Solar cycle: Observations and Characteristics

Andrés Muñoz-Jaramillo

www.solardynamo.org

Georgia State University
University of California - Berkeley
Stanford University

HOW DOES THE SOLAR CYCLE OPERATE?

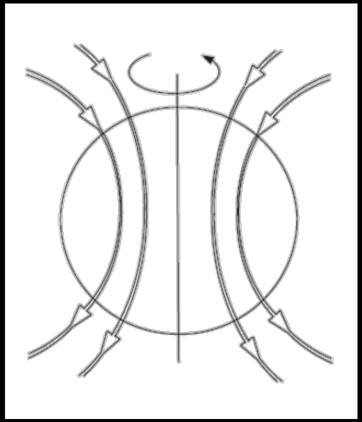
Solar Cycle Propagation

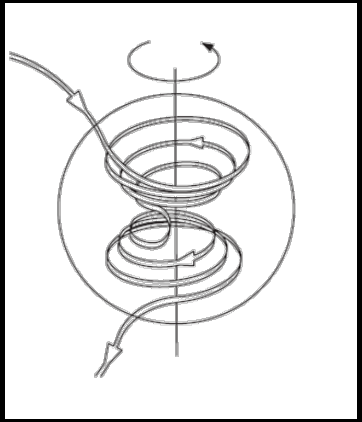
Poloidal

$r - \theta$

Toroidal

ϕ





Credit: J. J. Love

Polar Flux

Sunspot Numbers/Area

Solar Cycle Propagation

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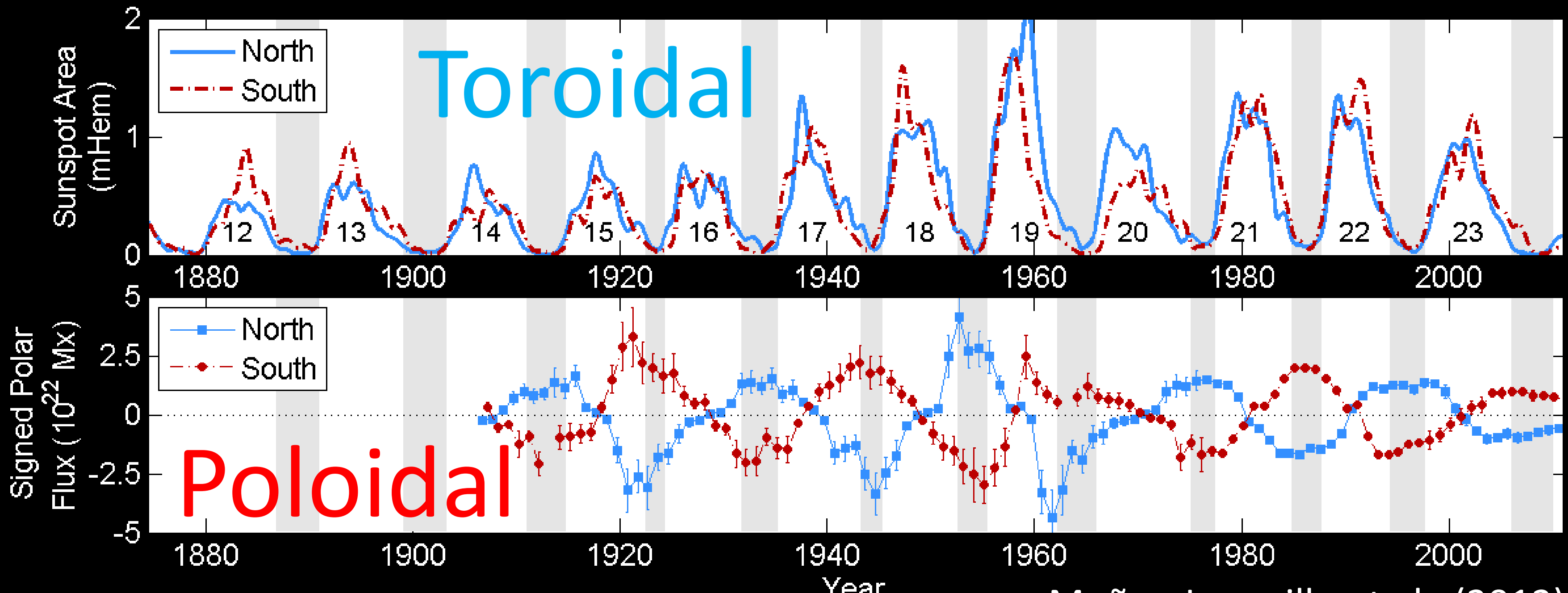

Muñoz-Jaramillo et al. (2012)

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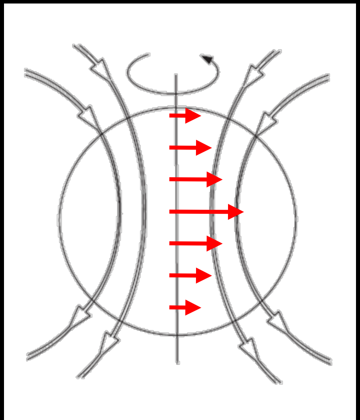
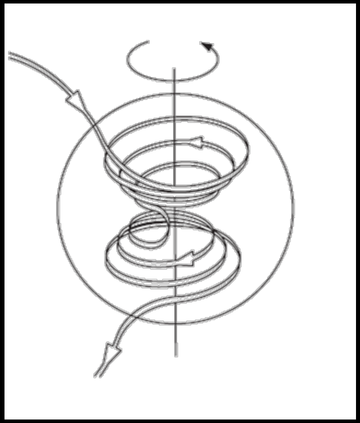
r - θ



Differential Rotation →

Toroidal

φ



Credit: J. J. Love

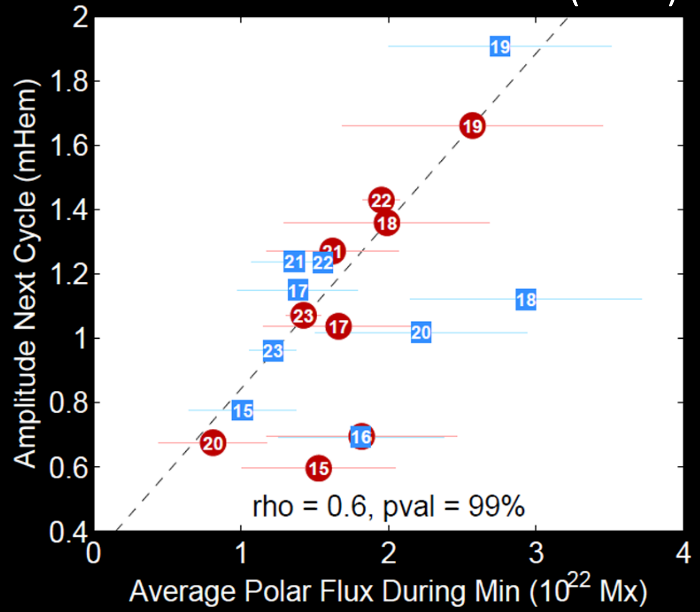
Solar Cycle Propagation

Differential Rotation

Poloidal $\xrightarrow{\text{Differential Rotation}}$ Toroidal

$r - \theta$ $\qquad$ ϕ

Muñoz-Jaramillo et al. (2013)



Solar Cycle Propagation

Poloidal $\xrightarrow{\text{Differential Rotation}}$ Toroidal ✓

$r - \theta$ $\xleftarrow{\quad ? \quad}$ ϕ

Small-Scale and Local

- Also known as α-effect.
- Limited by the relative amount energy available in convection.

Large-Scale and Global

- Also known as Babcock-Leighton effect.
- Limited to strong flux-tubes.

Solar Cycle Propagation

Differential Rotation

Poloidal

$r - \theta$

Toroidal

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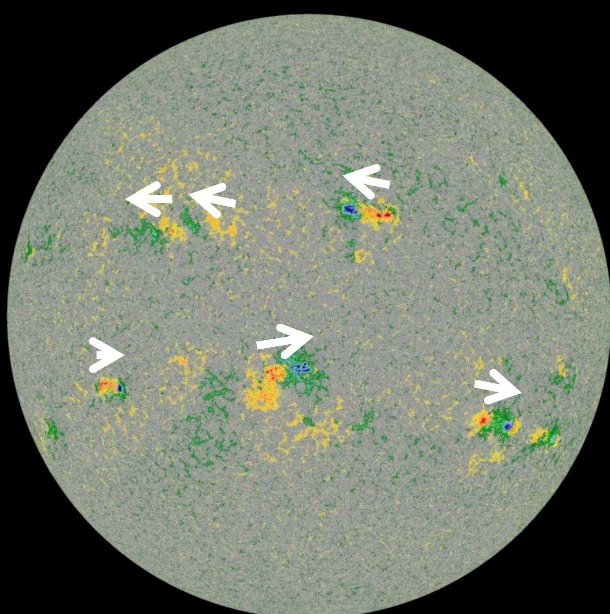
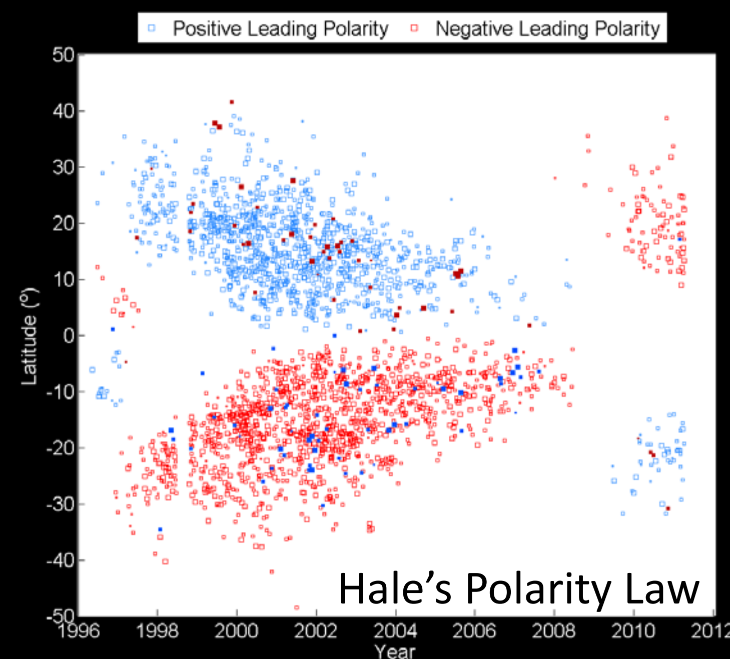
Emergence and Decay of Tilted Active Regions





