Online Advanced Study Program on Helicities in Astrophysics and Beyond- Extension Program 2021.04.16

Modeling, Observing and MHD Simulations of Relative Magnetic Helicity and its applications to the solar activity

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Outline

1. Magnetic Helicity Modeling Relative Magnetic Helicity

2. Magnetic Helicity in Newly Emerging Active Regions

3. Magnetic Helicity with Solar Cycles

4. Magnetic Helicity in the Solar Eruption

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Definition of magnetic helicity

19th century, Gauss discovered a simple formula which counts the linking of two Curves when study the asteroid orbits which linked the Earth's orbit. (Epple 1998)

Link number of two curves:

$$L_{12} = -\frac{1}{4\pi} \oint_1 \oint_2 \frac{\mathrm{d}\boldsymbol{x}}{\mathrm{d}\sigma} \cdot \frac{\boldsymbol{r}}{r^3} \times \frac{\mathrm{d}\boldsymbol{y}}{\mathrm{d}\tau} \, \mathrm{d}\tau \, \mathrm{d}\sigma.$$

Helicity of N flux tube:

$$K = \sum_{i=1}^{N} \sum_{j=1}^{N} L_{ij} \Phi_i \Phi_j.$$

$$N \to \infty \quad \Phi_i \to 0$$

$$K = -\frac{1}{4\pi} \int\int \boldsymbol{B}(\boldsymbol{x}) \cdot \frac{\boldsymbol{r}}{r^3} \times \boldsymbol{B}(\boldsymbol{y}) \, \mathrm{d}^3x \, \mathrm{d}^3y.$$

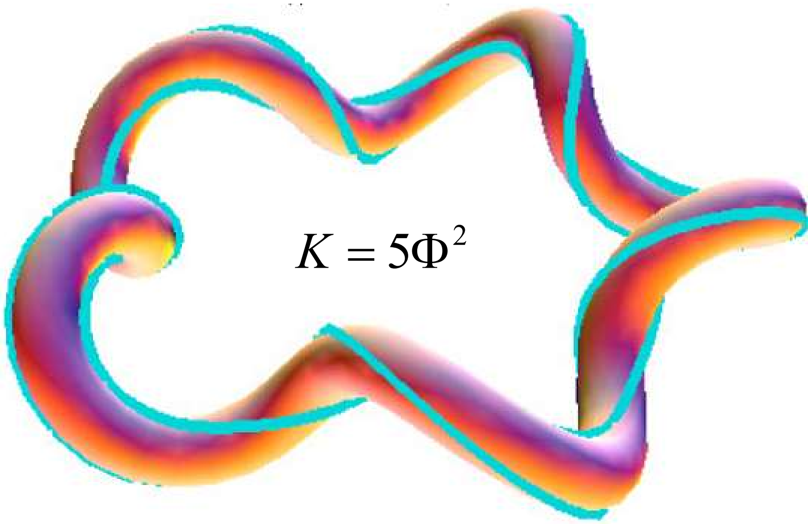
Coulomb Gauge:

$$\boldsymbol{A}(\boldsymbol{x}) = -\frac{1}{4\pi} \int \frac{\boldsymbol{r}}{r^3} \times \boldsymbol{B}(\boldsymbol{y}) \, \mathrm{d}^3y$$

Magnetic Helicity:

$$K = \int \boldsymbol{A} \cdot \boldsymbol{B} \, \mathrm{d}^3x.$$

The unit is Mx^2

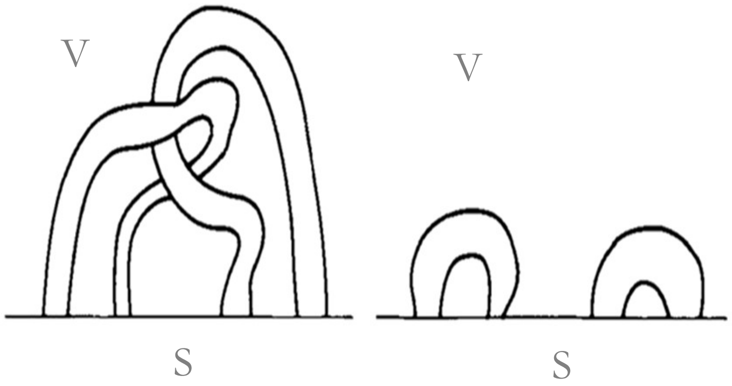


Berger (1999)

Definition of Relative Magnetic Helicity

Requirement of Invariance of magnetic helicity

$$H_m = \int \mathbf{A} \cdot \mathbf{B} d^3x \qquad H'_m = \int_v \left(\mathbf{A} + \nabla \psi\right) \cdot \mathbf{B} d^3x = H_m$$ **ONLY IF** $\vec{B} \cdot \widehat{n} \,|_s = 0$



$$\mathbf{B}_1 = \mathbf{B}\left(x \in V\right) \qquad \mathbf{B}_2 = \mathbf{P}(x \in V)$$

$$\mathbf{B} = \nabla \times \mathbf{A} \qquad \mathbf{P} = \nabla \times \mathbf{A}_p$$

Berger and Field (1984)

$$H_R = \int \left(\vec{A} + \vec{A}_p\right) \cdot \left(\vec{B} - \vec{P}\right) dV,$$

Finn-Antonsen Formula (1985)

IF $\nabla \cdot \boldsymbol{A_P} = 0 \qquad \boldsymbol{A_P} \cdot \hat{n}|_S = 0$

$$\frac{dH_R(V)}{dt} = -2\int_V \left(\vec{E} \bullet \vec{B}\right) dV + 2\oint_S \left(\vec{A}_P \times \vec{E}\right) \bullet d\vec{S}$$

Modeling Relative Magnetic Helicity in Cartesian Coordinate

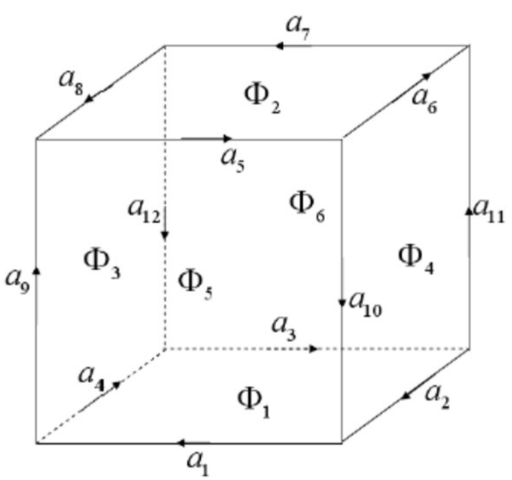
Formulas:

Divergence Free $\nabla \cdot \mathbf{A}_p{}' = 0$ $\quad \nabla \cdot \mathbf{A}' = 0$ $\quad \mathbf{A}_p \cdot \hat{n}\,|_s = 0$

Definition of Vector Potential $\nabla \times \mathbf{A}' = \mathbf{B}$ $\quad \nabla \times \mathbf{A}_p{}' = \mathbf{P}$

1: Boundary conditions of the vector potential

$$\hat{\mathbf{T}}'\mathbf{X} = \mathbf{F}'$$



$$\hat{\mathbf{T}}' = \begin{bmatrix} 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 & 0 & -1 & 1 & 0 & 0 & 1 \\ 0 & -1 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 1 & 1 & 0 \\ -1 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & -1 & -1 & 0 & 0 \\ 1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & -1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & -1 & 0 & 0 & 0 \end{bmatrix}$$

$$\mathbf{X} = (a_1, a_2, a_3, \ldots, a_{12})^{T}$$

$$\mathbf{F}' \quad (\Phi_1, \Phi_2, \Phi_3, \Phi_4, \Phi_5, 0, 0, 0, 0, 0, 0, 0)^{T}$$

$$A_{px}(a_i) = \frac{\pi a_i}{2L_x}\sin(\pi x/L_x), \quad i = 1, 3, 5, 7$$

$$A_{py}(a_i) = \frac{\pi a_i}{2L_y}\sin(\pi y/L_y), \quad i = 2, 4, 6, 8$$

$$A_{pz}(a_i) = \frac{\pi a_i}{2L_z}\sin(\pi z/L_z), \quad i = 9, 10, 11, 12$$

$$A_{px} = -\frac{\partial\varphi}{\partial y}, \qquad A_{py} = \frac{\partial\varphi}{\partial x}, \qquad A_{pz}|_{z=0} = 0.$$

$$\Delta\varphi(x, y) = B_z(x, y, z = 0)$$

Modeling Relative Magnetic Helicity in Cartesian Coordinate

2. Resolving the Poisson Equation of Vector potential

Yang , Buechner, Santos & Zhang (2013)
Yang , Buechner, Skala & Zhang (2018)

$$\nabla\times\left(\nabla\times\vec{A}_p\right)=\nabla\left(\nabla\bullet\vec{A}_p\right)-\Delta\vec{A}_p=0 \qquad \Delta\vec{A}=-\vec{J}$$

$$\nabla\times\left(\nabla\times\vec{A}\right)=\nabla\left(\nabla\bullet\vec{A}\right)-\Delta\vec{A}=\vec{J} \qquad \Delta\vec{A}_p=0$$

The solution of Poission/Laplace equation doesn't satisfy the gauge of Vector potentail

3. Modify vector potential $\nabla\times\mathbf{M}_p+\mathbf{A}_p$

$$\begin{cases}\Delta M_z=\left(\nabla\times\mathbf{A}_p\right)_z-P_z\\ M_z\left(z=0,l_z\right)=0\\ \dfrac{\partial M_z}{\partial x}\left(x=0,l_x\right)=0\\ \dfrac{\partial M_z}{\partial y}\left(y=0,l_y\right)=0\end{cases},\quad \begin{cases}\Delta M_y=\left(\nabla\times\mathbf{A}_p\right)_y-P_y\\ M_y\left(y=0,l_y\right)=0\\ \dfrac{\partial M_y}{\partial x}\left(x=0,l_x\right)=0\\ \dfrac{\partial M_y}{\partial z}\left(z=0,l_z\right)=0\end{cases},\quad \begin{cases}\Delta M_x=\left(\nabla\times\mathbf{A}_p\right)_x-P_x\\ M_x\left(x=0,l_x\right)=0\\ \dfrac{\partial M_x}{\partial y}\left(y=0,l_y\right)=0\\ \dfrac{\partial M_x}{\partial z}\left(z=0,l_z\right)=0\end{cases}$$

Mixed-type boundary condition

Similar for **A**

(4) Modify the boundary condition of Vector Potentials and clean the Divergence

$$\begin{cases}\Delta\phi=-\nabla\cdot\mathbf{A}_P\\ \left.\dfrac{\partial\phi}{\partial n}\right|_s=-\left(\nabla\times\mathbf{M}_p\right)\cdot\hat{n}\Big|_s\end{cases}$$

Hermann von Helmholtz

$$\mathbf{A_p}'=\mathbf{A_p}+\nabla\times\mathbf{M}_p+\nabla\phi_p$$

$$\mathbf{A}'=\mathbf{A}+\nabla\times\mathbf{M}+\nabla\phi$$

$$H_R=\int\left(\vec{A}+\vec{A}_p\right)\cdot\left(\vec{B}-\vec{P}\right)dV,$$

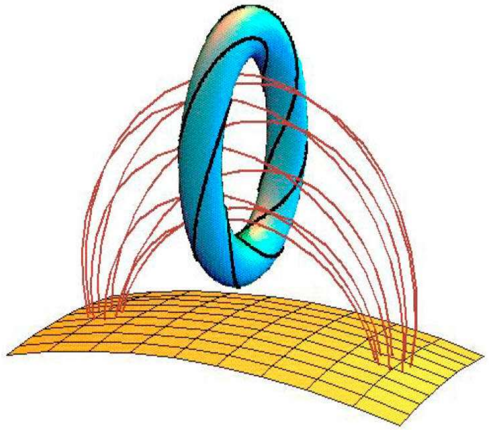
Remote Magnetic Helicity Calculation System

Please Register Here: http://sun.bao.ac.cn/NAOCHSOS/rmhcs.htm

Download Address: https://github.com/youngastronomy/RMHCS

Calculate Relative Magnetic Helicity through this system in IDL just run

rh3d_remote,bx,by,bz,*name*=name,email=email



INTERNATIONAL SPACE SCIENCE INSTITUTE

Magnetic Helicity estimations in models and observations of the solar magnetic field

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*Etienne Pariat**, LESIA - Observatoire de Paris Meudon (France)*
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Yang Liu, Stanford University (USA)
Georgoulis Manolis, Academy of Athens (Greece)
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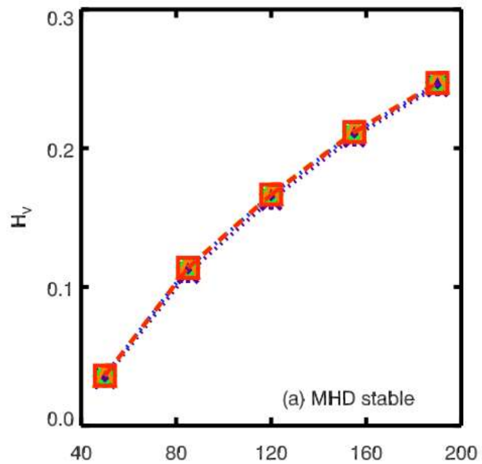
http://www.issibern.ch/teams/magnetichelicity/



Note:

The maximul size of data is **256x256x256, less in 10 minutes.**
the data can be resized to small volume to obtain the very similar results.

Valori et al. 2016 Space Science Review

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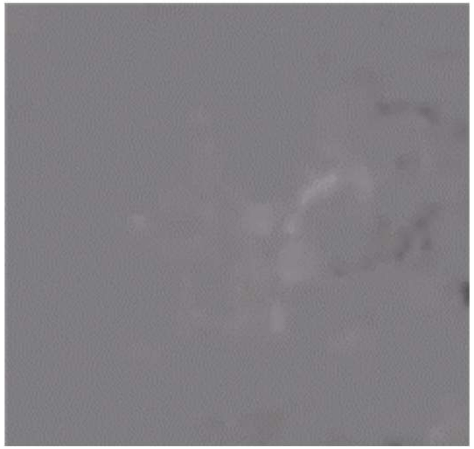
Modeling Relative Magnetic Helicity in Observations

General formula for relative magnetic helicity evolution in a volume

$$\frac{dH_R(V)}{dt} = -2\int_V \left(\vec{E}\bullet\vec{B}\right)dV + 2\oint_S \left(\vec{A}_P\times\vec{E}\right)\bullet d\vec{S}$$

Dissipation + Helicity Flux across boundary

Emerging and Shearing
Of One Newly Emerging
Active Regions



Ideal MHD:

$$\frac{dH_R}{dt} = 2\int_S \left(\left(\vec{A}_P\bullet\vec{V}\right)\vec{B} - \left(\vec{A}_P\bullet\vec{B}\right)\vec{V}\right)\bullet d\vec{S}$$

Shearing + Emerging

$$\frac{dH_R}{dt} = -2\int_S \left(\vec{A}_P\cdot\vec{U}_{LCT}\right)B_n d\vec{S}$$

Chae et al. (2001)
Demoulin and Berger (2003)

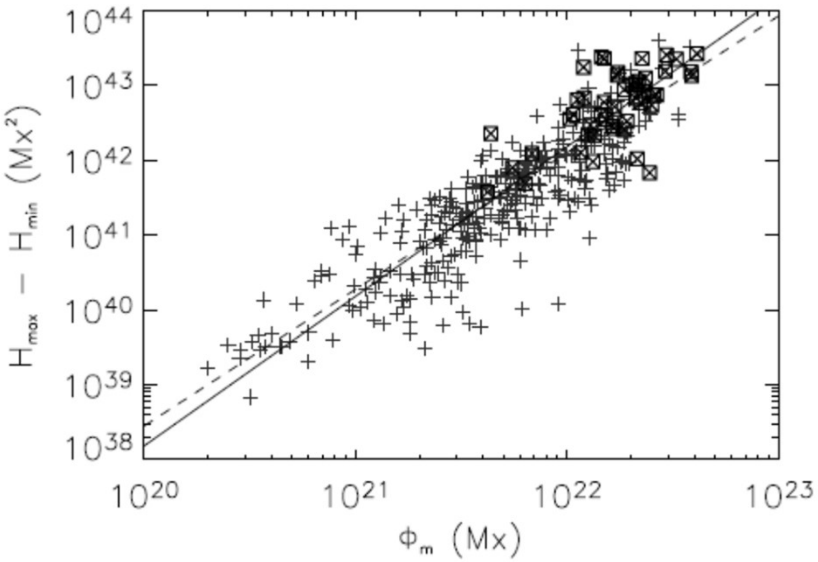
Combine Shearing and Emerging Term together

$$H_m(t) = \int_0^t \frac{dH_R(t)}{dt}dt,$$

Newly Emerging Active Regions including t=0

How Twisted in emerging flux tube?

