

# Physics 681: Solar Physics and Instrumentation – Lecture 23

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## Sunspots

- ❑ Magnetic field is source-free  $\Rightarrow$  the total flux through the solar surface is always zero
- ❑ Flux erupts in the form of loops (not always as bipolar structure)
- ❑ Bipolar configurations are oriented roughly along the east-west direction (the leading spot is slightly closer to the equator)
- ❑ Joy's law: the inclination increase with increasing heliographic latitude
- ❑ Arch-filament systems in H $\alpha$
- ❑ Pores are sunspots without a penumbra (as large as 11,000 km)
- ❑ Smallest sunspots with penumbra (2,500 km umbral diameter)
- ❑ Theoreticians' spot: symmetric spot slowly decreasing in size during stage H of the Zürich classification.
- ❑ Decay rate of spots:  $\frac{dA}{dt} = -1.5 \times 10^8 \text{ m}^2 / \text{s}$



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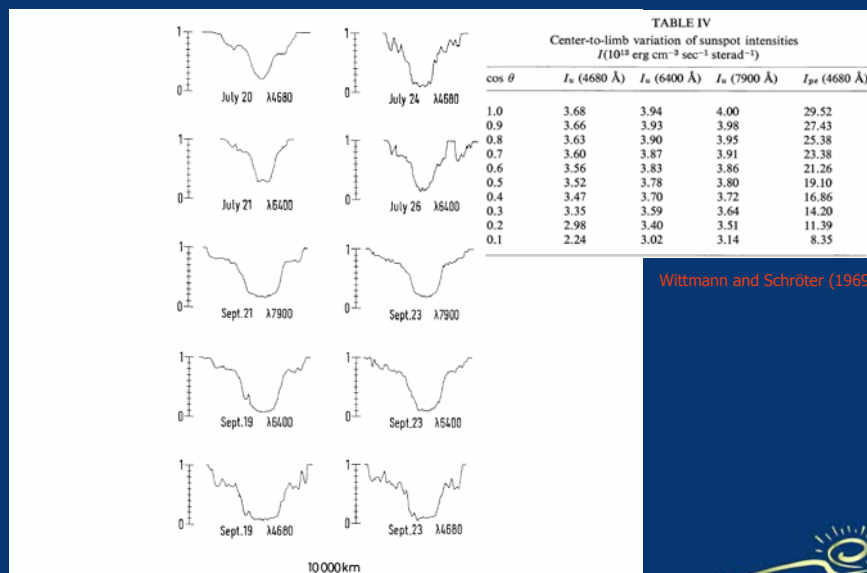
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# Zürich Classification

- A. A single spot, or group of spots, appears. There is no penumbra, and no obvious bipolar configuration.
- B. A group of spots without penumbrae. The group is dominated by two spots that mark the two magnetic polarities; that is, the bipolar character is clearly noticeable.
- C. Bipolar group; one of the principal spots has a penumbra.
- D. Bipolar group; both principal spots have a penumbra, but at least one of them still has a simple structure. The group extends over less than  $10^\circ$  on the Sun.
- E. Large bipolar group, extending over more than  $10^\circ$  on the Sun. Both principal sunspots have a penumbra and often a complex structure. Numerous small spots are present.
- F. Very large, and very complex, bipolar group, extending over  $\geq 15^\circ$ .
- G. Large bipolar group, of extent  $\geq 10^\circ$ . The small spots in between the principal ones have disappeared.
- H. Unipolar spot with penumbra, diameter (incl. penumbra)  $\geq 2.5^\circ$ .
- I. As H, but diameter  $< 2.5^\circ$ .

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Wittmann and Schröter (1969)

Fig. 3. Some examples of the sunspot intensity profiles after the corrections described in section 3 have been applied. The east direction is towards the left.

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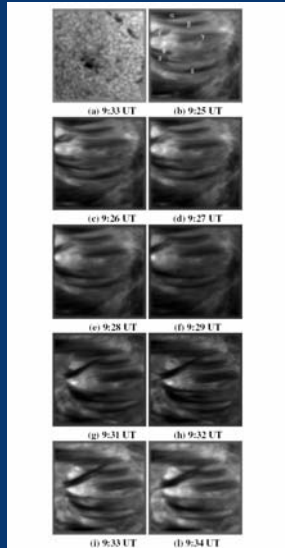


Fig. 10. Image taken at 5577.15 Å and a sequence of images of the same field of view taken at 6562.808 Å b-h on July 27. In all images of this and the other figures, North is at the top, West on the right and the field of view is  $\sim 24,000 \times 24,000 \text{ km}^2$ .