Solar Cycle Propagation

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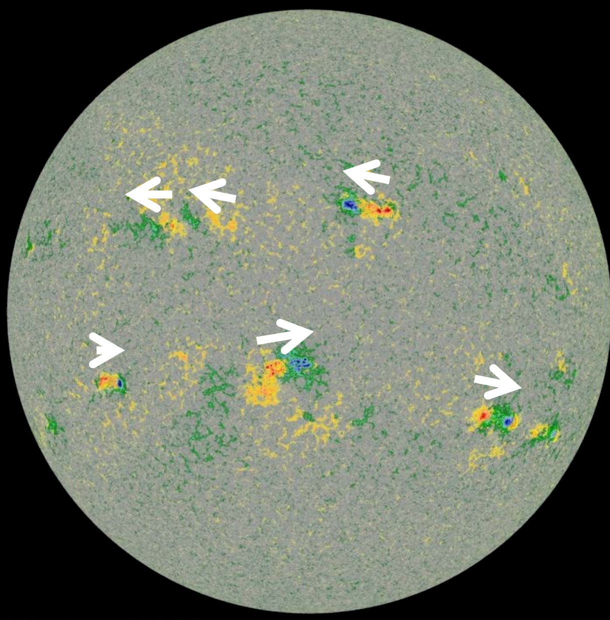
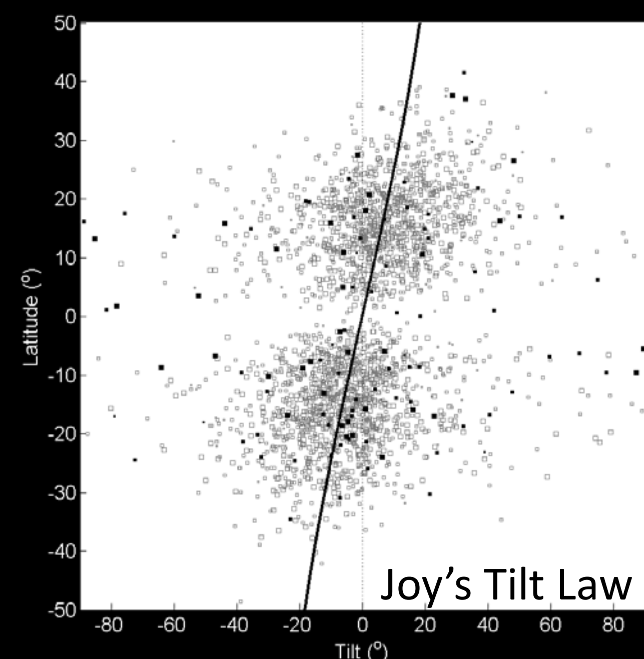
$\xleftarrow{\text{Emergence and Decay of Tilted Active Regions}}$

Emergence and Decay of Tilted Active Regions





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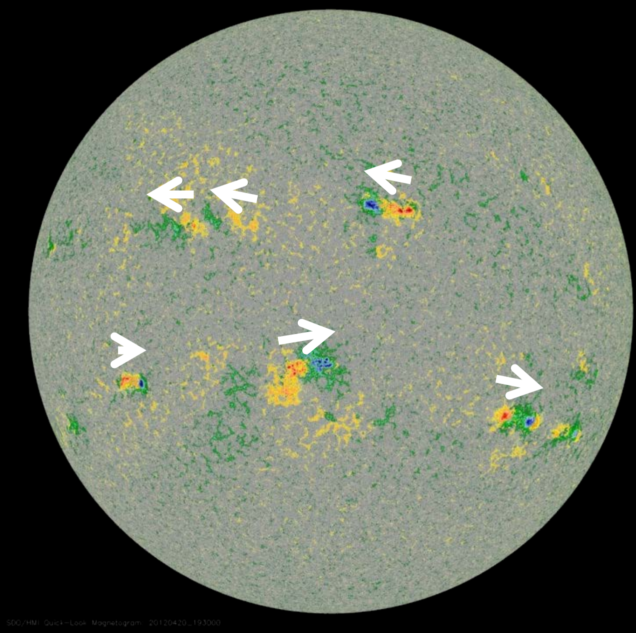

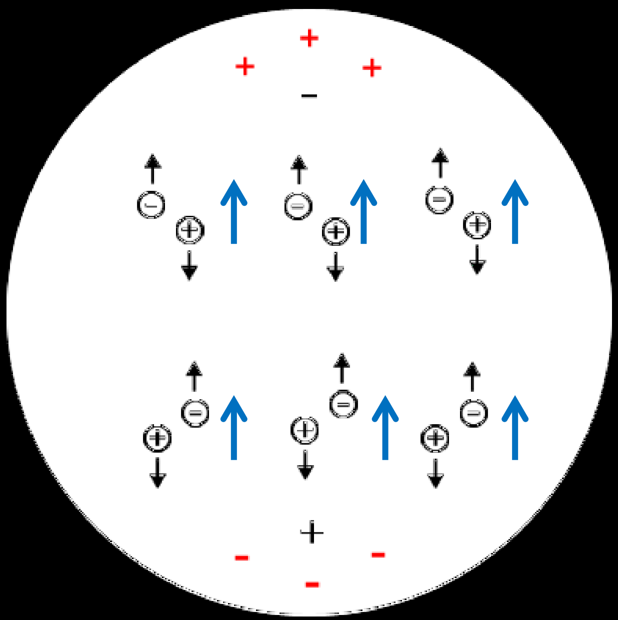

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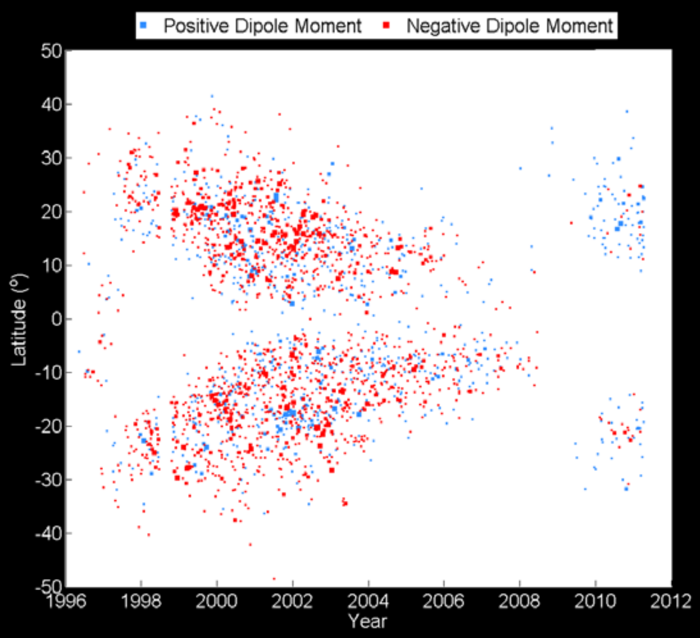

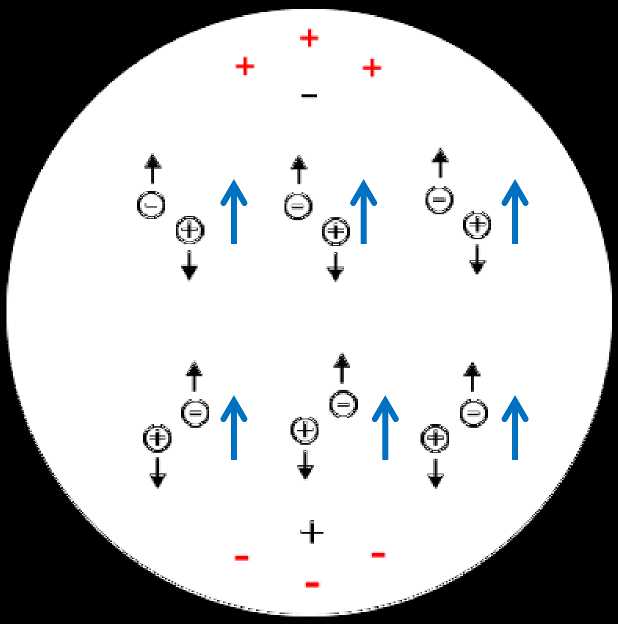

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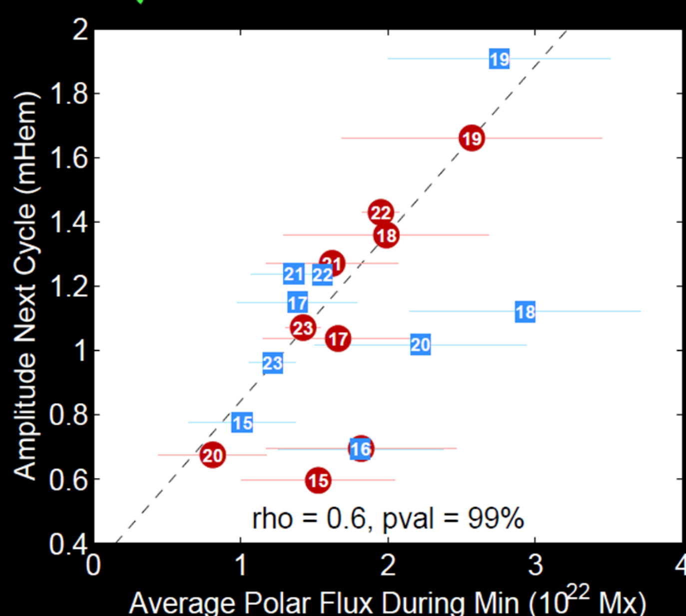
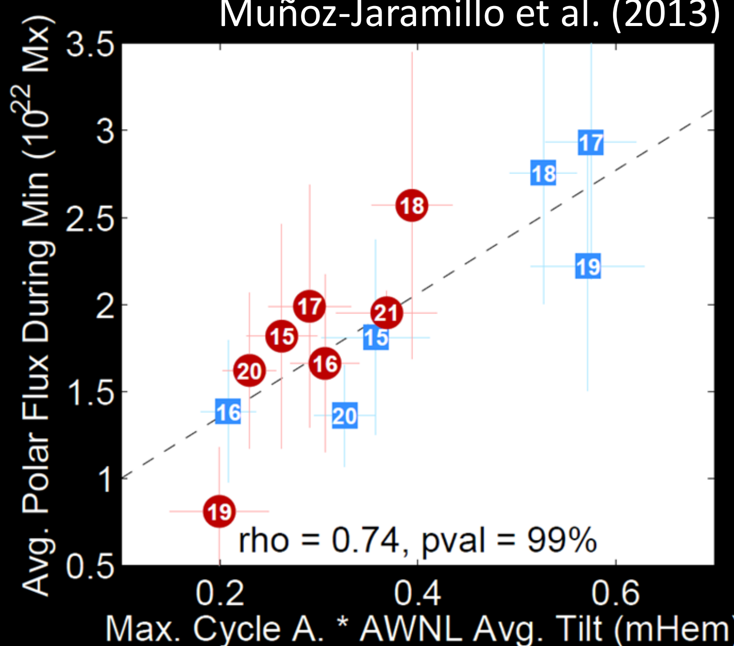
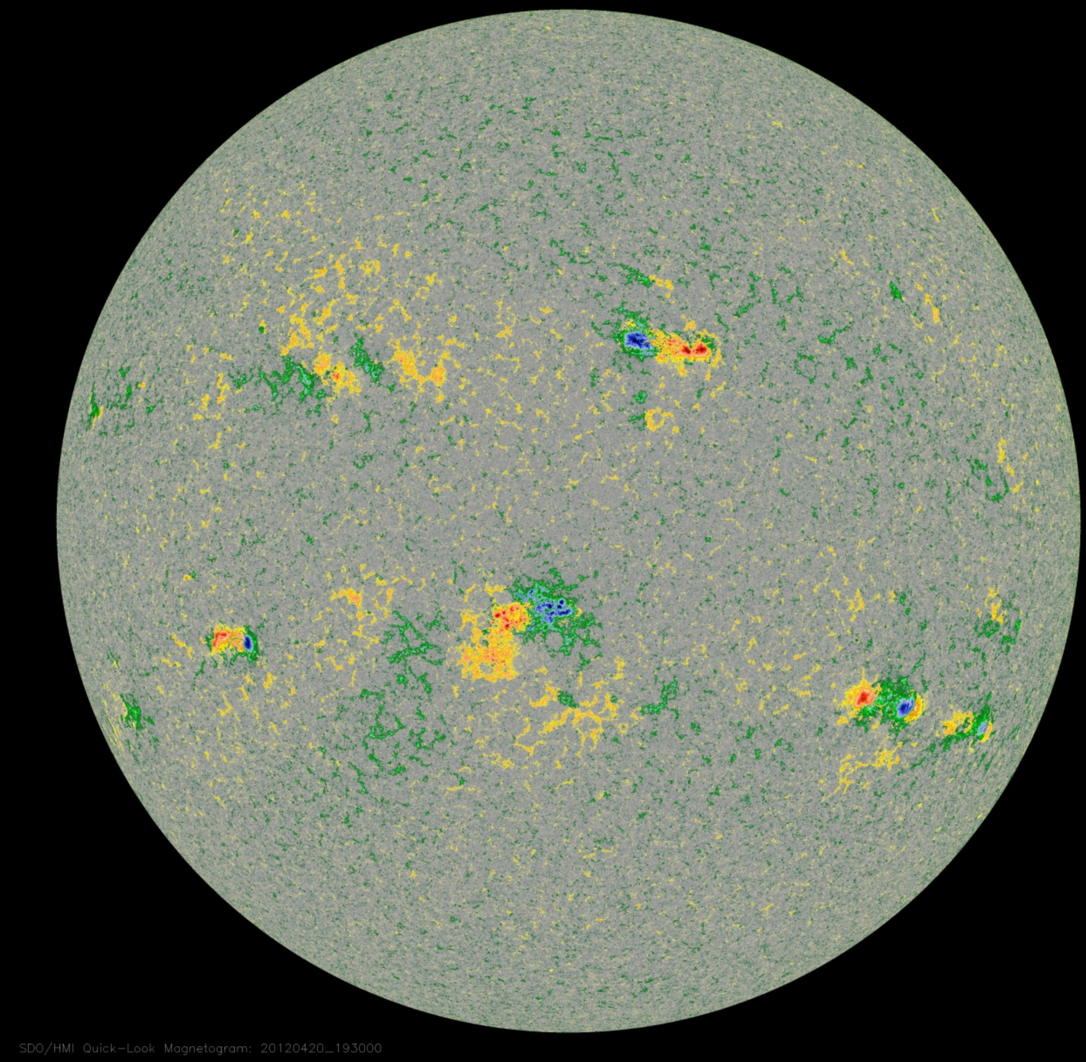


