University of Glasgow | School of Physics & Astronomy

SUPA course: The Sun's Atmosphere

Session 2017-18

Lecture 8 on "The photosphere and how we study it"

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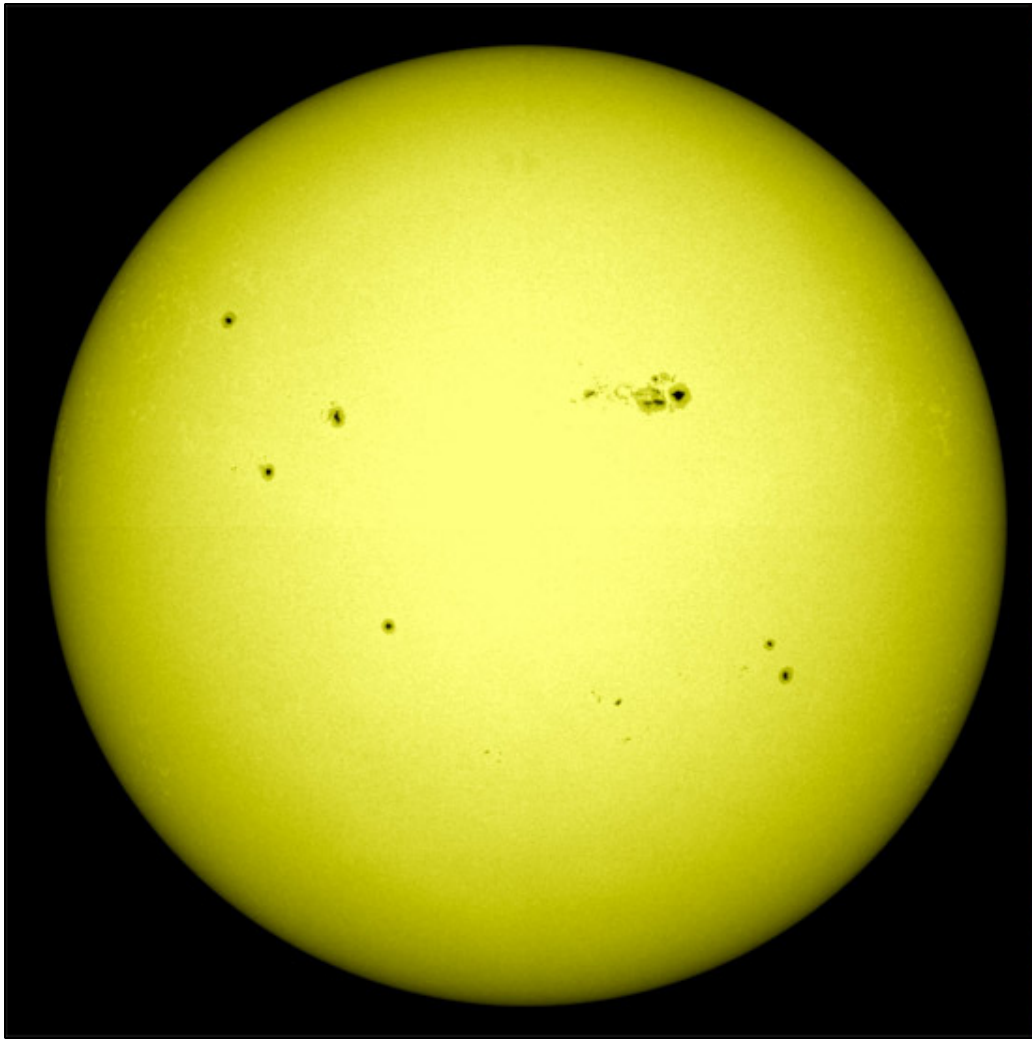
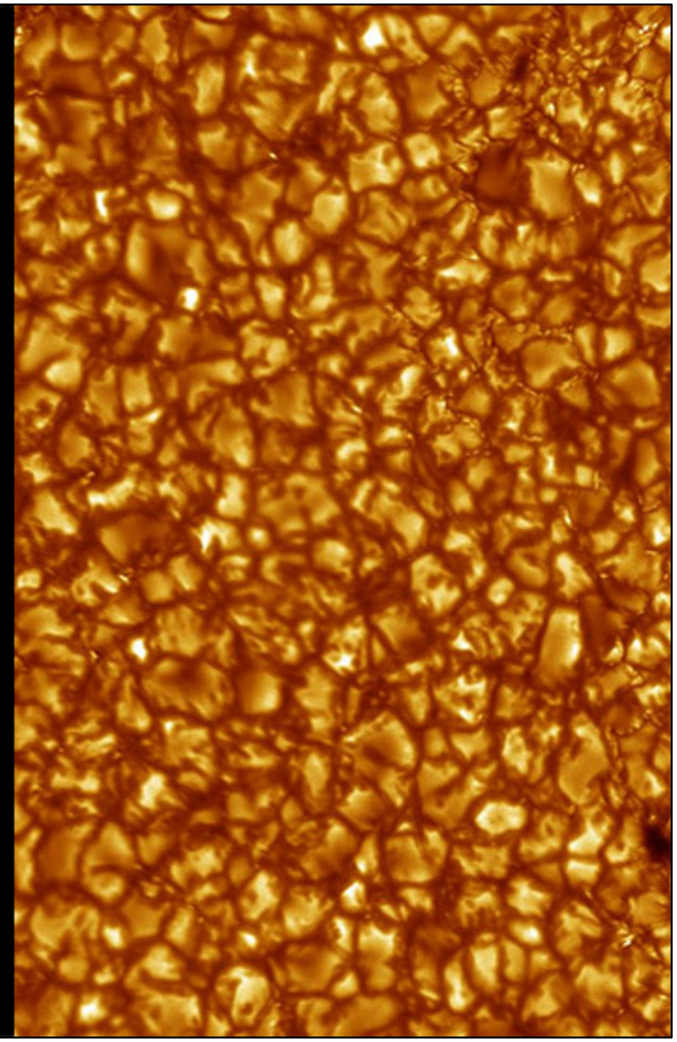
The course thus far:

Lecture 1: Structure and dynamics of the solar atmosphere
Lecture 2: Plasma physics and particle interactions
Lecture 3: Particle acceleration and transport
Lecture 4: MHD I
Lecture 5: MHD II
Lecture 6: Radiation transport I
Lecture 7: Radiation transport II
Shifting gears to observational methods
Lecture 8: The photosphere
Lecture 9: Solar magnetism

The photosphere





Half a degree

About 20x40’’

How do we study the photosphere?

1. Imaging spectropolarimetry: line profiles at each pixel, at each polarization state, at each time.
2. Inversion of the spectra for physical parameters.
5. Large-scale numerical simulations of the physics.

The problems: line-of-sight effects; lack of computer power; unknown physics

Basic observational facts

I. Limb darkening: the edges of the Sun are darker than than its center:

$I_\nu = \Sigma\, a_i\, \mu^l$, where $\mu = \cos(\theta)$ with θ the local vertical angle (the traditional representation)

