University of Glasgow | School of Physics & Astronomy

SUPA: The Sun's Atmosphere

Session 2021-22

Lecture 9: "The photosphere, how we study it, and why it matters"

Hugh Hudson
620 Kelvin Bldg
hugh.Hudson@glasgow.ac.uk

Monday, 7 February 2022

The course thus far :

10/01/2022	Lecture 1: Introduction (Labrosse)
11/01/2022	Lecture 2: Solar atmosphere (Labrosse)
17/01/2022	Lecture 3: Plasma physics 1 (Kontar)
17/01/2022	Lecture 4: Plasma physics 3 (Kontar)
24/01/2022	Lecture 5: MHD 1 (MacTaggart)
25/01/2022	Lecture 6: MHD 2 (MacTaggart)
01/02/2022	Lecture 8: Radiation transport (Labrosse)
07/02/2022	Lecture 9: The solar photosphere (Hudson)
08/02/2022	Lecture 10: Solar magnetism (Hudson)

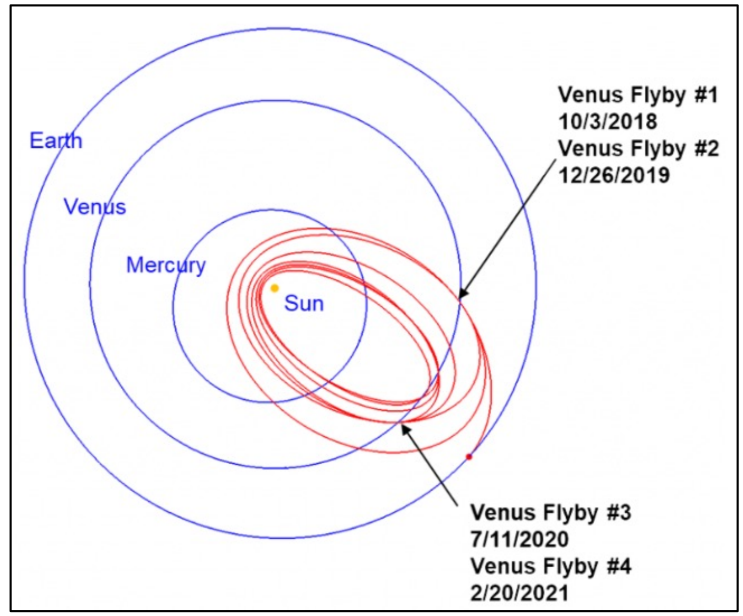
Useful homework questions based on this material

- What is the minimum Earth detectable by photometry of a Sun-like star?
- How round is the Sun?
- How big does a solar optical telescope need to be?
- 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 Files and at

http://www.ssl.berkeley.edu/~hhudson/presentations/supa.220207/

New solar observational tools

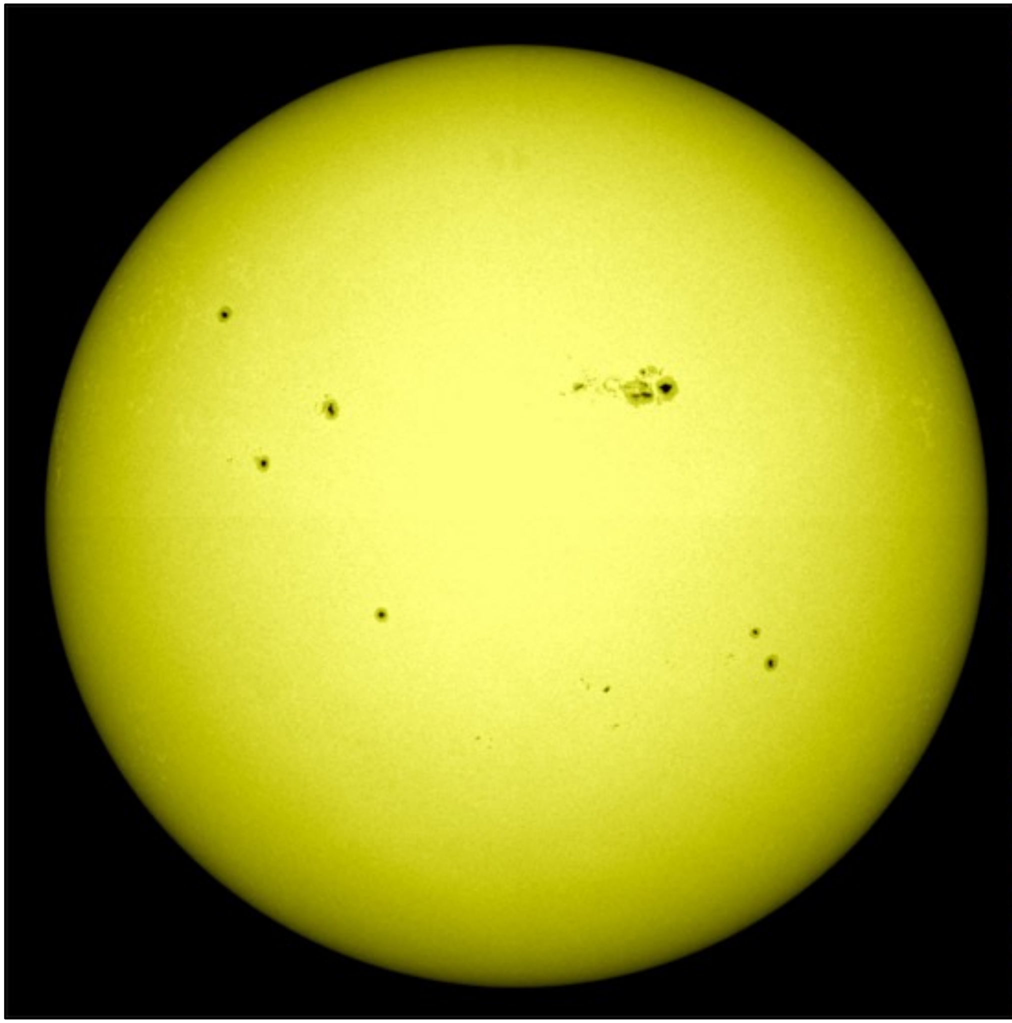


DKIST - a 4-m solar optical/IR telescope

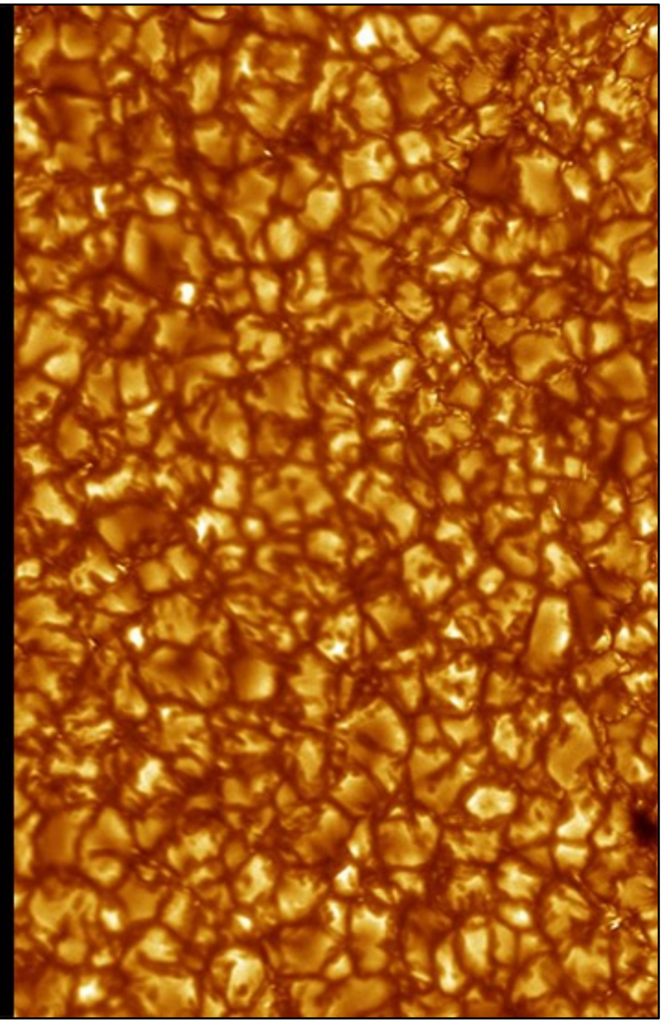
PSP - a space probe that dares to approach the solar surface

Plus: radio waves, X-rays, gamma rays, “solar cosmic rays”, EUV, stereoscopy… and more

