Long-term studies of photospheric magnetic fields on the Sun

Alexei Pevtsov

National Solar Observatory
Boulder, Colorado, USA

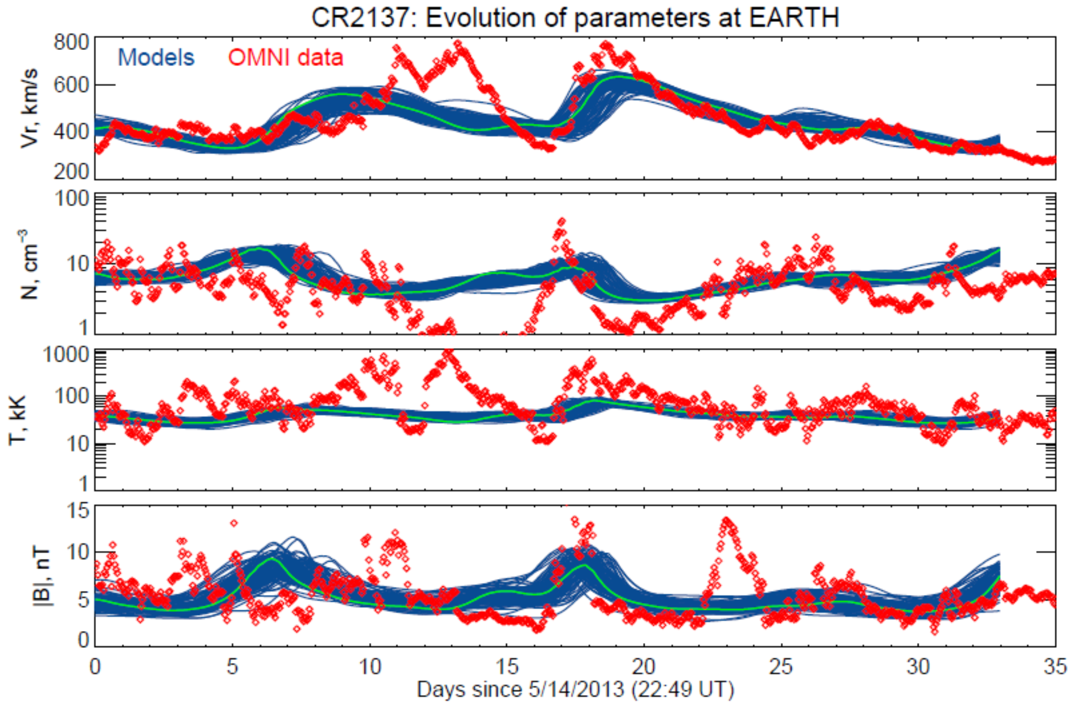
Outline

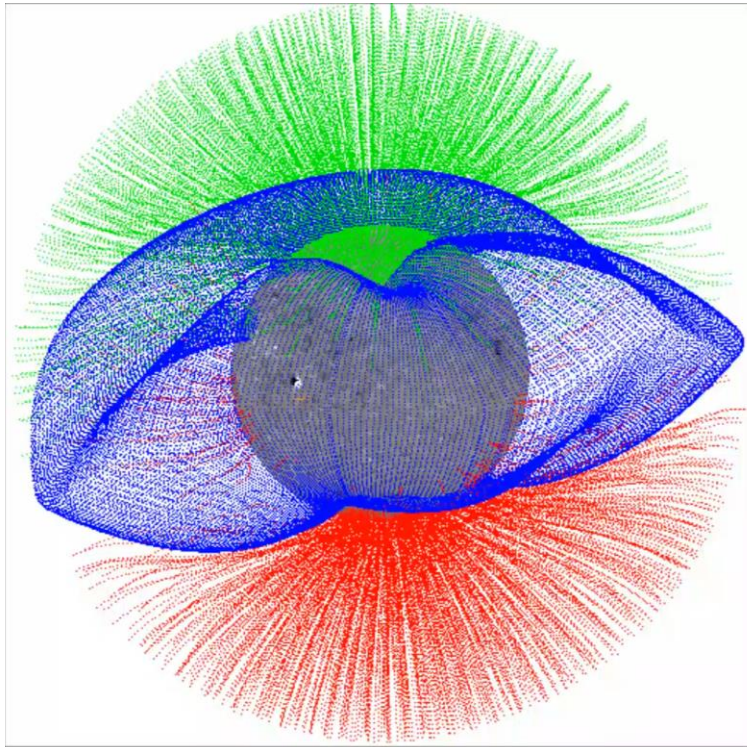
- Discovery of magnetic fields on the Sun
- Measurements of magnetic field
- (Now well-known) properties of solar magnetic fields and opened questions
- Solar activity via synoptic maps
- Magnetic fields from different instruments
- Vector magnetic field measurements and helicity

Why do we need magnetic field observations?

Space weather:
Planet habitability:

- Solar/stellar dynamo/cycles/nature of stellar magnetism
- Flare/CME activity
- Modeling solar/stellar wind
- Modeling topology of magnetic fields in solar and stellar atmosphere



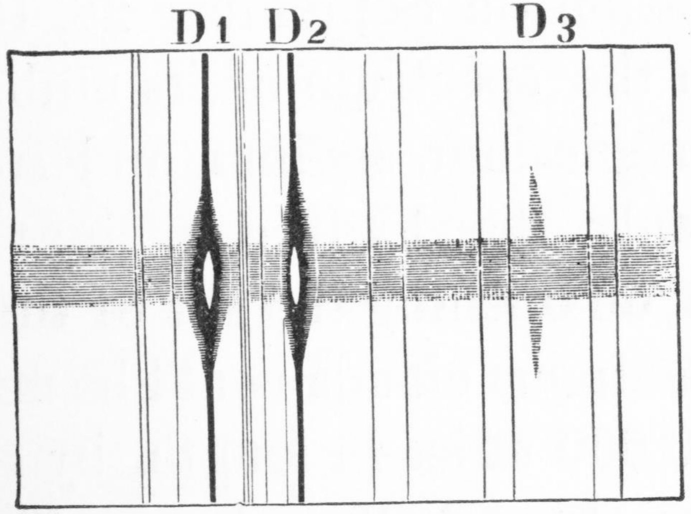


Pevtsov, A.A., Bertello, L., MacNeice, P. (2015) DOI: 10.1016/j.asr.2015.05.043

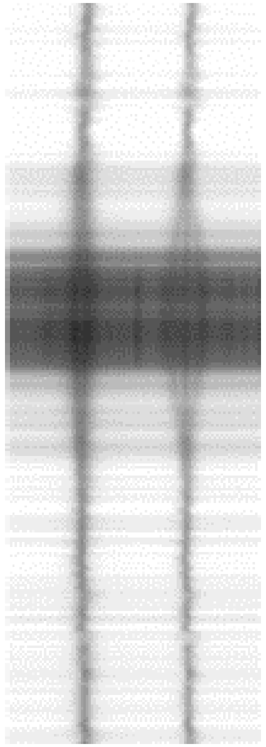
Discovery of magnetic fields

- 1896 - Zeeman effect discovered by Dutch physicist Pieter Zeeman
- 1870 – line splitting (D-line), C.A. Young
- 1892 – Some spectral lines broaden in sunspots (e.g., Cortie, A. L.)
- 1898 – Vanadium lines broaden significantly in sunspots

FIG. 36.



REVERSAL OF THE D-LINES.

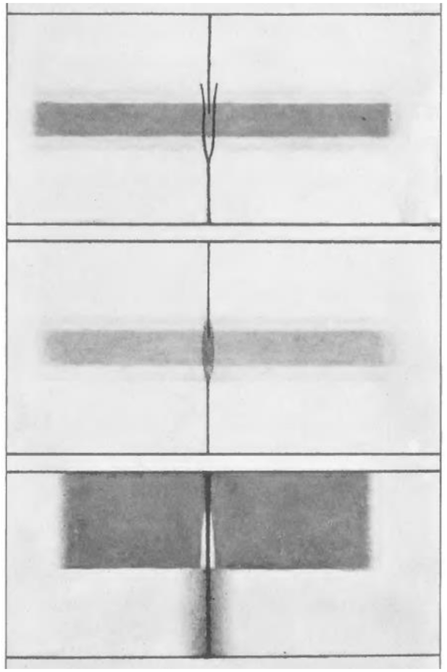


Hinode

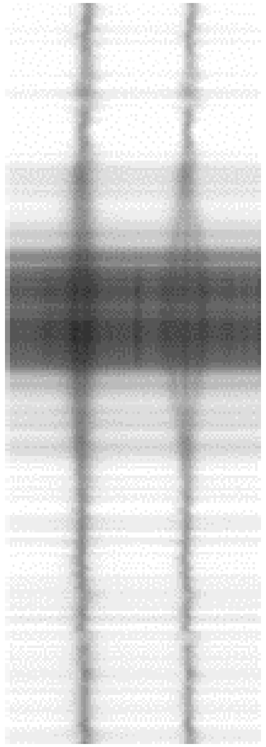
Discovery of magnetic fields

- 1905-06 – early tests for presence of magnetic field in sunspots by Hale (negative result).
- 1906 – Mitchell observation (C.A. Young PhD Advisor)

5250 A - 2200 G
5781 A - 3160 G
6064 A - 2160 G
6137 A - 2690 G
6173 A - 2360 G



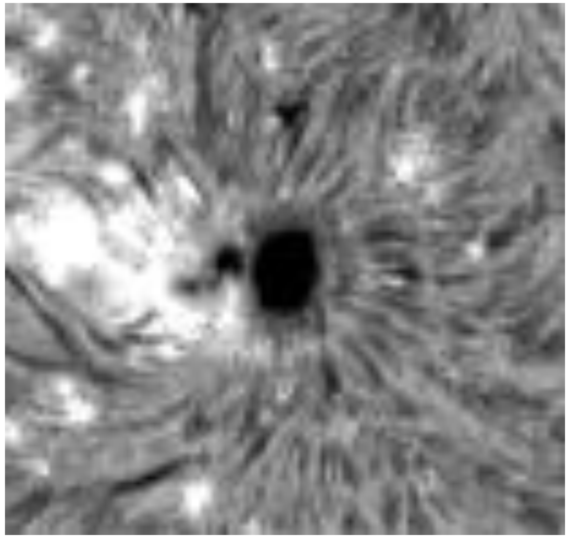
Mitchell (1906)