II. The surface shows convective structures plus blemishes: sunspots and faculae

III. At any given wavelength, we see mainly a 2D projection of the 3D structure

Limb darkening law

- The simplest limb darkening law is the "gray atmosphere" approximation

  - opacity independent of wavelength

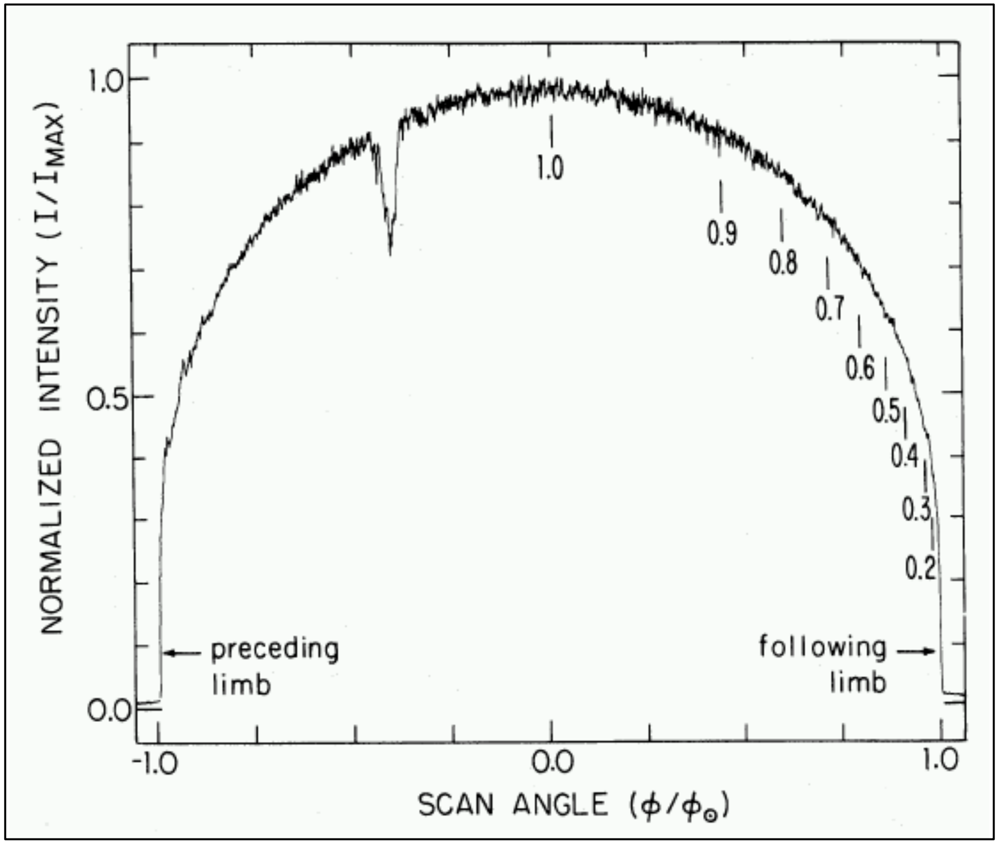
  - diffusion approximation for radiative transfer

  - linearization via $S(\tau) = a + b\tau$ (*Eddington-Barbier)*
- The result, which works quite well for the bolometric intensity, is the approximate form

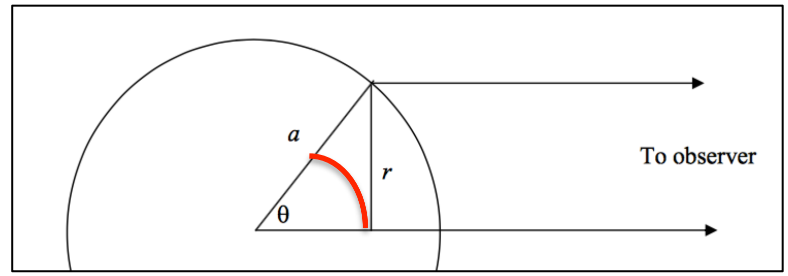
$$I/I_0 = (3\mu+2)/5$$

as derived in Lecture 6. Note that one needs an intuitive feeling for "source function" and "optical depth"

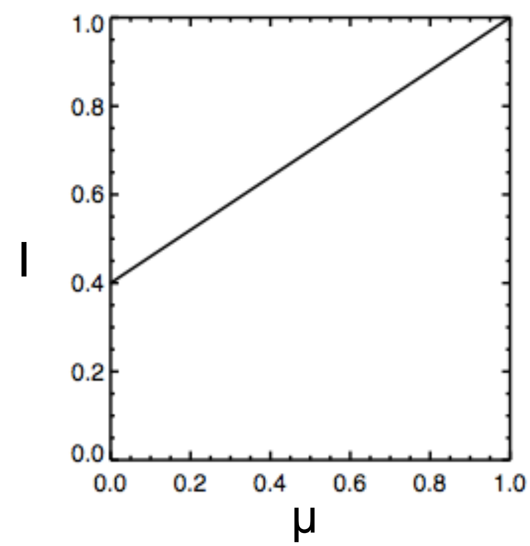
Limb darkening



A typical drift scan, showing values of μ = cos(θ) and other things.

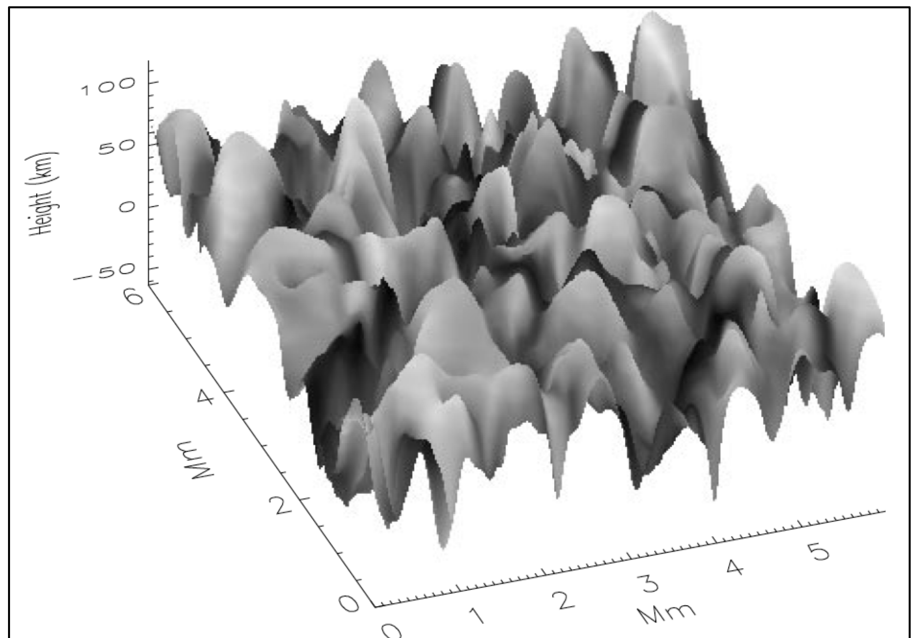


The vertical angle θ, with μ = cos(θ)



