

# COLLAGE 2019

## Magnetic Field Structures over a Solar Cycle

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Apr 04 2019

# Outline

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- PFSS Model for coronal field
- Solar cycle
- Babcock-Leighton mechanism & surface flux transport

# PFSS Model for Coronal Field

# PFSS Model

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- Assuming lower corona is current free,  $\mathbf{B}$  can be expressed as a scalar potential

$$\mathbf{B} = -\nabla\Psi$$

- $\mathbf{B}$  vector in spherical coord

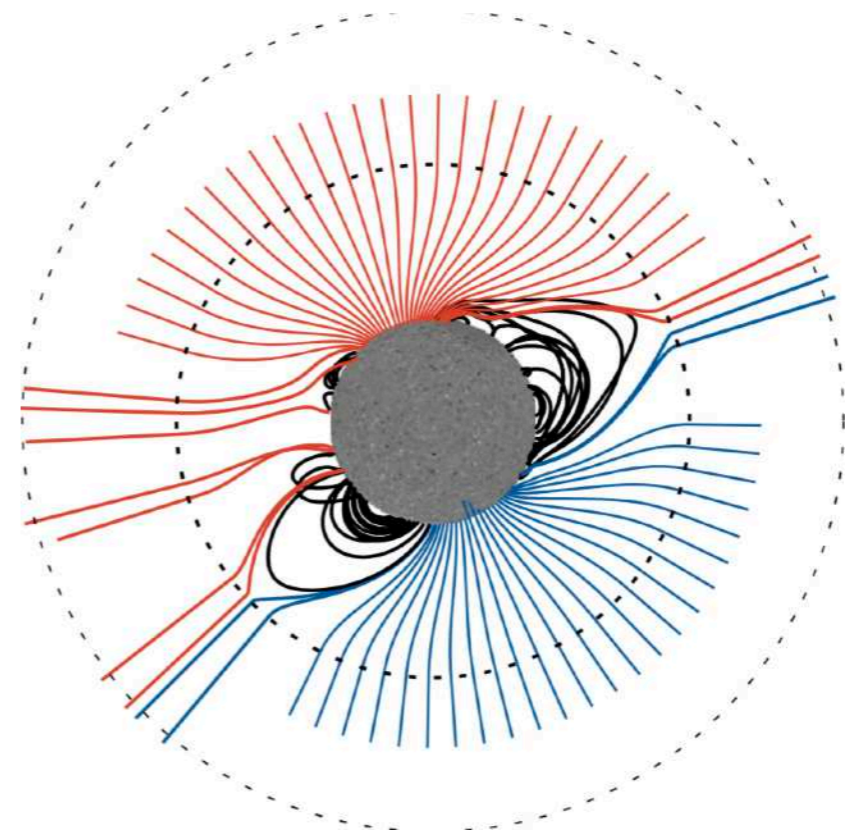
$$B_r = -\frac{\partial\Psi}{\partial r}$$

$$B_\theta = -\frac{1}{r}\frac{\partial\Psi}{\partial\theta}$$

$$B_\phi = -\frac{1}{r\sin\theta}\frac{\partial\Psi}{\partial\phi}$$

- Coronal field governed by Laplace eq.

$$\nabla^2\Psi = 0$$



Sun (2012)

# PFSS Model

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- Inner boundary: photosphere radial field

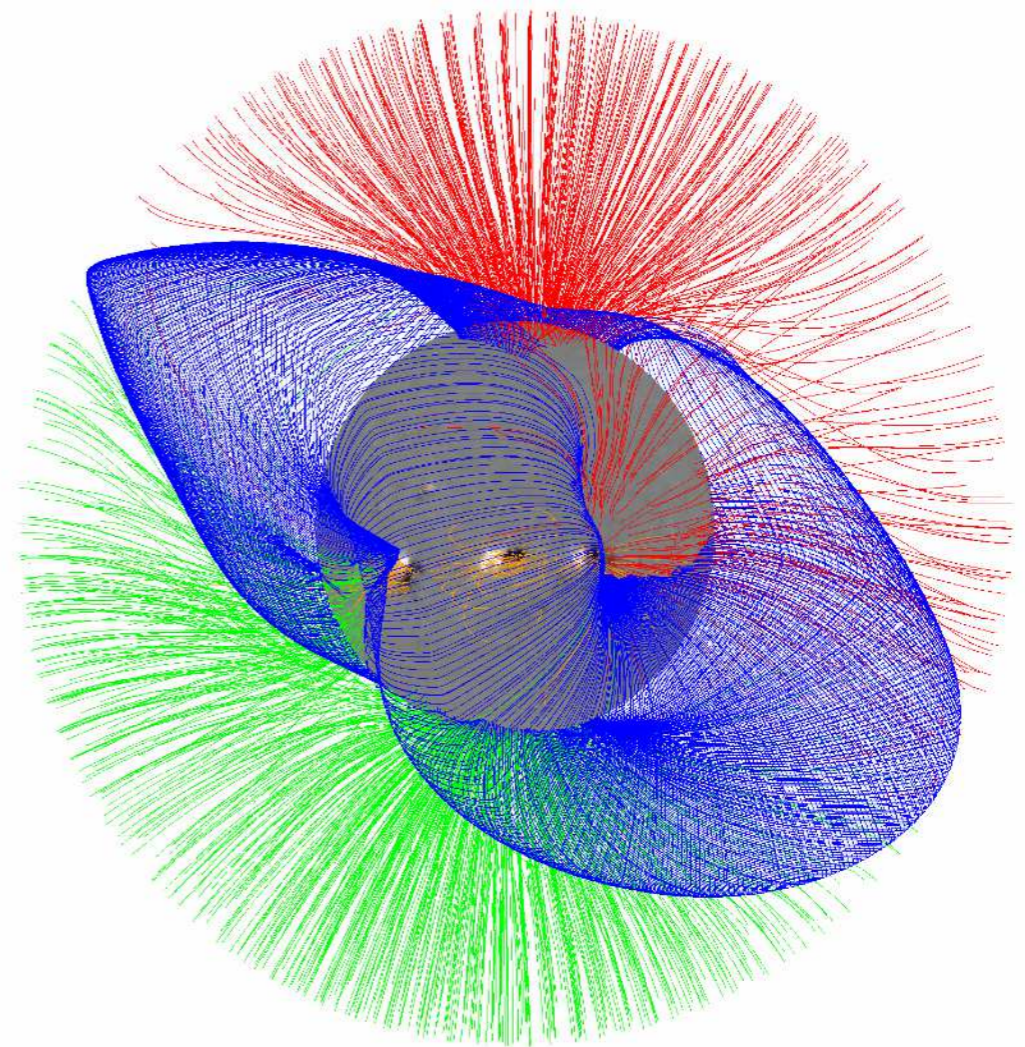
$$-\frac{\partial \Psi}{\partial r} \Big|_{r=R_{\odot}} = B_r(\text{obs})$$

- Outer boundary: source surface where field becomes radial and open

$$\Psi \Big|_{r=R_s} = 0$$
$$R_s = 2.5R_{\odot}$$

- General solution of Laplace equation:

$$\Psi = \sum_{l=0}^{\infty} r^{-(l+1)} \sum_{m=-l}^l a_{lm} Y_l^m(\theta, \phi) + \sum_{l=0}^{\infty} r^l \sum_{m=-l}^l b_{lm} Y_l^m(\theta, \phi)$$



NSO/GONG

# PFSS Model Solution

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- Matching outer boundary

$$\sum_{l=0}^{\infty} R_s^{-(l+1)} \sum_{m=-l}^l a_{lm} Y_l^m(\theta, \phi) + \sum_{l=0}^{\infty} R_s^l \sum_{m=-l}^l b_{lm} Y_l^m(\theta, \phi) = 0, \text{ or, } a_{lm} = -R_s^{2l+1} b_{lm}$$

- Matching inner boundary

$$\sum_{l=0}^{\infty} (l+1) R_{\odot}^{-(l+2)} \sum_{m=-l}^l a_{lm} Y_l^m(\theta, \phi) - \sum_{l=0}^{\infty} l R_{\odot}^{l-1} \sum_{m=-l}^l b_{lm} Y_l^m(\theta, \phi) = B_r(R_{\odot}, \theta, \phi)$$

- Use normalization properties of spherical harmonics

$$\oint d\Omega Y_l^m(\theta, \phi) Y_{l'}^{m'}(\theta, \phi) = \delta_{ll'} \delta_{mm'}$$

- Surface integral of observed field

$$(l+1) R_{\odot}^{-(l+2)} a_{lm} - l R_{\odot}^{l-1} b_{lm} = \oint d\Omega B_r(R_{\odot}, \theta, \phi) Y_l^m(\theta, \phi)$$

# PFSS Widget

<https://tinyurl.com/pfss-wid>

Not Secure — spacephysics.ucla.edu

HOME Rotatable Potential Fields Rotatable Simple Source Surface Fields **Rotatable Realistic Source Surface Models** Realistic Source Surface Magnetic Map

## Potential Field: Rotatable Realistic Source Surface Models

This module allows you to examine the magnetic topology of realistic potential field models.

Data set:  
 Input values  Minimum dipole  Minimum tilted dipole  
 Intermediate quadrupole  Maximum case 1  Maximum case 2  
 Maximum case 3

**Dipole coefficients**

$g_{10}, g_{11}$ :    $Tm^3$   
 $h_{11}$ :   $Tm^3$

**Quadrupole coefficients**

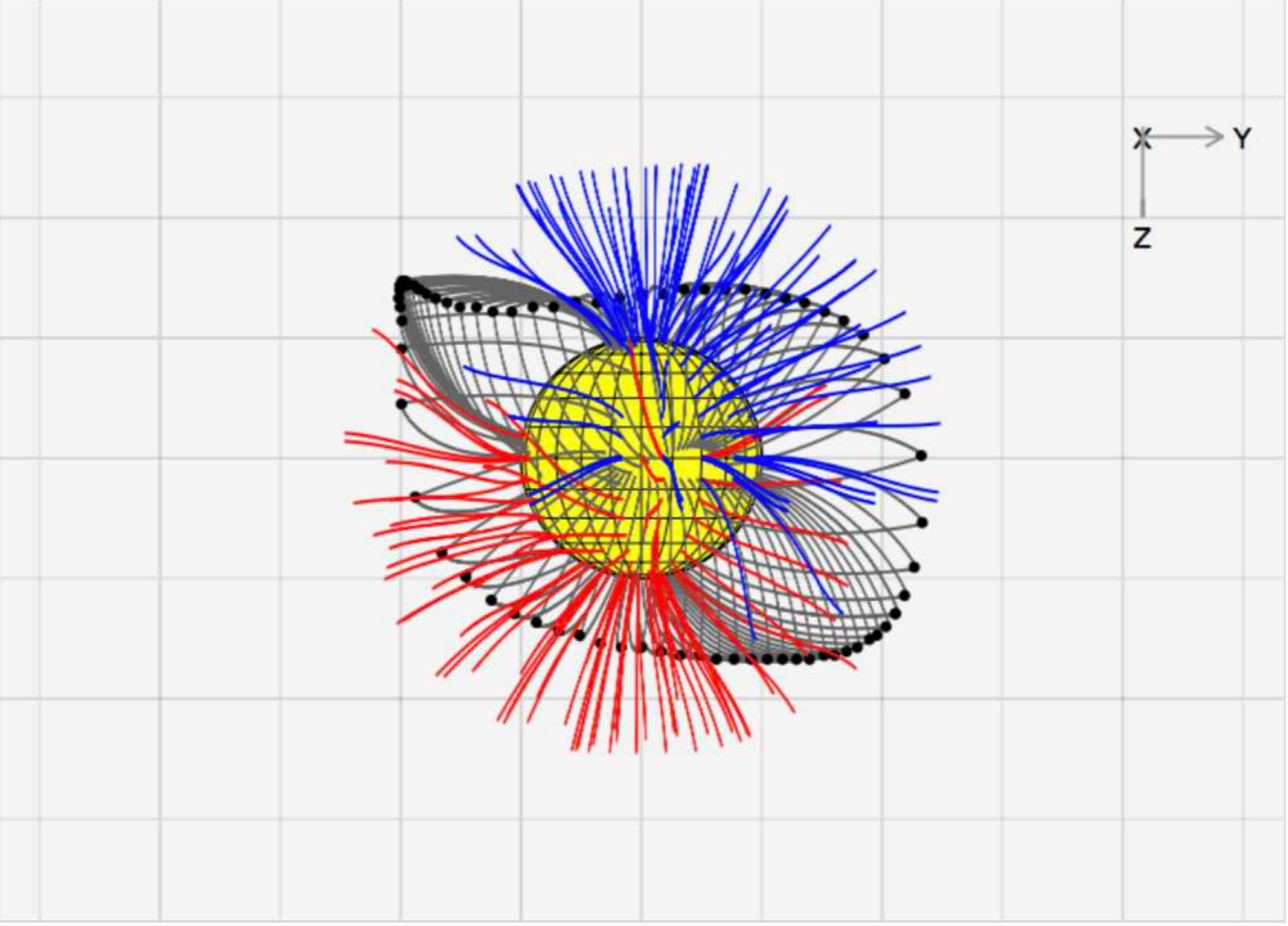
$g_{20}, g_{21}$ :    $Tm^3$   
 $g_{22}$ :   $Tm^3$   
 $h_{21}, h_{22}$ :    $Tm^3$

**Octupole coefficients**

$g_{30}, g_{31}$ :    $Tm^3$   
 $g_{32}, g_{33}$ :    $Tm^3$   
 $h_{31}, h_{32}$ :    $Tm^3$   
 $h_{33}$ :   $Tm^3$

**View configuration**

Latitude:  °  
Longitude:  °  
View angle:  °  
Source surface radius:   $R_{\odot}$

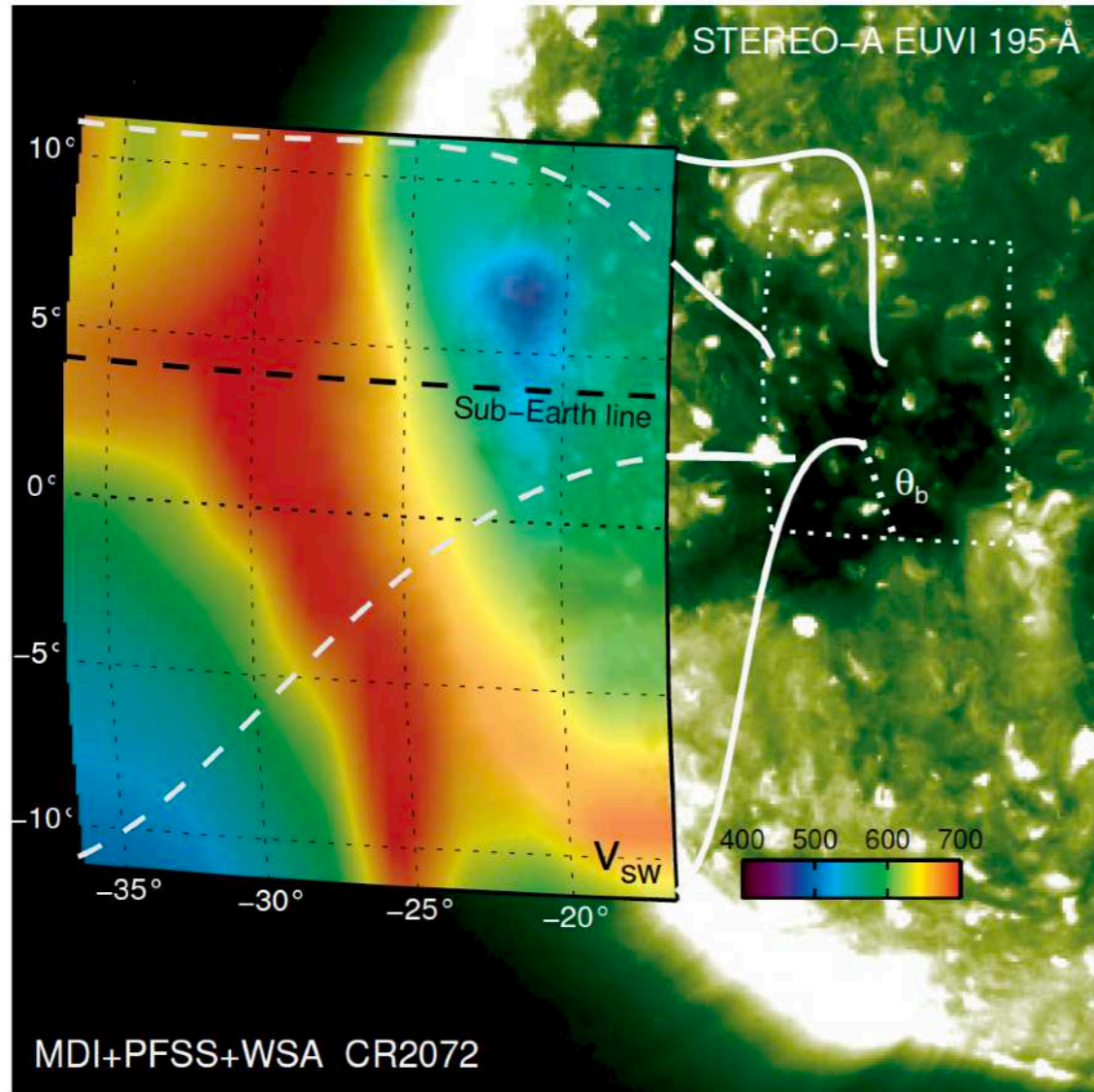


This option uses coefficients from the Wilcox Solar Observatory (WSO). You can fill in the WSO coefficients up to order 3. Select the **Input values** option to evaluate the data input by you, or one of the other six options to display a set of WSO coefficients for different solar configurations. The source surface around the Sun is an imaginary radius at which magnetic field lines go radial. Usually the source surface is taken to be in a range of 2 to 3 times the radius of the Sun,  $R_{\odot}$ . You can vary solar radii value from a minimum value of 1 to a maximum value of 6. In the display, gray lines are closed field lines, red lines are open field lines (inward), and blue lines are open field lines (outwards). Small black circles map out the neutral line on the source surface, dividing the outward radial fields there from the inward radial fields. Regions with neither closed nor open field lines plotted here are regions with closed field lines that do not reach the source surface.