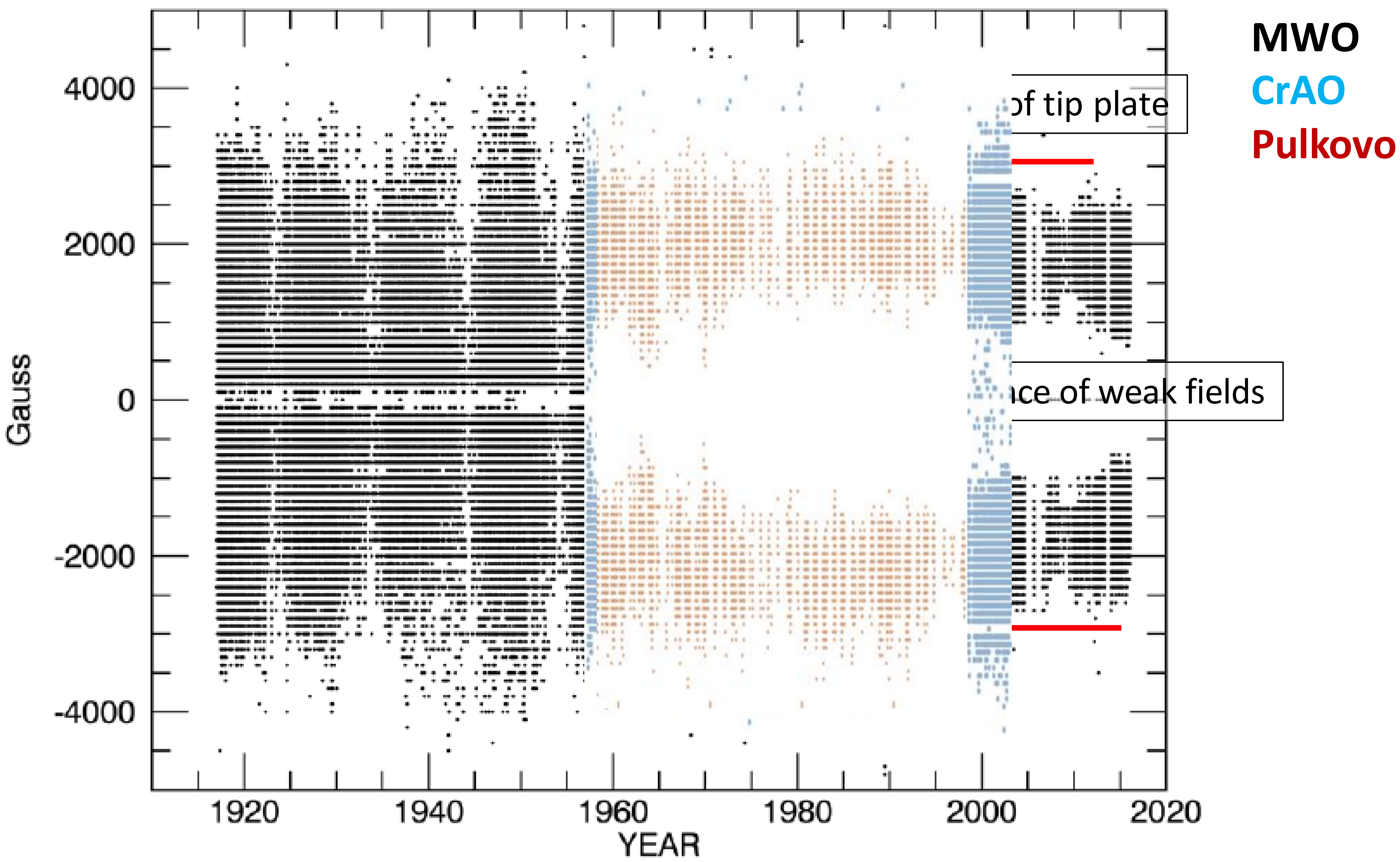


Hinode

First Observations of magnetic fields in Astrophysics

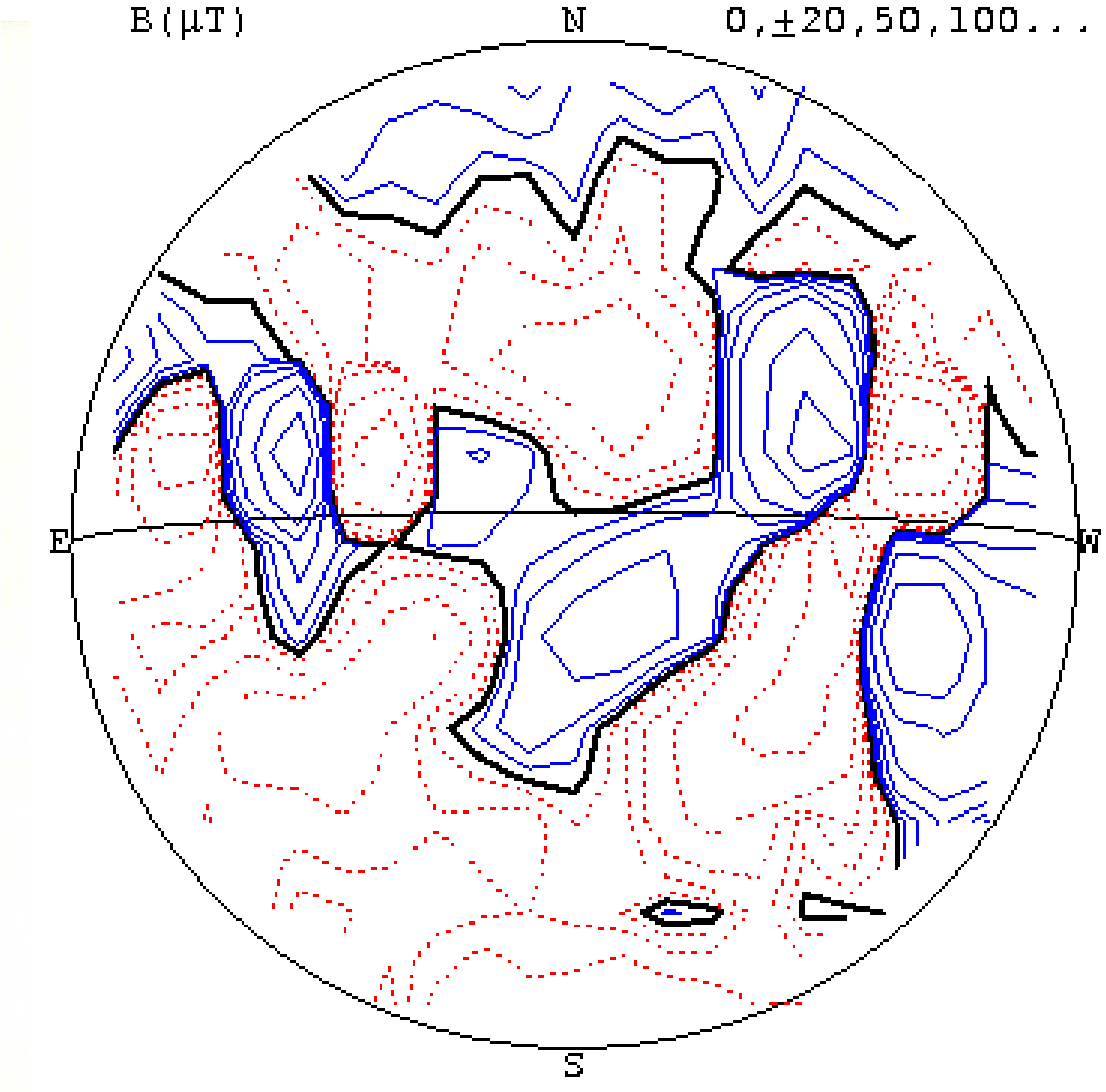
- 1907 – improvements to spectroheliograms (H-alpha whirls)
- 1908 – first measurements in astrophysics by G.E. Hale (Mount Wilson Observatory)
- Since 1917 – regular daily observations of magnetic fields in sunspots

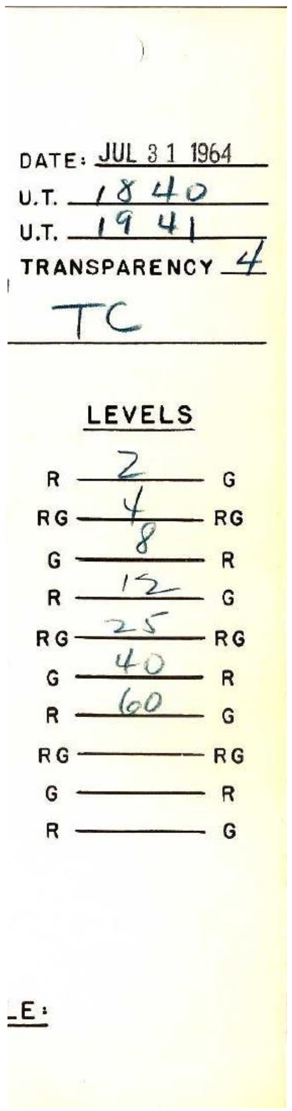




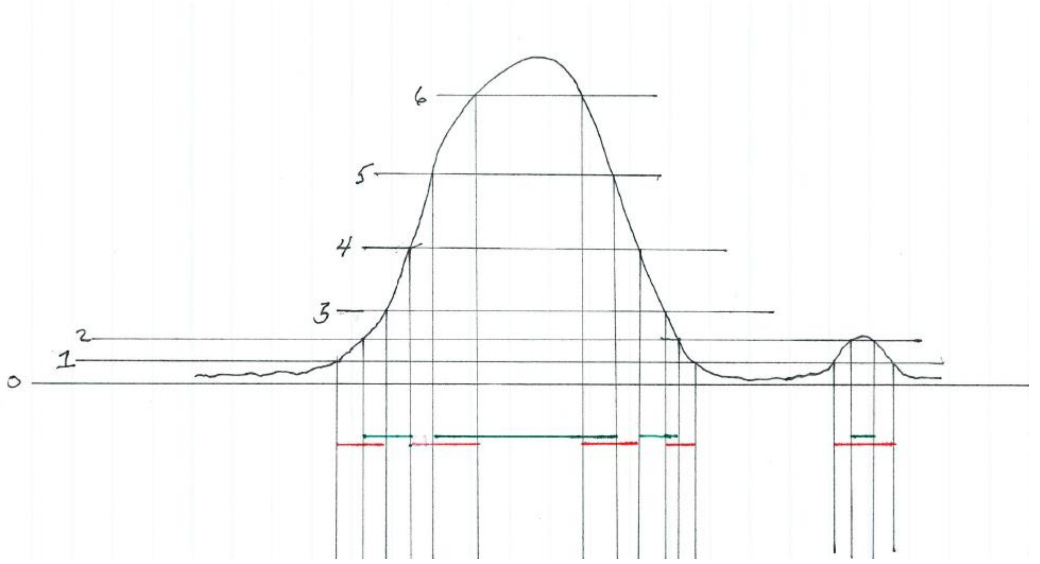
Pevtsov et al (2019)

Full disk magnetographs

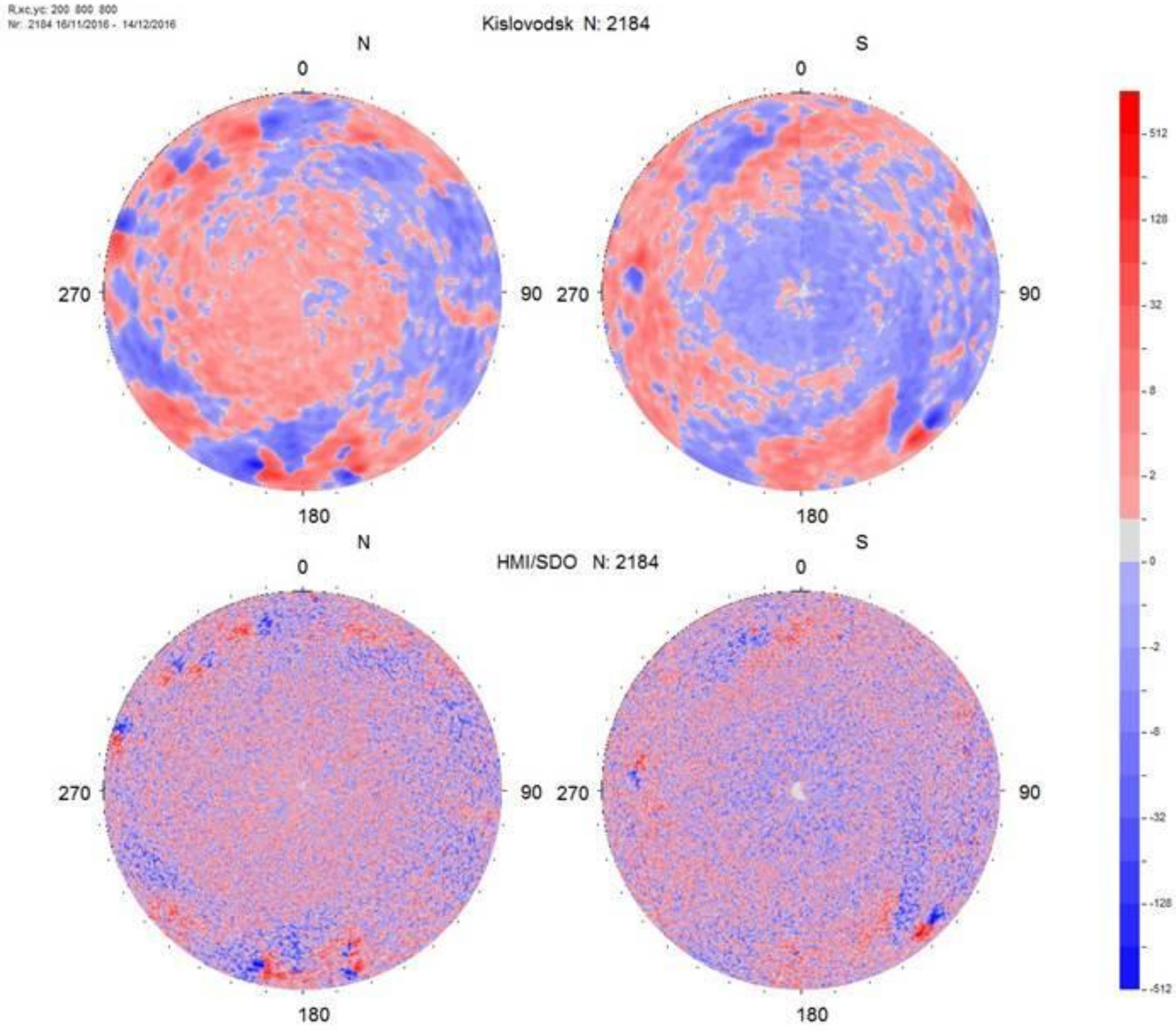




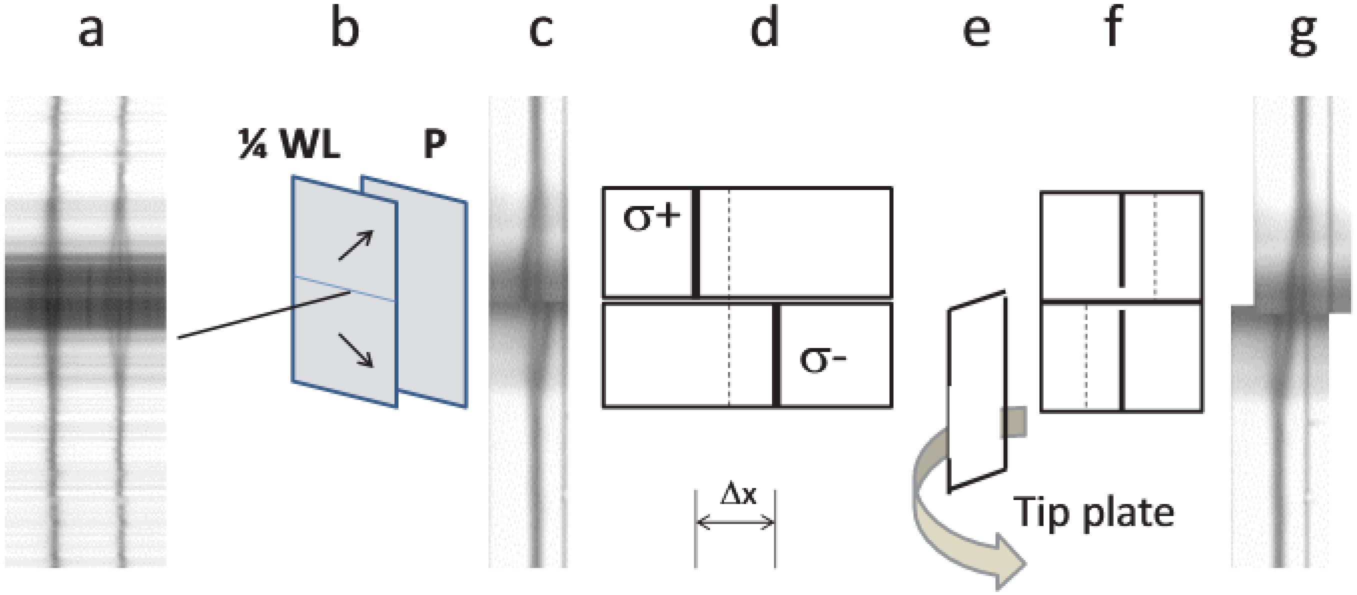
- Early 1950th - H. W. Babcock (Hale Laboratory telescope in Pasadena), after 1957 at MWO
- 1963-1968, X-Y servo plotter display
- Mount Wilson Observatory (MWO, 1967 – 2013)
- 1974-2013 (KPVT, 512ch, SP), VSM/SOLIS
- 1976 – present (WSO)



Comparison of the polar magnetic field.

