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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/USAP2007/TheSun2007.pdf

Our Sun: a Star Close-Up

Outline

- **The Sun: An Introduction (9:30-10:15)**
 - The Sun's Uniqueness
 - Solar Structure and Terminology
 - Current Problems in Solar Physics
- **The Sun as a Star (10:30–11:15)**
 - The Sun among the Stars
 - Evolution of the Sun
 - Solar Neutrinos
- **The Sun: A Magnetic Star (11:30-12:15)**
 - Flux Tube Observations and Theory
 - Faculae
 - The Solar Cycle
- **Astronomical Projects (14:00–17:00)**

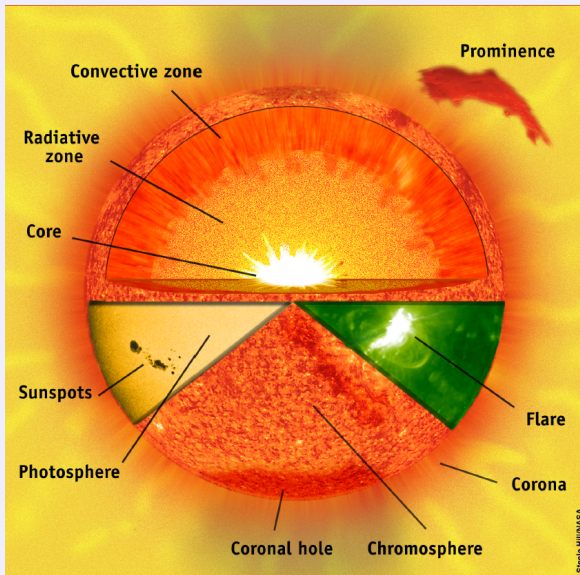
What makes the Sun Unique?

