# Simulation from “Magnetohydrodynamic Simulation of the X2.2 Solar Flare on 2011 February 15: I. Comparison with the Observations” by Inoue et al. (2014) & comparison with observation by others

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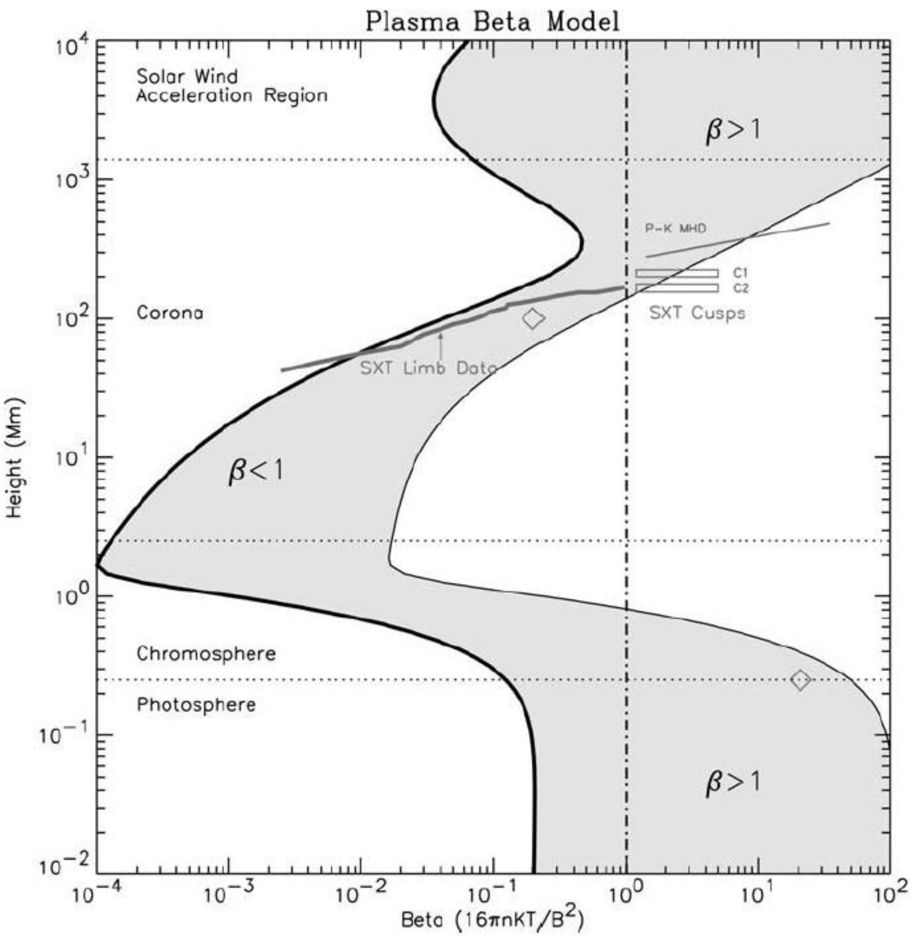
# Outline

1. “Magnetohydrodynamic Simulation of the X2.2 Solar Flare on 2011 February 15: I. Comparison with the Observations” by Inoue et al. (2014)
2. Comparison between Inoue’s study & my study of 2011 Feb. 15 X2.2 flare
3. Comparison between Inoue’s study & “Sudden Photospheric Motion and Sunspot Rotation Associated with the X2.2 Flare on 2011 February 15” by Wang et al. (2014) using my study
4. Conclusions

# “Magnetohydrodynamic Simulation of the X2.2 Solar Flare on 2011 February 15: I. Comparison with the Observations” by Inoue et al. (2014)

NLFFFF extrapolation and MHD simulation of 2011 Feb. 15 flare and its associated AR 11158

# Non-Linear Force Free Field (NLFFF)




(Gary 2001)

- We cannot see magnetic fields in empty space on the Sun, so we have to model/simulate using measured B-field at photosphere
- Plasma β ~ plasma pressure/magnetic pressure ( $2\mu_0 \frac{p}{B^2}$ )
- If β << 1, like in upper chromosphere & lower corona, then you can neglect all the lowest-order non-magnetic force, and assume Lorentz force vanishes (plasma "frozen"?)

$$\mathbf{j} \times \mathbf{B} = \mathbf{0},$$
$$\mathbf{j} = \frac{1}{\mu_0}\nabla \times \mathbf{B}$$
$$\nabla \cdot \mathbf{B} = 0,$$

⇒

$$(\nabla \times \mathbf{B}) \times \mathbf{B} = \mathbf{0},$$
$$\nabla \cdot \mathbf{B} = 0.$$

⇓

$\nabla \times \mathbf{B} = 0$ Current-free or potential B-field

OR

**Active Region!** $\mathbf{B} \parallel \nabla \times \mathbf{B}$ "force-free" field

⇒

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

If α is not constant along field lines (function of position) in the volume under consideration, it's called Non-linear Force Free Field (NLFFF)

# NLFFF simulation – MHD relaxation method

① Compute ϕ from measured B-field

② Apply ① to the reduced set of time-dependent MHD equations as bottom boundary conditions in 3-D ϕ box

③ Numerically iterate to get the solution of NLFFF equations

- After plugging initial non-equlibrium state - large deviation from the equilibrium is expected at the bottom boundaries
- Deviations accumulate in velocity field (velocity field is capped at some maximum value so that it won't go to large value)
- The velocity field "relaxes" and goes to zero, converging to stationary state, e. g. NLFFF

# MHD simulation developed by Inoue et al. (?)

$$\rho = |\boldsymbol{B}|$$

$$\frac{\partial \rho}{\partial t} = -\boldsymbol{\nabla} \cdot (\rho \boldsymbol{v}) + \xi \nabla^2 (\rho - \rho_0)$$

Mass/density conservation

$$\frac{\partial \boldsymbol{v}}{\partial t} = -(\boldsymbol{v} \cdot \boldsymbol{\nabla})\boldsymbol{v} + \frac{1}{\rho}\boldsymbol{J} \times \boldsymbol{B} + \nu \boldsymbol{\nabla}^2 \boldsymbol{v}.$$

Momentum conservation

$$\frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{\nabla} \times (\boldsymbol{v} \times \boldsymbol{B} - \eta_i \boldsymbol{J}) - \boldsymbol{\nabla} \phi,$$