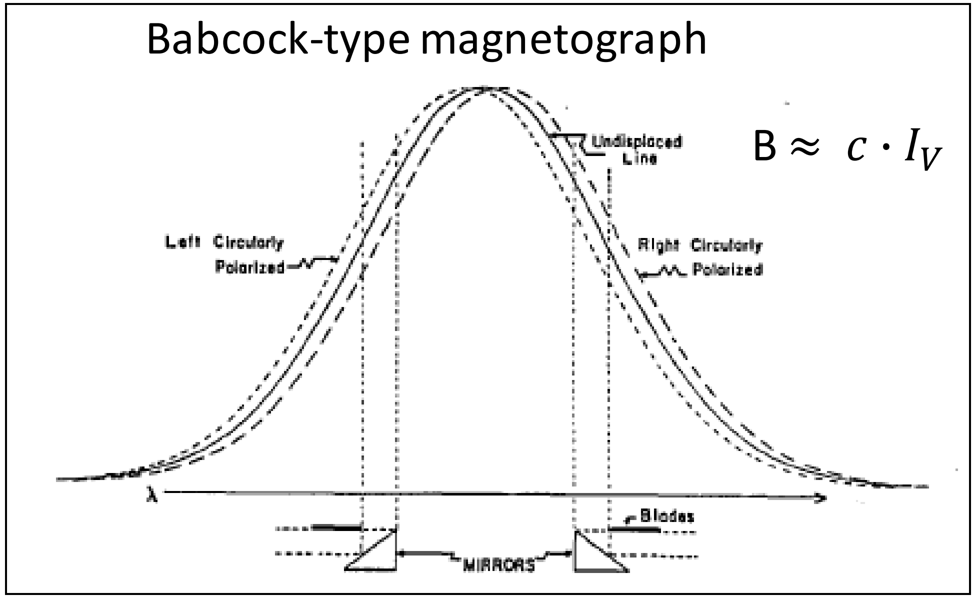


How do we measure magnetic fields



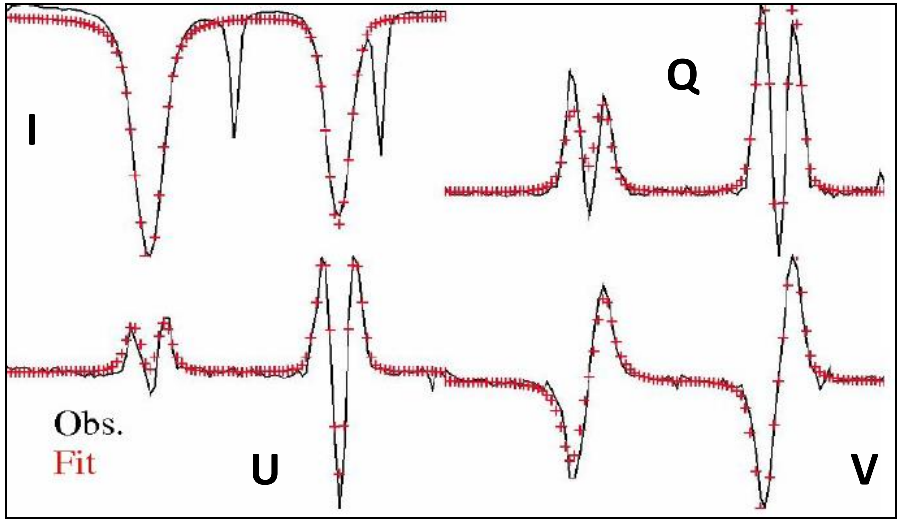
$$B = \frac{s\,\Delta x\,10^{13}}{9.34\,g\,\lambda^2}$$

MWO “sunspot drawings”,
CrAO (total field strength)



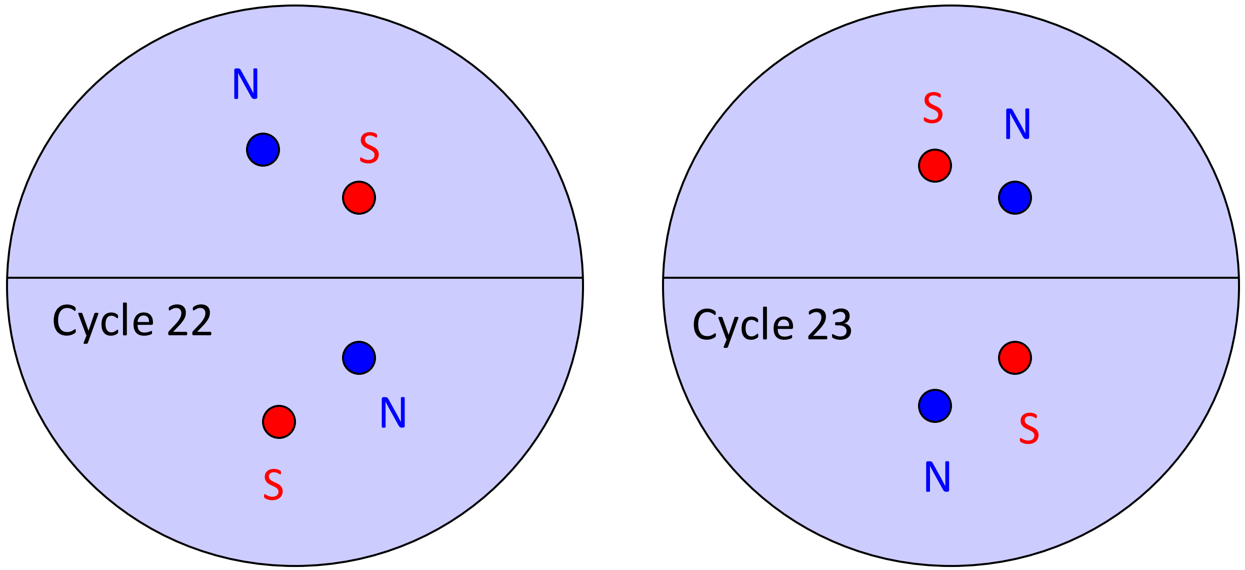
$$B \approx c \cdot I_V$$

GONG, MWO, KPVT (LOS field)



Stokes Polarimeters:
SOLIS/VSM, HMI/SDO
(full vector)

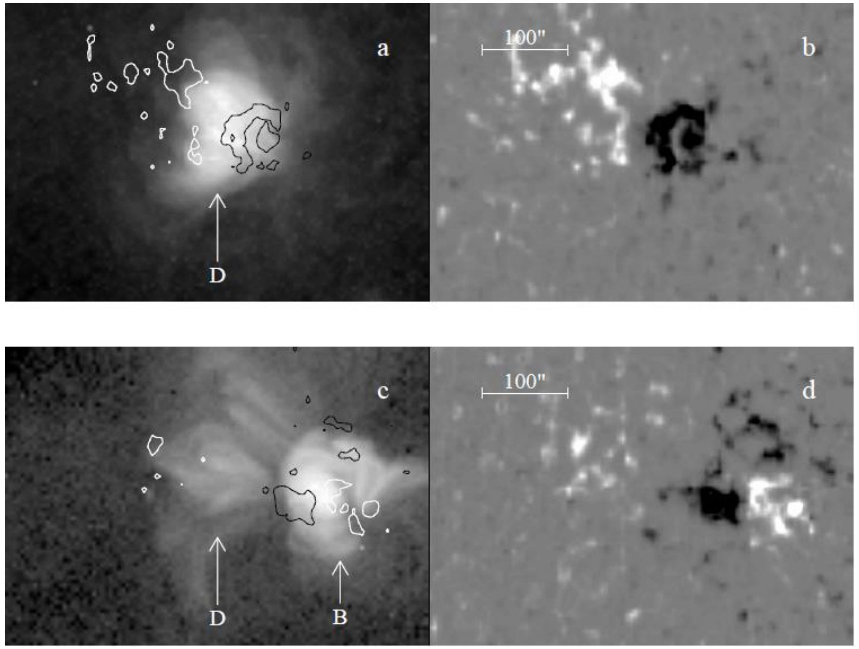
(Hale) Polarity and (Joy) tilt orientation

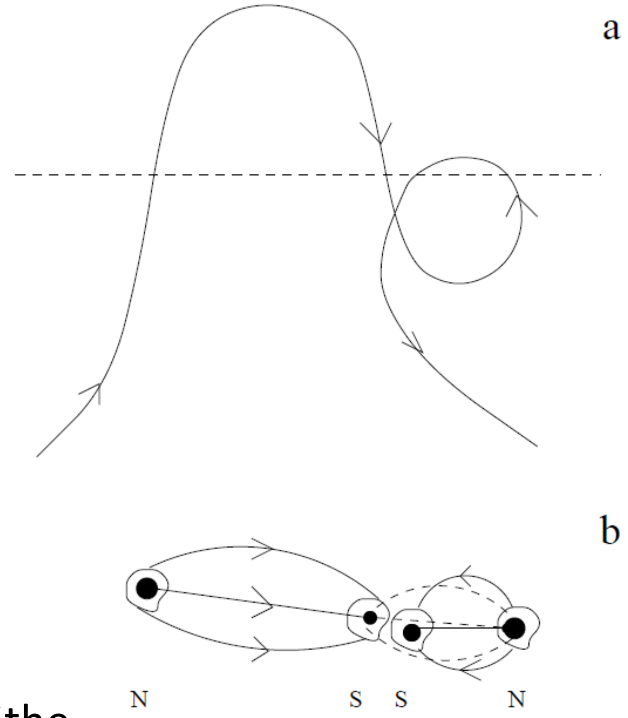


Hale et al. 1919 (1913-1917 – 3.7% irregular (non-Hale polarity) – vary between 1.4-6.3%
Stenflo & Kosovichev (2012) - about 4%, Li and Ulrich (2012) – 6.5%-9.1%

Non-Hale polarity ARs

Stenflo & Kosovichev (2012) – presence of two toroidal fluxes with opposite orientation

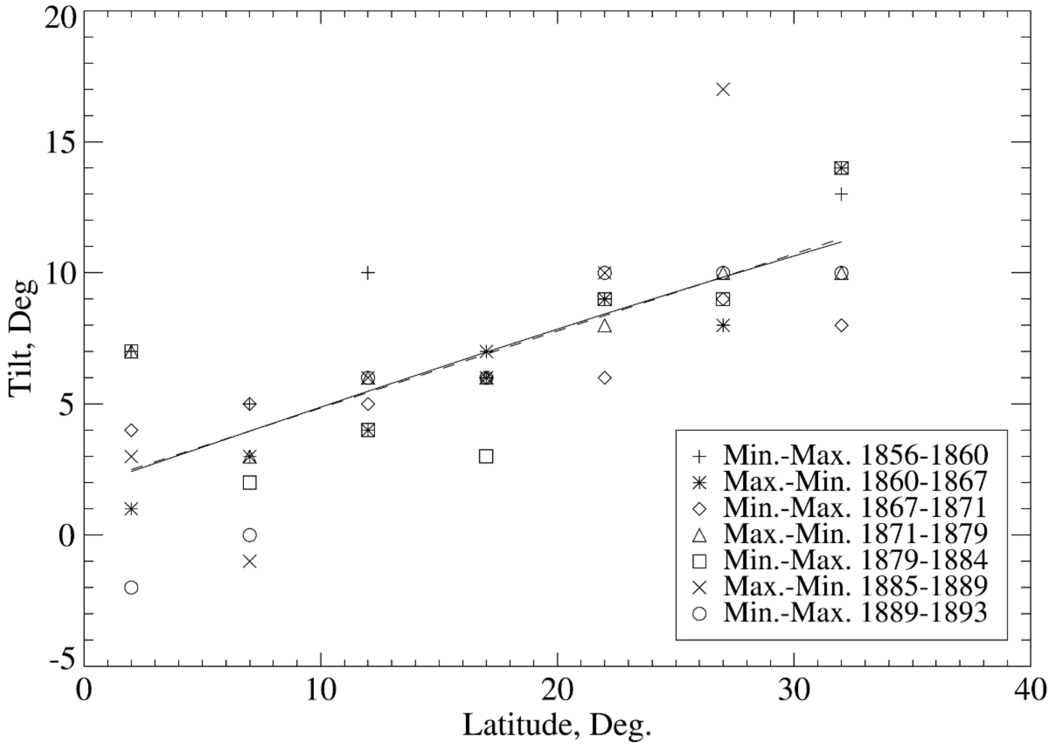




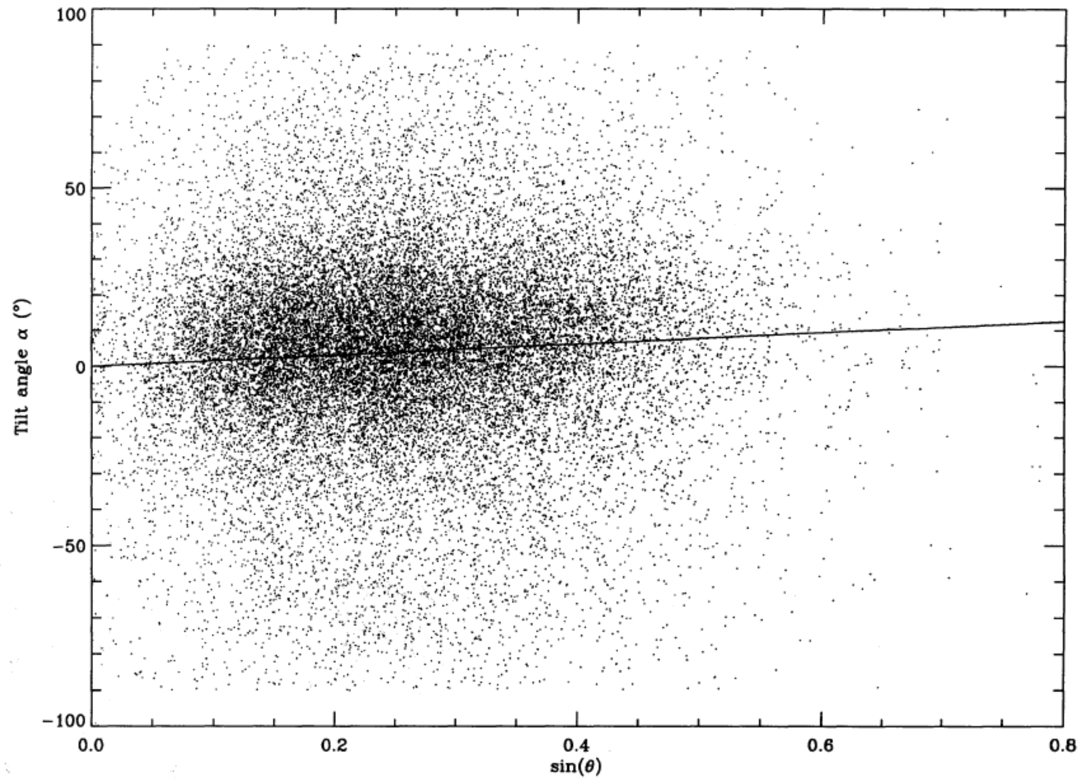
Pevtsov & Longcope (1998), ; helicity (twist) – writhe
Lopez Fuentes et al (2003) – gradual rotation/transformation from non-Hale to Hale orientation