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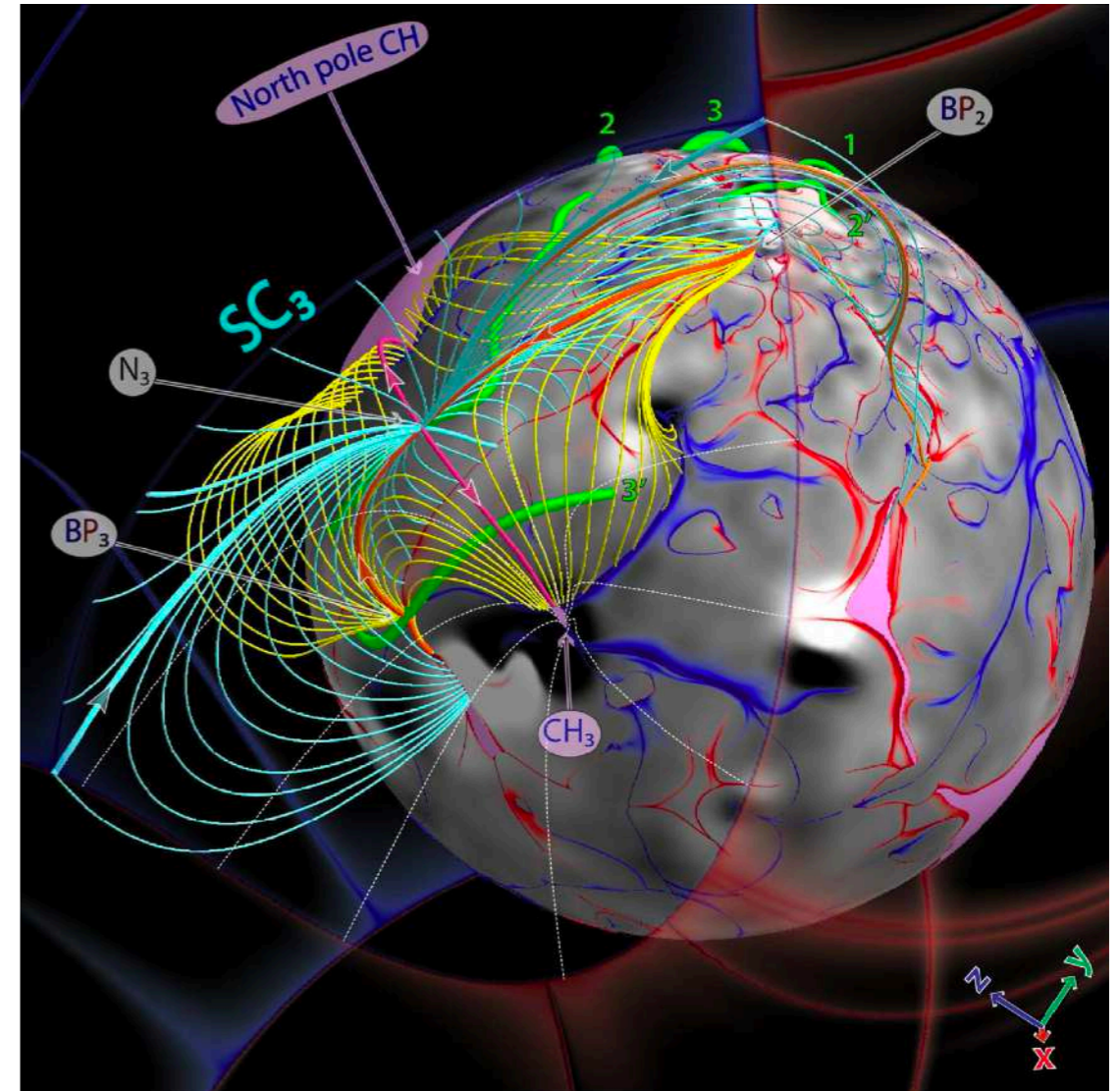
# Utility of PFSS Model

Mapping Solar Wind: WSA Model



Sun (2012)

Topology Analysis for Sympathetic Flares



Titov et al. (2012)

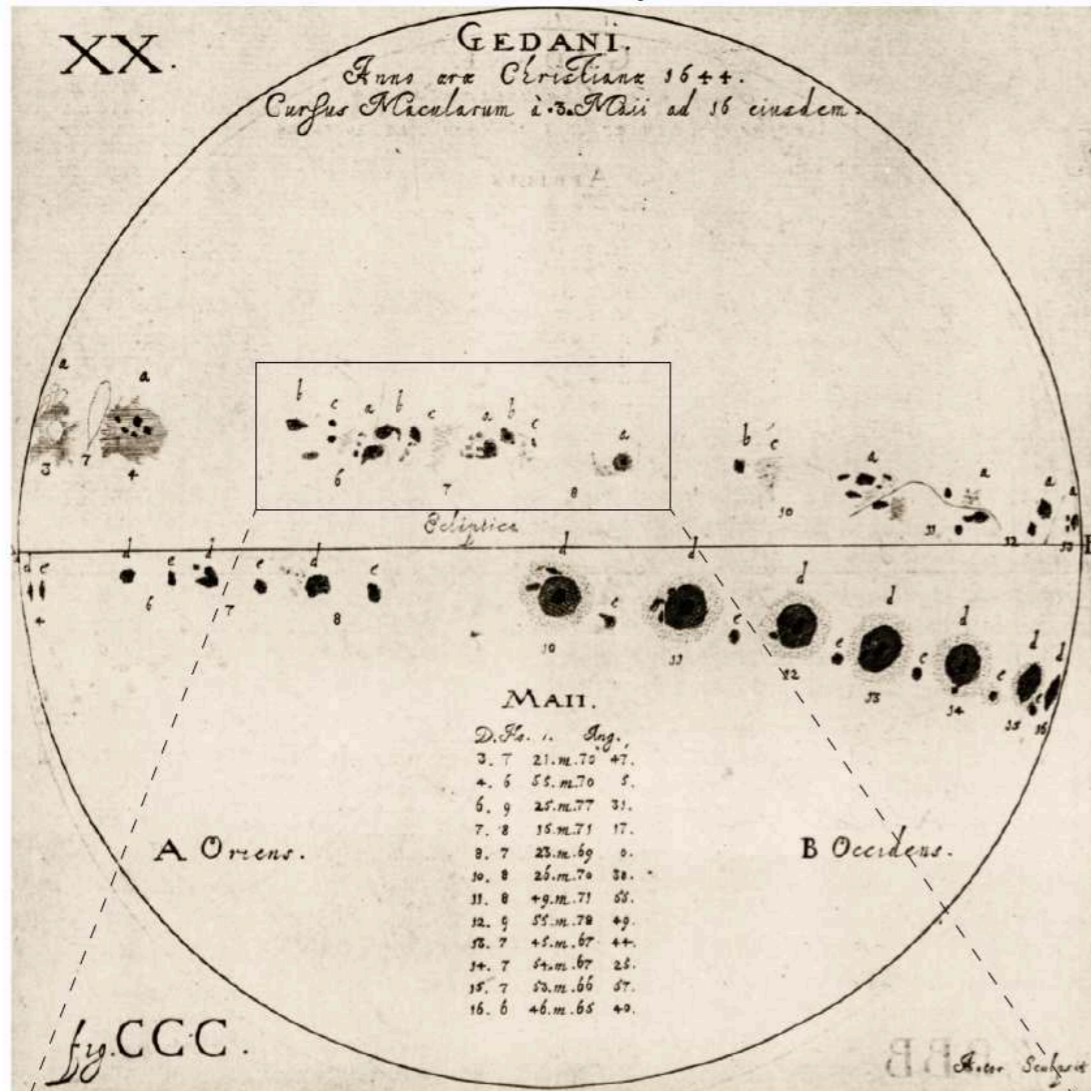
$$v \propto f^{-1} = \frac{B_r(R_s)R_s^2}{B_r(R_\odot)R_\odot^2}$$



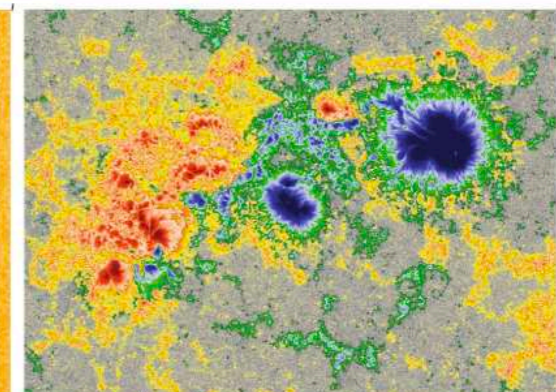
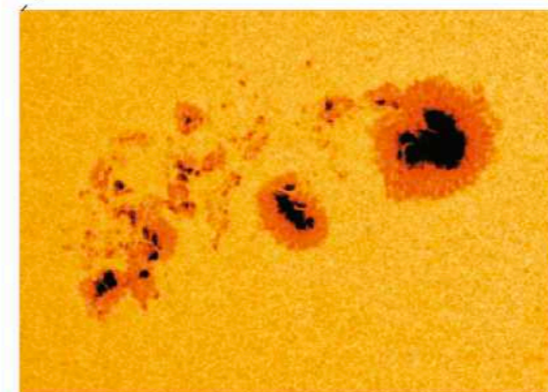
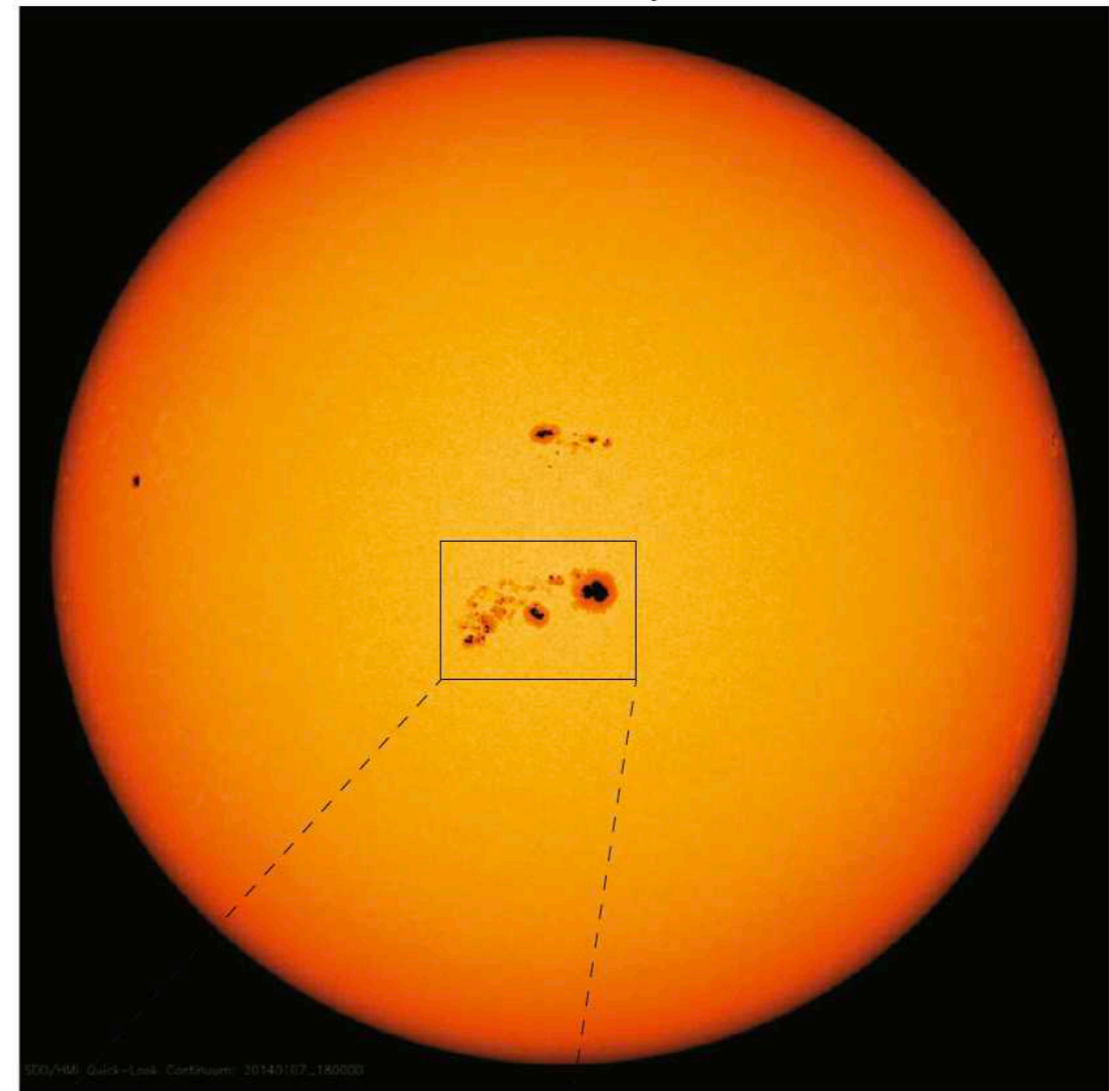
# Solar Cycle

# Sunspot Number

Hevelius 3–16 May 1644

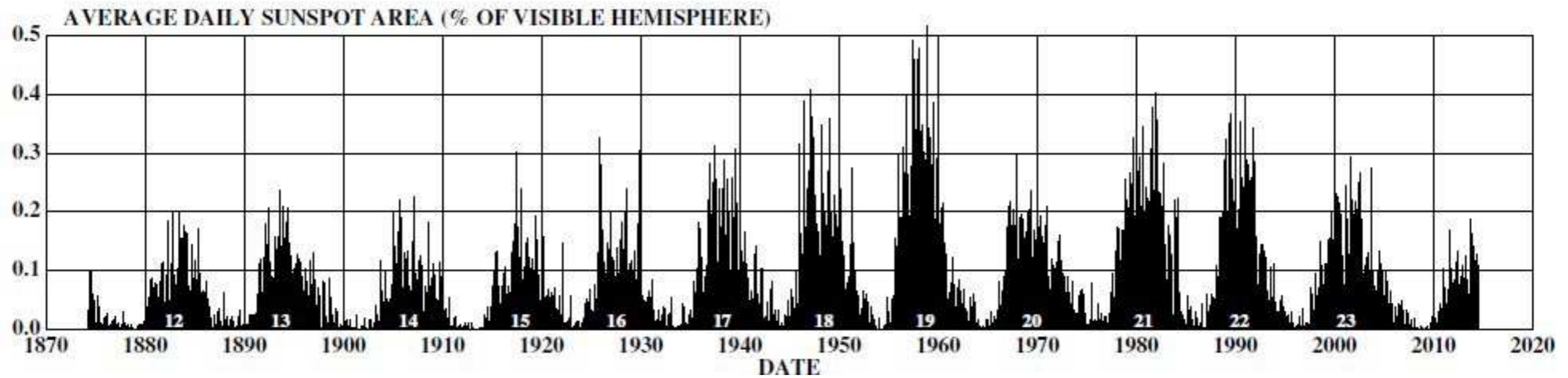
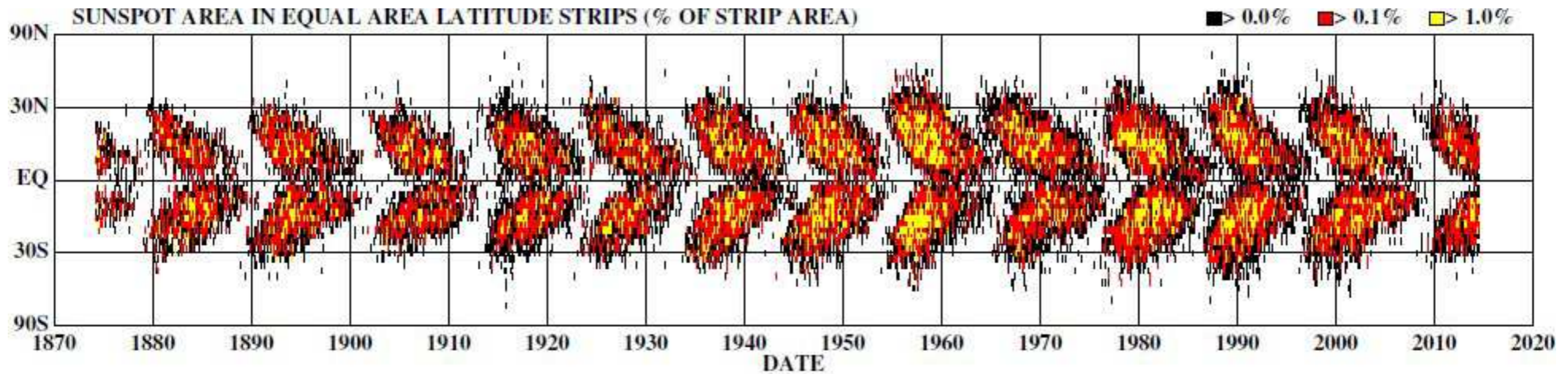


