Lecture Information

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- www.astro.uu.nl/~keller
- Solar Physics
  - observations of solar magnetic fields using polarization
  - realistic numerical, radiative MHD simulations (A.Vögler)
- Experimental Astrophysics (Instrumentation)
  - Dutch Open Telescope (DOT) at La Palma, Canary Islands
  - polarimeters for solar magnetic field studies
  - direct imaging of exoplanetary systems with large telescopes
  - high-resolution techniques such as Adaptive Optics

Literature

- Michael Stix, **The Sun: An Introduction**, Second Edition, Springer
- PDF file of this lecture with movies and links at www.astro.uu.nl/~keller/Teaching/USAP2008/TheSun2008.pdf

Outline

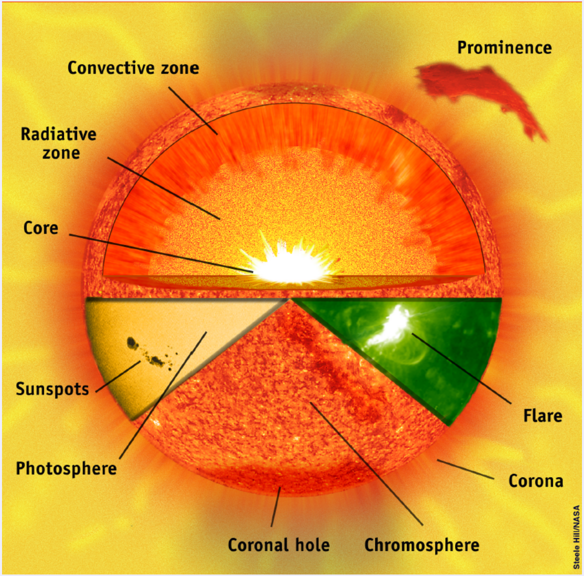
What makes the Sun Unique?

What makes the Sun Unique?

Some Answers

- Sun is the closest star
- Only star with well-resolved atmosphere
  - electromagnetic radiation
  - particle detection
- Only star with well-observed interior
  - helioseismology
  - neutrinos
- Only star of importance for life on Earth

Solar Structure and Terminology



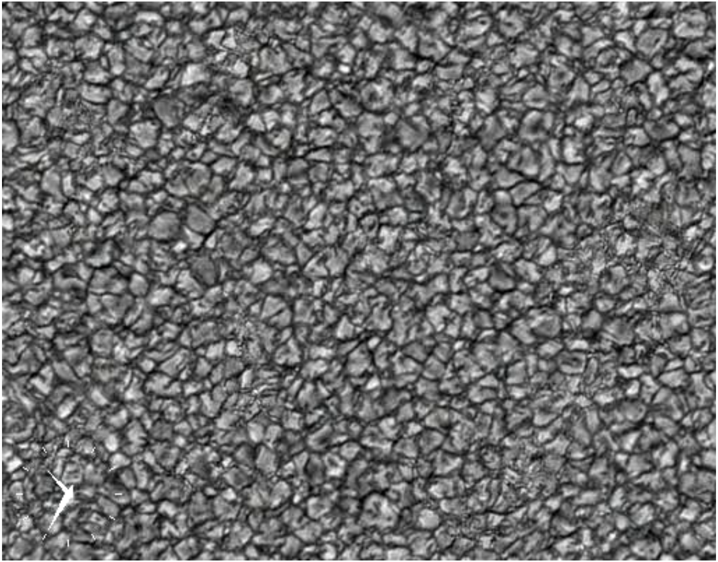
sohowww.nascom.nasa.gov/bestofsoho/PAGE2/

Basic Facts

Solar radius	695,990 km	109 Earth radii
Solar mass	$1.989 \cdot 10^{30}$ kg	333,000 Earth masses
Solar luminosity	$3.846 \cdot 10^{33}$ erg/s	
Surface temperature	5770 K	
Surface density	$2.07 \cdot 10^{-7}$ g/cm^3	$1.6 \cdot 10^{-4}$ Air density
Surface composition	70% H, 28% He,	
	2% CNO by mass	
Central temperature	15,600,000 K	
Central density	150 g/cm^3	8 times Gold density
Central composition	35% H, 63% He,	
	2% CNO by mass	
Solar age	$4.57 \cdot 10^9$ yr	

