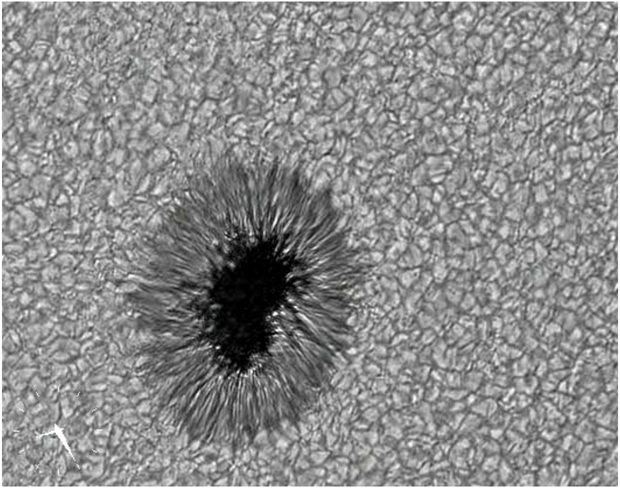
Lecture 13: Sunspots

Outline

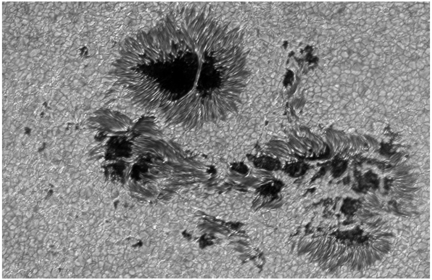
1. Terminology and History
2. Sunspot Structure
3. Sunspot Evolution

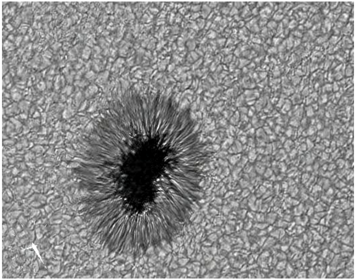
Sunspot Terminology



DOT Blue Continuum Movie of AR10425

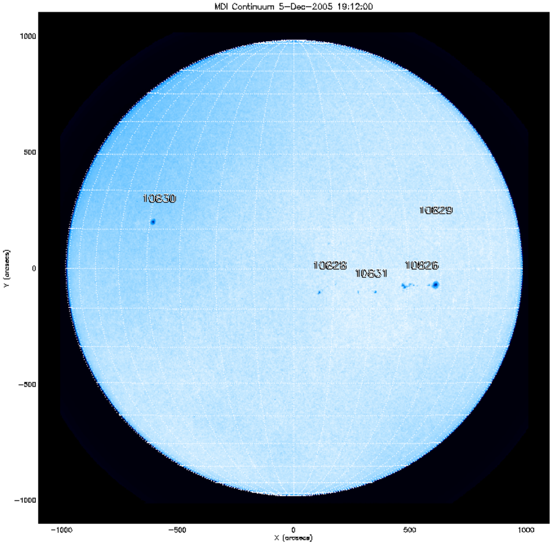
Basic Appearance





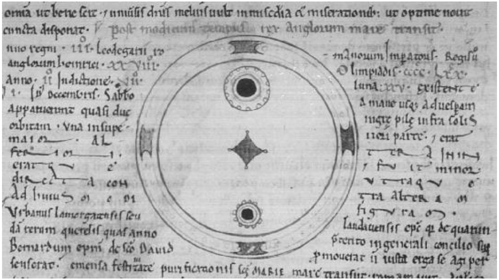
- sunspots often appear in *sunspot groups*
- sunspots consist of *umbra* and *penumbra*
- *pores* are sunspots without penumbrae
- umbral structures: *umbral dots* and *light bridges*
- *penumbral filaments*
- umbra and penumbra have well-defined, structured boundaries
- sunspot is much more stable than granulation
- bright penumbral grains move inward

Active Region Numbers



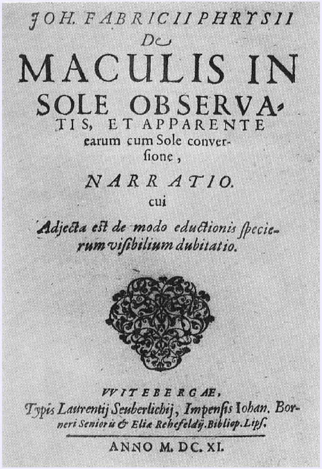
www.solarmonitor.org

History before Telescopes



www.hao.ucar.edu/Public/images/worcester.jpg

- Theophrastus of Athens reports sunspots around 330 BC
- 112 descriptions of sunspots in official historical records from China between 28 BC and 1638 AD
- 8 December 1128, John of Worcester makes the first diagram of the Sun containing two large spots
- Kepler misinterpreted sunspot as Mercury transit in 1607