Muñoz-Jaramillo et al. (2013)



THE SOLAR CYCLE AND THE LARGE SCALE SOLAR MAGNETIC FIELD

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



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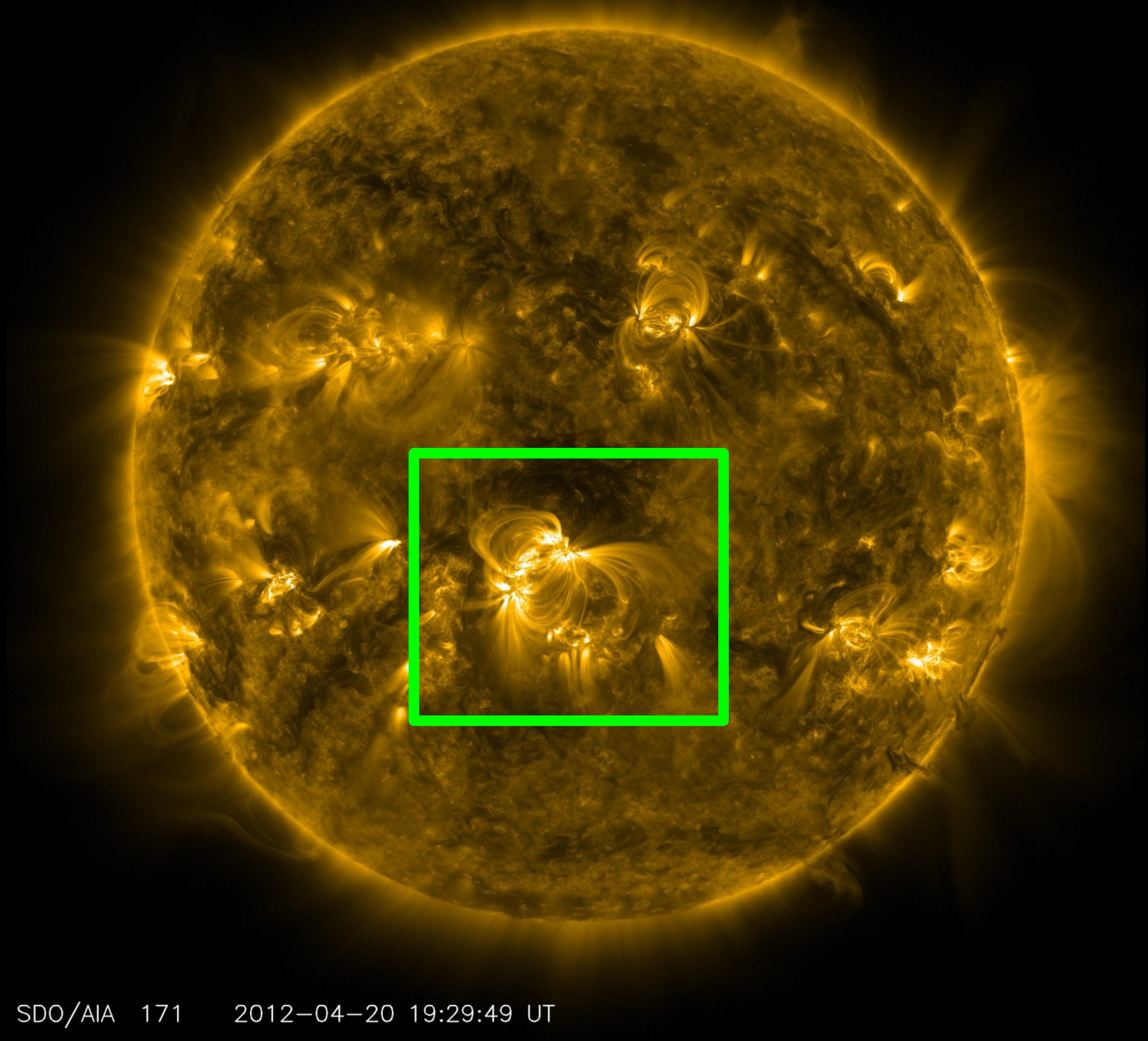

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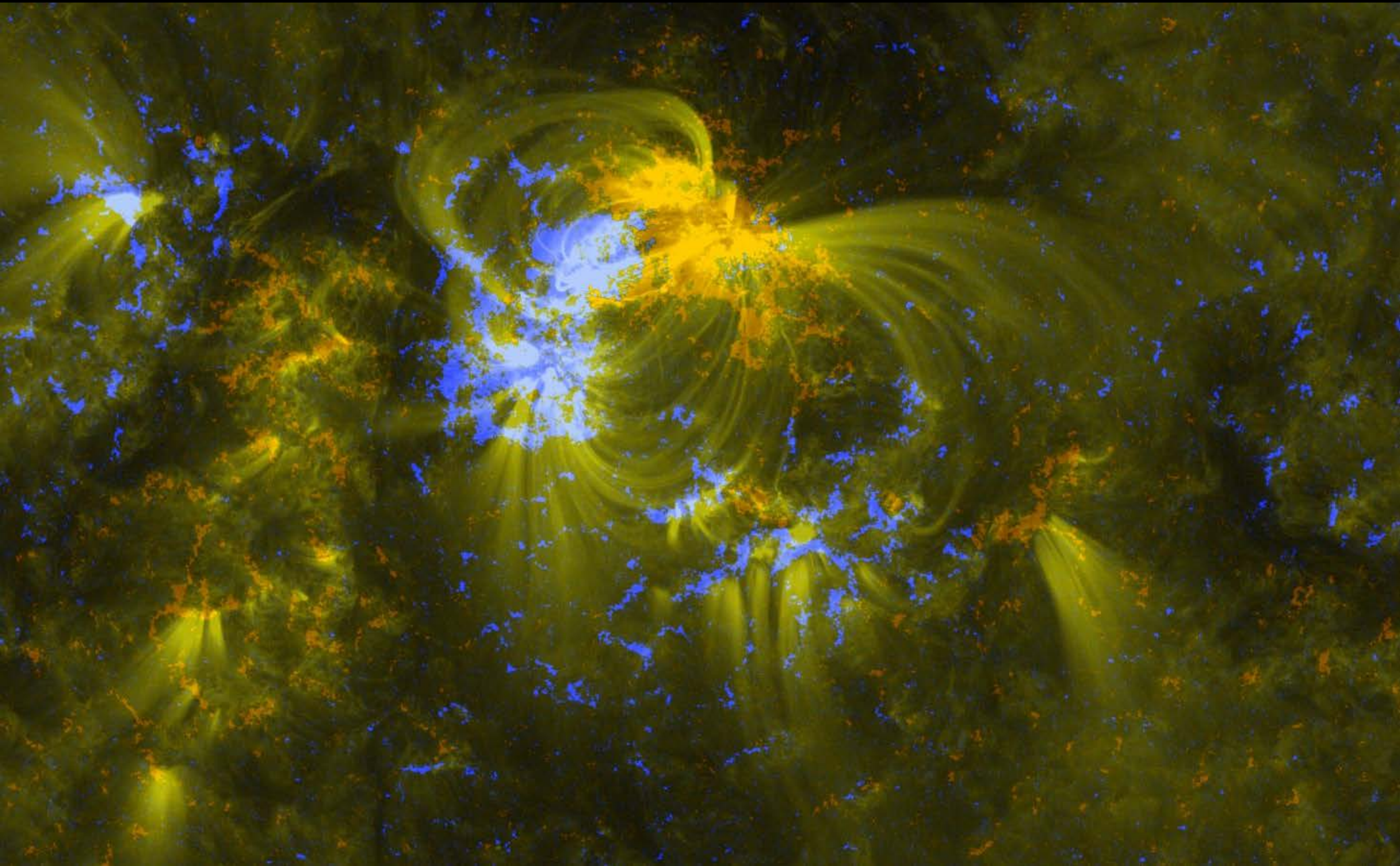
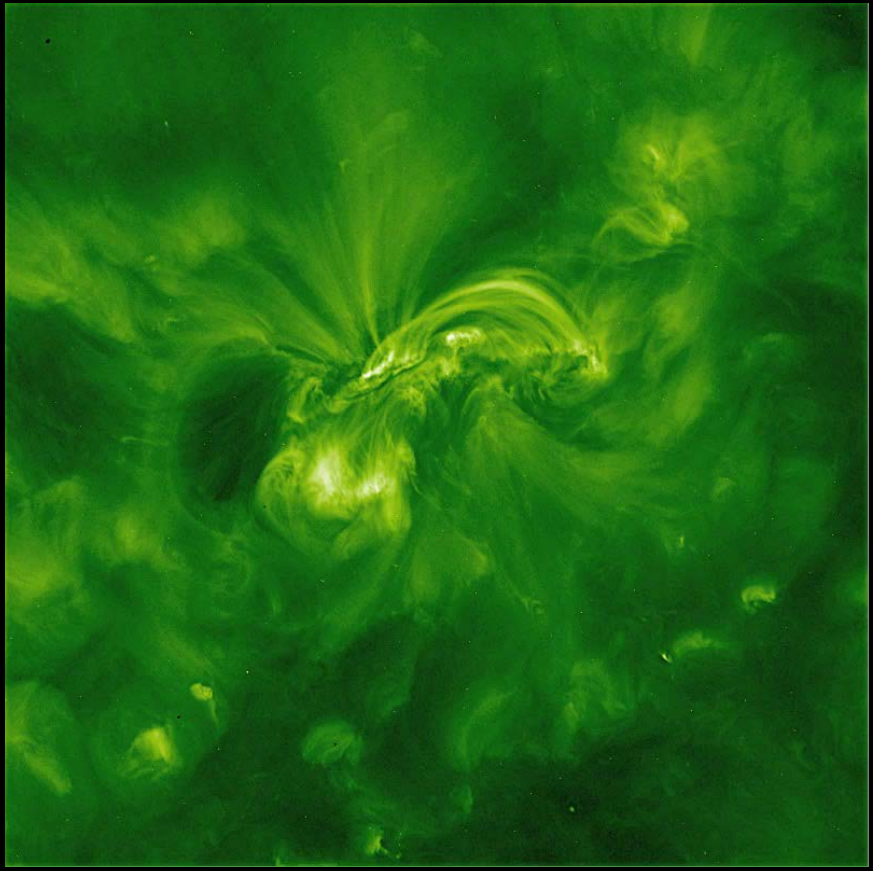
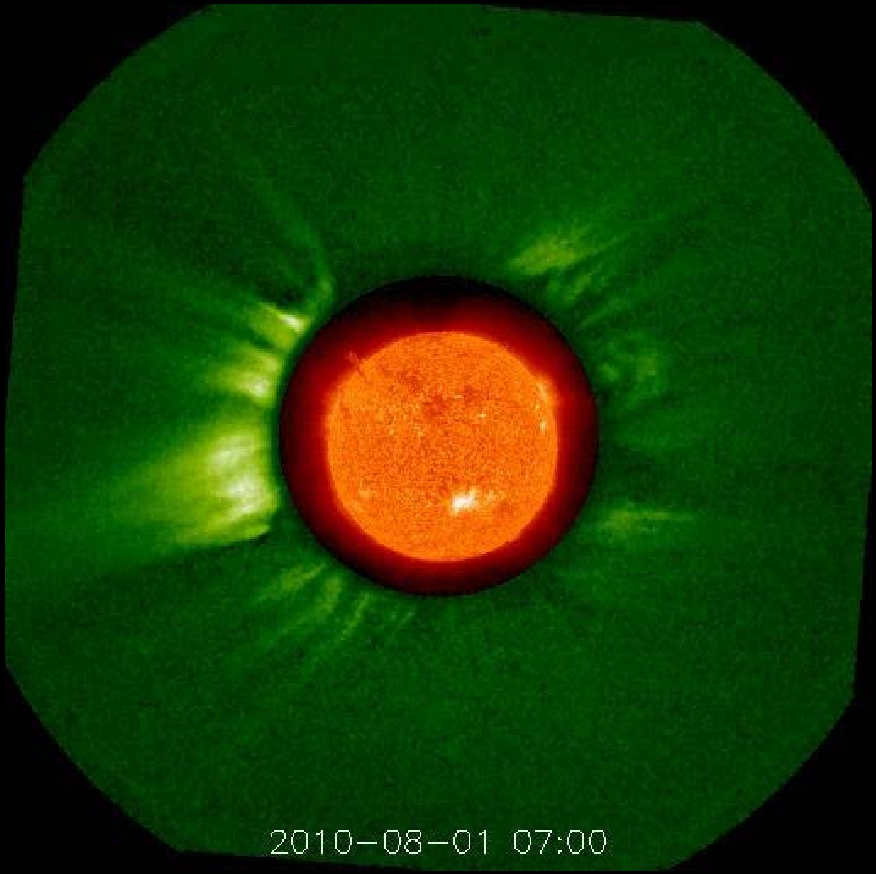


