University of Glasgow | School of Physics & Astronomy

SUPA: The Sun's Atmosphere

Session 2023-24

Lecture 8: "The photosphere, how we study it, and why it matters"

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The Sun’s Atmosphere

Date			Topic	Lecturer
Mon	08-Jan	0	Intro	Iain Hannah
Tue	09-Jan	1	Overview Structure & Dynamics	Iain Hannah
Mon	15-Jan	2	Particle Acceleration & Transport 1	Eduard Kontar
Tue	16-Jan	3	Particle Acceleration & Transport 2	Eduard Kontar
Mon	22-Jan	4	MHD Basics 1	Emma Hunter
Tue	23-Jan	5	MHD Basics 2	Emma Hunter
Mon	29-Jan	6	Radiation Transport 1	Nicolas Labrosse
Tue	30-Jan	7	Radiation Transport 2	Nicolas Labrosse
Mon	05-Feb	8	Photosphere and Magnetism 1	Hugh Hudson
Mon	12-Feb	9	Photosphere and Magnetism 2	Hugh Hudson
Mon	19-Feb	10	EUV to Infrared Plasma Diagnostics 1	Sargam Mulay
Mon	26-Feb	11	EUV to Infrared Plasma Diagnostics 2	Sargam Mulay
Tue	27-Feb	12	Radio Plasma Diagnostics	Yingjie Luo
Mon	04-Mar	13	Flares & CMEs	Iain Hannah
Tue	05-Mar	14	X-ray/Gamma-ray Plasma Diagnostics	Iain Hannah
Mon	11-Mar	15	Space Weather	Iain Hannah
Tue	06-Feb	T1	Tutorial 1 - Oral Exam 1 Prep	Iain Hannah
Tue	20-Feb	T2	Tutorial 2 - Project Intro	Iain Hannah
Tue	12-Mar	T3	Tutorial 3 - Oral Exam 2 Prep	Iain Hannah
Mon	18-Mar	T4	Tutorial 4 - Project Prep	Iain Hannah

Useful homework questions based on this material

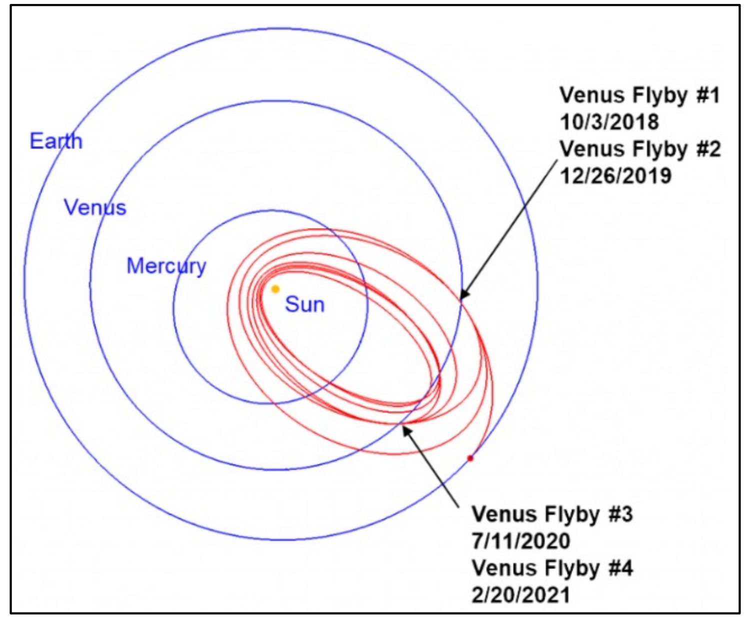
- What is the minimum Earth detectable by photometry of a Sun-like star?
- How round is the Sun?
- How big does a solar optical telescope need to be?
- How deep can a Wilson depression be?

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/tsa.240205/

New solar observational tools

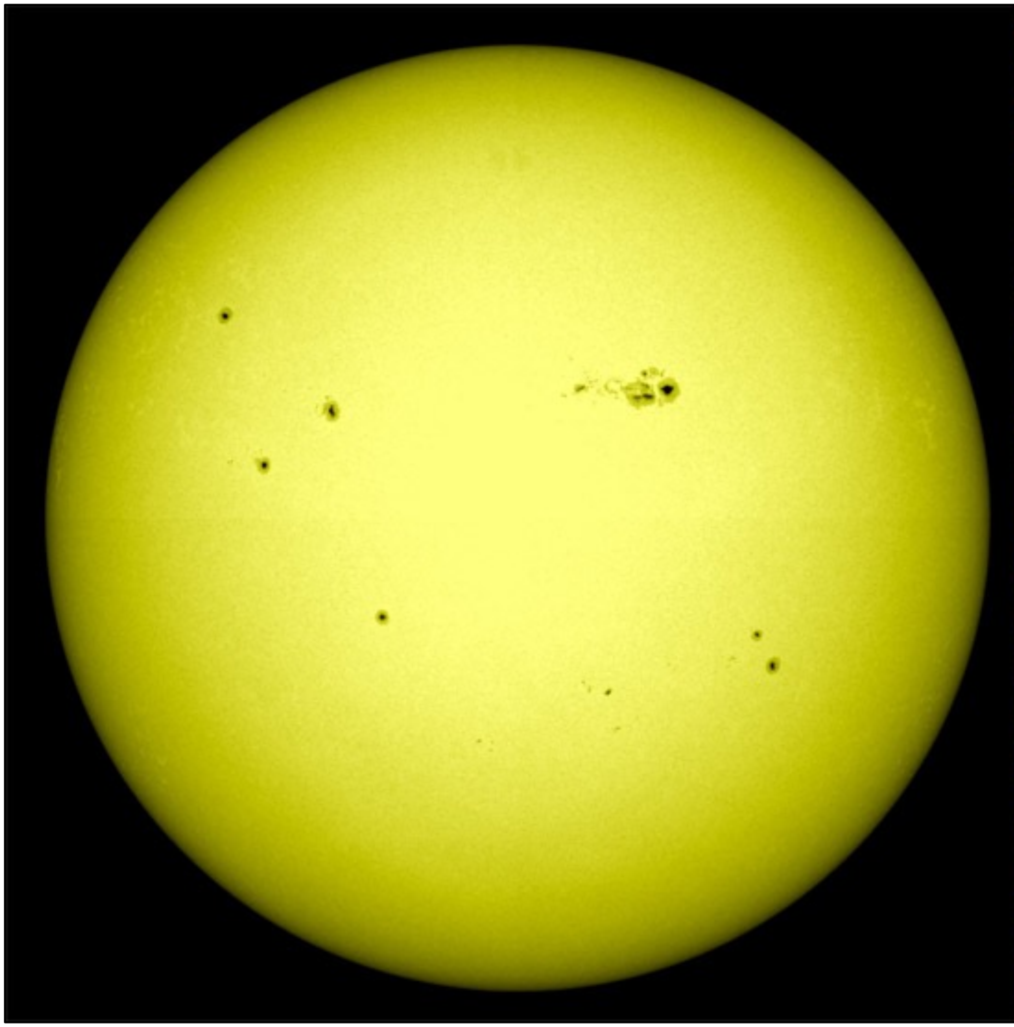
DKIST - a 4-m solar optical/IR telescope

