On the Non-force-free Magnetic Field and Solar Eruptions

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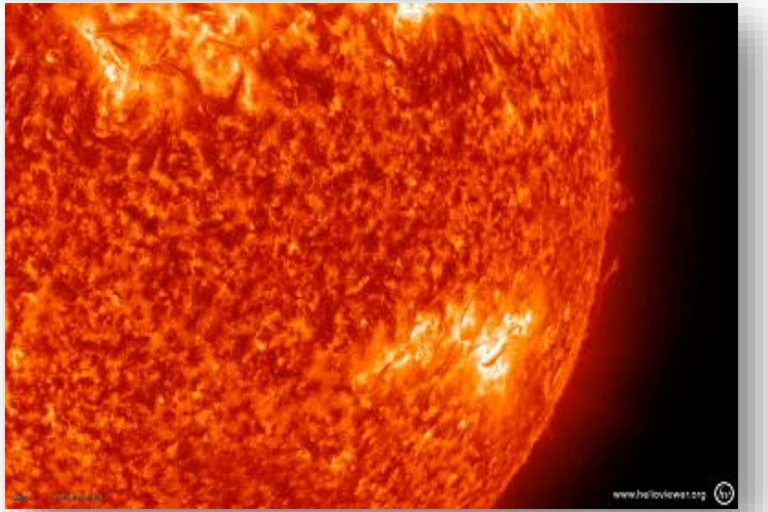
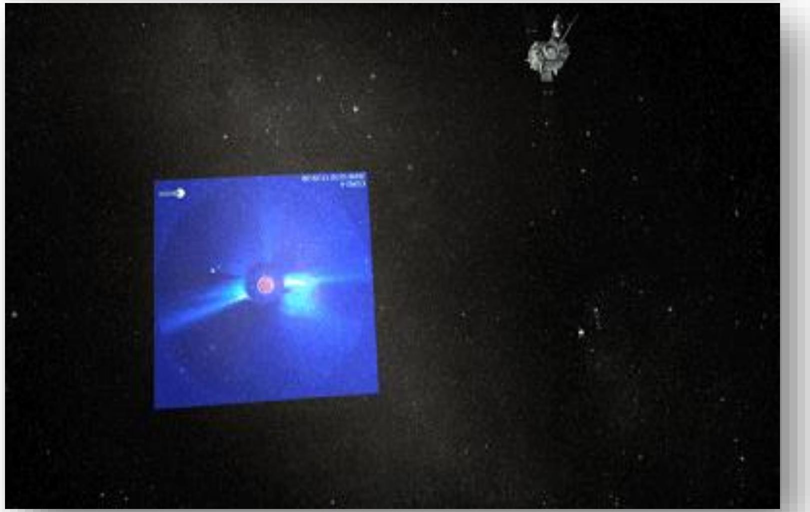
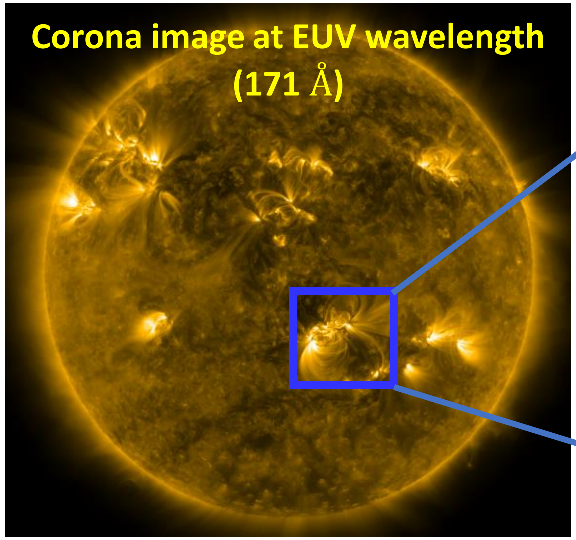
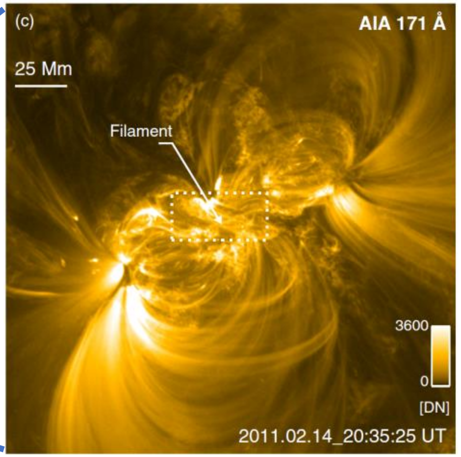
Solar eruption and its impact

- **Solar eruptive events: coronal mass ejections (CMEs)**
  - ✓ 10^{11}-10^{13} kg plasma along with magnetic field expelled from the Sun
  - ✓ Harmful effects: disturbances in communication system, damages on satellites, power cutoffs, etc.

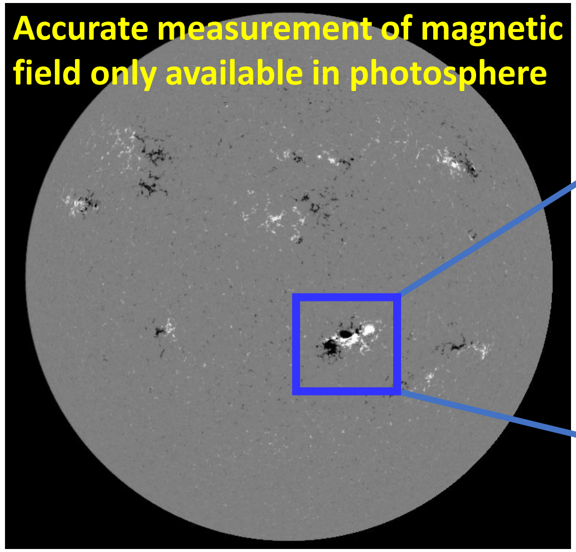
Solar Activity	Interplanetary Propagation	Impact on the Earth
		

