フレア予測

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Outlook

- 太陽活動予測の重要性
- フレア予測は何をすべきか？
- フレア予測の方法と課題
  - 学習アルゴリズム、物理アルゴリズム
  - シミュレーションモデル
- 今後何をすべきか？

太陽活動予測の重要性

- 爆発的太陽活動の予測
  - フレア予測、SEP予測、CME予測、太陽風予測

Cycle 24で実現！！

- 太陽黒点活動予測
  - 太陽周期活動の予測、グランドミニマの発生予測

Cycle 30までには実現！！

宇宙天気予報、宇宙気候予測

太陽地球環境変動原因の理解のため

科学的理解度の検証

フレア予測は何を予測すべきか？

- いつ
    - 3日前、24時間前、1時間前、5分前
- どこで
    - どの活動領域、活動領域のどの部分
- 何をどれほど
    - GOES X-ray クラス
    - CME
    - SEP
    - 磁気嵐

フレア予測の方法 1

- 学習アルゴリズム
  - Automated Solar Activity Prediction:
    - Space Weather Prediction Center
    - Colak & Qahwaji 2009

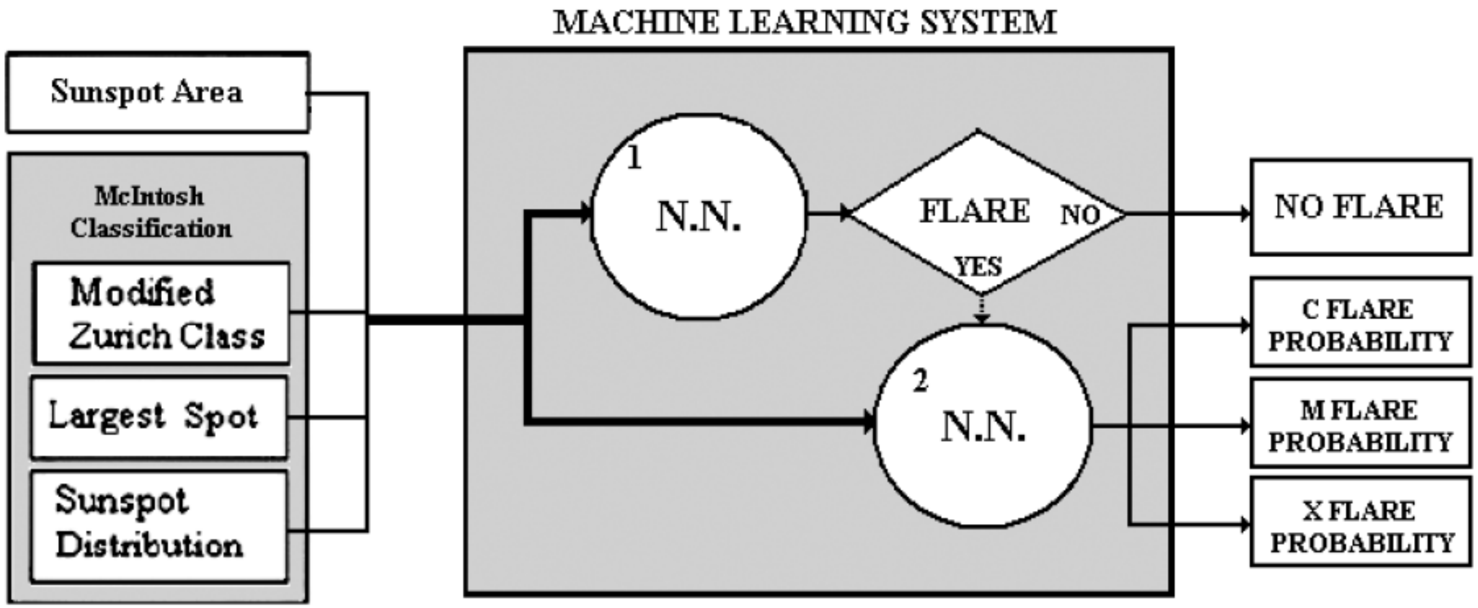


Figure 2. Machine-learning system for flare prediction.

is the degree of compactness in the interior of the group. Figure 1 illustrates the sequence within each of the three components of the classification. Table I lists the logical sequence for determining the McIntosh classification.

The definitions are formulated to require only white-light observations in the interest of consistency among all synoptic observatories. The definitions must begin with the distinction between unipolar and bipolar groups, implying a difference in a magnetic

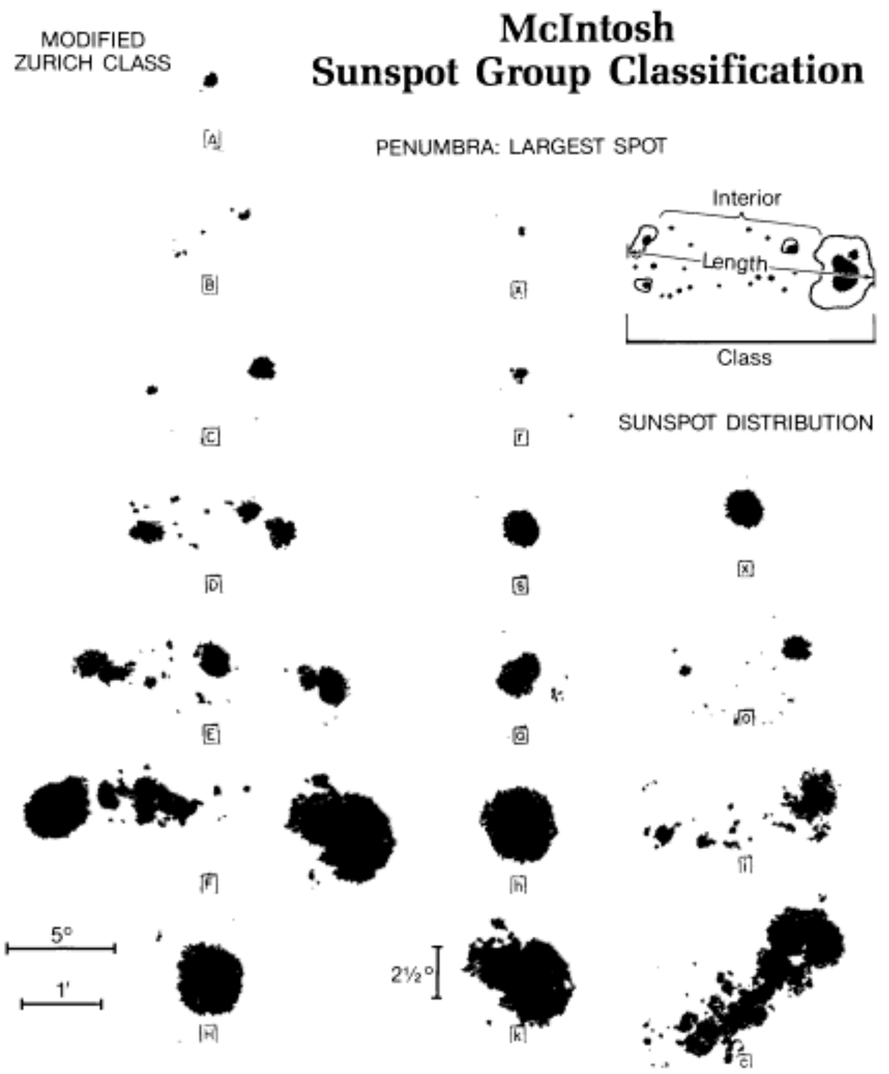
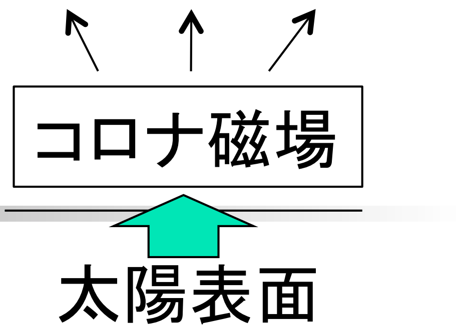


Fig. 1. The 3-component McIntosh classification, with examples of each category.

- Event Probabilities 19 Jan-21 Jan
  - Class M 10/10/10 Class X 01/01/01 Proton 01/01/01
- Skill for X flare:

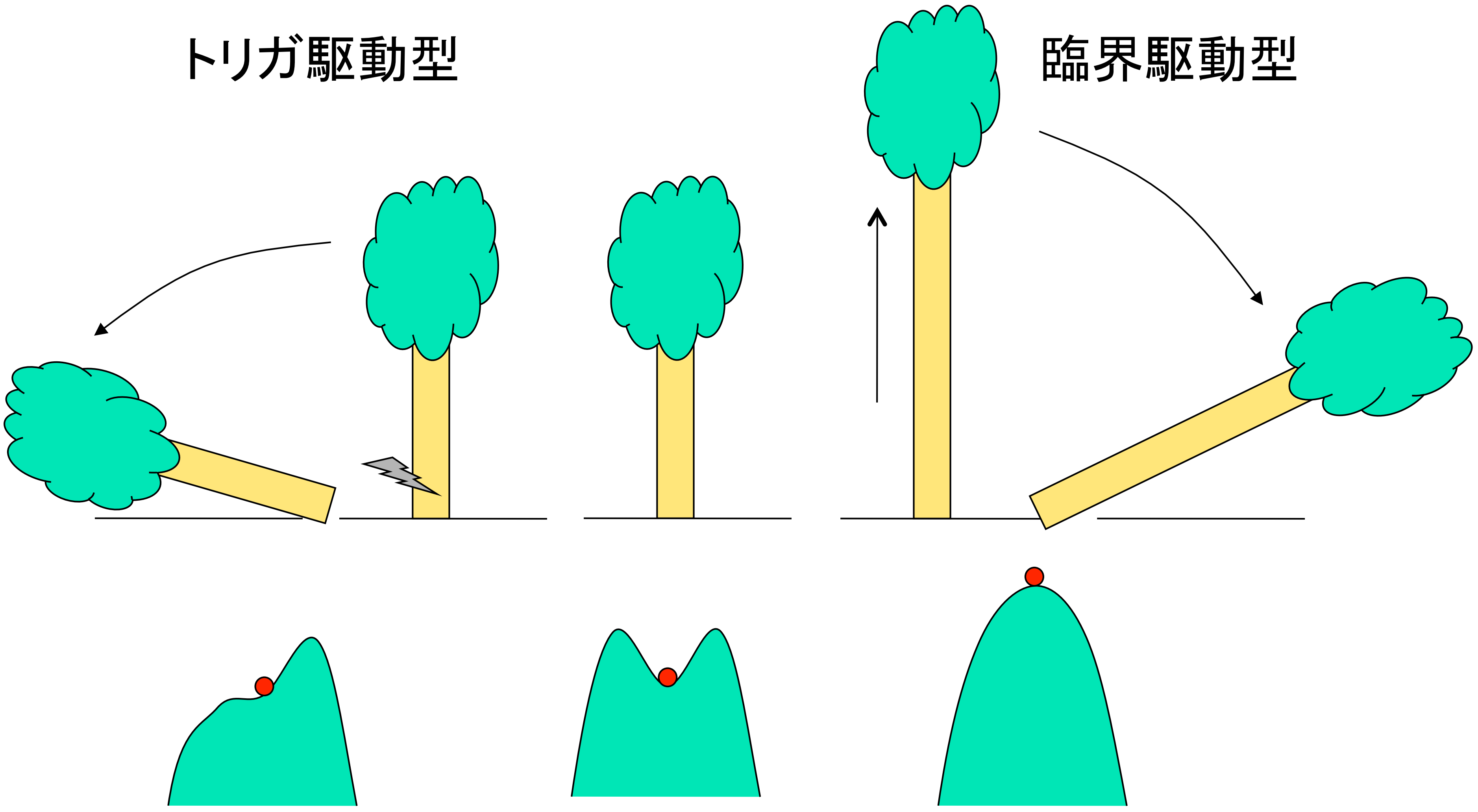
1day	2day	3day	year (events)
0.112	-0.147	-0.171	2006 (4)
0.242	0.147	0.127	2005 (13)
0.052	-0.001	-0.044	2004 (9)
0.200	0.093	0.076	2003 (17)
-0.037	-0.050	-0.033	2002 (12)
-0.061	-0.034	-0.006	2001 (18)

突発現象の発生機構



コロナ磁場

太陽表面



トリガ駆動型

臨界駆動型

unstable state
loss-of-equilibrium

meta-stable state

unstable state

フレア予測の方法　2

- 物理的予測アルゴリズム
  - フレア発生に関係する物理量を発見的方法で見出す。例：Leka & Barnes 2007, Yamamoto & Sakurai

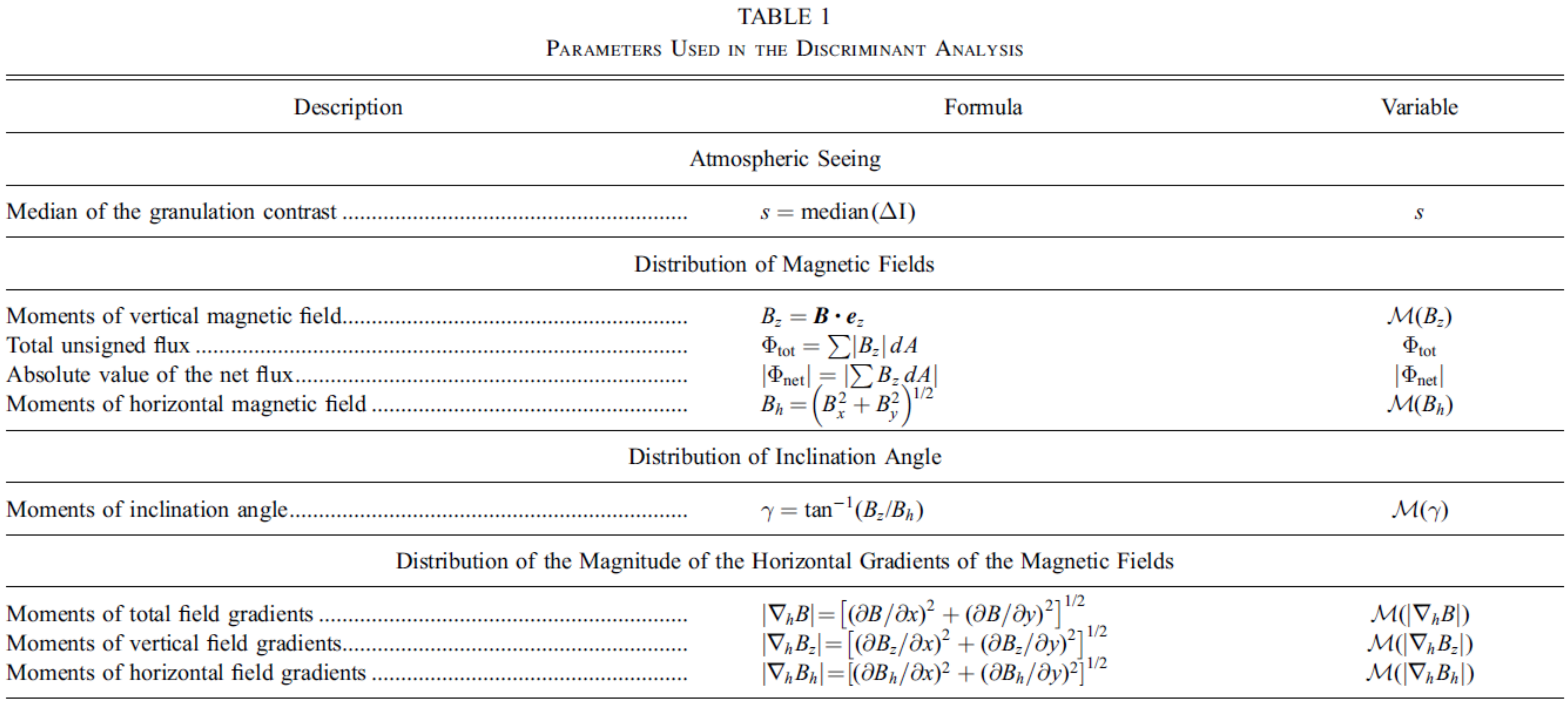


TABLE 1

PARAMETERS USED IN THE DISCRIMINANT ANALYSIS

Description	Formula	Variable
Atmospheric Seeing		
Median of the granulation contrast	$s = \mathrm{median}(\Delta \mathrm{I})$	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 $>\Psi_0$, $\Psi_0 = 45°, 80°$	$A(\Psi > \Psi_0) = \sum_{\Psi > \Psi_0} dA$	$A(\Psi > 45°),\ A(\Psi > 80°)$
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 $>\Psi_0$	$L(\Psi_{\rm NL} > \Psi_0) = \sum_{\Psi_{\rm NL} > \Psi_0} dL$	$L(\Psi_{\rm NL} > 45°),\ L(\Psi_{\rm NL} > 80°)$
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 $>\psi_0$	$A(\psi > \psi_0) = \sum_{\psi > \psi_0} dA$	$A(\psi > 45°),\ A(\psi > 80°)$
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 $\overline{x}$, 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).