The photosphere

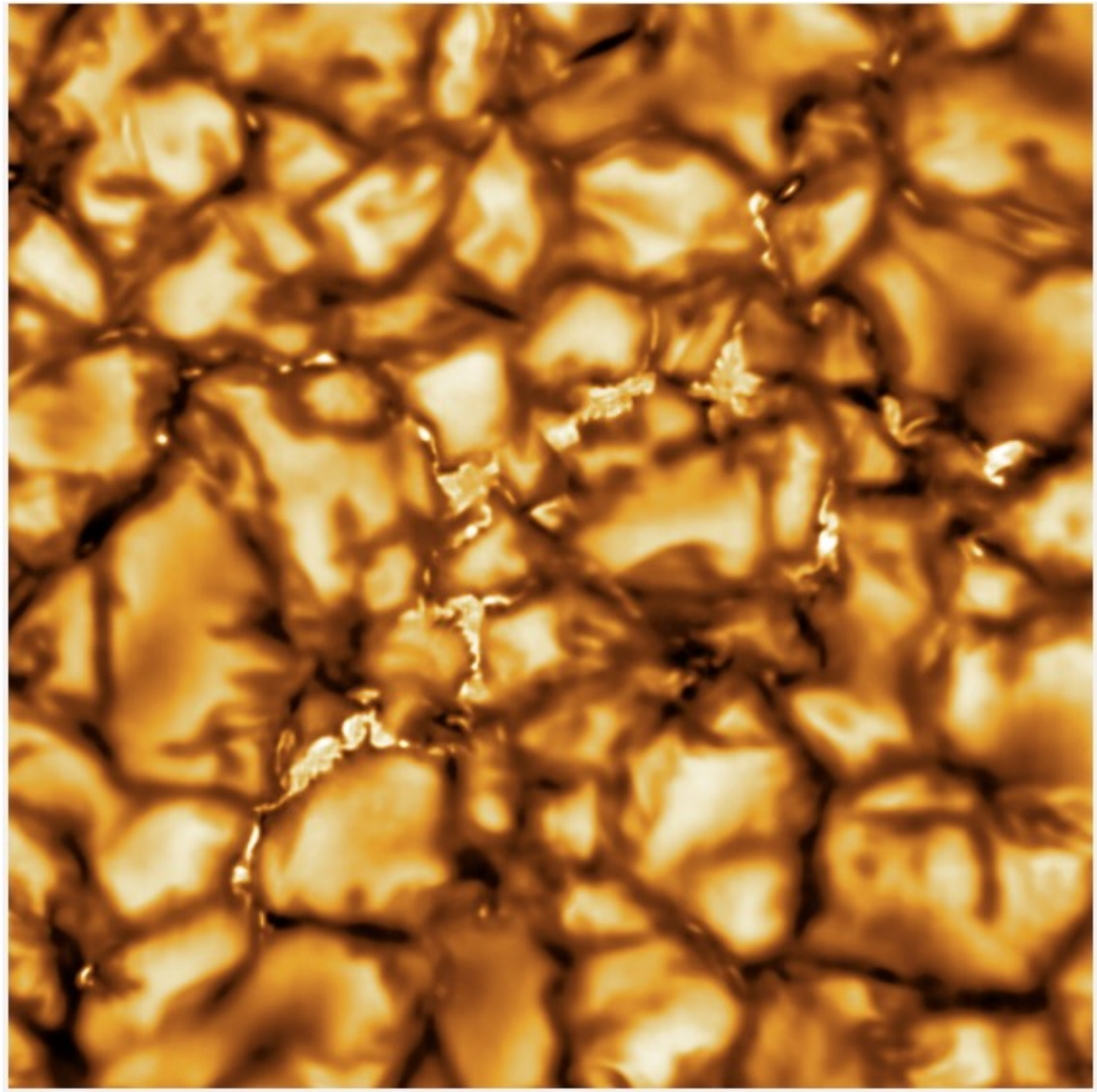


Half a degree



About 20” x 40’’
or
15 Mm x 30 Mm

The state of the art: DKIST



How do we study the photosphere?

1. Imaging spectropolarimetry: line profiles at each pixel, at each polarization state, at each time: *data* = $f(x,y,\lambda,p,t)$; *error* = $\delta f(x,y,\lambda,p,t)$
2. “Inversion” of the spectra for physical parameters: *e.g.*, $T_e(x,y,z)$
3. 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

II. The surface shows convective structures on two 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

Limb darkening law

- The simplest limb darkening law is the “gray atmosphere” approximation

  - opacity independent of wavelength

  - diffusion approximation for radiative transfer

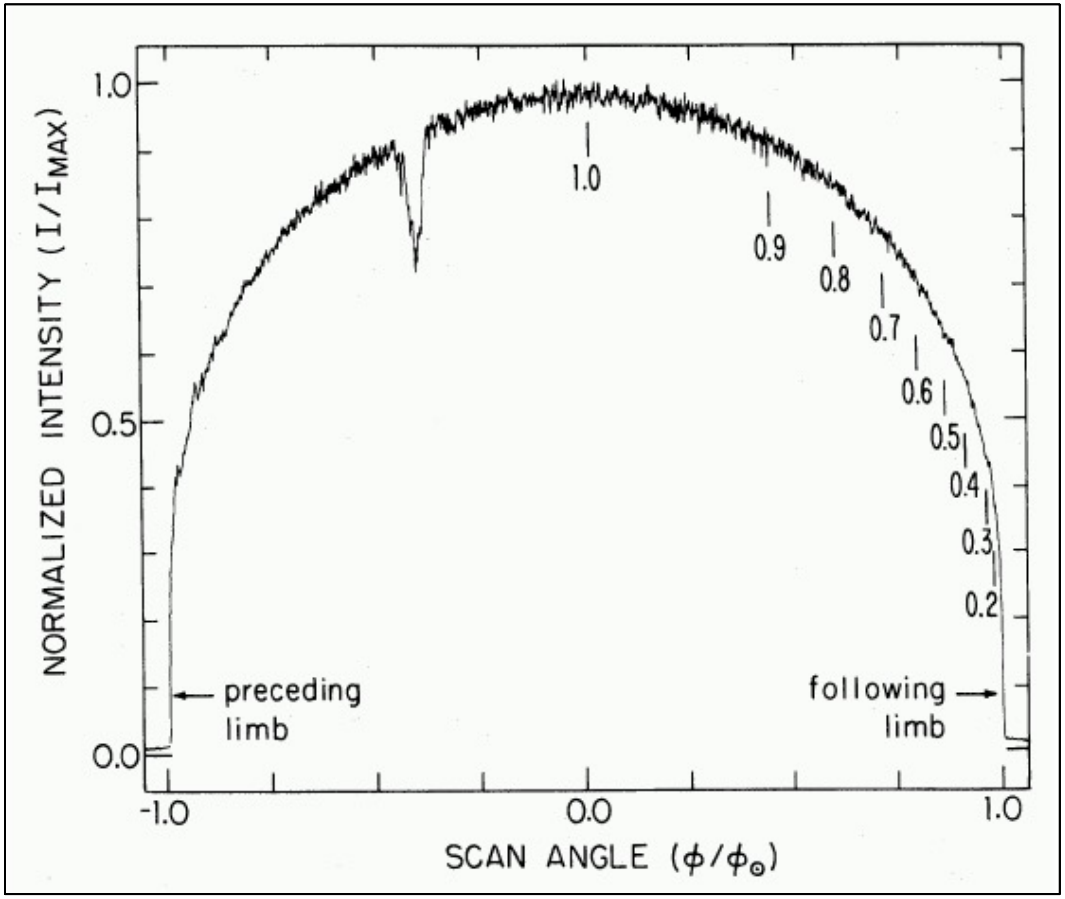
  - linearization via $S(\tau) = a + b\tau$ (*Eddington-Barbier)*

- The result, which works quite well for the bolometric intensity, is the approximate form

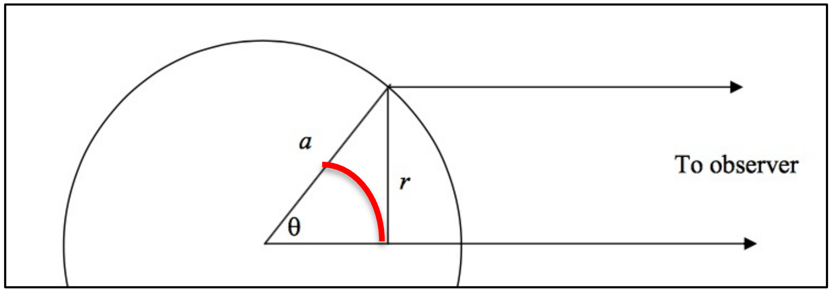
$$I/I_0 = (3\mu+2)/5$$

as derived in Lecture 7. Note that one needs an intuitive feeling for “source function” and “optical depth”

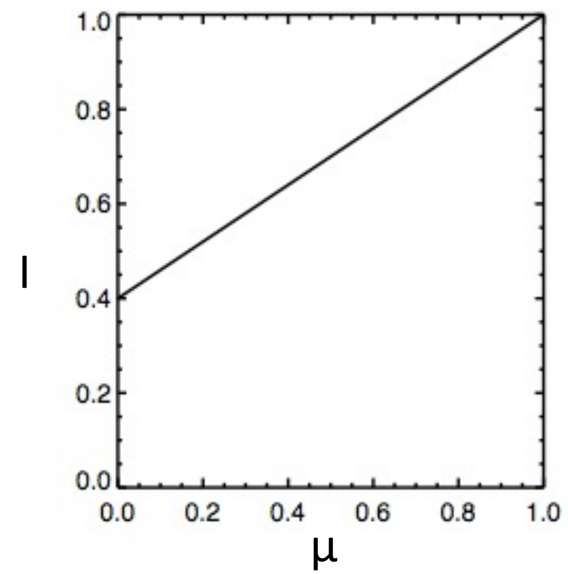
Limb darkening



A typical drift scan, showing values of $\mu = \cos(\theta)$ and other things.

