The Solar Cycle: Observations and Characteristics

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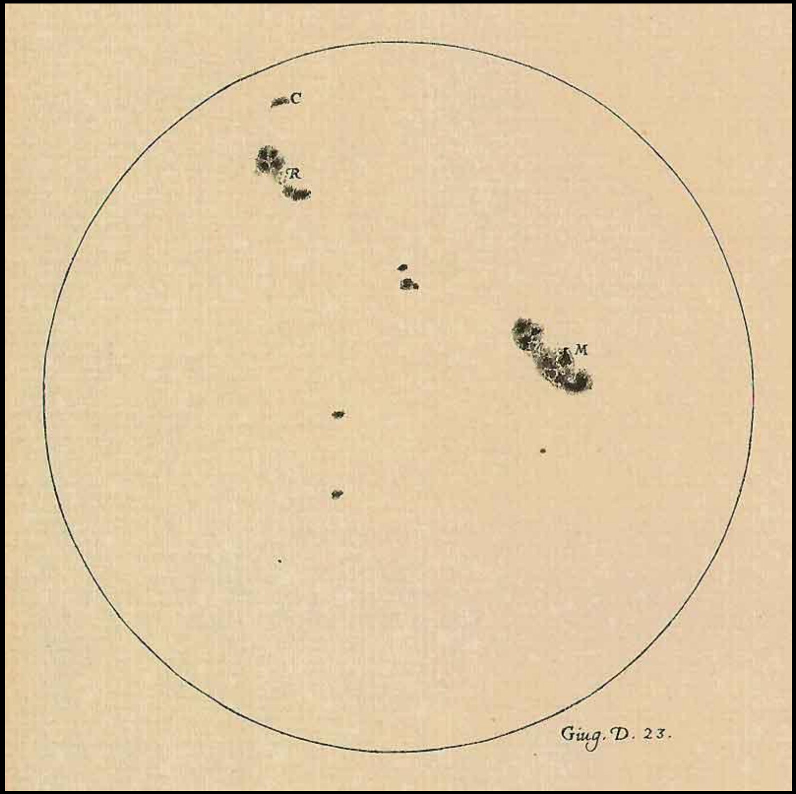
MAIN CHARACTERISTICS

A historical perspective

Sunspots were first studied with the advent of the telescope (1610)



Drawing by Galileo (circa 1610)

SOHO/MDI

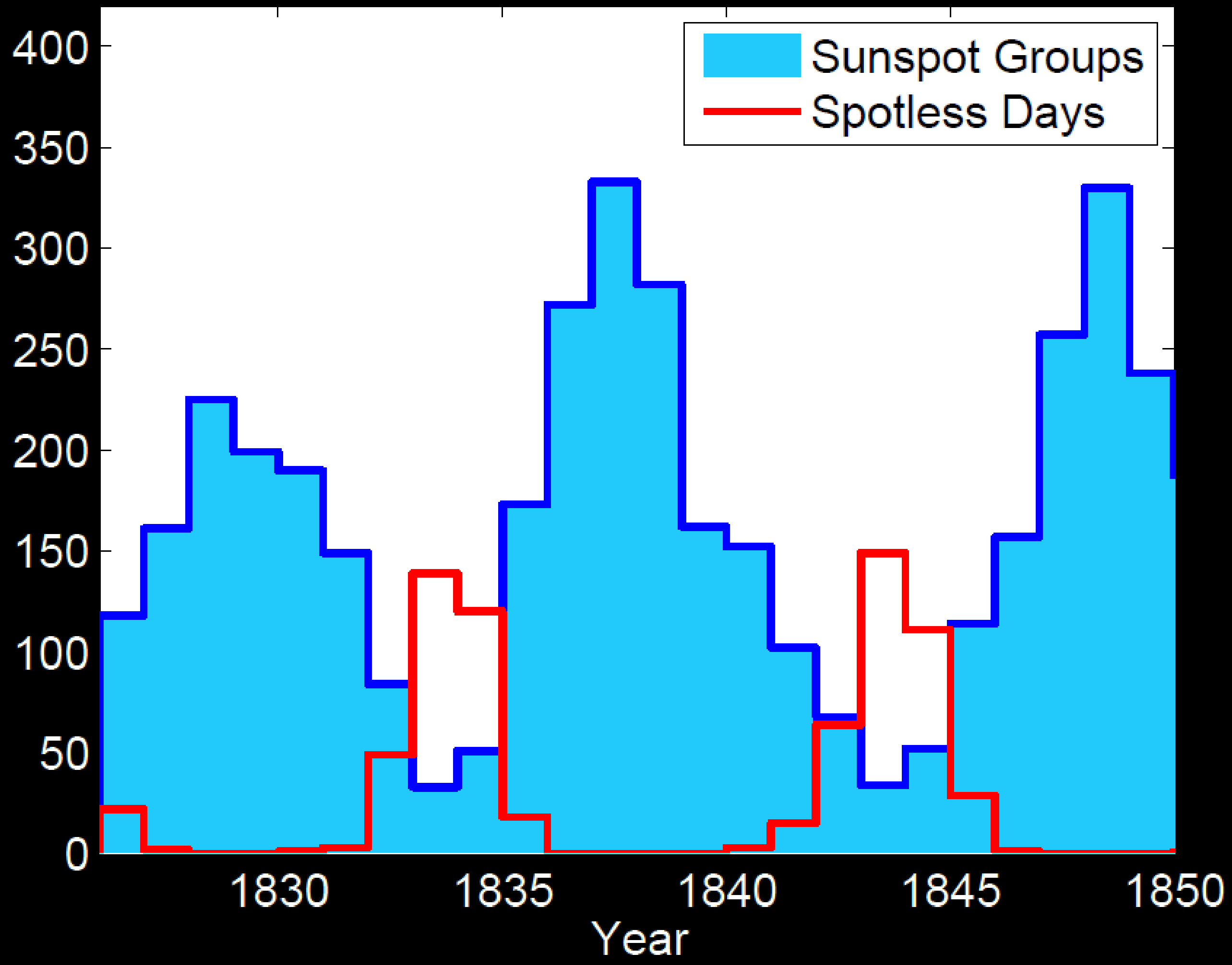
But it was not until 1843 that their number was found to change with time

(Schwabe 1843)

Jahr.	Gruppen.	Fleckenfreie Tage.	Beobachtungs-Tage.
1826	118	22	277
1827	161	2	273
1828	225	0	282
1829	199	0	244
1830	190	1	217
1831	149	3	239
1832	84	49	270
1833	33	139	267
1834	51	120	273
1835	173	18	244
1836	272	0	200
1837	333	0	168
1838	282	0	202
1839	162	0	205
1840	152	3	263
1841	102	15	283
1842	68	64	307
1843	34	149	312
1844	52	111	321
1845	114	29	332
1846	157	1	314
1847	257	0	276
1848	330	0	278
1849	238	0	285
1850	186	2	308

But it was not until 1843 that their number was found to change with time

(Schwabe 1843)



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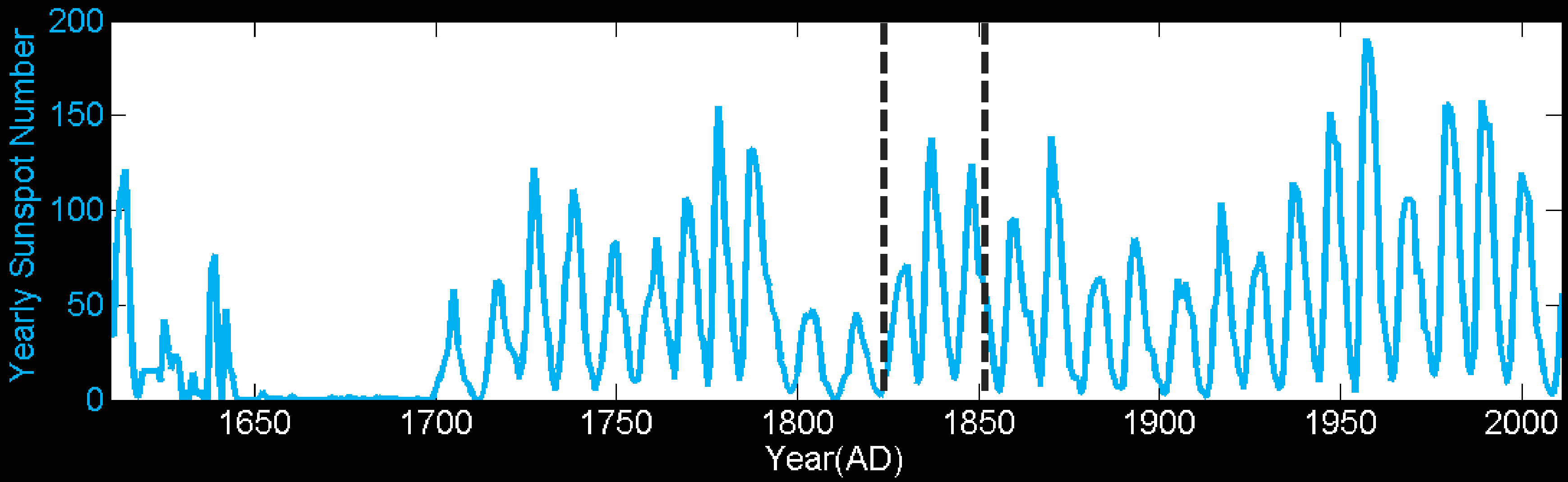
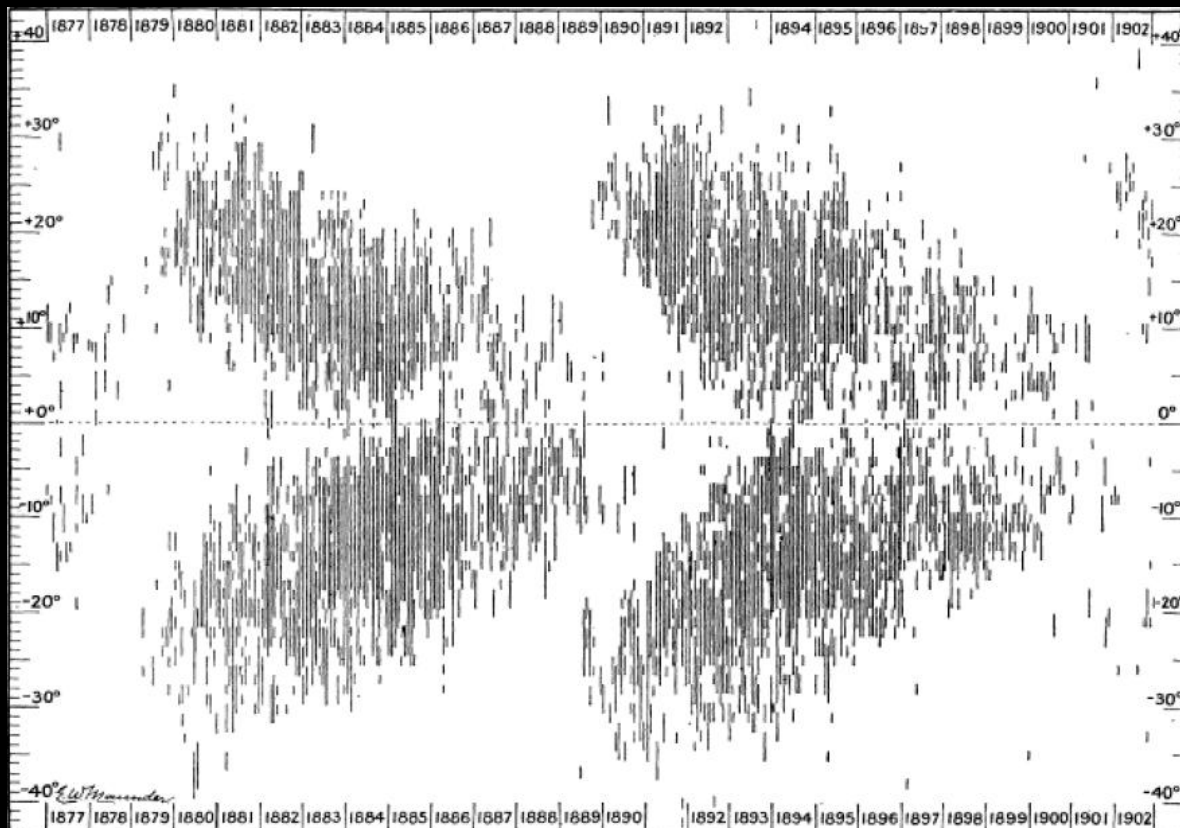


- Alternating peaks in solar activity (maxima), followed by quiet periods (minima).

- Time variation is predominantly cyclic, mean period is 11 years.

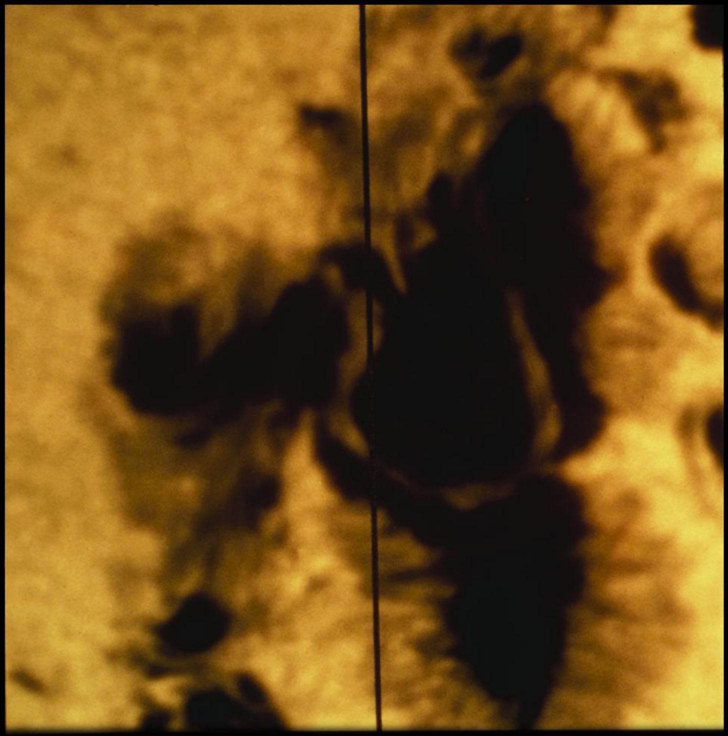
Sunspots don't appear completely at random on the surface of the Sun.

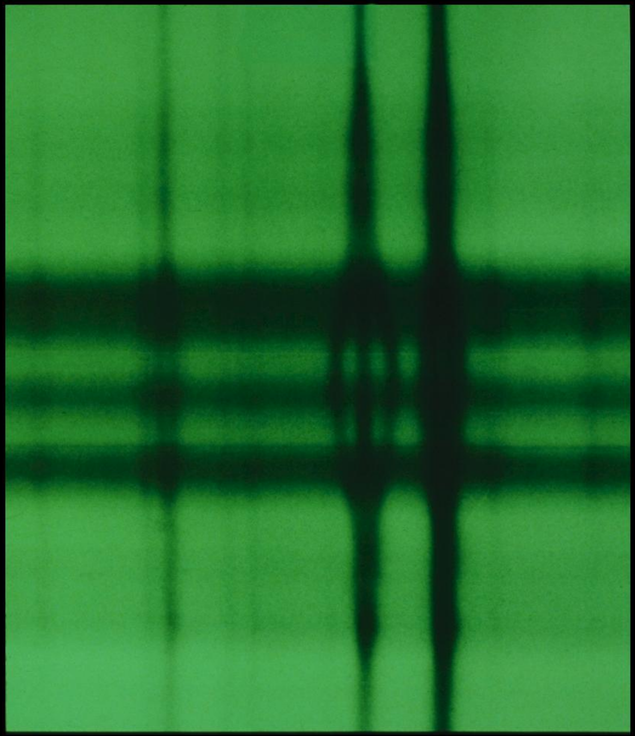
(Mounder 1904)



- Different "active latitudes" are associated with different stages of the cycle

Sunspots are associated with regions of strong magnetic field (Hale 1908)





- Magnetic field is measured using the Zeeman effect.

Sunspots are associated with regions of strong magnetic field (Hale 1908)

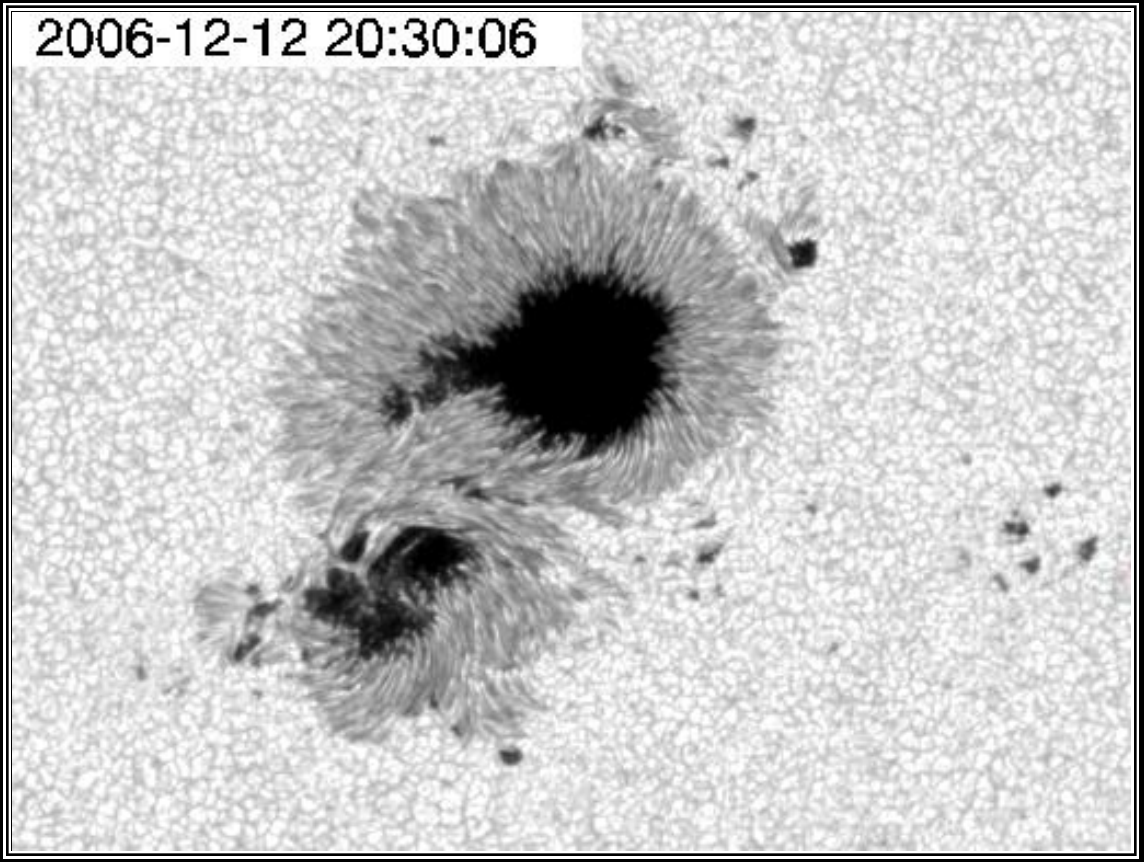


Image from Hinode

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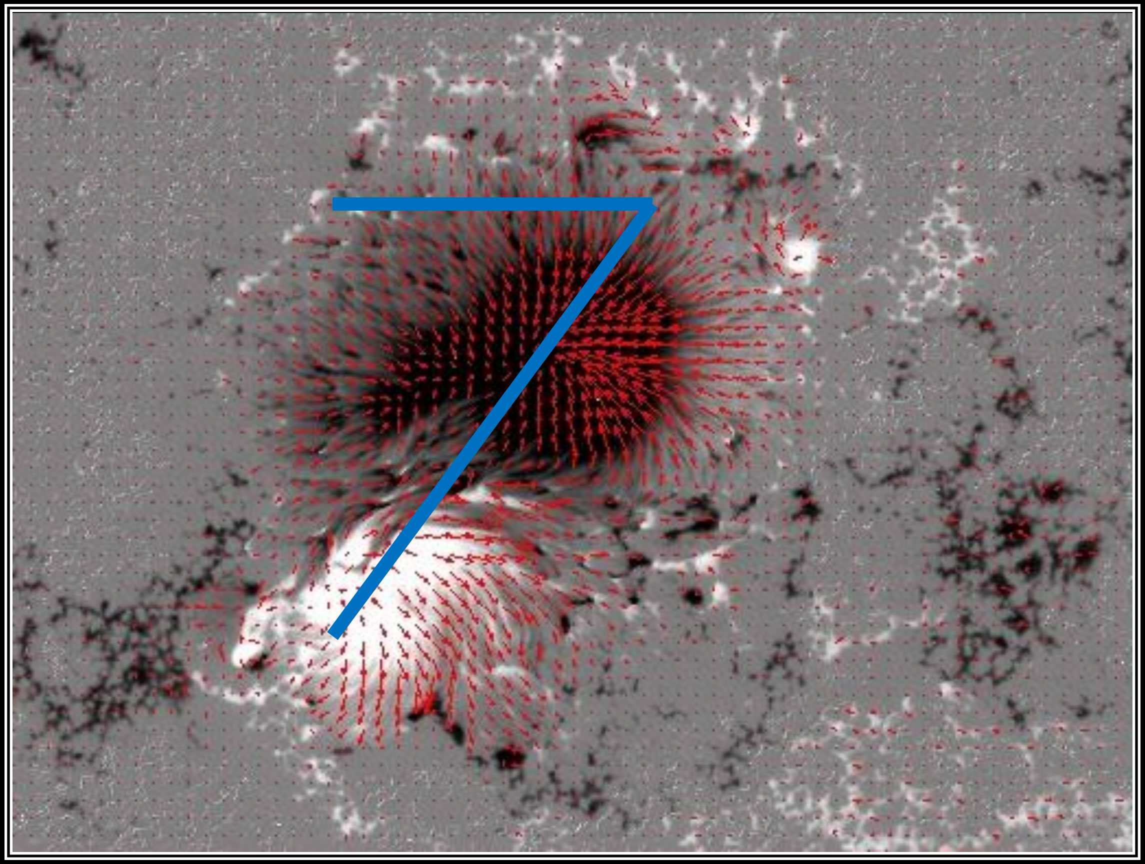
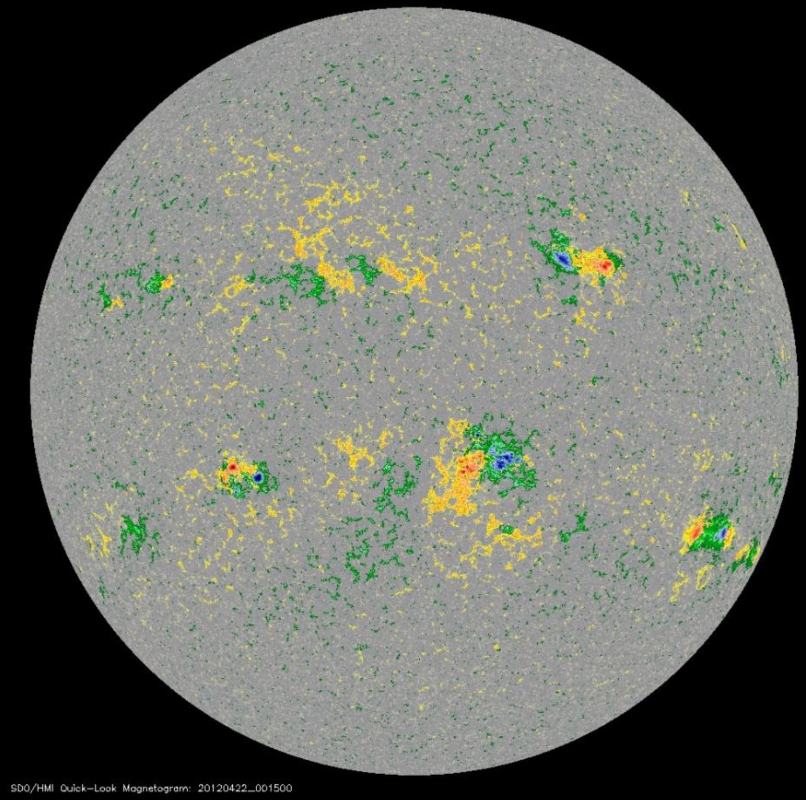