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

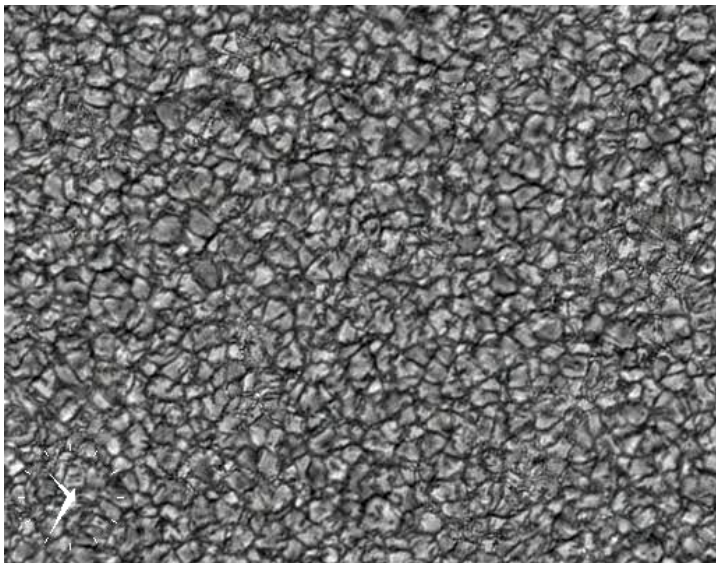
Solar Structure and Terminology



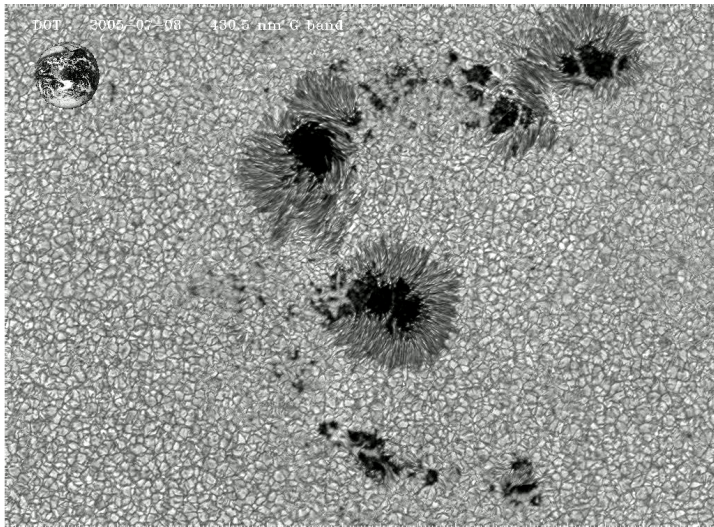
Basic Facts

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	

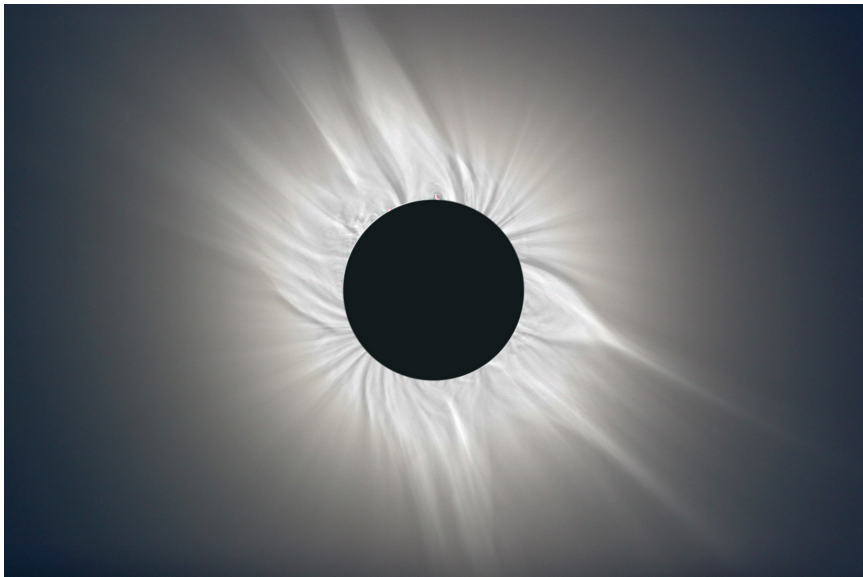
The Photosphere



The Chromosphere

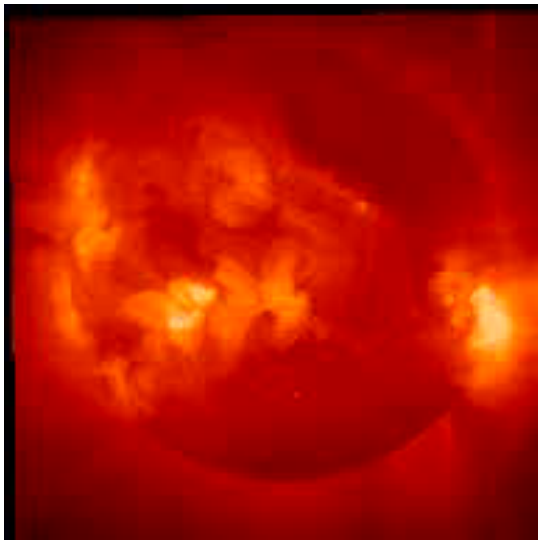


The Corona seen during a Solar Eclipse



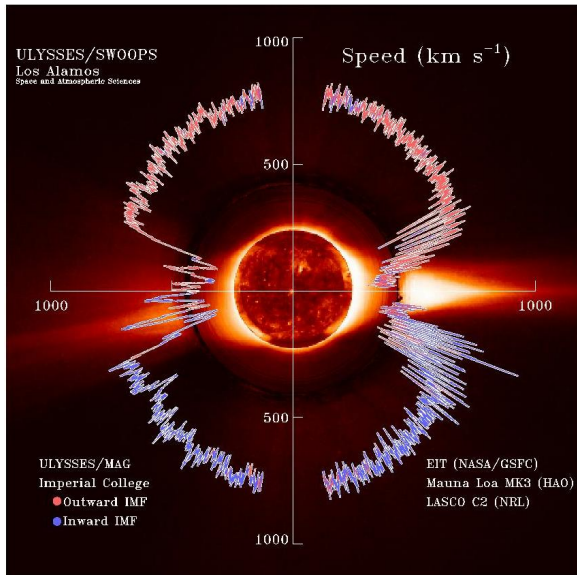
antwrp.gsfc.nasa.gov/apod/ap060407.html

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



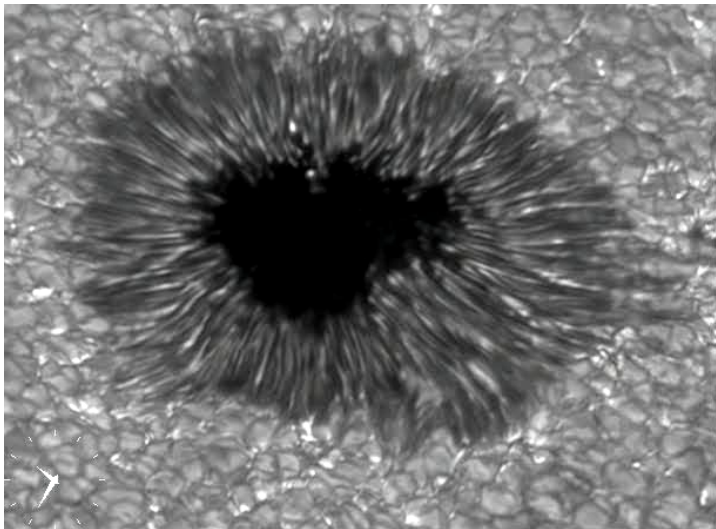
www.windows.ucar.edu/cgi-bin/tour_def/sun/atmosphere/corona.html

The Solar Wind

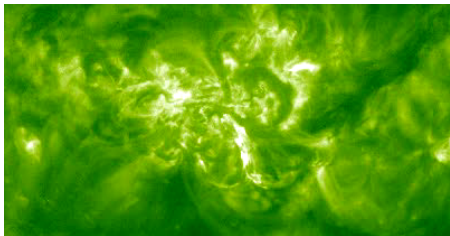


Activity (Magnetic Field Phenomena)

Sunspots

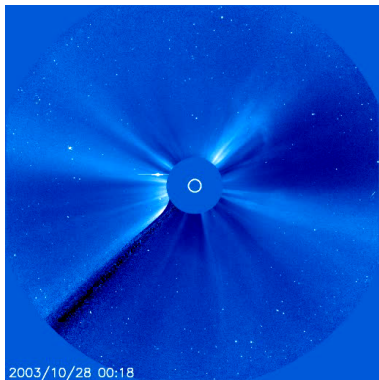


Flares



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

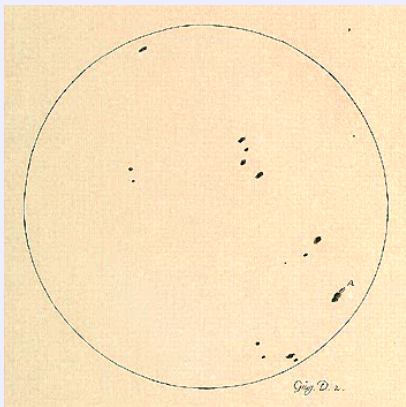
Coronal Mass Ejection



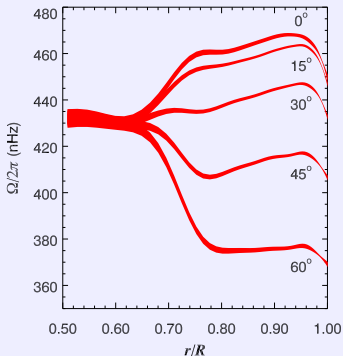
2003/10/28 00:18

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

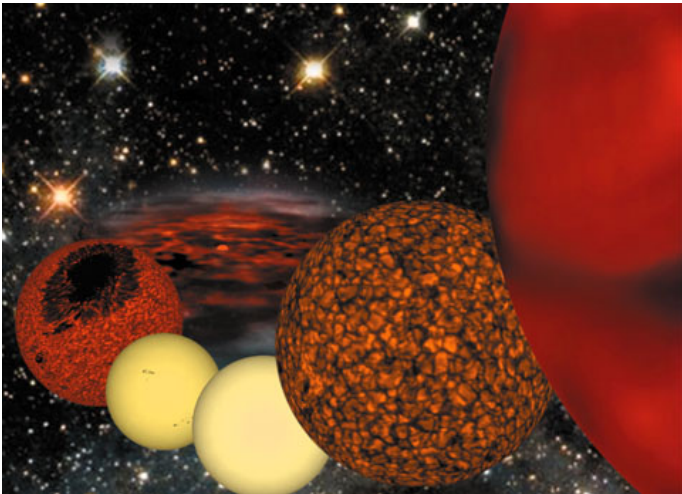
- Christoph Scheiner in 1630: slower rotation at higher latitudes
- helioseismology reveals internal solar rotation rate
- only convection zone shows differential rotation