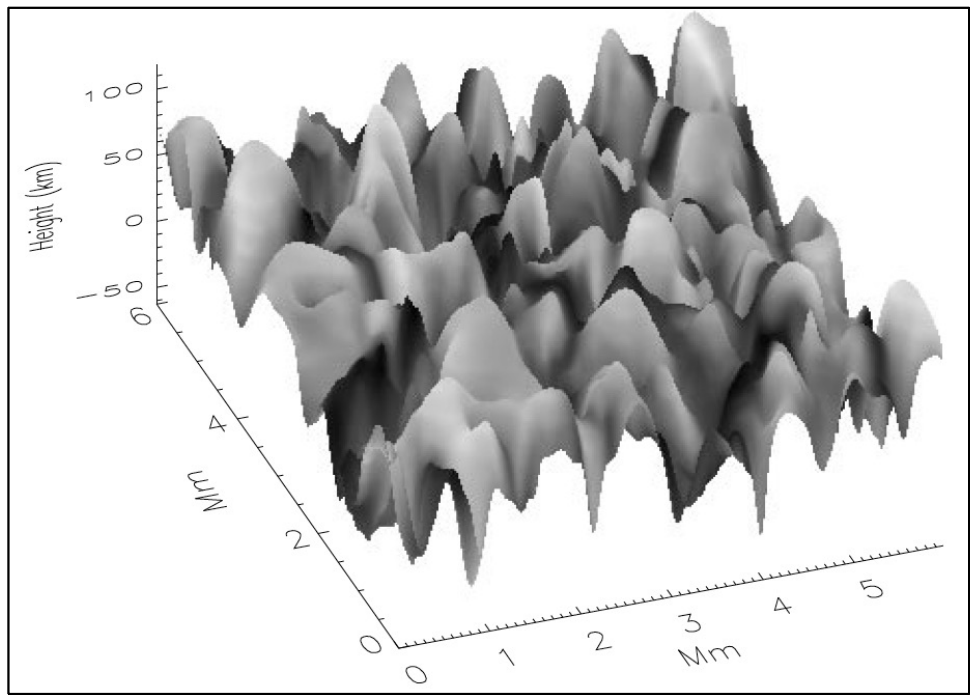


The vertical angle θ, with $\mu = \cos(\theta)$



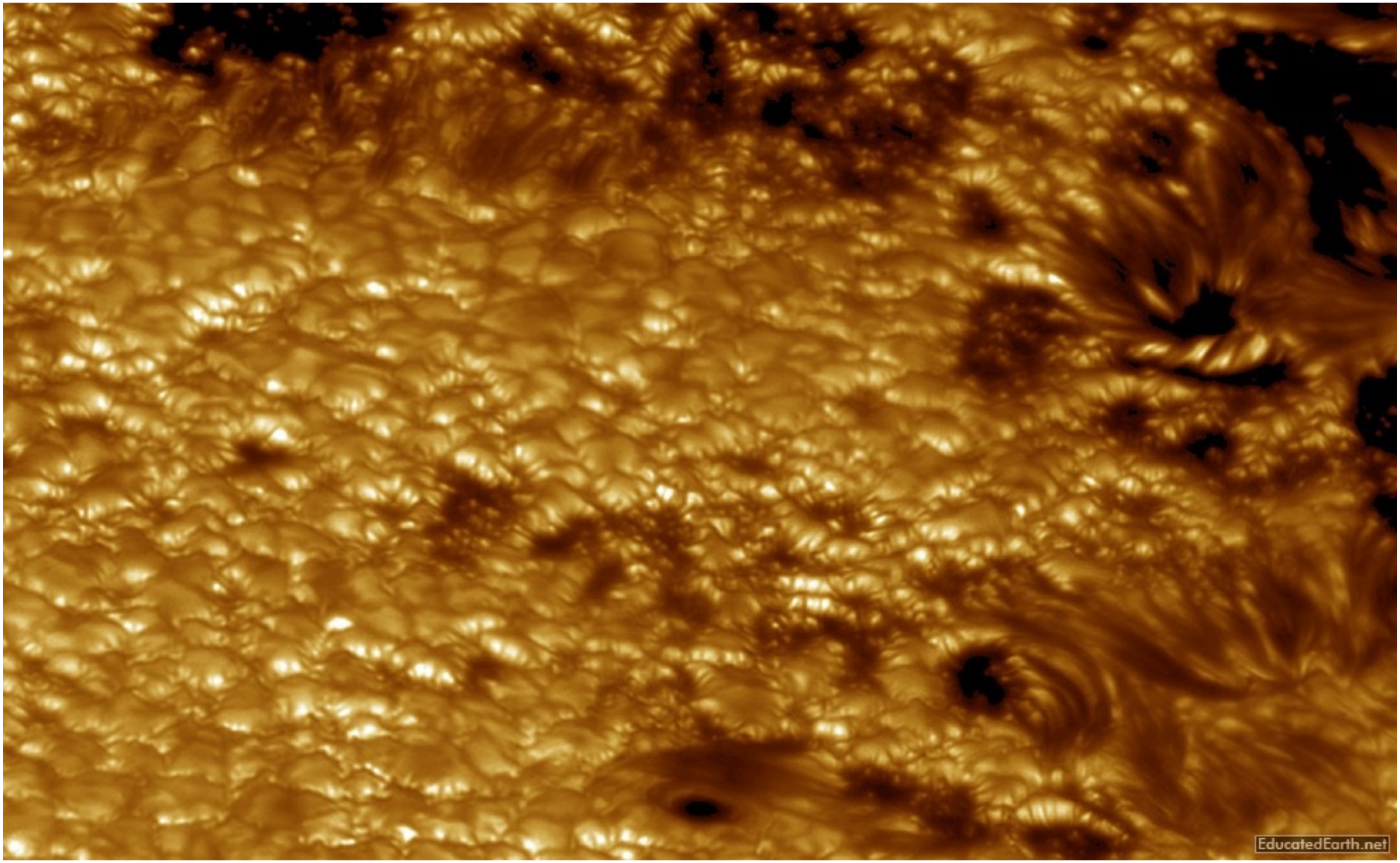
Limb darkening and 3D

- 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_ν (T) must decrease with height
- Could rough structure ("rugosity") also play a role?

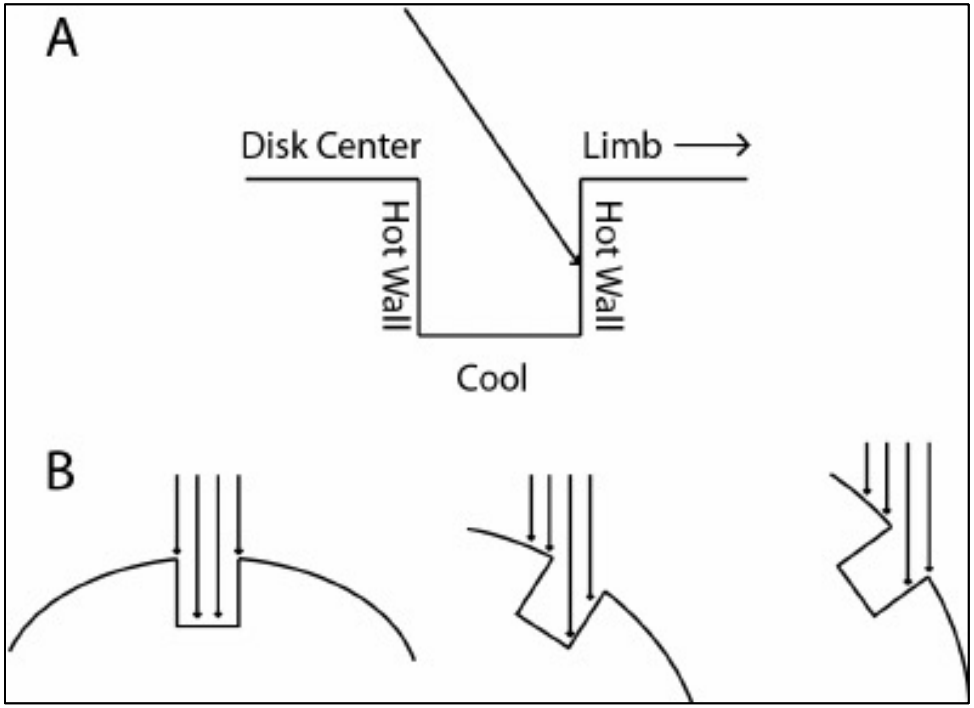


Stein & Nordlund 1998

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

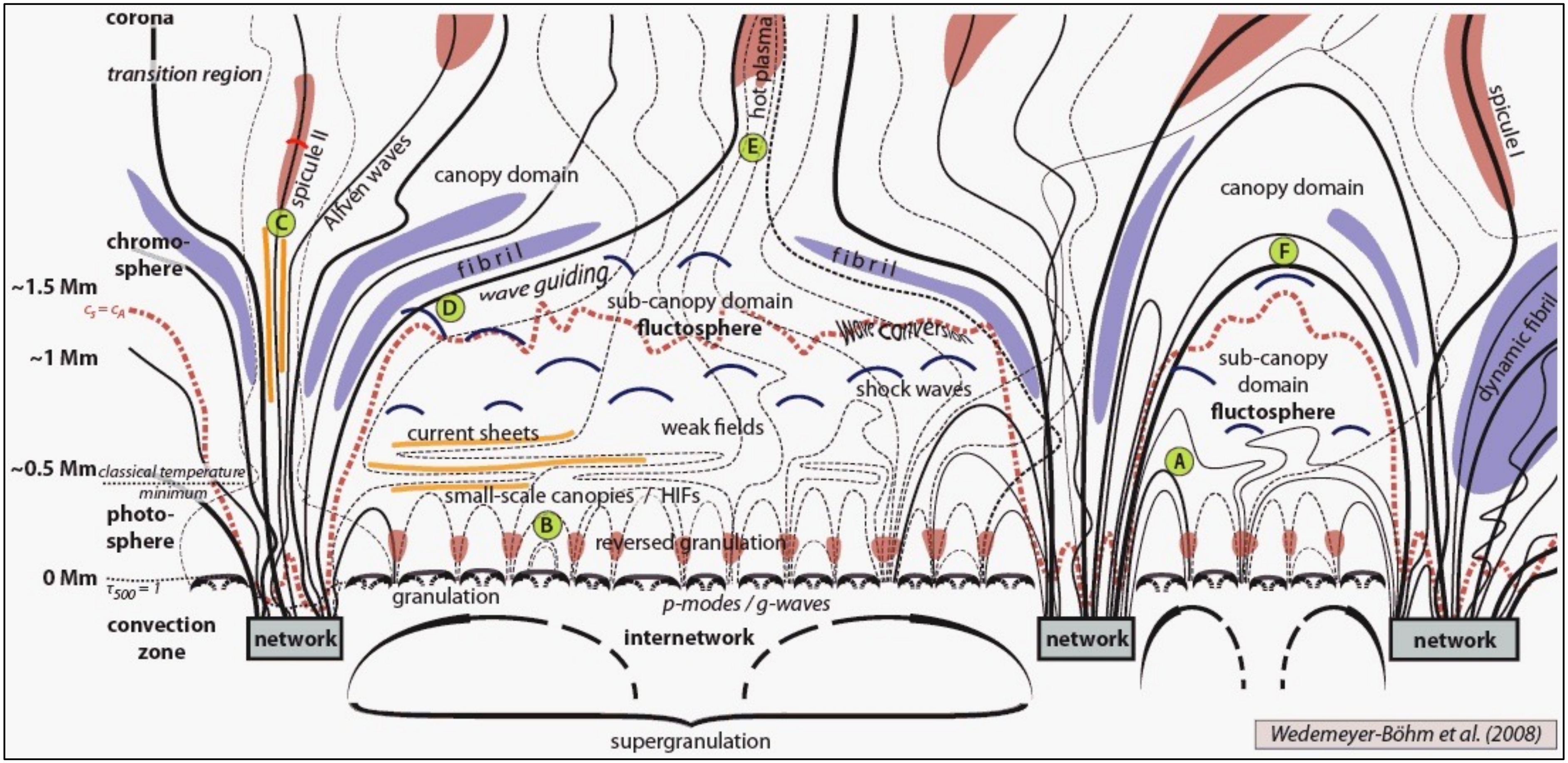
Significance

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

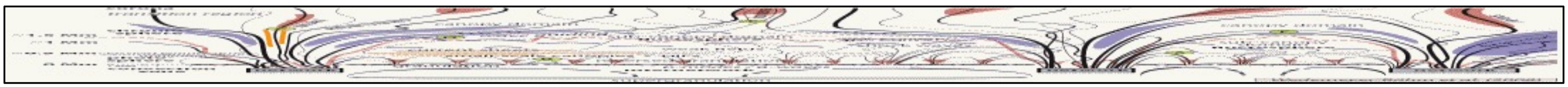
1) The radiation field detaches from the matter
2) The plasma loses collisionality
3) Plasma beta ($\beta = P_g/P_B$) drops precipitously
4) Composition changes (the FIP effect)
5) Unbalanced coronal currents form
6) Temperature rockets upwards

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

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.

