University of Glasgow | School of Physics & Astronomy
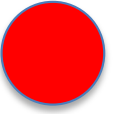
ASTRO5010: The Sun's Atmosphere

Session 2024-25

Lecture 10: "The photosphere, how we study it,
and why it matters"

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Monday, 24 February 2025

Useful homework questions based on this material

- What is the minimum Earth detectable by photometry of a Sun-like star?
- How round is the Sun?
- What limits the ability of a telescope to resolve the finest details?
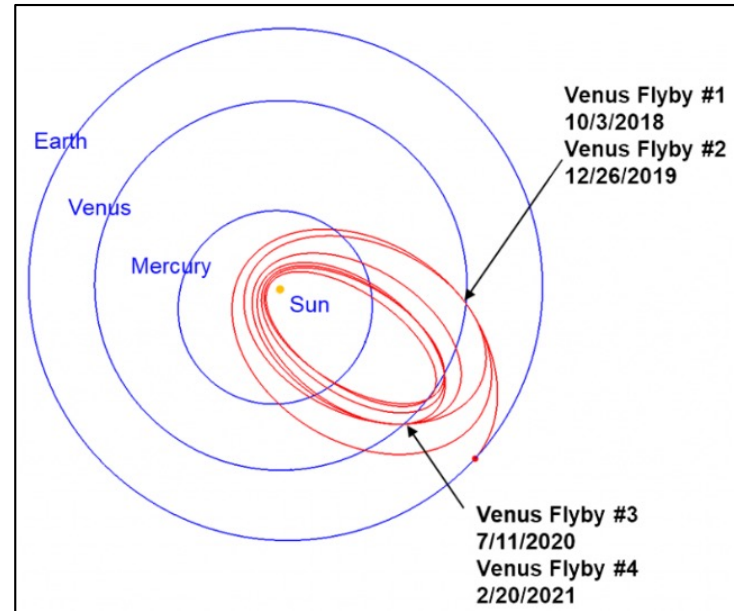- How deep can a Wilson depression be?

These are questions to be answered by rough approximation, and the necessary facts should be here on the slides. I will post discussion of these items on Moodle and at

http://www.ssl.berkeley.edu/~hhudson/presentations/tsa.250224/
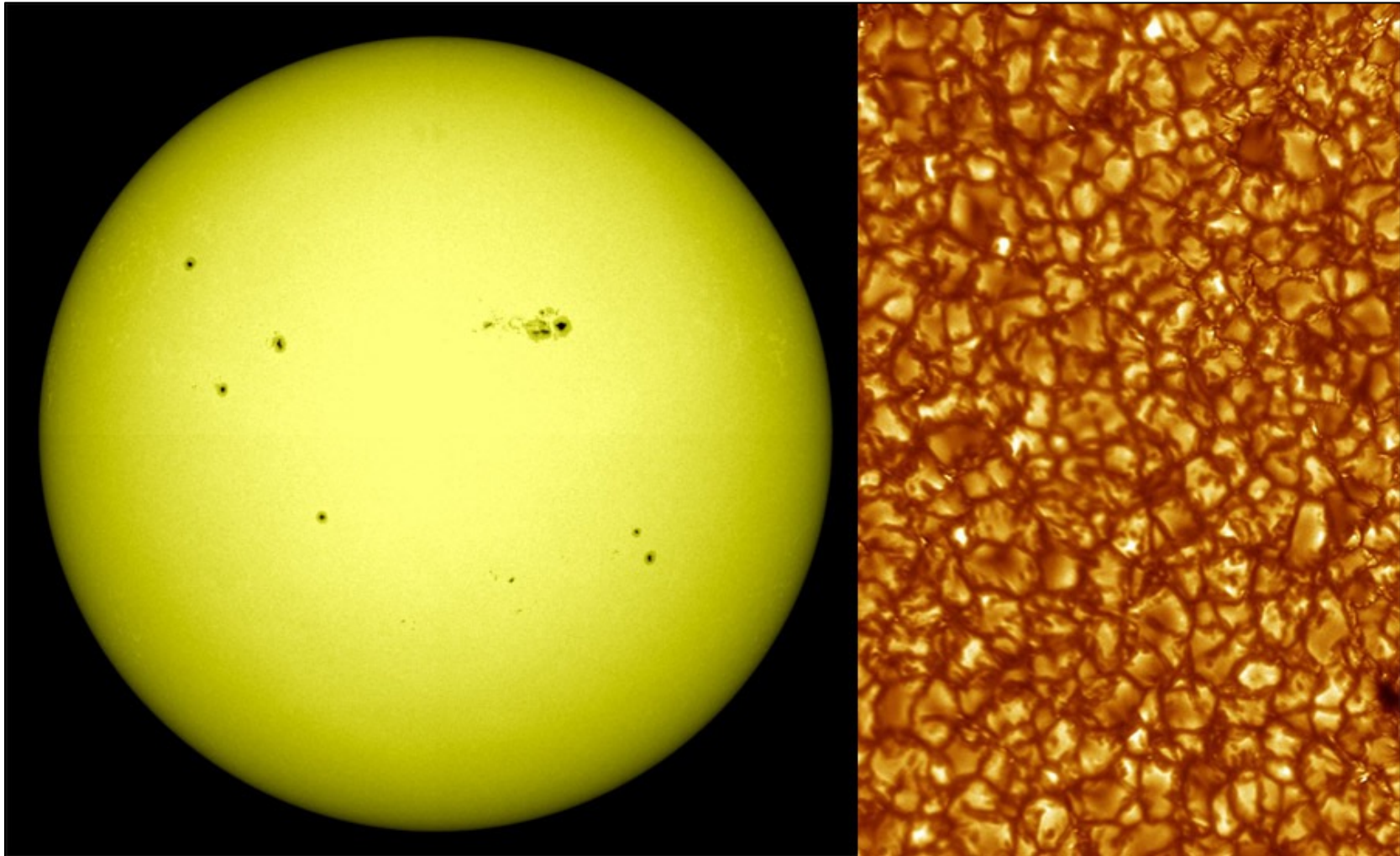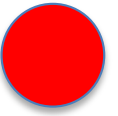
New solar observational tools

DKIST - a 4-m solar optical/IR telescope

PSP - a space probe that dares to approach the solar surface

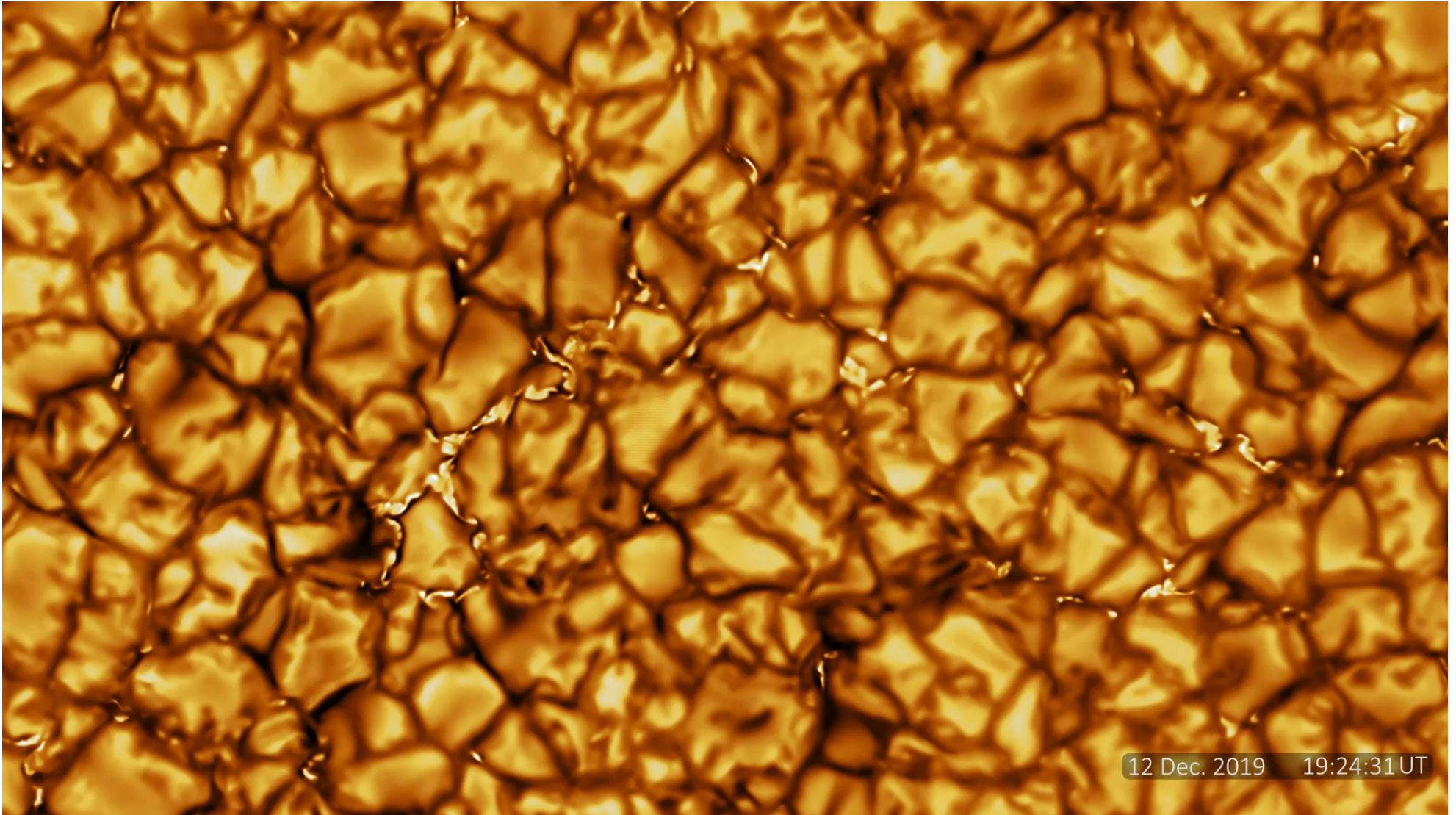Plus: radio waves, X-rays, gamma rays, "solar cosmic rays", EUV, stereoscopy... and more

The photosphere

Half a degree

About 20" x 40''
or
15 Mm x 30 Mm

The state of the art: DKIST

12 Dec. 2019   19:24:31 UT

How do we study the photosphere?