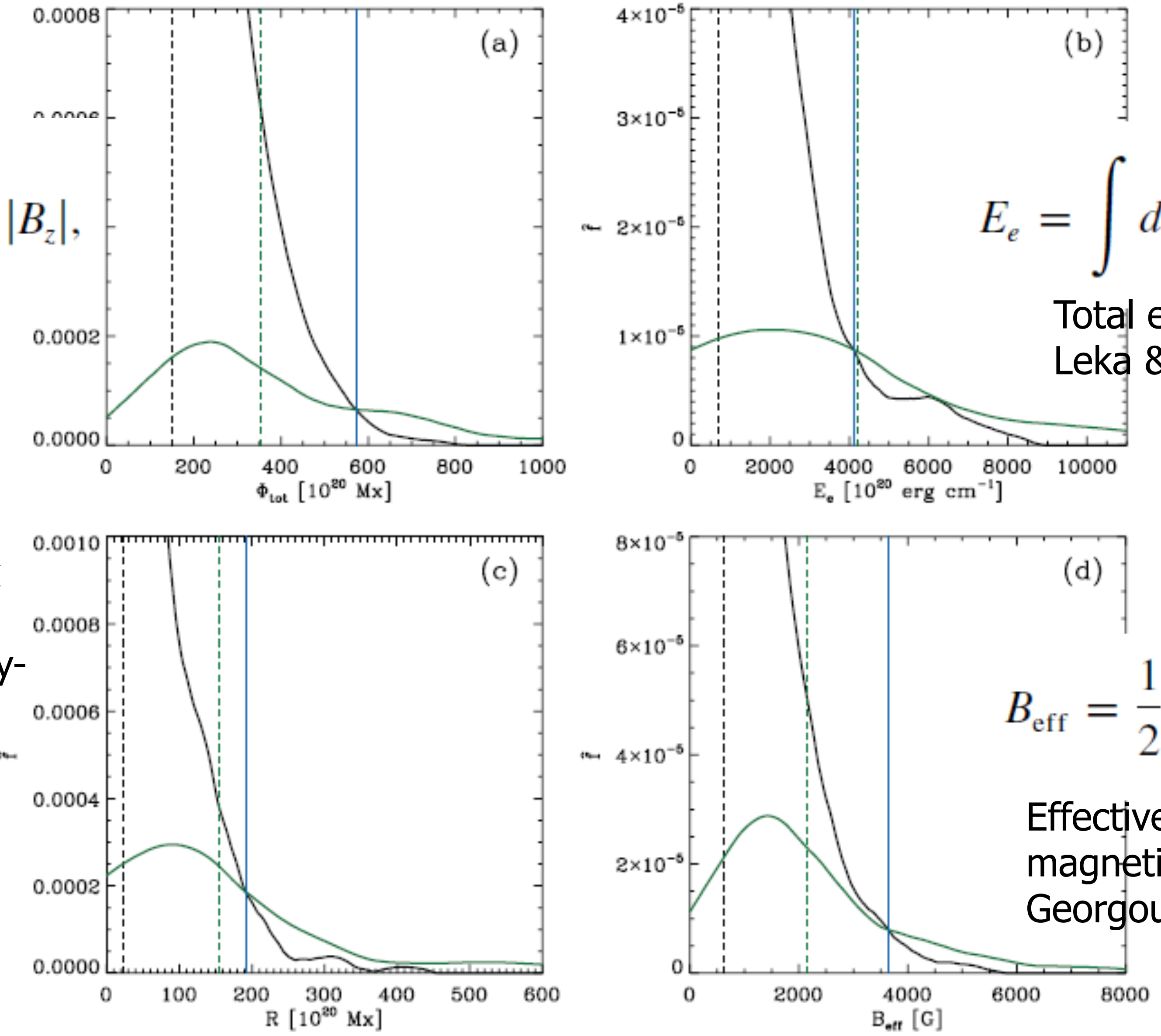
[c] Abramenko et al. (1996); Bao et al. (1999).

[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)



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

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

Total excess energy
Leka & Barnes 2003

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

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

Effective connected magnetic field
Georgoulis & Rust 2007

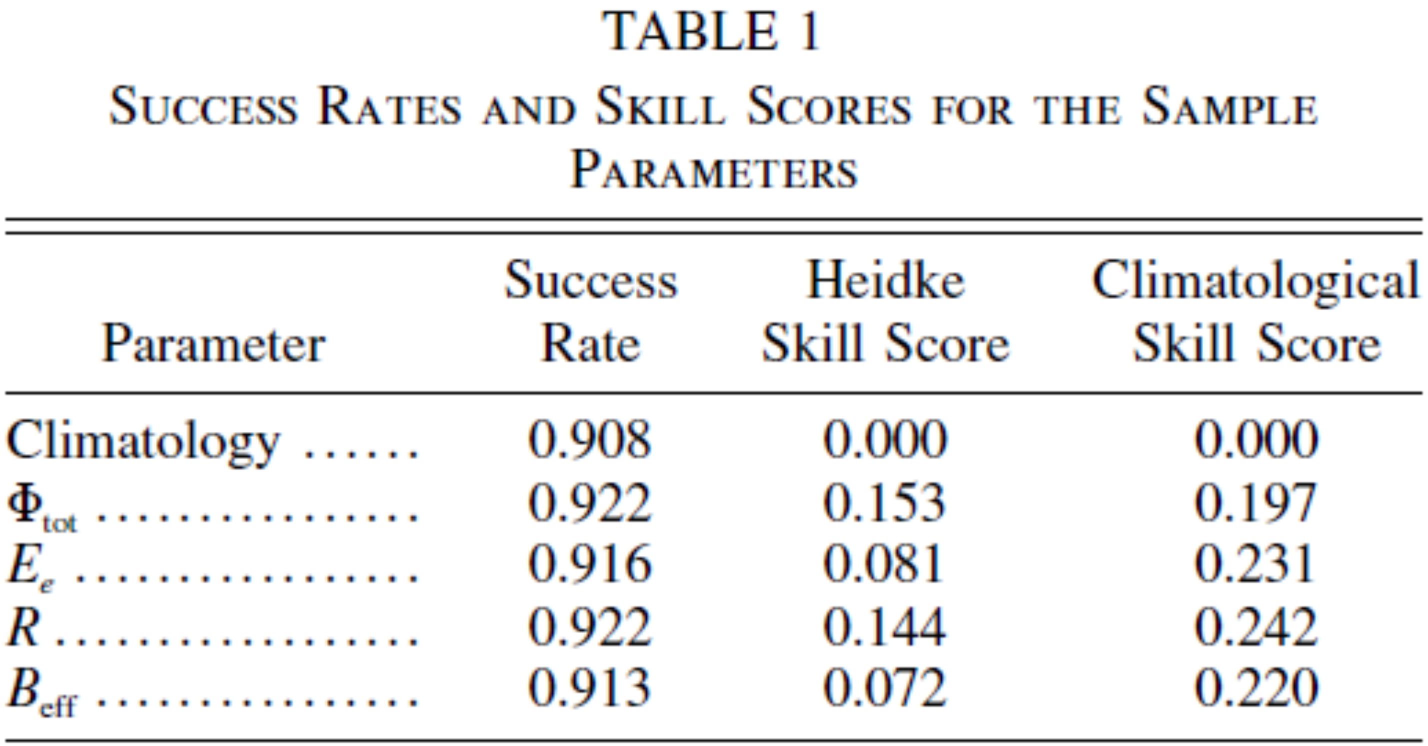


TABLE 1

SUCCESS RATES AND SKILL SCORES FOR THE SAMPLE PARAMETERS

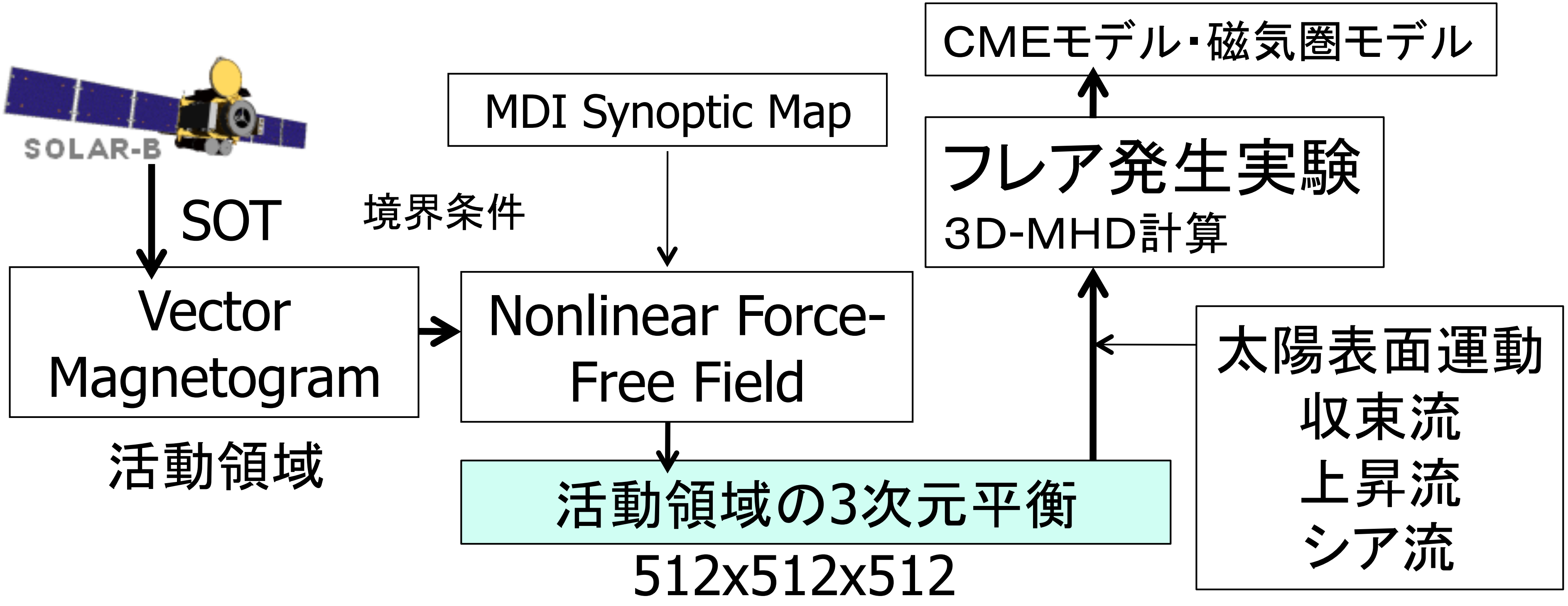
Parameter	Success Rate	Heidke Skill Score	Climatological Skill Score
Climatology ……	0.908	0.000	0.000
Φ_{tot} ………………	0.922	0.153	0.197
E_e ………………	0.916	0.081	0.231
R ………………	0.922	0.144	0.242
B_{eff} ………………	0.913	0.072	0.220

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

Wheatland (2005)	0.258
SWPC	0.262

フレア予測の方法3

- ３次元数値モデル



SOT

Vector Magnetogram

活動領域

境界条件

MDI Synoptic Map

Nonlinear Force-Free Field

活動領域の3次元平衡

512x512x512

フレア発生実験

3D-MHD計算

CMEモデル･磁気圏モデル

太陽表面運動

収束流

上昇流

シア流

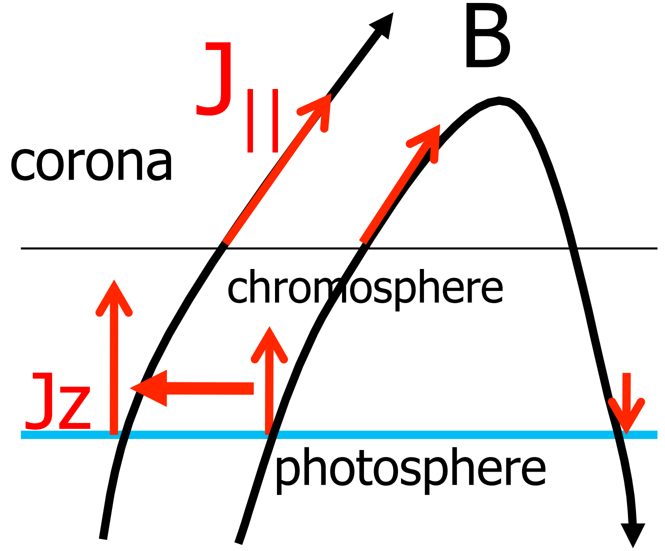
NLFFモデルの問題

$$\nabla \times \mathbf{B} = \alpha \mathbf{B} \qquad (\mathbf{B} \cdot \nabla \alpha = 0)$$

