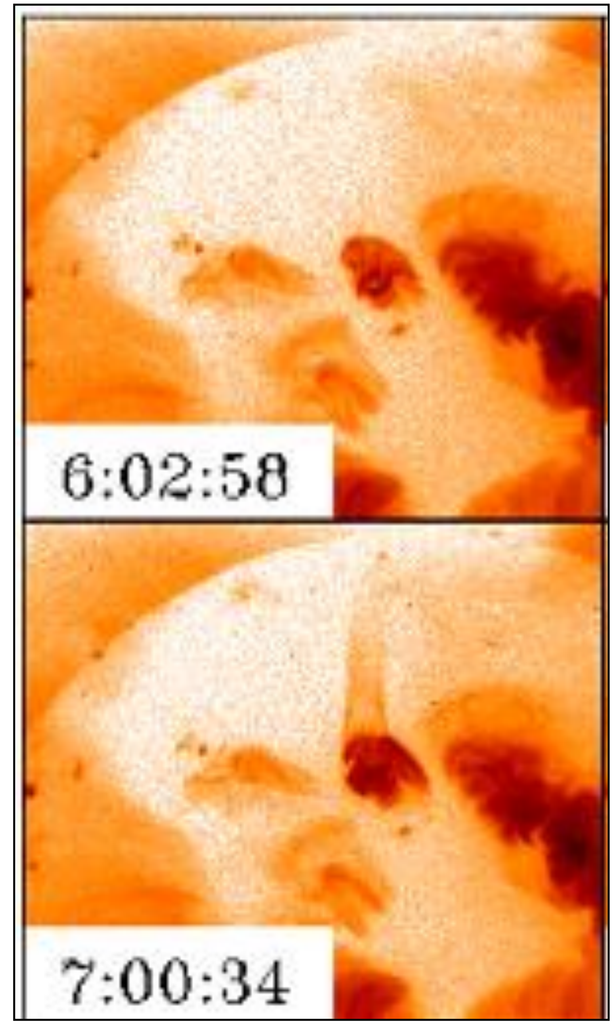
Plasmoid-Induced-Reconnection
(Shibata 1999)

Jets from microflares

- Yohkoh/SXT discovered X-ray jet
  (Shibata et al. 1992,
  Strong et al. 1992,
  Shimojo et al. 1996)





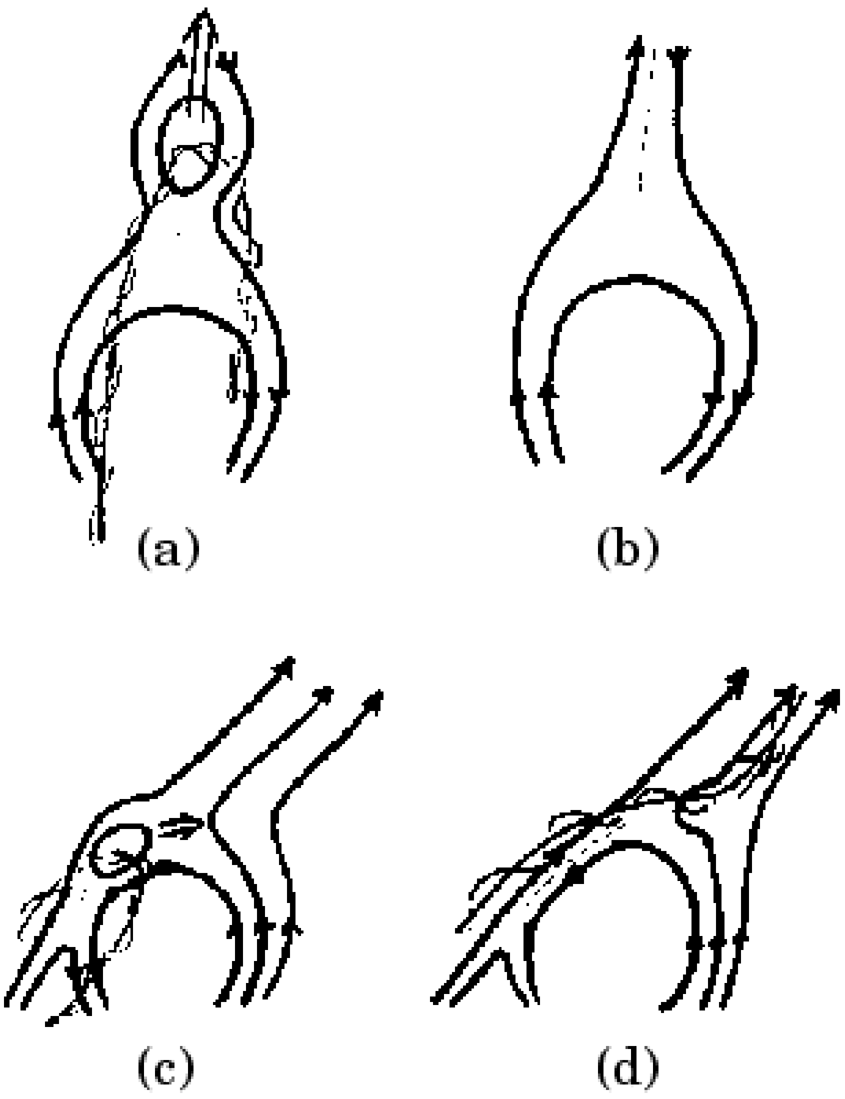


Anemone (Shibata et al. 1994)

Summary of “flare/CME” observations with Yohkoh

“flares”	Size (L)	Lifetime (t)	Alfvén 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
Long duration (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

Unified model
(plasmoid-induced reconnection model)
(Shibata 1996, 1999)



(a,b) : giant arcades, LDE/impulsive flares, CMEs

(c,d) : impulsive flares, microflares, jets

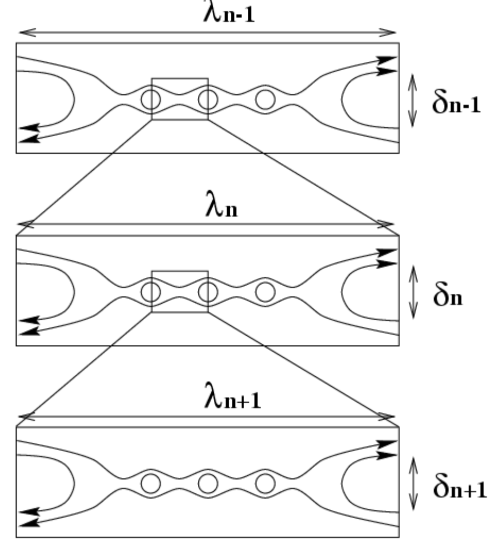
Energy release rate $= \dfrac{dE}{dt} \approx \dfrac{B^2}{4\pi} V_{in} L^2 \approx 10^{-2} \dfrac{B^2}{4\pi} V_A L^2$

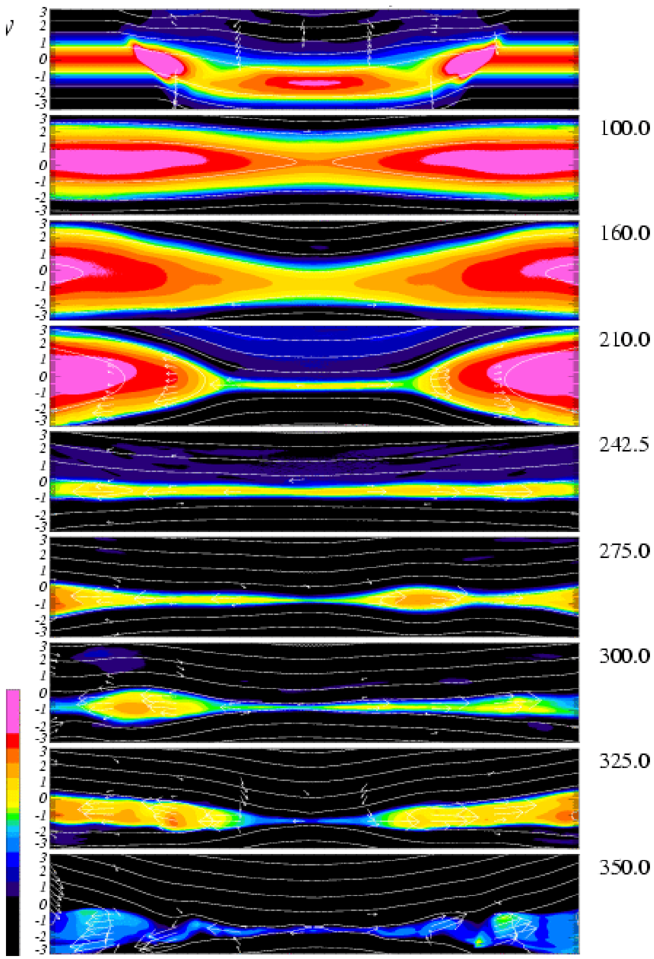
Remaining basic questions on reconnection