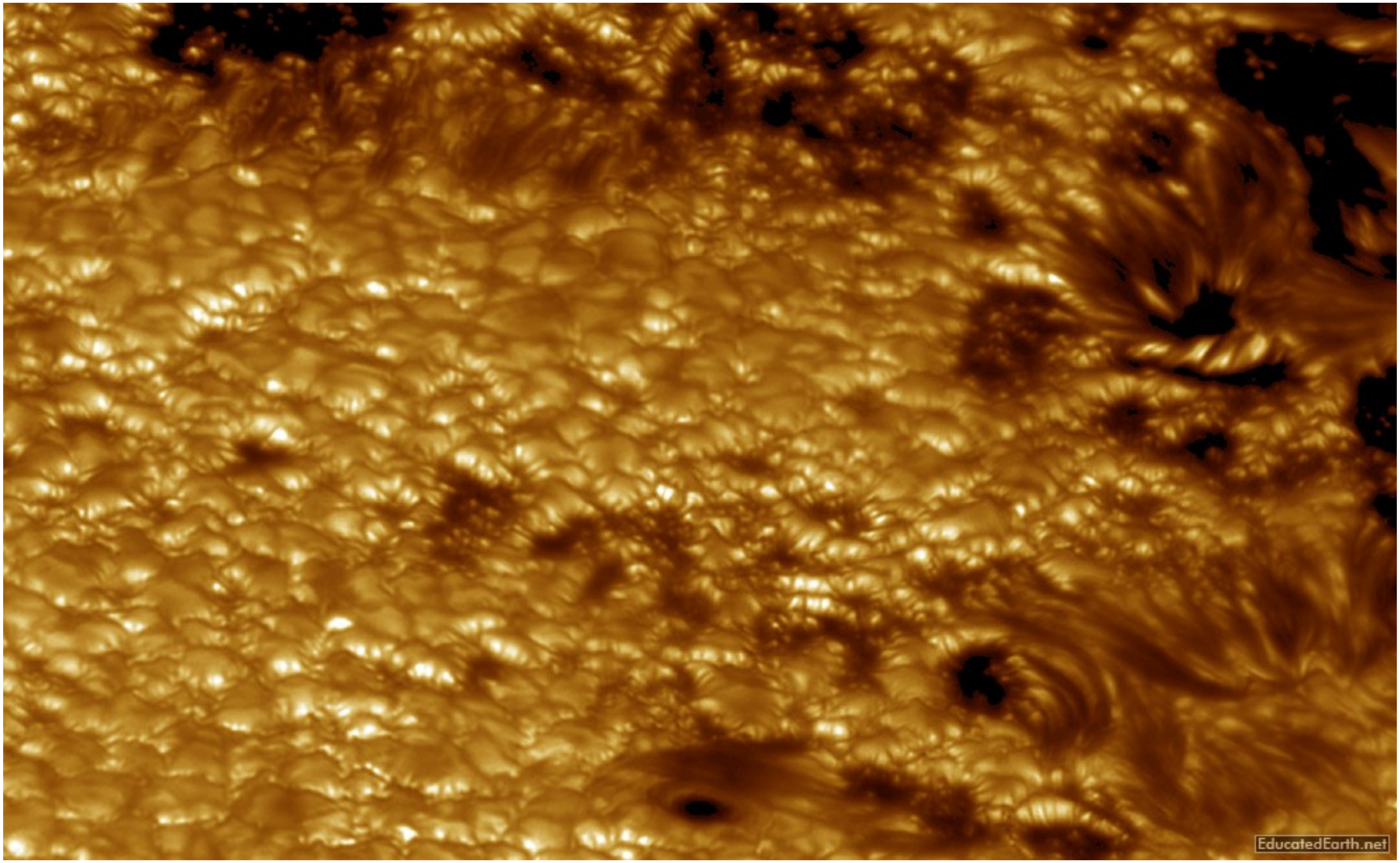
Limb darkening and 3D

- Limb darkening can readily be explained by a simple opacity model: $S_\nu = a + b\tau$ (the source function S assumed to depend linearly upon optical depth). Thus T and $B_\nu(T)$ must decrease with height
- Could rough structure ("rugosity") also play a role?

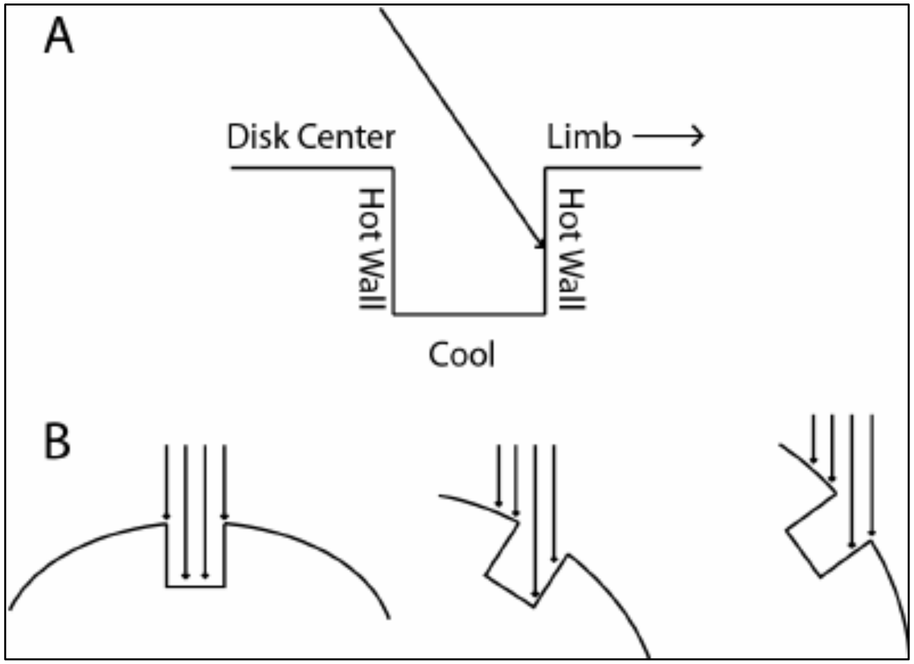


Stein & Nordlund 1998

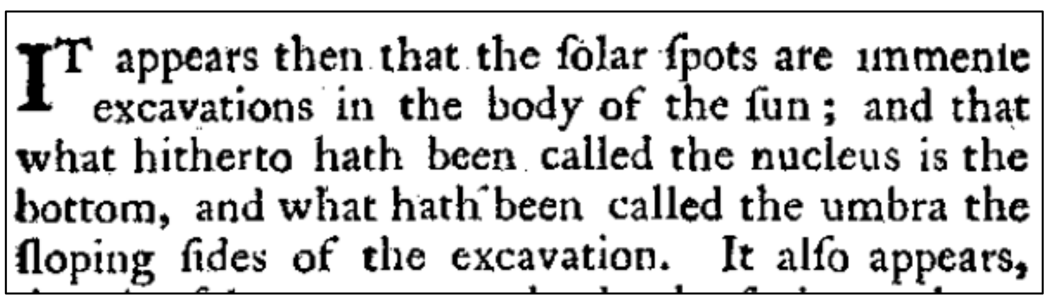
The third dimension



Magnetic height structure



The bottom of the flux tube is cool, like a sunspot, because of magnetic suppression of convective motions (Spruit, 1976). His “hot wall” model effectively explains faculae, if not *plage.*


IT appears then that the ſolar ſpots are immenſe excavations in the body of the ſun; and that what hitherto hath been called the nucleus is the bottom, and what hath been called the umbra the ſloping ſides of the excavation. It alſo appears,