SDO/HMI 7 January 2014

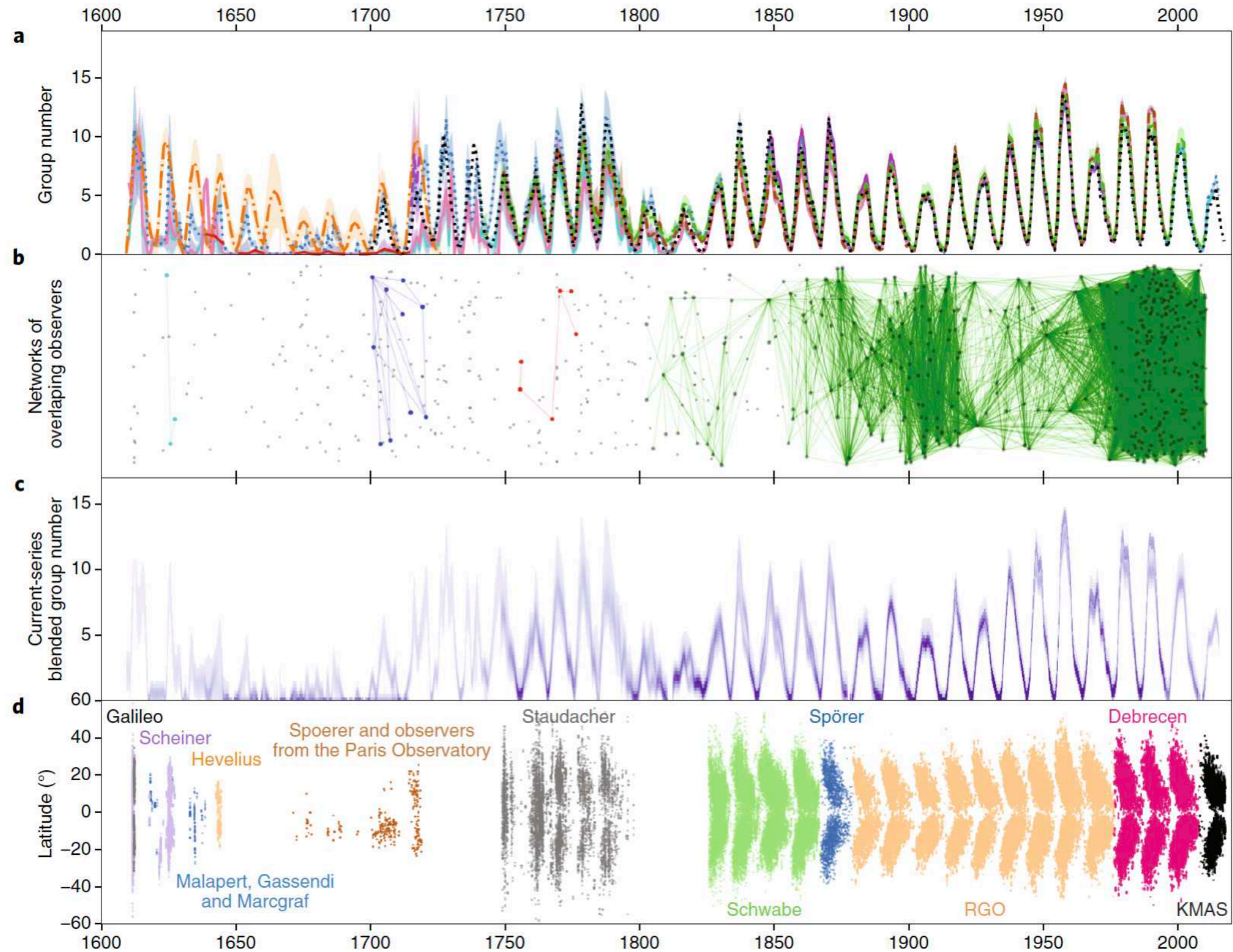


# Butterfly Diagram

Defining cycle minimum/maximum

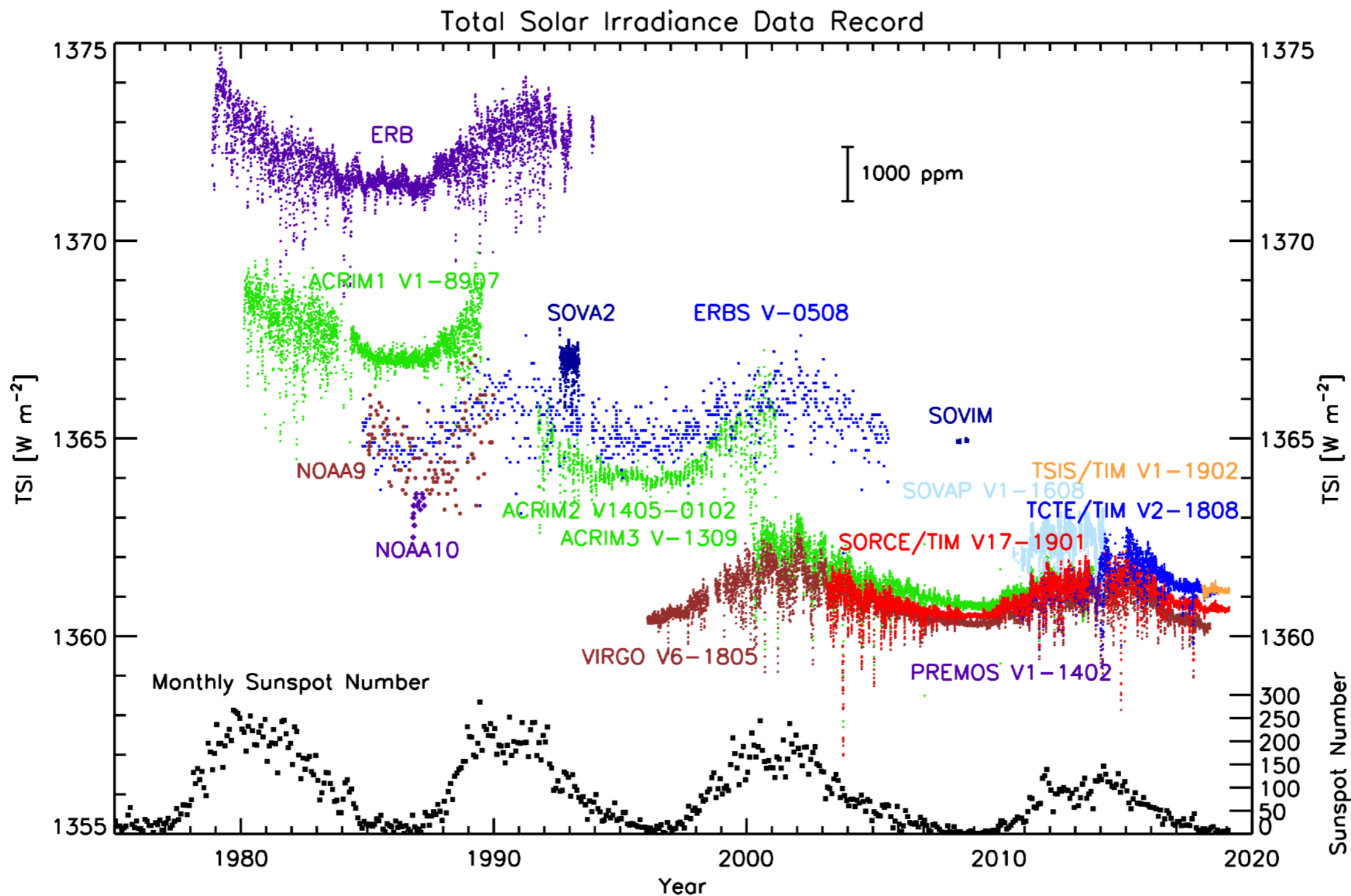


# Historic View



# Total Solar Irradiance

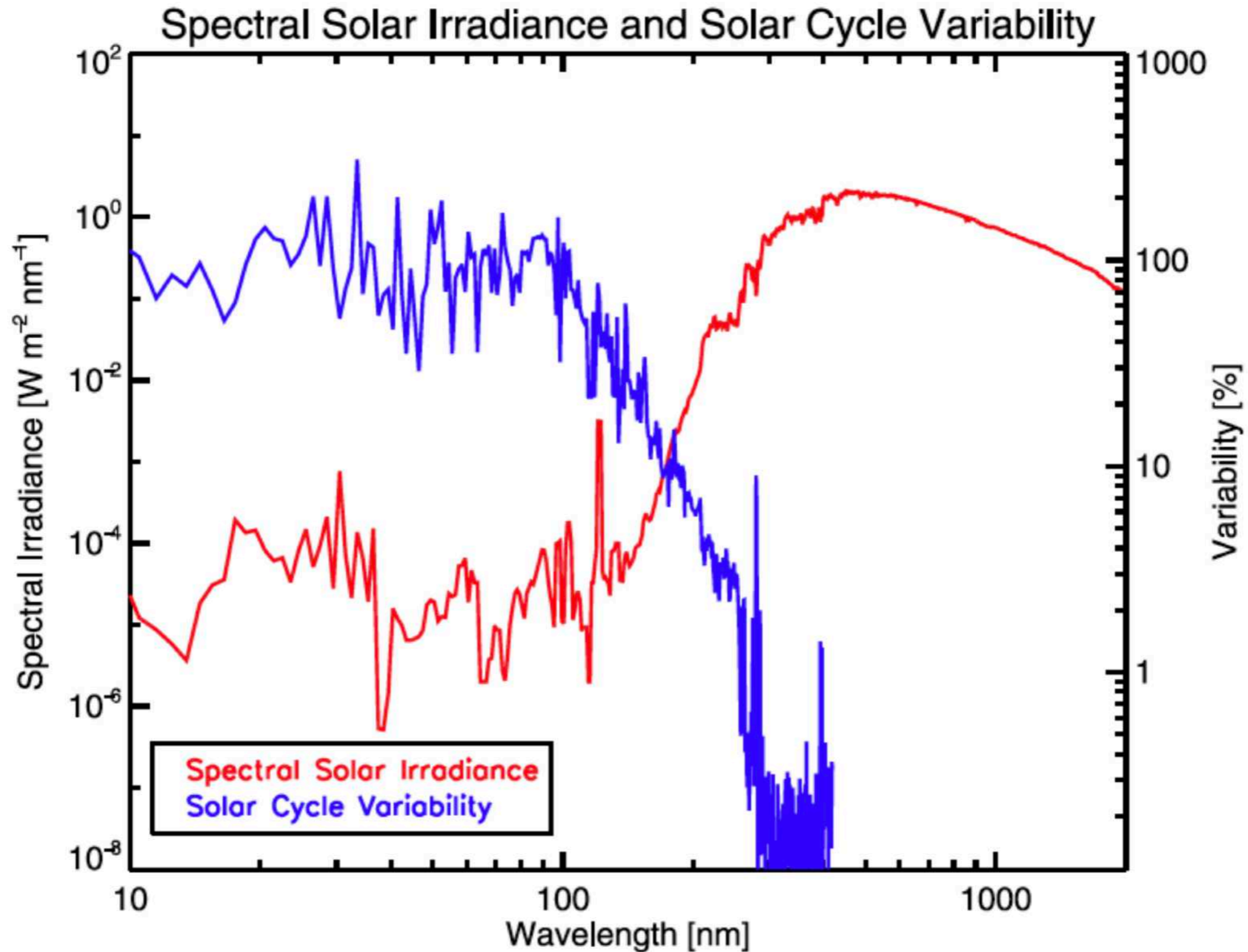
Variability?



Courtesy G. Kopp

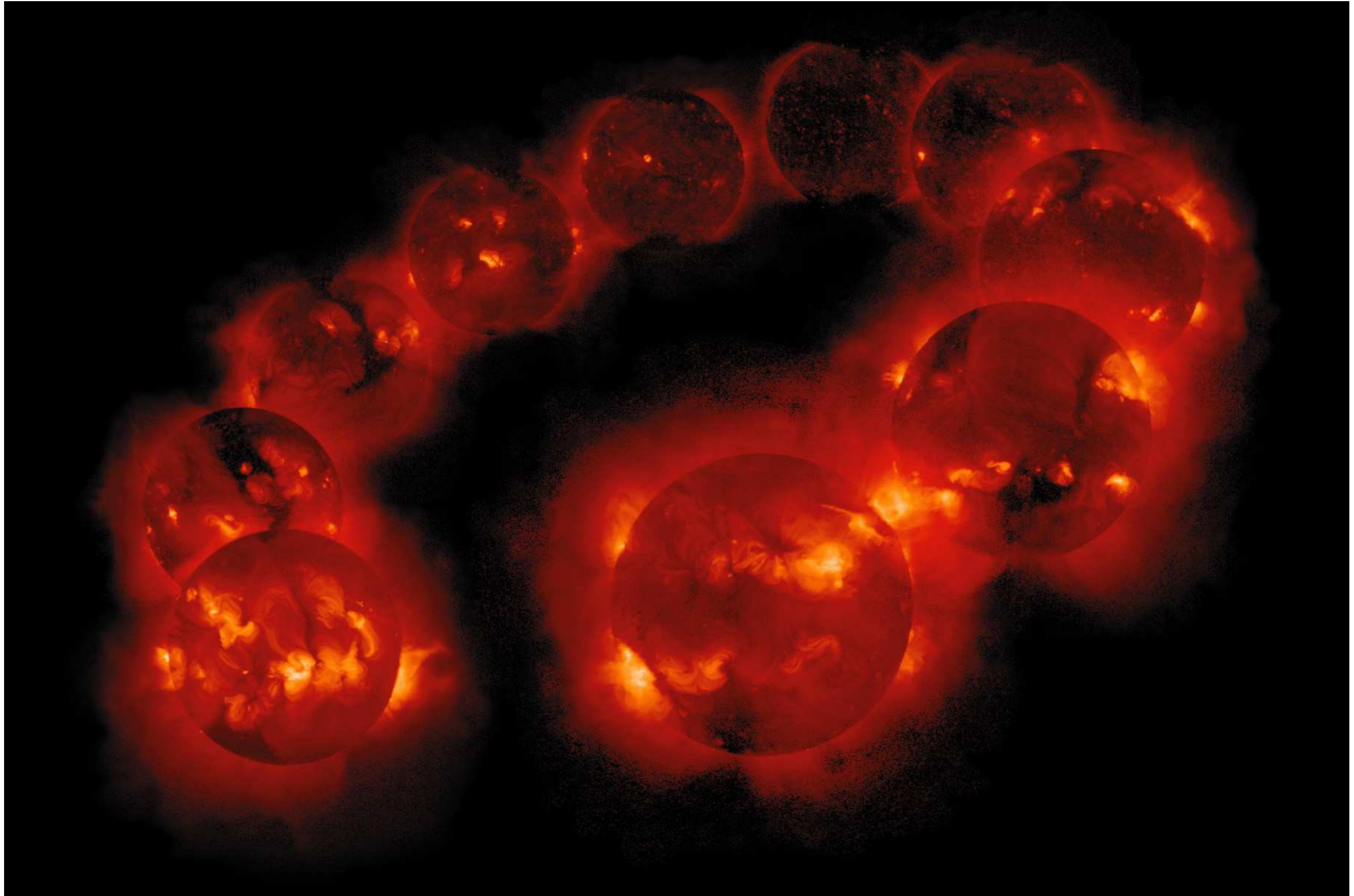
# Spectral Irradiance Variability

What features determine the variability in different wavelengths?



# X-Ray View Over a Cycle

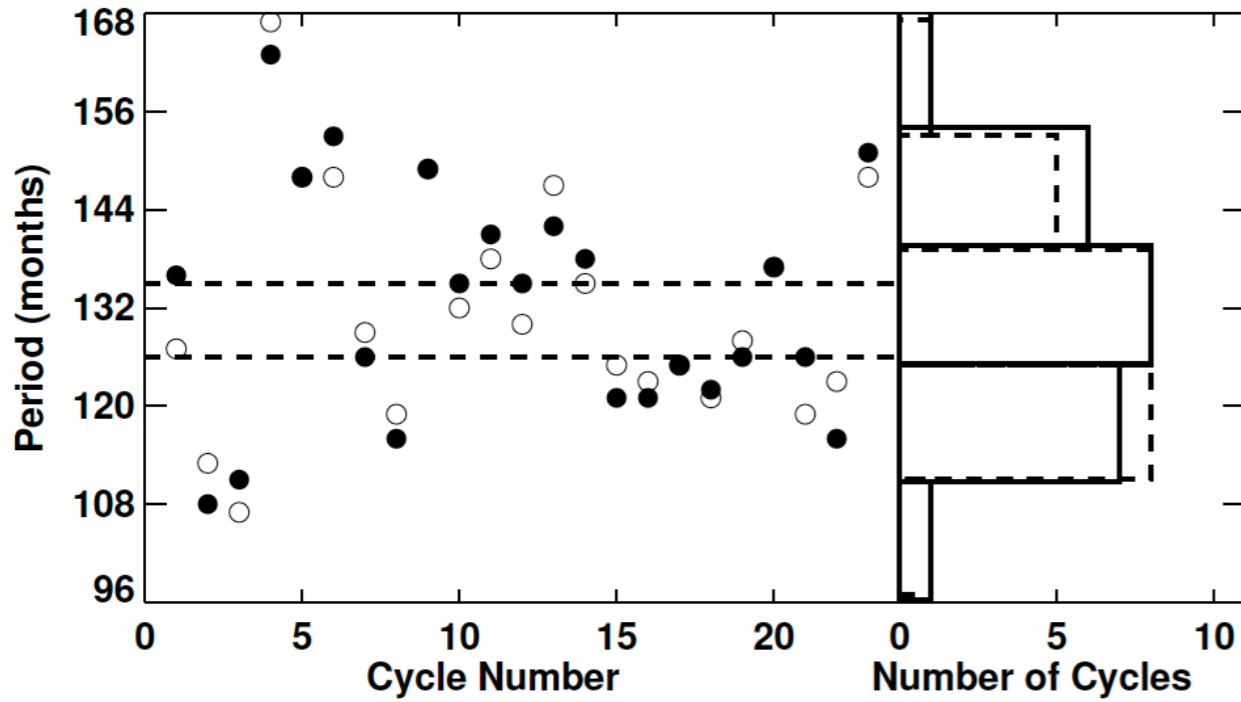
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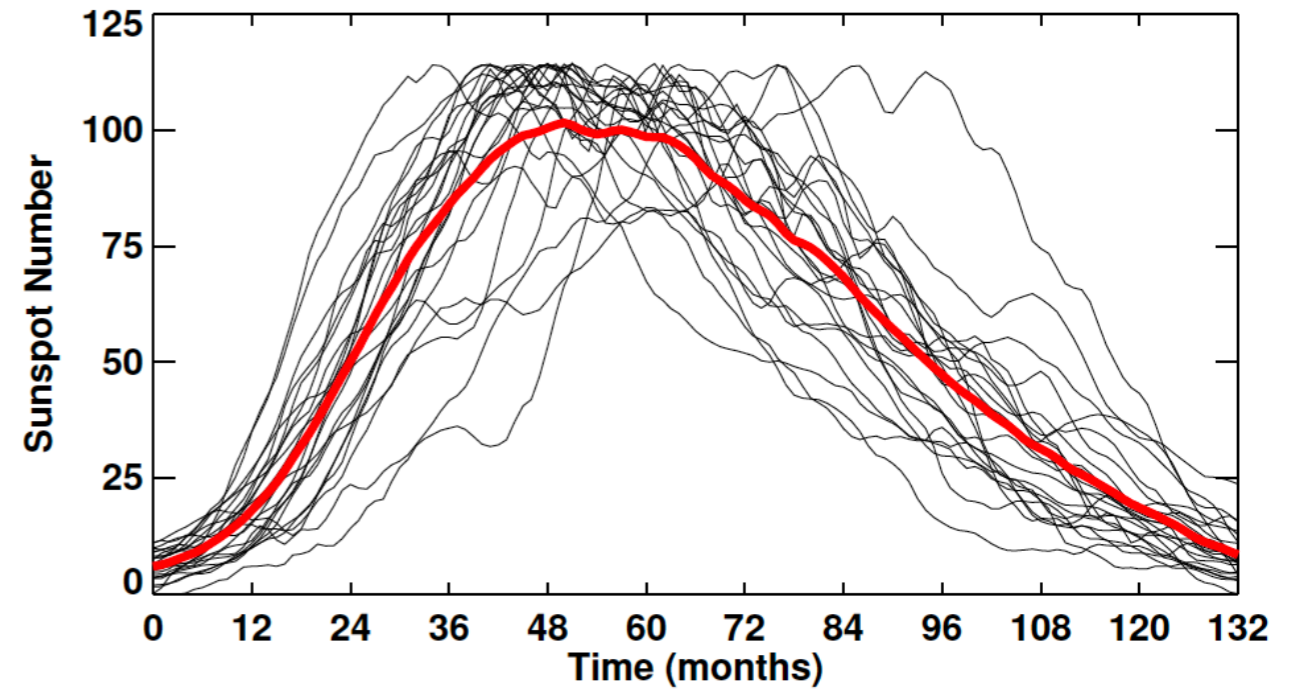
Credit: Yohkoh/ISAS/LMSAL/NAOJ/U. Tokyo/NASA