JOH. FABRICII PHRYSII
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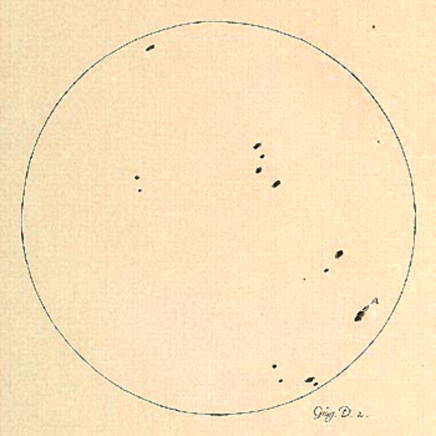
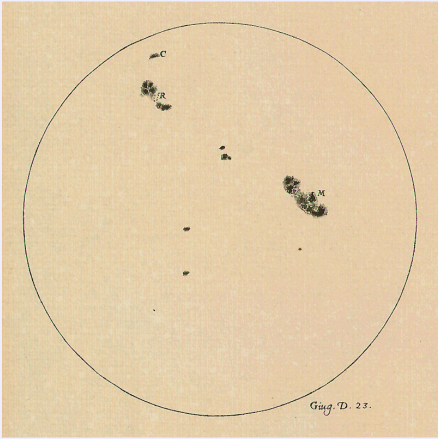
neri Senioris & Eliæ Rehefeldij. Bibliop. Lipſ.
ANNO M. DC. XI.

web.hao.ucar.edu/
public/education/sp/images/fabricius.html

Johann Goldsmid (Fabricius)

... Having adjusted the telescope, we allowed the sun's rays to enter it, at first from the edge only, gradually approaching the center, until our eyes were accustomed to the force of the rays and we could observe the whole body of the sun. We then saw more distinctly and surely the things I have described [sunspots]. Meanwhile clouds interfered, and also the sun hastening to the meridian destroyed our hopes of longer observations; for indeed it was to be feared that an indiscreet examination of a lower sun would cause great injury to the eyes, for even the weaker rays of the setting or rising sun often inflame the eye with a strange redness, which may last for two days, not without affecting the appearance of objects.



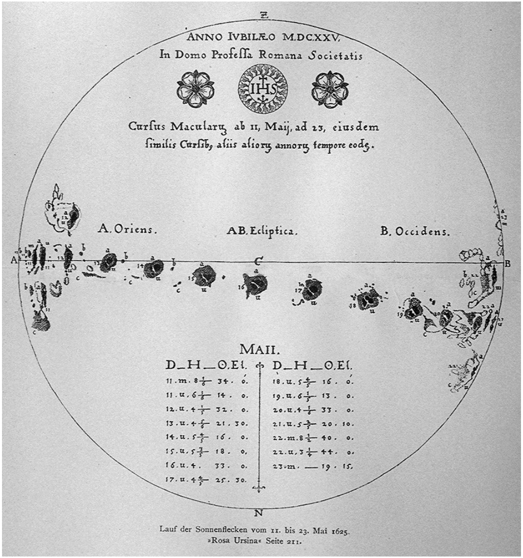


galileo.rice.edu/sci/observations/sunspot_drawings.html

History after Telescopes

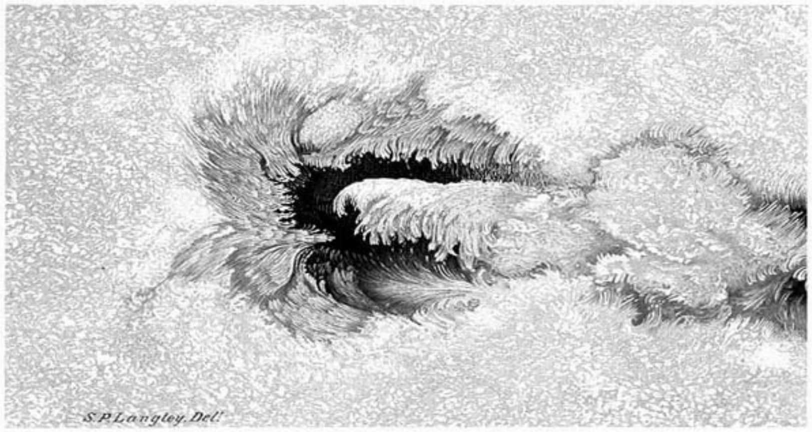
Other contemporary observations by Galileo Galilei (Italy), Christoph Scheiner (Germany), and Thomas Harriott (England)