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 acceleration:** 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

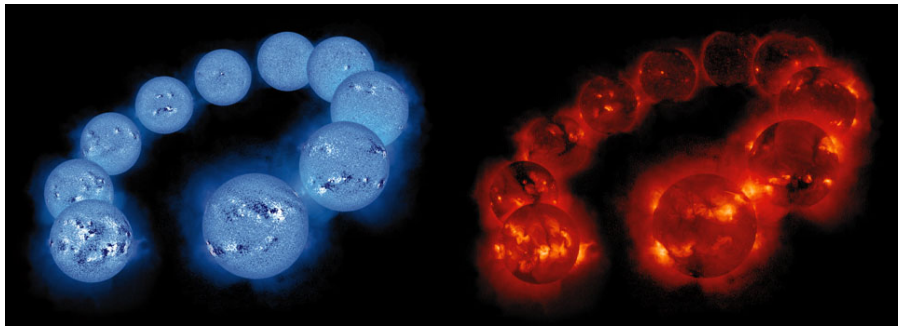
An Artist's Impression



trace.lmsal.com/POD/NAS2002_otherimages.html

Magnetic Activity

The 11-Year Solar Cycle

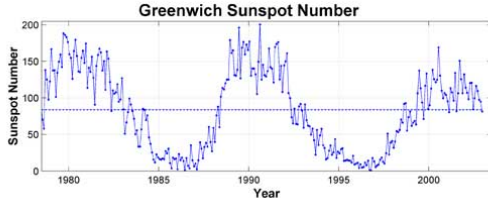
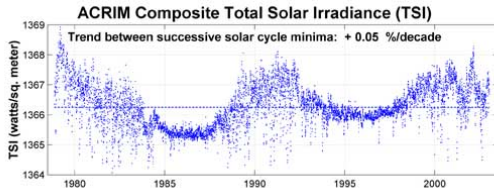


trace.lmsal.com/POD/NAS2002_otherimages.html

*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

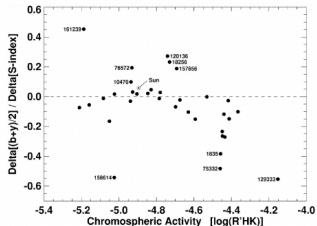
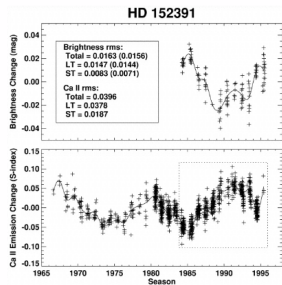
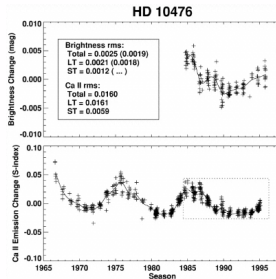
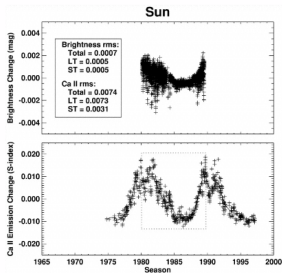


earthobservatory.nasa.gov/Newsroom/NasaNews/2003/2003032011367.html

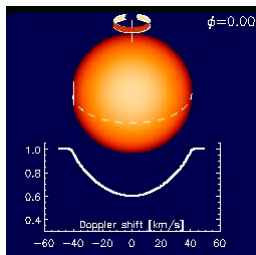
The Solar (not so) Constant

- 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



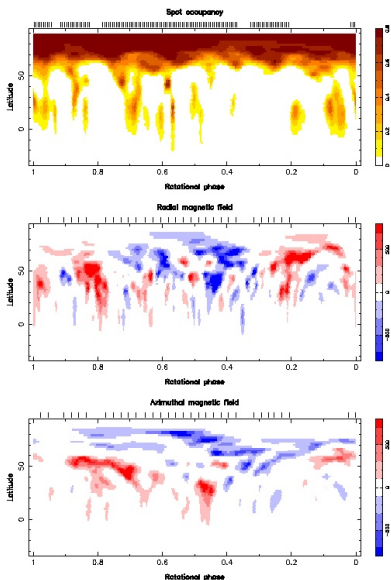
Doppler Imaging



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

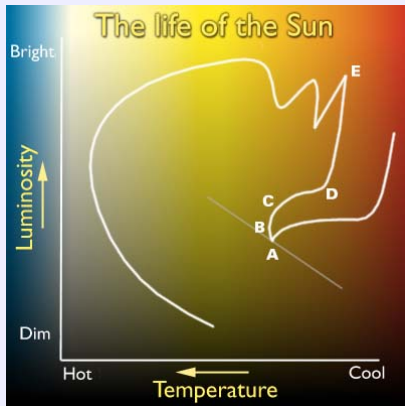


www.ast.obs-mip.fr/users/donati/map.html

Evolution of the Sun

The Past Sun

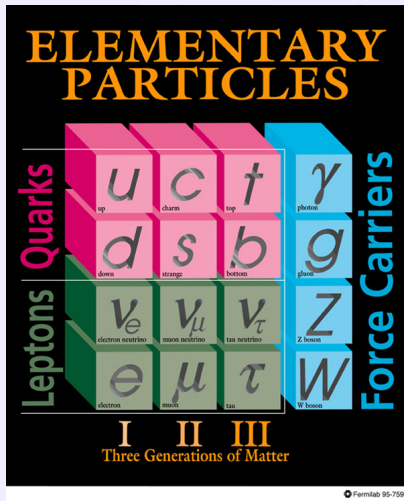
- numerical models of stellar evolution
 - include all relevant physics including rotation
 - solve PDEs for each time step
 - adjust abundances after each time step
 - have to produce currently observed Sun
- current age: 4.57×10^9 years (22 times around galaxy center)
- very young Sun:
 - 70% of current 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

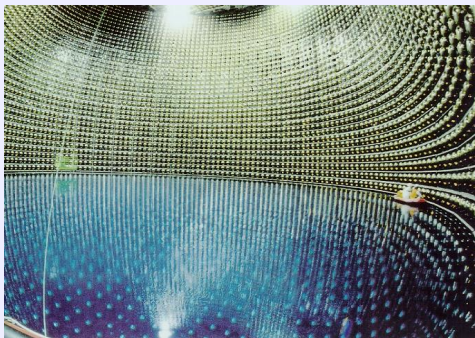
- B** 50% of available H in core used up (now)
- C** all H in core used up, H fusion in shell, 40% larger, twice as bright
- D** 1.5×10^9 years later $3 \times$ current size, temperature 4300 degrees; 0.25×10^9 years later, 100 times larger, 500 times more luminous
- E** critical core temperature, all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