Image from Hinode

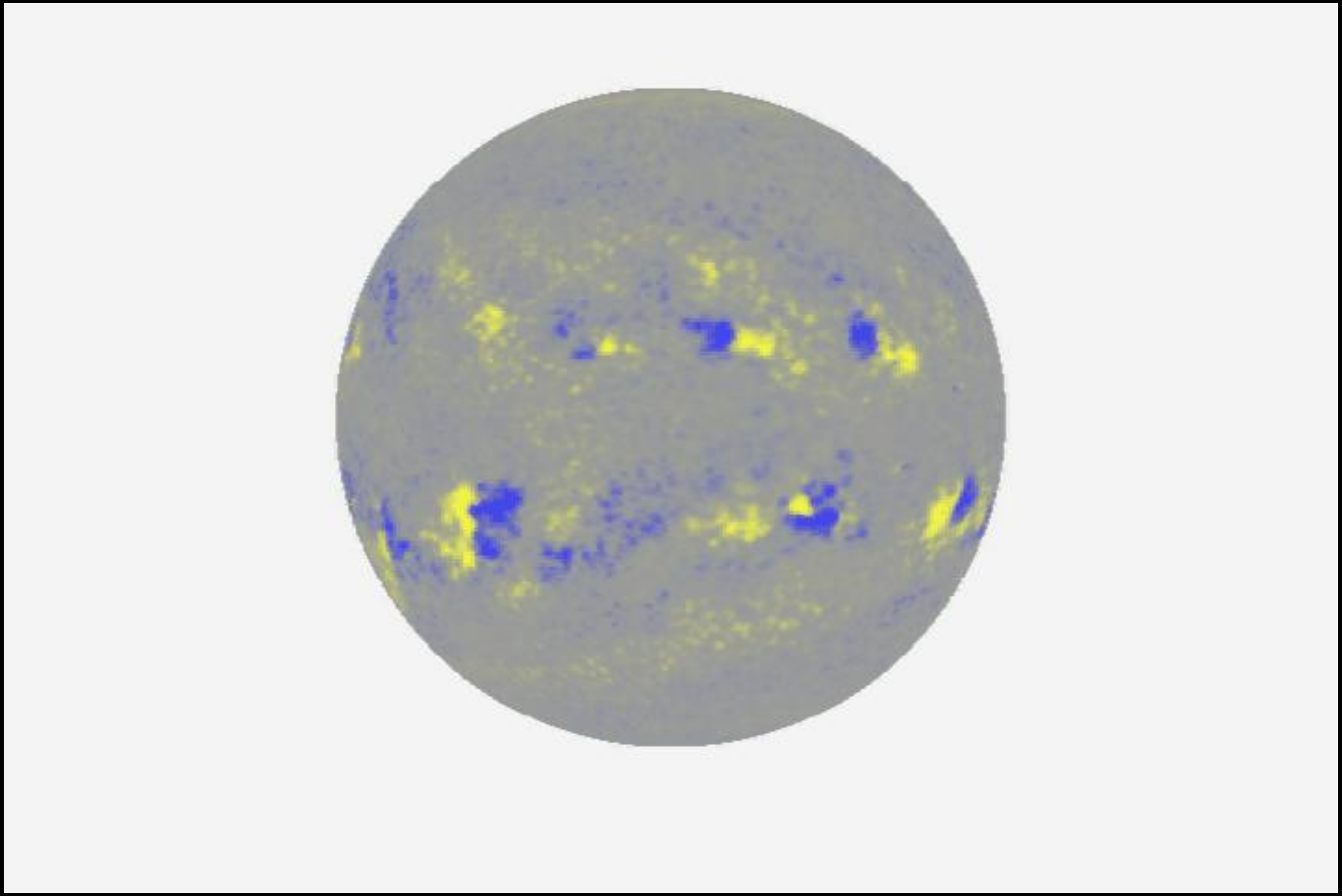
- A sunspot pair is commonly known as an **Active region**.
- Active regions have systematic tilt, which increases with latitude.

Sunspots are associated with regions of strong magnetic field (Hale 1908)



- A sunspot pair is commonly known as an **Active region**.
- Active regions have systematic tilt, which increases with latitude.
- The polarity orientation is opposite in the two hemispheres.

The most visible features of the cycle are associated with active regions



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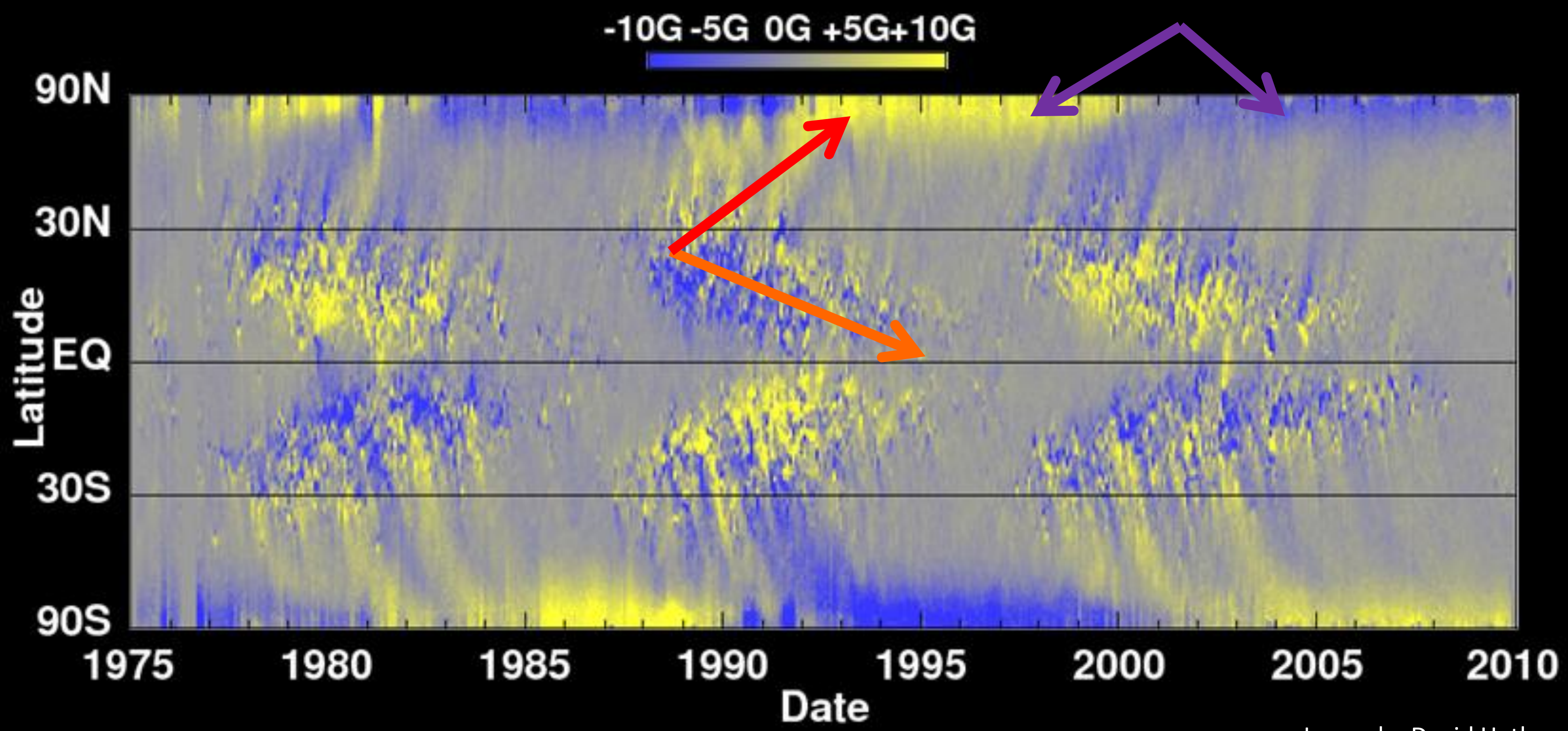


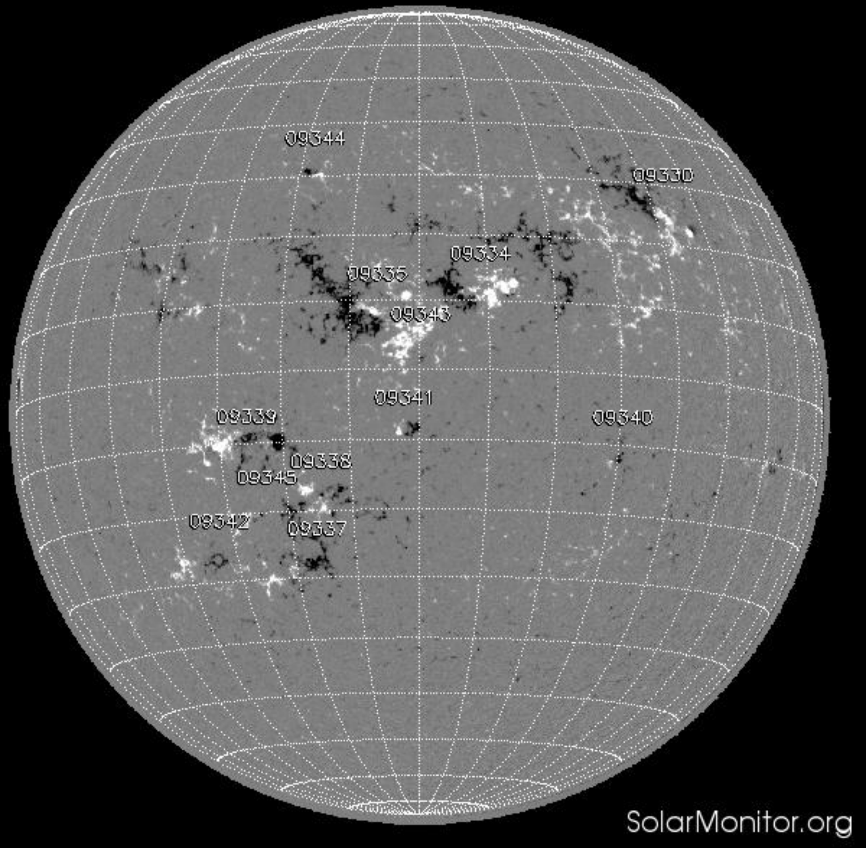
Image by David Hathaway

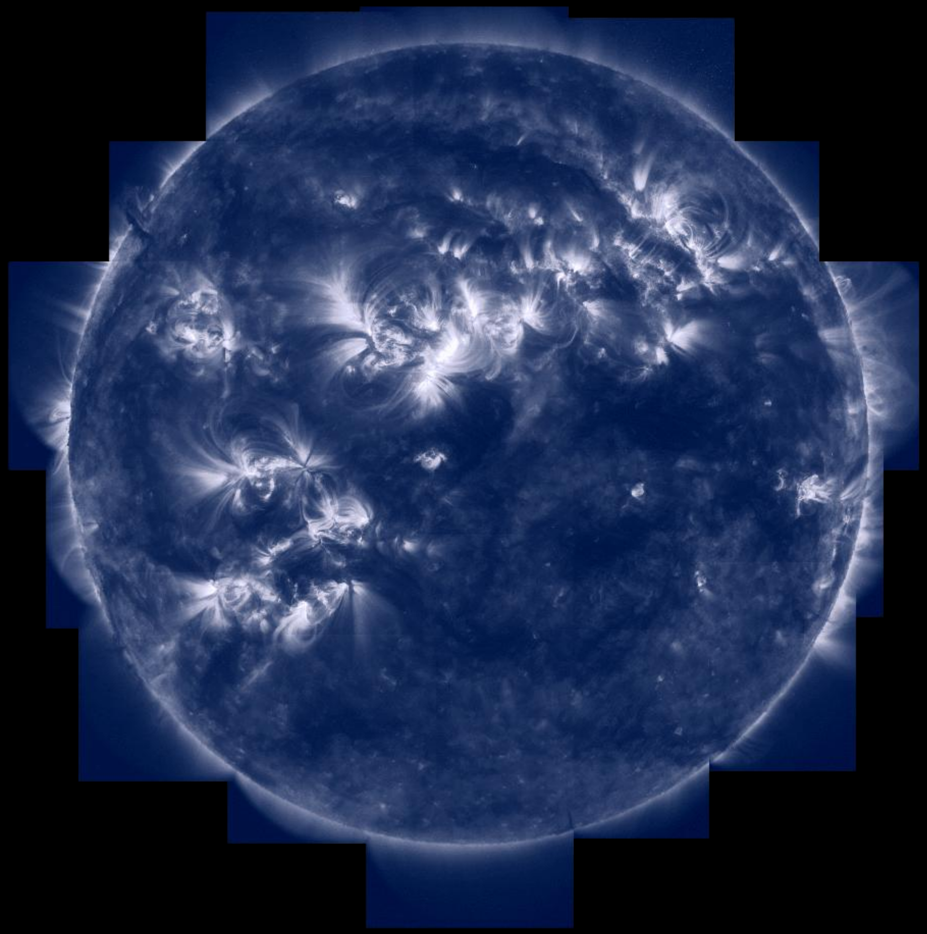
- Equatorward migration of Active Regions.
- Poleward migration of their decayed diffuse field
- Polar field reversal at the maximum of the cycle.

THE SOLAR CYCLE AND THE HELIOSPHERE

More than just the Sun

Active Regions have a very complex associated magnetic field with a lot of free energy





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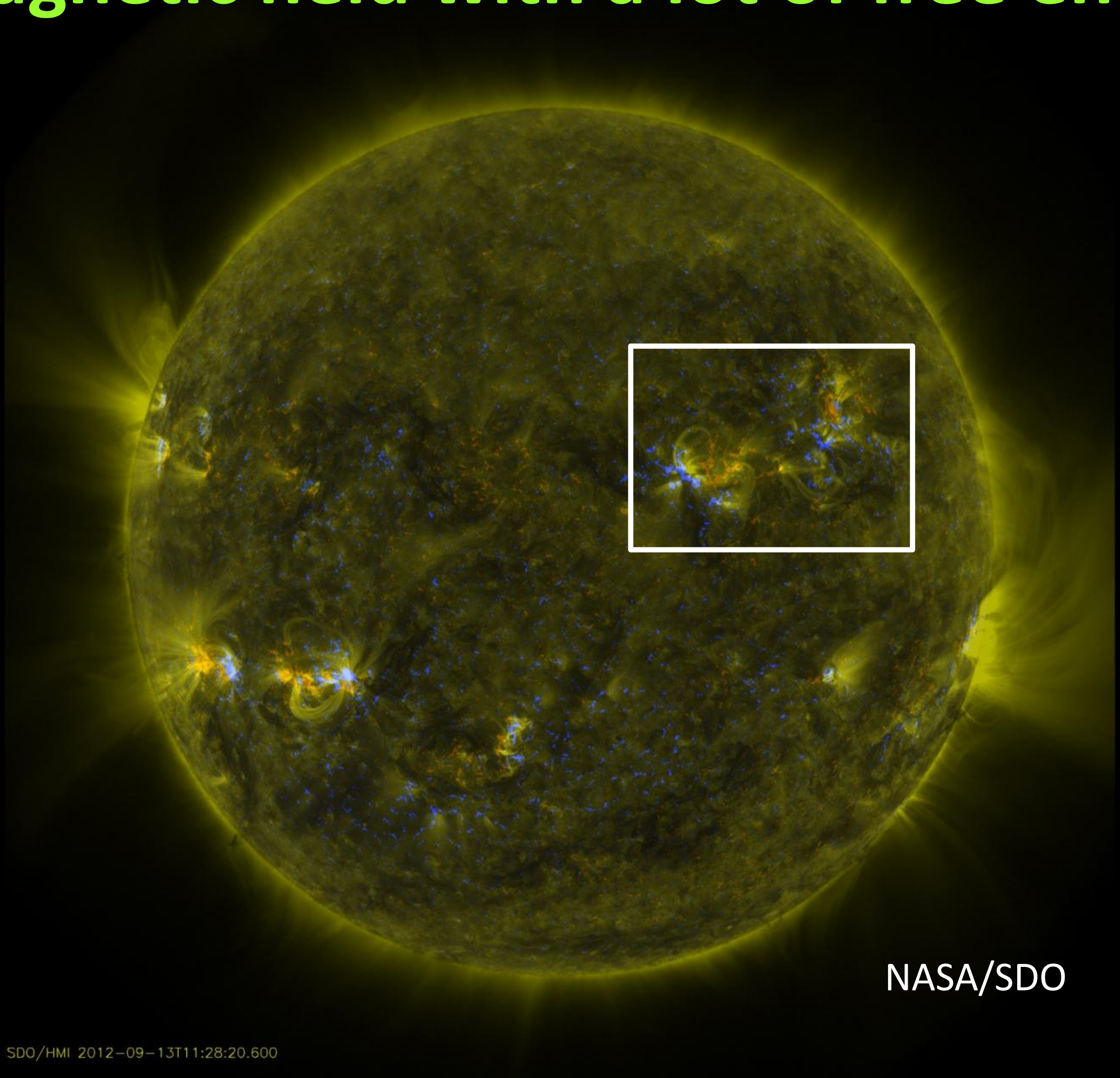
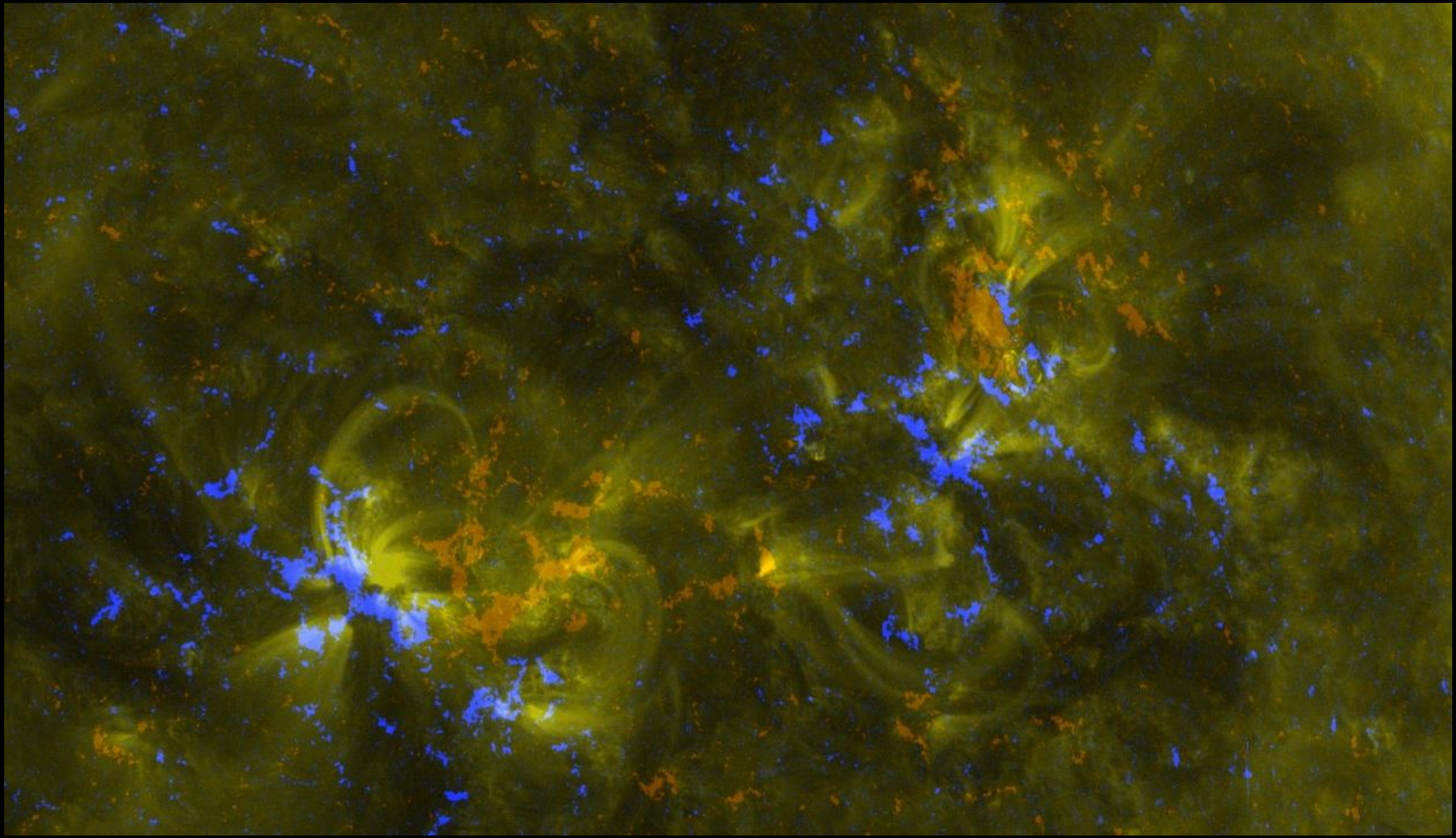


NASA/SDO

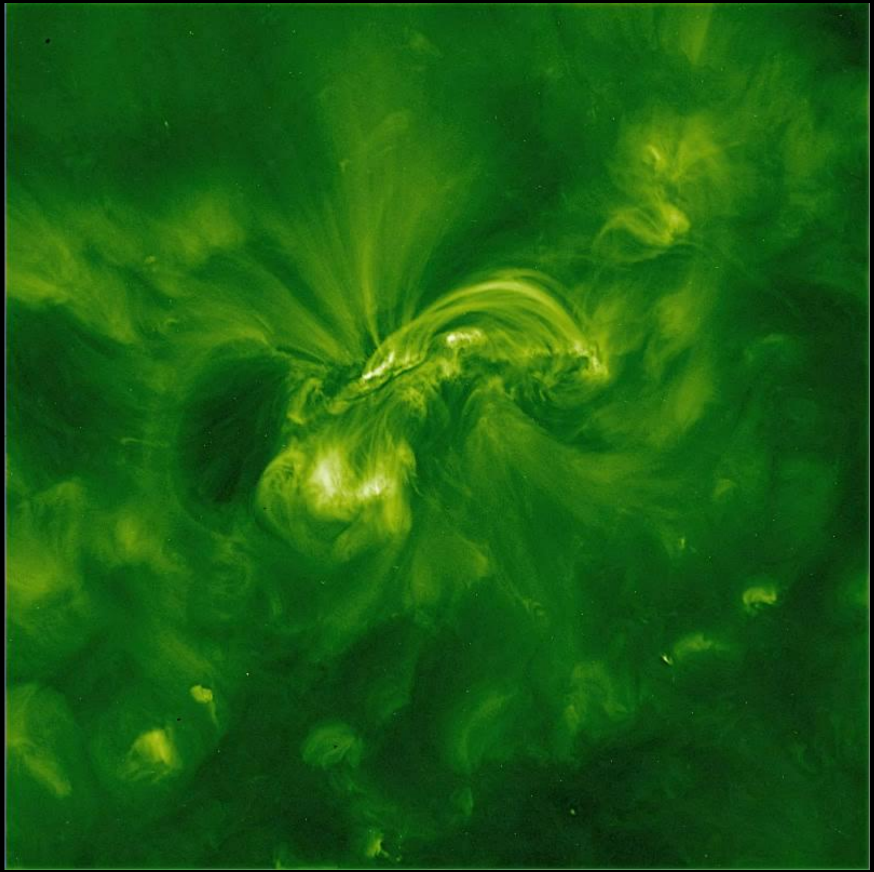
Active Regions have a very complex associated magnetic field with a lot of free energy