# Cycle Parameters

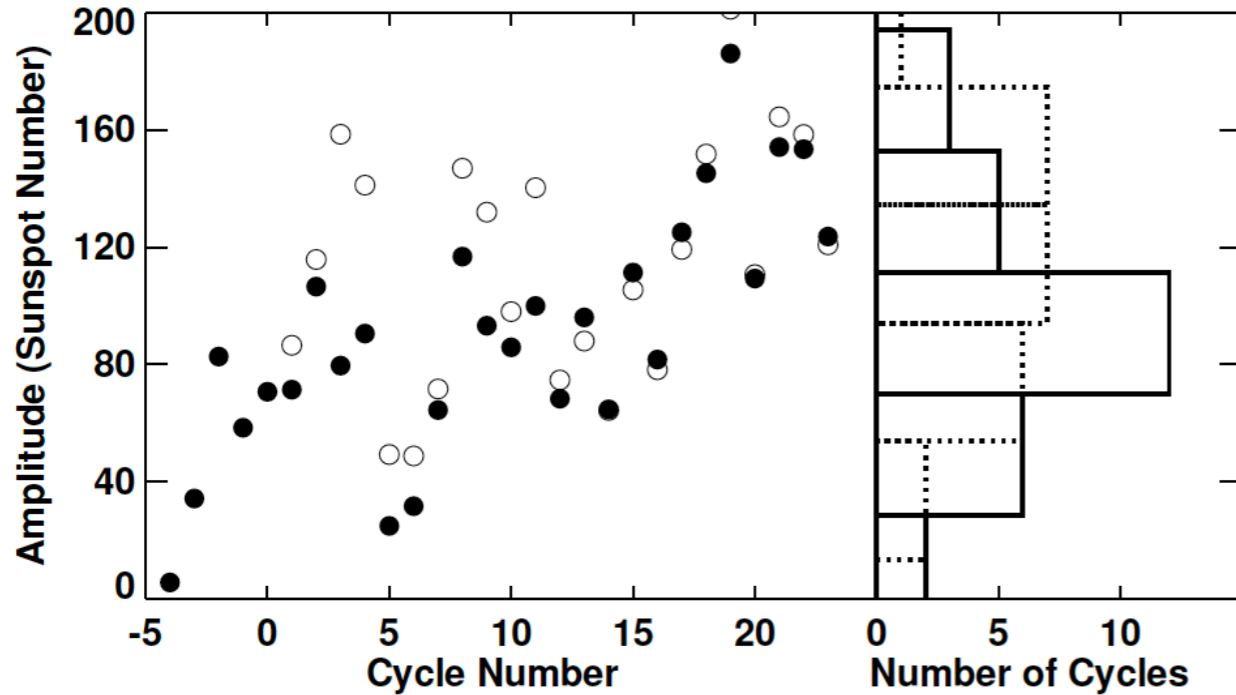
## Period



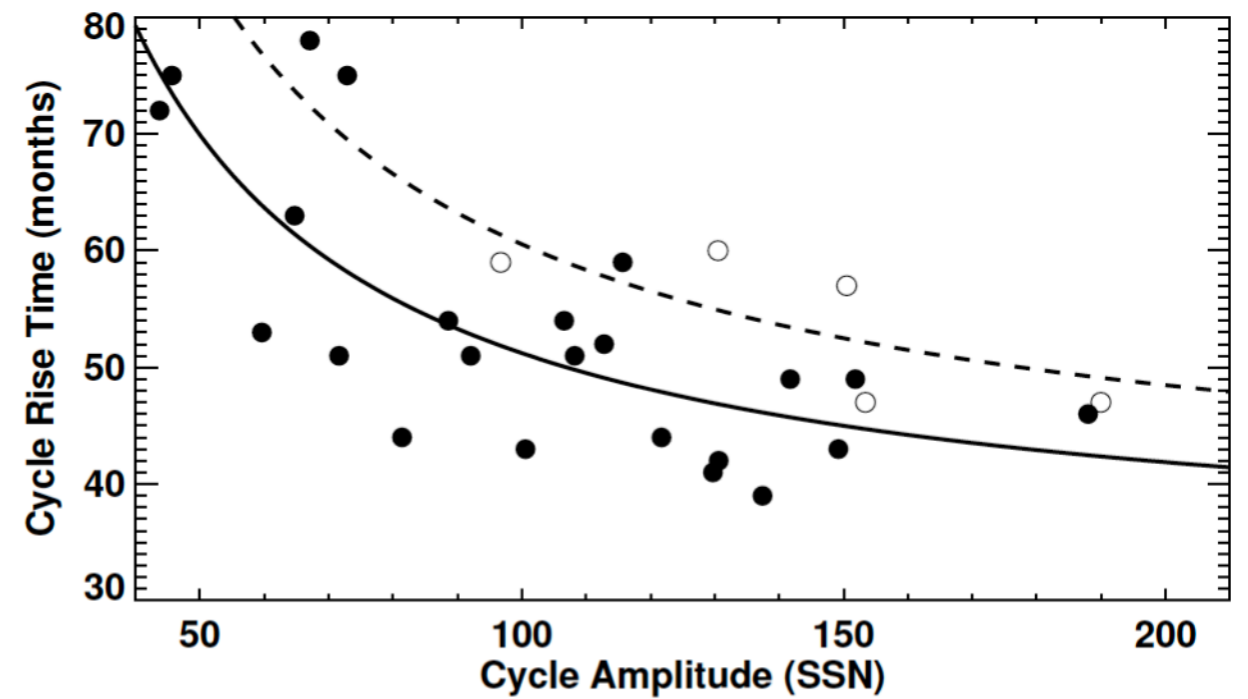
## Gnevyshev Gap



## Amplitude



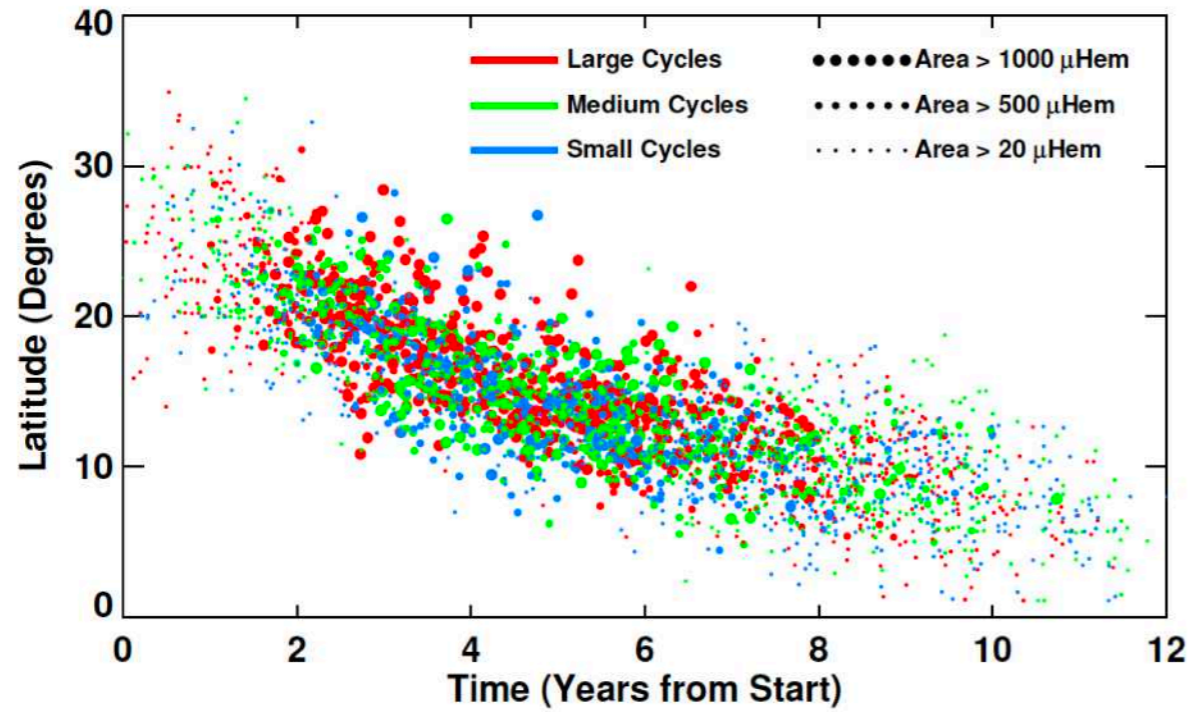
## Waldmeier Effect



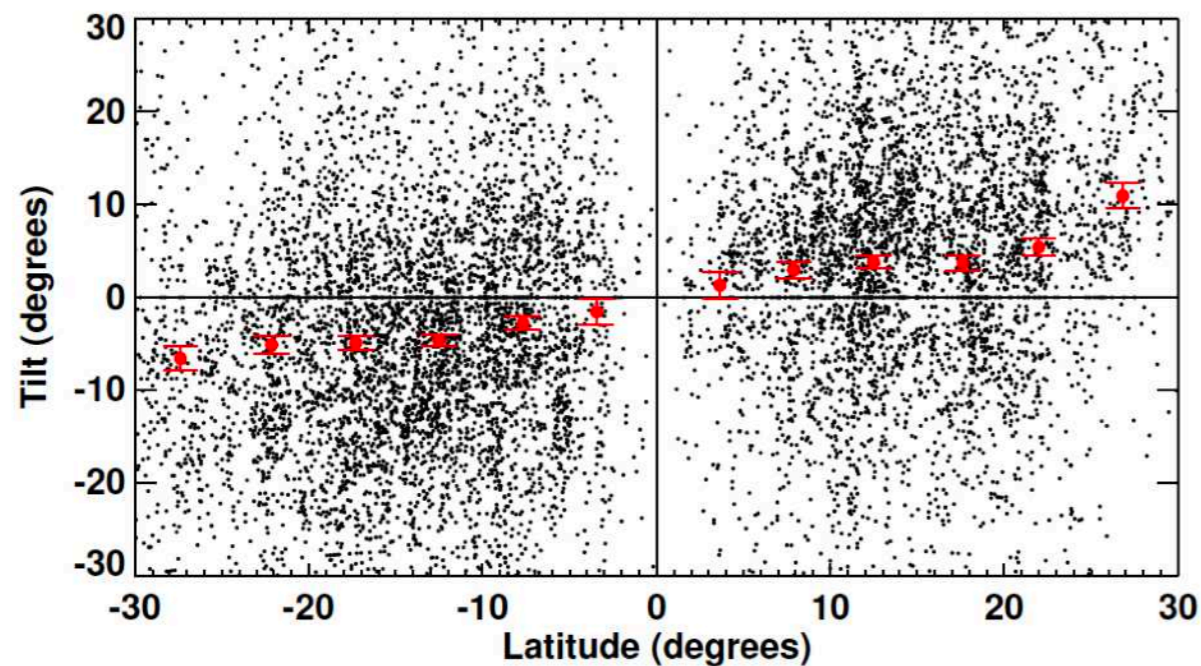


# Spörer's, Hale's, & Joy's Law

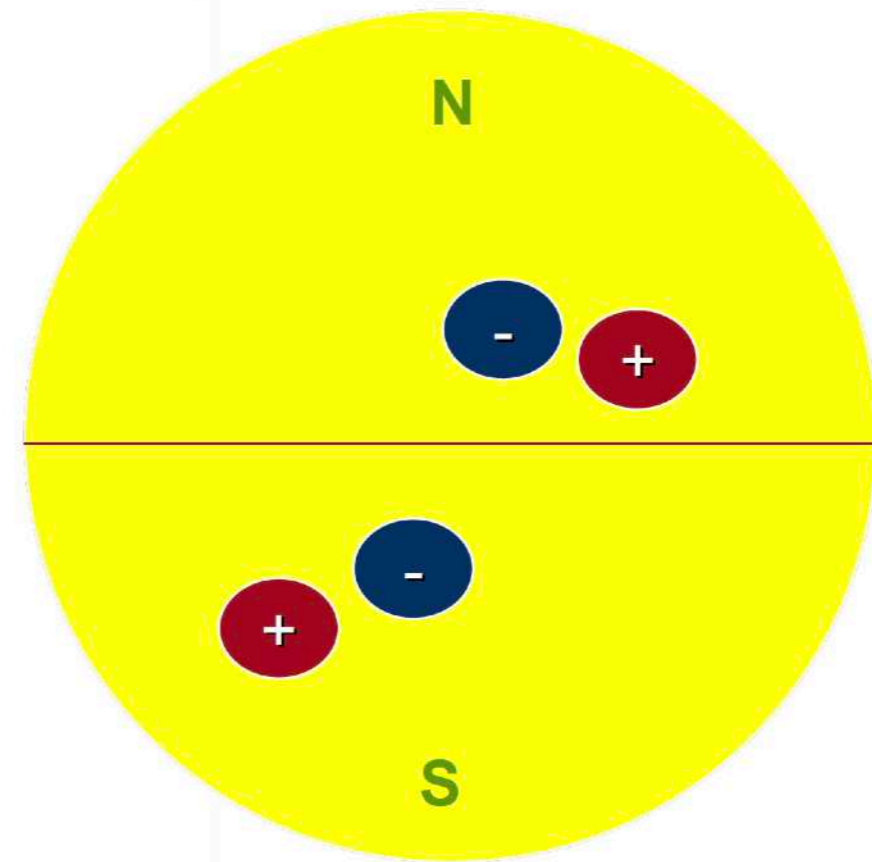
Spörer's Law



Joy's Law



Hale's Law

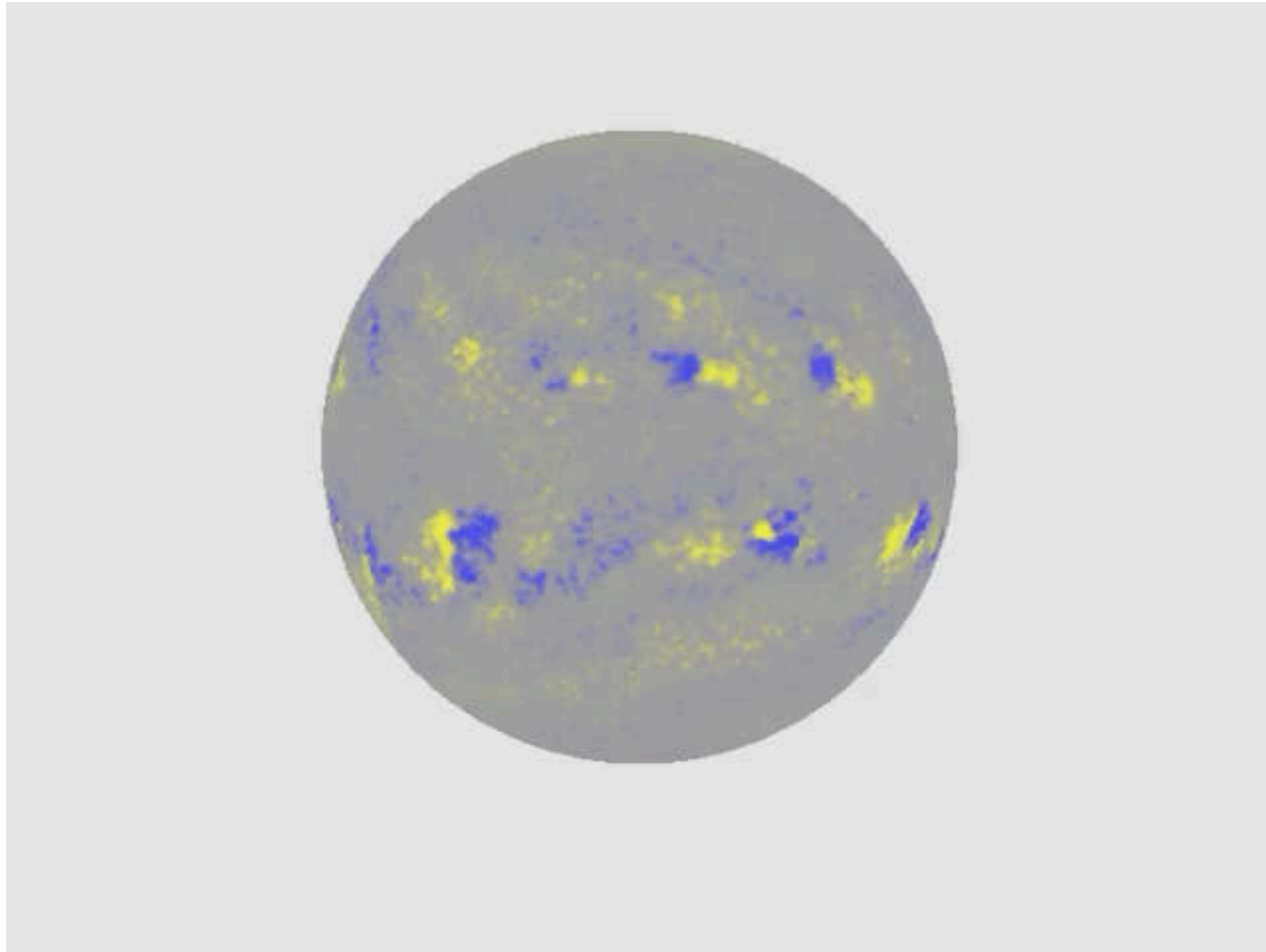


Hathaway (2015)

Courtesy S. Solanki

# Evolution of Magnetic Field

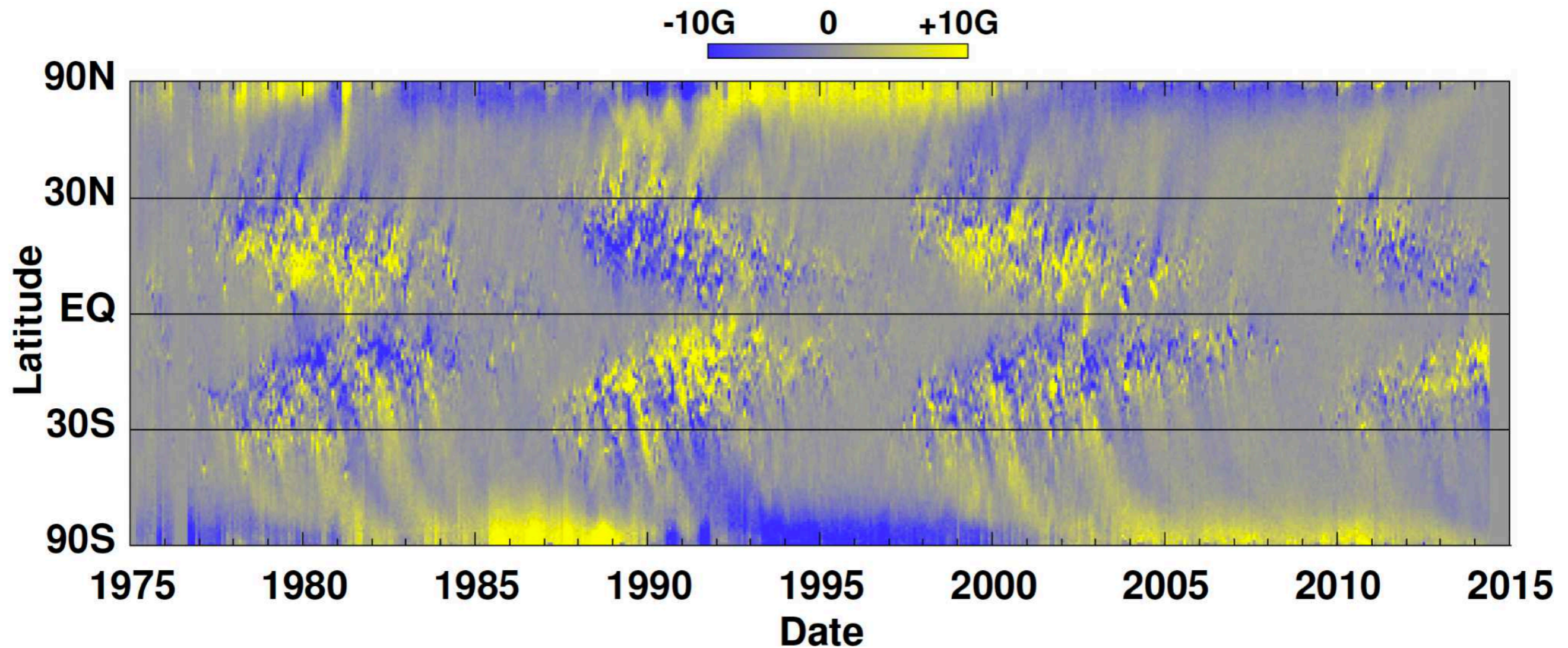
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# Magnetic Butterfly Diagram

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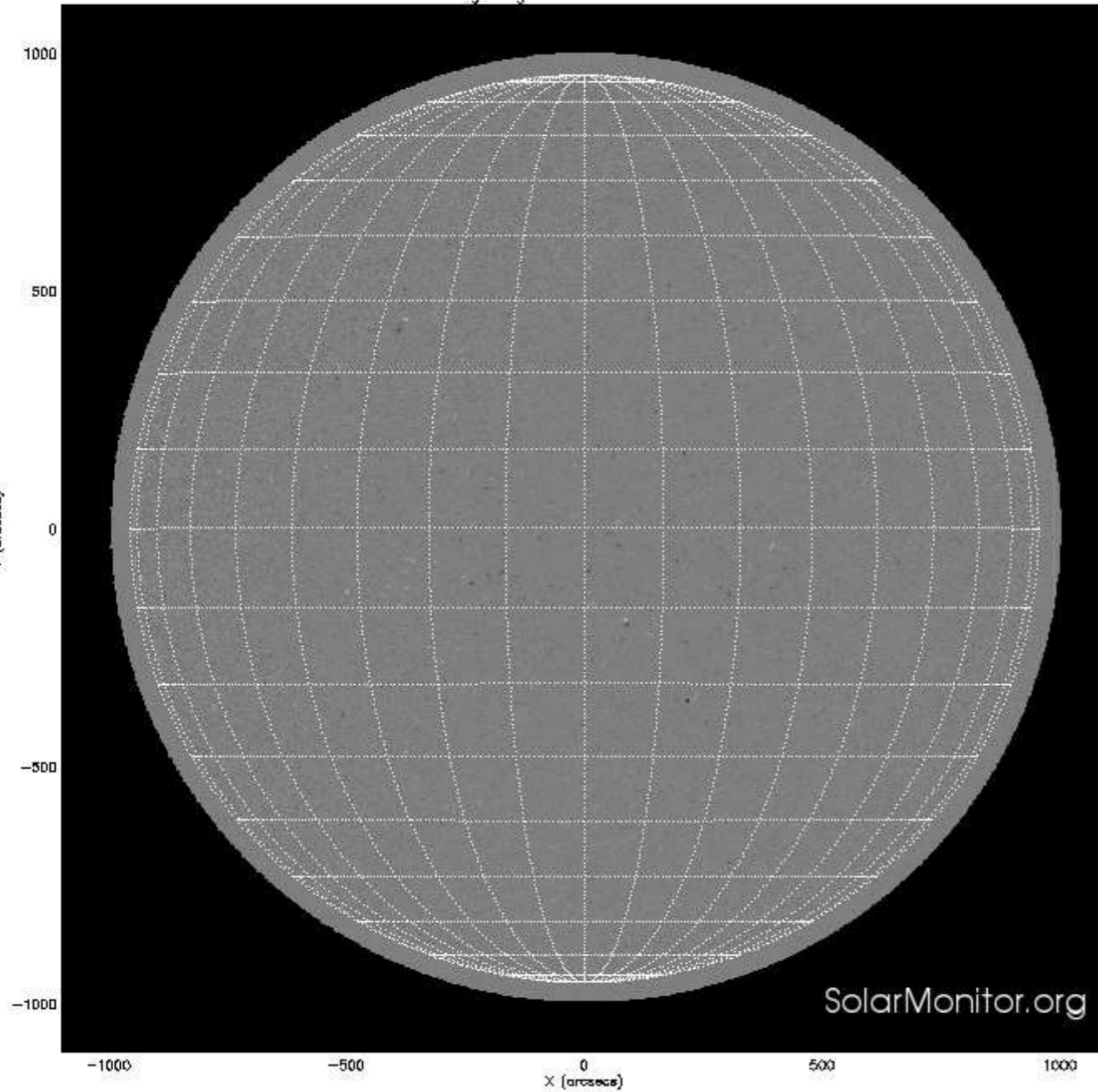
Spörer's Law; N/S asymmetry; polarity reversal



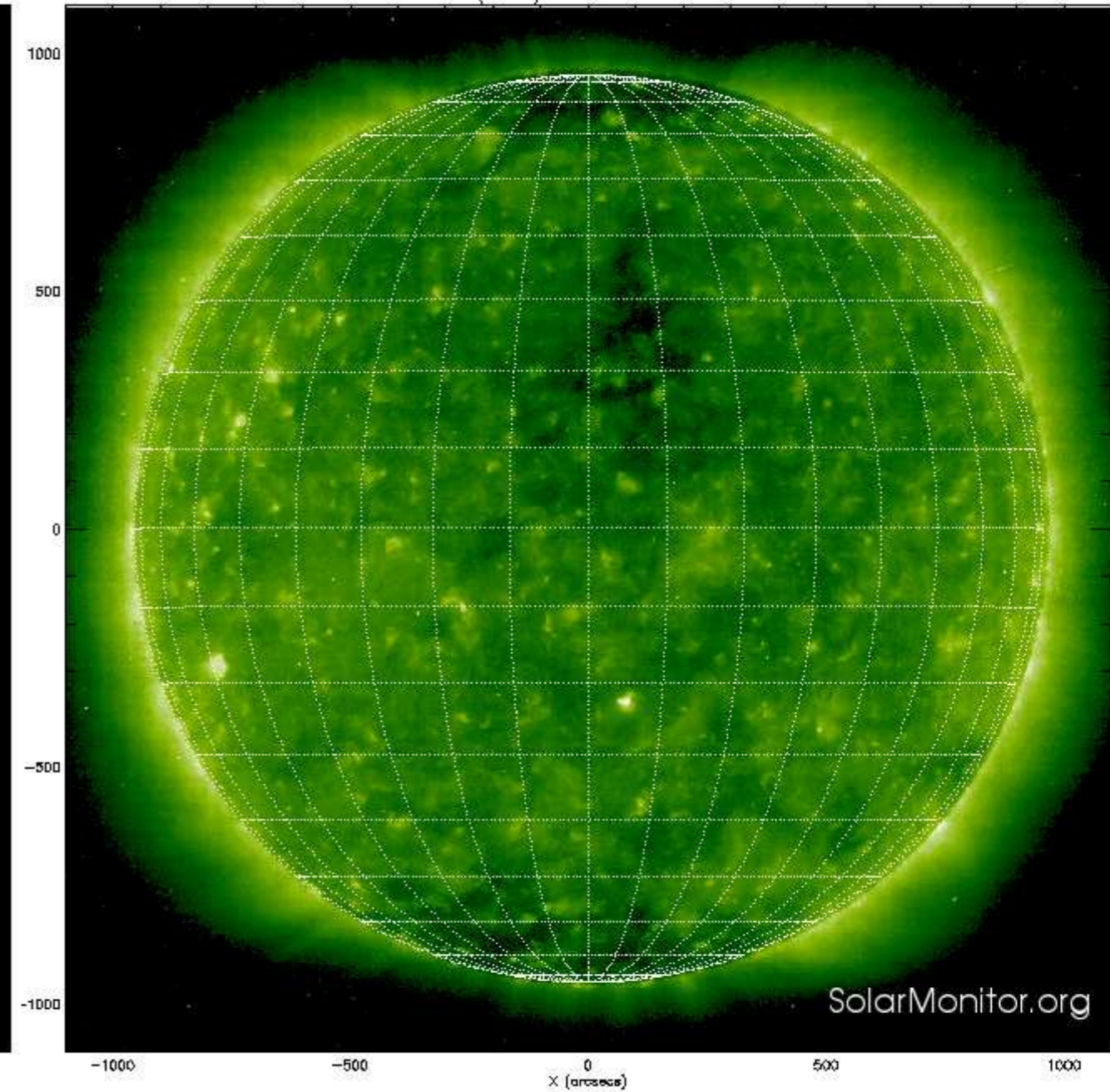
# Minimum Phase

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MDI Magnetogram 4-Jun-2008 21:28:00