Relaxation
- magneto-friction
- zero-β MHD
- optimization

Grad-Rubin like method

Boundary Integral method



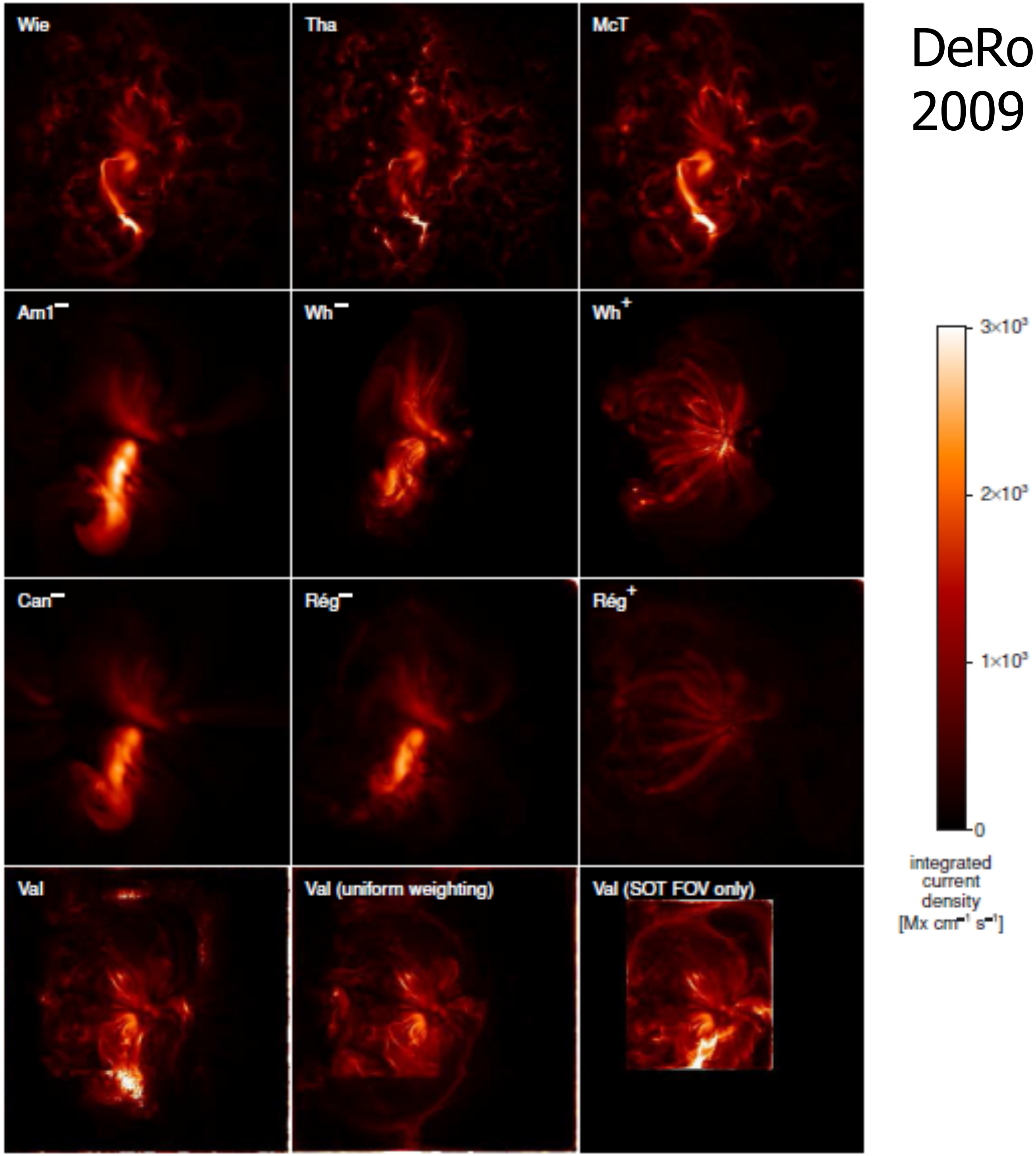
- Magnetofrictional method & div B cleaning (Dedner et al. 2002)

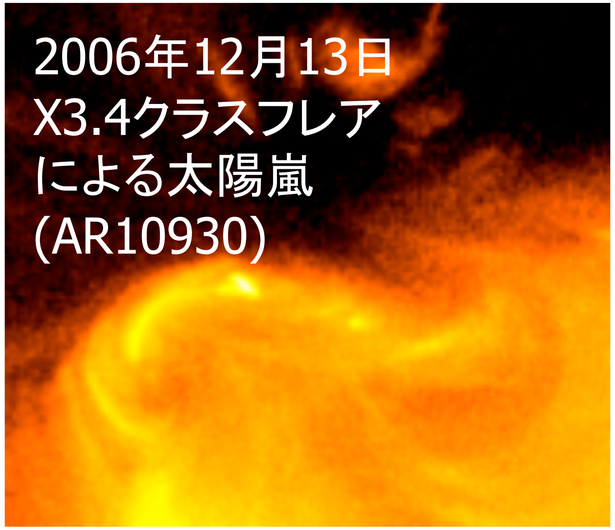
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B} - \eta \mathbf{J} - \nabla \varphi)$$

$$\frac{\partial \varphi}{\partial t} = -\sigma \nabla \cdot \mathbf{B} - \tau^{-1} \varphi$$

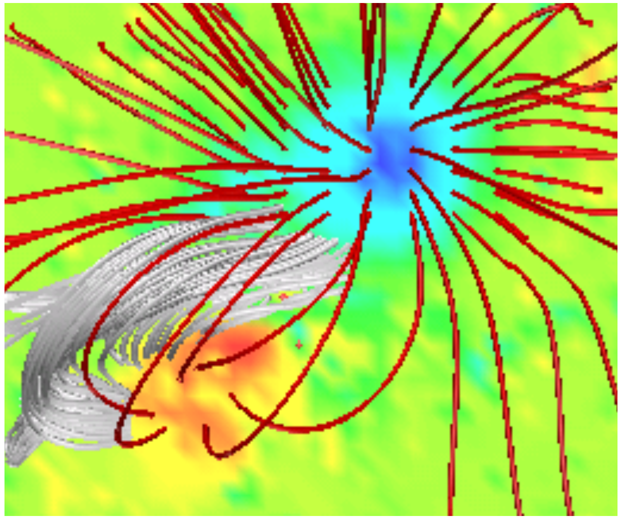
- multi-grid technique
- Parallelization with MPI
- 512x512x512 grids

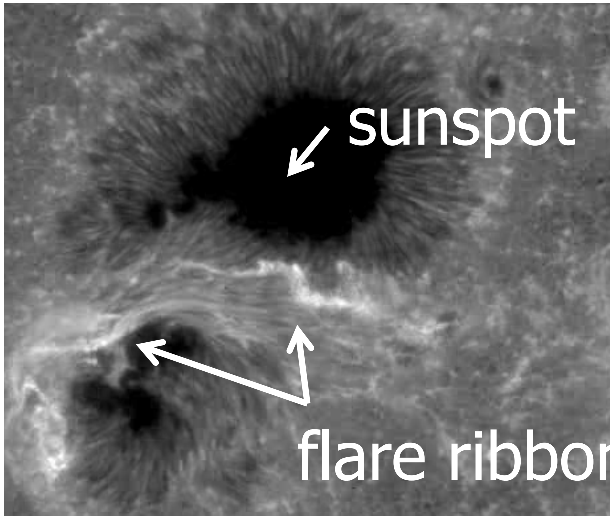
DeRosa et al. 2009

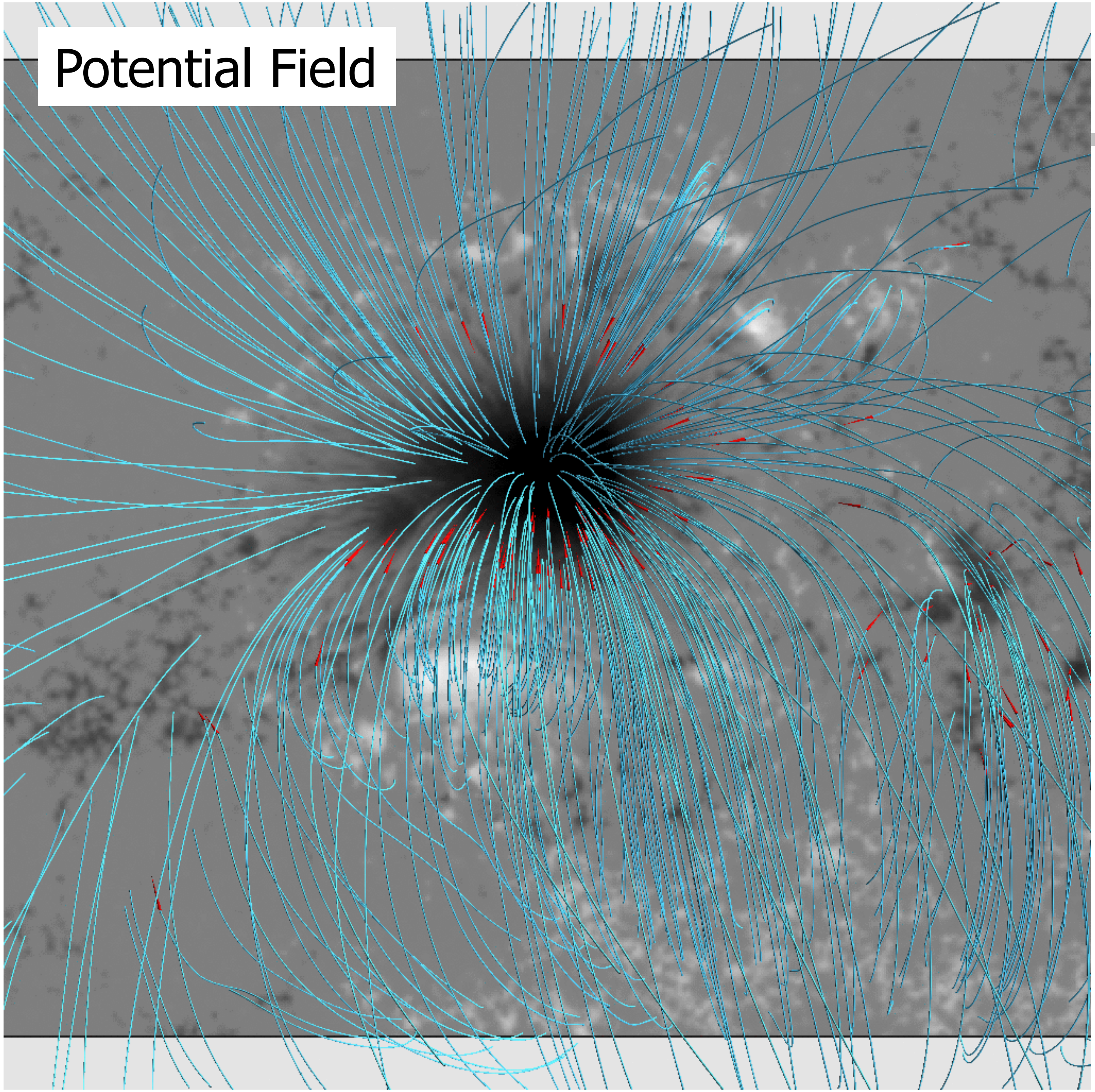




2006年12月13日
X3.4クラスフレア
による太陽嵐
(AR10930)

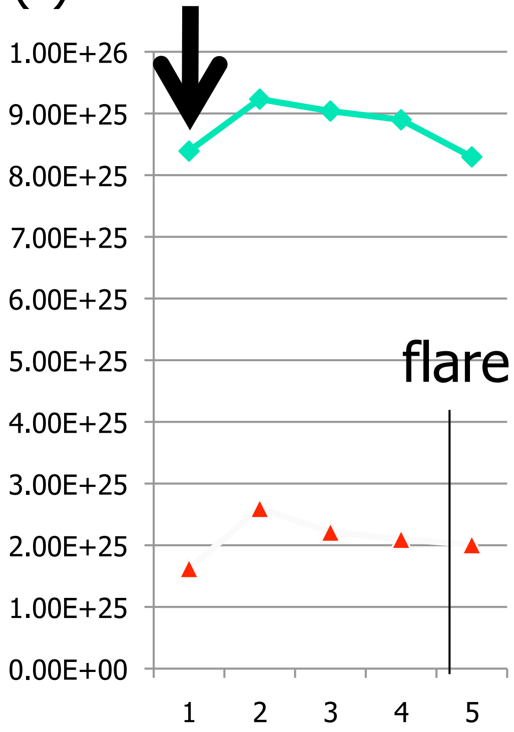




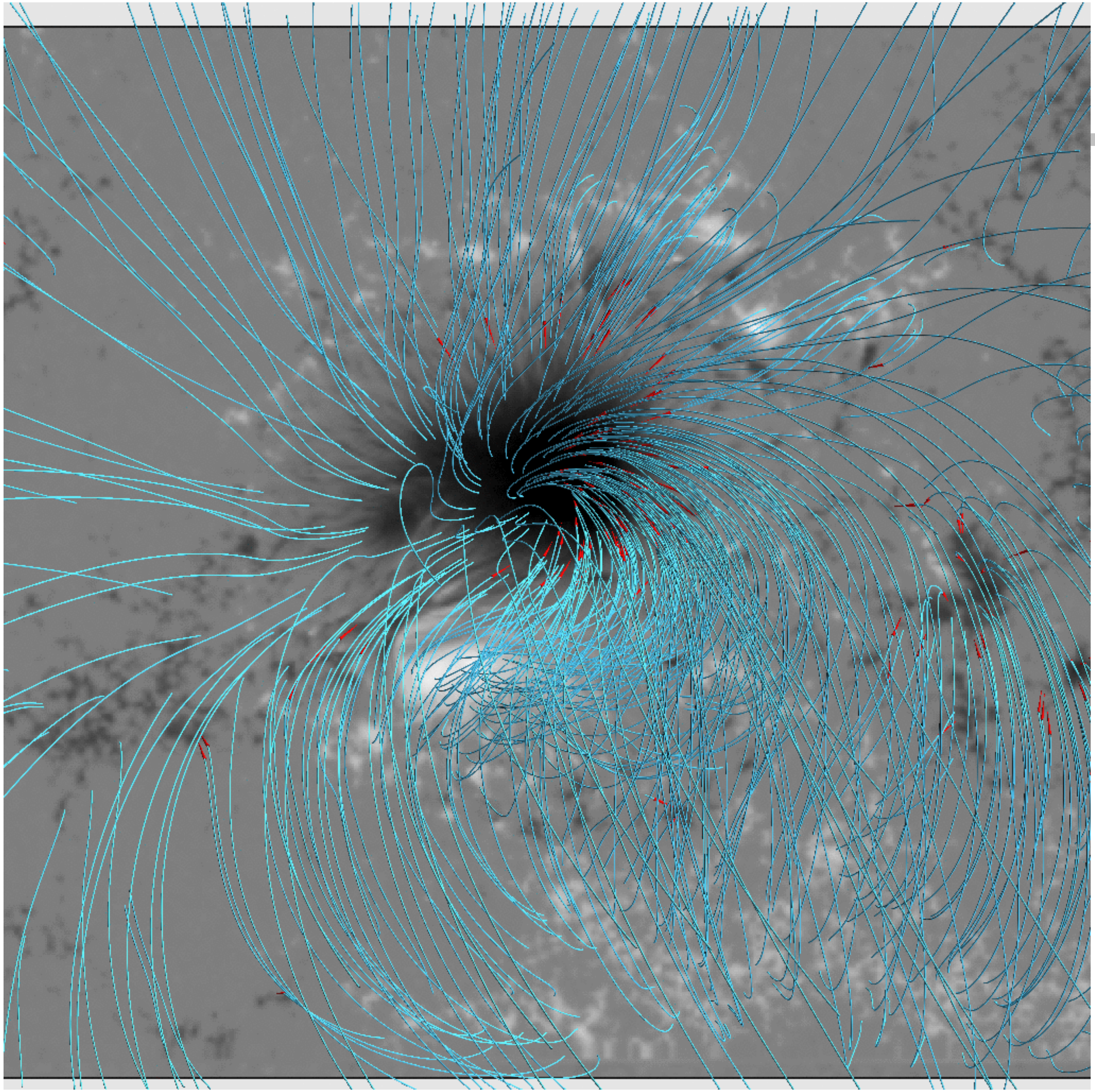


2006_12_11
17:00 UT

Total Magnetic Energy
Magnetic Free Energy
(J)



