Magnetic Field and Helicity of Solar Active Regions from Observations

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Major cooperation in the study of magnetic fields with
Yu Gao, Haiqing Xu, Shangbin Yang, Xiao Yang & Jihong Liu … (China)
K.K. Kuzanyan, D. D. Sokoloff, V. Pipin (Russia)
T. Sakurai (Japan)
Axel Brandenburg (Sweden)
J. Buechner (Germany)
Junwei Zhao, A. Pevtsov (USA)
Nindos (Greece)
D. Moss (UK)
N. Kleeorin, I. Rogachevskii (Israel)
....

Magnetic non-potentiality and helicity in individual solar active regions

Based on the ground and space observations of solar vector manetograms

Magnetic shear, current, energy and helicity inferred from solar vector magnetograms

- Magnetic shear

$$\theta_T \propto \angle(\mathrm{B}_o, \mathrm{B}_p)$$

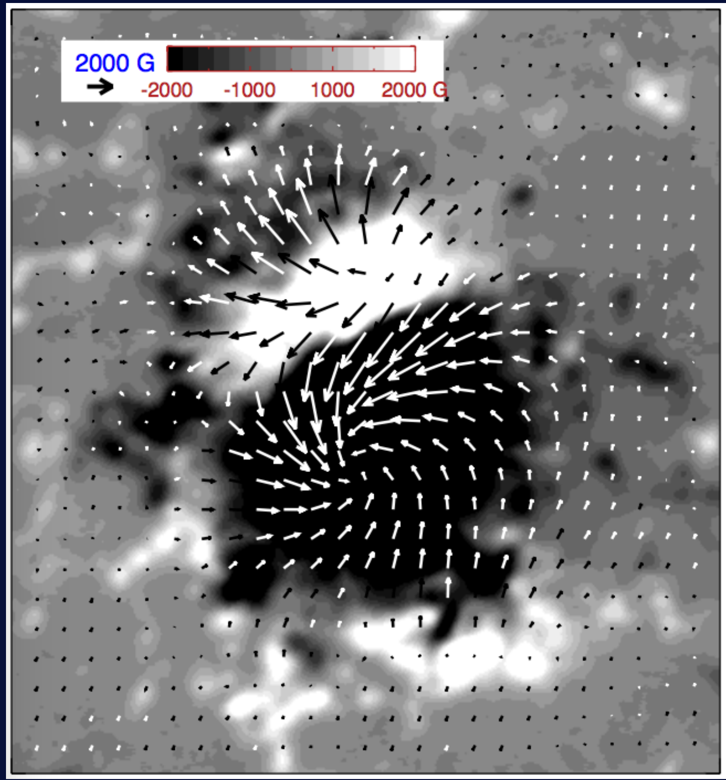
- Current density

$$J_z = (\nabla \times \mathrm{B})_z$$

- Magnetic free energy density

$$\rho_{free} = \frac{1}{8\pi}(\mathrm{B}_o^2 - \mathrm{B}_p^2)$$

- Current helicity density



$$h_c = \mathrm{B} \cdot \nabla \times \mathrm{B} = \underbrace{\mathrm{B}_z \cdot (\nabla \times \mathrm{B})_z}_{\text{Observable}} + \underbrace{\mathrm{B}_t \cdot (\nabla \times \mathrm{B})_t}_{\text{Some problem}}$$

Observable ***Some problem***

- Cross helicity

$$h_x = \mathrm{v} \cdot \mathrm{B}$$

从太阳矢量磁图推论磁剪切、电流和螺度

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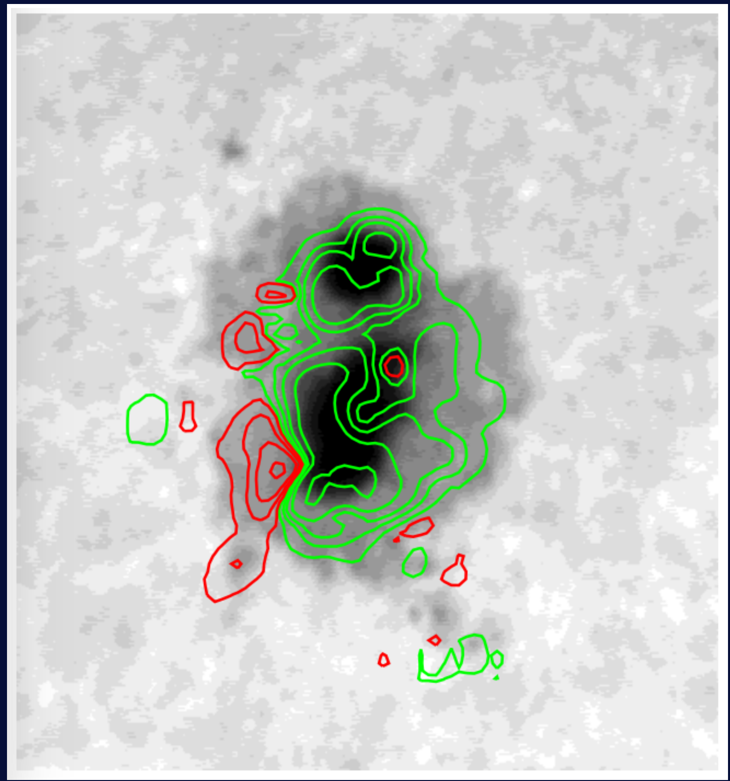

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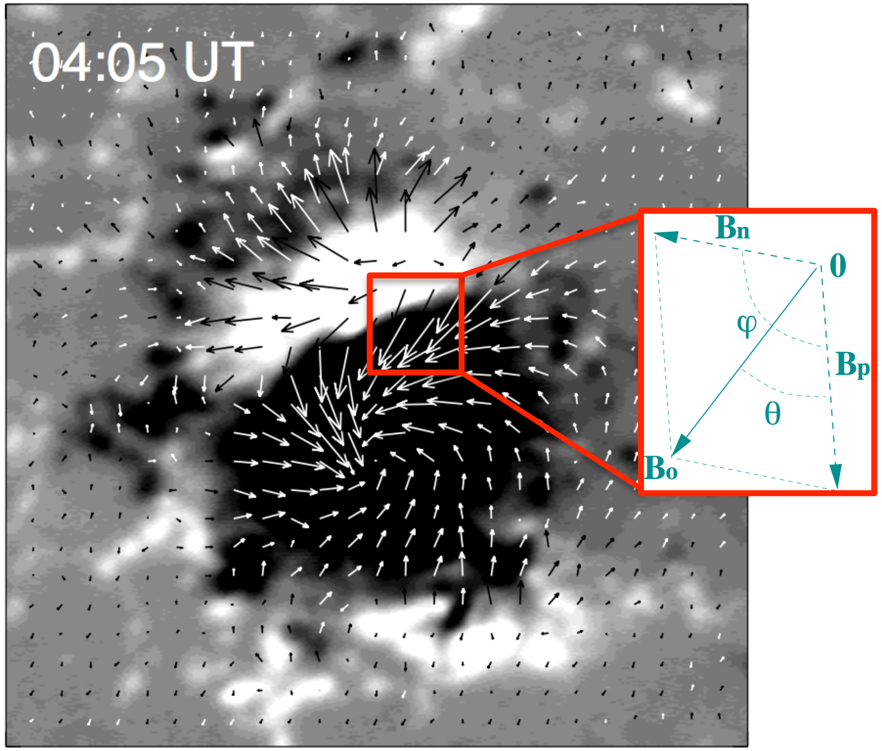
- Cross helicity

$$h_x = \mathrm{v} \cdot \mathrm{B}$$

Photospheric Vector Magnetic Fields Provide Fundamental Information on Accumulation of Free Magnetic Energy of ARs Above Photosphere



B_o是观测量，而非势场B_n和势场B_p是虚拟或衍生量

The $\mathbf{B}_o$ is observational quantity, while the non-potential field $\mathbf{B}_n$ and potential field $\mathbf{B}_p$ are fictitious quantities.

- The relationship among the observed (B_o), potential (B_p) and non-potential (B_n) components of magnetic field

$$\mathbf{B}_o = \mathbf{B}_p + \mathbf{B}_n$$

- Total free magnetic energy

$$E_{free} = \iiint_v \rho_{free}\, dv = \frac{1}{8\pi} \iiint_v (\mathbf{B}_o^2 - \mathbf{B}_p^2)\, dv$$

- The free magnetic energy density of ARs

$$\rho_{free} = \frac{1}{8\pi}(\mathbf{B}_o^2 - \mathbf{B}_p^2) = \frac{1}{8\pi}(\mathbf{B}_n^2 + 2\mathbf{B}_n \cdot \mathbf{B}_p)$$

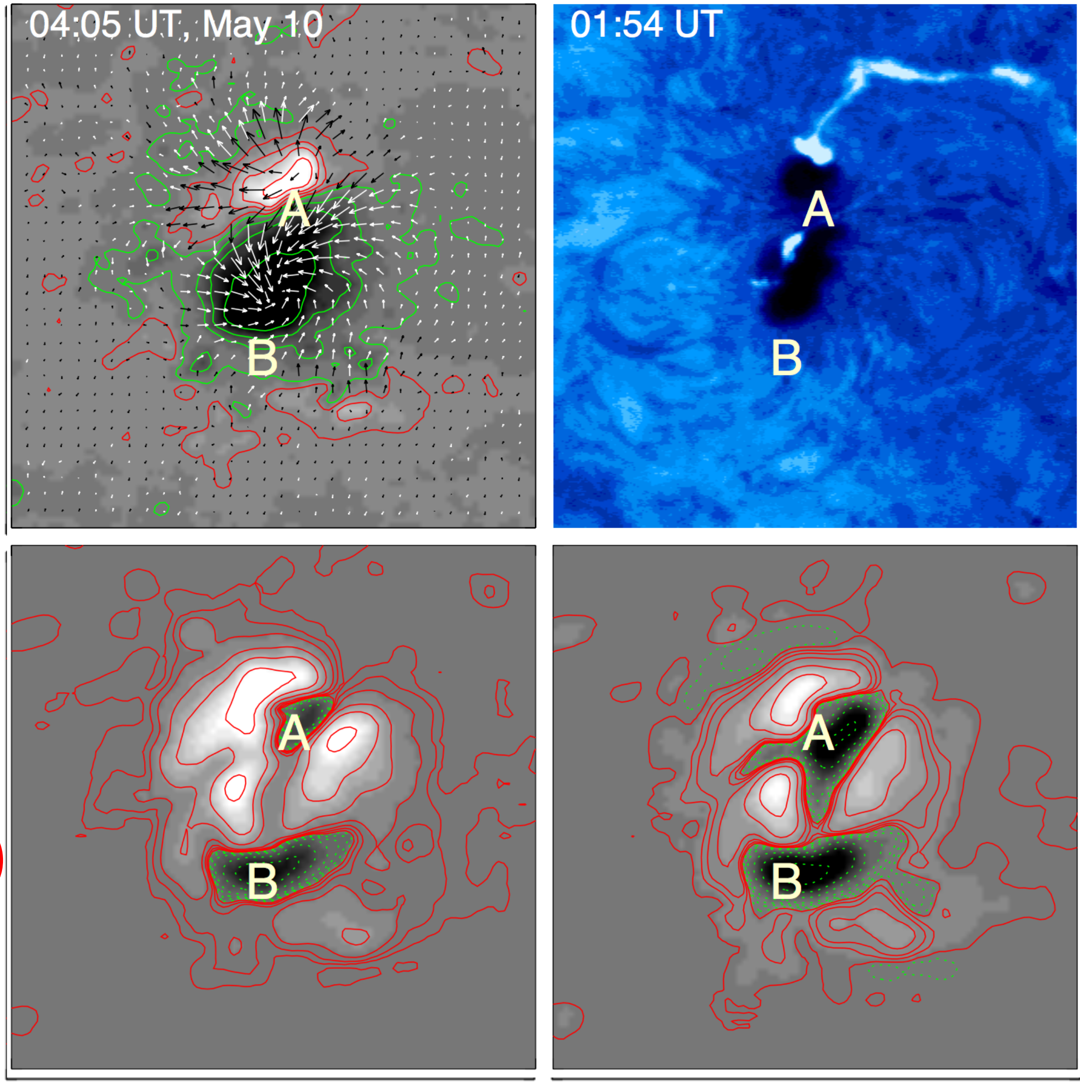
Relates to calculated potential field

Zhang, H. 2016, SoPh, 291, 3501

Similar analysis of the non-potential energy of ARs by: Lu, Y., Wang, J., Wang, H., 1993, SoPh., 148, 119; Yang, X., et al., 2012, SoPh., 280, 165

Relationship between photospheric magnetic field and energy densityAR6619 on May 1991