Induction equation

$$\eta_{NLFFF} = \eta_0 + \eta_1 \frac{|\boldsymbol{J} \times \boldsymbol{B}||\boldsymbol{v}|^2}{|\boldsymbol{B}|^2}$$

$$\boldsymbol{J} = \boldsymbol{\nabla} \times \boldsymbol{B}.$$

Ohm's law

$$\frac{\partial \phi}{\partial t} + c_h^2 \boldsymbol{\nabla} \cdot \boldsymbol{B} = -\frac{c_h^2}{c_p^2}\phi,$$

- MHD-like equations for pressure-less plasma
- ρ = |B|: initial condition in all MHD and NLFFF calculation, "to ease the relaxation by equalizing the Alfven speed in space"
- B = magnetic flux density
- v = velocity
- J = electric current density
- ϕ = potential
- ν = viscosity ($10^{-3}$, constant)
- $c_h$ & $c_p$: constant
- η = resistivity
- Last equation was added to reduce the deviation from observed B-field at boundary area

Inoue et al. (2014)

# NLFFF extrapolation & MHD simulation

- Potential field was calculated using Green function method (Sakurai 1982)
- For MHD simulation, the anomalous resistivity (due to reconnection) was considered, using

$$\eta_{MHD} = \begin{cases} \eta_0 & J < j_c, \\ \eta_0 + \eta_2(\frac{J-j_c}{j_c})^2 & J > j_c, \end{cases}$$

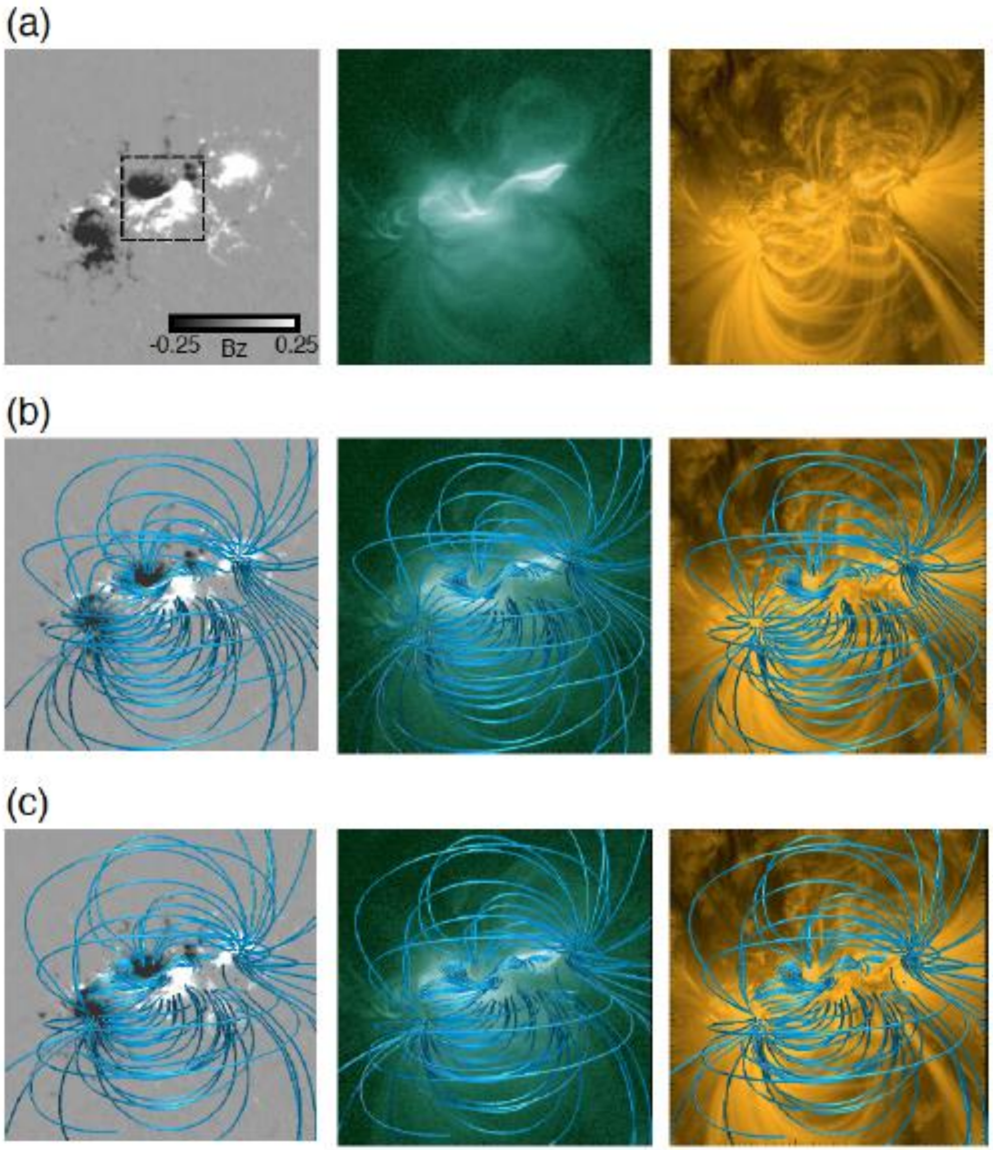
- "Released boundary condition" = tangential component of B-field are released on all of the boundaries

Table 1: Each Run for NLFFF or MHD simulation, employing equations of density evolution, resistivity formula, initial and boundary conditions.

| Run | type | density | resistivity | Initial condition | Boundary condition |
|---|---|---|---|---|---|
| Run A | NLFFF | eq.(1) | eq.(7) | Potential field | Fix |
| Run B | MHD Simulation | eq.(1) | constant | NLFFF | Release |
| Run C | MHD Relaxation | eq.(1) | anomalous | NLFFF | Fix |
| Run D | MHD Simulation | eq.(1) | anomalous | $t$ =1 in Run C | Release |
| Run E | MHD Simulation | eq.(2) | anomalous | $t$ =1 in Run C | Release |
| Run F | MHD Simulation | eq.(1) | constant | $t$ =1 in Run C | Release |

Inoue et al. (2014)