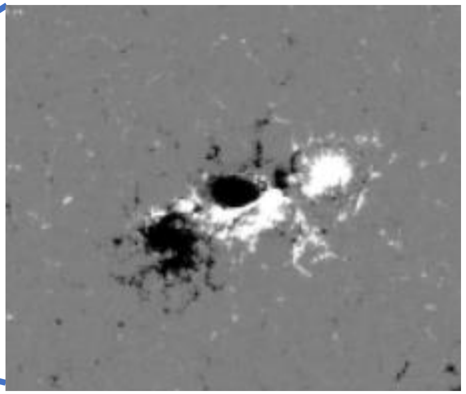
Key Factor: Magnetic Field



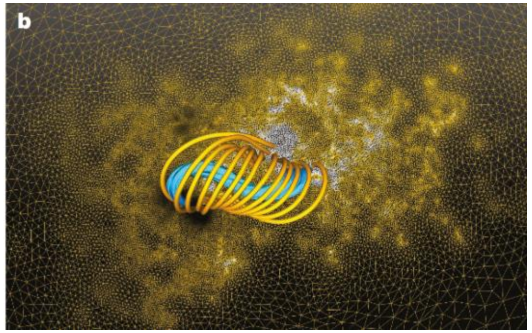


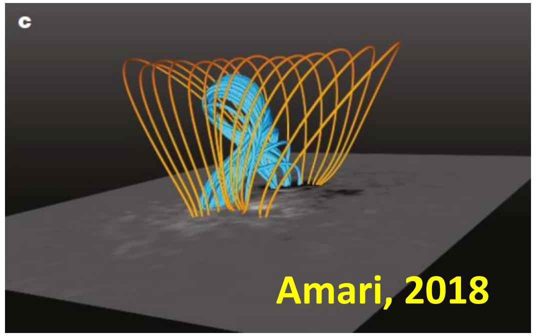
- **Active region**
  - ✓ Main source of solar eruptive events
  - ✓ Area with strong and compact magnetic fields distribution
  - ✓ **Eruption determined by magnetic fields**





Extrapolation



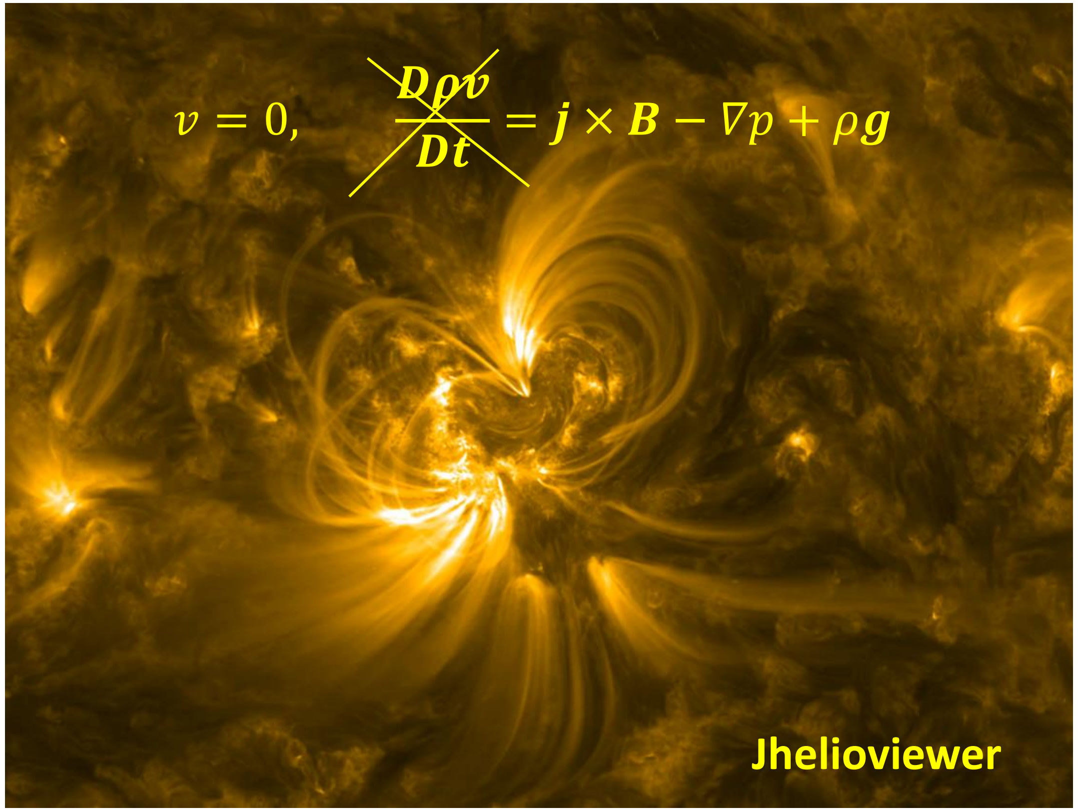


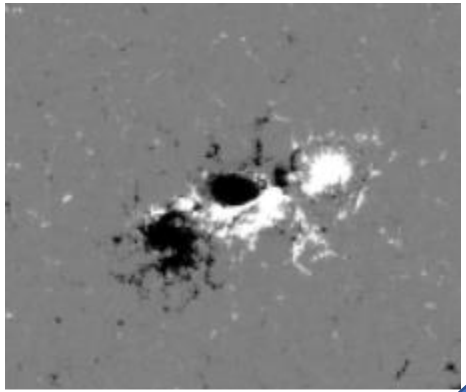
Outline

- Basis of solar magnetic field extrapolation
- The analytical non-force-free magnetic field extrapolation
- The numerical non-force-free magnetic field extrapolation
- Applications to Solar Eruption Studies
- ISSI & ISSI-BJ international team