Photospheric
Vector magnetgram

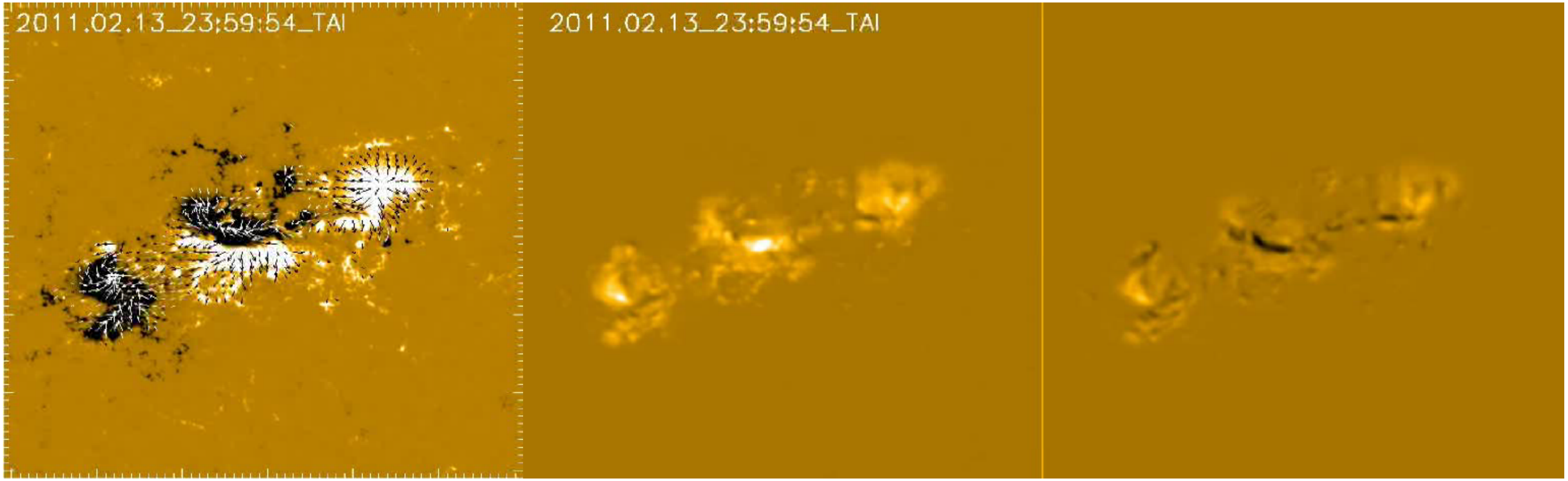


Hβ-chromospheric
filtergram

$$\rho_{free} = \frac{1}{8\pi}(\mathbf{B}_n^2 + 2\mathbf{B}_n \cdot \mathbf{B}_p)$$

$$\frac{1}{4\pi} 2\mathbf{B}_n \cdot \mathbf{B}_p$$

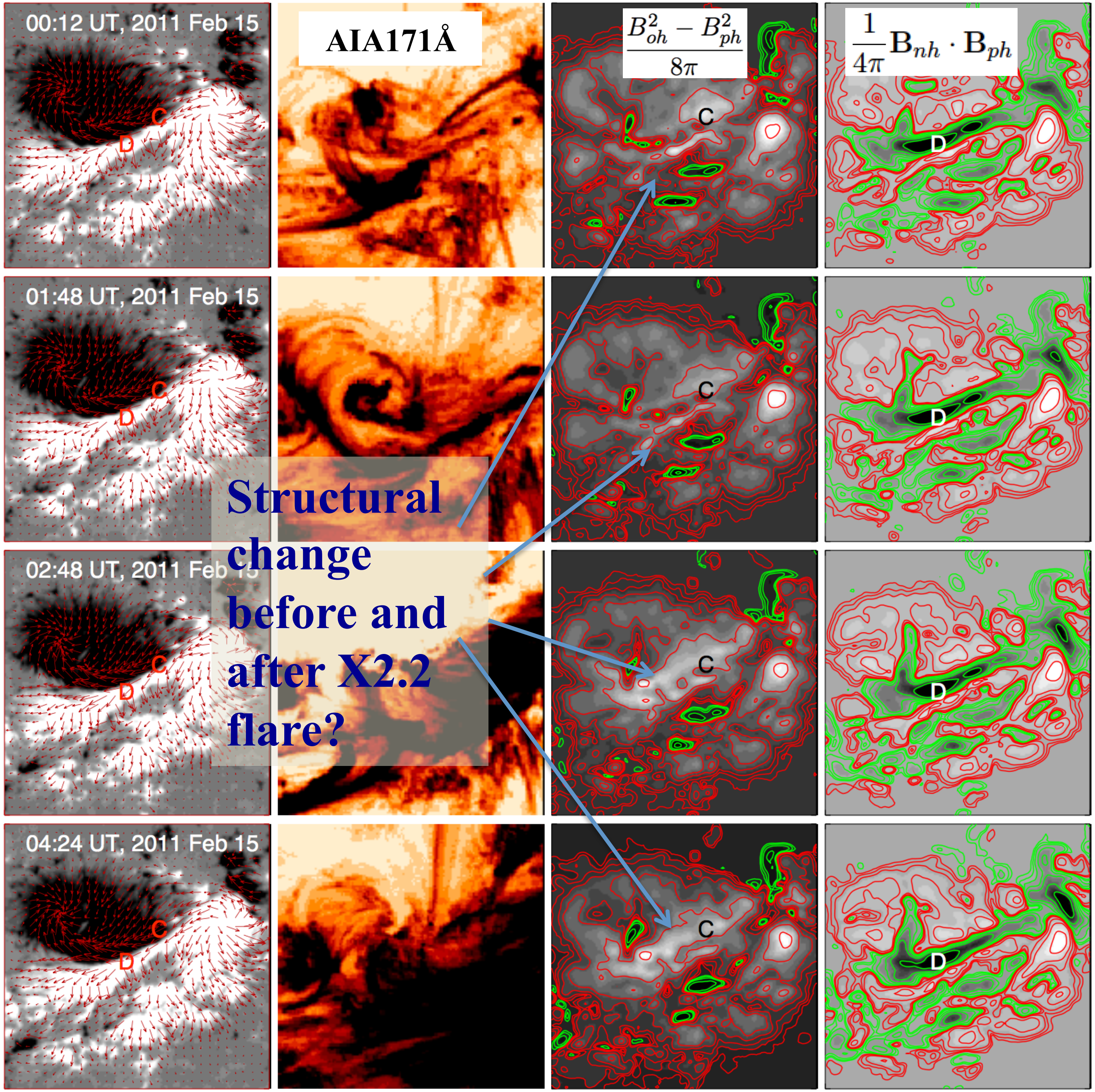
Evolution of free magnetic energy and shear parameters in AR NOAA 11158 in 2011 February inferred by HMI



$$\boxed{\mathbf{B}_o = \mathbf{B}_n + \mathbf{B}_p}$$

$$\boxed{\rho_{free} = \frac{\mathbf{B}_{oh}^2 - \mathbf{B}_{ph}^2}{8\pi}} = \boxed{\frac{\mathbf{B}_{nh} \cdot \mathbf{B}_{ph}}{4\pi}} + \frac{1}{8\pi}\mathbf{B}_{nh}^2$$

$$\rho_{free} = \frac{1}{8\pi}(\mathbf{B}_o^2 - \mathbf{B}_p^2) = \frac{1}{8\pi}(\mathbf{B}_n^2 + 2\mathbf{B}_n \cdot \mathbf{B}_p + \mathbf{B}_p^2 - \mathbf{B}_p^2) = \frac{1}{8\pi}(\mathbf{B}_n^2 + 2\mathbf{B}_n \cdot \mathbf{B}_p)$$



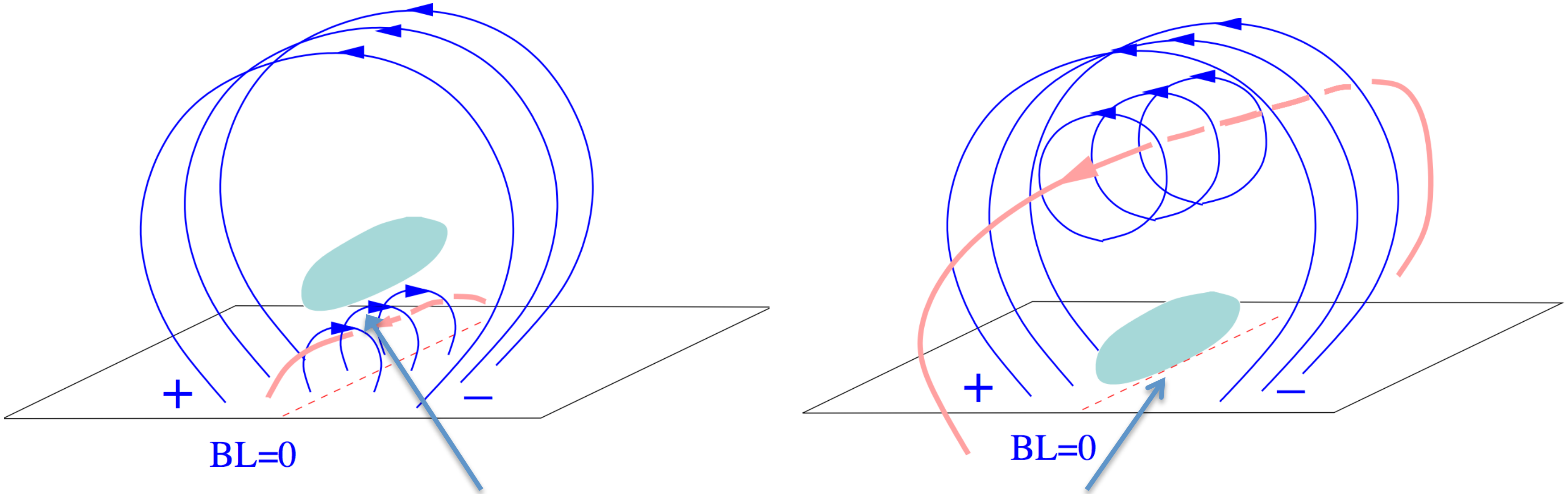
AR NOAA 11158 in 2011 February

X2.2 flare (start at 01:44, peak at 01:45, end at 01:56 UT)

Topological distribution of helical magnetic field in delta active regions

With reversely twisted magnetic loop

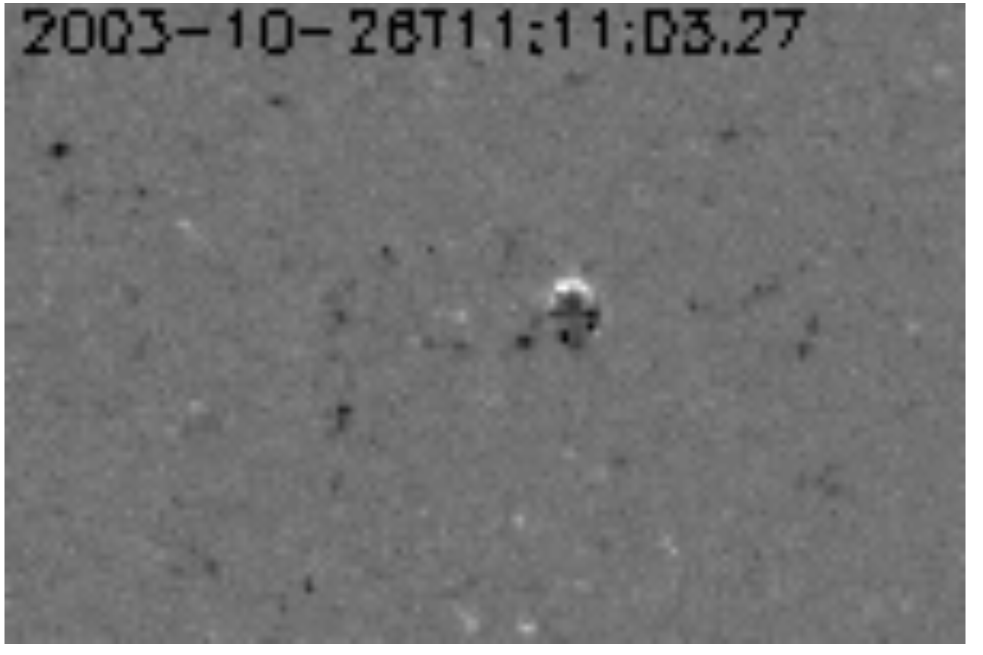
With normally twisted magnetic loop



Negative free magnetic energy density regions?

Relevant Key Feature: Magnetic Helicity

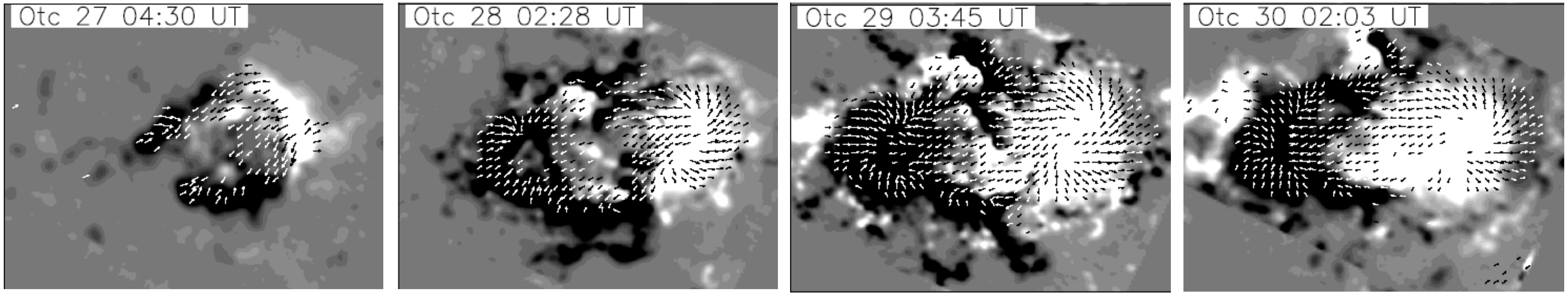
Fast emergence of AR 10488 (MDI) in 2003 October



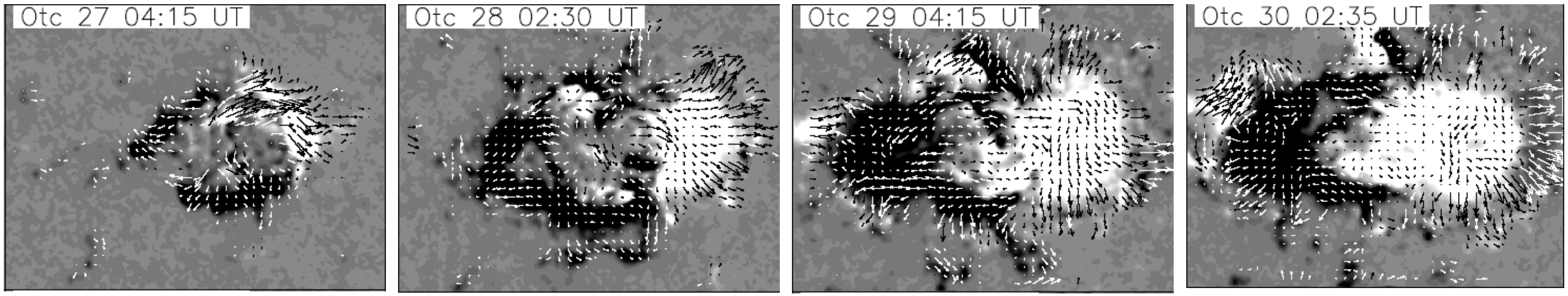
Liu J. & Zhang H., 2006, Solar Phys.