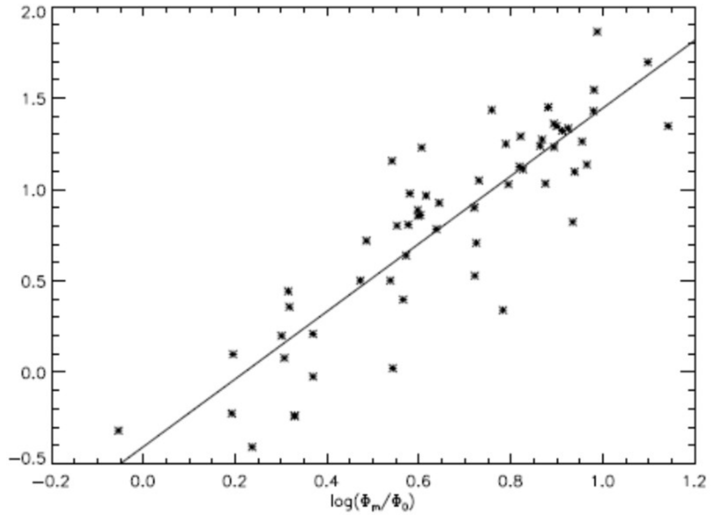
393 Larger ARs



$$H \propto |\Phi|^{1.8}$$

LaBonte, et al. 2007, ApJ,671,955

58 Newly Emerging ARs (Simple, small)



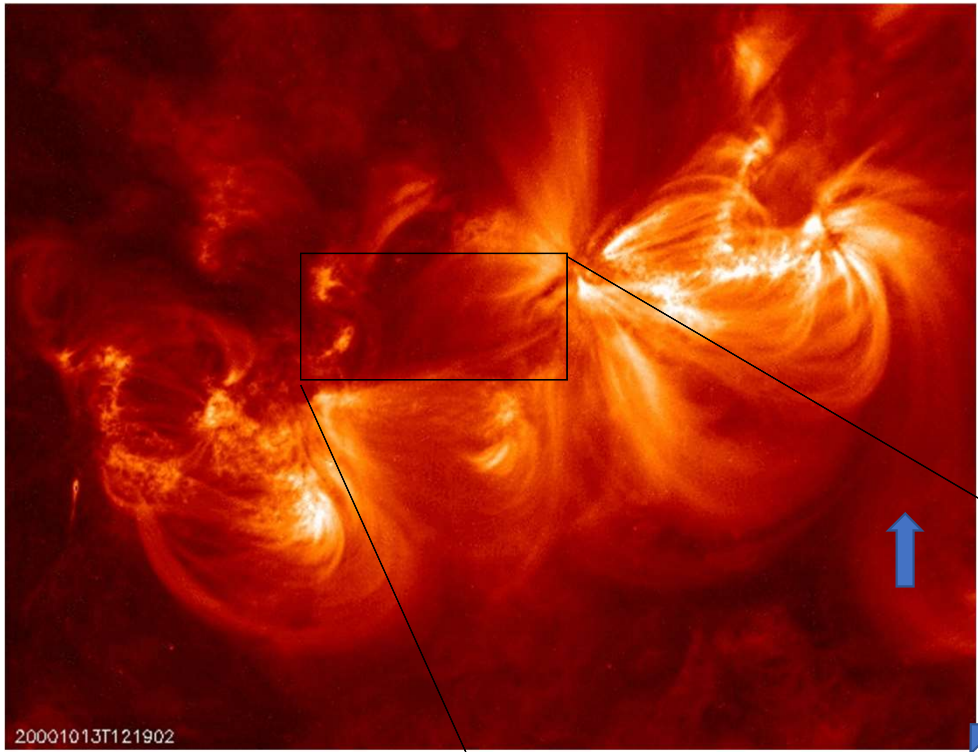
$$\log \frac{H_{\max} - H_{\min}}{H_0} = a \log \frac{\Phi_m}{\Phi_0} + b$$

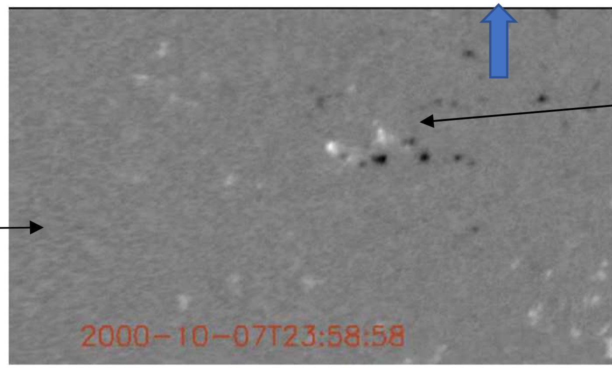
（a=**1.85** b=-0.41） Yang et al. 2009

No matter how big of the solar active regions, they are both twisted similarly in global topology.

Magnetic helicity exchange between neighboring emerging ARs

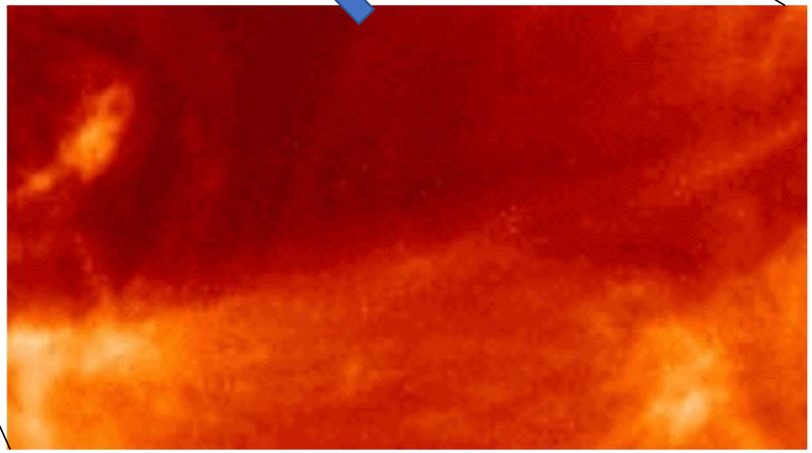
S. Yang, J. Büchner, and H. Zhang 2009, ApJ, L25

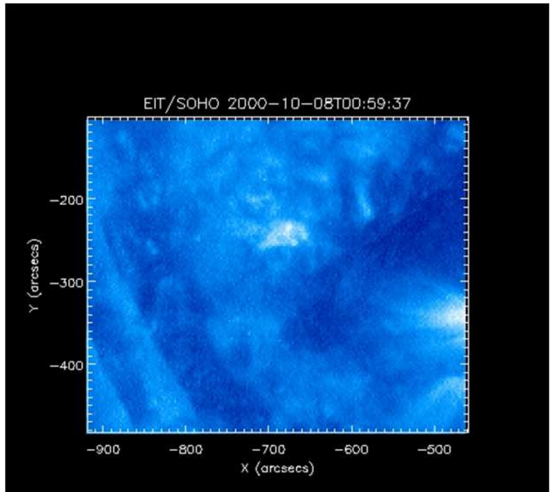




NOAA 9188

NOAA 9192



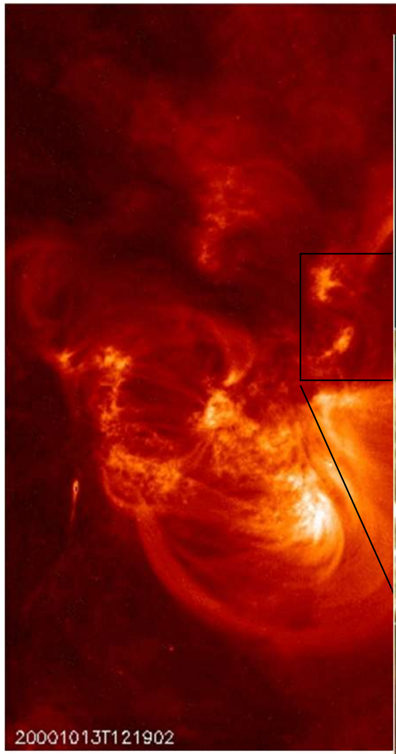


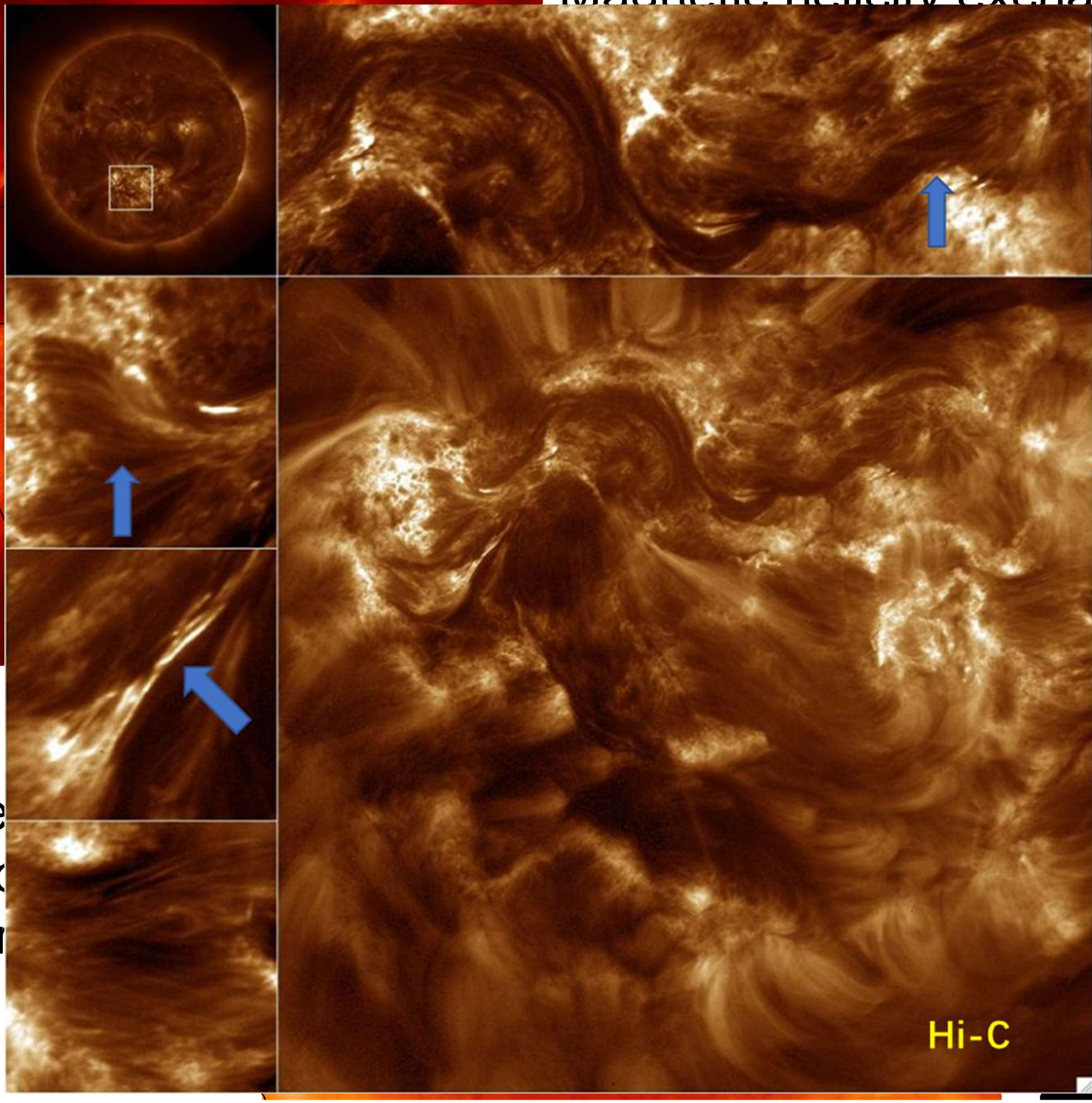
Twist motion appeared in the exchange process From Trace Observation

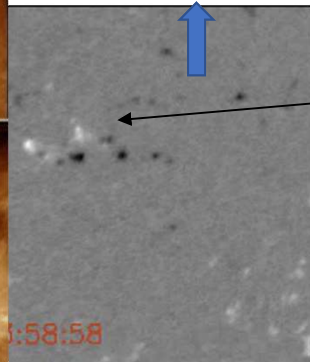
Magnetic helicity exchange between

ARs

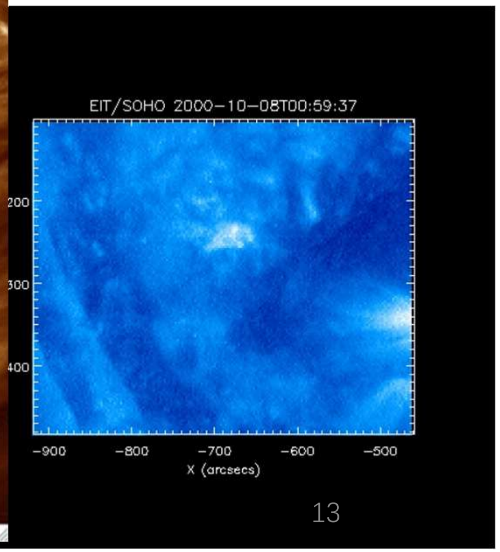
. Zhang 2009, ApJ, L25







NOAA 9188

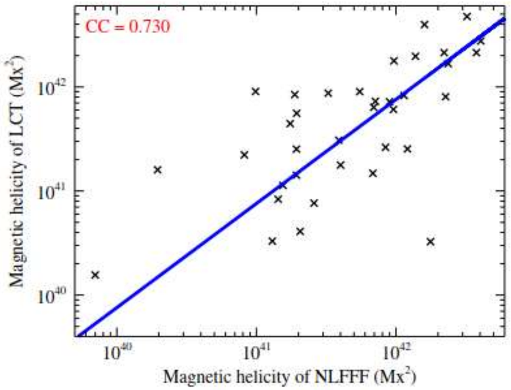


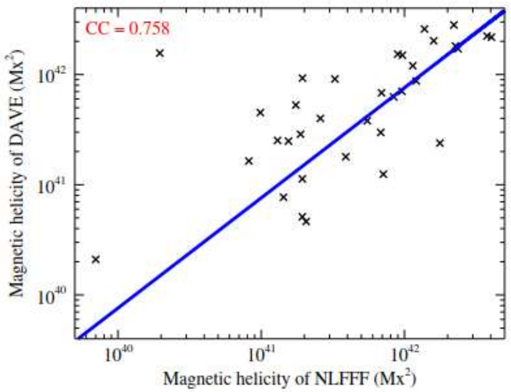
Twist motion appe

the exchange proc

From Trace Obser

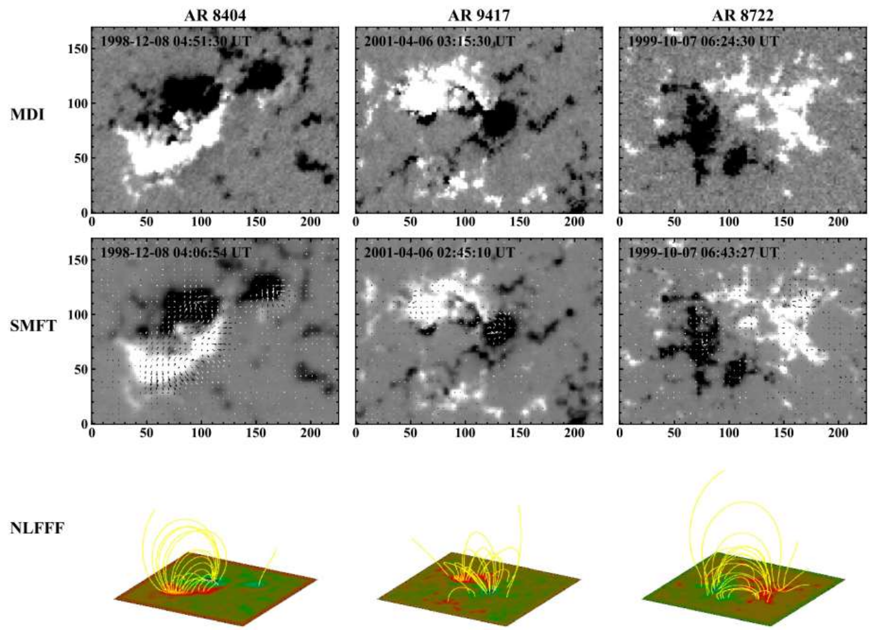
Comparison of helicity flux and accumulated magnetic helicity