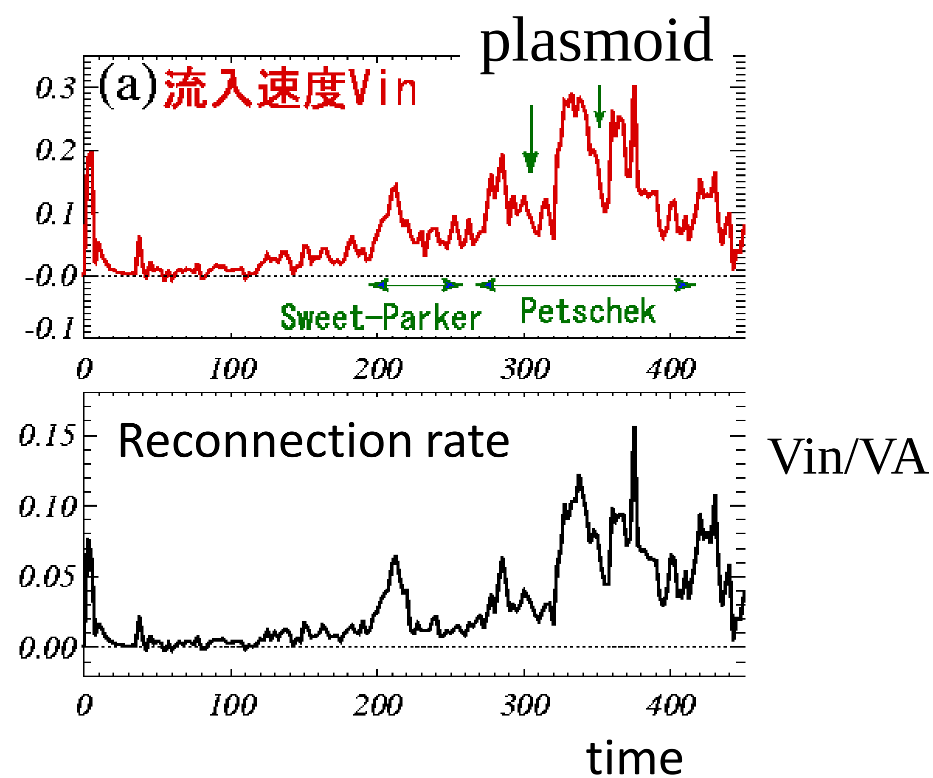
- Triggering mechanism ?
- What determines the reconnection rate ?
- What fraction of released energy goes to nonthermal particle energies ?

MHD simulations show plasmoid-induced reconnection in a fractal current sheet

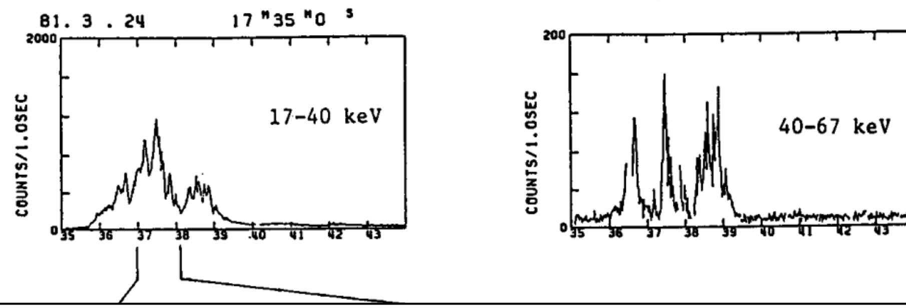
(Tanuma et al. 2001, Shibata and Tanuma 2001)

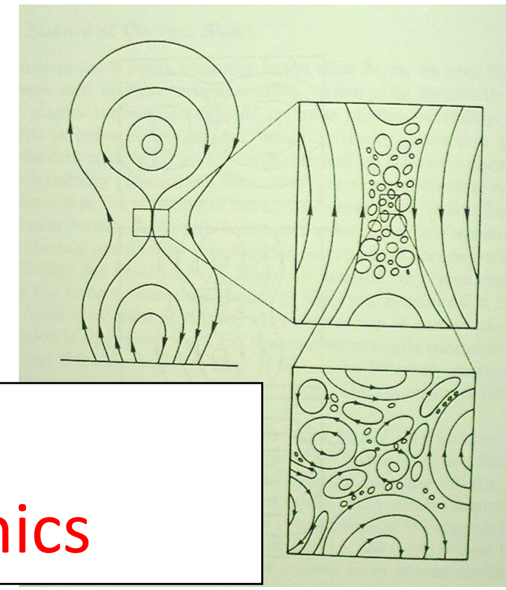






Observation of hard X-rays and microwave emissions show fractal-like time variability, which may be a result of fractal plasmoid ejections





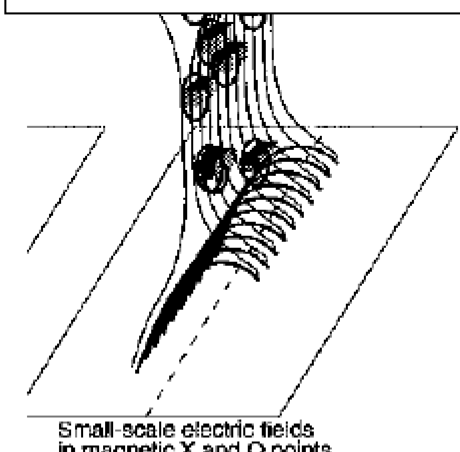
This fractal structure enable to connect micro and macro scale structures and dynamics

173700 173800

Fig.1. Time profiles of 1981 March 24 event. Two energy bands are illustrated in the upper two panels. One division of the time axis corresponds to one minute. In the bottom panel, an expanded time profile of the energy band 17 - 40 keV is shown with the time resolution of 0.125 sec.

(Ohki 1992)

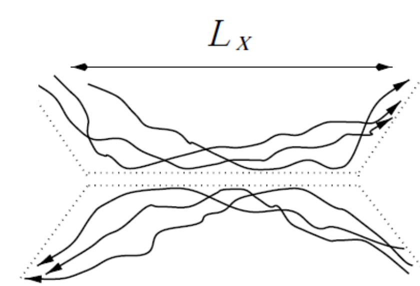
(Tajima-Shibata 1997)



Aschwanden 2002

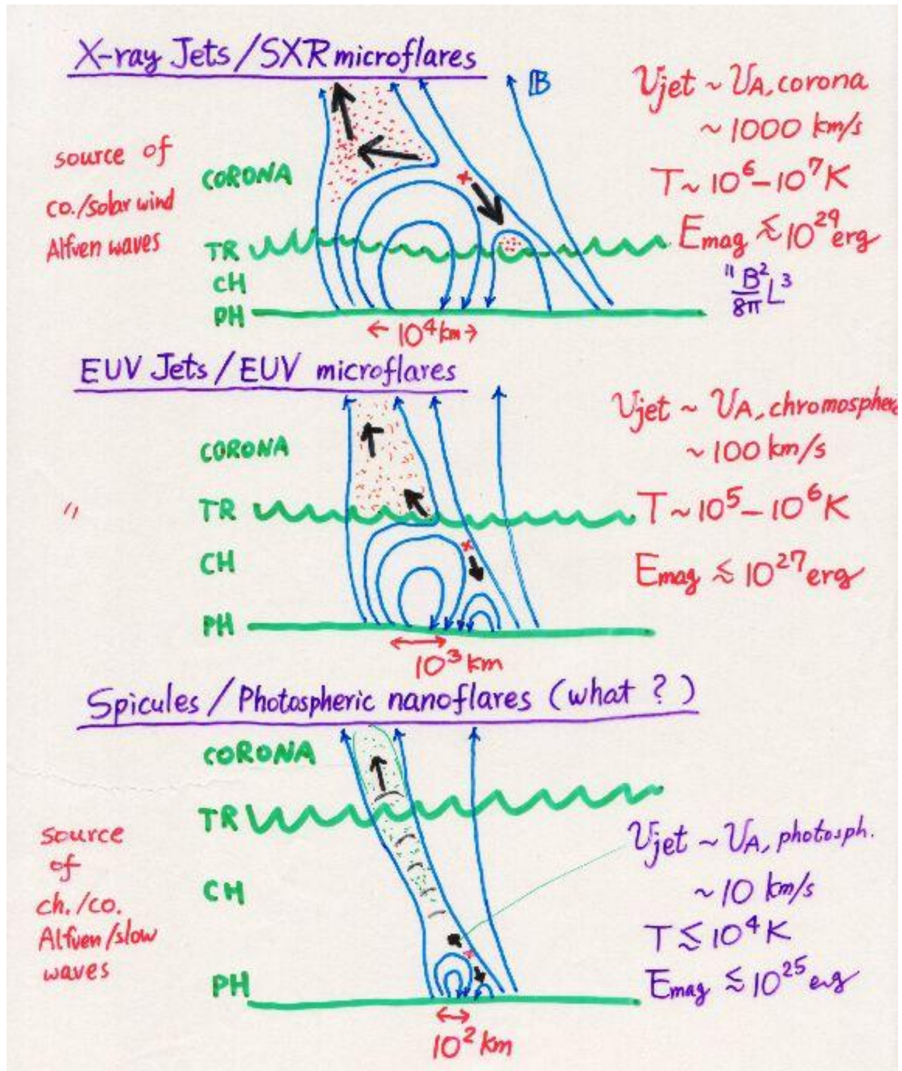
Fractal current sheet

Benz and Aschwanden 1989
Zelenyi 1996, Karlicky 2004



Lazarian and Vishniac 1999

Prediction of ubiquitous jets in the solar atmosphere (Shibata 1998)