1. Imaging spectropolarimetry: line profiles at each pixel, at each polarization state, at each time: *data = f(x,y,λ,p,t); error = δf(x,y,λ,p,t)*
2. *Time-domain astronomy*
3. "Inversion" of the spectra for physical parameters: *e.g., T_e(x,y,z,t)**
4. Large-scale numerical simulations of the physics

The problems: line-of-sight effects; resolution, lack of computer power; unknown physics
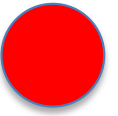
Basic observational facts

I. **Limb darkening**: the edge of the visible Sun is darker than than its center: $I_\nu = \Sigma\, a_i\, \mu^i$, where $\mu = \cos(\theta)$ with θ the local vertical angle and $\{a_i\}$ a set of coefficients (often 2)

II. The surface shows convective structures on two obvious scales (granulation, about 1 arc sec; and supergranulation, about 1 arc min) plus blemishes: **sunspots** and faculae

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

IV. Density and temperature at $\tau_{5000} = 1$ are about 10^{17} g/cm^3 and 5800 K (*scale height* ~140 km)
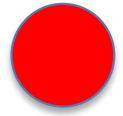
Sun-like stars, Earth-like exoplanets?

Spectral class:	G5V
Mass:	1.9885×10^{30} kg
Radius:	696,342 km
Rotation:	25.05 days at equator
Gravity:	274 m/s^2
Age:	4.6×10^9 y
Luminosity:	3.828×10^{26} W
Metallicity:	$Z = 0.0122$
Variability:	The Hale cycle (~22 y)
	Few % rms at 1 arc sec

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

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

as derived in Lectures 6-7. Note that one needs an intuitive feeling for "source function" and "optical depth"

Solar Rotation
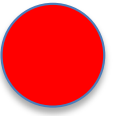
- The Sun rotates *differentially*, about 30% faster at the equator ("equatorial acceleration").

- This property can be traced by sunspot motions in the 17th century, but note that thare are "proper motions" superposed on these flows.

- Other bodies (Jupiter, Earth) also have zonal winds.

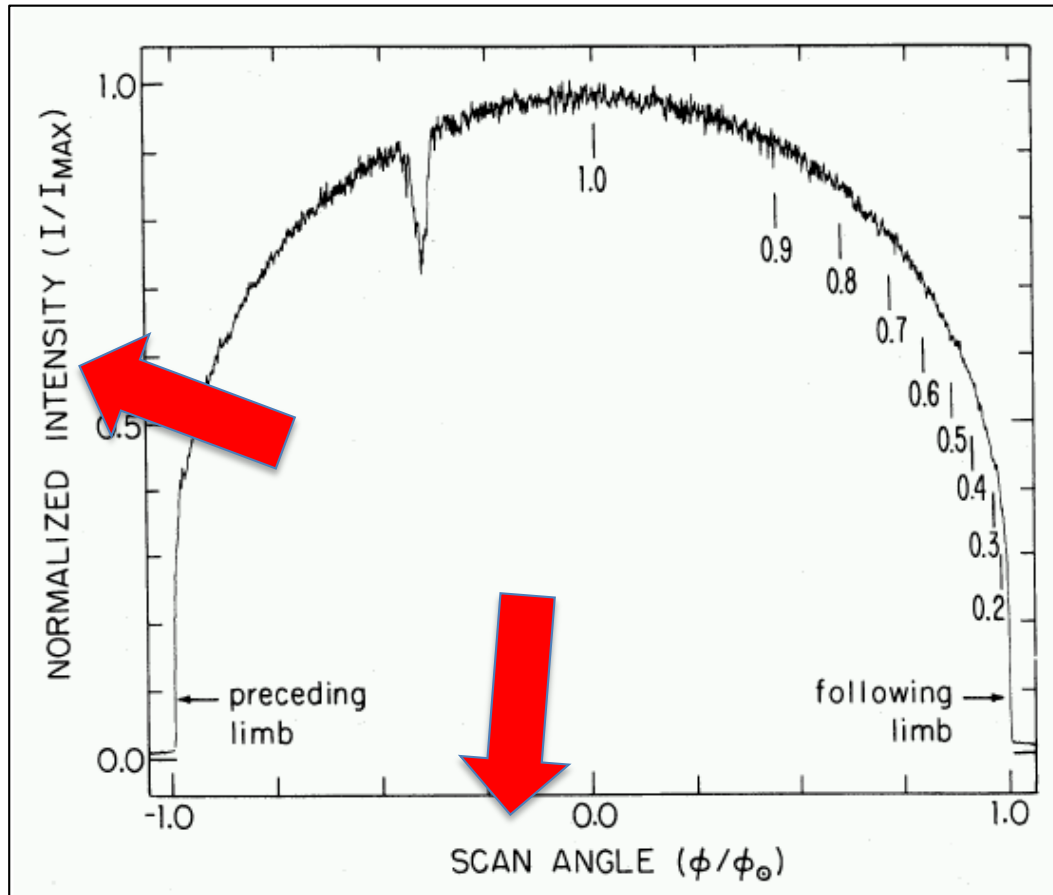- Differential rotation implies *shear* and major consequences for solar magnetism.
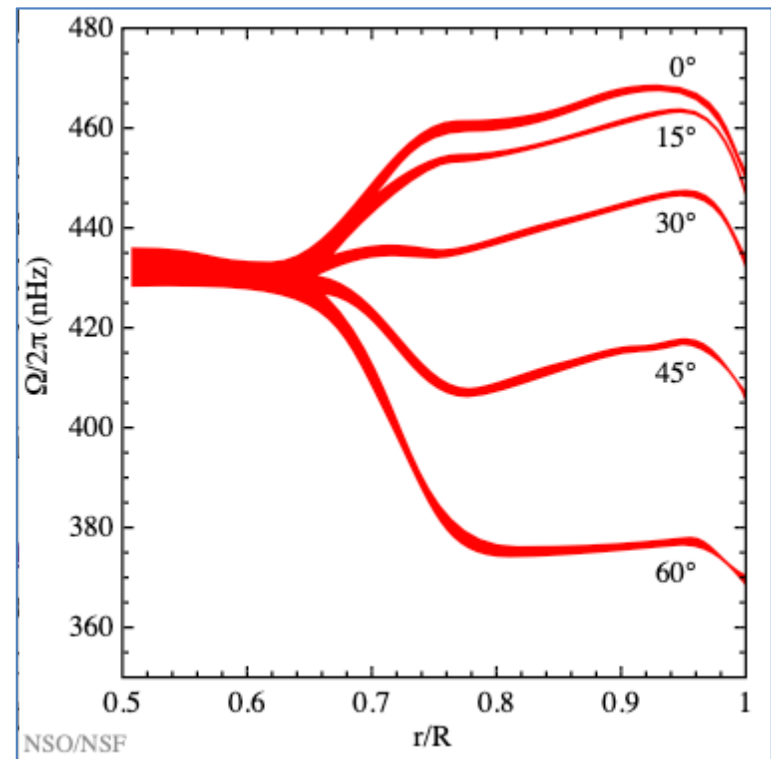
Limb darkening
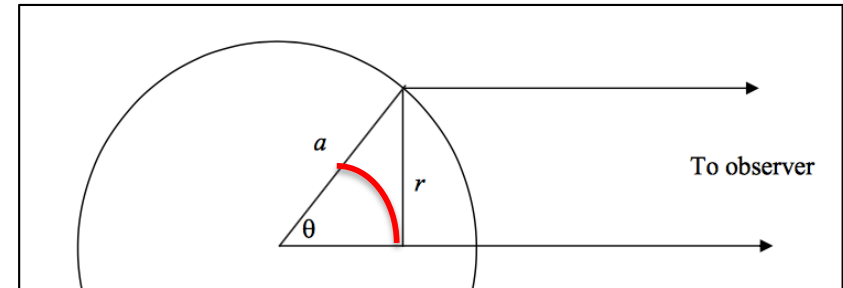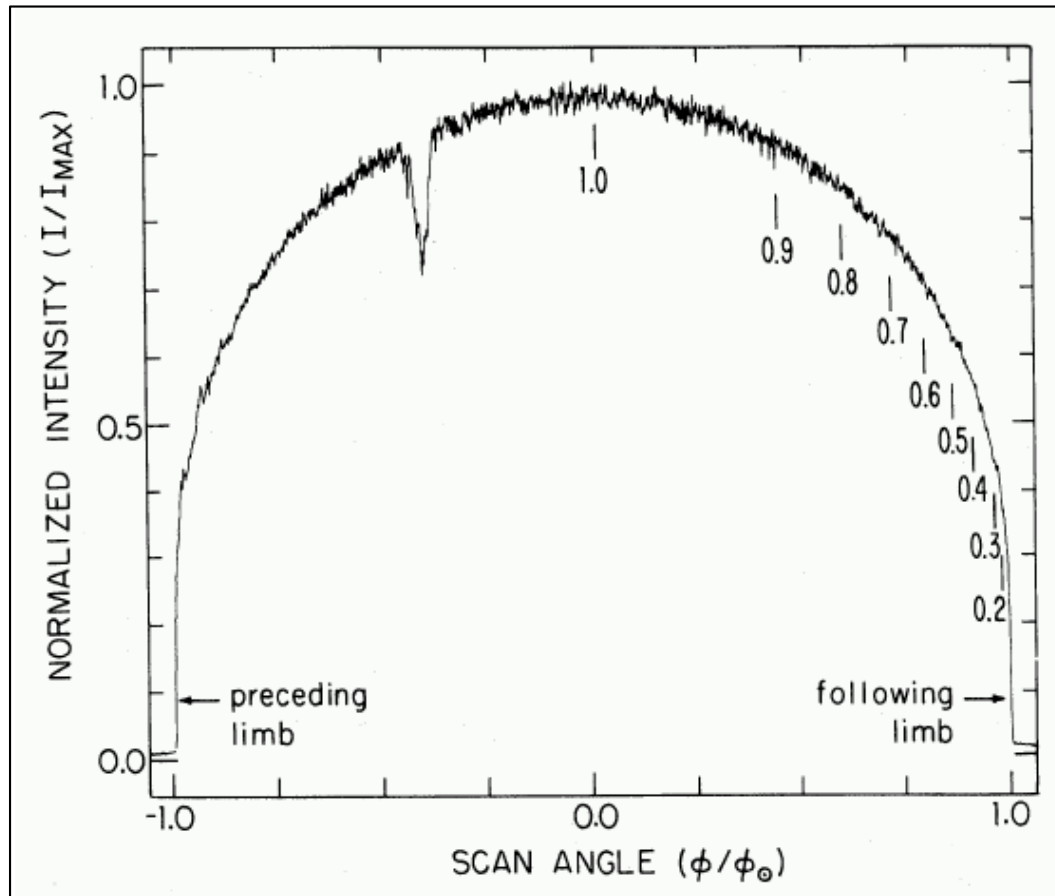
A typical drift scan, showing values of μ = cos(θ) and other things.
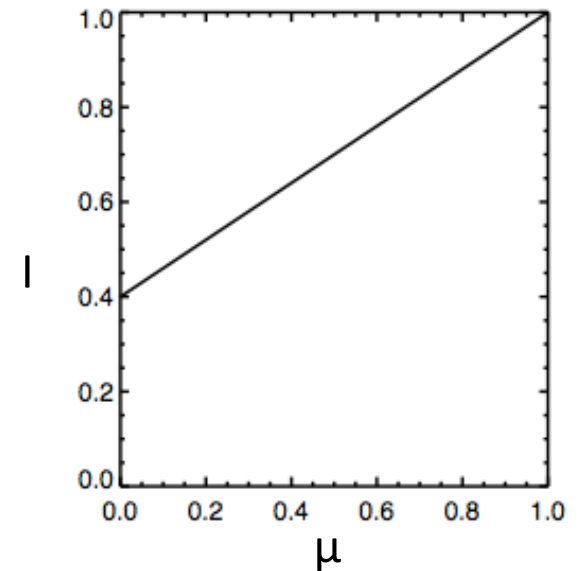
The vertical angle θ, with μ = cos(θ)
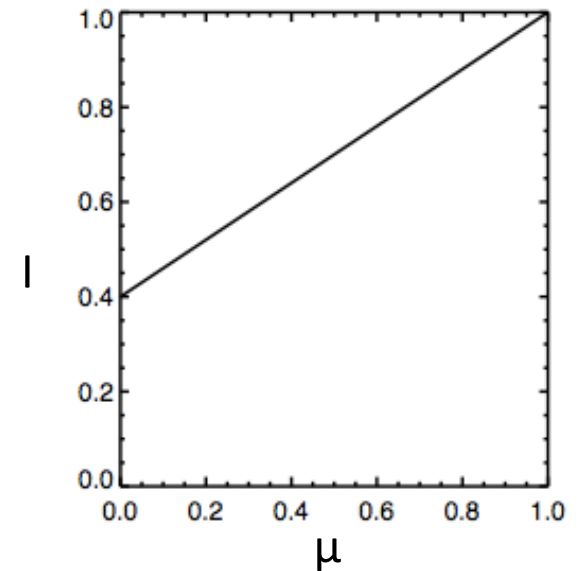
Limb darkening