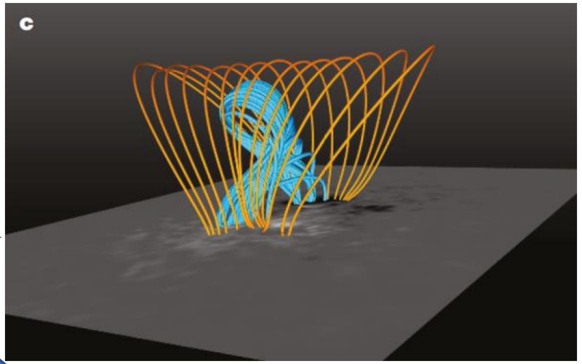
Basis of the magnetic field extrapolation

- **Characteristic of the solar atmosphere**





Extrapolation: A boundary value problem



Magneto-hydro-static state **/non-force-free field**
$\boldsymbol{j} \times \boldsymbol{B} - \nabla p + \rho \boldsymbol{g} = \boldsymbol{0}$
$\nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{j}$
$\nabla \cdot \boldsymbol{B} = 0$

- ✓ **Over 1 decade (nonlinear case)**
- ✓ **Some applications**

Force-free field
$\boldsymbol{j} \times \boldsymbol{B} = \boldsymbol{0}$ (No Lorentz force)
$\nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{j}$
$\nabla \cdot \boldsymbol{B} = 0$

- ✓ **Over 4 decades (nonlinear case)**
- ✓ **Widely used in research studies**

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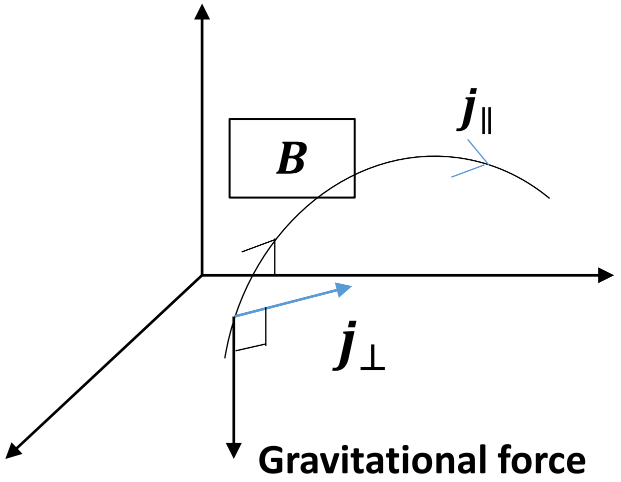
In this talk:
Magneto-hydro-static extrapolation
= non-force-free field extrapolation

The analytical MHS extrapolation

$$\boldsymbol{j} \times \boldsymbol{B} - \nabla p + \rho \boldsymbol{g} = 0$$

$$\nabla \times \boldsymbol{B} = \boldsymbol{\mu_0 j}$$

$$\nabla \cdot \boldsymbol{B} = 0$$



Form Neukirch's talk

BC Low (1985,1991): $\nabla \times \boldsymbol{B} = \underbrace{\boxed{\boldsymbol{a} e^{-\kappa z} \nabla B_z \times \boldsymbol{e_z}}}_{(\boldsymbol{j}_{\perp})} + \underbrace{\boxed{\alpha \boldsymbol{B}}}_{(\boldsymbol{j}_{\parallel})}$

Analytical solution:

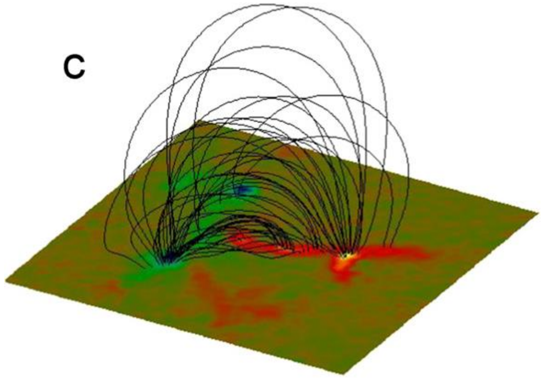
$$\begin{cases} \dfrac{d^2 \tilde{B}_z}{dz^2} + \{\alpha_0^2 + (h^2 + k^2)[f(z) - 1]\}\tilde{B}_z = 0 \\ \tilde{B}_x = \dfrac{1}{h^2 + k^2}\left(ih \dfrac{d\tilde{B}_z}{dz} + ik\alpha_0 \tilde{B}_z\right) \\ \tilde{B}_y = \dfrac{1}{(h^2 + k^2)}\left(ik \dfrac{d\tilde{B}_z}{dz} - ih\alpha_0 \tilde{B}_z\right) \\ p = p_0(z) - \dfrac{1}{8\pi} f(z) B_z^2 , \\ \rho = -\dfrac{1}{g}\dfrac{dp_0}{dz} + \dfrac{1}{4\pi g}\left[\dfrac{1}{2}\dfrac{df}{dz} B_z^2 + f(\boldsymbol{B} \cdot \nabla) B_z\right] \end{cases}$$

e.g. Low 1985, 1991 1992, 1993, 2005; Bogdan & Low 1986; Neukirch 1995, 1997, 1999; Neukirch & Rastatter 1999; Petrie & Neukirch 2000; Al-Salti et al. 2010; Gent et al. 2013; MacTaggart et al. 2016; Wilson & Neukirch 2018; Neukirch & Wiegelmann 2019

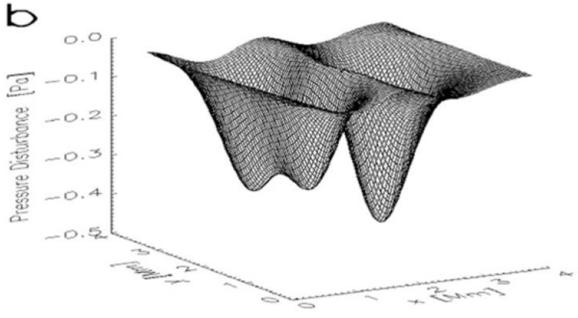
An application

Inputs	LOS magnetogram	a (control the strength of Lorentz force)	α (control the linear force-free electric current)	κ (determine the height of the non-force-free layer)
	From observation	Free parameter	Free parameter	Free parameter

