The Sun's large-scale magnetic structure

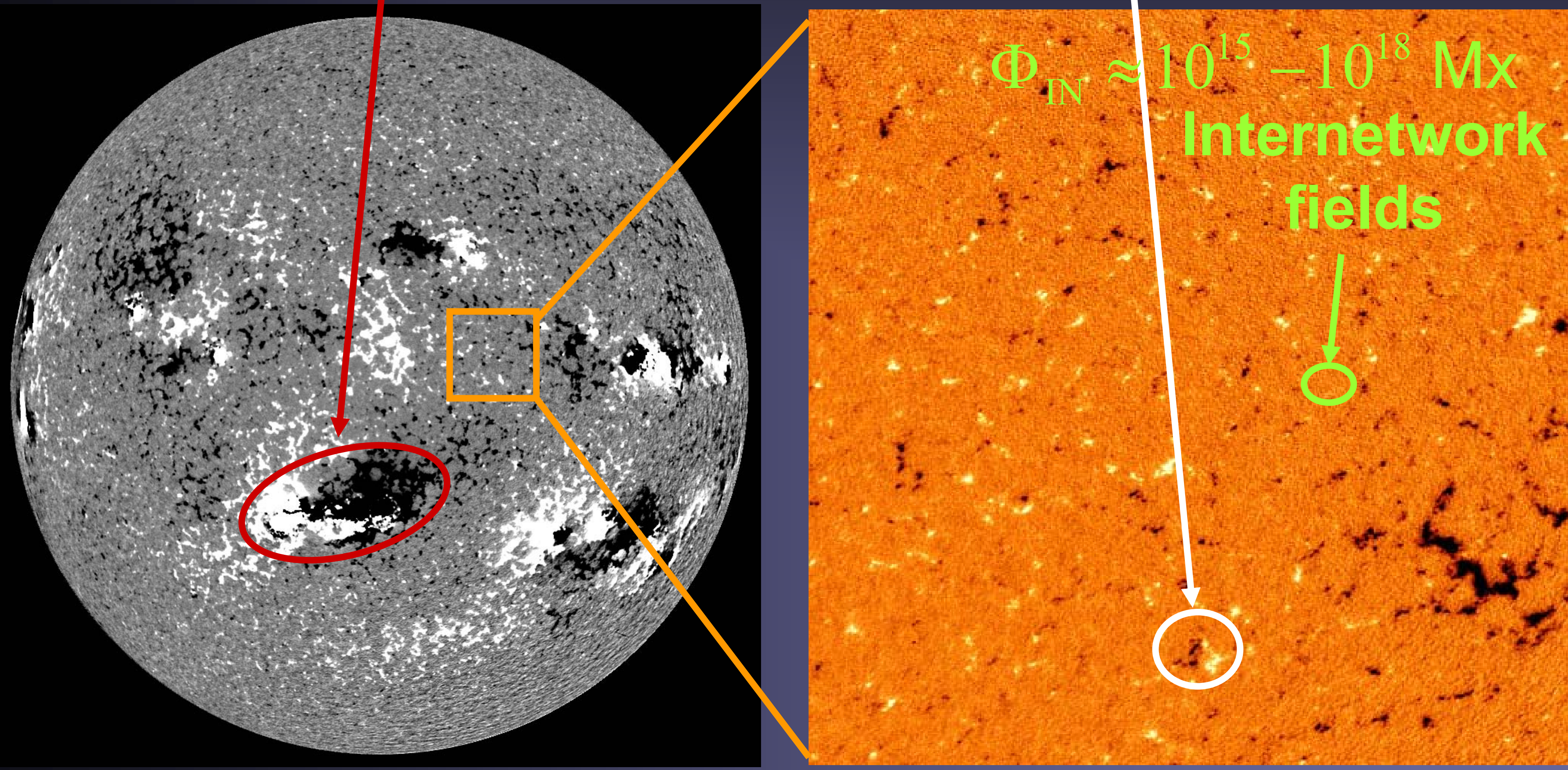
Magnetic flux per region

Active regions

$\Phi_{act\ reg} \approx 5 \cdot 10^{20} ... 5 \cdot 10^{22}$ Mx

Ephemeral regions

$\Phi_{eph\ reg} \approx 10^{18} - 5 \cdot 10^{20}$ Mx



SOHO/MDI magnetograms

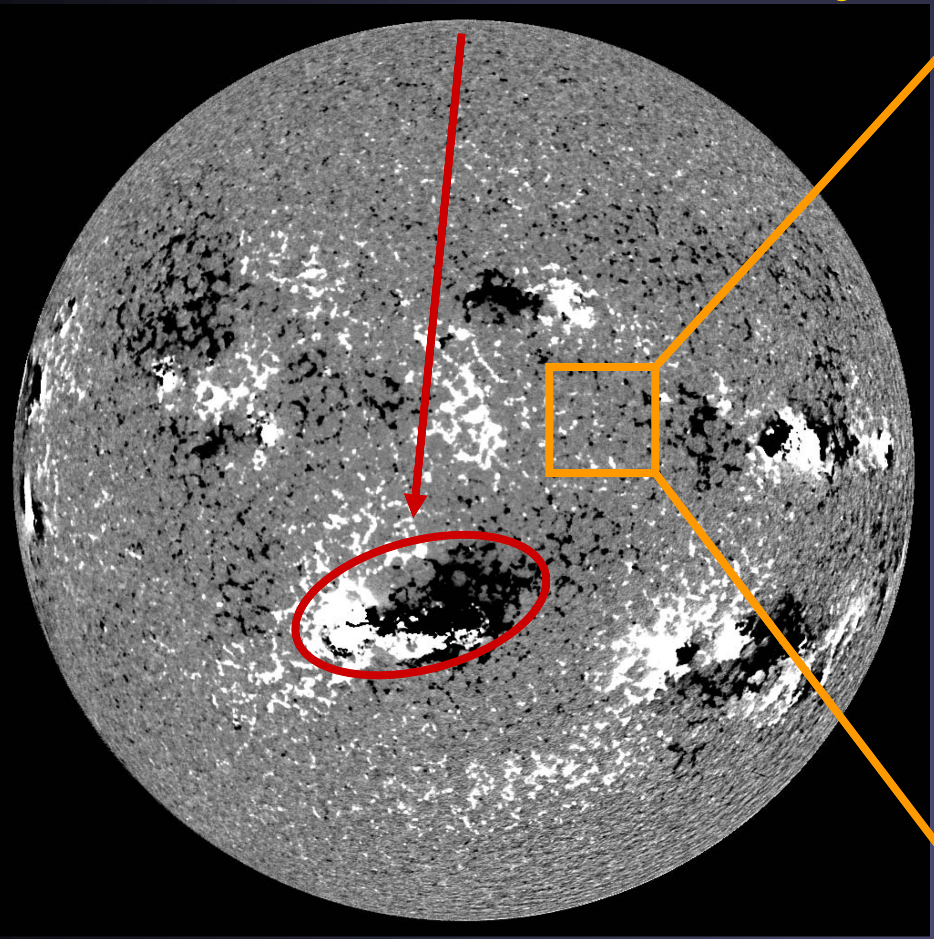
Magnetic flux emerging over solar cycle

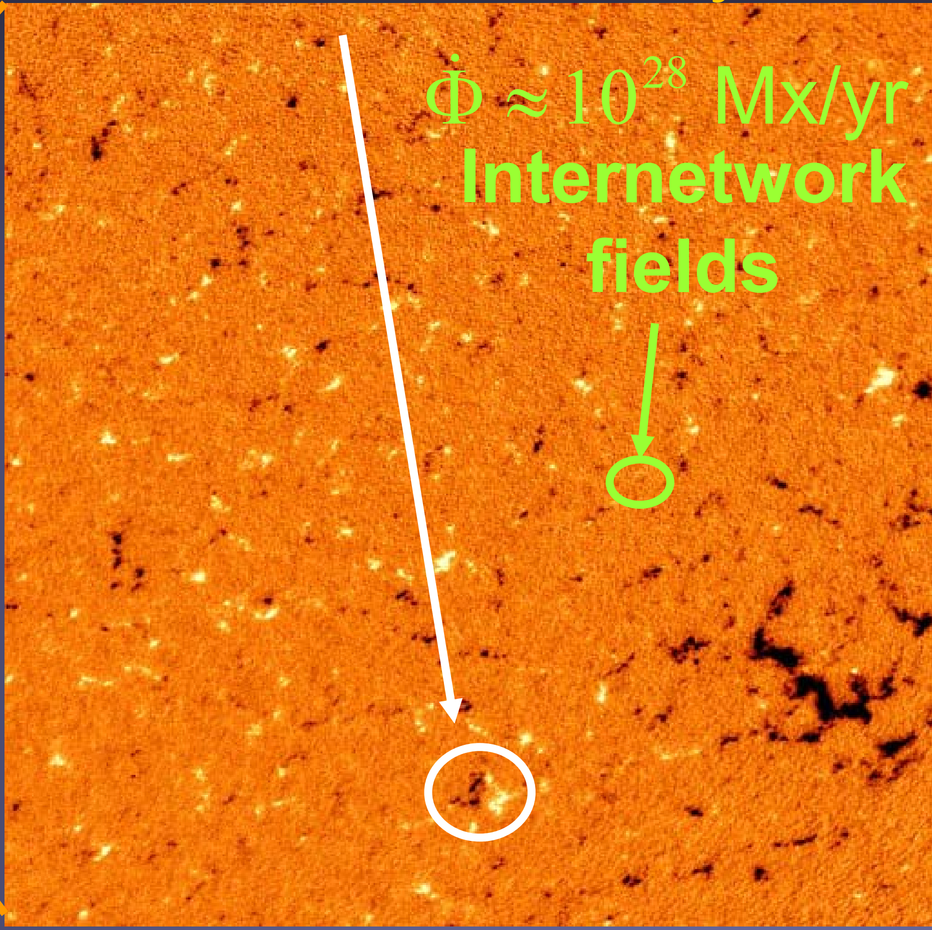
Active regions

$\dot{\Phi} \approx 3 \cdot 10^{23} \ldots 3 \cdot 10^{24}$ Mx/yr

Ephemeral regions

$\dot{\Phi} \approx 2 \ldots 4 \cdot 10^{26}$ Mx/yr





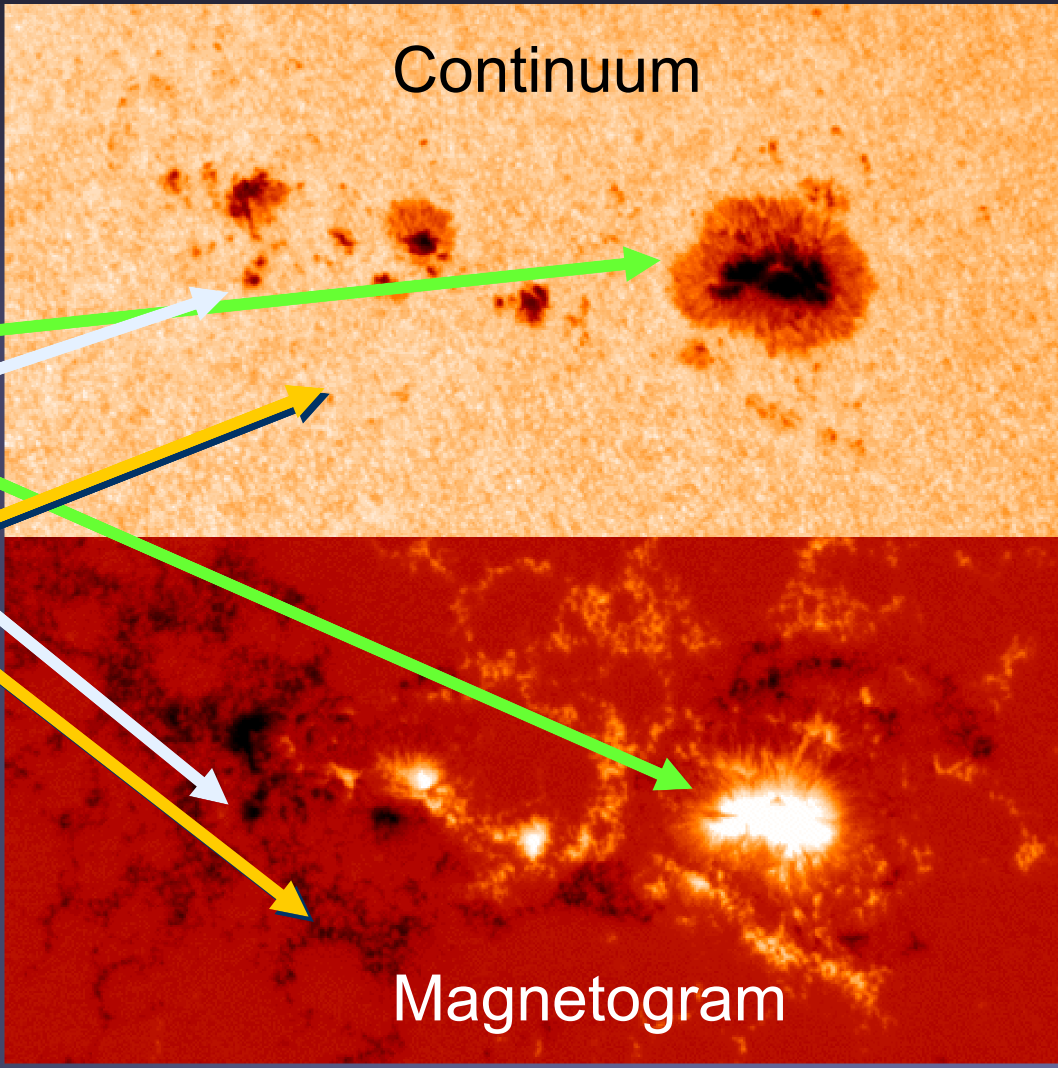
SOHO/MDI magnetograms

What are active regions composed of?

