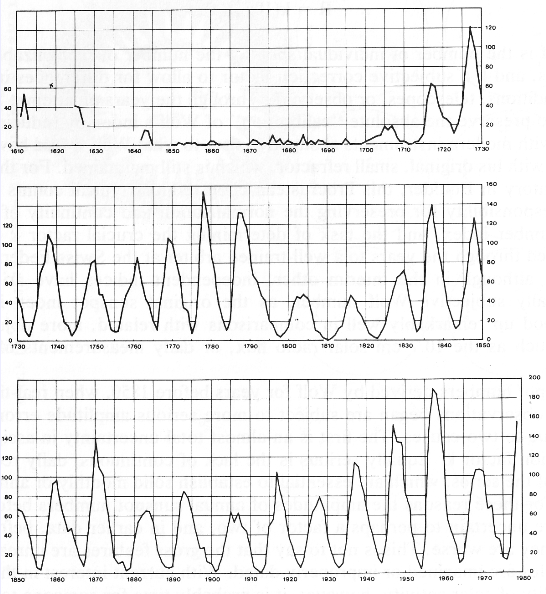
Lecture 14: Solar Cycle

Outline

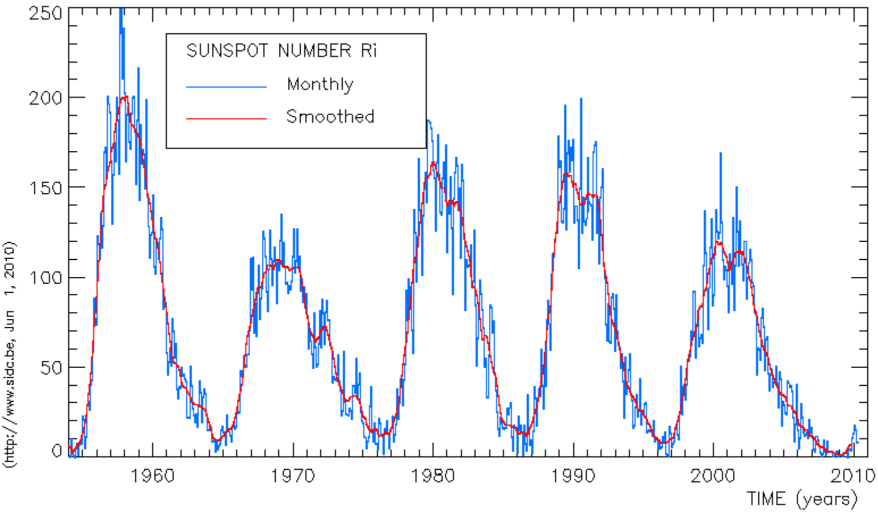
1. Observations of the Solar Cycle
2. Babcock-Leighton Model



Sunspot Number

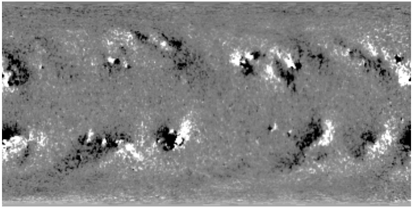
- 11-year (average) cycle period
- as short as 8 years
- as long as 15 years
- amplitude is variable
- stronger cycles are shorter
- Maunder minimum is real
- many things correlate with solar cycle