MHS solution



Pressure disturbance



Wiegelmann et al. 2015

- **Advantages:** Fast
- **Disadvantages:** can’t resolve the nonlinear feature

Outline

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- The numerical magneto-hydro-static extrapolation
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- ISSI & ISSI-BJ international team

In this talk:
Magneto-hydro-static extrapolation
= non-force-free field extrapolation

The numerical MHS extrapolation

$$\boldsymbol{j} \times \boldsymbol{B} - \nabla p + \rho \boldsymbol{g} = 0$$
$$\nabla \times \boldsymbol{B} = \boldsymbol{\mu_0 j}$$
$$\nabla \cdot \boldsymbol{B} = 0$$

- **MHD relaxation method (Zhu et al. 2013, 2016; Miyoshi et al. 2020)**
  - ✓ Drive the MHD system by slowly inject the vector magnetogram

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0,$$
$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot \left[\rho \boldsymbol{v}\boldsymbol{v} + \left(p + \frac{\boldsymbol{B}\boldsymbol{B}}{2}\right)\boldsymbol{I} - \boldsymbol{B}\boldsymbol{B}\right] = \rho \boldsymbol{g} - \mu \rho \boldsymbol{v},$$
$$\frac{\partial E}{\partial t} + \nabla \cdot \left[\left(E + p + \frac{\boldsymbol{B}\cdot\boldsymbol{B}}{2}\right)\boldsymbol{v} - \boldsymbol{B}(\boldsymbol{B}\cdot\boldsymbol{v})\right] = -\mu \rho v^2,$$
$$\frac{\partial \boldsymbol{B}}{\partial t} - \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) = 0,$$

- **Grad-Rubin method (Gilchrist & Wheatland 2013; Gilchrist et al. 2016)**
  - ✓ Hyperbolic part for evolving p and σ
  - ✓ Elliptic part for evolving B

$$\begin{cases} \nabla \tilde{p}^{[k+1]} \cdot \mathbf{B}^{[k]} = \left[\frac{p_0(z)}{H_0(z)} - \frac{p_0(z) + \tilde{p}^{[k+1]}}{H(\mathbf{r})}\right] B_z^{[k]} \\ \nabla \sigma^{[k+1]} \cdot \mathbf{B}^{[k]} = -\nabla \cdot \mathbf{J}_\perp^{[k+1]}, \end{cases}$$

$$\begin{cases} \nabla \times \mathbf{B}^{[k+1]} = \mathbf{J}^{[k+1]}, \\ \nabla \cdot \mathbf{B}^{[k+1]} = 0, \end{cases}$$

- **Optimization method (Wiegelmann & Neukirch 2006; Zhu & Wiegelmann 2018, 2019, 2022)**
  - ✓ Minimize functional defined by the MHS equations

$$L = \int_V \left[\frac{B^2}{B^2 + p}\left|(\nabla \times \boldsymbol{B}) \times \boldsymbol{B} - \nabla p - \rho g \hat{z}\right|^2 + |\nabla \cdot \boldsymbol{B}|^2)\right] dV$$

Inputs for the application

Numerical MHS extrapolation:

Inputs	Vector magnetogram	Plasma pressure in the photosphere	Temperature in the 3D domain
	From observation	By assumption	By assumption

Force-free-field extrapolation (nonlinear):

Inputs	Vector magnetogram
	From observation

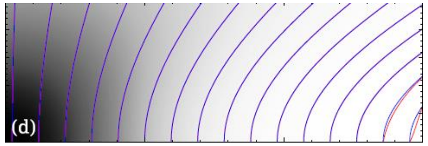
Analytical MHS extrapolation:

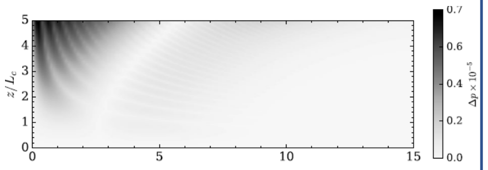
Inputs	LOS magnetogram	a (control the strength of Lorentz force)	α (linear force-free electric current)	κ (determine the height of the non-force-free region)
	From observation	Free parameter	Free parameter	Free parameter, usually set to 2 km