1. Magnetic helicity flux Integration of Newly Emerging Active Regions
2 NLFFF magnetic field and Calculate its Relative magnetic helicity

Consistence generally but some difference is still there



How is magnetic helicity is redistributed in filament, solar corona, solar wind, Interplanetary, magnetic cloud etc. is still an open question.

Wang Quan et al. (2021a)

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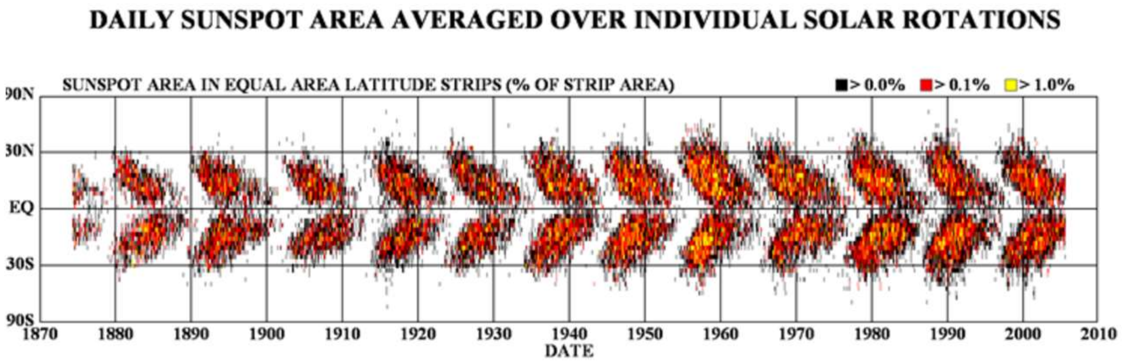
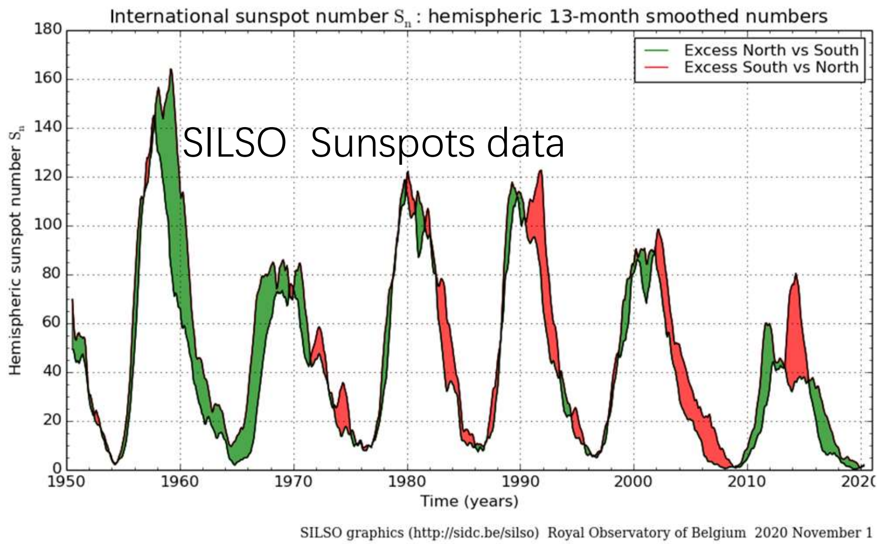
Imbalance of Solar Cycle: Observation Facts



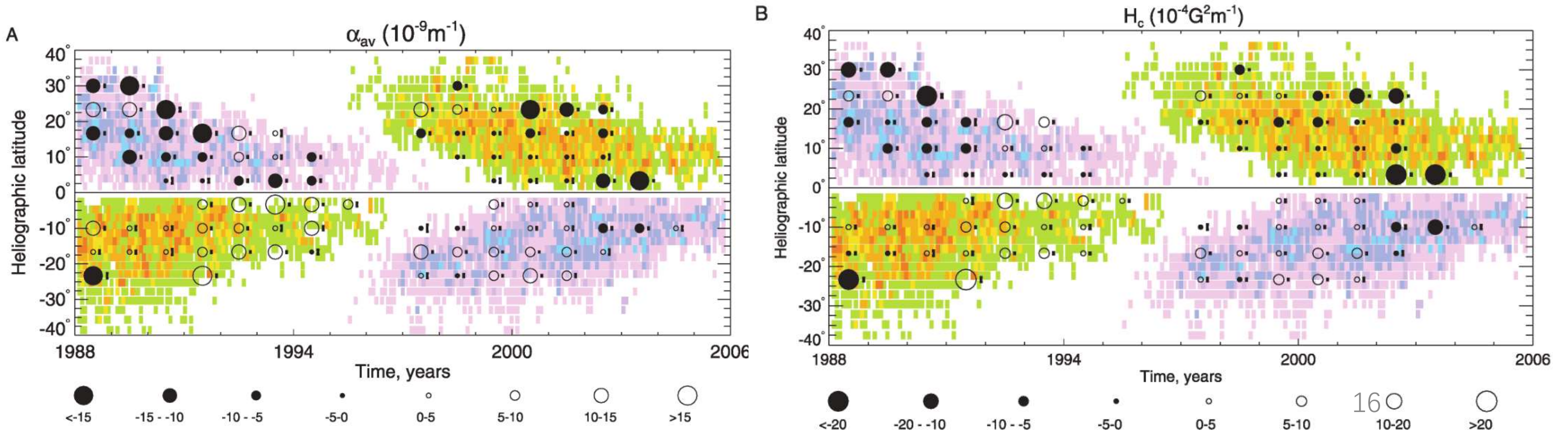


Seehafer (1990)
Bao & Zhang (1998)
etc…

HHR（Helicity Hemisphere Rule）

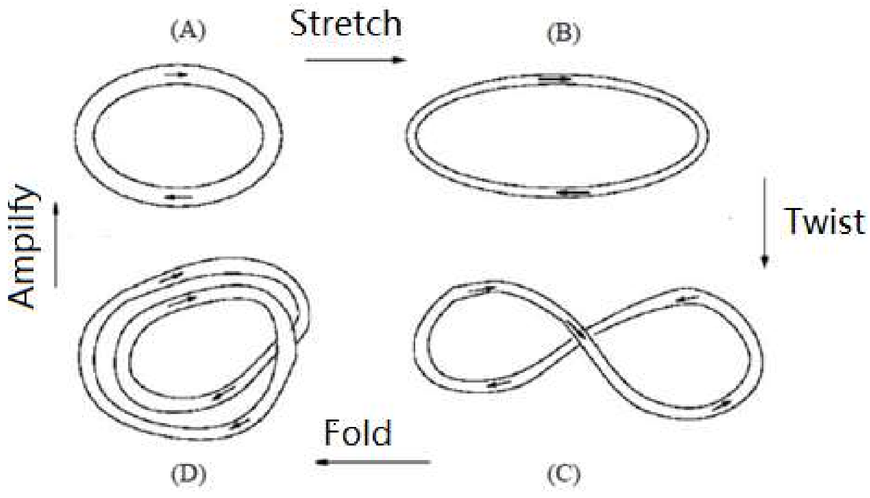
Current helicity diagram from Huairou Solar Observation Station

Zhang et al. (2010) MNRAS



Magnetic heliciy in Solar dynamo

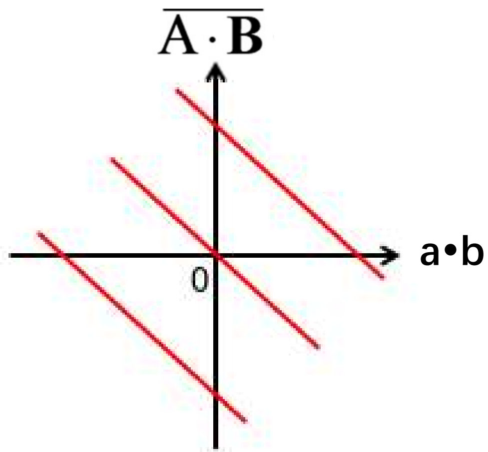
Magnetic helicity is conserved in the limit of large Rm



A schematic illustration of the stretch-twist-fold-merge dynamo.

$$\chi^{(tot)} = \overline{\mathbf{A}\cdot\mathbf{B}} + \mathbf{a}\cdot\mathbf{b} \quad \Rightarrow \quad \overline{\mathbf{A}}\cdot\overline{\mathbf{B}} = -\,\mathbf{a}\cdot\mathbf{b} + \chi^{(tot)}$$

$$\chi^{(tot)} = ?\ \ (-, 0, +)$$



Frisch et al. (1975, 76)
Hubbard & Brandenburg (2012)
Pipin et al. (2013)

What’s the magnetic helicity evolution in one solar cycle from observation?

Magnetic heliciy in Solar dynamo

Magnetic helicity is conserved in the limit of large Rm

Twist

amo.

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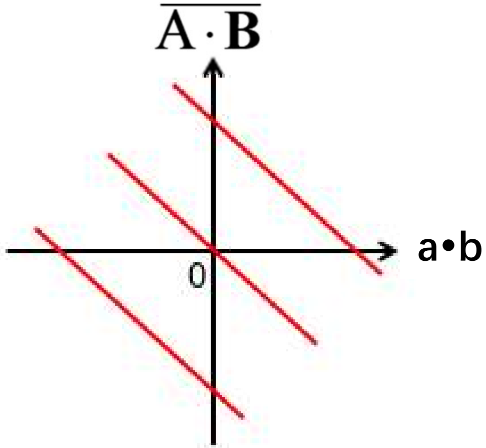

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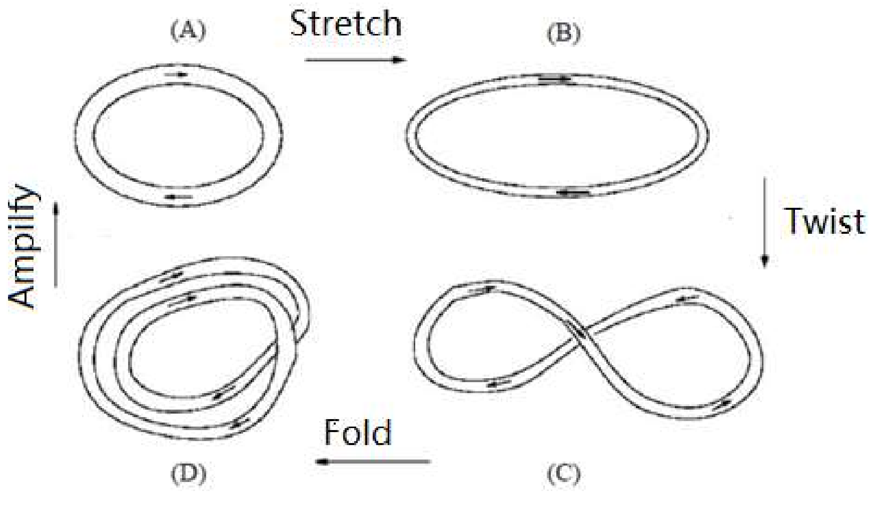

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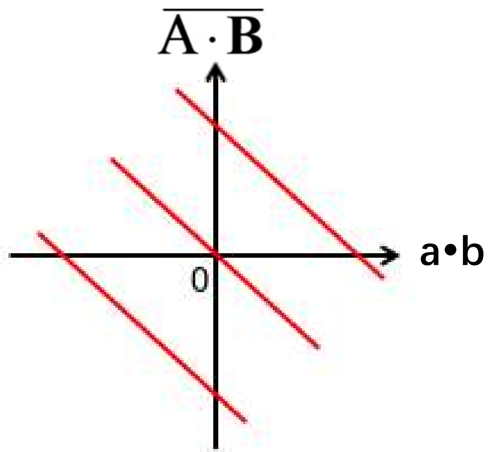

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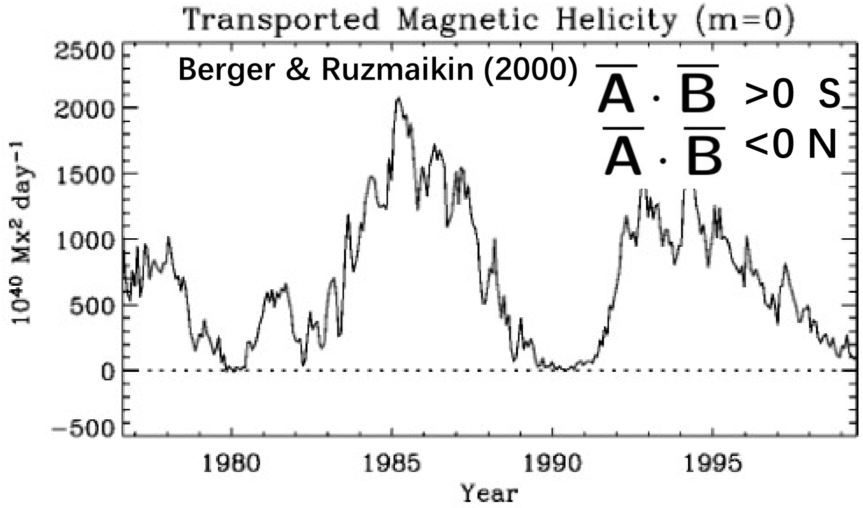