Drawings by Christoph Scheiner



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

Drawings by Samuel Langley (1834–1906)

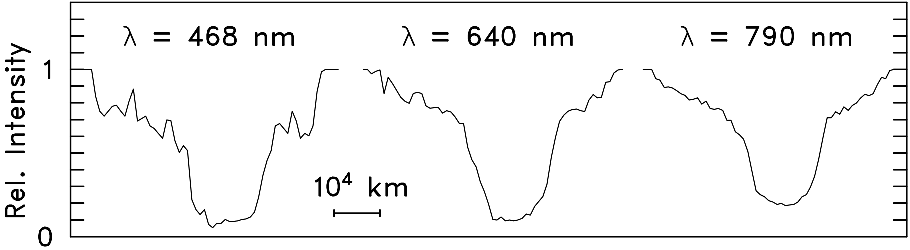


www.ociw.edu/ociw/babcock/howardtalk.pdf

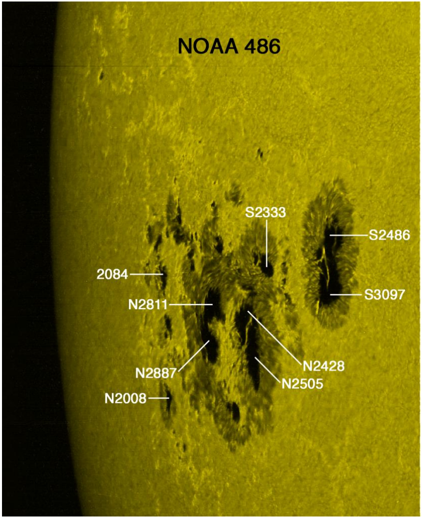
Why are these drawings comparable in quality to some of the best pictures from modern telesopes?

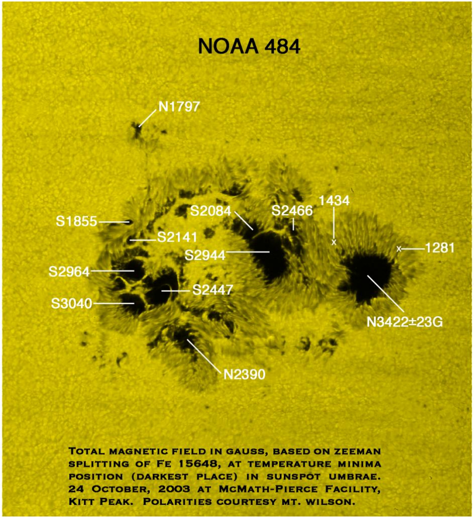
Sunspots in Numbers

- diameter: 10'000 – 100'000 km
- intensity of umbra: 5% of quiet photosphere at 500 nm
- intensity of penumbra: 80% of quiet photosphere at 500 nm
- temperature of umbra: 3500 K



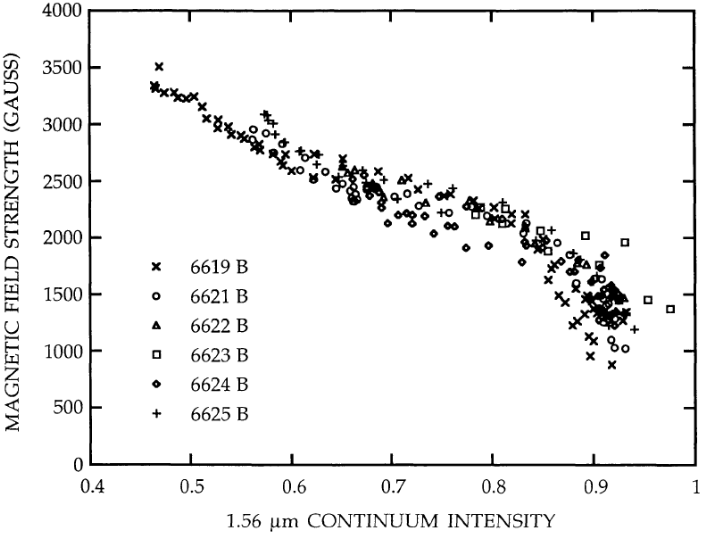
Sunspot Field Strengths: 2000-4000 Gauss