Tests

- **Grad-Rubin method:**

Field lines comparison **Pressure deviation**

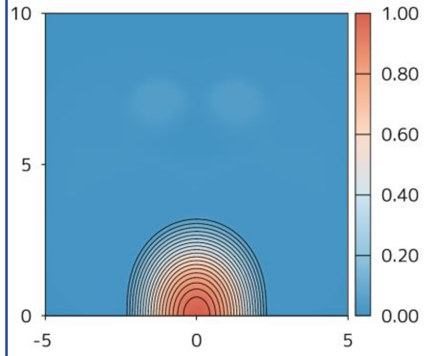


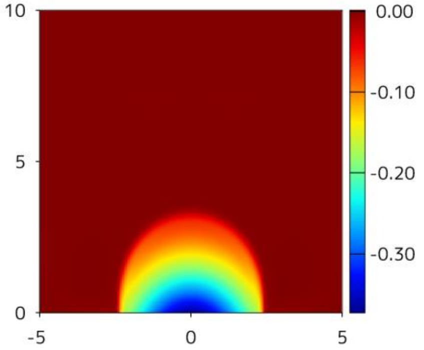


Gilchrist et al. 2016

- **MHD Relaxation method:**

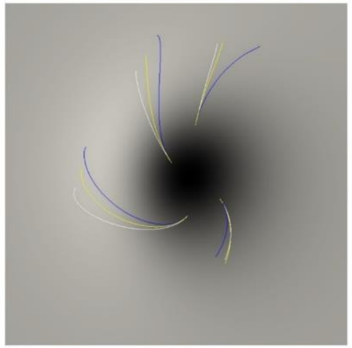
Field lines **Pressure**





Miyoshi et al. 2020

- **Optimization method:**

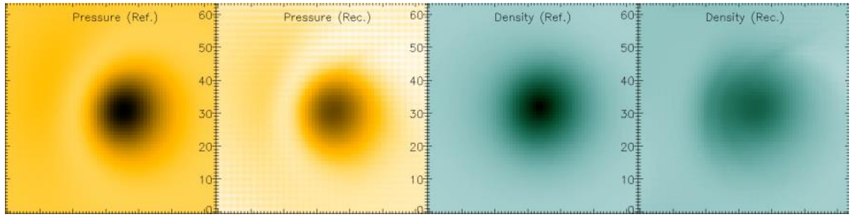


White: reference model

Yellow: MHS extrapolation

Blue: NLFFF extrapolation

Pressure comparison **Density comparison**

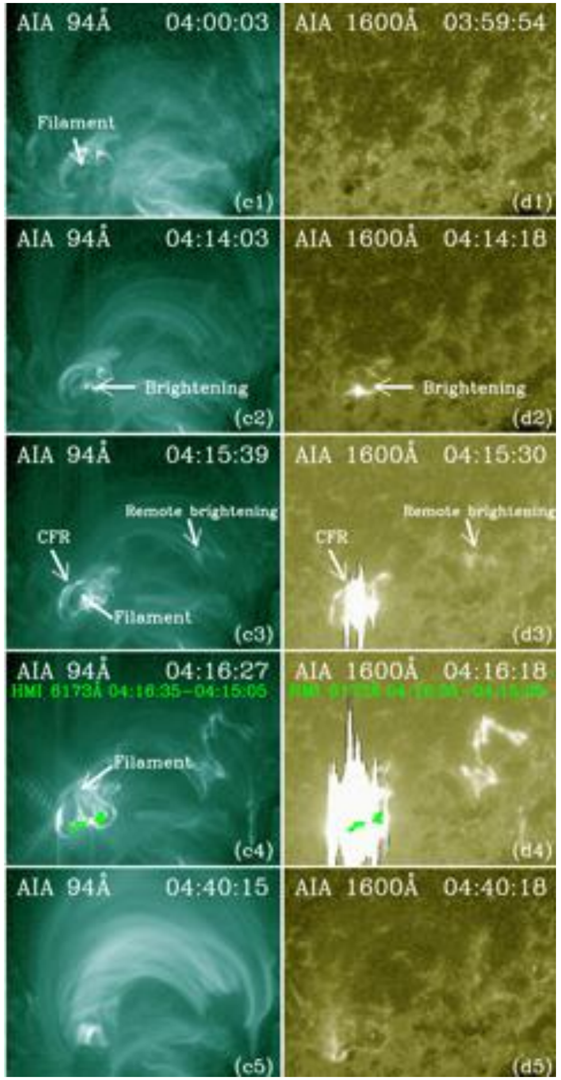


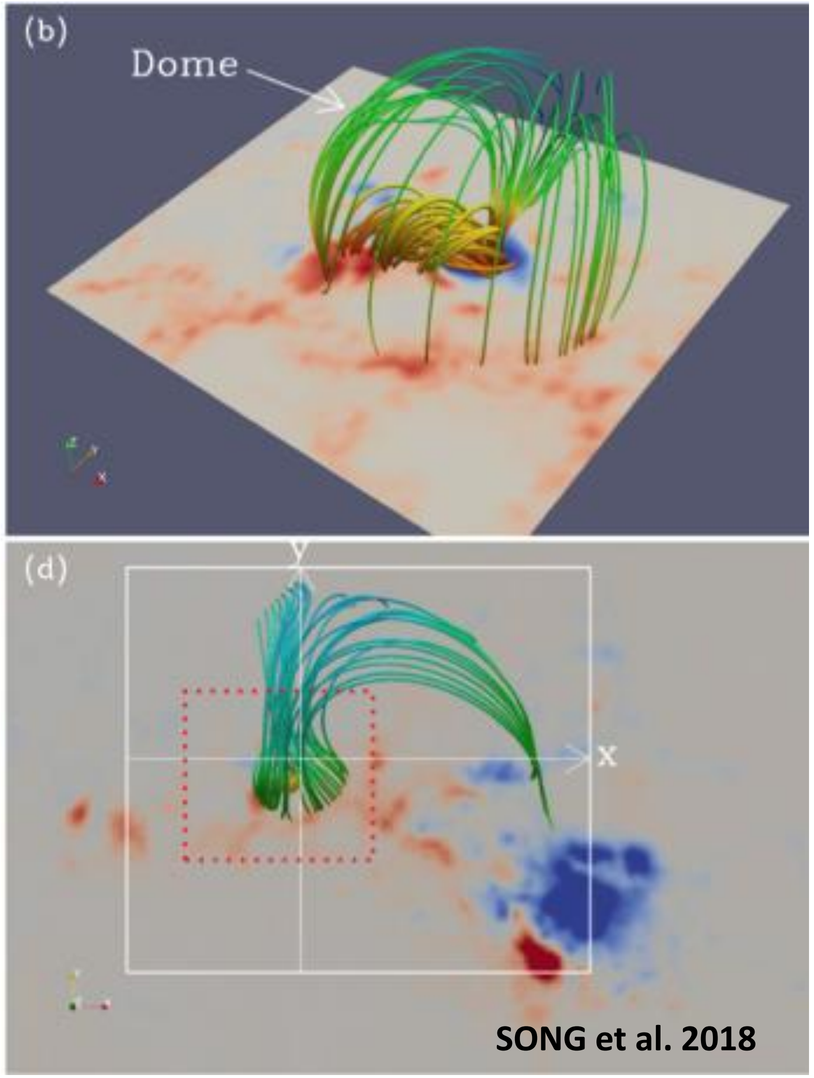
Zhu et al. 2018

Outline

- Basic of solar magnetic field extrapolation
- The analytical magneto-hydro-static extrapolation
- The numerical magneto-hydro-static extrapolation
- Applications to Solar Eruption Studies
  - ✓ White-light flare
  - ✓ Blowout jet
  - ✓ Global magnetic structure in the corona
- ISSI & ISSI-BJ international team