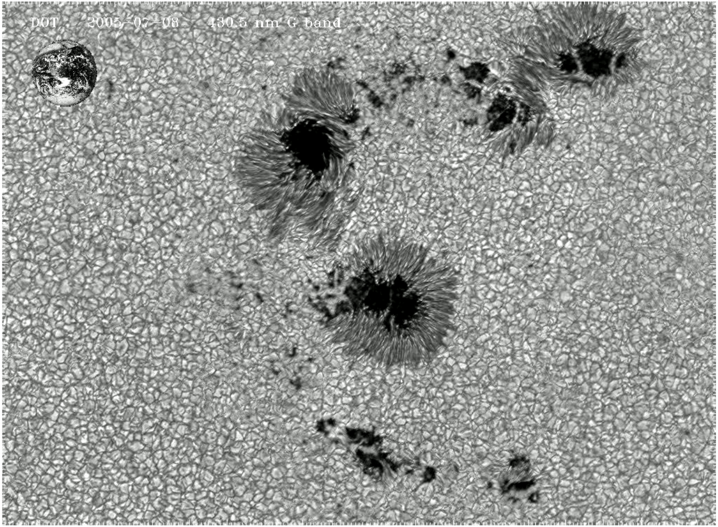
solarscience.msfc.nasa.gov/

The Photosphere



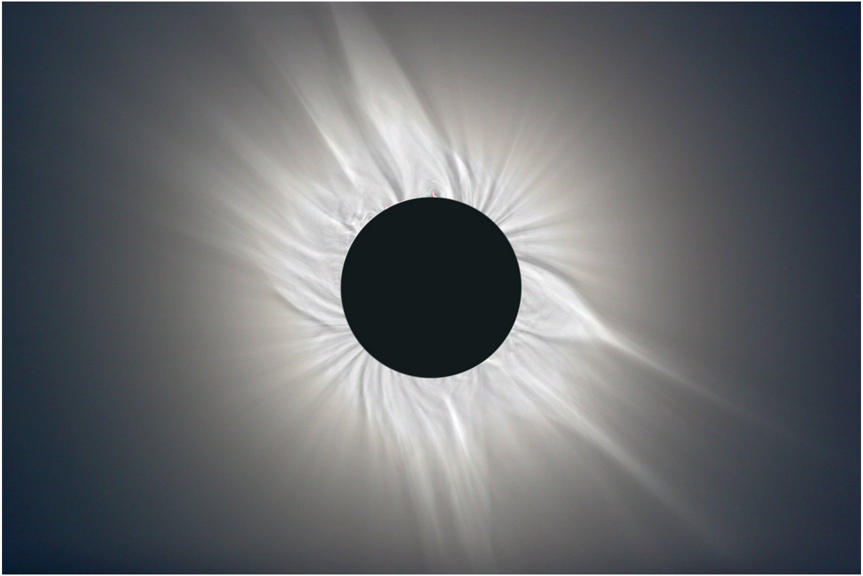
dotdb.phys.uu.nl/DOT/Data/2003_05_02

The Chromosphere



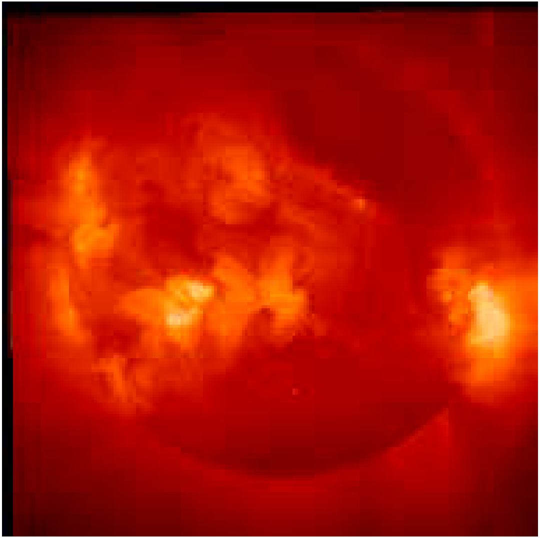
dot.astro.uu.nl/DOT_specials.html

The Corona seen during a Solar Eclipse



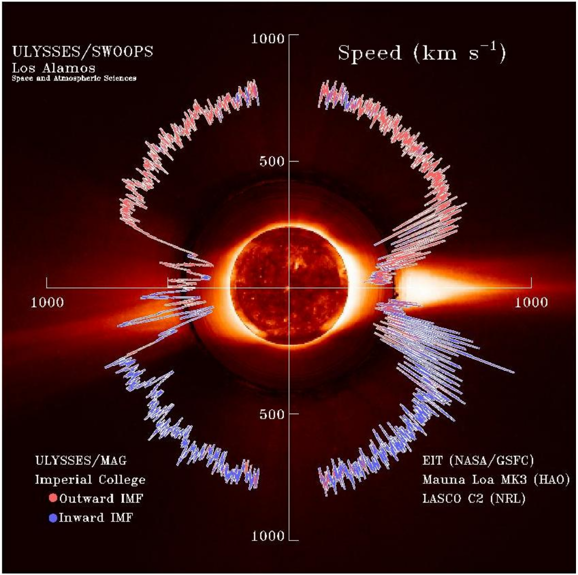
antwrp.gsfc.nasa.gov/apod/ap060407.html

The Corona in 1992 seen in X-Rays from the Yohkho Satellite



www.windows.ucar.edu/cgi-bin/tour_def/sun/atmosphere/corona.html

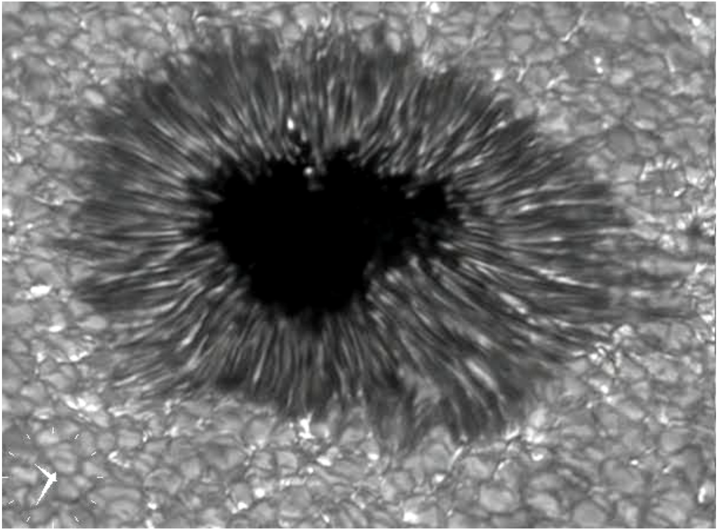
The Solar Wind



solarscience.msfc.nasa.gov/SolarWind.shtml

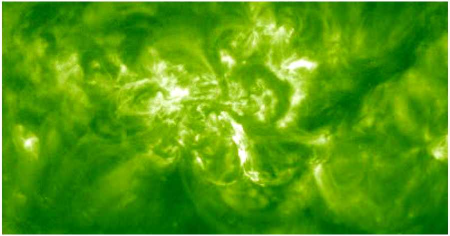
Activity (Magnetic Field Phenomena)

Sunspots



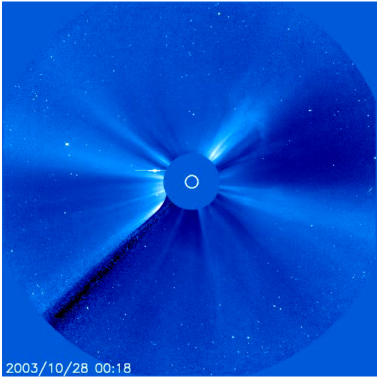
dotdb.phys.uu.nl/DOT/Data/1999_09_20

Flares



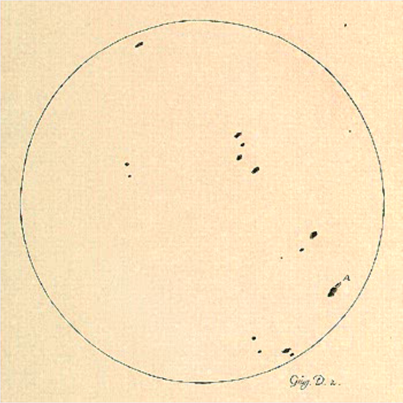
sohowww.nascom.nasa.gov/hotshots/2003_10_28/

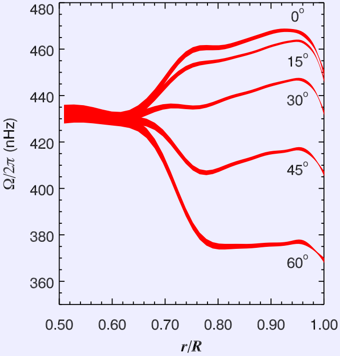
Coronal Mass Ejection



sohowww.nascom.nasa.gov/hotshots/2003_10_28/

Rotation





galileo.rice.edu/sci/observations/sunspot_drawings.html

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

Differential Rotation

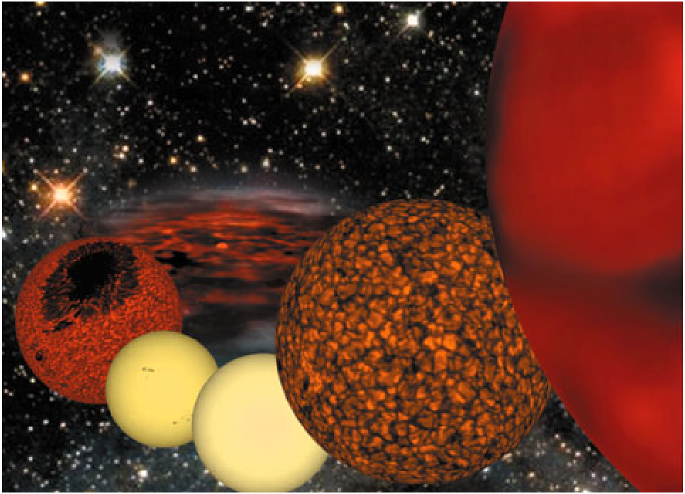
- Christoph Scheiner in 1630: slower rotation at higher latitudes
- helioseismology reveals internal solar rotation rate
- only convection zone shows differential rotation