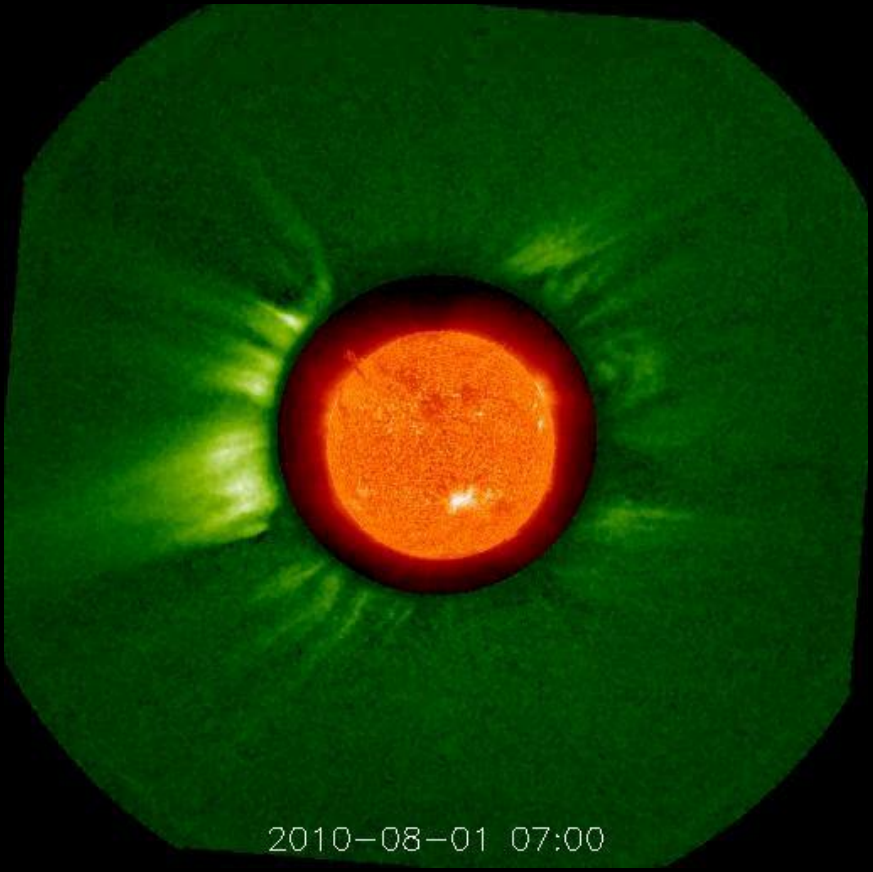
NASA/SDO

Violent reconfigurations of the solar magnetic field release this energy in the form of:

Flares

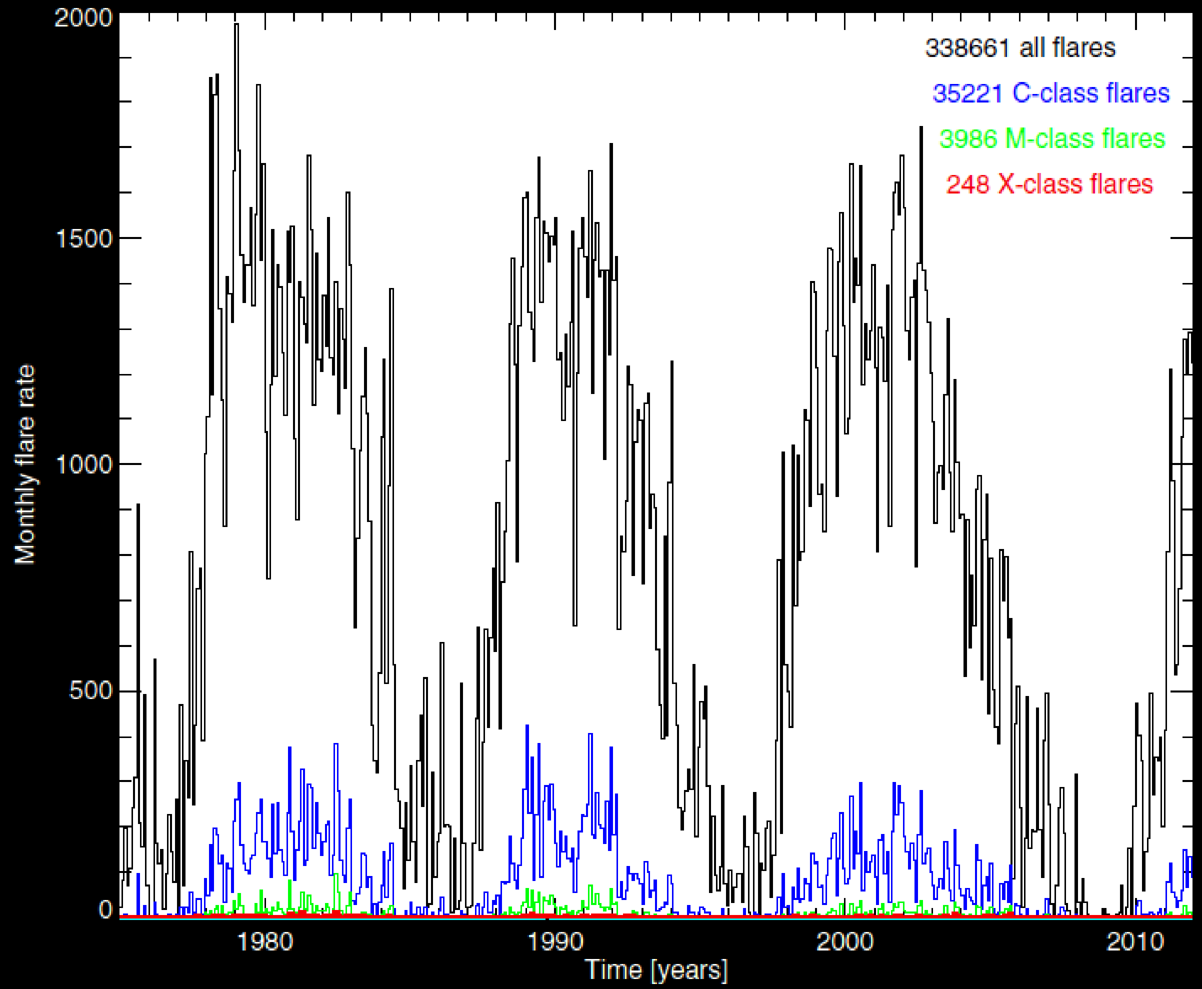


Coronal Mass Ejections



These highly energetic events are modulated by the solar cycle

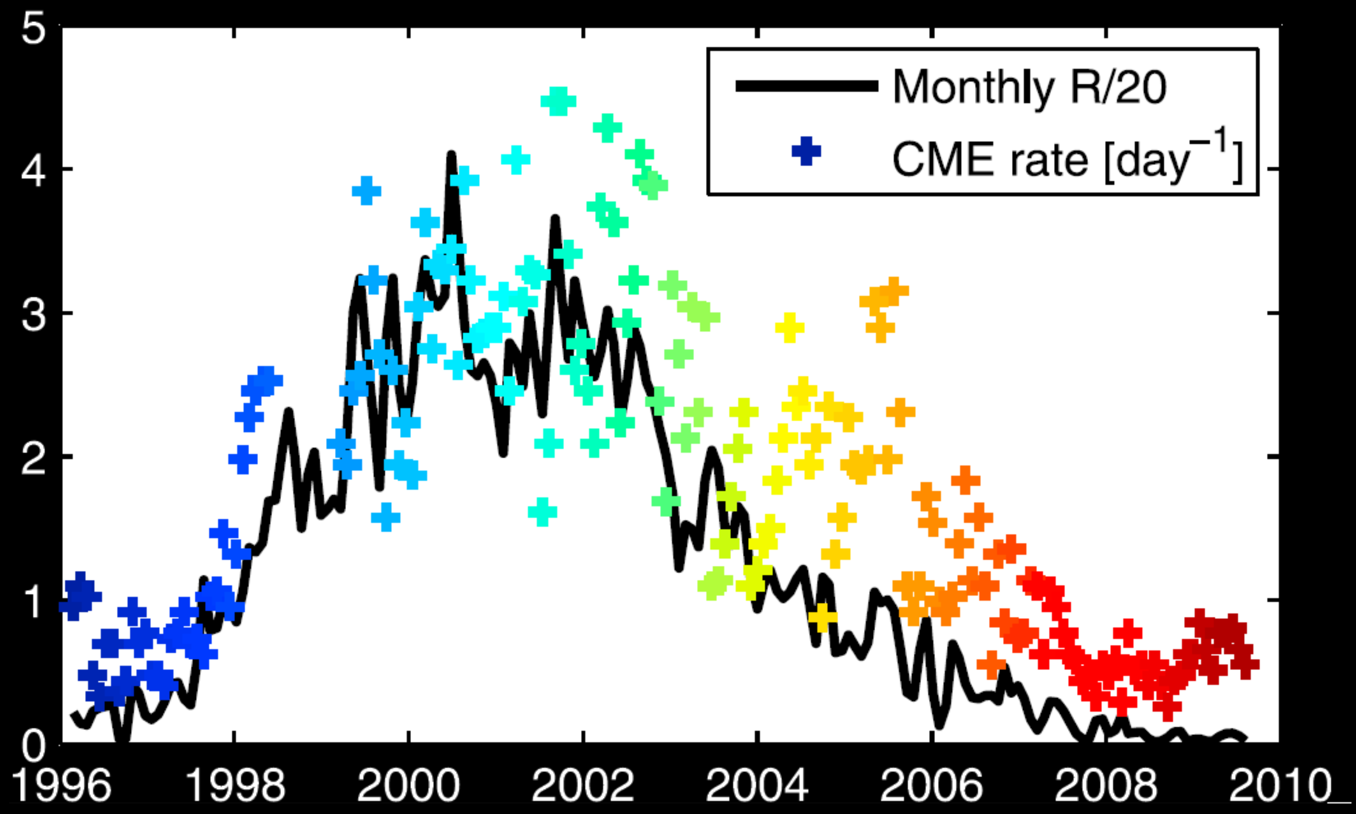
Both Flares…



Aschwanden & Freeland 2012

These highly energetic events are modulated by the solar cycle

… and CMEs

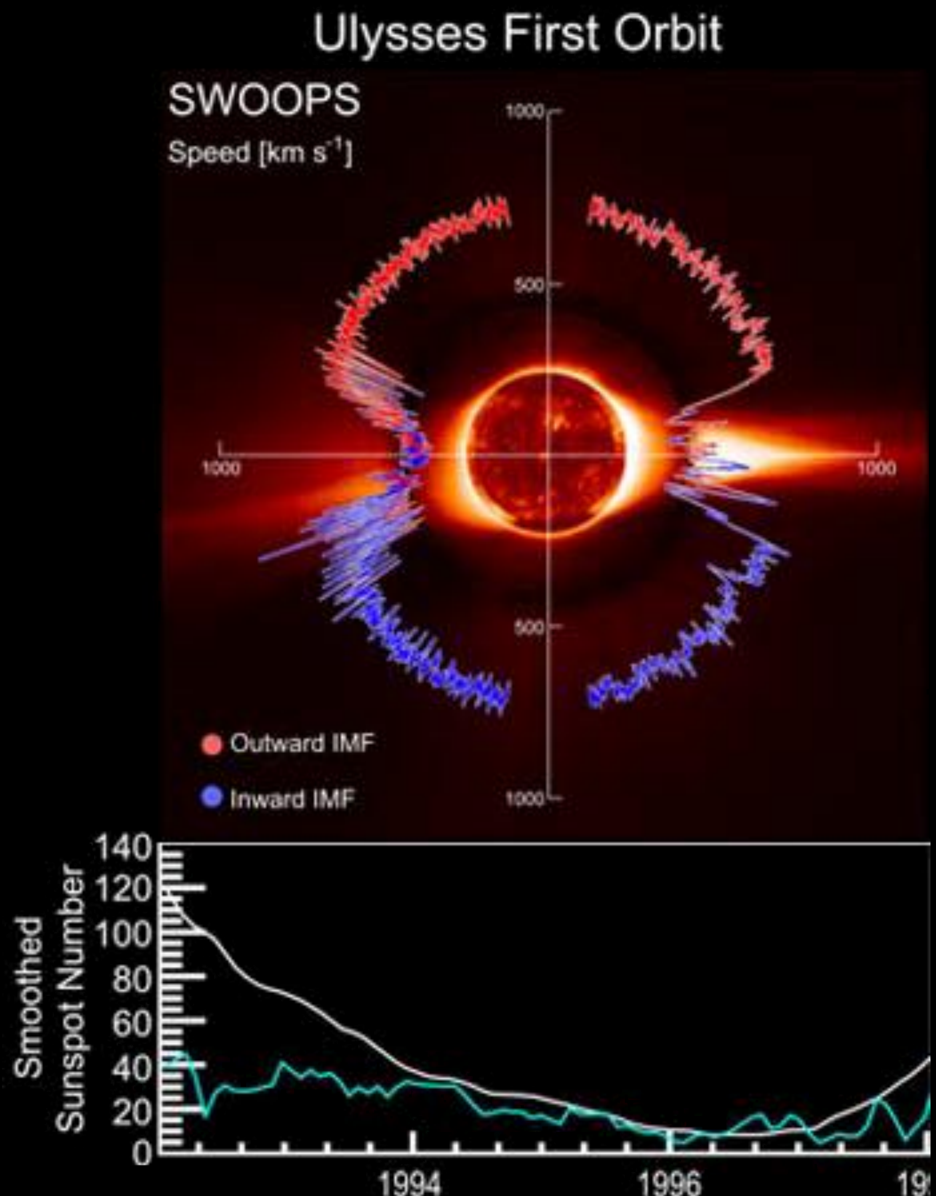


Owens & Lockwood 2012

Solar wind properties also change with the cycle

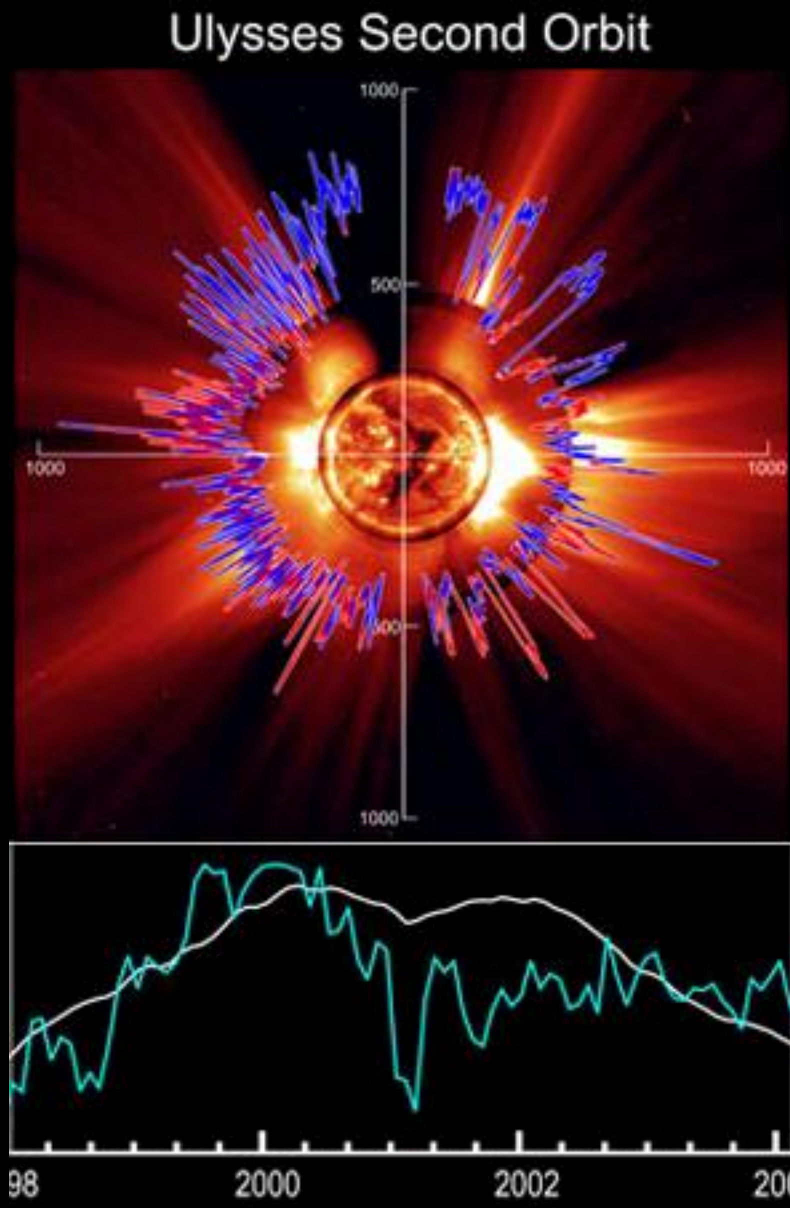
- Hot plasma that expands in all directions from the solar corona.
- Fast solar wind emanates from coronal holes at a speed up to 800 km/s.
- Slow solar wind emanates from other regions in the corona at speeds up to 400 km/s.
- Solar wind carries the Sun's magnetic field out into the solar system.

Solar wind properties also change with the cycle



At solar minimum

Solar wind properties also change with the cycle



At solar maximum

Solar wind properties also change with the cycle

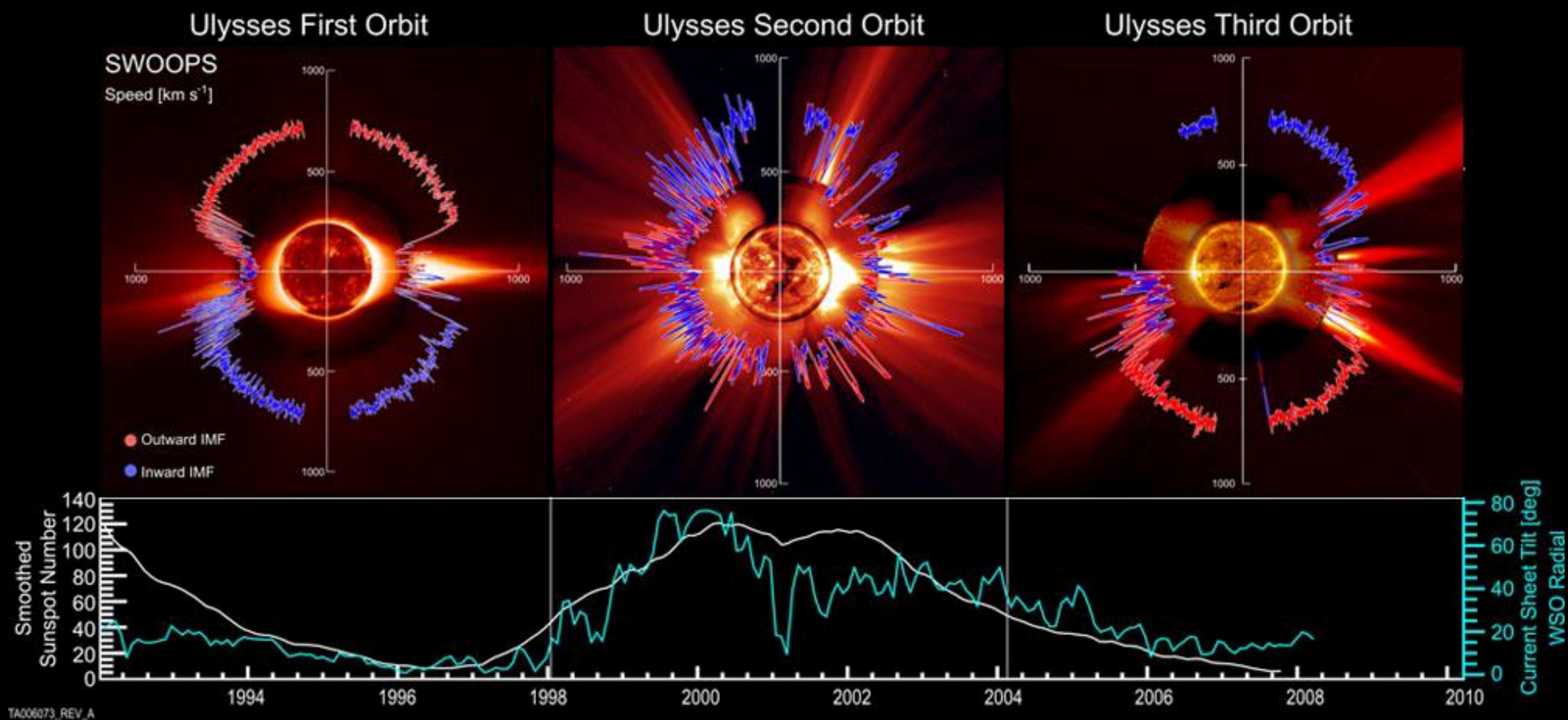
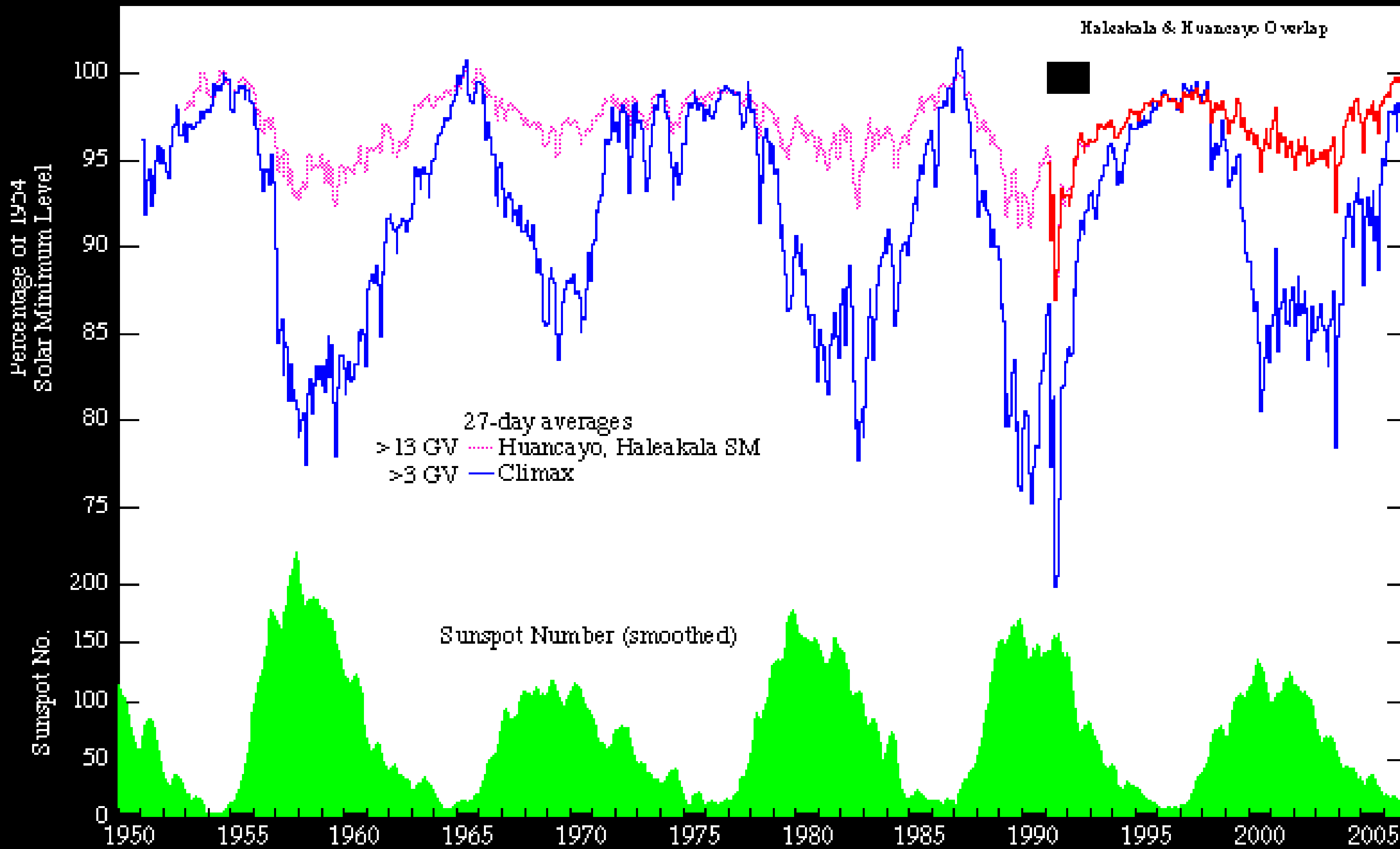