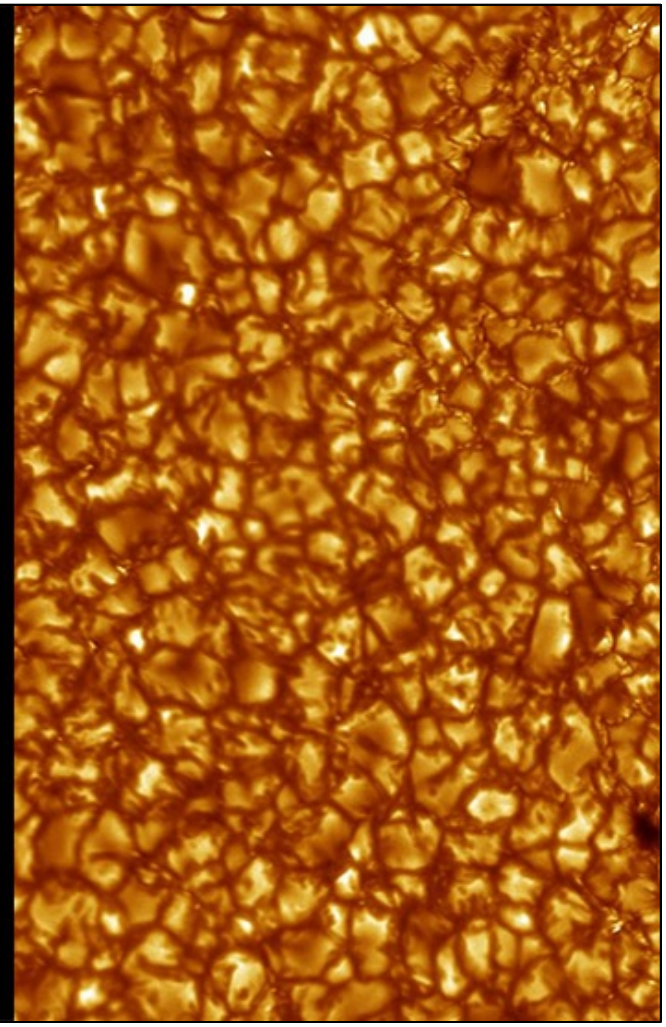


PSP - a space probe that dares to approach the solar surface

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

The photosphere

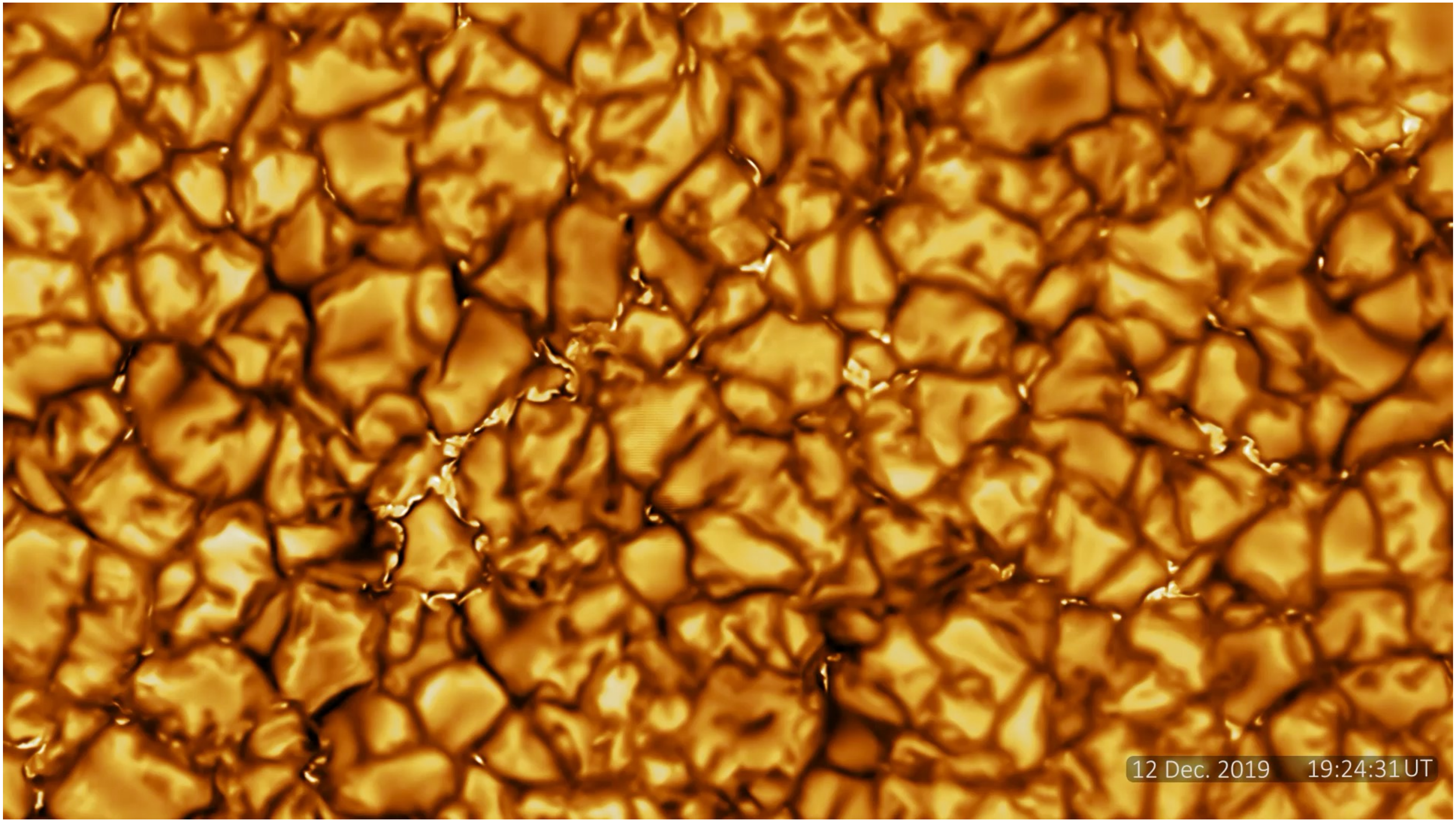




Half a degree

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. *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: $I_\nu = \Sigma\, a_i\, \mu^\iota$, 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 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.

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:	$Z = 0.0122$

Limb darkening law

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

  - opacity independent of wavelength

  - diffusion approximation for radiative transfer

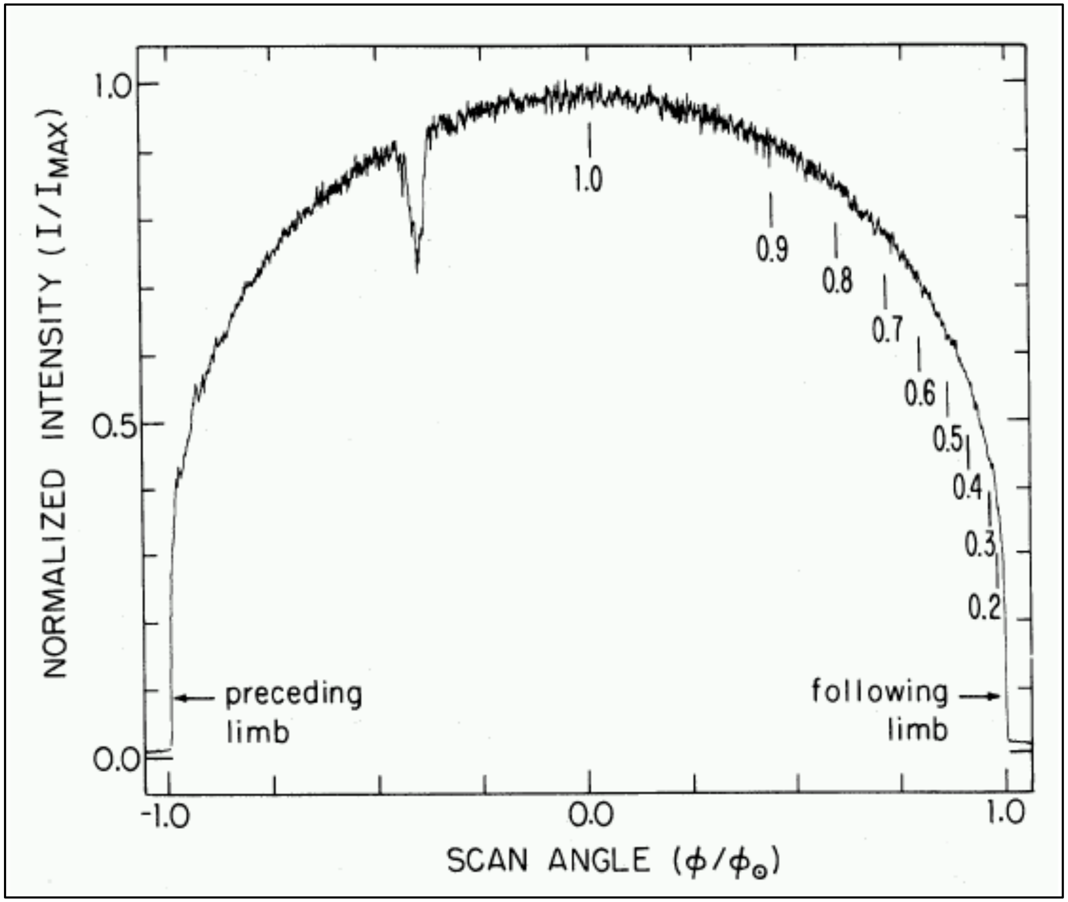
  - linearization via $S(\tau) = a + b\tau$ (*Eddington-Barbier)*

