The 2nd Solar-C Science Definition Meeting
March 11-14, 2010@ISAS, Sagamihara, Japan

Space Weather Study
- Flare Forecast -

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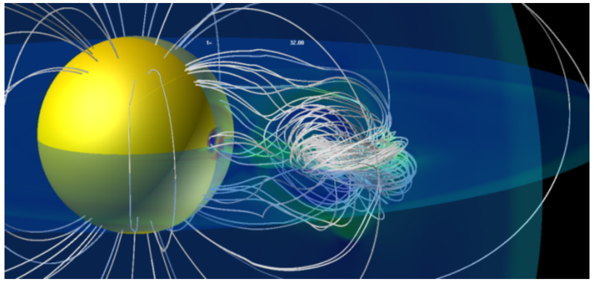
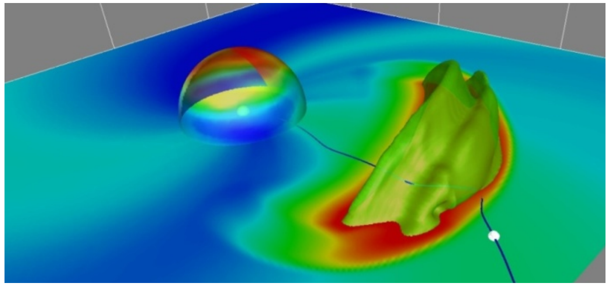
The Process of Space Weather

source → propagation → impact



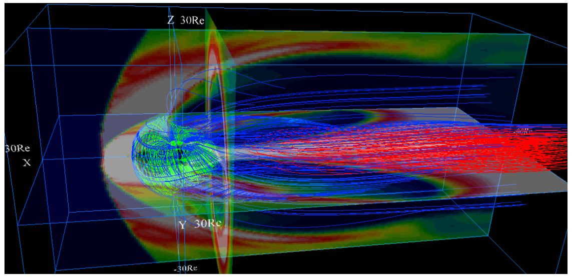
The Sun

Flare, CME



Interplanetary

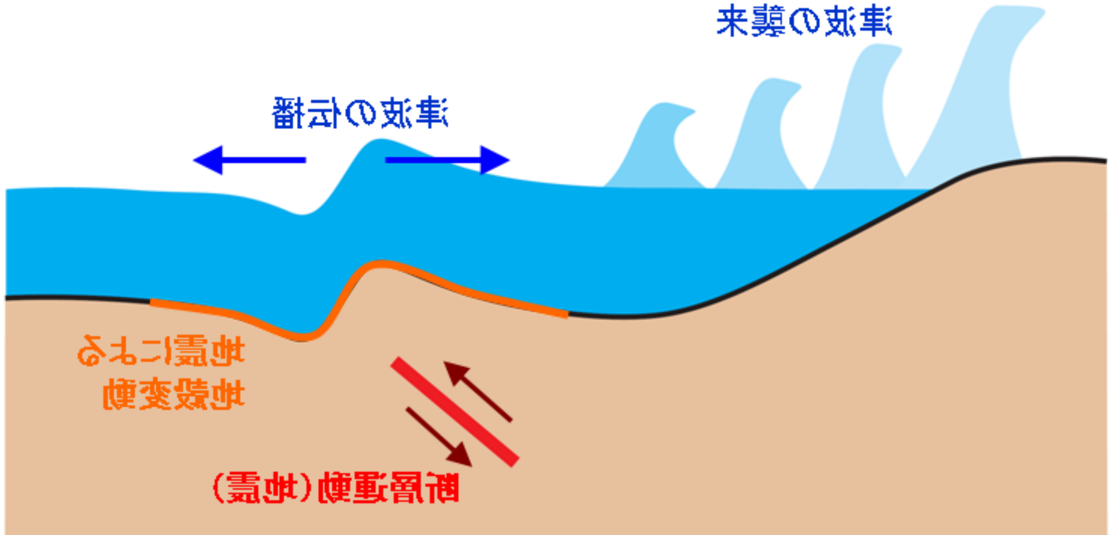
ICME, Shocks



Geo-space

Storm, Sub-storm, etc

earthquake

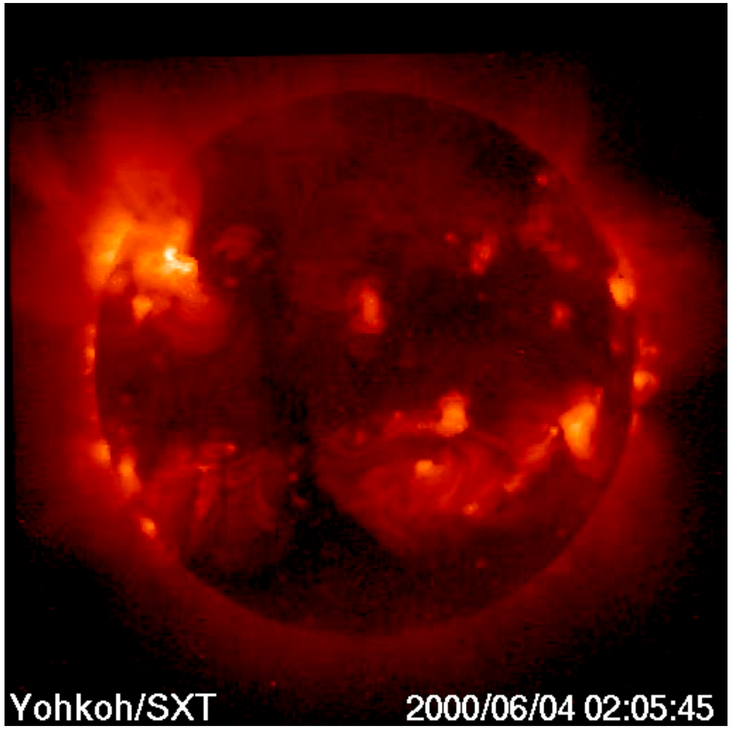


tsunami

Why should we forecast flares ?

- As the Space Weather Forecast
- To evaluate the level of scientific understanding

When

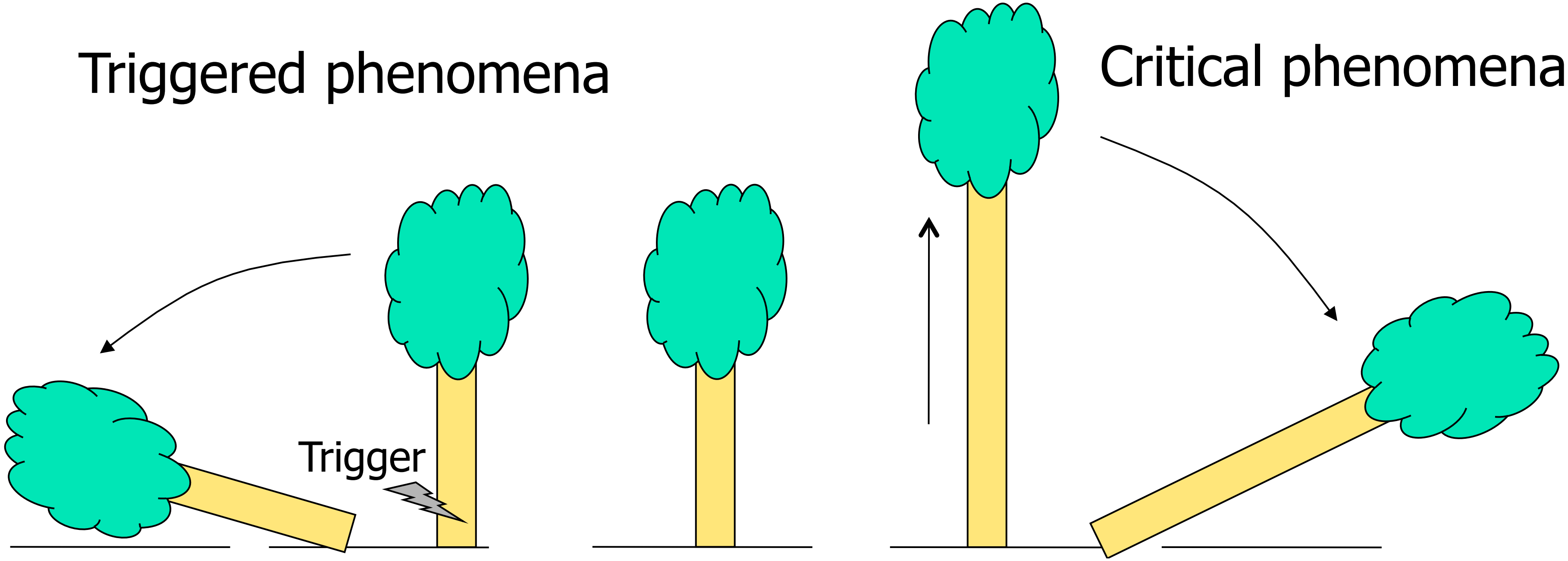


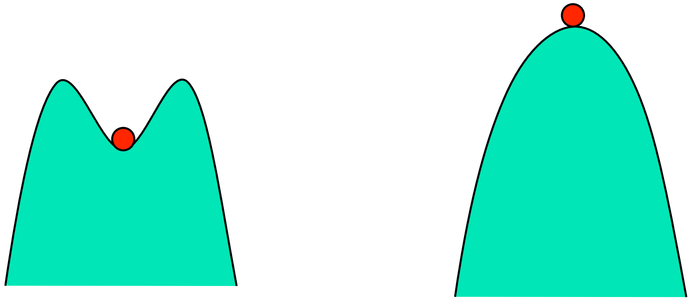
How

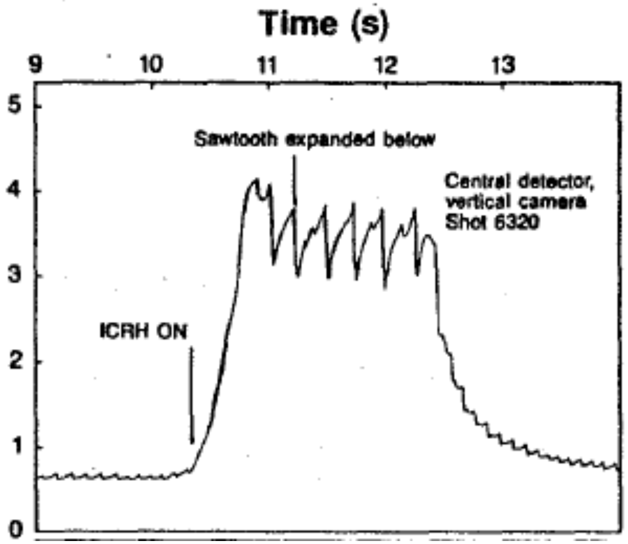
Two types of onset process

Triggered phenomena

Critical phenomena





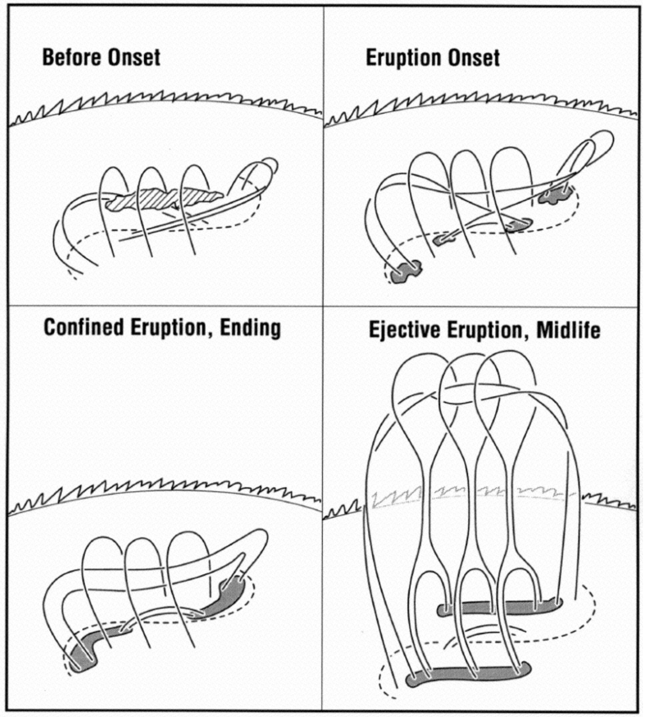


Sawtooth
in tokamak

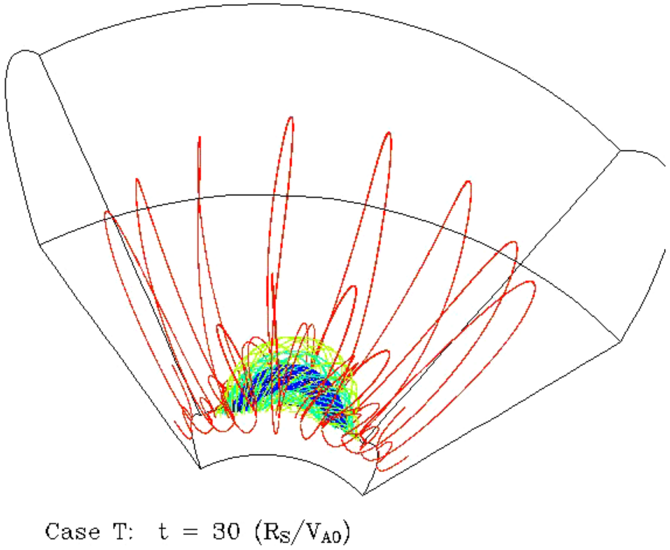
Triggered or Critical

Triggered phenomena

Critical phenomena



Moor et al. 2001



Fun & Gibson 2007

tether cutting model
flux cancellation model

ideal kink model
catastrophe model

Method 1: Machine-learning

- Automated Solar Activity Prediction:
  - Space Weather Prediction Center
  - Colak & Qahwaji 2009, HN Wang et al. 2008

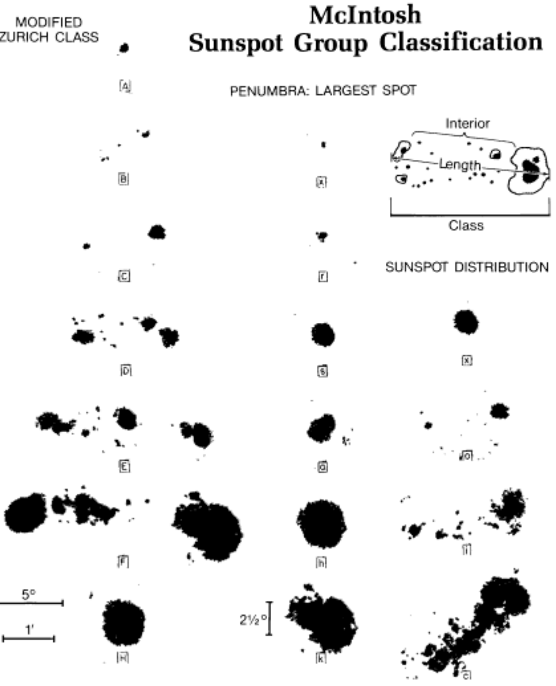


Fig. 1. The 3-component McIntosh classification, with examples of each category.