www.noao.edu/image_gallery/html/im0972.html

Empirical Temperature - Field Strength Relation



Kopp & Rabin 1992

Theoretical Temperature – Field Strength Relation

- magnetohydrostatic force balance

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

- radial component in cylindrical coordinate system

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

- for untwisted field ($B_\phi=0$)

$$\frac{\partial p}{\partial r}=\frac{B_z}{\mu_0}\left(\frac{\partial B_r}{\partial z}-\frac{\partial B_z}{\partial r}\right)$$

- integrate from radius r to field-free region outside of spot

$$p_e(z)-p(r,z)=\frac{B_z^2(r,z)}{2\mu_0}+\frac{1}{\mu_0}\int_r^\infty B_z\frac{\partial B_r}{\partial z}dr'$$

continuing ...

- from previous slide

$$p_e(z) - p(r,z) = \frac{B_z^2(r,z)}{2\mu_0} + \frac{1}{\mu_0}\int_r^\infty B_z \frac{\partial B_r}{\partial z} dr'$$

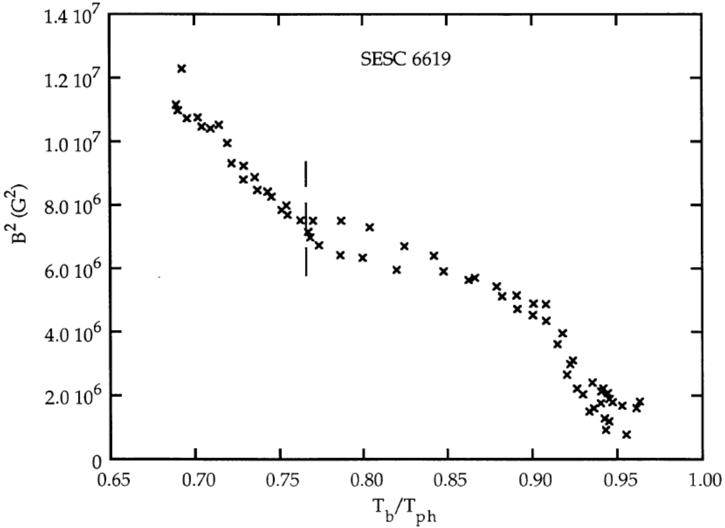
- for simple magnetic field configurations can rewrite this as

$$p_e(z) - p(r,z) = \frac{B^2(r,z)}{2\mu_0}(1 + f(r,z))$$

- and using perfect gas law, write this as

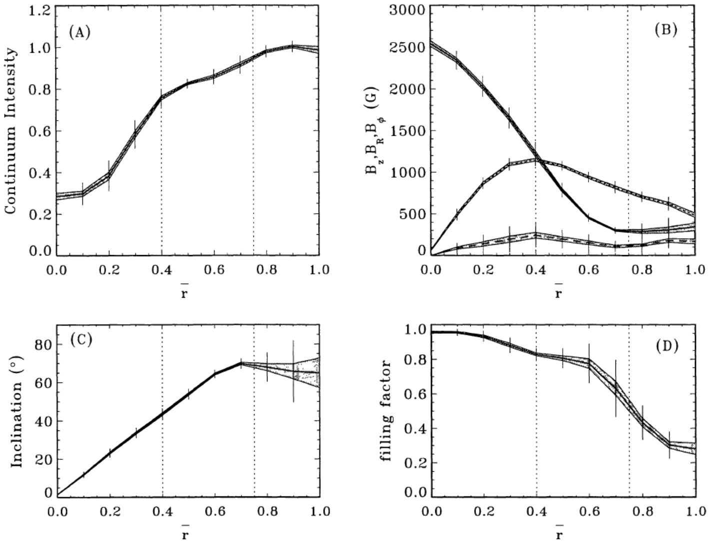
$$\frac{T(r,z)}{T_e(z)} = \frac{\mu(r,z)}{\mu_e(z)} \frac{\rho_e(z)}{\rho(r,z)} \left(1 - \frac{1 + f(r,z)}{2\mu_0 p_e(z)} B^2(r,z)\right)$$