フレア発生 33時間前



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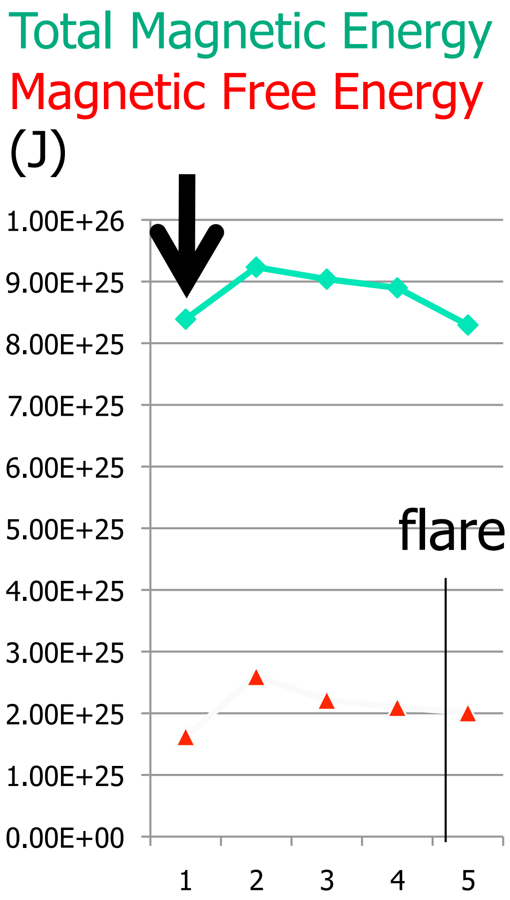
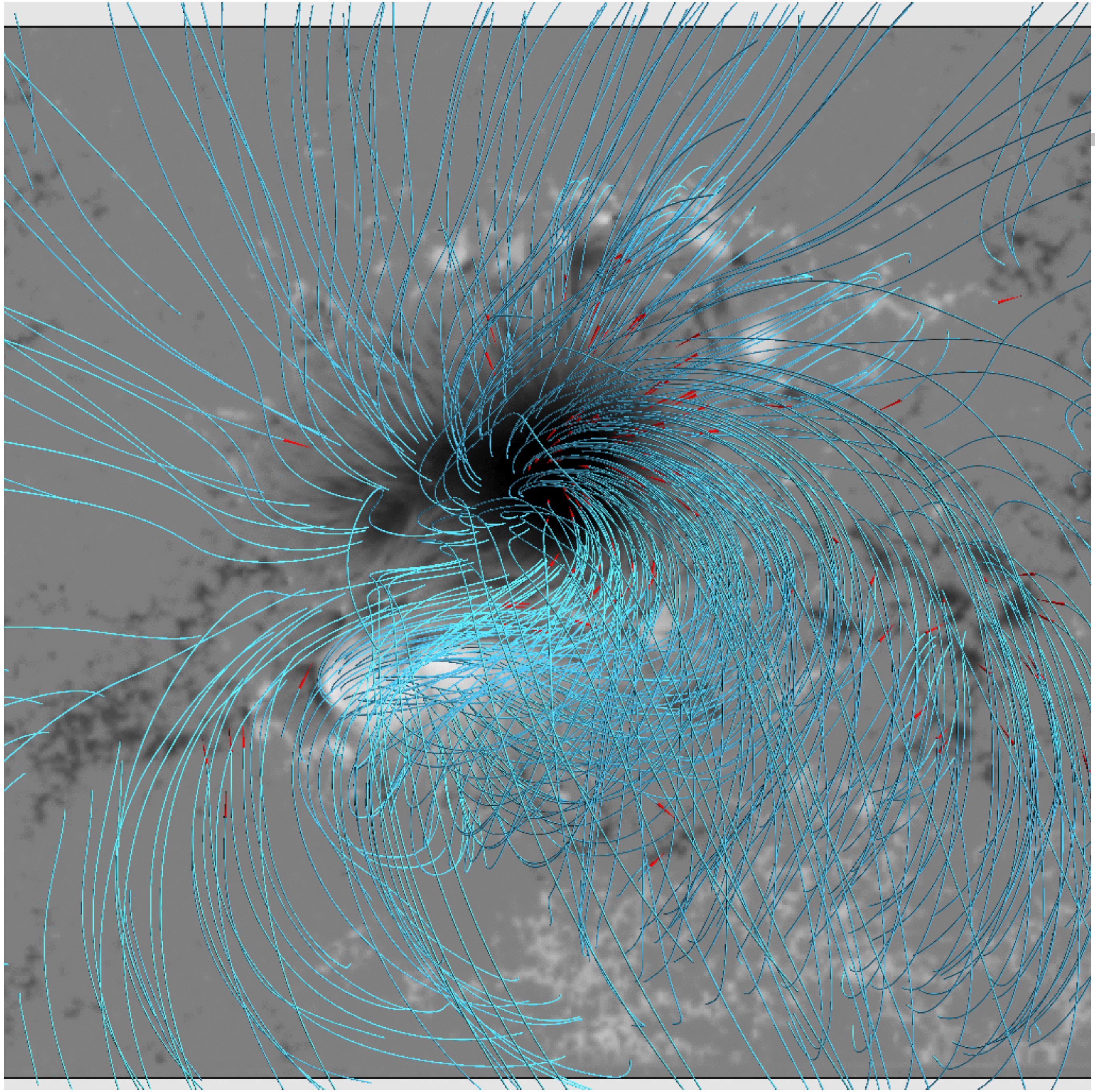
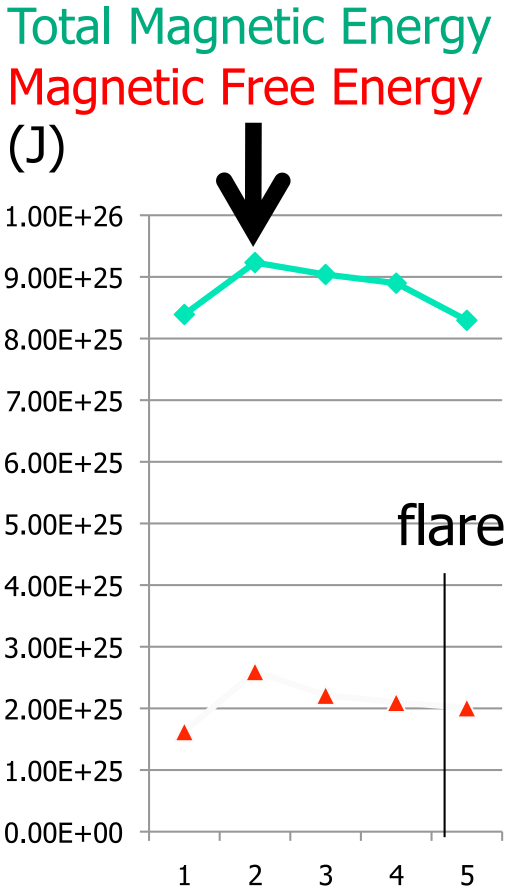
17:00 UT