Image taken from ESA

Changes in the solar wind and solar magnetic field modulate the galactic cosmic ray flux on Earth

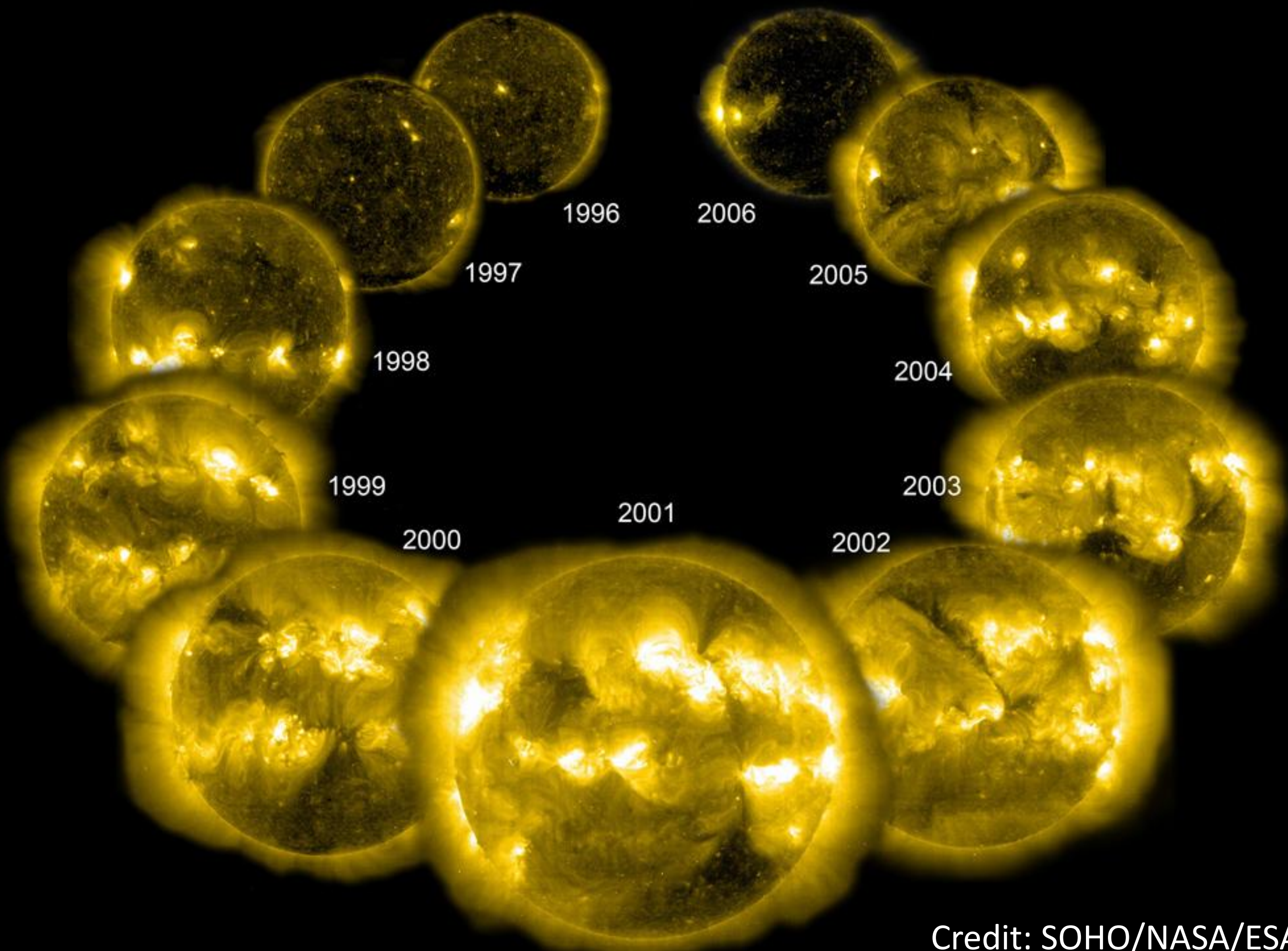
- High energy particles coming from outside the solar system.
- Scattered by magnetic irregularities propagating in the solar wind.
- Modulation is weaker for high-energy cosmic rays.
- Cosmic rays generate isotopes that can be used to study long-term solar activity.

Changes in the solar wind and solar magnetic field modulate the galactic cosmic ray flux on Earth



The solar cycle also modulates the radiative output of the Sun

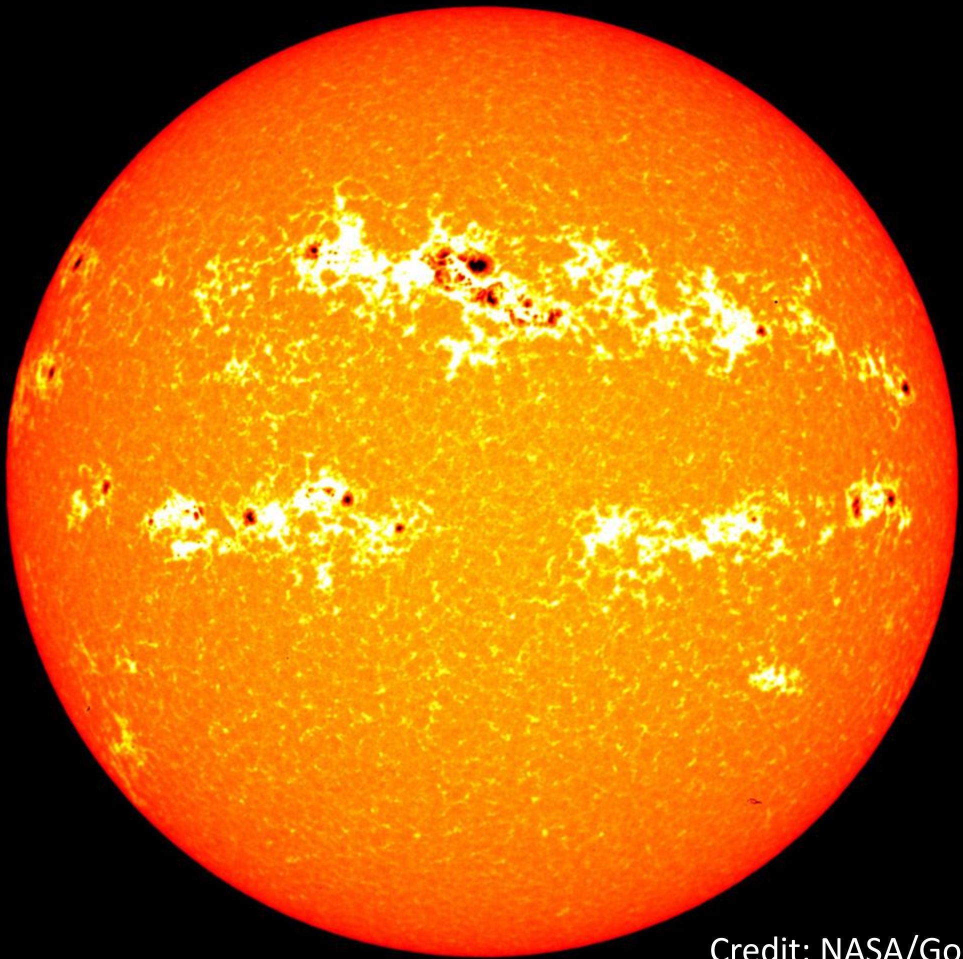
- Particularly evident in UV and X-rays



Credit: SOHO/NASA/ESA

The solar cycle also modulates the radiative output of the Sun

- This happens all through the spectrum



Credit: NASA/Goddard/SORCE

The solar cycle also modulates the radiative output of the Sun

- Cycle modulation can be observed in total solar irradiance

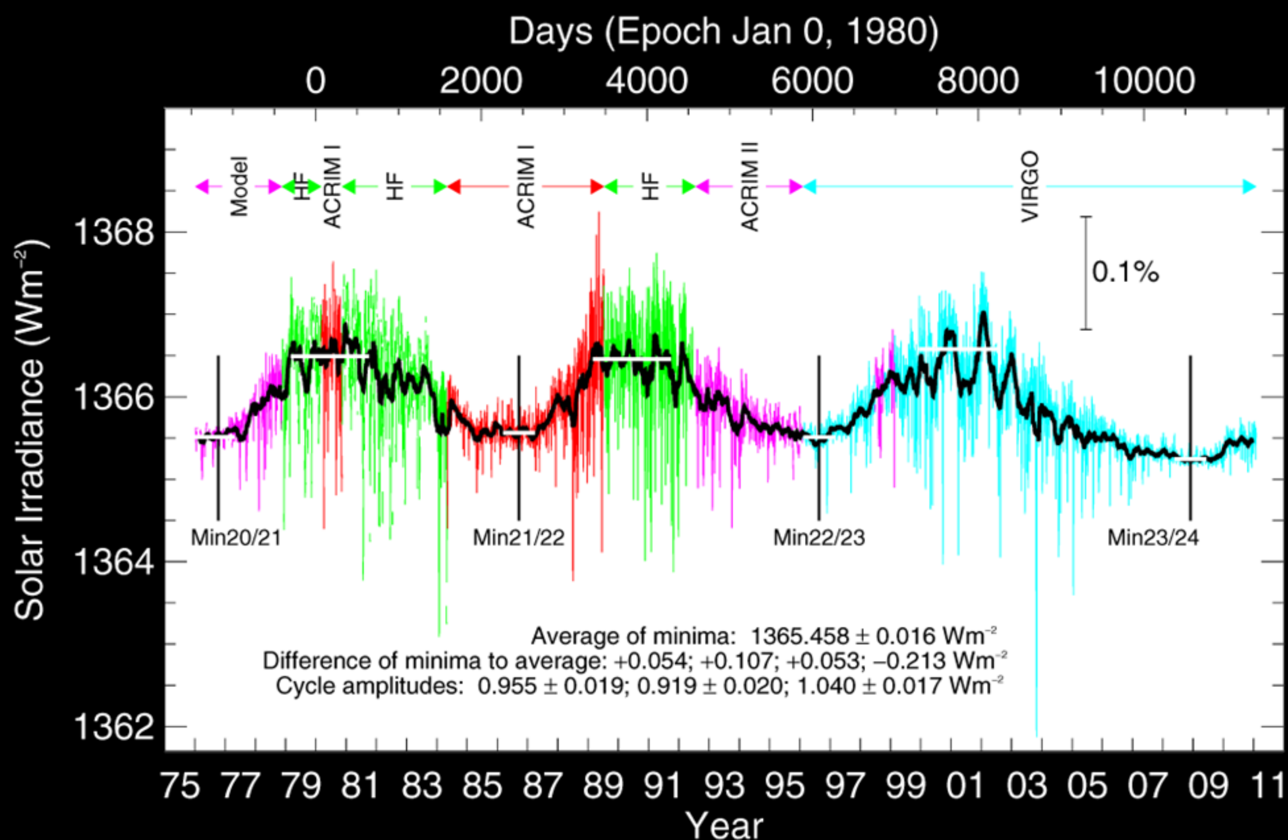


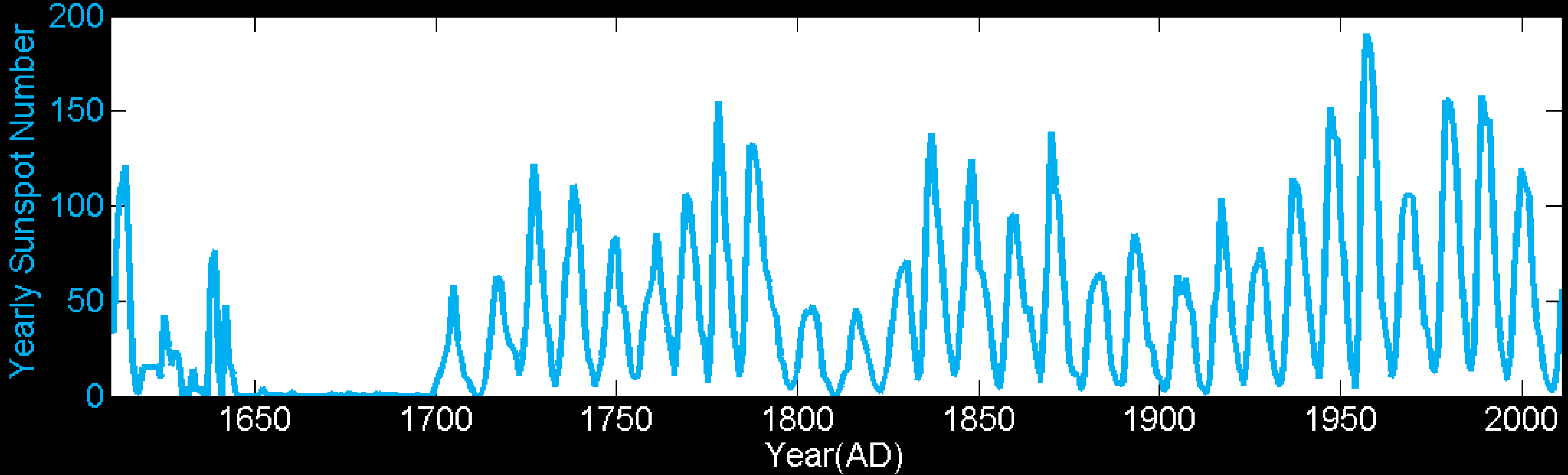
Image taken from PMOD-WRC

Consequences for the Earth

- Changes in the amount of energetic events and the background solar wind define the shape and dynamics of the Earth's magnetosphere.
- Changes in cosmic ray flux may affect cloud formation and coverage (Svensmark 1998).
- Irradiance variations directly affect the upper layers of the Earth's atmosphere changing drag on low-orbit satellites.
- Additional coupling between solar activity and Earth's climate may be also taking place.

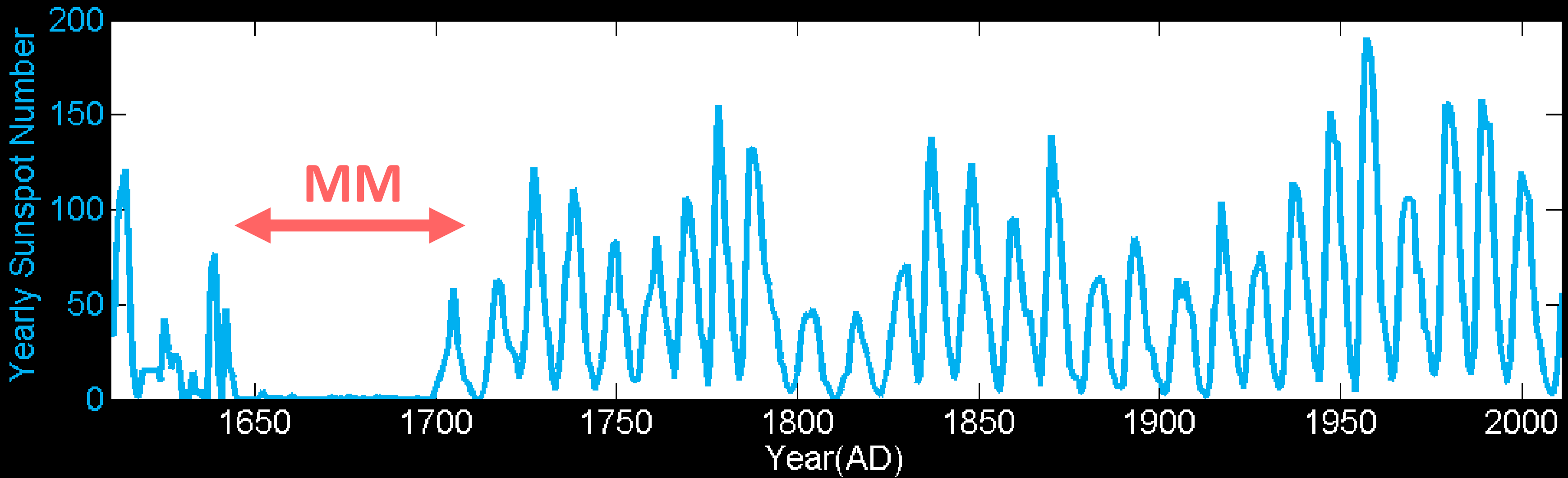
LONG-TERM CYCLE VARIABILITY

Apart from the main 11 year oscillation there is a large variability in cycle amplitude



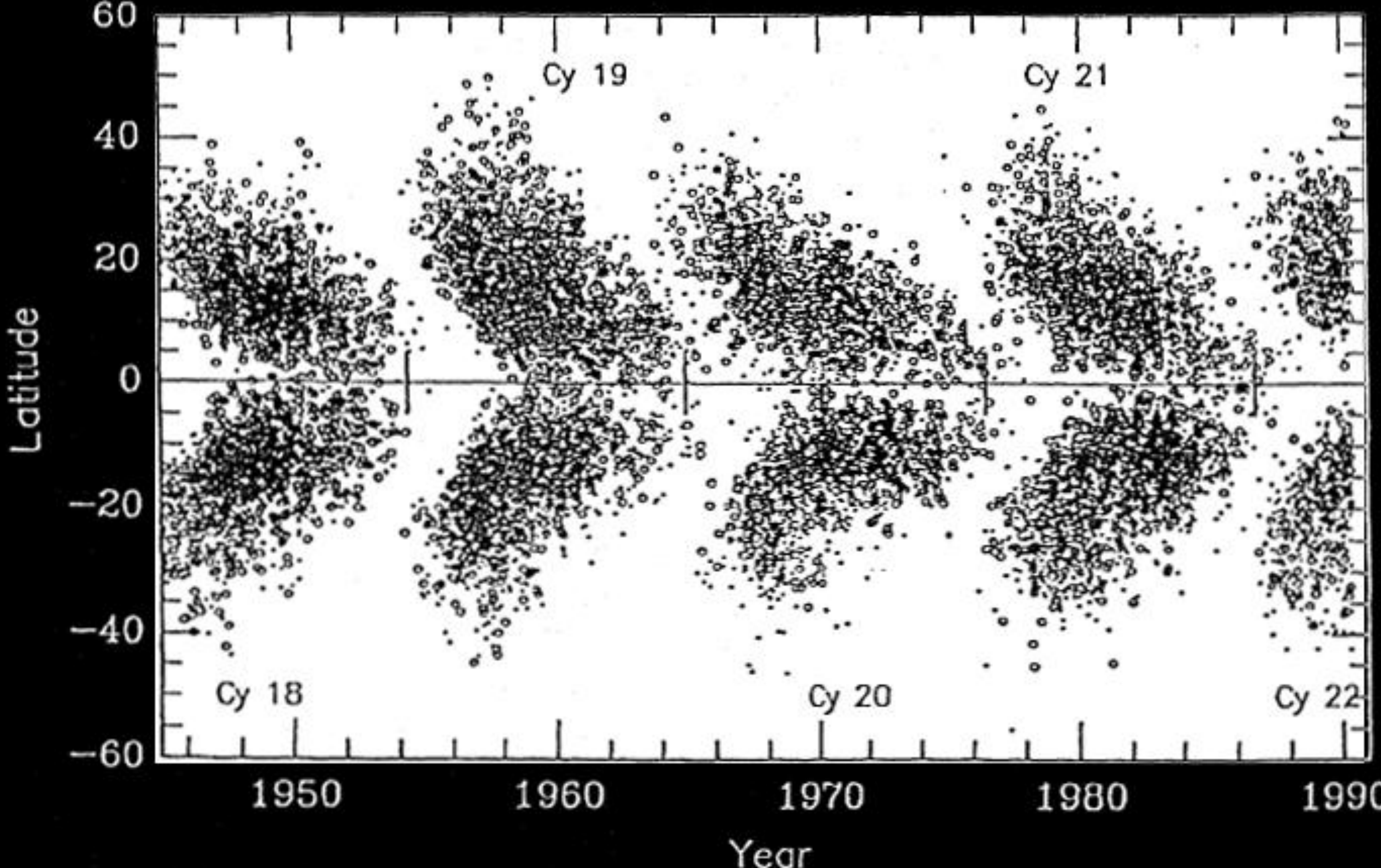
- Strongest (weakest) cycle has an SSN amplitude of 188 (43). Mean is 90 +/- 41.
- Longest (shortest) cycle has a duration of 14 (9) years. Mean is 11 +/- 14 months.
- Data taken from Hathaway (2010).

Apart from the main 11 year oscillation there is a large variability in cycle amplitude



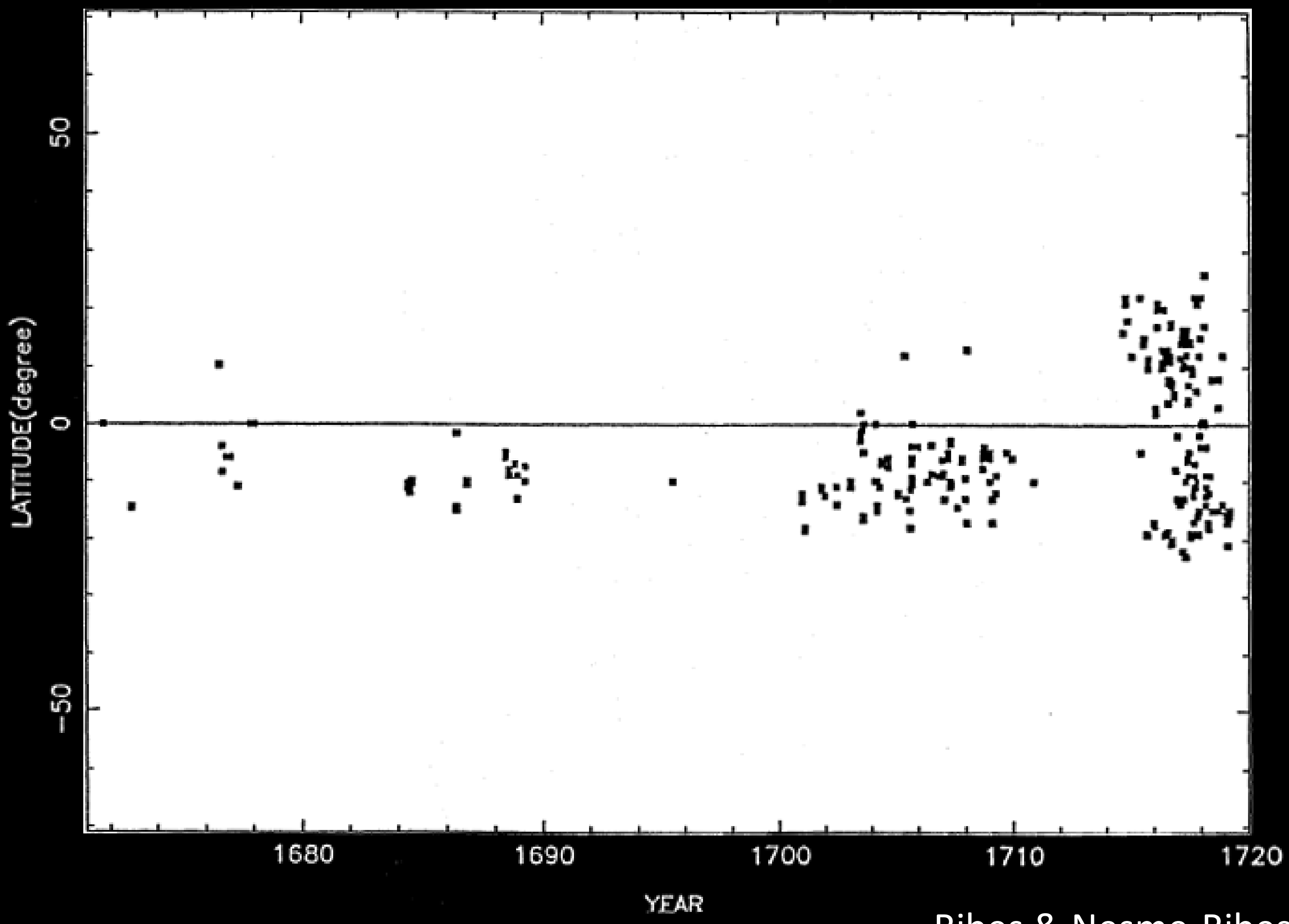
- The Sun appears to enter periods in which several cycles have similar amplitudes (global maxima and minima).
- The most striking is known as the Maunder minimum (1645-1715; Eddy 1976).