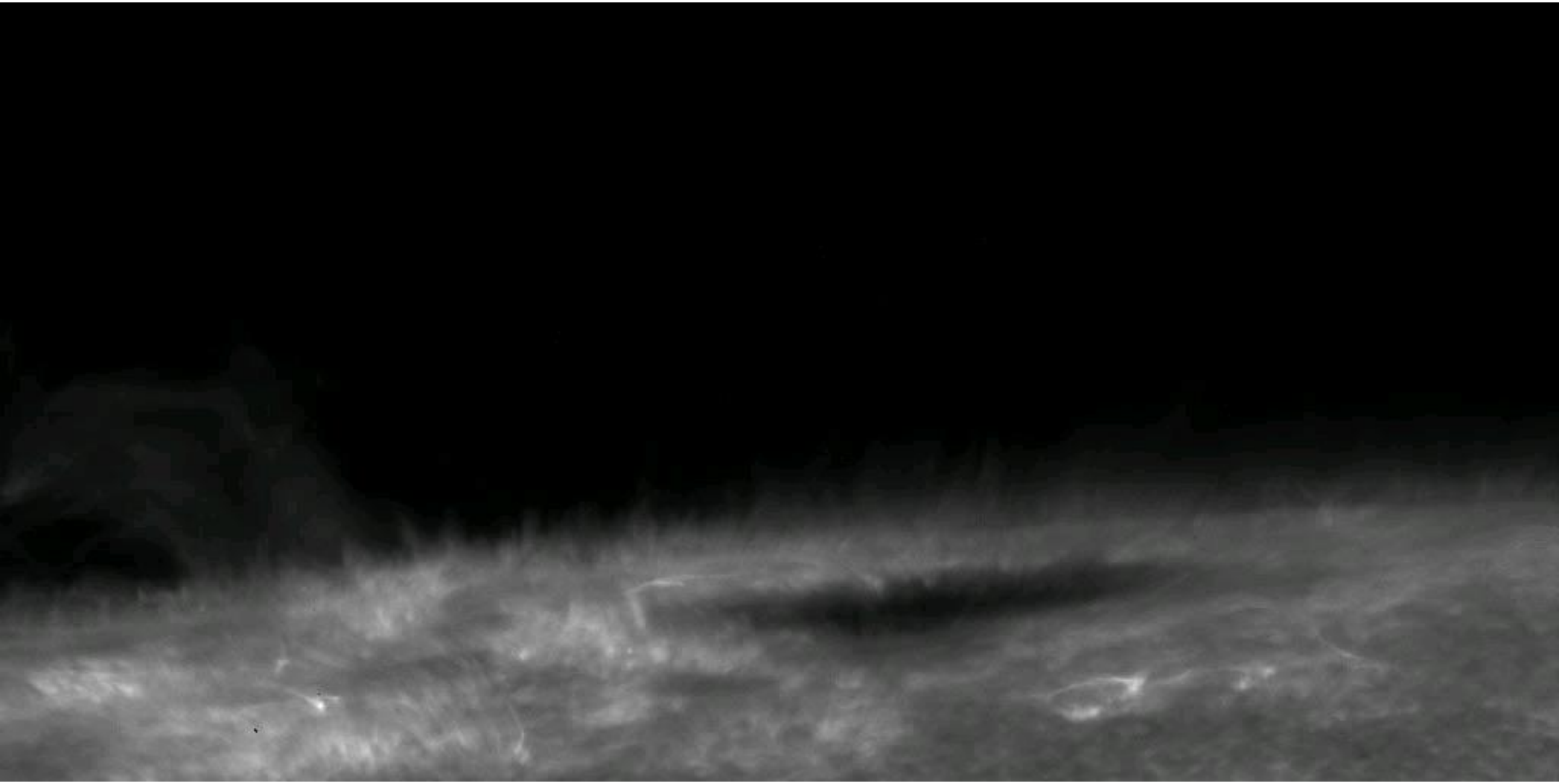
Question

- Has Hinode really observed ubiquitous cool jets ?

Answer: Yes !

Discovery of chromospheric anemone jets

(Shibata et al. 2007 Science 318, 1591)



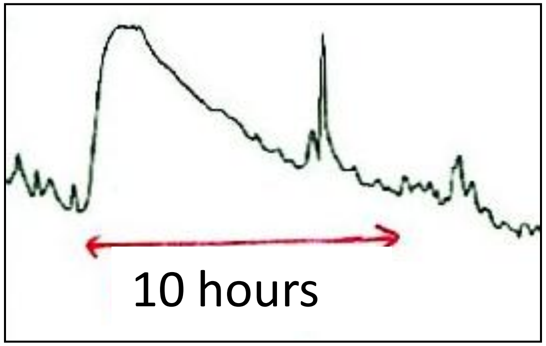
2006 Dec 17 20:00-21:00 UT CaII H broad band filter images taken with Hinode/SOT

Stellar Flares

Observations of Stellar Flares

Solar Flare

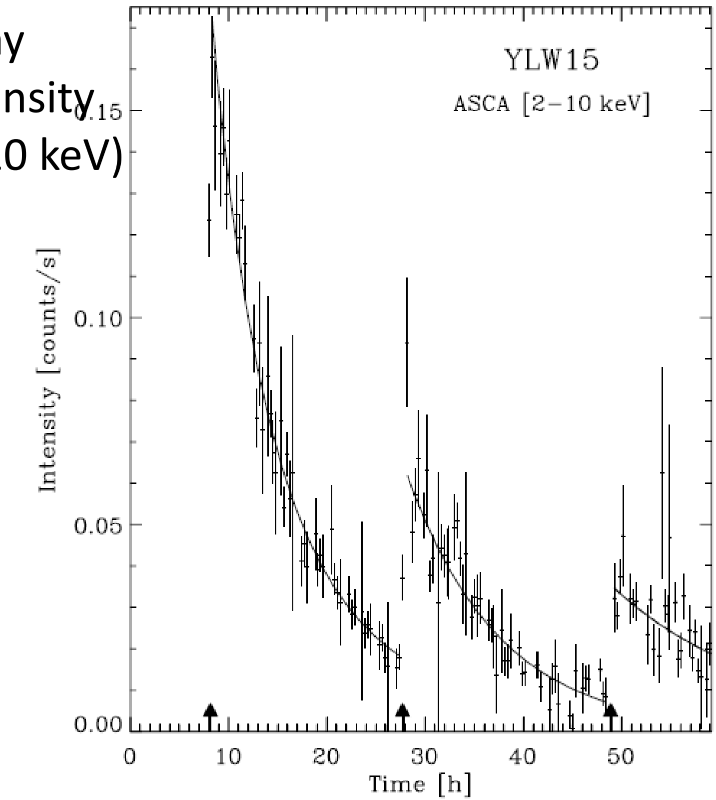
X-ray
Intensity
(3-24keV)



time

Protostellar Flare of YLW15

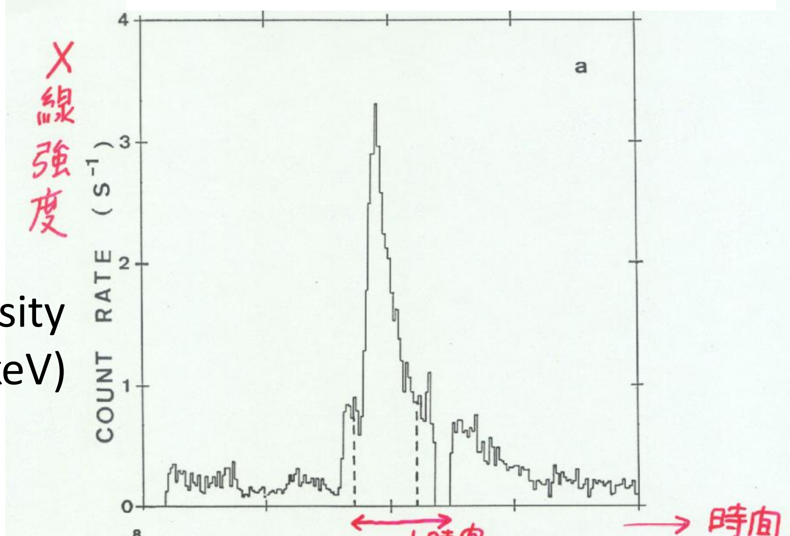
X-ray
Intensity
(2-10 keV)



time

Stellar Flare of Prox Cen

X-ray
Intensity
(~ 1 keV)