Tilt orientation (Joy's law)

Zirin (1988) introduced term "Joy's Law"

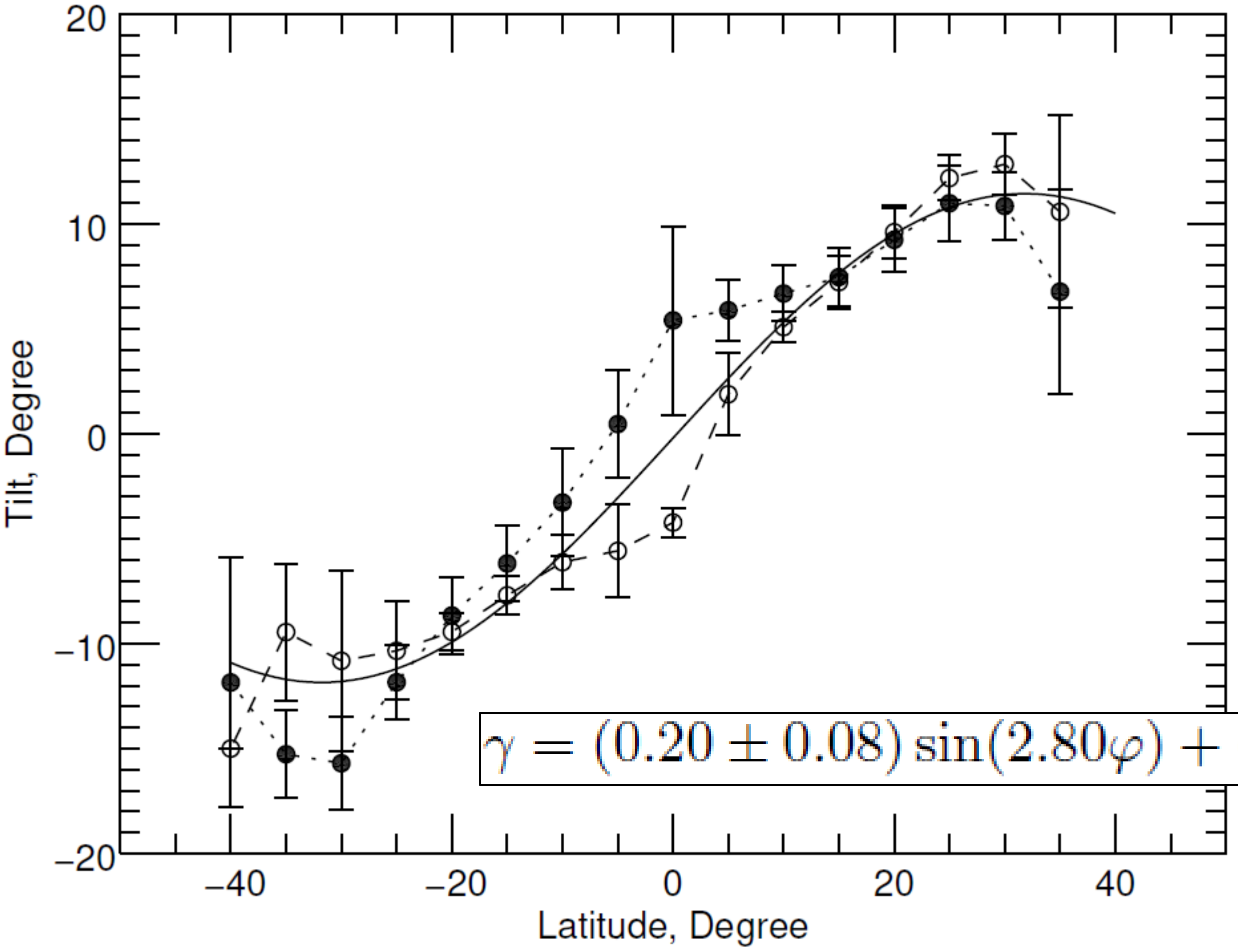


Hale et al. (1919); Pevtsov et al (2014)



Fisher, Fan, Howard (1995)

Active region tilts using MWO data

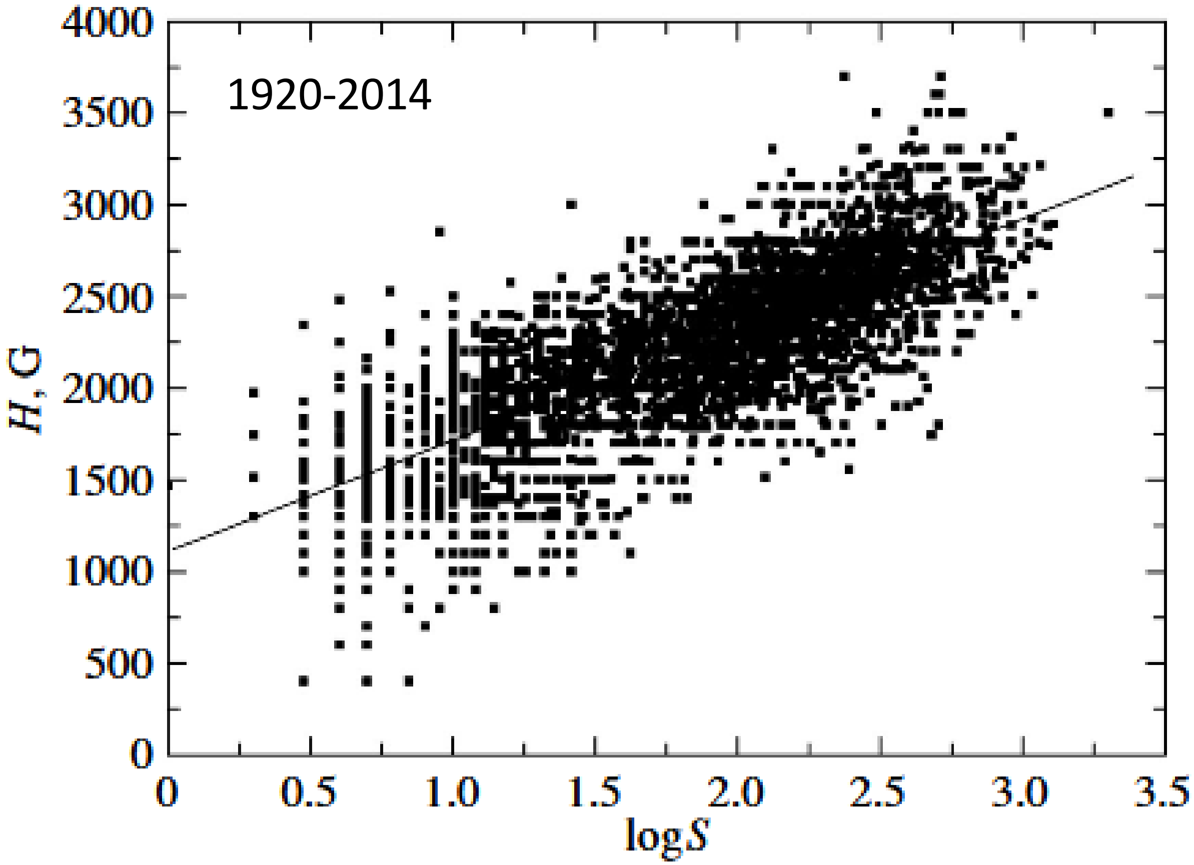


$$\gamma = (0.20 \pm 0.08)\sin(2.80\varphi) + (-0.00 \pm 0.06)$$

- Maximum in mid-latitudes
- Non-zero tilt at solar equator
- Different offset for odd-even cycles
- What does it mean?

Tlatova et al (2018)

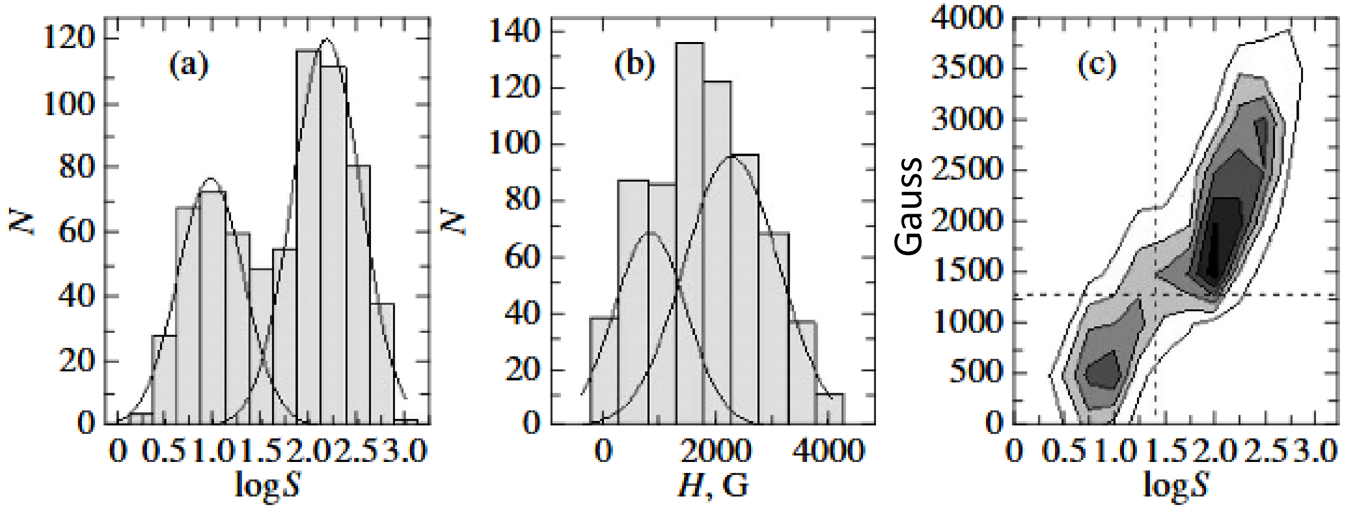
Sunspot Area-flux relation

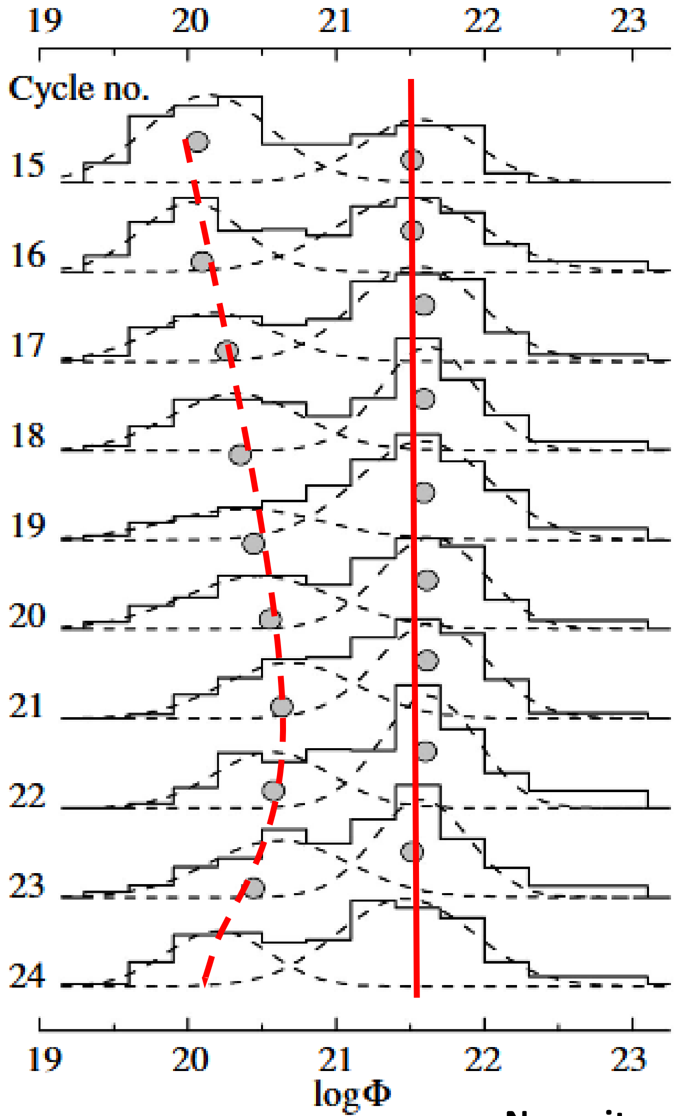


- Magnetic - gas pressure balance
- One can use area (1876) as proxy for magnetic flux (1917)