Current Problems in Solar Physics

- **oxygen abundance**: numerical simulations imply metal abundances that are in disagreement with helioseismic frequencies
- **FIP-effect**: photospheric and solar wind abundances are not the same
- **origin of supergranulation**: physical mechanism
- **coronal heating process**: energy source, transport, dissipation mechanisms
- **solar wind accelleration**: physical mechanism
- **nature of flares**: source of magnetic energy, instability, forecasting
- **origin of solar cycle**: physics of the (large-scale) dynamo
- **origin of small-scale fields**: leftovers from sunspot cycle or small-scale dynamo in surface layers

The Sun among the Stars

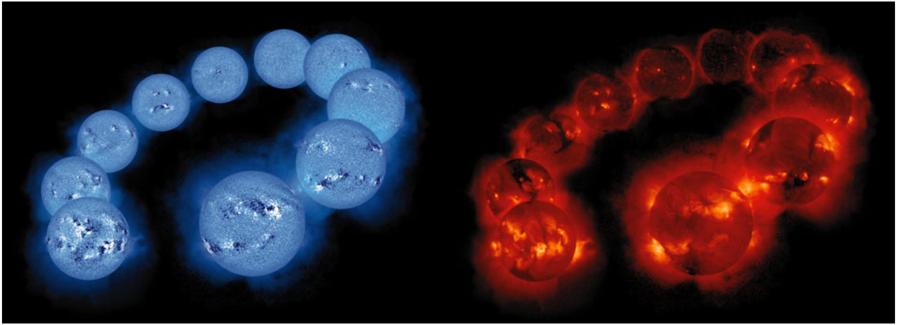
An Artist's Impression



trace.lmsal.com/POD/NAS2002_otherimages.html

Magnetic Activity

The 11-Year Solar Cycle

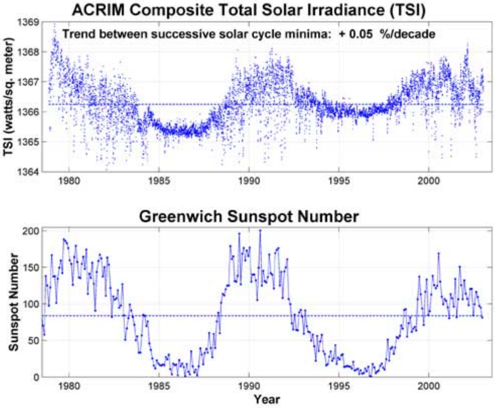


trace.lmsal.com/POD/NAS2002_otherimages.html

If the Sun had no magnetic field,
it would be as uninteresting as many astronomers think it is.

R.B.Leighton: unpublished remark (ca. 1965)

Irradiance and Sunspots

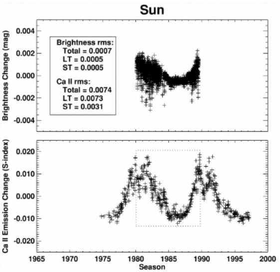


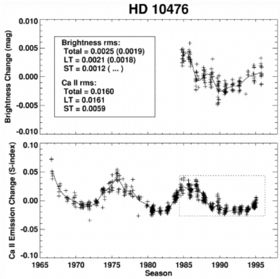
earthobservatory.nasa.gov/Newsroom/NasaNews/2003/2003032011367.html

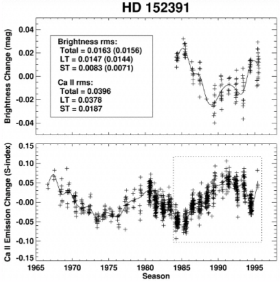
The Solar (not so) Constant

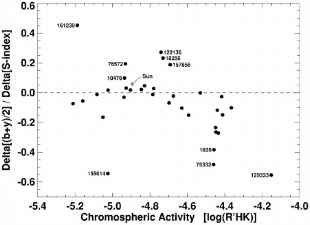
- correlation between irradiance and magnetic activity
- sunspots only temporarily reduce irradiance
- faculae more than compensate sunspot deficit
- solar constant varies by about 0.1%

Stellar Irradiance vs. Magnetic Variations



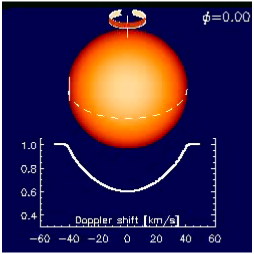






Radick et al. 1998

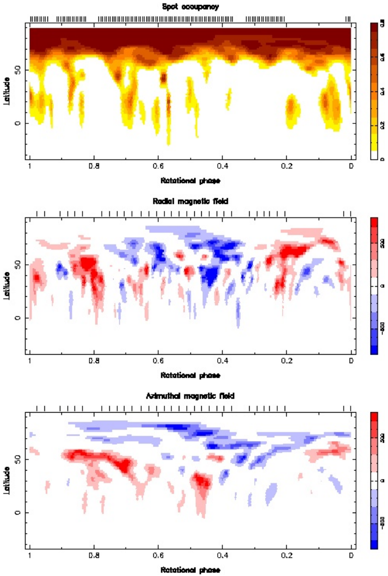
Doppler Imaging



www.astro.uu.se/˜oleg/structures.html

- quickly rotating stars
- many spectra per rotation period
- fit with 'spotted' star model
- also possible for polarized spectra

Zeeman Doppler Imaging

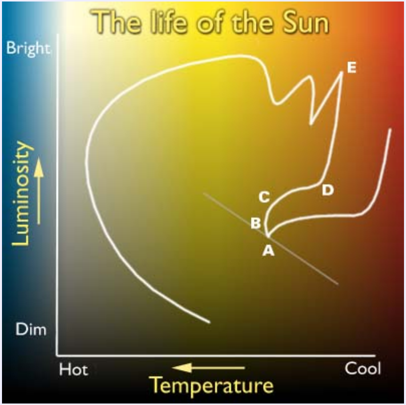


www.ast.obs-mip.fr/users/donati/map.html

Evolution of the Sun

The Past Sun

- numerical models of stellar evolution
  - include all relevant physics including rotation
  - solve PDEs for each time step
  - adjust abundances after each time step
  - have to produce currently observed Sun
- current age: 4.57×10^9 years (22 times around galaxy center)
- very young Sun:
  - 70% of current luminosity
  - 125 K colder surface
  - 13% smaller
  - very active chromosphere and corona
  - strong solar wind
  - rotation period only 9 days
- how could life on Earth start and survive?

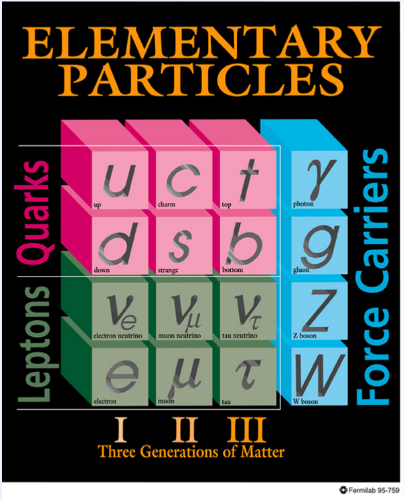


www.astro.uva.nl/demo/sun/leven.htm

The Future of the Sun

- B 50% of available H in core used up (now)
- C all H in core used up, H fusion in shell, 40% larger, twice as bright
- D 1.5×10^9 years later $3\times$ current size, temperature 4300 degrees; 0.25×10^9 years later, 100 times larger, 500 times more luminous
- E critical core temperature, all He fuses into C, explosion throws out $\frac{1}{3}$ of solar mass into space, planetary nebula and white dwarf (2000 kg/cm^3)