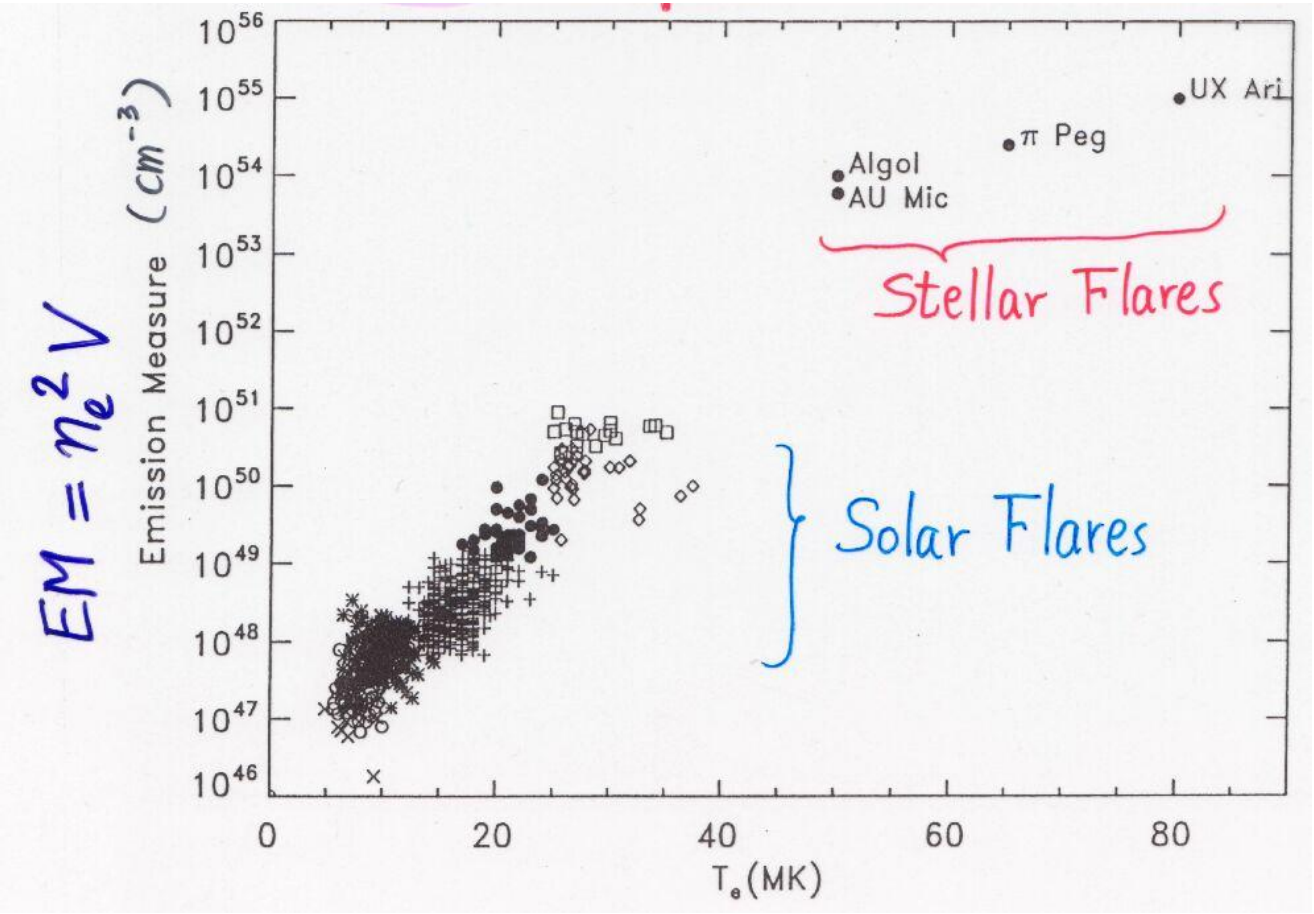
time

Can stellar and protostellar flares be explained by magnetic reconnection mechanism ?

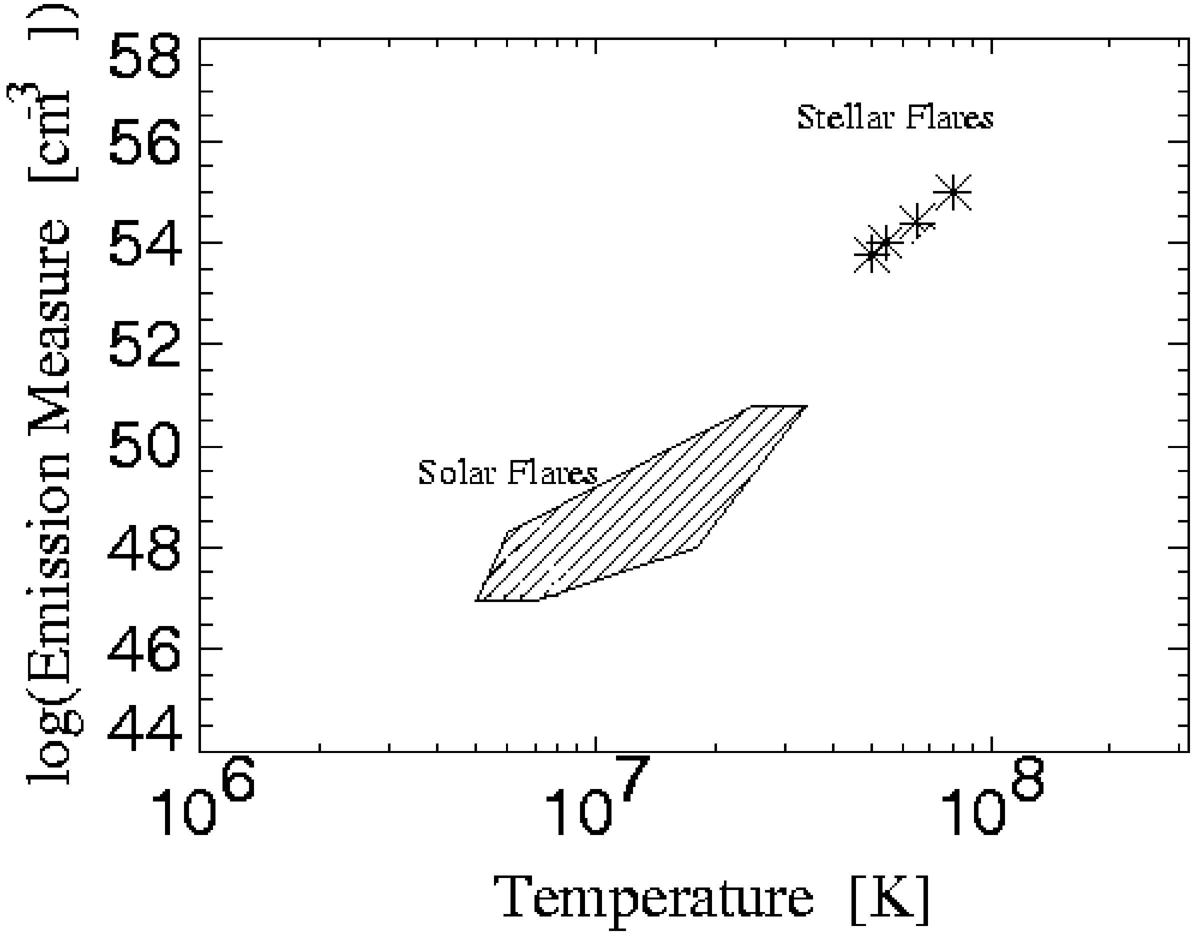
- Yes !
- Indirect evidence has been found in empirical correlation between
  Emission Measure ($EM = n^2 L^3$)
  and Temperature
  (Shibata and Yokoyama 1999, 2002)

Emission Measure（EM＝n^2V）of Solar and Stellar Flares increases with Temperature（T）

（n：electron density、V： volume）(Feldman et al. 1995)



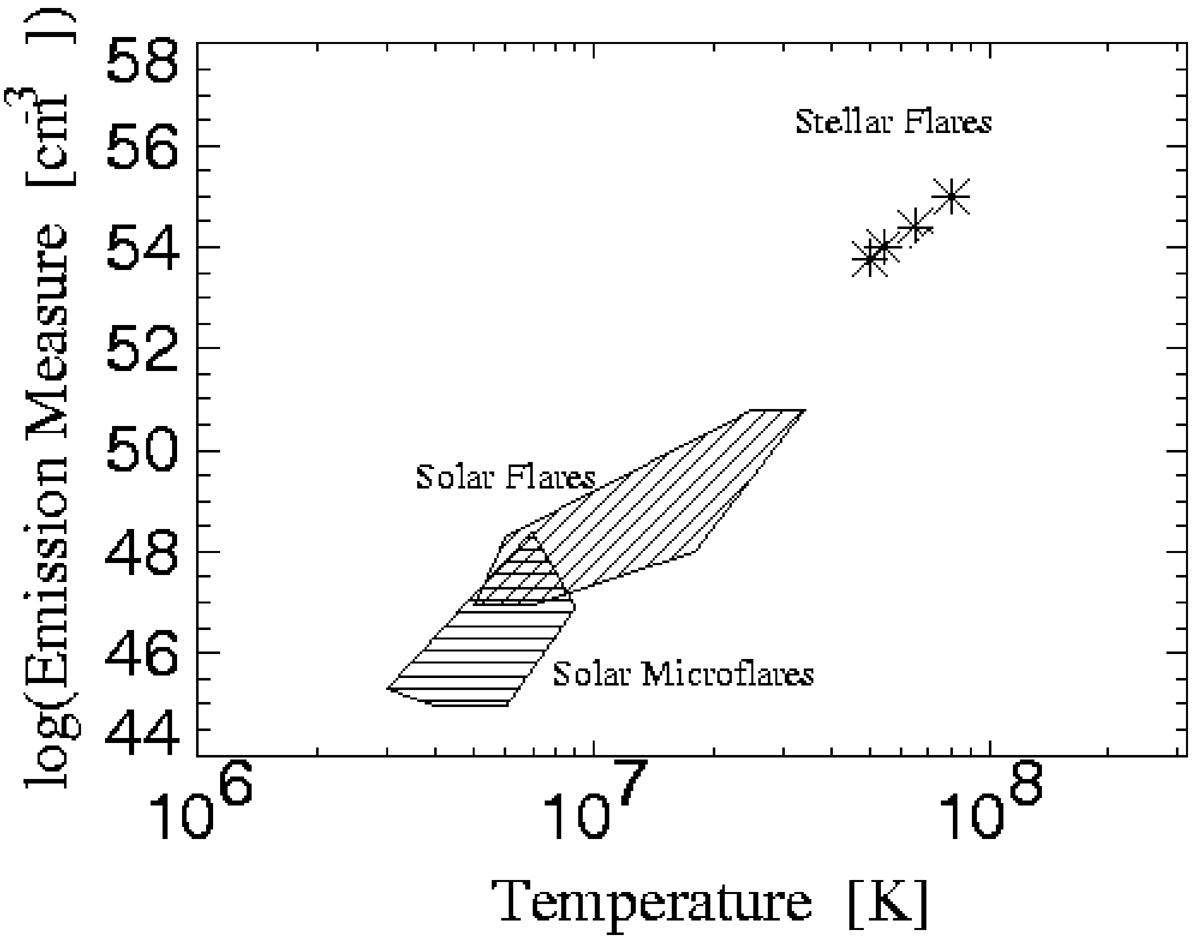
EM－T relation of Solar and Stellar Flares