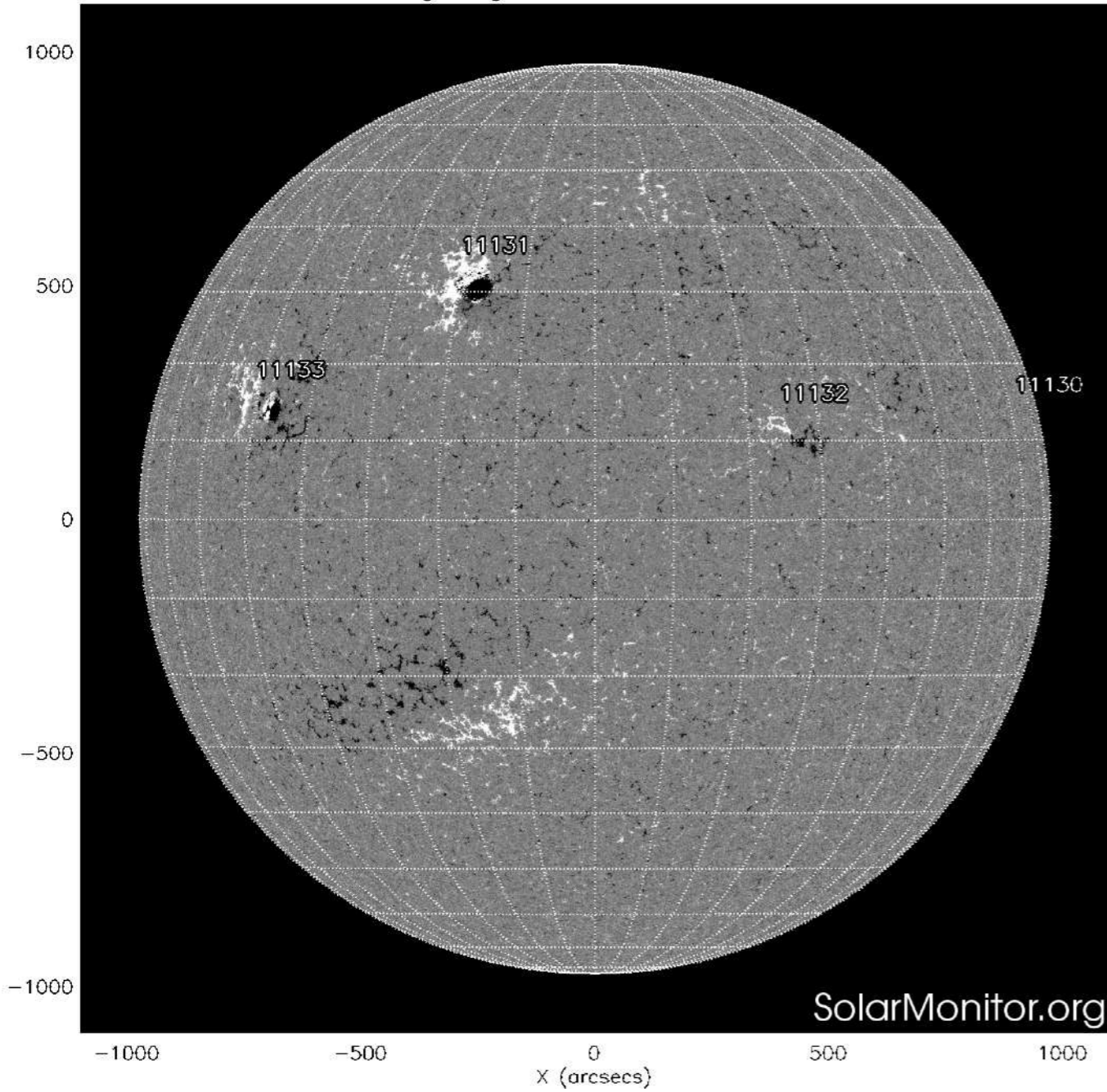
EIT Fe XII (195 Å) 4-Jun-2008 02:23:27.930



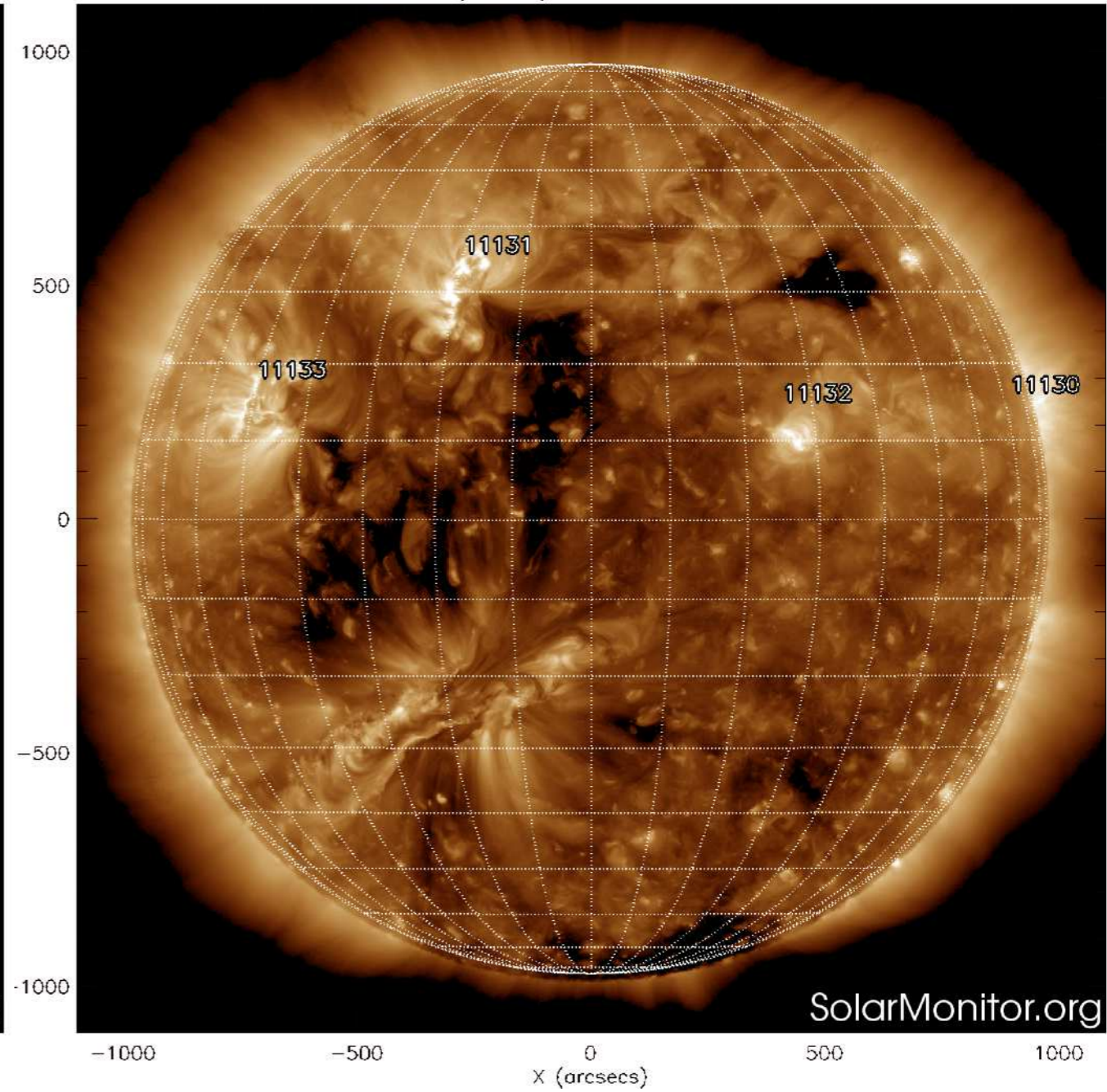
# Ascending Phase

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SDO HMI Magnetogram 6-Dec-2010 22:06:26.100



SDO AIA Fe XII (193 Å) 6-Dec-2010 23:38:31.840

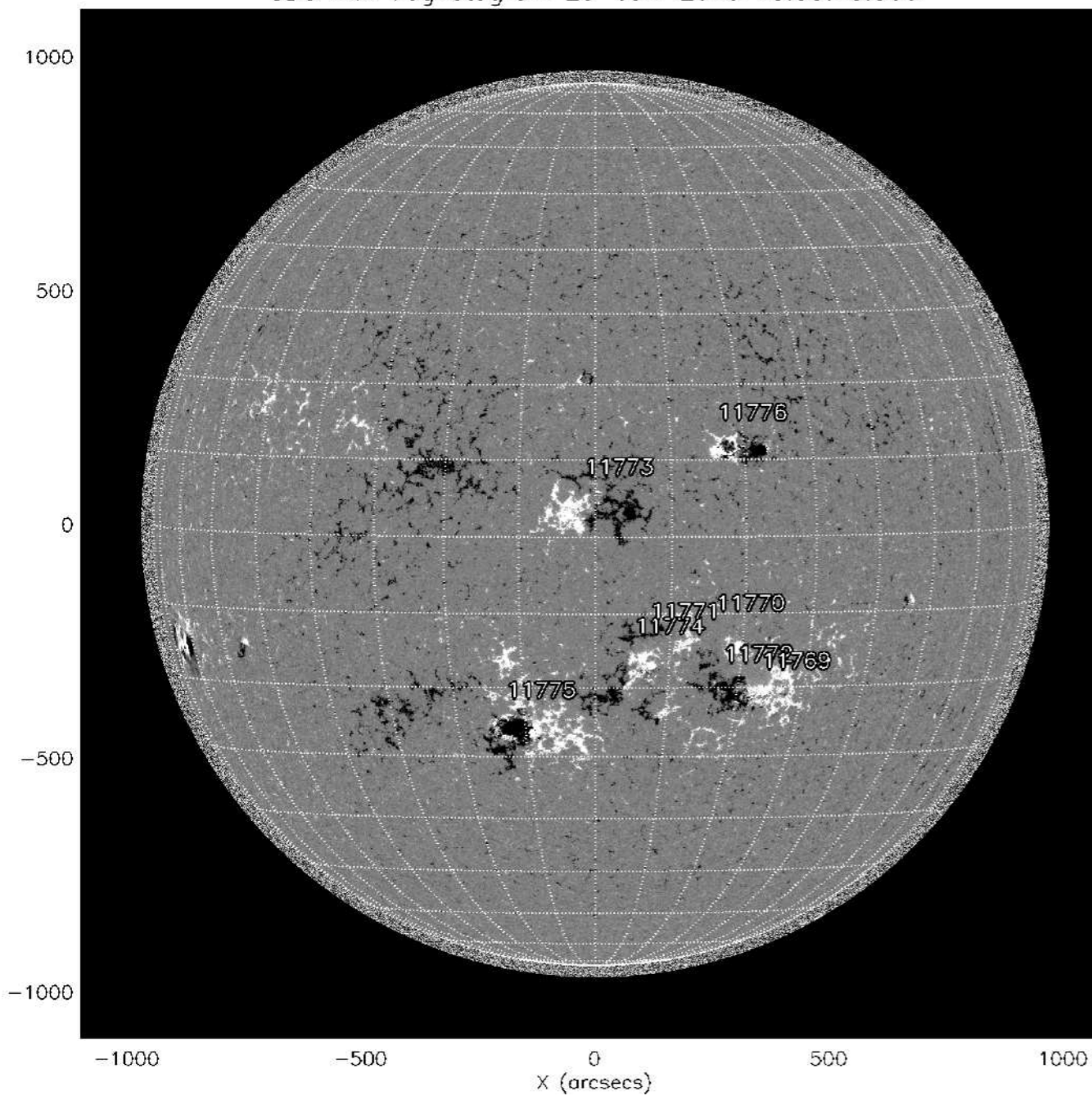


SDO/HMI, AIA 19.3 nm

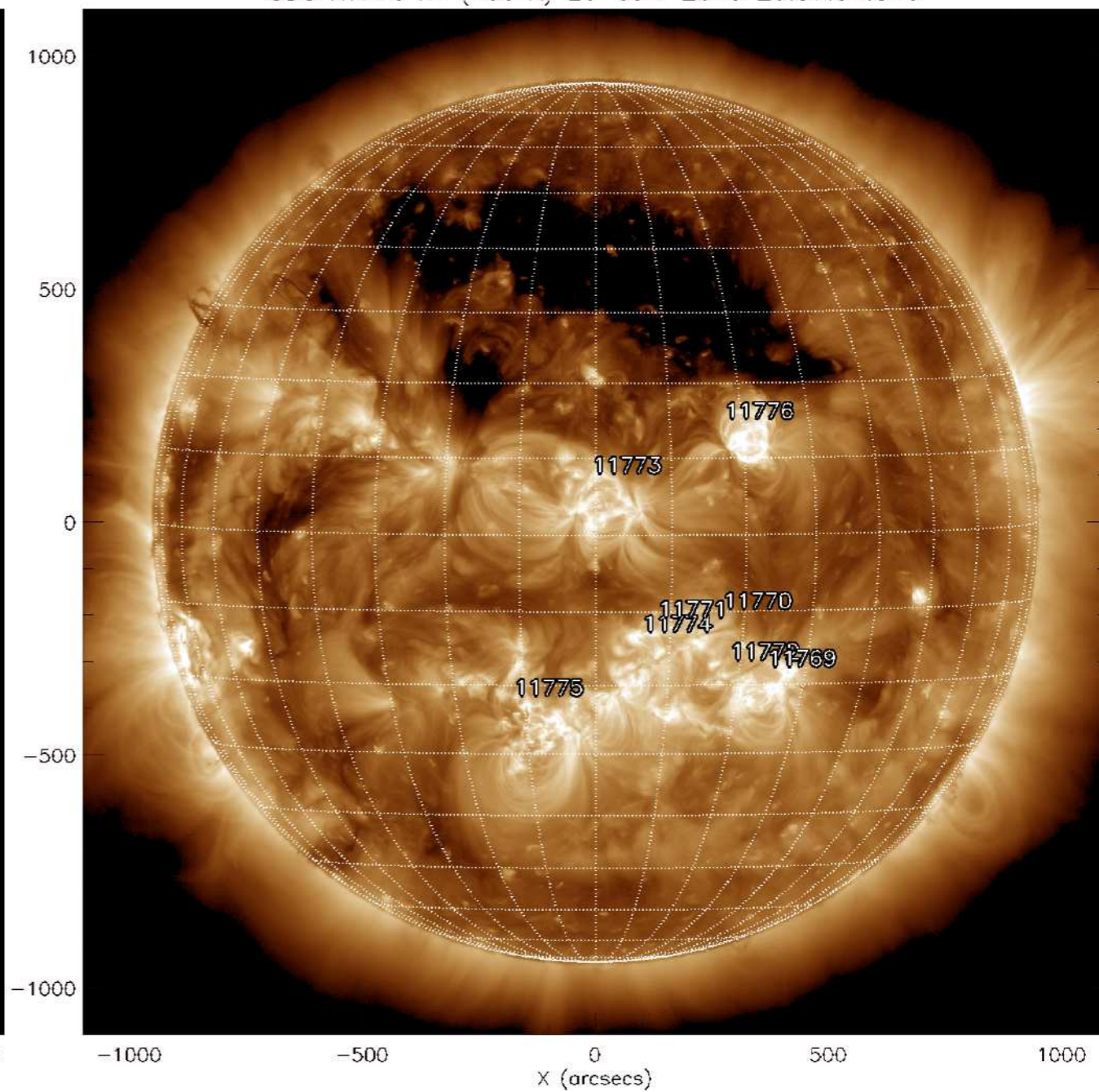
# Maximum Phase

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SDO HMI Magnetogram 20-Jun-2013 18:33:40.500



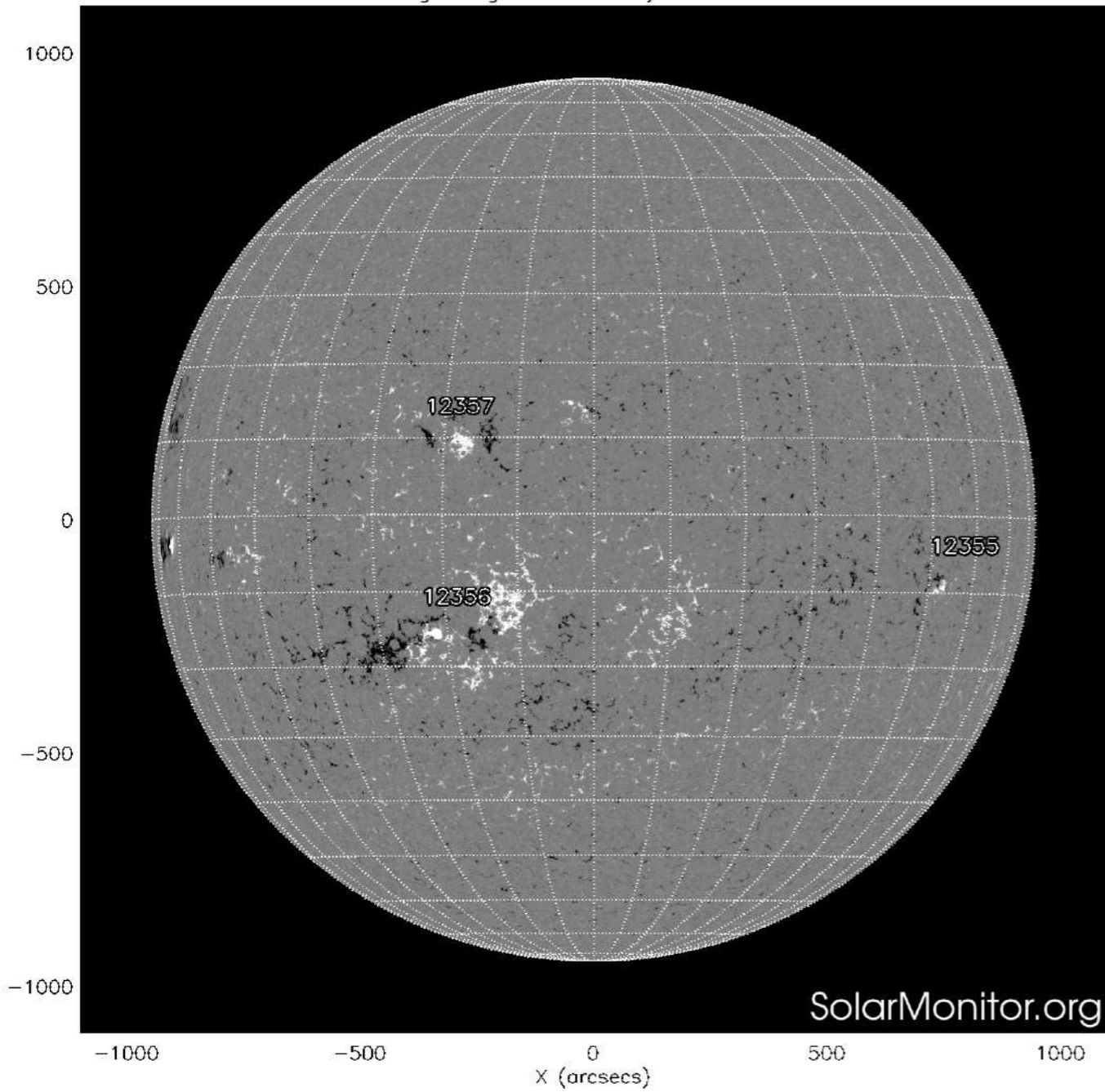
SDO AIA Fe XII (193 Å) 20-Jun-2013 20:57:54.840