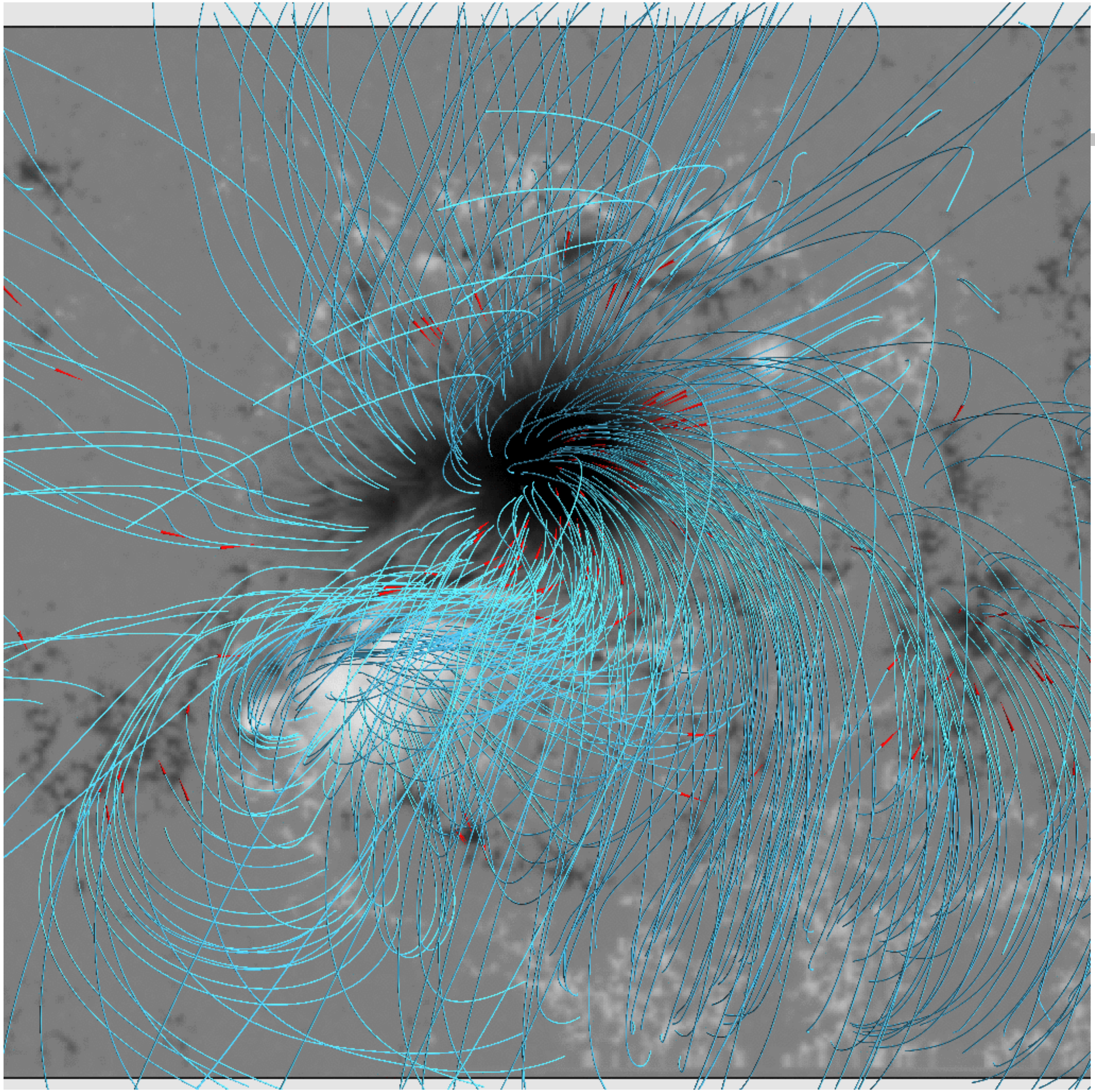
フレア発生
21時間前



2006_12_12
03:50 UT

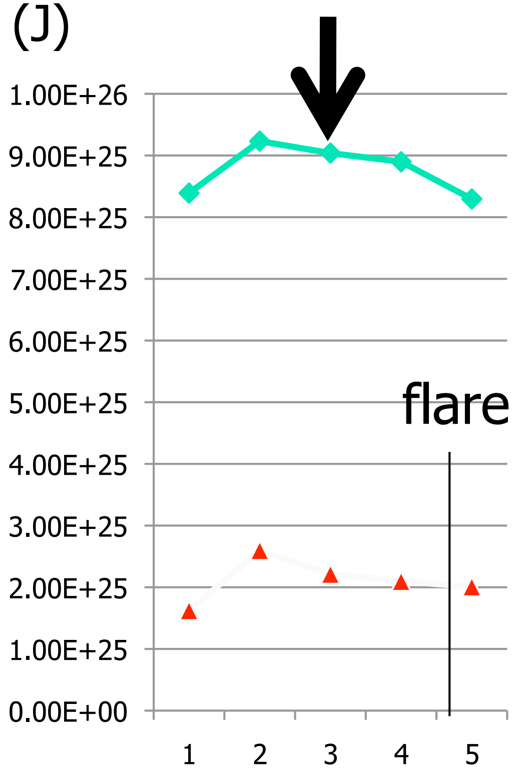


フレア発生
8時間前

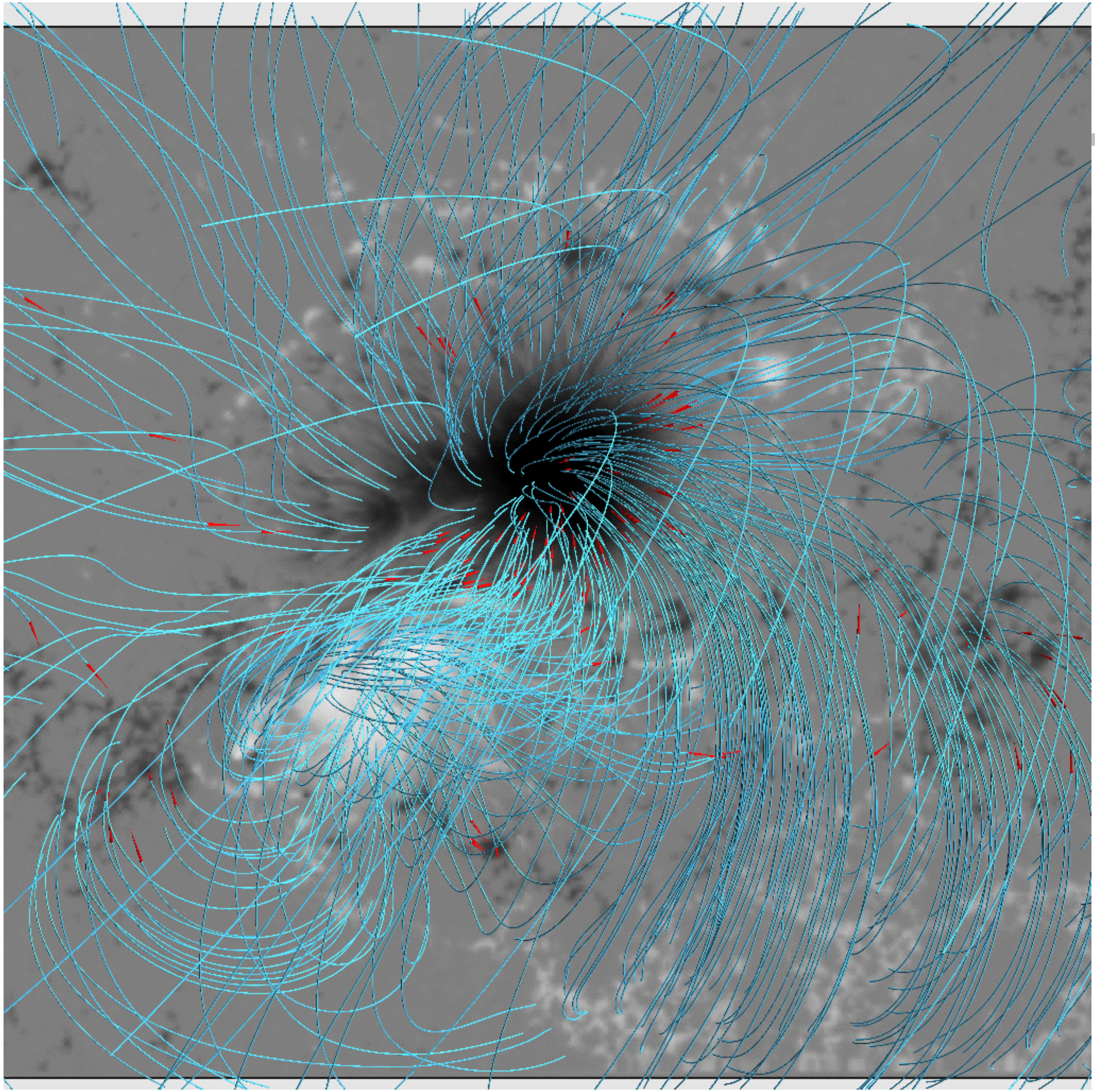


2006_12_12
17:40 UT

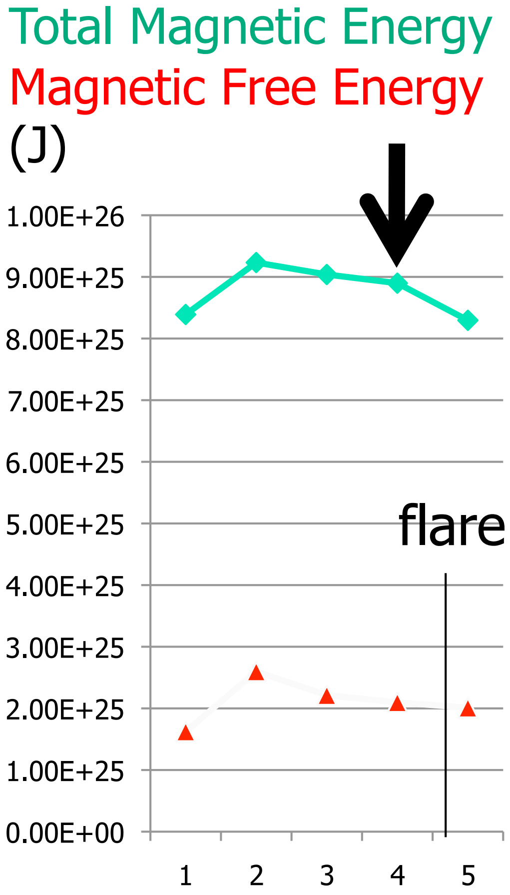
Total Magnetic Energy
Magnetic Free Energy
(J)



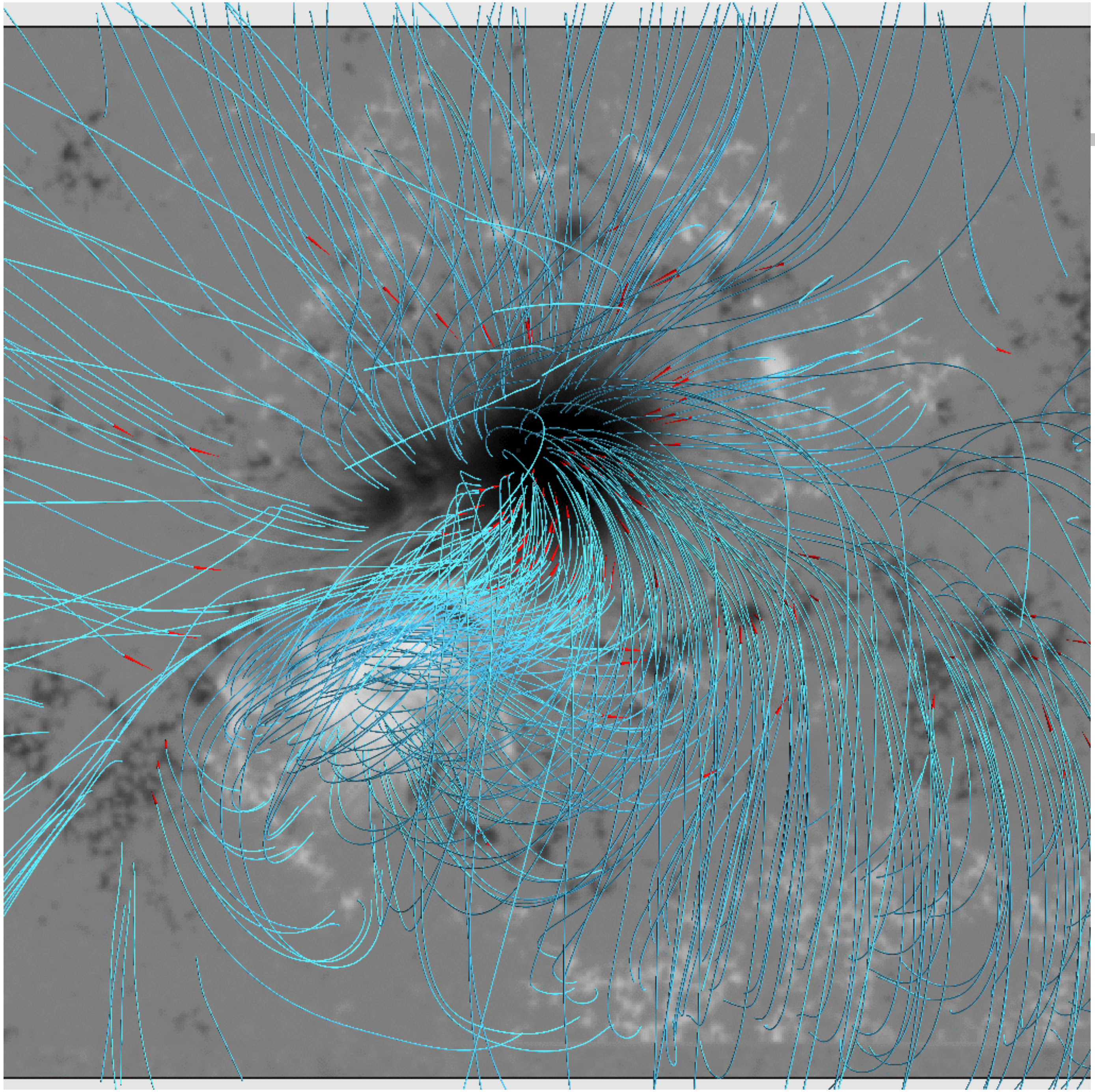
フレア発生
5時間前



2006_12_12
20:30 UT

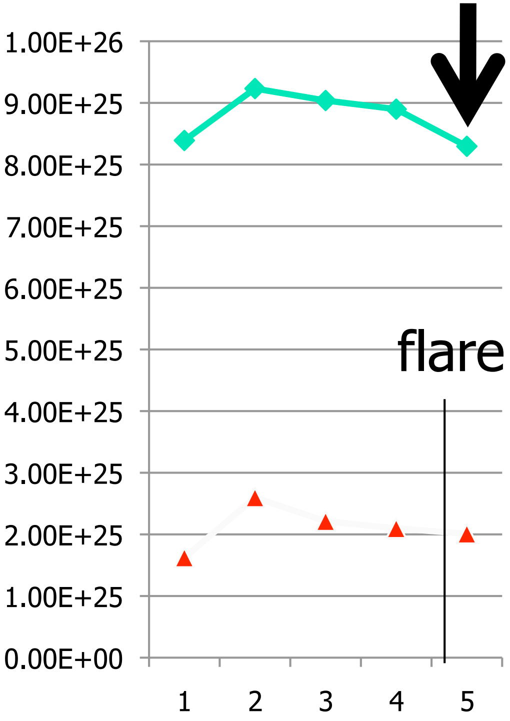


フレア発生
5時間後

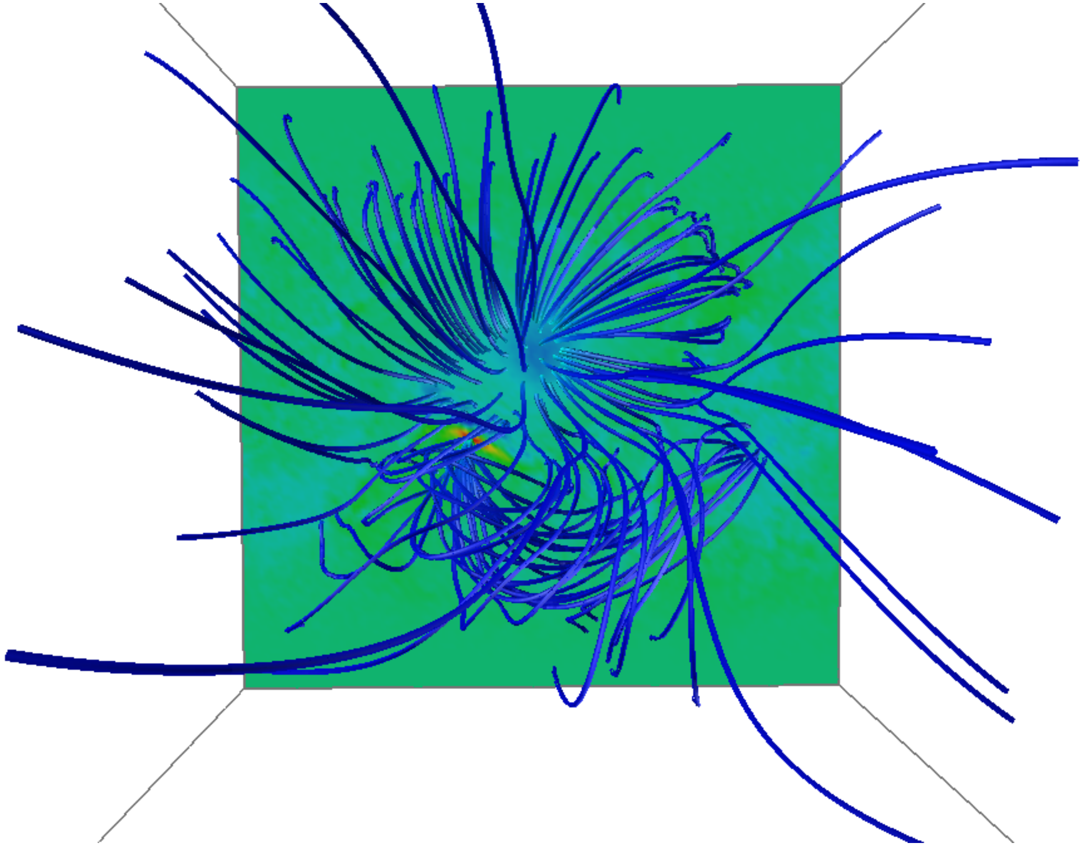


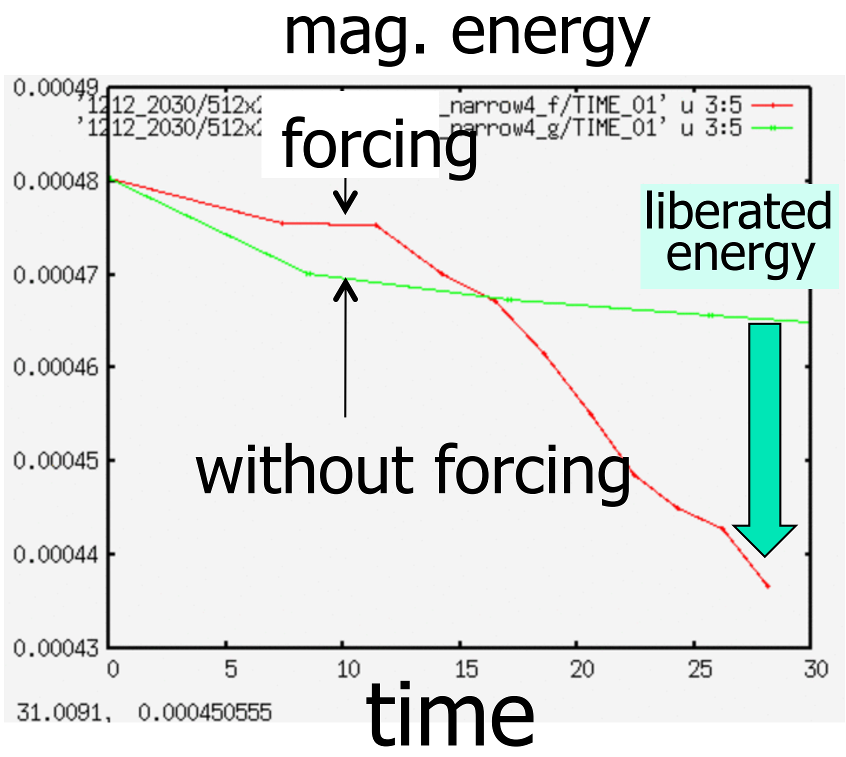
2006_12_13
07:00 UT

Total Magnetic Energy
Magnetic Free Energy
(J)