Magnetic structure of active regions is determined by

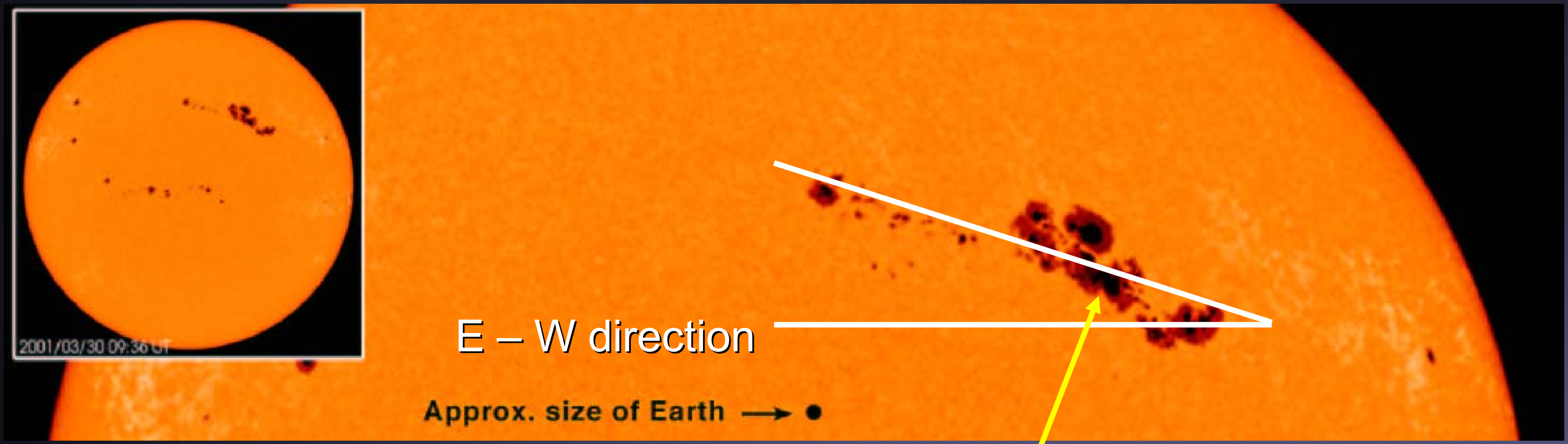
- sunspots
- pores
- plage or facular magnetic elements

- Spots: $\Phi=10^{20}$-10^{22}
- Pores: $\Phi=3\cdot10^{18}$-$3\cdot10^{20}$
- MEs: $\Phi=10^{17}$-$3\cdot10^{18}$



Emergence and evolution of active region seen in white light (sunspots)

Tilt angle of sunspot groups



Following spots closer to pole

Tilt angle $\gamma \propto \sin(\lambda)$

("Joy´s law")

Here λ = latitude

Magnetic field in the convection zone

- Magnetic field in AR & ER is produced by dynamo located near bottom of convection zone (in overshoot layer)

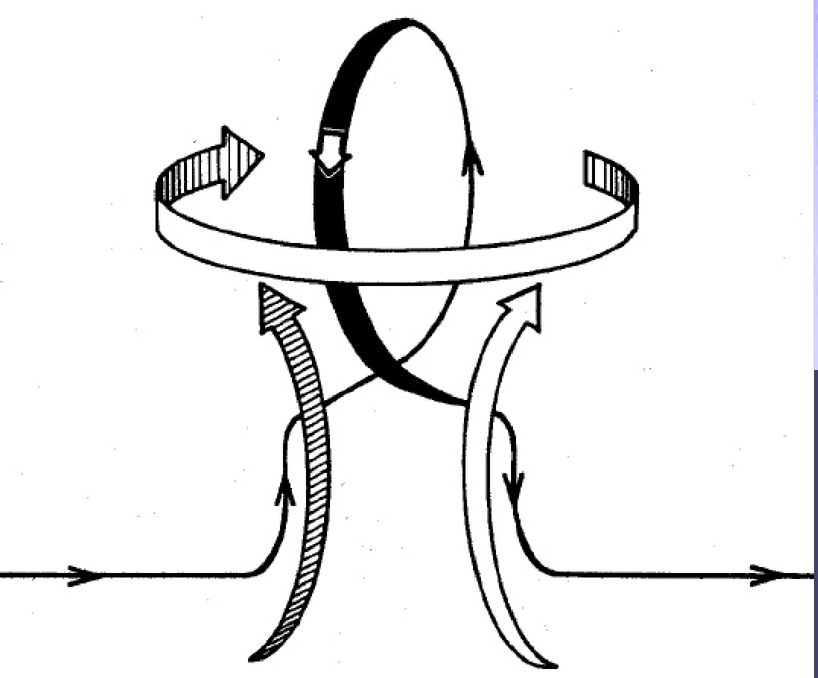
➔toroidal flux tubes in pressure balance with surroundings:

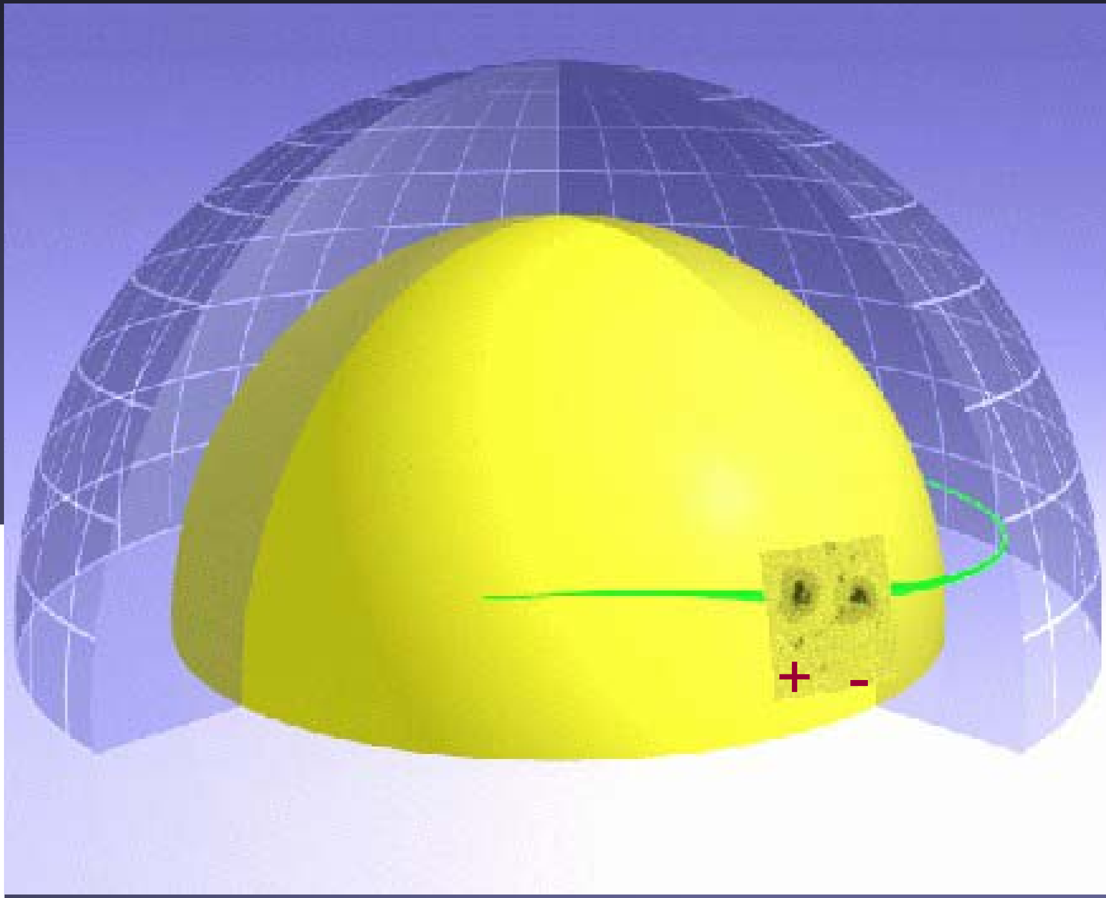
$$\frac{B_i^2}{8\pi} + P_i = P_e + \frac{B_e^2}{8\pi}$$

- If $B_{\mathrm{i}} > B_e$ and $T_{\mathrm{i}} = T_{\mathrm{e}}$, then $\rho_{\mathrm{i}} < \rho_e$ ➔ intense B-fields are evacuated and buoyant relative to surroundings (Parker instability).
- Buoyancy dominates over curvature for $B \geq 10^5$ G (Ferriz Mas & Schüssler 1992)
- Flux tubes form loops that move towards and eventually break through the solar surface

Emergence at surface

- Active region lies at intersection of flux tube with solar surface
- Each polarity corresponds to a footpoint of loop
- Loop rises on into corona

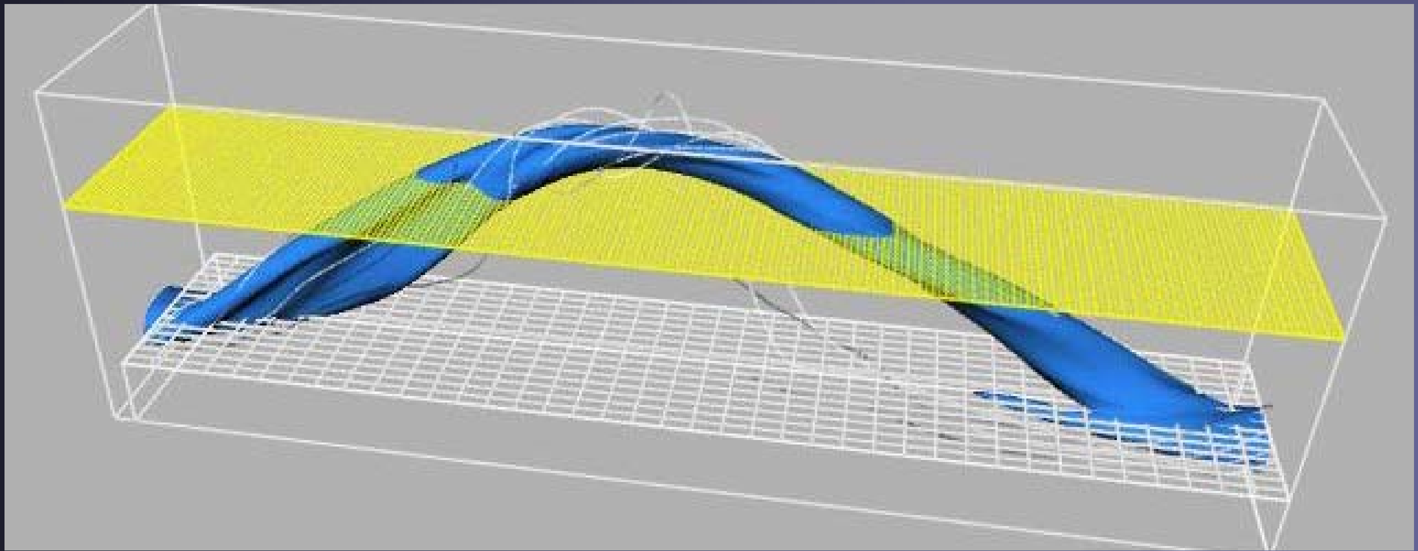




Coriolis force causes rising tube to writhe & get a poloidal comp.