# NLFFF extrapolation – Run A



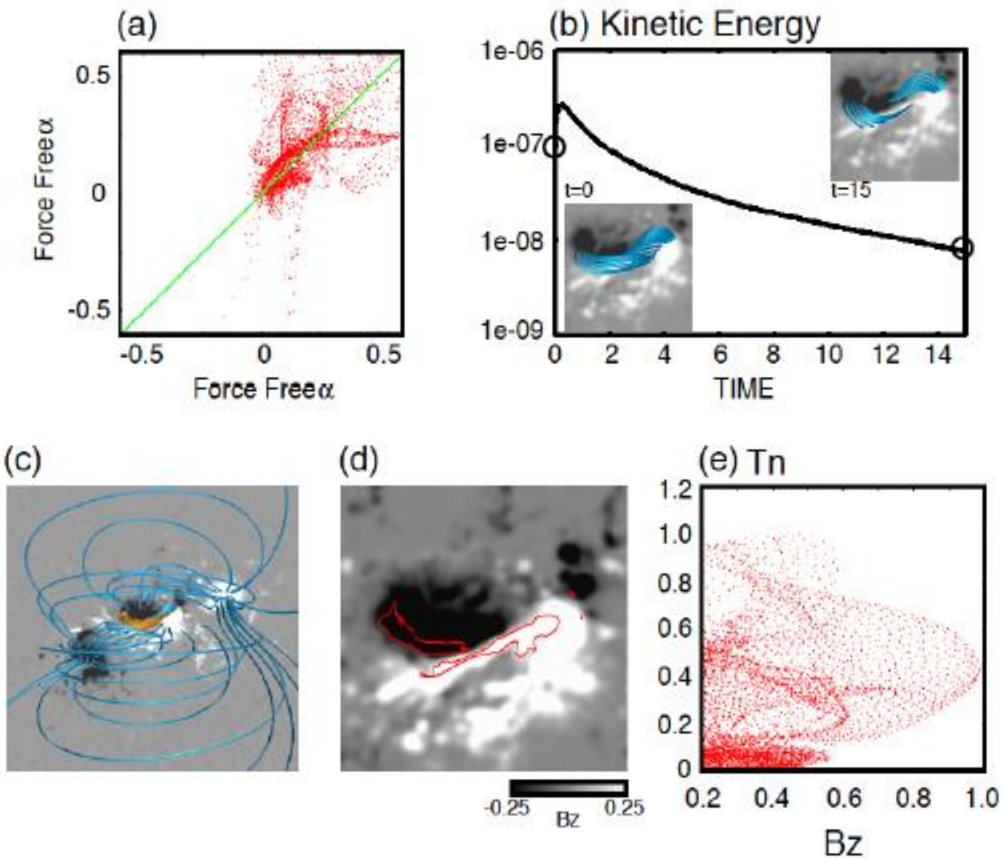

- I. C. = potential field
- B. C. = fixed
- Resistivity:

$$\eta_{NLFFF} = \eta_0 + \eta_1 \frac{|\boldsymbol{J} \times \boldsymbol{B}||\boldsymbol{v}|^2}{|\boldsymbol{B}|^2}$$

- Strongly sheared field lines are formed above PIL, although large loops deviate from observed loops

Inoue et al. (2014)

# MHD simulation – Run B




- I. C. = NLFFF from Run A
- B. C. = tangential component released on bottom boundary (relaxation)
- Constant resistivity

(a) estimated α on opposite footpoints of each field line

(b) Temporal evolution of the kinetic energy – NLFFF can't meet an equilibrium & deviation from the initial state due to the released B. C. cause velocity increase, but relaxes back to potential field eventually

(c) Orange lines = lines with $T_n > 0.5$

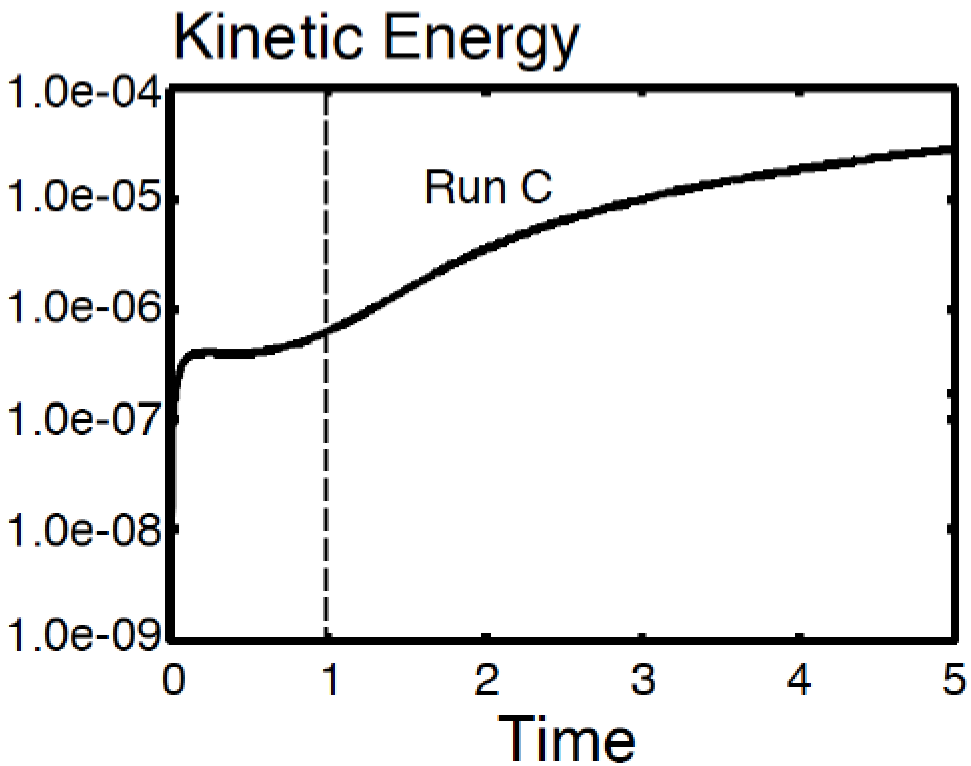
$$T_n = \frac{1}{4\pi} \int \alpha dl$$

(d) Traced area of orange lines in (c)

(e) $T_n$ distribution over the area with $B_z > 500$G on the positive polarity: most twists are <1, suggesting the stable state against kink mode instability (?)