Violent reconfigurations of the solar magnetic field release this energy in the form of:

Flares

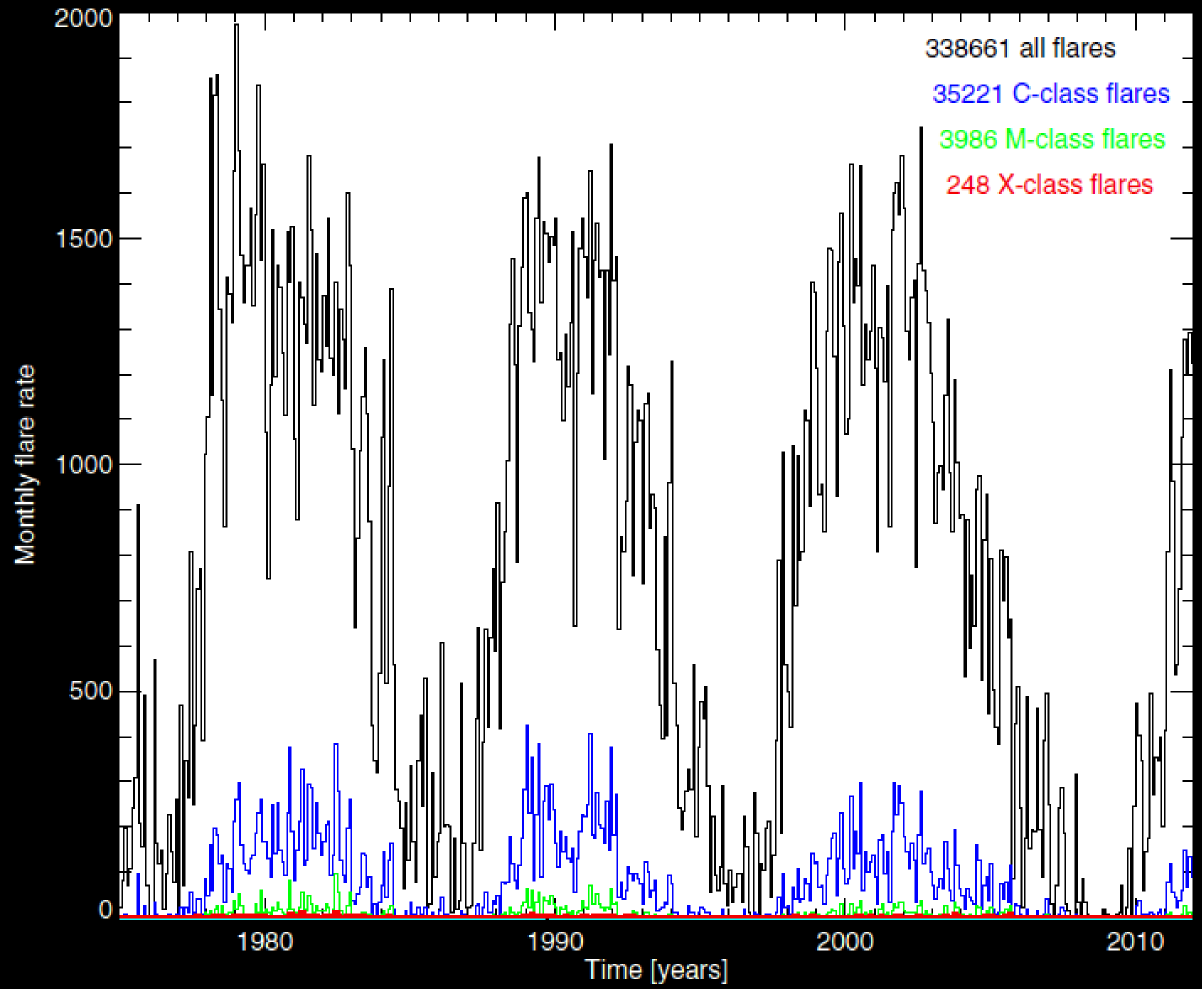


Coronal Mass Ejections



These highly energetic events are modulated by the solar cycle

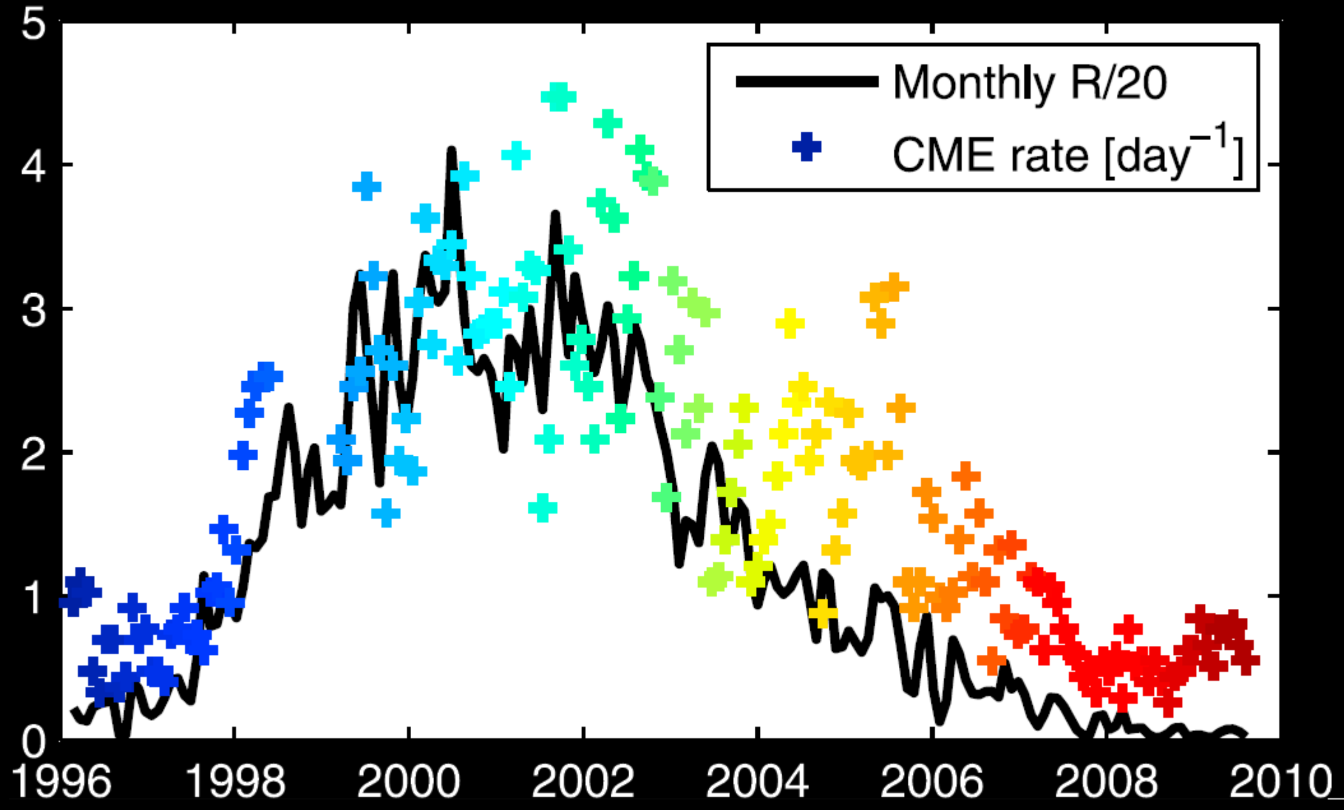
Both Flares…



Aschwanden & Freeland 2012

These highly energetic events are modulated by the solar cycle

… and CMEs



Owens & Lockwood 2012

The presence of active regions has a strong impact on the connectivity of the solar corona