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

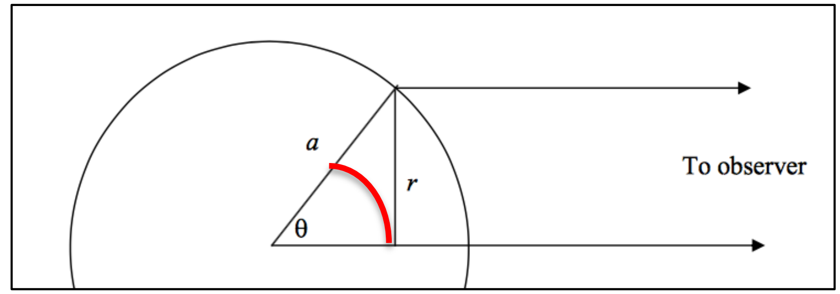
$$I/I_0 = (3\mu+2)/5$$

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

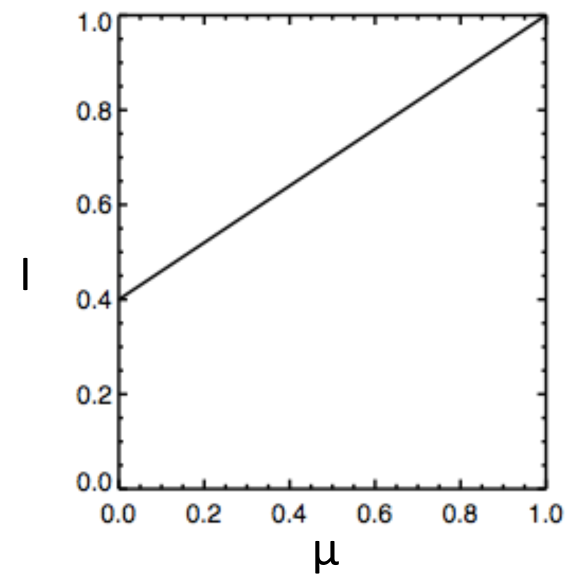
Limb darkening



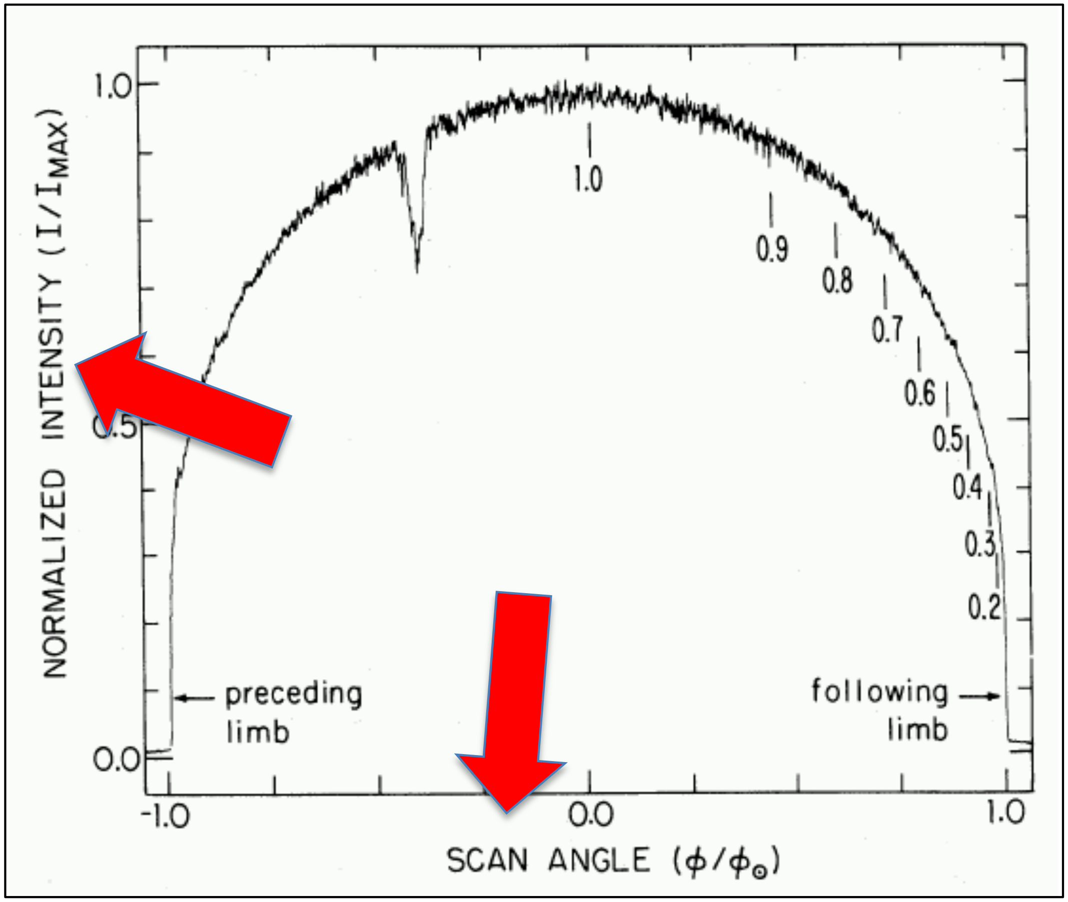
A typical drift scan, showing values of μ = cos(θ) and other things.



The vertical angle θ, with μ = cos(θ)

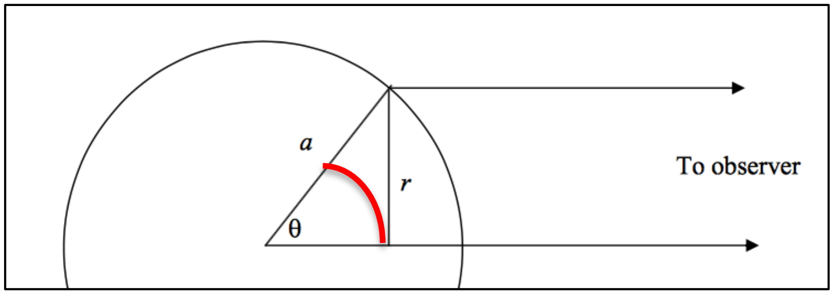


Limb darkening

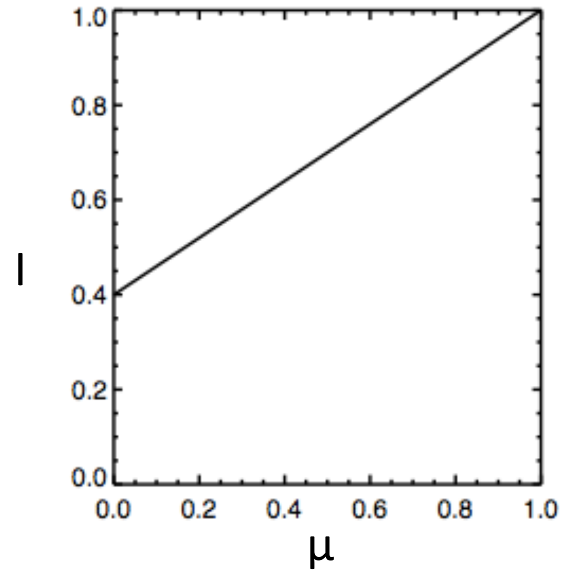


A typical drift scan, showing values of μ = cos(θ) and other things.

n.b. Data measure flux, not "intensity"



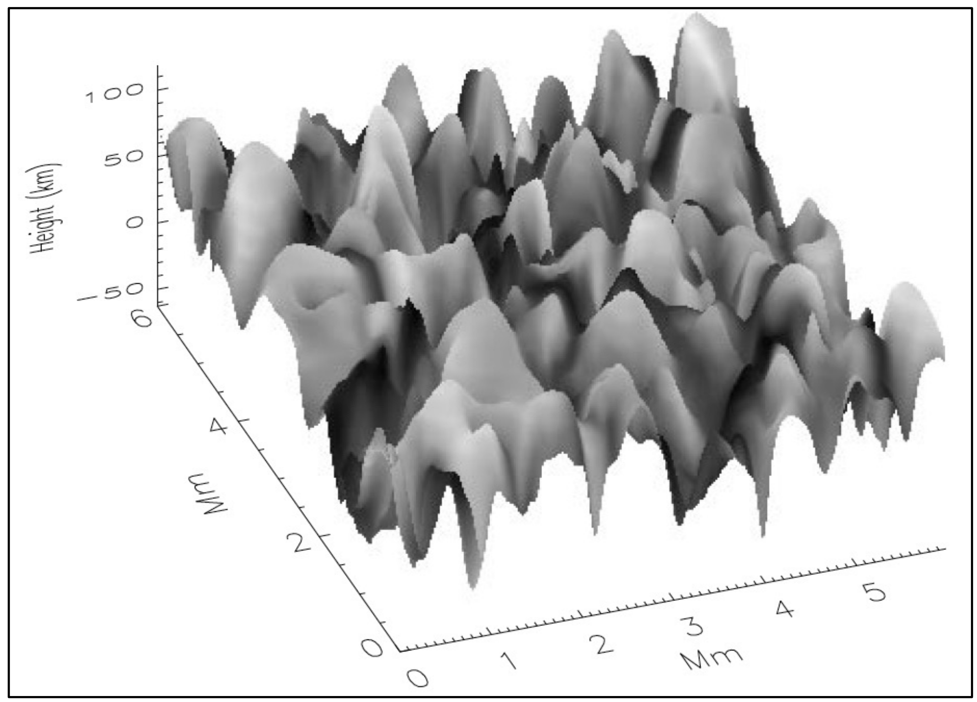
The vertical angle θ, with μ = cos(θ)