Velocity vector can be inferred by local correlative tracker technique

Development of magnetic shear and twist in AR10488 in the photosphere



The emergence of twisted field with the rotation of transverse field

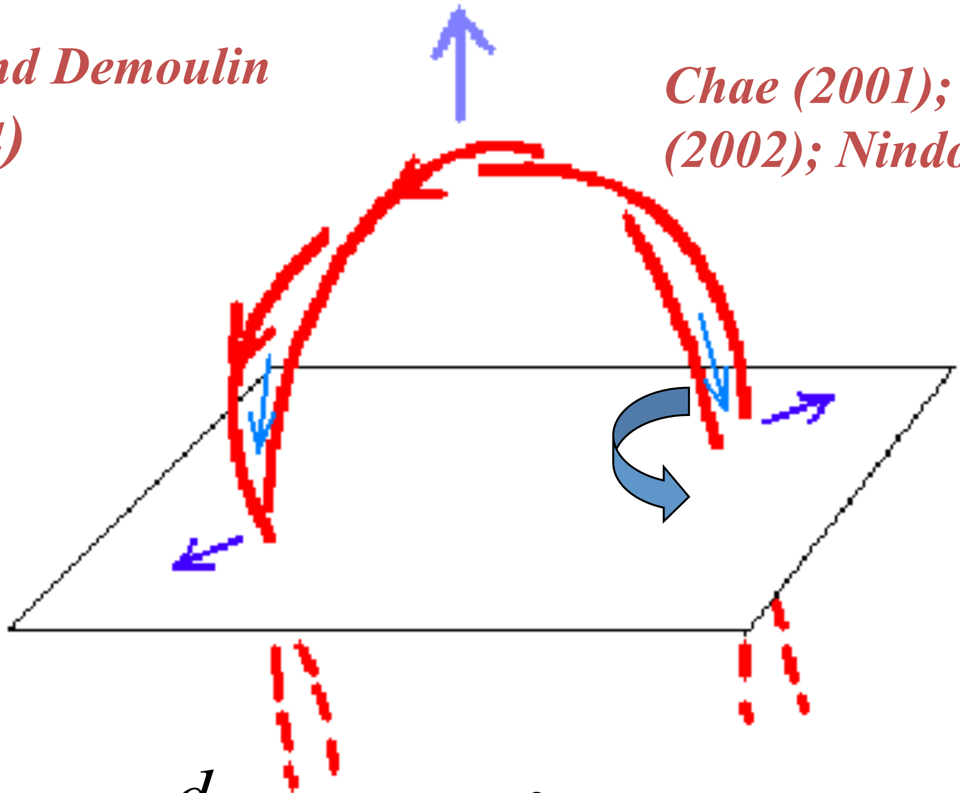


Horizontal velocity field in the photosphere inferred by local correlative tracker technique

Helicity flows through the photosphere and the relationship with photospheric helicity density

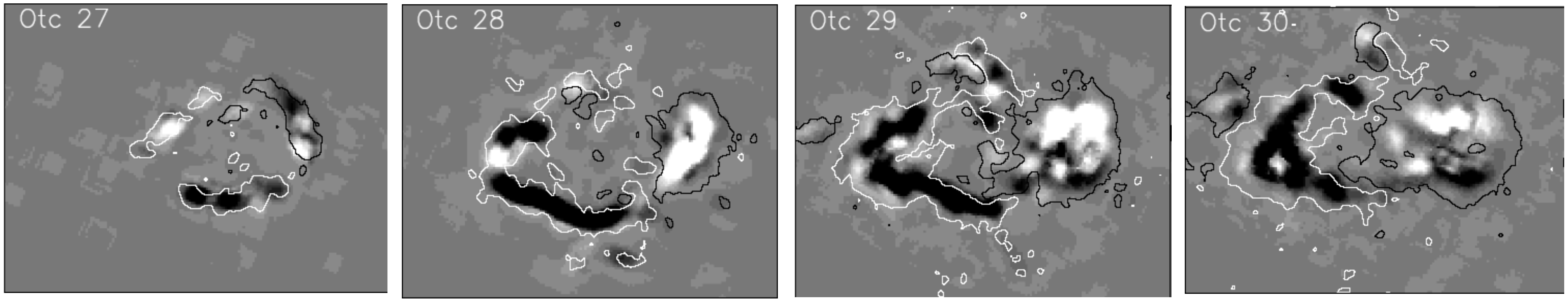
Berger (2003) and Demoulin and Berger (2004)

Chae (2001); Kosano et al. (2002); Nindos et al. (2002, 2003)

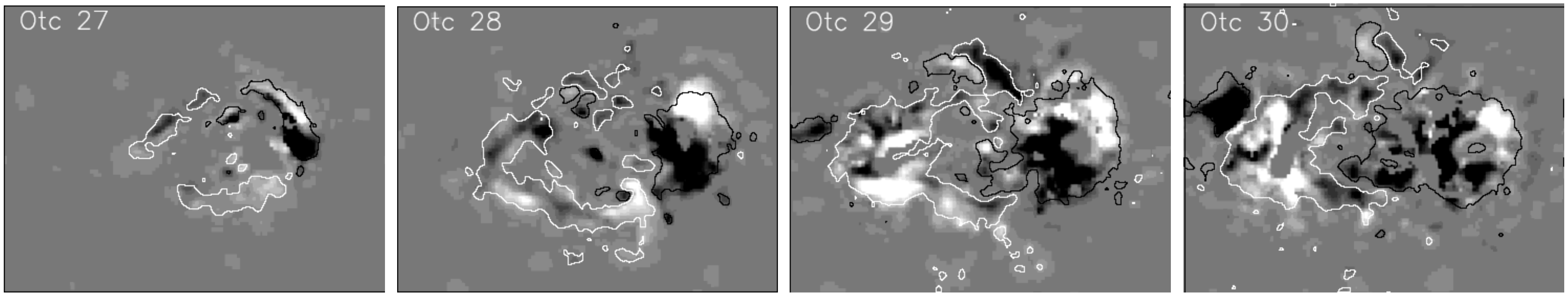


$$\frac{d}{dt}H = -2\oint_{photo}(Ut \cdot Ap)Bzd^2x$$

Development of magnetic helicity density in AR10488 in the photosphere



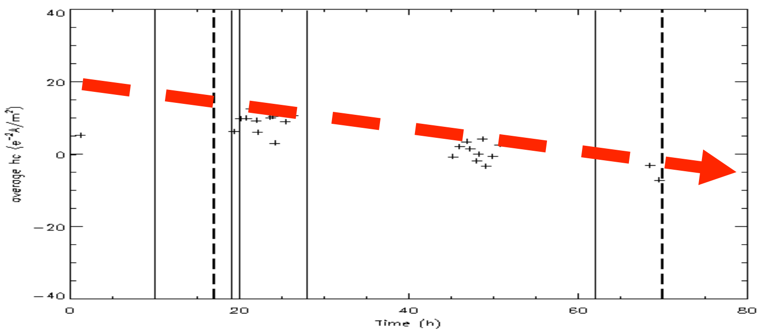
The change of current helicity density in photosphere



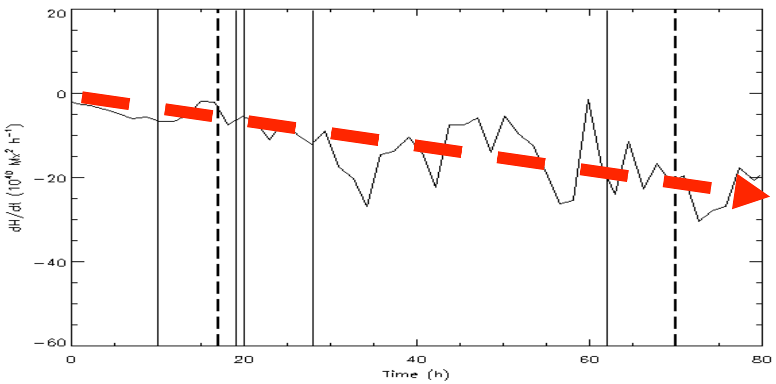
Injective rate of magnetic helicity from the sub-photosphere

Mean photospheric current helicity density and injective rate of magnetic helicity into the corona in AR10488

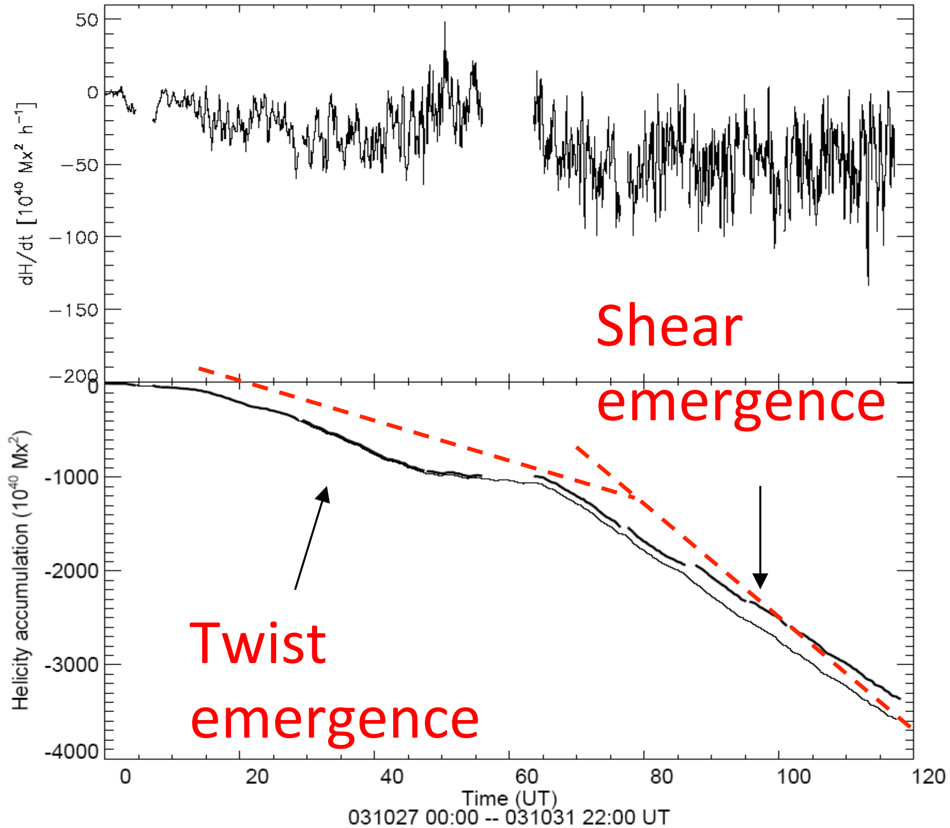
Evolution of mean current helicity density



Injective mean magnetic helicity density



Accumulation of magnetic helicity from the subatmosphere



Magnetic fields, helicity with solar cycles, and spectral index

Based on the observations of solar vector manetograms mainly

To global properties of magnetic fields of the Sun from individual active regions

Solar dynamo and current helicity transfer with observation

太阳发电机和电流螺度输运

Kleeorin, N., Kuzanyan, k., Moss, D., Rogachevskii, I., Sokoloff, D. and Zhang, H.,, Astron. Astrophys., 2003, 1097, 1105;

H. Zhang, D. Moss, N. Kleeorin, K. Kuzanyan, I. Rogachevskii, D. Sokoloff, Y. Gao, and H. Xu, ApJ, 2012, 751, 47

$$\frac{\partial B_0}{\partial t} = \nabla \times (U_0 \times B_0) + \nabla \times \varepsilon + \lambda \nabla^2 B_0$$

$$\varepsilon = \overline{u \times b} \approx \alpha B_0 - \lambda \nabla \times B_0 \qquad \alpha = -\frac{1}{3}\tau(\overline{u \cdot \nabla \times u} - \overline{b \cdot \nabla \times b})$$

Solar dynamo
太阳发电机

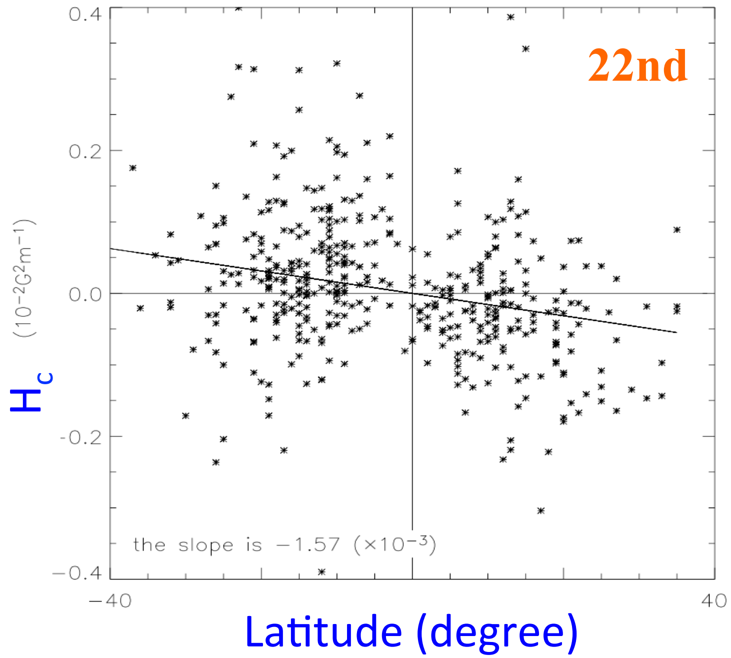
$$\frac{\partial \bar{h}}{\partial t} = -2\alpha B_0^2 - \frac{\bar{h}}{T} - \nabla \cdot F + 2\lambda B_0 \cdot \nabla \times B_0$$