Empirical Temperature - Field Strength Relation



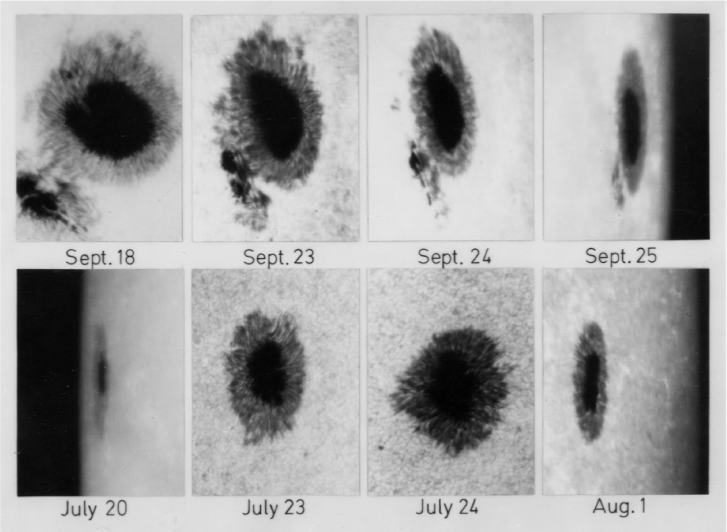
Kopp & Rabin 1992

Azimuthally Averaged Sunspot Quantities



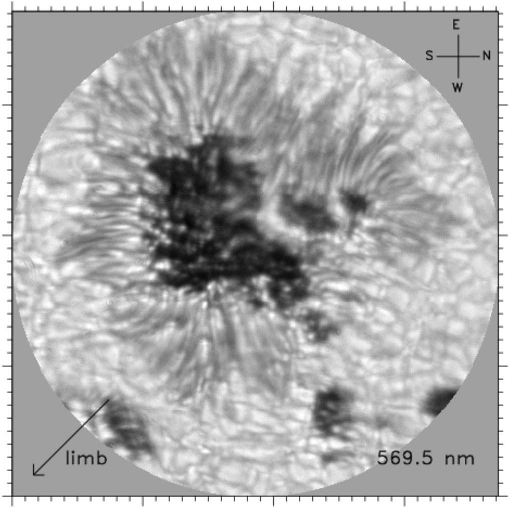
Keppens & Martinez Pillet 1996

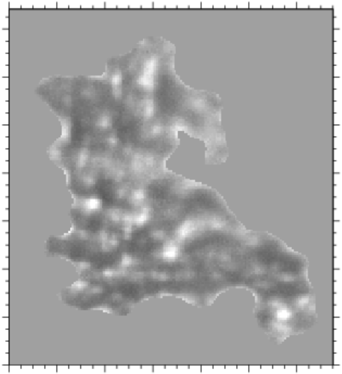
Wilson Depression



sunspot umbrae are lower than quiet photosphere (Wilson 1769)