Inoue et al. (2014)

# MHD simulation – Run C



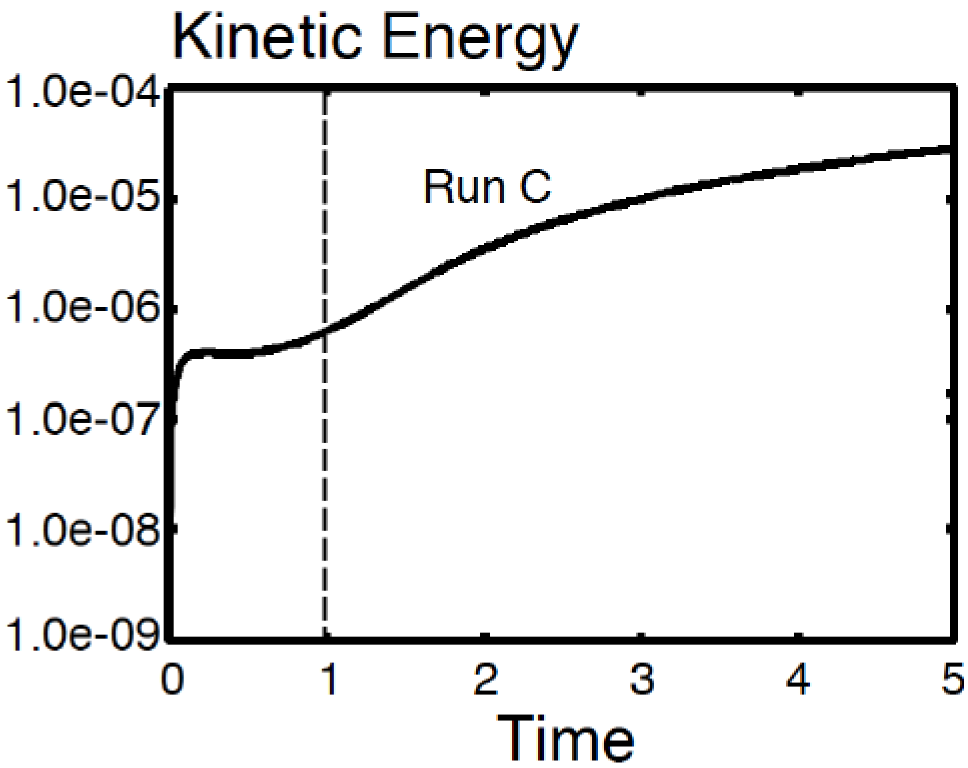

- I. C. = NLFFF from Run A
- B. C. = fixed
- Resistivity = anomalous, it enhances the reconnection in the strong current region, probably generating more strongly twisted lines

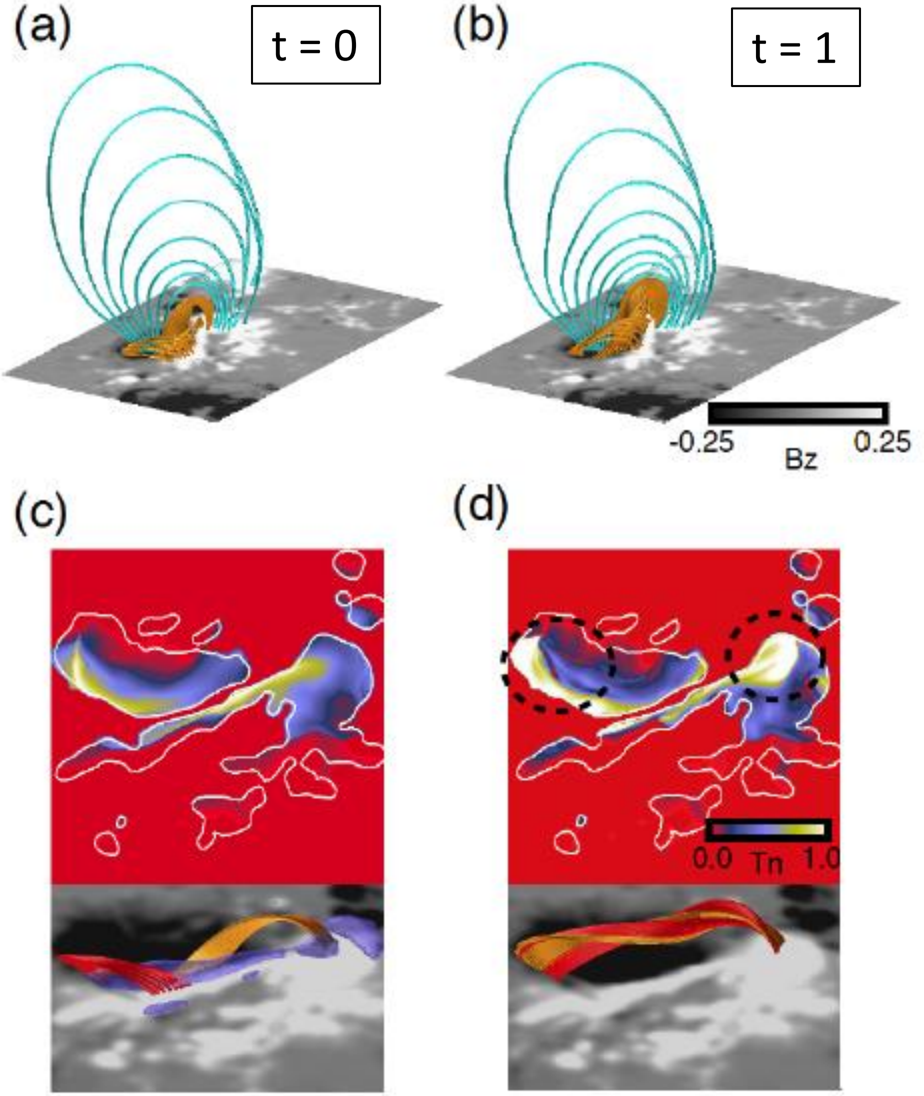
$$\eta_{MHD} = \begin{cases} \eta_0 & J < j_c, \\ \eta_0 + \eta_2 \left(\frac{J - j_c}{j_c}\right)^2 & J > j_c, \end{cases}$$

- Velocity limit is released
- After t ~ 0.5 - converts into dynamic phase through the reconnection due to the anomalous resistivity

Inoue et al. (2014)