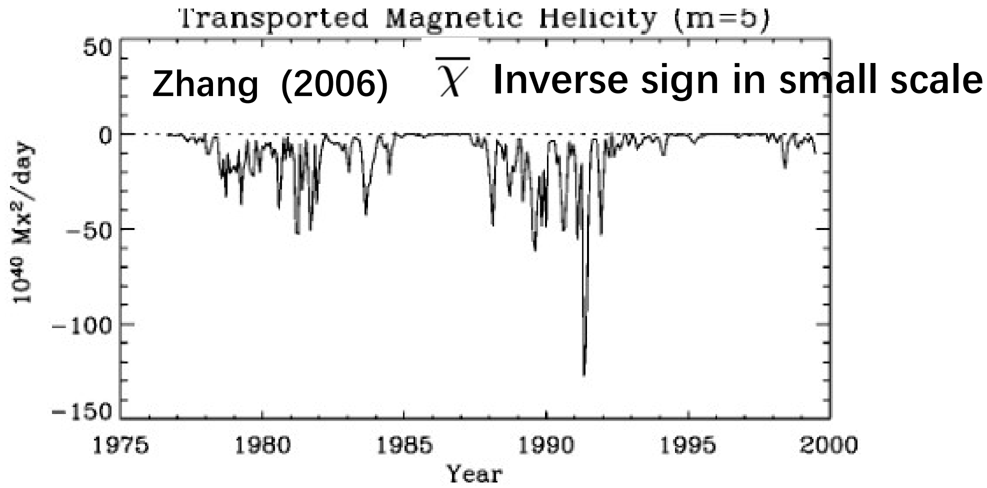


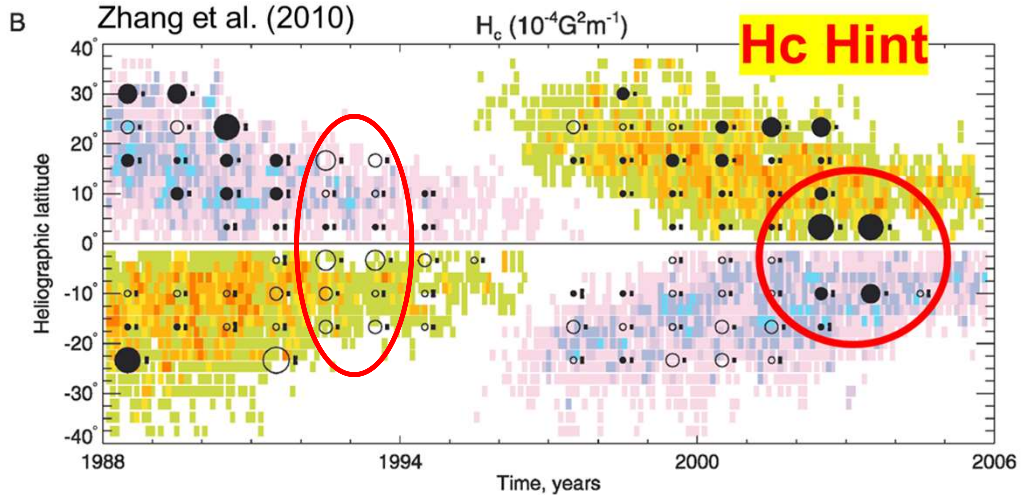
FIG. 3.—*Top and middle*: Same as in Fig. 2 but for strong fields ($|B_z| >$ 1000 G). *Bottom*: Same as in Fig. 2 but for $m = 5$ mode.

Table 1
Results of the Analysis Applied to the Timeseries of Figure 1

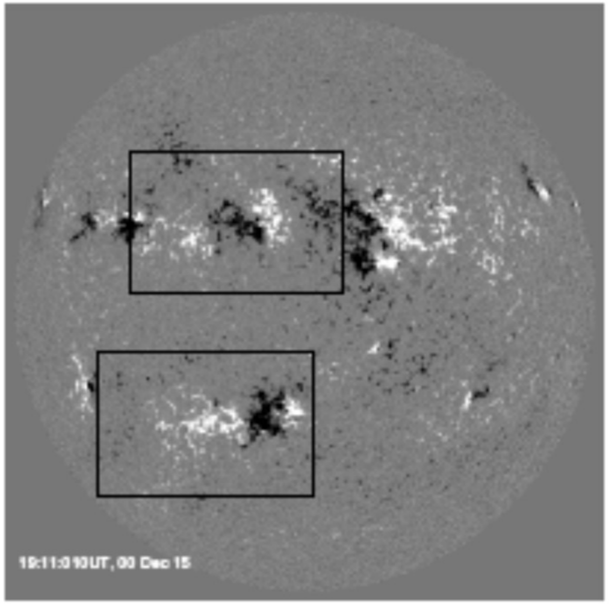
Figure	N	Hemisphere	$\Delta H_{m(+)}$ ($\times 10^{44}$ Mx^2)	$\Delta H_{m(-)}$ ($\times 10^{44}$ Mx^2)	ε_{H_m}	Differential Rotation?
1(a)	393	Both	5.37	−5.45	−0.0076	YES
1(b)	197	Northern	0.9	−4.23	−0.65	YES
1(c)	196	Southern	4.47	−1.22	0.57	YES
1(d)	393	Both	4.12	−4.28	−0.019	NO
1(e)	197	Northern	1.66	−2.53	−0.21	NO
1(f)	196	Southern	2.46	−1.75	0.17	NO

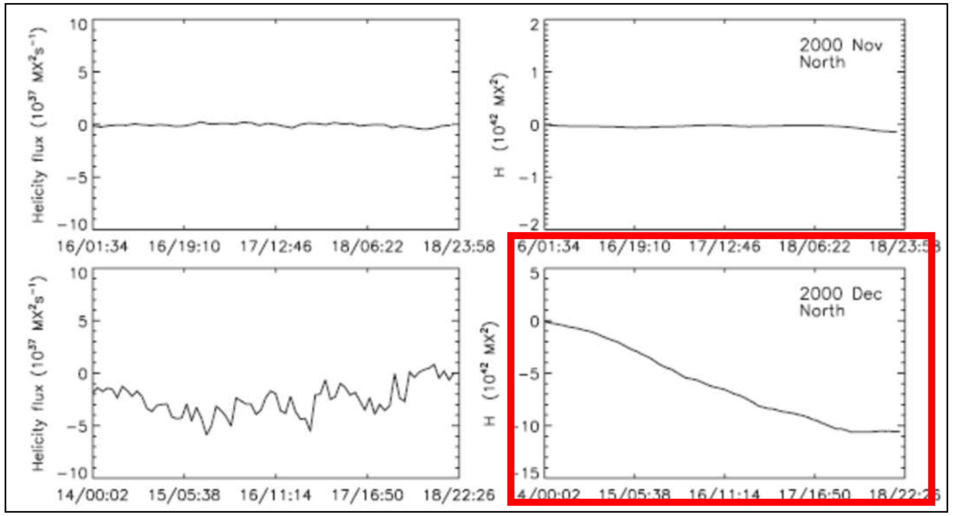
Net Magnetic helicity in 23rd Solar cycle is approximately Zero.

M. K. Georgoulis et al. (2009)



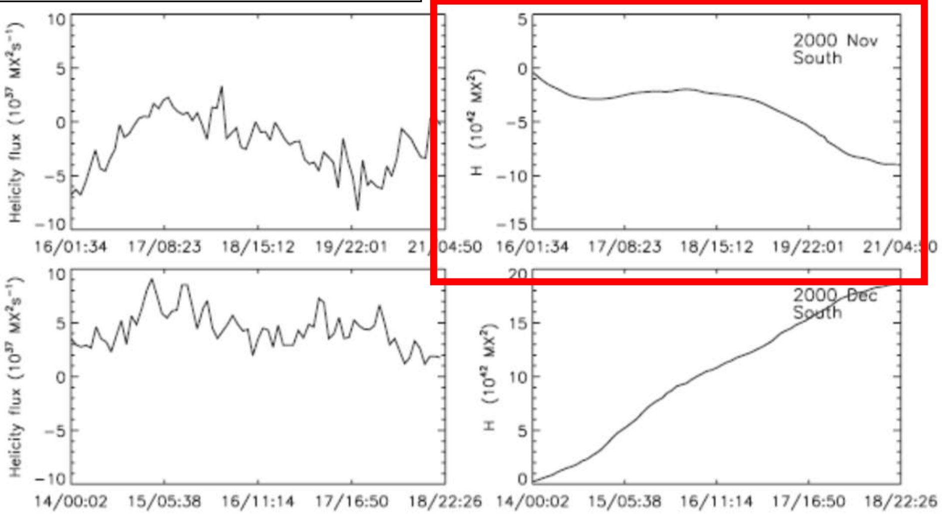
Two Hemispheres have the same sign of helicity transport





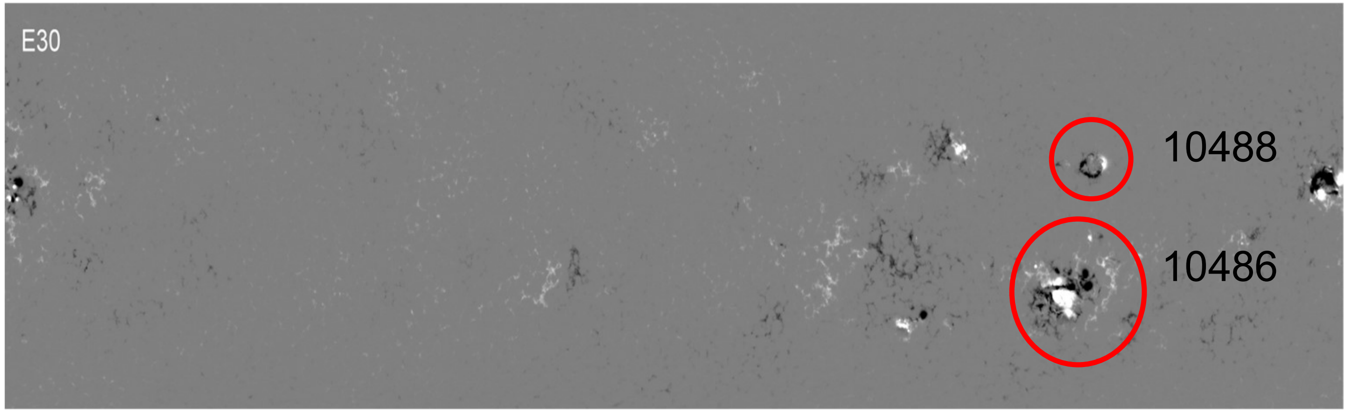
Northern AR

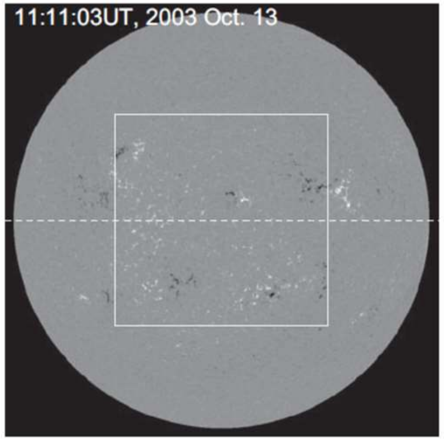
Southern AR



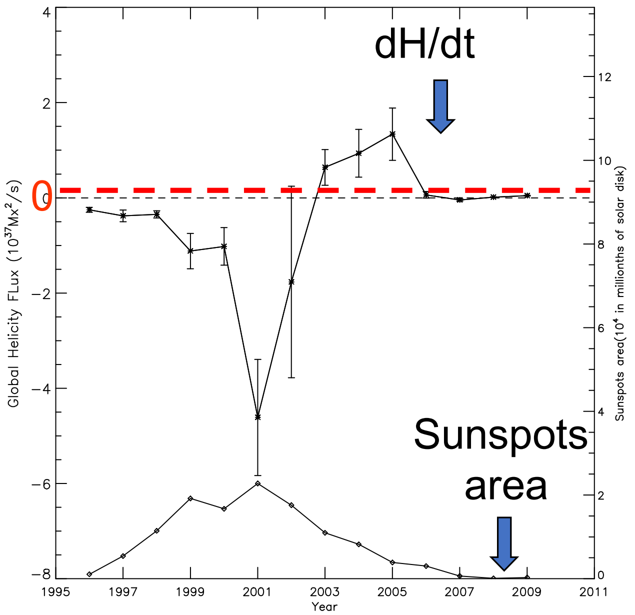
Zhang Hongqi, Yang Shangbin, Gao Yu, Su Jiangtao, Sokoloff, D. D. & Kuzanyan. K 2010, ApJ, 719, 1955

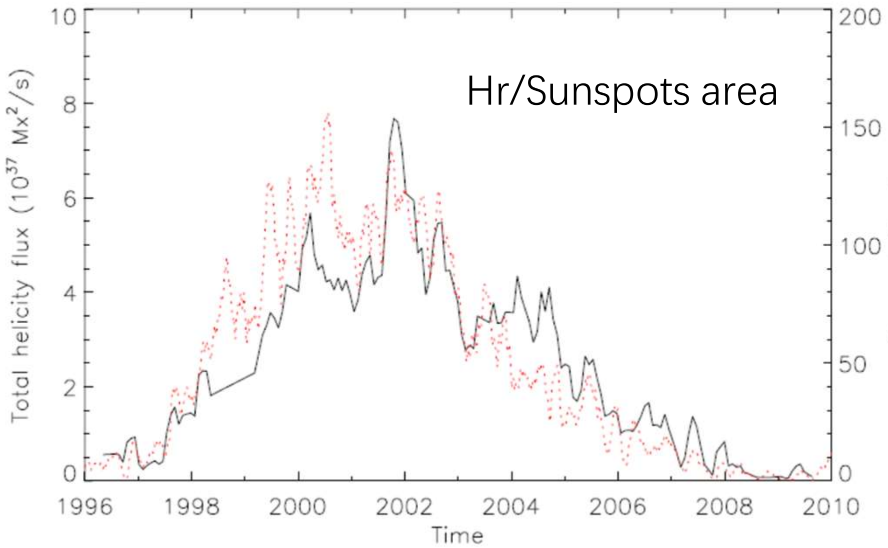
Imbalance of magnetic helicity with solar cycles-23 solar cycle





MDI (1996-2009)