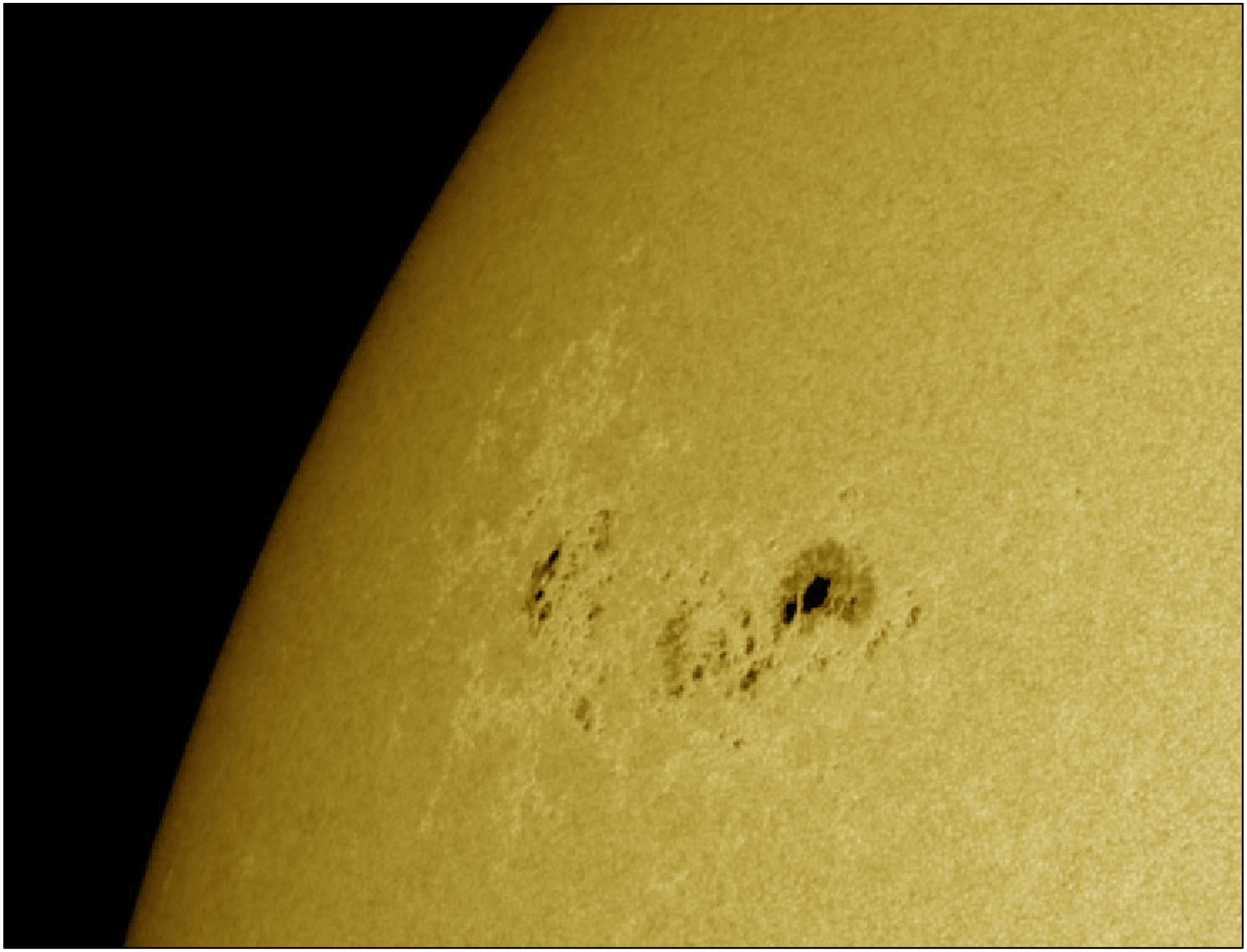
Important research areas involving the photosphere

1) The emergence of magnetism through the atmosphere (next lecture)
2) The total solar irradiance (TSI, a.k.a. “the solar constant”) and stellar variability

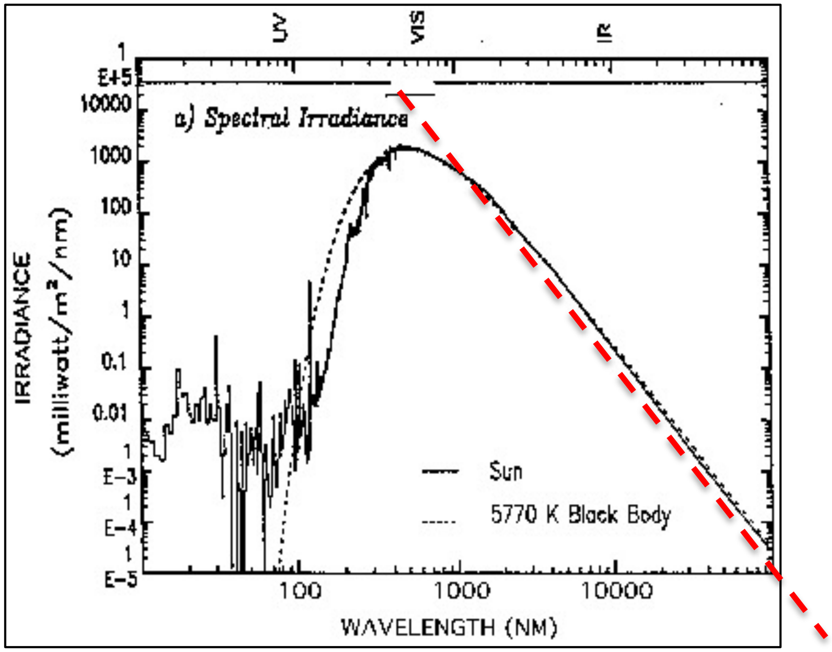
   - To be discussed here
3) “White light flares”

   - Not covered explicitly here, see future SUPA/TSA lecture

Sunspots are dark blotches, thus affecting the total solar irradiance (TSI)



Recall the “semi-empirical” models



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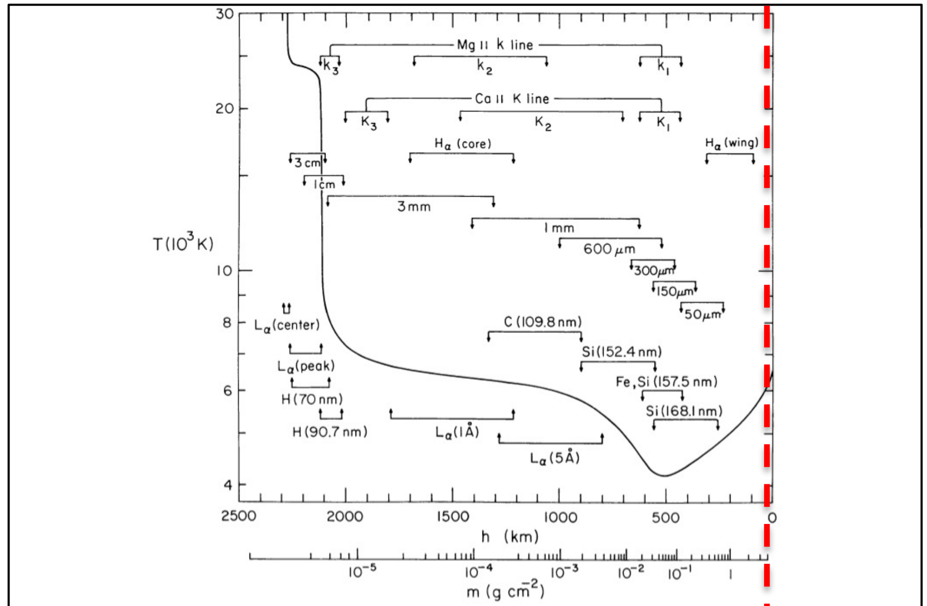


FIG. 1.—The average quiet-Sun temperature distribution derived from the EUV continuum, the Lα line, and other observations. The approximate depths where the various continua and lines originate are indicated.

- 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 hydrodynamics (and MHD).