Results of flux tube rise computations

- To get correct emergence latitudes & tilt angles $B \geq 10^5$ G at base of convection zone (Choudhury & Gilman, Fan, etc.)
- Lower B lead to emergence latitudes >30^o and too strong tilt angles, or the FTs never reach the surface ($P_i > P_e$)
- Computations in 3-D show: flux tubes must be twisted above a critical amount in order to survive up to the surface without being shredded



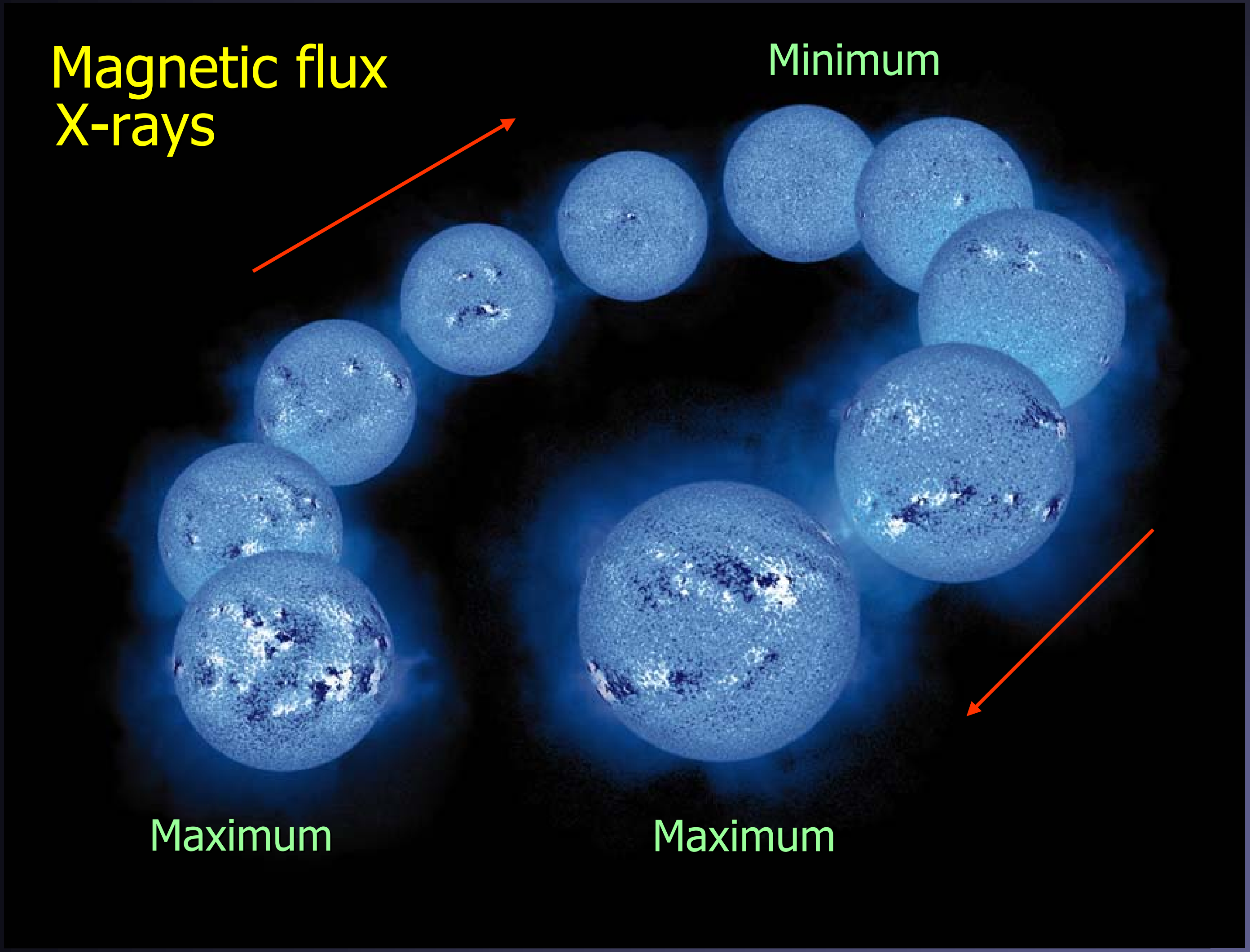
One kind of field, or different kinds? Is magnetic morphology self-similar?

Self-similarity of features of different sizes: they have a fractal dimension d, which connects Perimeter P and Area A of a feature (d is obtained statistically)

$$P \propto A^{d/2} \qquad d \approx 1.6$$

(Roudier & Muller 1987, Ribes et al. 1996, Meunier 2004, Criscuoli et al. 2007, etc.)

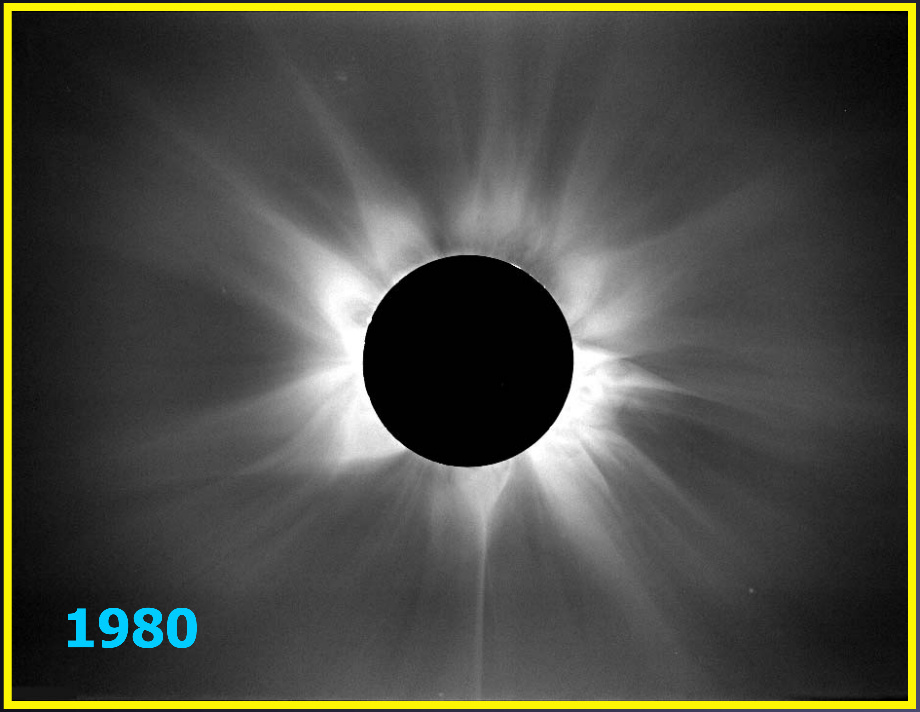
The Solar Activity Cycle



The short-wave radiation varies strongly through the activity cycle: from a factor 2 in the UV (<100nm) up to a factor 100 in X-rays.

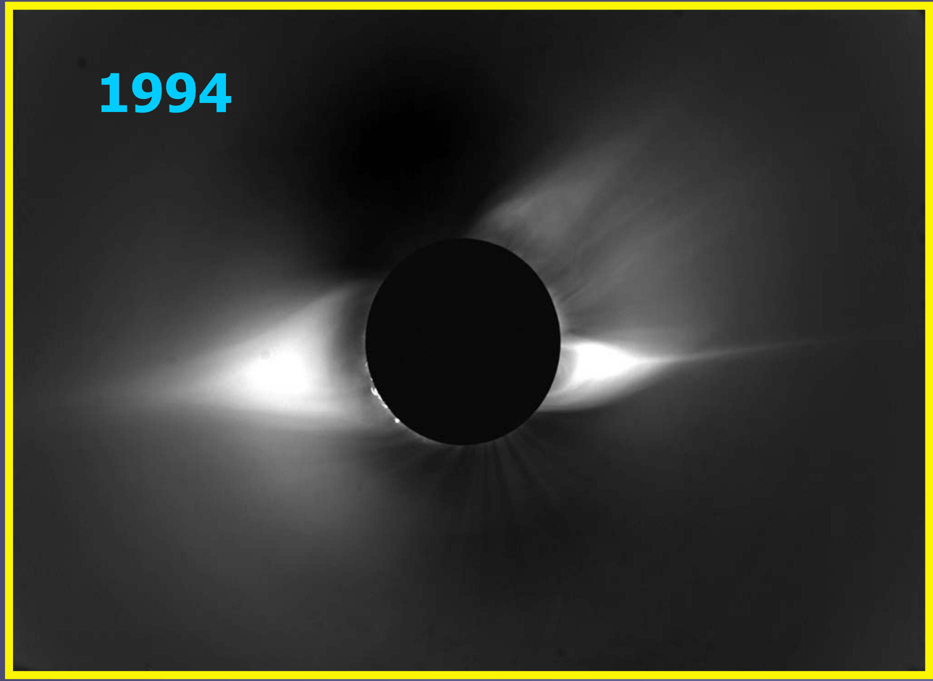
The magnetic flux at the solar surface also varies quasi-periodically over the 11-year solar cycle.