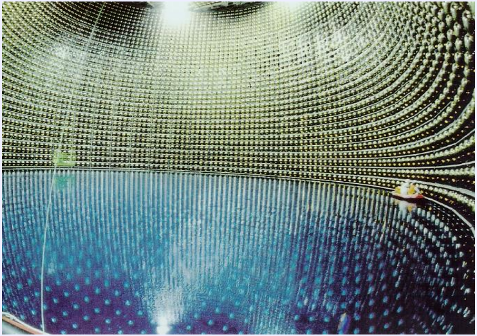
Solar Neutrinos



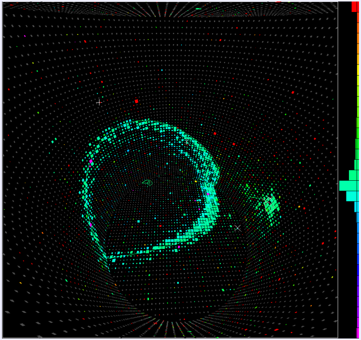
www.fnal.gov/pub/presspass/vismedia/gallery/graphics.htm

Neutrino Properties

- Neutrino (ν) predicted around 1930 by Wolfgang Pauli to save energy conservation for certain radiactive decays
- first neutrino detection published in 1956
- 6 different kinds: ν_e, ν_μ, ν_τ and their anti-particles $\bar{\nu}_\mathrm{e}$, $\bar{\nu}_\mu$, $\bar{\nu}_\tau$
- no electrical charge, almost massless, propagate at almost the speed of light, have only weak interaction
- interact barely with matter, could penetrate one light year of lead without problems



antwrp.gsfc.nasa.gov/apod/ap971028.html

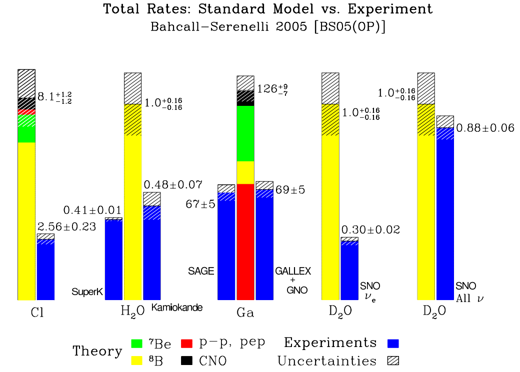


neutrino.kek.jp/figures.html

Detecting Solar Neutrinos

- knowledge of stellar interiors largely based on model calculations
- *helioseismology* provides only limited information about core
- neutrinos are the only direct measurement of fusion process
- on Earth each cm^2 is penetrated every second by $4{\cdot}10^{10}$ solar ν_e
- weak interaction only, ν hard to detect $\Rightarrow$ very large detectors
- Super-Kamiokande in Japan: 50,000 tons of water to image Cerenkov radiation

The Data



www.sns.ias.edu/˜jnb/SNviewgraphs

Observations and Standard Models Disagree

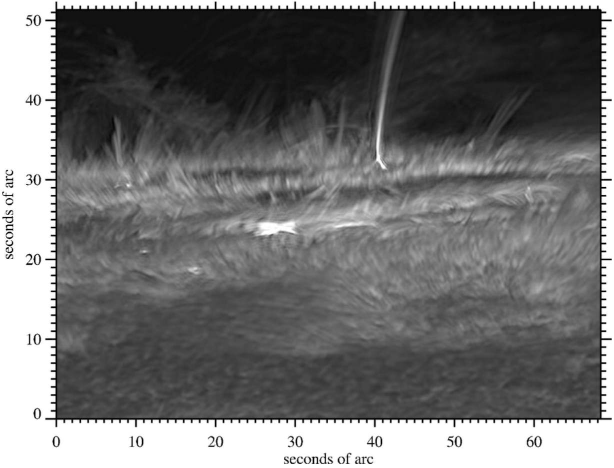
- Wrong standard solar model? But helioseismology excludes non-standard solar core models
- Wrong standard model of particle physics? But neutrinos might have mass

The Solution

- Mikheyev–Smirnov–Wolfenstein effect
- interaction with matter: ν_e and e^- can interact through W^- or Z^0, ν_μ and ν_τ can only interact with e^- through Z^0
- most neutrinos from Sun will pass through resonance density region inside the Sun
- even very small mixing angles and mass differences can make most ν_e into ν_μ
- all solar data and also reactor experiments deliver consistent combinations of mixing angle and difference of squared masses

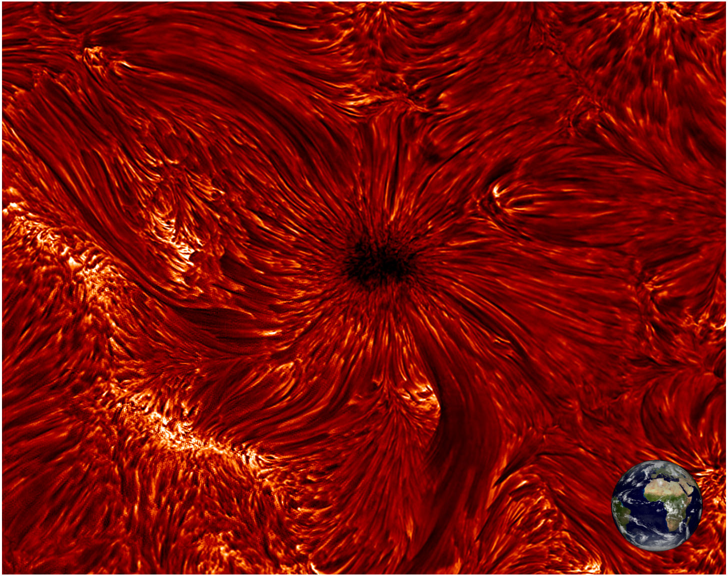
Flux Tubes: Observational Evidence

CaII K close to the limb



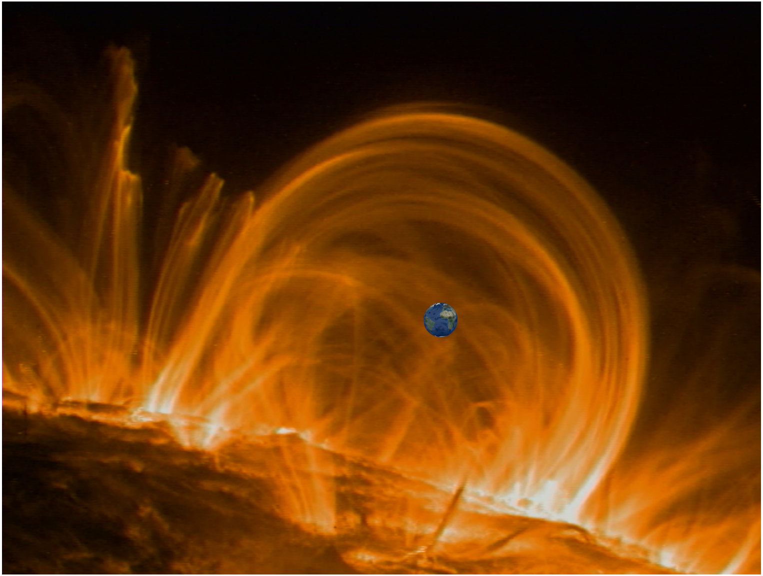
dot.astro.uu.nl/promotion/images/20031104-surge-ca.png