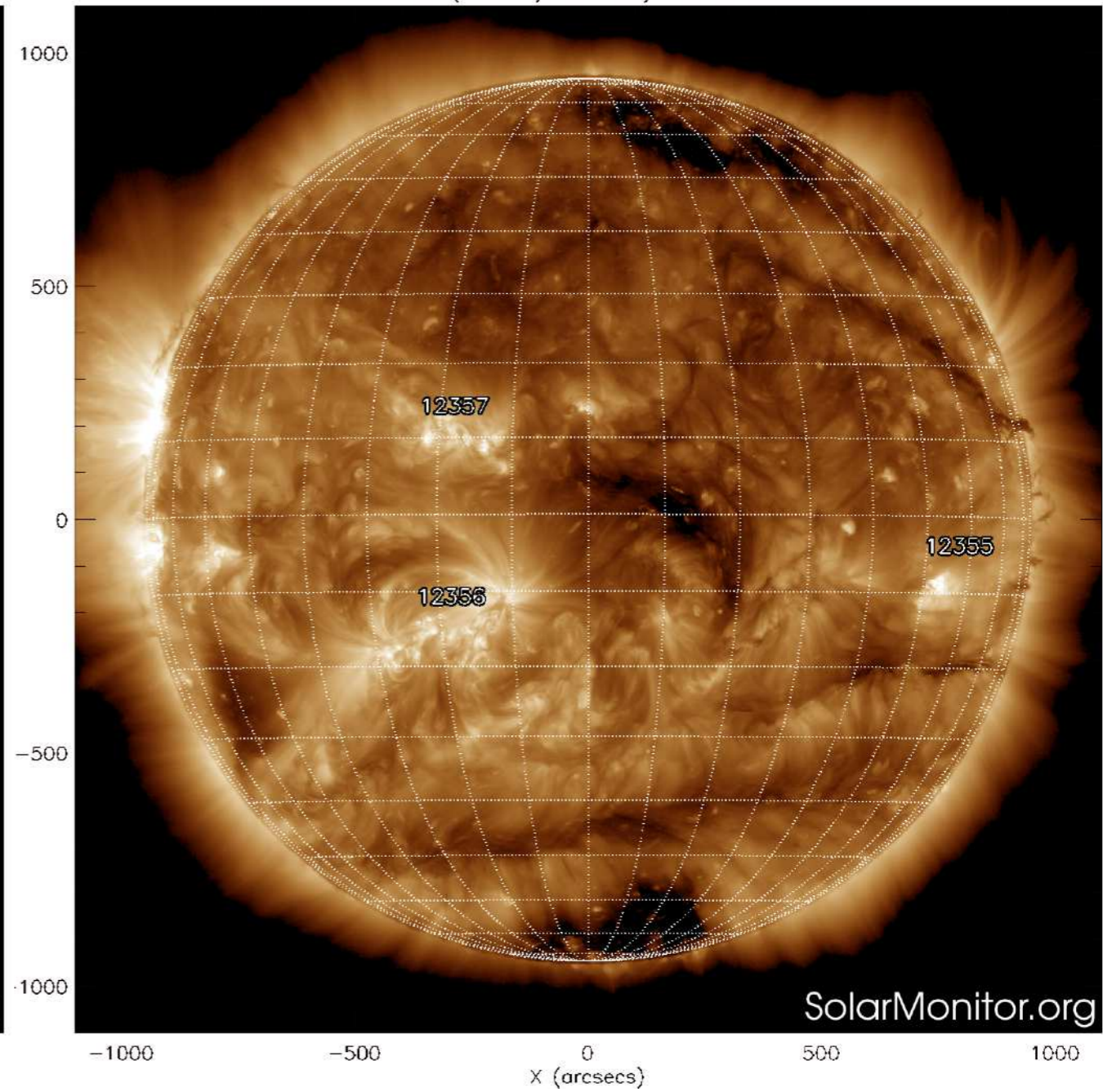
SDO/HMI, AIA 19.3 nm

# Declining Phase

SDO HMI Magnetogram 31-May-2015 22:46:24.400



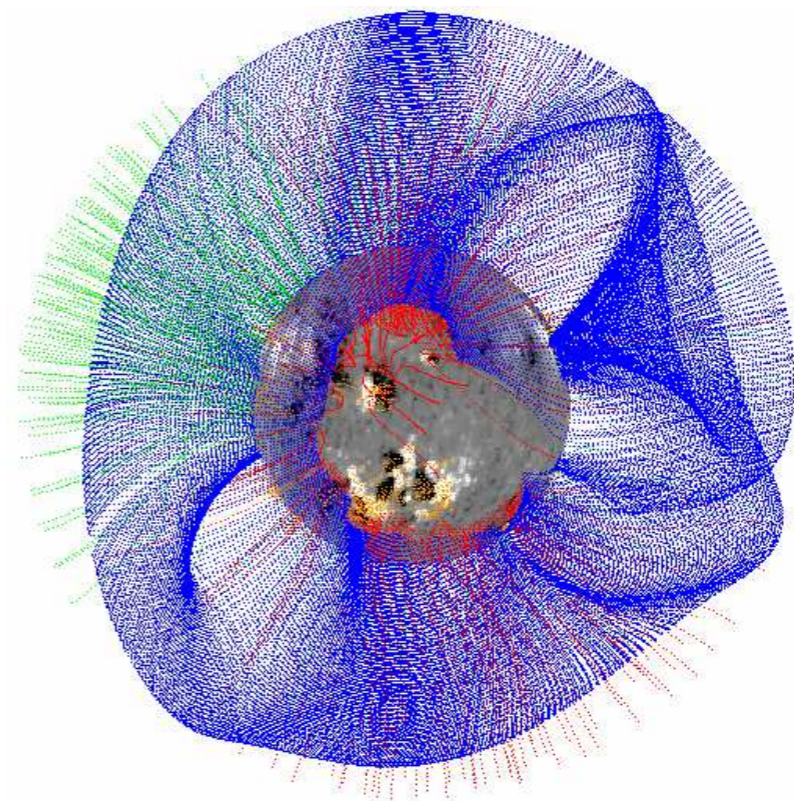
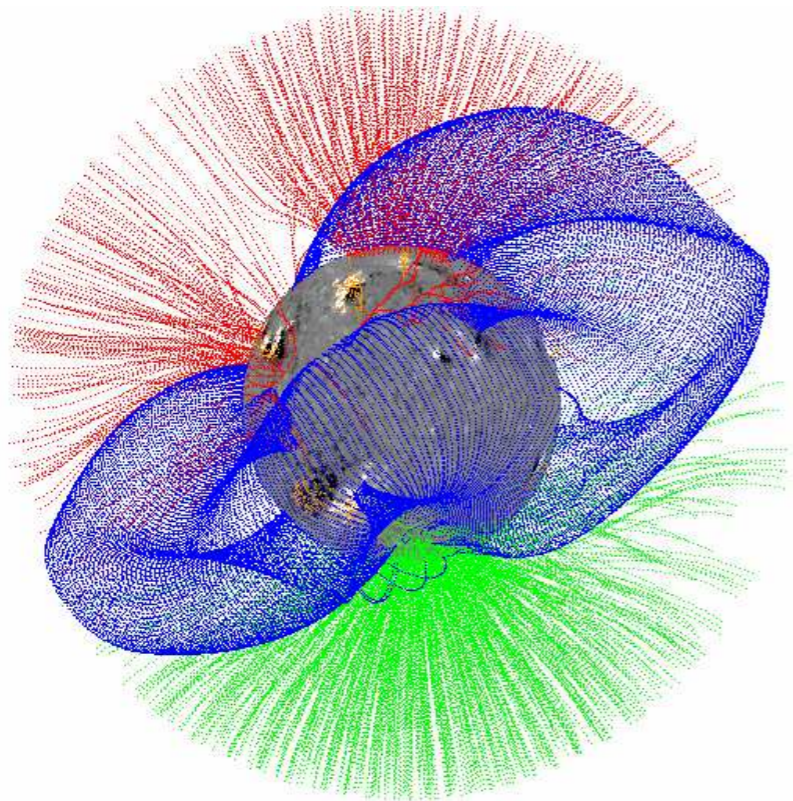
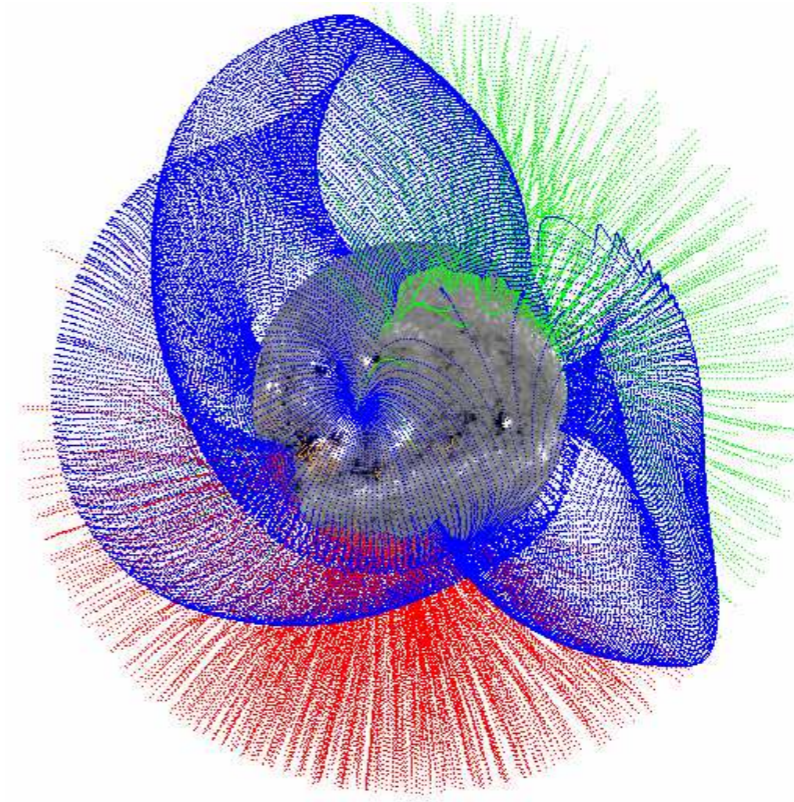
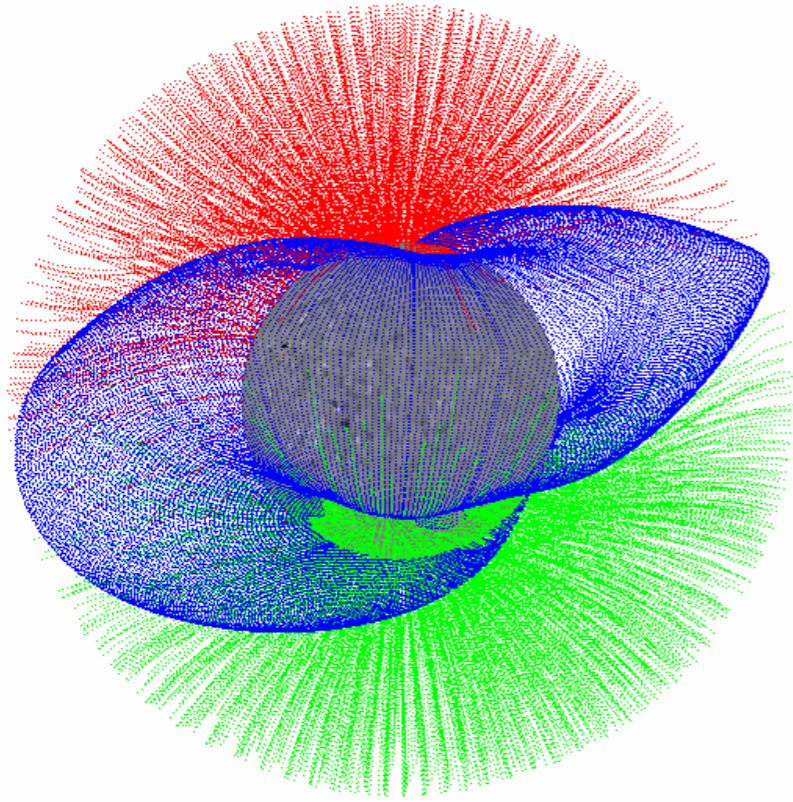
SDO AIA Fe XII (193 Å) 31-May-2015 23:30:42.840



SDO/HMI, AIA 19.3 nm

# Magnetic Topology

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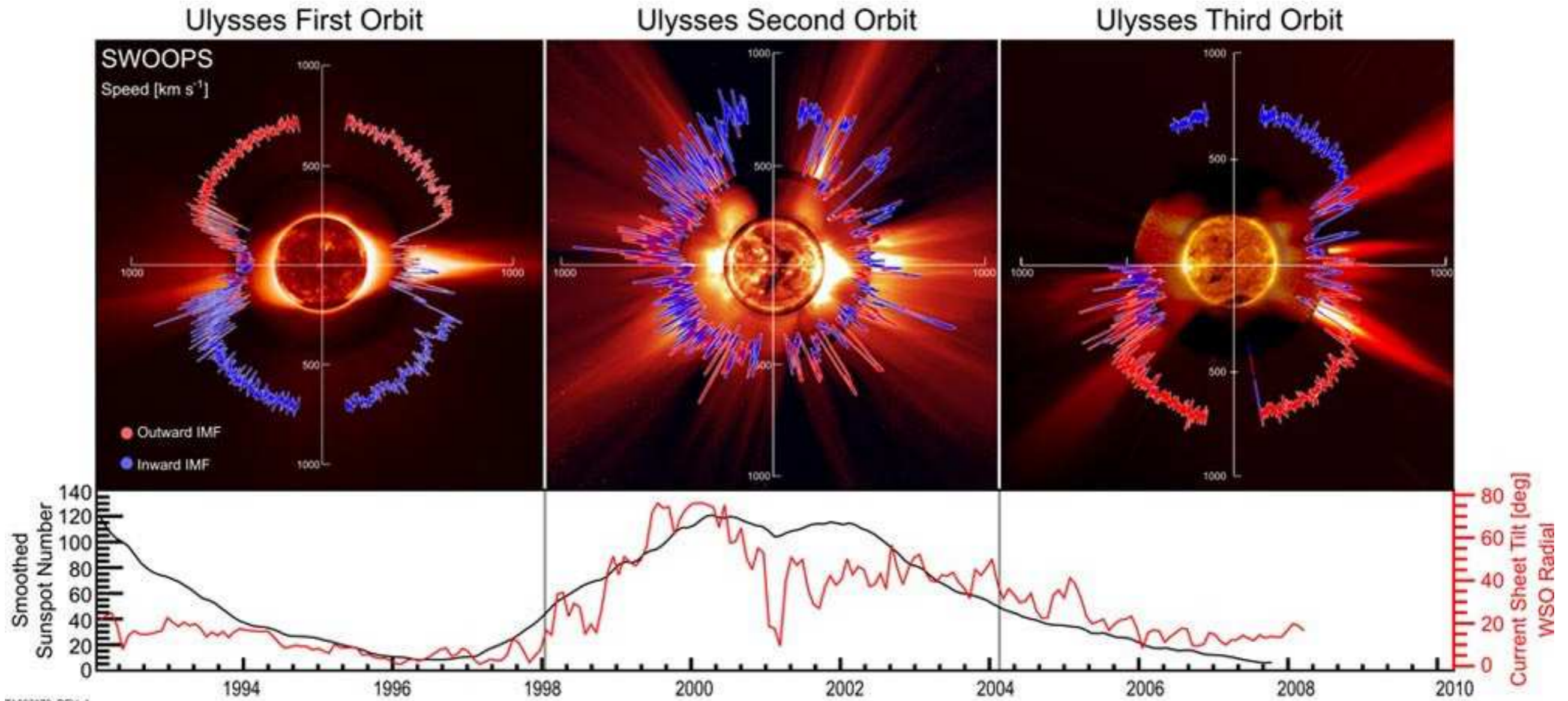


# Total Solar Eclipse Images

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# Solar Wind Over a Cycle

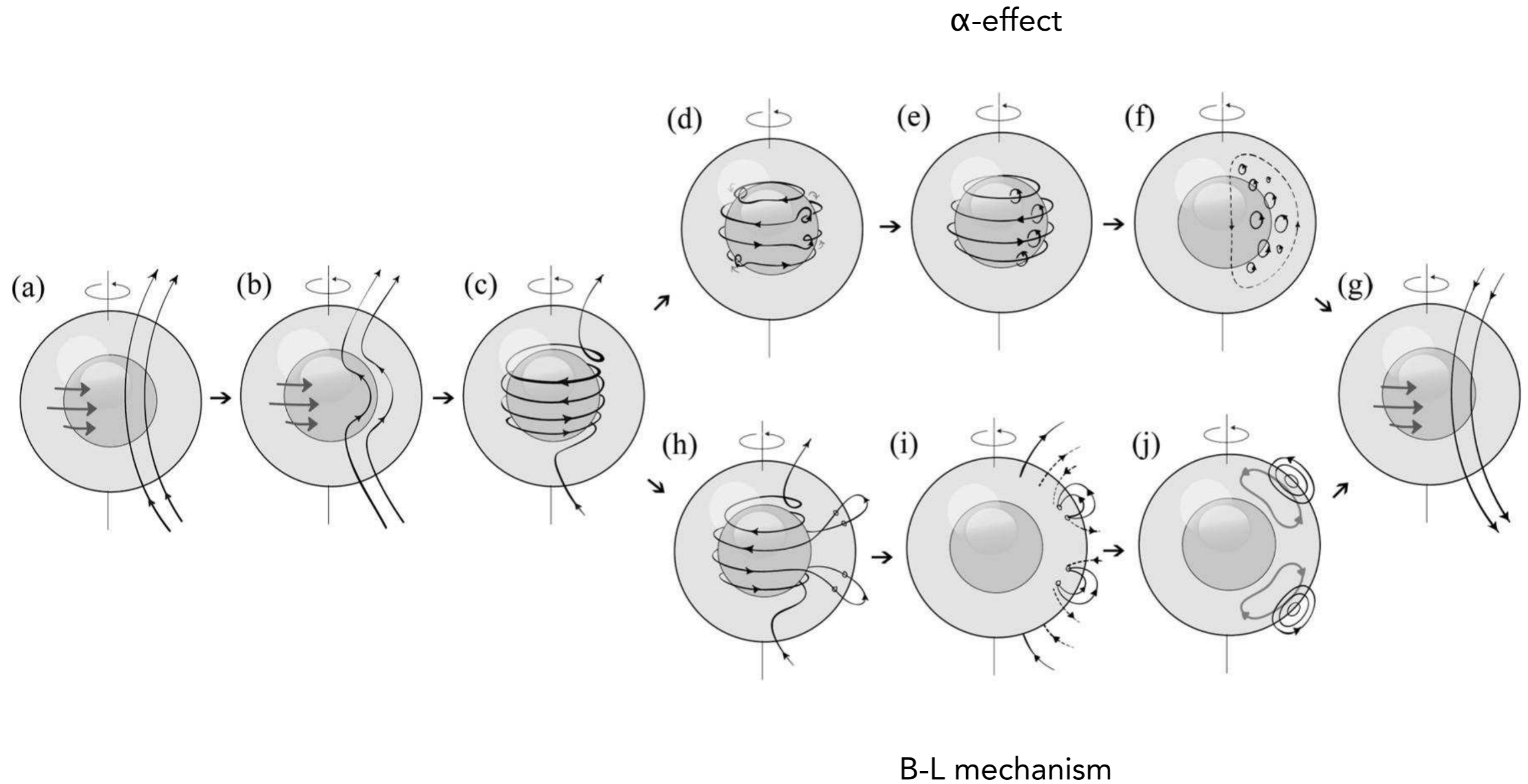


$$\tan \theta \sim |k_{11}| / |k_{10}|$$

# Babcock-Leighton Mechanism & Surface Flux Transport

# Babcock-Leighton Mechanism

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# Surface Flux Transport

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- $B_r$  evolution within a thin spherical shell near surface
- Induction equation with source & diffusion

$$\frac{\partial B_r}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})_r + \kappa \nabla^2 B_r + S(\theta, \phi, t)$$

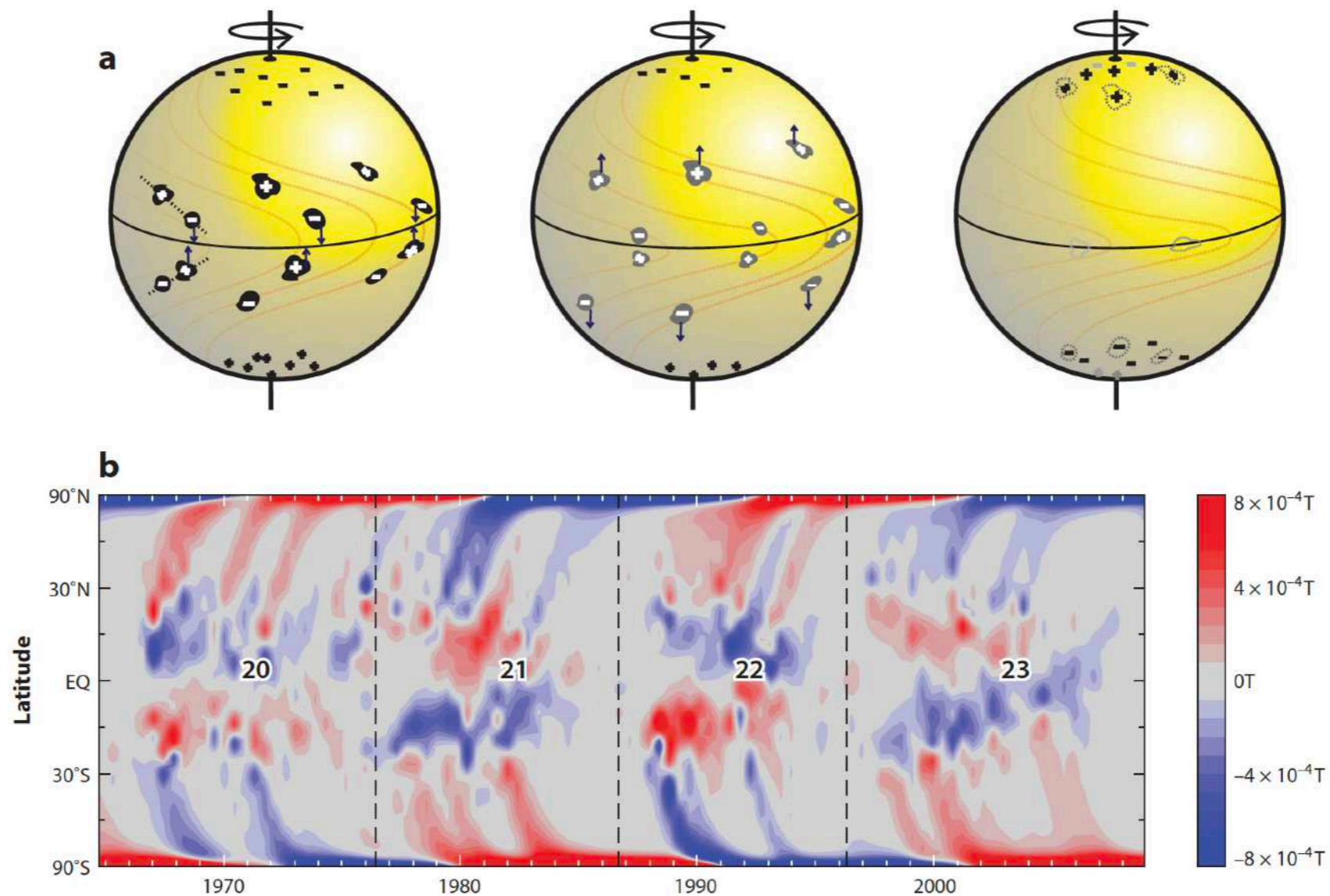
or,

$$\frac{\partial B_r}{\partial t} = -\omega(\theta) \frac{\partial B_r}{\partial \phi} - \frac{1}{R_\odot \sin \theta} \frac{\partial}{\partial \theta} [\sin \theta v(\theta) B_r] + \frac{\kappa}{R_\odot^2} \left[ \frac{1}{\sin \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial B_r}{\partial \theta} \right) + \frac{1}{\sin^2 \theta} \frac{\partial^2 B_r}{\partial \phi^2} \right] + S(\theta, \phi, t)$$