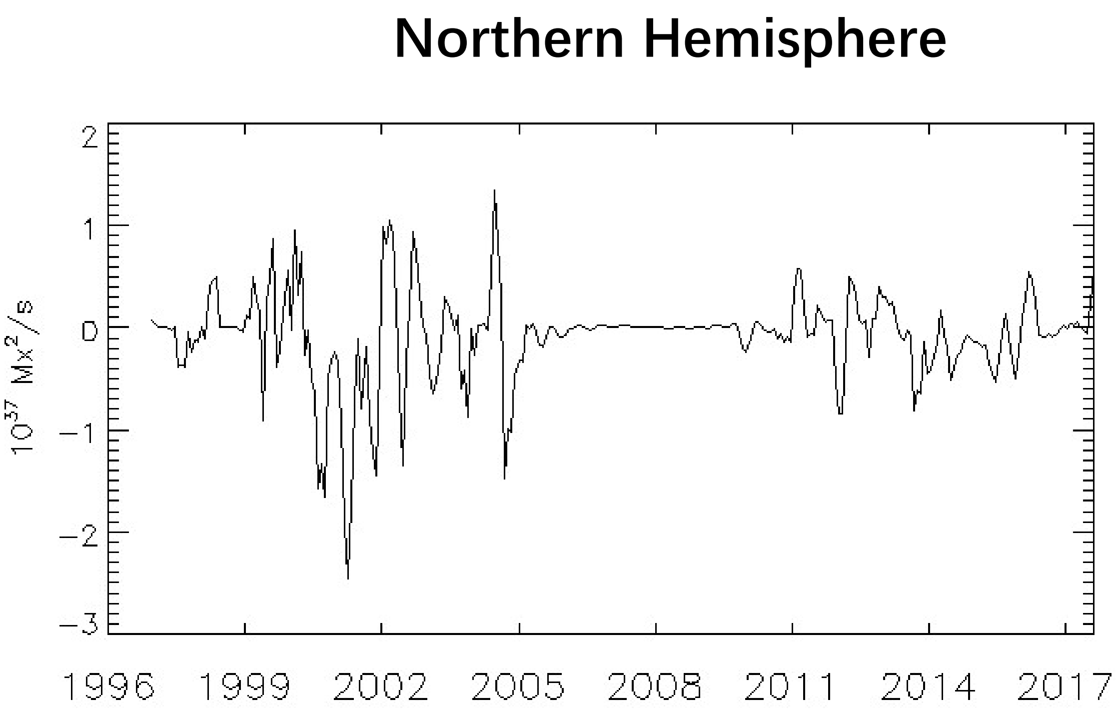
$\sim 10^{46} Mx^2$

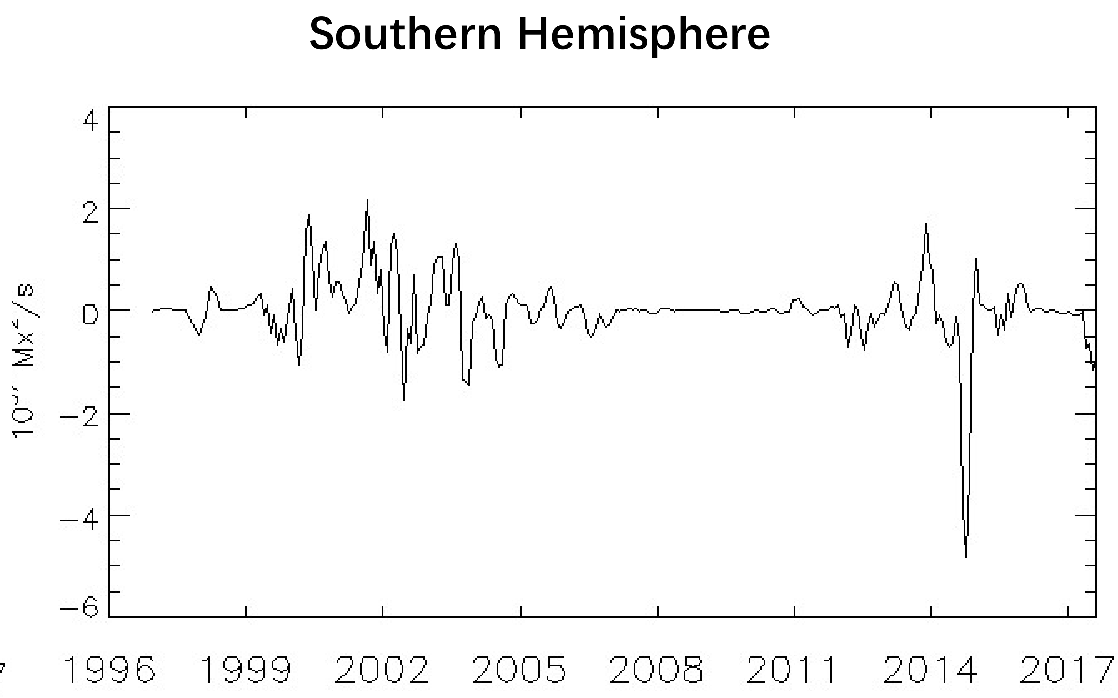
Solar Cycle

Yang Shangbin & Zhang Hongqi 2012,ApJ

Zhang Hongqi and Yang Shangin 2013，ApJ

Imbalance of magnetic helicity fluxes with solar cycles 23-24





Mixture of positive and negative helicity flux with solar cycles

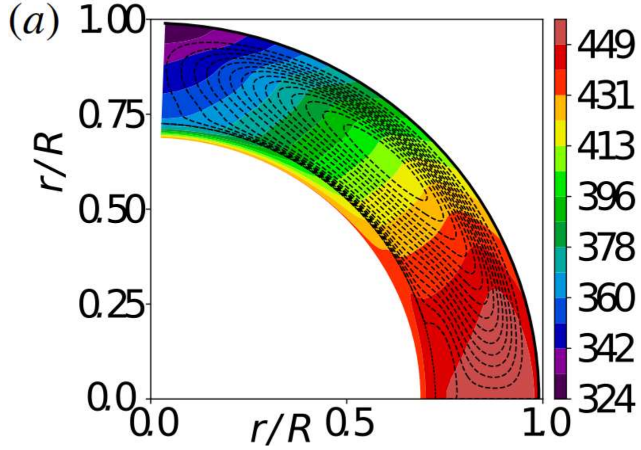
Solar Dynamo Modeling

$$\frac{\partial \overline{\boldsymbol{B}}}{\partial t} = \nabla \times (\boldsymbol{\mathcal{E}} + \overline{\mathbf{U}} \times \overline{\boldsymbol{B}})$$

- MeanField Dynamo **Pipin, V. V. & Kosovichev (2018, 2019)**

α-effect Pumping effect Diffusive Tensor

$$\mathcal{E}_i = (\alpha_{ij} + \gamma_{ij}^{(\Lambda)})\overline{B}_j + \eta_{ijk}\nabla_j\overline{B}_k.$$



Meridional flow

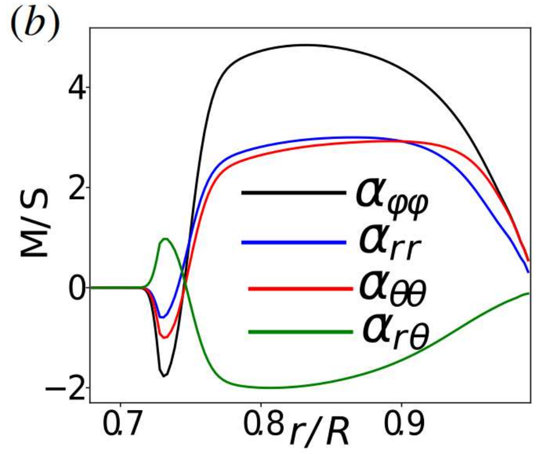
- Total helicity Conservation $\overline{\chi}^{(\mathrm{tot})} = \overline{\boldsymbol{A}\cdot\boldsymbol{B}} = \overline{\boldsymbol{A}}\cdot\overline{\boldsymbol{B}} + \overline{\boldsymbol{a}\cdot\boldsymbol{b}}$ Large Scale+Small Scale

$$\frac{\mathrm{d}}{\mathrm{d}t}\int \overline{\chi}^{(\mathrm{tot})}\,\mathrm{d}V = -2\eta\int\{\overline{\boldsymbol{B}}\cdot\overline{\boldsymbol{J}} + \overline{\boldsymbol{b}\cdot\boldsymbol{j}}\}\,\mathrm{d}V - \int \nabla\cdot\boldsymbol{\mathcal{F}}^{\chi}\,\mathrm{d}V$$

Hubbard & Brandenburg (2012)

$$\frac{\partial \overline{\chi}^{(\mathrm{tot})}}{\partial t} = -\frac{\overline{\chi}}{R_m\tau_c} - 2\eta\overline{\boldsymbol{B}}\cdot\overline{\boldsymbol{J}} - \nabla\cdot\boldsymbol{\mathcal{F}}^{\chi} - (\overline{\boldsymbol{U}}\cdot\nabla)\overline{\chi}^{(\mathrm{tot})}.$$

Small-scale Current-Dissipation Helicity flux at the boundary Large Scale flow



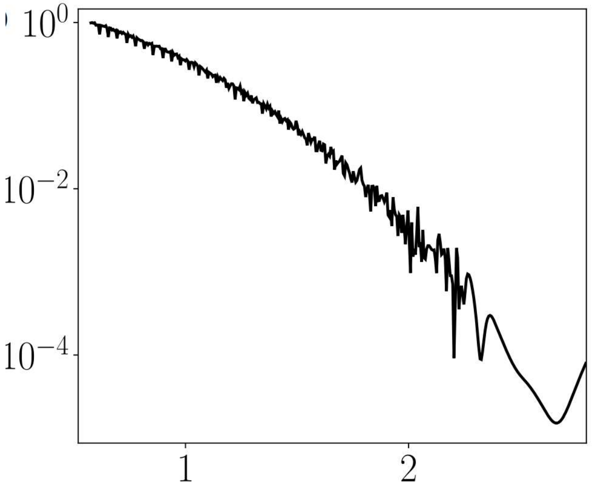
α-effect (lat=45°)

Dynamo Parameter Setting

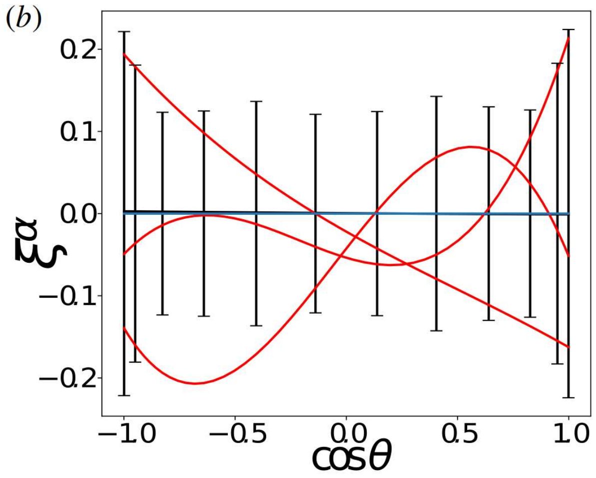
Guerrero, Chattejee & Brandenburg (2010)

$$\alpha_{ij} = C_\alpha (1 + \xi^{(\alpha)}(t,\theta))\alpha_{ij}^{(H)} + \alpha_{ij}^{(M)},$$

$$\frac{\partial \overline{\chi}^{(\mathrm{tot})}}{\partial t} = -\frac{\overline{\chi}}{R_m \tau_c} - 2\eta \overline{\boldsymbol{B}} \cdot \overline{\boldsymbol{J}} - \nabla \cdot \boldsymbol{F} - \frac{\tau_\xi(r)}{\tau_{0r}} \sin^2\theta (\xi^{(\chi)}(t,\theta)\overline{\chi} + \xi^{(m)}(t,\theta)\overline{\chi}^{(m)})$$



RENEWAL Time Distribution

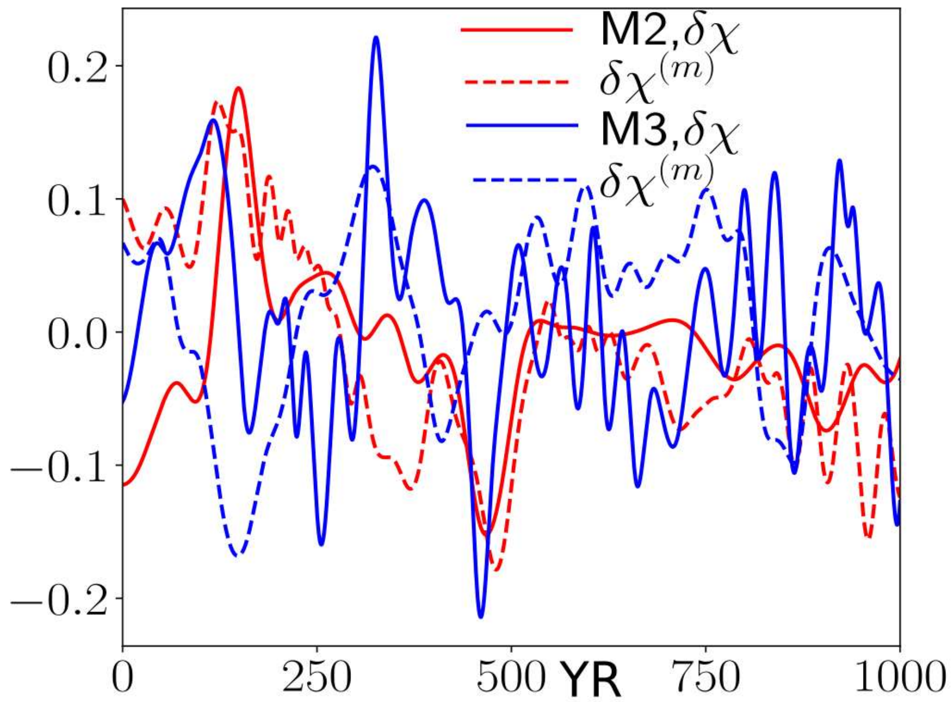


Latitude Distribution

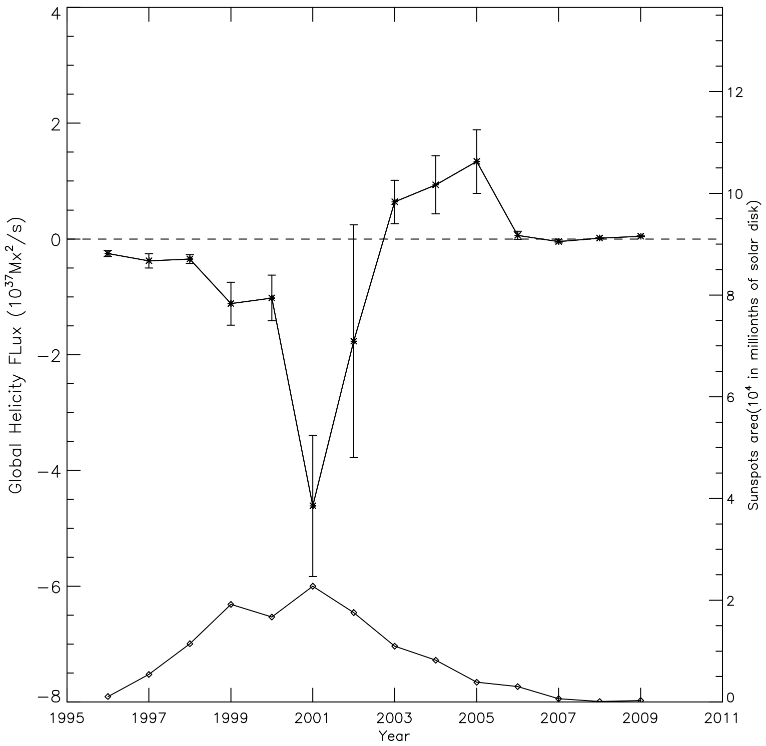
Model	$\xi^{(\alpha)}$	$\xi^{(\chi)}$	$\xi^{(m)}$
M1	Yes	No	No
M2	$\langle\xi^{(\alpha)}\rangle$	No	Yes
M3	$\langle\xi^{(\alpha)}\rangle$	Yes	No
M4	$\langle\xi^{(\alpha)}\rangle$	Yes	Yes

$$\tau_\xi(r) = \tfrac{1}{2}[1 - \mathrm{erf}(100(r_0 - r))]$$

Model Simulation



Observations



Show the imbalance evolution of magnetic helicity with solar cycles in the observations