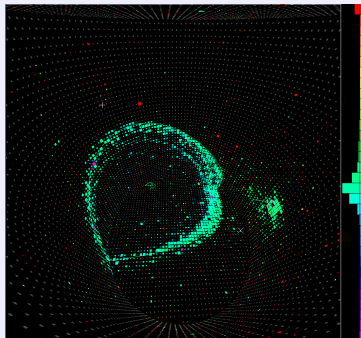
www.fnal.gov/pub/presspass/vismedia/gallery/graphics.htm

Neutrino Properties

- Neutrino (ν) predicted around 1930 by Wolfgang Pauli to save energy conservation for certain radioactive decays
- first neutrino detection published in 1956
- 6 different kinds: ν_e , ν_μ , ν_τ and their anti-particles $\bar{\nu}_e$, $\bar{\nu}_\mu$, $\bar{\nu}_\tau$
- 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



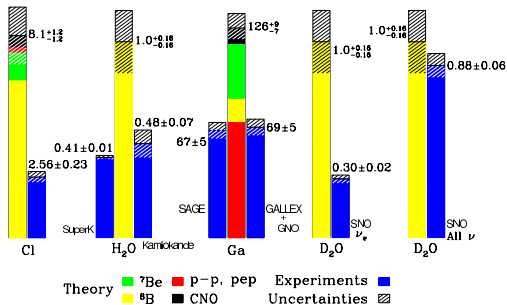
neutrino.kek.jp/figures.html

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

Total Rates: Standard Model vs. Experiment
Bahcall-Serenelli 2005 [BS05(OP)]



www.sns.ias.edu/~jnb/SNviewgraphs

Observations and Standard Models Disagree

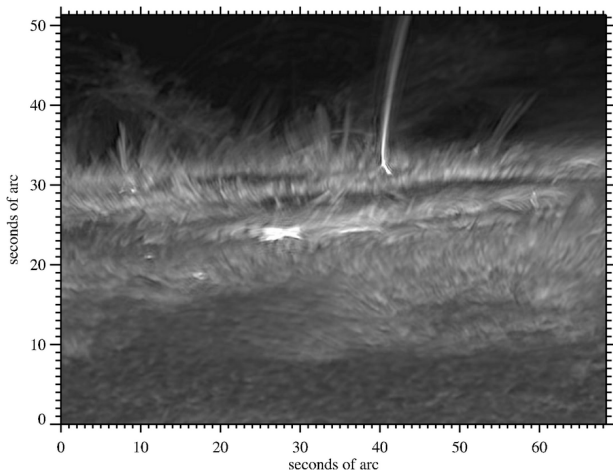
- Wrong standard solar model? But helioseismology excludes non-standard solar core models
- Wrong standard model of particle physics? But neutrinos might have mass

The Solution

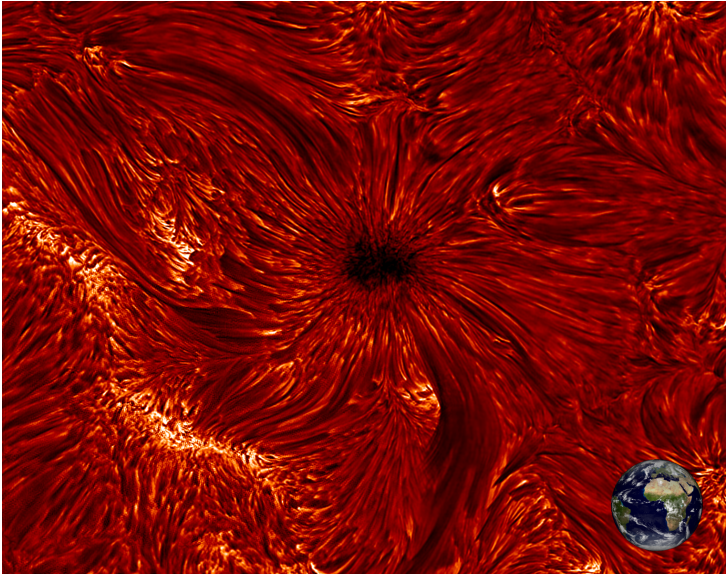
- Mikheyev–Smirnov–Wolfenstein effect
- interaction with matter: ν_e and e^- can interact through W^- or Z^0 , ν_μ and ν_τ can only interact with e^- through Z^0
- most neutrinos from Sun will pass through resonance density region inside the Sun
- even very small mixing angles and mass differences can 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