Images by Miloslav Druckmüller

Solar Maximum

Solar Minimum

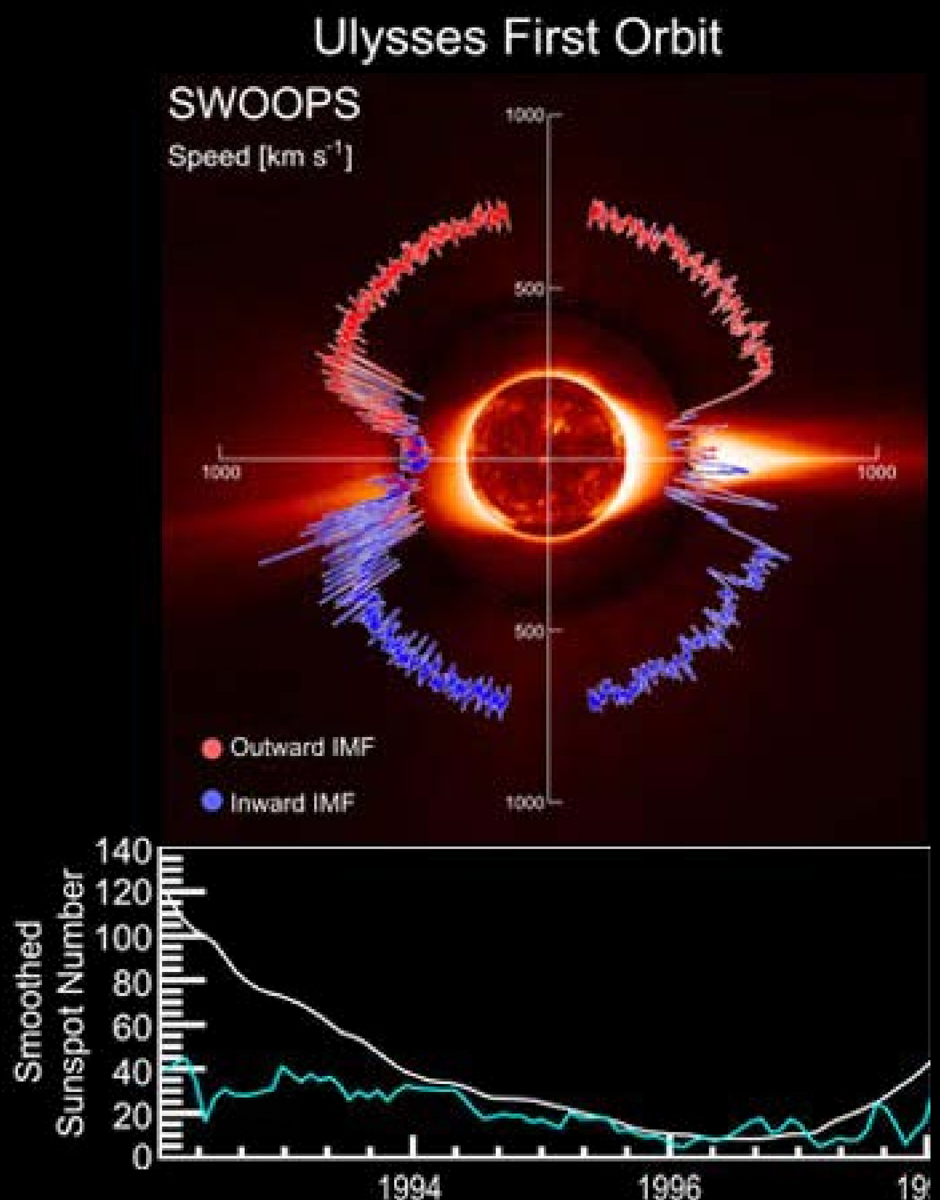
Solar wind properties also change with the cycle

Images by Miloslav Druckmüller

Solar Maximum

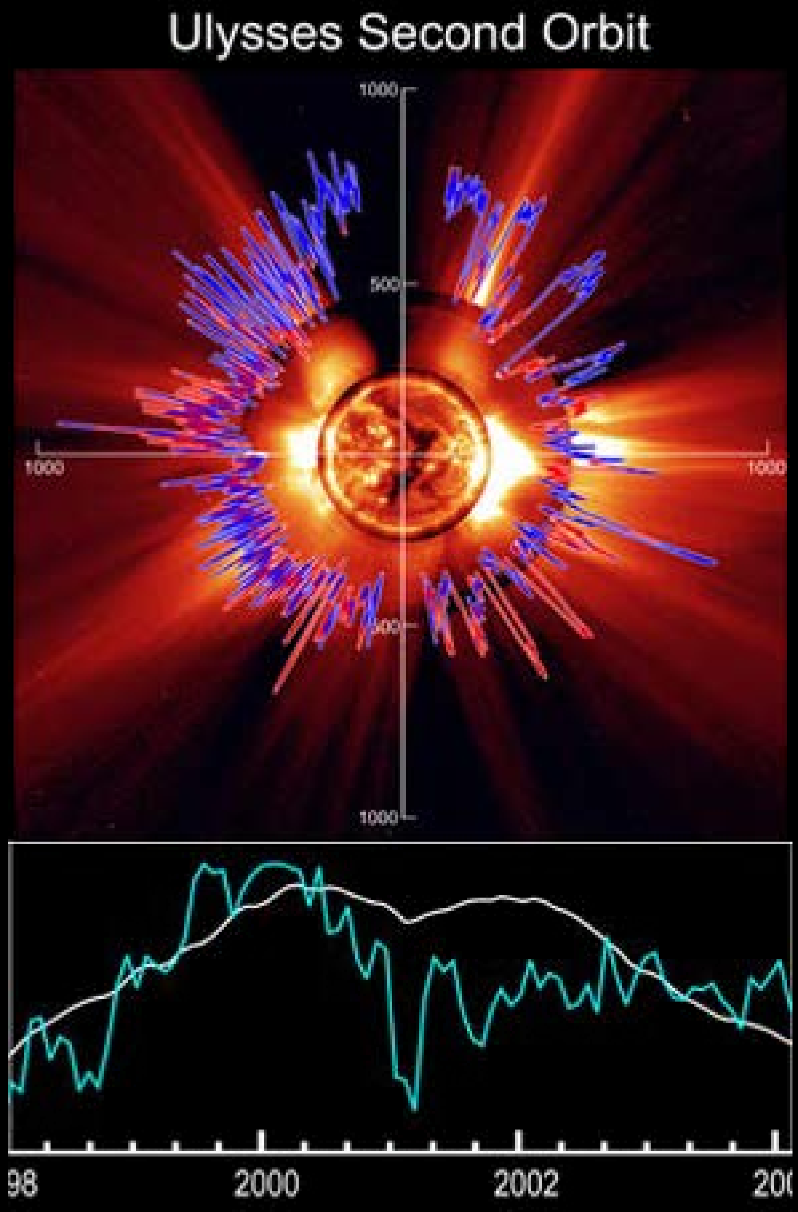
Solar Minimum

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

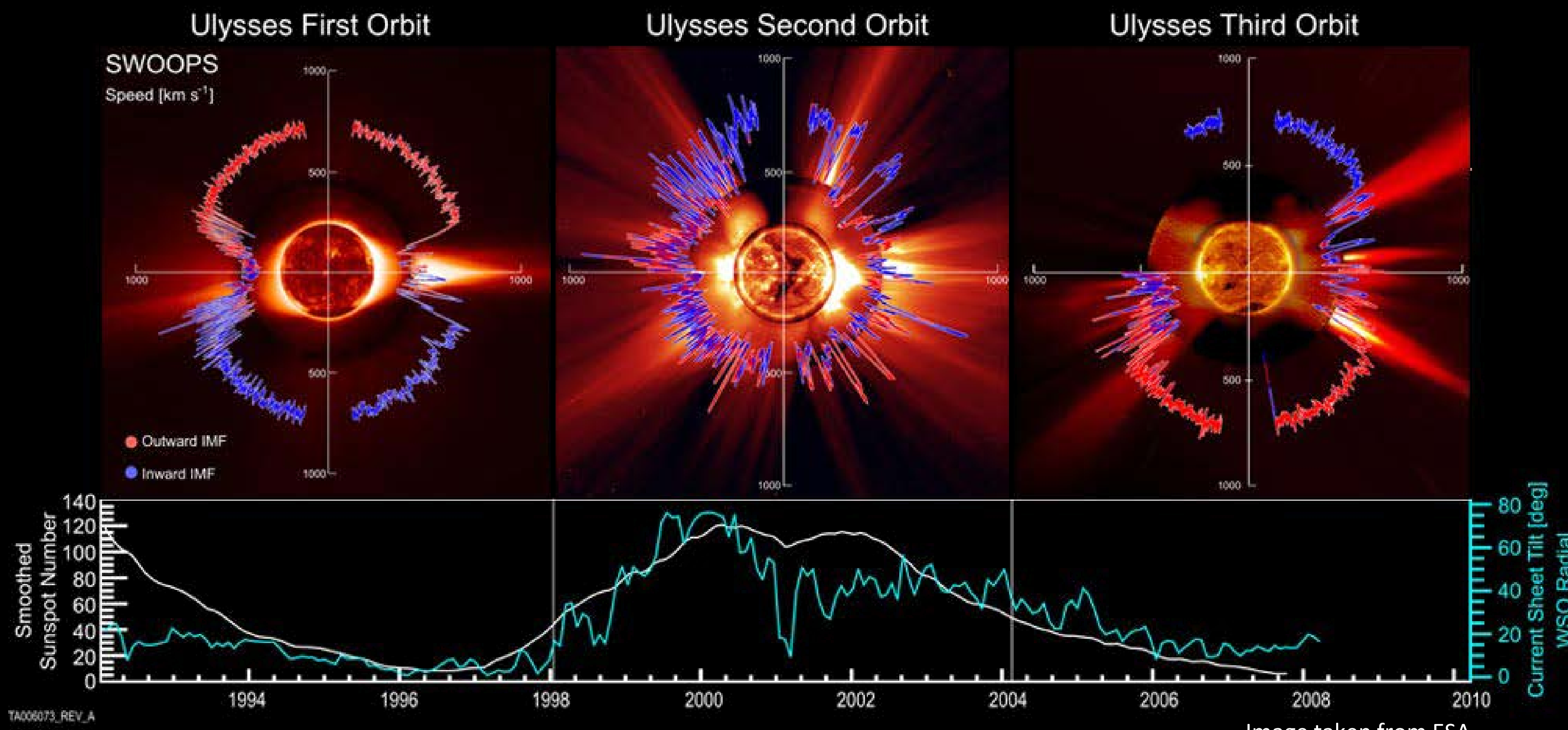
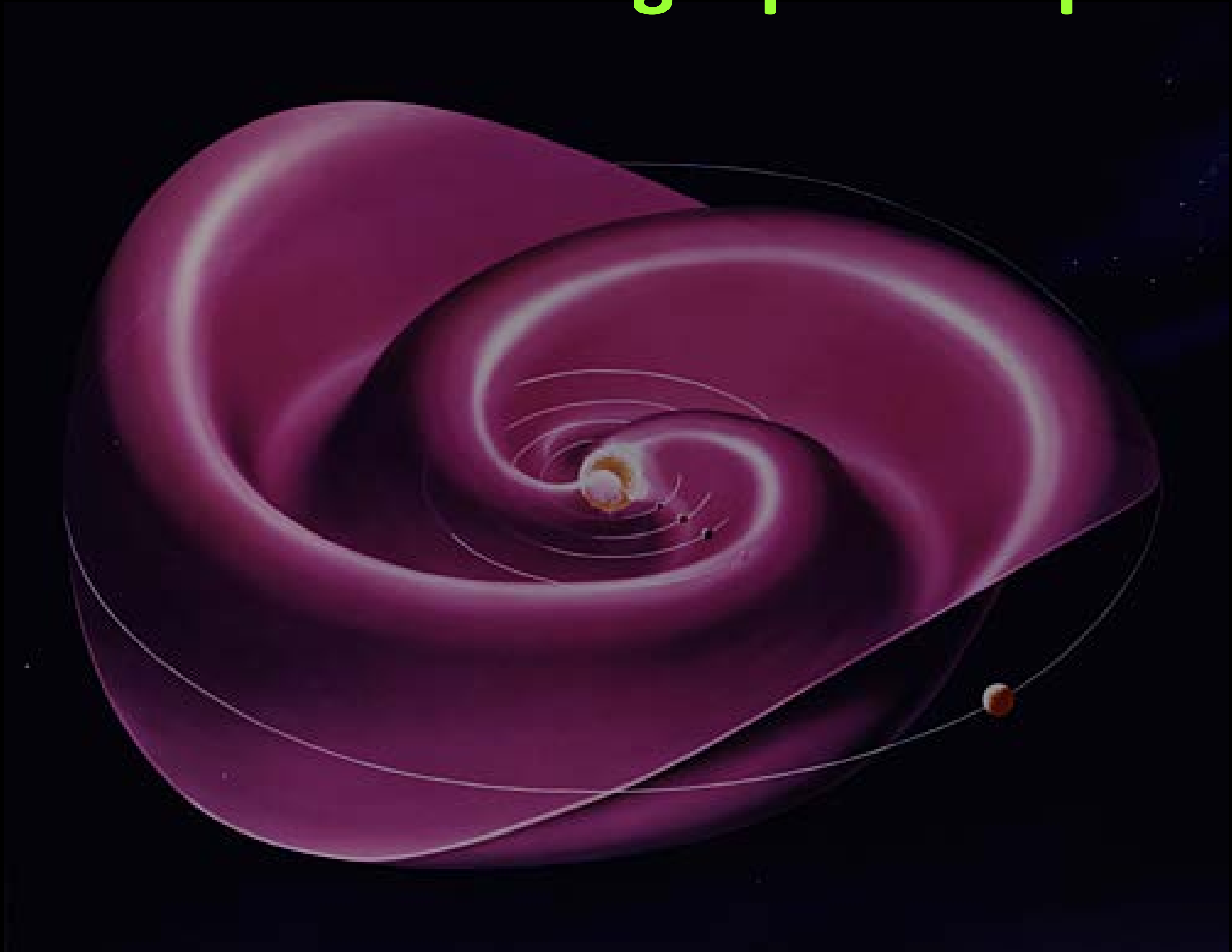