Ringnes & Jensen (1960); Ringnes (1965); Tlatov & Pevtsov (2014); Nagovitsyn et al (2016)

Sunspot Area-Flux Long-Term Variations

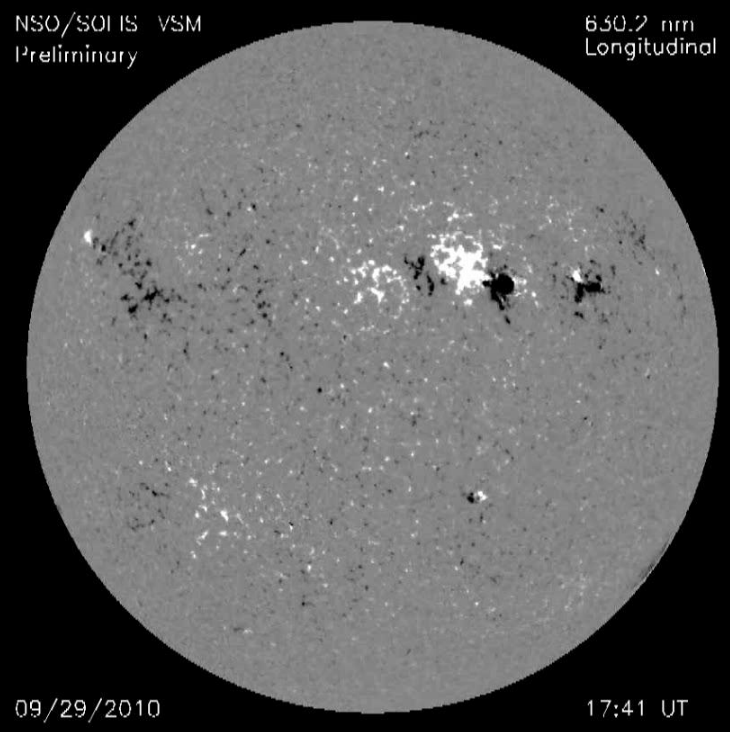




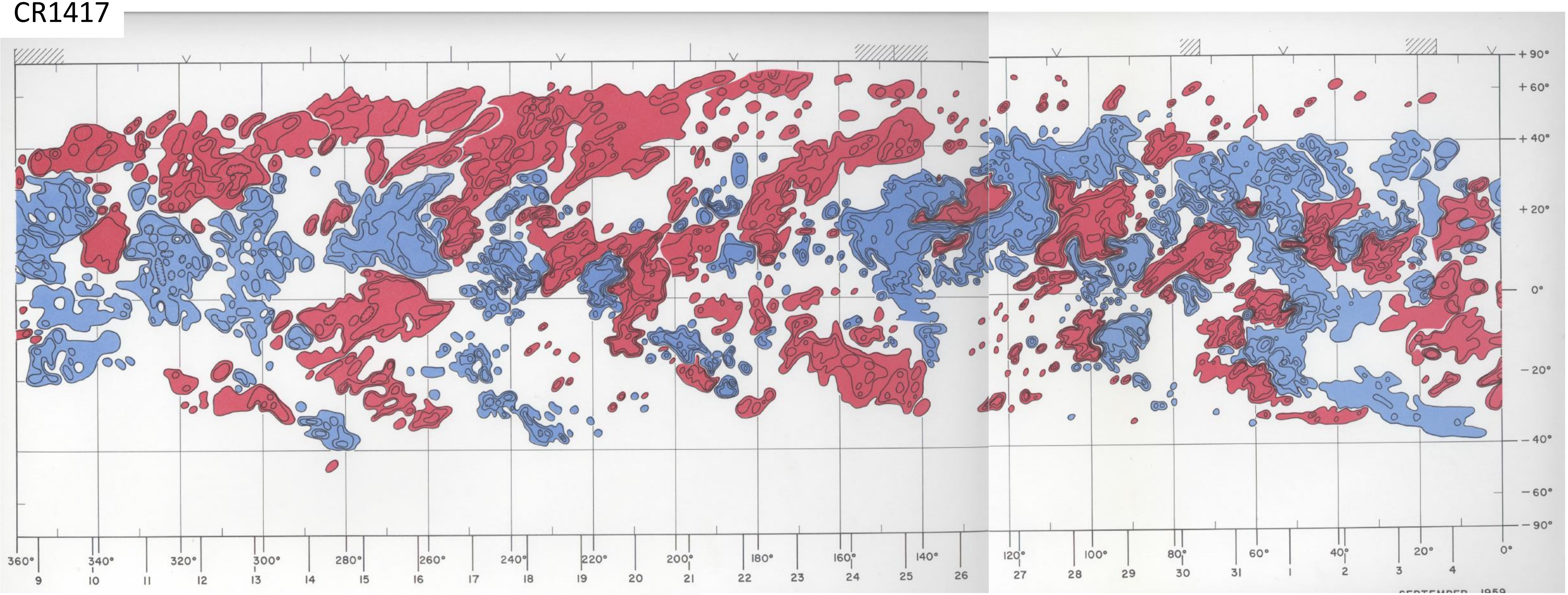
- Two components in sunspot distribution (small-large sunspots)
- Indication of two dynamo layers in dynamo region?

Nagovitsyn et al (2016)

Solar activity via Synoptic maps



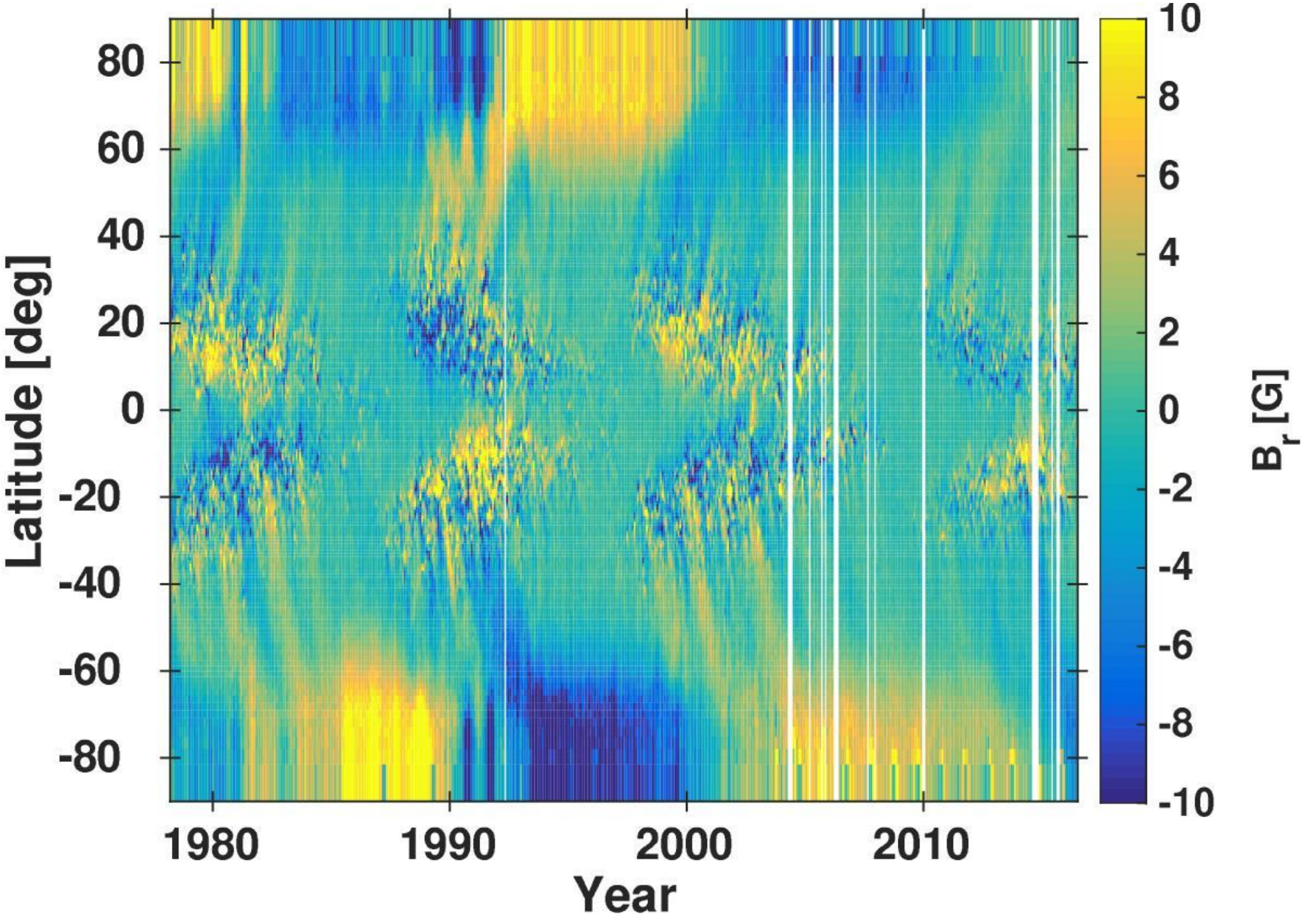
CR1417



August 1959

Atlas of solar magnetic fields, by Howard, R.; Bumba, V.; Smith, S. F.. Washington, DC (USA): Carnegie Institution of Washington, Publication No. 626, 1967

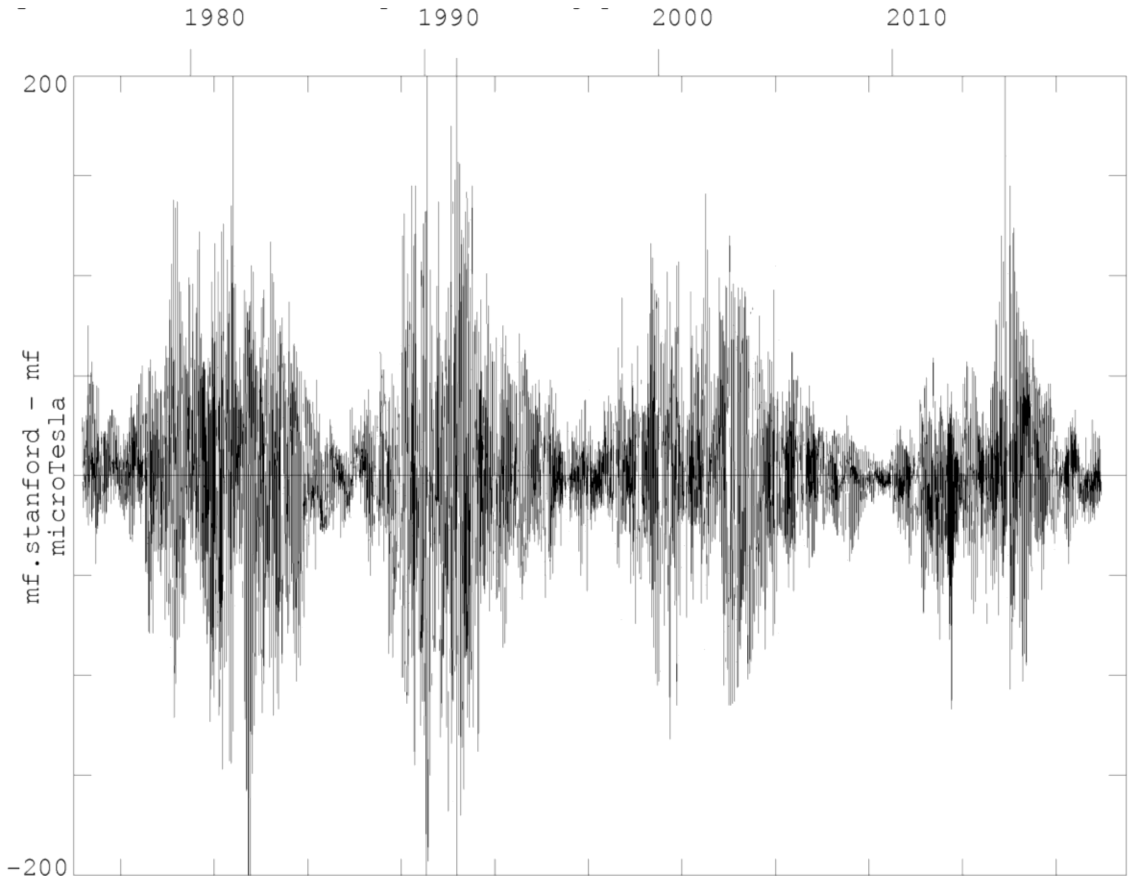
Super-synoptic maps

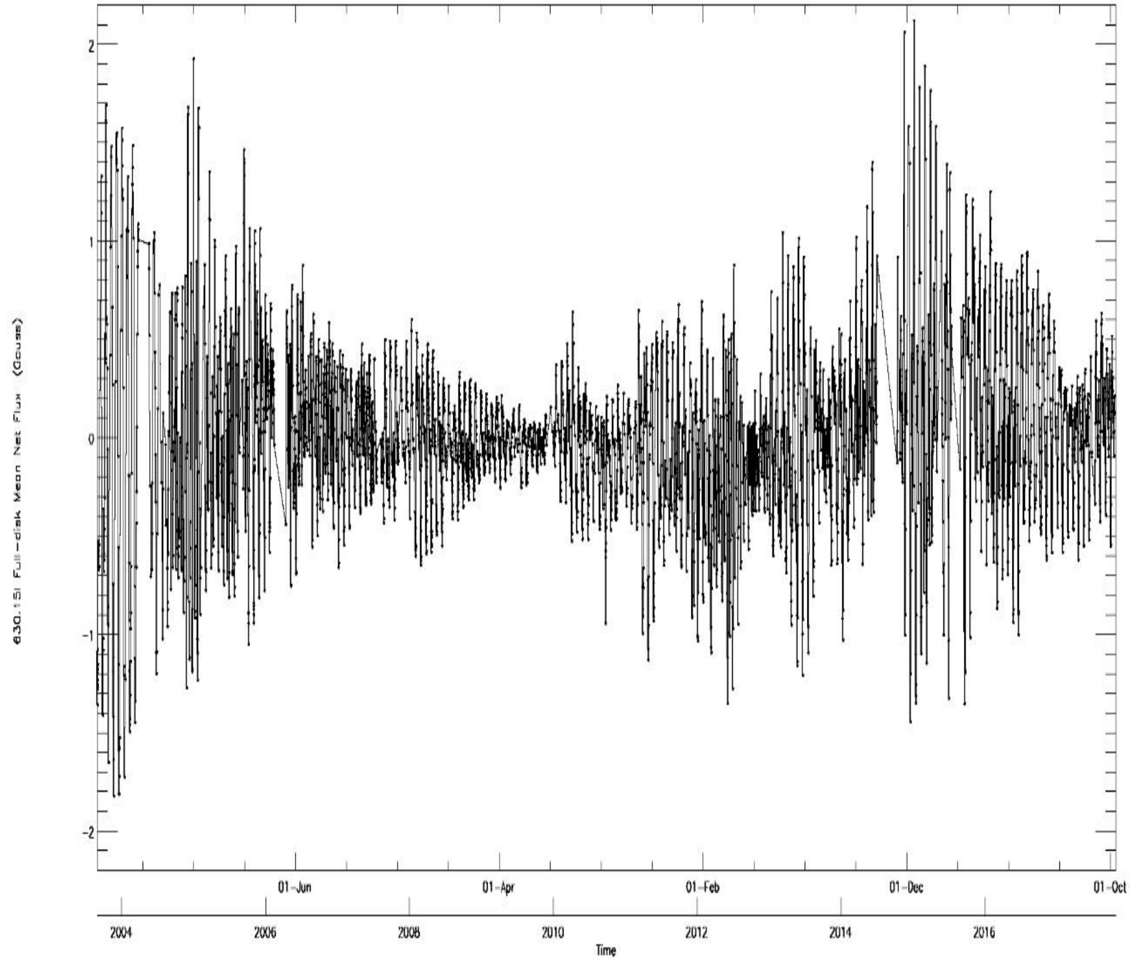


Virtanen et al (2017)