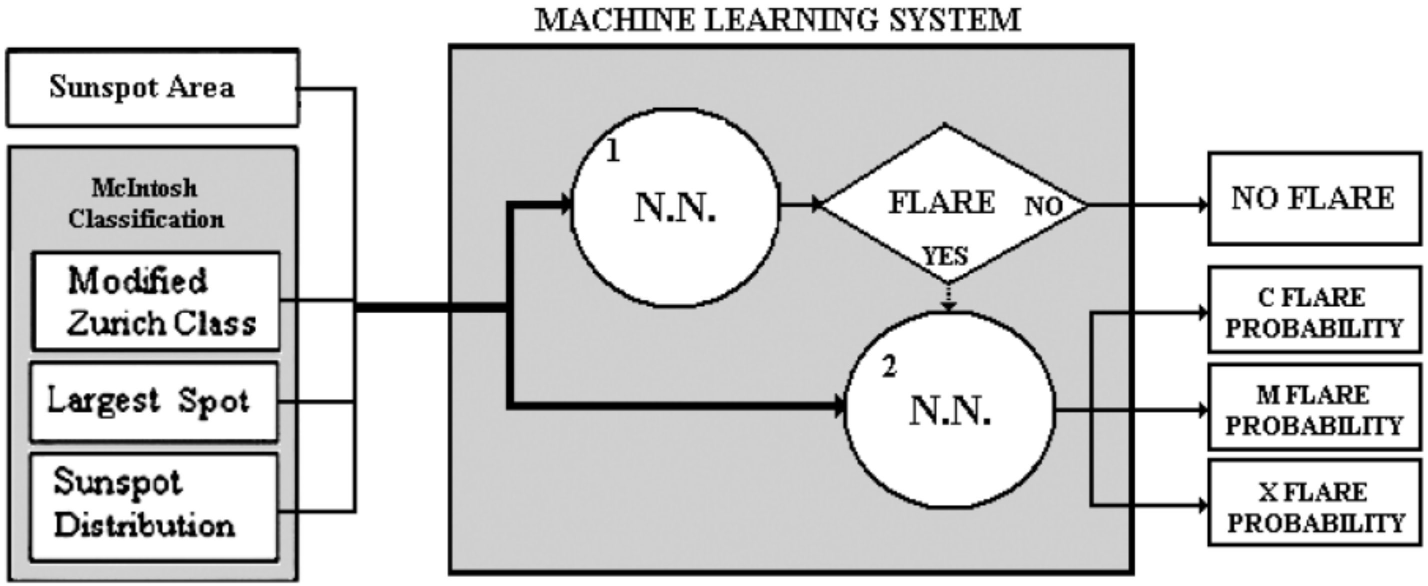


Figure 2. Machine-learning system for flare prediction.

Colak & Qahwaji 2009

Skill Score

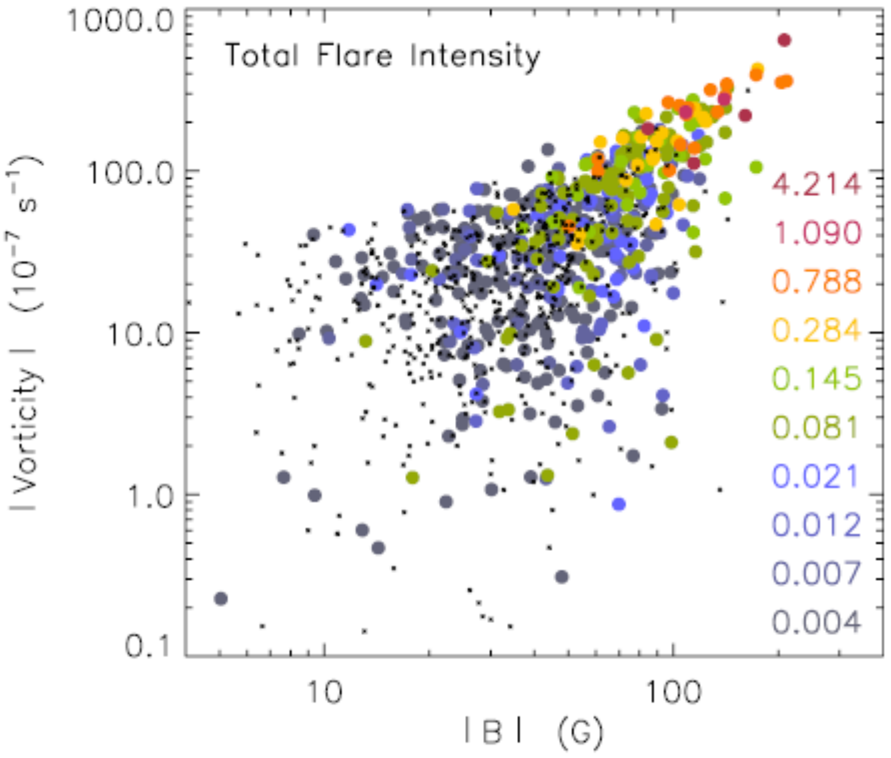
$$SS = \frac{n_{ff} - (n_q - n_{qq})}{n_f}$$

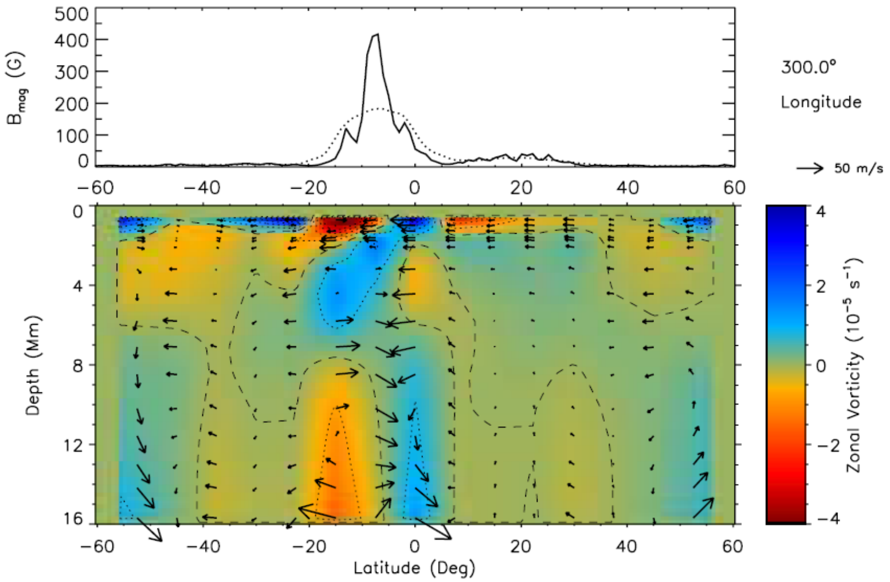
- Skill Score of SWPC for X flare

1day	2day	3day	year (events)
0.112	-0.147	-0.171	2006 (4)
0.242	0.147	0.127	2005 (13)
0.052	-0.001	-0.044	2004 (9)
0.200	0.093	0.076	2003 (17)
-0.037	-0.050	-0.033	2002 (12)
-0.061	-0.034	-0.006	2001 (18)

Flares and Subsurface vorticity

- Komm & Hill 2009 JGR



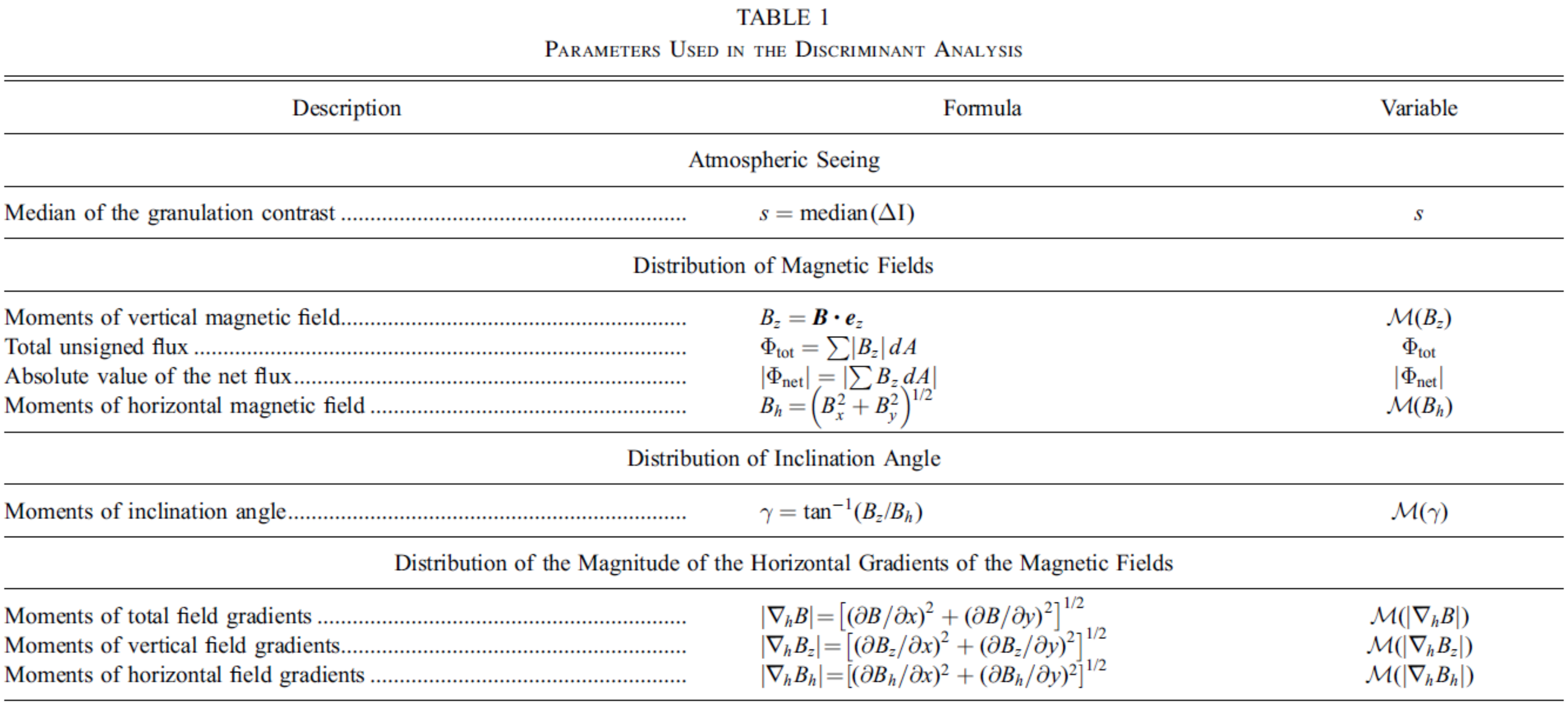


Method 2: Correlative Analysis

- To find magnetic quantity, which is most correlated to the onset of flares.
  - Leka & Barnes 2007, Yamamoto & Sakurai 2009

TABLE 1

PARAMETERS USED IN THE DISCRIMINANT ANALYSIS



Description	Formula	Variable
	Atmospheric Seeing	
Median of the granulation contrast	$s = \mathrm{median}(\Delta I)$	s
	Distribution of Magnetic Fields	
Moments of vertical magnetic field	$B_z = \boldsymbol{B} \cdot \boldsymbol{e}_z$	$\mathcal{M}(B_z)$
Total unsigned flux	$\Phi_{\mathrm{tot}} = \sum \lvert B_z \rvert \, dA$	Φ_{tot}
Absolute value of the net flux	$\lvert \Phi_{\mathrm{net}} \rvert = \lvert \sum B_z \, dA \rvert$	$\lvert \Phi_{\mathrm{net}} \rvert$
Moments of horizontal magnetic field	$B_h = \left(B_x^2 + B_y^2 \right)^{1/2}$	$\mathcal{M}(B_h)$
	Distribution of Inclination Angle	
Moments of inclination angle	$\gamma = \tan^{-1}(B_z/B_h)$	$\mathcal{M}(\gamma)$
	Distribution of the Magnitude of the Horizontal Gradients of the Magnetic Fields	
Moments of total field gradients	$\lvert \nabla_h B \rvert = \left[(\partial B/\partial x)^2 + (\partial B/\partial y)^2 \right]^{1/2}$	$\mathcal{M}(\lvert \nabla_h B \rvert)$
Moments of vertical field gradients	$\lvert \nabla_h B_z \rvert = \left[(\partial B_z/\partial x)^2 + (\partial B_z/\partial y)^2 \right]^{1/2}$	$\mathcal{M}(\lvert \nabla_h B_z \rvert)$
Moments of horizontal field gradients	$\lvert \nabla_h B_h \rvert = \left[(\partial B_h/\partial x)^2 + (\partial B_h/\partial y)^2 \right]^{1/2}$	$\mathcal{M}(\lvert \nabla_h B_h \rvert)$