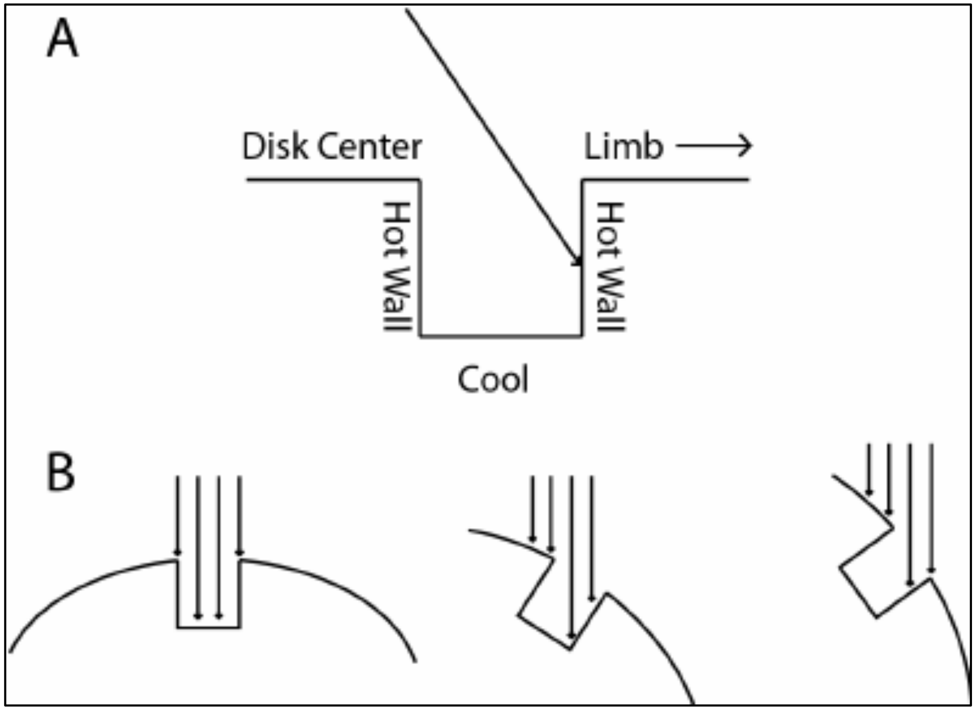
Limb darkening and 3D

- Limb darkening can readily be explained by a simple opacity model: $S_\nu = a + b\tau$ (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?

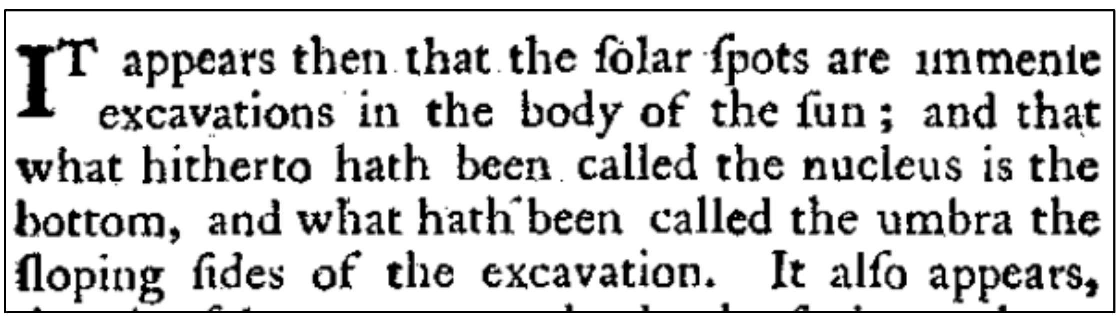
Stein & Nordlund 1998



Magnetic height structure



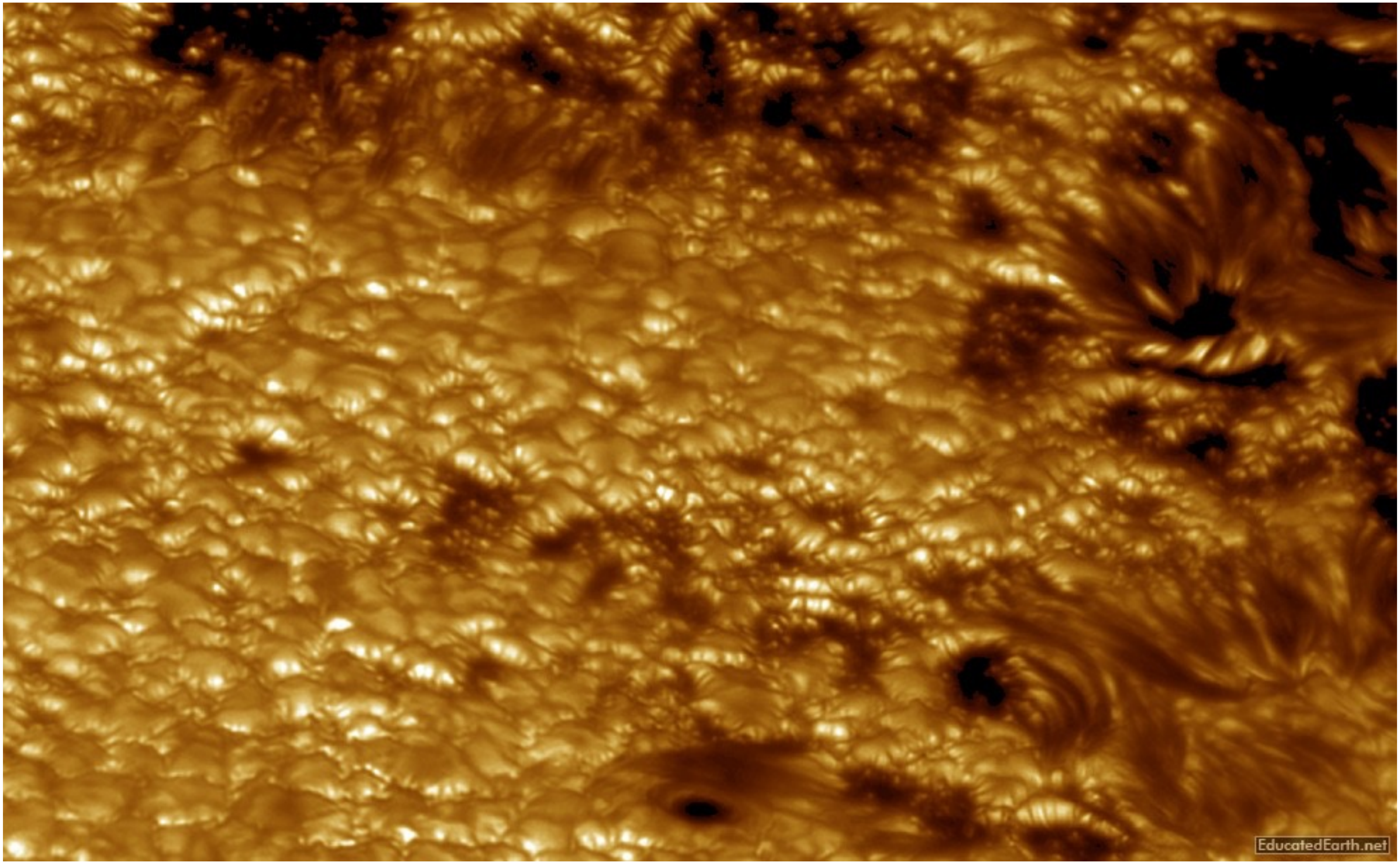
The bottom of the flux tube is cool, like a sunspot, because of magnetic suppression of convective motions (Spruit, 1976). His "hot wall" model effectively explains faculae, if not *plage.*