Spadaro et al. (2004)

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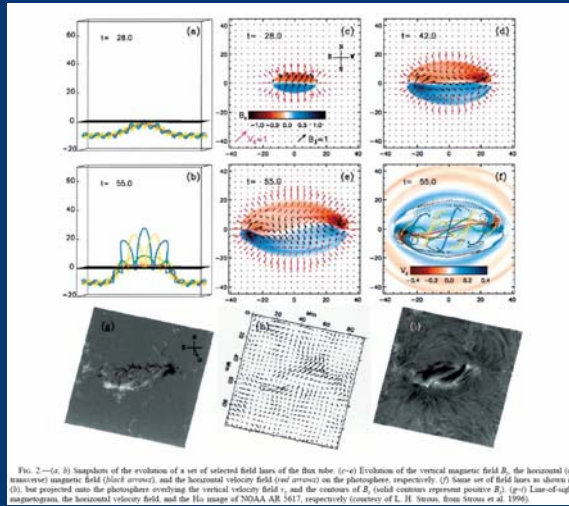


Fig. 2—(a, b) Snapshots of the evolution of a set of selected field lines of the flux tube. (c–f) Evolution of the vertical magnetic field  $B_z$ , the horizontal (or azimuthal) magnetic field (black arrows), and the horizontal velocity field (red arrows) on the photosphere, respectively. (g) Same set of field lines as shown in (f), but projected onto the photosphere overlying the vertical velocity field  $v_h$ , and the contours of  $B_z$  (solid contours represent positive  $B_z$ ). (h–i) Line-of-sight magnetogram, the horizontal velocity field and the Hi image of NOAA AR 3617, respectively (courtesy of L. H. Stone, from Stone et al. 1996).

Fan (2001)



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- ❑ Size scale of sunspots according to McIntosh (1981)
- ❑ Fine structure of spots  $\leftrightarrow$  granulation
- ❑ Small sunspots  $\leftrightarrow$  mesogranulation
- ❑ Spot distribution within group  $\leftrightarrow$  supergranulation
- ❑ Distribution of groups on the solar surface  $\leftrightarrow$  convection on global scale (giant cells)
- ❑ Maximum field strength of a sunspot  $B_{\max} = 0.3 \text{ T}$
- ❑ Symmetric sunspot (stage H in Zürich classification)
 
$$B(s) = B(0) / \left(1 + s^2 / s_{\text{spot}}^2\right)$$
- ❑ Sunspot relative number ( $g$  number of spot groups,  $f$  total number of spots, and  $k$  constant accounting for instrument, seeing, and observer)
 
$$R = k(10g + f)$$
- ❑  $R$  is proportional to the sunspot area and the total magnetic flux penetrating the visible hemisphere in sunspots



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# Sunspot Models

- Atmospheric model
- Derive a solar model for sunspots (see Chapter IV)
- Use CLV (spectral lines and continua) to determine atmospheric parameters
- The sunspot atmosphere resembles stars of spectral type K and M, i.e., strong CH and CN lines and many other molecular lines
- Only *mean* models are calculated neglecting fine structure and other inhomogeneities
- Wilson effect: decrease of opacity (with decreasing temperature and density)  $\Rightarrow$  spot temperature profile is shifted several hundred kms downward with respect to the photosphere  $\Rightarrow$  the spot represents a dip in the solar surface
- Spots near the limb: the disc-side penumbra is apparently narrower than the limb-side penumbra