Distribution of Vertical Current Density		
Moments of vertical current density	$J_z = C(\partial B_y/\partial x - \partial B_x/\partial y)$	$\mathcal{M}(J_z)$
Total unsigned vertical current	$I_{\rm tot} = \sum \lvert J_z \rvert \, dA$	$I_{\rm tot}$
Absolute value of the net vertical current	$\lvert I_{\rm net} \rvert = \lvert \sum J_z \, dA \rvert$	$\lvert I_{\rm net} \rvert$
Sum of absolute value of net currents in each polarity	$\lvert I_{\rm net}^B \rvert = \lvert \sum J_z(B_z > 0)\, dA \rvert + \lvert \sum J_z(B_z < 0)\, dA \rvert$	$\lvert I_{\rm net}^B \rvert$
Moments of vertical heterogeneity current density[a]	$J_z^h = C(b_y \, \partial B_x/\partial y - b_x \partial B_y/\partial x)$	$\mathcal{M}(J_z^h)$
Total unsigned vertical heterogeneity current	$I_{\rm tot}^h = \sum \lvert J_z^h \rvert \, dA$	$I_{\rm tot}^h$
Absolute value of net vertical heterogeneity current	$\lvert I_{\rm net}^h \rvert = \lvert \sum J_z^h \, dA \rvert$	$\lvert I_{\rm net}^h \rvert$
Distribution of Twist Parameter		
Moments of twist parameter[b]	$\alpha = C J_z / B_z$	$\mathcal{M}(\alpha)$
Best-fit force-free twist parameter[b]	$\boldsymbol{B} = \alpha_{\rm ff} \nabla \times \boldsymbol{B}$	$\lvert \alpha_{\rm ff} \rvert$
Distribution of Current Helicity		
Moments of current helicity[c]	$h_c = C B_z (\partial B_y/\partial x - \partial B_x/\partial y)$	$\mathcal{M}(h_c)$
Total unsigned current helicity	$H_c^{\rm tot} = \sum \lvert h_c \rvert \, dA$	$H_c^{\rm tot}$
Absolute value of net current helicity	$\lvert H_c^{\rm net} \rvert = \lvert \sum h_c \, dA \rvert$	$\lvert H_c^{\rm net} \rvert$
Distribution of Shear Angles		
Moments of 3D shear angle[d]	$\Psi = \cos^{-1}(\boldsymbol{B}^p \cdot \boldsymbol{B}^o / B^p B^o)$	$\mathcal{M}(\Psi)$
Area with shear $>\Psi_0$, $\Psi_0 = 45^\circ$, 80°	$A(\Psi > \Psi_0) = \sum_{\Psi > \Psi_0} dA$	$A(\Psi > 45^\circ)$, $A(\Psi > 80^\circ)$
Moments of neutral line shear angle	$\Psi_{\rm NL} = \cos^{-1}(\boldsymbol{B}_{\rm NL}^p \cdot \boldsymbol{B}_{\rm NL}^o / B_{\rm NL}^p B_{\rm NL}^o)$	$\mathcal{M}(\Psi_{\rm NL})$
Length of neutral line with shear $>\Psi_0$	$L(\Psi_{\rm NL} > \Psi_0) = \sum_{\Psi_{\rm NL} > \Psi_0} dL$	$L(\Psi_{\rm NL} > 45^\circ)$, $L(\Psi_{\rm NL} > 80^\circ)$
Moments of horizontal shear angle[e]	$\psi = \cos^{-1}(\boldsymbol{B}_h^p \cdot \boldsymbol{B}_h^o / B_h^p B_h^o)$	$\mathcal{M}(\psi)$
Area with horizontal shear $>\psi_0$	$A(\psi > \psi_0) = \sum_{\psi > \psi_0} dA$	$A(\psi > 45^\circ)$, $A(\psi > 80^\circ)$
Distribution of Photospheric Excess Magnetic Energy Density		
Moments of photospheric excess magnetic energy density[d]	$\rho_e = (\boldsymbol{B}^p - \boldsymbol{B}^o)^2 / 8\pi$	$\mathcal{M}(\rho_e)$
Total photospheric excess magnetic energy	$E_e = \sum \rho_e \, dA$	E_e

NOTES.—The $\mathcal{M}(x)$ denotes taking the first four moments of the distribution of the variable x: the mean $\bar{x}$, the standard deviation $\sigma(x)$, the skew $\varsigma(x)$, and the kurtosis $\kappa(x)$. The C indicates physical constants that are included in the calculation but not listed here for clarity.

[a] Zhang (2001).

[b] Leka & Skumanich (1999).

[c] Abramenko et al. (1996); Bao et al. (1999).

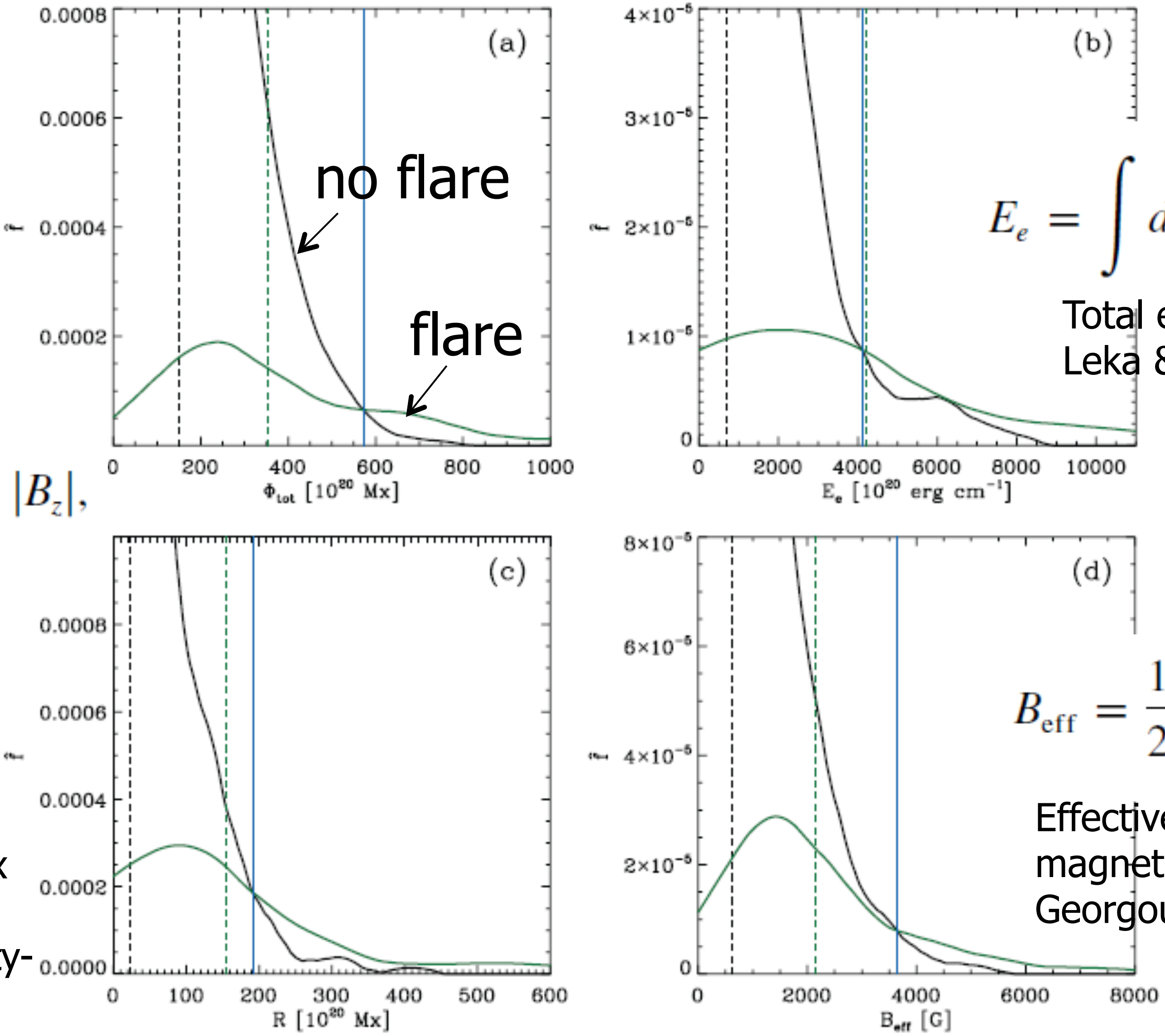
[d] Wang et al. (1996).

[e] Hagyard et al. (1984), although B_h is used here, rather than $B_\perp$.

Evaluating the performance of solar flare forecasting methods, Barnes and Leka 2008

(M&X class within 1d)

Event number ↑



no flare

flare

$$\Phi_{\text{tot}} = \int d^2x \, |B_z|,$$

$$E_e = \int d^2x \, (\boldsymbol{B} - \boldsymbol{B}_p)^2,$$

Total excess energy
Leka & Barnes 2003

$$B_{\text{eff}} = \frac{1}{2} \sum_{i \neq j} \frac{\psi_{ij}}{|\boldsymbol{x}_i - \boldsymbol{x}_j|^2},$$

Effective connected
magnetic field
Georgoulis & Rust 2007

R: unsigned flux
over the high-
gradient polarity-
separation lines
Schrijver 2007

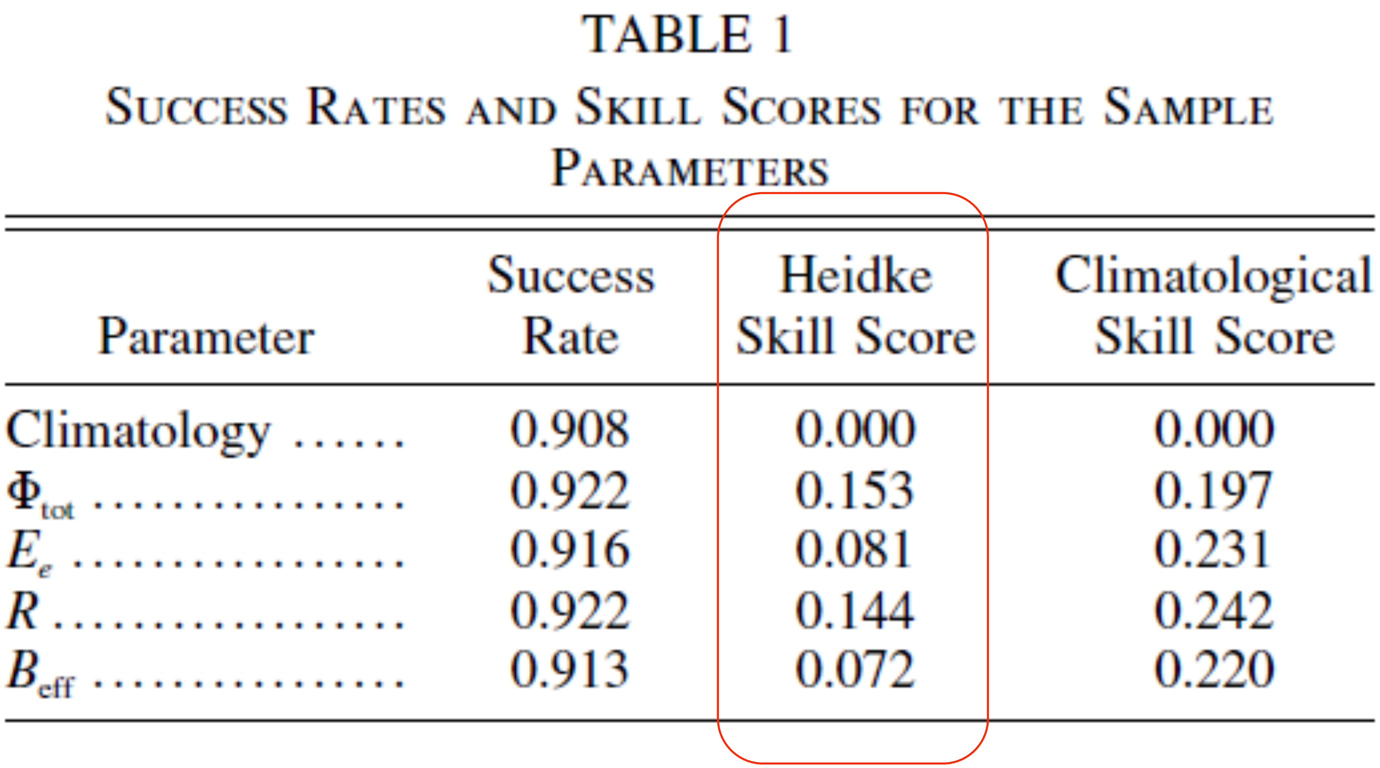


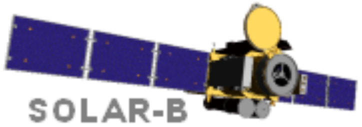
TABLE 1

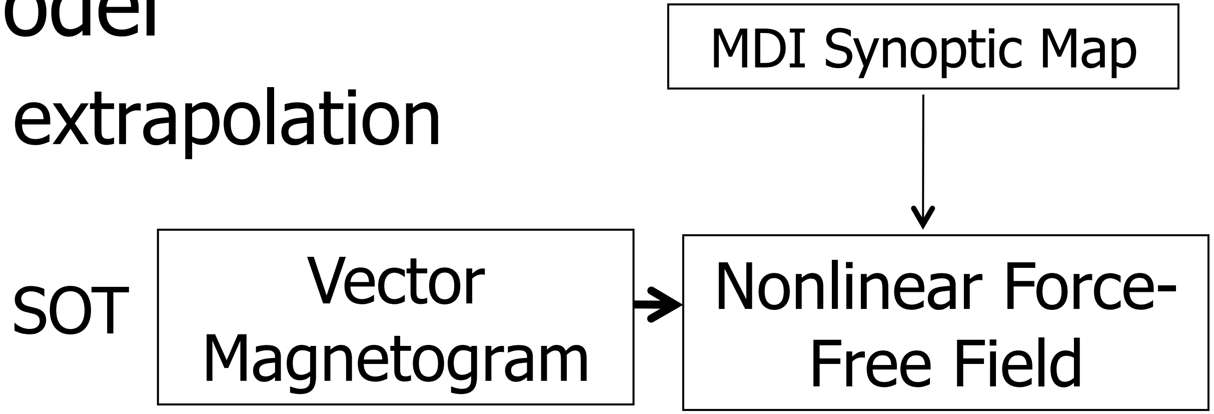
SUCCESS RATES AND SKILL SCORES FOR THE SAMPLE PARAMETERS

Parameter	Success Rate	Heidke Skill Score	Climatological Skill Score
Climatology	0.908	0.000	0.000
Φ_{tot}	0.922	0.153	0.197
E_e	0.916	0.081	0.231
R	0.922	0.144	0.242
B_{eff}	0.913	0.072	0.220