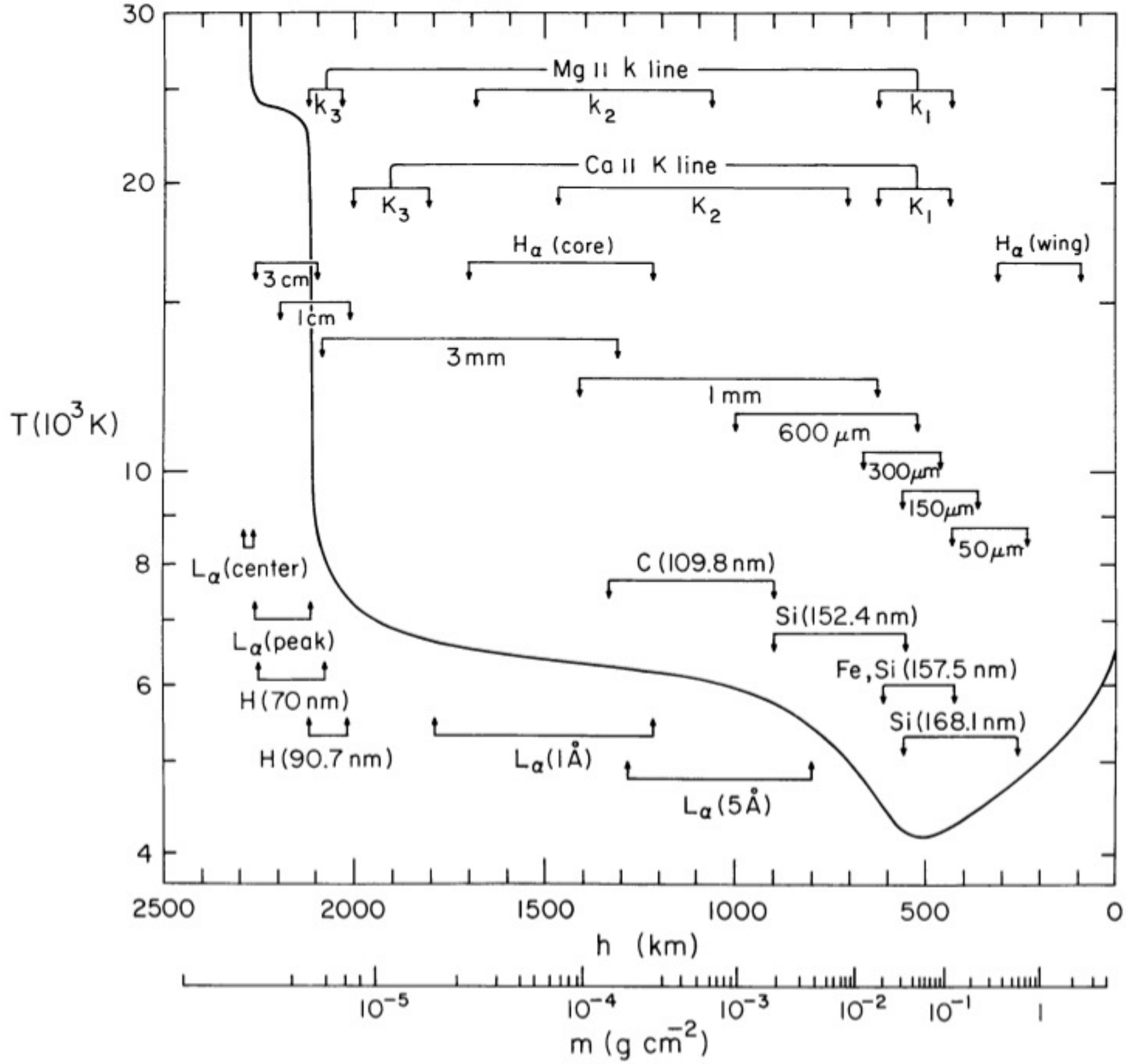
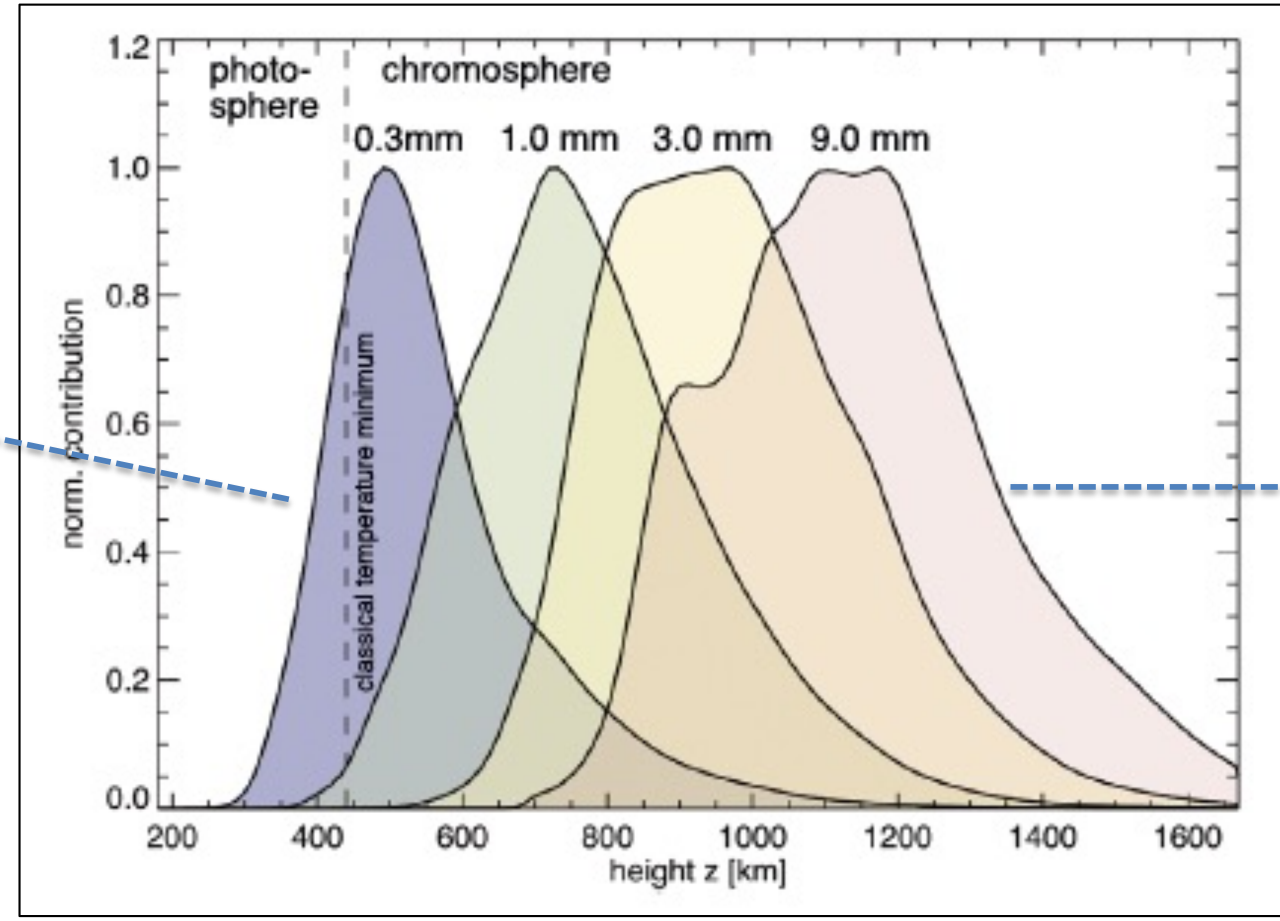


FIG. 1.—The average quiet-Sun temperature distribution derived from the EUV continuum, the Lα line, and other observations. The approximate depths where the various continua and lines originate are indicated.

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



Photosphere

Photosphere + Corona

These wavelengths are now accessible, at high resolution, via the amazing ALMA mm-submm wave telescope.

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!"

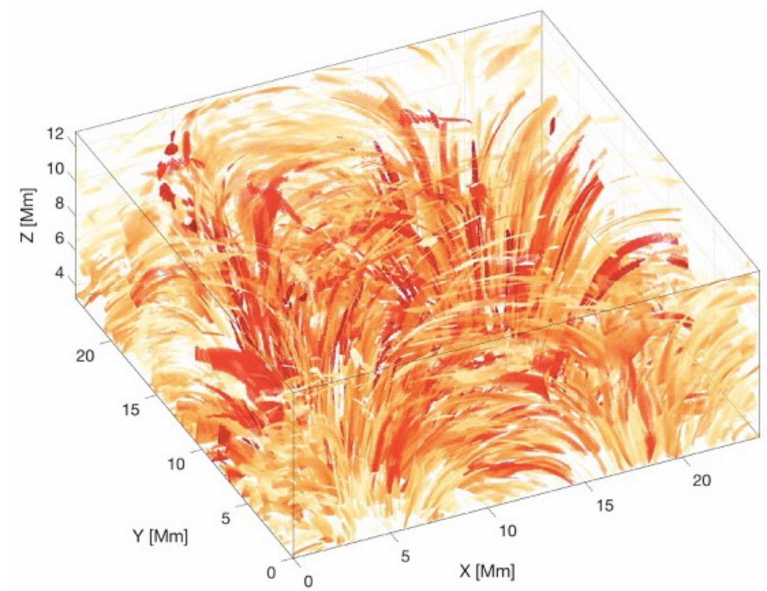
- which photon?

- is magnetic structure unimportant?

- what does one mean by "resolve"?