Solar corona during eclipses

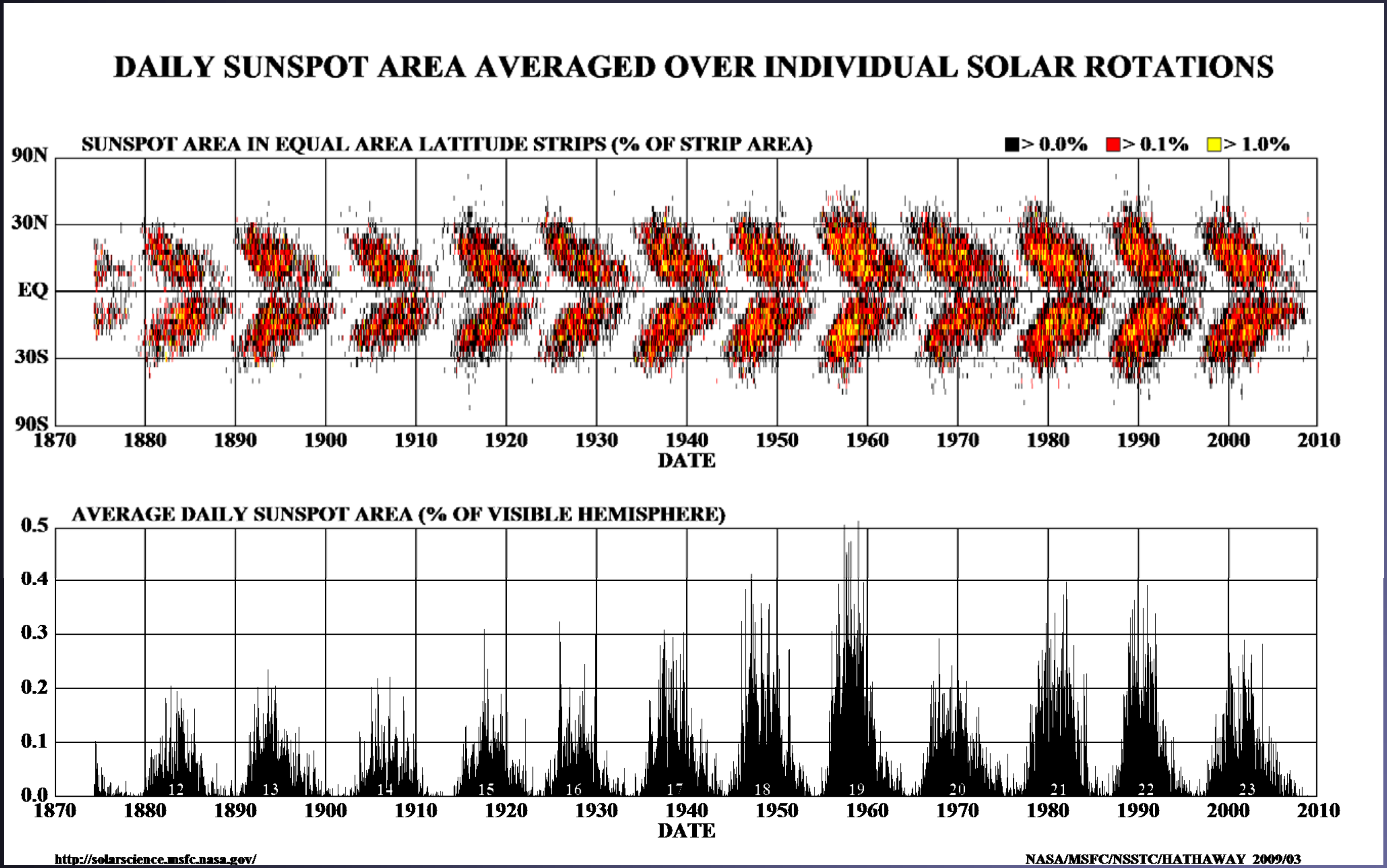


Activity maximum

Activity minimum

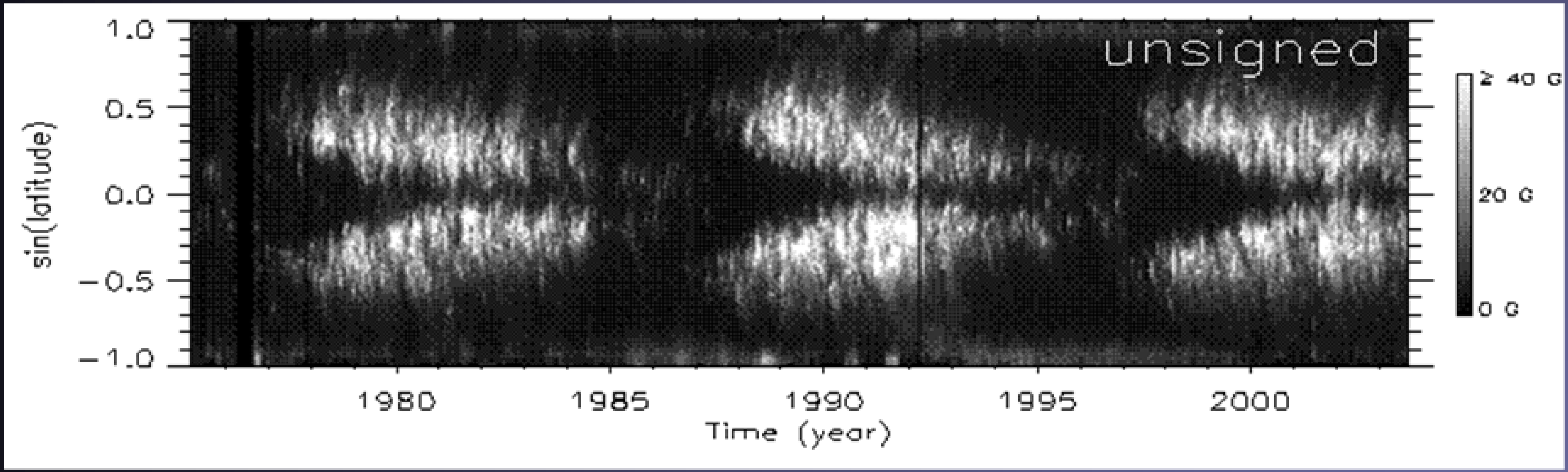


The butterfly diagram



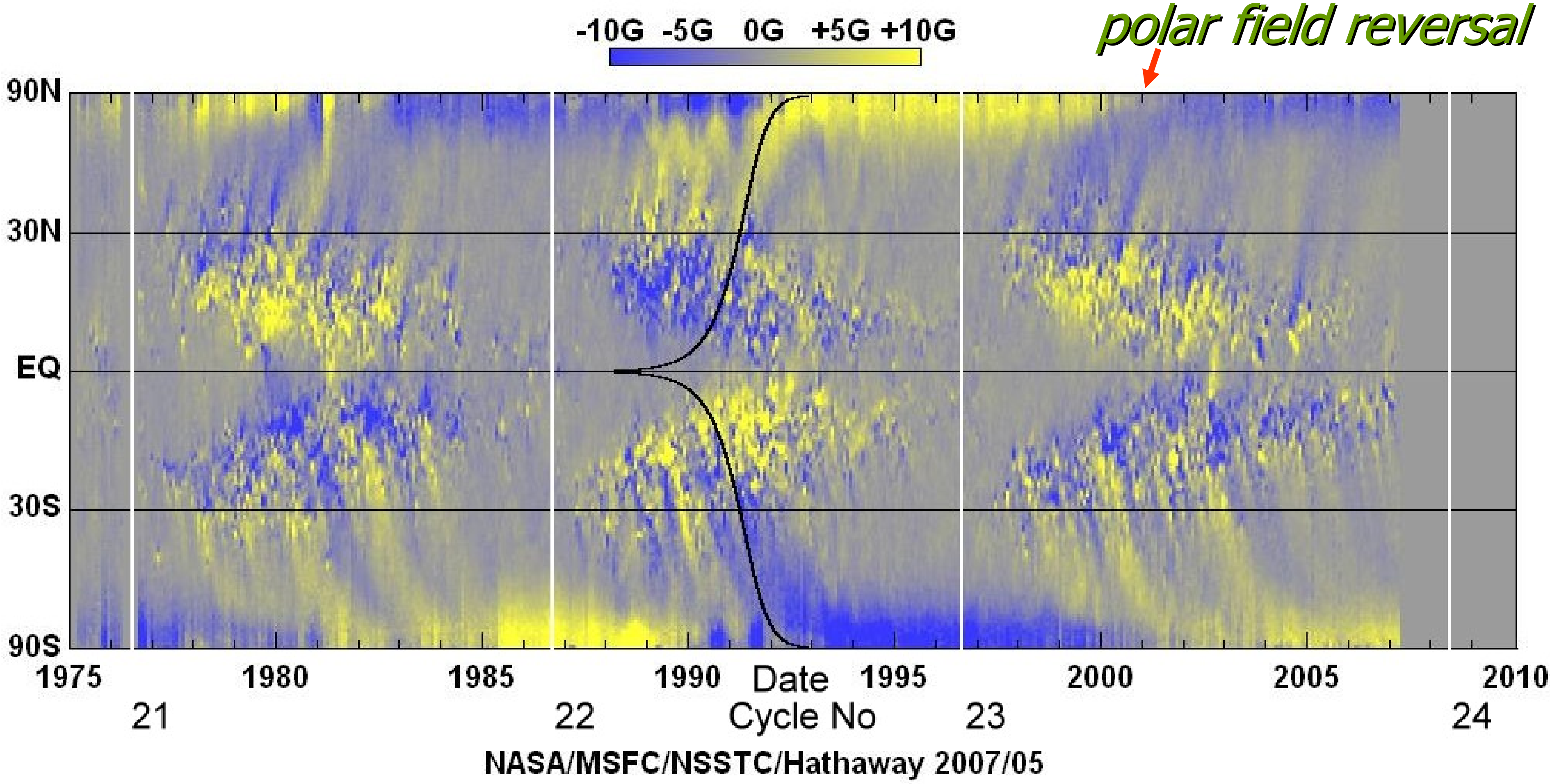
Magnetic butterfly diagram: Azimuthal averages of unsigned flux

- Unsigned flux displays very similar butterfly diagram to the sunspots (no major surprise)
- There are signs of additional features:
  - flux moving periodically to the poles from active bands
  - some concentration of field at the poles



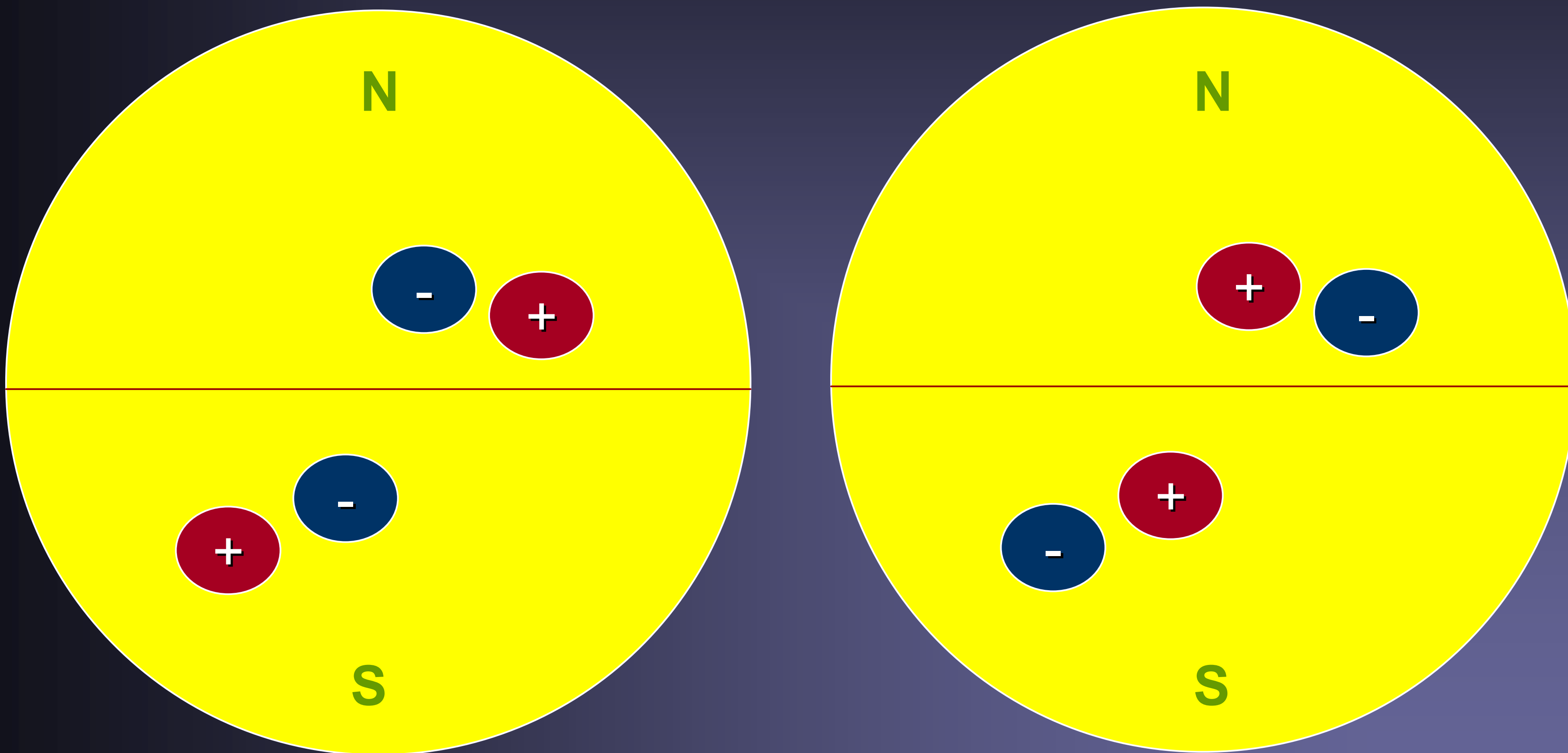
Butterfly diagram of magnetic flux

Azimuthal average of net magnetic flux
Active regions now weaker, since bipolar
Polar fields stronger, since unipolar