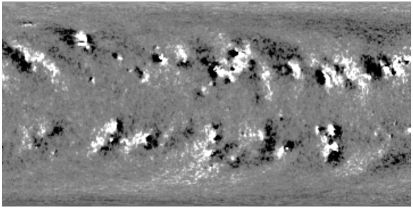
Up-to-date Sunspot Numbers



sidc.oma.be/html/wolfmms.html

Hale’s Polarity Law

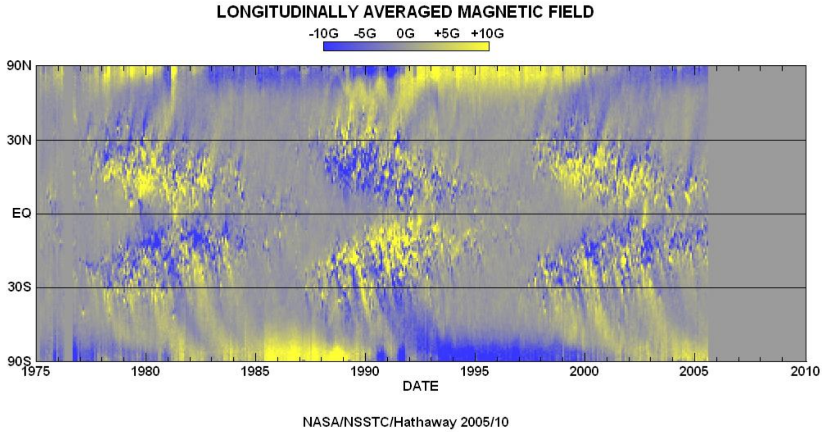




www.nso.edu

- magnetic Carrington maps on 2 July 1988 and 28 May 1999
- bipolar groups have constant magnetic polarity during one cycle
- magnetic polarity is opposite on opposite hemispheres

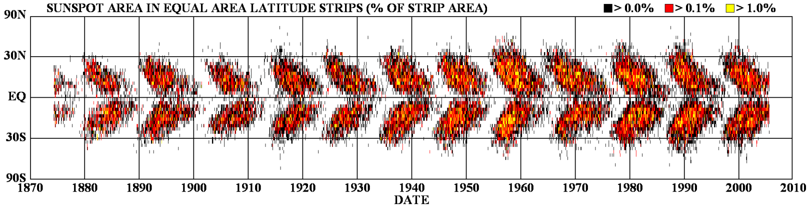
Polar Fields



science.nasa.gov/ssl/pad/solar/dynamo.htm

- polar fields change polarity in synchrony with bipolar regions
- unipolar fields at the poles
- 22-year magnetic cycle (*Hale Cycle*)

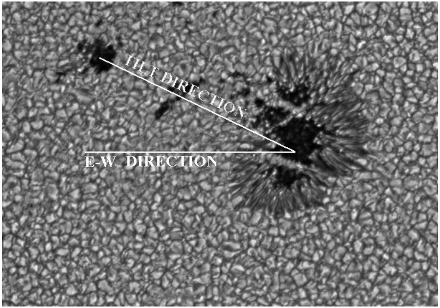
Spörer's Law

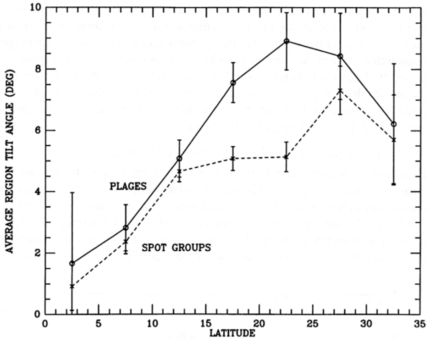


science.nasa.gov/ssl/pad/solar/sunspots.htm

- latitude dependence with cycle noted by Scheiner and Carrington
- studied in detail by Gustav Spörer
- *butterfly diagram*