Yang, Pipin, Sokoloff et al. 2020, Journal of Plasma Physics, vol. 86, 775860302

Outline

1. Modeling Relative Magnetic Helicity

2. Magnetic Helicity in Newly Emerging Active Regions

3. Magnetic Helicity With Solar Cycles

4. Magnetic Helicity in the Solar Eruption

Theoretical analysis-I

Sturrock 2001, ApJ, 548

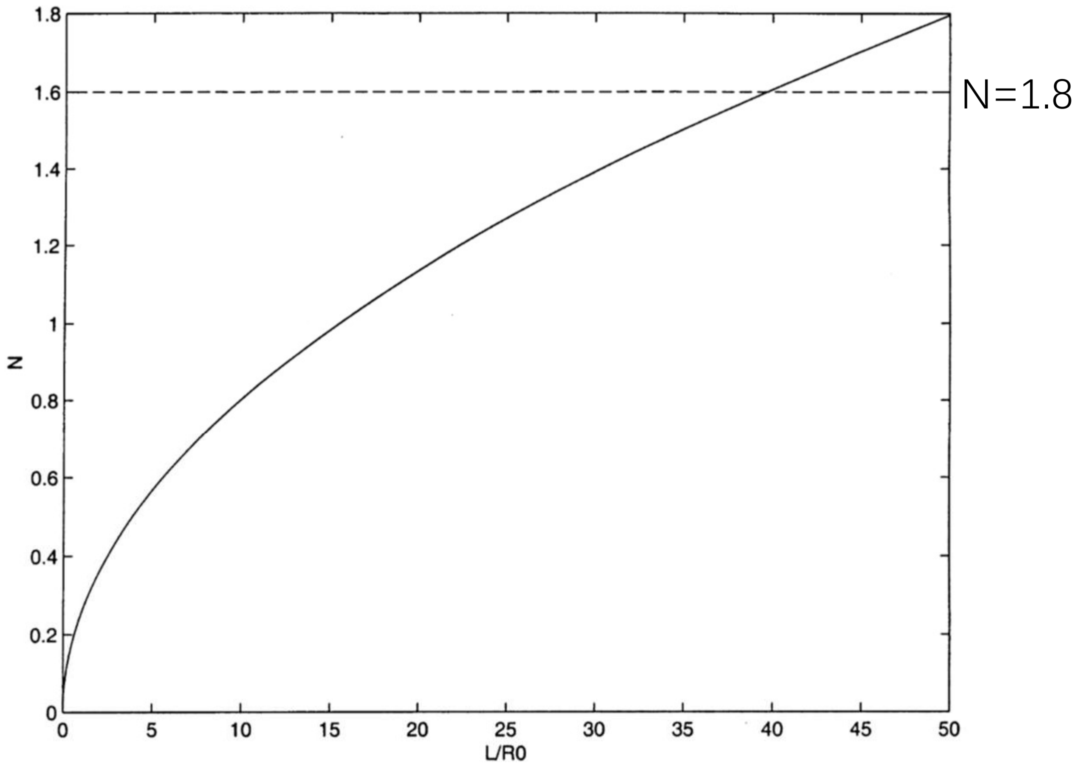


FIG. 4.—Comparison of the energetic condition for eruption and the stability condition.

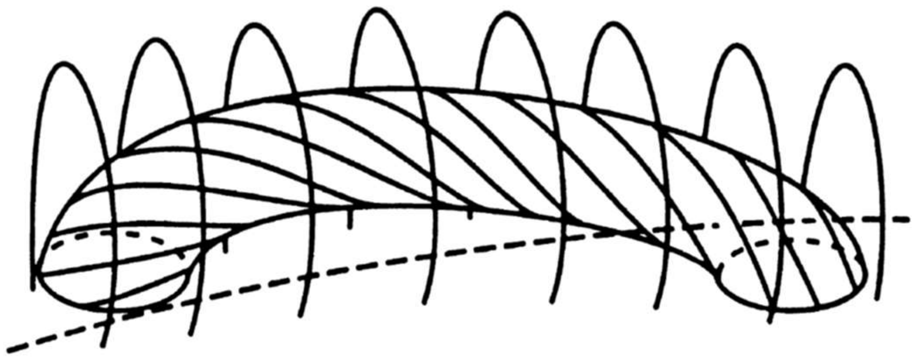


FIG. 1.—Schematic model of a long twisted flux tube held down by an overlying magnetic arcade.

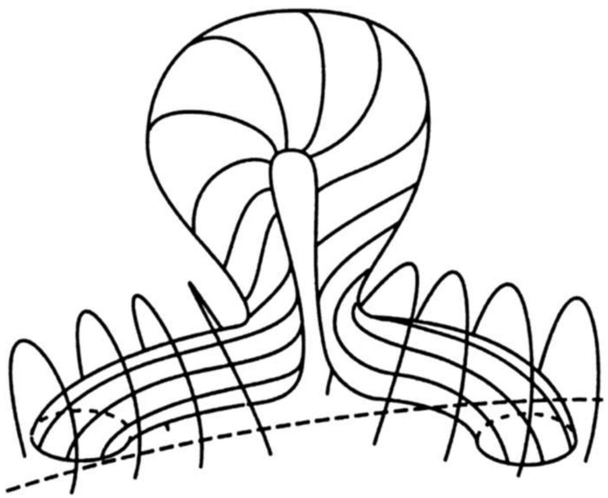
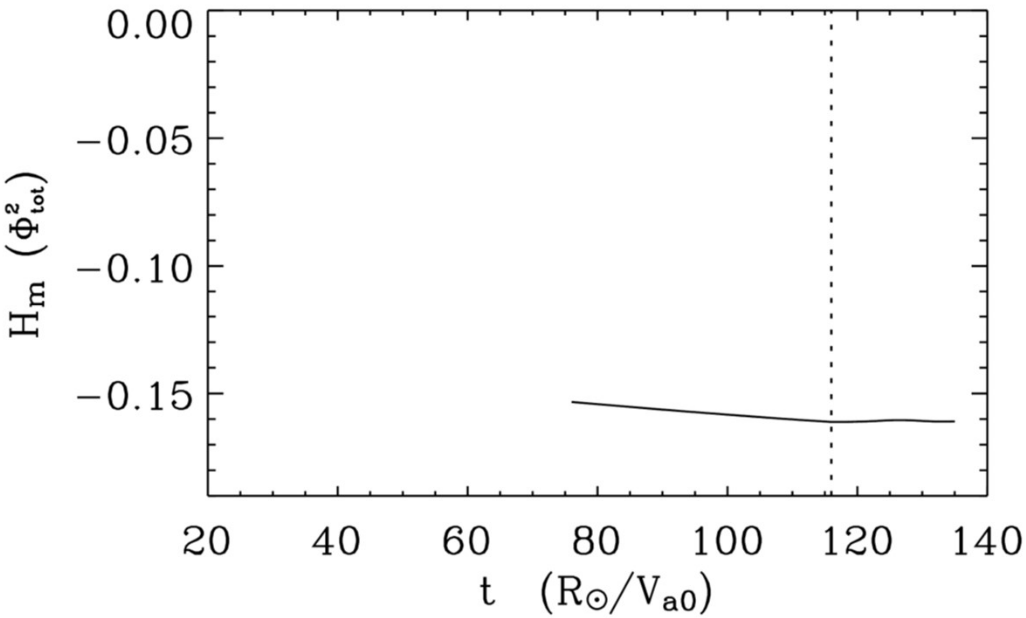


FIG. 2.—Schematic depiction of the evolution of the flux tube following the eruption of part of the tube through the arcade.

Ideal MHD simulation

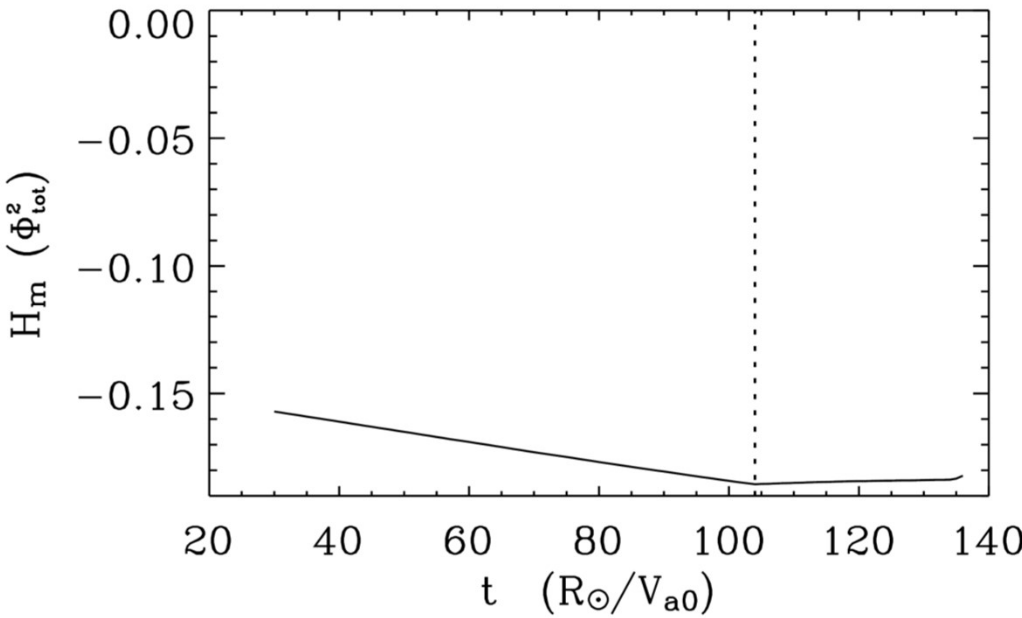
Fan (2006,2007)

Case of Kink instability



N=-0.16 when eruption happened

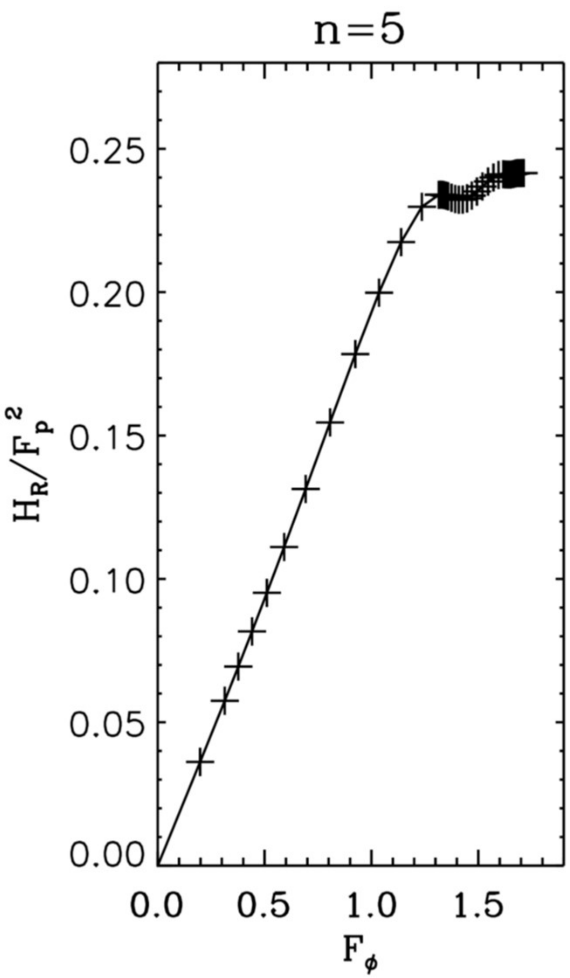
Case of torus instability



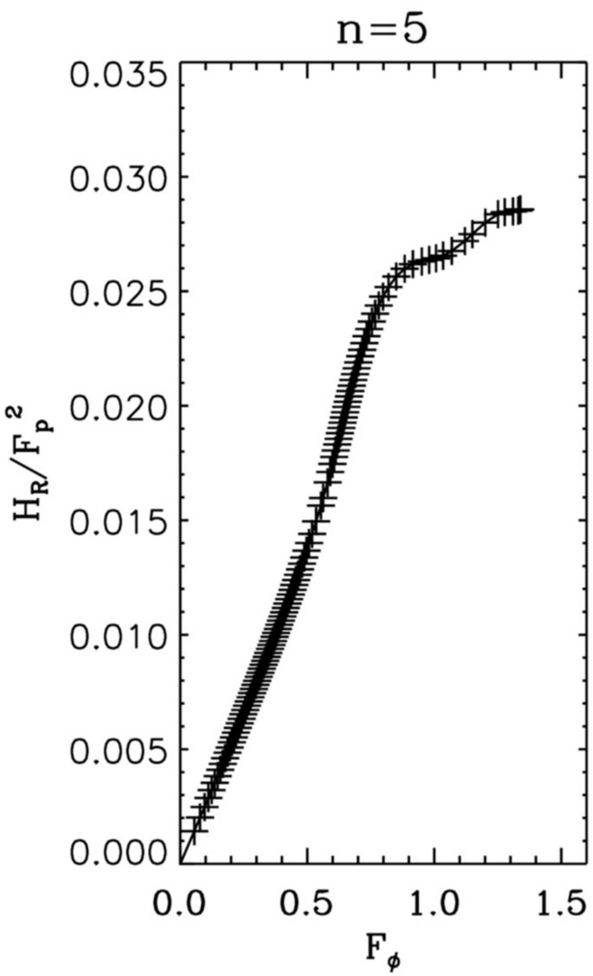
N=-0.18 when eruption happened

Theoretical analysis-II

Zhang & Flyer (2008)



Dipole



Multipolar

Arnold 1974 : For a divergence-free vector field ξ, E(ξ) ≥ C · |H(ξ)|, where C is a positive constant dependent on the shape and size of the compact domain M.

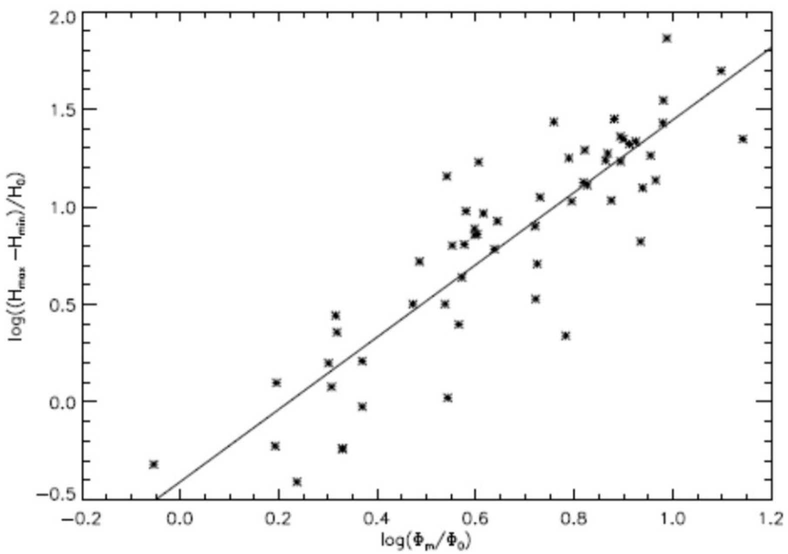
$$-C^{-1}\left|E_m\right| \leq H_m \leq C^{-1}\left|E_m\right|$$

Magnetic helicity Bounded by Energy.