Method 3: 3D Model

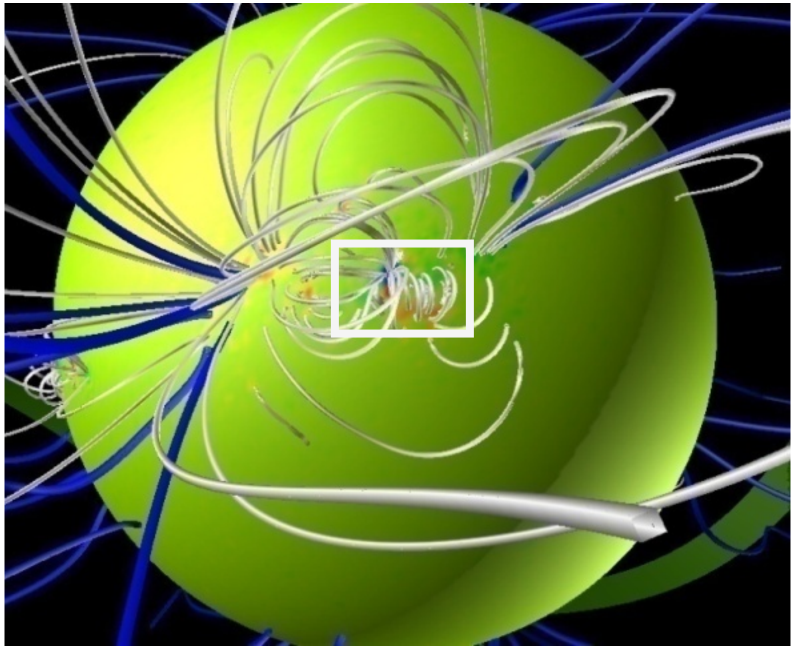
- Static Model
  - NLFFF extrapolation

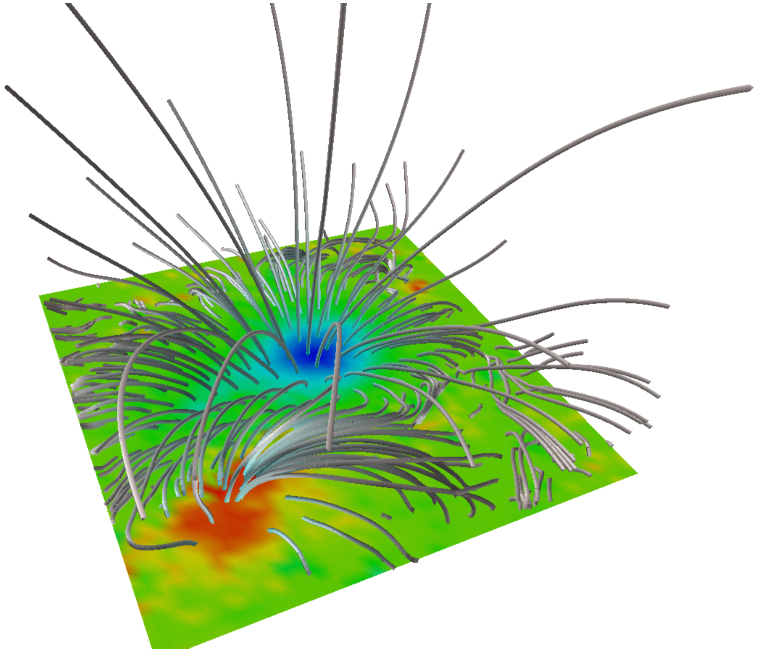




SOT → Vector Magnetogram → Nonlinear Force-Free Field

MDI Synoptic Map → Nonlinear Force-Free Field





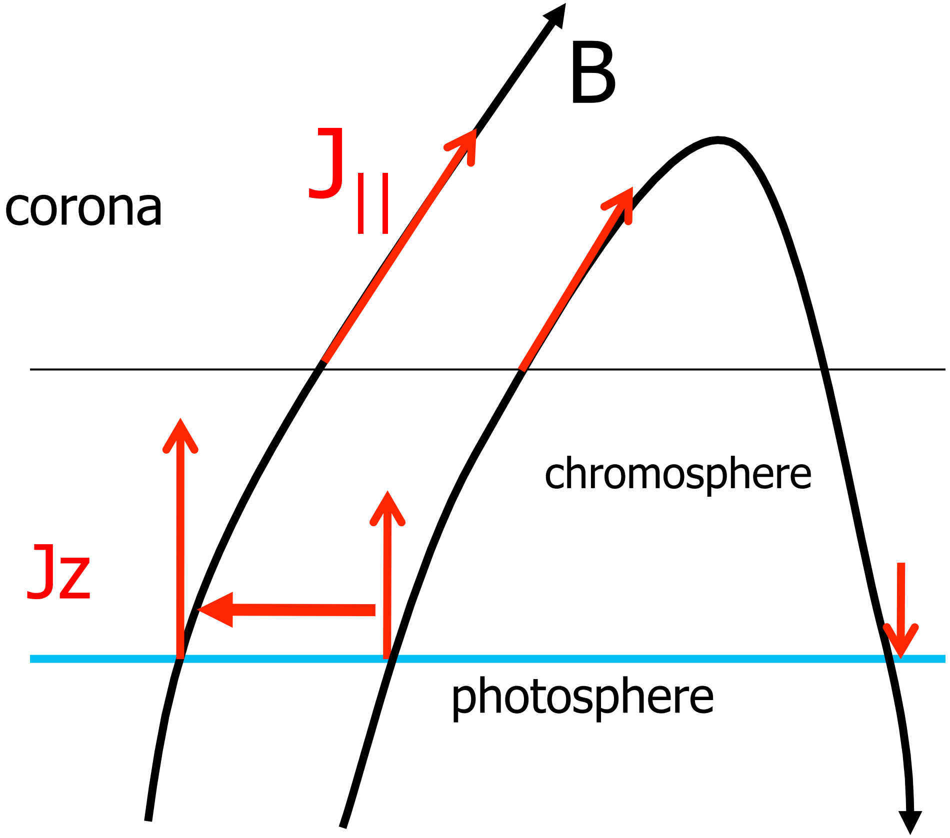
Chromospheric model is needed

- Photospheric data is NOT consistent with NLFF equation.

$$\nabla \times \mathbf{B} = \alpha \mathbf{B}$$

$$\Updownarrow$$

$$\mathbf{B} \cdot \nabla \alpha = 0$$

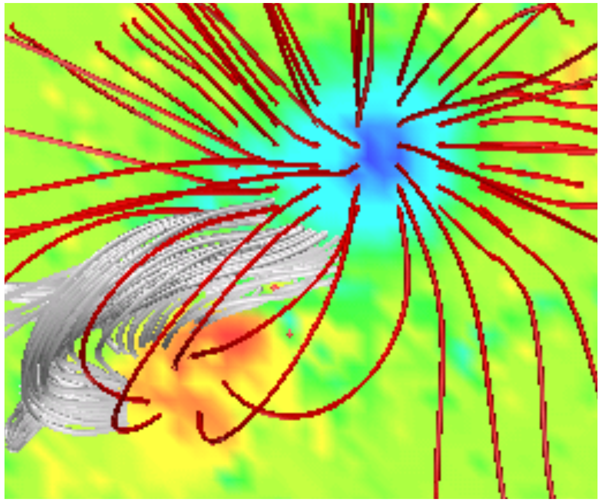


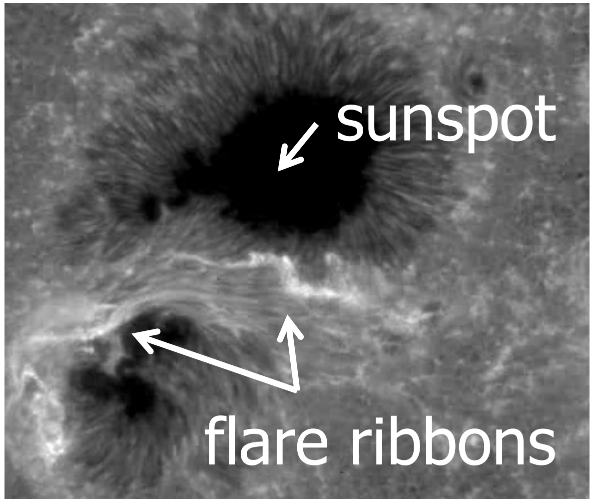
“pre-conditioning” has to be applied to photospheric data.

AR 10930 (2006 Dec. 13)