Magnetic cycle: Hale's polarity law

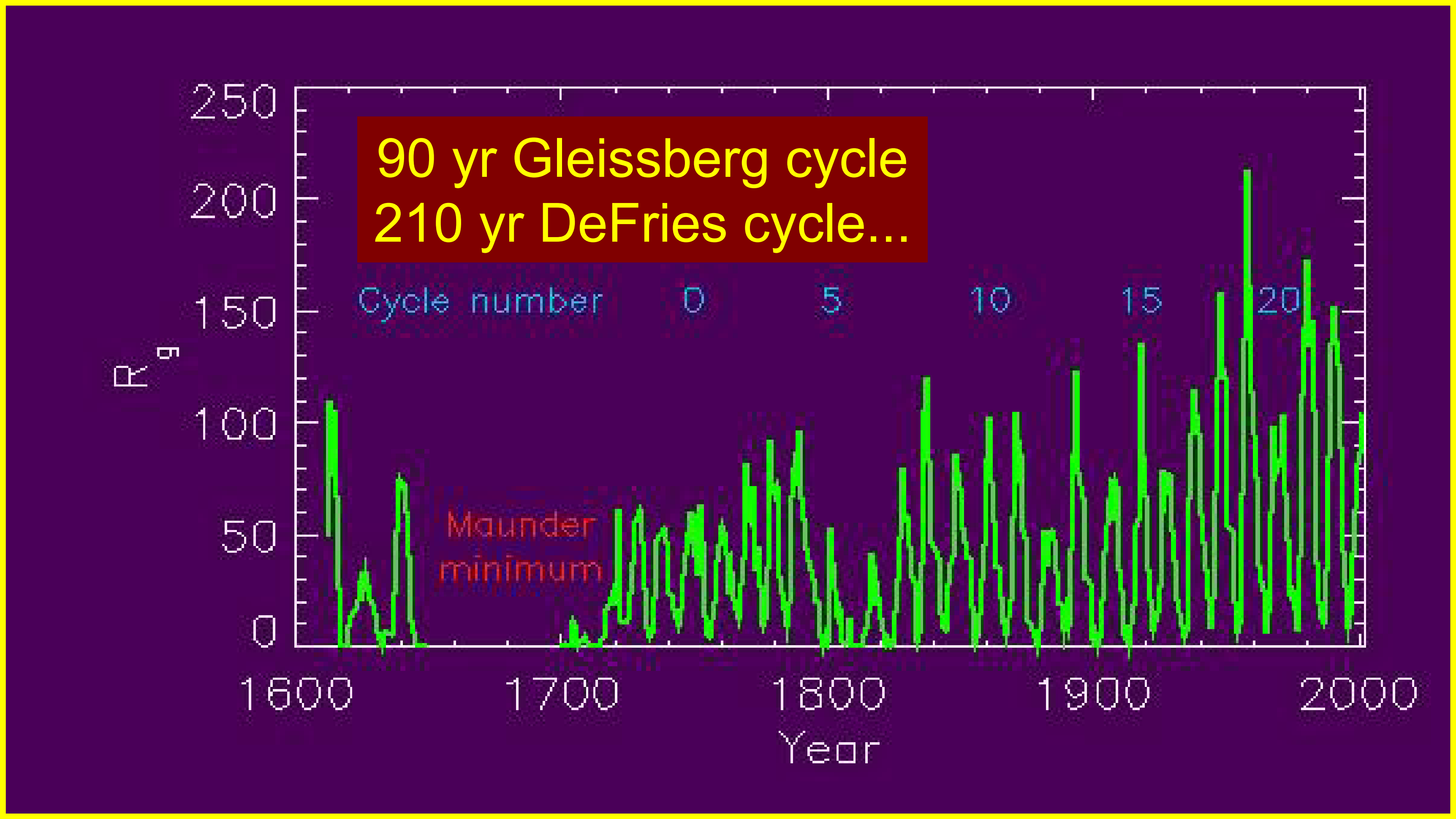
Polarity is re-established after 22 years, length of magnetic cycle



cycle n

cycle n+1

Telescopically measured number of sunspots since 1610



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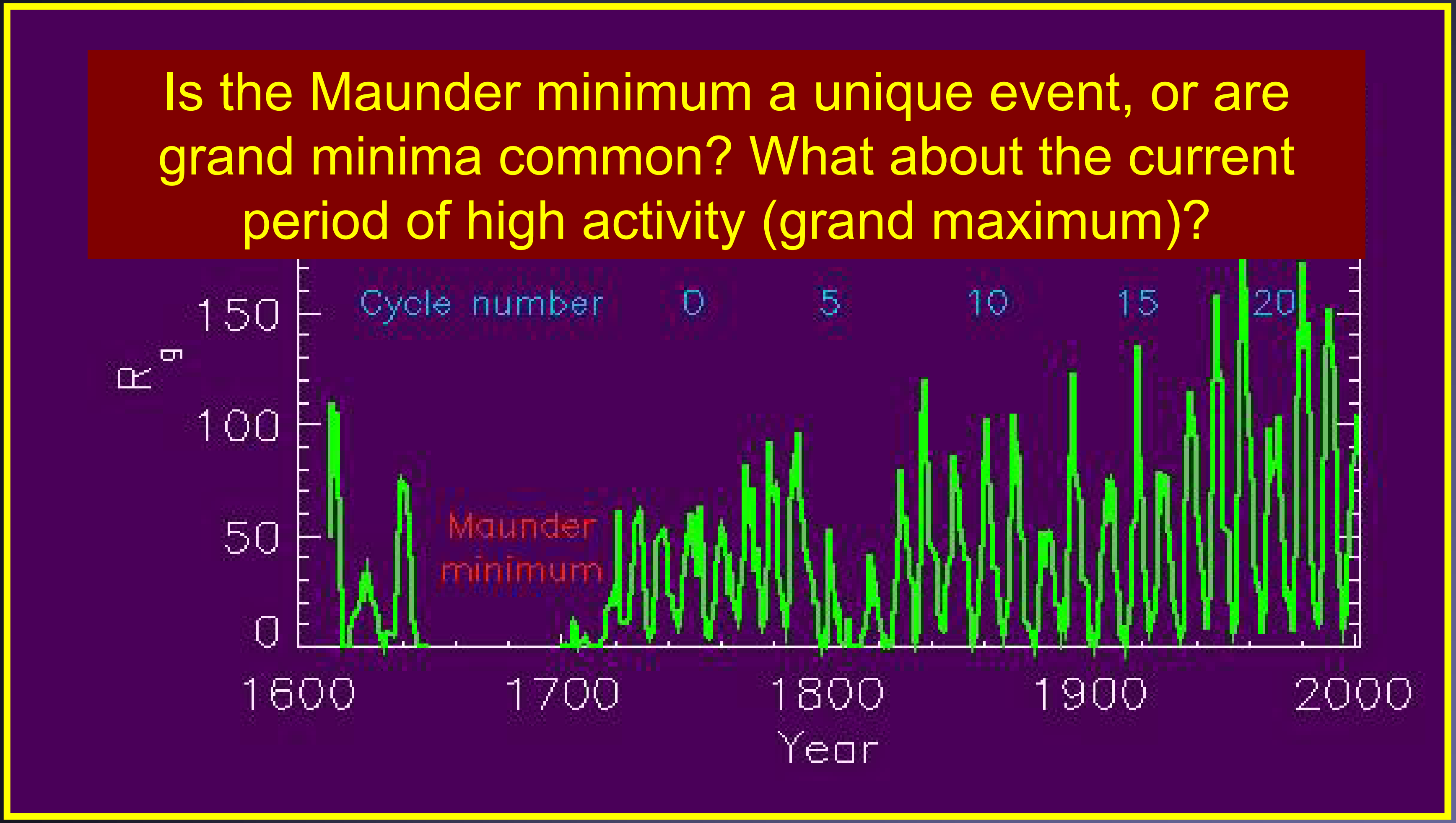
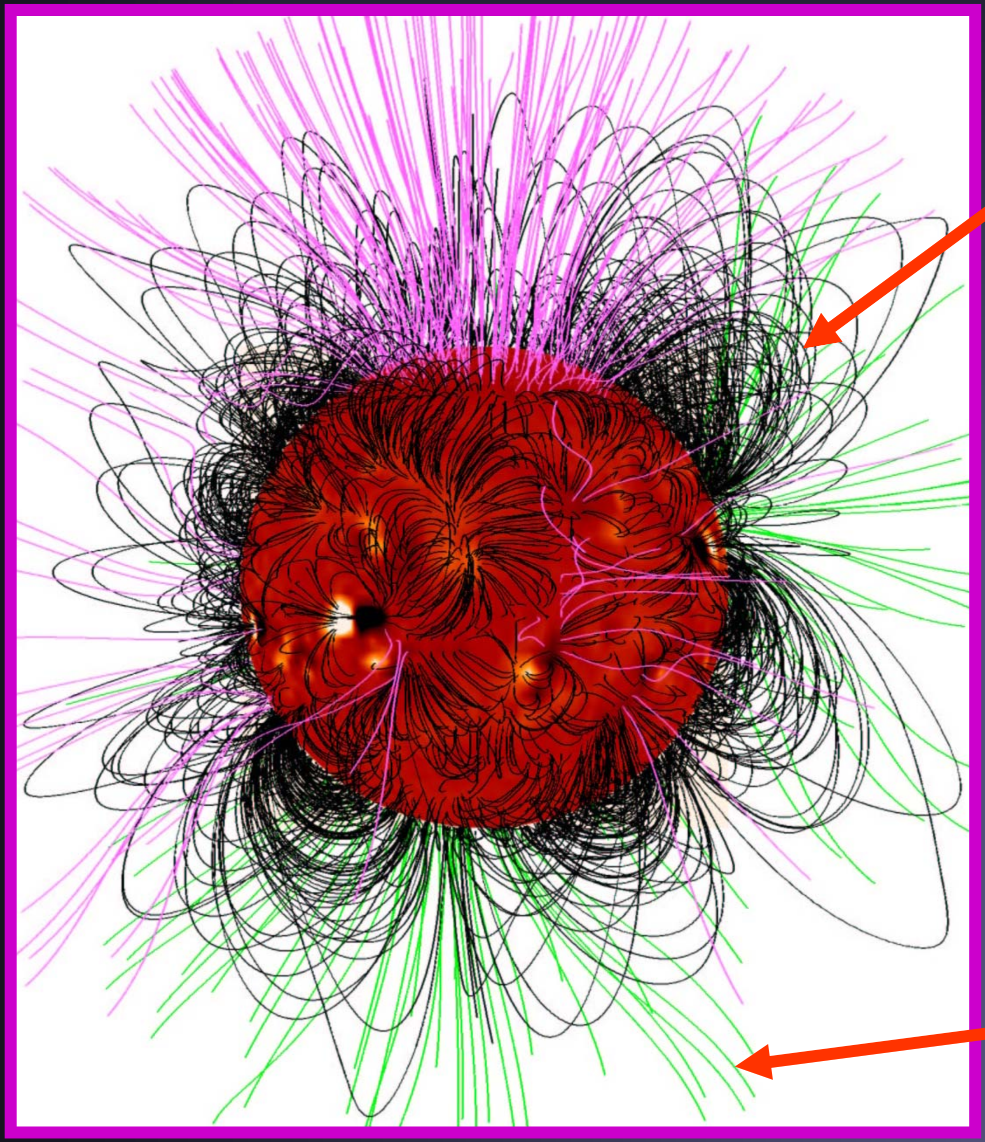