Joy's Law

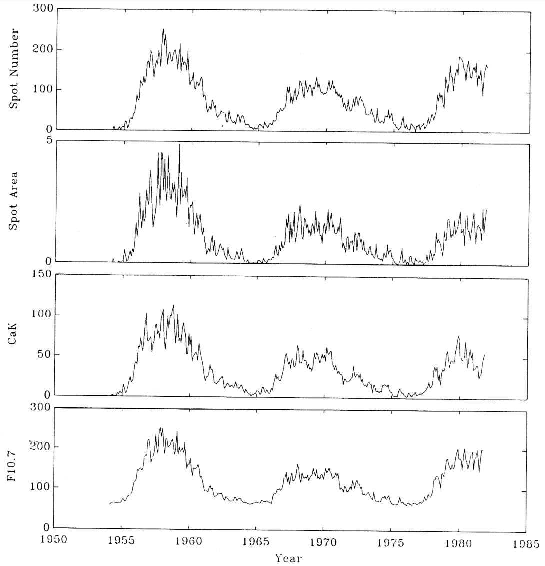




science.nasa.gov/ssl/pad/solar/dynamo.htm

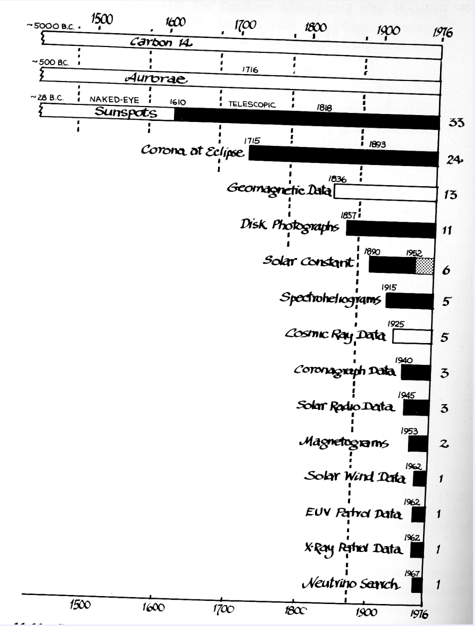
www.ociw.edu/ociw/babcock/howardtalk.pdf

- sunspot groups are tilted with respect to equator
- tilt angle depends on lattitude (*Joy's Law*)
- leading spots are closer to equator than following



Other Cycle Indicators

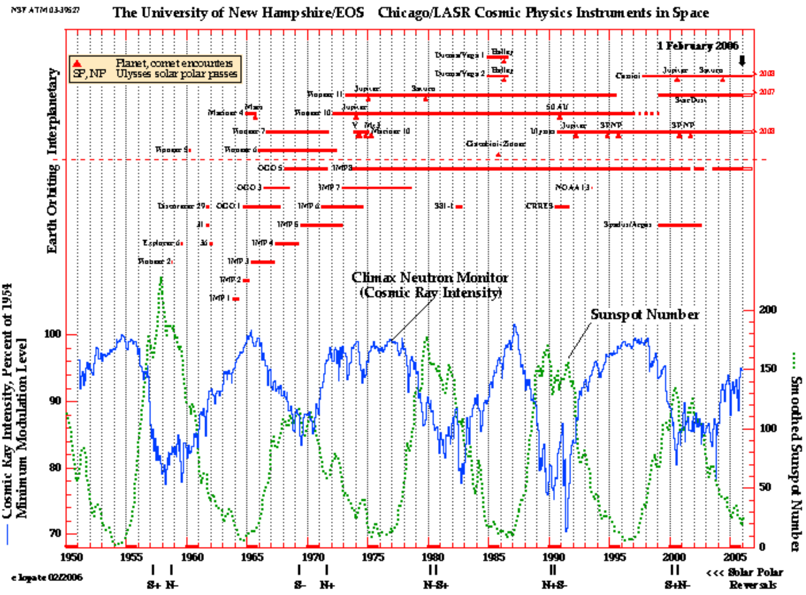
- many solar parameters depend on solar cycle
- emission in chromospheric lines
- radio emission
- cosmic rays



Long-Term Records

- potential records longer than sunspot observations
- aurorae
- radioactive isotopes due to cosmic rays

Neutron Flux

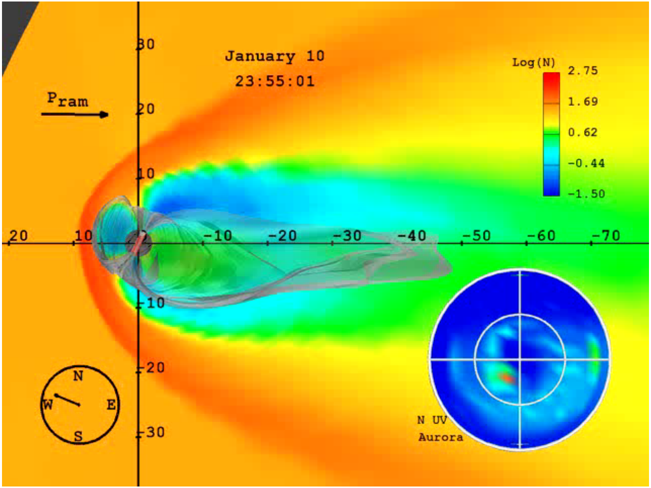


ulysses.sr.unh.edu/NeutronMonitor/Misc/neutron2.html

Cosmic Rays

- *cosmic rays*: particles originating from outside the Earth's atmosphere, electrically charged, often with high energies, mostly atomic nuclei
- galactic cosmic rays from outside the solar system
- anomalous cosmic rays coming from interstellar space at edge of heliopause
- *Solar Energetic Particles* from solar flares and coronal mass ejections
- galactic cosmic rays produce neutrons in the Earth's atmosphere
- solar cosmic rays rarely have high enough energy to produce neutrons
- solar and Earth's magnetic field deflect cosmic rays
- $\Rightarrow$ anti-correlation between cosmic ray flux and sunspot cycle