# MHD simulation – Run C

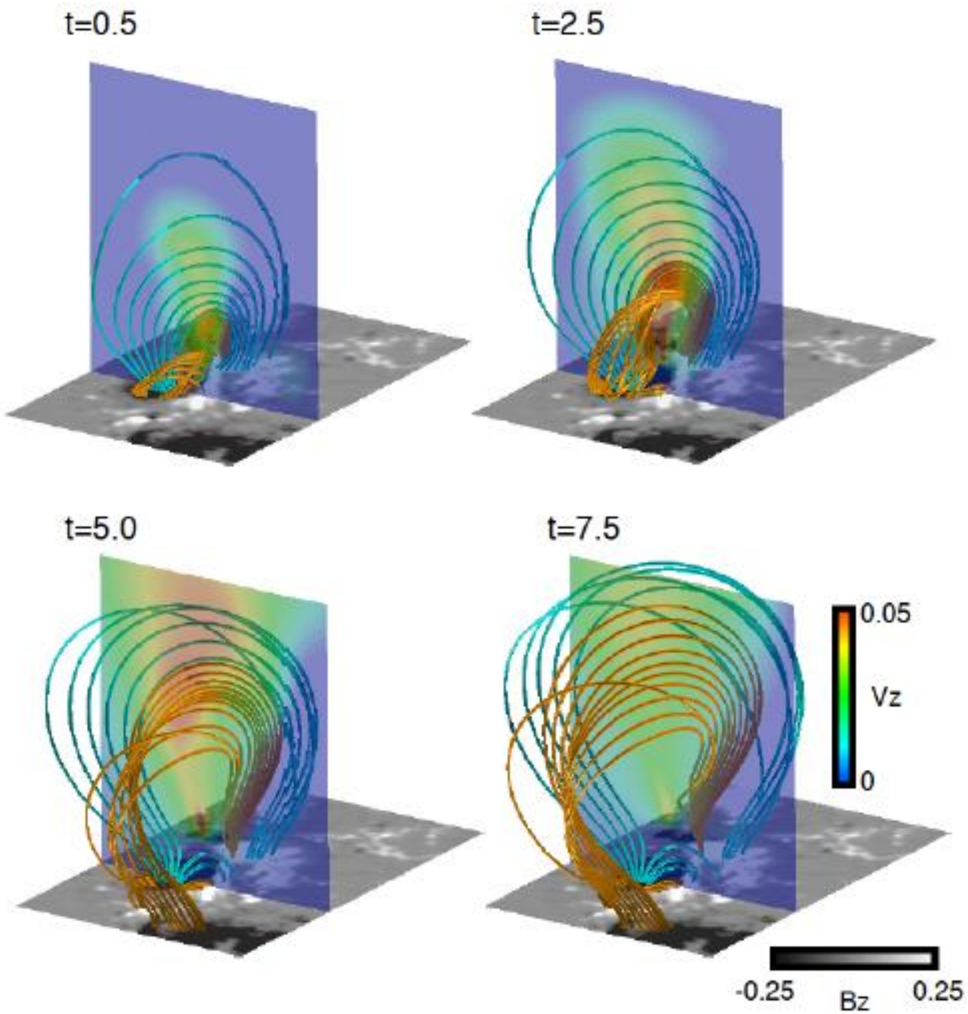



- Change of topology from (c) to (d) is reminiscent of the tether-cutting reconnection

Inoue et al. (2014)