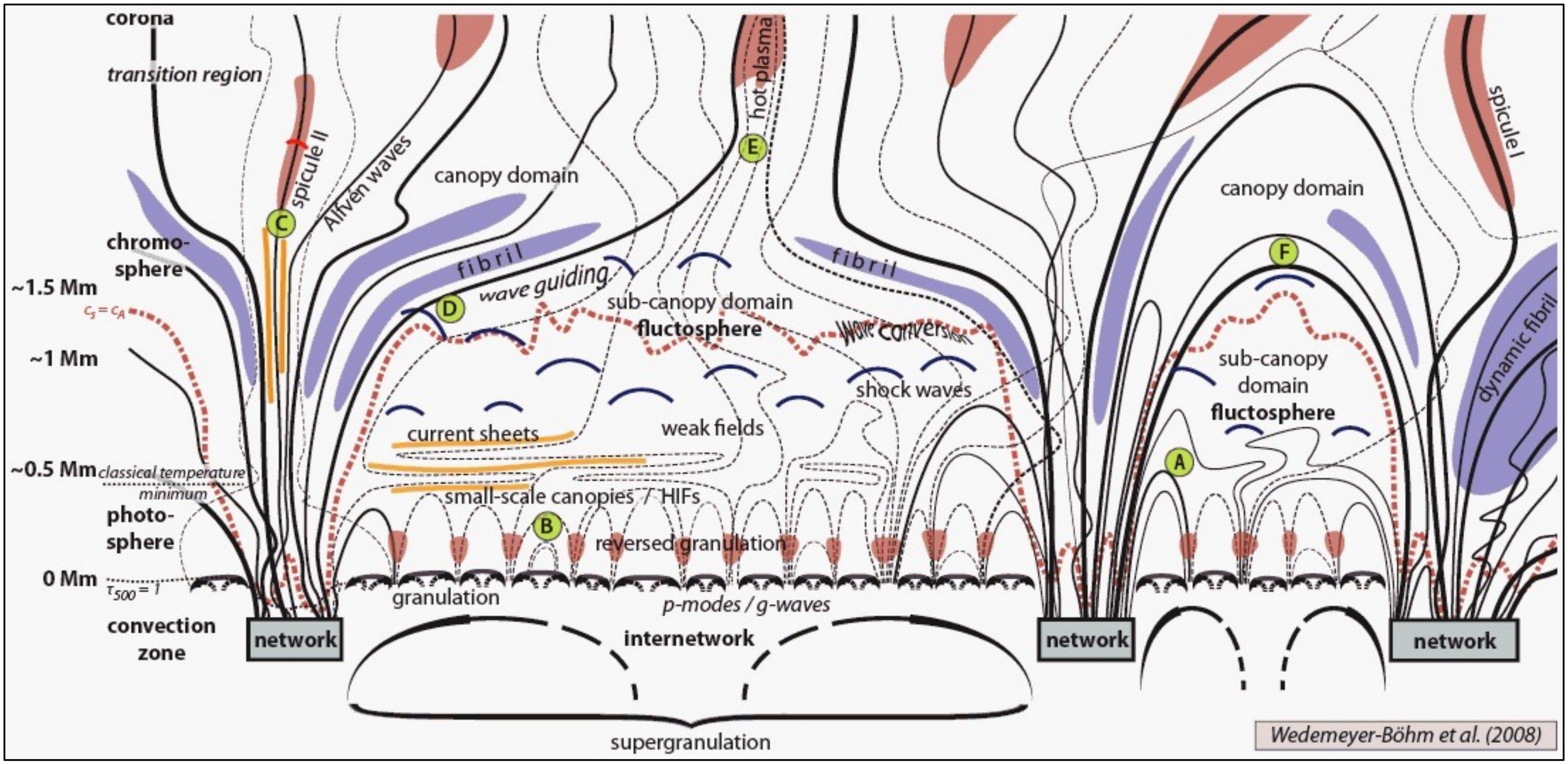
IT appears then that the ſolar ſpots are immenſe excavations in the body of the ſun; and that what hitherto hath been called the nucleus is the bottom, and what hath been called the umbra the ſloping ſides of the excavation. It alſo appears,

Wilson, 1784

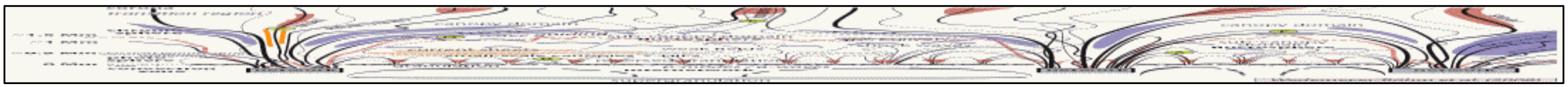
The third dimension



The transition layers

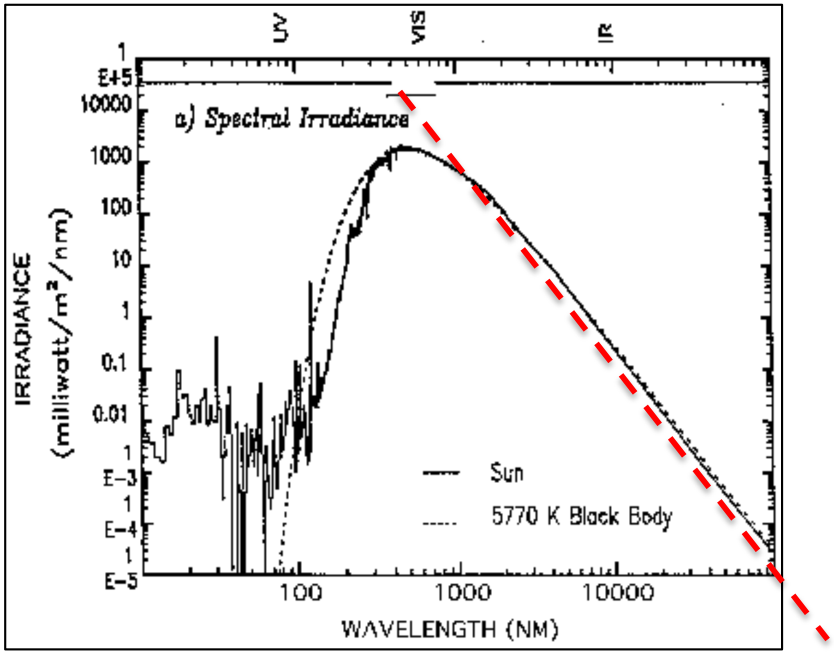


Gravity and structure



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.

Recall the “semi-empirical” models



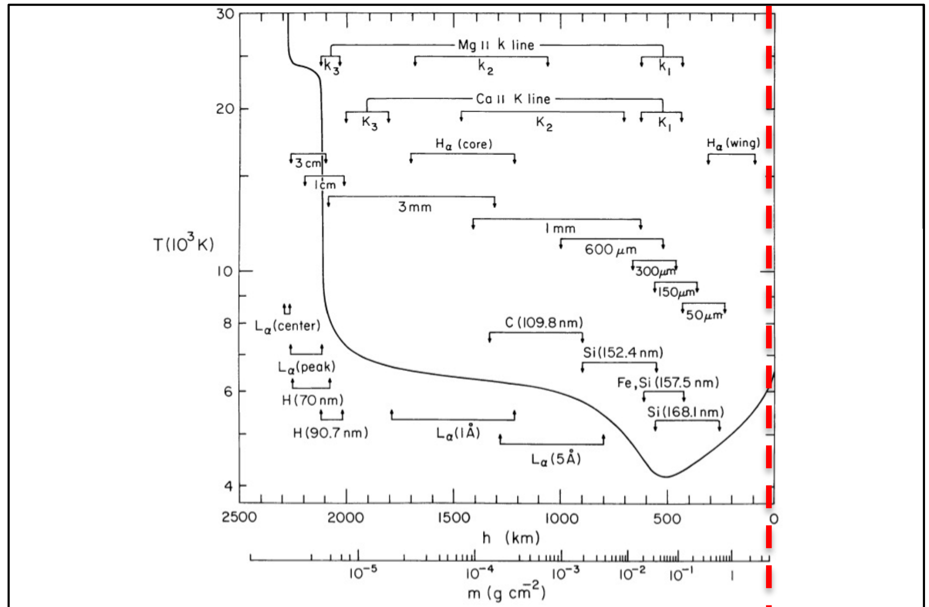


FIG. 1.—The average quiet-Sun temperature distribution derived from the EUV continuum, the Lα line, and other observations. The approximate depths where the various continua and lines originate are indicated.

- 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 hydrodynamics (and MHD).

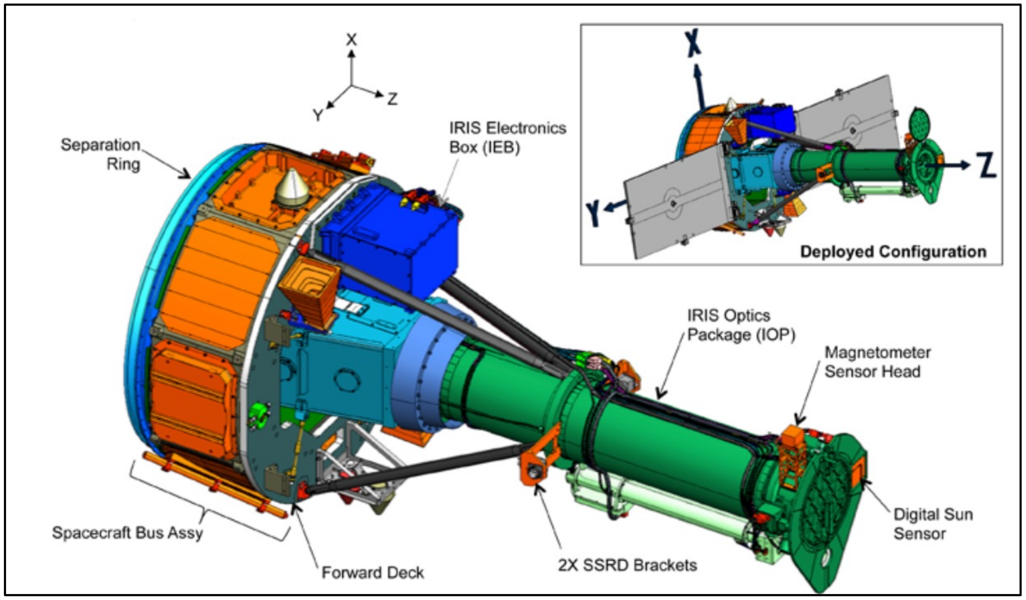
The significance of the photosphere/corona interface

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).