- Surface flow: differential rotation & meridional flow; measurable
- Diffusion: supergranular dispersion, etc.; empirically determined
- Source: flux emergence; measurable

# Surface Flux Transport

- Toroidal field (sunspot) conversion to poloidal field (dipole)
- Essential ingredient: Hale's law, Joy's law, & cross equatorial cancellation

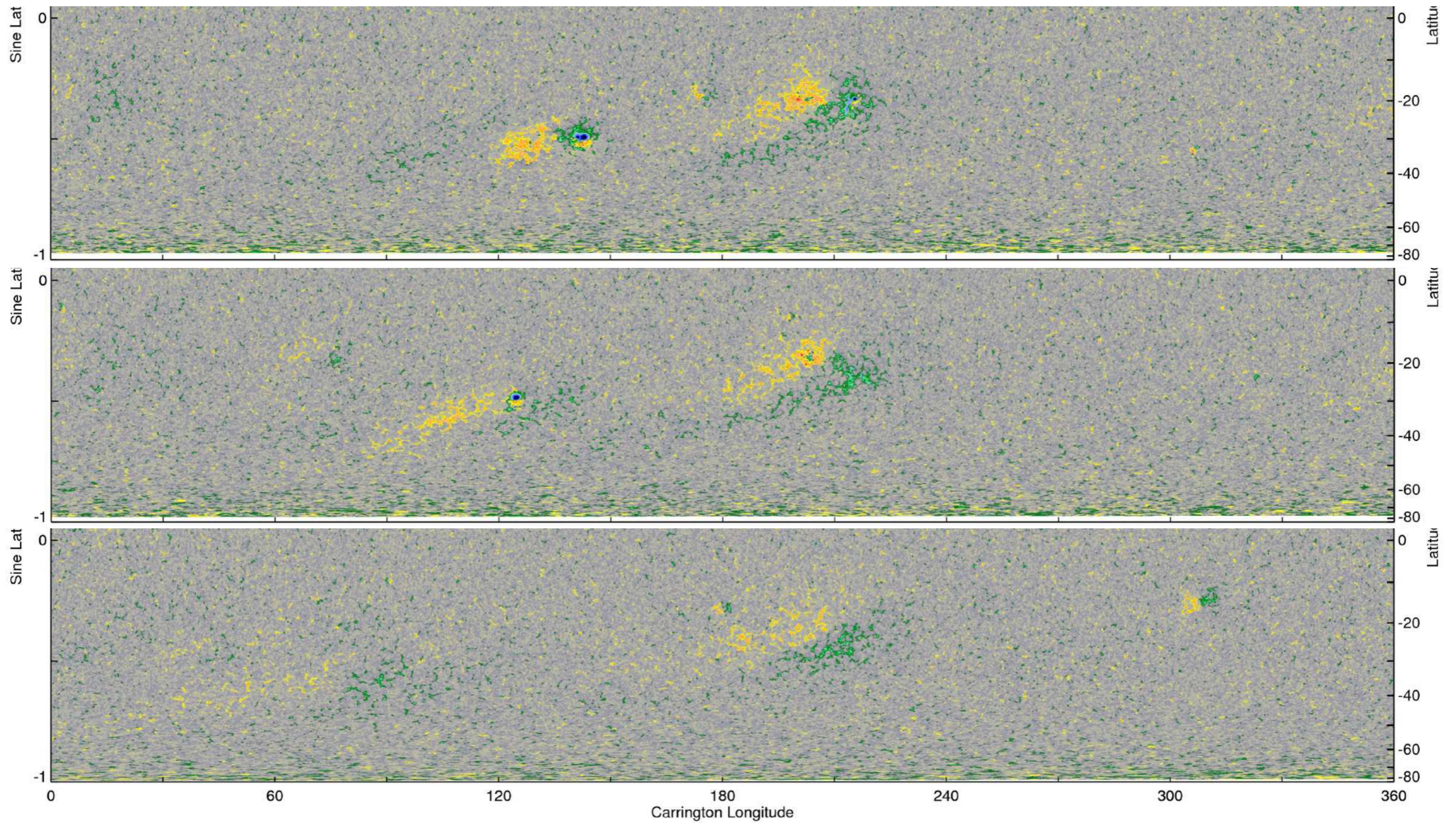


Charbonneau (2014)

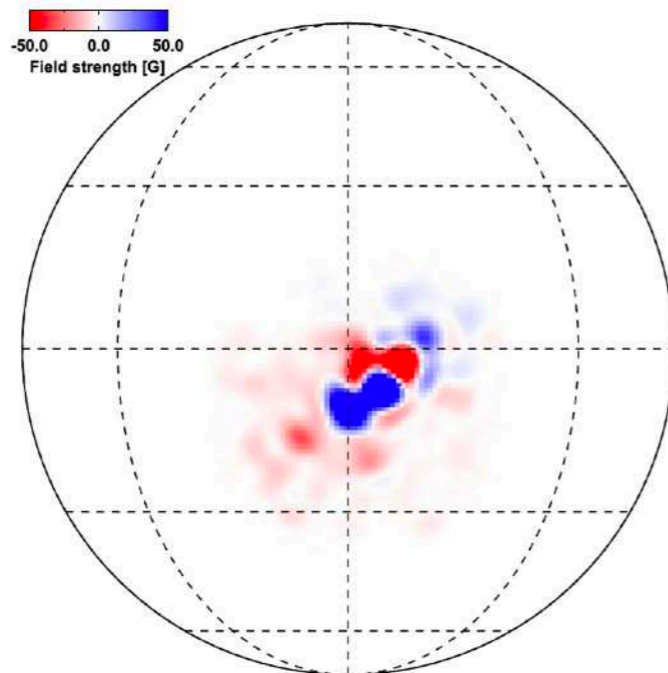
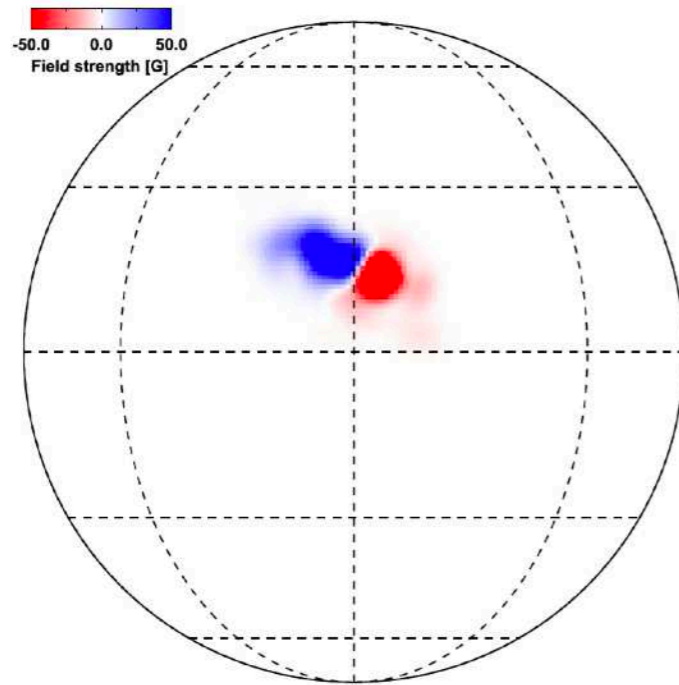
# Active Region Flux Dispersal

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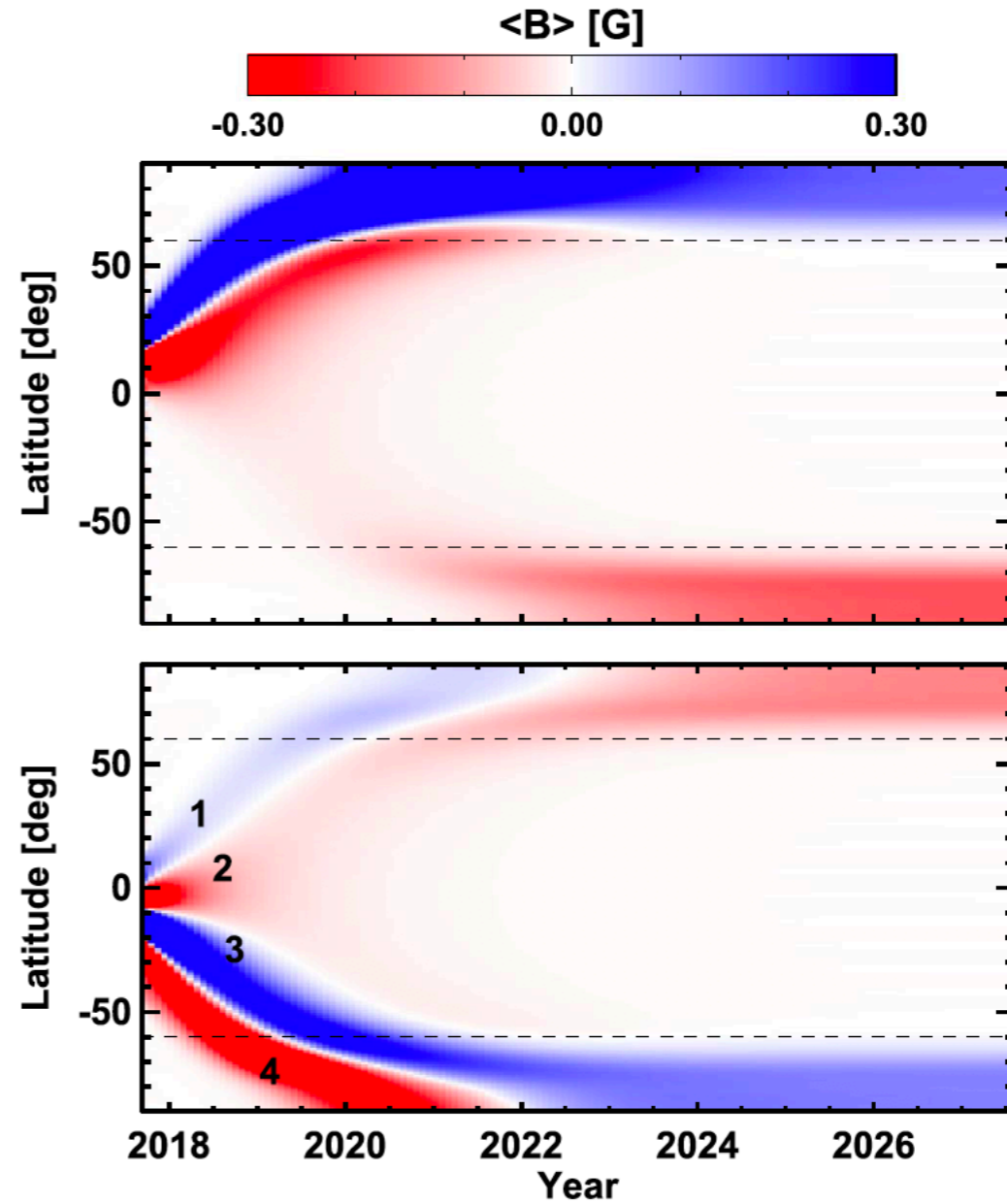
HMI CR 2102-2104



# Active Region Flux Dispersal

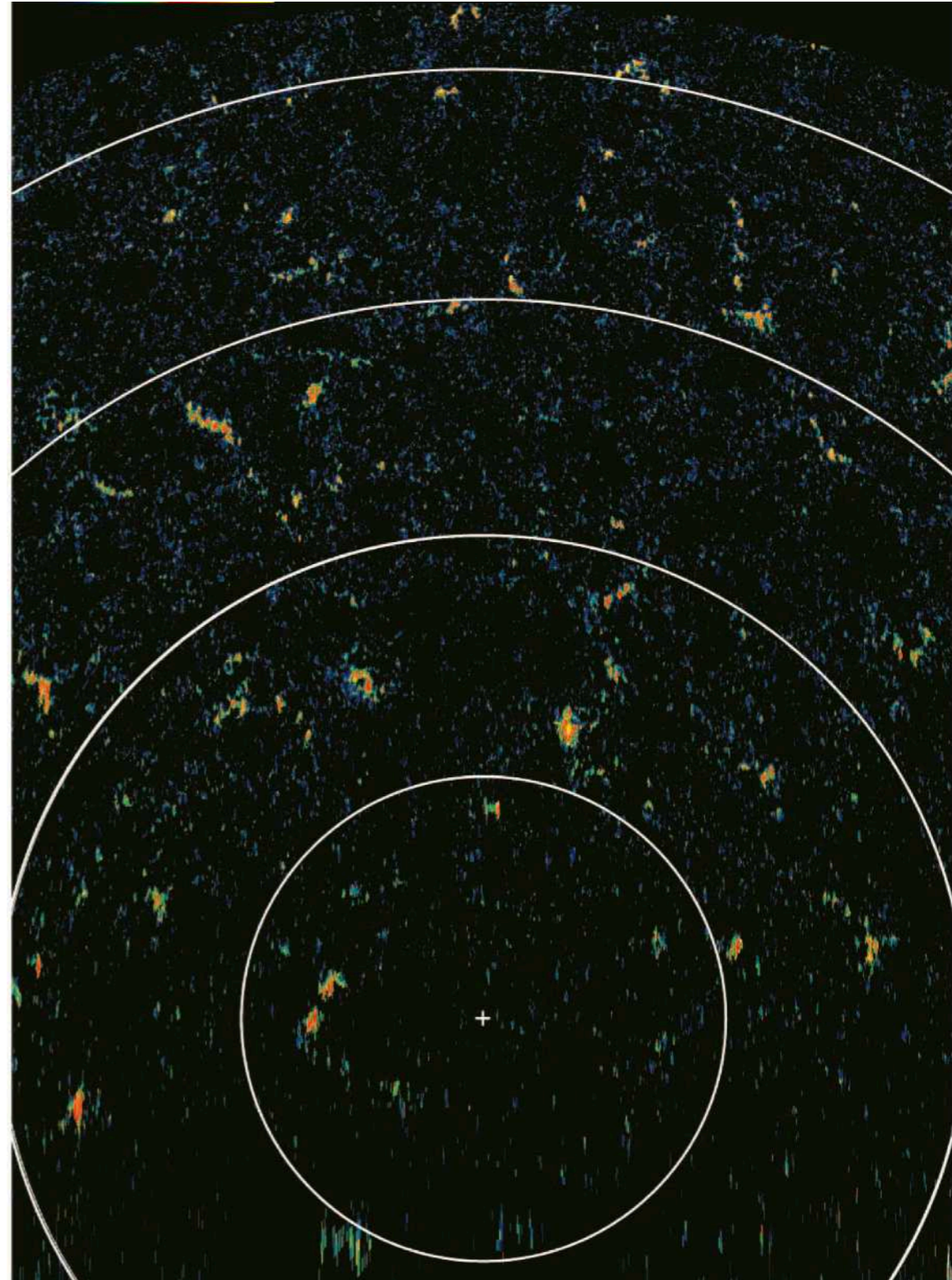
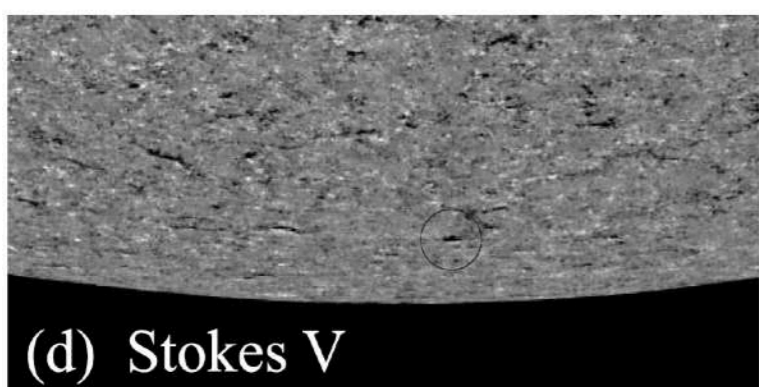
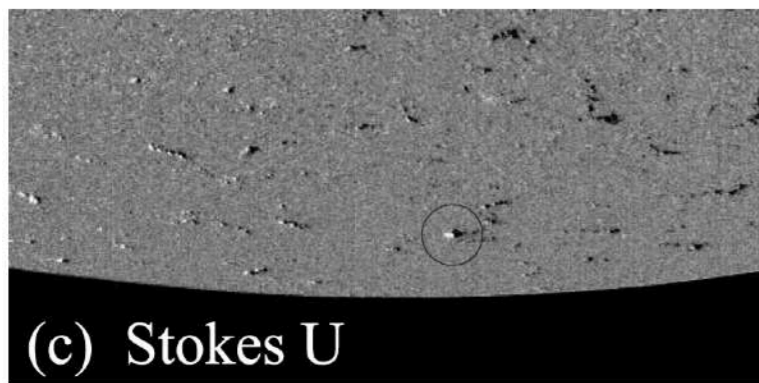
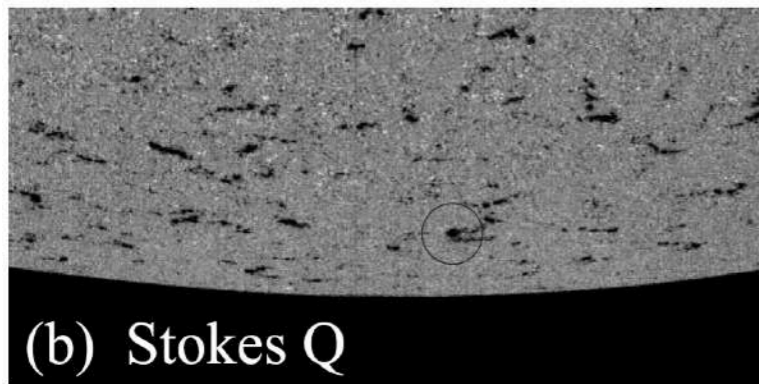
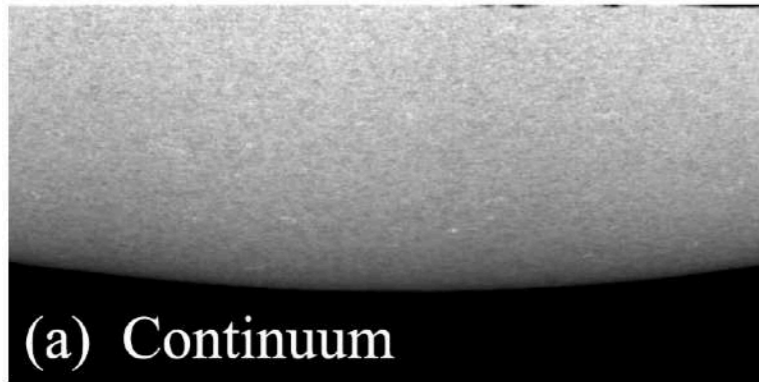