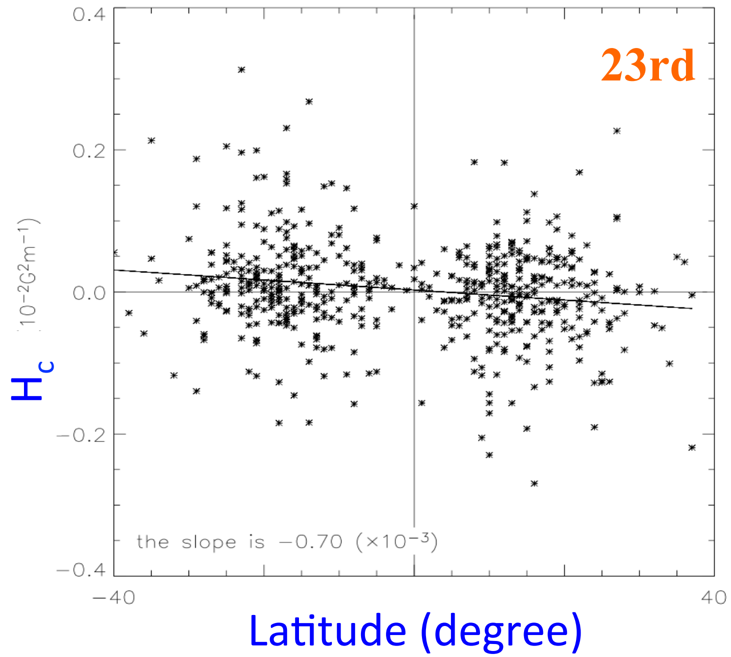
$$\bar{h} = \overline{a \cdot b} \qquad \overline{b \cdot (\nabla \times b)} = \left(\frac{\partial^2 h}{\partial x \partial y} \right)_{(r \to 0)} \qquad T^{-1} = \frac{2\lambda}{h} \left(\frac{\partial^2 h}{\partial x \partial y} \right)_{(r \to 0)}$$

Helicity transfer
螺度输运

Kleeorin and Rogachevskii, PhREvE, 1999

Latitudinal Distribution of mean current density of ARs in 22nd and 23rd Solar Cycles

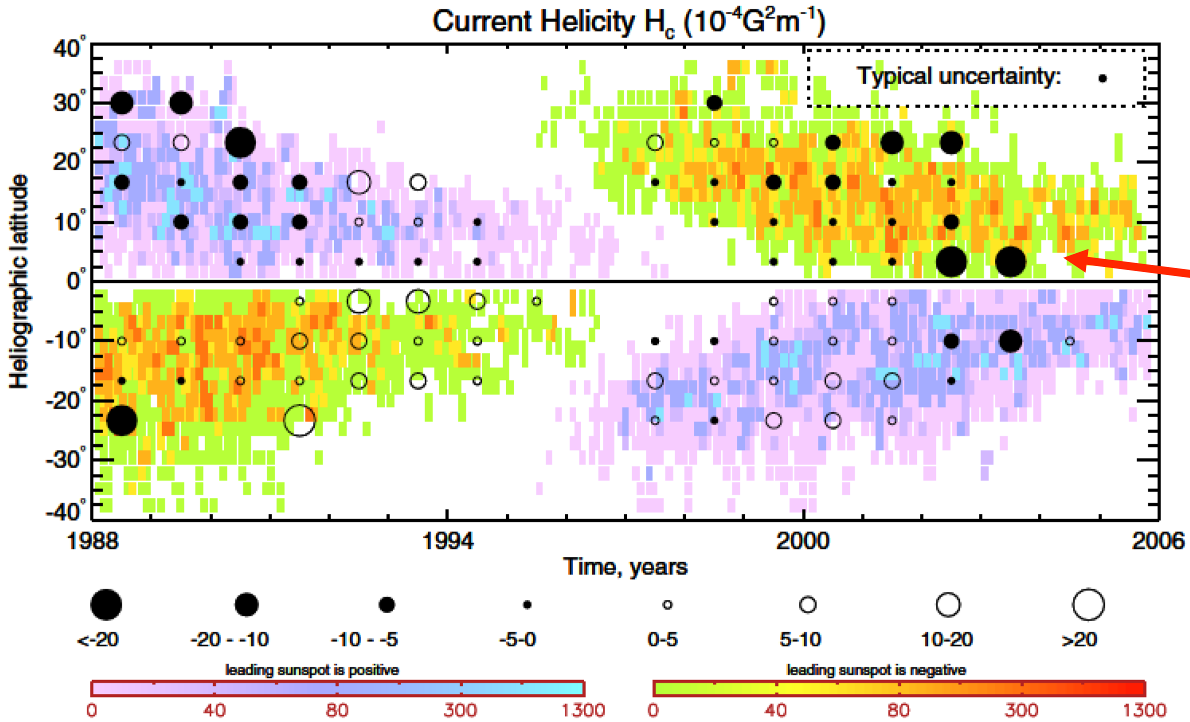




In this study (**Gao et al. 2008**), 984 active regions (6205 magnetograms in all) have been selected from 1988 to 2005, in which 431 active regions are in the 22nd solar cycle and 553 active regions are in the 23rd solar cycle.

Hemispheric Helicity Sign Rule (Hale, 1908; Ding et al. 1986; **Seehafer 1990; Pevtsov et al. 1995; Abramenko et al. 1996; Bao & Zhang 1998; Hagino & Sakurai 2004; Zhang et al. 2010; Hao & Zhang 2012 ……)**

Mean current helicity density of ARs in 22nd and 23rd solar cycle with sunspot butterfly-gram inferred by Huairou vector magnetograms



- **Maximum of current helicity is delay for 2 years than that of sunspots?**
- **Same sign of current helicity tends to occur near the solar minimum (beginning and end of wing)?**

$$\overline{B_z \cdot (\nabla \times B_\perp)}$$

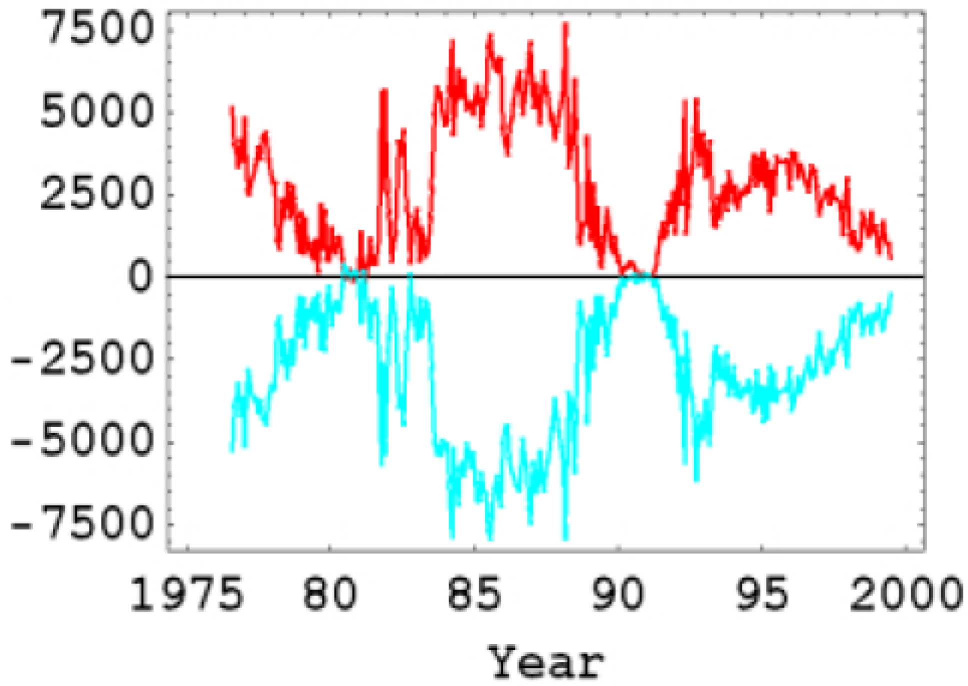
Gao Y. et al., 2008;

Zhang, H., Sakurai, T., Pevtsov, A., Gao, Y., Xu, H., Sokoloff, D. D. & Kuzanyan, K. 2010, MNRAS, 402, L30

After the calculation of more than 6600 vector magnetograms of ARs

Helicity Production by Solar Rotation

M A. Berger & A. Ruzmaikin (JGR, 2000)



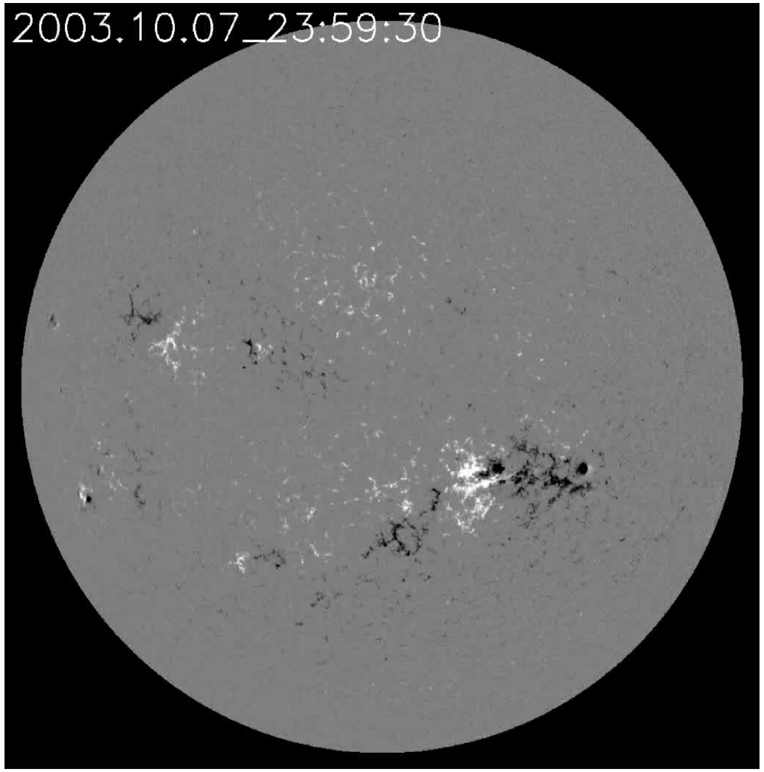
Net transfer of helicity into the southern corona and wind $dH_{CS}/dt = \dot{H}(V_S \rightarrow C_S)$ (predominantly positive curve), and into the northern corona and wind $dH_{CN}/dt = \dot{H}(V_N \rightarrow C_N)$ (predominantly negative curve). The units are 10^{40} Mx^2/day.

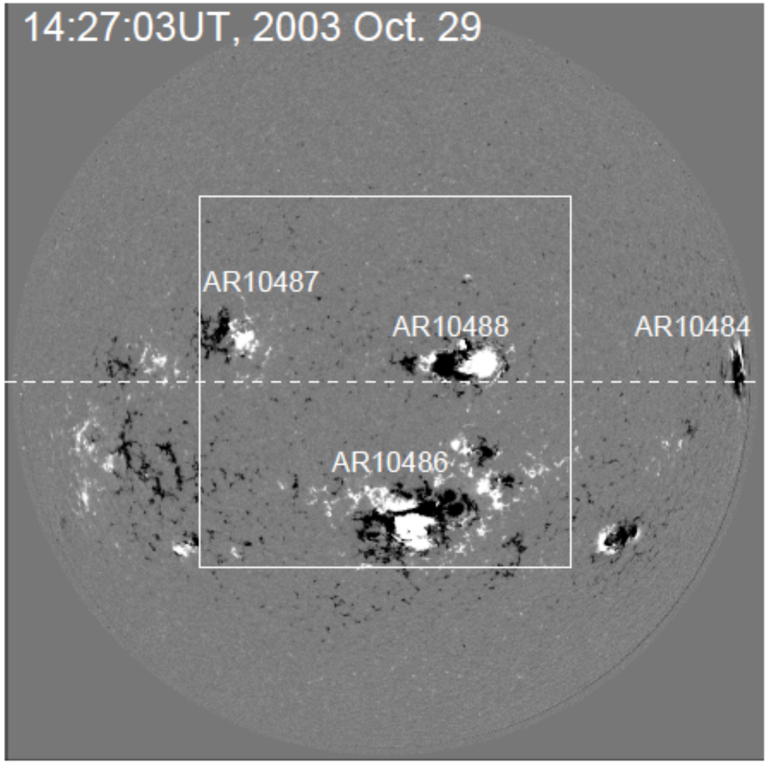
The Ω effect contribution can be captured in a surface integral, even though the helicity itself is stored deep in the convection zone. They (B&R) then evaluate this surface integral using solar magnetogram data and differential rotation curves. Throughout the 22 year cycle studied (1976 -1998) the helicity production in the interior by differential rotation had the correct sign compared to observations of coronal structures — negative in the north and positive in the south.

The net helicity flow into each hemisphere over this cycle was approximately 4×10^{46} Mx^2.