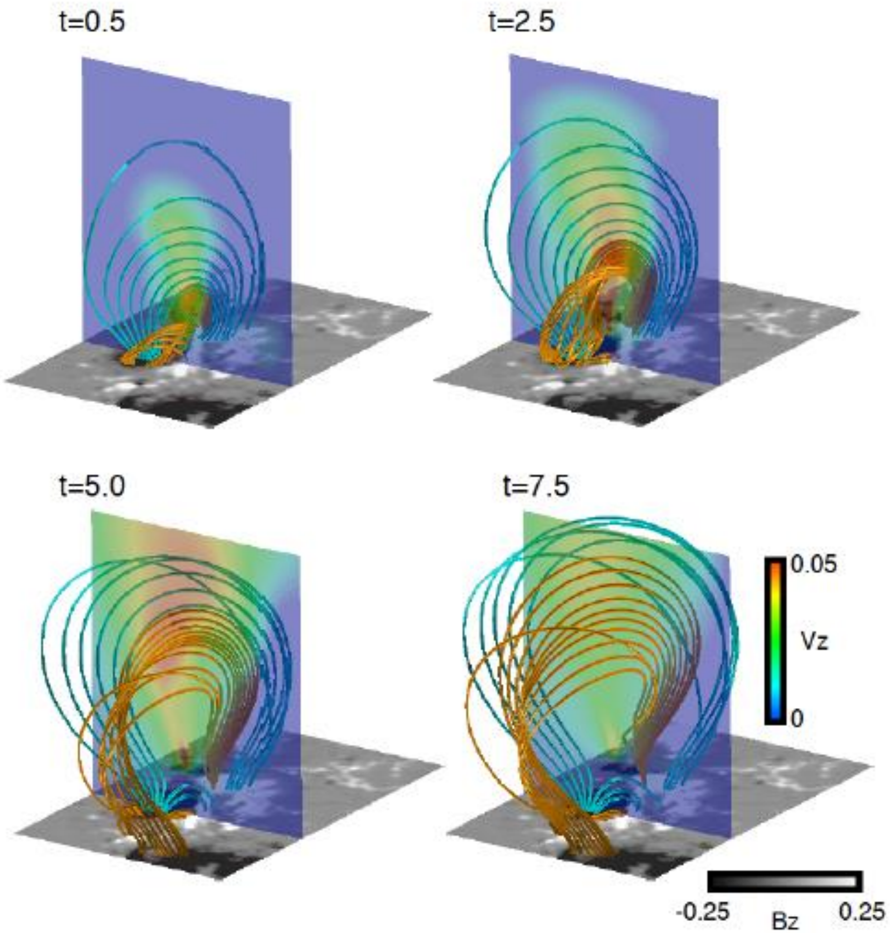
# MHD simulation – Run D

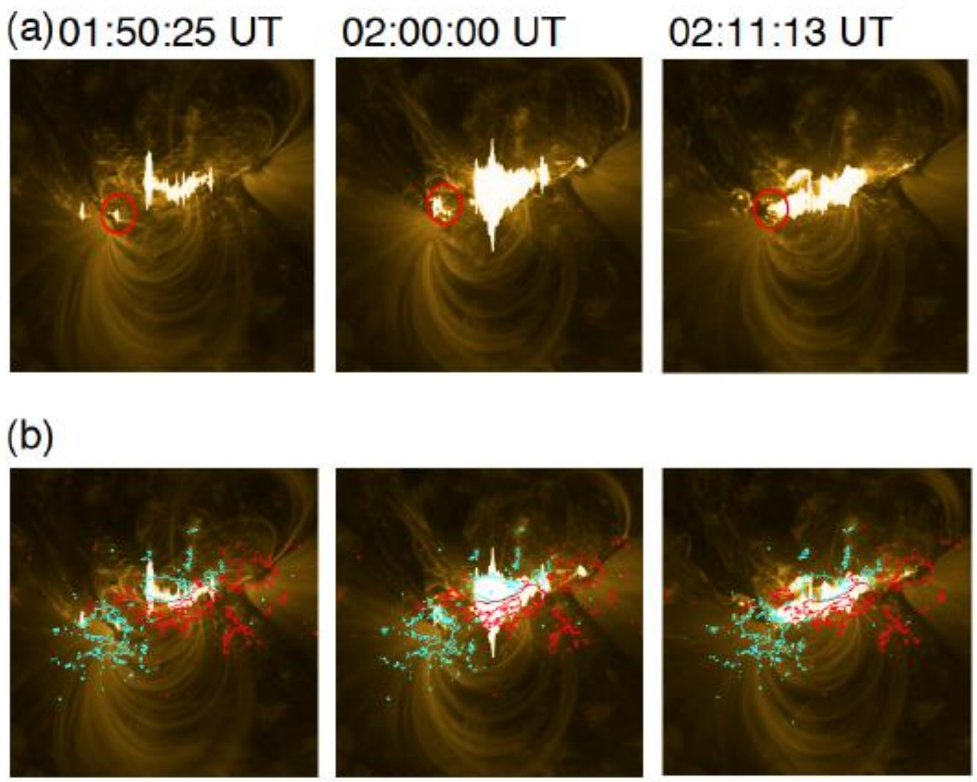



- I. C. = (t = 1) of Run C
- B. C. = tangential component released on bottom boundary (relaxation)
- Resistivity = anomalous
- Velocity limit = released?

Inoue et al. (2014)

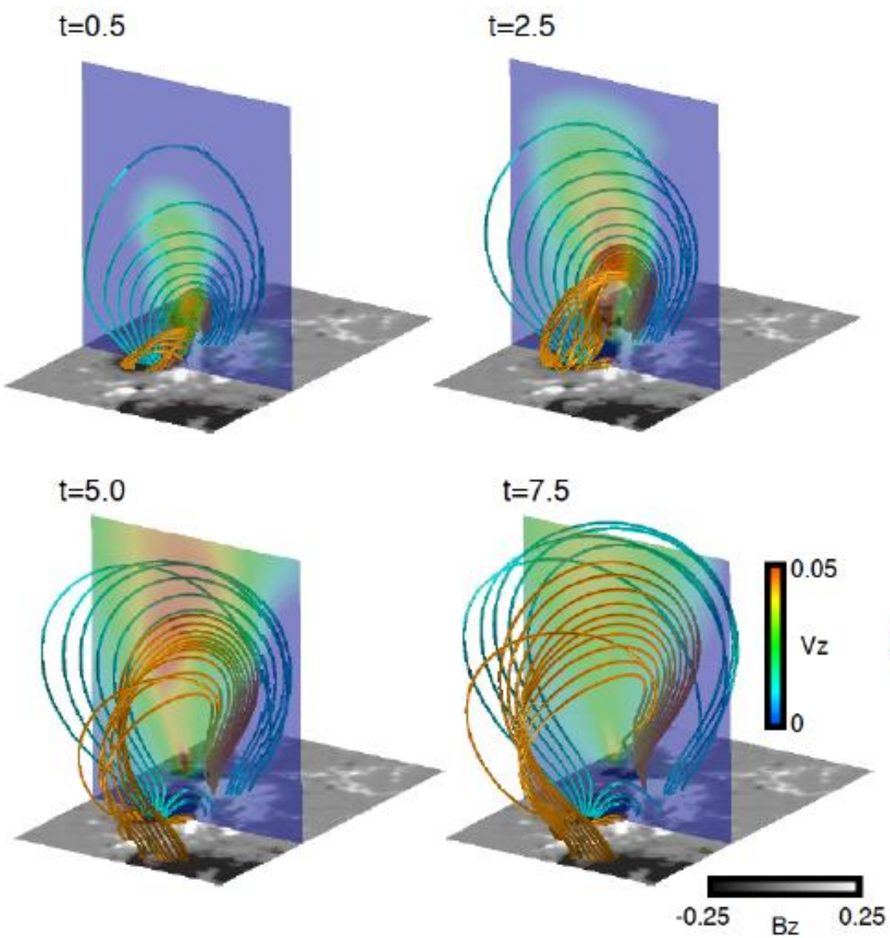
# MHD simulation – Run D, comparison with observation

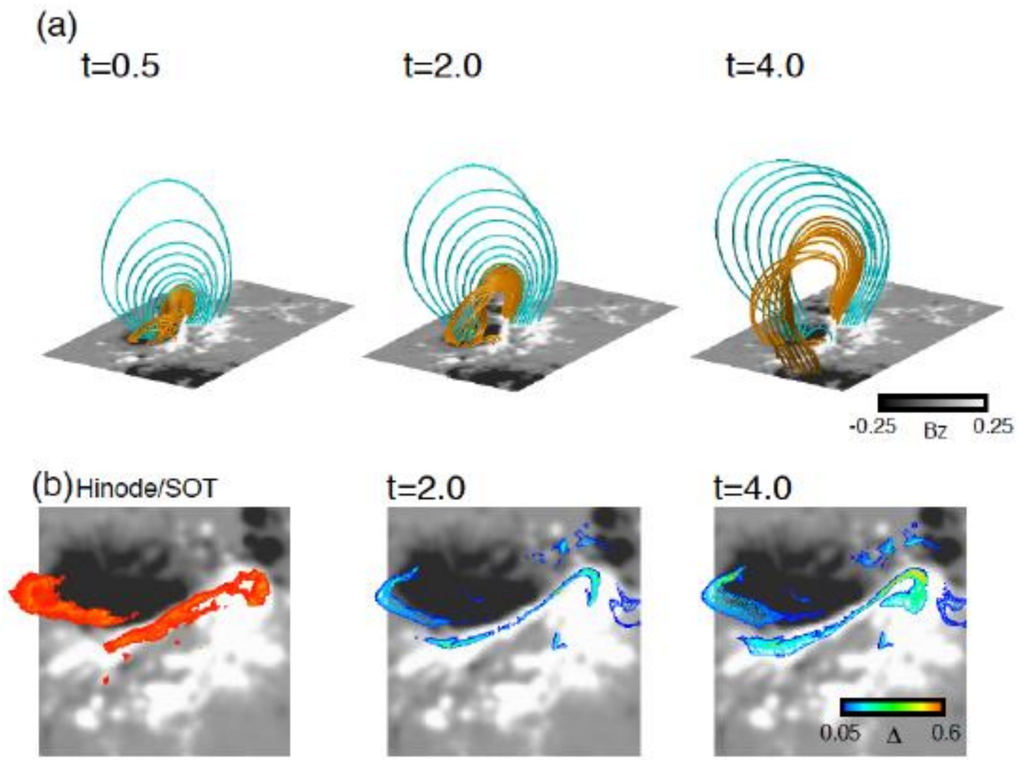



Inoue et al. (2014)