Sunspot region in Hα



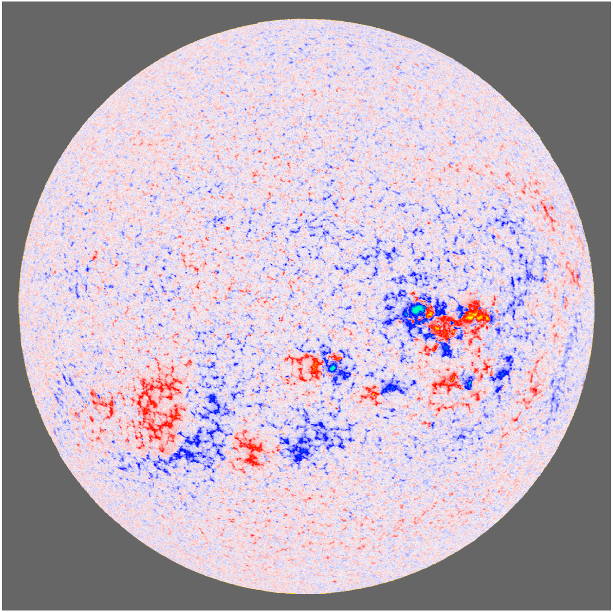
dot.astro.uu.nl/promotion/images/20040929-apod-ha.tif

Coronal TRACE Loopsat EUV wavelengths



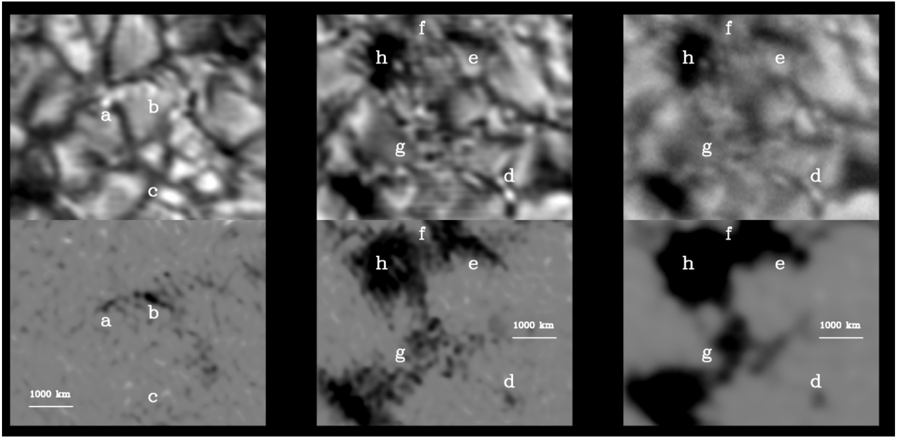
antwrp.gsfc.nasa.gov/apod/ap000928.html

SOLIS VSM Magnetogram (magnetic field map)



solis.nso.edu

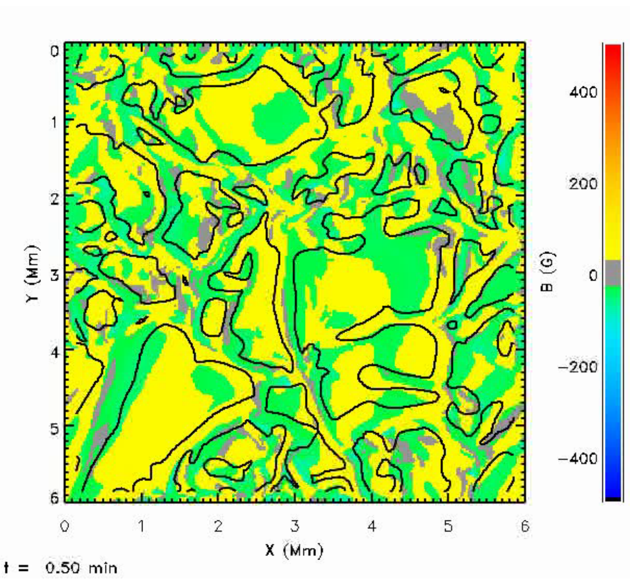
Direct Detection of Concentrated Fields



Keller C.U., 1992, Nature 359, 307–308

Evidence from Numerical MHD Simulations

Stein & Nordlund, Quiet Sun



Thin Flux Tube Approximation

Force Balance

- all relative length scales are large compared to tube diameter
- neglect diffusion term in induction equation
- equation of motion (momentum conservation)

$$\rho\left(\frac{\partial\vec{v}}{\partial t}+\vec{v}\cdot\nabla\vec{v}\right)=-\nabla p+\vec{j}\times\vec{B}+\vec{F}_{\text{gravity}}+\vec{F}_{\text{viscosity}}$$

- magnetohydrostatic ($\vec{v}=0\Rightarrow F_{\text{viscosity}}=0$)
- force balance

$$\nabla p-\vec{j}\times\vec{B}=\vec{F}_{\text{gravity}}$$

- with $\mu_0\vec{j}=\nabla\times\vec{B}$ and $\vec{B}\times\left(\nabla\times\vec{B}\right)=\frac{1}{2}\nabla B^2-\left(\vec{B}\cdot\nabla\right)\vec{B}$

$$\nabla\left(p+\frac{B^2}{2\mu_0}\right)-\frac{1}{\mu_0}\left(\vec{B}\cdot\nabla\right)\vec{B}=\vec{F}_{\text{gravity}}$$

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Radial Force Balance

- force balance in general coordinate system

$$\nabla \left(p + \frac{B^2}{2\mu_0} \right) - \frac{1}{\mu_0} \left(\vec{B} \cdot \nabla \right) \vec{B} = \vec{F}_{\text{gravity}}$$

- in cylindrical coordinates, radial component

$$\frac{\partial}{\partial r} \left(p + \frac{B^2}{2\mu_0} \right) - \frac{1}{\mu_0} \left(B_r \frac{\partial B_r}{\partial r} + B_z \frac{\partial B_r}{\partial z} - \frac{B_\phi^2}{r} \right) = 0$$

- with $B_{r,\phi} = 0$

$$\frac{\partial}{\partial r} \left(p + \frac{B^2}{2\mu_0} \right) = 0$$

- and therefore *horizontal pressure balance*

$$p_{\text{inside}} + \frac{B^2}{2\mu_0} = p_{\text{outside}}$$

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Vertical Force Balance

- in the z-direction (along the field lines)