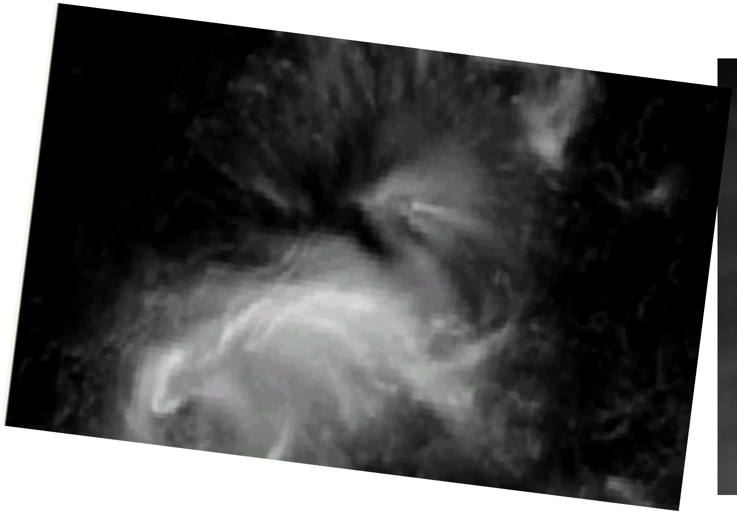
NLFF model

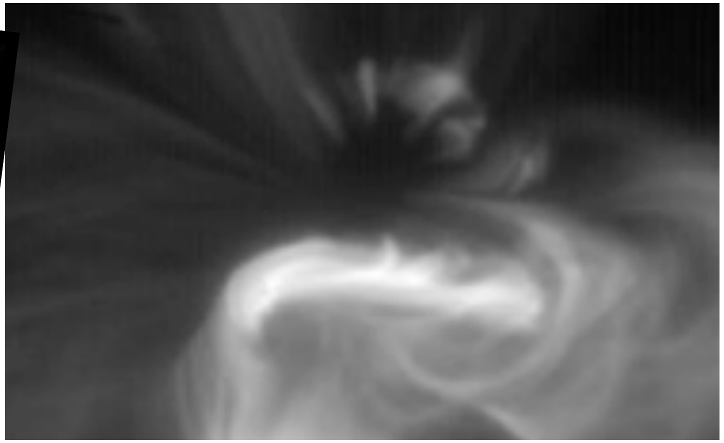
Observation



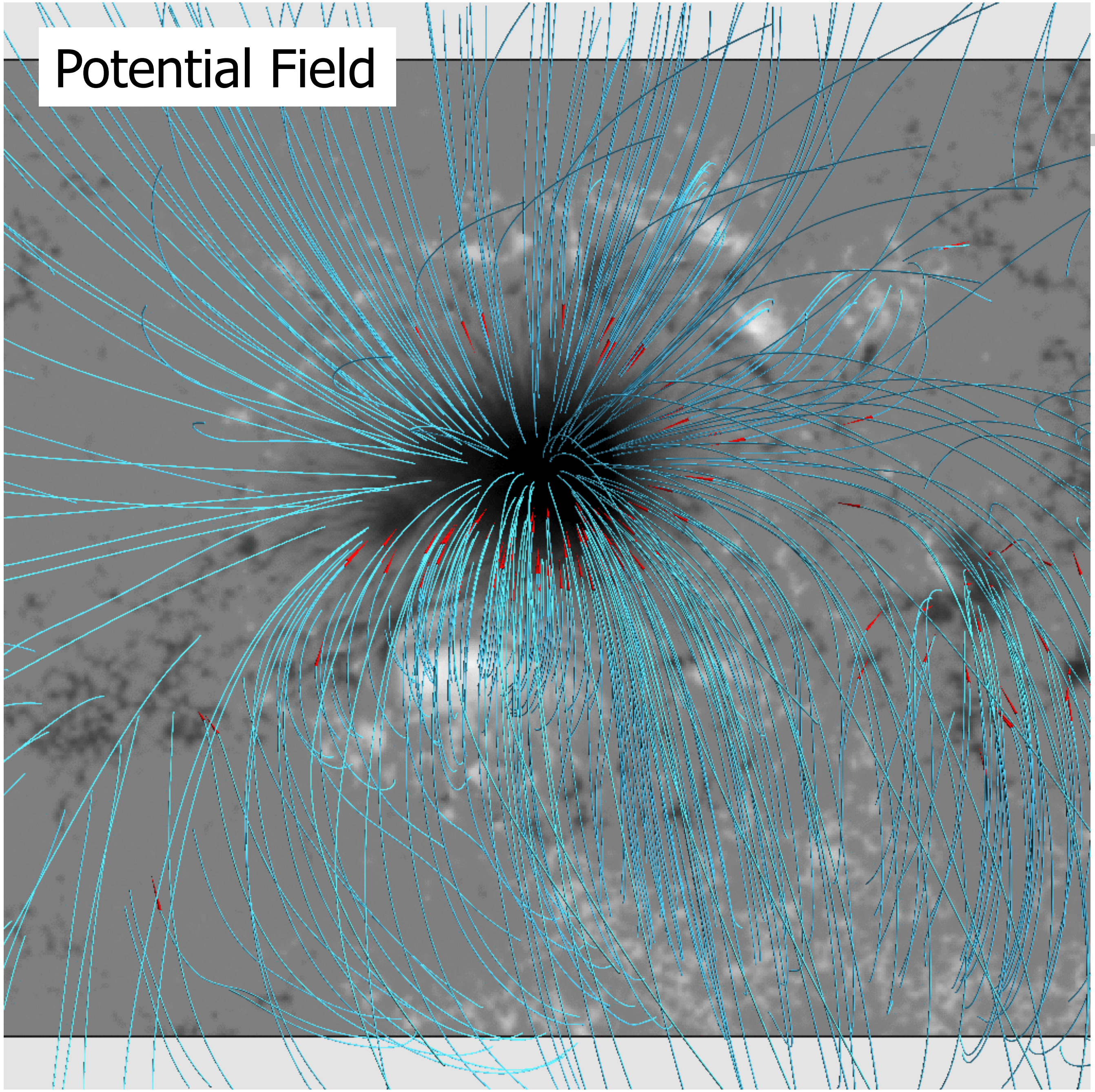


SOT

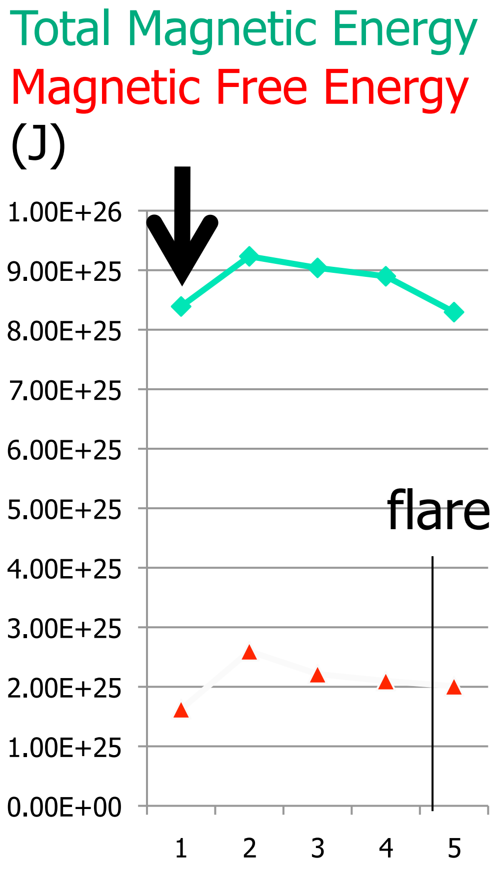


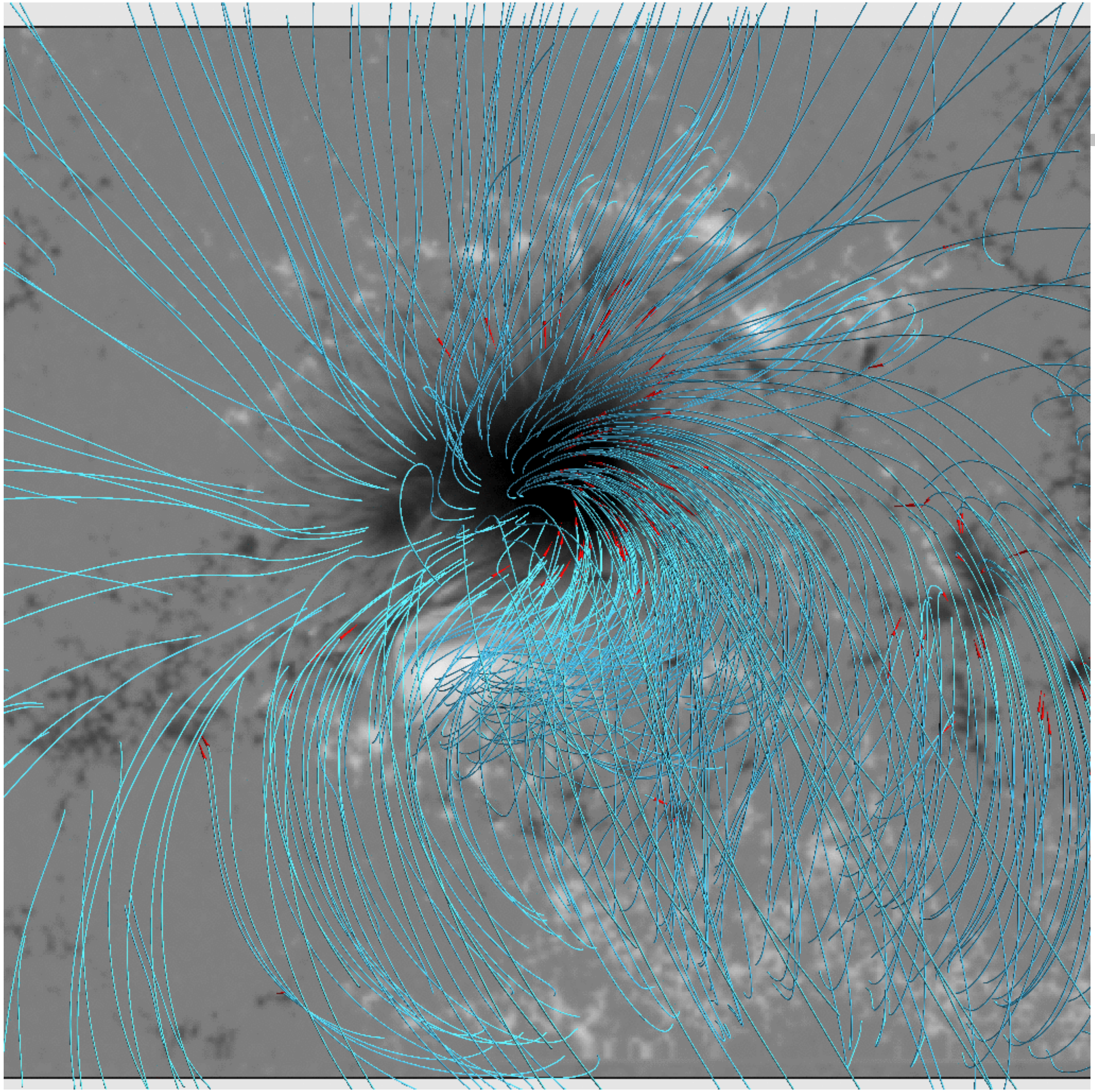


XRT



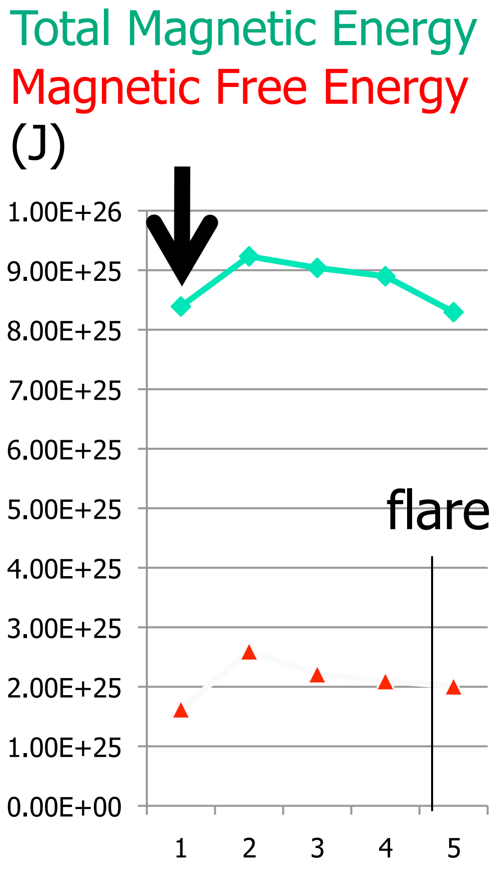
2006_12_11
17:00 UT


Total Magnetic Energy
Magnetic Free Energy
(J)