Sun-Magnetosphere Interaction

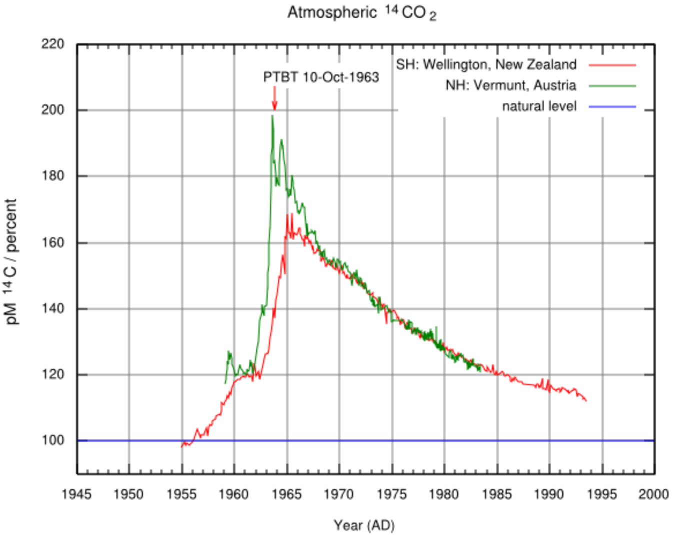


Carbon-14

$$^{14}\mathrm{N} + \mathrm{n} \Rightarrow ^{14}\mathrm{C} + ^{1}\mathrm{H}$$

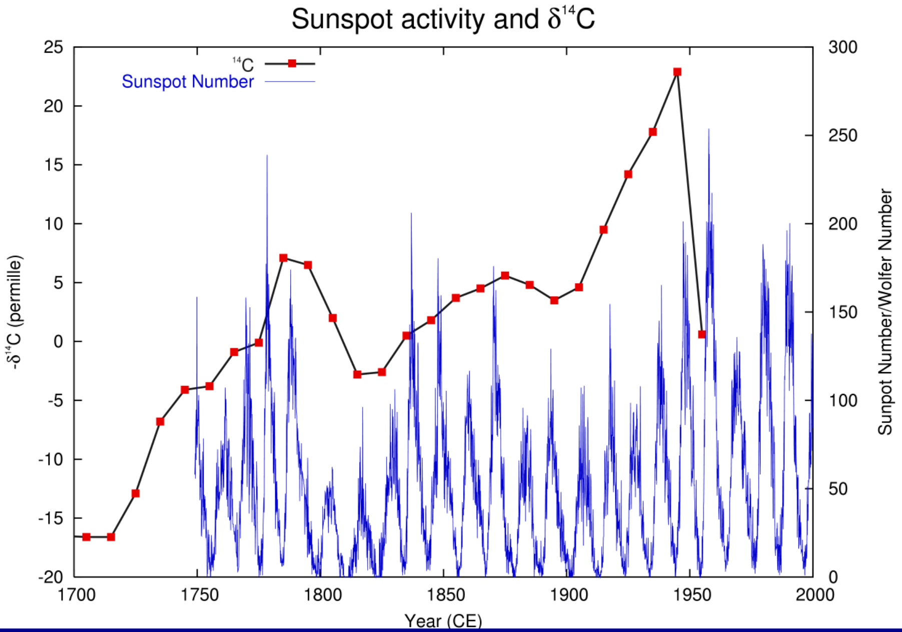
- mostly produced between 9 and 15 km
- fast oxidation to carbon dioxide
- radioactive CO^2 part of carbon cycle
- half-life of about 5730 years
- photosynthesis in plants absorbs ^{14}C
- atmospheric ^{14}C content: equilibrium between production by cosmic rays, radioactive decay, exchange with other reservoirs
- ^{14}C 'frozen' into dead plants and decays
- knowing initial ^{14}C concentration is basis of radiocarbon dating
- calibration with dated material such as tree-rings