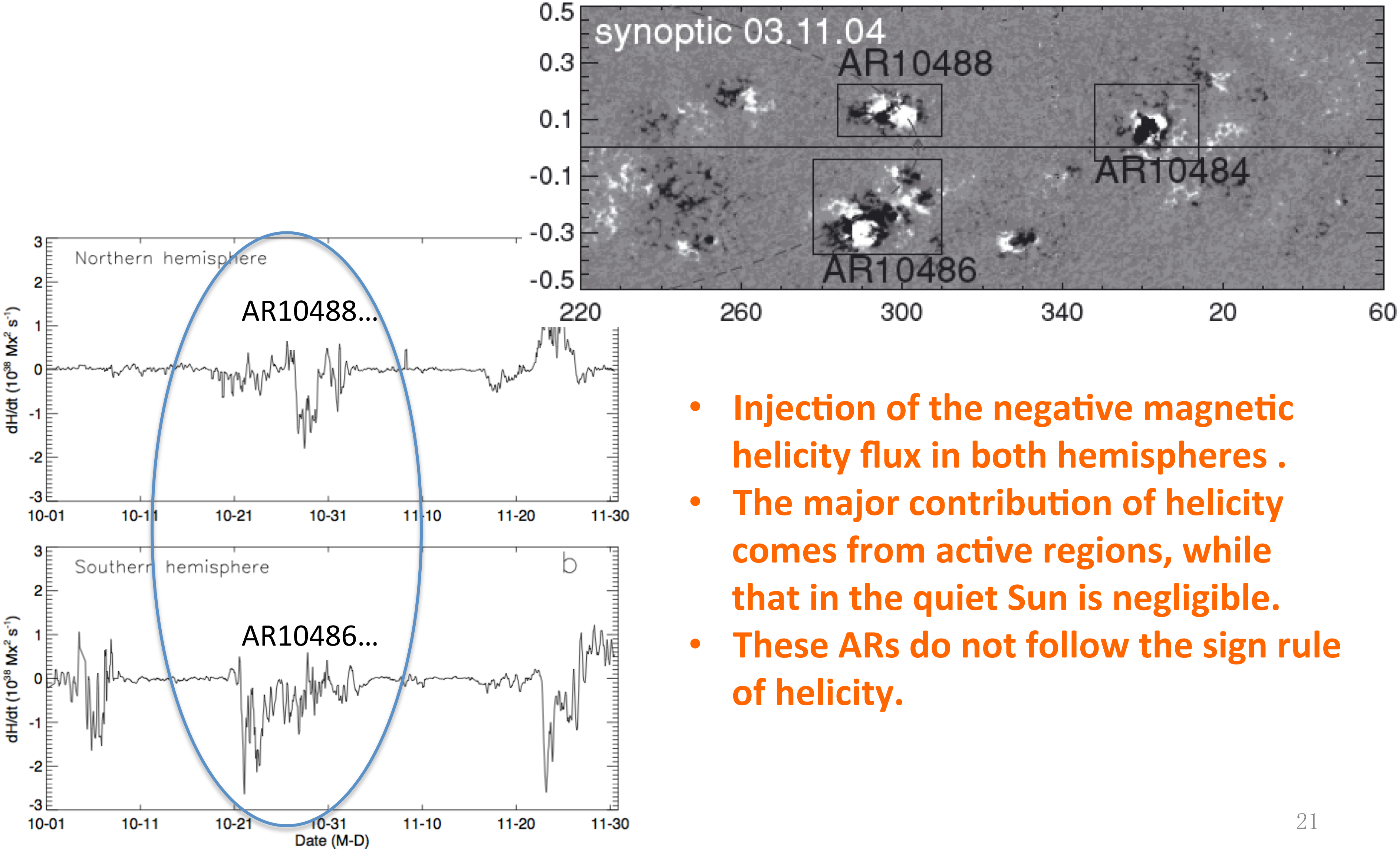
Magnetic helicity flux in northern and southern hemisphere in 1996-2009 inferred from 96m MDI full disk magnetograms

Yang and Zhang, 2012, ApJ; Zhang and Yang, 2013, ApJ



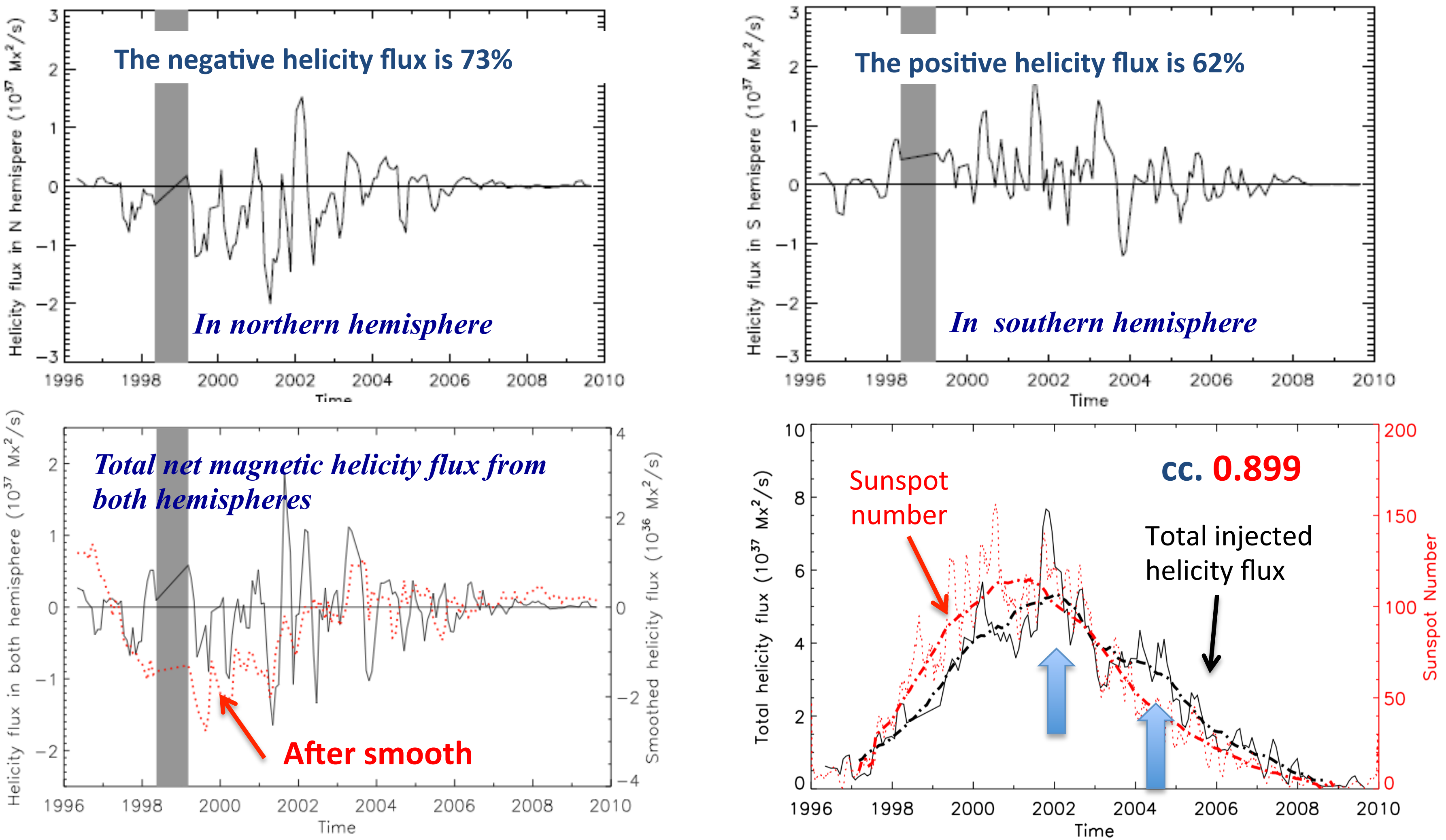


Injective magnetic helicity flux from N and S hemisphere on Oct.-Nov. 2003 from 96m MDI full disk magnetograms



- Injection of the negative magnetic helicity flux in both hemispheres .
- The major contribution of helicity comes from active regions, while that in the quiet Sun is negligible.
- These ARs do not follow the sign rule of helicity.

Injection of magnetic helicity flux with 23rd solar cycle inferred from 96m full disk magnetograms



- It is estimated about the total magnetic helicity 5×10^{46}Mx^2 for a solar cycle.

Yang and Zhang, 2012, ApJ & Zhang and Yang, 2013, ApJ

Spectrum tensors of turbulent magnetic field

H. Zhang, A. Brandenburg and D. Sokoloff, 2014, ApJL

Isotropic homogeneous turbulence, the spectrum tensor of fluctuating magnetic fields include: energy spectrum (E) and helicity spectrum (H_m) :

$$\langle \hat{B}_i(\mathrm{k},t)\hat{B}_j(\mathrm{k}',t')\rangle = \Gamma_{ij}(\mathrm{k},t)\delta^2(\mathrm{k}-\mathrm{k}')$$

$$\Gamma_{ij}(k,t) = \frac{E(k,t)}{4\pi k^4}(k^2\delta_{ij} - k_i k_j) + \frac{iH_m(k,t)}{8\pi k^4}\varepsilon_{ijk}k_k$$

$$\frac{1}{2}\langle B^2\rangle = \int_0^\infty E_m(k,t)dk$$

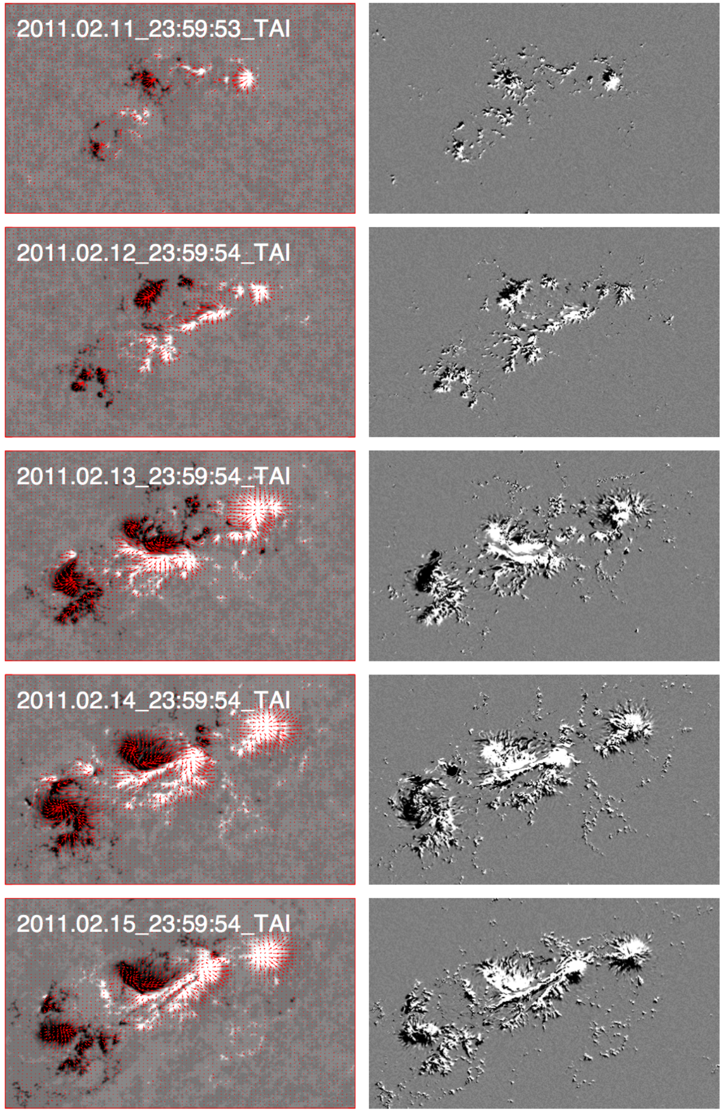
$$\langle \mathbf{A}\cdot\mathbf{B}\rangle = \int_0^\infty H_m(k,t)dk \qquad H_m(k,t) \approx \frac{1}{k^2}H_c(k,t)$$

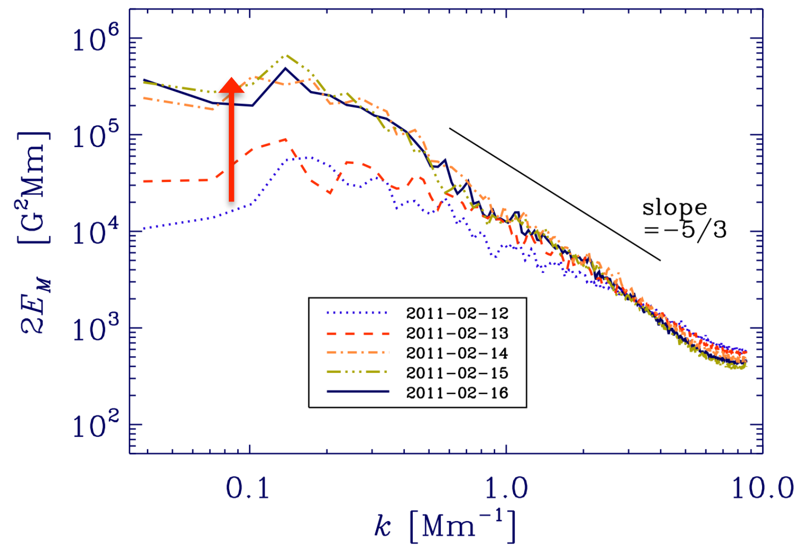
Isotropic homogeneous turbulence, the spectrum tensor 各向同性均匀湍流磁场谱张量