Log-log plot of Feldman etal (1995)'s figure

Shibata and Yokoyama, 1999, 2002

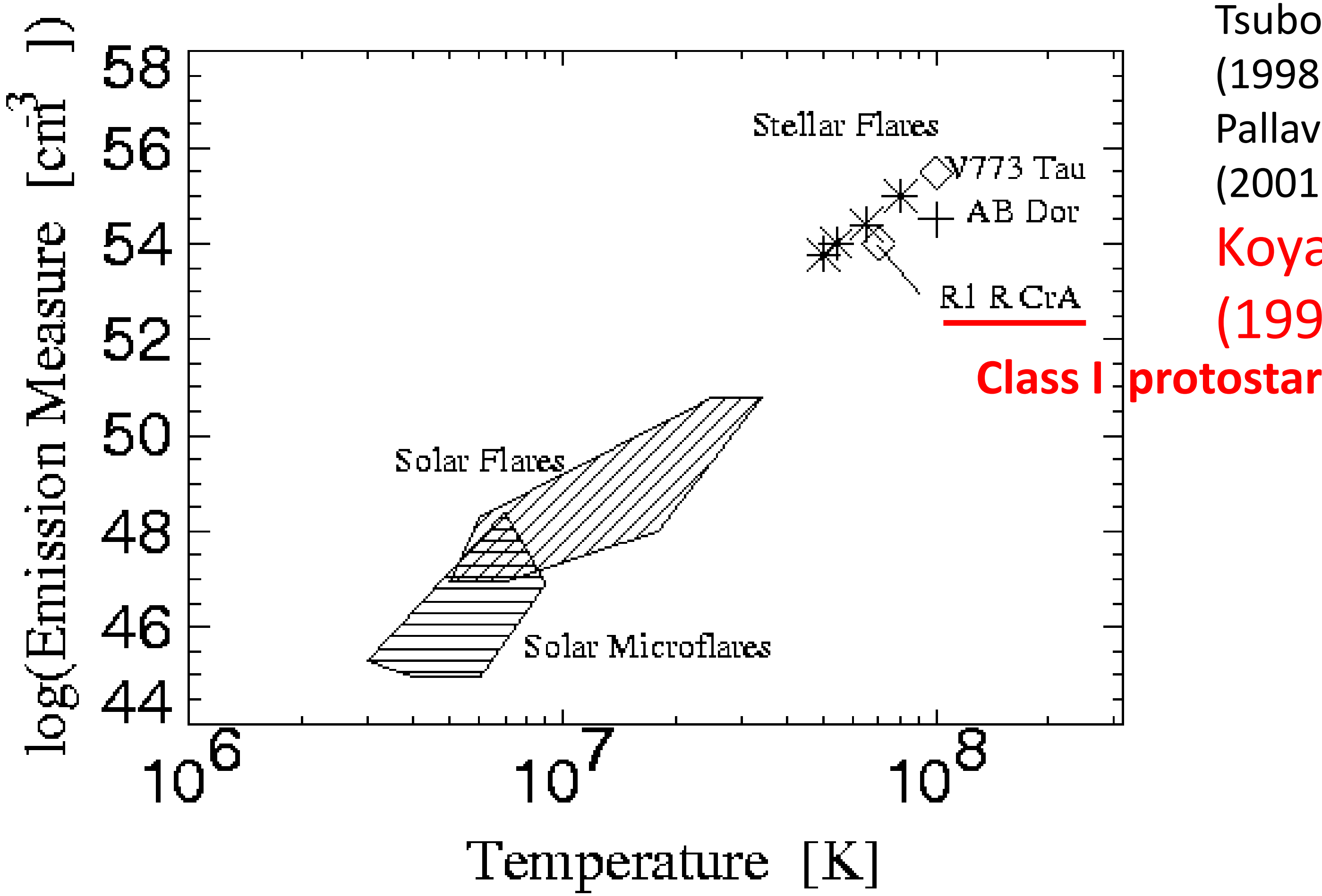
EM－T relation of Solar and Stellar Flares



microflare
(Shimizu 1995)

Shibata and Yokoyama, 1999, 2002

young-star and protostellar flares



Tsuboi (1998)
Pallavicini (2001)
Koyama (1996)

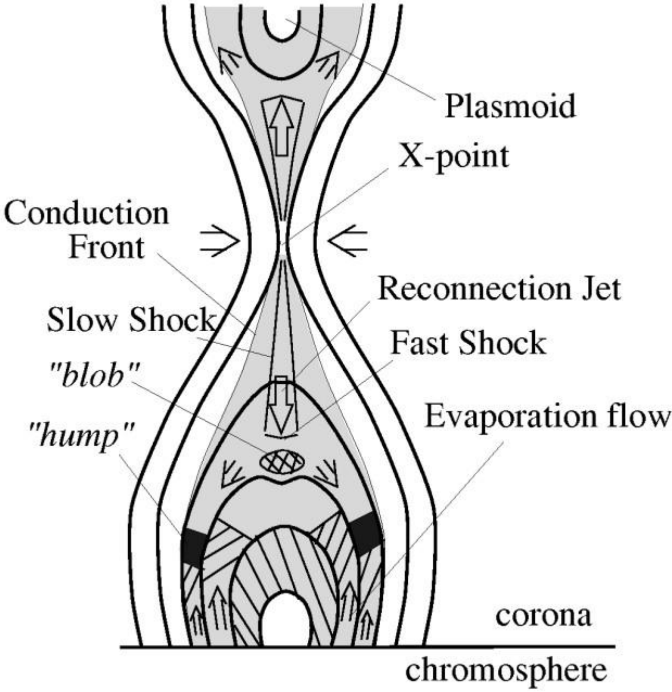
Shibata and Yokoyama (1999) ApJ 526, L49

Flare Temperature Scaling Law

- 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

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

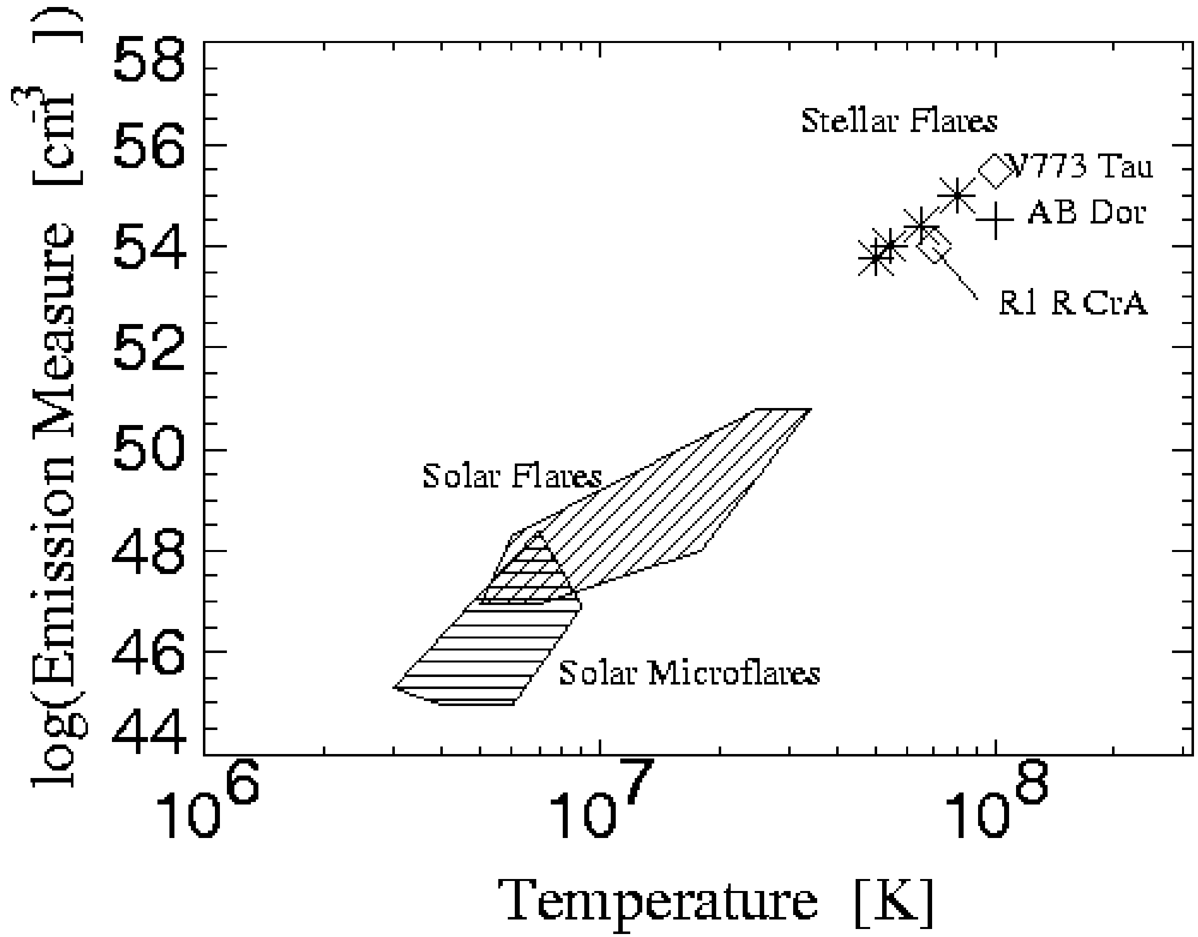
- Dynamical equilibrium (evaporated plasma must be confined in a loop)