Wilson, 1784

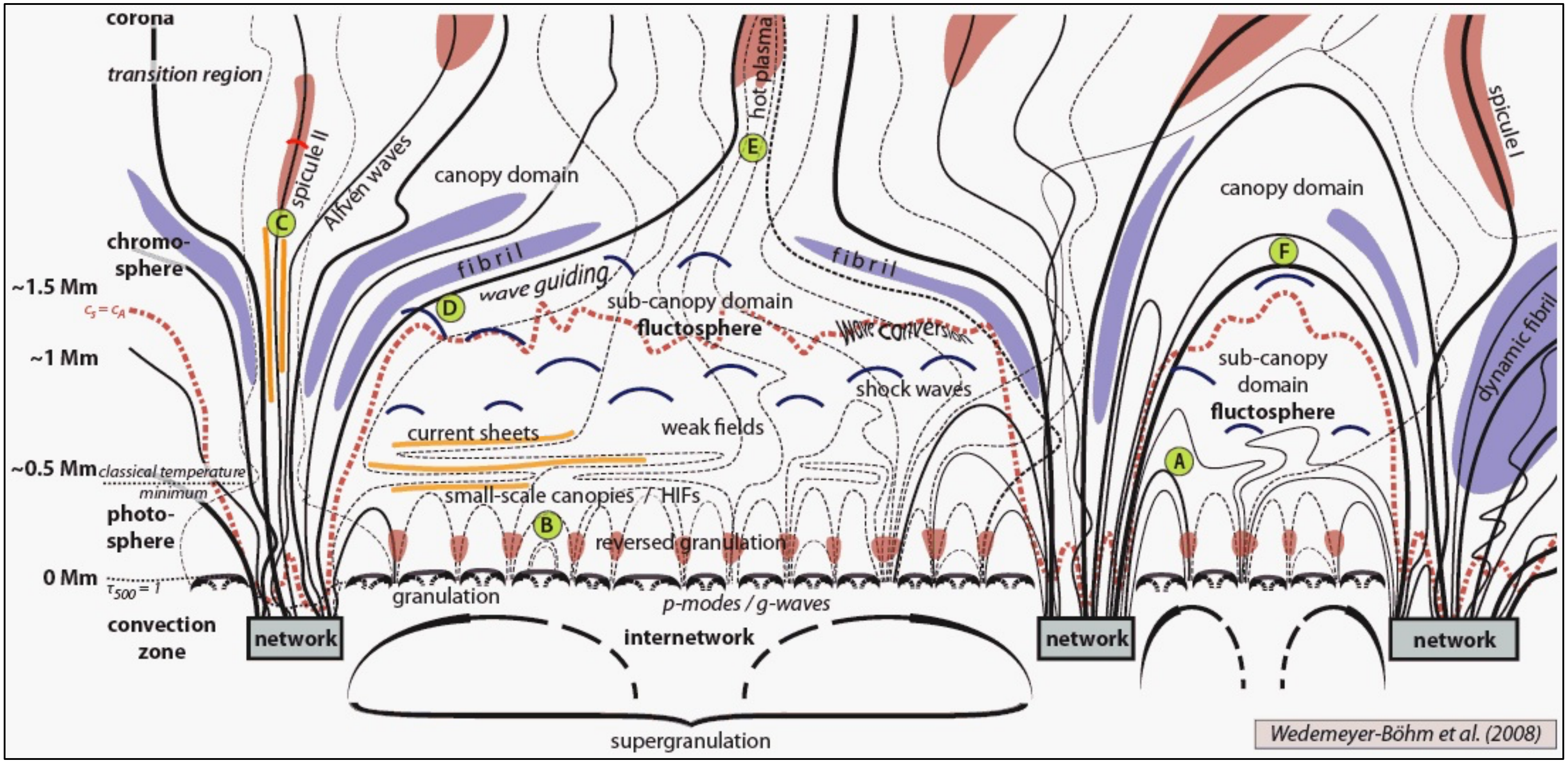
Significance

The photosphere lies at the bottom of the solar "atmosphere", and it marks the site of many fundamental changes in physical properties:

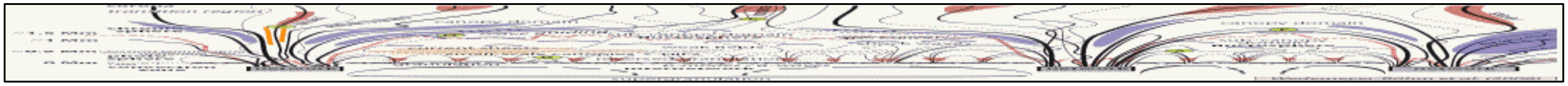
1) The radiation field detaches from the matter
2) The plasma loses collisionality
3) Plasma beta ($\beta = P_g/P_B$) drops precipitously
4) Composition changes (the FIP effect)
5) Unbalanced coronal currents form
6) Temperature rockets upwards

The defining structural term is gravity.

The transition layers

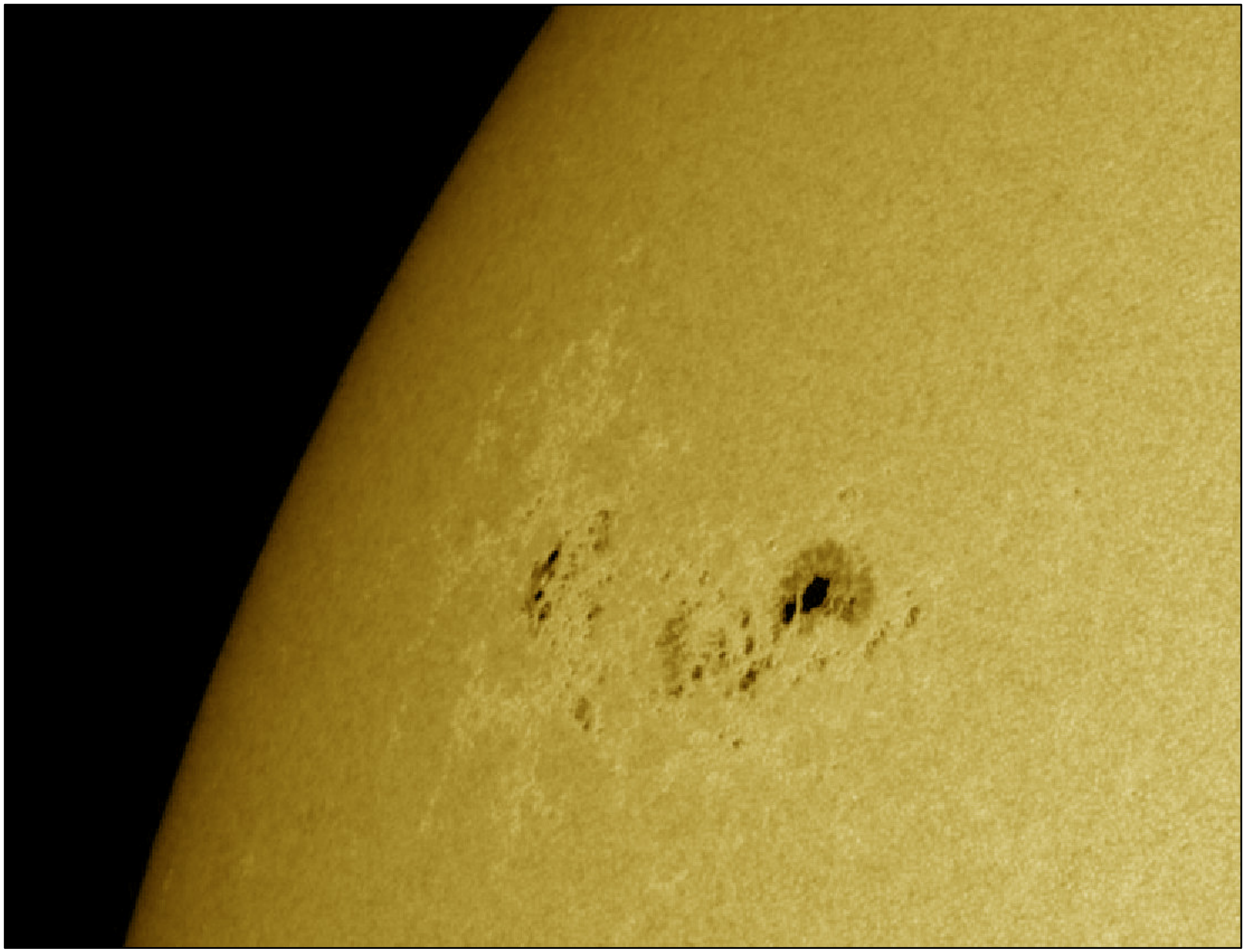


Gravity and structure



Here it is roughly to scale. The vertical extent of the entire transition layer is less than about 1% of the solar radius – about the diameter of Earth.

Sunspots as blotches, affecting the total solar irradiance (TSI)



Let's check one property: the luminosity

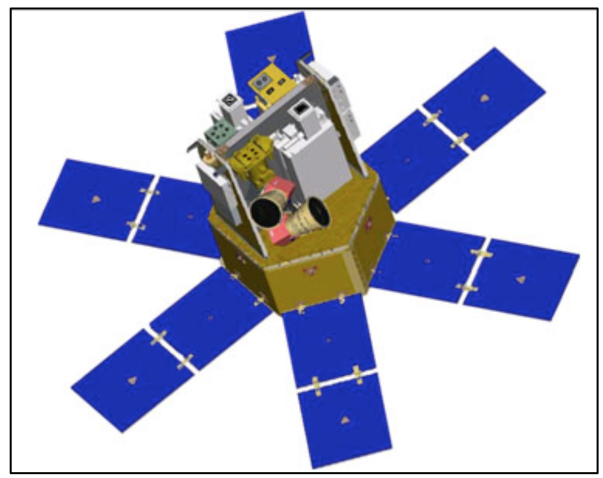
• Is it really 3.83 x 10^{33} erg/s?