Open and closed magnetic flux



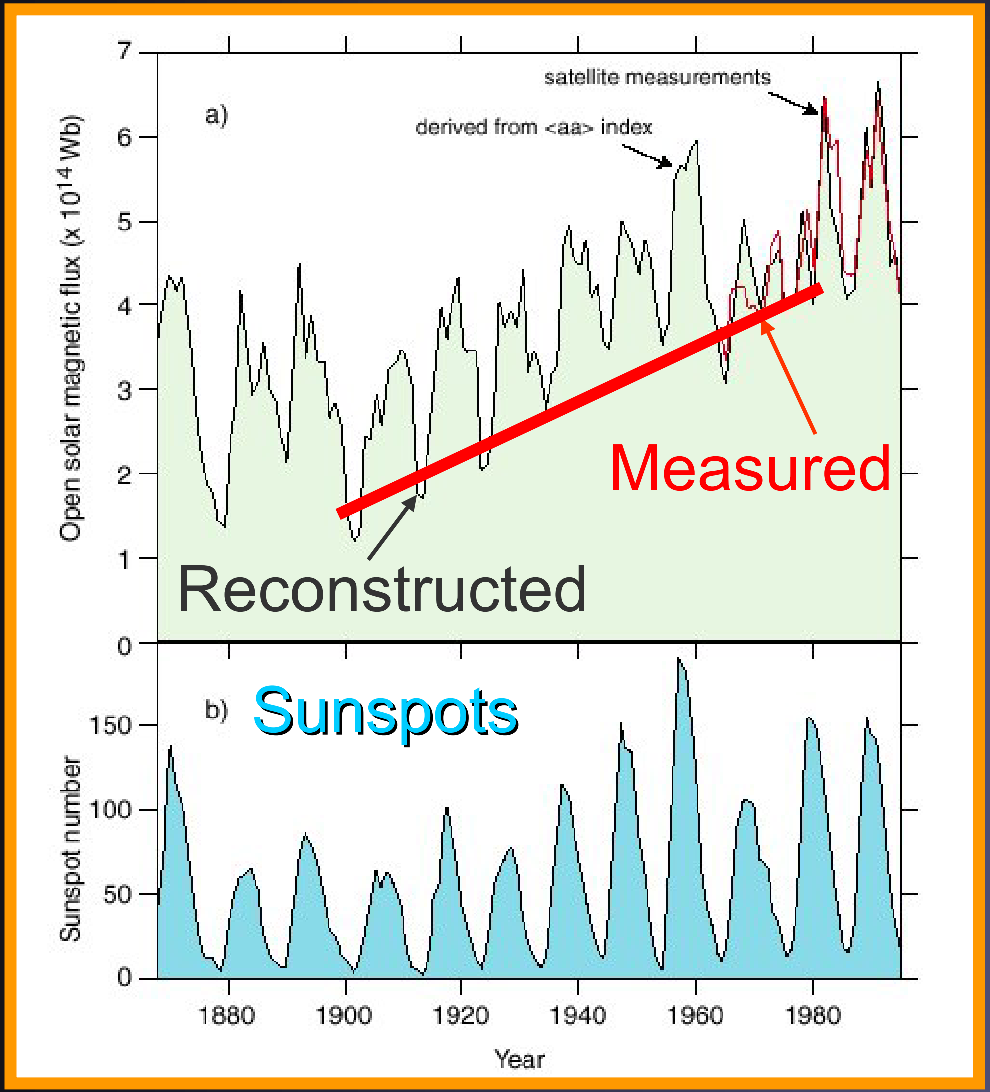
Closed flux: slow solar wind

Most of the solar flux returns to the solar surface within a few $R_\odot$ (closed flux)

A small part of the total flux through the solar surface connects as open flux to interplanetary space

Open flux: fast solar wind

Evidence for Secular Change: Interplanetary Magnetic Field



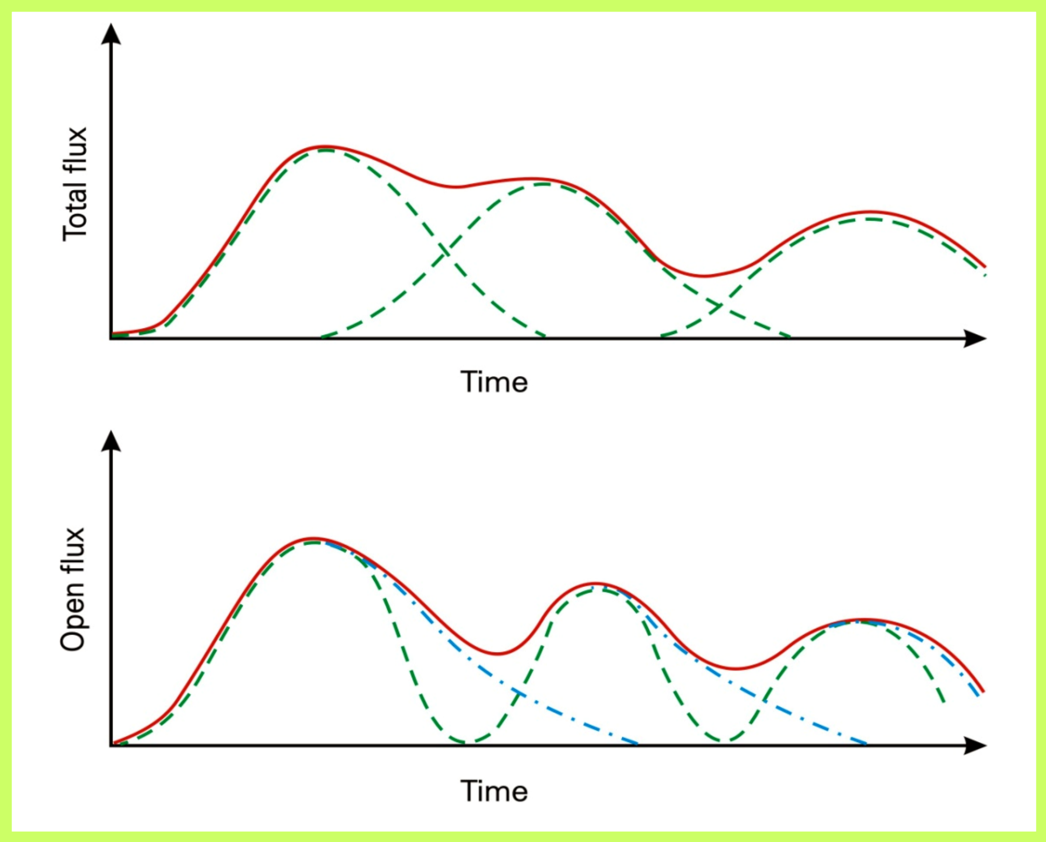
- Reconstructed from geomagnetic aa index
- Interplanetary B-field (≈ Sun's open flux; Ulysses) doubled during the last century

➔ What produced this doubling?

Lockwood et al. 1999, Rouillard et al. 2007

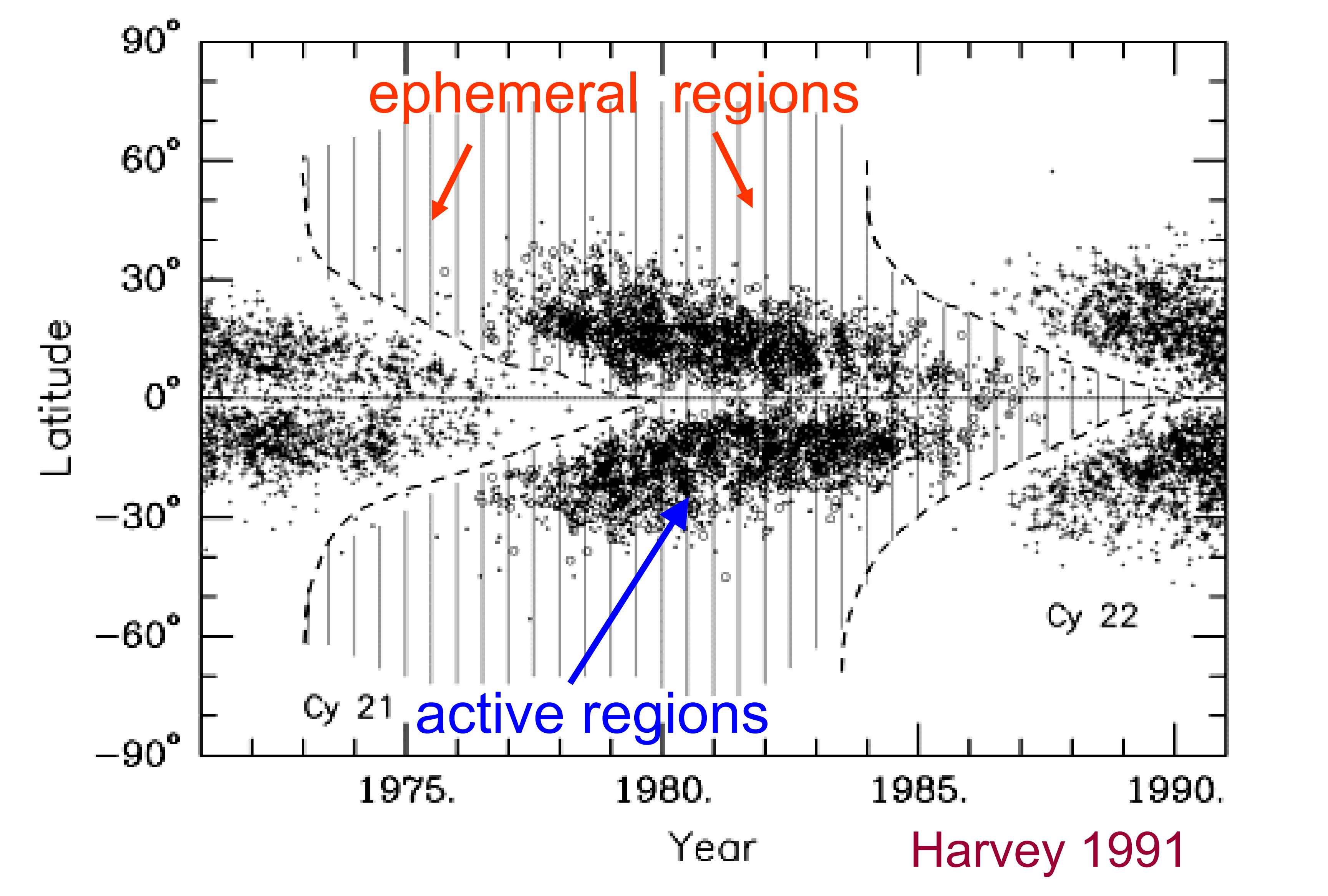
Secular Change of the Sun's Magnetic Flux: a Mechanism

- Underlying concept: overlapping solar cycles (Wilson et al. 1991: extended solar cycle). Overlap can be produced by
  - emergence of flux of new cycle (e.g. in ephemeral regions) before end of previous cycle (K. Harvey 1992)
  - long lifetime (decay time) of open (and closed) flux