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# Wilson Effect

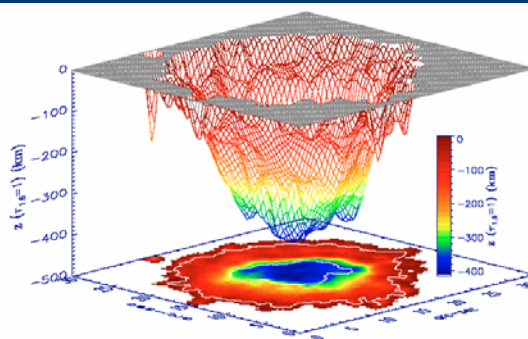


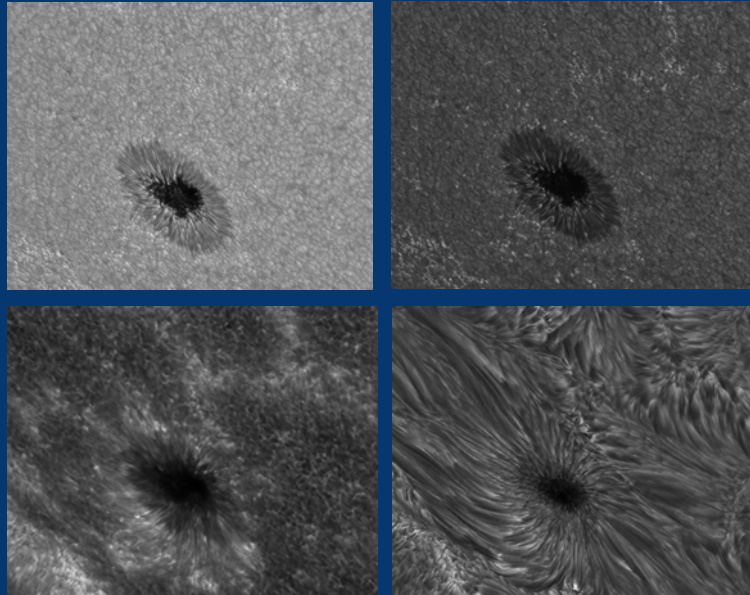
Fig. 7. Wilson depression ( $Z_W$ ) of the observed sunspot. The inner and outer contours represent the umbral and penumbral boundaries obtained from the continuum image, respectively.

Matthew et al. (2004)



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[http://dotdb.phys.uu.nl/DOT/Data/2004\\_09\\_27/index.html](http://dotdb.phys.uu.nl/DOT/Data/2004_09_27/index.html)

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- Magnetohydrostatic model
- Magnetic flux tube embedded in the solar plasma
- Magnetic field interrupts heat transport  $\Rightarrow$  Where does the heat go?  
 $\Rightarrow$  annular cell "moat" around flux tube with divergent flow away from the sunspot
- Magnetohydrostatic equilibrium (no dynamic effects such as moat flow or slow decay of the spot)  
$$-\nabla P + \rho \mathbf{g} + \mathbf{j} \times \mathbf{B} = 0$$
- Assume lateral equilibrium, choose self-similar B from one z-level to the next, derive PDE depending on total flux and  $\Delta P$
- Convective energy transport is reduced but not entirely suppressed
- Discontinuous transitions from umbra/penumbra and penumbra/field-free gas  $\Rightarrow$  current sheets
- The depth of the penumbra is comparable to its horizontal extend
- The penumbra contains more than 50% of the total flux (minimum flux  $\approx 3 \times 10^{13}$  Wb)
- Minimum inclination of the magnetopause from the vertical  $\approx 25^\circ$
- Perturbations propagate with Alfvén velocity  $c_A = B_{z0} / (\mu \rho_0)^{1/2}$

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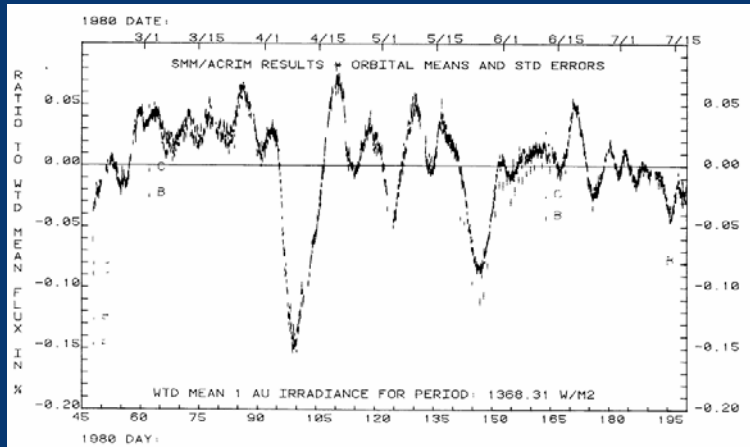


Fig. 2. The 1AU total solar irradiance measured by the ACRIM channel A sensor is shown as a percentage variation about the weighted mean for the first 153 days of the Solar Maximum Mission. The individual tic-marks represent the mean irradiance for the sunlit portion of one orbit. The vertical bars through each tic-mark are the ( $\pm 1\sigma$ ) standard errors of the orbital means. The tic-marks with associated 'B' and 'C' designations are the channel B and C measurements during comparisons with channel A.

Willson (1981)

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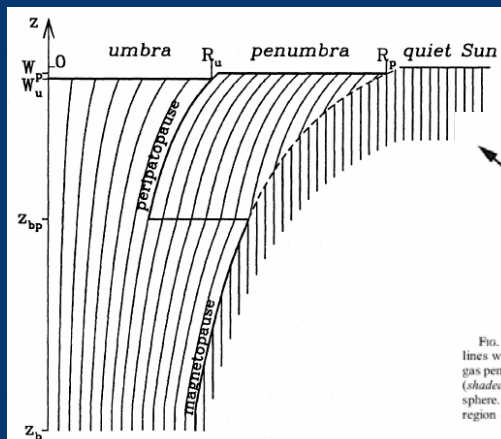


Fig. 2. A schematic representation of the assumed heat flow in the sunspot model. The dashed line corresponds to the partially permeable part of the magnetopause. Its remaining part and the whole peripatopause do not transmit energy