Image taken from ESA

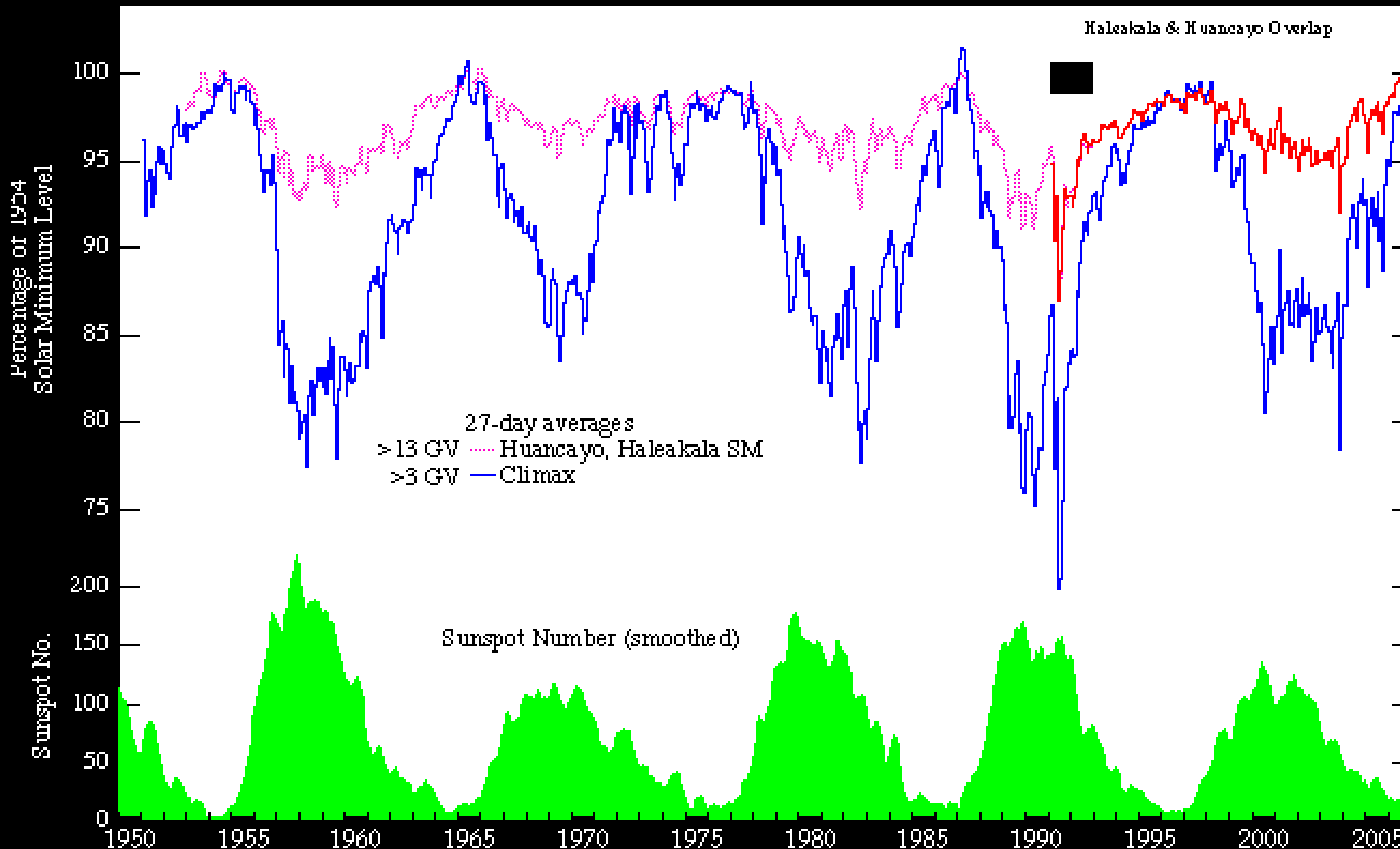
Solar wind drags the magnetic field outwards forming a parker spiral.



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

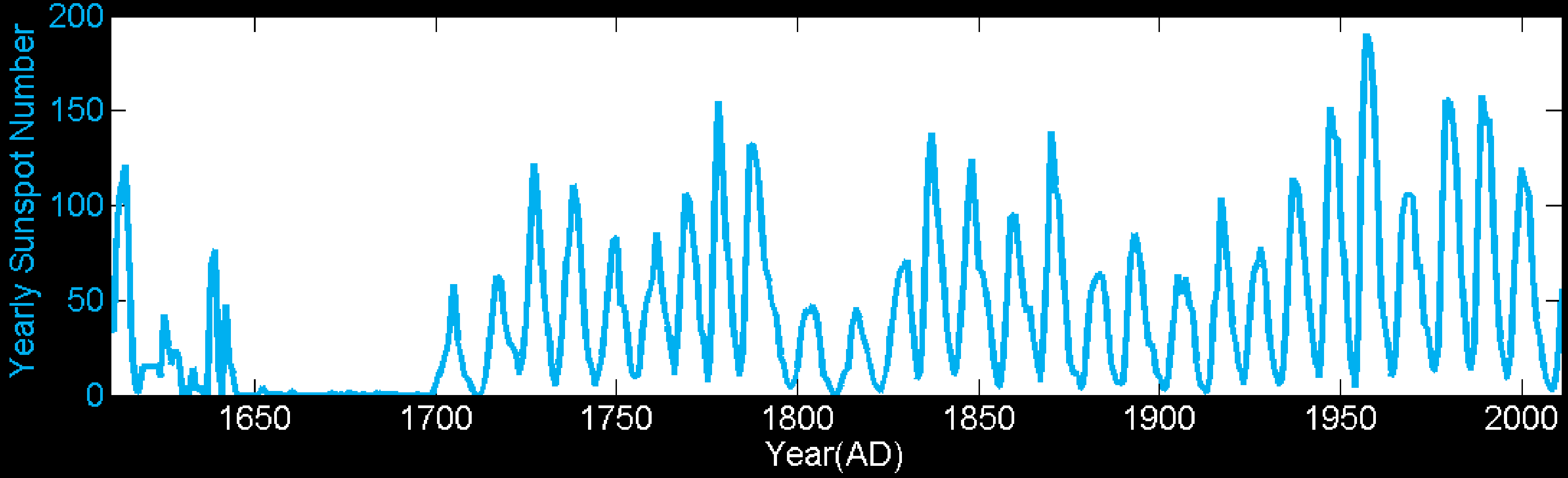
- High energy particles coming from outside the solar system.
- Scattered by magnetic irregularities propagating in the solar wind.
- Modulation is weaker for high-energy cosmic rays.
- Cosmic rays generate isotopes that can be used to study long-term solar activity.