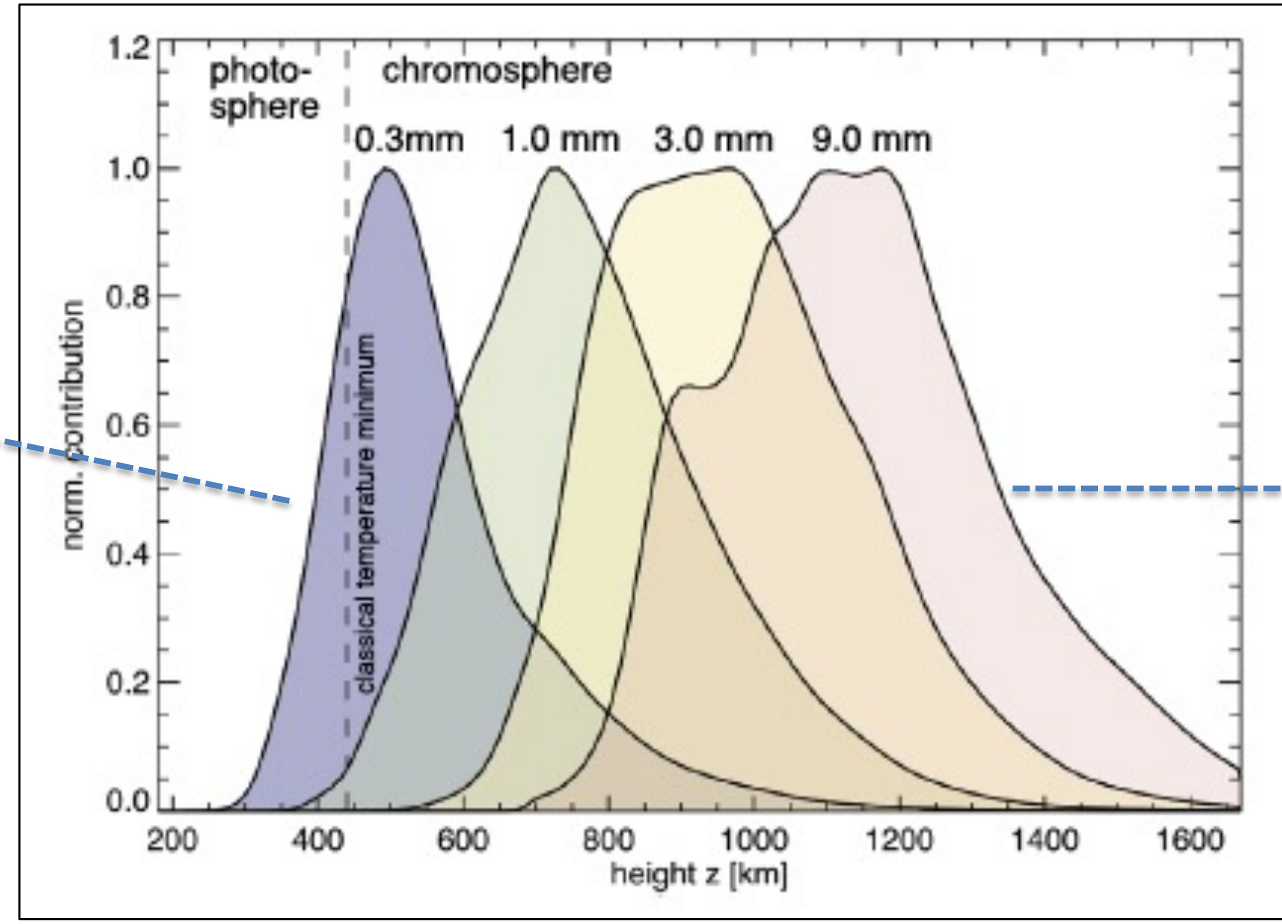
IRIS and ALMA



The "Interface Region Imaging Spectrograph" This is the current definitive EUV (100 nm) solar space observatory	The "Atacama Large Millimeter Array" This is the current definitive mm-wave solar observatory

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

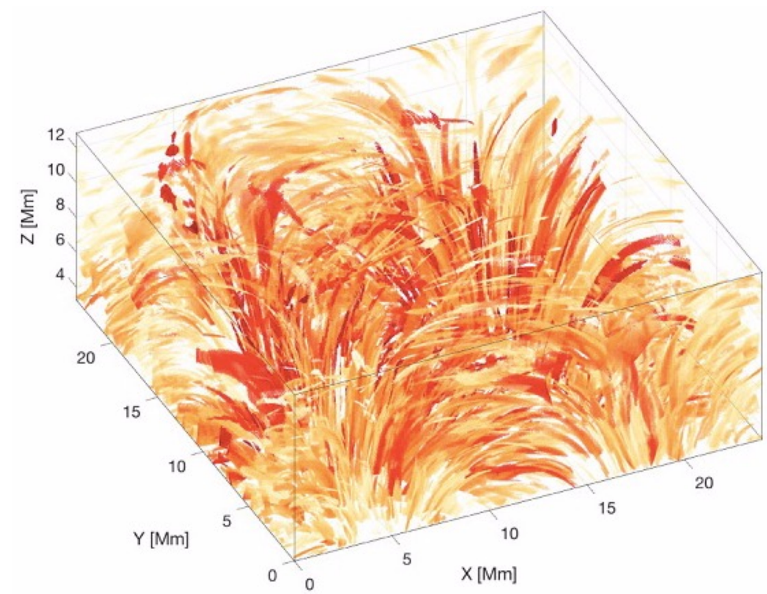
Photosphere



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
BIFROST_en024048_hion_lgne_385.fits	Nov 11, 2018 at 8:44 PM	504 MB
BIFROST_en024048_hion_lgp_385.fits	Nov 11, 2018 at 8:44 PM	504 MB
BIFROST_en024048_hion_lgr_385.fits	Nov 11, 2018 at 8:44 PM	504 MB
BIFROST_en024048_hion_lgtg_385.fits	Nov 11, 2018 at 8:45 PM	504 MB
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,[1,2★] Alec MacKinnon,[1] Mikolaj Szydlarski[3] and Mats Carlsson[3]
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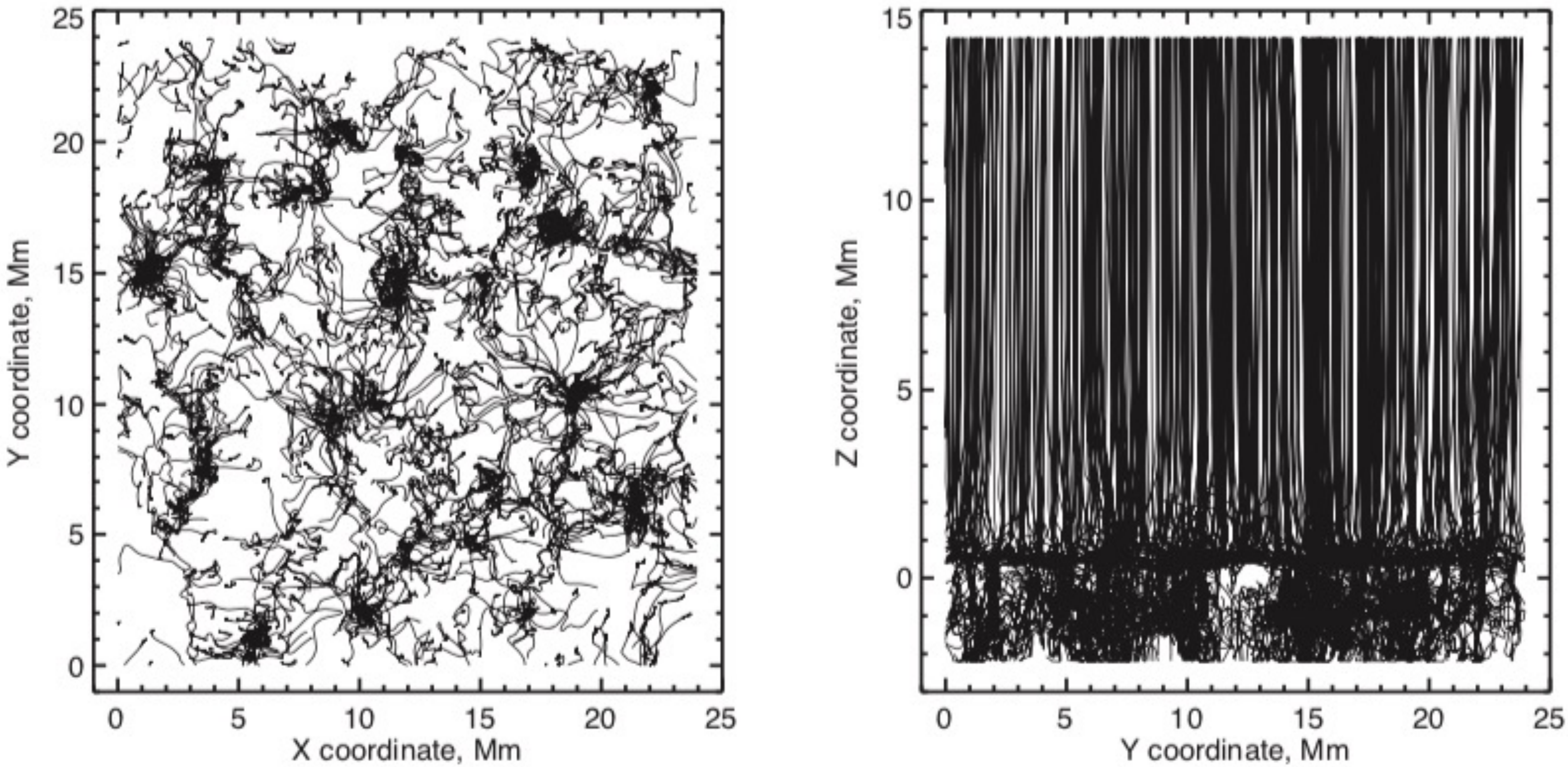
[2]Space Sciences Laboratory, University of California, Berkeley, CA 94720-7450, USA
[3]Institute of Theoretical Astrophysics, University of Oslo, NO-0315 Oslo, Norway