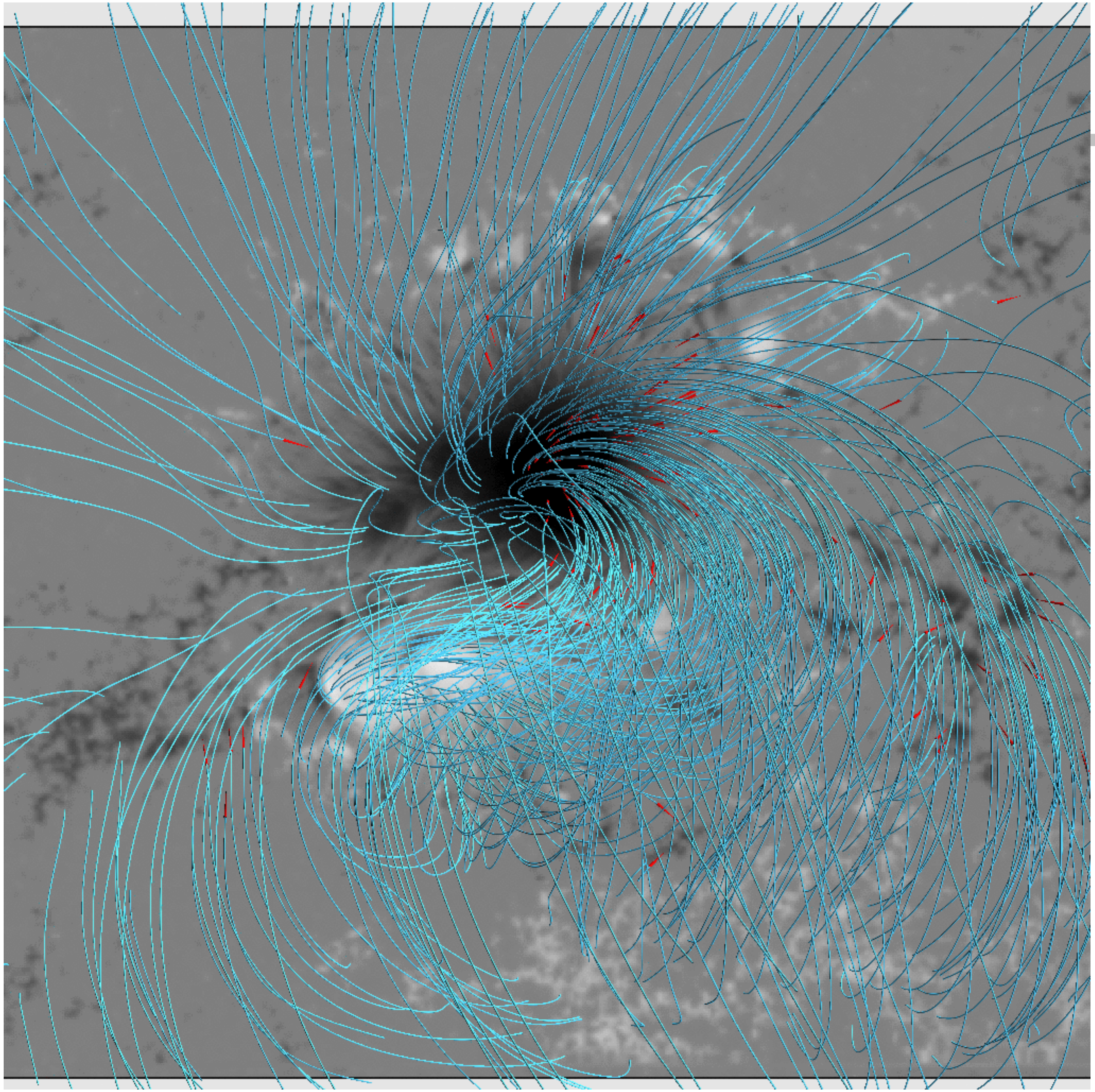


33h prior to the flare

2006_12_11
17:00 UT

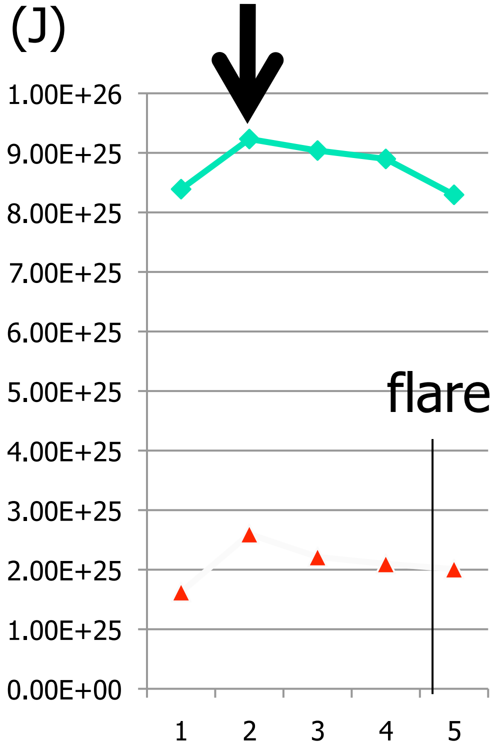


21h prior to the flare

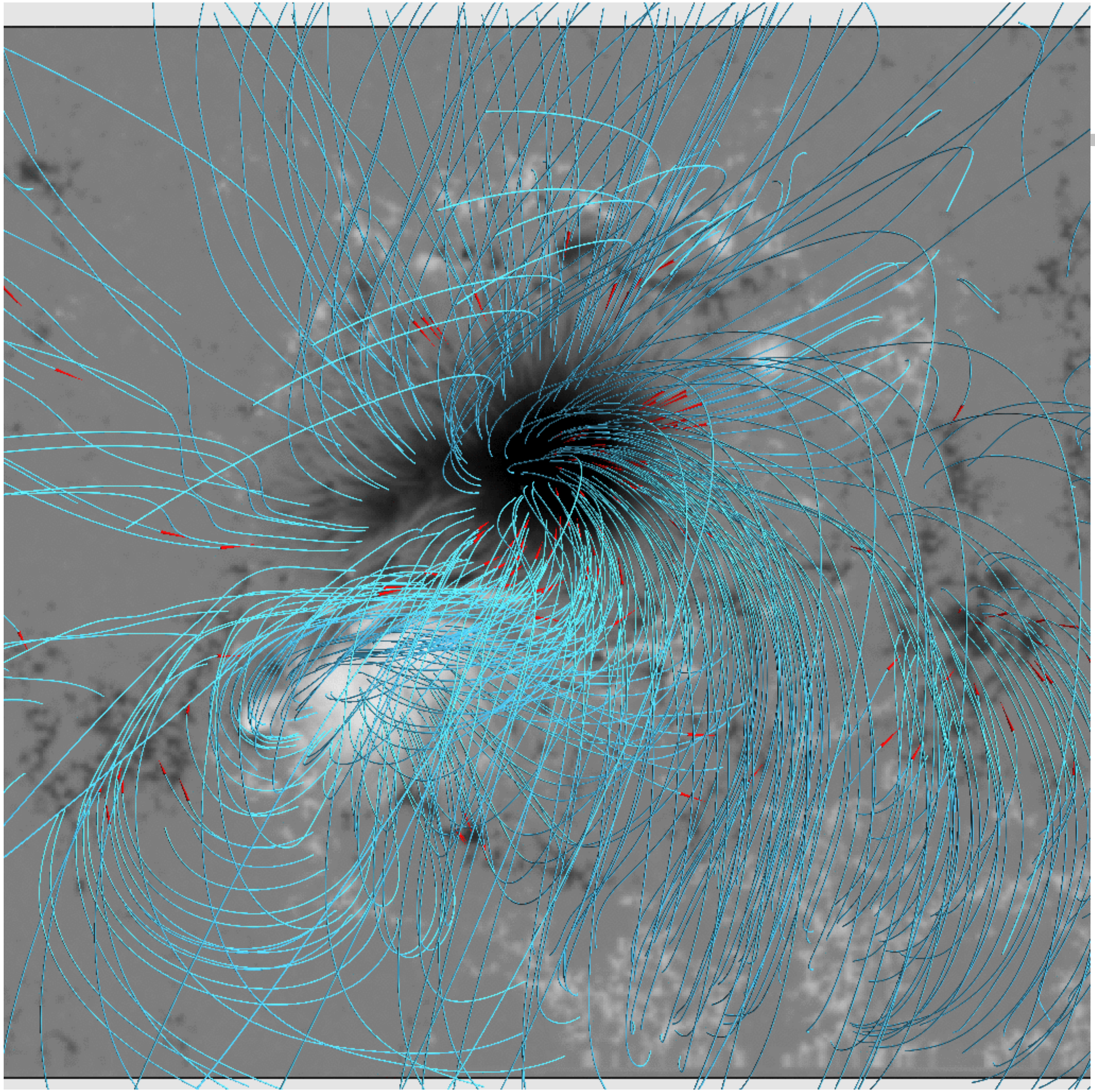


2006_12_12
03:50 UT

Total Magnetic Energy
Magnetic Free Energy

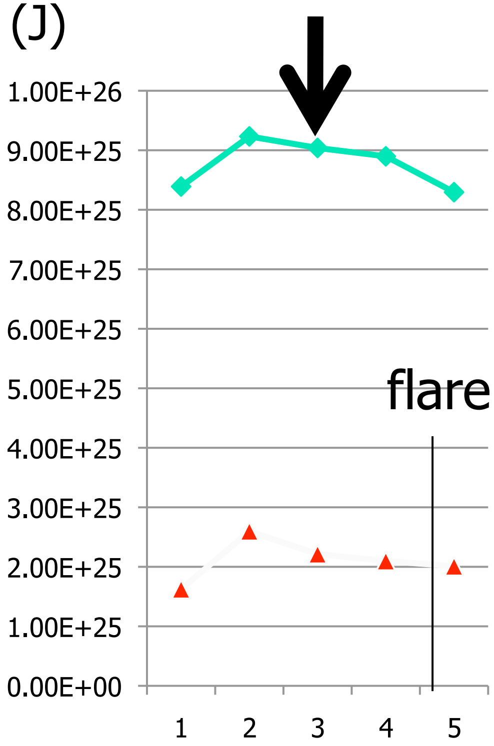


8h prior to the flare

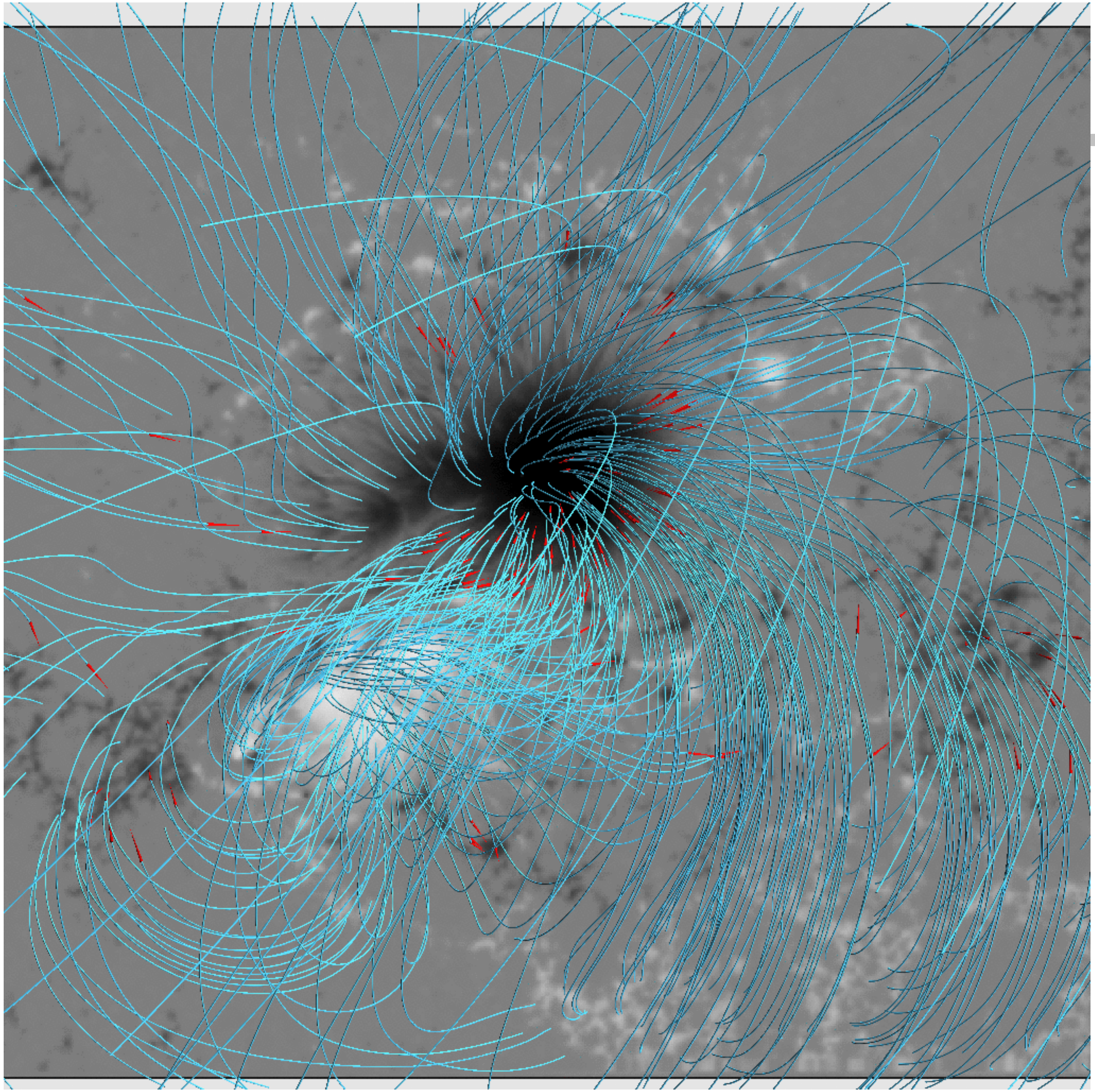


2006_12_12
17:40 UT

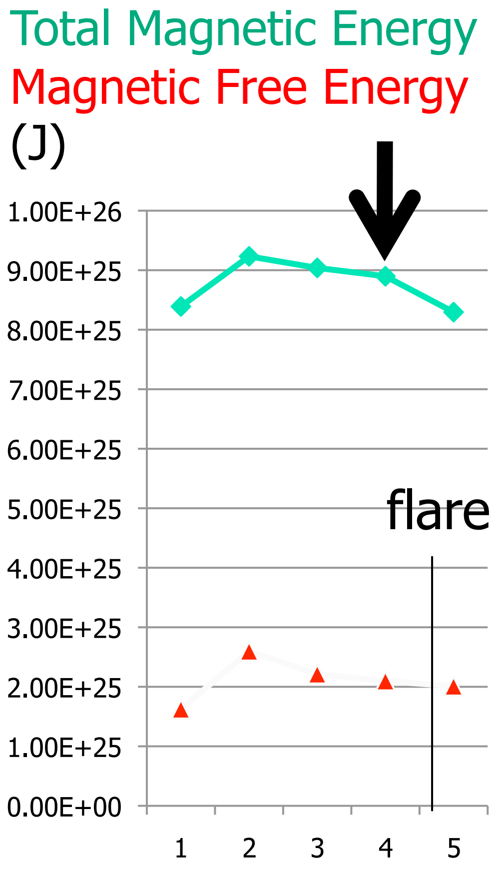
Total Magnetic Energy
Magnetic Free Energy
(J)