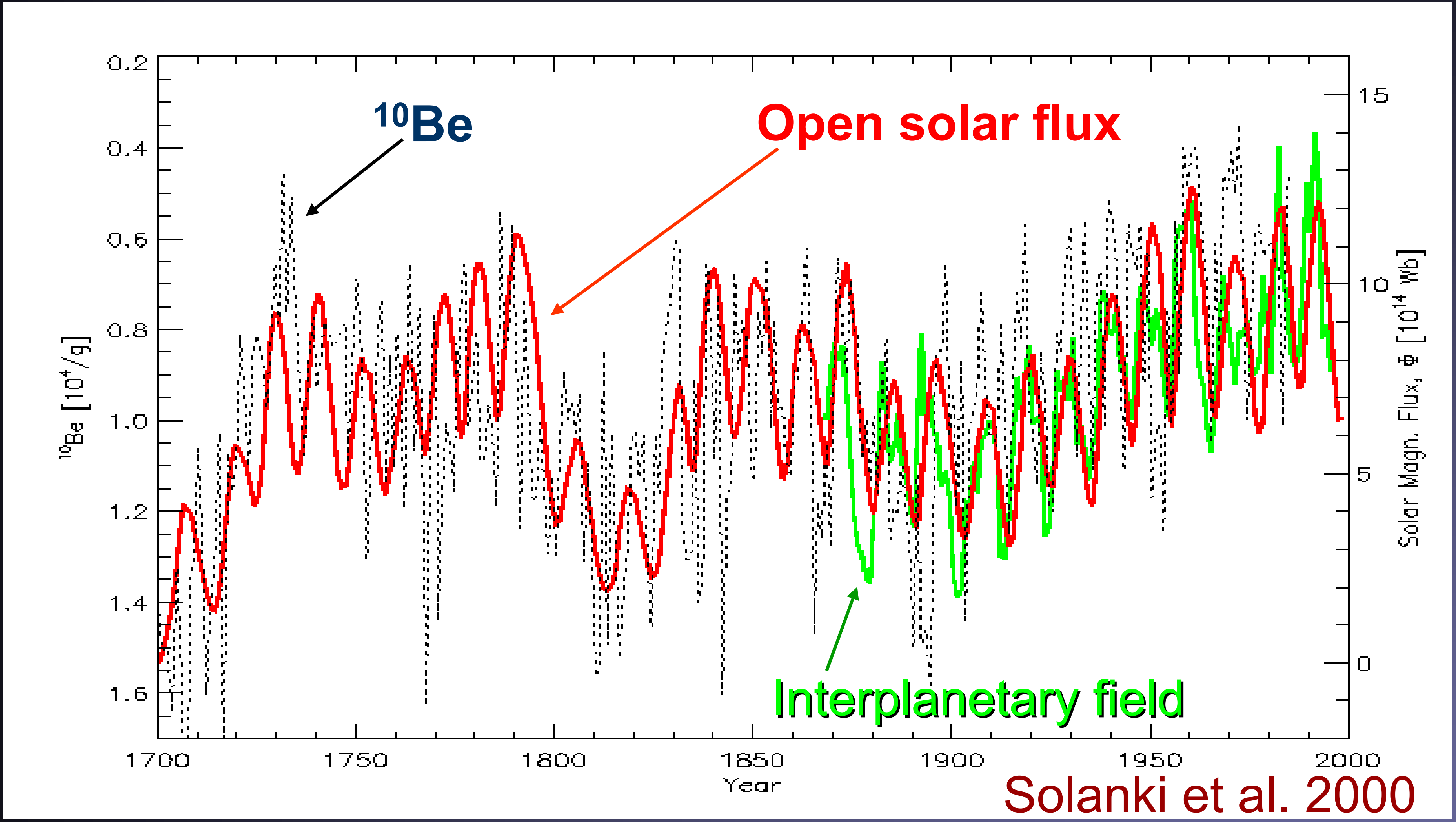


Solanki et al. 2000, 2002

Ephemeral Regions: Extended Cycle

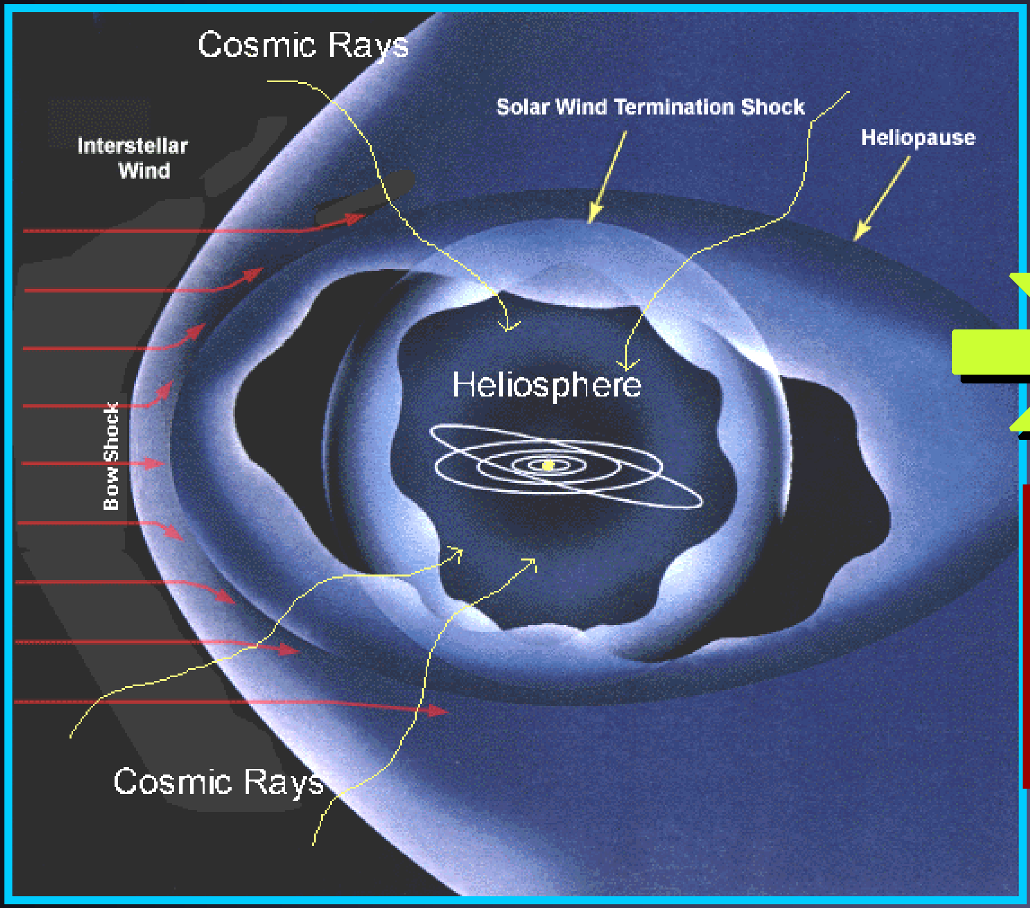


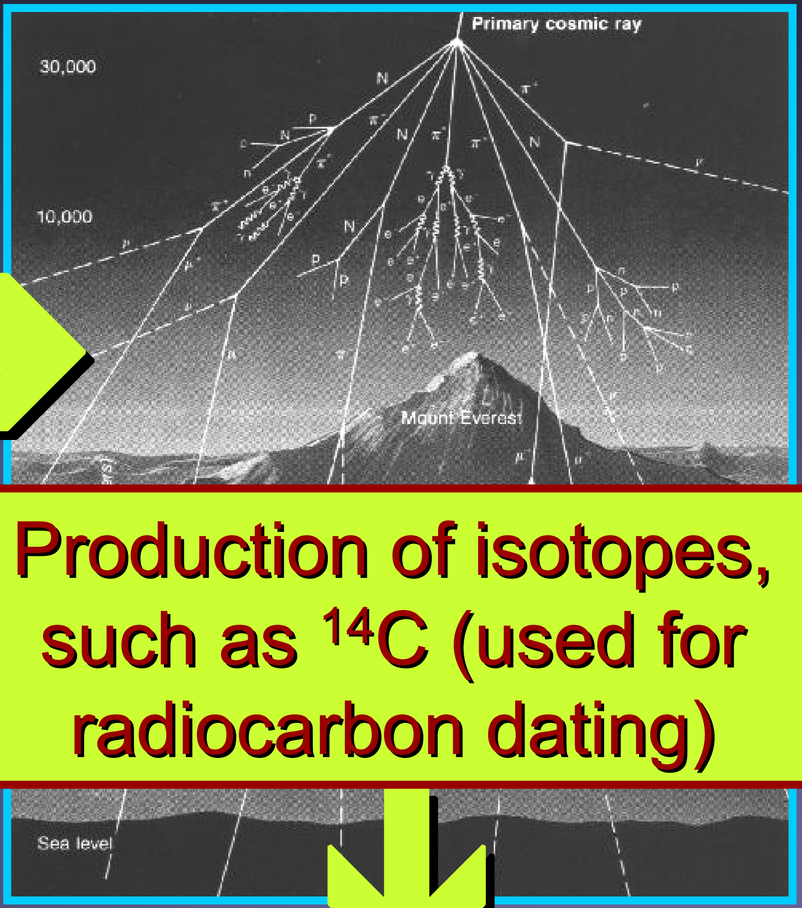
Reconstruction of Open Flux back to 1700



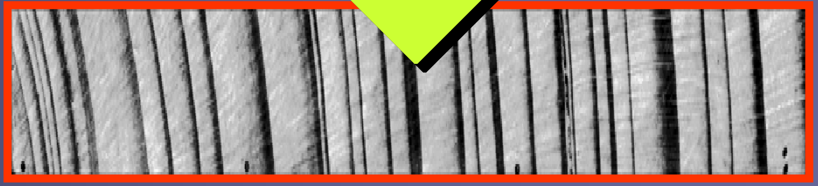
Model also predicts very similar trend for solar total magnetic flux → solar irradiance should also show secular trend

Cosmic Rays, the Sun & Tree Rings



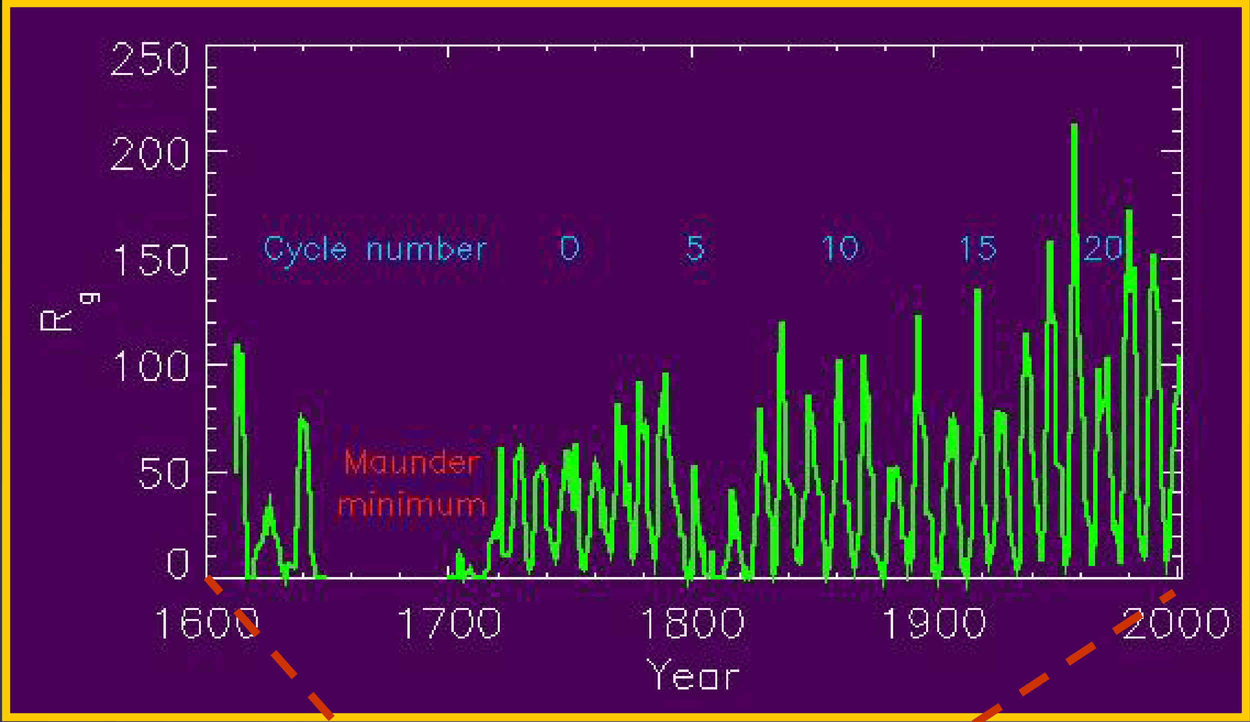


Production of isotopes, such as ^{14}C (used for radiocarbon dating)