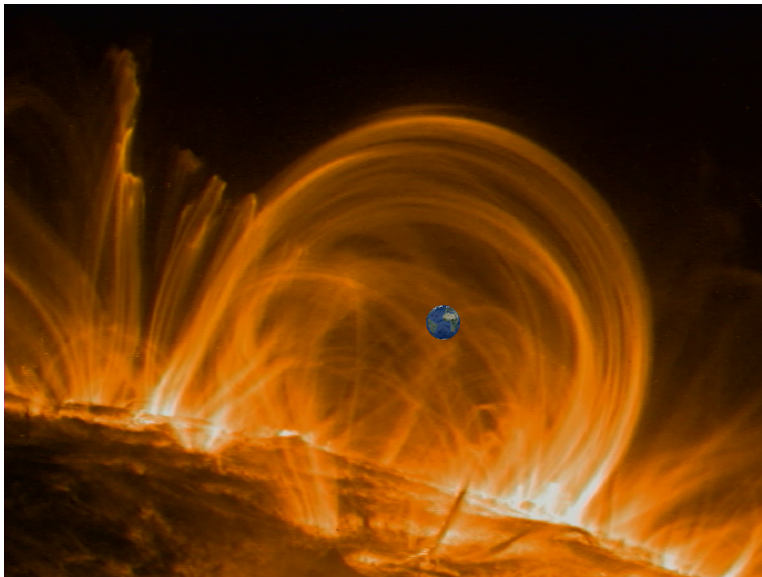
Call K close to the limb



Sunspot region in $H\alpha$

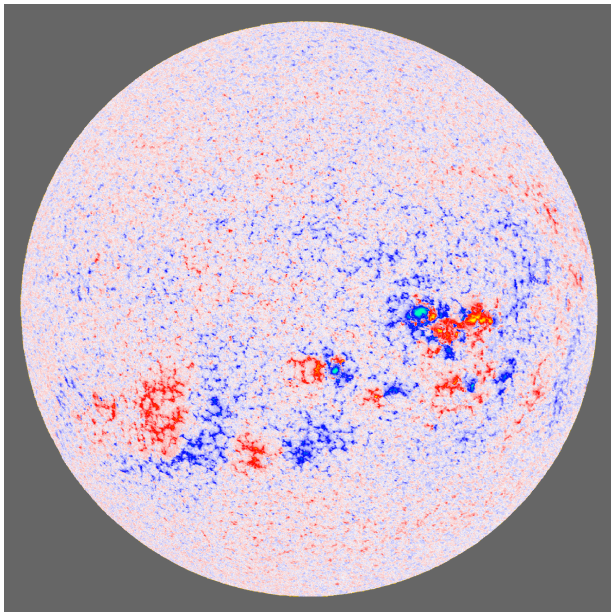


Coronal TRACE Loopsat EUV wavelengths

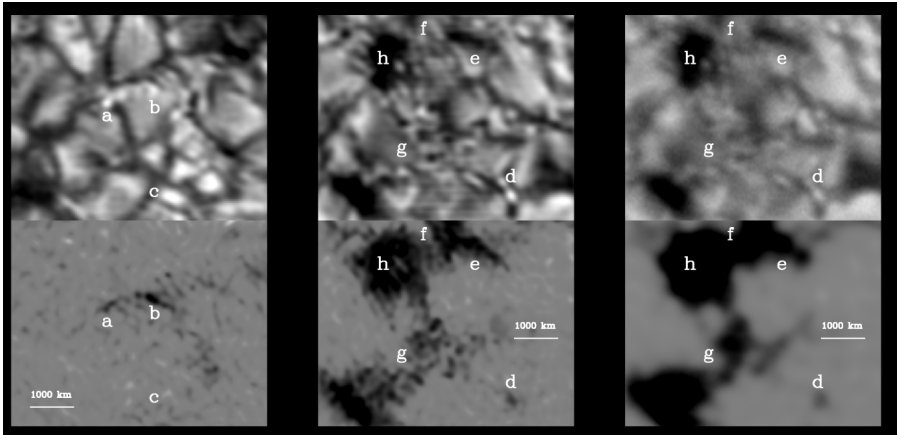


antwrp.gsfc.nasa.gov/apod/ap000928.html

SOLIS VSM Magnetogram (magnetic field map)



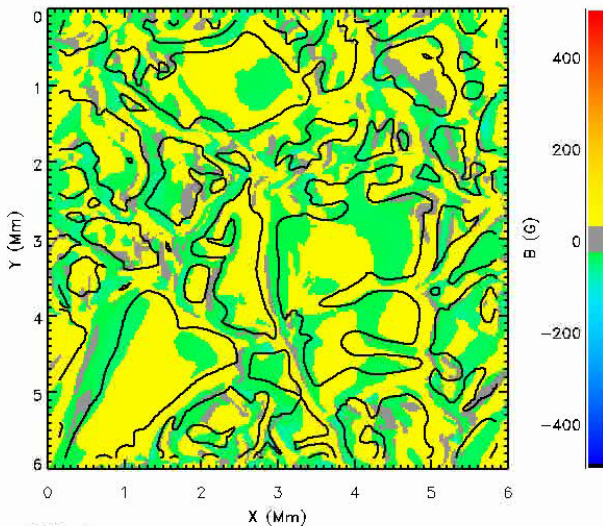
Direct Detection of Concentrated Fields



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

Evidence from Numerical MHD Simulations

Stein & Nordlund, Quiet Sun



$t = 0.50 \text{ min}$

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 $\vec{B} \times (\nabla \times \vec{B}) = \frac{1}{2} \nabla B^2 - (\vec{B} \cdot \nabla) \vec{B}$

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

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Radial Force Balance

- force balance in general coordinate system

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

- in cylindrical coordinates, radial component

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

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

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

- and therefore *horizontal pressure balance*

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

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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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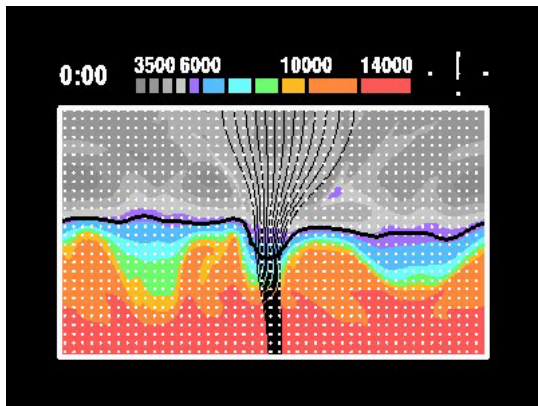
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2-D Simulation of Magnetic Flux Tube in Solar Photosphere