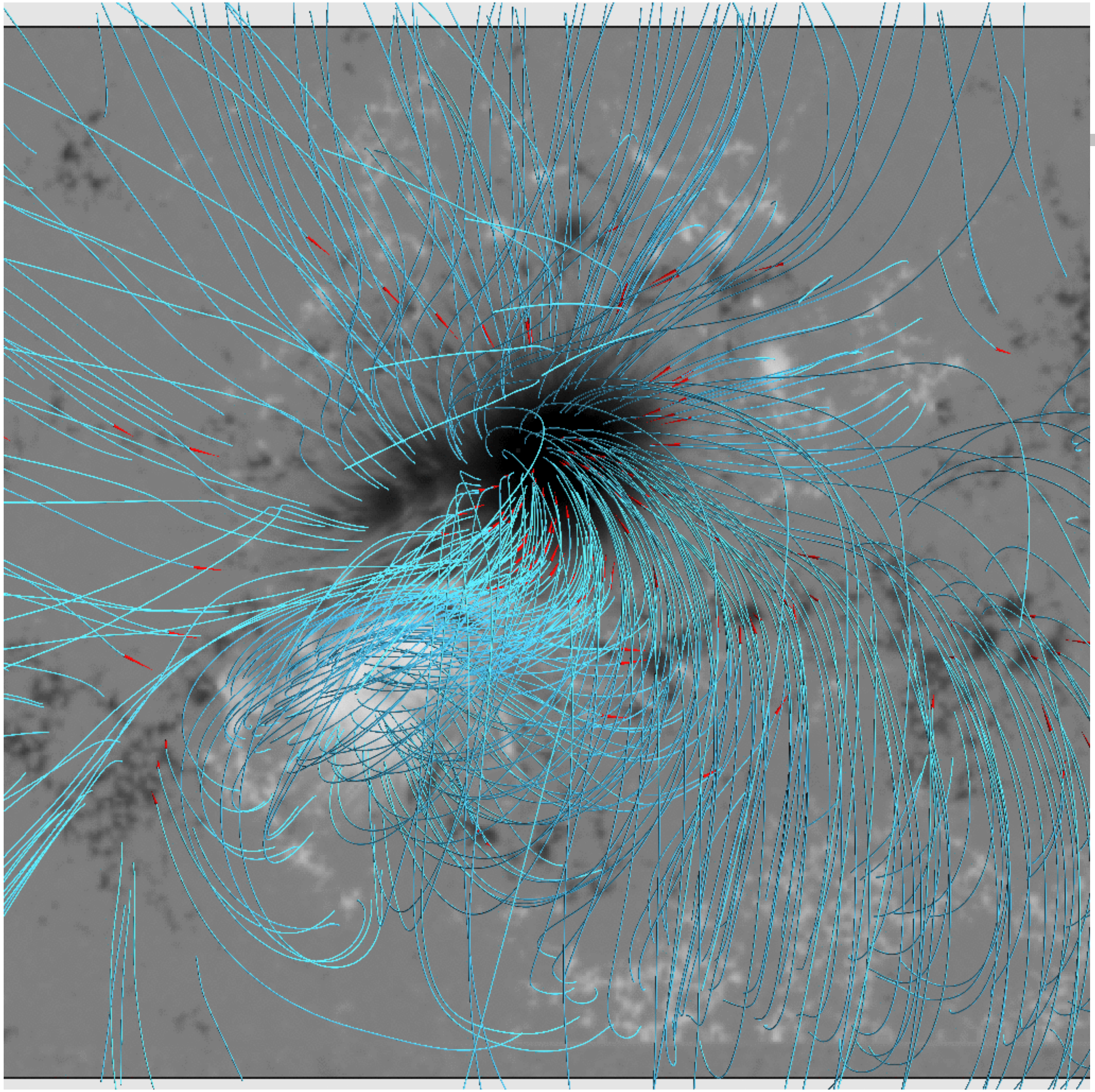


5h prior to the flare



2006_12_12
20:30 UT

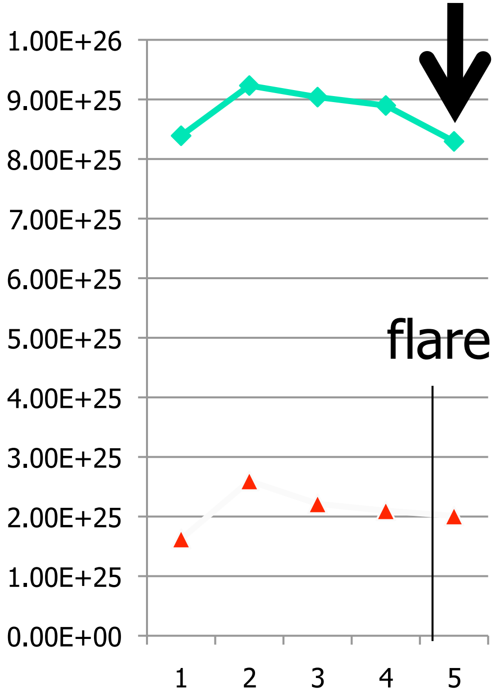




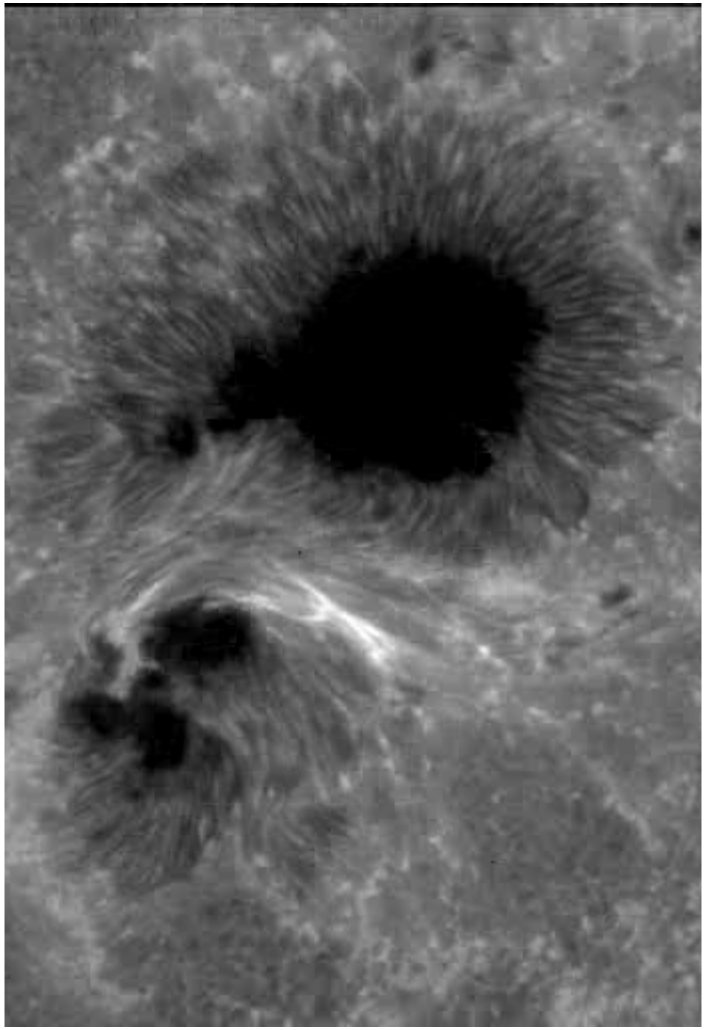
5h after the flare

2006_12_13
07:00 UT

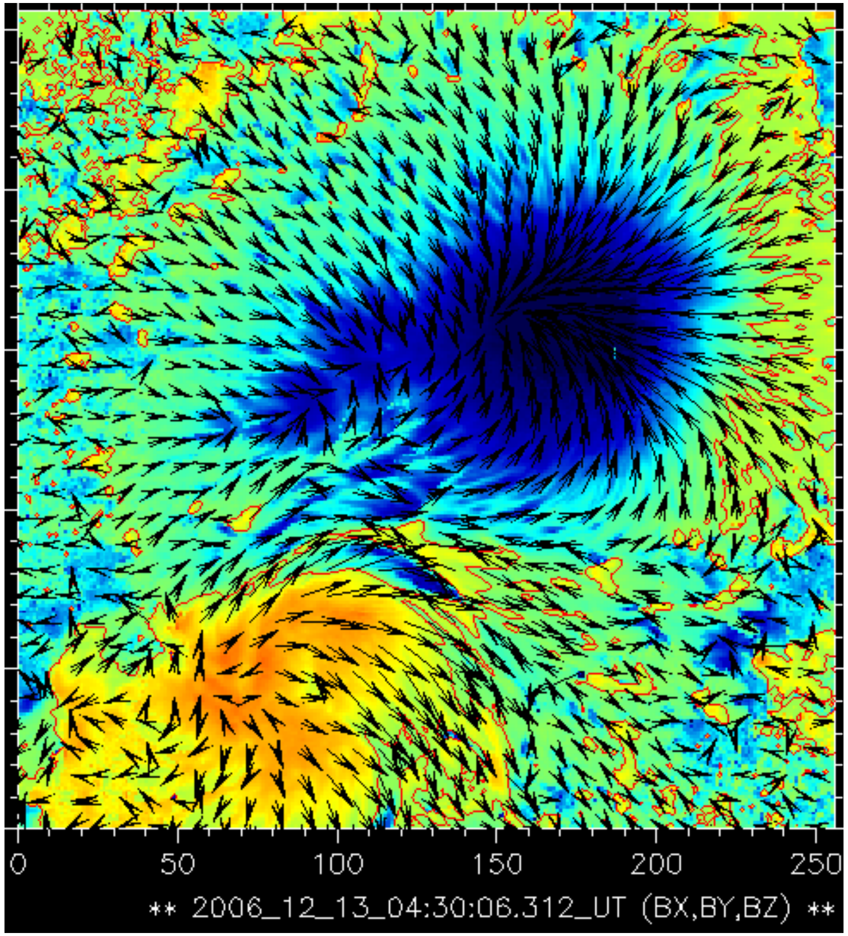
Total Magnetic Energy
Magnetic Free Energy
(J)



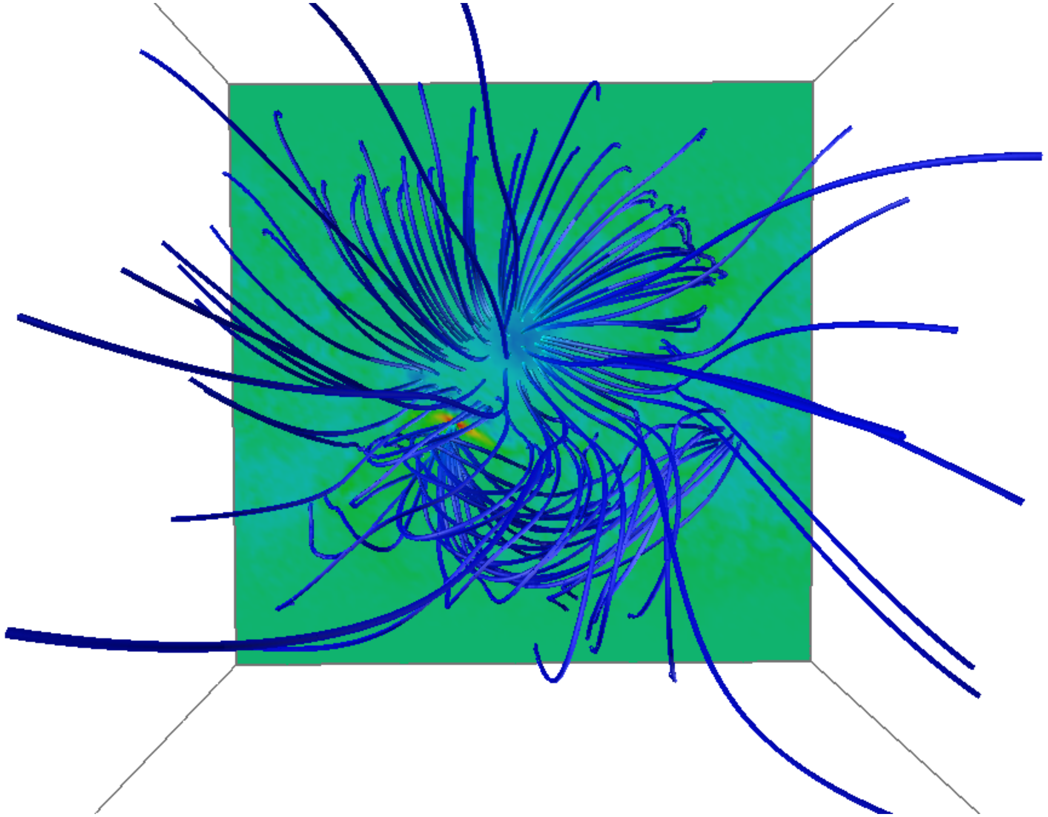
pre-flare brightening and magnetic field

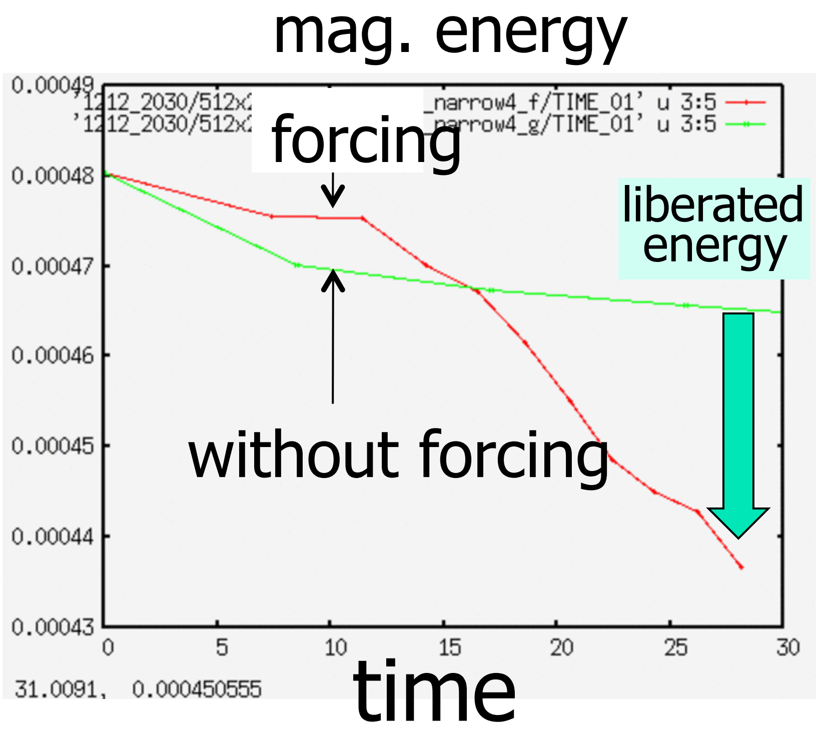


2006.12.13 01:42:37

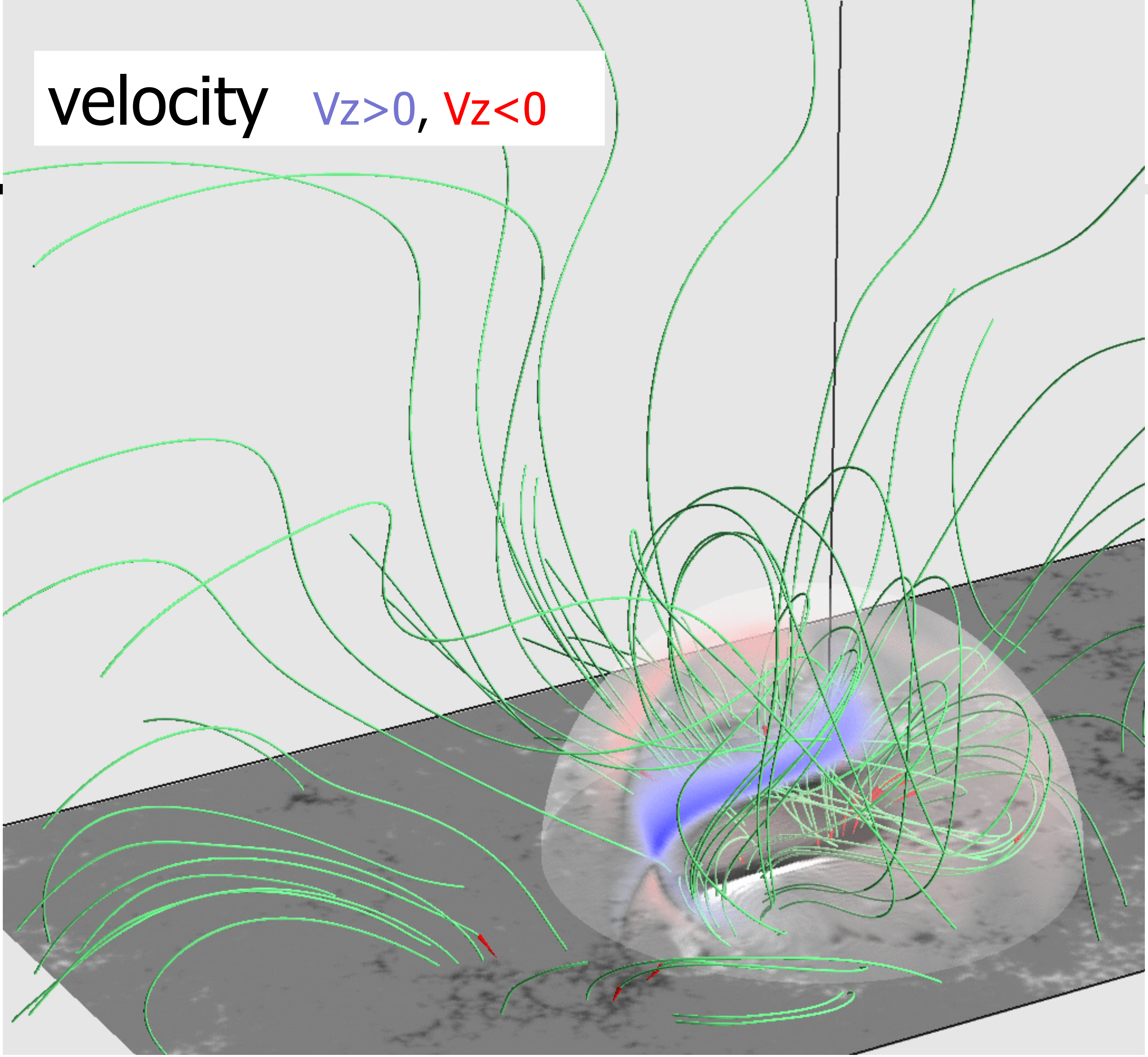


Numerical experiment of the flare

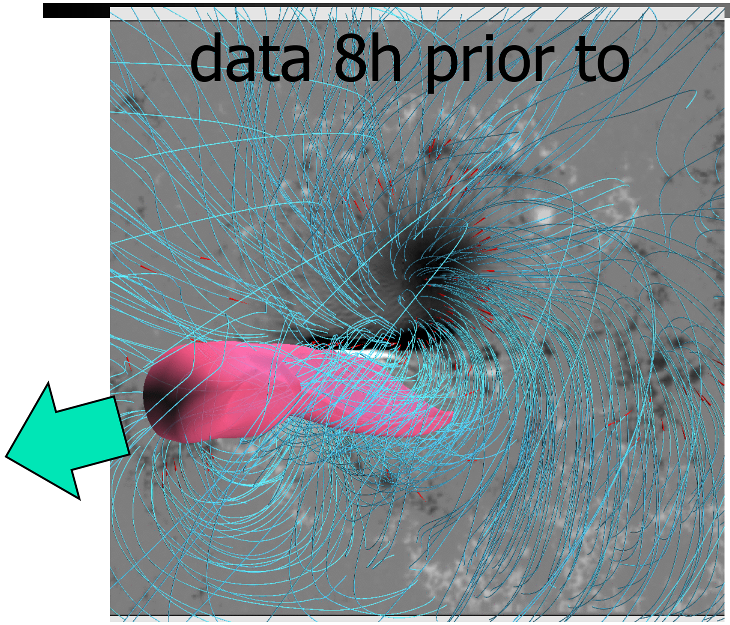




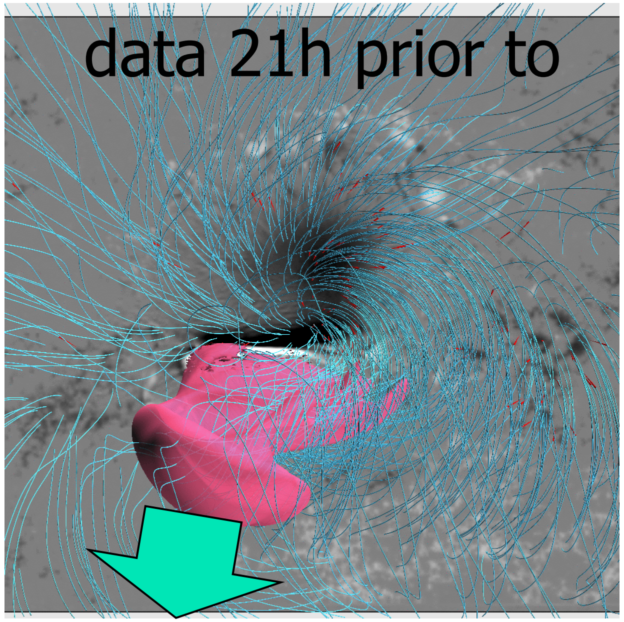
Small forcing on the foot-point is able to trigger energy liberation, which corresponds to flare.