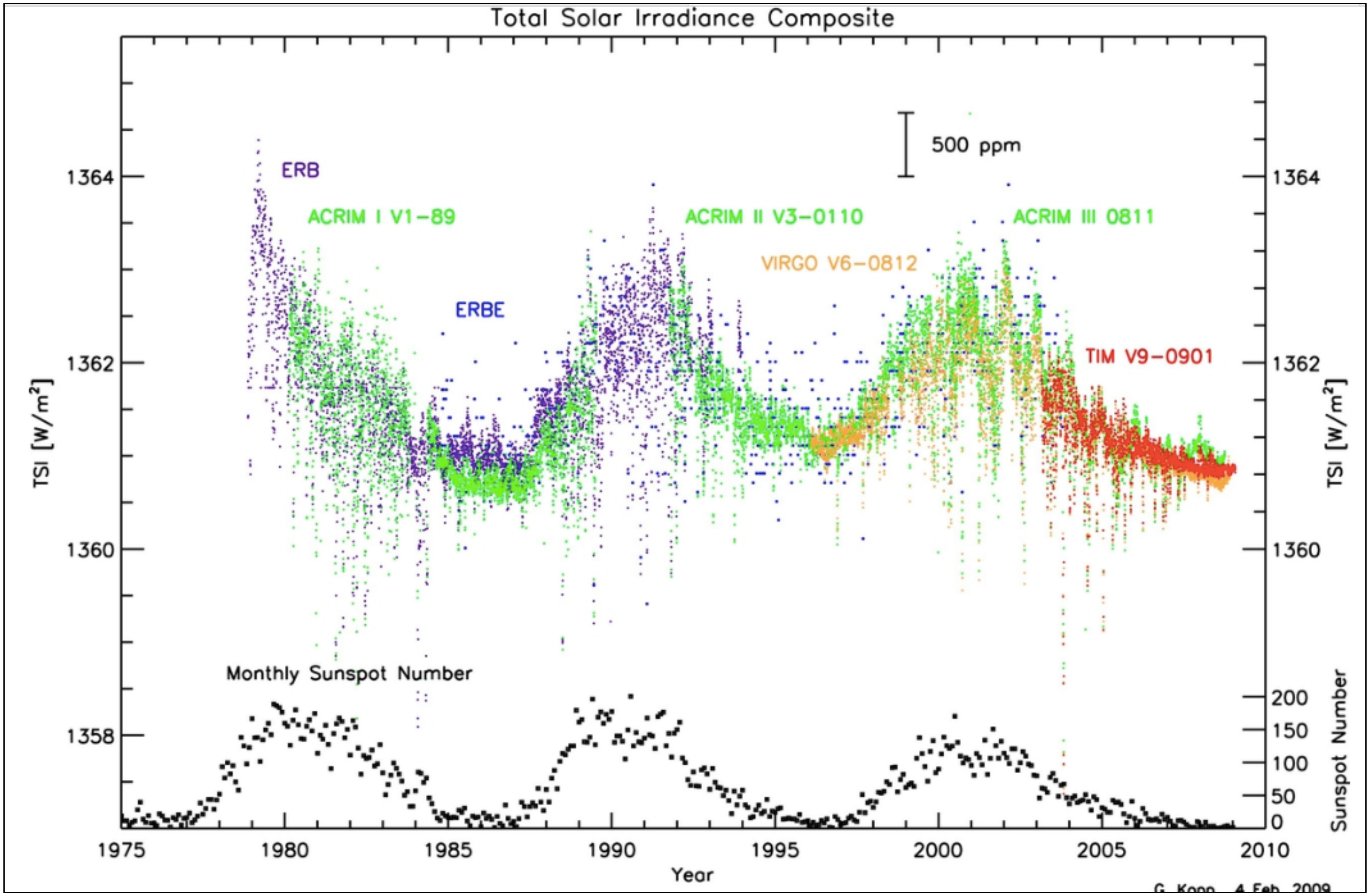
- Why only three significant figures?
- Does it vary with time?

• How do we measure it?

- The "total solar irradiance " (TSI)
- A series of satellite instruments, dating back to 1980
- Limb darkening. The radius. Flux vs. luminosity

The SORCE satellite





Yes, the irradiance varies. Does that mean that the luminosity does?

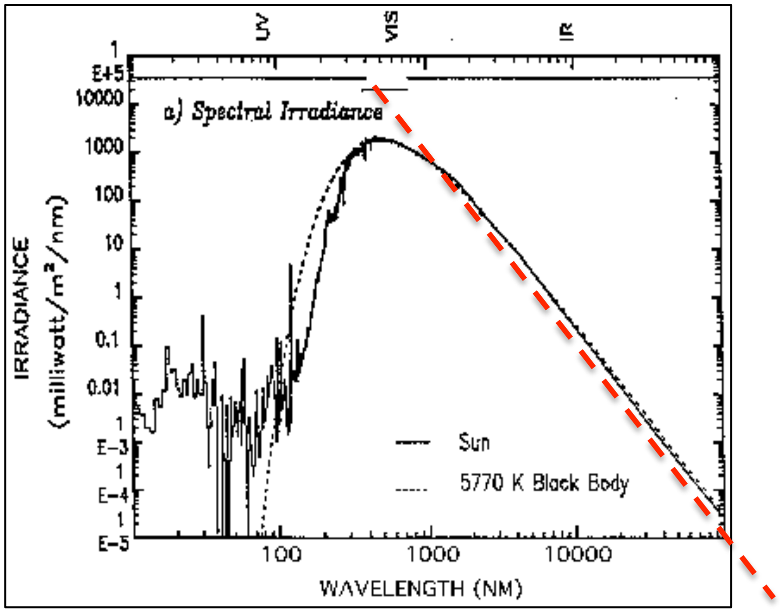
Kopp & Lean, GRL 2011
"A new, lower value of total solar irradiance: Evidence and climate significance"

- The mean total irradiance used to be 1365.4 ± 1.3 W/m^2
- This paper (2011) announced a value 1360.8 ± 0.5 W/m^2

Checking, we need a value for the astronomical unit, defined now as 149,597,870,700 m, thus the luminosity

$$L_\odot = 4\pi(AU)^2\, S = 3.8269 \pm 0.0014 \times 10^{26}\ \mathrm{J/s}$$

Recall the “semi-empirical” models



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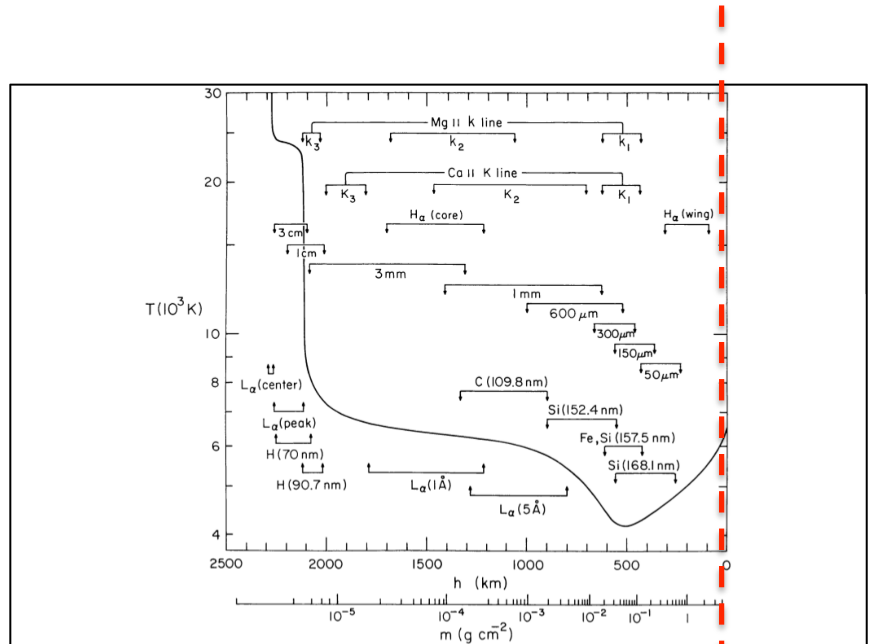


FIG. 1.—The average quiet-Sun temperature distribution derived from the EUV continuum, the Lα line, and other observations. The approximate depths where the various continua and lines originate are indicated.

- From Lecture 1, the solar spectral energy distribution (“SED”, also known as “spectrum”) in the UV leads to a model height variation.
- The physics consists of radiative-transfer theory plus the law of hydrostatic equilibrium.