Basic Questions

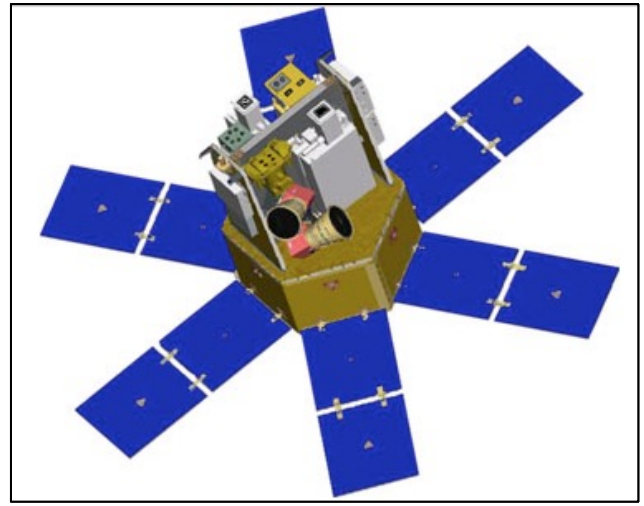
1) How far away is the Sun? – That's for the astronomers
2) How bright is the Sun? – Basic research in the 1980s
3) How round is the Sun? – Current research
4) What (other than convection) determines solar structure? – this is the subject of Lecture 9 next week.

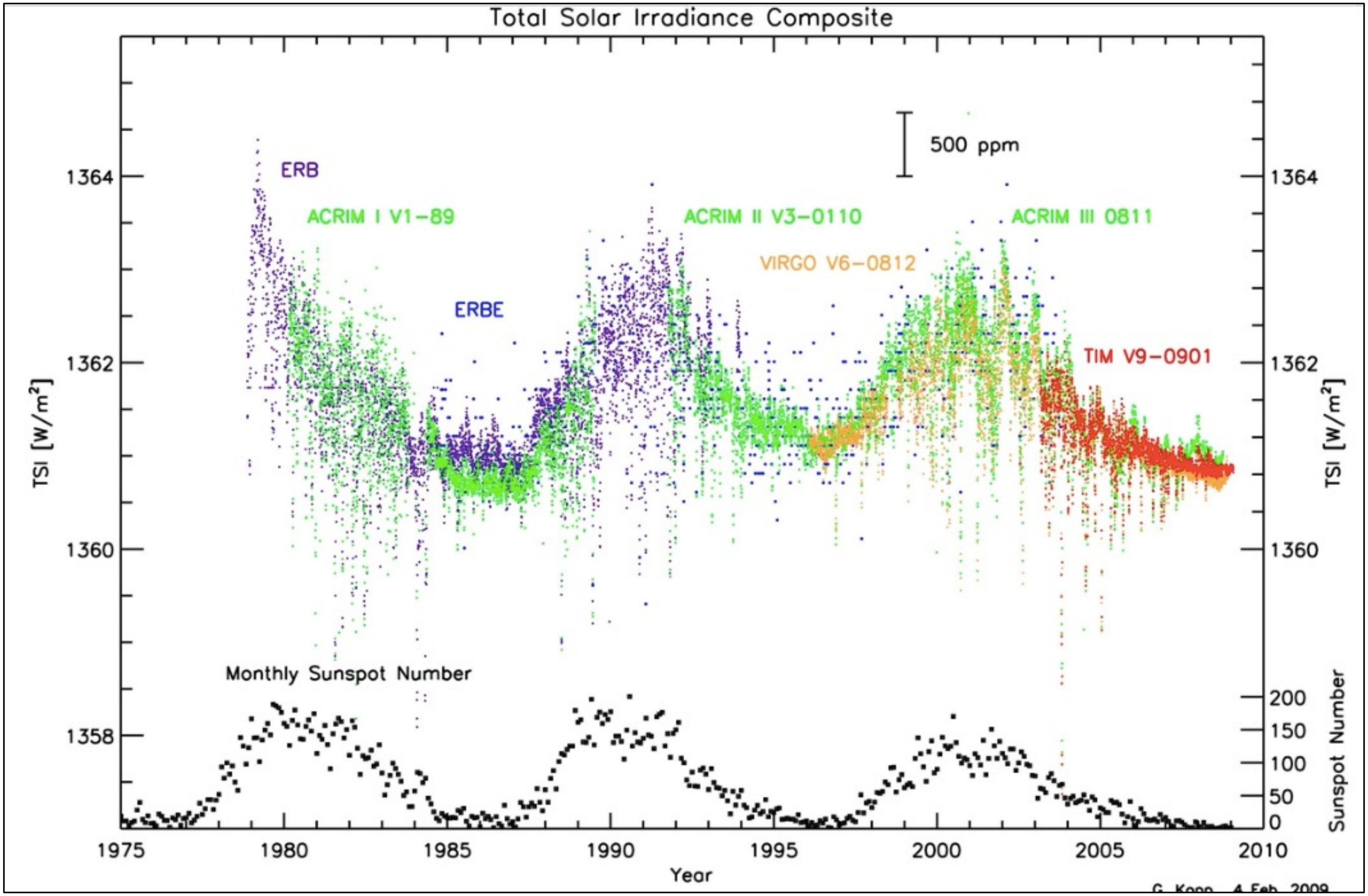
How bright is the Sun?

- 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

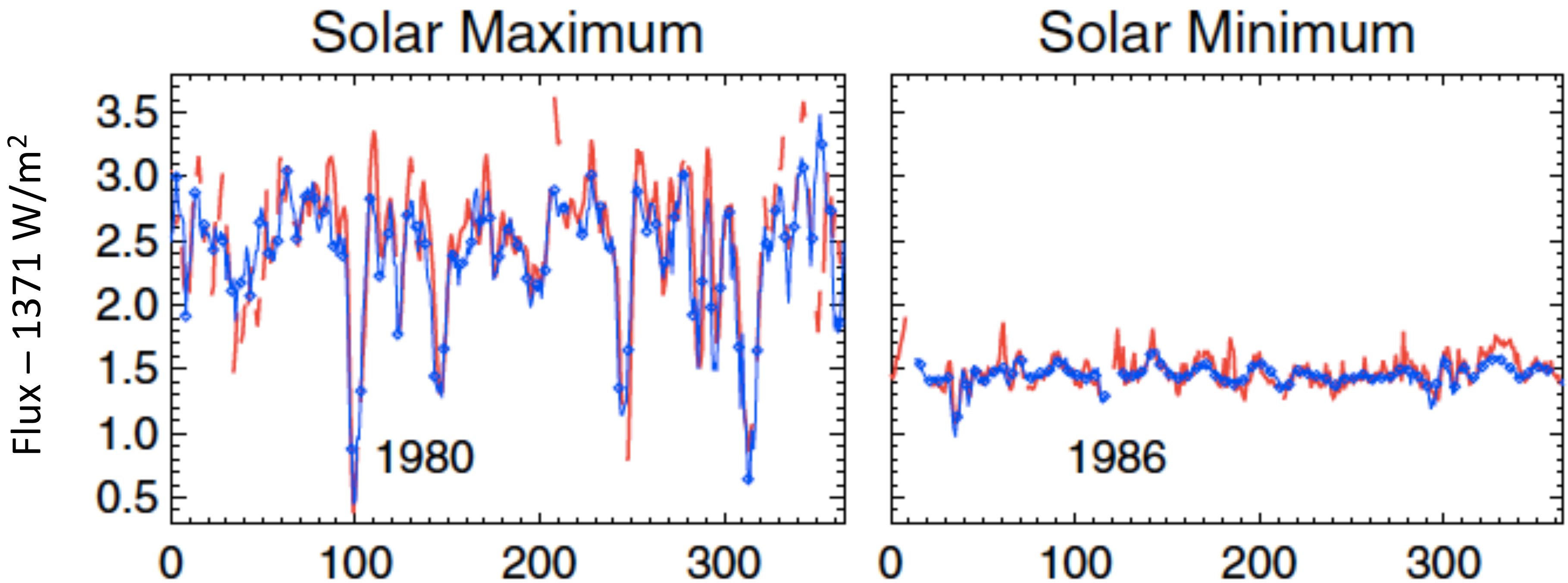
The SORCE satellite





Yes, the irradiance varies. Does that mean that the luminosity does?
Yes, the Sun is systematically brighter when there are sunspots.