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



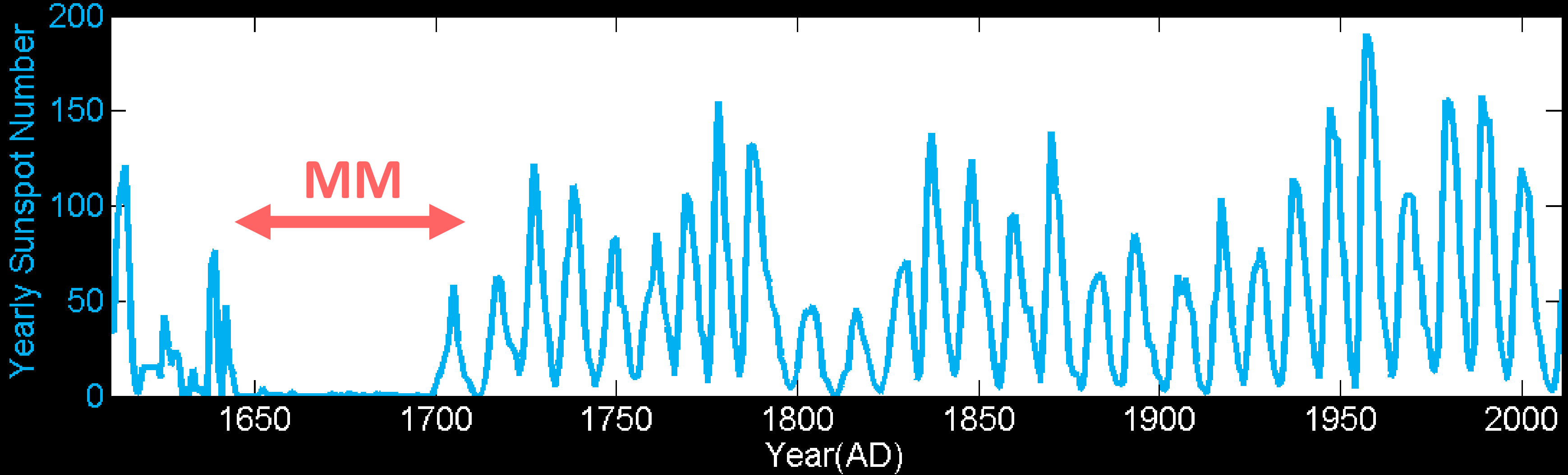
LONG-TERM CYCLE VARIABILITY

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



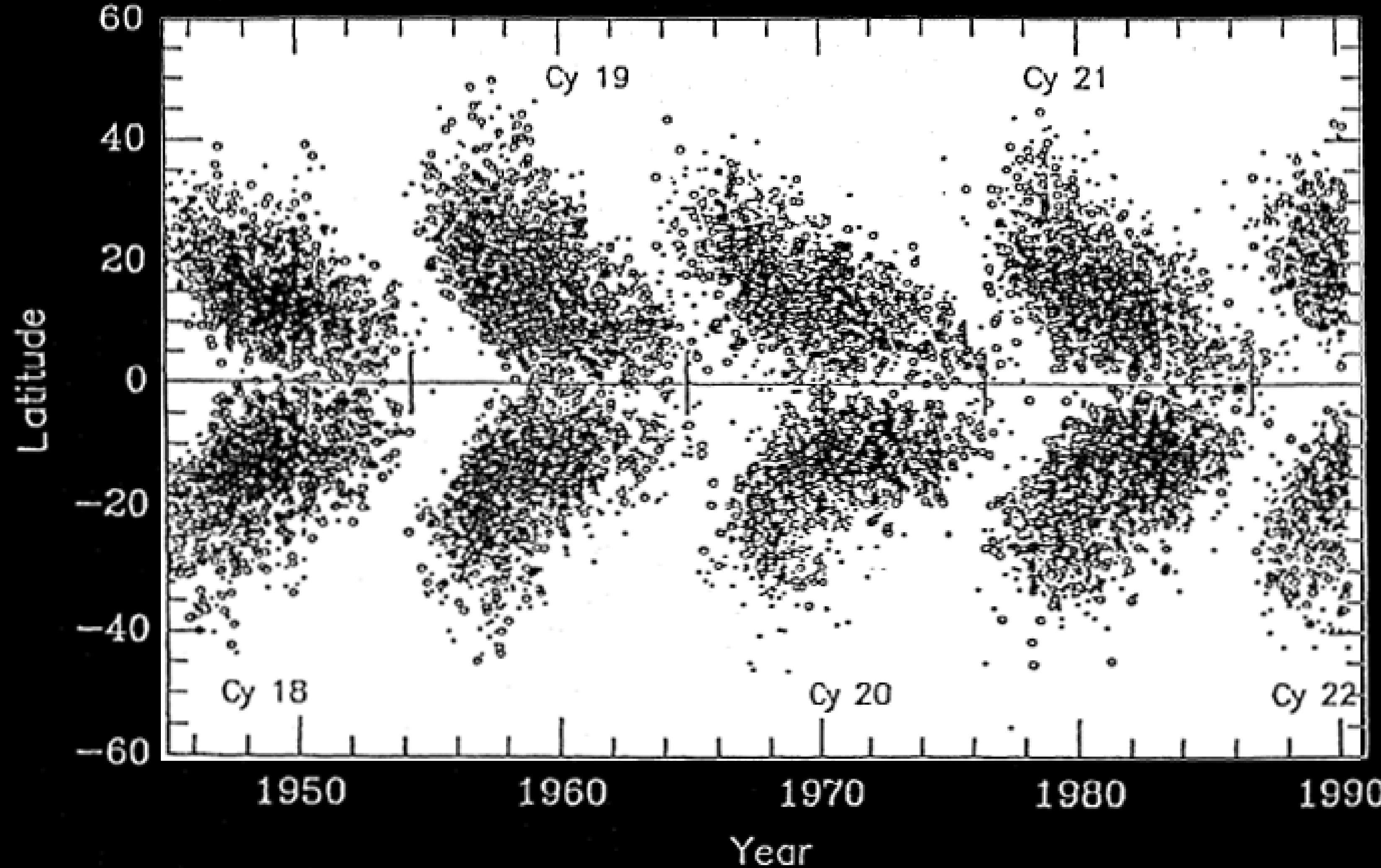
- Strongest (weakest) cycle has an SSN amplitude of 188 (43). Mean is 90 +/- 41.
- Longest (shortest) cycle has a duration of 14 (9) years. Mean is 11 +/- 14 months.
- Data taken from Hathaway (2010).

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 with few sunspot observations



Ribes & Nesme-Ribes 1993

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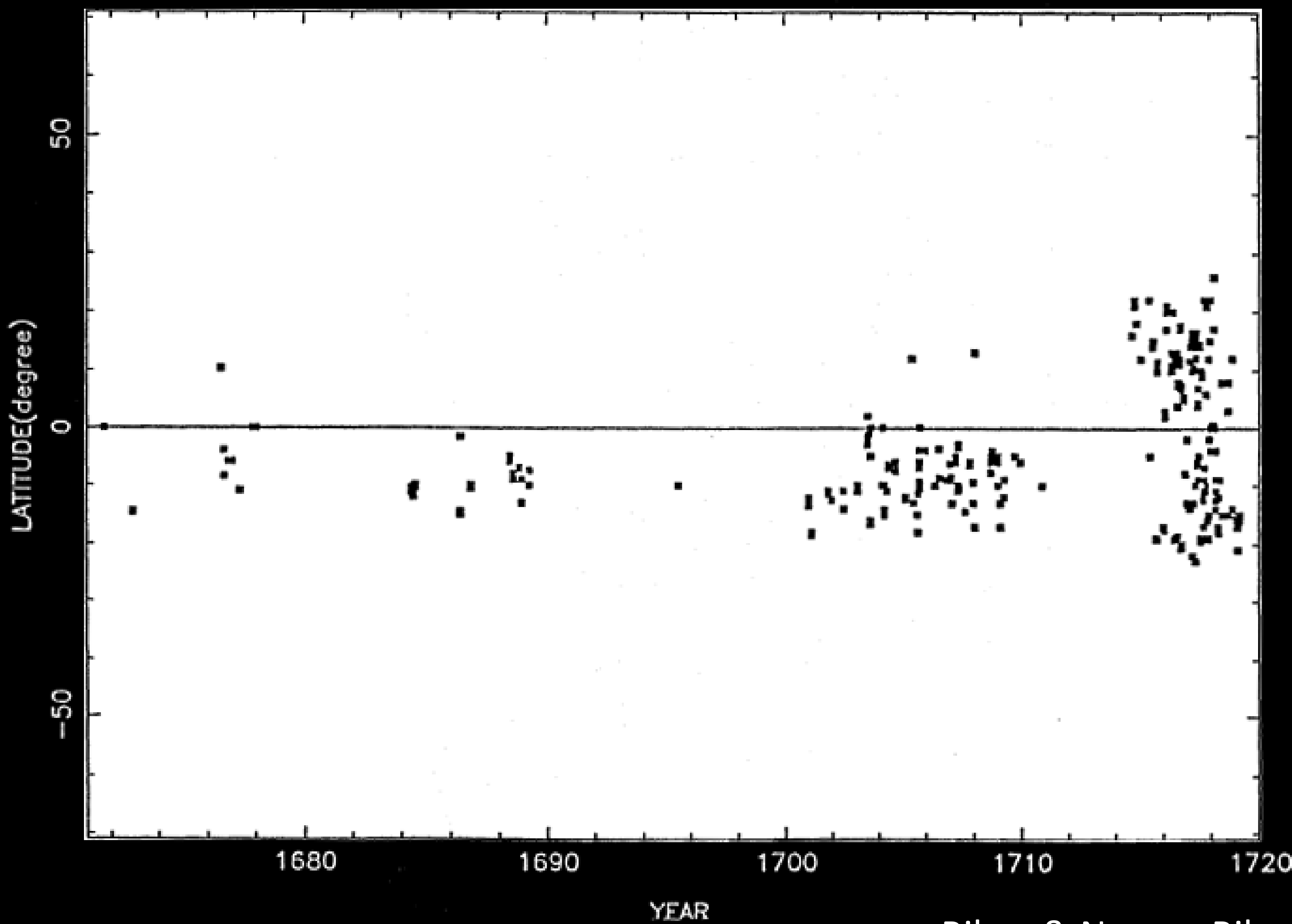
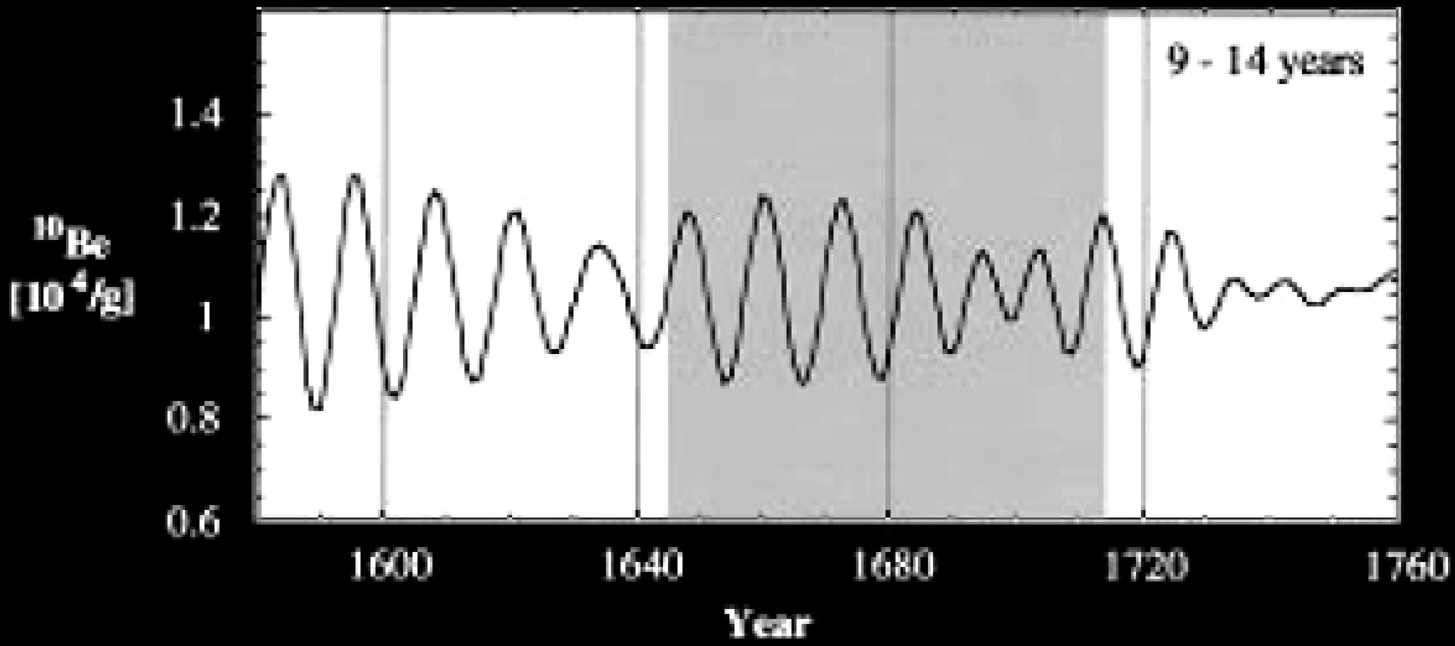


Ribes & Nesme-Ribes 1993

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).

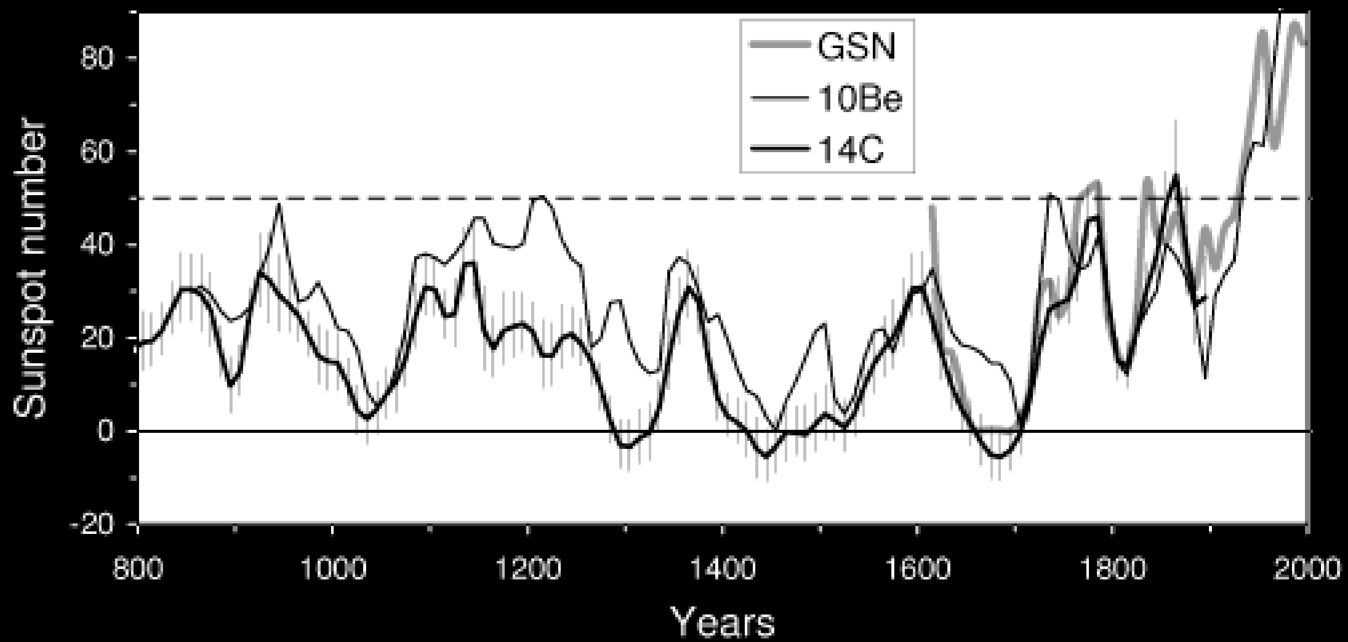


Beer et al. 1998

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).
- The solar cycle seems to be working during the Maunder minimum, but perhaps not as a Babcock-Leighton dynamo.
- For the latest work check Vaquero et al. 2015.