A typical drift scan, showing values of μ = cos(θ) and other things.
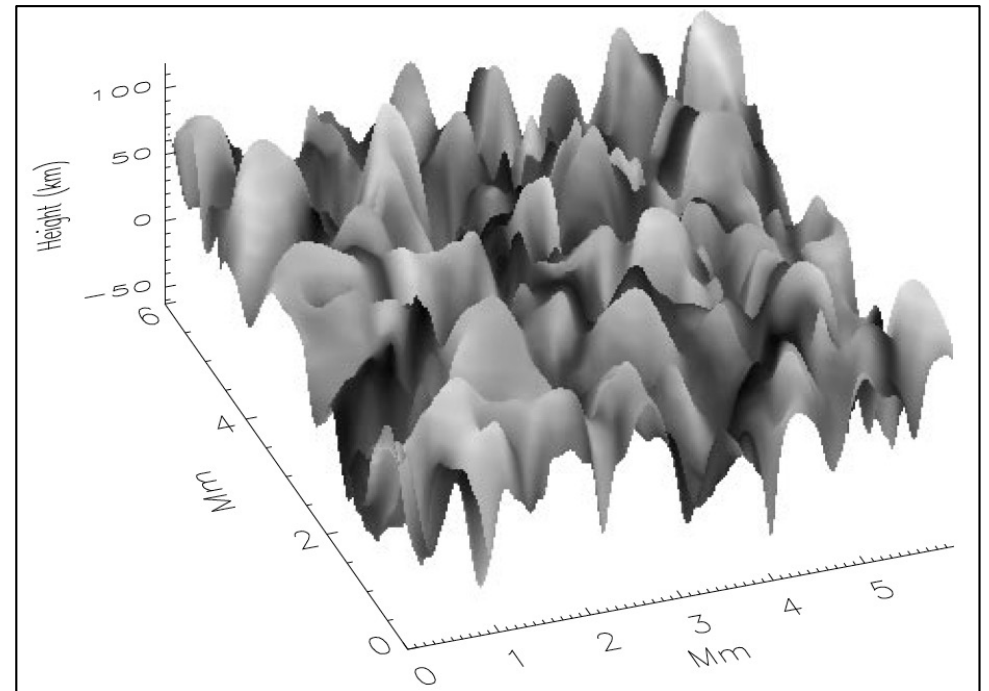
n.b. Data measure flux, not "intensity"
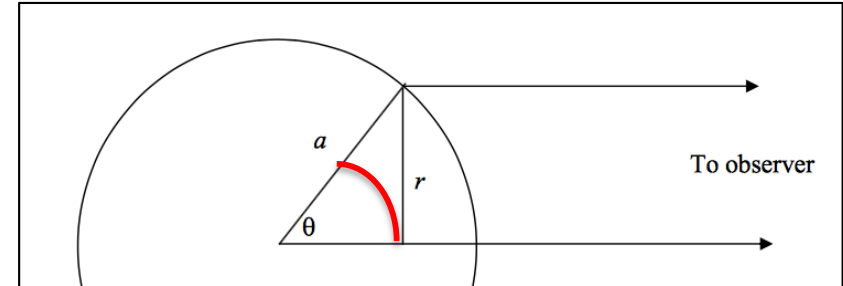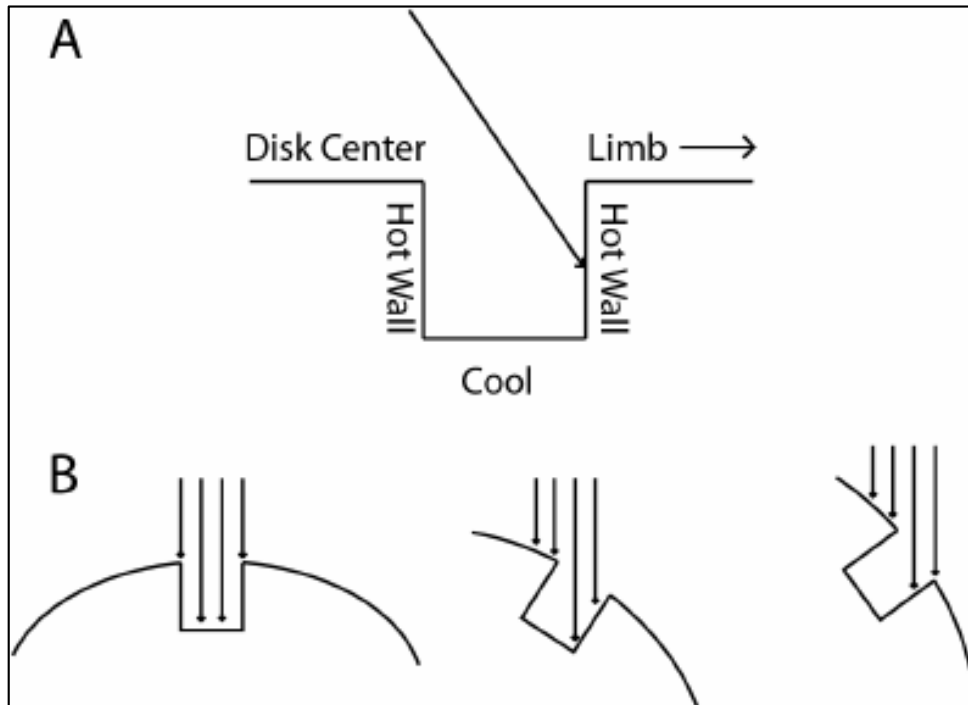

The vertical angle θ, with μ = cos(θ)

Limb darkening and 3D

- Limb darkening can readily be explained by a simple opacity model: $S_v = a + b\tau$ (the source function S assumed to depend linearly upon optical depth). Thus T and B_v (T) must decrease with height

- Could rough structure ("rugosity") also play a role?

Stein & Nordlund 1998

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 the chromospheric *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,
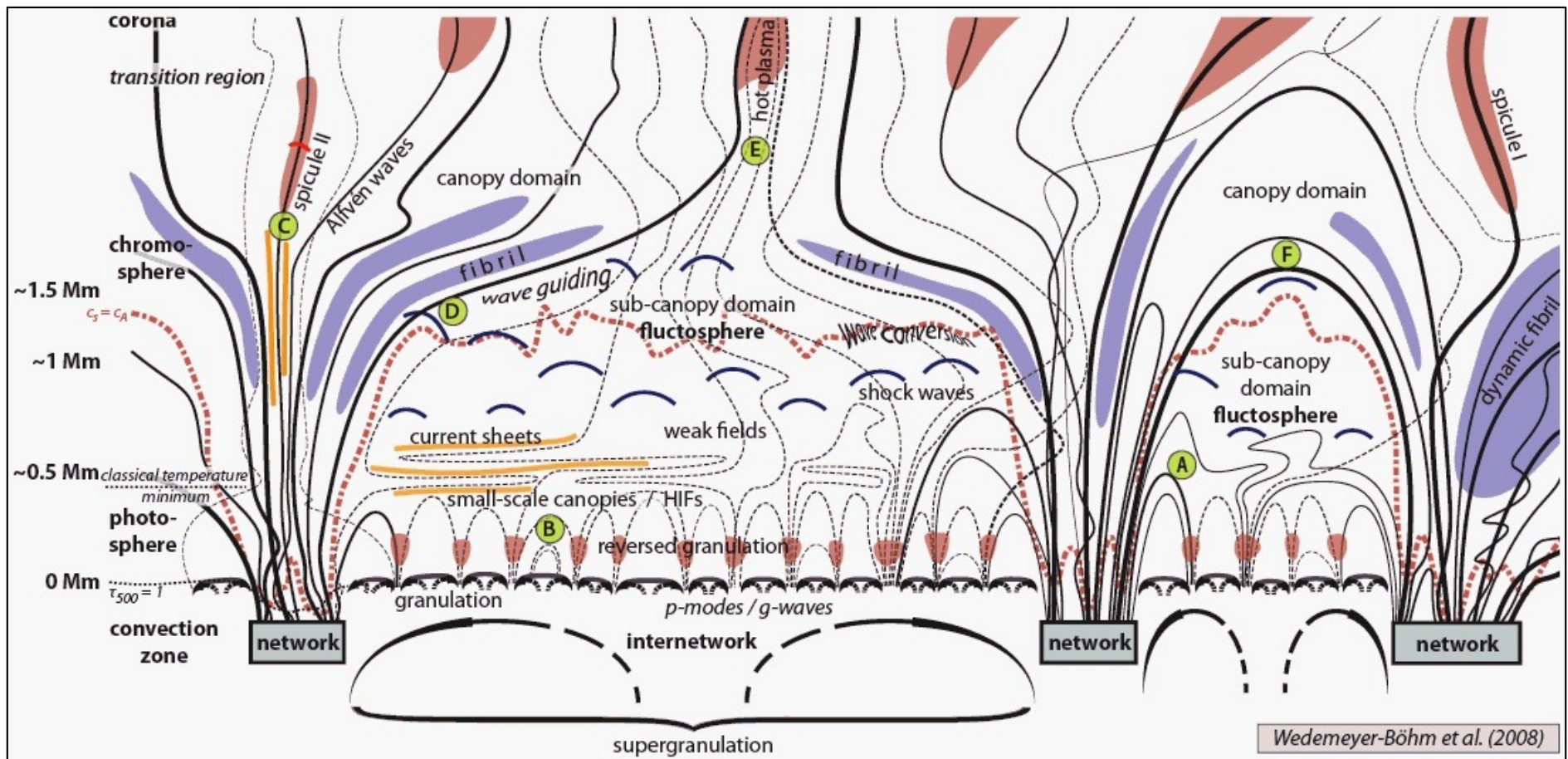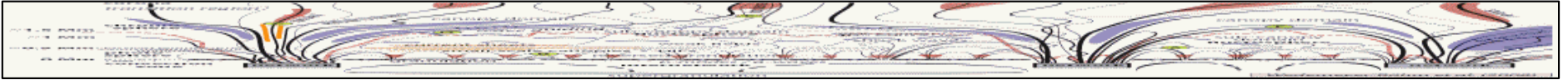
Wilson, 1784