$$\frac{\partial p}{\partial z} = -\rho g$$

- with ideal gas law $\rho = \frac{\mu p}{kT}$

$$\frac{\partial p}{\partial z} = -\frac{\mu g}{kT} p$$

- pressure as a function of height z

$$p(z) = p(z_0) \exp\left(-\int_{z_0}^{z} \frac{1}{H(z')} dz'\right)$$

- with the *pressure scale height*

$$H(z) = \frac{kT}{\mu g}$$

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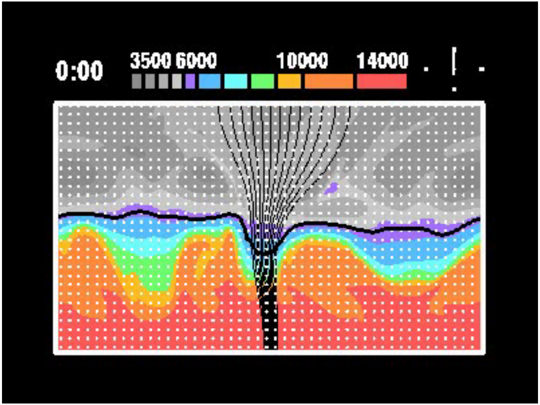
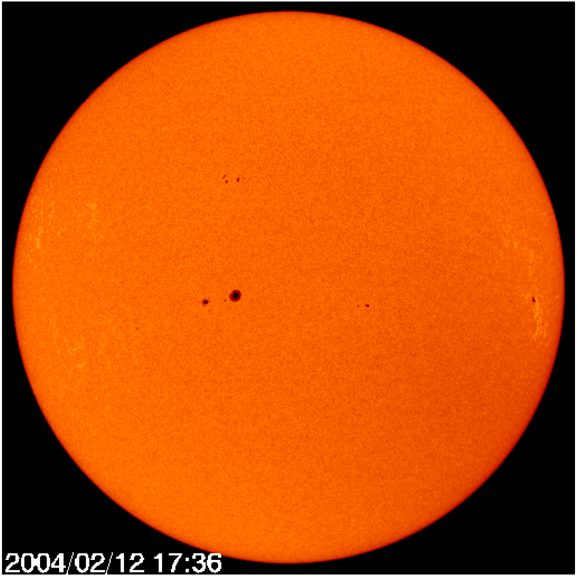
2-D Simulation of Magnetic Flux Tube in Solar Photosphere



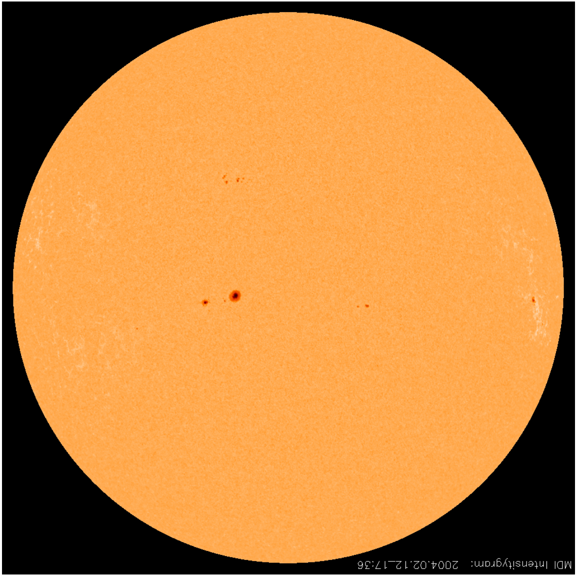
http://www3.kis.uni-freiburg.de/˜steiner

Faculae

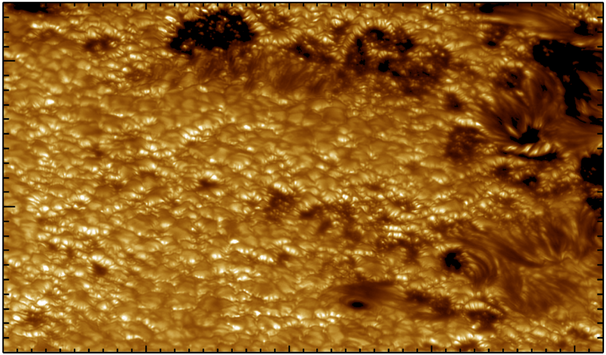
The Sun in White Light as seen by SoHO



The Sun without Limb Darkening

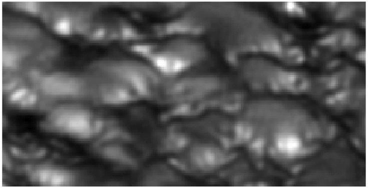


1-m Swedish Solar Telescope Observations by Lites et al. (2004)



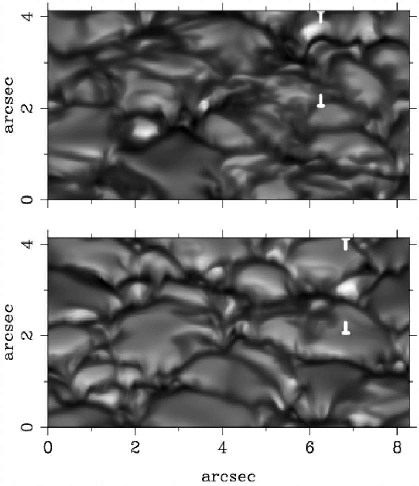
- 3-D impression when looking at images
- Faculae appear predominantly in plages
- Facular brightenings on disk-center side of granules
- Brightening can extend over about 0.5 arcsec
- Narrow, dark lanes centerward of the facular brightening

Observations by Lites et al. (2004)

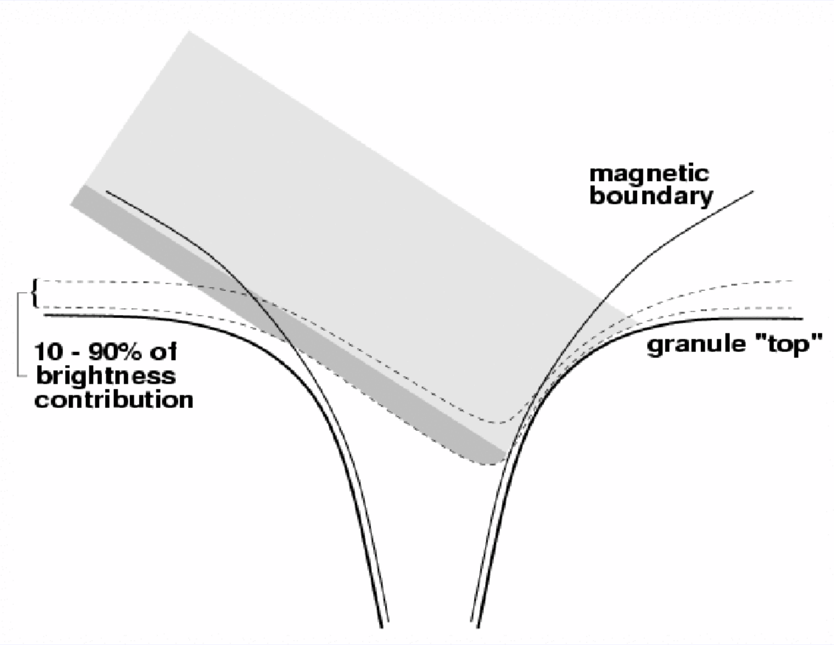


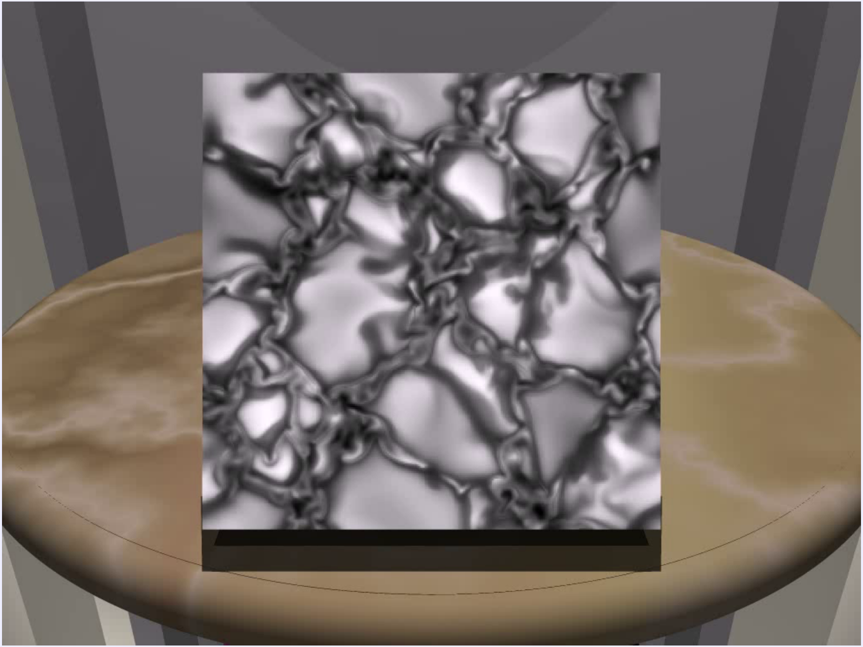
Simulations by Keller, Schüssler, Vögler, Zakharov, ApJL 607, L59 (2004 May 20)