A time almost without sunspots



Ribes & Nesme-Ribes 1993

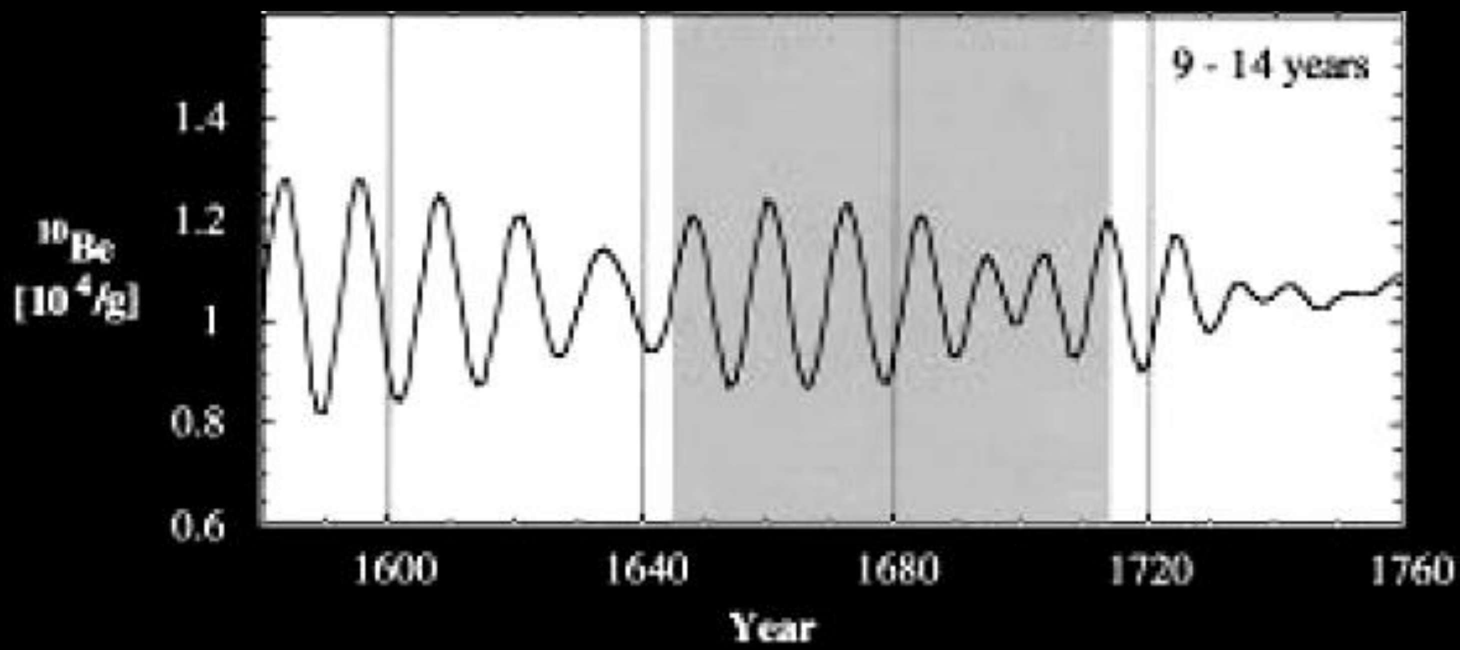
A time almost without sunspots



Ribes & Nesme-Ribes 1993

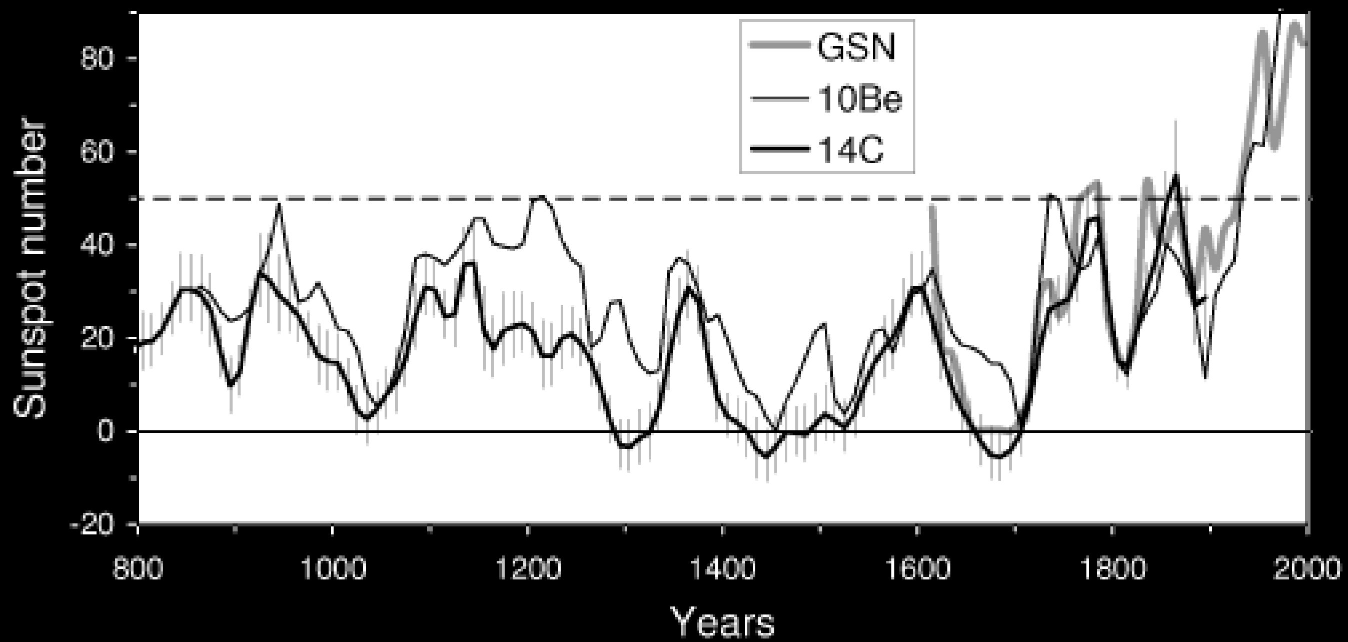
What happened to the cycle during this period?

- Cosmogenic isotopes can be used to study the long term evolution of the cycle.
- Main isotopes used are C^{14} (half-life of 5730 years) and Be^{10} (half-life of 1.5×10^6 years).



Beer et al. 1998

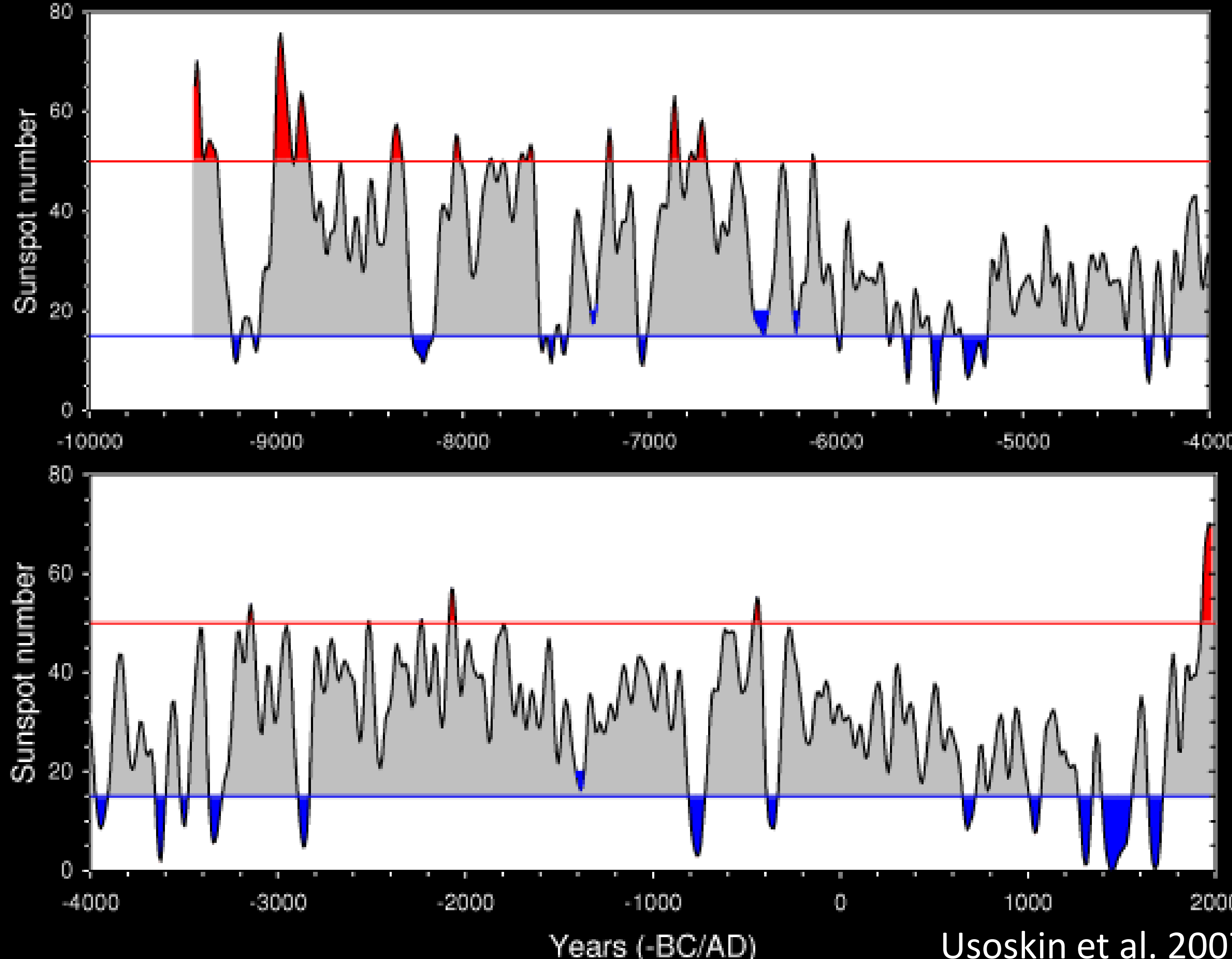
Cosmogenic isotopes can also be used as a proxy of past solar activity



Usosking et al. 2003 & Solanki et al. 2004

- During the last 1200 years there have been 3 grand minima and 1 grand maxima.

Cosmogenic isotopes can also be used as a proxy of past solar activity



Usoskin et al. 2007

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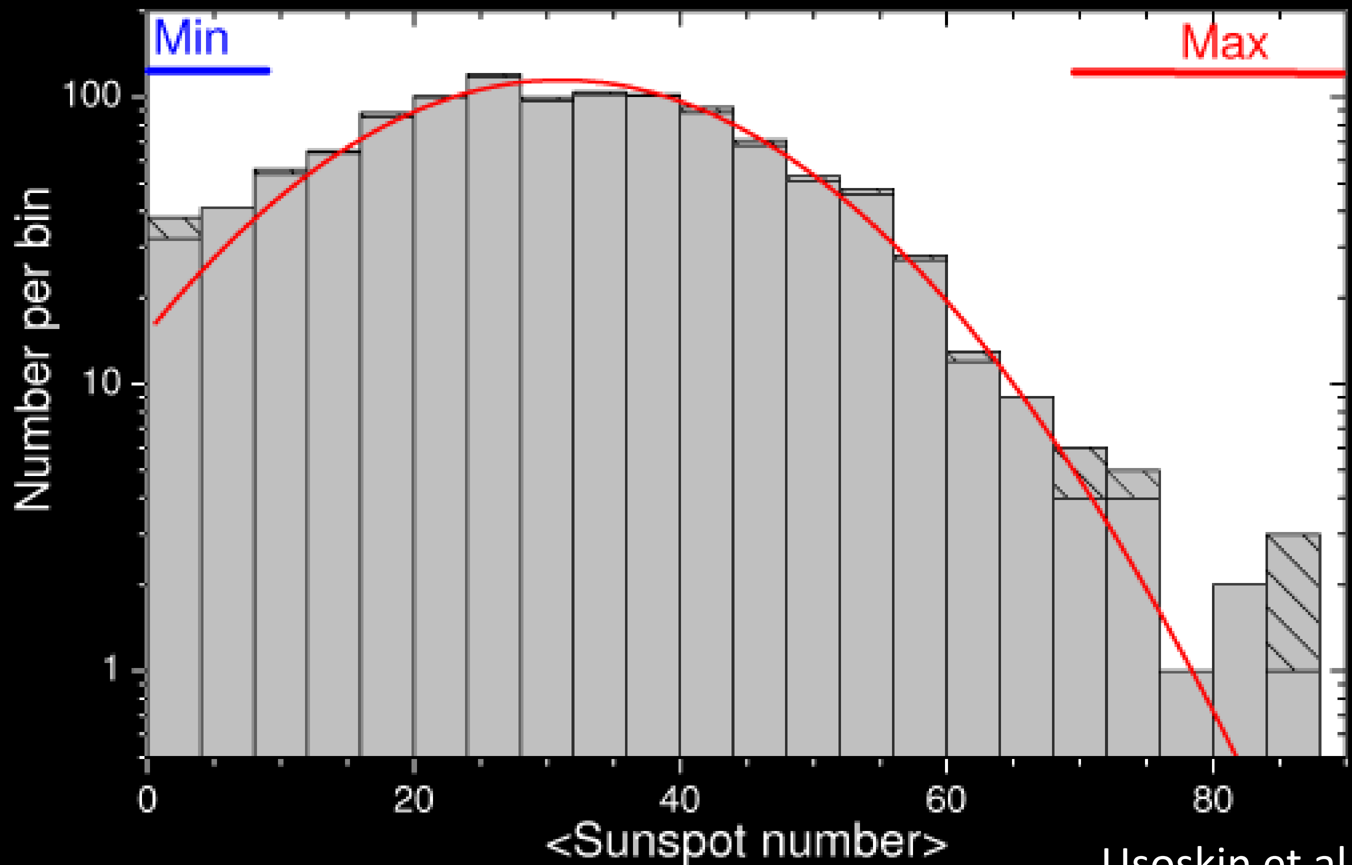
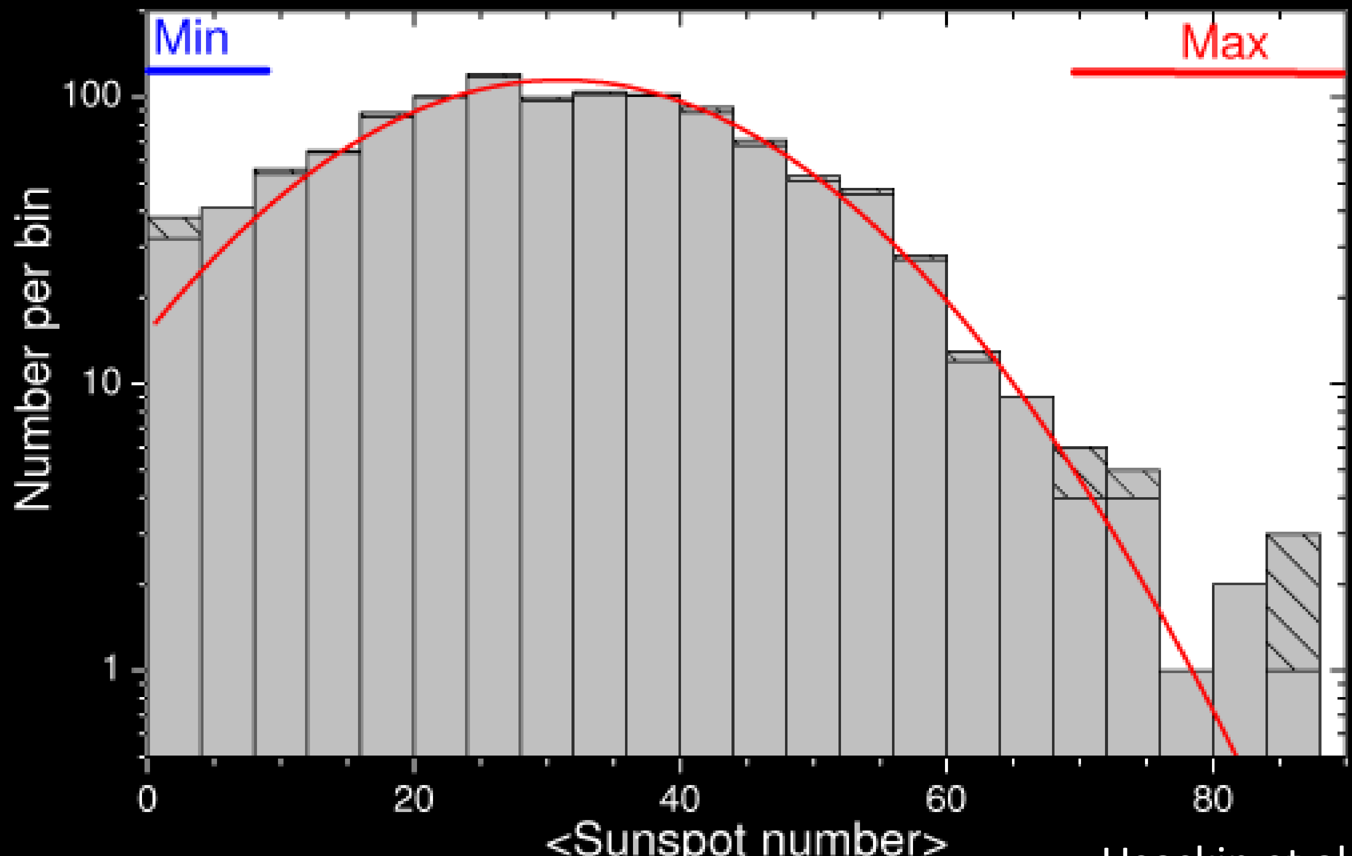


Usoskin et al. 2007

- Sunspot number distribution shows two significant deviations from normality for grand maxima and minima

Cosmogenic isotopes can also be used as a proxy of past solar activity



Usoskin et al. 2007

- Overall the Sun seems to spend 1/10th of the time in grand maxima and 1/6th in grand minima.

Why is important to study long-term solar variability?

- Grand minima and maxima remain poorly understood and can teach us a lot about the inner workings of the cycle.
- Long-term solar changes are important to understand climate change.
- Long-term proxies increases the data pool we have to understand the cycle.

SUMMARY

- The solar cycle is a process that is magnetic in nature.
- Its main characteristics are determined by the emergence and decay of active regions.
- The solar cycle is the main determinant factor in setting the conditions in the heliosphere.
- Some cycle properties change in time-scales spanning multiple cycles.
- Understanding long-term solar variability is important when considering changes in the Heliosphere and the Earth's climate.

ANY MORE QUESTIONS?

The Solar Cycle: Understanding and Theory

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Department of Physics and Astronomy, University of Utah

Most determinant characteristics of the Sun (from the point of view of the cycle)

- **Hot**
  - With temperatures between 15’000,000 a 6,000 degrees.
  - Matter exists in a highly ionized state (plasma – very conductive).
- **Big**
  - You can fit a million Earths inside it.

The Solar Plasma

- Highly ionized (made of free electrons and ions; highly conductive because it's **Hot**).