<http://www3.kis.uni-freiburg.de/~steiner>

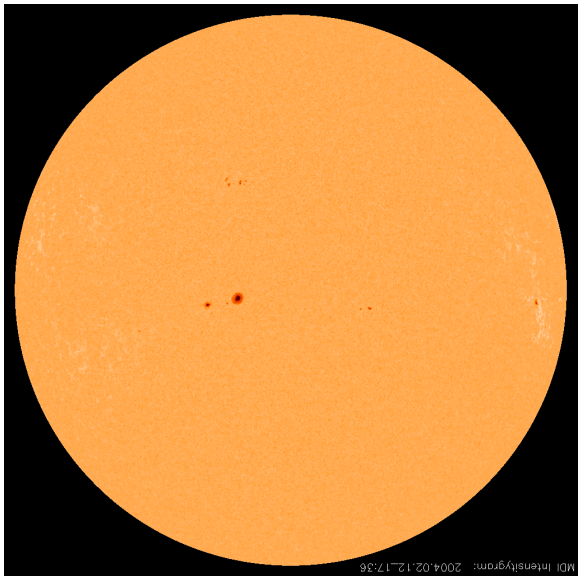
Faculae

The Sun in White Light as seen by SoHO

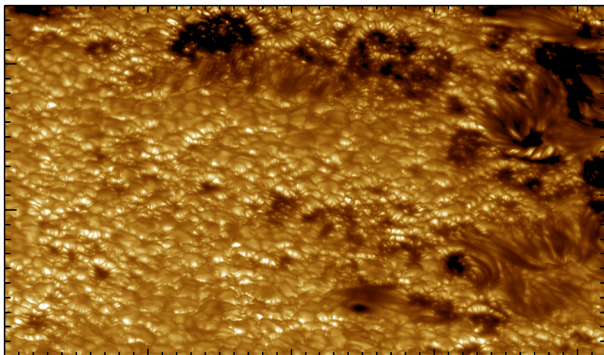


2004/02/12 17:36

The Sun without Limb Darkening

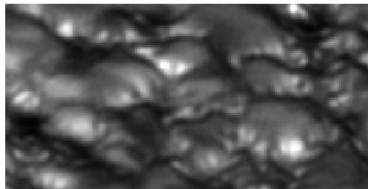


MDI Intensitygram: 2004.02.12.17:36



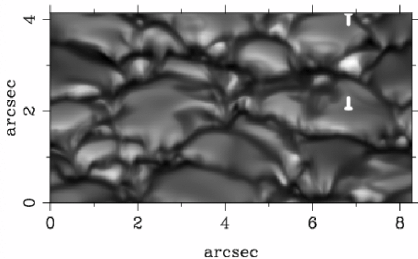
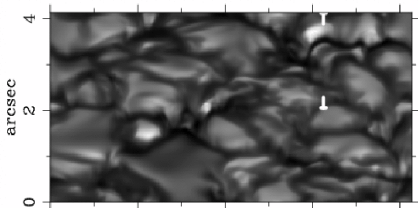
- 3-D impression when looking at images
- Faculae appear predominantly in plages
- Facular brightenings on disk-center side of granules
- Brightening can extend over about 0.5 arcsec
- Narrow, dark lanes centerward of the facular brightening

Observations by Lites et al. (2004)

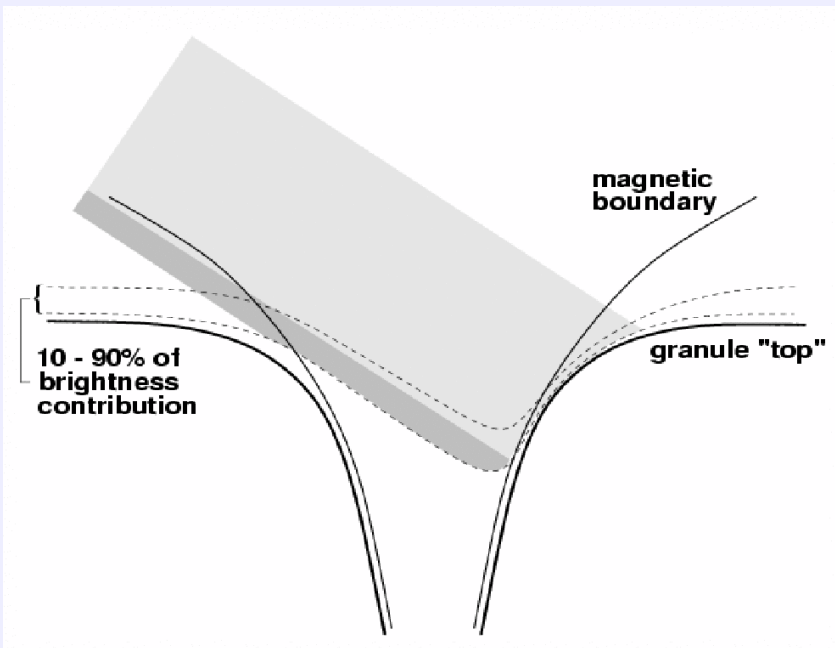


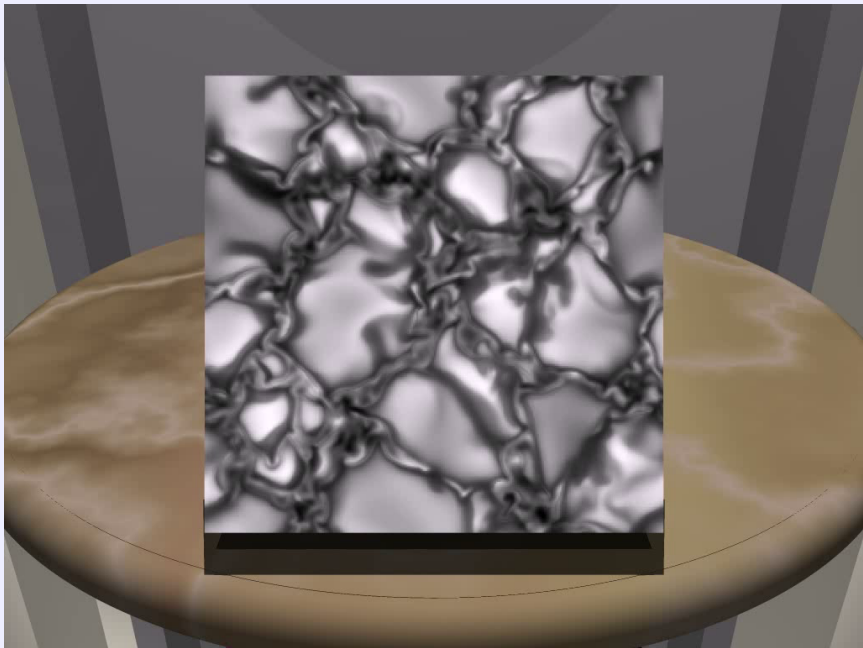
Simulations by Keller,
Schüssler, Vögler, Zakharov,
ApJL 607, L59 (2004 May 20)