Carbon-14 in Modern Times

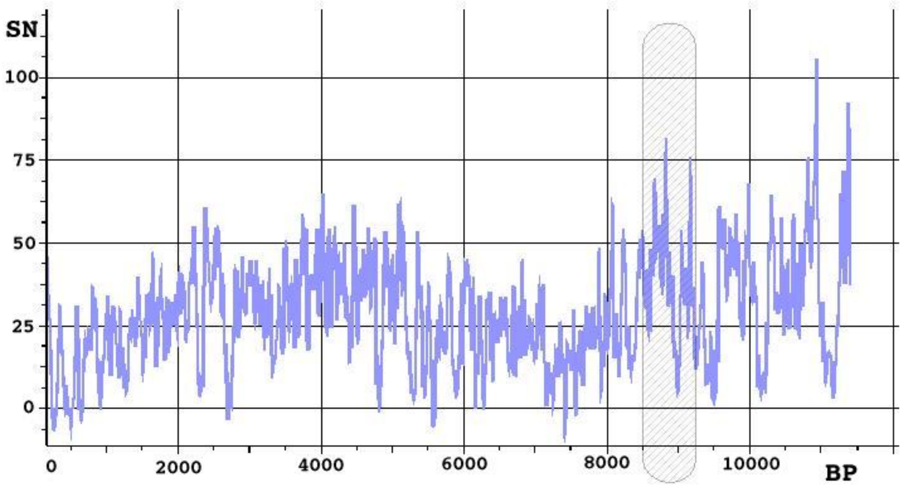


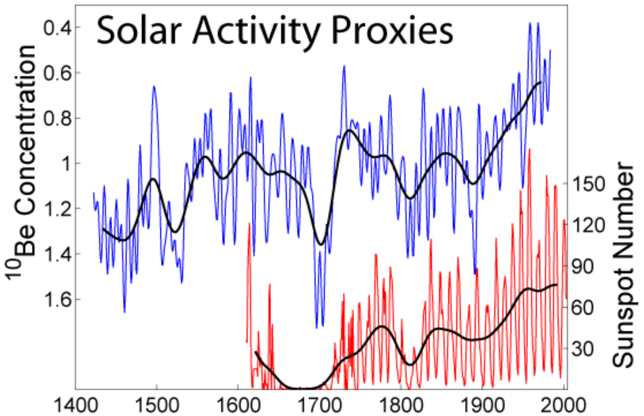
en.wikipedia.org/wiki/Radiocarbon_dating

Solar Magnetic Field Relation



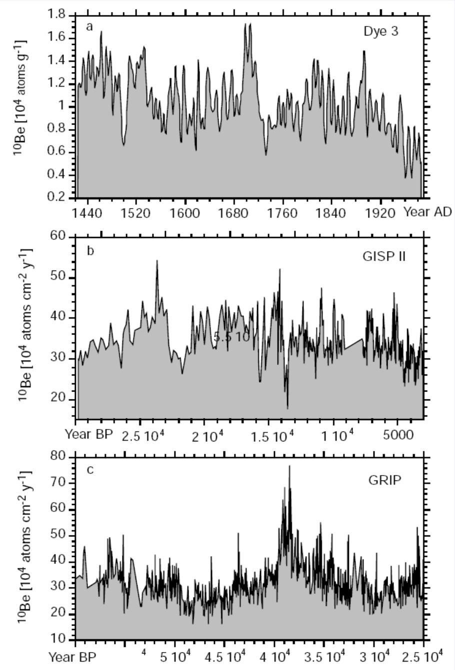
Reconstructed Sunspot Numbers





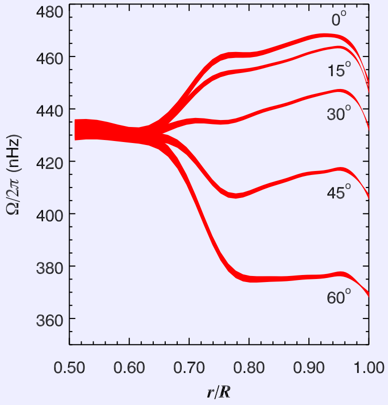
Beryllium-10

- fragmentation of nitrogen, oxygen by cosmic rays makes ^{10}Be
- half-life $1.51 \cdot 10^6$ years, long-term cycle behavior
- ^{10}Be attaches to aerosols, then precipitates
- time in atmosphere only weeks to 2 years



Long-Term ^{10}Be Variation

- short-term variations reflect 11-year cycle
- medium-term variations reflect cycle amplitude
- long-term variations consistent with geomagnetic field variations
- both medium and long-term variations show periodicity of 205 years