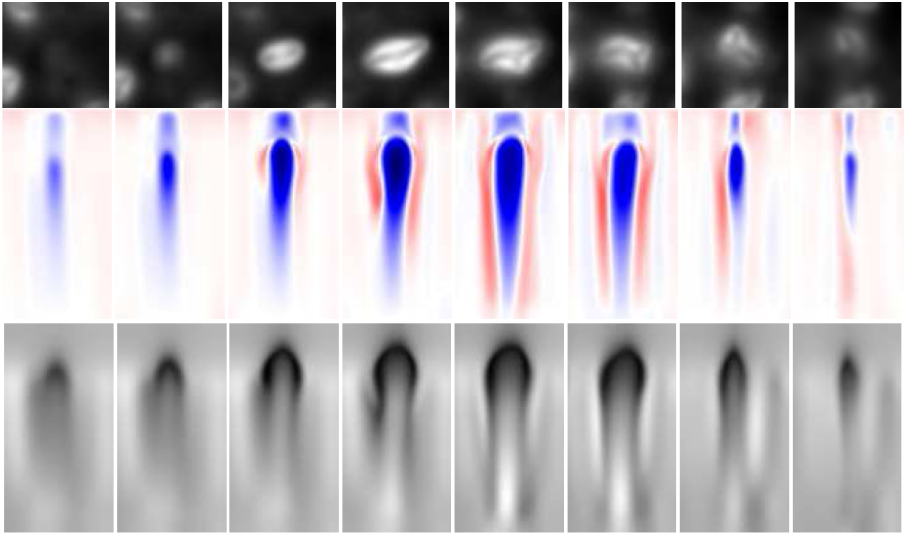
Umbral Dots





Tritschler & Schmidt 2002

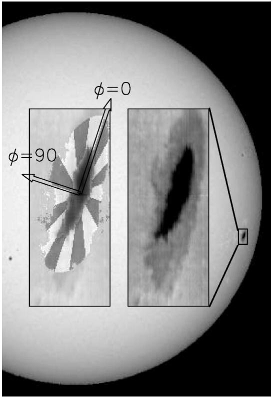
Umbral Dots Simulations

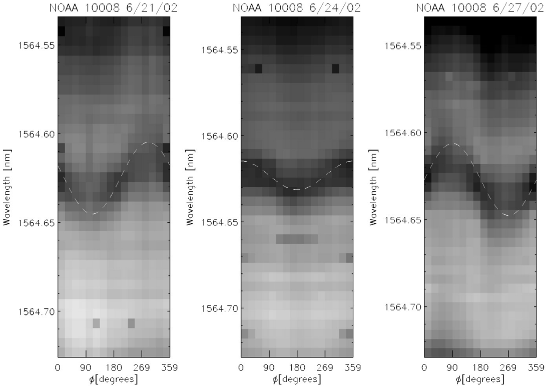


0 min 2.1 6.3 10.5 16.8 23.3 29.7 37.1

Schüssler & Vögler 2006

Evershed Effect: Radial Outflow

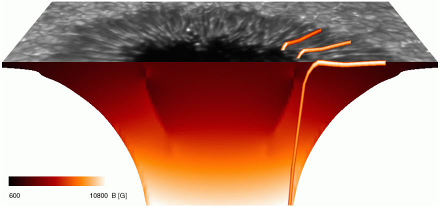


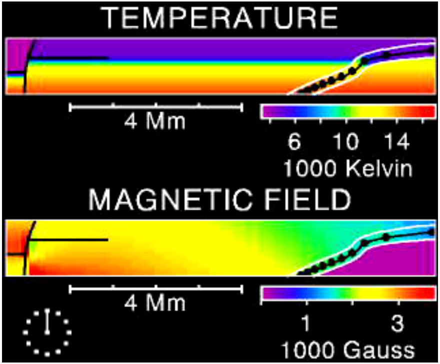


Penn et al. 2003

spectral lines show outflow of up to 10 km/s^{-1}

Penumbral Filament Simulations (R.Schlichenmaier)