The third dimension
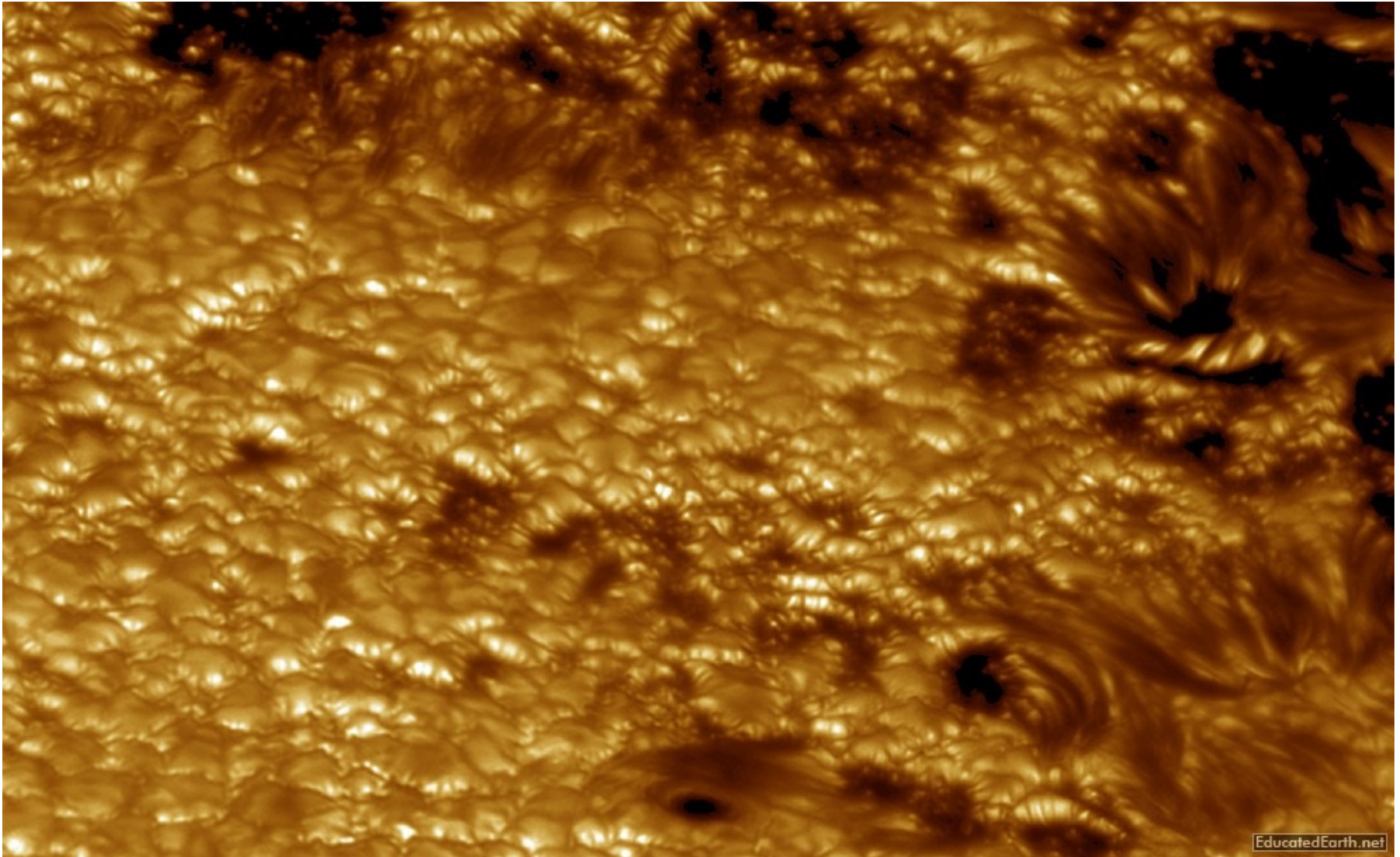
What is the direction to Sun center?

The transition layers

Wedemeyer-Böhm et al. (2008)

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.

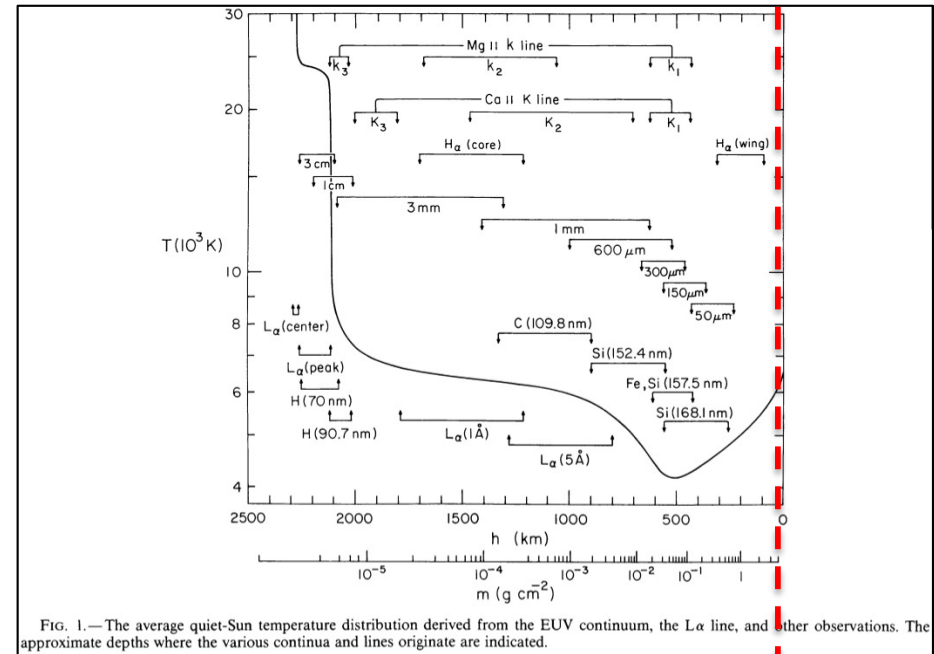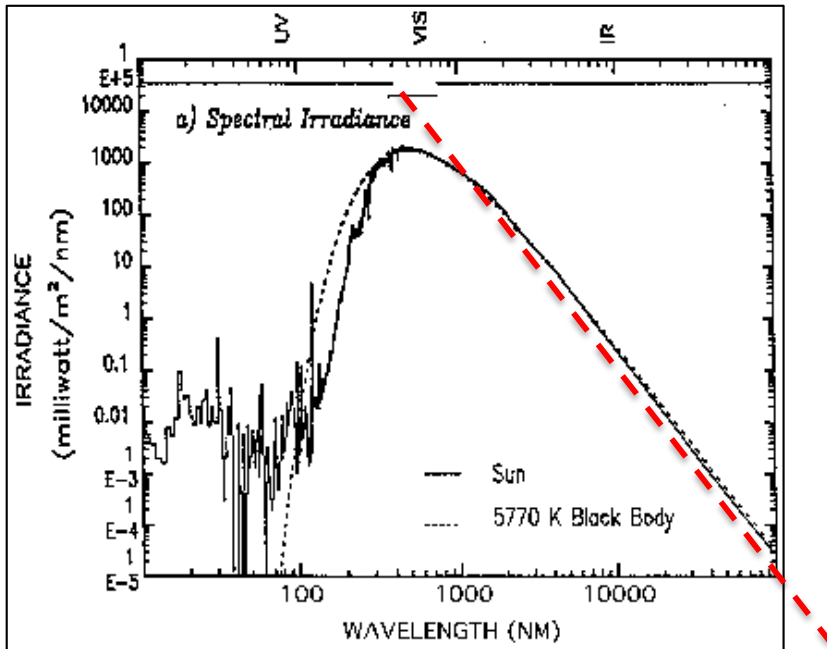# Recall the "semi-empirical" models

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.

• The solar spectral energy distribution ("SED", also known as "spectrum") in the UV leads to a model height variation.
• The physics includes radiative-transfer theory and magnetohydrodynamics (MHD).

The significance of the photosphere/corona interface
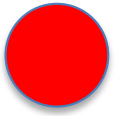
The photosphere lies at the bottom of the solar atmosphere, and at this boundary many fundamental changes in physical properties occur:

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 greatly increases upwards

The defining structural term is gravity (outside magnetic regions).