- From the point of view of the cycle non-relativistic:

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} \qquad \mathbf{J} = \sigma\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right)$$

- Combining all with the induction equation:

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \rightarrow \frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left(\mathbf{v} \times \mathbf{B} - \overbrace{\frac{1}{\mu_0 \sigma}}^{\eta} \nabla \times \mathbf{B} \right)$$

The resistive MHD induction equation

Evolution → $$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left(\underbrace{\mathbf{v} \times \mathbf{B}}_{\text{Plasma Flows}} - \underbrace{\eta \nabla \times \mathbf{B}}_{\text{Diffusion}} \right)$$

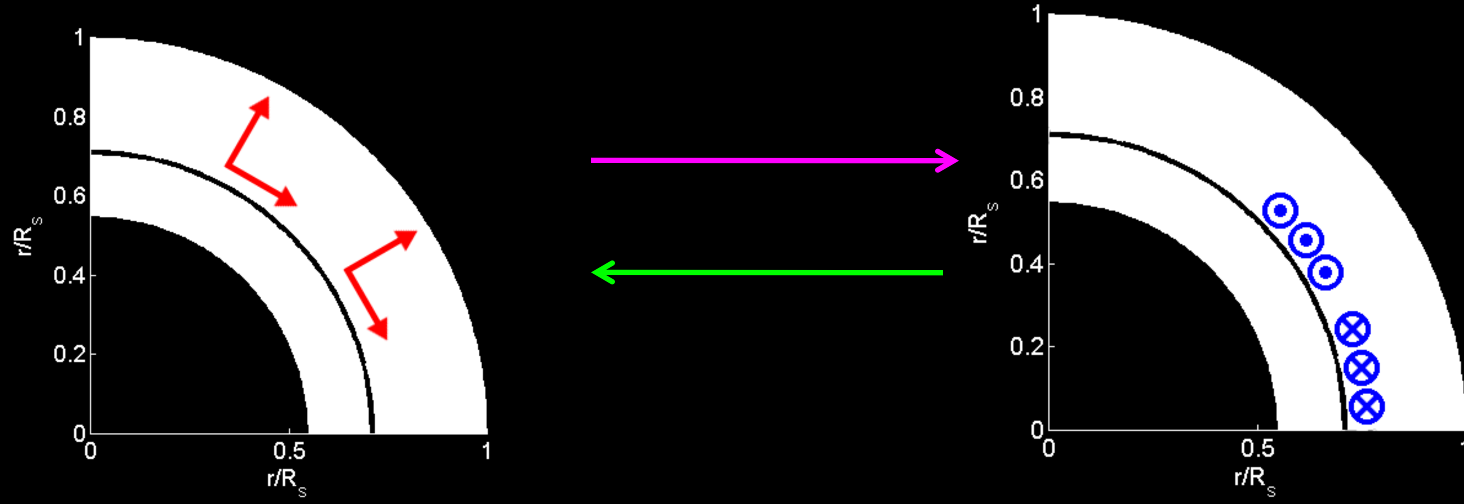
- The relative importance of these two terms defines the physical characteristics of the system (Big & Hot).

$$R_m = \frac{\mathbf{v} \times \mathbf{B}}{\eta \nabla \times \mathbf{B}} \sim \frac{vB}{\frac{\eta B}{L}} \sim \frac{v}{\frac{1}{\mu_0 \sigma L}}$$

- In the Sun, plasma flows are more important than diffusion – Flux is frozen (Alfvén 1942)

CURRENT UNDERSTANDING OF THE CYCLE

The Solar Cycle in a Nutshell



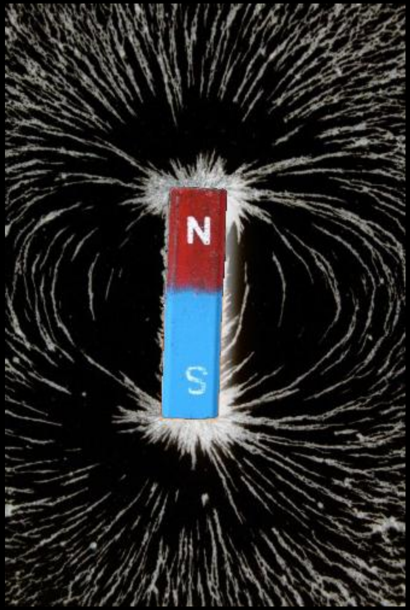
Poloidal

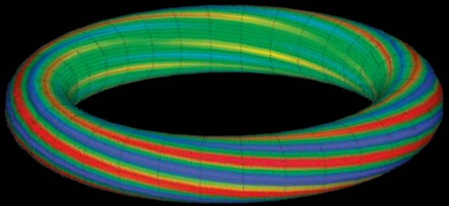
$r - \theta$

Toroidal

ϕ

The Solar Cycle in a Nutshell





Poloidal

r - θ

Toroidal

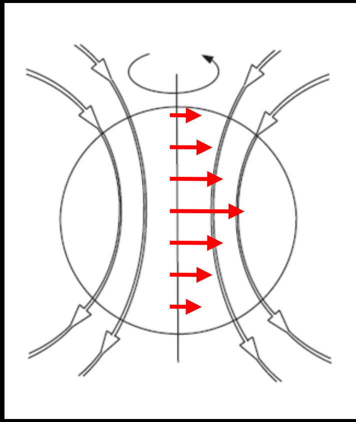
ϕ

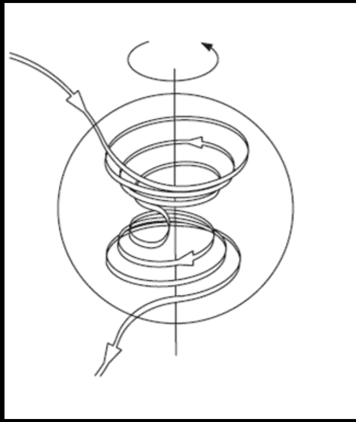
The Solar Cycle in a Nutshell

Differential Rotation

Poloidal → Toroidal

r - θ   φ





Credit: J. J. Love

The Solar Cycle in a Nutshell

Differential Rotation

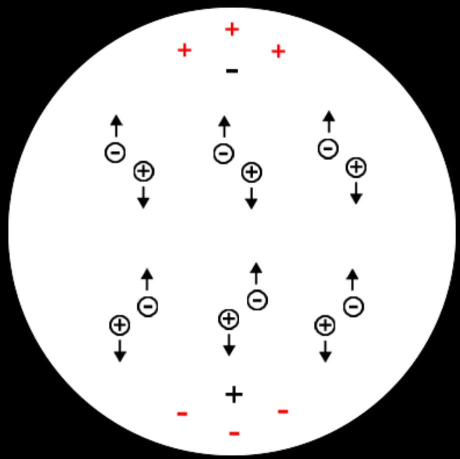
Poloidal

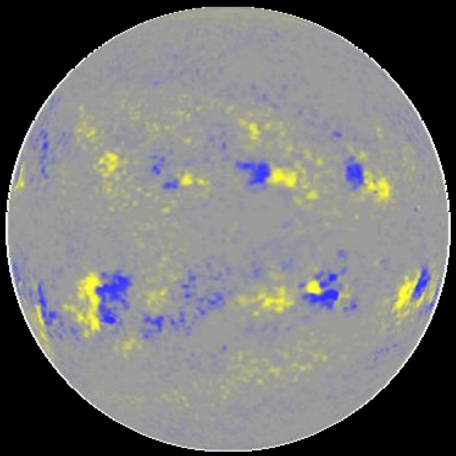
$r - \theta$

Toroidal

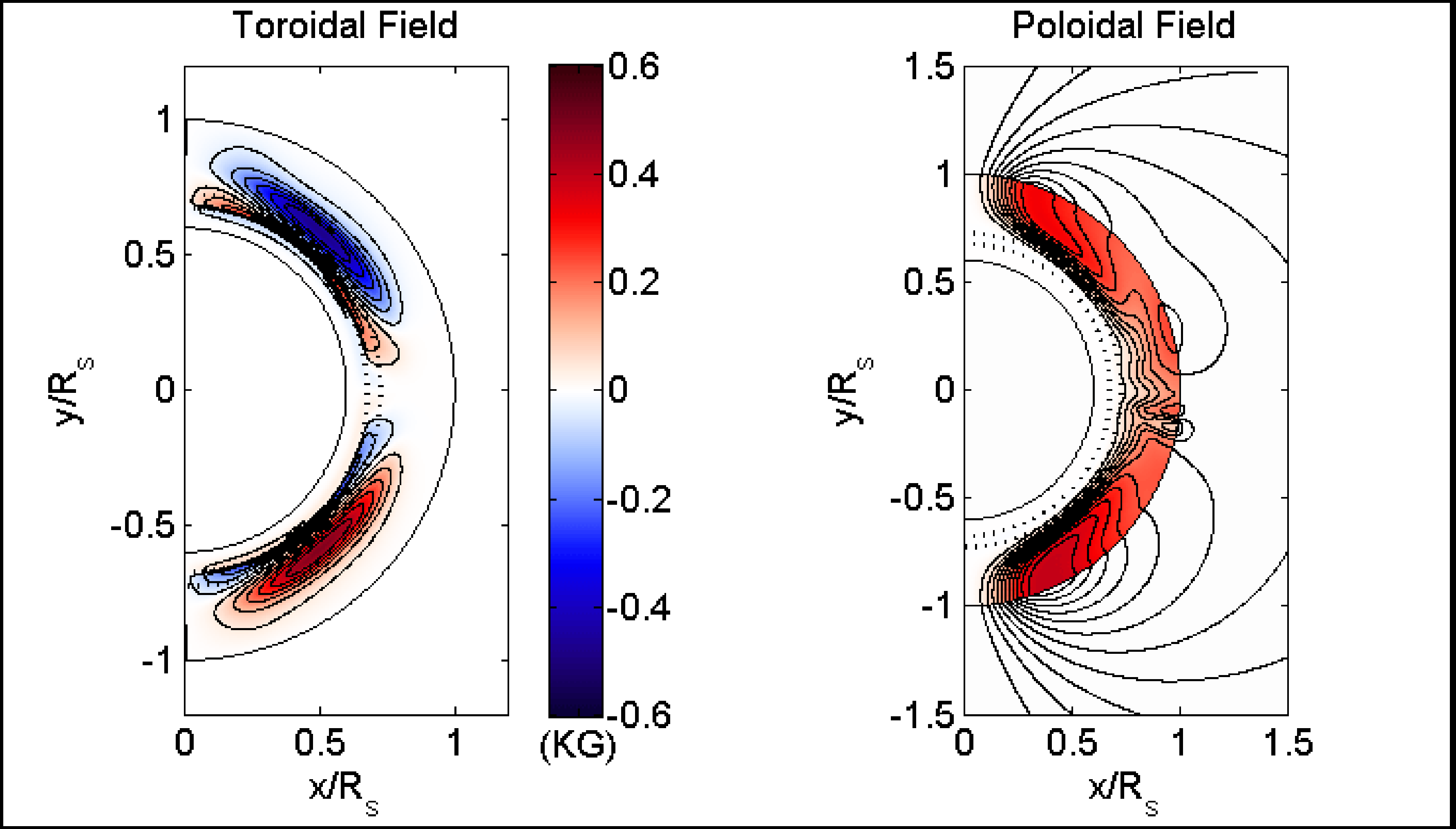
ϕ

Emergence and Decay of Active Regions (Sunspots)



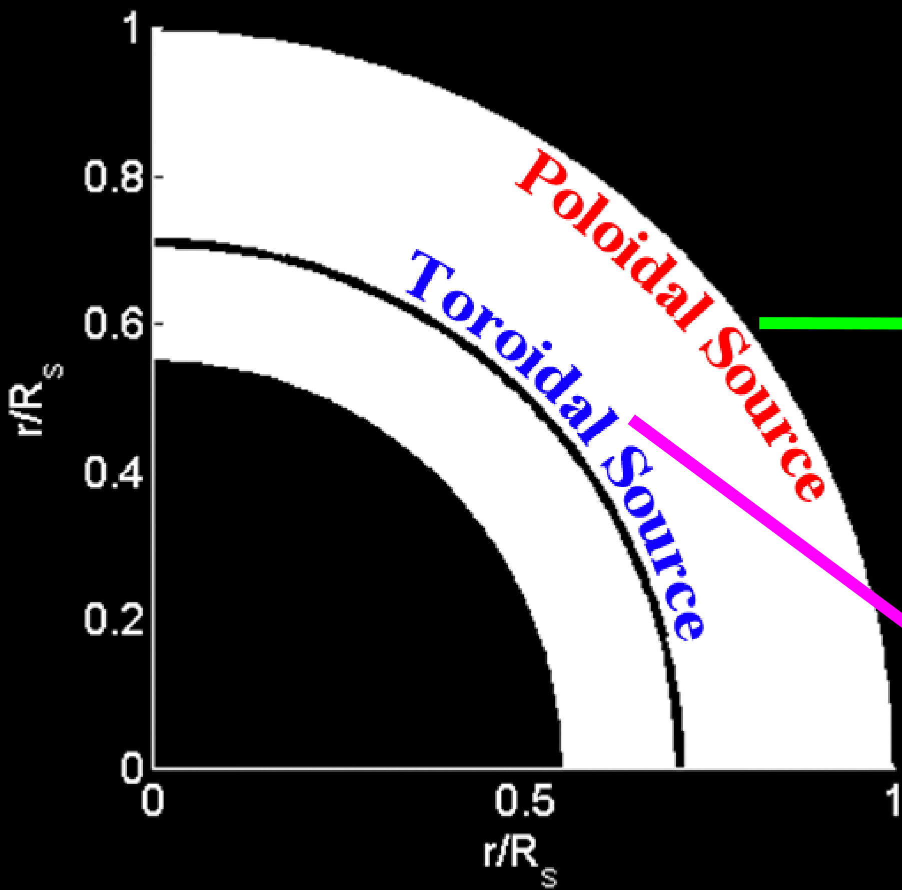


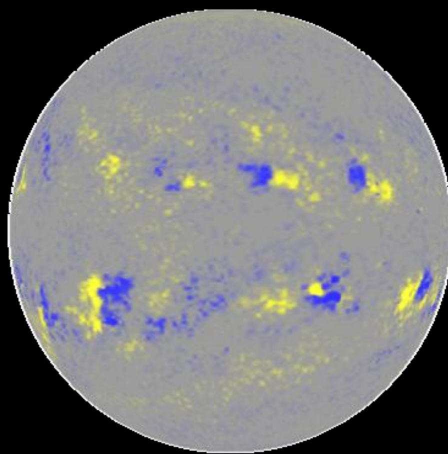
The Solar Cycle in a Nutshell



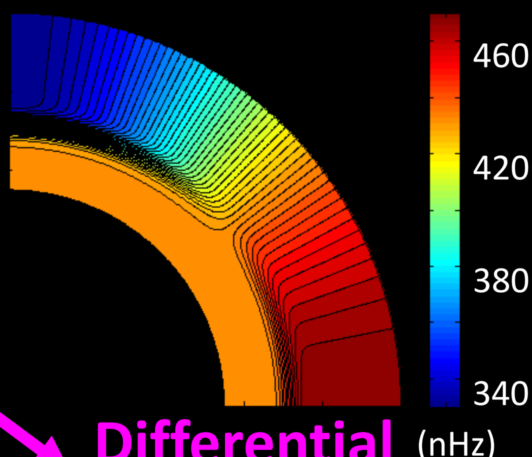
SOLAR PLASMA FLOWS

In the Sun, toroidal and poloidal sources are spatially separated



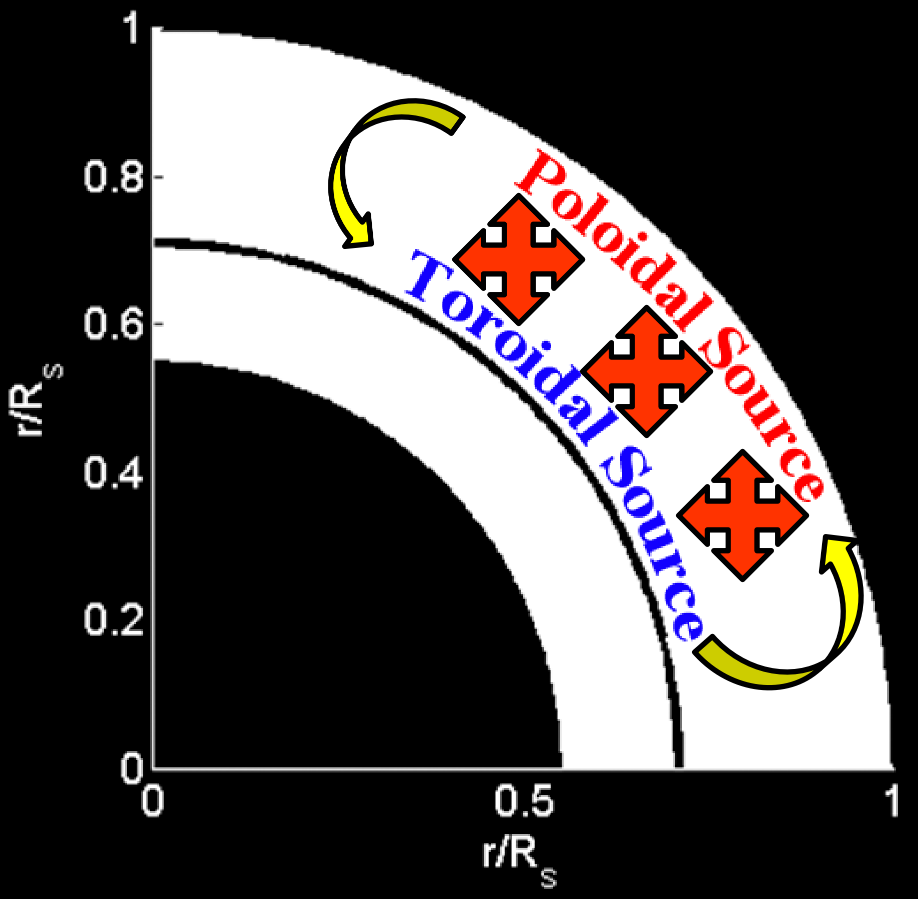


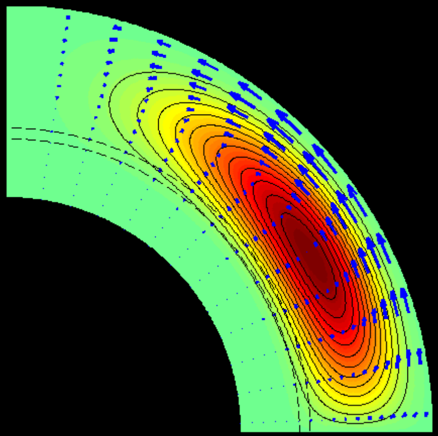
AR Emergence and Decay



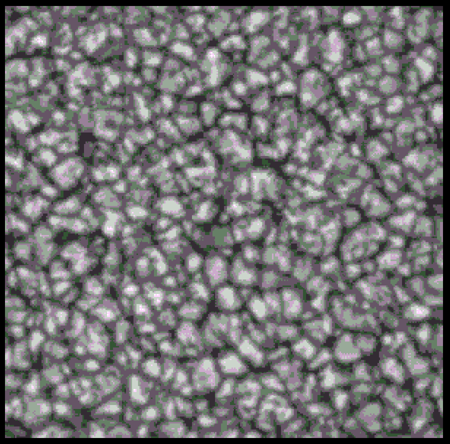
Differential Rotation

The magnetic field is transported between source regions by two velocity flows



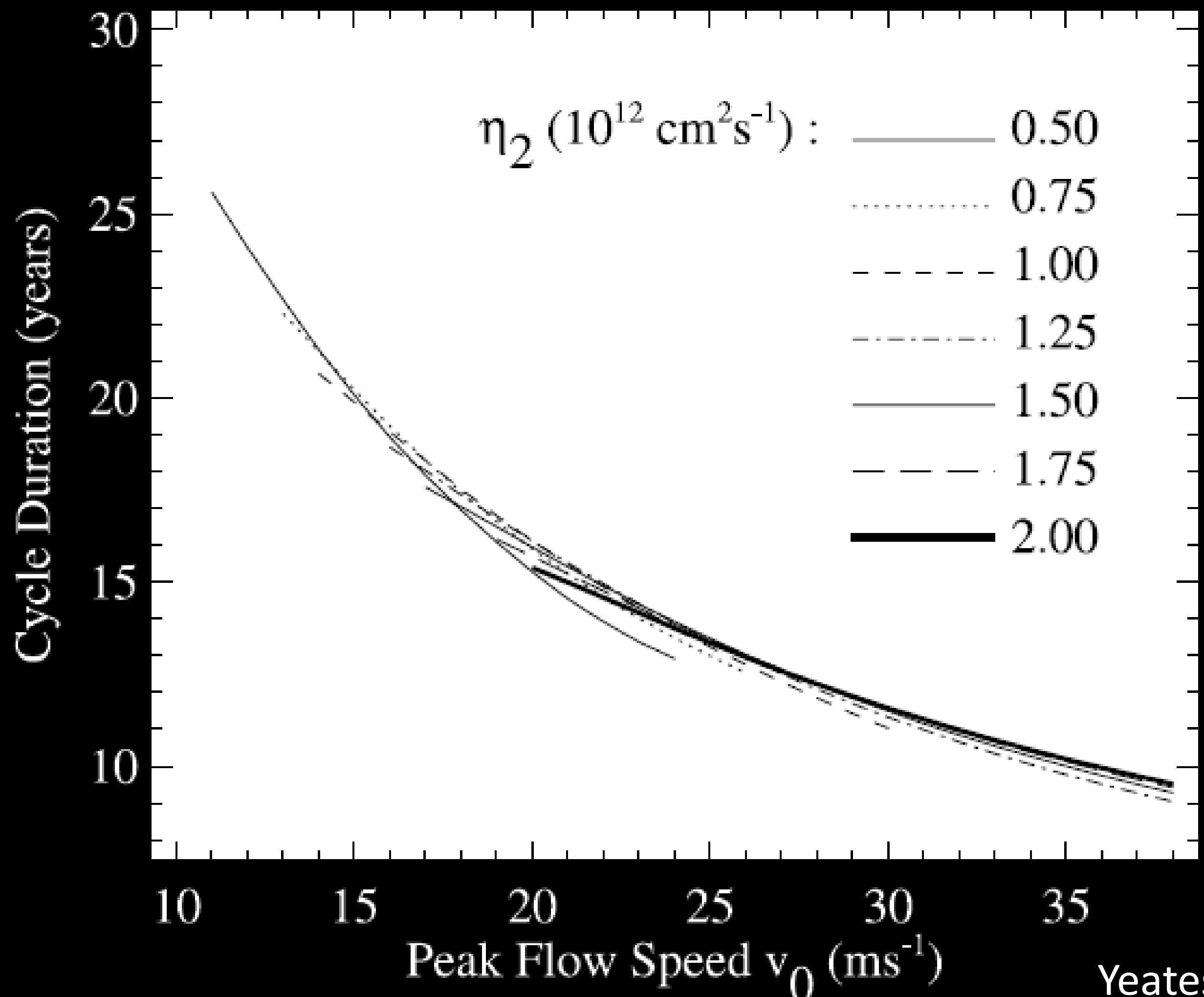


Meridional Flow



Turbulent Diffusivity

Together, these flows set the duration of the cycle



Yeates et al. 2008

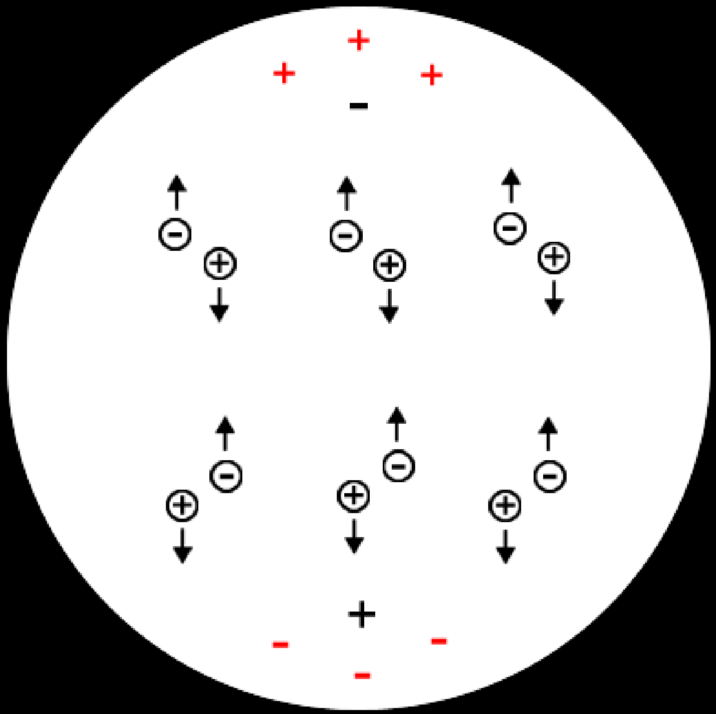
THE MAGNETIC FIELD SOURCES AND THE AMPLITUDE OF THE CYCLE

With differential rotation things are relatively simple

- Solar differential rotation has been observed to vary only by 1% across the cycle.
- There is a linear relationship between differential rotation shear and the creation of toroidal field.

On the other hand, the poloidal source is quenched for strong magnetic fields.

- In order to generate poloidal field, active regions need to have a systematic tilt.



On the other hand, the poloidal source is quenched for strong magnetic fields.

- In order to generate poloidal field, active regions need to have a systematic tilt.
- This tilt is imparted by convection during a flux-tube's rise time.