Moffatt, H.K., Magnetic field generation in electrically conducting fluids, 1978

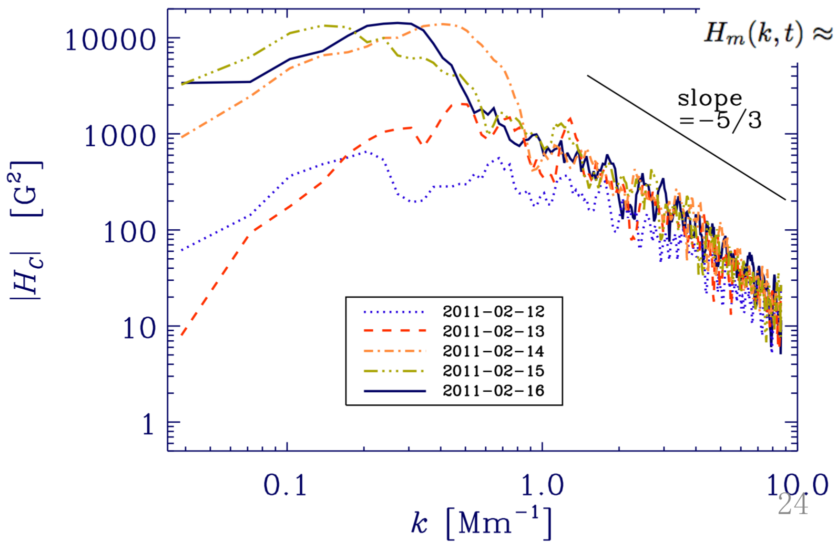
Batchelor, G.K., 1953, An Introduction to Fluid Dynamics, Cambridge University Press

Relationship Between Magnetic Energy and Helicity Spectrum in Active Regions (AR11158)



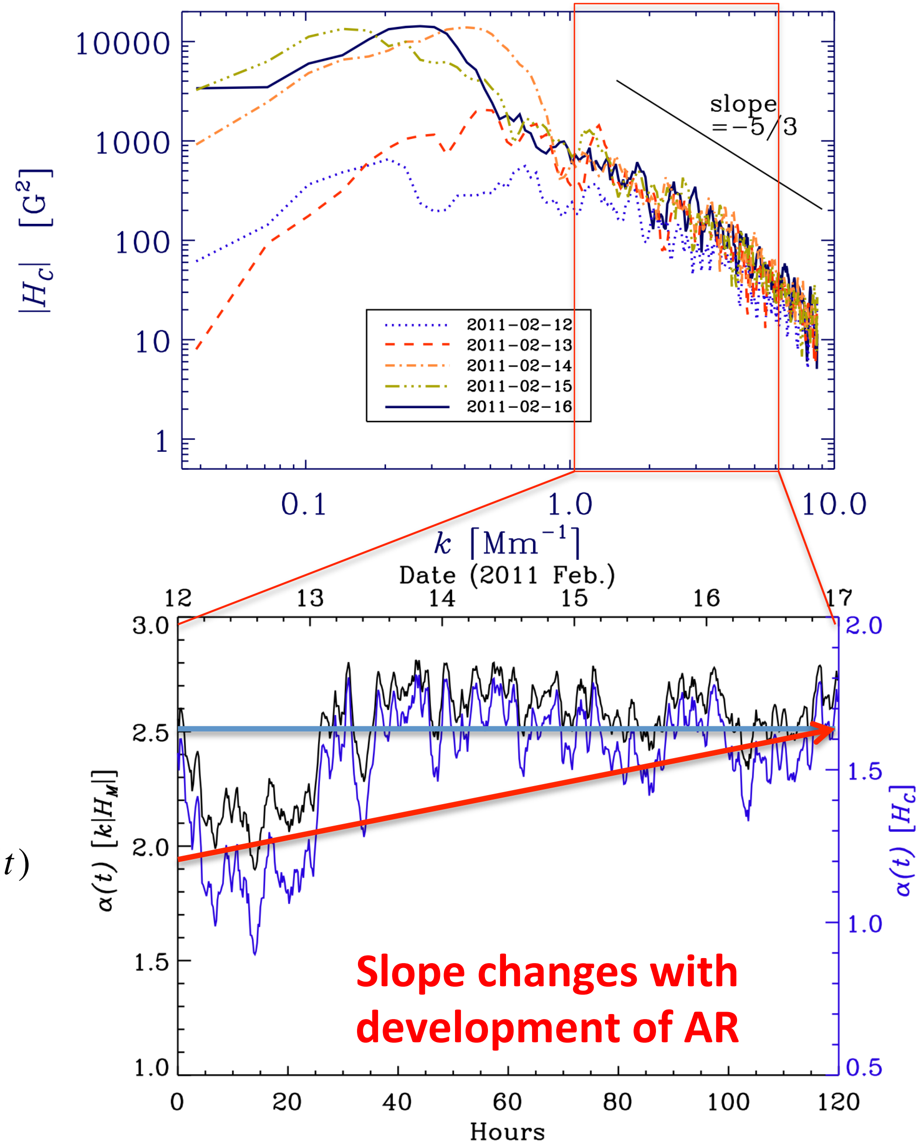


$$H_m(k,t) \approx \frac{1}{k^2} H_c(k,t)$$



H. Zhang, A. Brandenburg and D. Sokoloff, 2014, ApJL

Evolution of Current Helicity Spectrum in AR11158 on 2011 Feb. 11 - 15

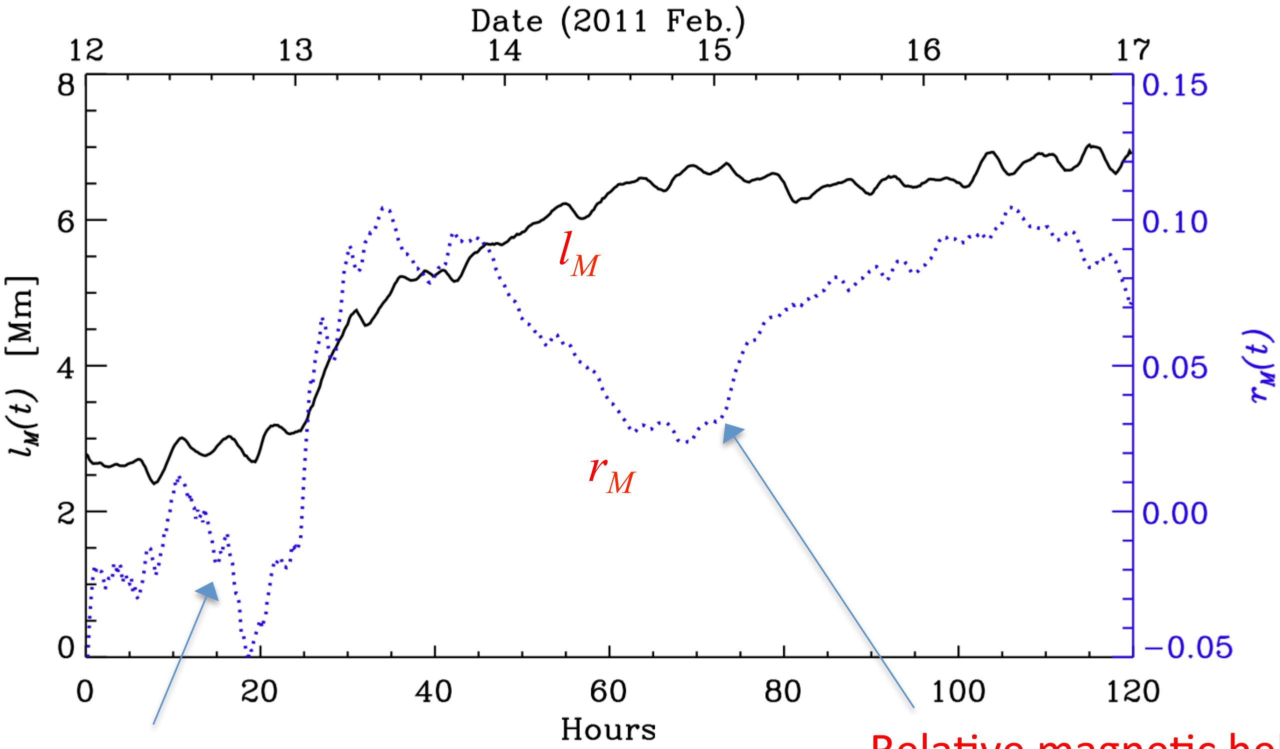


$$H(k) \propto k^{-\alpha(t)}$$

H. Zhang, A. Brandenburg and D. Sokoloff, 2014, ApJL

Evolution of Relative Scales of Magnetic Energy and Helicity Spectrum in AR11158

H. Zhang, A. Brandenburg and D. Sokoloff, 2016 ApJ



Integral scale of magnetic field

$$l_M = \int k^{-1} E_M(k)dk \Big/ \int E_M(k)dk$$

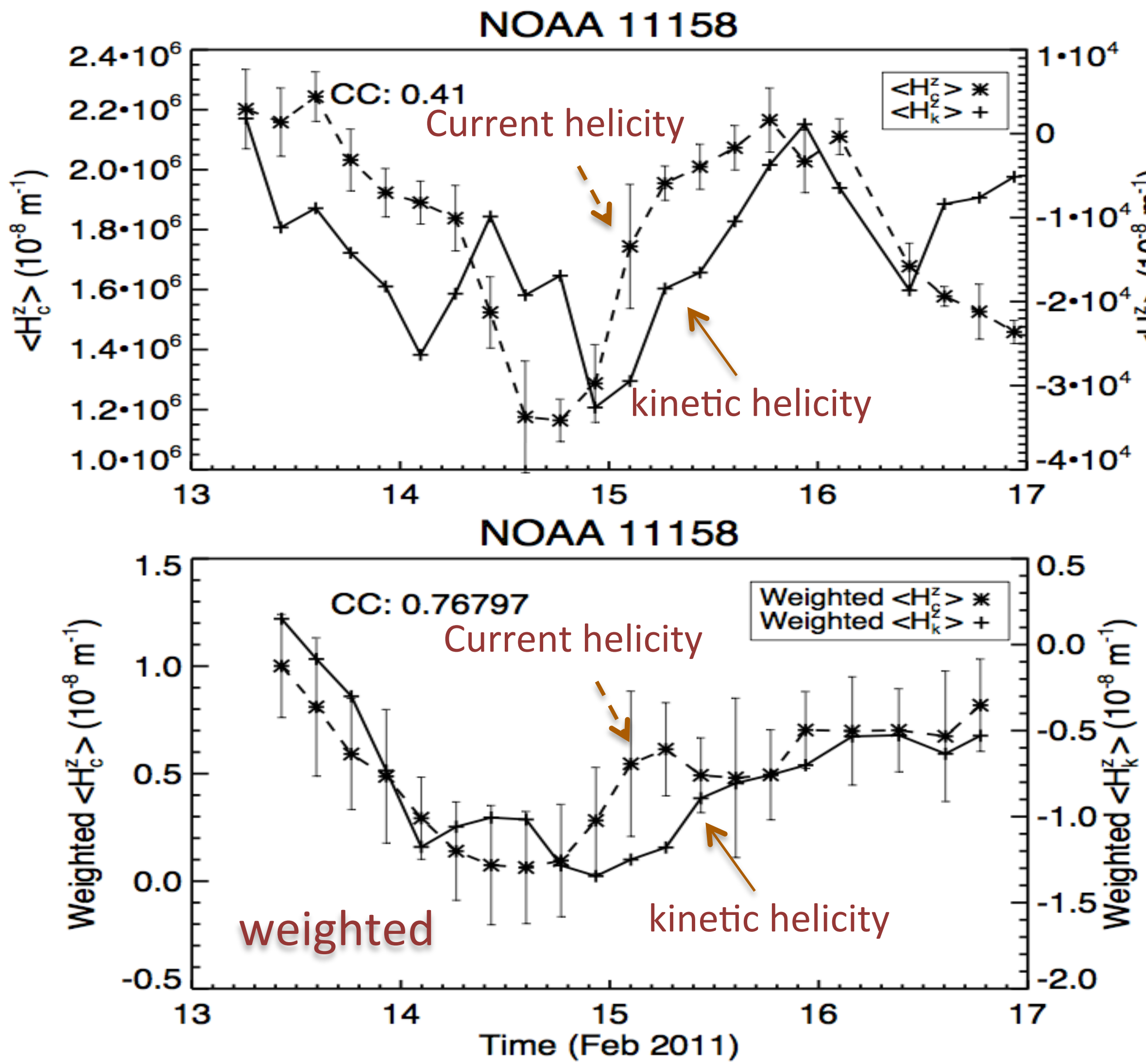
Relative magnetic helicity

$$r_M = H_M \Big/ 2l_M E_M$$

$$|\mathcal{H}_M| = \left|\int H_M dk\right| \leq 2\int k^{-1} E_M(k)dk \equiv 2\ell_M \mathcal{E}_M$$

(e.g. Kahniashvili et al. 2013)

Correlation between mean current and kinetic helicity in AR 11158



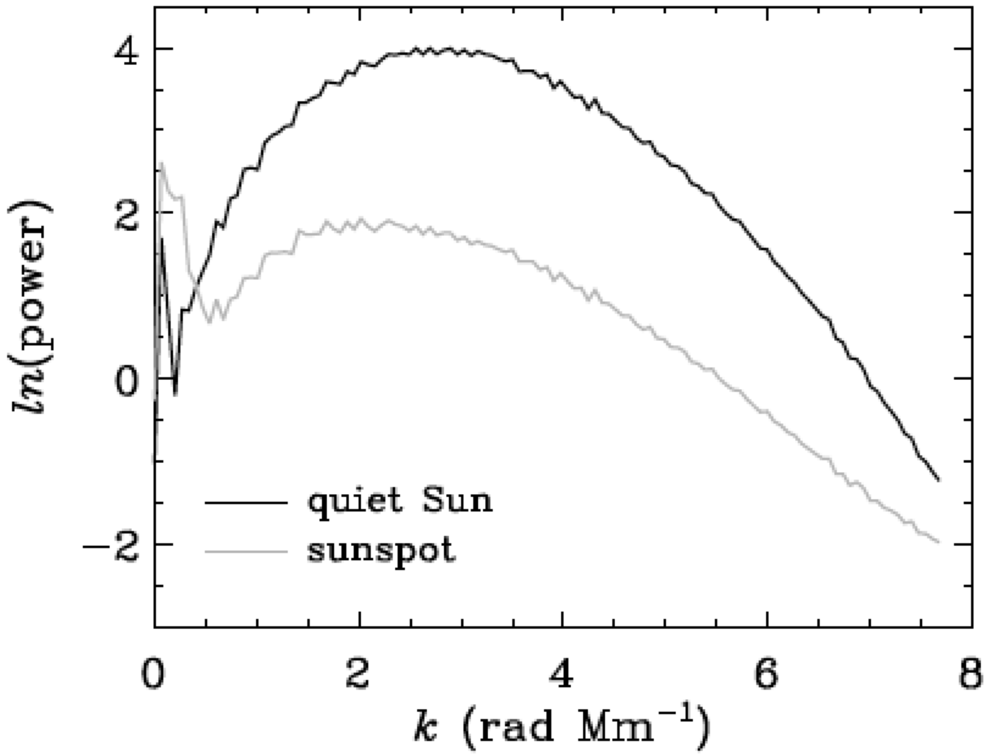
Gao Y., Zhao J. & Zhang H., 2012

$$\alpha^V = -\frac{\tau_{corr}}{3}\left\langle \vec{v}\cdot\nabla\times\vec{v}\right\rangle$$

$$\alpha^H = \frac{\tau_{corr}}{3\mu\rho}\left\langle \vec{B}\cdot\nabla\times\vec{B}\right\rangle$$