Simulation, 200 G

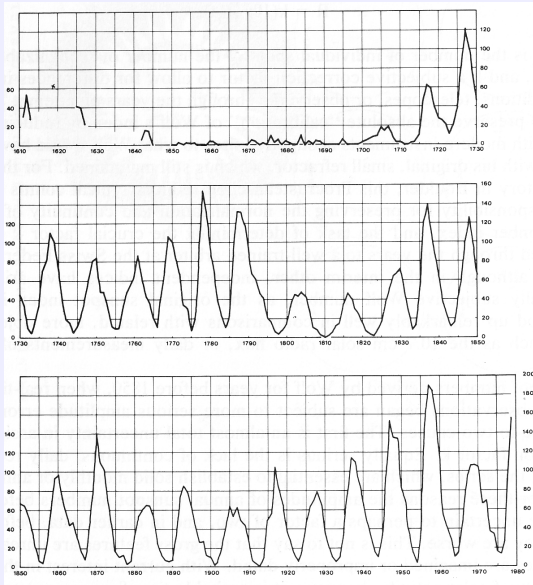


Simulation, 400 G





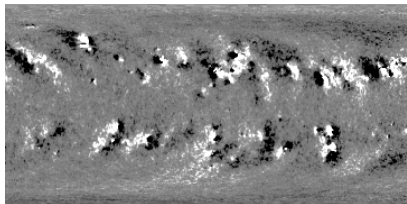
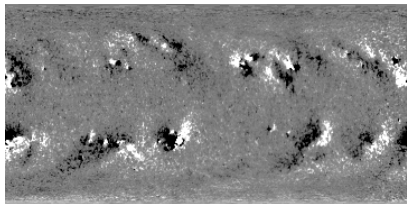
Observations of the Solar Cycle



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

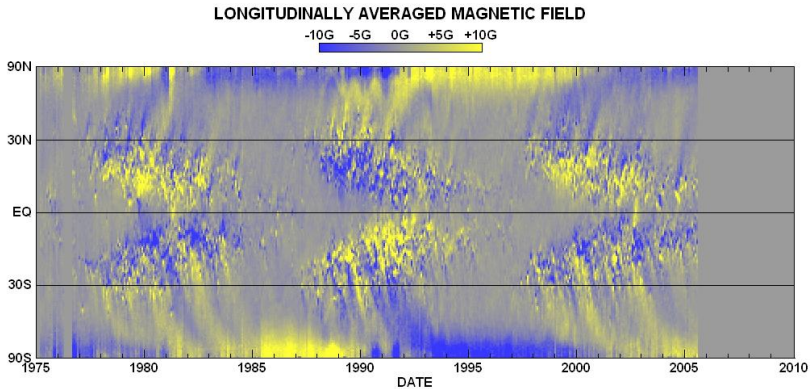
Hale's Polarity Law



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

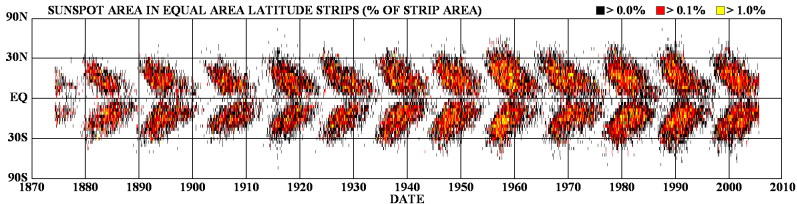


NASA/NSSTC/Hathaway 2005/10

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*)

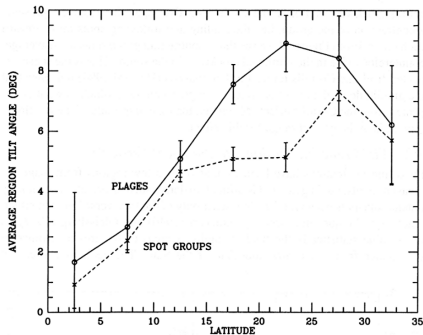
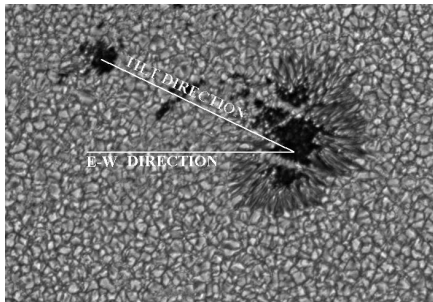
Spörer's Law



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*

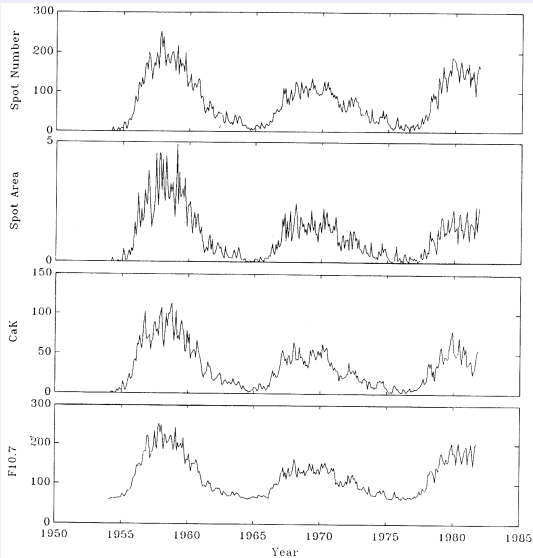
Joy's Law



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

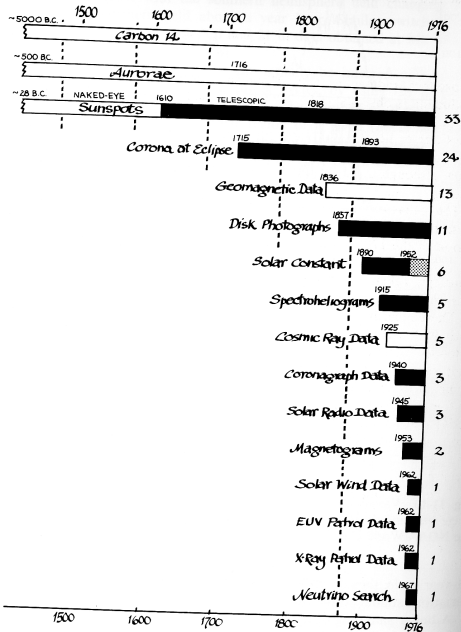
www.ociw.edu/ociw/babcock/howardtalk.pdf

- sunspot groups are tilted with respect to equator
- tilt angle depends on latitude (*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