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
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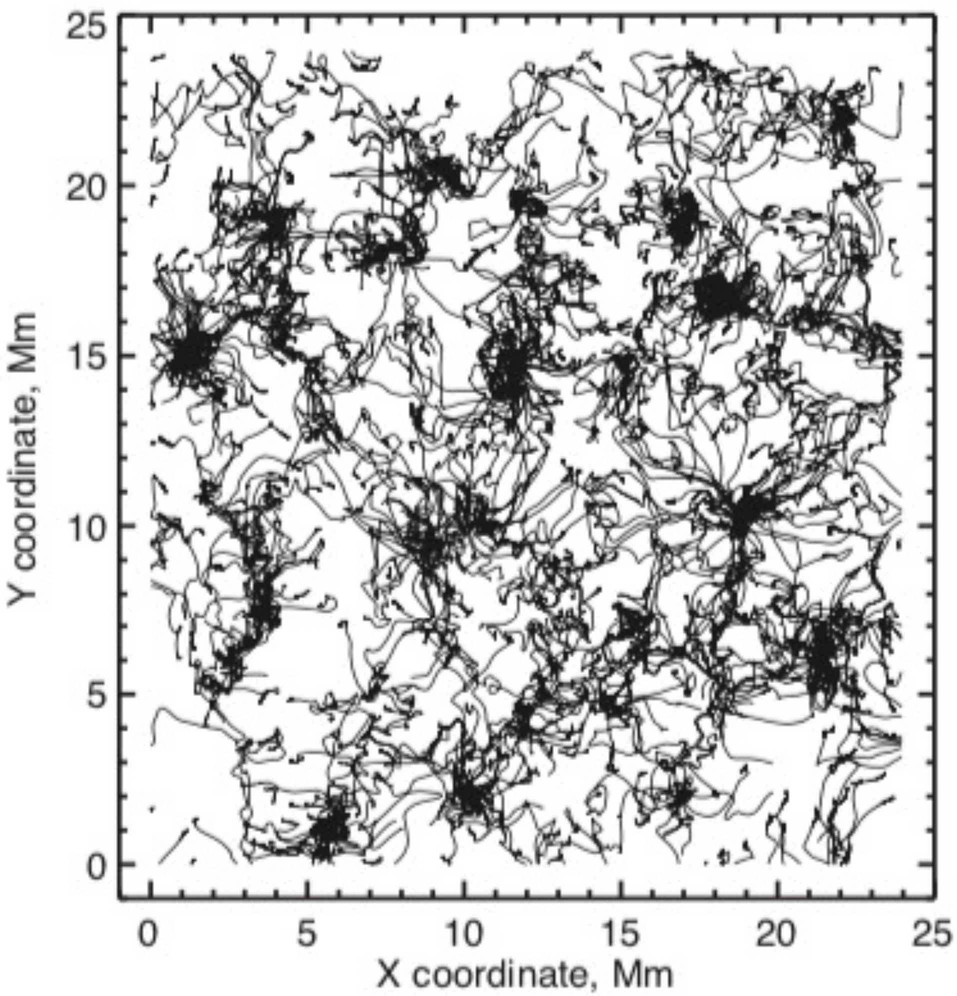
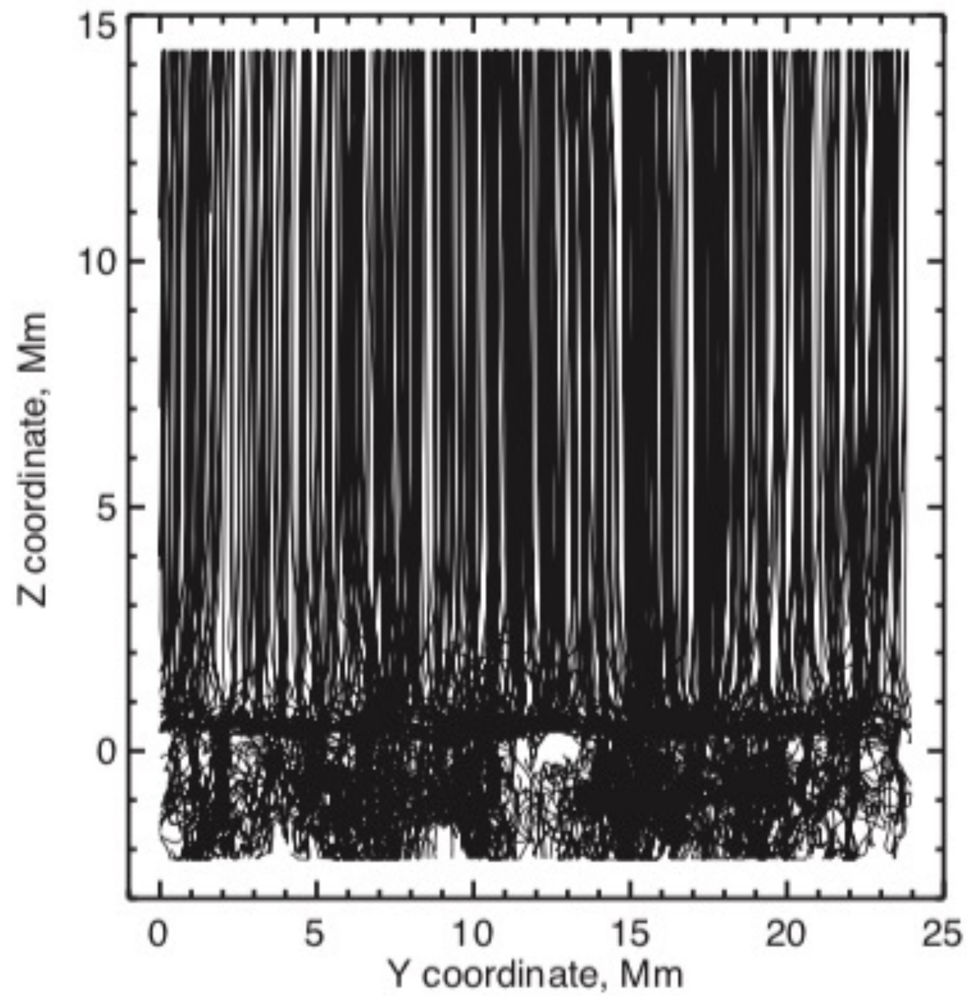
BIFROST_en024048_hion_uz_385.fits	Nov 11, 2018 at 8:45 PM	504 MB

*Bifrost (Norse mythology, “Rainbow bridge to heaven”, think aurora); also state-of-the-art 3D/MHD model atmosphere (the Oslo group).

Cosmic ray interactions in the solar atmosphere

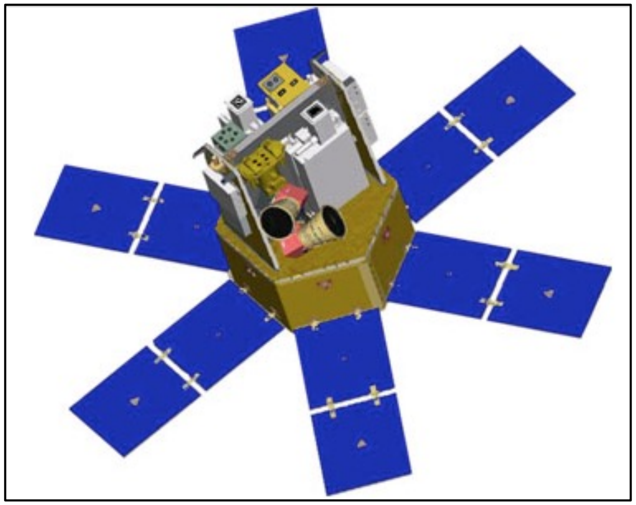
Hugh S. Hudson,[1,2]★ Alec MacKinnon,[1] Mikolaj Szydlarski[3] and Mats Carlsson[3]
[1] School of Physics and Astronomy, University of Glasgow, G12 8QQ Glasgow, UK
[2] Space Sciences Laboratory, University of California, Berkeley, CA 94720-7450, USA
[3] Institute of Theoretical Astrophysics, University of Oslo, NO-0315 Oslo, Norway





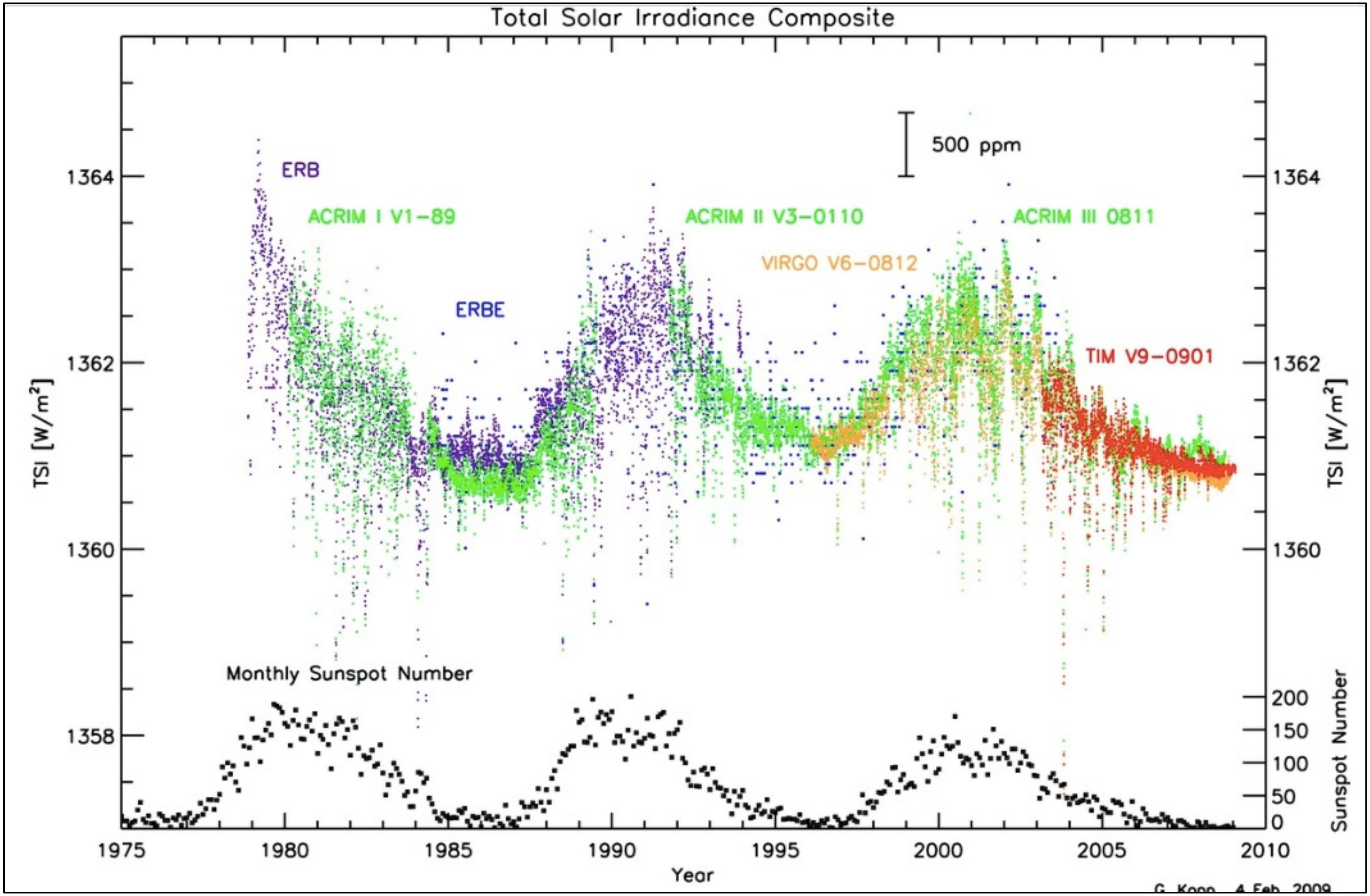
Let's check one property: the luminosity