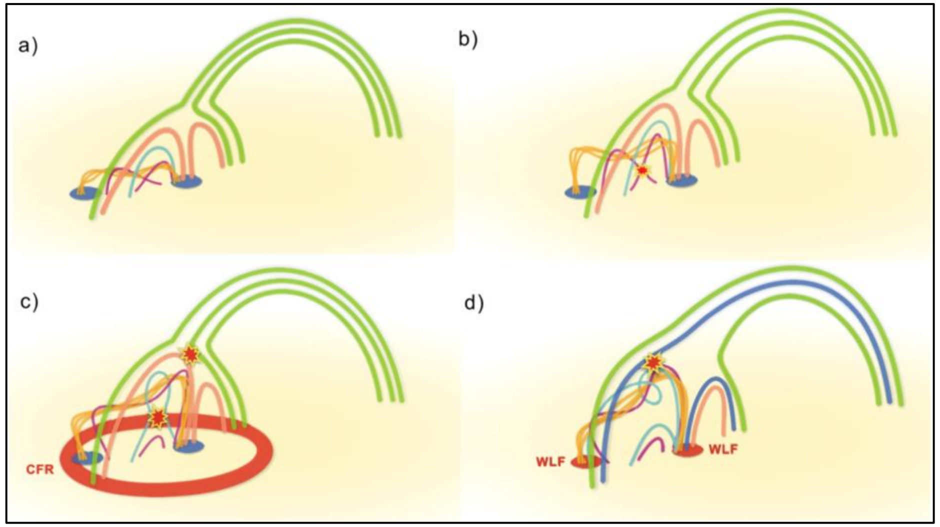
White-light flare



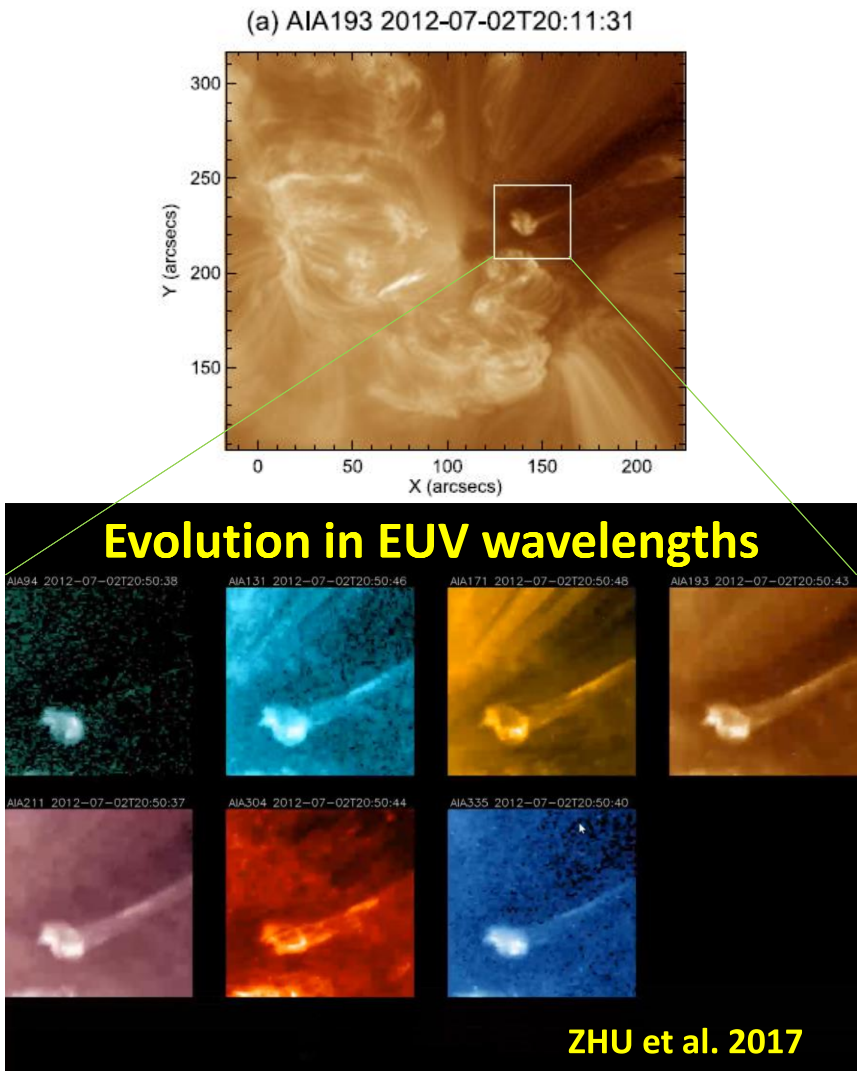


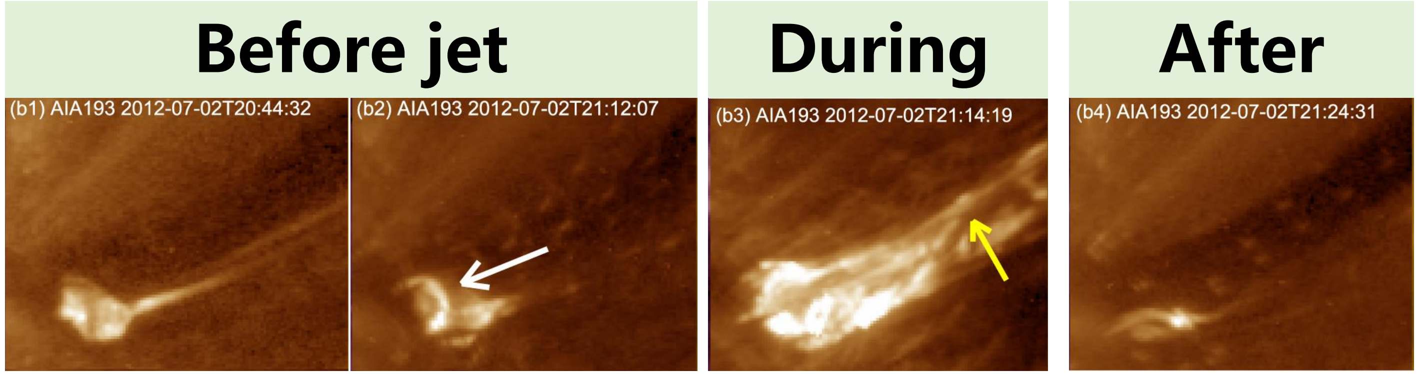
SONG et al. 2018

- 2012 May 10th, 04:18 UT