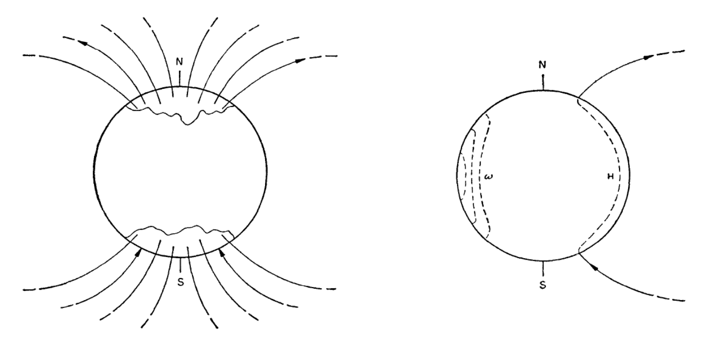


soi.stanford.edu/press/GONG_MDI_03-00/

Differential Rotation

- Christoph Scheiner measured the equatorial rotation rate and noticed slower rotation at higher latitudes
- helioseismology provides in-depth measurements of the internal solar rotation rate
- only convection zone shows differential rotation

Babcock-Leighton Model



Babcock 1961

Stage 1: Poloidal Field

- start with a pure dipole field (poloidal field)
- located at constant depth under surface
- magnetic field layer thickness d_b assumed to be 0.05 solar radii
- exits at about ± 55 degrees latitude

Poloidal Field (continued)

- $\nabla \cdot \vec{B} = 0$ in integral form implies magnetic flux Φ conserved

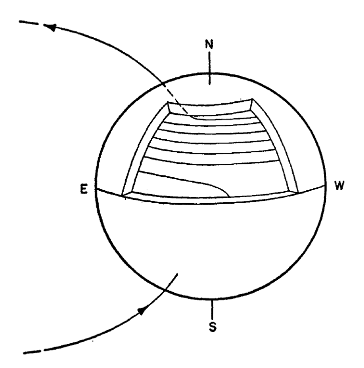
$$\Phi = B_\theta 2\pi d_B R_\odot \cos\phi = \text{constant}$$

B_θ Poloidal component of magnetic field
d_B Thickness of magnetic field layer
$R_\odot$ Solar radius
ϕ Latitude ($\phi = 0$ at equator)

- field strength given by

$$B_\theta = \frac{B_0}{\cos\phi}$$

with field strength at equator $B_0 \approx 20$ Gauss



Babcock 1961

Stage 2: Amplification

- differential rotation
  $\omega = 14.38^\circ - 2.77^\circ \sin^2 \phi$
- differential rotation winds up magnetic field

Amplification (continued)

- assume that amplification starts 3 years before start of new cycle
- compared to polar rotation, wind-up after *n* years is

$$\theta = 17.6\,(n + 3)\sin^2\phi$$

  in radians per year
- inclination angle of field lines

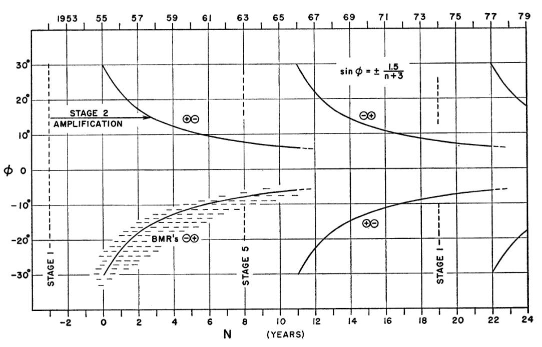
$$\tan\psi = \frac{\partial\theta}{\partial\phi} = 35.2\,(n + 3)\sin\phi\cos\phi$$

- magnetic field

$$B = B_0\frac{1}{\cos\phi\cos\psi}$$

- for $\psi \approx \frac{\pi}{2}$

$$B = B_0\frac{\tan\psi}{\cos\phi} = 35.2\,(n + 3)\,B_0\sin\phi$$



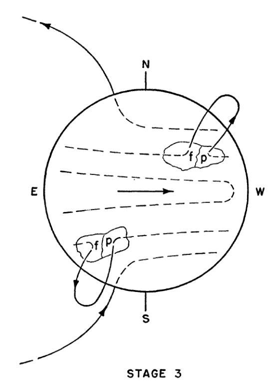
Babcock 1961

Amplification (continued)