velocity Vz>0, Vz<0

X-ray Ejections & X-ray Wave

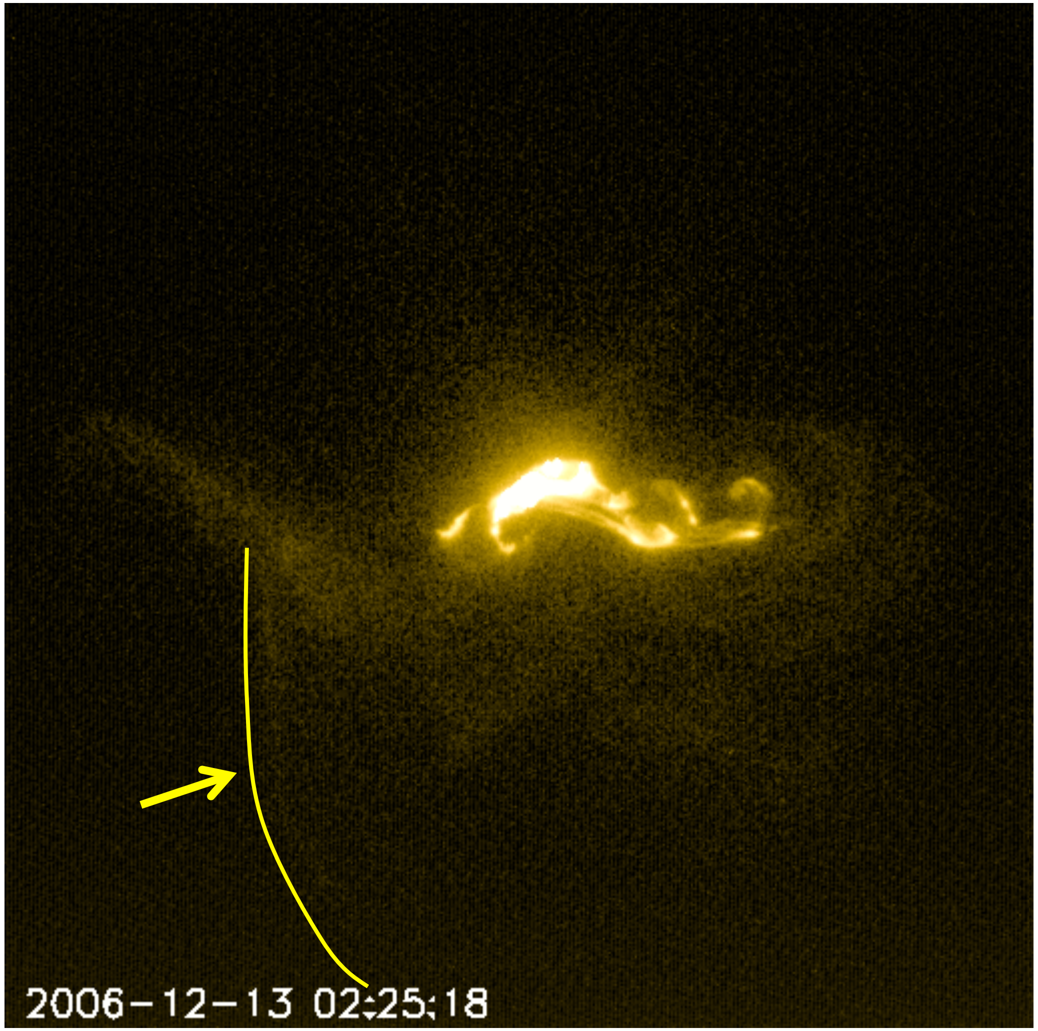


data 8h prior to



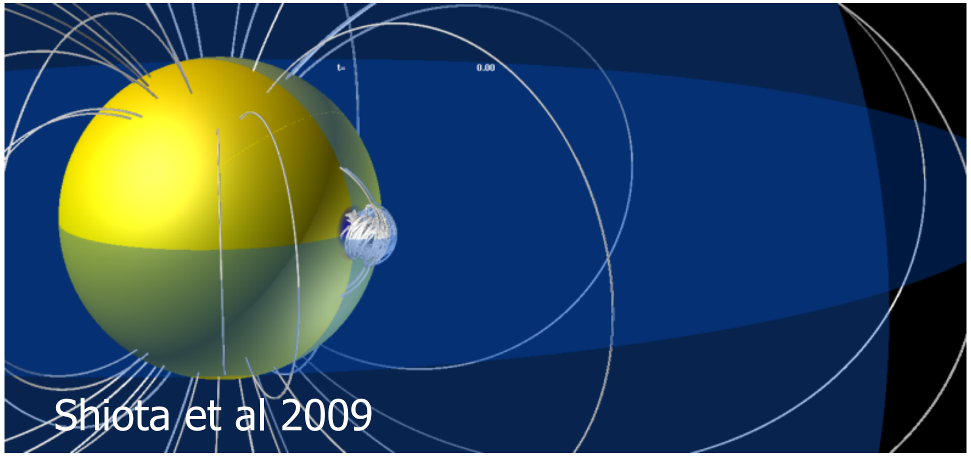
data 21h prior to

courtesy of Asai-san



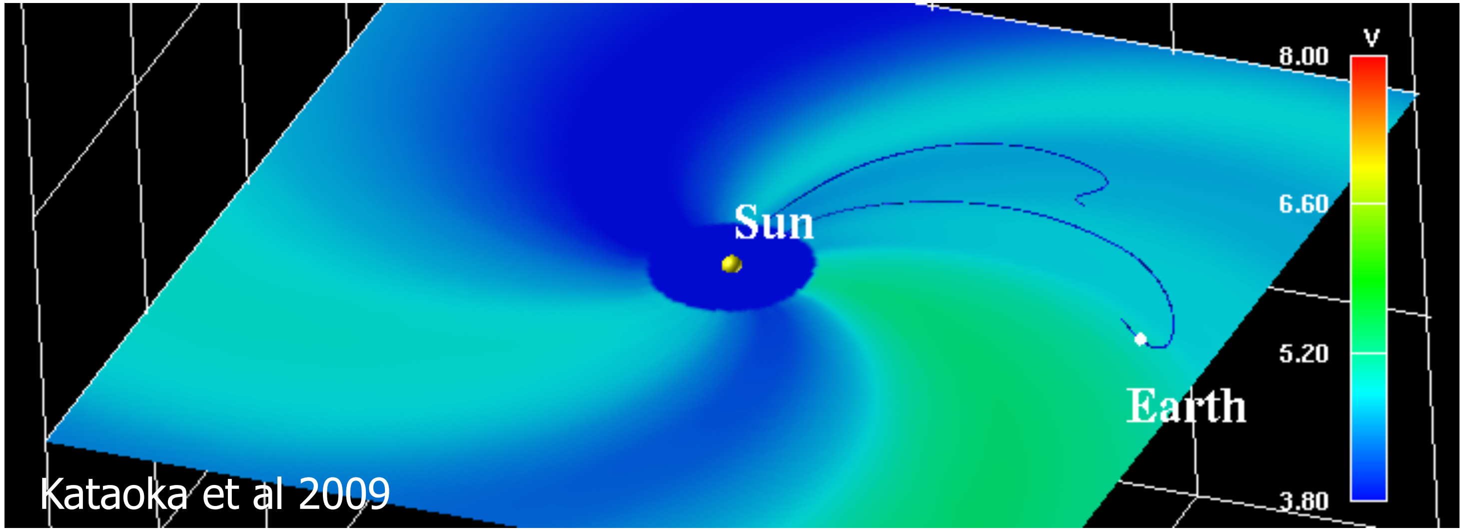
2006-12-13 02:25:18

Extension to CME model



Shiota et al 2009

- Solar wind model
- CME model
- ICME model
- Magnetosphere model



Kataoka et al 2009

Summary

- The methods to forecast flares is now being developed in terms of several algorithms.
- The data-driven MHD model using Hinode’s vector magnetogram is very promising to reproduce flare activity as well as to evaluate the “vulnerability” of active region. However, it is still premature to predict when flare occurs.
- Solar flare might be a triggered process rather than a critical process. So, we probably need higher-cadence data to find the real trigger.
- Solar-C/B could be a powerful tool for forecasting flare. However, many experiments to do using Hinode’s data is not completed yet.

Inversion of the Induction eq.

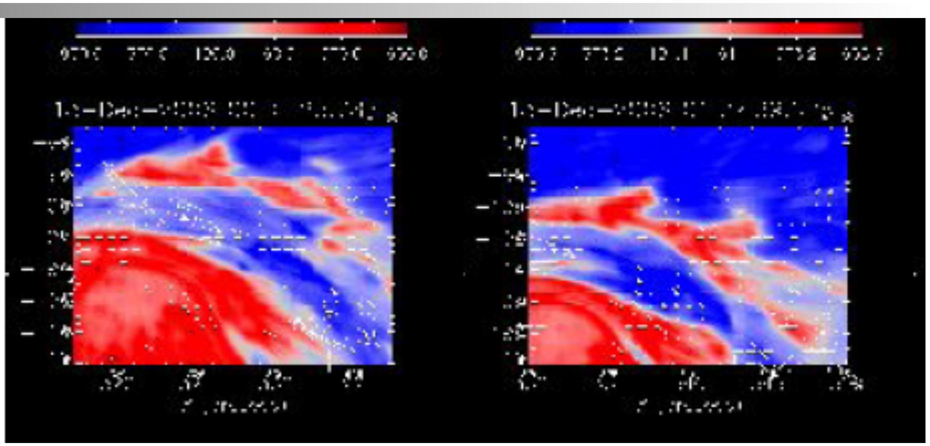
- LCT
- Kusano et al. 2002

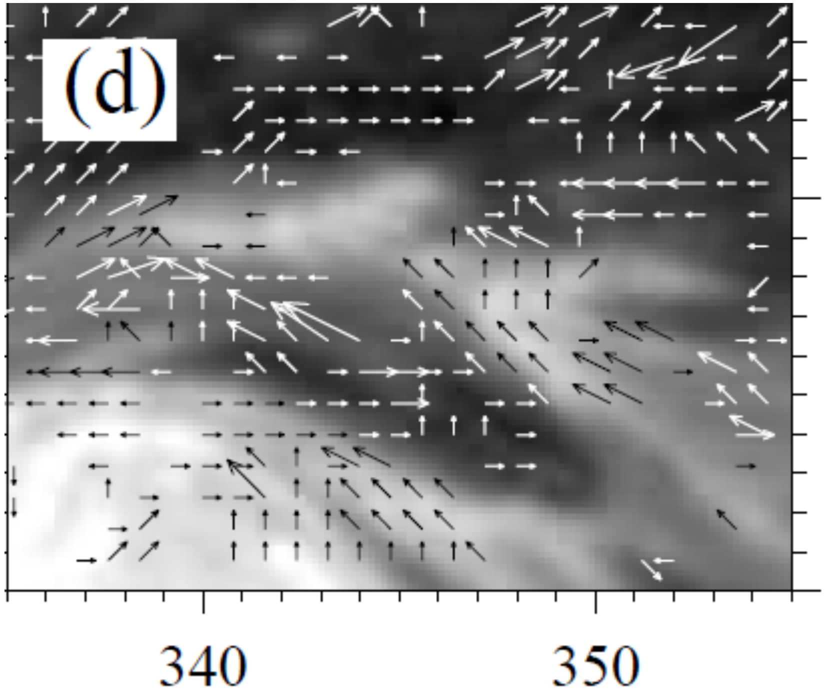
$$\frac{\partial B_z}{\partial t} = [\nabla \times (\mathbf{V} \times \mathbf{B})]_z$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B})$$

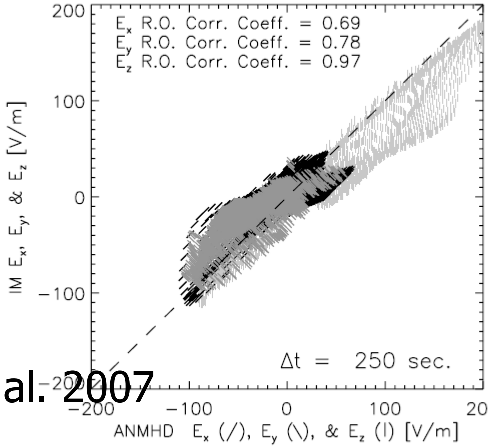
∂_z が必要

Fisher et al.2010





山本さんから提供 2009 Hinode-3



Welsch et al. 2007