Total Flux

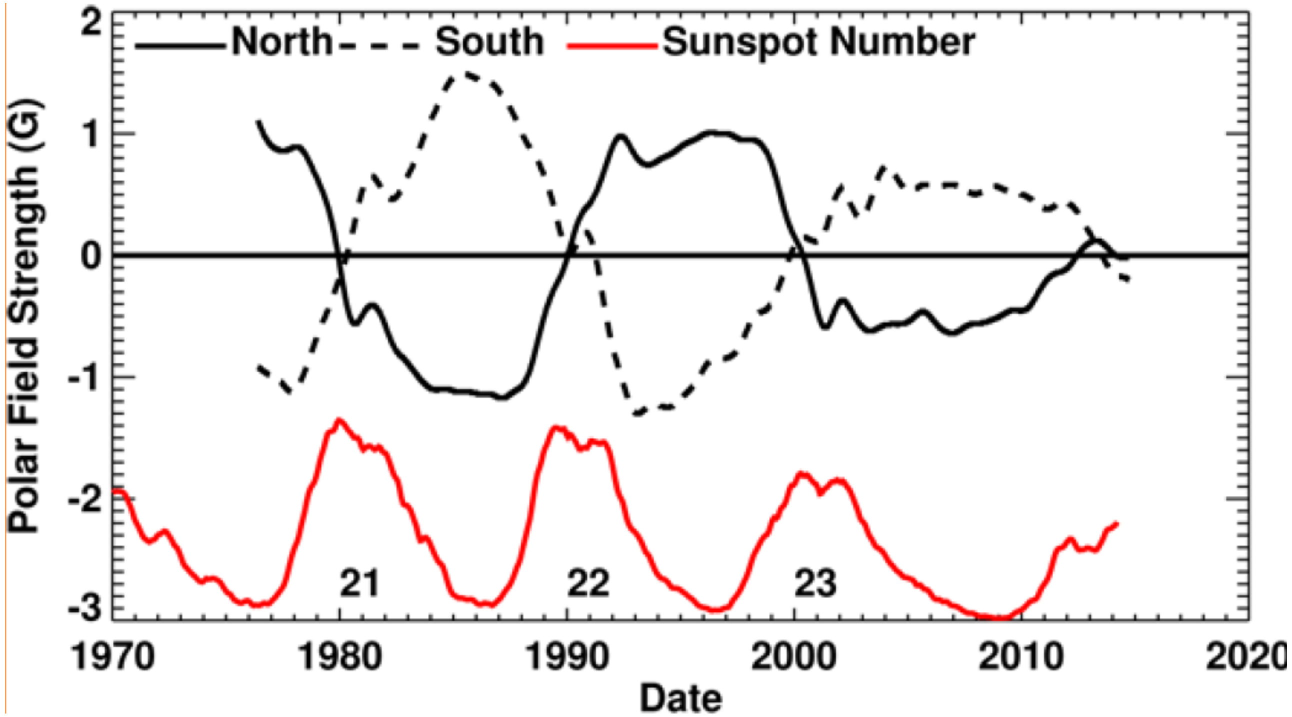
VSM/SOLIS, 2003-2017

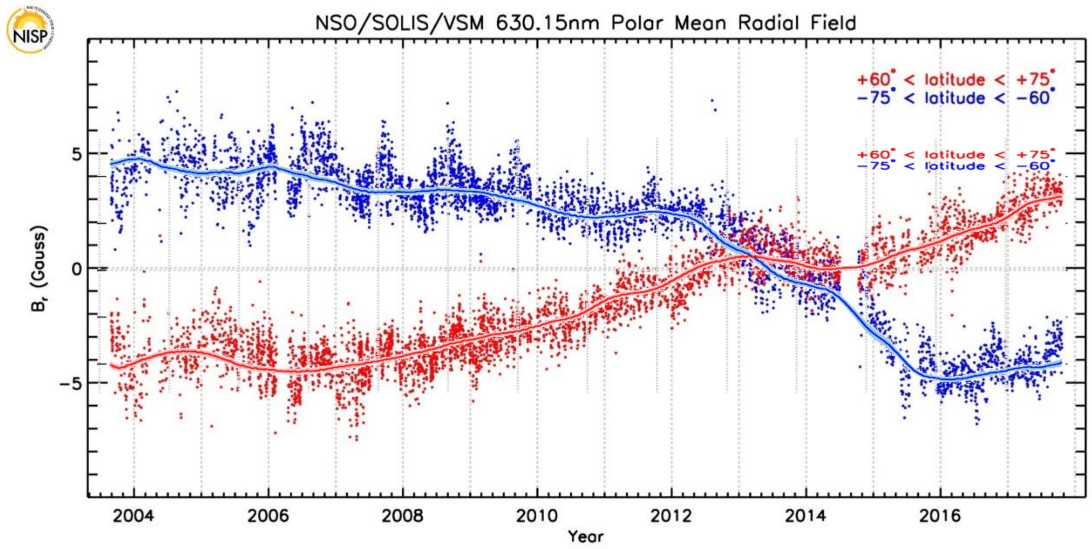




WSO, 1976-2019

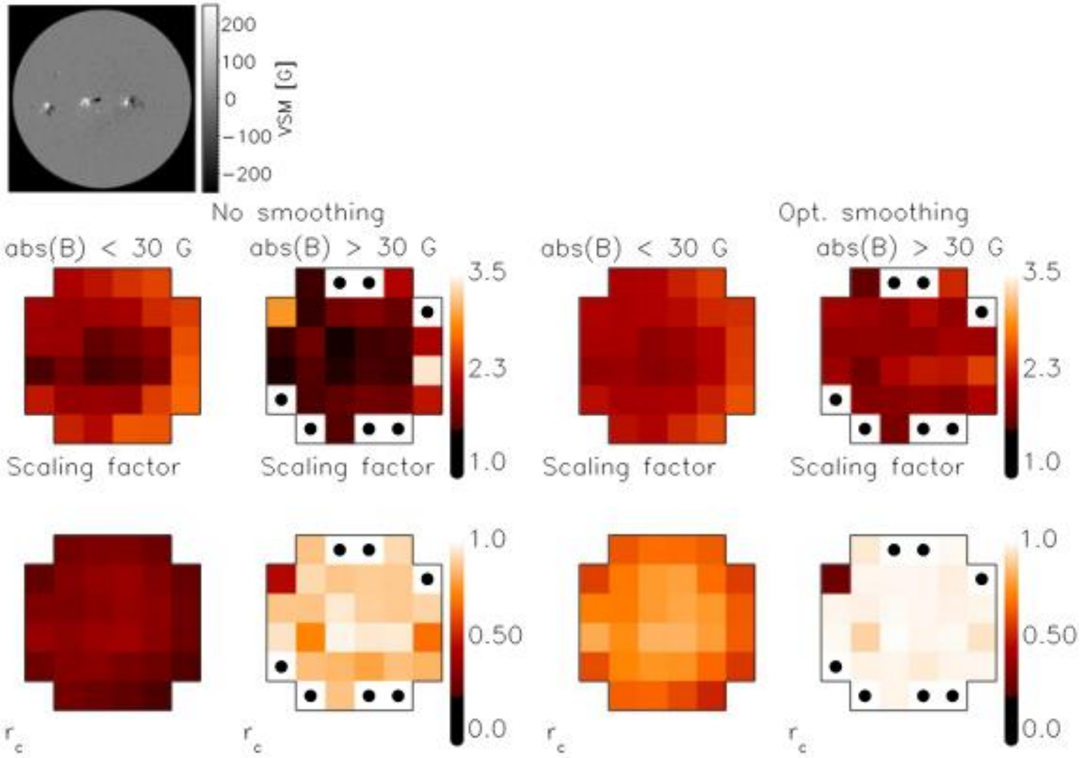
Polar Flux



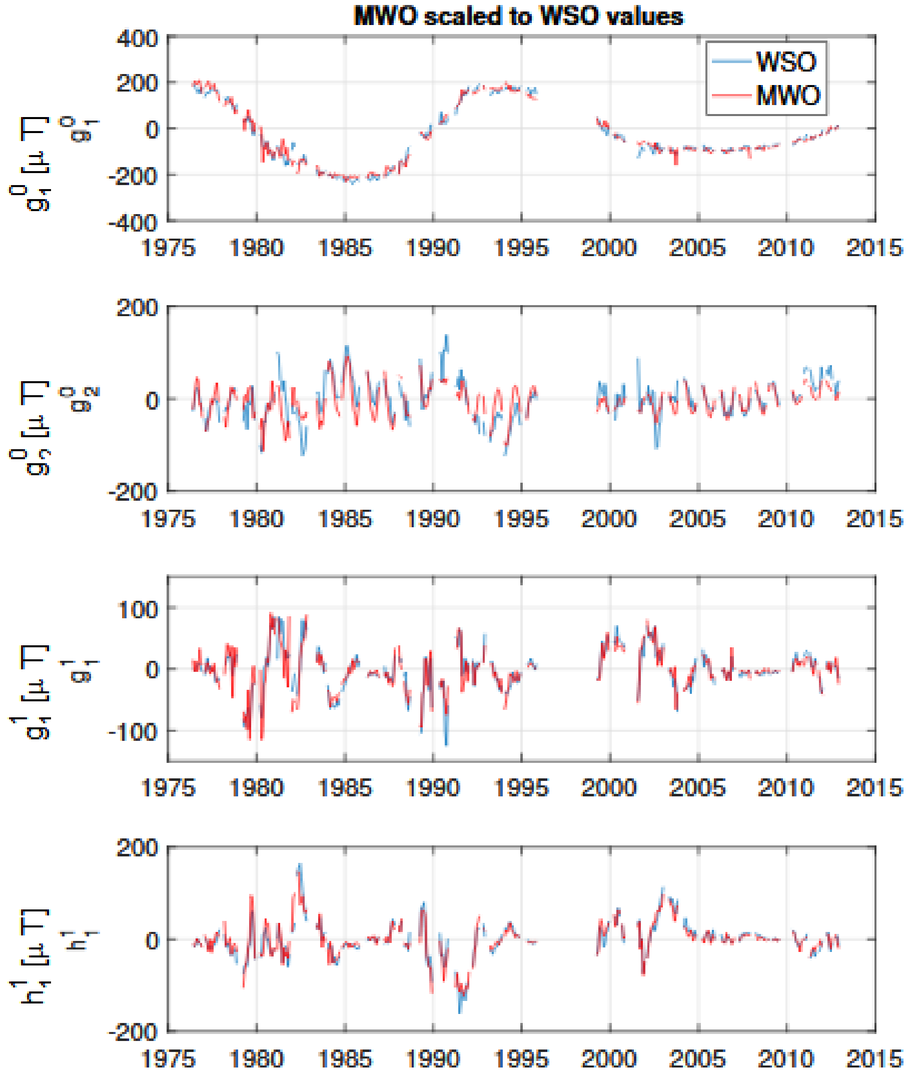


Are polar fields (non-) radial? Ulrich Tran (2013) – poleward inclination , Petrie (2015) – near radial, Virtanen et al (2019) – equatorward inclination.