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.

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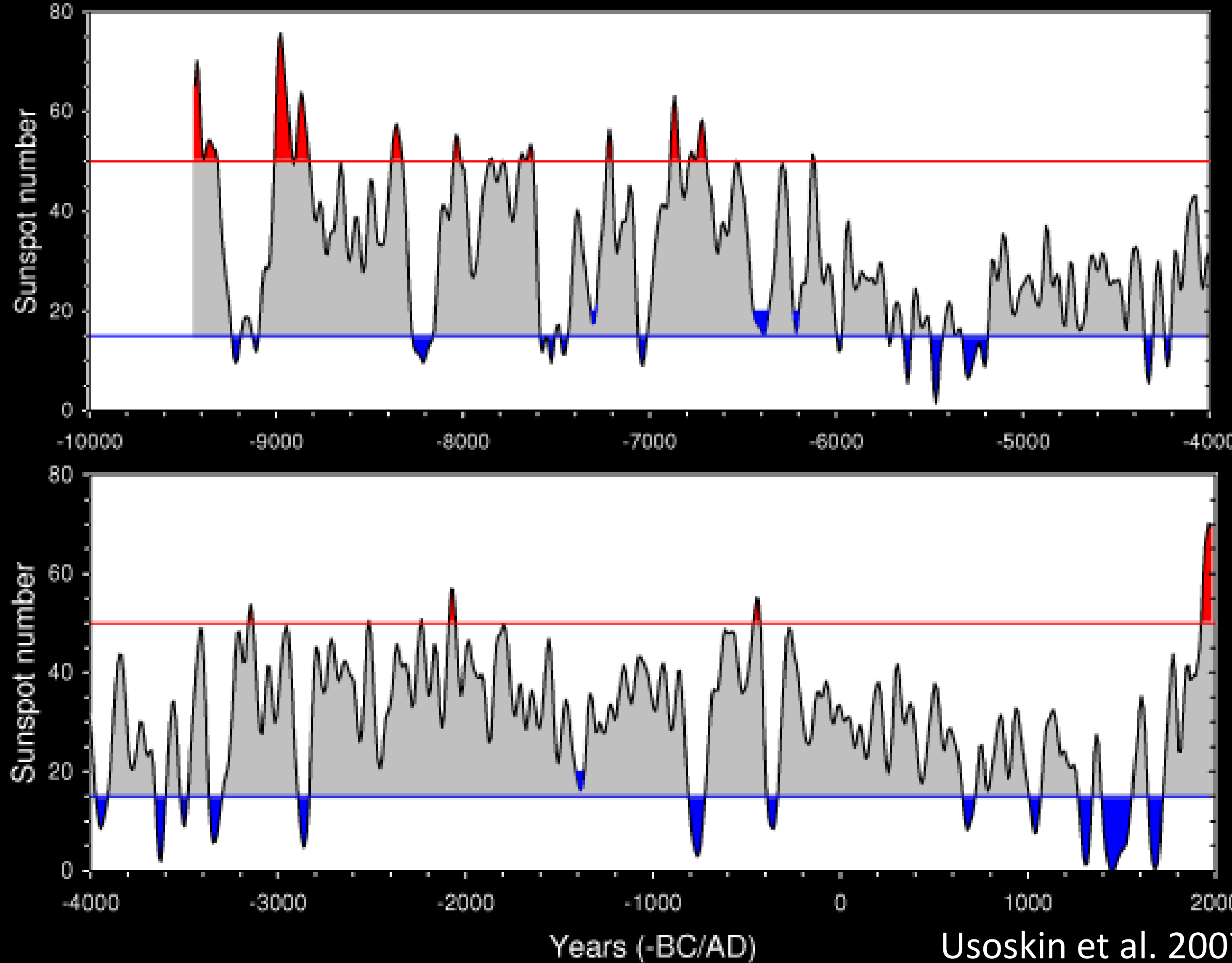

Usoskin et al. 2007

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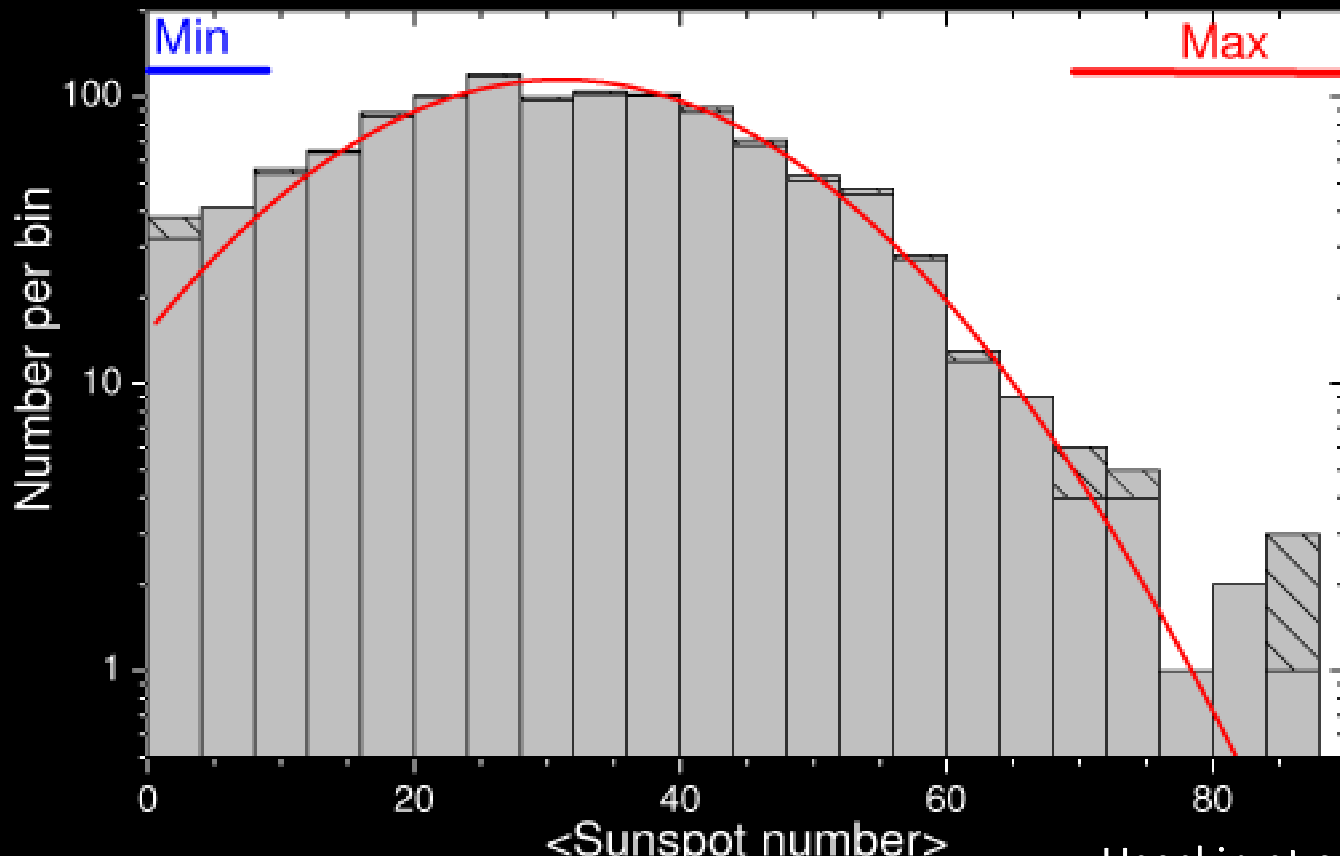
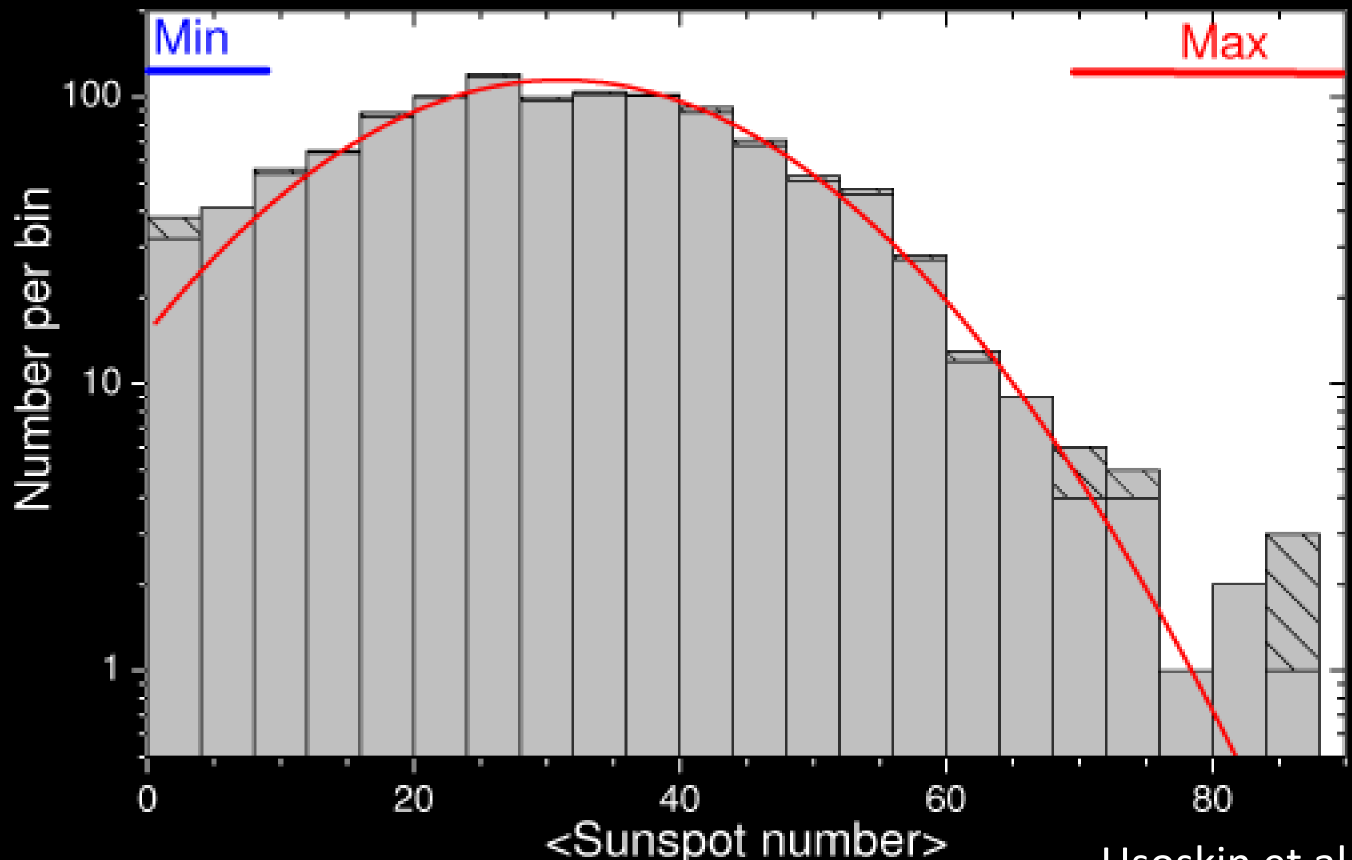


Usoskin et al. 2007

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

Grand maxima may be an artifact!

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



Usoskin et al. 2007

- Overall the Sun seems to spend 1/6th of the time 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 Sun is currently operating as a Babcock-Leighton Dynamo.
- 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.