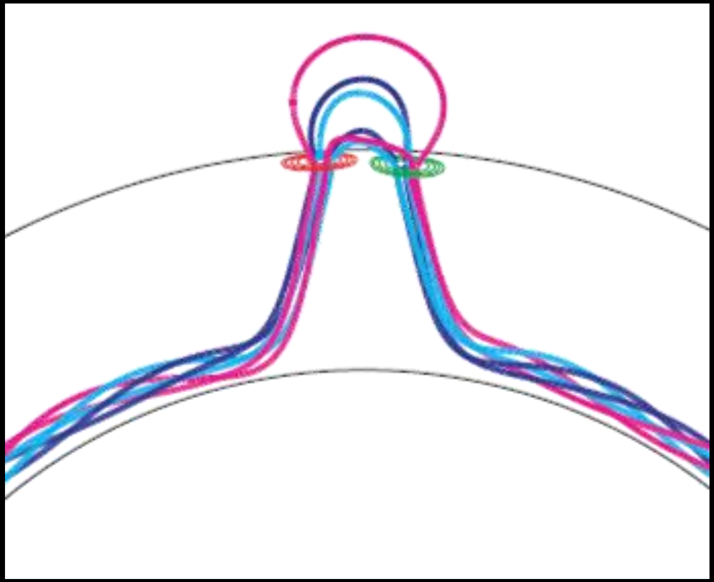
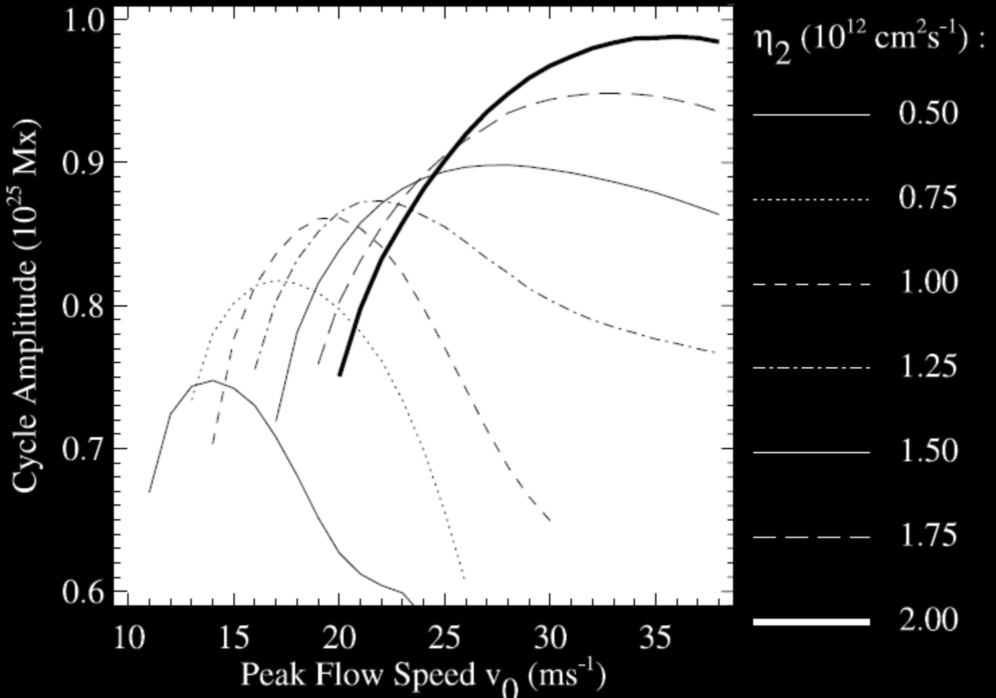


Image by A. van Ballegooijen

- The stronger the flux-tube's magnetic field, the smaller the resultant active region's tilt (Weber et al. 2012).

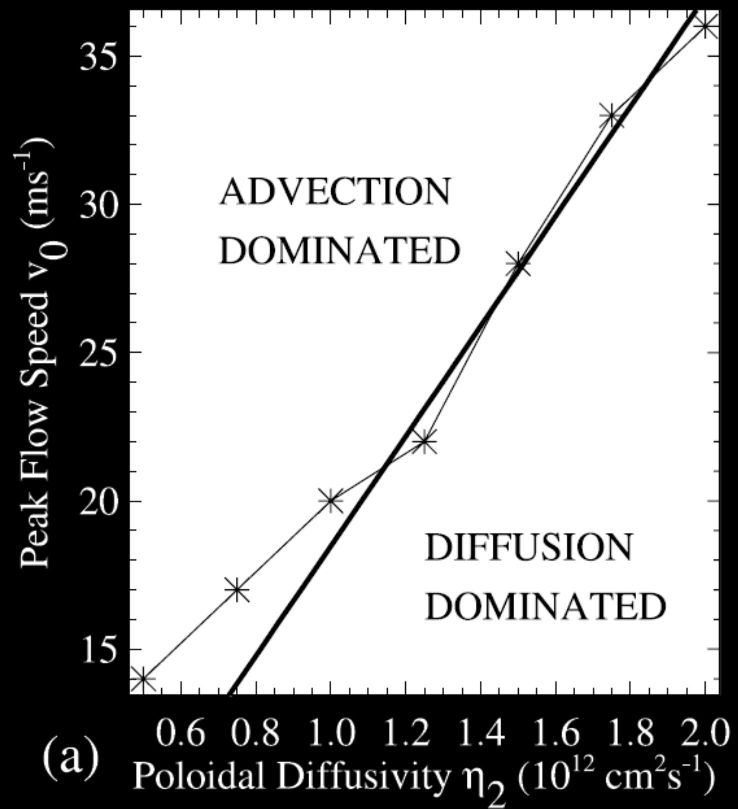
Changes in meridional flow and turbulent diffusivity also affect cycle amplitude



Yeates et al. 2008

- For a fixed diffusivity, increasing meridional flow speed raises the amplitude of the cycle and, after a critical value, lowers it.

Changes in meridional flow and turbulent diffusivity also affect cycle amplitude



Yeates et al. 2008

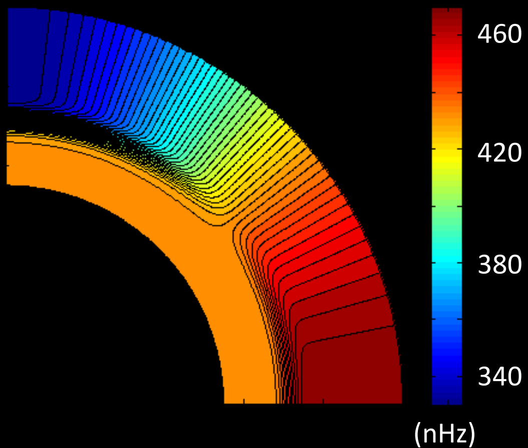
- This critical point corresponds to values for which diffusive and advective transport timescales are the same.

Changes in meridional flow and turbulent diffusivity also affect cycle amplitude

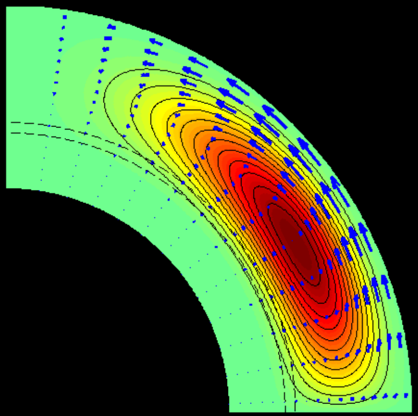
- In the advection dominated regime ($T_{mf} < T_{diff}$), increasing the meridional flow reduces the amount of cancellation of field due to diffusion.
- In the diffusion dominated regime ($T_{mf} < T_{diff}$) increasing the meridional flow reduces the time that differential rotation has to amplify the field.

The most important ingredients of the cycle are:

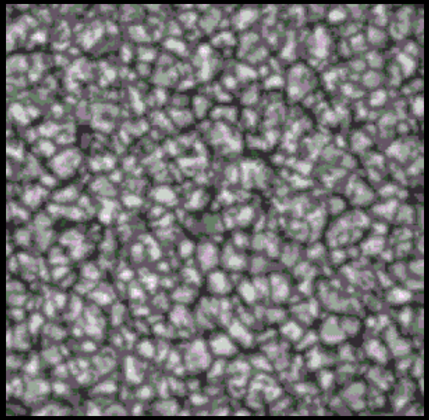
Differential Rotation



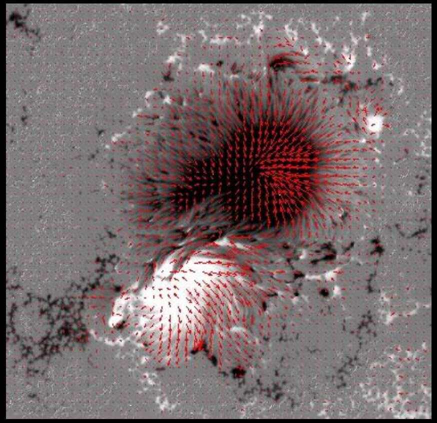
Meridional Flow



Turbulent Diffusivity



Active Region emergence and decay



MODELING THE SOLAR CYCLE

The Magneto-Hydrodynamic (MHD) equations

Mass Conservation:

$$\frac{\partial \rho}{\partial t} + \overbrace{\nabla \cdot \left(\rho \mathbf{v} \right)}^{\text{Mass Sources}} = 0$$

Conservation of Momentum:

$$\rho \frac{\partial \mathbf{v}}{\partial t} + \overbrace{\rho \left(\mathbf{v} \cdot \nabla \right) \mathbf{v}}^{\text{Inertia}} = \underbrace{-\nabla p}_{\text{Pressure}} + \underbrace{\overbrace{\frac{\left(\mathbf{B} \cdot \nabla \right) \mathbf{B}}{\mu_0}}^{\text{Magnetic Tension}} - \overbrace{\nabla \left(\frac{B^2}{2\mu_0} \right)}^{\text{Magnetic Pressure}}}_{\text{Lorenz Force}}$$

The Magneto-Hydrodynamic (MHD) equations

Energy Conservation (ideal gas):

$$\frac{\rho^{\gamma}}{\gamma-1}\frac{d}{dt}\left(\frac{p}{\rho^{\gamma}}\right) = -\underbrace{\nabla\cdot\mathbf{q}}_{\text{Heat Conduction}} - \underbrace{L_r}_{\text{Radiative Function}} + \underbrace{\frac{j^2}{\sigma}}_{\text{Ohmic Dissipation}} + \underbrace{H}_{\text{Other Heating Sources}}$$

Induction Equation:

$$\frac{\partial\mathbf{B}}{\partial t} = \nabla\times\left(\underbrace{\mathbf{v}\times\mathbf{B}}_{\text{Plasma Flows}} - \underbrace{\eta\nabla\times\mathbf{B}}_{\text{Diffusion}}\right)$$

Low Order Models

- They model the solar cycle as an oscillator.

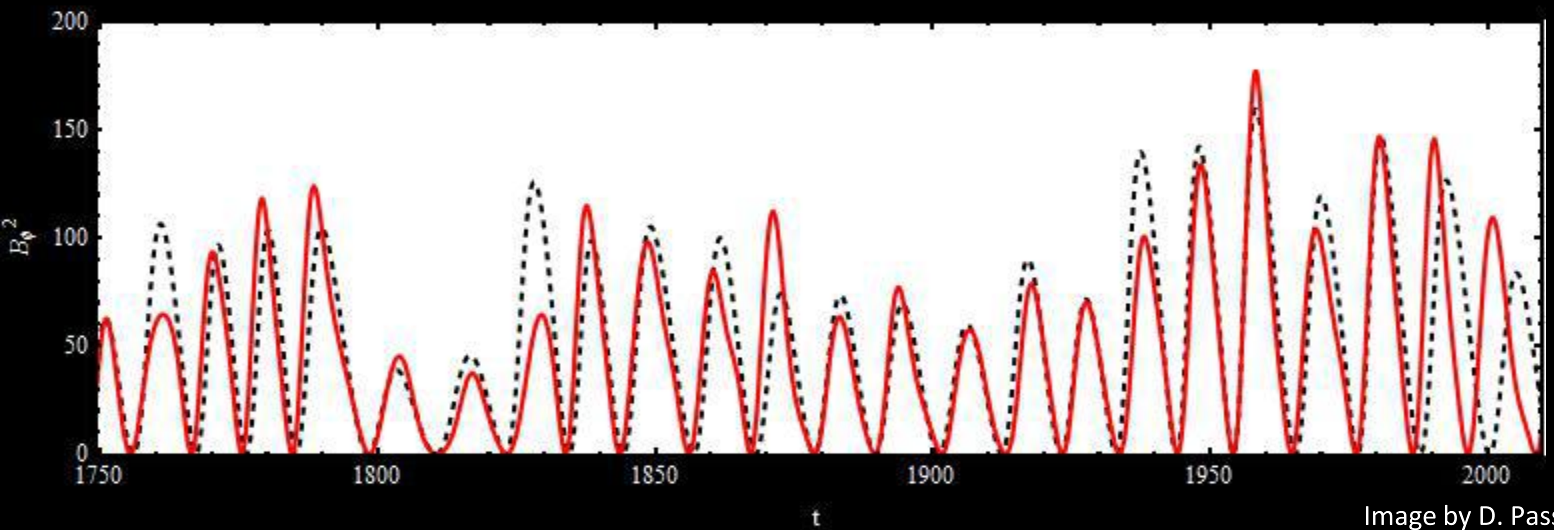


Image by D. Passos

- They allow us to study the mathematical properties of the cycle.

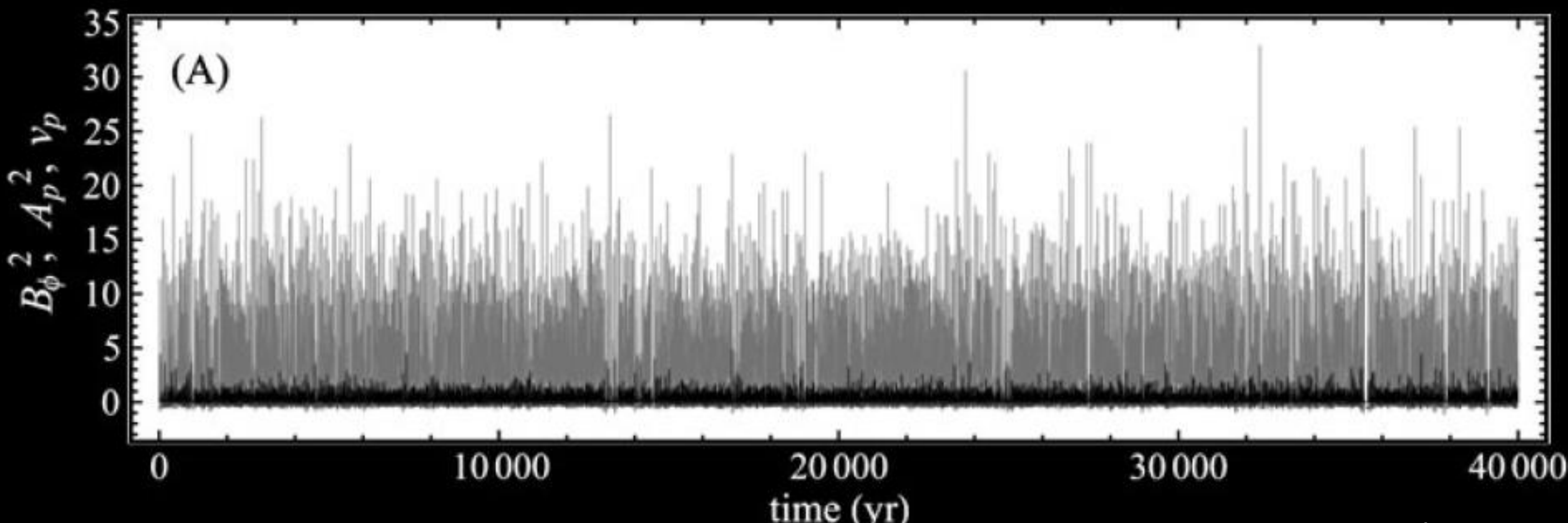
Low Order Models

- **Main Advantages:**
  - Very, very inexpensive computations.

- **Main Disadvantages:**
  - Very simple.

Low Order Models

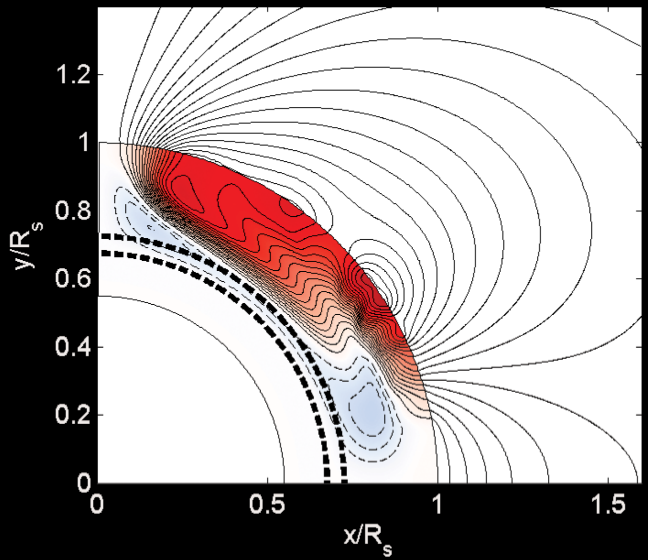
- Used, for example, to study the long-term modulation of the solar cycle.

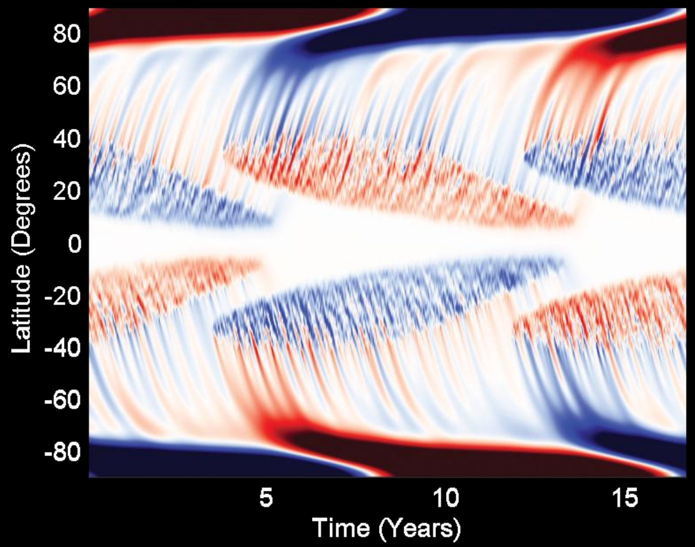


Passos et al. 2012

Kinematic Dynamo Models

- Based on the induction equation assuming axial symmetry.





Muñoz-Jaramillo et al. 2010

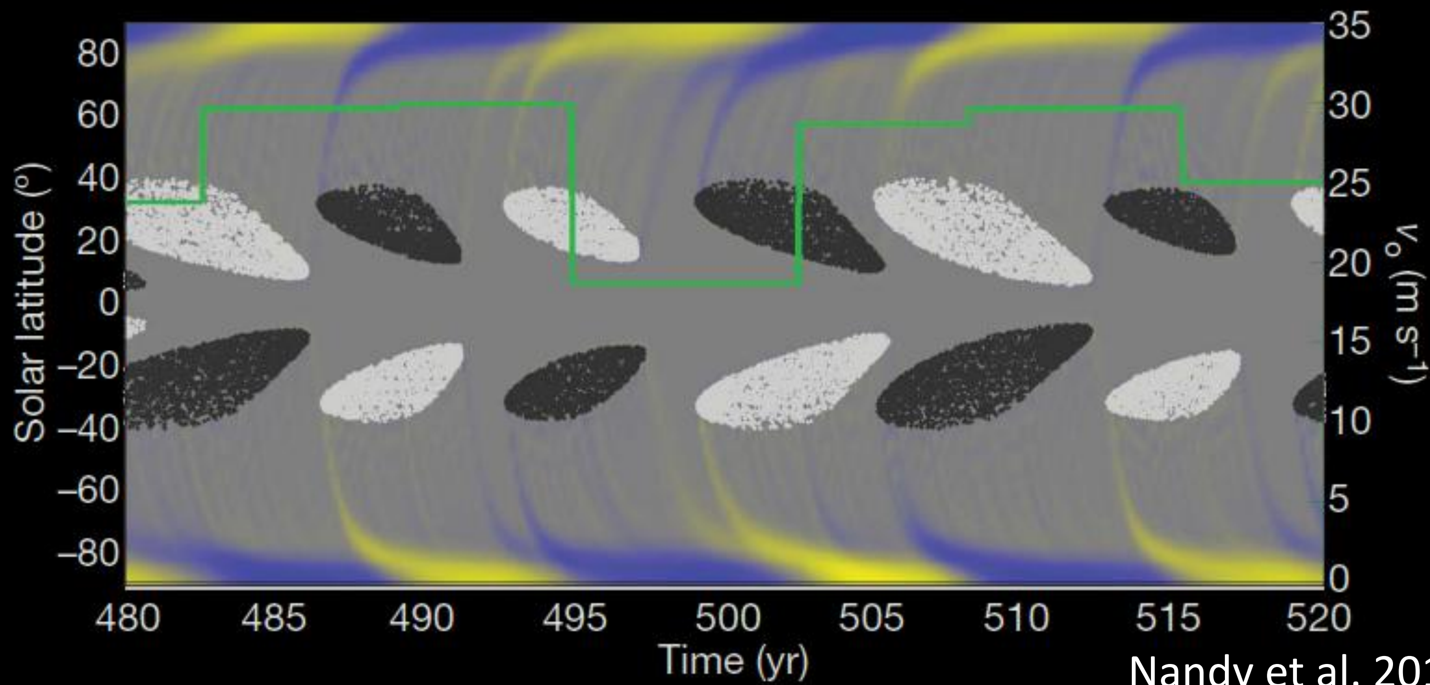
- They allow us to study a self-excited cycle with freedom to explore different approaches due to inexpensive computations.

Kinematic Dynamo Models

- **Main Advantages:**
  - Relatively inexpensive computations.
  - Self-excited.
  - Very successful at reproducing cycle characteristics.
- **Main Disadvantages:**
  - Large amount of free parameters.
  - Phenomenological approach to modeling.

Kinematic Dynamo Models

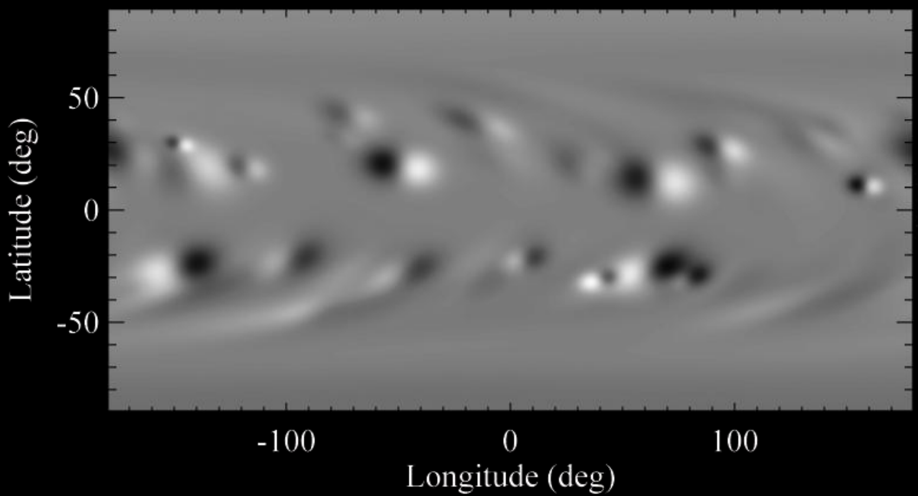
- **Used, for example, to study the causes that led to the prolonged solar minimum of cycle 23.**

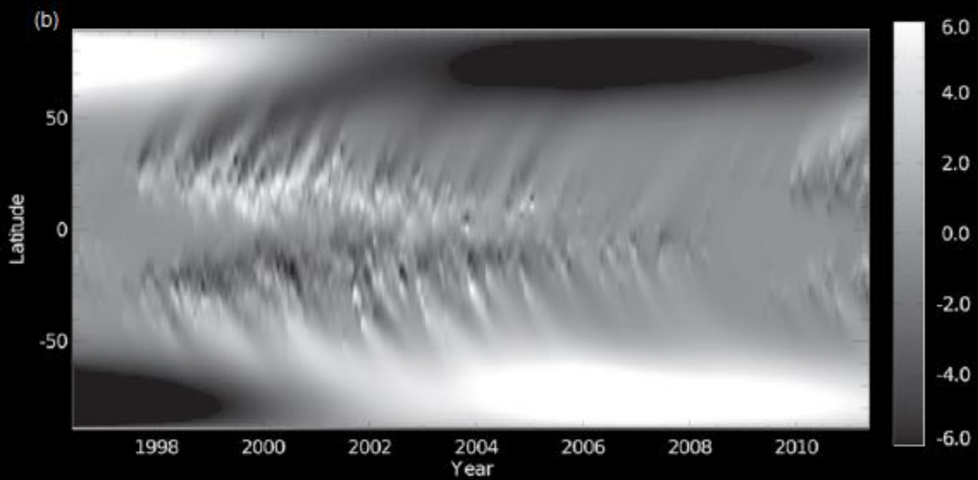


Nandy et al. 2011

Surface Flux Transport Simulations

- Based on the induction equation and limited to the surface of the Sun





Yeates & Mackay 2012

- They allow us to study a the evolution of the surface magnetic field and its interaction with the corona and solar wind.