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

- Using Flare Temperature scaling law, we have

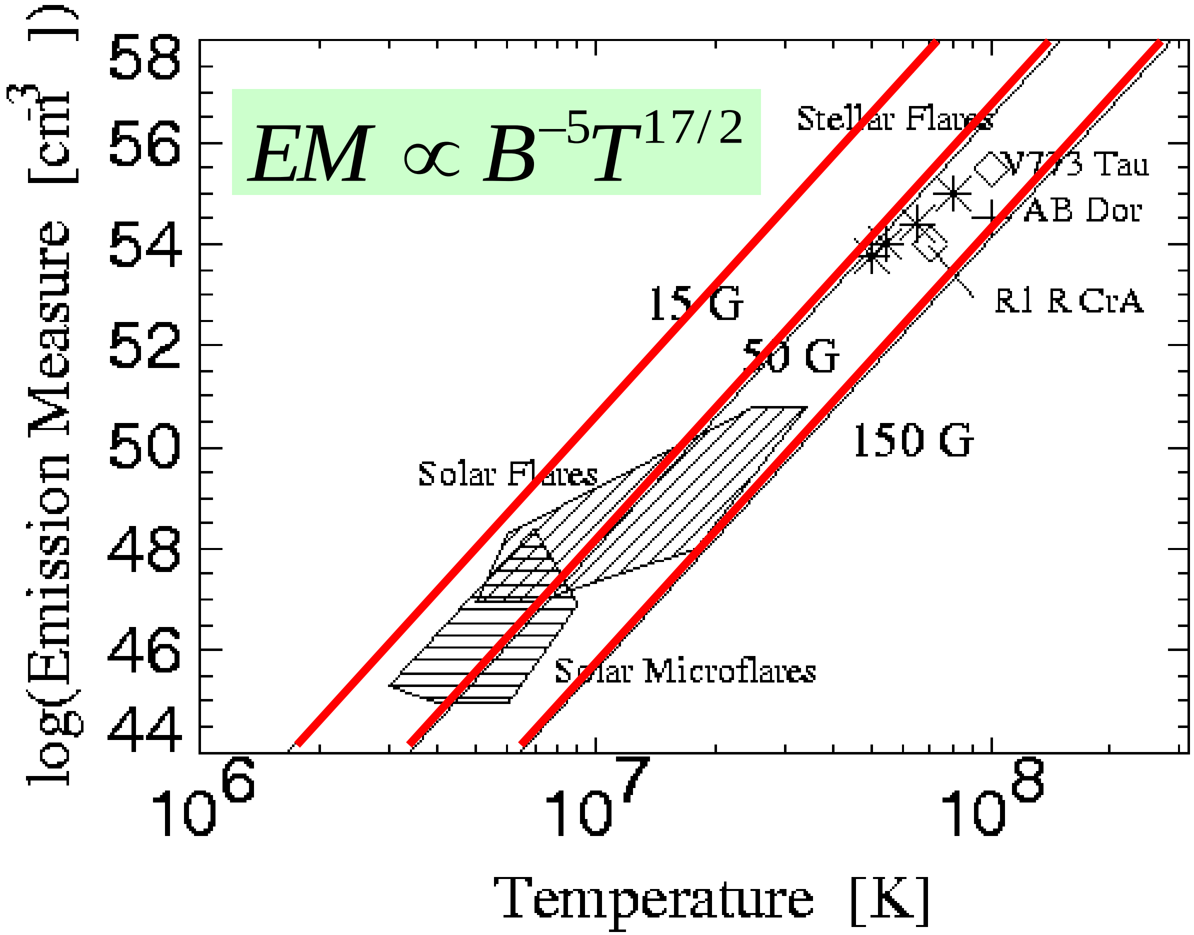
$$EM \propto B^{-5} T^{17/2}$$

EM-T correlation for solar/stellar flares



Shibata and Yokoyama (1999, 2002)

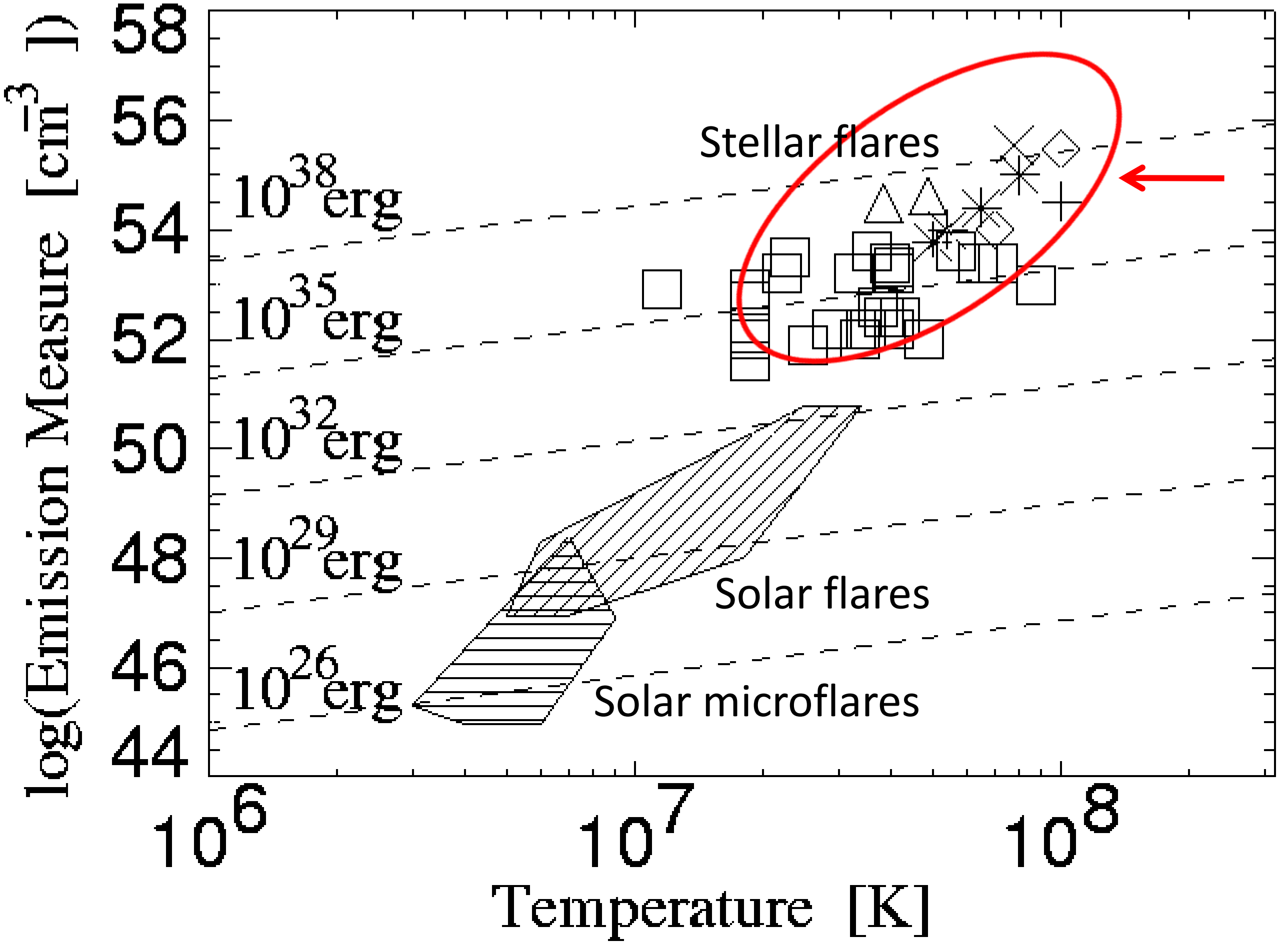
Magnetic field strength（B）＝constant



Magnetic field strengths of solar and stellar flares are comparable ~ 50-100 G

Shibata and Yokoyama (1999, 2002)