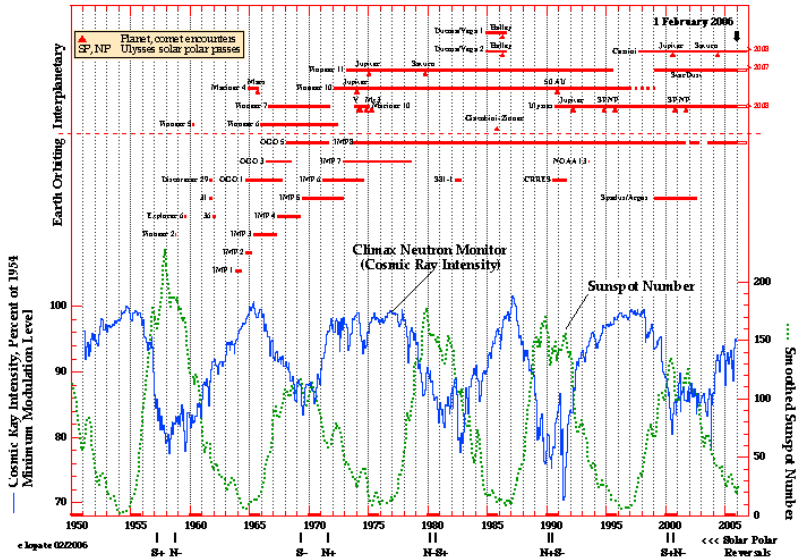
Long-Term Records

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

Neutron Flux

NSF ATM 03-19627

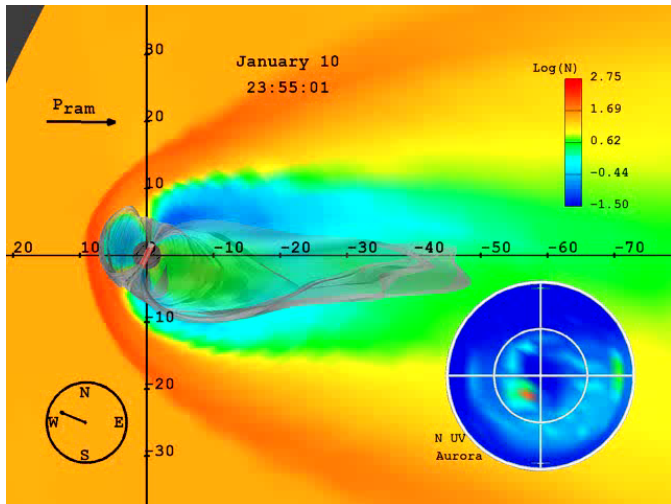
The University of New Hampshire/EOS Chicago/LASR Cosmic Physics Instruments in Space



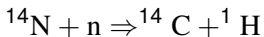
Cosmic Rays

- 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
- ⇒ anti-correlation between cosmic ray flux and sunspot cycle

Sun-Magnetosphere Interaction

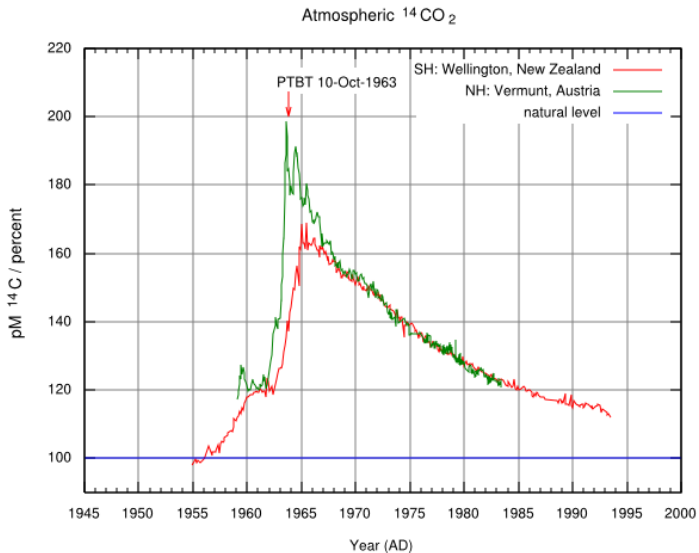


Carbon-14



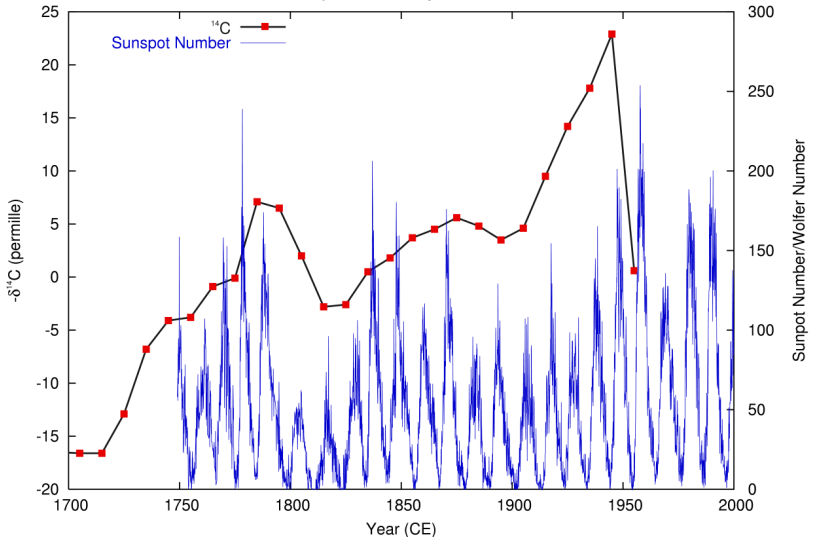
- mostly produced between 9 and 15 km
- fast oxidation to carbon dioxide
- radioactive CO^2 part of carbon cycle
- half-life of about 5730 years
- photosynthesis in plants absorbs ^{14}C
- atmospheric ^{14}C content: equilibrium between production by cosmic rays, radioactive decay, exchange with other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

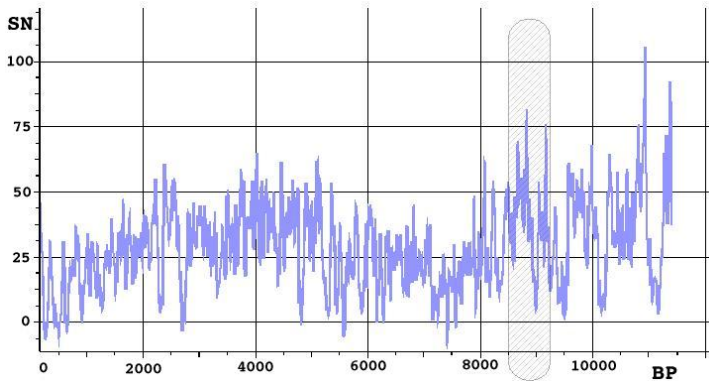


Solar Magnetic Field Relation

Sunspot activity and $\delta^{14}\text{C}$



Reconstructed Sunspot Numbers



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