Hinode and ALMA
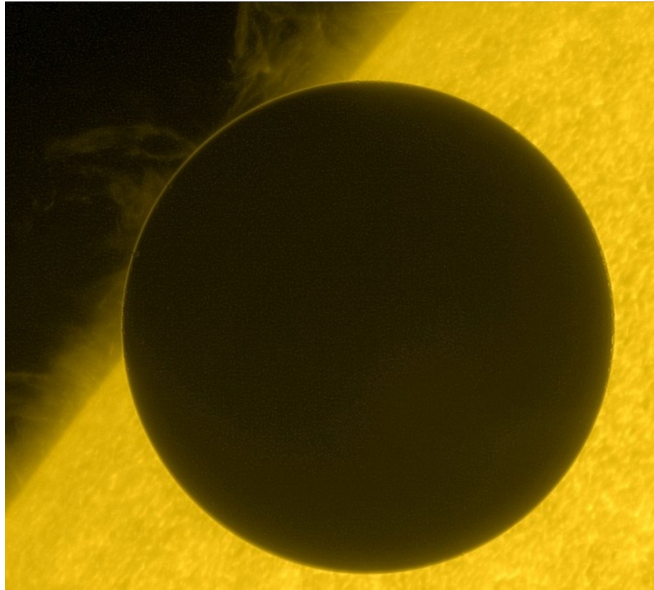
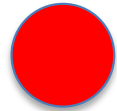The *Hinode* optical telescope sees a transit of Venus

Hinode is the current definitive solar space observatory

The "Atacama Large Millimeter Array"

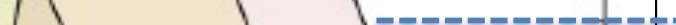This is the current definitive mm-wave solar observatory

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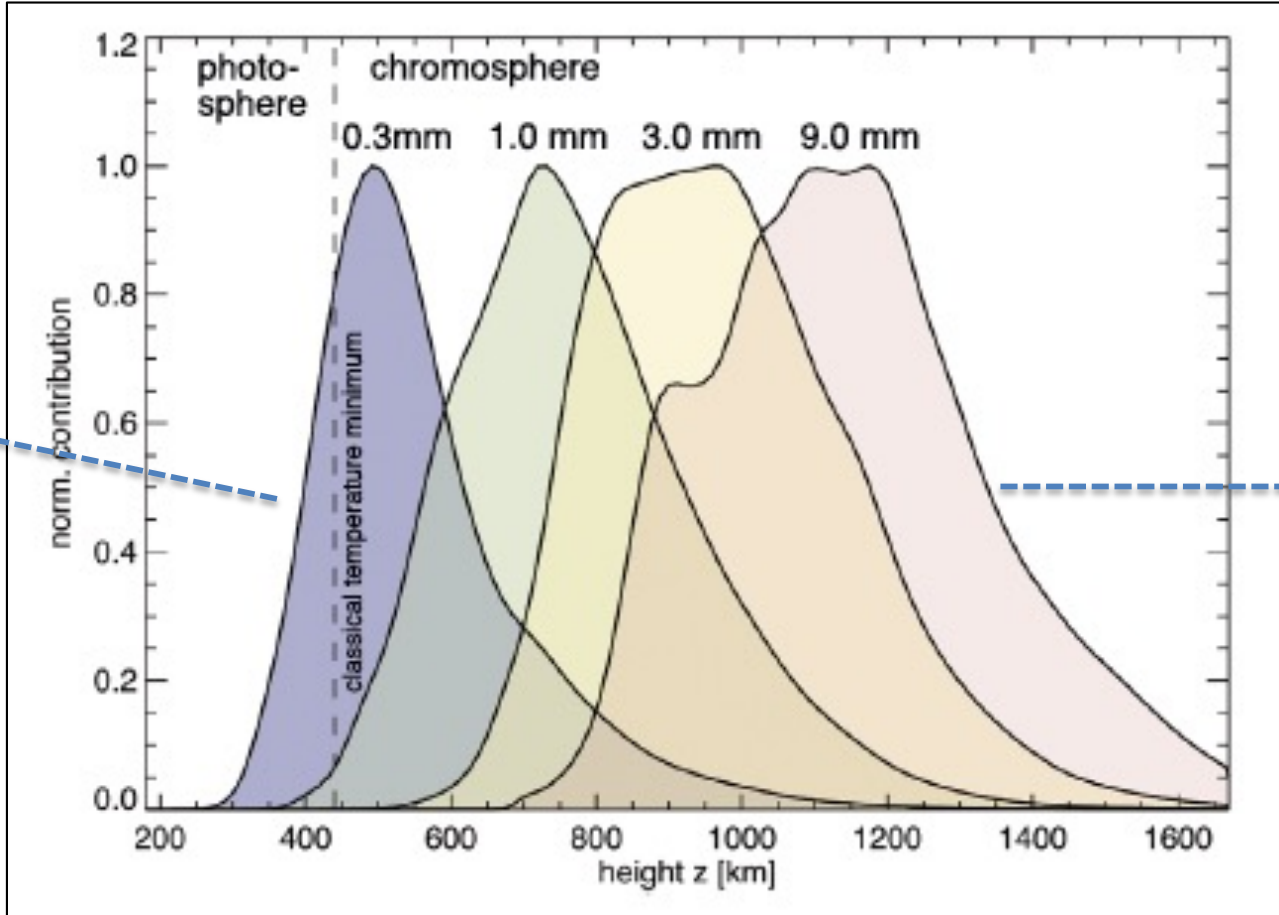
Photosphere

Photosphere + Corona

Numerical simulations

- Hydrodynamics theory and MHD work well for the interior of the Sun and the photosphere itself.

- The next layers up, however, require more finesse.

- The "contribution function" itself, a 1D concept, directly implies stable hydrostatic layering.

- Thus elaborate numerical simulations – 3D MHD, with radiative transfer – have grown up.
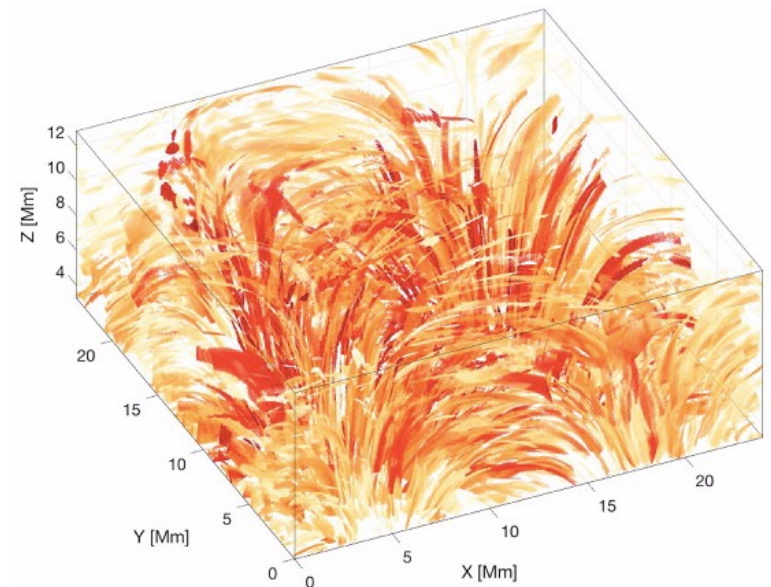
Half of a Bifrost* time step

Name		Date Modified	Size
🖼	BIFROST_en024048_hion_bx_385.fits	Nov 11, 2018 at 8:43 PM	504 MB
🖼	BIFROST_en024048_hion_by_385.fits	Nov 11, 2018 at 8:43 PM	504 MB
🖼	BIFROST_en024048_hion_bz_385.fits	Nov 11, 2018 at 8:43 PM	504 MB
🖼	BIFROST_en024048_hion_lgn6_385.fits	Nov 11, 2018 at 8:44 PM	504 MB
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🖼	BIFROST_en024048_hion_uz_385.fits	Nov 11, 2018 at 8:45 PM	504 MB

Each data file contains one time step of simulated structure on
a specified rectilinear 3D grid.

*Bifrost (Norse mythology, "Rainbow bridge to heaven", think of the aurora);
it's also a state-of-the-art 3D/MHD model atmosphere.*

# Cosmic ray interactions in the solar atmosphere
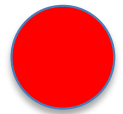
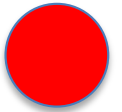Hugh S. Hudson [ID],[1,2]★ Alec MacKinnon,[1] Mikolaj Szydlarski[3] and Mats Carlsson[3]