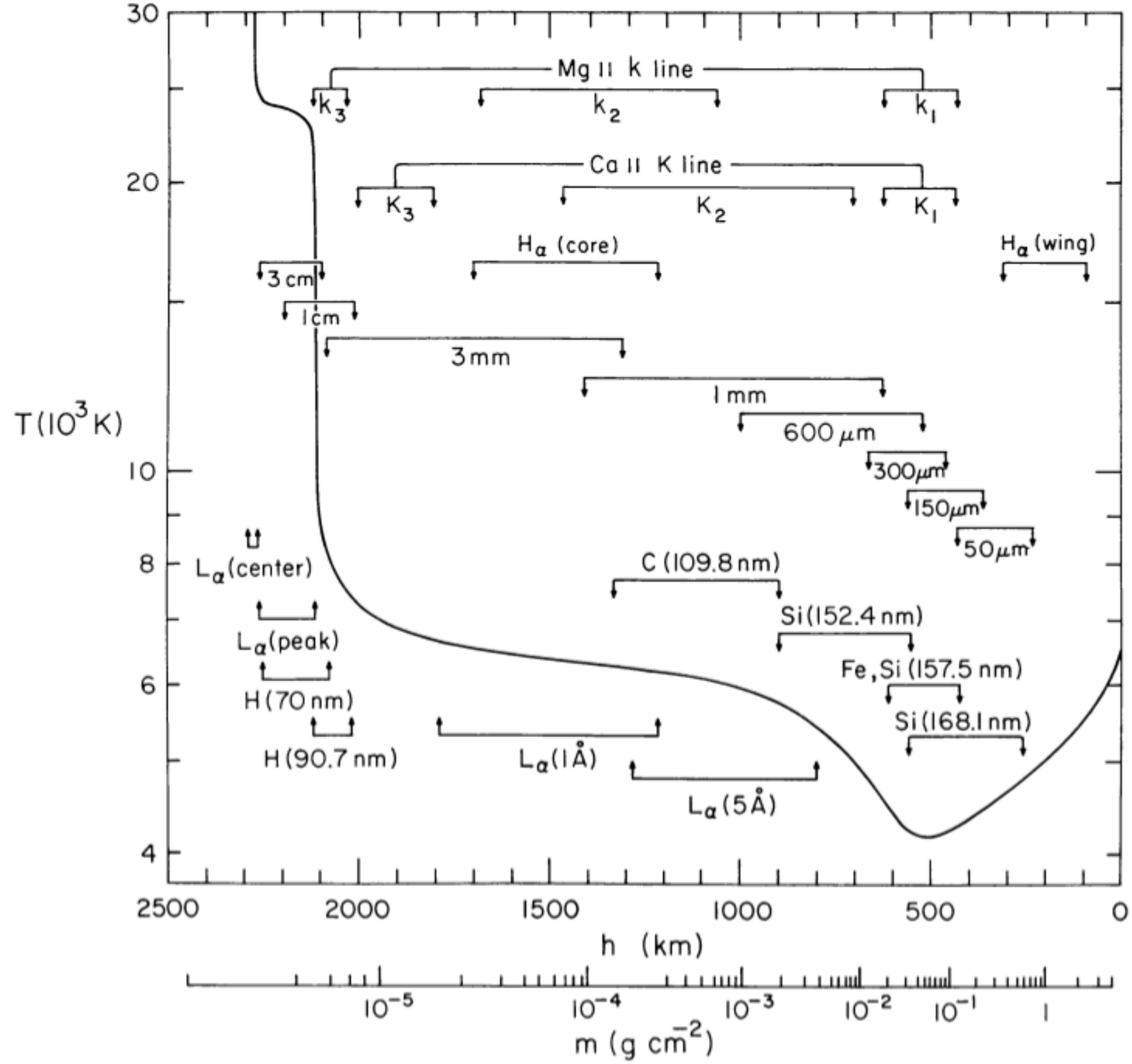
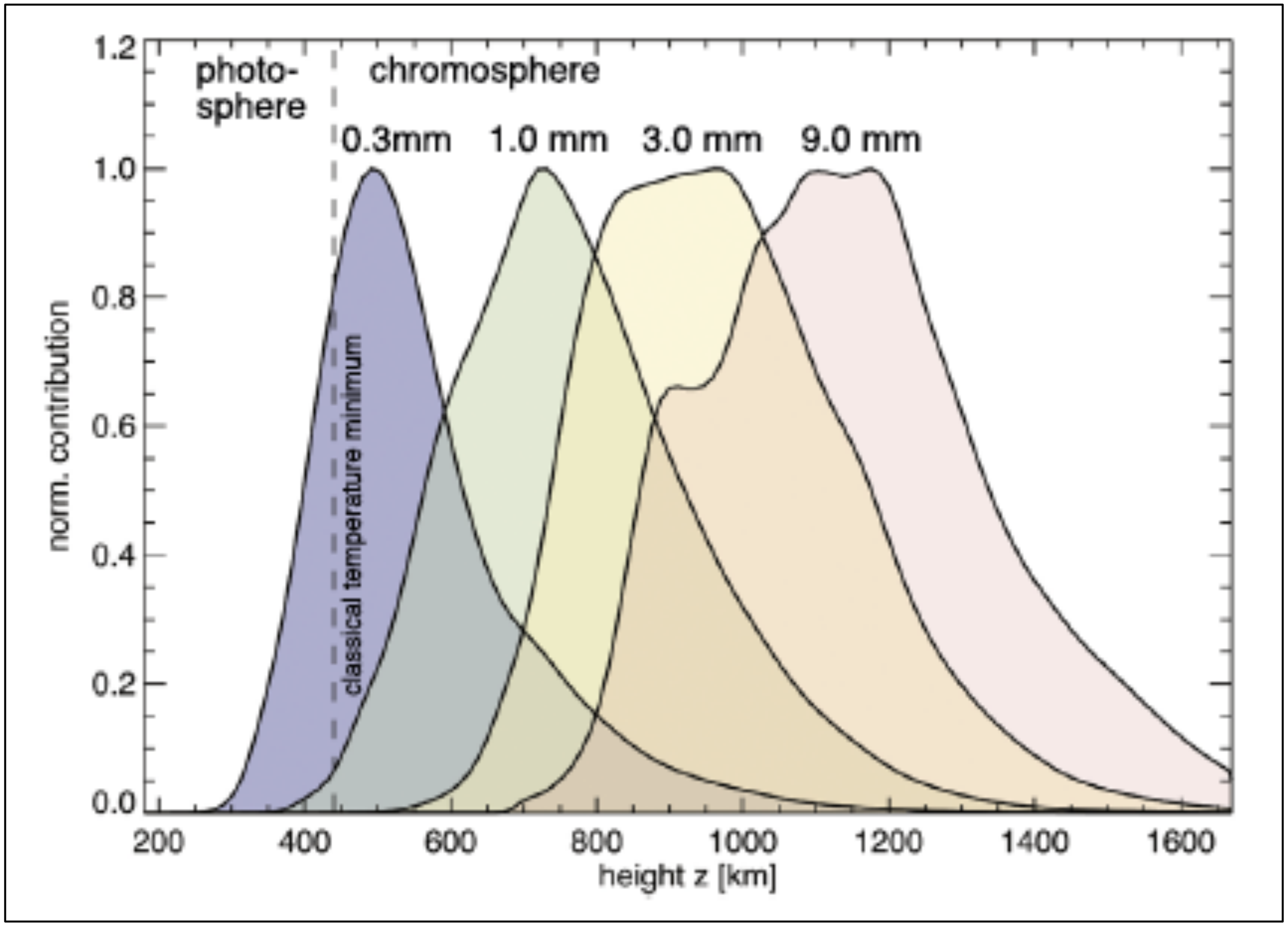


FIG. 1.—The average quiet-Sun temperature distribution derived from the EUV continuum, the Lα line, and other observations. The approximate depths where the various continua and lines originate are indicated.

Contribution function, $B_\nu(T)e^{-\tau(T)}$



Observational issues

- The surface of the Sun is very smooth, but not quite exactly. It is optically thick by definition, and we have no direct way to see it in 3D.
- Higher angular resolution continually produces discoveries (at present, about 100 km).