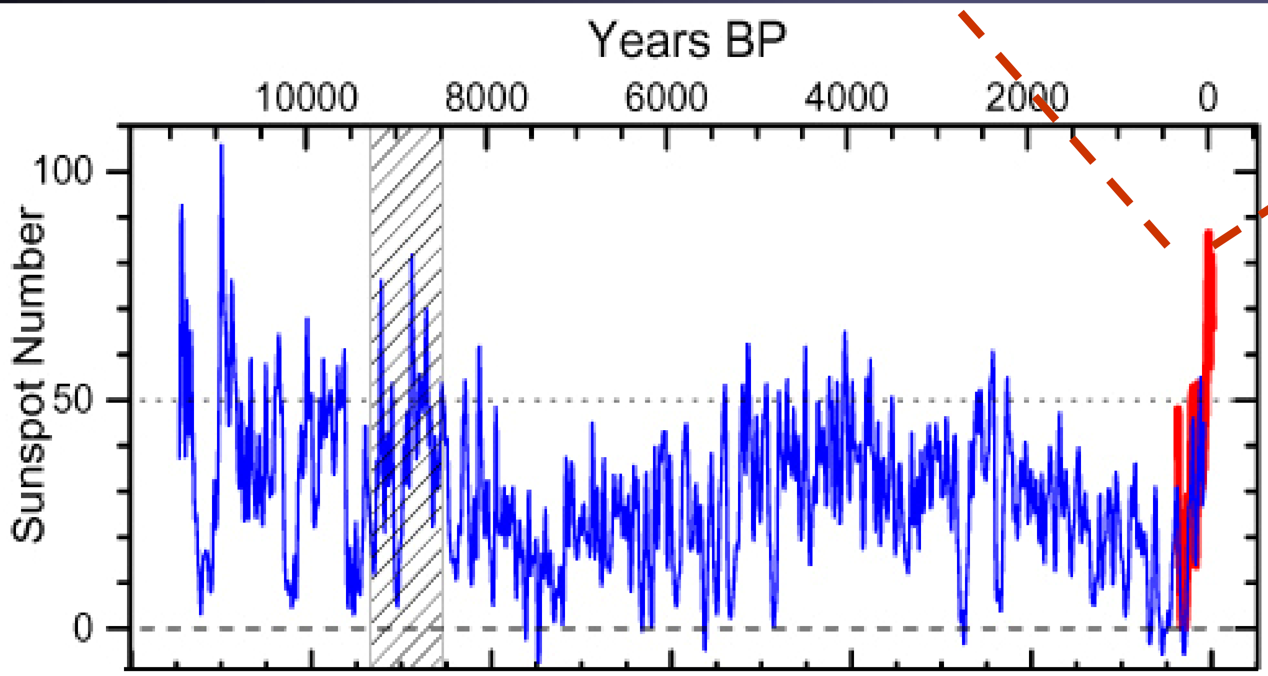


Flux of cosmic rays is changed by solar activity

Beyond the telescopic record



From cosmogentic ^{14}C (or ^{10}Be)



Solanki et al. 2004; Usoskin et al. 2006; 2007; Vonmoos et al. 2007; Abreu et al. 2008

Beyond the telescopic record

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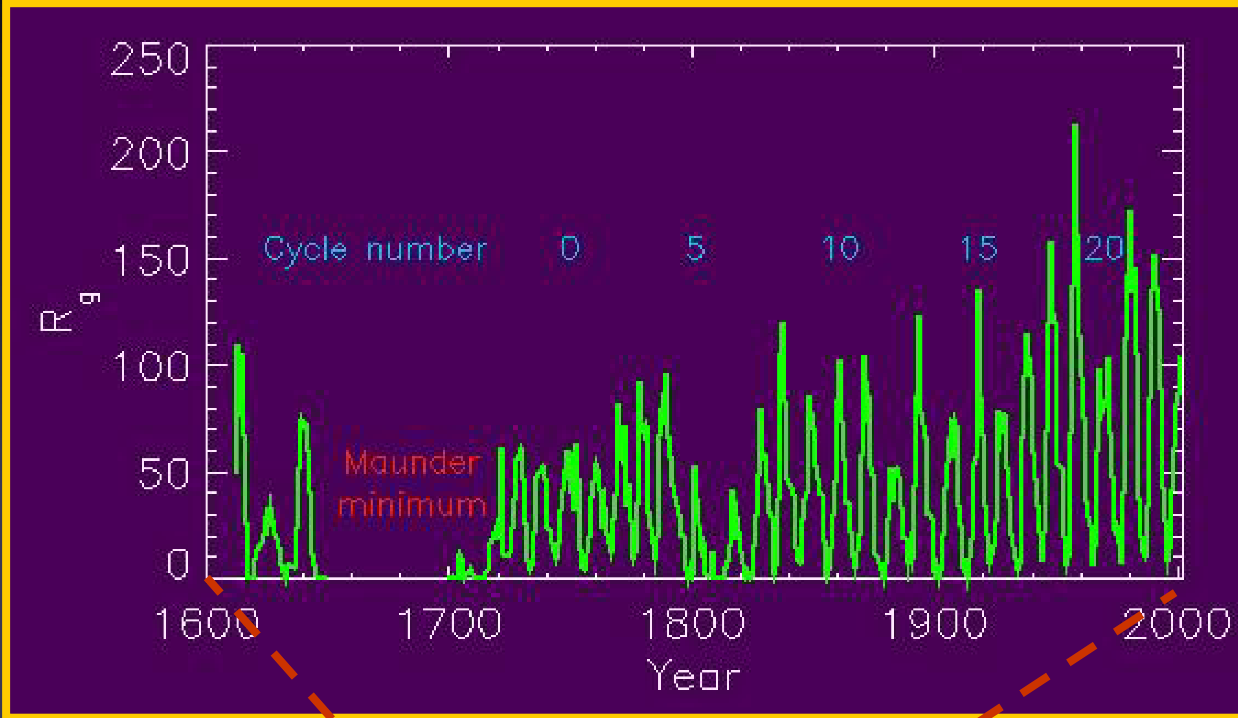
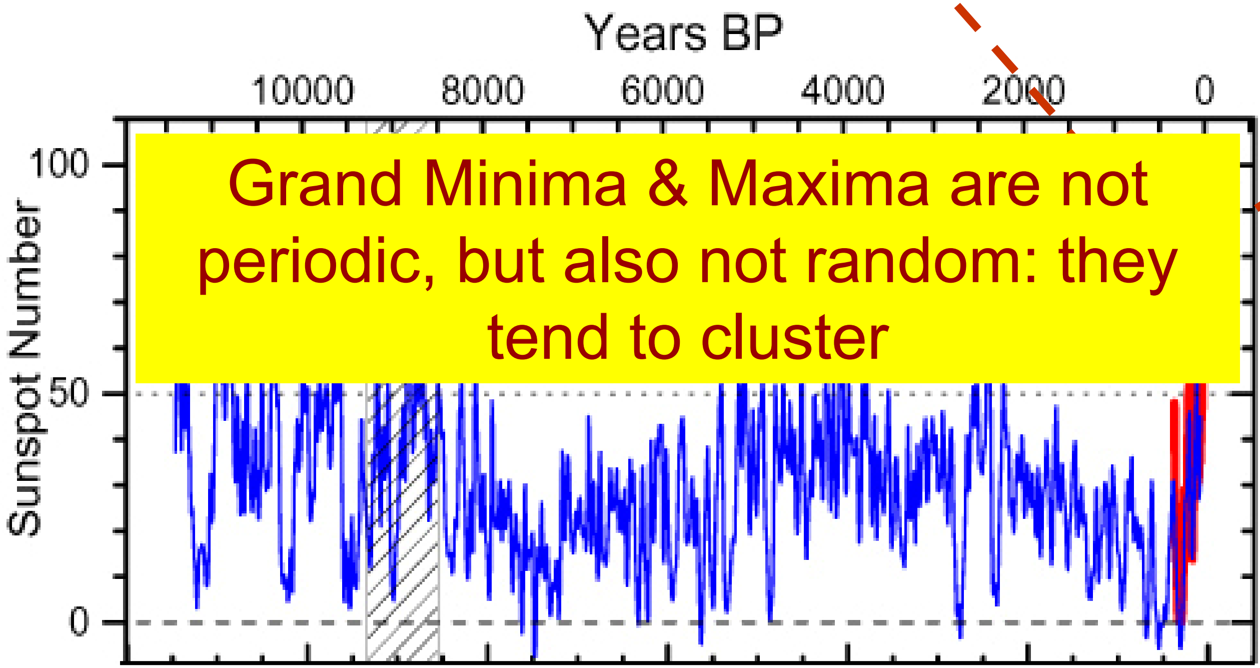




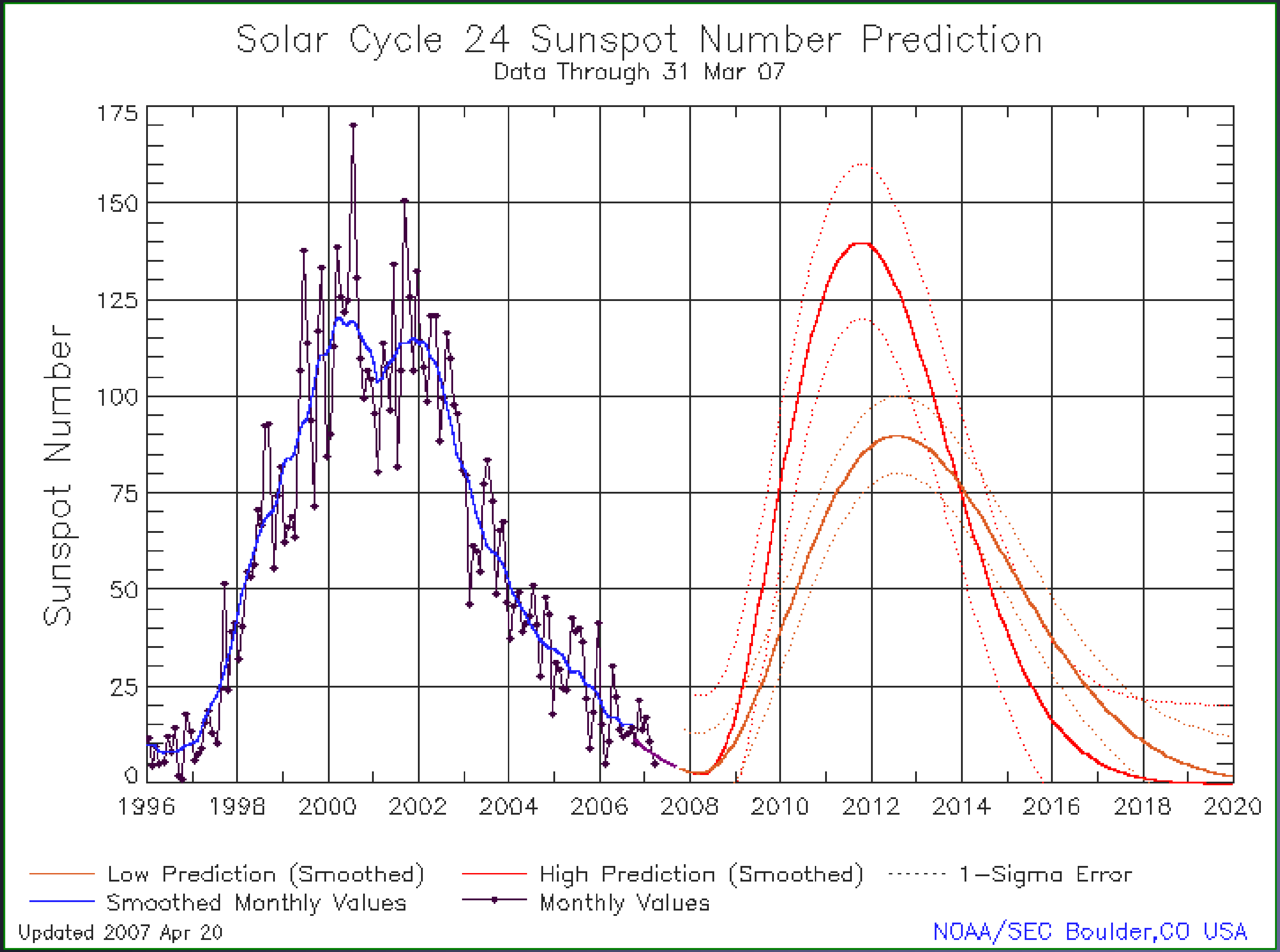
Grand Minima & Maxima are not periodic, but also not random: they tend to cluster

Solanki et al. 2004; Usoskin et al. 2006; 2007; Vonmoos et al. 2007; Abreu et al. 2008

Are we living in special solar times?

- Last 50-60 years have seen strongest activity cycles during the last 400 years. Sun has spent only a few % of the last 10000 years at such high activity levels
- Since 2006 we are in a particularly long and weak minimum, weakest in 80 years
  - exceptionally few sunspots
  - open flux is very low
  - irradiance is very low
  - solar wind is exceptionally weak
- What does the future hold for solar activity? Are we about to leave the Grand Maximum of activity?

How will the next cycle be?



Predicted next cycle: how does it compare with reality?