[1] School of Physics and Astronomy, University of Glasgow, G12 8QQ Glasgow, UK
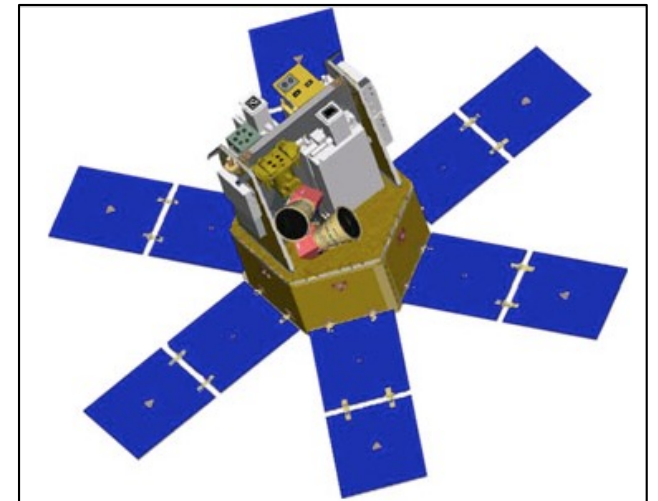[2] Space Sciences Laboratory, University of California, Berkeley, CA 94720-7450, USA
[3] Institute of Theoretical Astrophysics, University of Oslo, NO-0315 Oslo, Norway
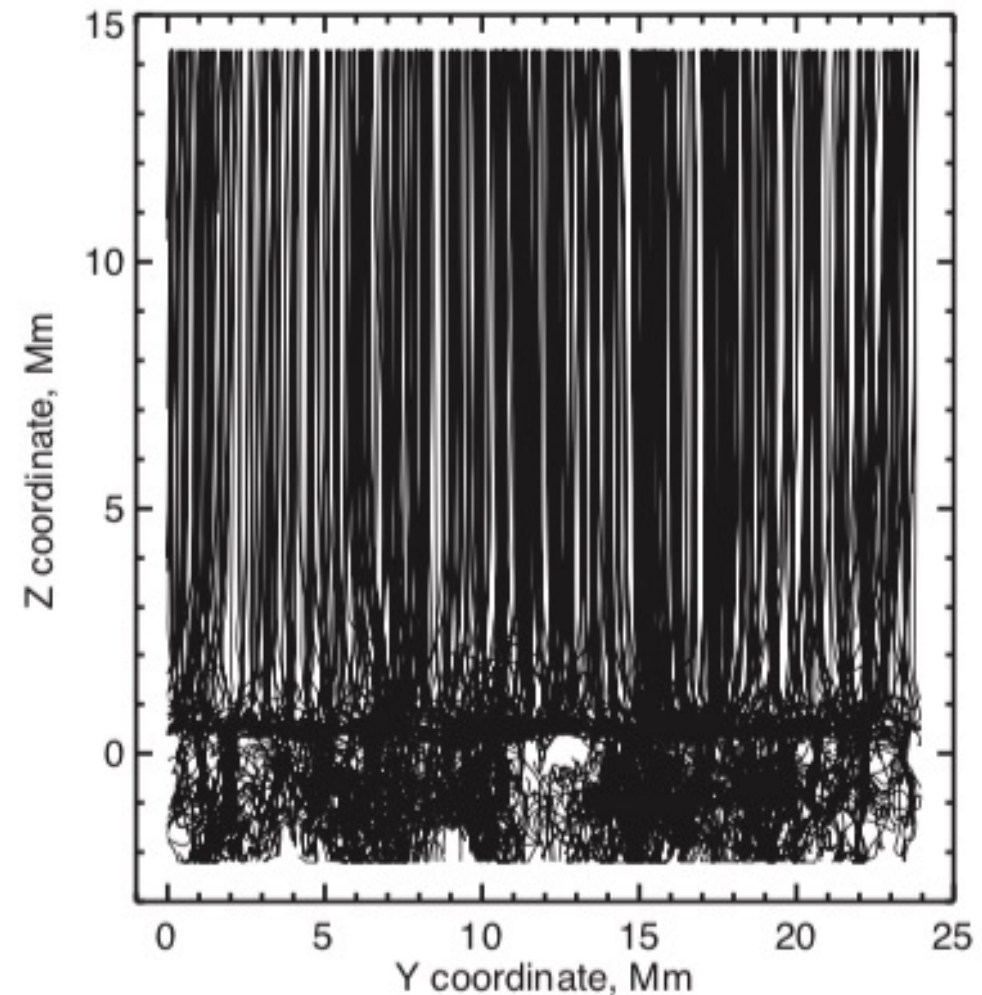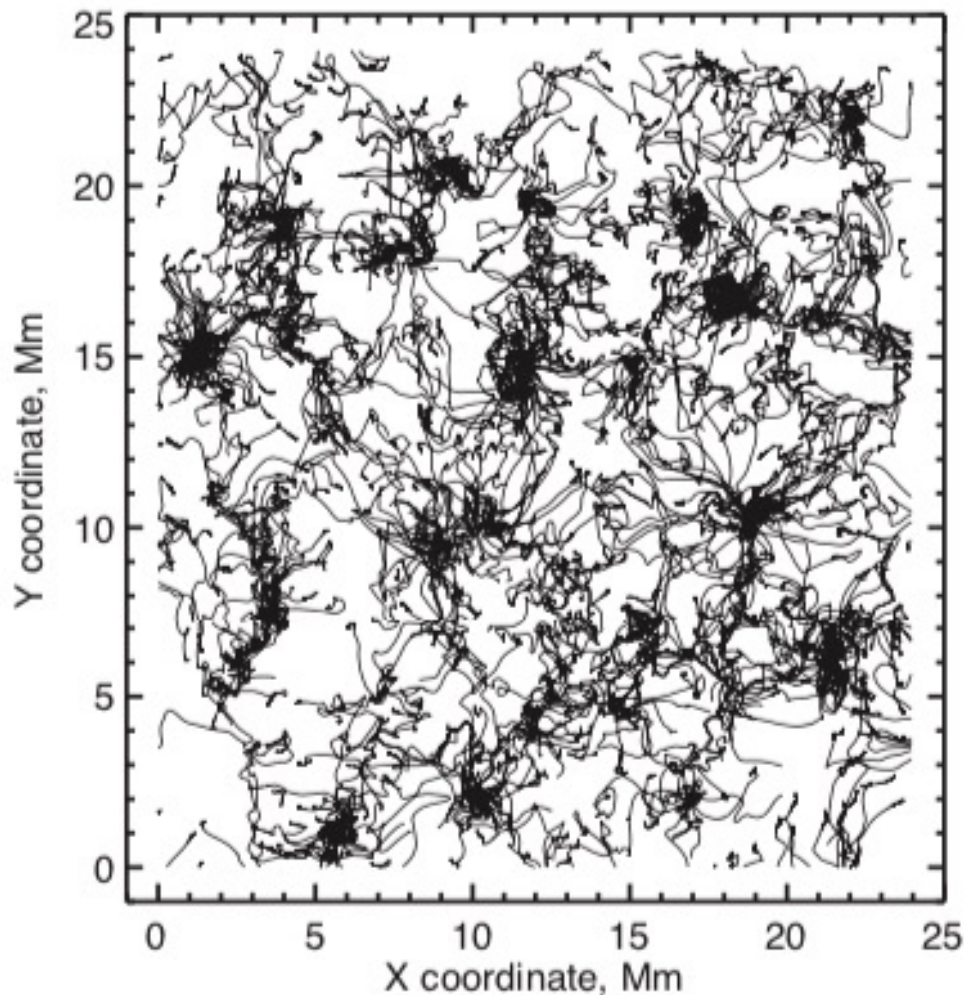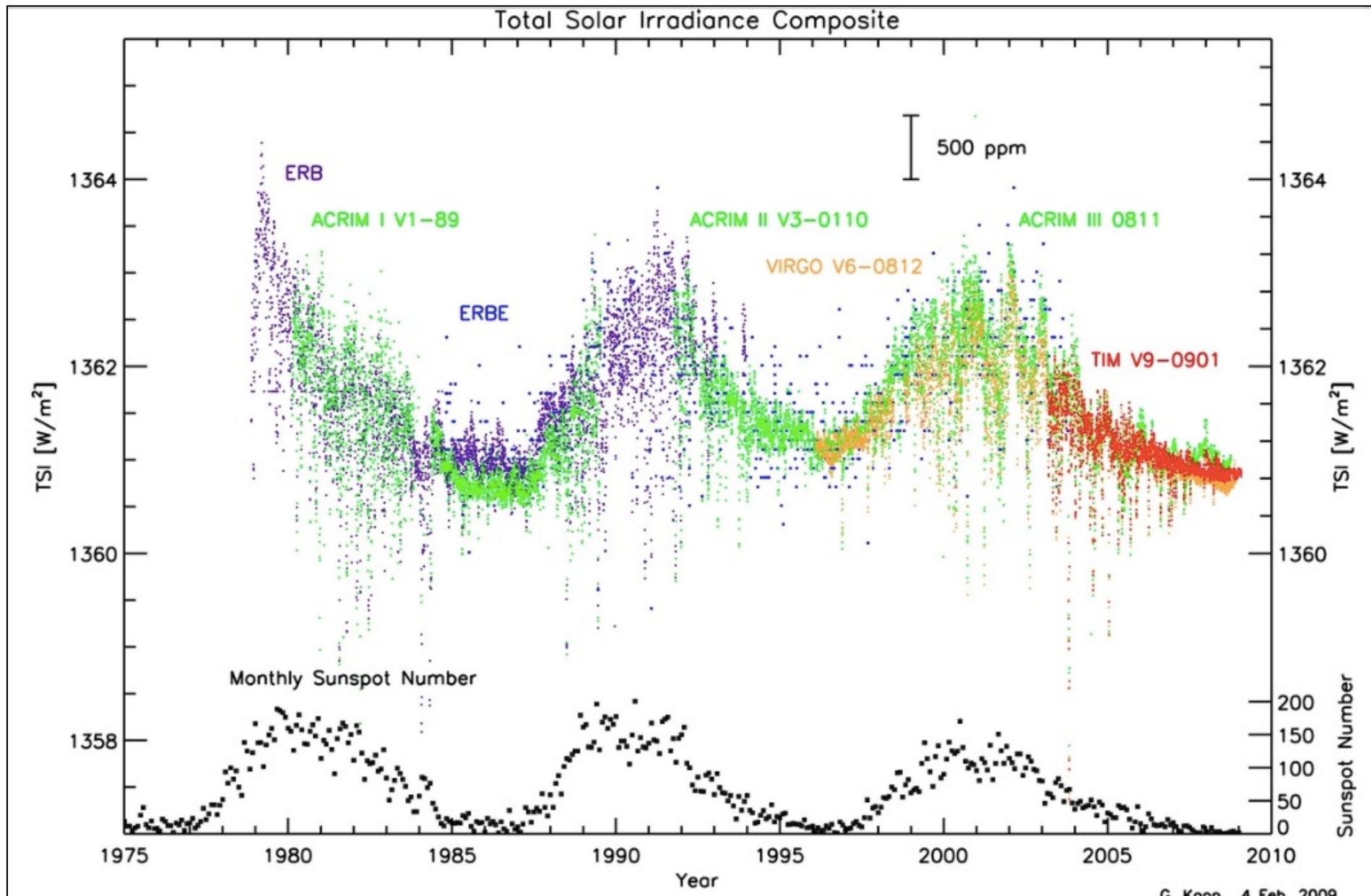
How bright is the Sun?

The SORCE satellite

- Is it really 3.83×10^{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 solar irradiance varies. Does that mean that the luminosity does?
Yes, the Sun is systematically brighter when there are sunspots.

Sunspot deficits, facular excesses
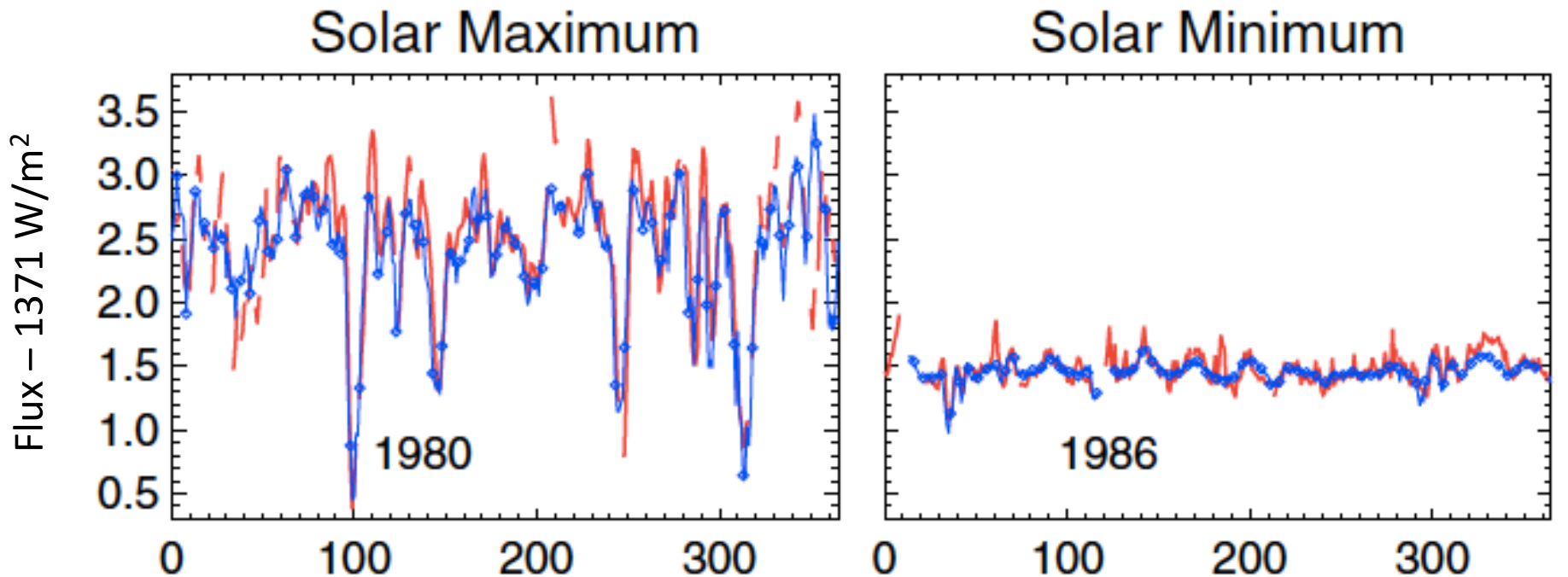
Fröhlich & Lean, 2004