Schmidt and Jahn (1994)

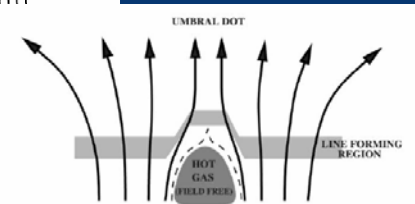


Fig. 10.—Cartoon representation of a UD in the cluster model. The solid lines with arrows represent field lines in the umbra. A hot plume of field-free gas penetrates from deep subphotospheric layers up to near the visible surface (shaded area). The dashed line represents the canopy underneath the photosphere. The (relative) Wilson depression produces a shift in the formation region of the lines toward higher layers in the UD.

Socas-Navarro et al. (2004)

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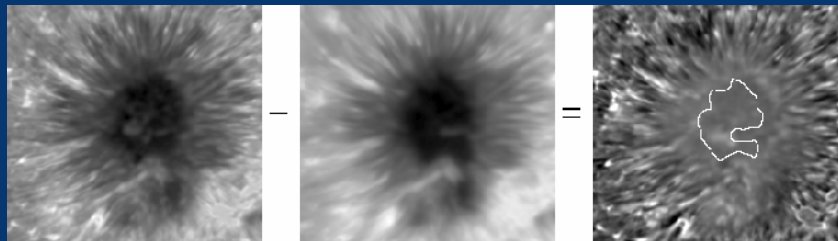


- ❑ A perturbation would traverse a sunspot in less than 1 hour  $\Rightarrow$  sunspots are stable (days to weeks)  $\Rightarrow$  perturbations must decay
- ❑ Interchange or flute instability
- ❑ Gravity provides stabilization (exchange of heavy exterior plasma with lighter, magnetized interior material)
- ❑ Sunspots decay in a diffusive way (turbulent diffusion)
- ❑ Umbral granulation and umbral dots
- ❑ Penumbra filaments
- ❑ Oscillatory convection (parcels of hot gas squeeze through the magnetic lines of force from below)
- ❑ The true subsurface structure of sunspots is not known at present
- ❑ The sunspot atmosphere is compressible, stably stratified, and has a magnetic field  $\Rightarrow$  oscillations!
- ❑ 3-minute (photospheric) and 5-minute (chromospheric) oscillations
- ❑ Running penumbral waves
- ❑ Evershed effect (radial outflow which abruptly stops at the penumbra/quiet Sun boundary, Siphon flow along flux tube, 5-15 km/s)

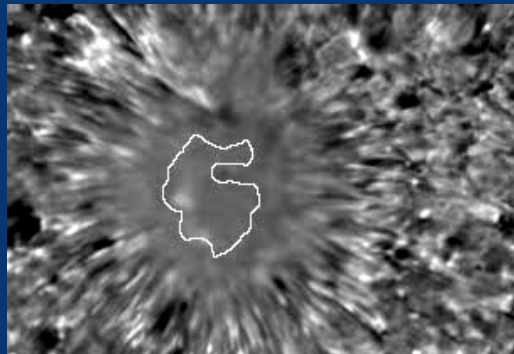


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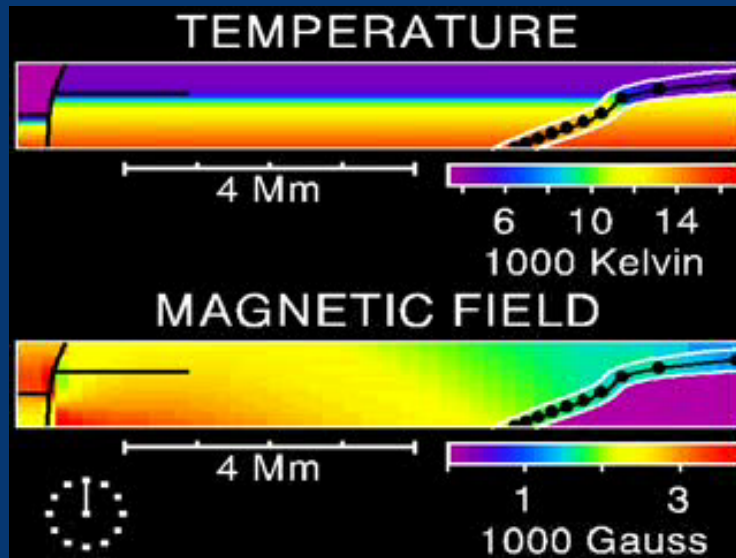


<http://www.astro.su.se/~rouppe/talks/estec01/0/index8.html>



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<http://www.kis.uni-freiburg.de/~schliche/index-Dateien/video.html>

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