# MHD simulation – Run D, comparison with observation




01:51 UT

Footpoints with Tn > 0.3

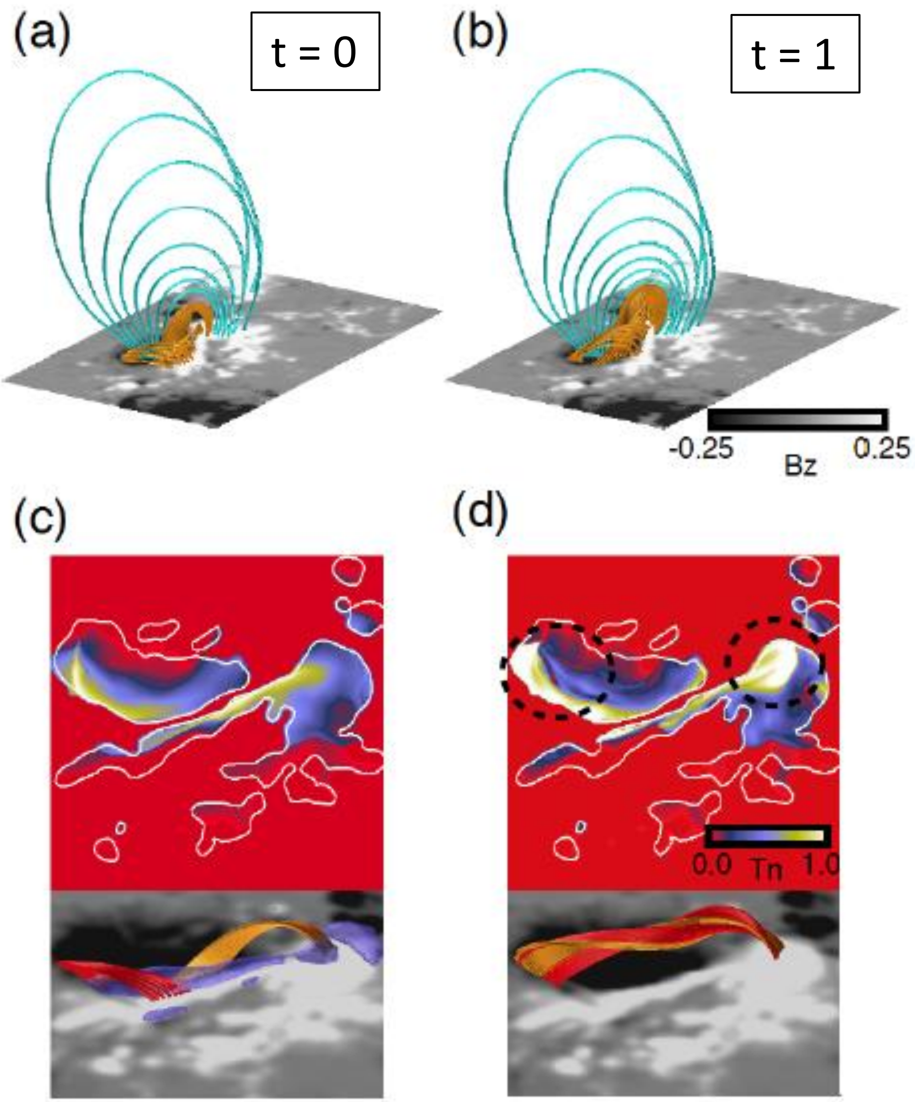
Inoue et al. (2014)

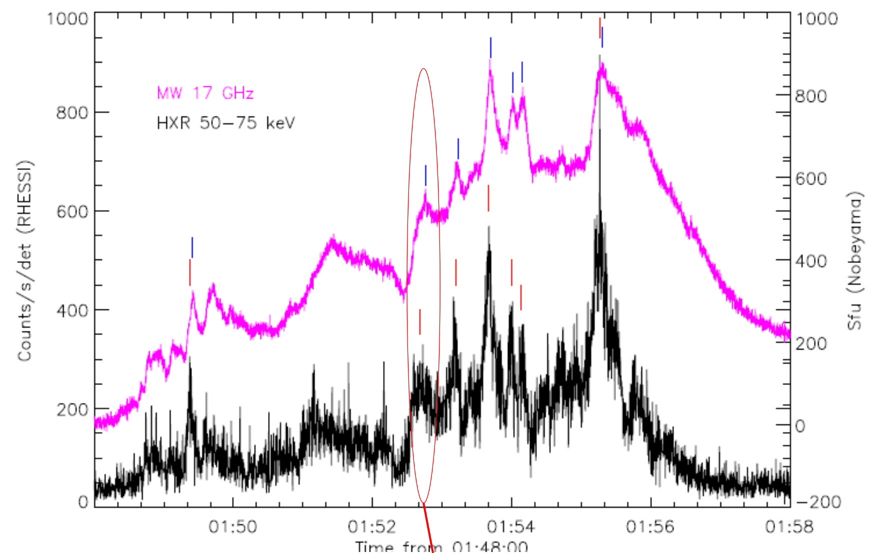
# Inoue et al. - conclusions

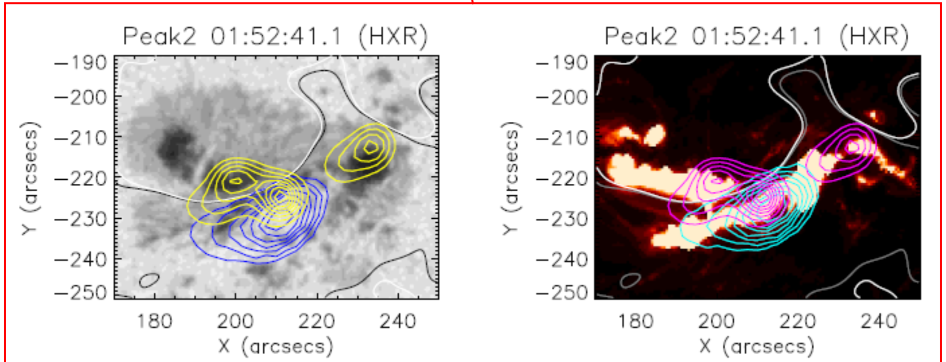
- NLFFF is found to be in stable state as long as reconnection does not occur (Run B, $T_n$ stays < 1)
- However, reconnection in NLFFF could form the strongly twisted lines with more than one-turn twist, then the system breaks the quasi-steady state (Run C,  KE diverges)
- Eventually, the twisted lines can erupt away (Run D)