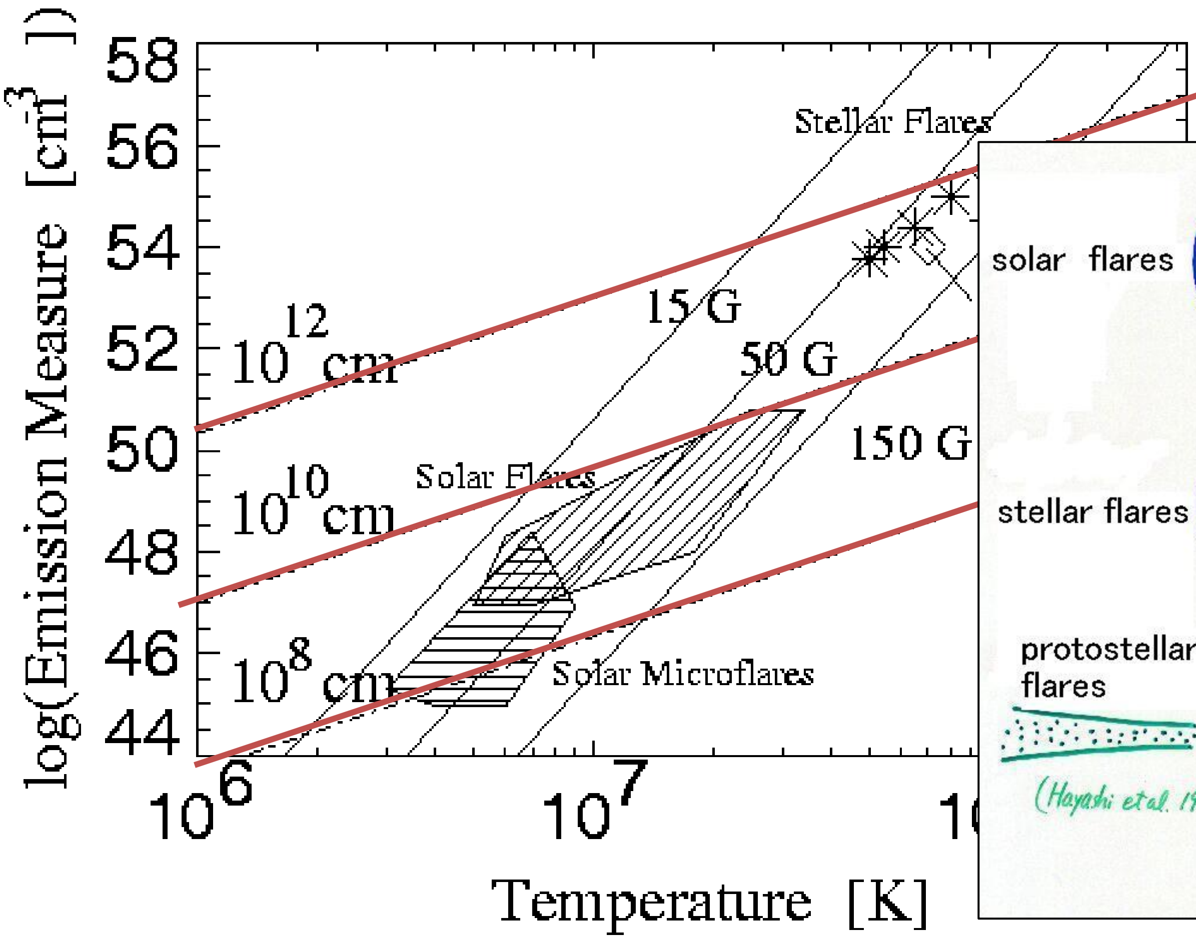
Total energy of stellar flares

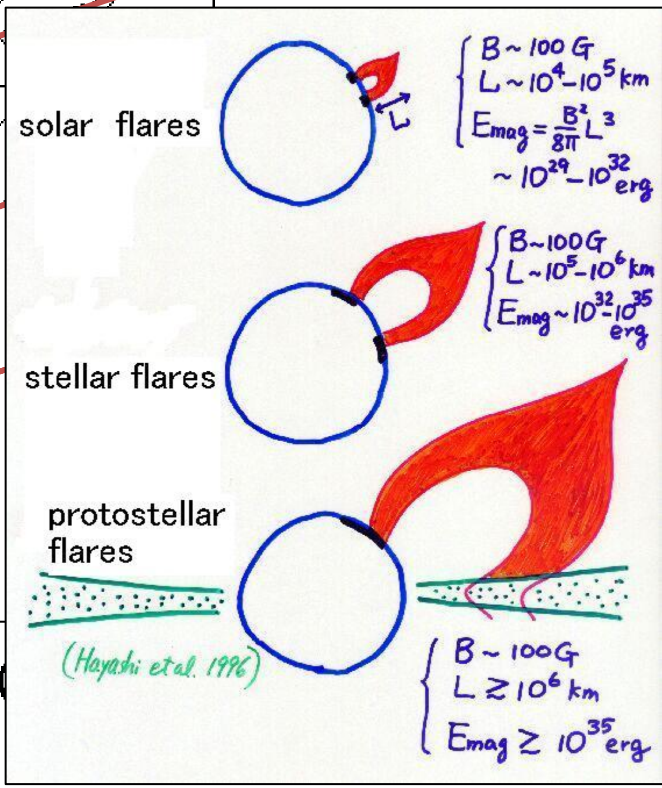


Superflares

Their energy
= 10-10^6
times that
of
the largest
solar flares

Q: What determines the total energy of flares ?
A: It is the loop length.





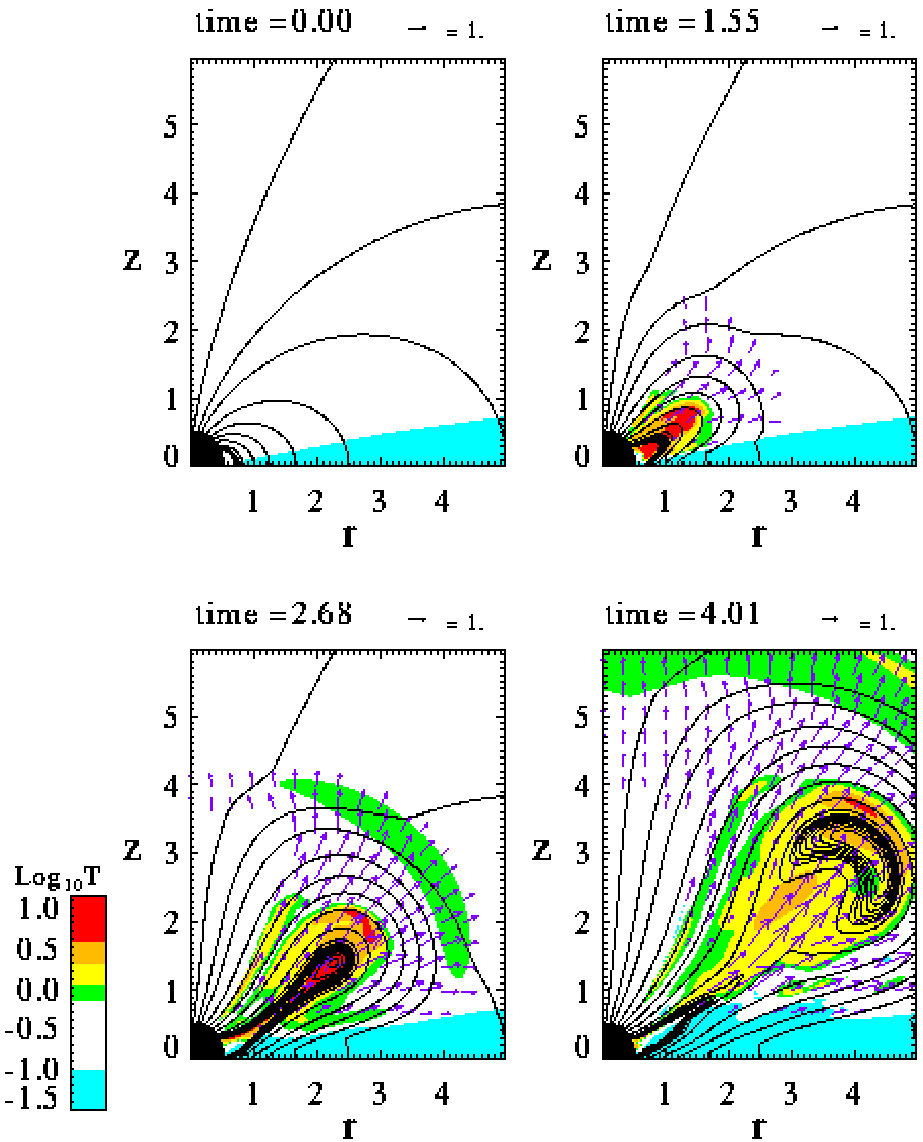
The reason why stellar flares are hot
=> loop lengths of stellar flares are large

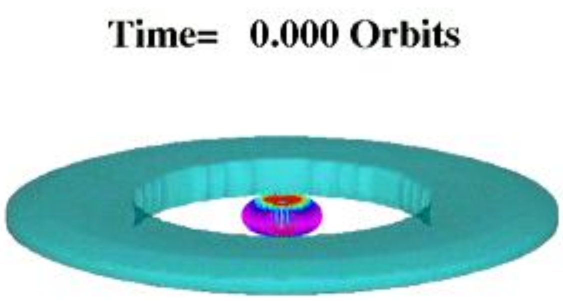
Cf Isobe et al. 2003,
Kawamiti et al. 2008