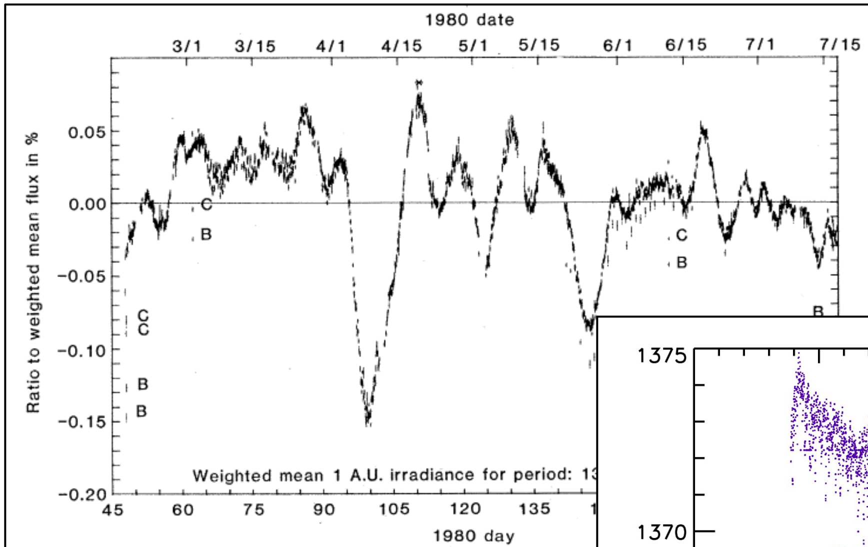
An incorrect argument often heard: "Angular resolution only needs to be good enough to resolve one photon mean free path!"

- which photon?

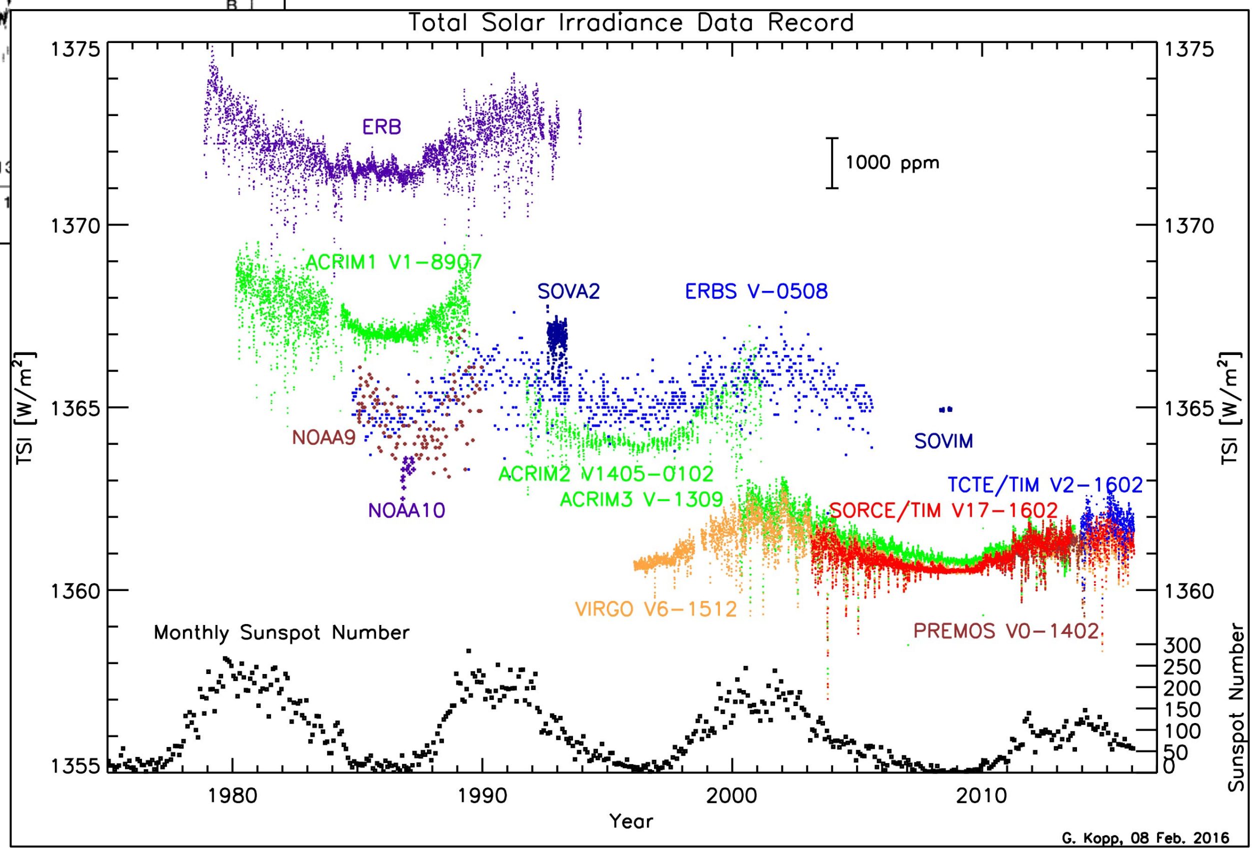
- is magnetic structure unimportant?

- what does one mean by "resolve"?

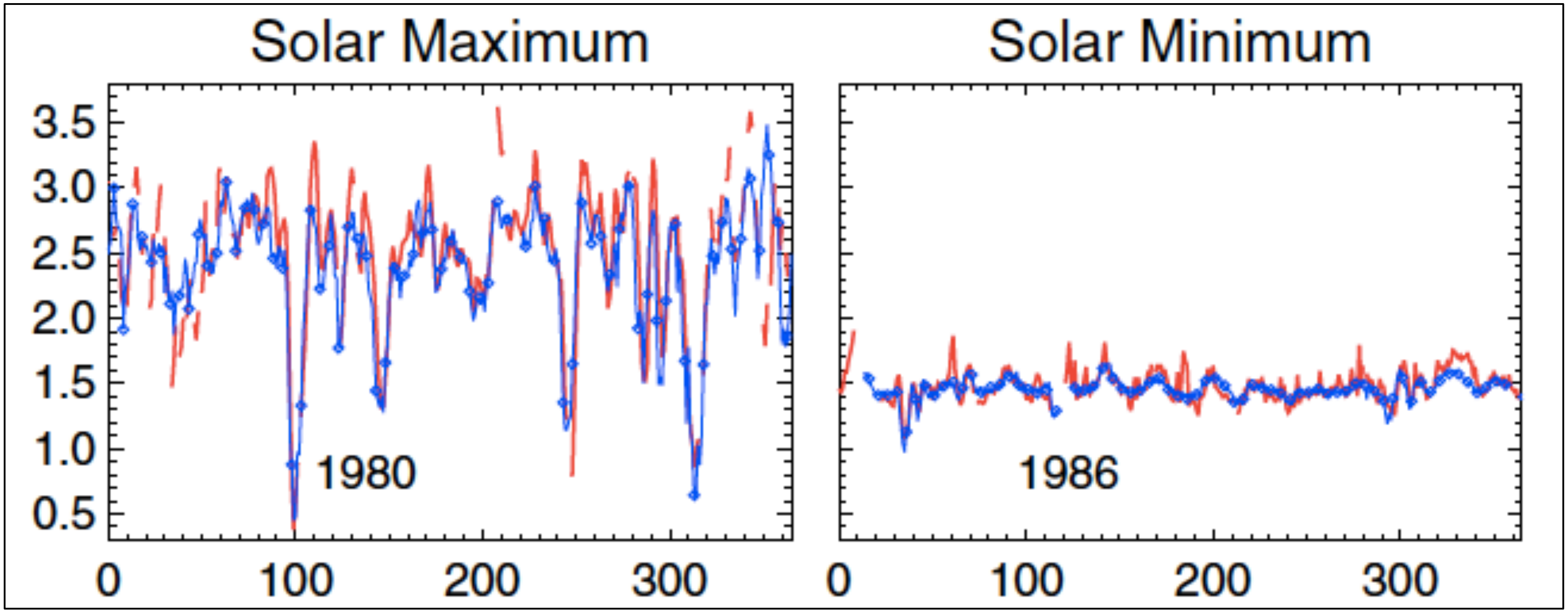
Total solar irradiance (TSI)