The SORCE satellite



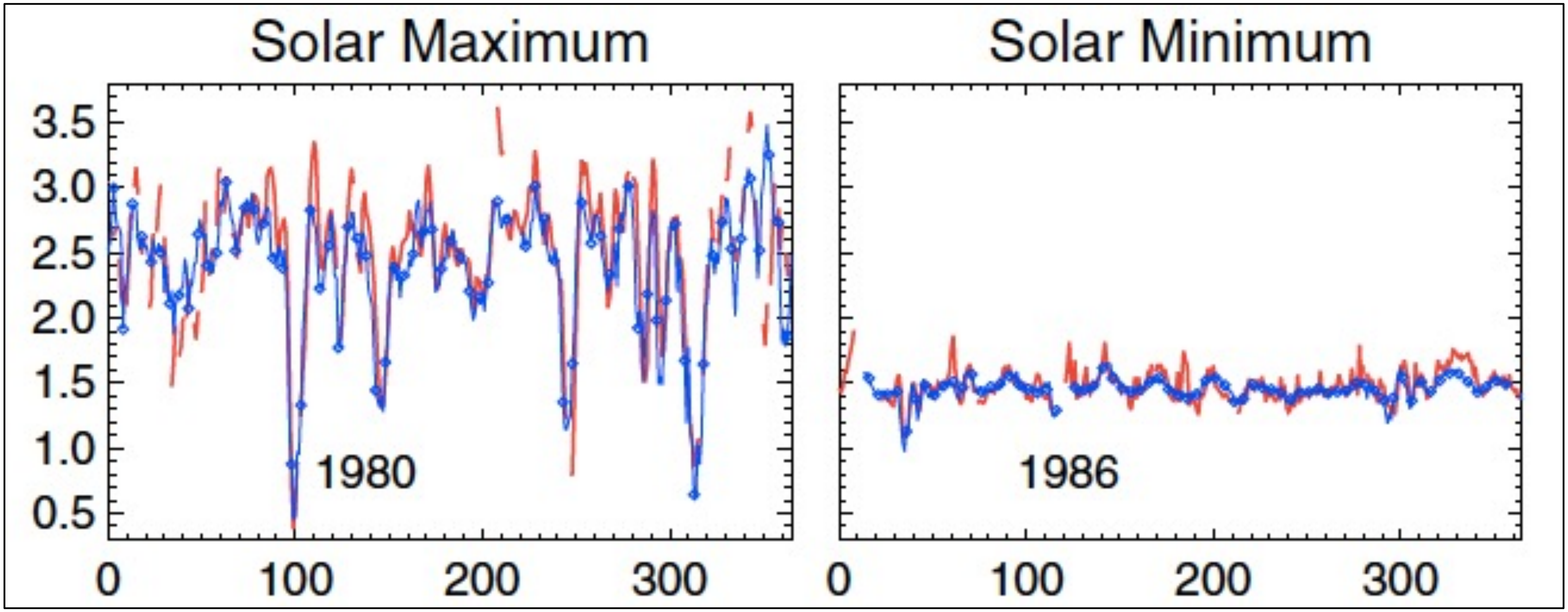
- Is it really 3.83 x 10^{33} erg/s?
  - Why only three significant figures?
  - Does it vary with time?

- 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



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

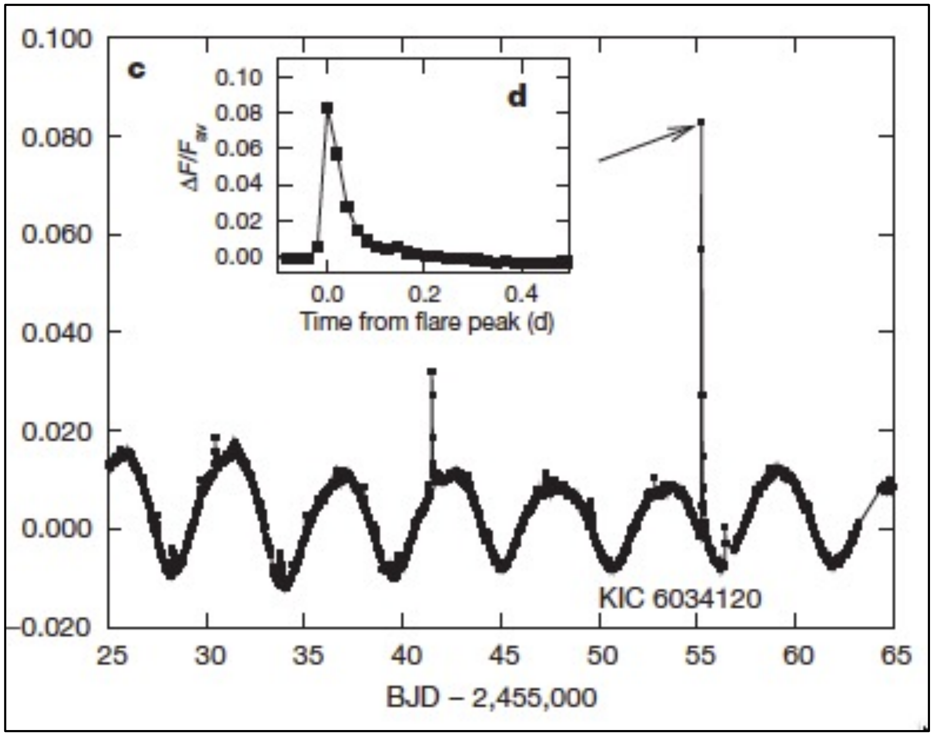
Sunspot deficits, facular excesses

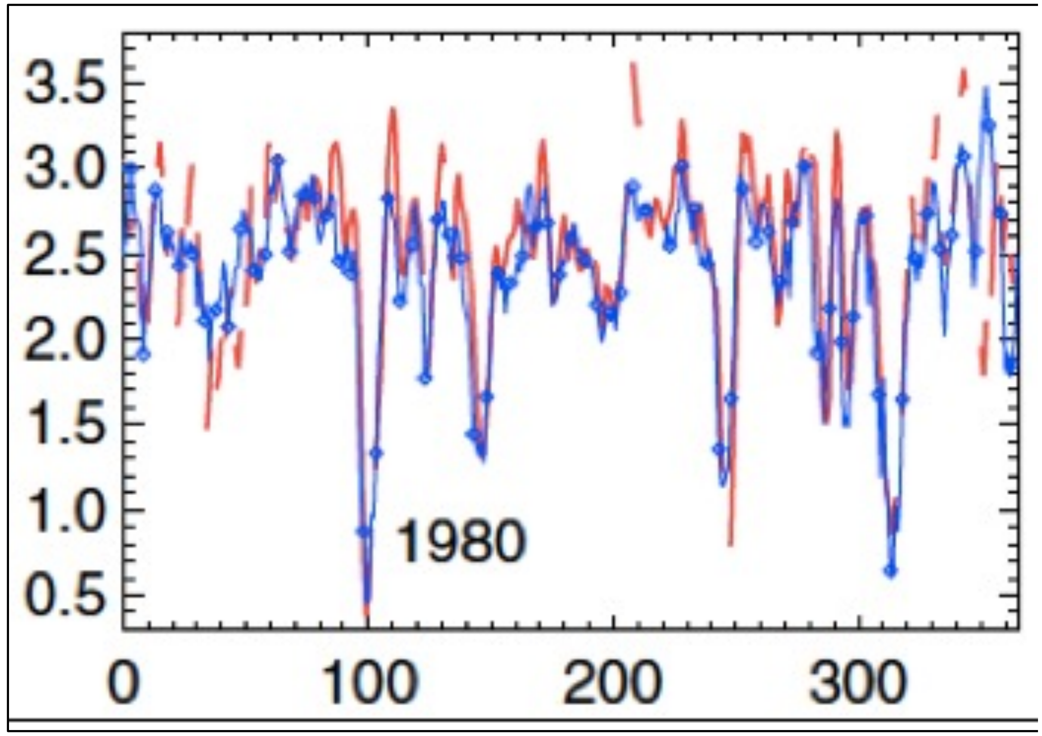


Fröhlich & Lean, 2004

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

Solar-stellar variability





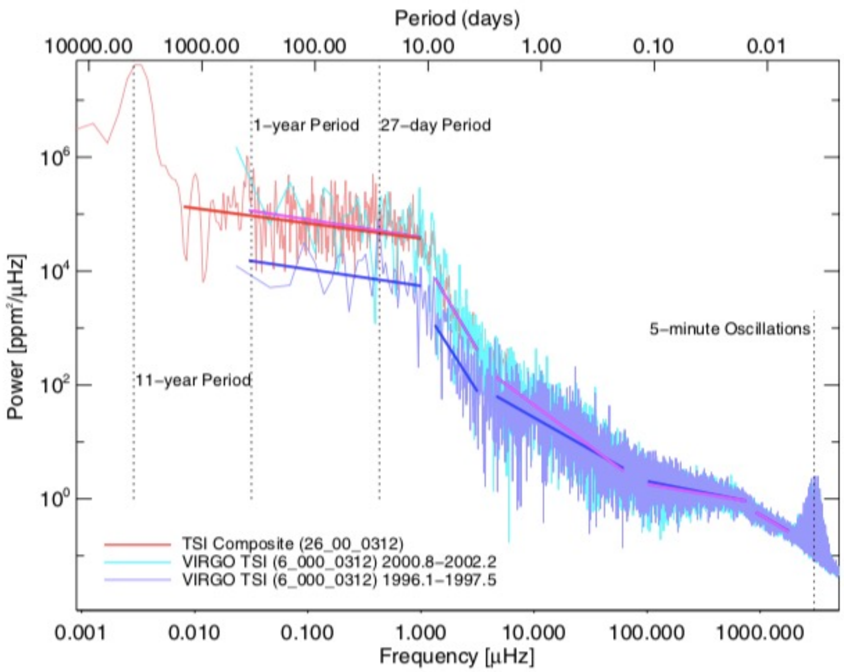
- A *Kepler* "superflare" on a solar-type star (Maehara et al. 2013)
- Note the non-solar pattern of quiescent variations

- 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: $v^2 R_\odot g_\odot^{-1}$ ~ 2.5 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 photospheric density ~10^{11} m^{-3}, temperature 5200 K, 10^{-4} ionized

How does the Sun vary?