- AR11476, M5.7 flare
- Magnetic structure: Fan-Spine + flux rope

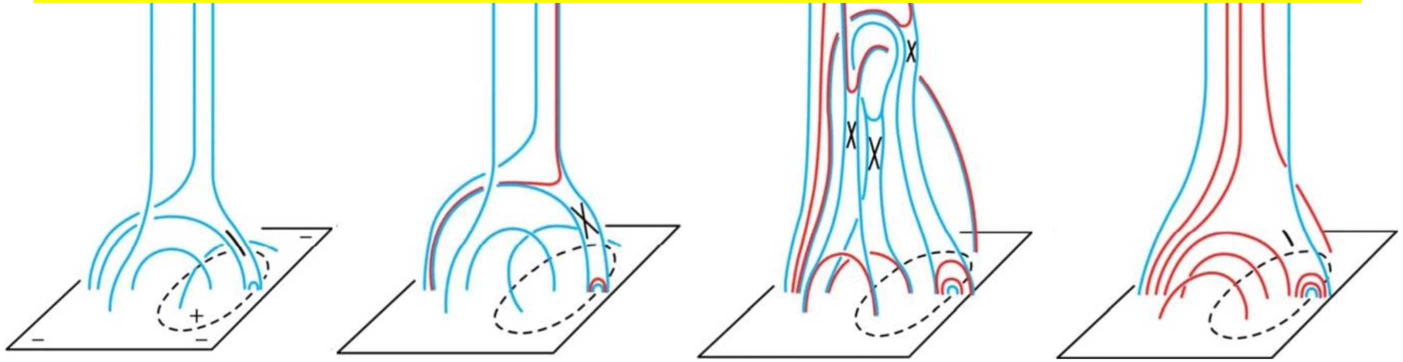


Blowout jet



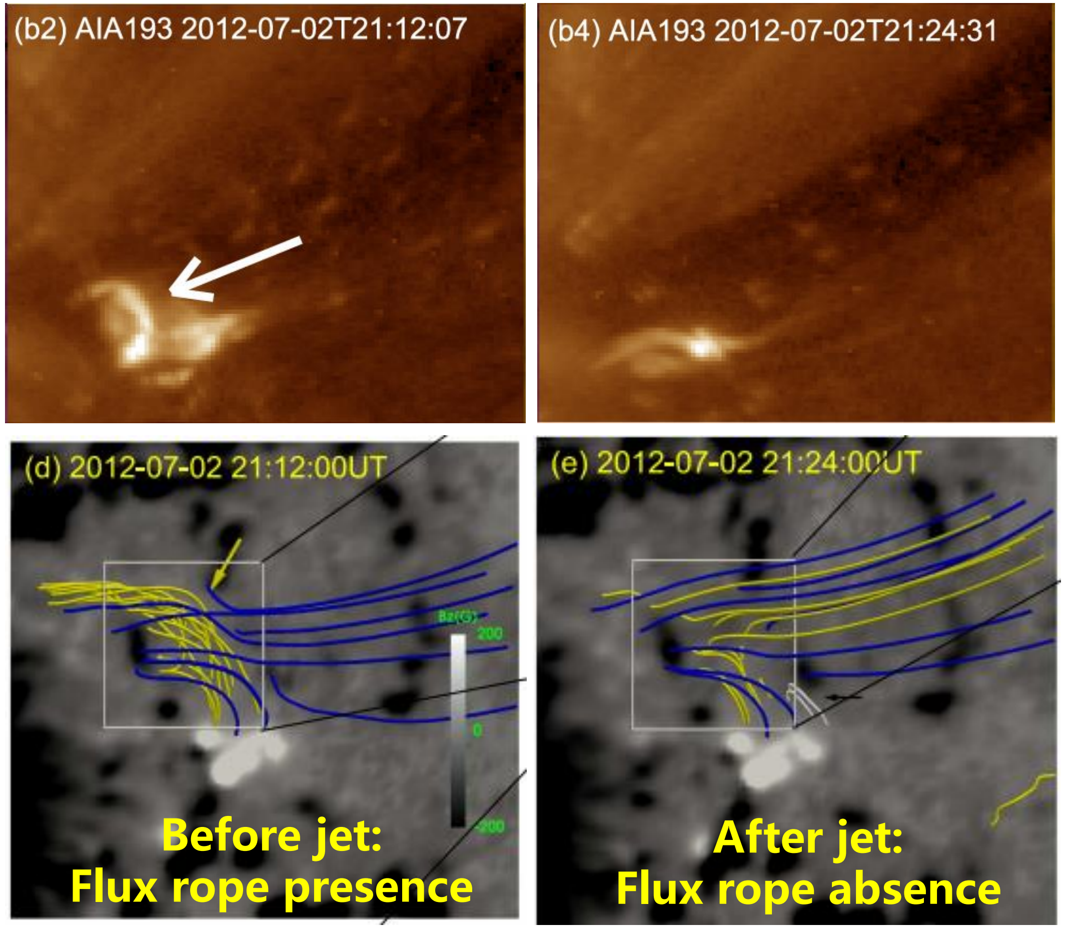


Reproduce the process by extrapolation?