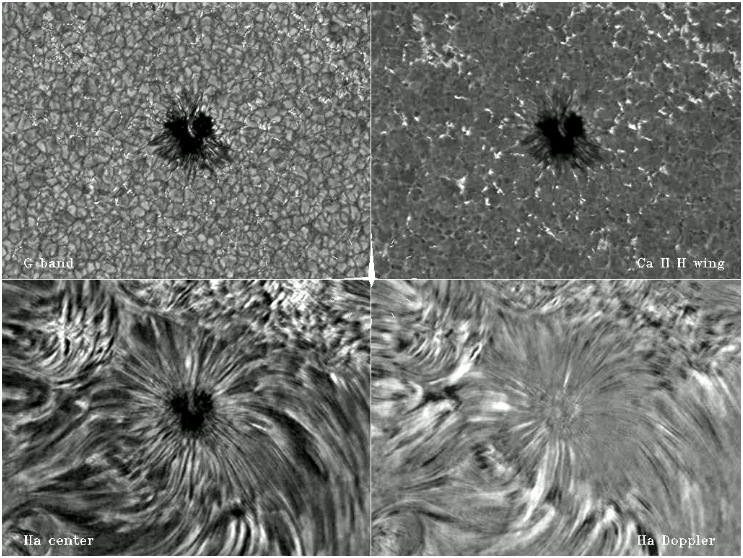




www.kis.uni-freiburg.de/ schliche/index-Dateien/video.html

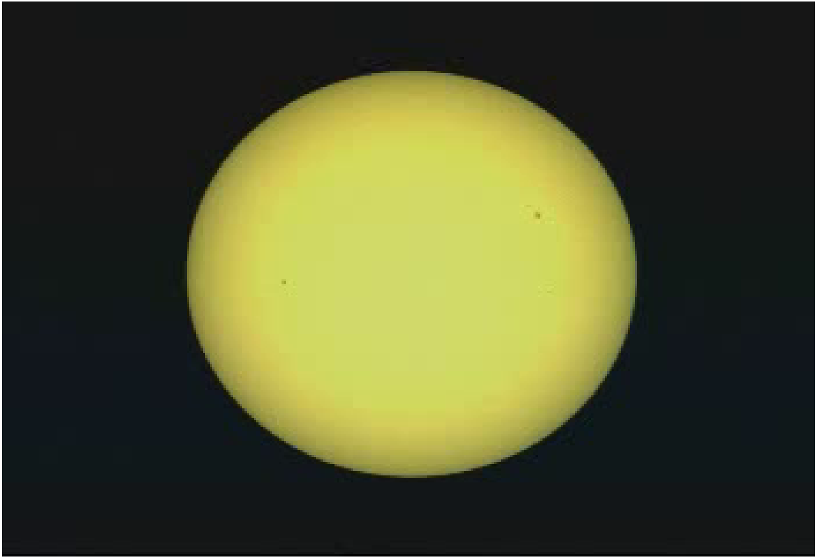
- thin magnetic flux tube in magnetohydrostatic sunspot model
- surrounding field-free area heats tube, it becomes buoyant
- cools off when reaching photosphere
- since field in tube decreases faster than background field, gas pressure builds up leading to outward flow

Sunspot Oscillations



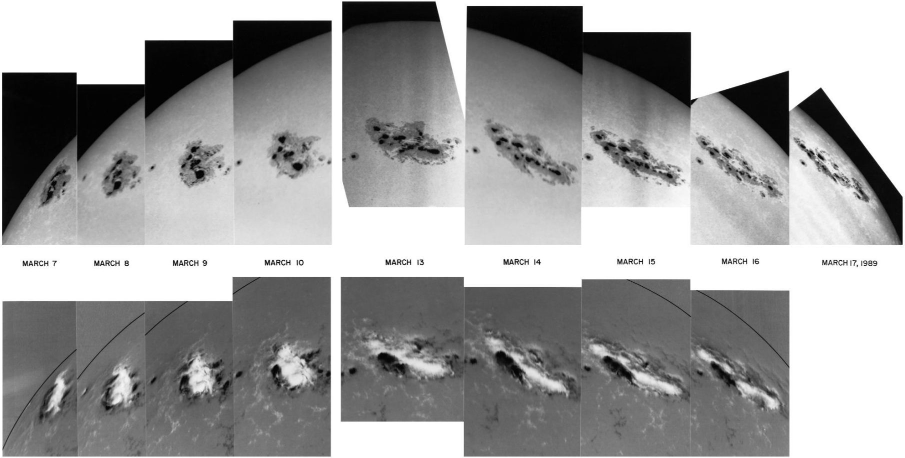
DOT 2005-07-13 AR10789

Large Sunspot Region from early 2001



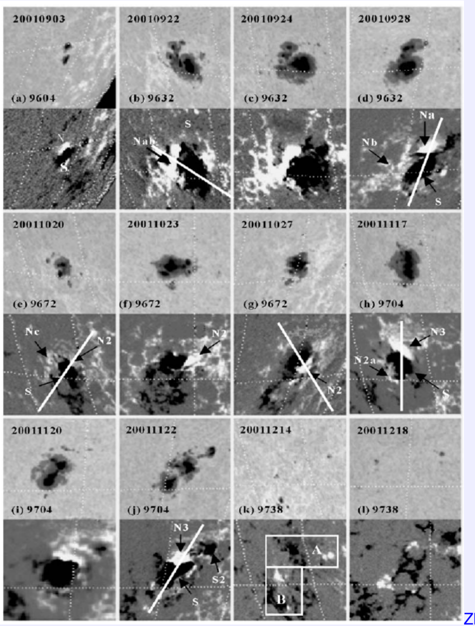
Best of SOHO Movies

Sunspot Region Evolution



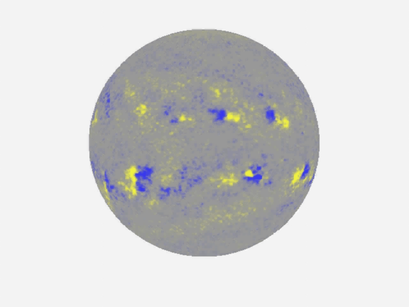
www.noao.edu/image_gallery/html/im0605.html