- The "solar constant" (energy flux) is about 1370 W/m^2.
- These measures can be modeled (red) in terms of image content.
- *Kepler* and *TESS p*hotometric observations now provide thousands of analogous solar-type stars for reference.
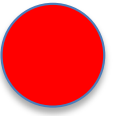
Solar-stellar variability
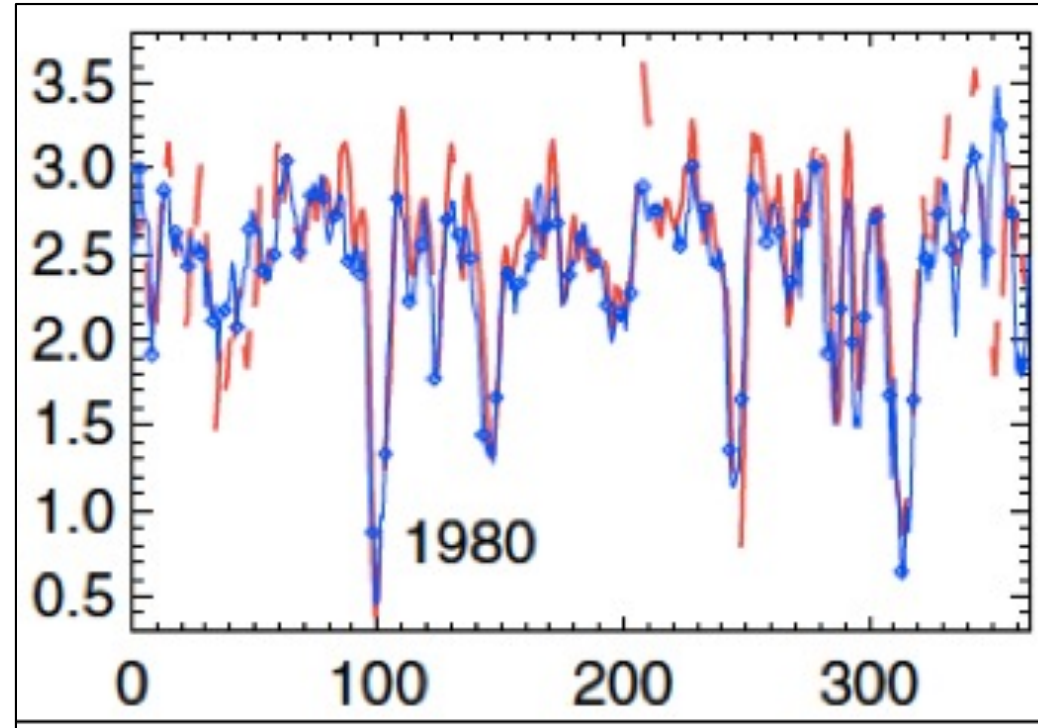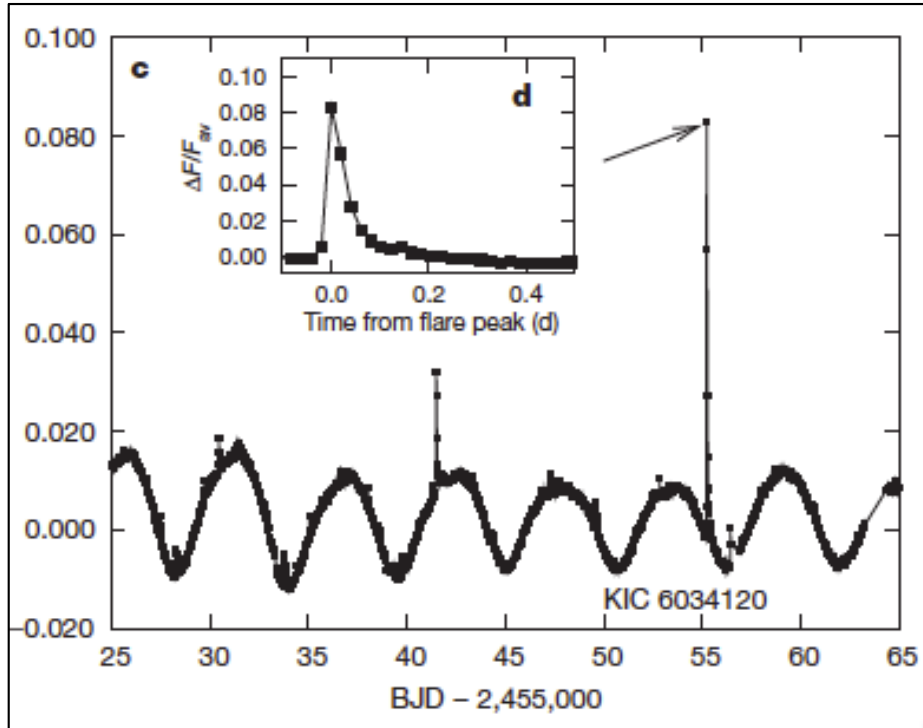
- A *Kepler* "superflare" on a solar-type star (Maehara et al. 2013)
- Note the non-solar pattern of quiescent variations

- The Sun at sunspot maximum
    - No flares at all
    - Clear sunspot dips
- The Sun may not be solar-type!

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: $v^2(R_\odot g_\odot)^{-1}$ -> 20 ppm.

- Except for sunspots and faculae, it is very smooth ($\tau = 1$ 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 photospheric density ~10^{11} m^{-3}, temperature 6420 K, 10^{-4} ionized
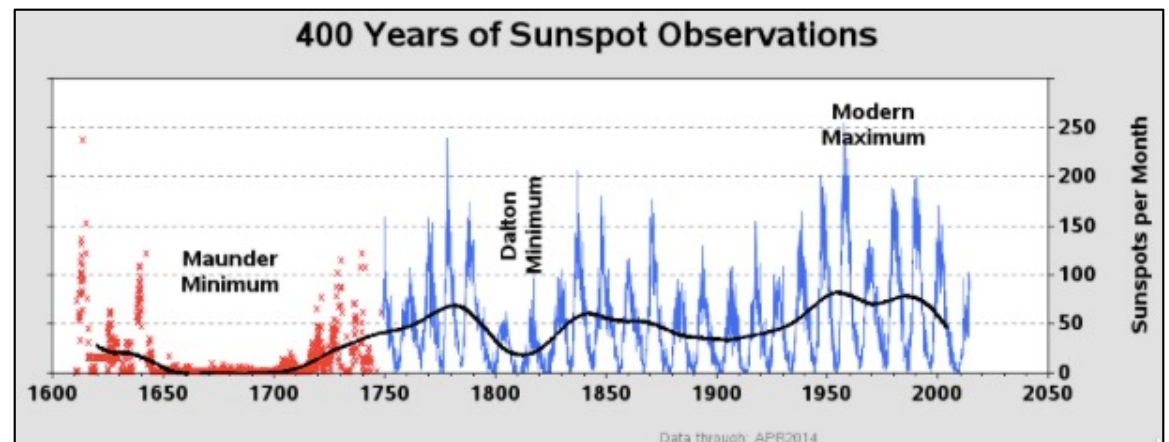
How does the Sun vary?
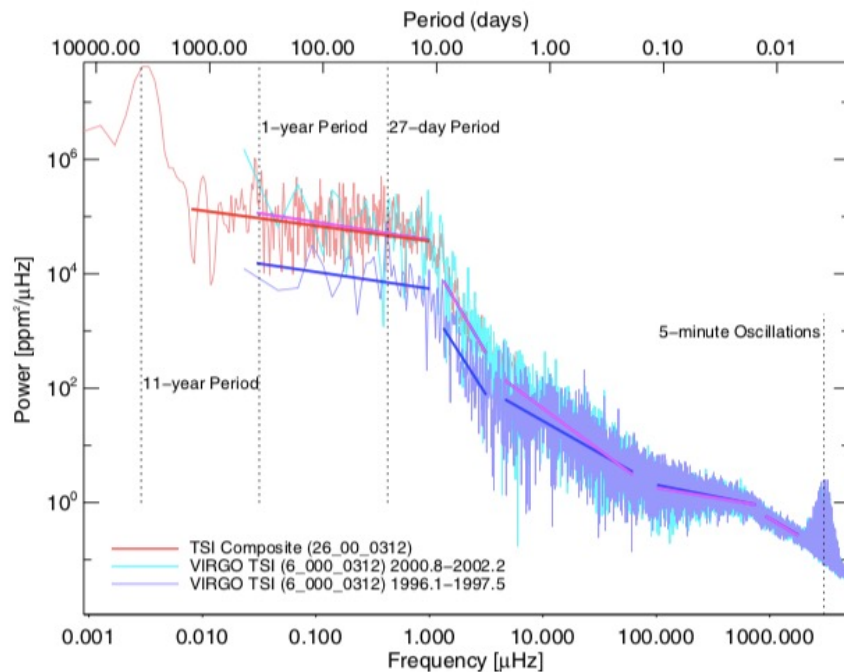
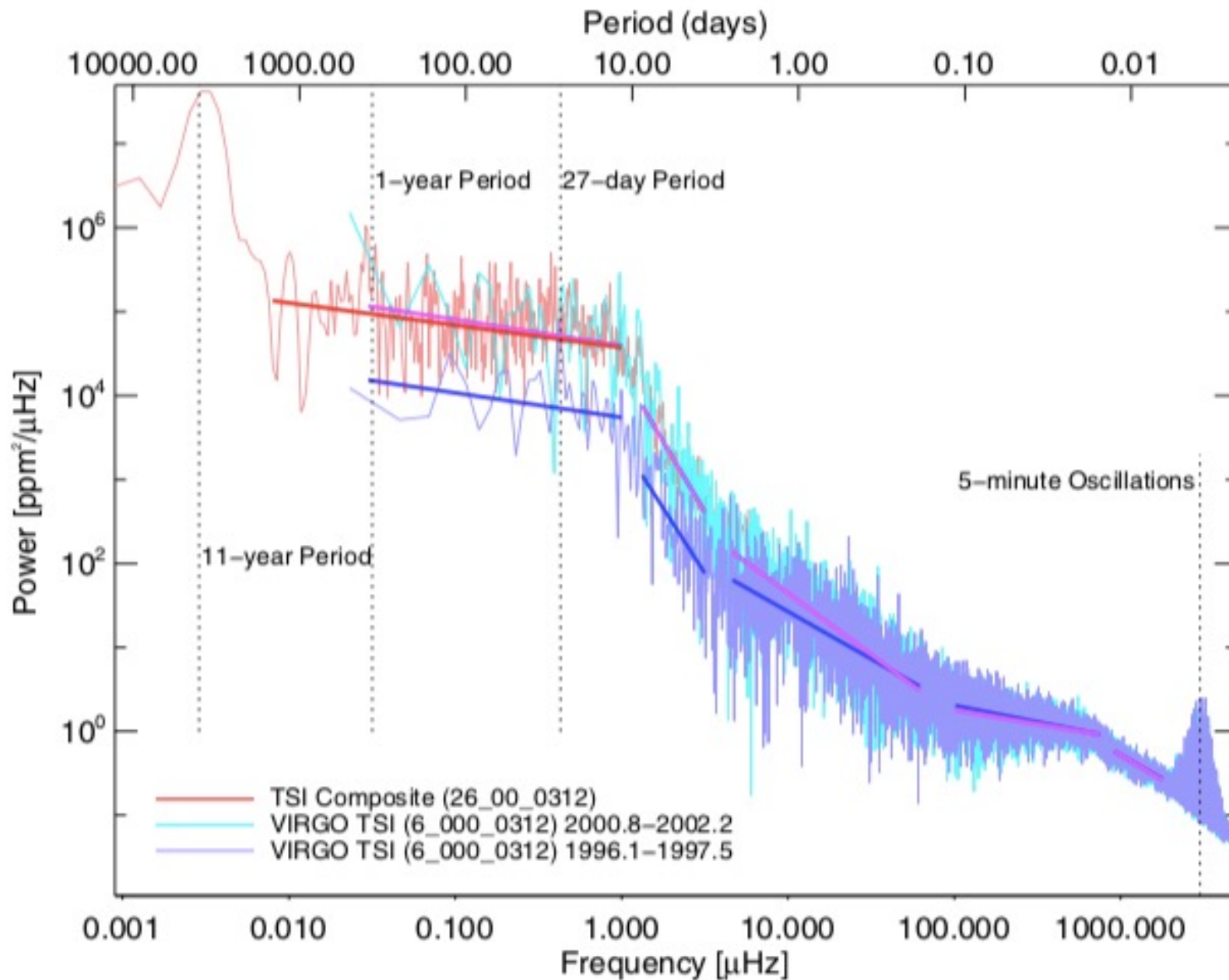Fröhlich & Lean, 2004