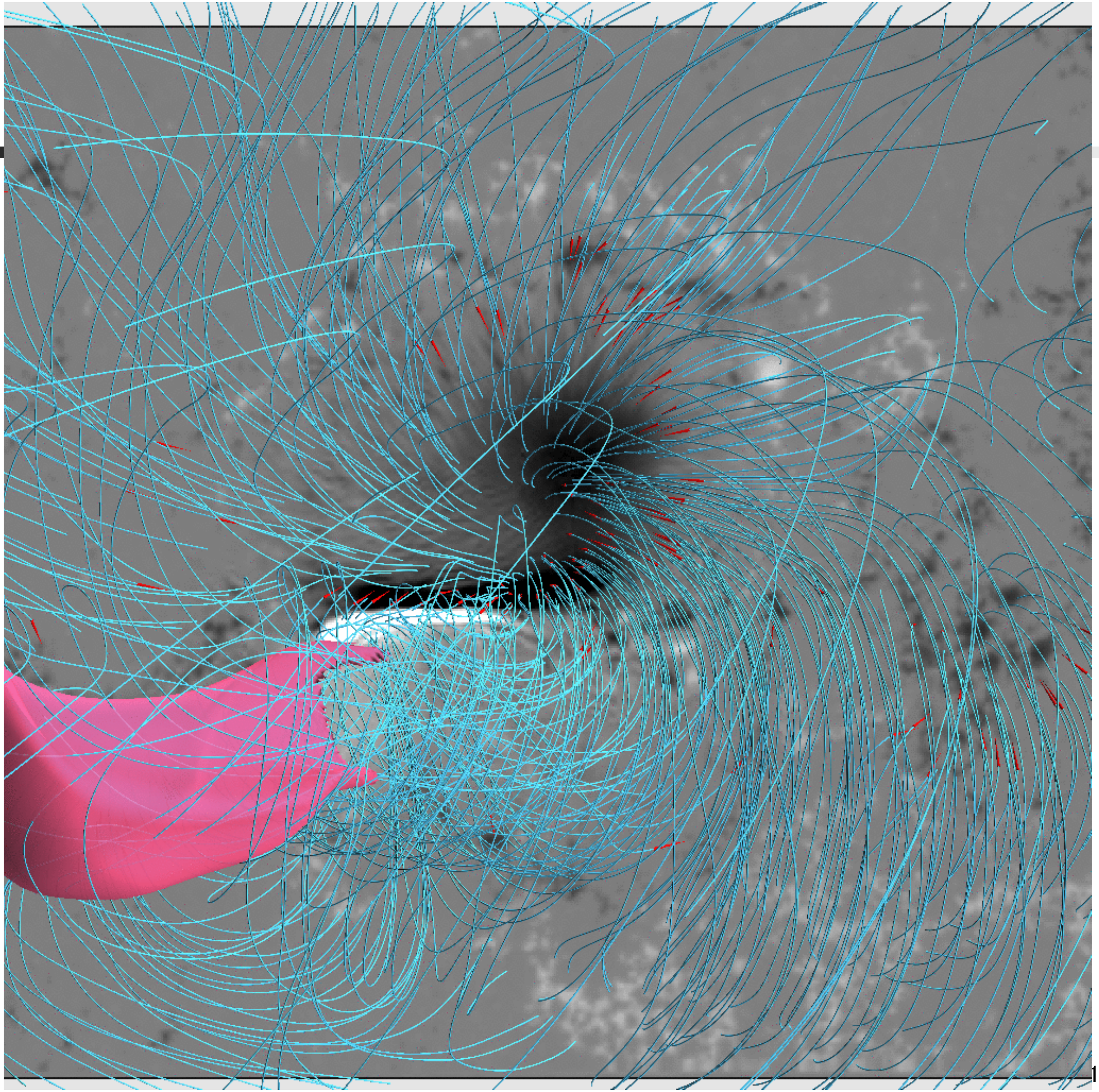


仮想的擾乱を加えたフレア実験





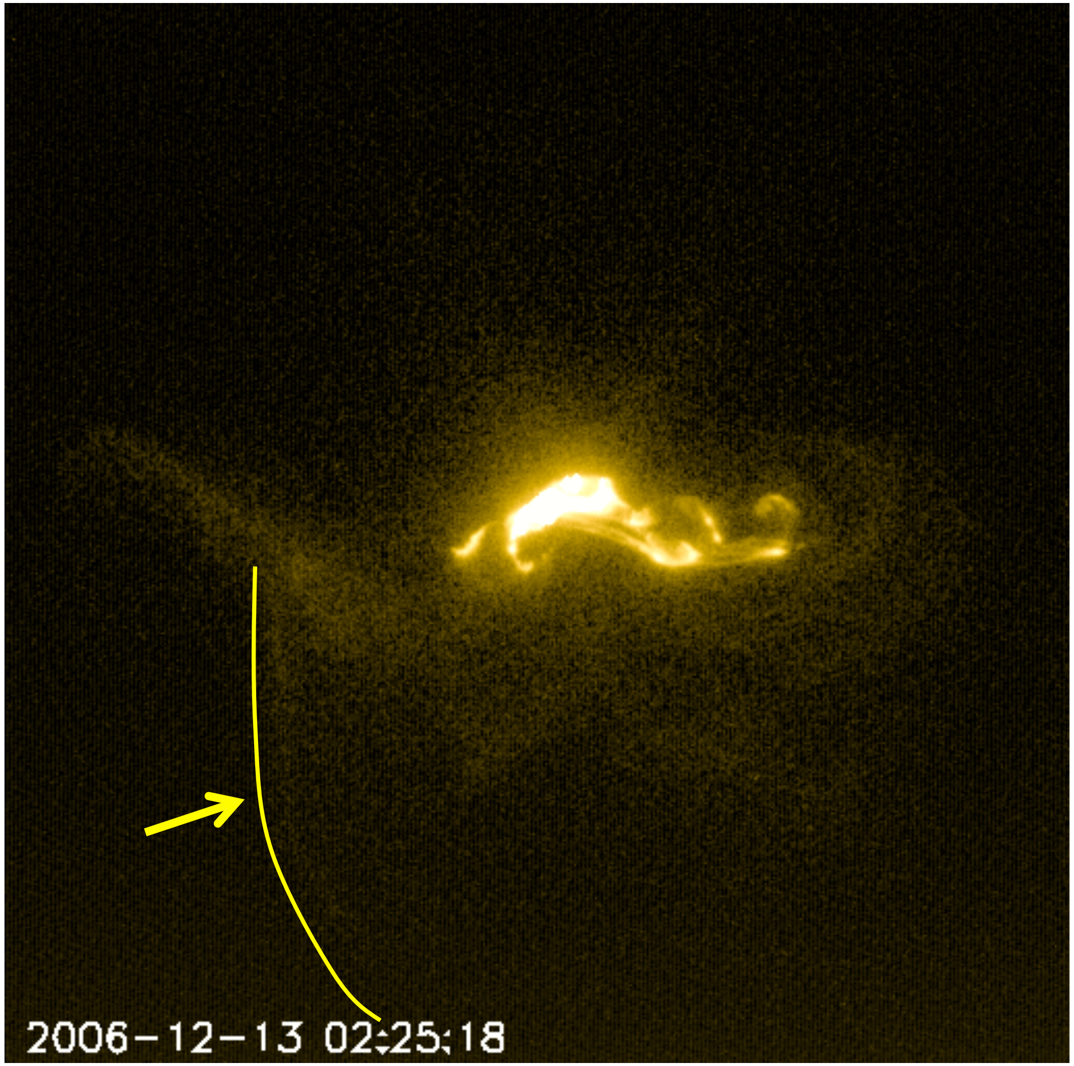
擾乱無しでは安定
収束流擾乱による不安定化
→　最適な擾乱の発見によるフレア発生可能性の推測

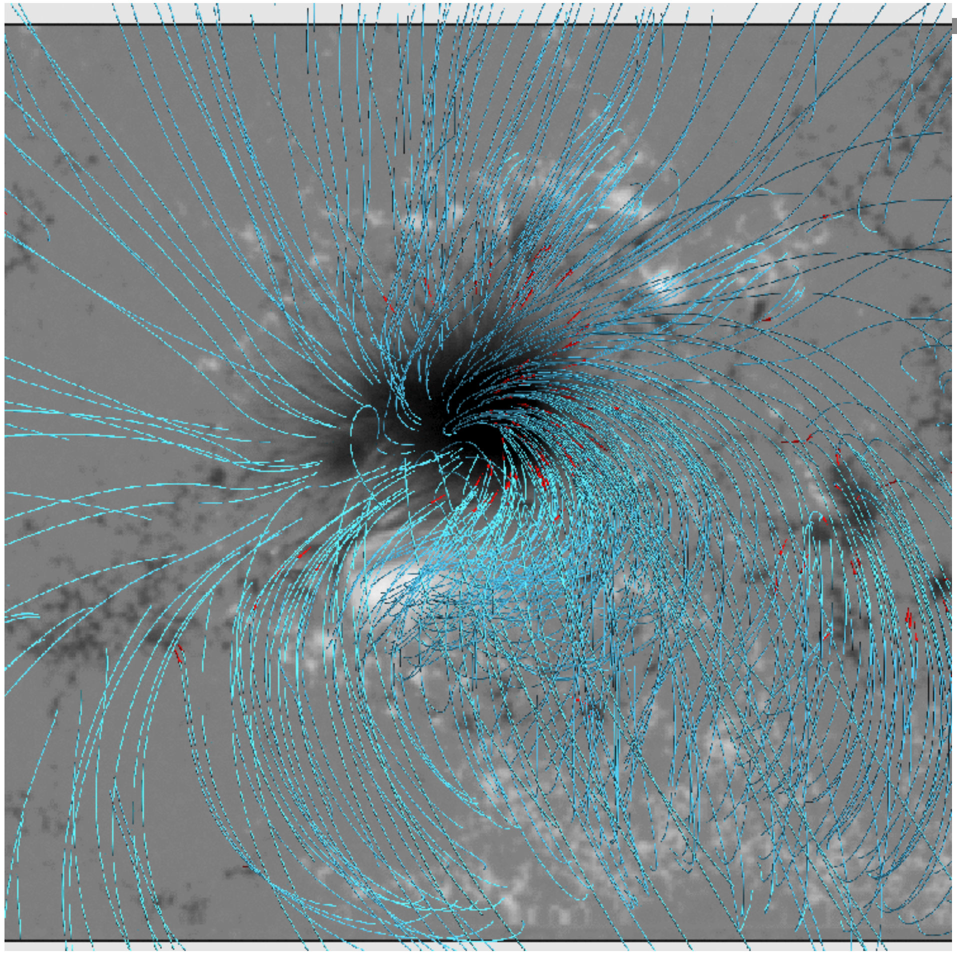


X-ray Ejections & X-ray Wave

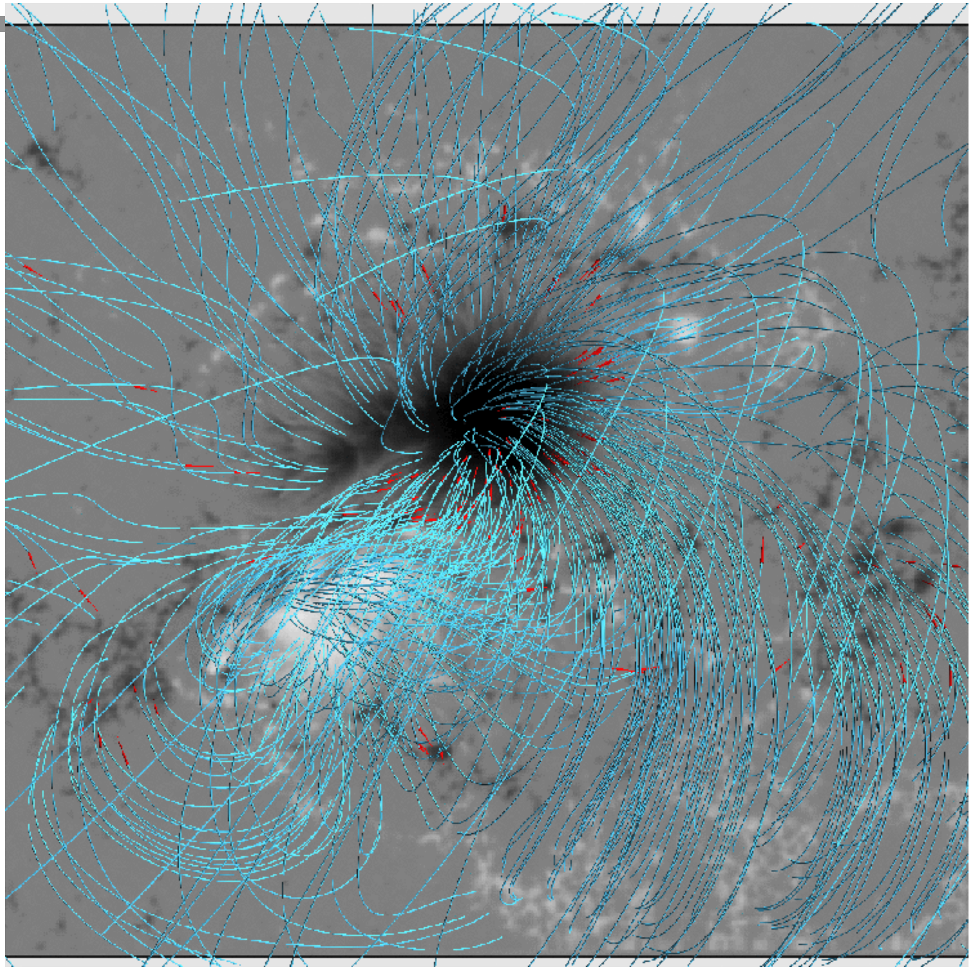
浅井さん提供

- A faint X-ray plasmoid is ejected from the sigmoid loop (02:18~02:22UT)
- V_{pl}~40-120 km/s
- It disappeares at 02:23UT
- X-ray wave-like phenomenon starts just after the disappearance
- V_{wave}~700 km/s