Willson et al. 1981



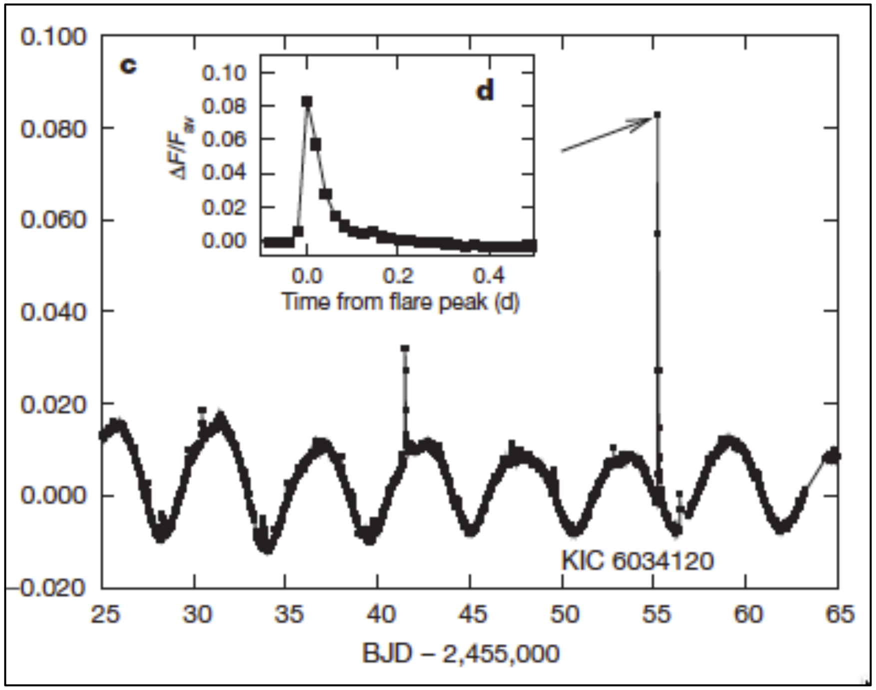
Sunspot deficits, facular excesses

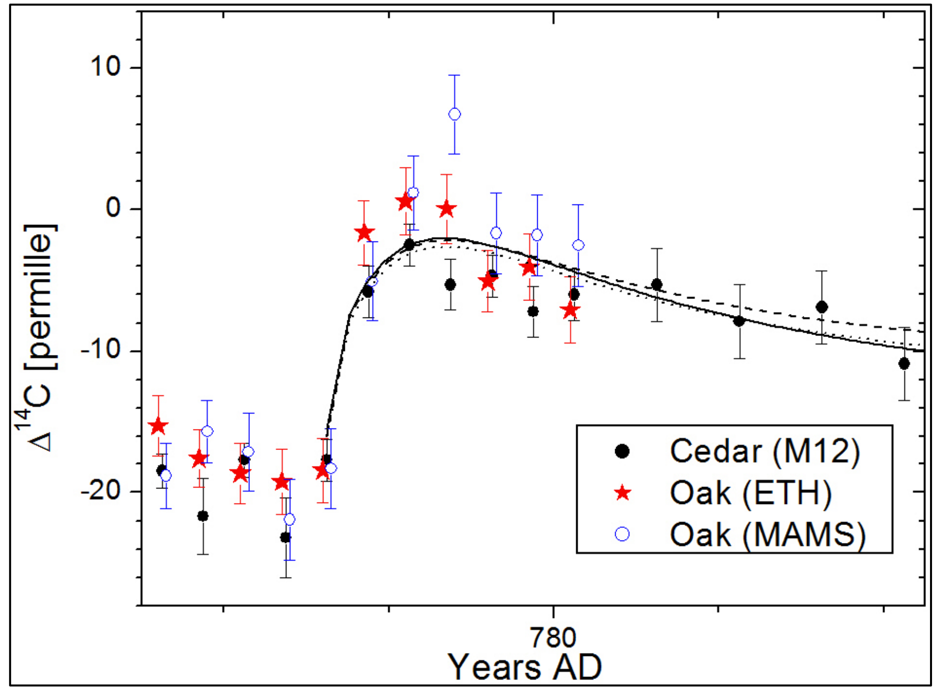


Frohlich & Lean, 2004

- The "solar constant" (mean TSI) is about 1370 W/m^2.
- These measures can be modeled precisely in terms of image content.
- *Kepler* photometric observations now provide thousands of analogous solar-type stars for reference.

Extreme events

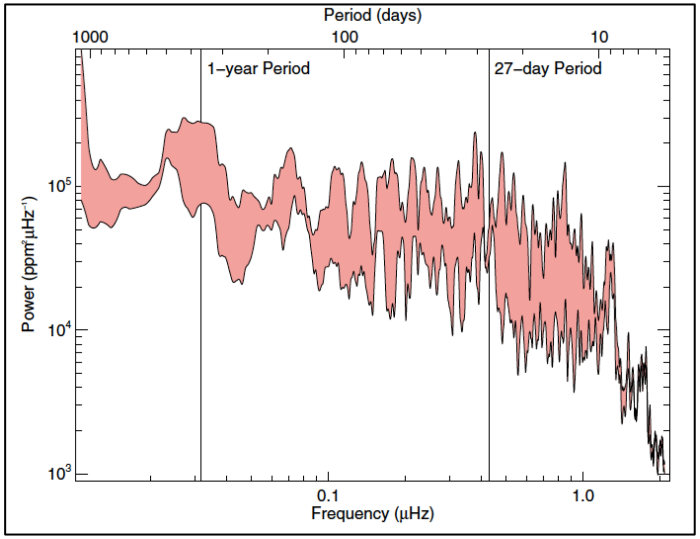




- A *Kepler* "superflare" on a solar-type star (Maehara et al. 2013)
- Note the non-solar pattern of quiescent variations

- A radioisotope event found in tree-ring data (Miyake et al. 2012)
- Solar or not? A debate rages on

How does the Sun vary?

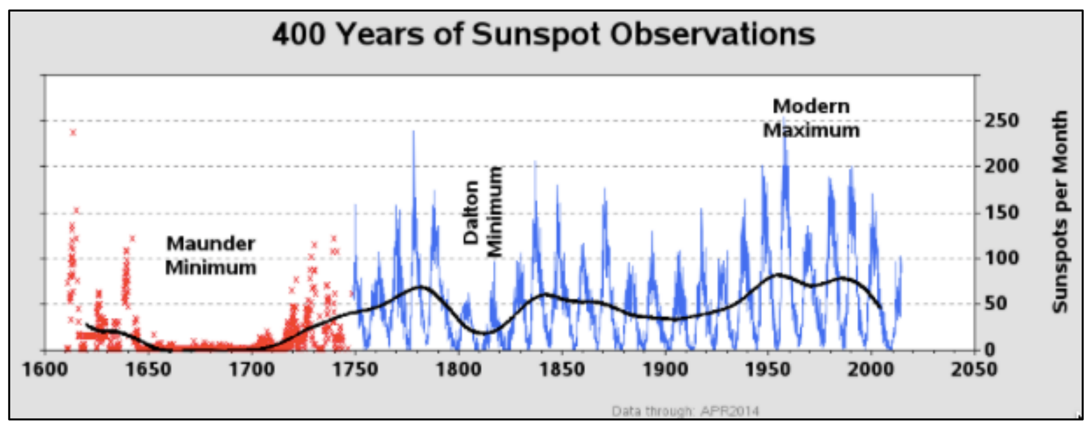


Fröhlich & Lean, 2004

Variability occurs on many scales:

- p-modes (few min)
- Convection (min to hours)
- Local magnetism (days)
- Rotation (~27d)
- Hale cycle (22 years)
- *Holocene (warming deniers)*
- Secular (eons)

Note the "Maunder minimum" of the 17^{th} century.



Basic properties

- Solar gravity is very strong: $g_\odot$= 274 m/s^2.
- Convection produces weak patterns (granulation and supergranulation, a.k.a. the network)
- The Sun is a slow rotator (~2 km/s), so its photosphere is very round: $v^2/(R_\odot g_\odot)$ ~ 5 ppm.
- Except for sunspots and faculae, it is very smooth (τ = 1 in granules about 30 km RMS, so of order 40 ppm).
- The radiation flux is very steady: $\Delta L_\odot/L_\odot$ < 0.1% on human time scales.
- The optical photosphere lies roughly at one Thomson length: of order one g/cm^2 (= 10 kg/m^2).
- The hydrostatic scale height at τ = 1 is about 100 km.