- critical value for emergence of sunspots $B_c \approx 1100$ Gauss
- latitude where field reaches critical value is

$$\sin\phi = \pm\frac{1.5}{n+3}$$

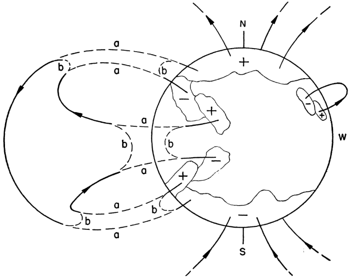
Stage 3: Formation of Bipolar Magnetic Regions



Babcock 1961

- depth-dependence of differential rotation and convective motion lead to inhomogenous magnetic field ⇒ flux tube approximation
- total pressure equilibrium $p_e = p_i + \frac{B^2}{2\mu_0}$
- temperature inside and outside the same ⇒ density lower inside magnetic field ⇒ buoyancy lifts magnetic field to the surface
- accounts for Hale's polarity law, Spörer's law
- Coriolis force also provides appropriate tilt angles (Joy's law)

Stage 4: Neutralization and Reversal of Dipole Field



Babcock 1961

- active regions diffuse ⇒ magnetic field diffuses
- opposite polarities drift towards equator and poles
- poleward migration in higher latitudes assisted by meridional flow

Stage 5: Reversed Dipolar Field

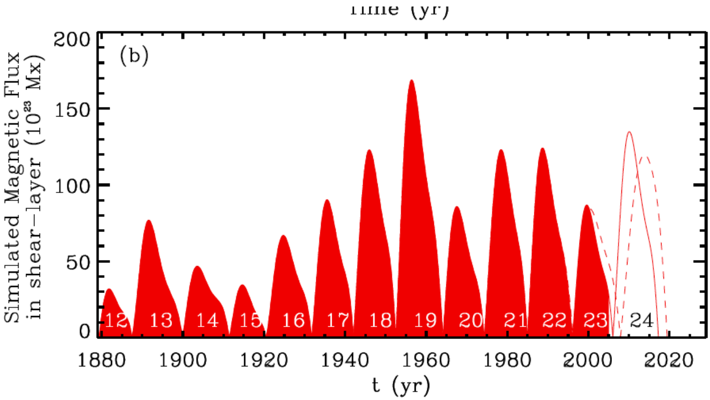
- residual magnetic field is a reversed dipole field
- obtained after about 11 years
- similar to Stage 1 but with reversed polarity

Discussion

- Babcock-Leighton dynamo replaced in 1960s by mean-field dynamo theory
- mean-field dynamo theory has fundamental problems
- revival of Babcock-Leighton-type models in early 1990s
- Babcock-Leighton model produces excessively strong polar surface magnetic fields
- physical mechanism responsible for the regeneration of the poloidal component of the solar magnetic field has not yet been identified with confidence (Charbonneau 2005)
- strong cycles last shorter than weak cycles, but diffusion time should be proportional to cycle strength

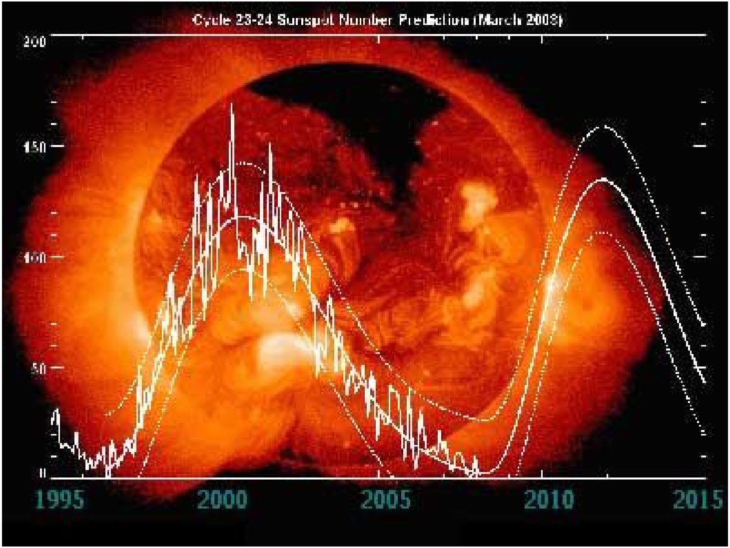
Cycle Predictions

Prediction in 2008



Dikpati (2008)

Prediction in 2008



Prediction in 2010