Convection power of the sunspot and the quiet-Sun region

Junwei Zhao & Dean-Yi Chou, 2013, SoPh, 287, 149



Power spectrum of velocity fields:

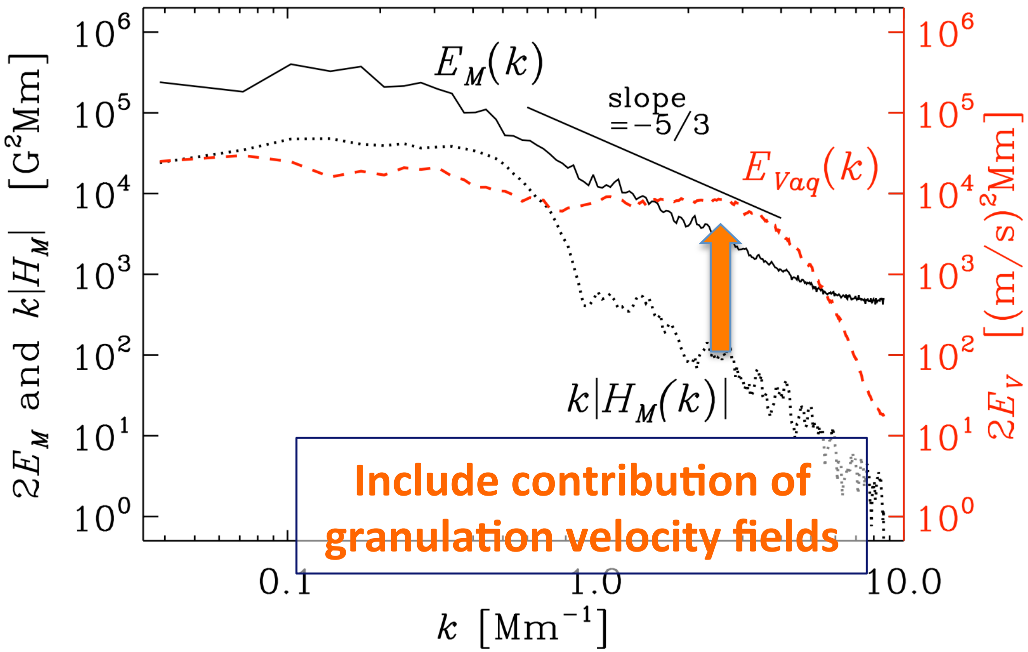
Chou, D.-Y., Labonte, B. J., Braun, D. C. and Duvall, T. L., Jr. 1991, ApJ, 372, 314

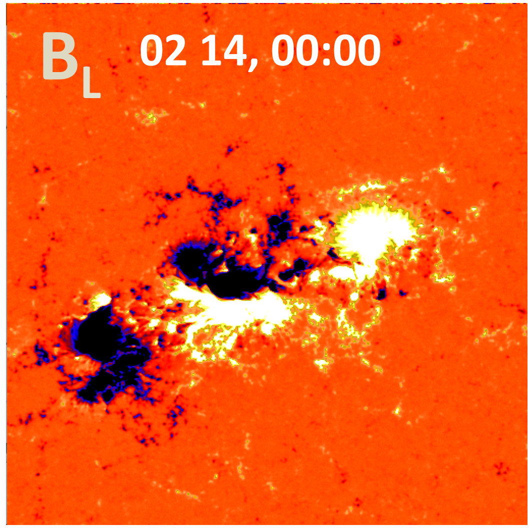
Ruzmaikin, A. A., Cadavid, A. C., Chapman, G. A., Lawrence, J. K. and Walton, S. R. 1996, ApJ, 471, 1022

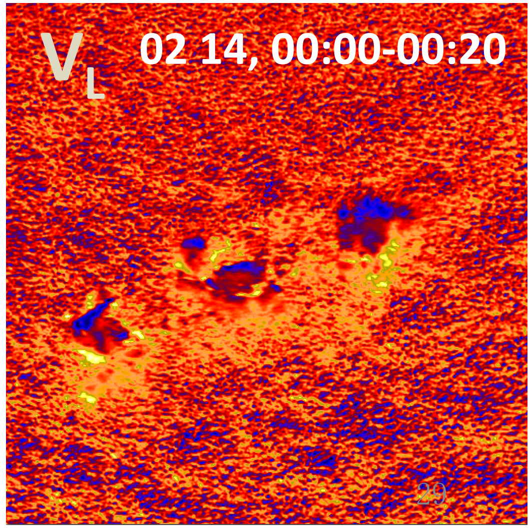
Zhao, Junwei and Chou, Dean-Yi, 2013, SoPh, 287, 149

Relationship between magnetic and velocity field spectrums in ARs from HMI

(NOAA11158 on Feb. 14, 2011)







The spectrum of mean velocity fields (average value over 20 min) of the active region is similar to Zhao and Chou (2013), and different from that of magnetic field

Power spectrum of velocity fields of active regions:

Chou, D.-Y., Labonte, B. J., Braun, D. C. and Duvall, T. L., Jr. 1991, ApJ, 372, 314

Ruzmaikin, A. A., Cadavid, A. C., Chapman, G. A., Lawrence, J. K. and Walton, S. R. 1996, ApJ, 471, 1022

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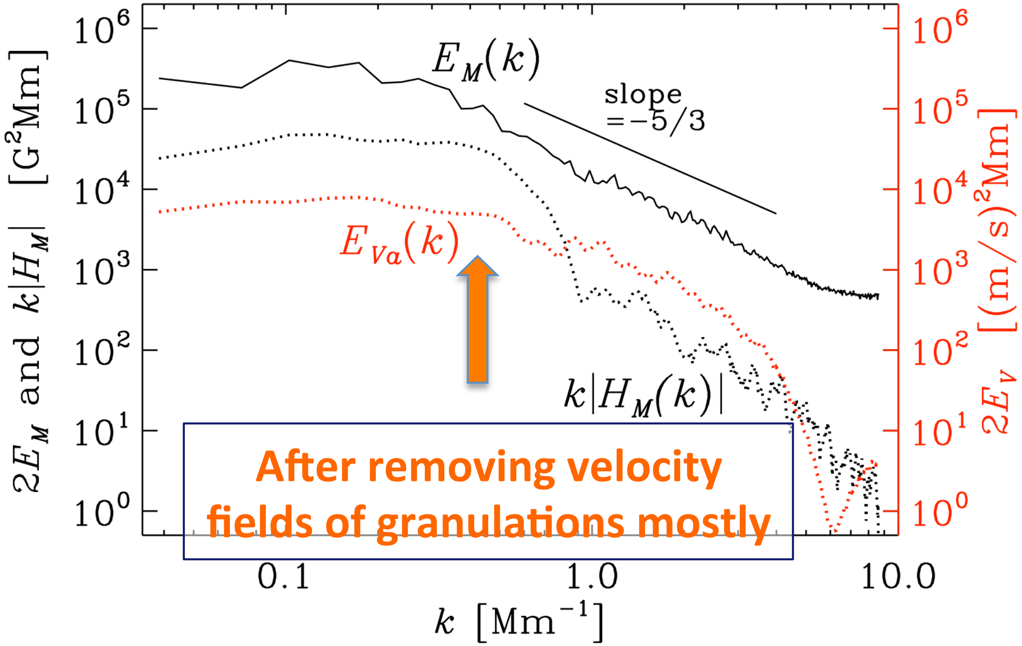
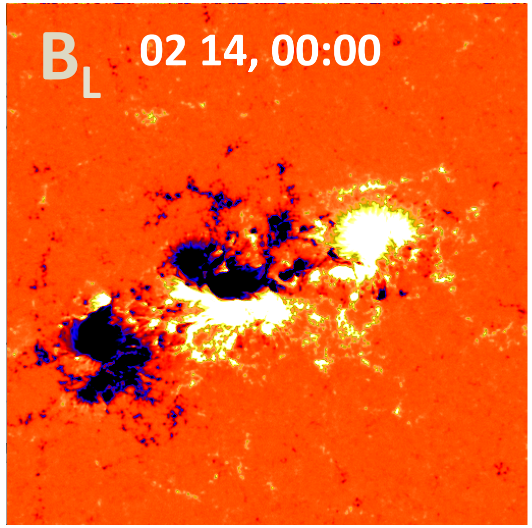
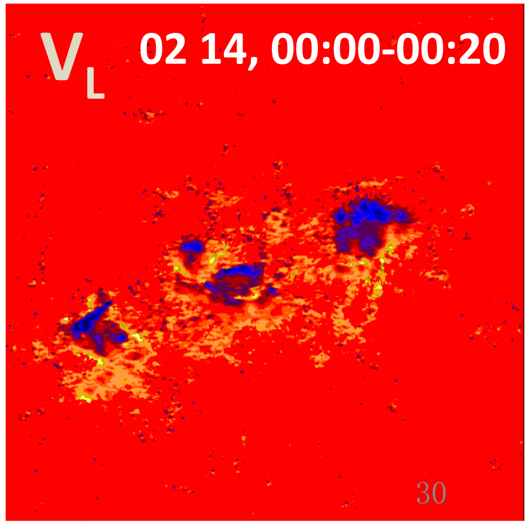
Relationship between magnetic and velocity field spectrums in ARs from HMI

(NOAA11158 on Feb. 14, 2011)





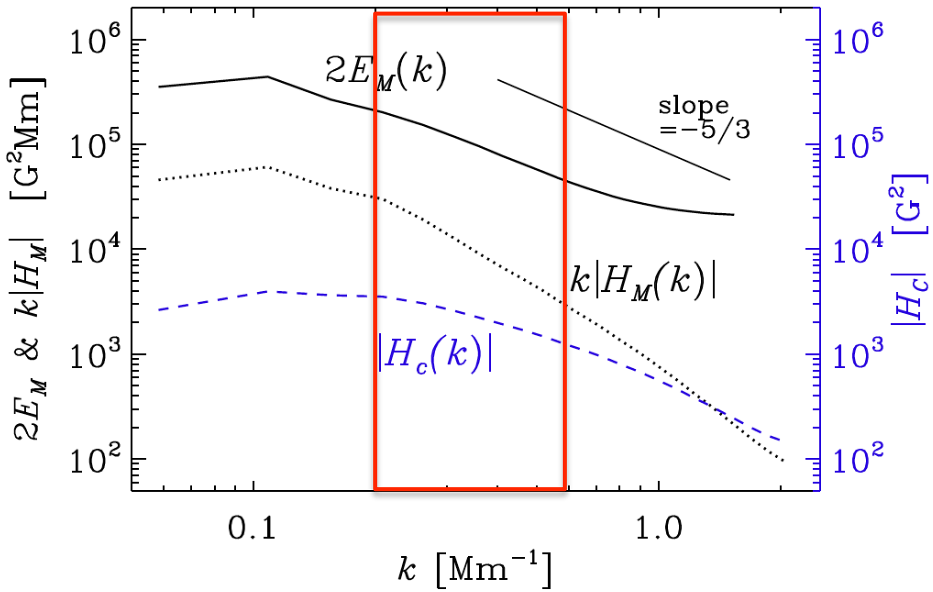


The similar tendency between the spectrum of magnetic fields and mean velocity fields (average value over 20 min) of the active region, as removing the contribution of granulation velocity.