Simulation, 200 G

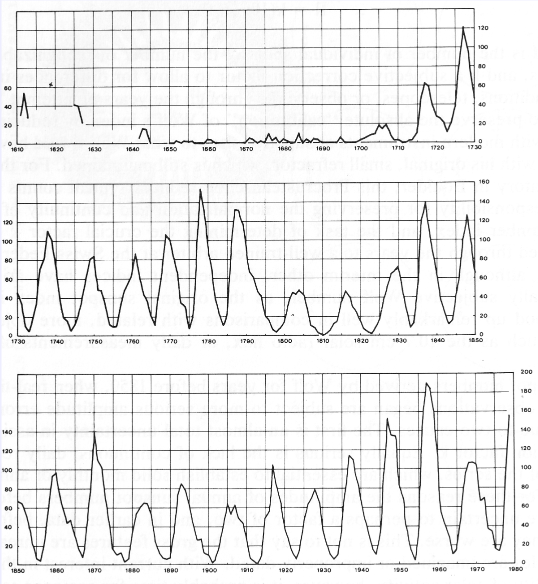


Simulation, 400 G


magnetic
boundary
granule "top"
10 - 90% of
brightness
contribution



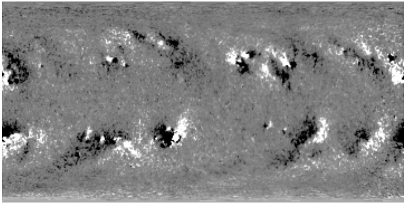
Observations of the Solar Cycle

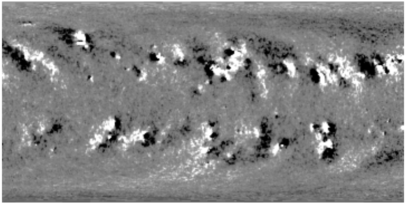


Sunspot Number

- 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

Hale's Polarity Law

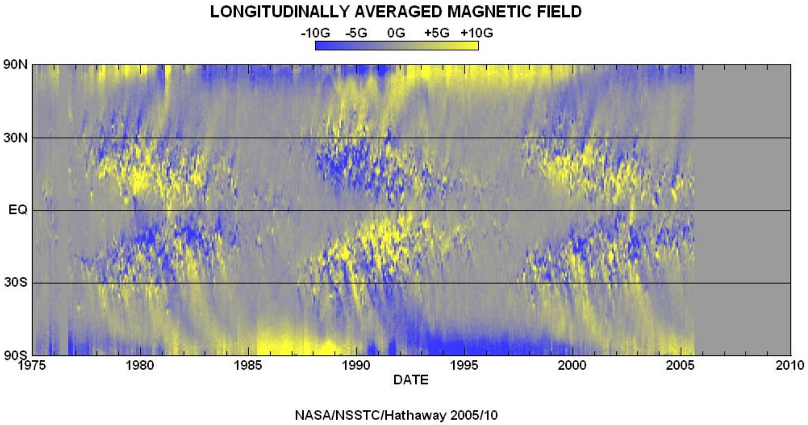




www.nso.edu

- 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

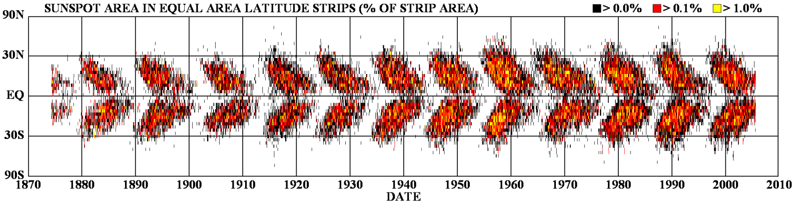
Polar Fields



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*)

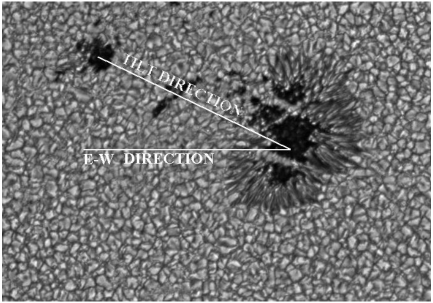
Spörer's Law

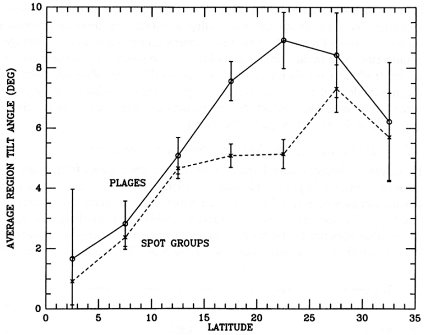


science.nasa.gov/ssl/pad/solar/sunspots.htm

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

Joy's Law

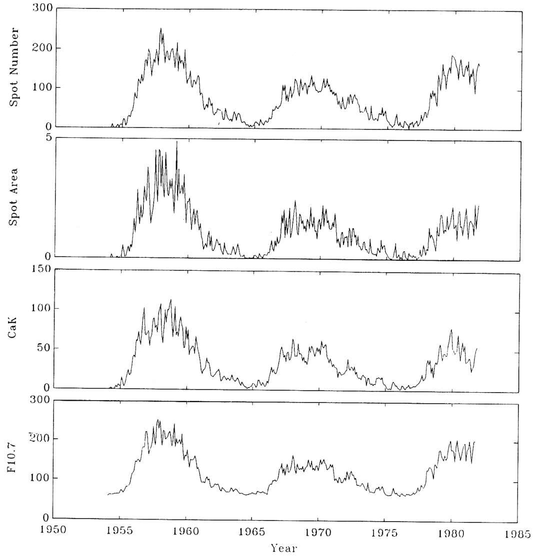




science.nasa.gov/ssl/pad/solar/dynamo.htm

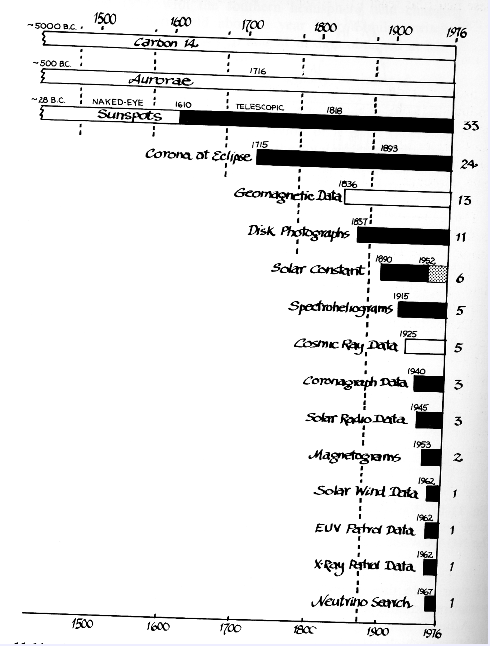
www.ociw.edu/ociw/babcock/howardtalk.pdf