SFT Model of Dipole Contribution





# Polar Field

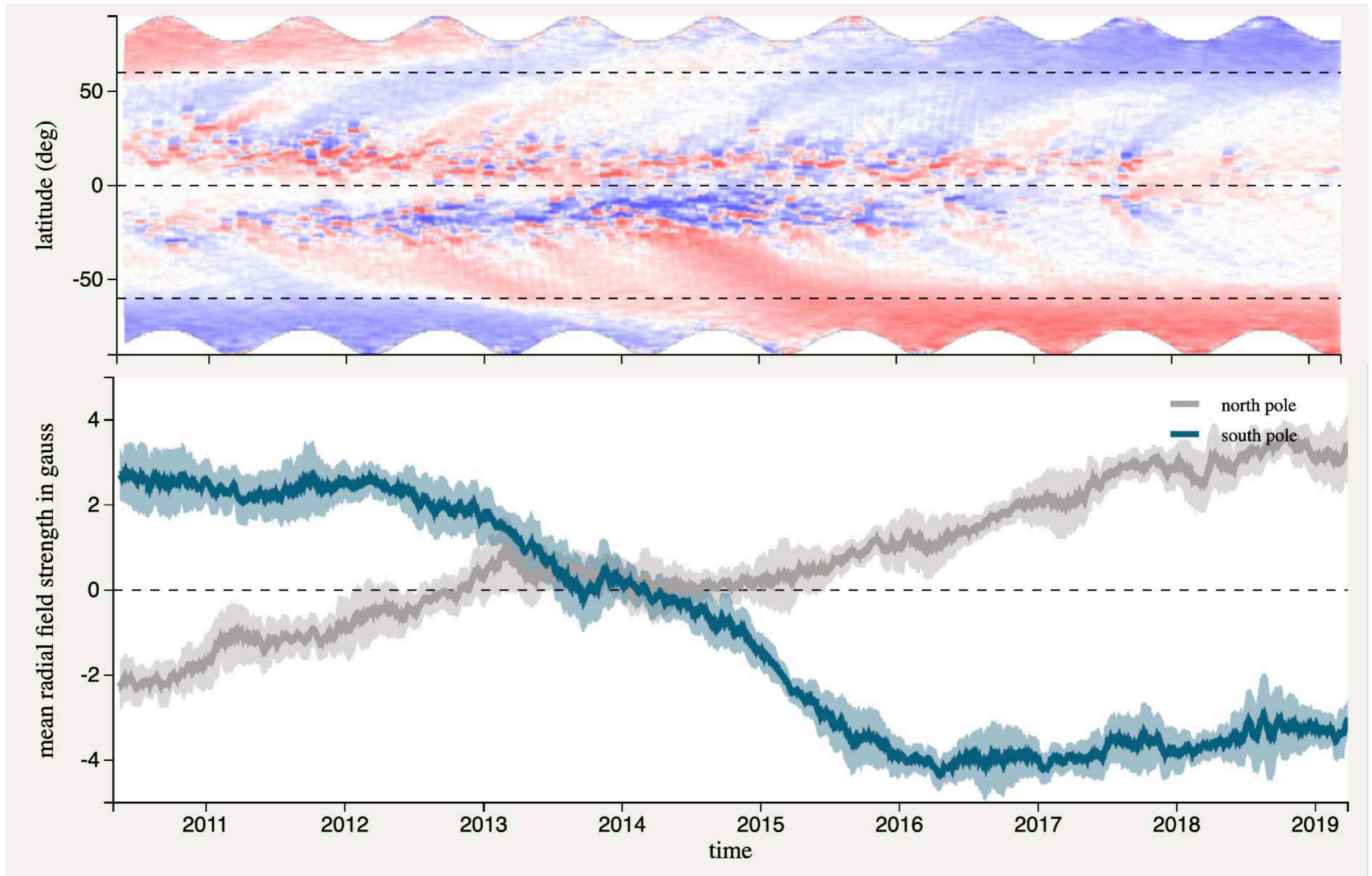


Hinode/SP

Tsuneta et al. (2008)

# Polar Field Reversal

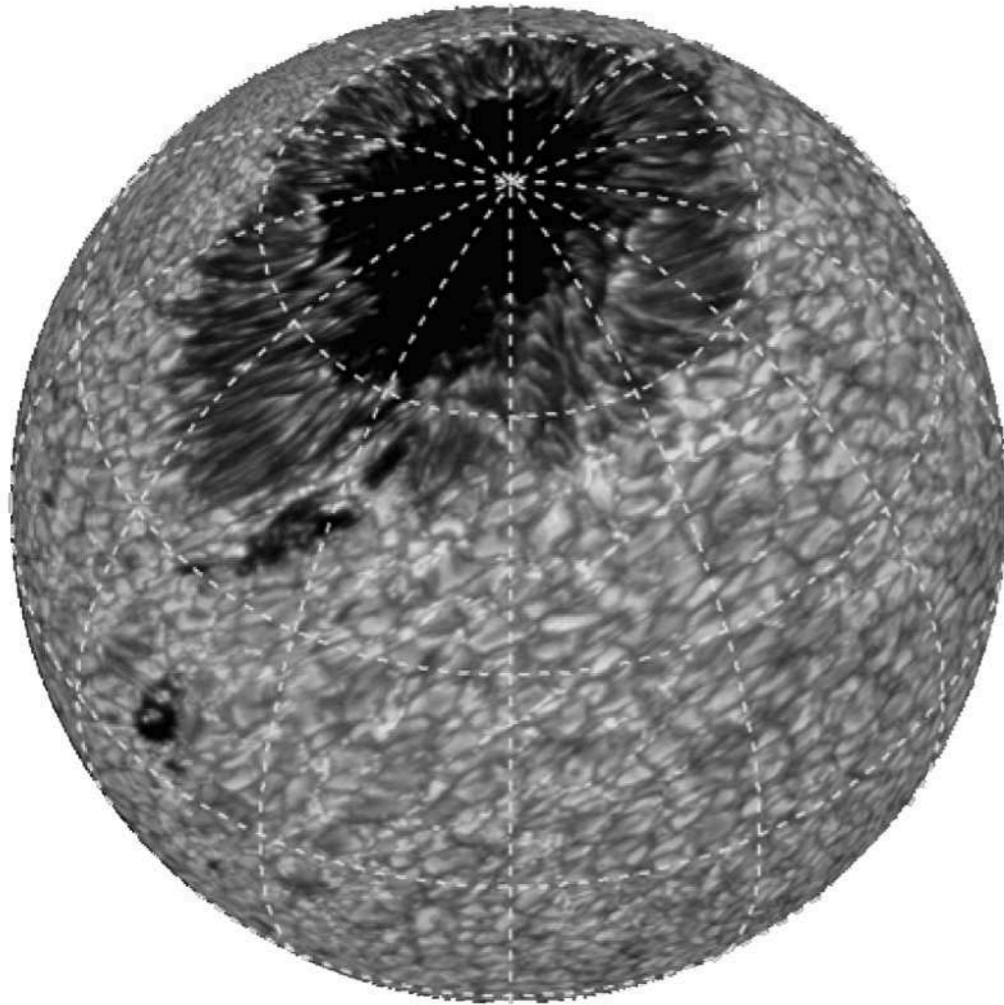
<https://github.com/mbobra/plotting-polar-field>



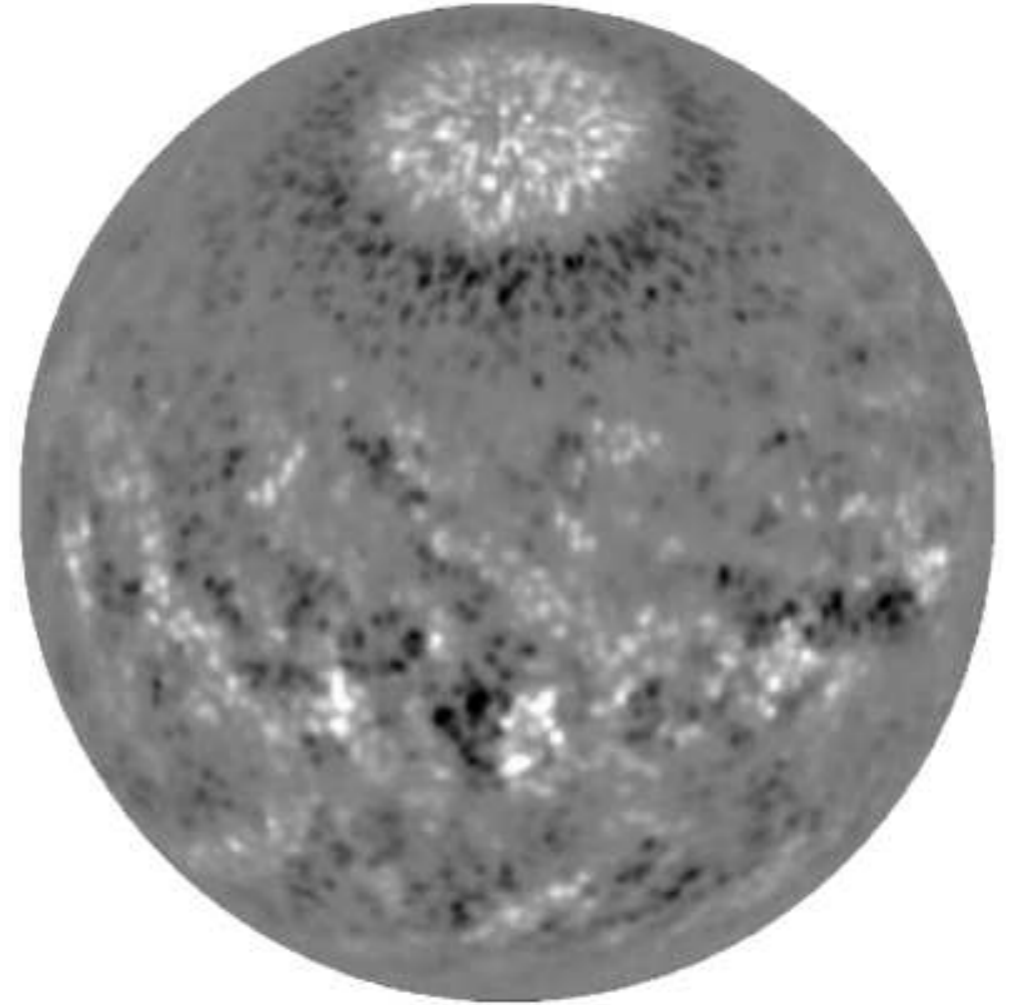
# Application on Active Stars

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Emergence rate 10 x + rotation period 6 d = polar field 30 x



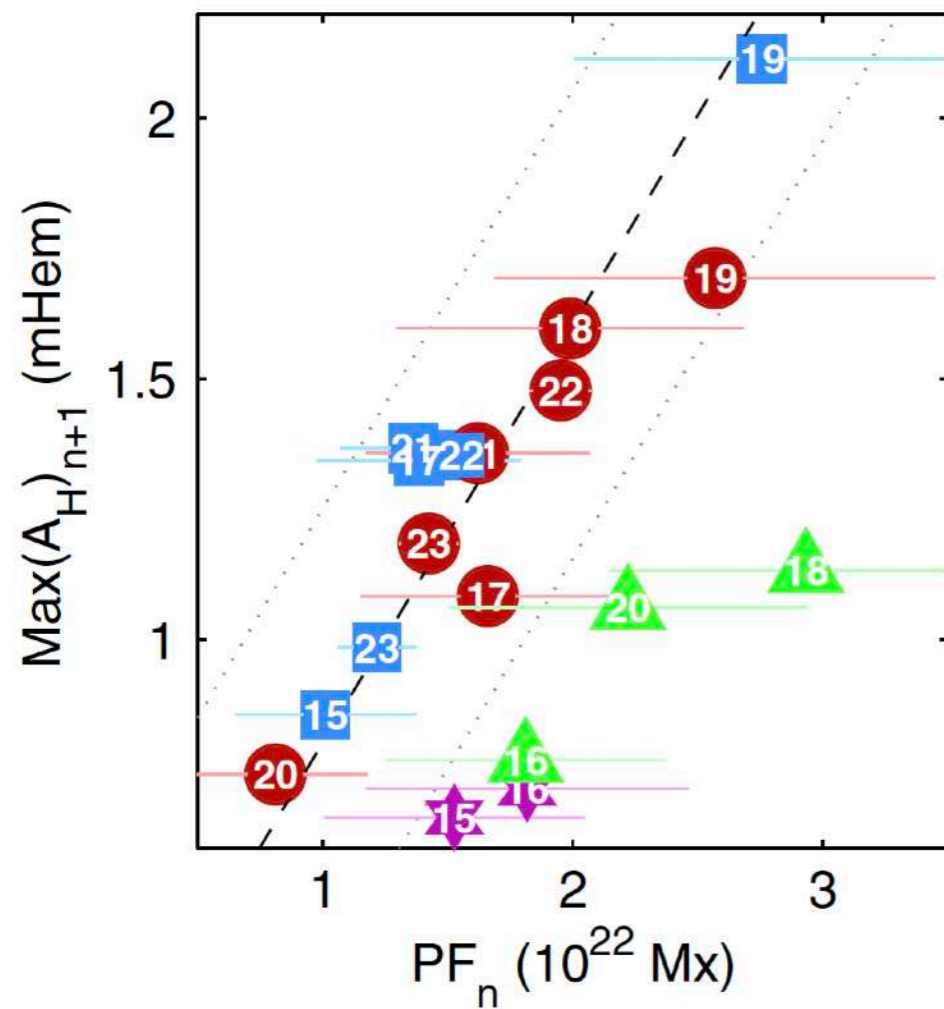
Courtesy S. Solanki



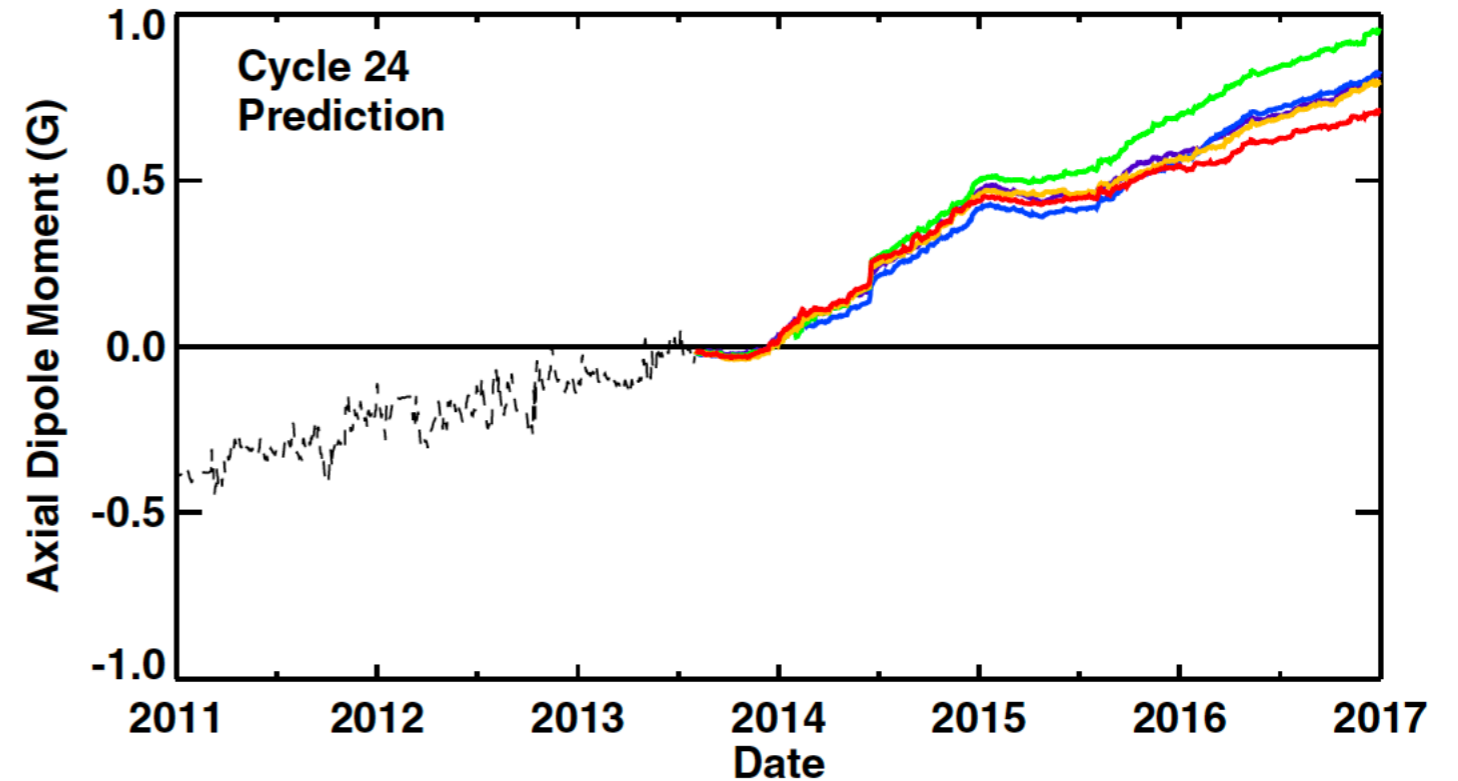
Schrijver & Title (2001)

# Cycle Prediction Based on B-L

Poloidal field (polar field at min) of Cycle N  $\triangleright$  Toroidal Field (SSN) of Cycle N+1



Muñoz-Jaramillo et al. (2013)

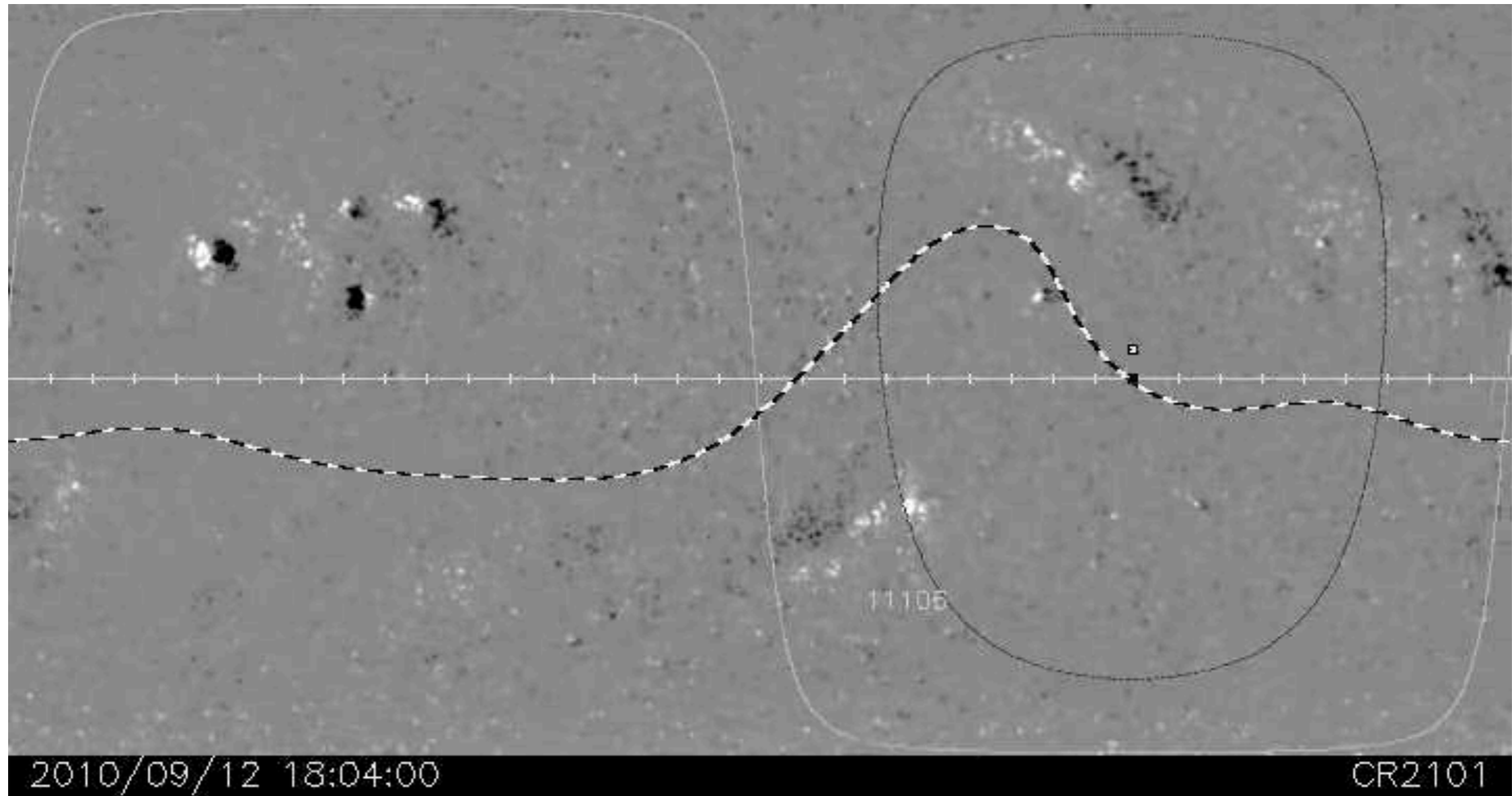


Upton & Hathaway (2014)

# Constructing Better Synoptic Maps

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Near-Real-Time Data Assimilation + Surface Flux Transport



Courtesy M. DeRosa