Shibata and Yokoyama (2002)

reconnection model of protostellar flare and jets

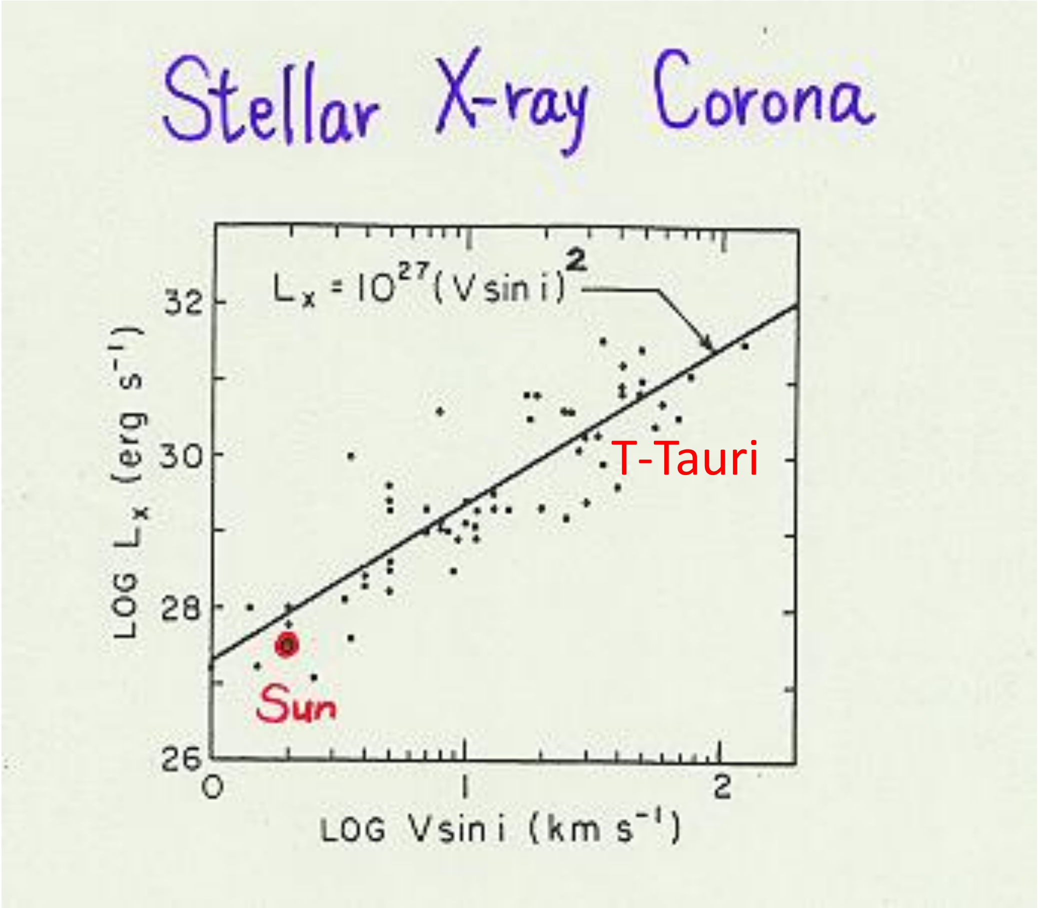
(Hayashi, Shibata, Matsumoto 1996)





Why young stars produce superflares ?

- Answer:
  because young stars are fast rotators.



Is there a possibility that superflares would occur on our present Sun ?

Immediate Answer:

Superflares would not occur on our present Sun because the Sun is not young so is slow rotator

But amazingly, Schaefer et al. (2000) discovered 9 superflares on ordinary solar type stars with slow rotation.

Are superflares really occurring on solar type stars ?
If so, what is the occurrence frequency of superflares ?

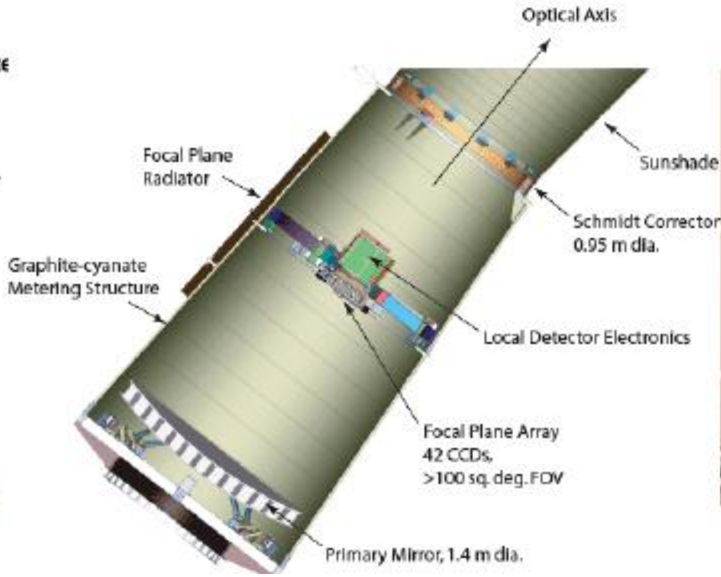
Discovery of Superflares on Solar type stars using Kepler satellite data

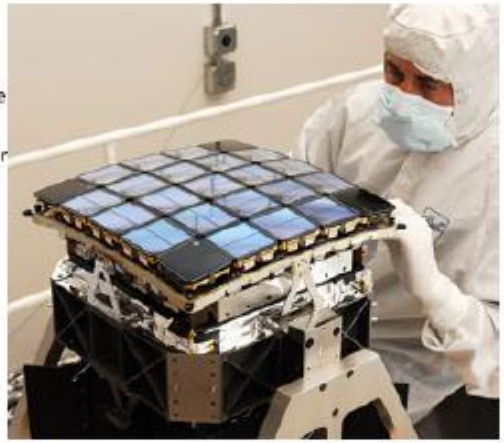
H. Maehara, et al.
(T. Shibayama, S. Notsu, Y. Notsu, T. Nagao,
S. Kusaba, S. Honda, D. Nogami, K. Shibata)

To be submitted soon (2011)

Kepler satellite

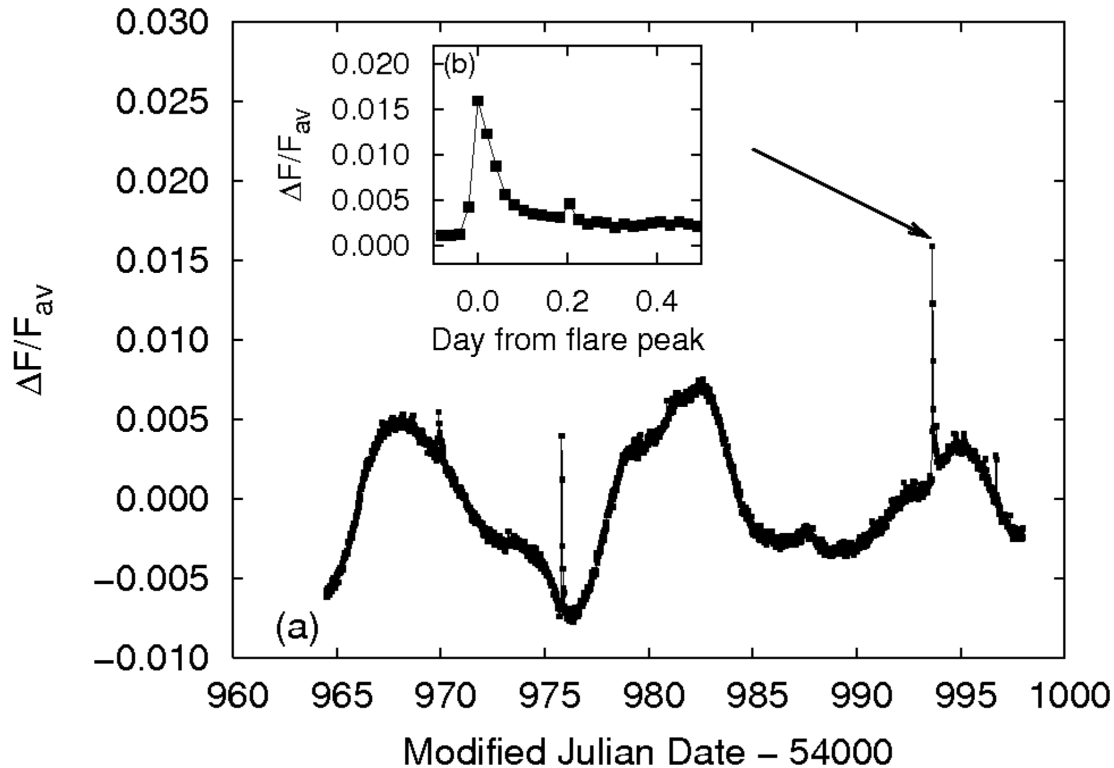
- Space mission to detect exoplanets by observing transit of exoplanets
- 42 CCD on primary focal plane of 95 cm optical telescope





typical superflare observed by Kepler

Brightness of a star and a flare



Total energy ~ 10^35 erg

Time (day)

Maehara et al. (2011)

Results of Superflare survey using Kepler Data

- Using the Kepler satellite data we searched for superflares on solar type stars (G type main sequence stars) and discovered 420 events.
- More than 50 superflares are found to occur on slowly rotating stars like our Sun (its period is 25 days).
- We conclude that superflares can occur on our Sun at present and the occurrence frequency of the superflare whose energy is 1000 times that of the most energetic flare of the Sun is once in 1000 years.
- If such superflares occur on our present Sun, the Earth and our civilization would be heavily damaged.

Summary

- Recent solar observations show various evidence of reconnection in solar flares, microflares, and nanoflares, leading to a unified model of solar flares.
- Plasmoid ejections are ubiquitous in flares and flare-like events, which may play a key role to induce fast reconnection in a fractal (turbulent) current sheet.
- Stellar flares can also be unified with a reconnection model, if we use the emission measure – temperature diagram.
- Using Kepler data, we found that superflares can occur on our present Sun and the occurrence frequency of the superflare whose energy is 1000 times that of the most energetic flare of the Sun is once in 1000 years.