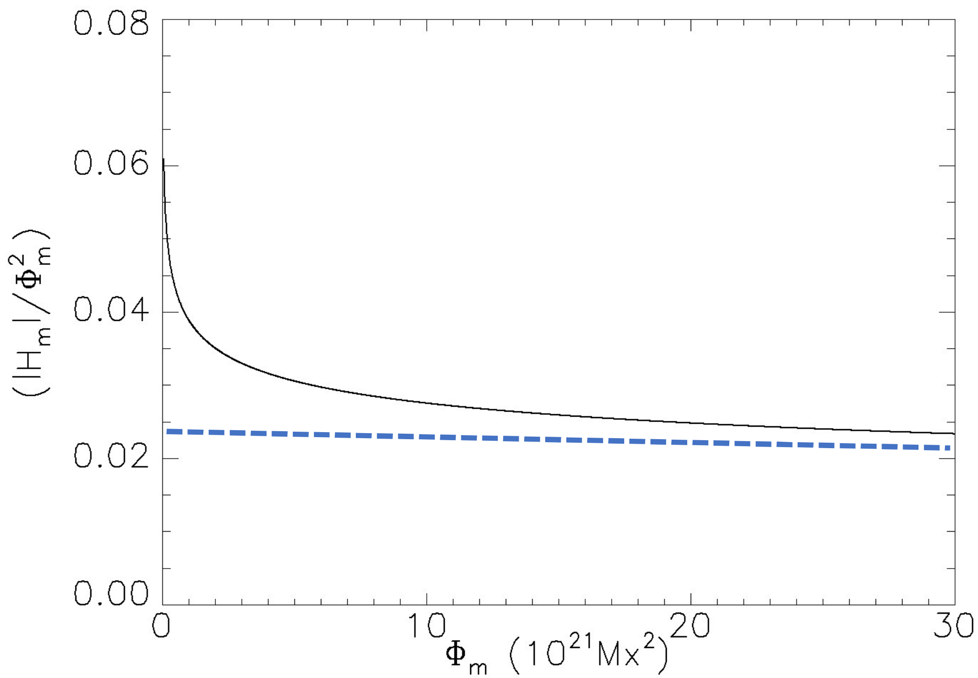
Up-limit of magnetic helicity is much smaller in the multipolar field than in the dipole field.

How about in the Observations and Simulations?

Normalized magnetic helicity in the newly emerging active regions



$$\log \frac{H_{\max} - H_{\min}}{H_0} = a \log \frac{\Phi_m}{\Phi_0} + b$$



As magnetic flux increased, the normalized helicity is approaching to the limit.

Modeling Relative magnetic helicity in MHD simulation

- Data-Driven 3D MHD Model (GOEMHD3)

Buchner et al. 2004ab; Buchner 2006; Santos and Buchner 2007
Santos et al. 2008; Skala et al. 2015; Yang et al. 2013; Yang et al. 2018

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot \rho \vec{u}$$

$$\frac{\partial \rho \vec{u}}{\partial t} = -\nabla \cdot \rho \vec{u}\vec{u} - \nabla p + \vec{j} \times \vec{B} - \nu \rho (\vec{u} - \vec{u}_0)$$

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times \left(\vec{u} \times \vec{B} - \eta \vec{j} \right)$$

$$\frac{\partial p}{\partial t} = -\nabla \cdot p\vec{u} - (\gamma - 1) p \nabla \cdot \vec{u} + (\gamma - 1) \eta j^2$$

$$\vec{E} = \vec{u} \times \vec{B} - \eta \vec{j} \qquad \nabla \times \vec{B} = \mu_0 \vec{j} \qquad p = 2nk_B T$$

Modeling Relative magnetic helicity in MHD simulation

- Data-Driven 3D MHD Model (GOEMHD3)

Buchner et al. 2004ab; Buchner 2006; Santos and Buchner 2007

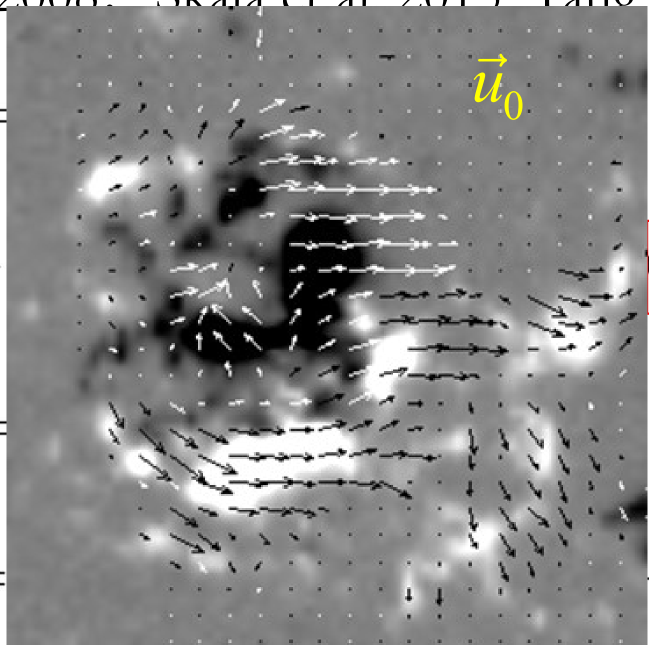
Santos et al. 2008; Skala et al. 2015; Yang et al. 2013; Yang et al. 2018

$$\frac{\partial \rho}{\partial t} = \ldots$$

$$\frac{\partial \rho \vec{u}}{\partial t} \ldots (\vec{u} - \vec{u}_0)$$

$$\frac{\partial \vec{B}}{\partial t} = \ldots$$

$$\frac{\partial p}{\partial t} = \ldots - 1)\eta j^2$$



$$\vec{E} = \vec{u} \times \vec{B} - \eta \vec{j} \qquad \nabla \times \vec{B} = \mu_0 \vec{j} \qquad p = 2nk_B T$$

Modeling Relative magnetic helicity in MHD simulated

- Data-Driven 3D MHD Model (GOEMHD3)

Buchner et al. 2004ab; Buchner 2006; Santos and Buchner 2007
Santos et al. 2008; Skala et al. 2015; Yang et al. 2013; Yang et al. 2018

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot \rho \vec{u}$$

Current depended anomalous resistivity

$$\eta = \eta_0 + \begin{cases} 0, & if |j| < j_{crit} \\ \eta_0 \left(\frac{|j|}{j_{crit}} - 1\right)^2 & if |j| \geq j_{crit} \end{cases}$$

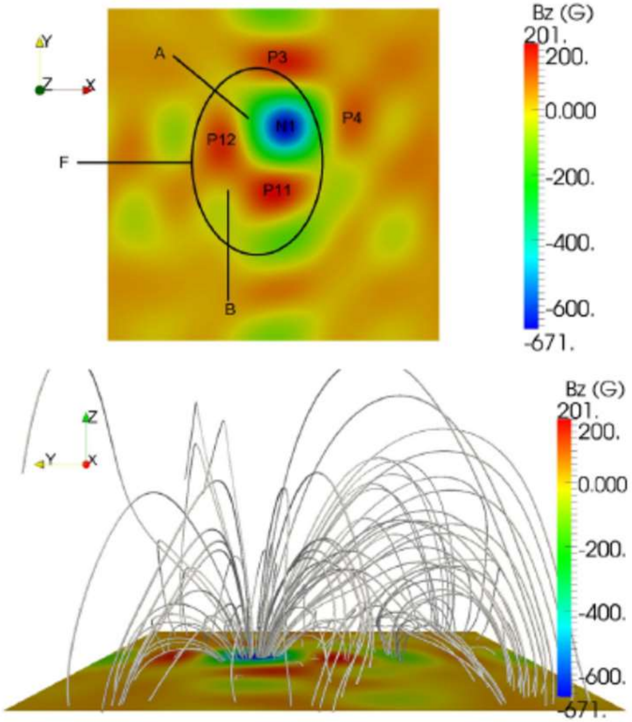
$$\frac{\partial p}{\partial t} = -\nabla \cdot p\vec{u} - (\gamma - 1) p \nabla \cdot \vec{u} + (\gamma - 1) \eta j^2$$

$$\vec{E} = \vec{u} \times \vec{B} - \eta \vec{j} \qquad \nabla \times \vec{B} = \mu_0 \vec{j} \qquad p = 2nk_B T$$

Modeling Relative magnetic helicity in MHD simulation

Case-I (magnetic reconnection without eruption)

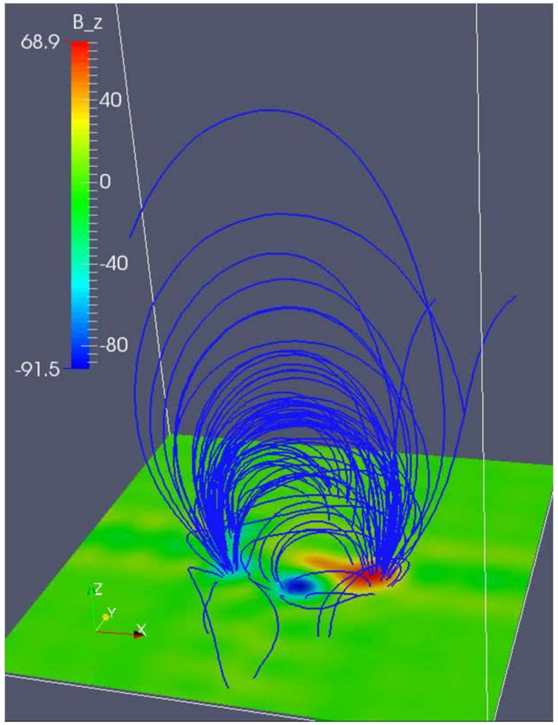
NOAA 8210



Yang et al. (2013) Solar Physics

Case-II (magnetic reconnection with eruption)

NOAA 11429



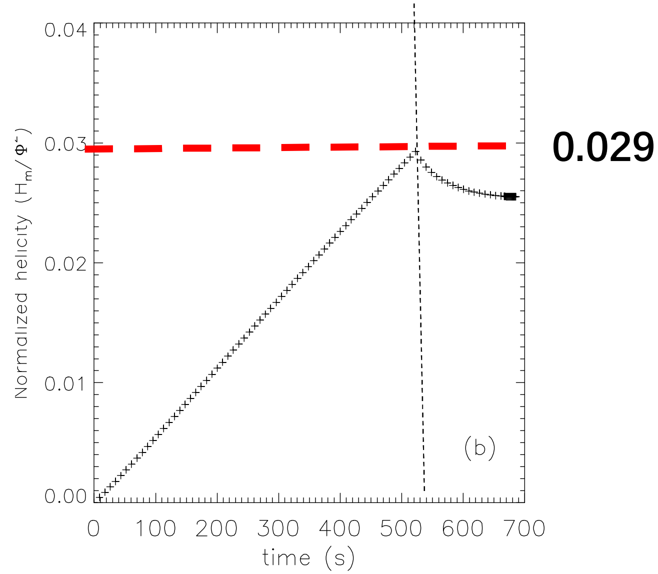
Yang et al. 2018, **A&A**

Our Simulation Results

Resistivity Model-I: Swith on/off
Yang et al. (2013)

$$\eta = \begin{cases} \eta_0 & |j| < j_{crit} \\ \eta_1 & |j| > j_{crit} \end{cases}$$

No Eruption
Only Reconnection

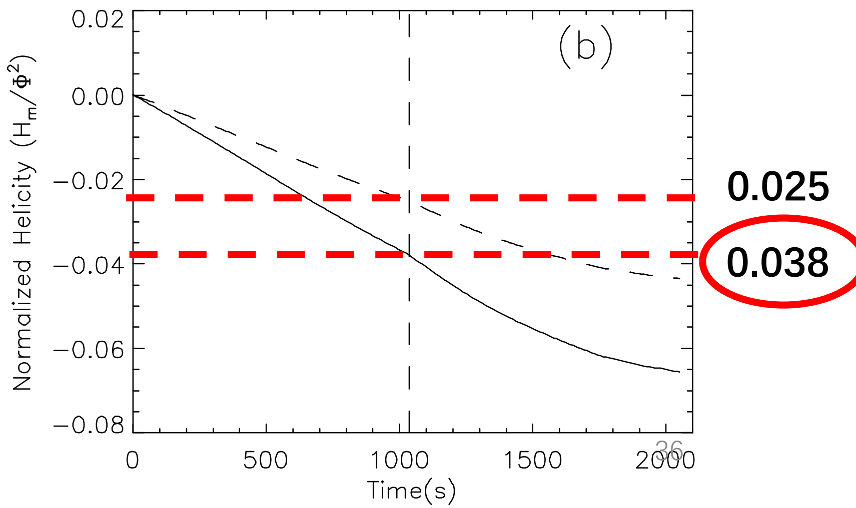


Resistivity Model-II: Current dependence
Yang et al. (2018)

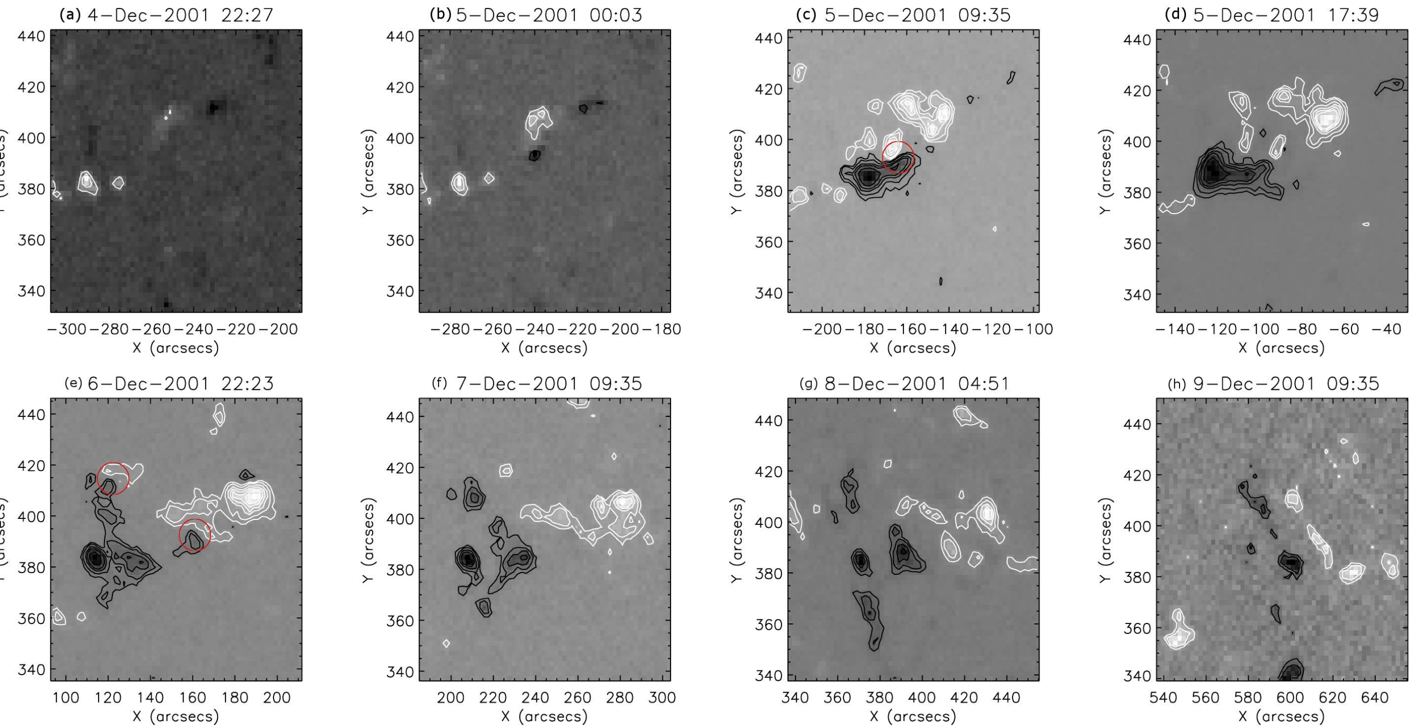
$$\eta = \eta_0 + \begin{cases} 0, & if |j| < j_{crit} \\ \eta_0\left(\frac{|j|}{j_{crit}} - 1\right)^2 & if |j| \geq j_{crit} \end{cases}$$