Magnetogram comparison

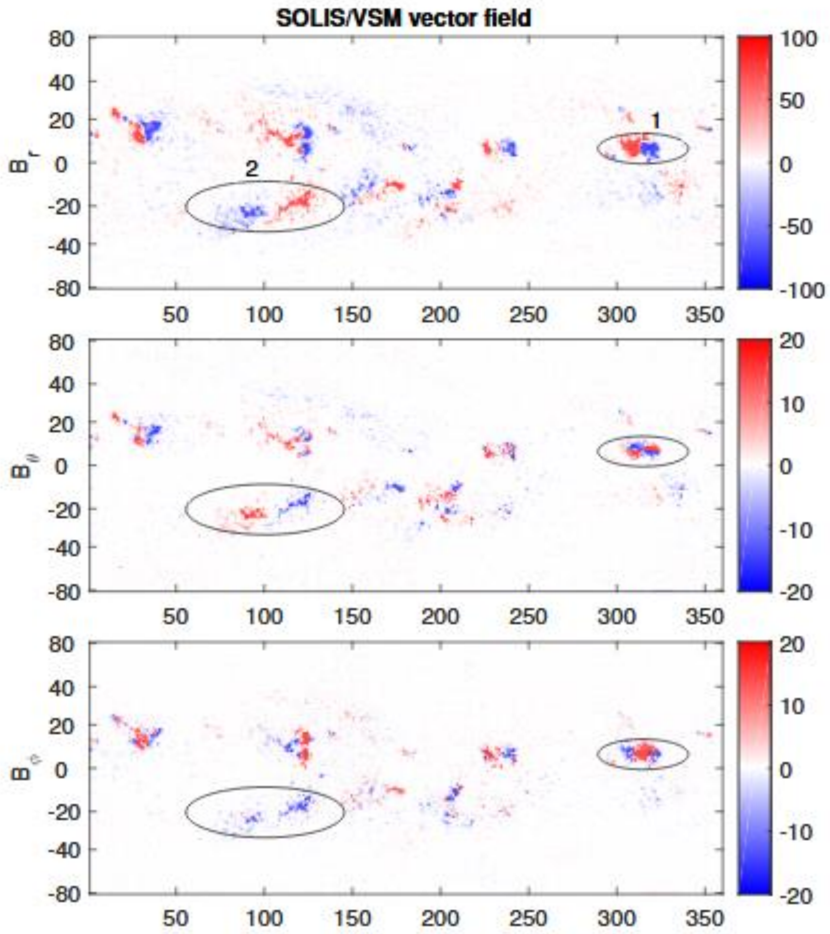


Pietarilla et al (2013)

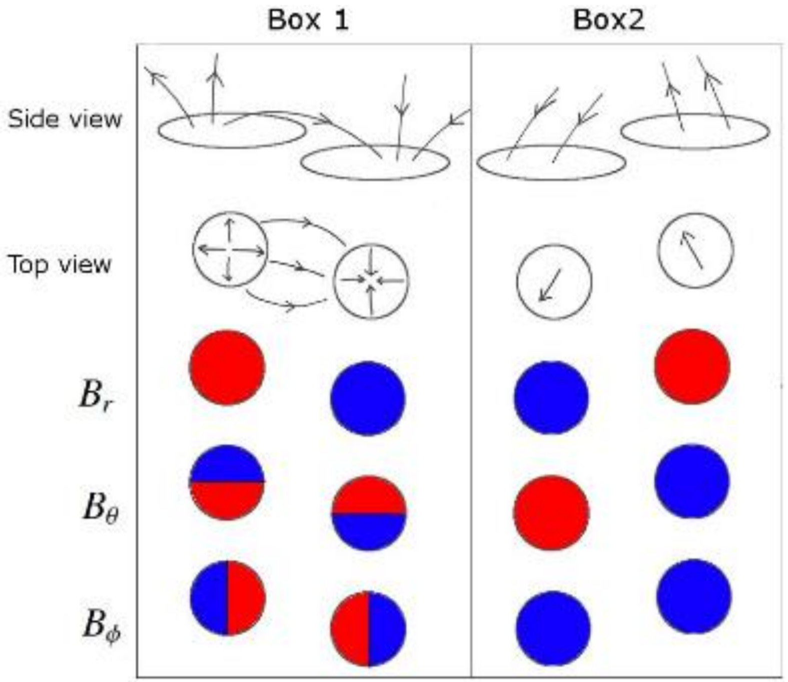


Virtanen & Mursula (2017)

Vector magnetograms (2003/2009-present)



Virtanen et al (2019)



Magnetic Helicity

$\mathbf{F}\cdot\nabla\times\mathbf{F}$ – helicity density of vector $\mathbf{F}$. Closed volume $(\mathbf{n}\cdot\mathbf{F}=0)$

$$\nabla\times\mathbf{F}=\begin{vmatrix} i & j & k \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\delta}{\delta z} \\ F_x & F_y & F_z \end{vmatrix}$$

Magnetic Helicity

↓

$$H_m=\int \mathbf{A}\cdot\mathbf{B}\,dD=\underset{(thin\ \ flux\ tube)}{(2\pi)^{-1}\Phi^2(T+W)},\qquad \nabla\times\mathbf{A}=\mathbf{B}$$

A – vector potential, B – magnetic induction.

$$H_c=\int \mathbf{B}\cdot\nabla\times\mathbf{B}\,dD$$ ← **Current Helicity**

$$H_k=\int \mathbf{V}\cdot\nabla\times\mathbf{V}dD$$

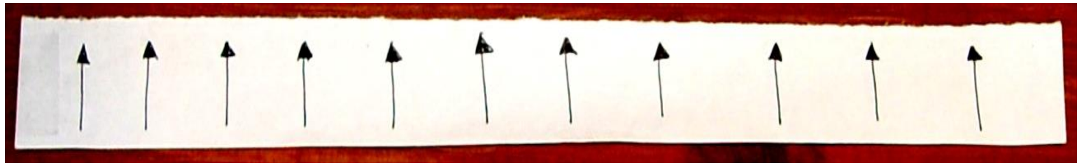
↑

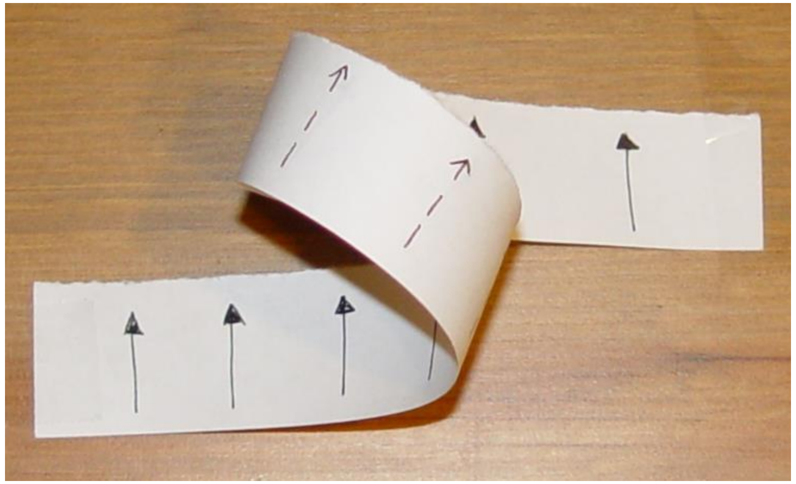
Kinetic Helicity

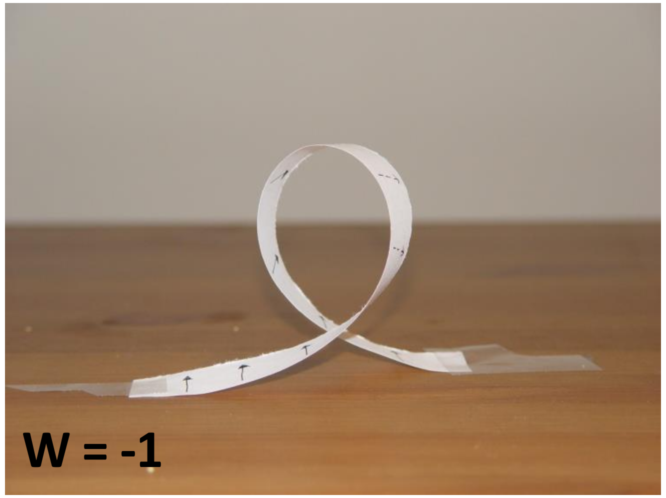
Helicity proxies, relative helicity, etc.

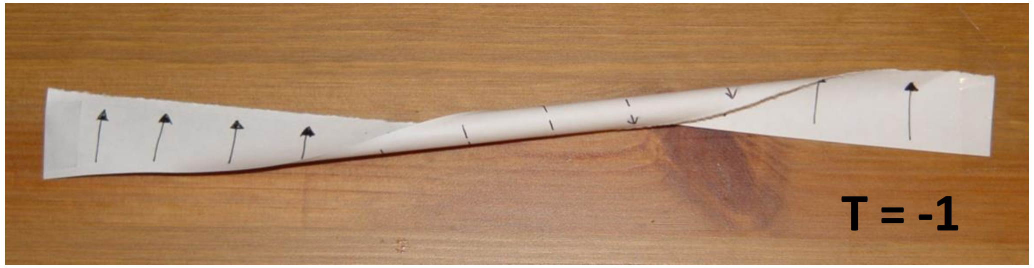
Cross–helicity: cross–correlation between the turbulent velocity and magnetic field: $\langle u'\cdot b'\rangle$

Writhe and Twist





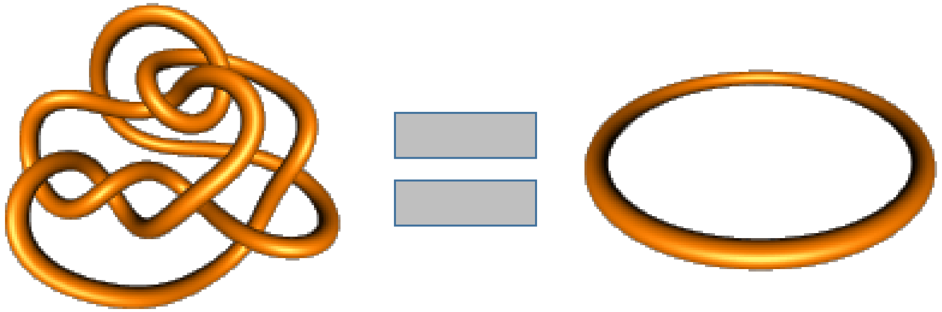




H = W+T

What is so important about magnetic helicity?

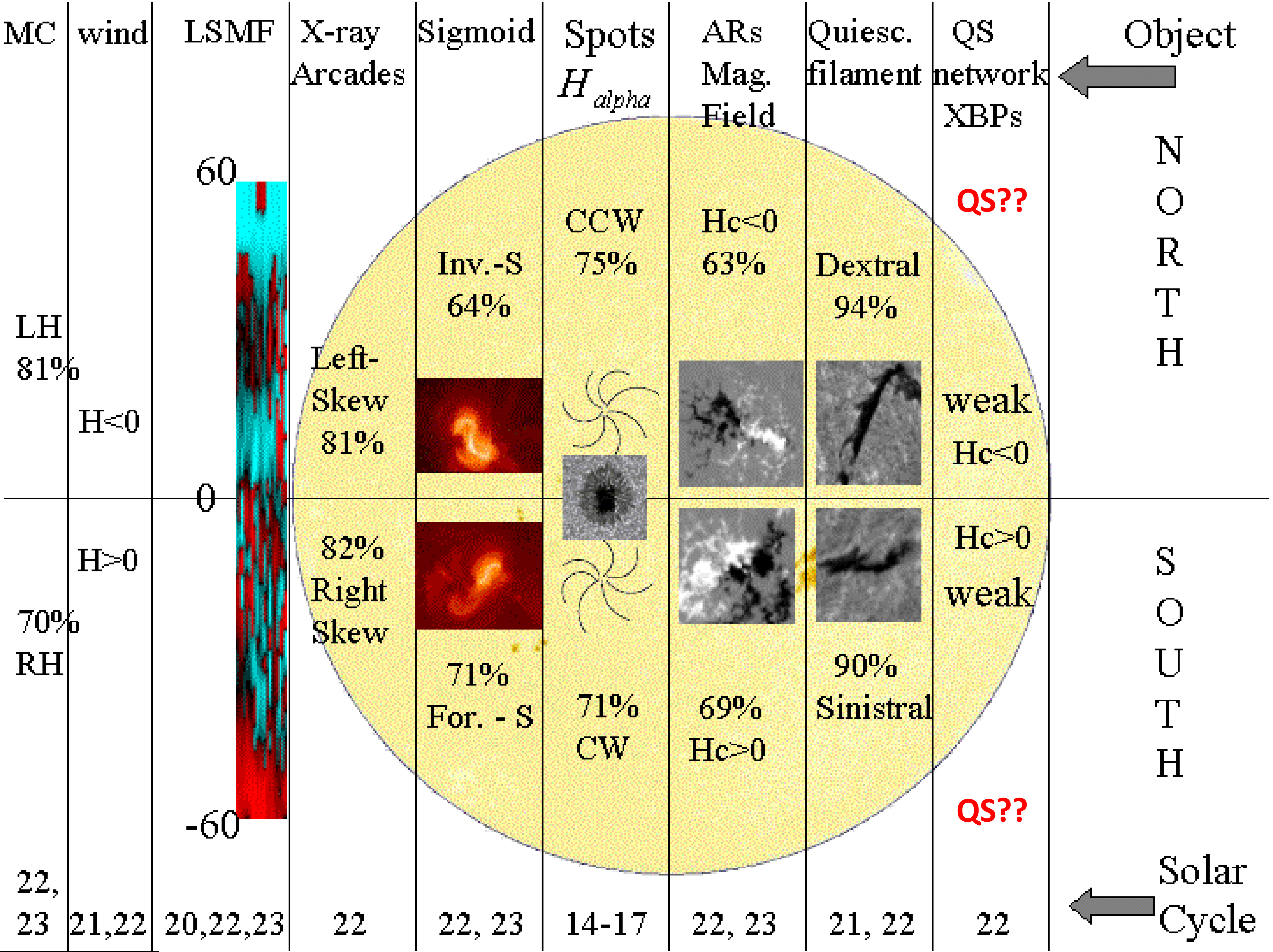
- topological invariant



- conserves better than energy (due to inverse cascading), e.g., in laboratory plasma experiments (Ji et al, 1995):
  - energy dissipation rate: 4%—10.5%
  - helicity dissipation rate: 1.3%—5.1%
- Plays important role in dynamo, reconnection, topology, and stability of magnetic systems

$$H_m = \int \mathbf{A} \cdot \mathbf{B} \, dD$$

Hemispheric helicity rule



Pevtsov (2002)