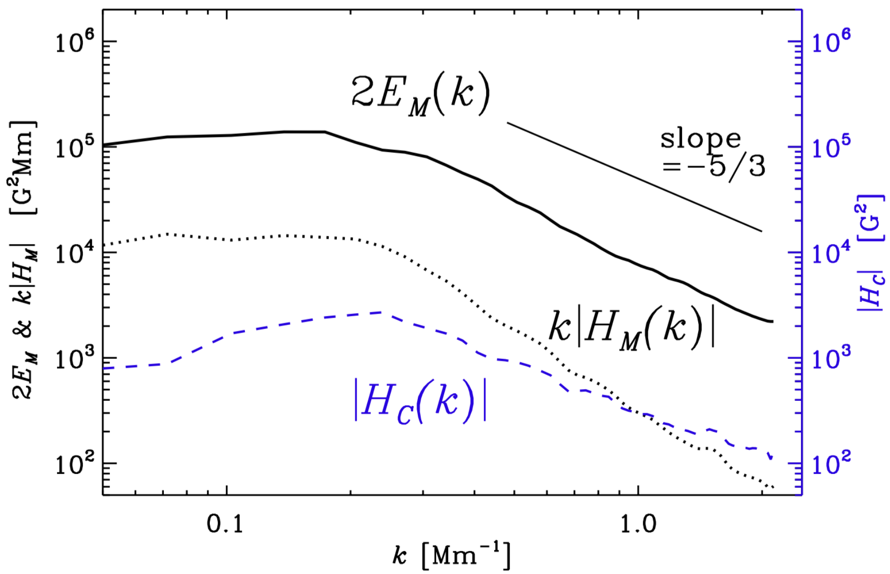
太阳活动区平均磁能和螺度谱的比较

Comparison on mean magnetic energy and helicity spectrum of ARs with solar cycles

H. Zhang, A. Brandenburg and D. Sokoloff, 2016 ApJ



6629 Huairou vector magnetograms ARs in 1988-2005

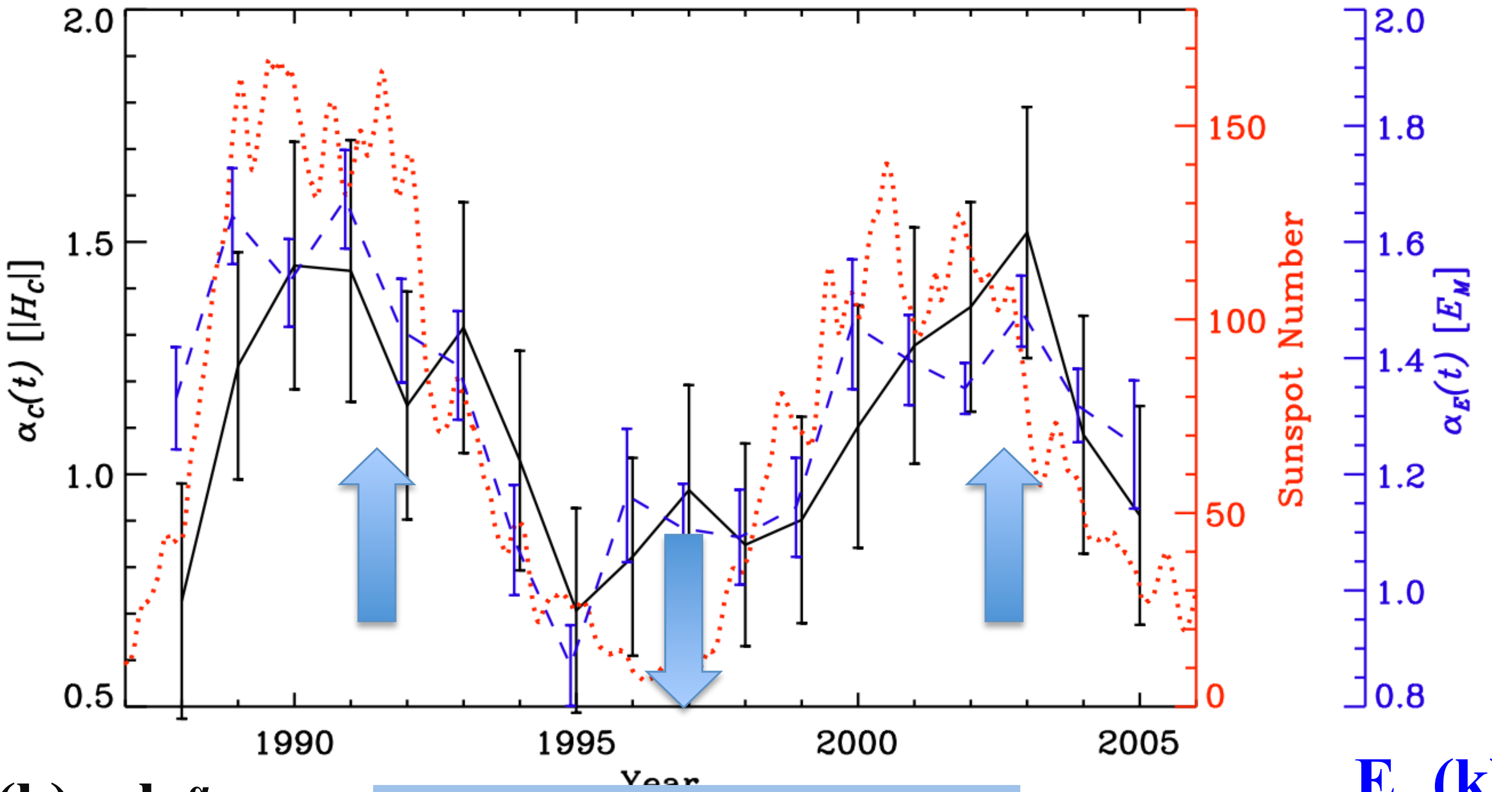


600 HMI vector magnetograms of AR 11158 on 2011 Feb. 12-16, the pixels have been compressed from 512×512 to 128×128.

$$H_m(k,t) \approx \frac{1}{k^2} H_c(k,t)$$

第22和23太阳活动周磁能和螺度平均功率谱斜率变化

Mean power law slope of energy and helicity spectrum of ARs in 22nd and 23rd solar cycles



two year smooth

$H_c(k) \sim k^{-\alpha}$

11 Years

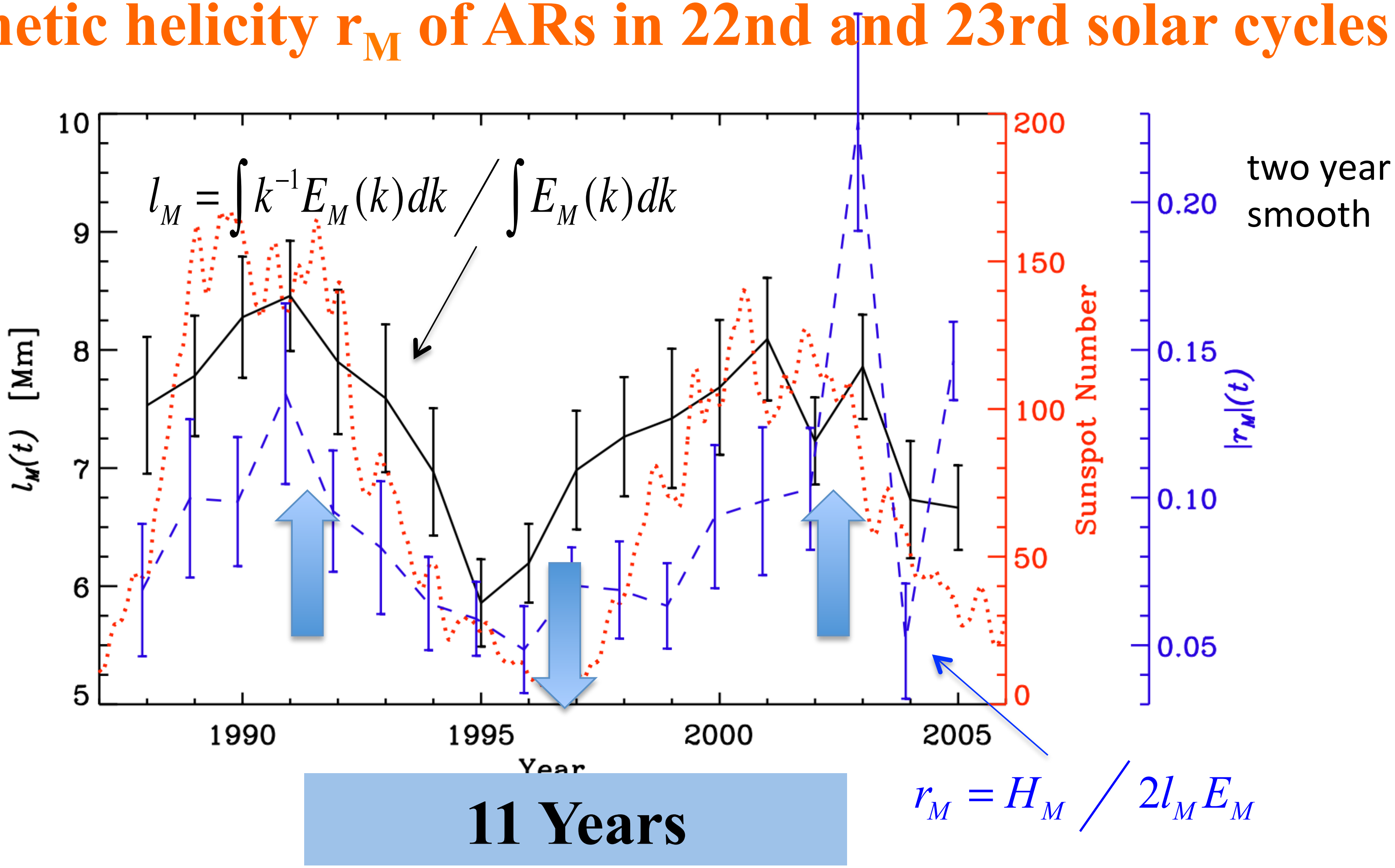
$E_m(k) \sim k^{-\alpha}$

After the calculation of more than 6600 vector magnetograms of ARs

H. Zhang, A. Brandenburg and D. Sokoloff, 2016 ApJ

第22和23太阳活动周平均磁能积分尺度和相对磁螺度变化

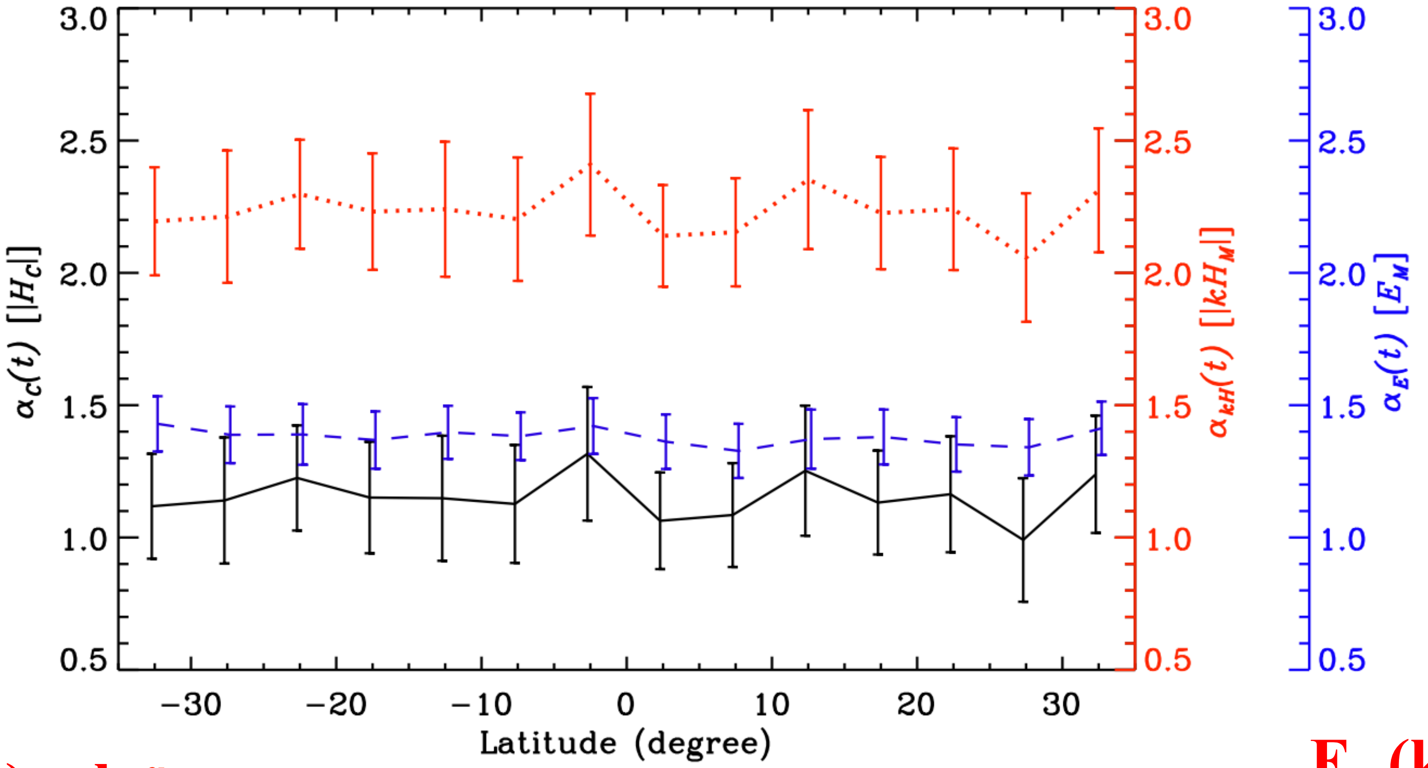
Mean integral scale l_M of magnetic energy and relative magnetic helicity r_M of ARs in 22nd and 23rd solar cycles



After the calculation of more than 6200 vector magnetograms of ARs

第22和23太阳活动周磁能和螺度平均功率谱斜率变化

Mean power law slope of energy and helicity spectrum of ARs in 22nd and 23rd solar cycles



$H_c(k) \sim k^{-\alpha}$

$E_m(k) \sim k^{-\alpha}$

$0.2 < k < 0.6$ (Mm^{-1})

After the calculation of more than 6600 vector magnetograms of ARs

Some discussions (1)

- **Observations of vector magnetic fields of active regions in the solar surface**

- Measurement of vector magnetic fields still is ***a fundamental topic***
- The powerful flare-CMEs probably relate to the ***redistribution of magnetic energy density*** in the solar surface; Evolution of ***non-potential magnetic fields*** and helicity
- ***Spectrum of*** magnetic field and helicity
- Relationship between ***magnetic and kinematic helicity***

Some discussions (2)

- **Magnetic (current) helicity and its with solar cycles**

- The changes of helicity with solar cycles reflect the ***complex formation process*** of the magnetic fields probably
- This means we still ***unclear*** the solar dynamo process completely
- It is ***a nonlinear process*** from the subatmosphere into the interplanetary space and mainly contributed from active regions

Thank you for your attention!