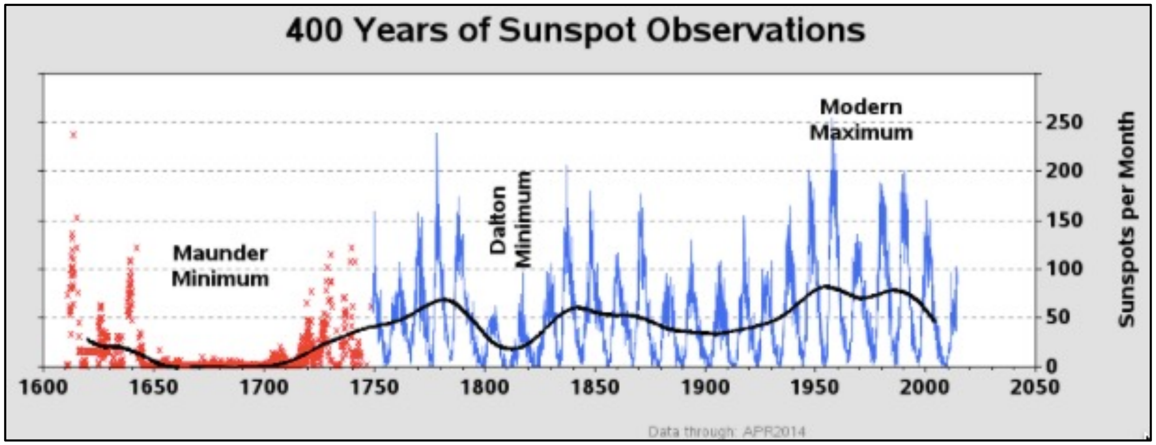


Fröhlich & Lean, 2004

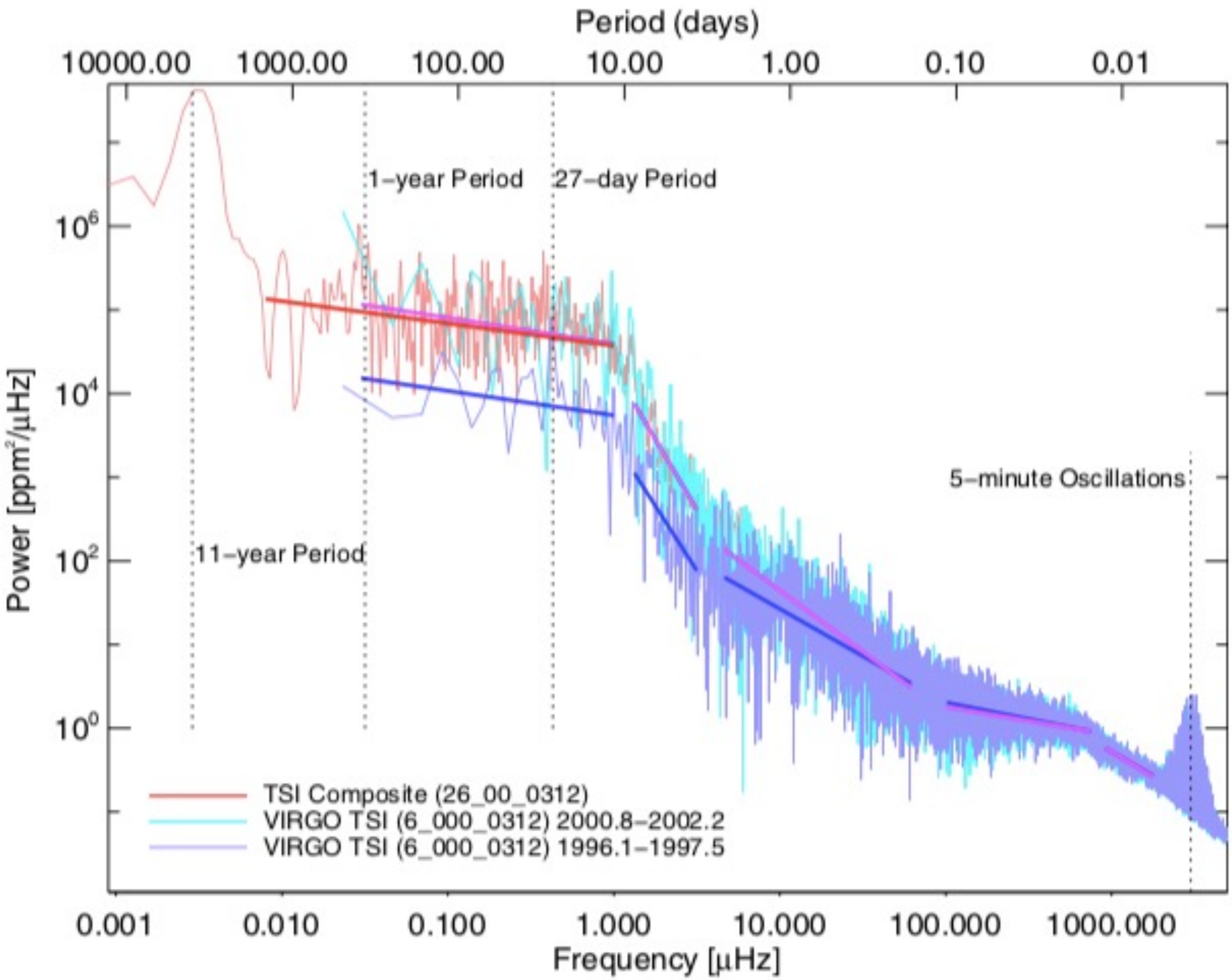
Variability occurs on many scales:

- 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 a power spectrum?



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p-modes, g-modes, and ripples

1941MNRAS.101..367C

THE NON-RADIAL OSCILLATIONS OF POLYTROPIC STARS

T. G. Cowling, M.A., D.Phil.

(Received 1941 November 6)

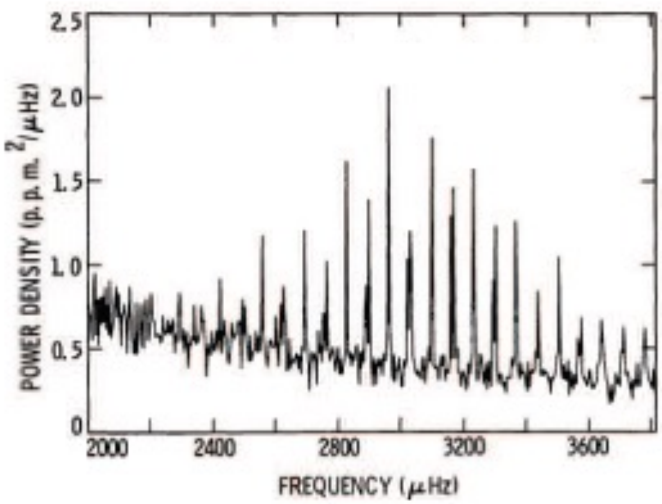
1. The problem of the non-radial oscillations of a fluid globe is of interest in the theory of the tidal distortion of binary stars. If the periods of rotation of the components

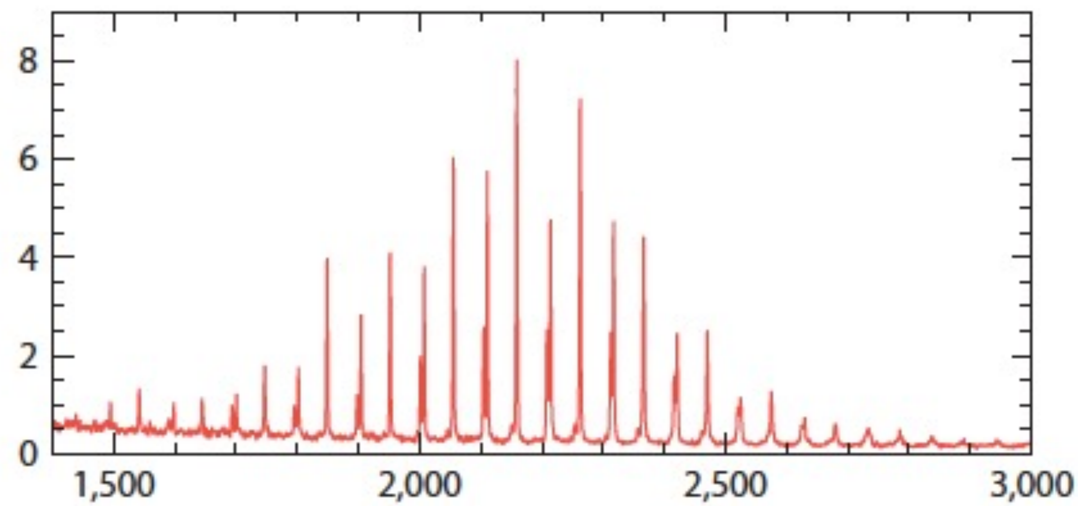
Classification of modes in the Cowling approximation

- p-modes: mainly acoustic standing waves, global
- g-modes: internal gravity waves, evanescent in the convection zone
- f-modes: surface waves

The solar interior also supports acoustic waves excited by flares

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