Variability occurs on many scales:
- p-modes (few min)
- Convection (min to hours)
- Local magnetism (days)
- Rotation (~27d)
- Hale cycle (22 years)
- *Holocene (10,000 years)*
- Secular (eons)

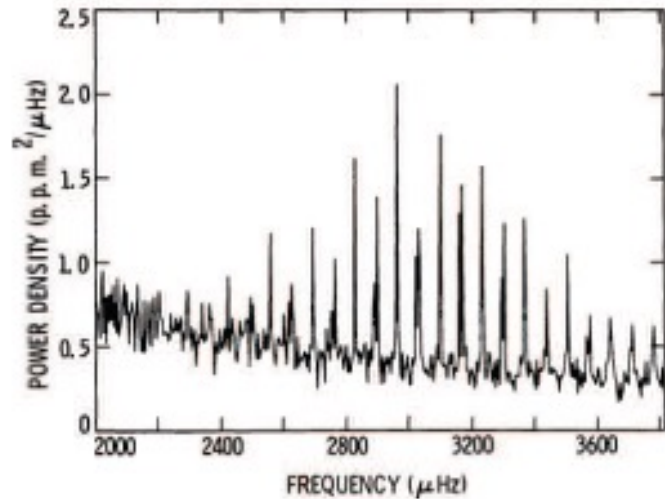Note the "Maunder minimum" of the 17th century.
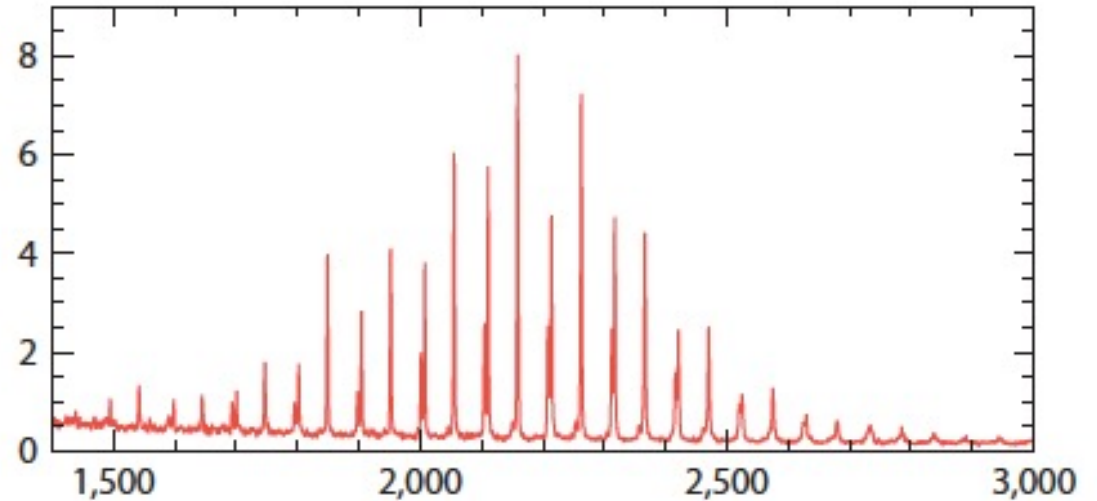
What is the solar power spectrum? ●
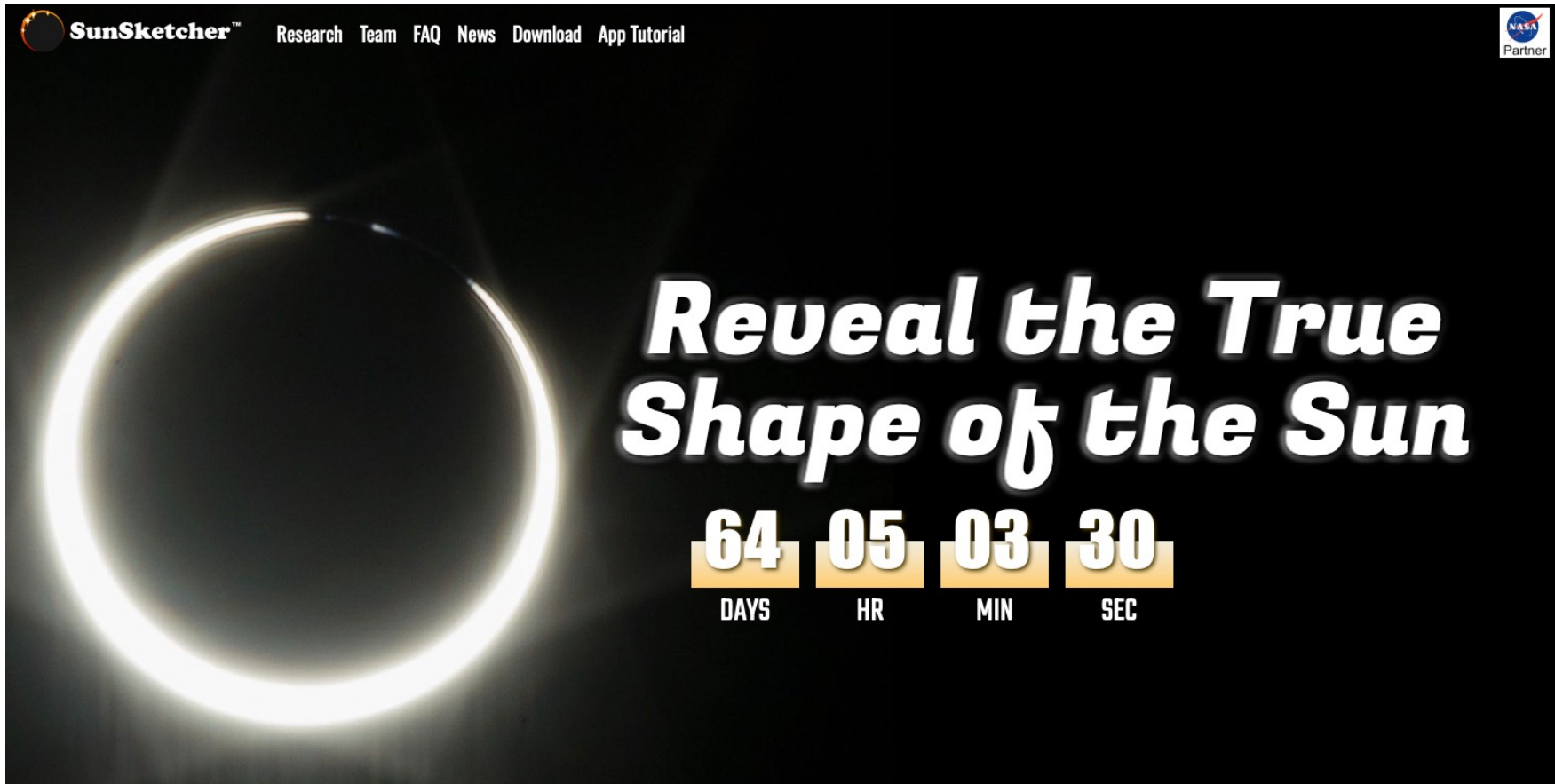
Solar and stellar p-modes

The Sun (Woodard, 1987)
- solar-type
- period ~27 d
- 4.85 x 10^{-6} pc
- m ~ -27

16 Cyg A (Chaplin & Miglio, 2013)
- solar-type
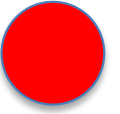- period ~27 d
- 21 pc
- m ~ 6

How round is the Sun?

Total Eclipse April 8 2024: SunSketcher.com

Useful homework questions based on this material

- What is the minimum Earth detectable by photometry of a Sun-like star?
- How round is the Sun?
- What limits the ability of a telescope to resolve the finest details?
- How deep can a Wilson depression be?

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http://www.ssl.berkeley.edu/~hhudson/presentations/tsa.250224/