Sunspot Evolution



Zhang & Tian 2005

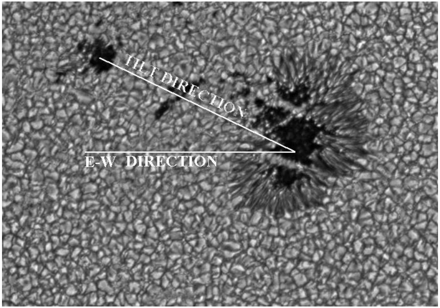
Active Region Development

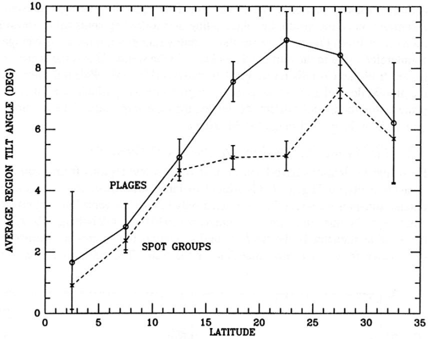


science.nasa.gov/ssl/pad/solar/dynamo.htm

- sunspots occur in two belts, symmetric around and parallel to the equator at $\pm$ (5°– 35°) lattitude
- sunspots are areas of strong magnetic fields
- sunspots often appear in pairs with opposite magnetic polarity (*bipolar groups*)
- polarity changes with hemisphere and solar cycle (*Hale's Law*)
- sunspot groups are inclined with respect to the equator

Sunspot Groups





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

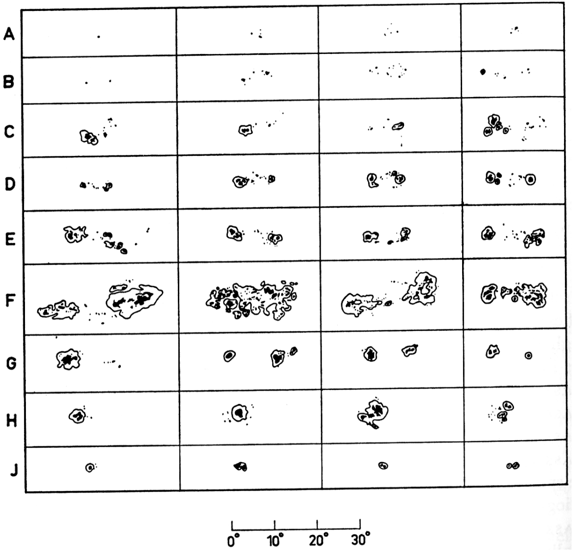
www.ociw.edu/ociw/babcock/howardtalk.pdf

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

Sunspot Lifecycle

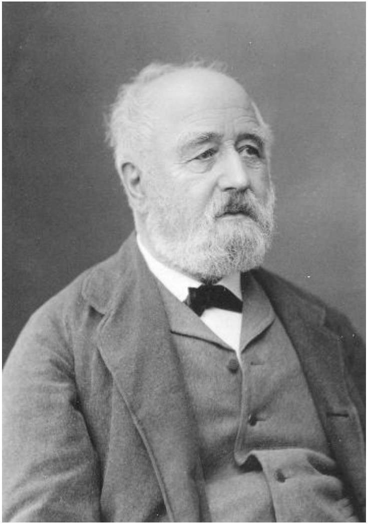
- appearance and disppearance of sunspot groups is always related to the same phenomena $\Rightarrow$ everything together makes up an *active region*
- appearance of magnetic field within a few days, strong increase in faculae, magnetic field becomes bipolar, small pores and spots appear, corona becomes bright above active region
- maximum activity takes 2 to 3 weeks, large bipolar groups form, active region expands to 200'000 km, flares occur
- disappearance takes 6 to 9 months, active region expands to 500'000 km, spots disappear, faculae of opposite polarities appear that are separated by a quiet prominence, slow disappearance of these phenomena
- sunspot lifetime: days to months, most less than 11 days

Zürich Sunspot Classification: Evolutionary Sequence



Waldmeier (1955)

Rudolf Wolf



web.hao.ucar.edu/public/education/sp/images/wolf.html

Sunspot Numbers

- discovery of sunspot cycle by Heinrich Schwabe in 1843
- Rudolf Wolf at ETH Zurich compares sunspot observations from different observers
- invents *Sonnenflecken Relativzahl* in 1847
- number of sunspot groups g, number of sunspots f

$$R = k(10g + f)$$

$k \approx 1$: observer-dependent calibration factor
- Sunspot Number is a good measure of fractional area of Sun covered by spots