# Relation to my study

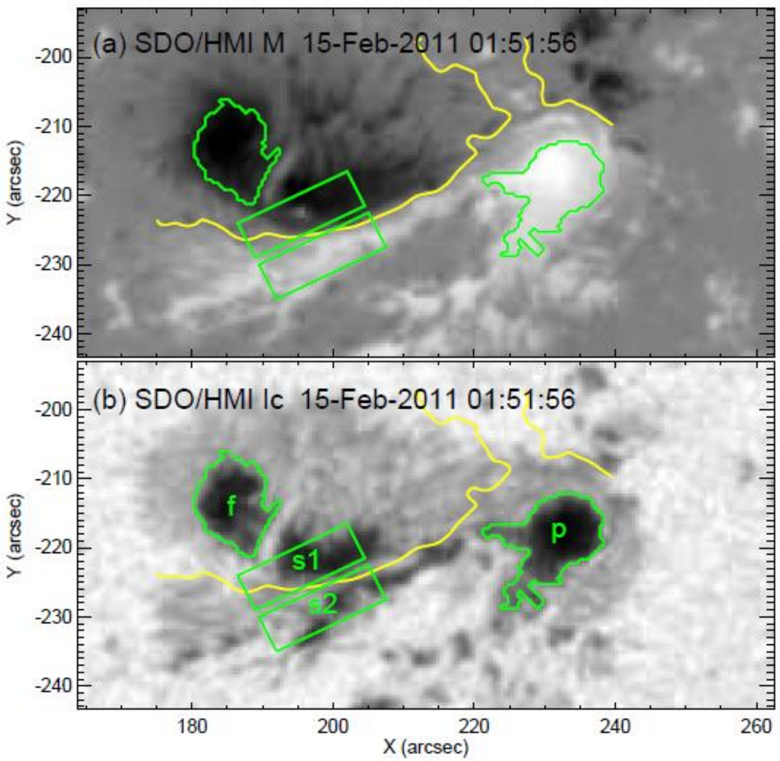
Inoue et al. (2014)

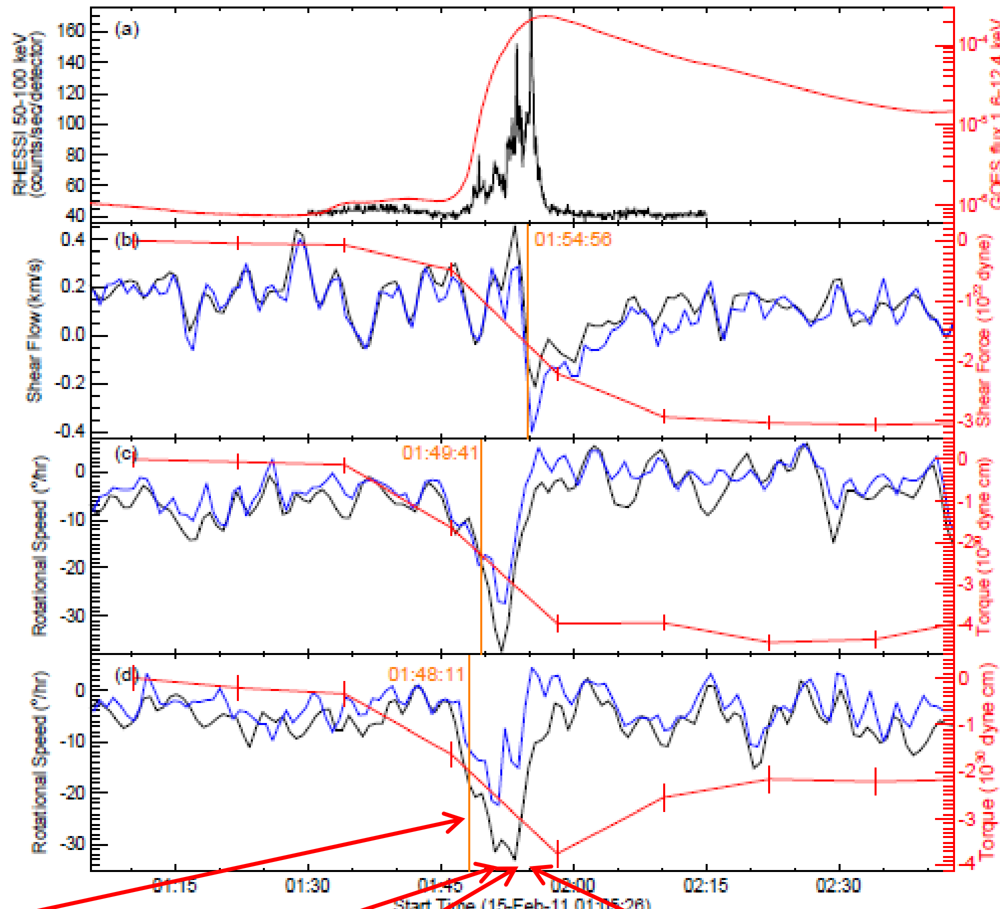


# Relation with my study AND "Sudden Photospheric Motion and Sunspot Rotation Associated with the X2.2 Flare on 2011 February 15" by Wang et al. (2014)




Wang et al. (2014)

01:48 ~ 49 Sunspot rotation begins (Wang)

01:51 ~ 52 Sunspot rotation maxima (Wang)

01:52:41 Peak 2 footpoint (Natsuha)

Shear flow reverse (Wang)
Twist enhancement (Inoue)

# Conclusions from the comparison between Inoue et al.'s simulation relating to Wang et al. (2014) and my study

1. The footpoints of Inoue et al.'s simulated B-field line seem to match with the first (short-lived & rather faint) HXR footpoint (and one more afar) that I observed
2. Sunspot rotation is related to B-field twisting? – (using my observation,) it seems that the time at which Wang et al.'s sunspot rotation was observed, and the time at which Inoue et al.'s simulation showed the B-field twist enhancement, do not match.

# References


- “Solar Force Free Magnetic Fields” by Wiegelmenn & Sakurai (2012)
- “Plasma beta above a solar active region: Rethinking the paradigm” by Gary (2001)
- “Magnetohydrodynamic Simulation of the X2.2 Solar Flare on 2011 February 15: I. Comparison with the Observations” by Inoue et al. (2014)
- “Sudden Photospheric Motion and Sunspot Rotation Associated with the X2.2 Flare on 2011 February 15” by Wang et al. (2014)