- 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

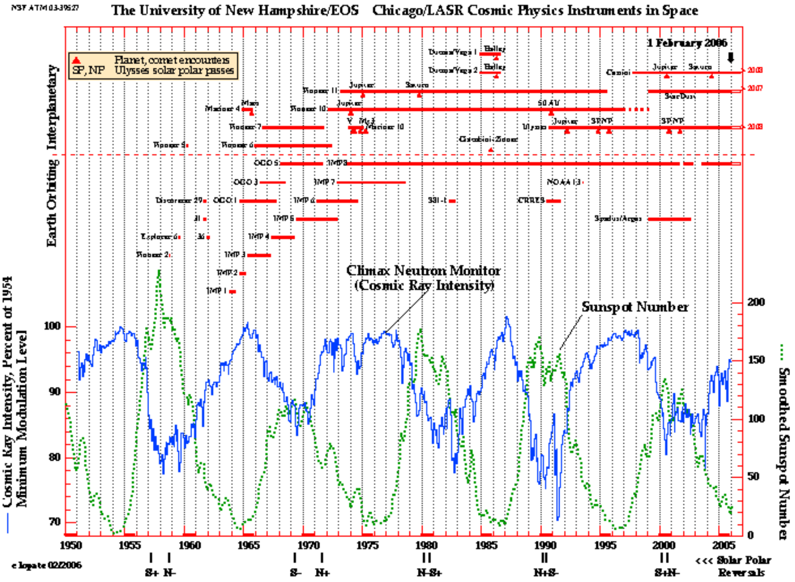
- many solar parameters depend on solar cycle
- emission in chromospheric lines
- radio emission
- cosmic rays



Long-Term Records

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

Neutron Flux

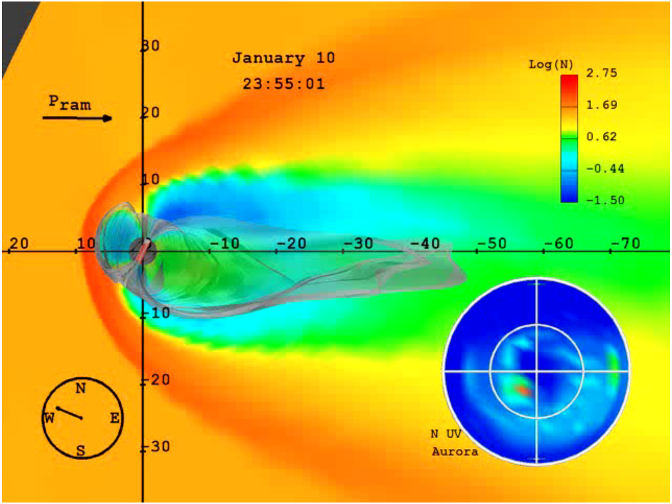


ulysses.sr.unh.edu/NeutronMonitor/Misc/neutron2.html

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

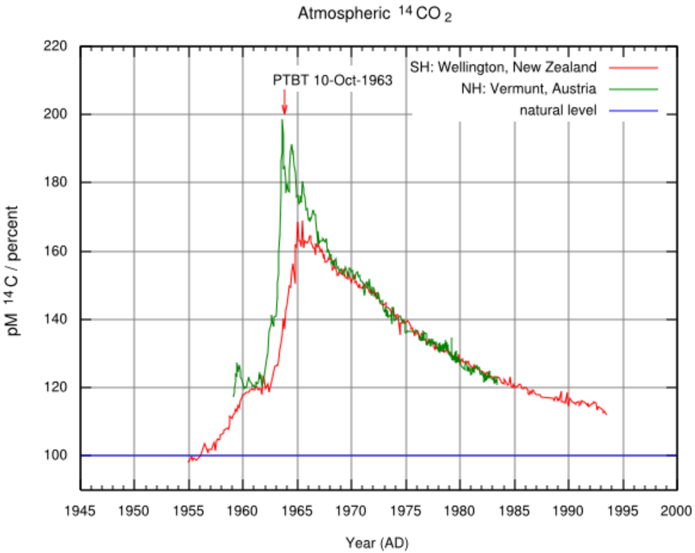


Carbon-14

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

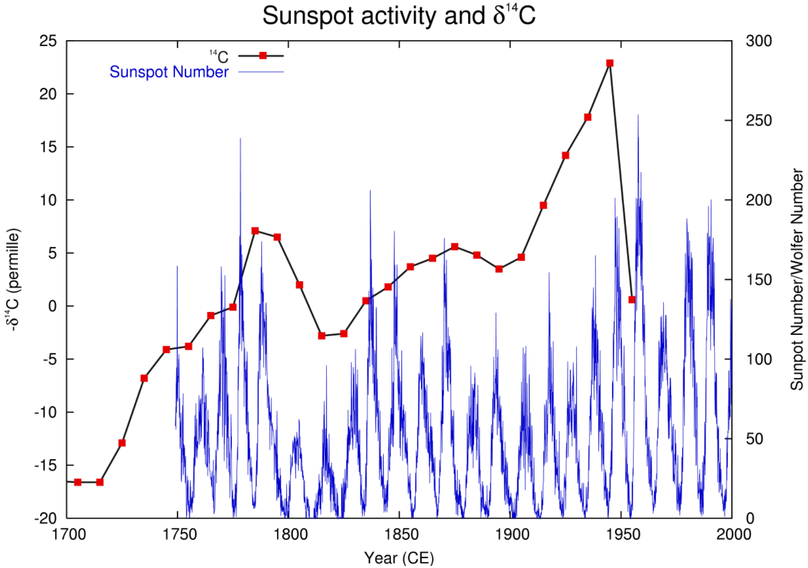
- mostly produced between 9 and 15 km
- fast oxidation to carbon dioxide
- radioactive CO^2 part of carbon cycle
- half-life of about 5730 years
- photosynthesis in plants absorbs ^{14}C
- atmospheric ^{14}C content: equilibrium between production by cosmic rays, radioactive decay, exchange with other 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



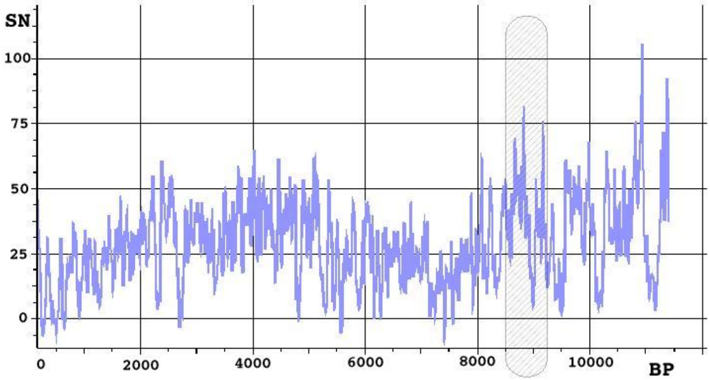
en.wikipedia.org/wiki/Radiocarbon_dating

Solar Magnetic Field Relation



en.wikipedia.org/wiki/Image:Carbon14-sunspot.png

Reconstructed Sunspot Numbers



en.wikipedia.org/wiki/Image:Sunspots_11000_years.jpg