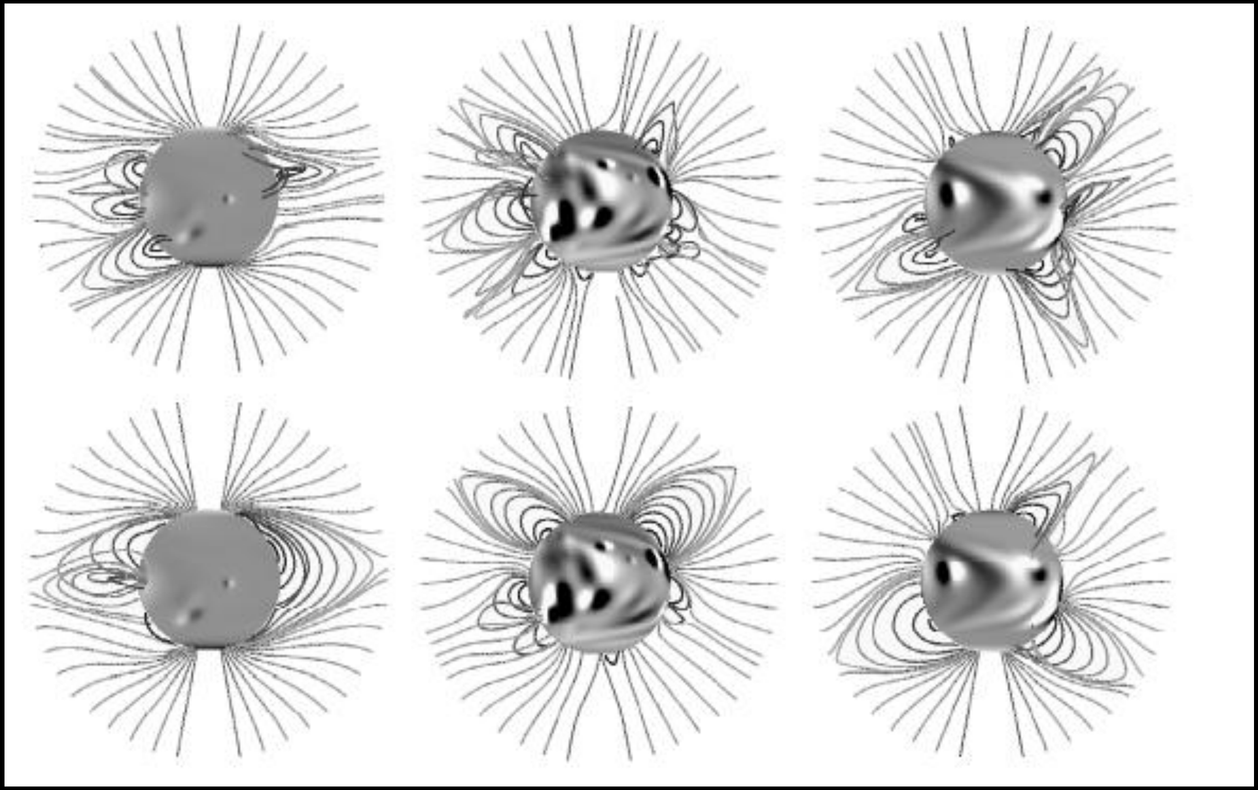
Surface Flux Transport Simulations

- **Main Advantages:**
  - Easy to couple with models of the solar corona.
  - Very successful for capturing the dynamics of the surface magnetic fields.

- **Main Disadvantages:**
  - Limited to the surface of the Sun.
  - Not self excited.

Surface Flux Transport Simulations

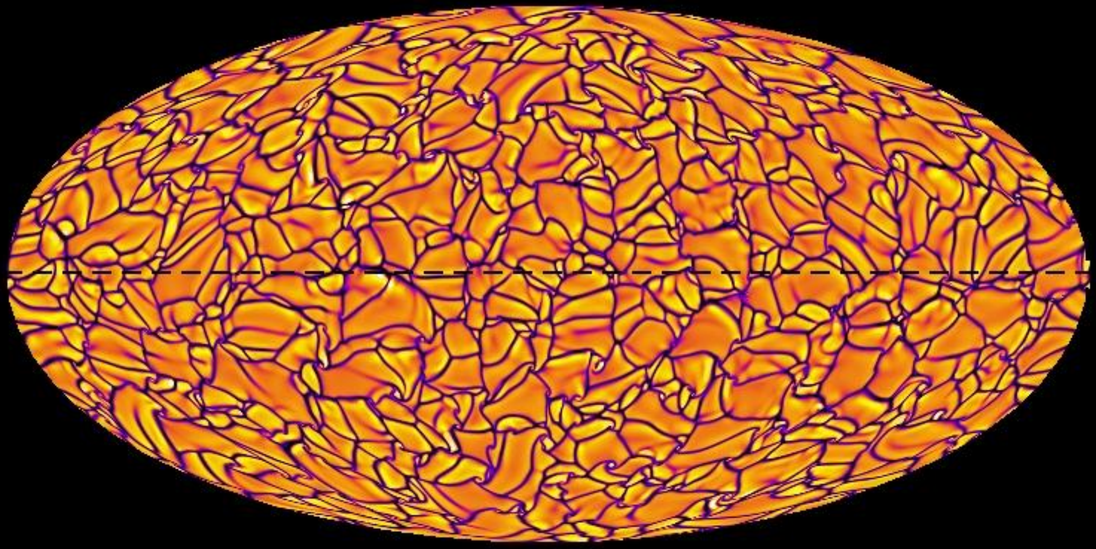
- Used, for example, to study the evolution of the open solar magnetic flux.

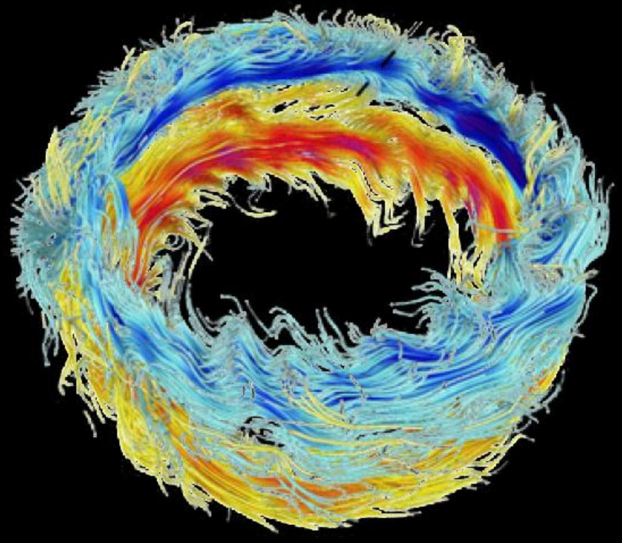


Yeates et al. 2010

Full MHD Simulations

- Solutions of the full magnetohydrodinamic (MHD) equations.





Brown et al. 2010

- They allow us to study an artificial Sun inside a computer, see what we can’t see, and go where we can’t go.

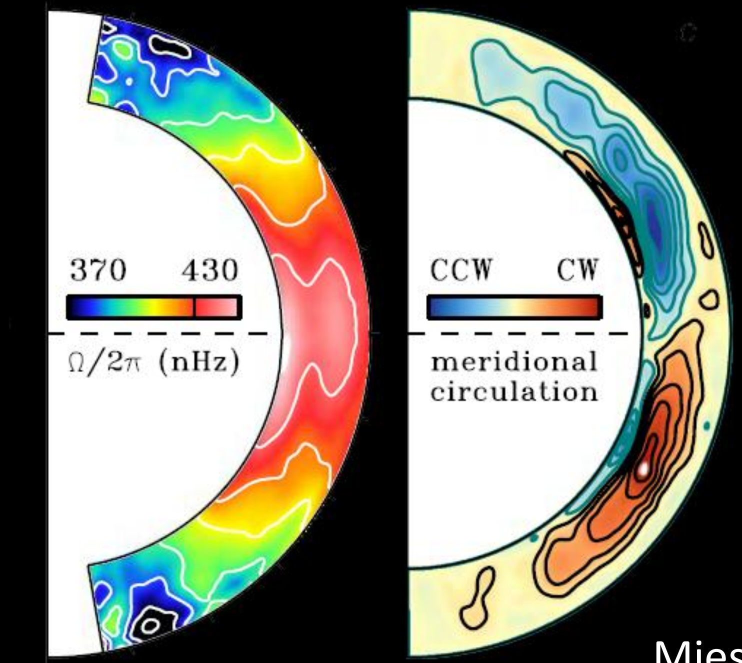
Full MHD Simulations

- **Main Advantages:**
  - Built upon basic plasma physics.
  - Self consistent evolution of both the magnetic and velocity fields.

- **Main Disadvantages:**
  - Extremely expensive computations.
  - Far from the physical regime in which the Sun operates.

Full MHD Simulations

- Used, for example, to study formation of the solar differential rotation and the meridional flow.

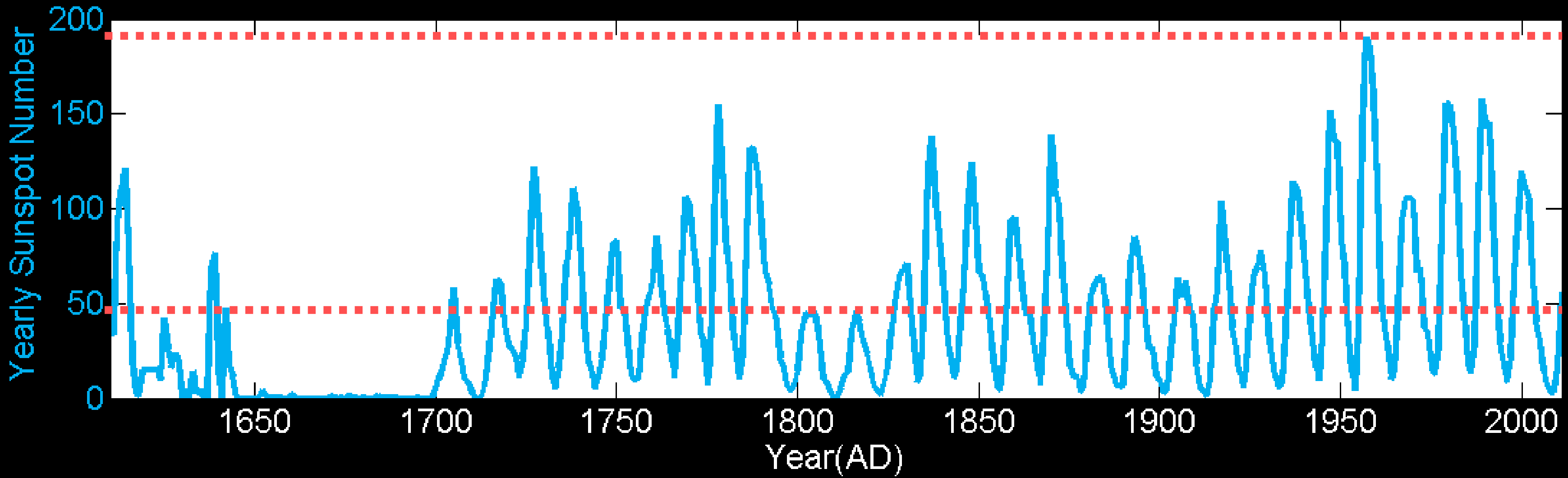


Miesch 2007

PREDICTING THE SOLAR CYCLE

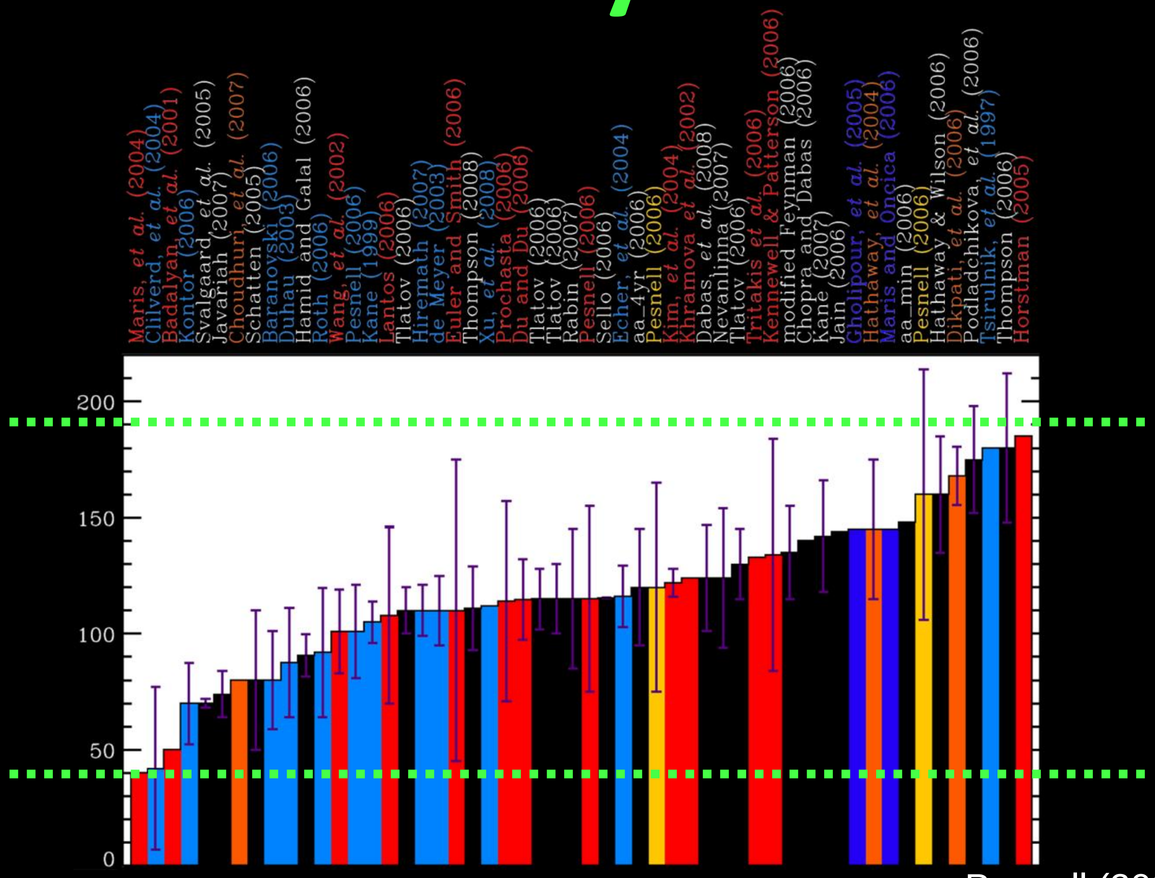
Trying to get a grip on long-term space weather

Predictions exist, but we are not quite there yet…



- Cycles have an amplitude that goes between 40 to 190 sunspots at solar maximum.

Predictions exist, but we are not quite there yet…



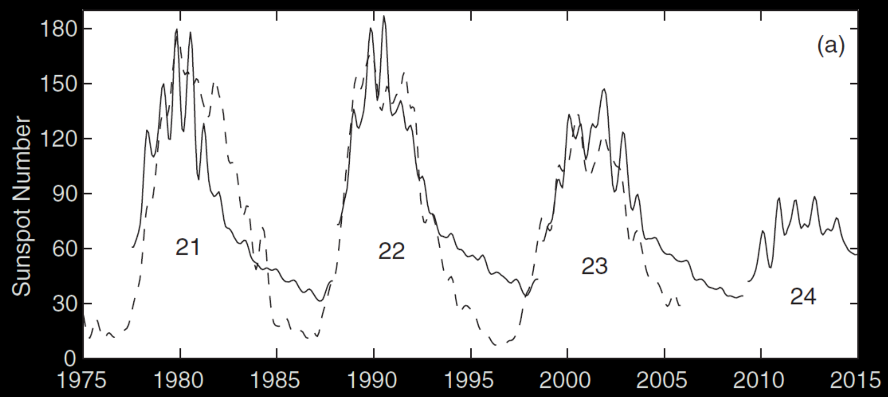
Pesnell (2008)

Range of predictions for this cycle (24) spans the entire range of all sunspot cycles directly observed!

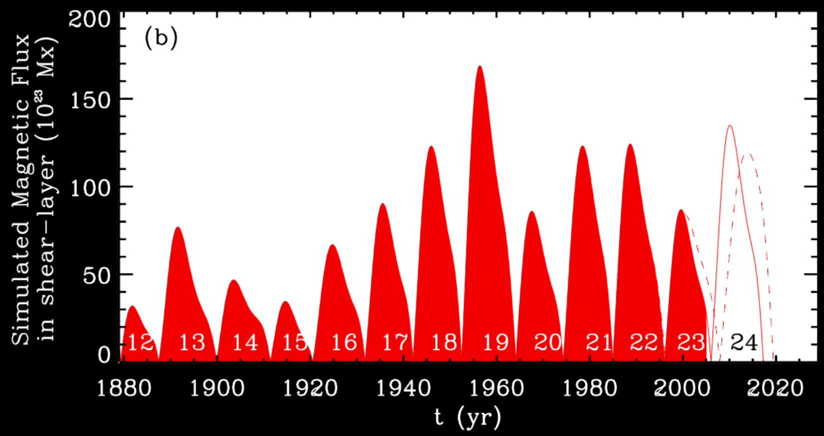
Types of solar cycle predictions

- Statistical/mathematical analysis of past sunspot data (no physics).
- Precursors: quantities that define the coming cycle early (invokes some physics).
- Solar dynamo models (physics-based).
  - Understanding of the dynamo mechanism required

Dynamo-based Predictions



Choudhuri et al. (2007)



Dikpati et al. (2006)

- Choudhuri et al. predict a much weaker solar cycle 24.
- Dikpati et al. predict a very strong solar cycle 24.

Why the difference?

The nature of flux-transport and the memory of the cycle

Dominated by
Turbulent Diffusion
Choudhuri et al. (2007)

Dominated by
Meridional flow
Dikpati et al. (2006)

- Different flux transport regimes have different intrinsic memory.

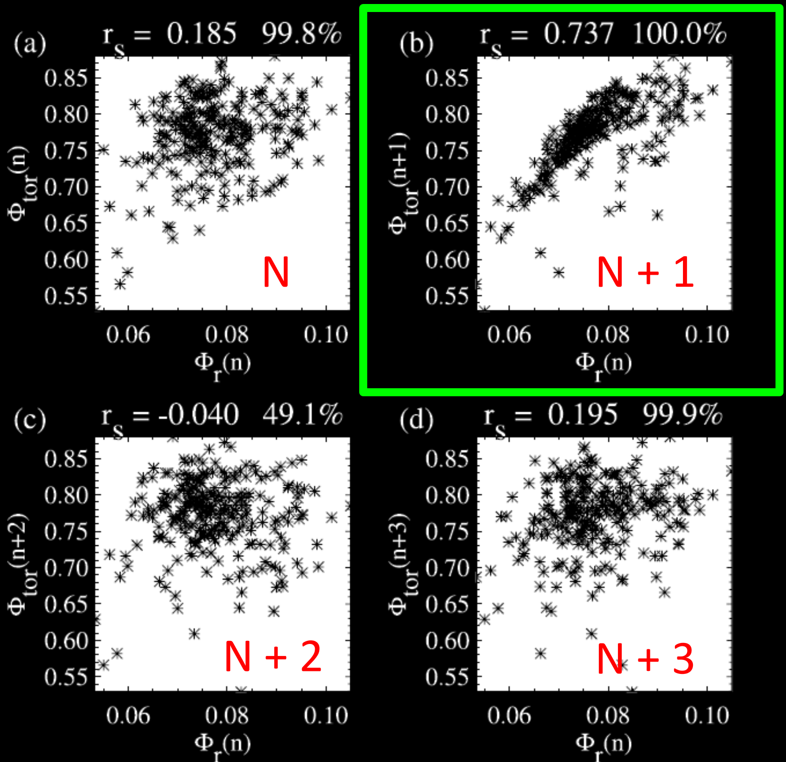
- Studied by introducing randomness in the poloidal field creation process.

Yeates, Nandy & Mackay. (2008)

The nature of flux-transport and the memory of the cycle

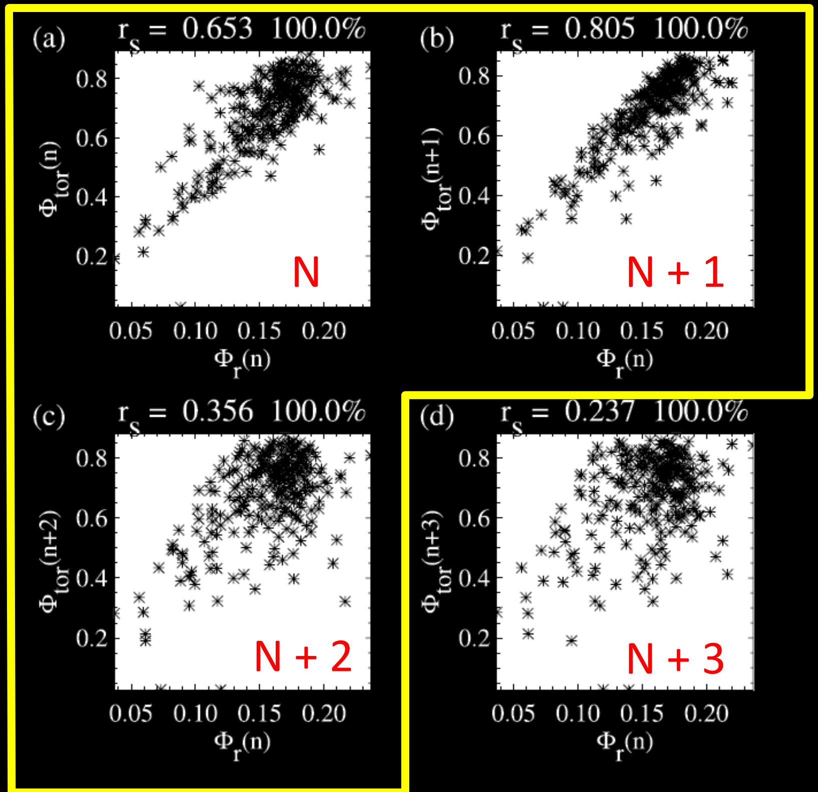
Dominated by Turbulent Diffusion

Choudhuri et al. (2007)



Dominated by Meridional flow

Dikpati et al. (2006)



There are still a lot of things to do

- Improving our long-term databases.
- Better assimilation of AR data.
- Systematic assimilation of helioseismic data.
- Understand better the nature of flux transport.

SUMMARY

- The solar cycle is a process that takes the global solar magnetic field between poloidal and a toroidal phases.
- The main ingredients of the solar cycle are: the differential rotation, the meridional flow, the turbulent diffusivity and active region emergence and decay.
- Large-scale plasma flows are crucial in setting the amplitude and duration of the cycle.
- There are several models used to understand the solar cycle, each with strength and weaknesses – all are useful!
- Solar cycle prediction is one of the main goals of solar physics, we have advanced much, but we are not there yet.

A great resource for learning about heliophysics

Living Reviews in Solar Physics

http://solarphysics.livingreviews.org

- Sun-Earth Connection.
- Solar Wind and Heliosphere.
- Solar Surface and Atmosphere.
- Solar-Stellar Connection.
- Solar Interior.
- Solar Activity.
- Instruments, Methods and Techniques.

ANY MORE QUESTIONS?