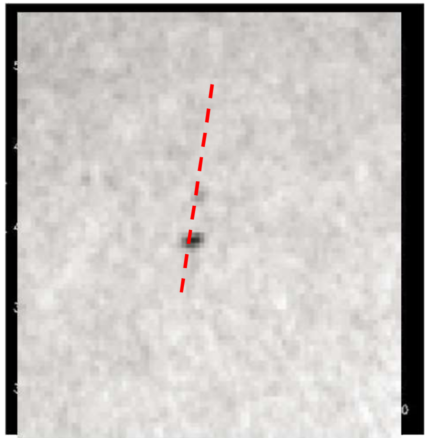
$$j_{crit} = nev_{dift} \quad (v_{drift} = v_{Thermal})$$

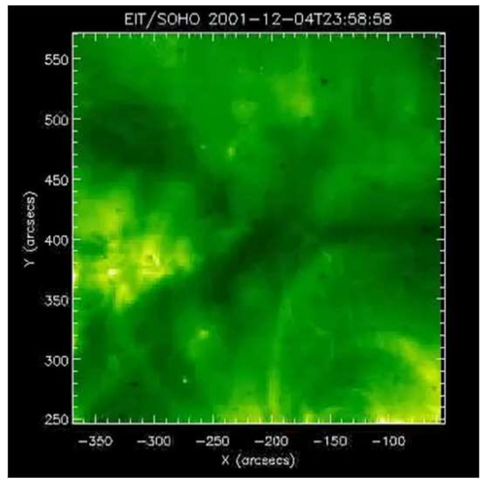
With Eruption
also Reconnection
Only 2% magnetic
Helicity escaped



Case Study NOAA9279



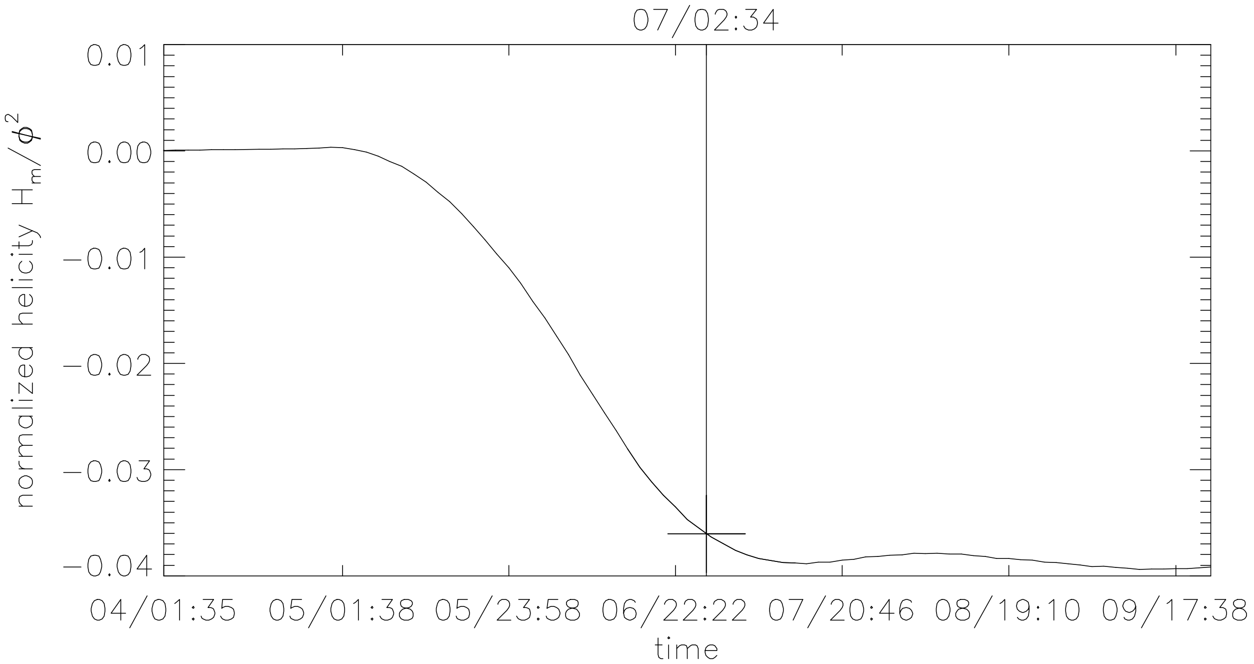


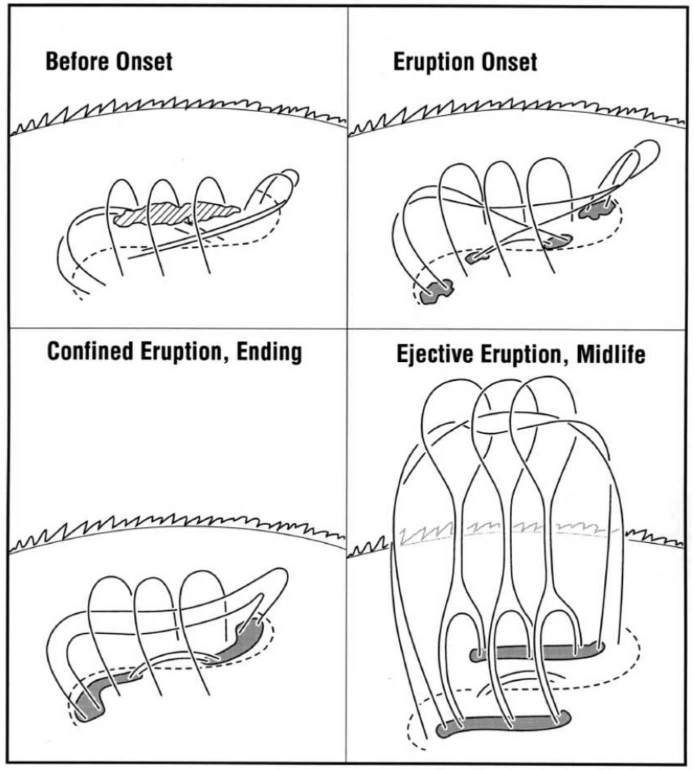


Once Emerging,   Once Eruption,   Once Pass though
Disappear before approaching the solar limb

Yang, S, et al. AdSpR. 2015

Magnetic Helicity accumulation of NOAA9729





Moore et al. 2001

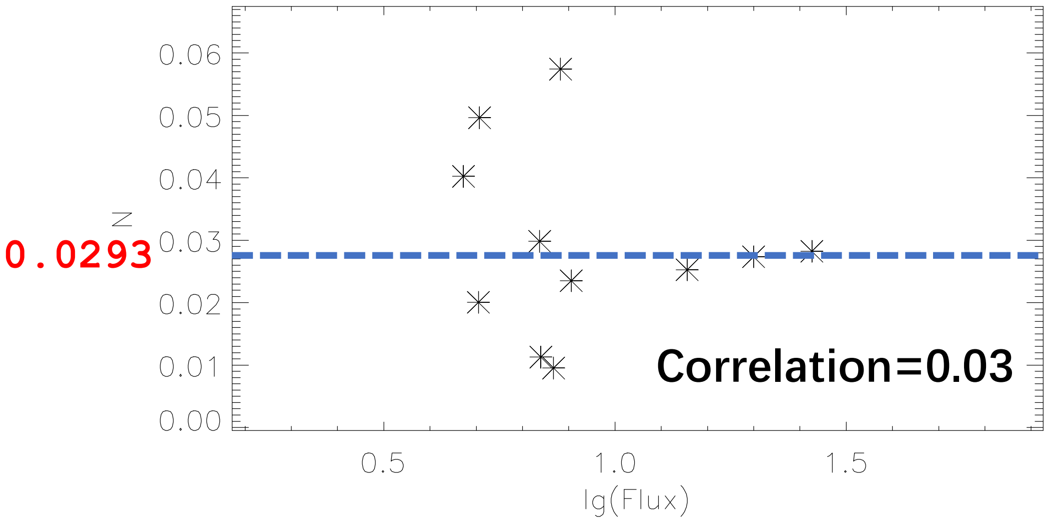
- The Solar Eruption occurred while helicity approached the maximum.
- The normalized Helicity (twist number) is 0.036 when solar eruption happened.
- Eruption process satisfy Tether-cutting Model

Eruption of ARs ----Statistic Study

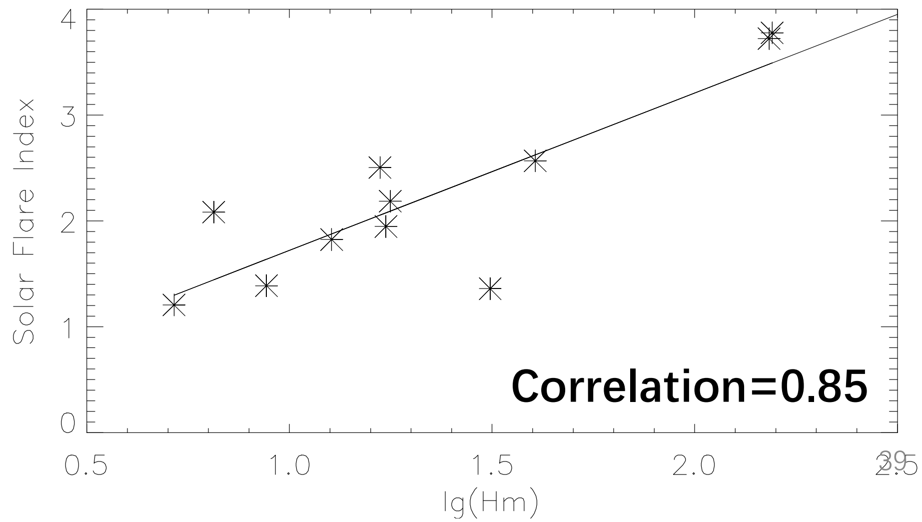
Chose 11 Newly Emerging AR in the 23rd Solar Cycle (SOHO/MDI DATA)

- Existence of maximum magnetic flux
- Helicity flux approach to obtain the helicity $H_m = H_{\max} - H_{\min}$
- Solar Flare Index SFI= Σ(1000X+100M+10C+1B+0.1A)
- The twist number N when Solar Flare happened: $N = N\left(t_{ref}\right)$ $t_{ref} = \frac{\sum t_i SFI_i}{SFI}$

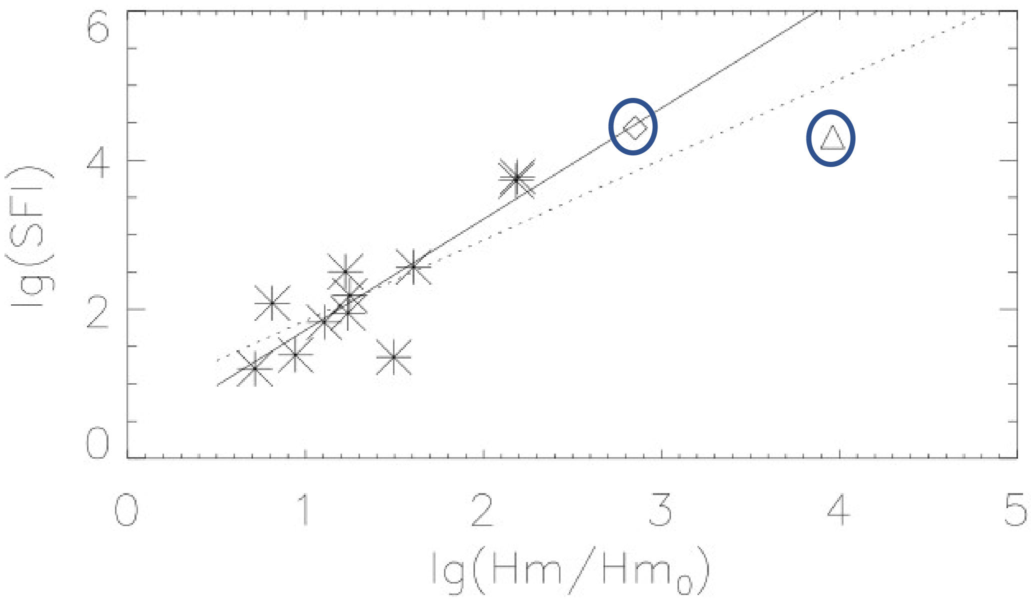
Flux -N



Hm-SFI

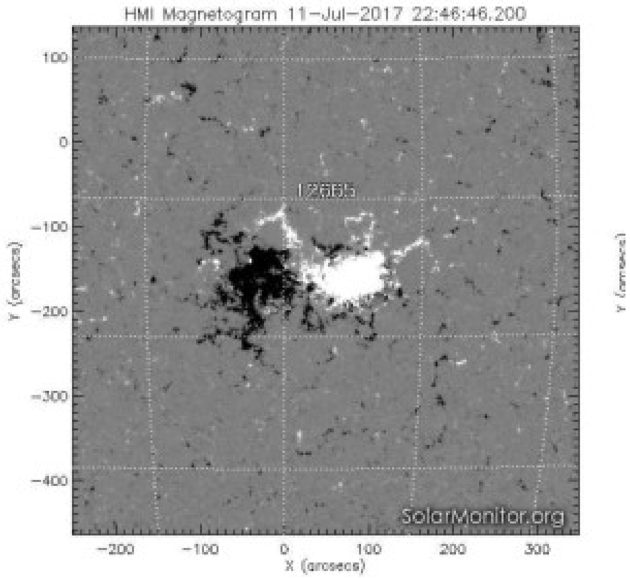


Checking using 24th powerful active regions

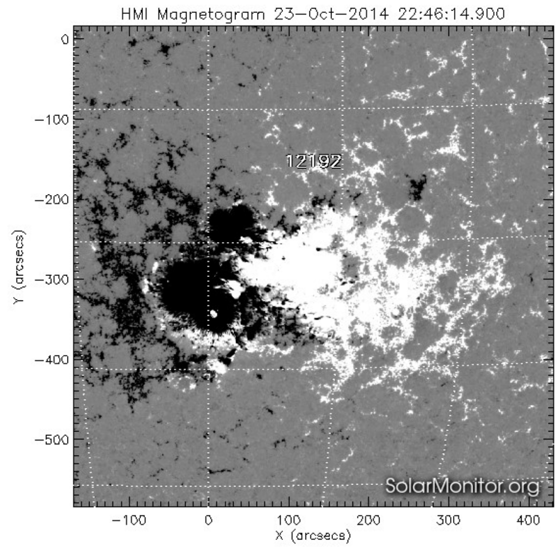


$$lg(SFI) = alg(H_m/H_{m0}) + b,$$

NOAA12673



NOAA12192



Yang et al. (2021） in revision

Summary

1. An efficient method of calculating relative magnetic helicity (RMH) in Cartesian coordinate is developed. Remote Magnetic Helicity Calculation System is also supplied.

2. Newly emerging active regions supply an approach to understand the distribution process of magnetic helicity transportation from convective zone to the interplanetary.

3. Magnetic helicity flux imbalance may play an important role to understand the solar dynamo. The conservation of magnetic helicity could behaviors in several cycles.

4.Normalized RMH when solar eruption happens shows the thresholds both in simulations and observations. Further investigations of the RMH evolution of ARs from the Simulation s and Observations are still needed.

Reference

- ✓ Shangbin Yang et al. 2020, J. Plasma Phys., vol. 86, 775860302.
- ✓ Shangbin Yang et al. 2018, A&A, vol. 613 Pages A27.
- ✓ Valori et al. 2016, Space Science Review, 201, 147
- ✓ Shangbin Yang et al. AdSpR, 2015 Vol. 55,1553.
- ✓ Shangbin Yang et al. 2013, Solar Physics., 283:369–382.
- ✓ Zhang Hongqi & Shangbin Yang 2013, 763:105.
- ✓ Shangbin Yang et al. 2012, ApJ,758:61.
- ✓ Shangbin Yang et al. 2009, ApJ, L25-L30.

Thanks for your attention!