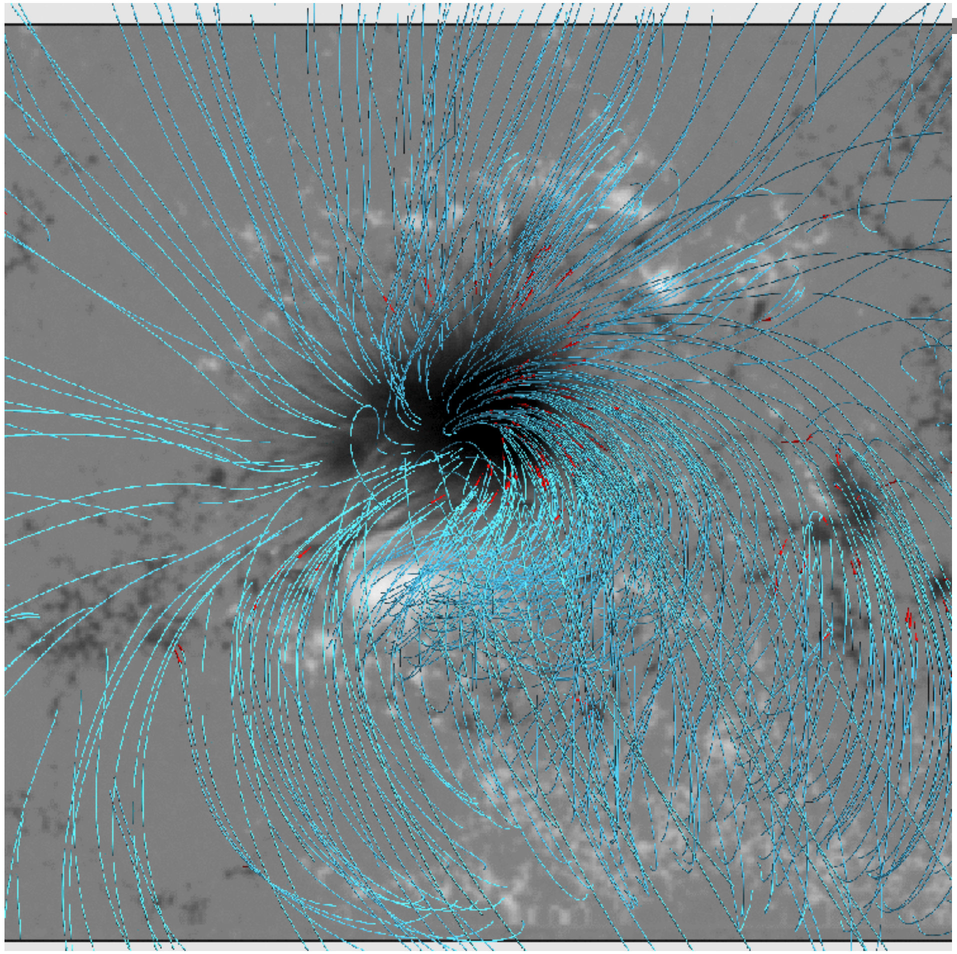




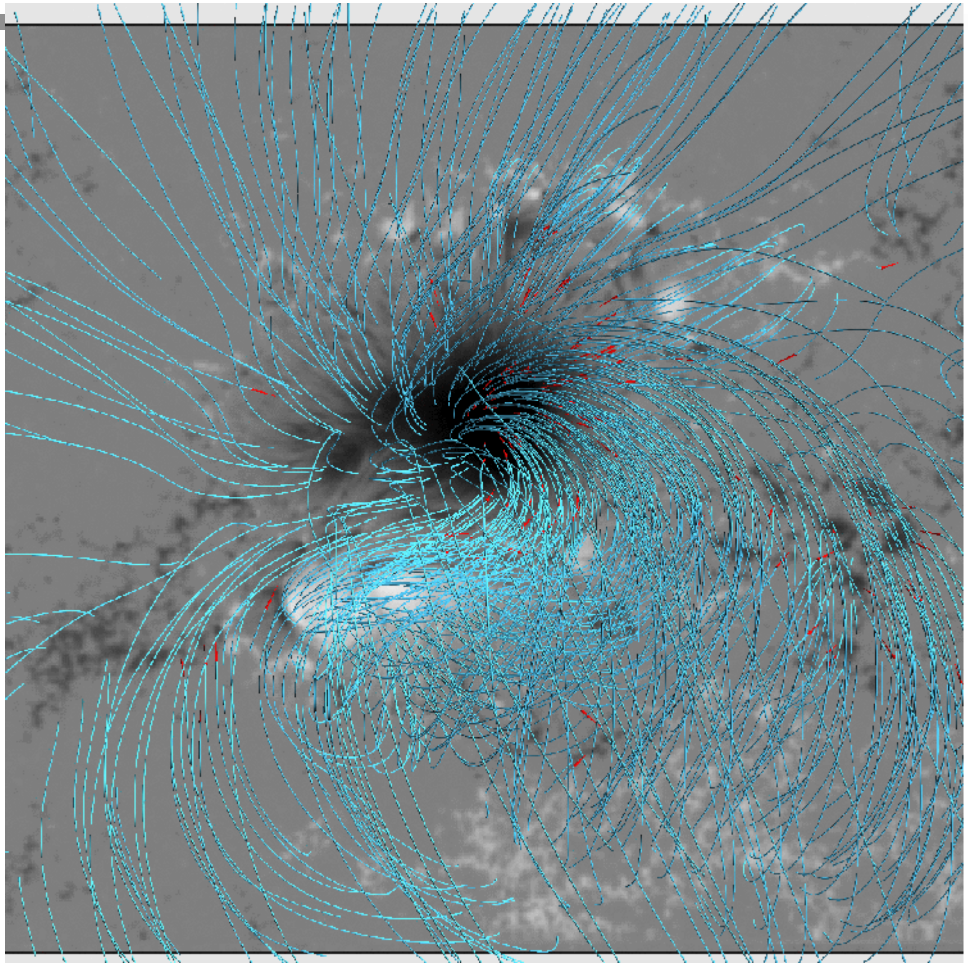
2006_12_11 17:00 UT



2006_12_12 20:30 UT

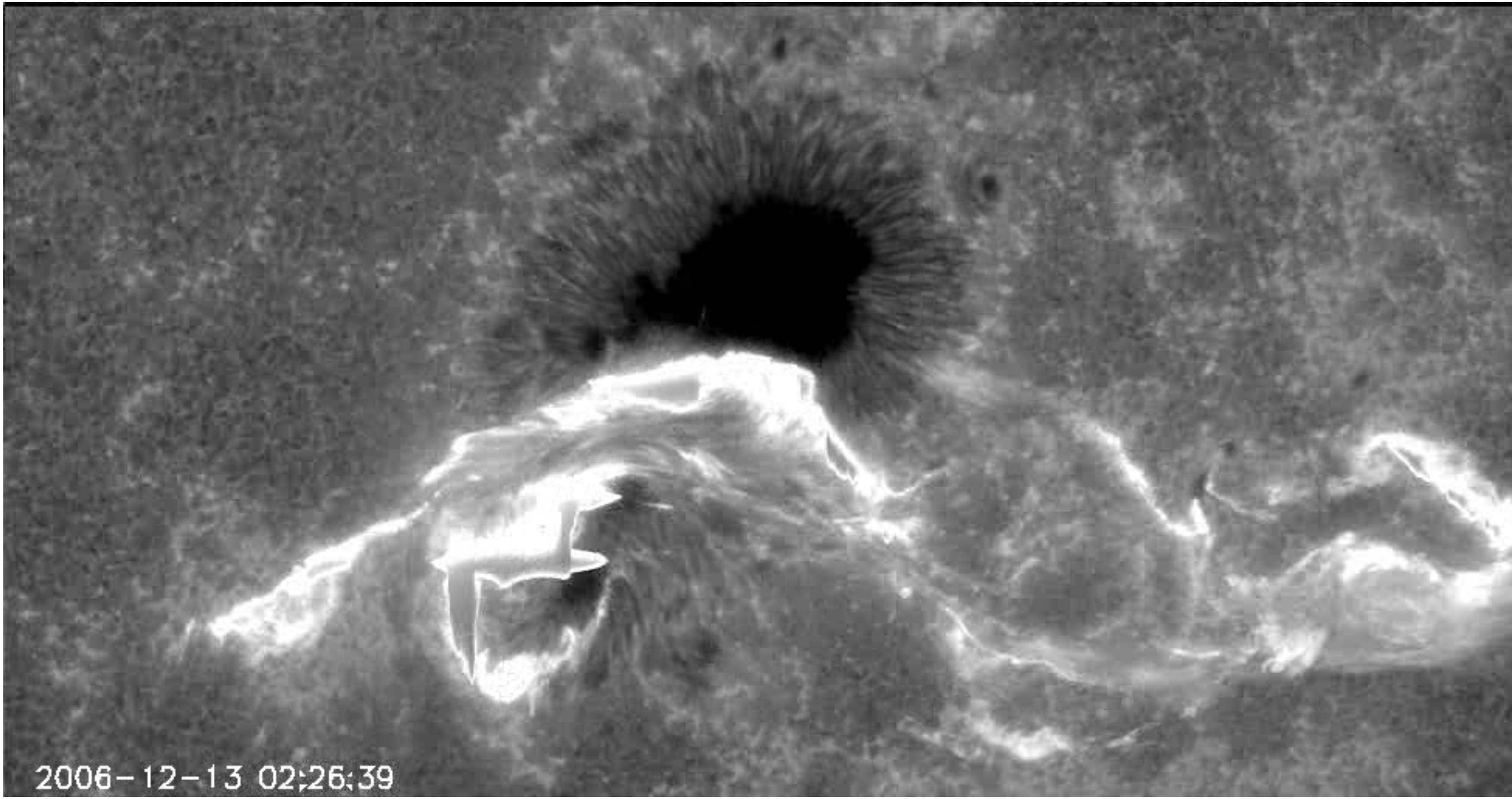


2006_12_11 17:00 UT



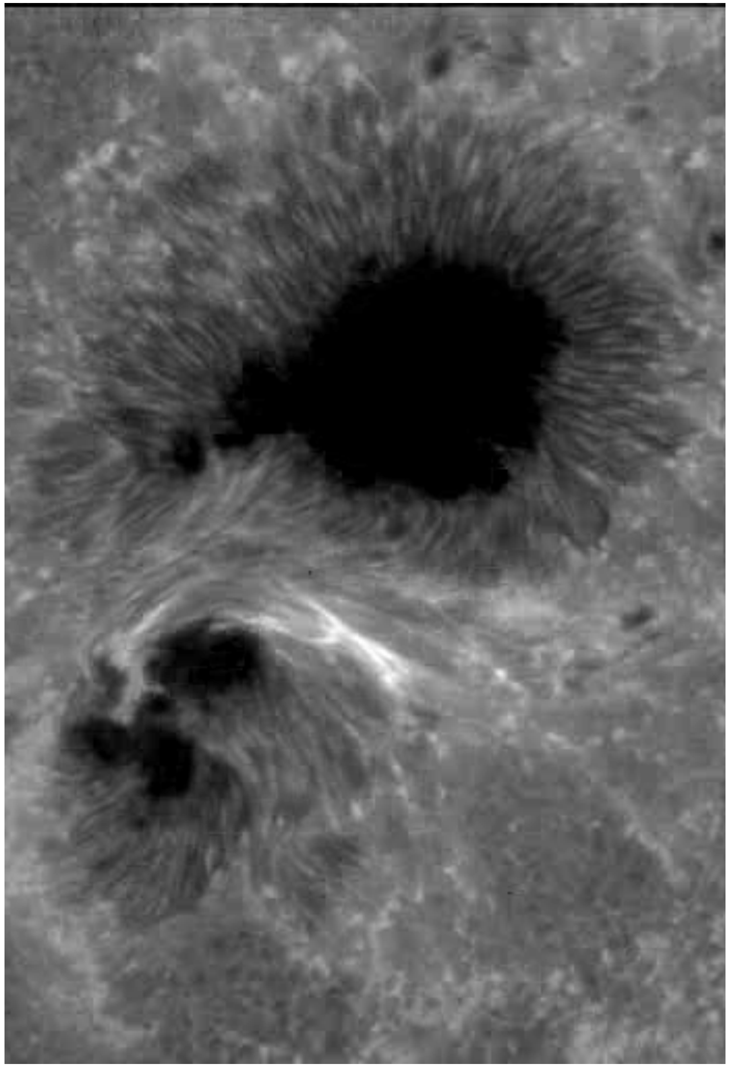
2006_12_12 03:50 UT

トリガ問題の解決には徹底的なプリフレアイベントの解明が必要

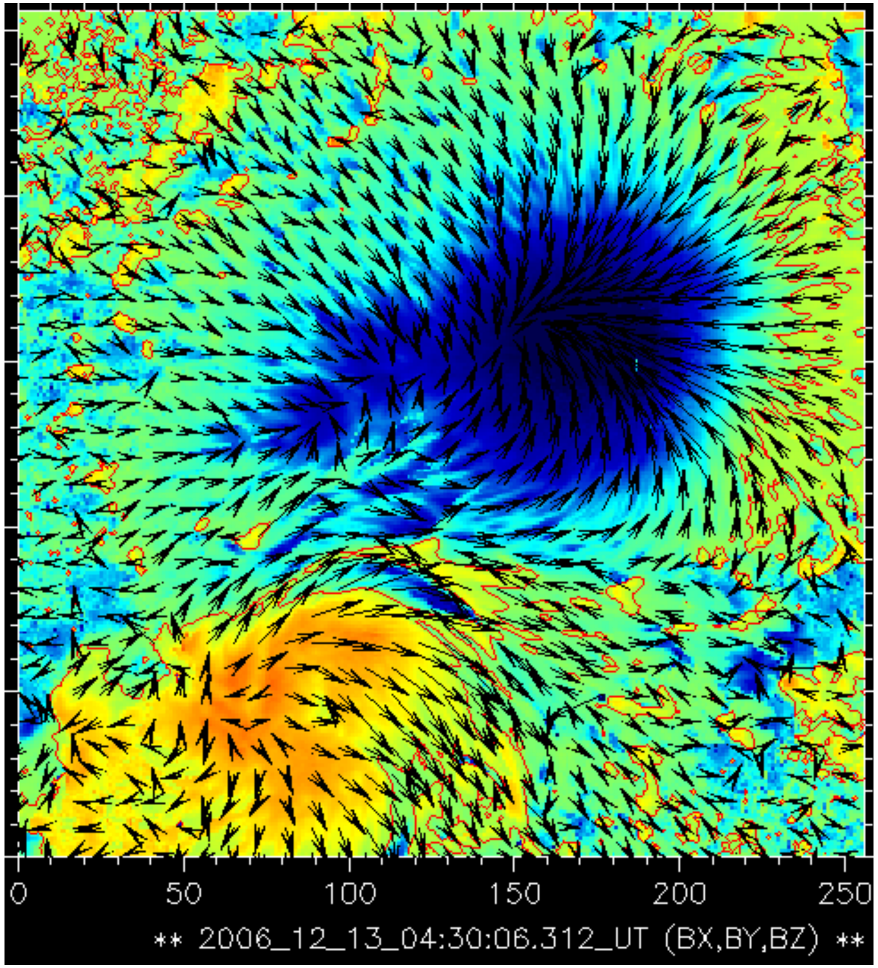


Hinode/SOT

pre-flare brightening and magnetic field

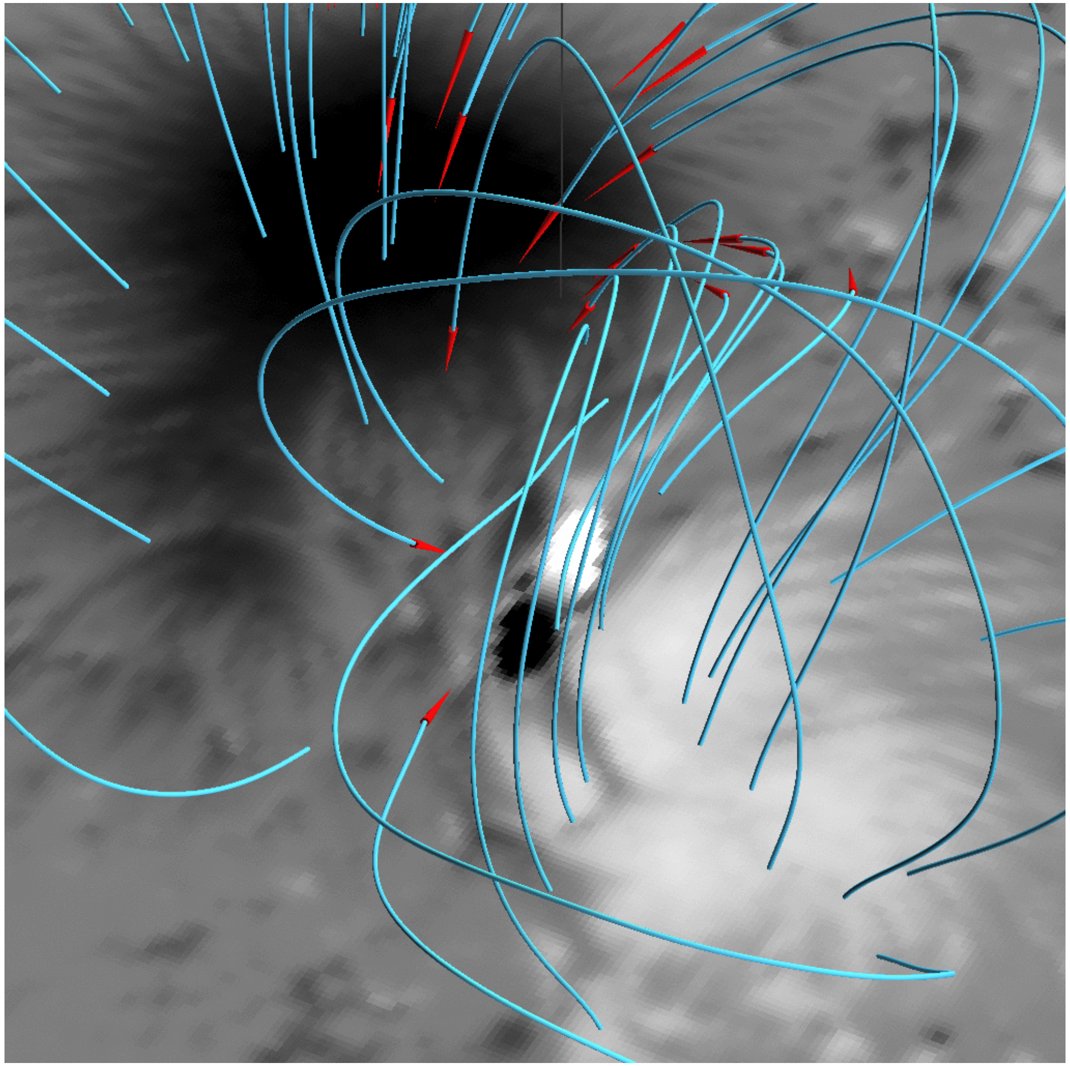


2006.12.13 01:42:37



▶

データ駆動モデルへの挑戦



太陽表面流速･電場解析の精緻化

- LCT
- 誘導方程式逆問題

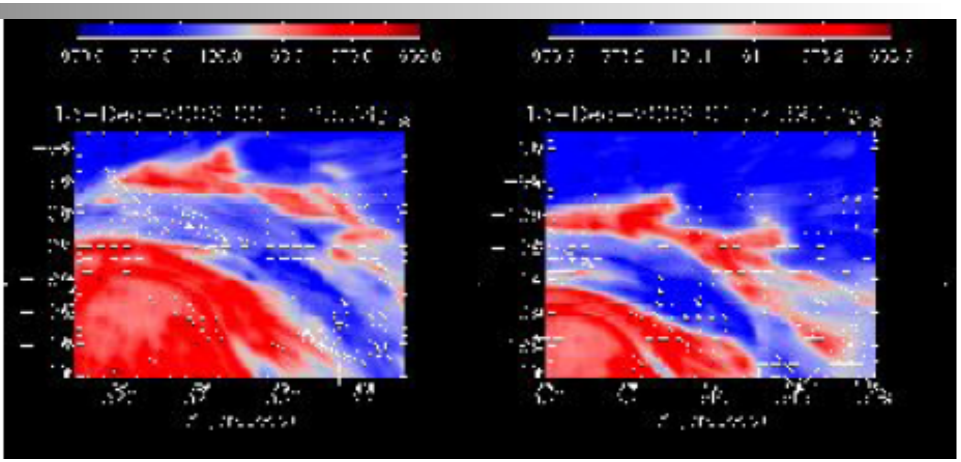
Kusano et al. 2002

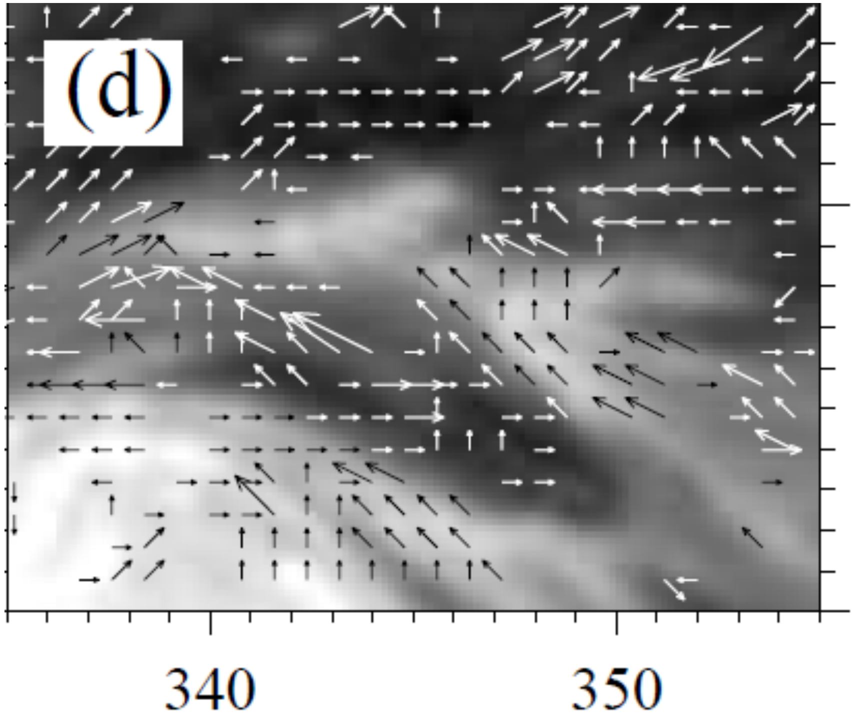
$$\frac{\partial B_z}{\partial t} = [\nabla\times(\mathbf{V}\times\mathbf{B})]_z$$

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

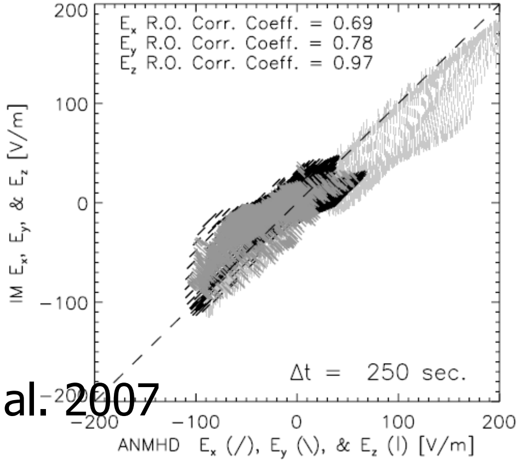
∂_z が必要

Fisher et al.2010



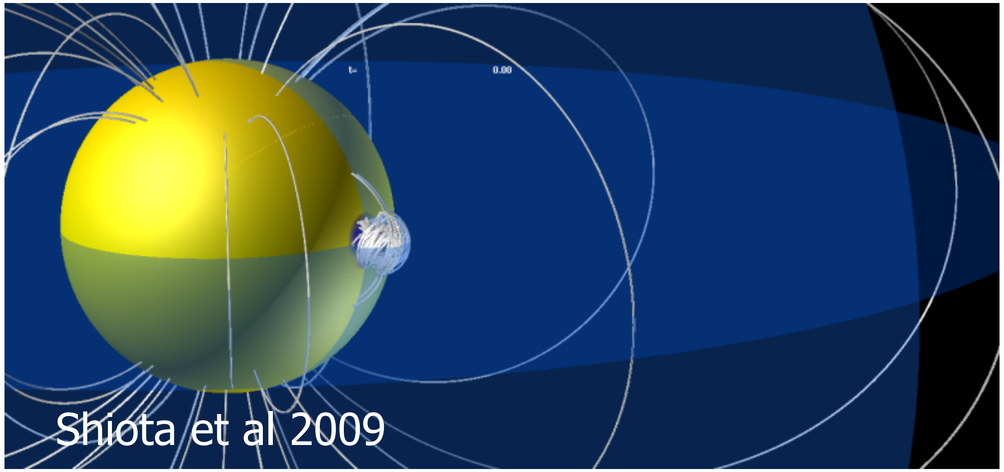


山本さんから提供 2009 Hinode-3