Standard Model

Blowout jet

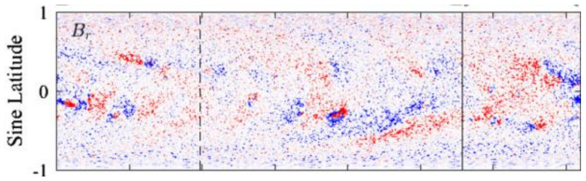


- **MHS extrapolation shows the blowout jet is caused by the blowing out of the magnetic flux rope at the source region**

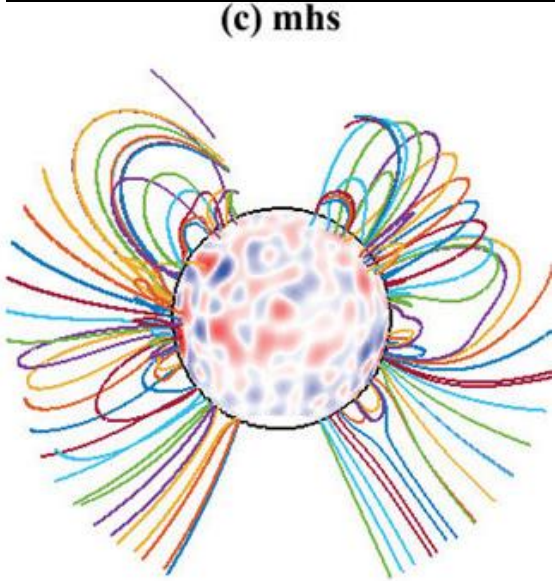
Global magnetic structure of the corona

- **The analytical MHS extrapolation during total solar eclipse**

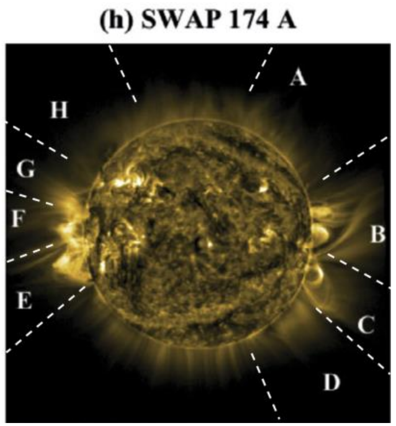
Synoptic magnetogram



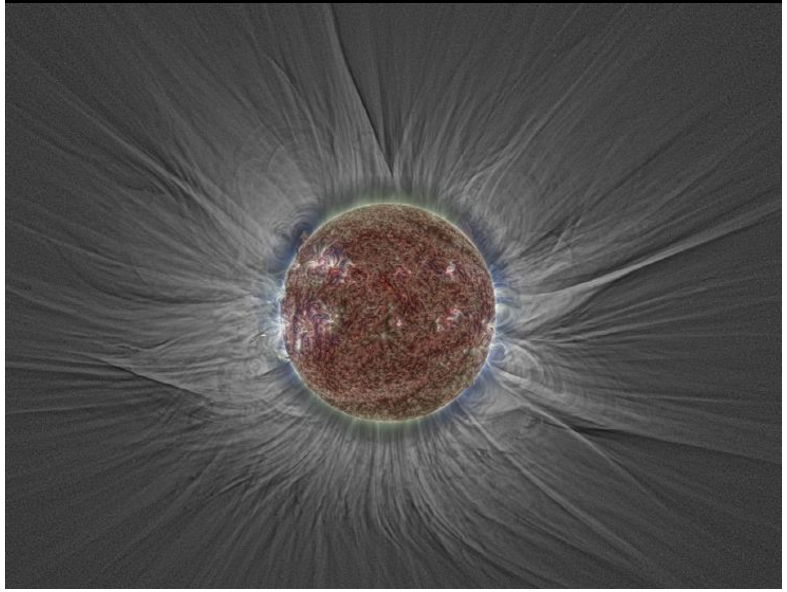
Analytical MHS solution



EUV 174 Å image



An EUV and white-light



Yeates, et al. 2018

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Cooperation: ISSI/ISSI-BJ international team

INTERNATIONAL SPACE SCIENCE INSTITUTE

Magnetohydrostatic Modeling of the Solar Atmosphere with New Datasets

ISSI Team led by Zhu Xiaoshuai & Chifu Iulia

INTERNATIONAL SPACE SCIENCE INSTITUTE - BEIJING
国际空间科学研究所-北京

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Takahiro Miyoshi	Hiroshima Univ., Japan
Jie Zhao	PMO, China
Yongliang Song	PMO, China
Xianyong Bai	NAOC, China
Ricardo Gafeira	Univ. of Coimbra, Portugal
Lilli Nadol	Univ. of St Andrews, UK
Daiki Yamasaki	JAXA, Japan

- Task 1: **Evaluate different MHS extrapolation techniques with known 3D reference models (both analytical and numerical). Identify problems in the modeling and make updates;**
- Task 2: Evaluate different MHS extrapolation techniques with DKIST (or GST, SST, IMaX/SUNRISE) photospheric vector magnetogram of an active region;
- Task 3: Use coronal images from multi-angle observations (EUI and AIA on board SolO and SDO, respectively) to constrain the magnetic field modeling.

First team meeting at ISSI-Beijing in July 2023

Thank you for your attention!