Magnetic helicity from HMI and VSM vector observations

Decomposition of the vector magnetic field into toroidal and poloidal components (Pipin et al (2019):

$$\mathbf{B} = \boldsymbol{\nabla} \times (\hat{\mathbf{r}}T) + \boldsymbol{\nabla} \times \boldsymbol{\nabla} \times (\hat{\mathbf{r}}S) =$$
$$= -\frac{\hat{r}}{r}\Delta_{\Omega}S + \hat{\theta}\left(\frac{1}{\sin\theta}\frac{\partial T}{\partial\phi} - \frac{\sin\theta}{r}\frac{\partial F_S}{\partial\mu}\right) + \hat{\phi}\left(\sin\theta\frac{\partial T}{\partial\mu} + \frac{1}{r\sin\theta}\frac{\partial F_S}{\partial\phi}\right)$$

$$B_r = -\frac{1}{r}\Delta_{\Omega}S,$$
$$B_\theta = \frac{1}{\sin\theta}\frac{\partial T}{\partial\phi} - \frac{\sin\theta}{r}\frac{\partial F_S}{\partial\mu},$$
$$B_\phi = \sin\theta\frac{\partial T}{\partial\mu} + \frac{1}{r\sin\theta}\frac{\partial F_S}{\partial\phi}$$

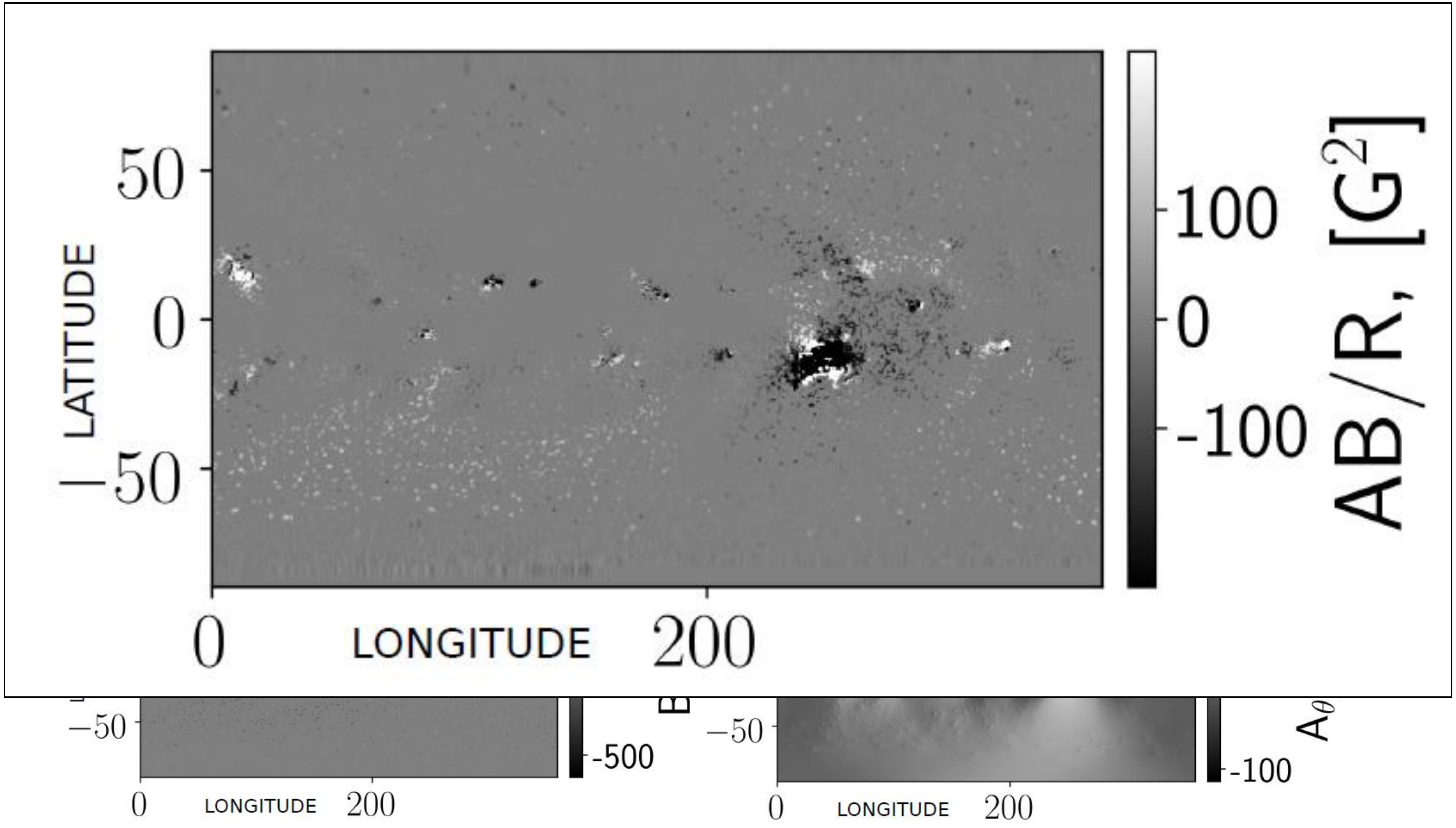
To find unique solution, the following gauge is applied:

$$\int_0^{2\pi}\int_{-1}^{1} S d\mu d\phi = \int_0^{2\pi}\int_{-1}^{1} T d\mu d\phi = \int_0^{2\pi}\int_{-1}^{1} F_S d\mu d\phi = 0.$$

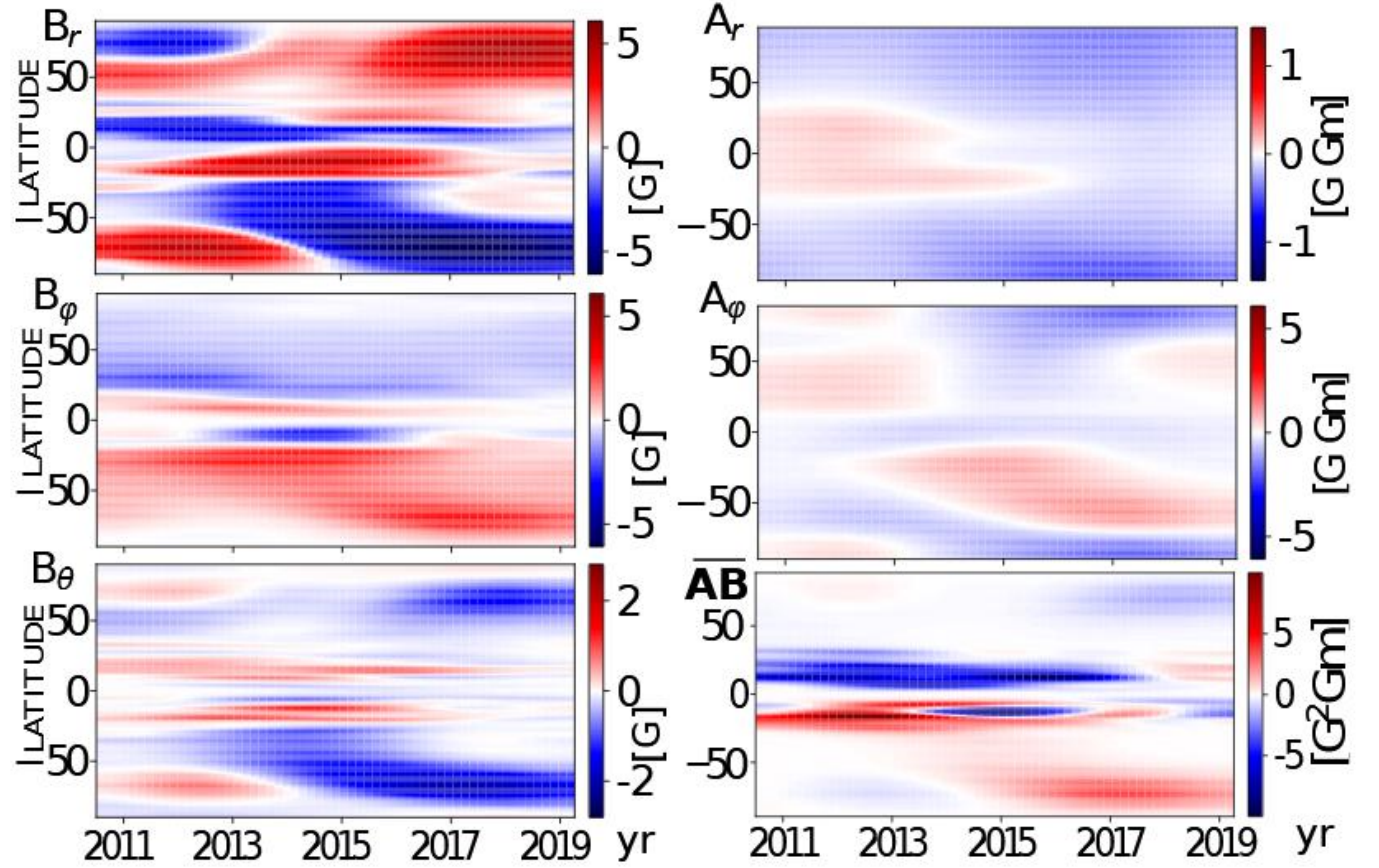
$$\mathbf{A} = \hat{\mathbf{r}}T + \boldsymbol{\nabla} \times (\hat{\mathbf{r}}S) =$$
$$= \hat{\mathbf{r}}T + \frac{\hat{\theta}}{\sin\theta}\frac{\partial S}{\partial\phi} + \hat{\phi}\frac{\sin\theta}{r}\frac{\partial S}{\partial\mu}$$

S, T – scalar potentials, $F_S = \partial(rS)/\partial r$

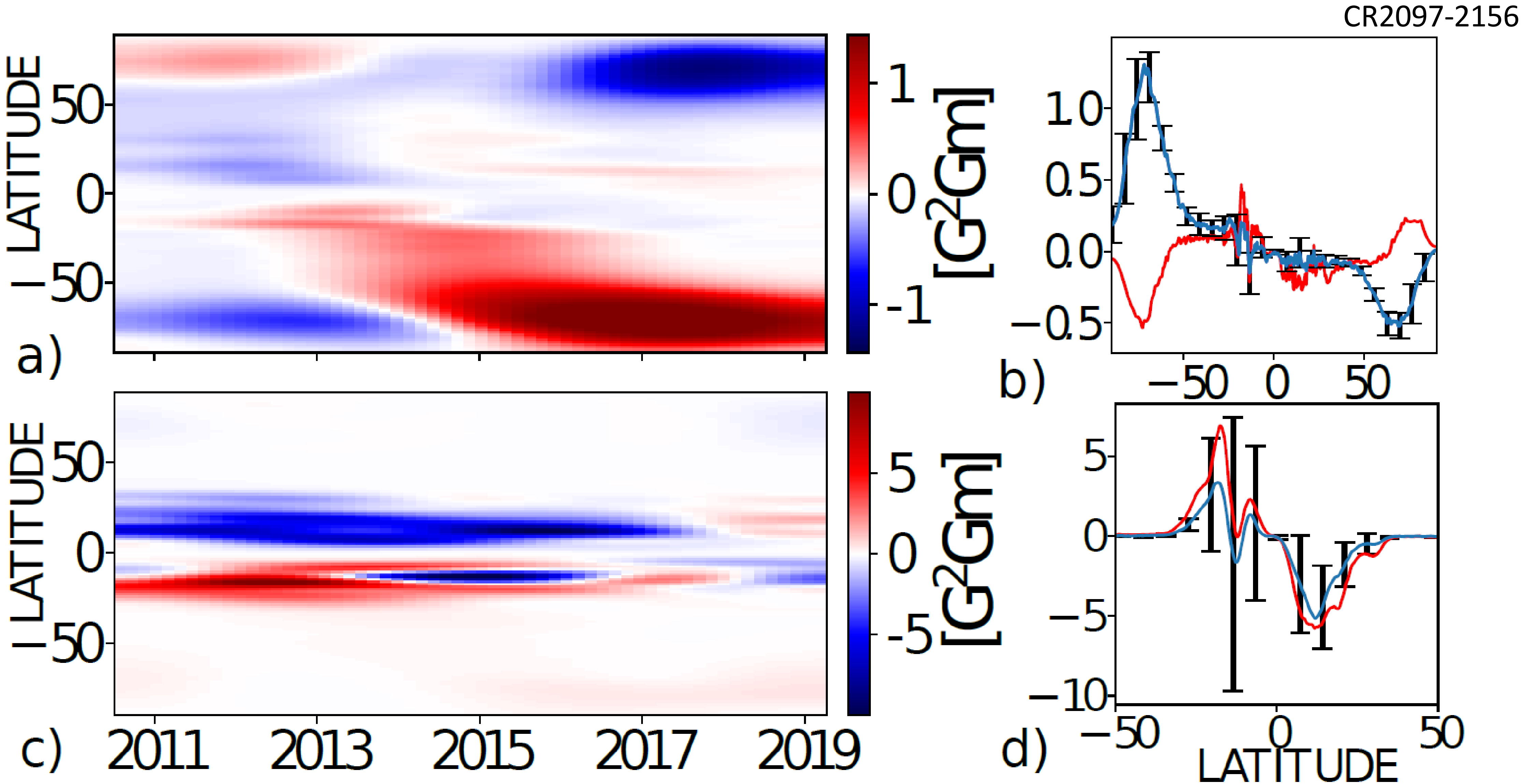
Synoptic maps of helicity (CR2156)



Magnetic field and Helicity in Cycle 24



Magnetic helicity in cycle 24



Summary

- Magnetic fields on the Sun were discovered in 1908
- Simplistic measurements of magnetic field in sunspots still continue in two observatories
- Some properties of Hale-polarity rule and Joy's (active region tilt) law may still require explanation
- Magnetic fields from different instruments may differ significantly
- New era of vector magnetic field measurements and helicity – more useful information and more questions