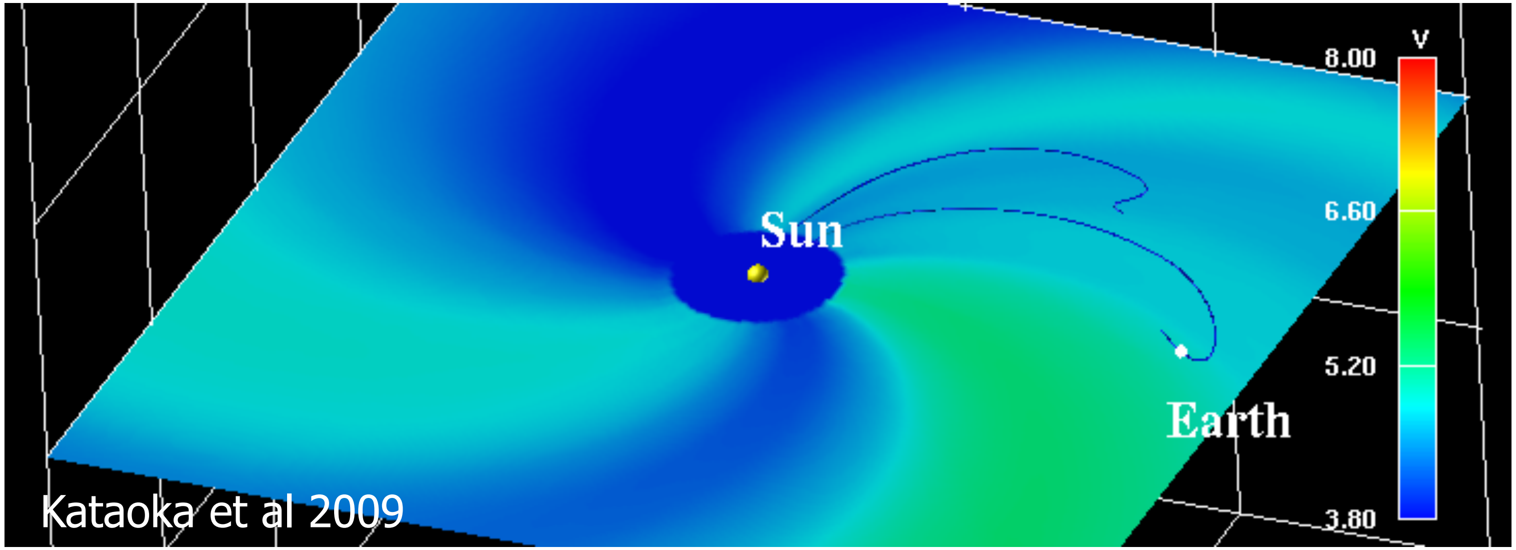


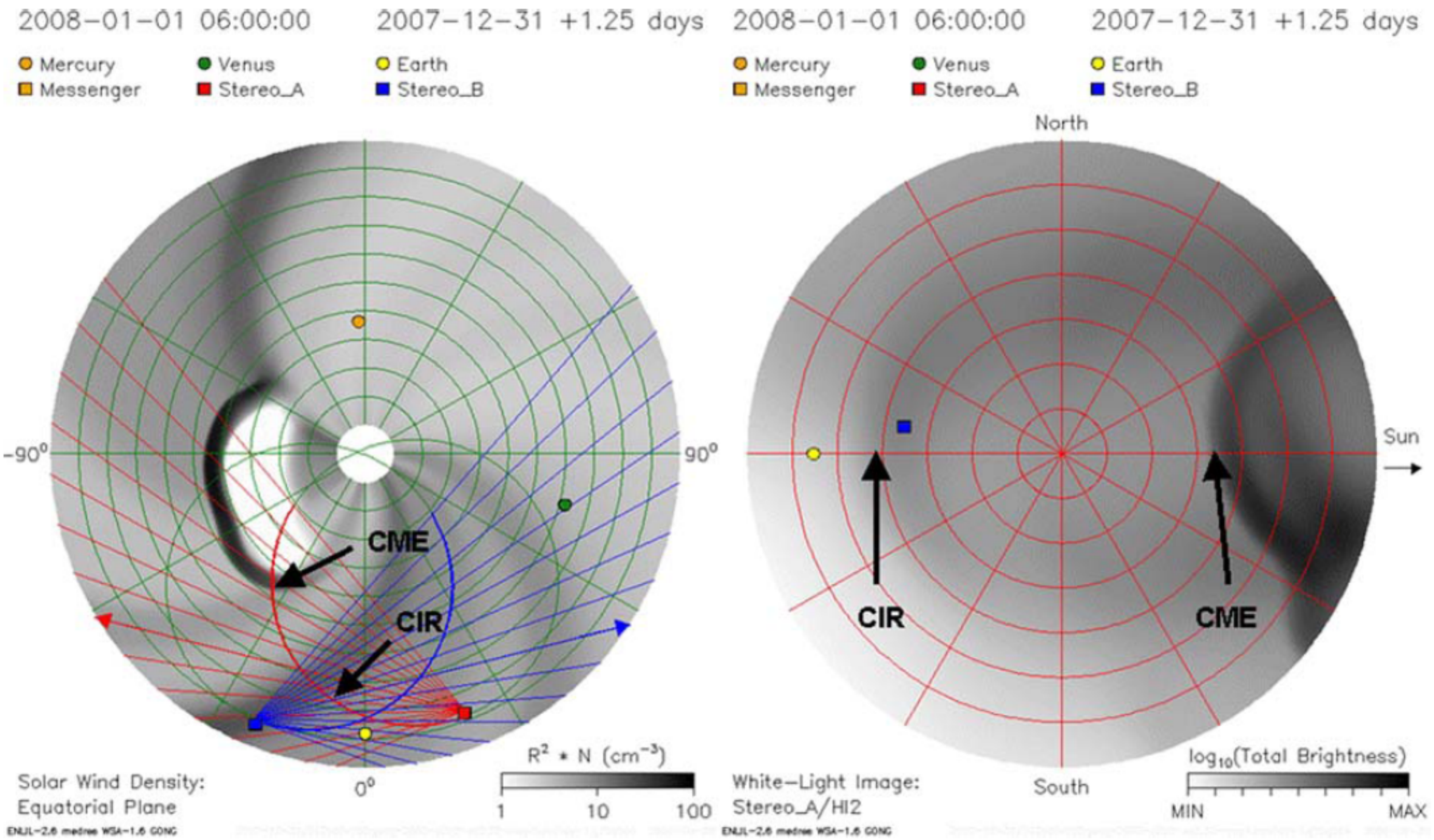
Welsch et al. 2007

宇宙天気モデルへの展開



- 太陽風モデル
  - コロナ加熱の物理として面白い。
- CME形成モデル
  - 非線形MHDとして面白い。
- CME伝播モデル
  - 宇宙天気にとっては必要。




2008-01-01 06:00:00
2007-12-31 +1.25 days
Mercury
Venus
Earth
Messenger
Stereo_A
Stereo_B
-90°
90°
0°
CME
CIR
R² * N (cm⁻³)
1
10
100
Solar Wind Density:
Equatorial Plane
ENLIL-2.6 medres WSA-1.6 GONG
2008-01-01 06:00:00
2007-12-31 +1.25 days
Mercury
Venus
Earth
Messenger
Stereo_A
Stereo_B
North
Sun
South
CIR
CME
log10(Total Brightness)
MIN
MAX
White-Light Image:
Stereo_A/HI2
ENLIL-2.6 medres WSA-1.6 GONG

まとめ

- 予測研究は応用のみならず科学的にも重要。
- フレア発生予測（学習アルゴリズム、物理アルゴリズム、MHDモデル）は何れも発達途上。
- シミュレーションと観測の同化モデル
  - 平衡モデルの改善（NLFFモデルは限界あり。彩層モデルの必要性）
  - トリガプロセスの解明
    - プレフレアイベントの徹底的な解明（高時間高空間分解データ）
    - 速度場・電場の同化手法改善（ただし、ひのででまだまだできるはず。）
    - "Vulnerability of Active Region"の定量化による予測をやってみたい。