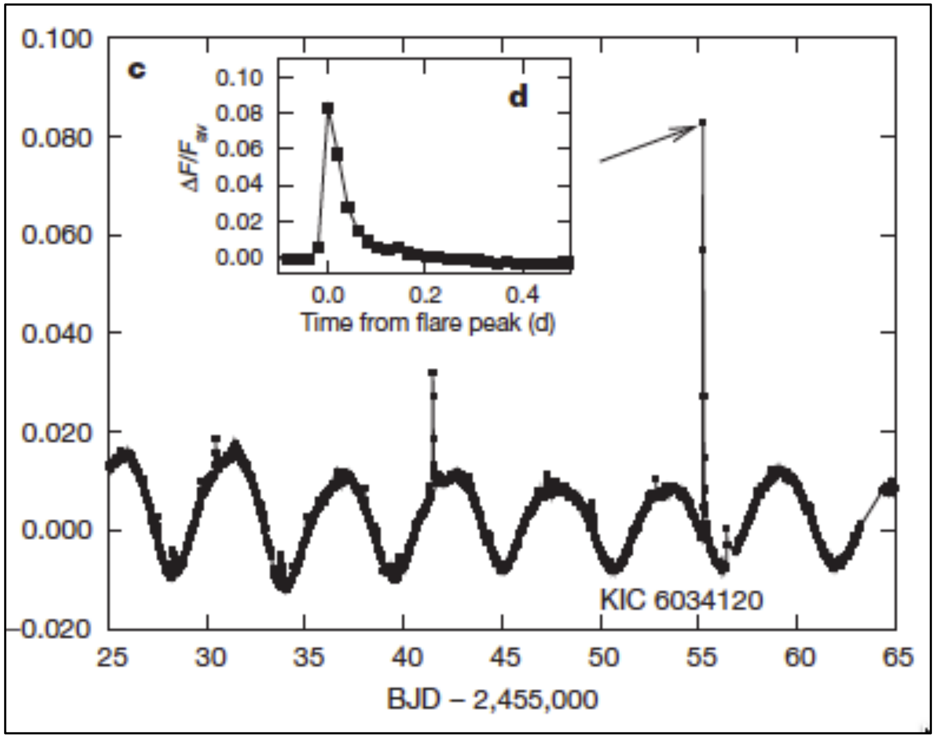
Sunspot deficits, facular excesses

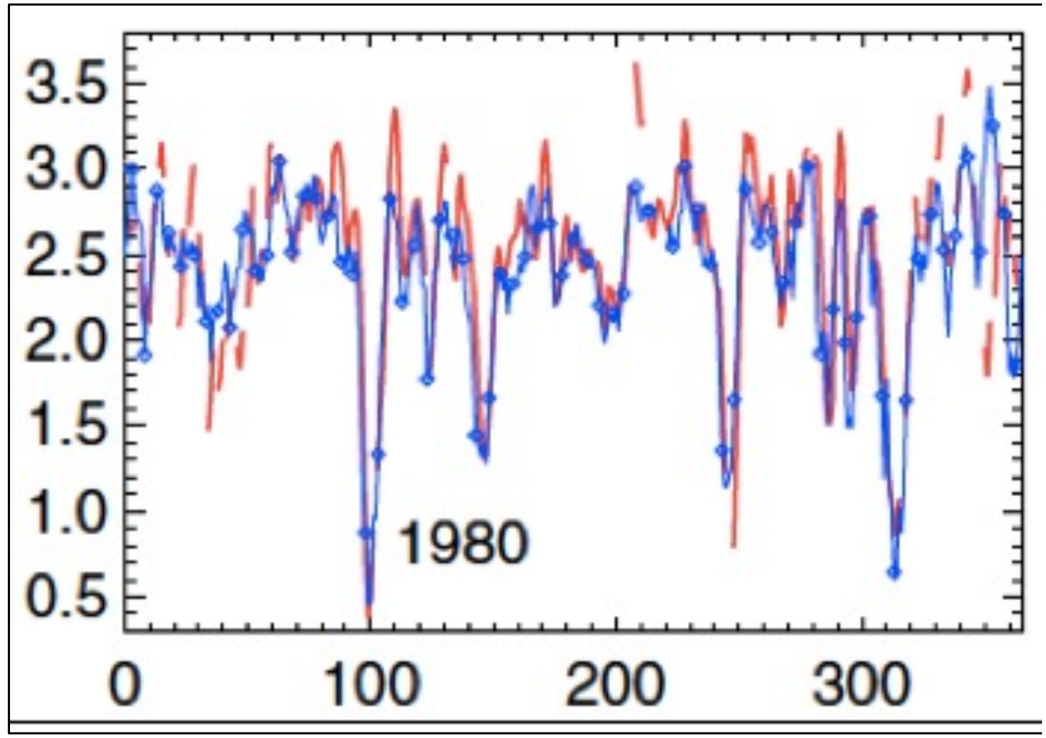


Fröhlich & Lean, 2004

- 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* photometric observations now provide thousands of analogous solar-type stars for reference.

Solar-stellar variability





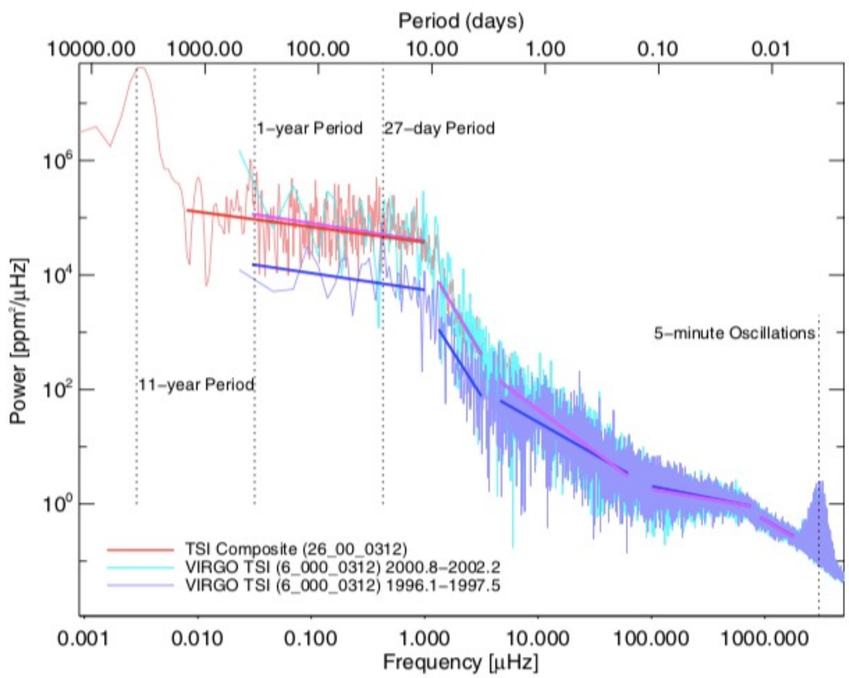
- A *Kepler* "superflare" on a solar-type star (Maehara et al. 2013)
- Note the non-solar pattern of quiescent variations

- 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: $v^2(R_\odot g_\odot)^{-1}$ -> 20 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 6420 K, 10^{-4} ionized

How does the Sun vary?

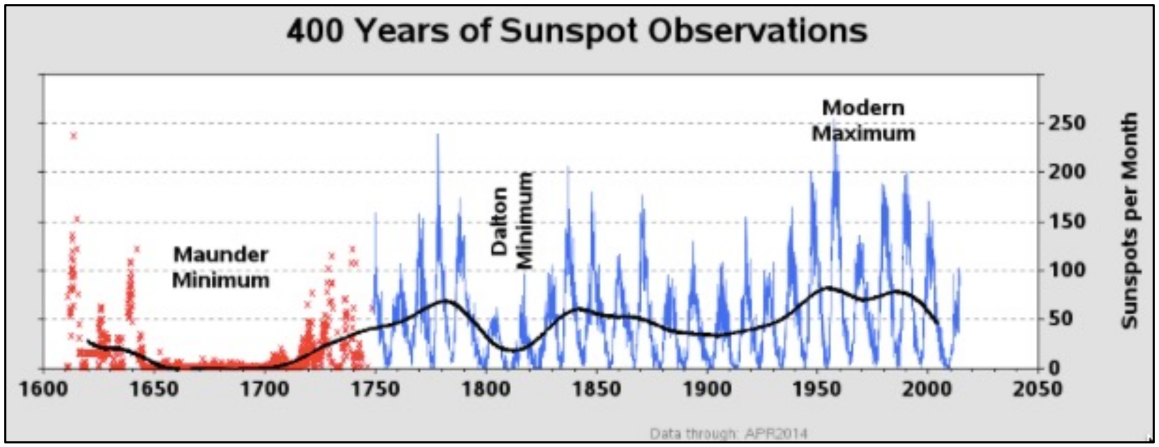


Fröhlich & Lean, 2004

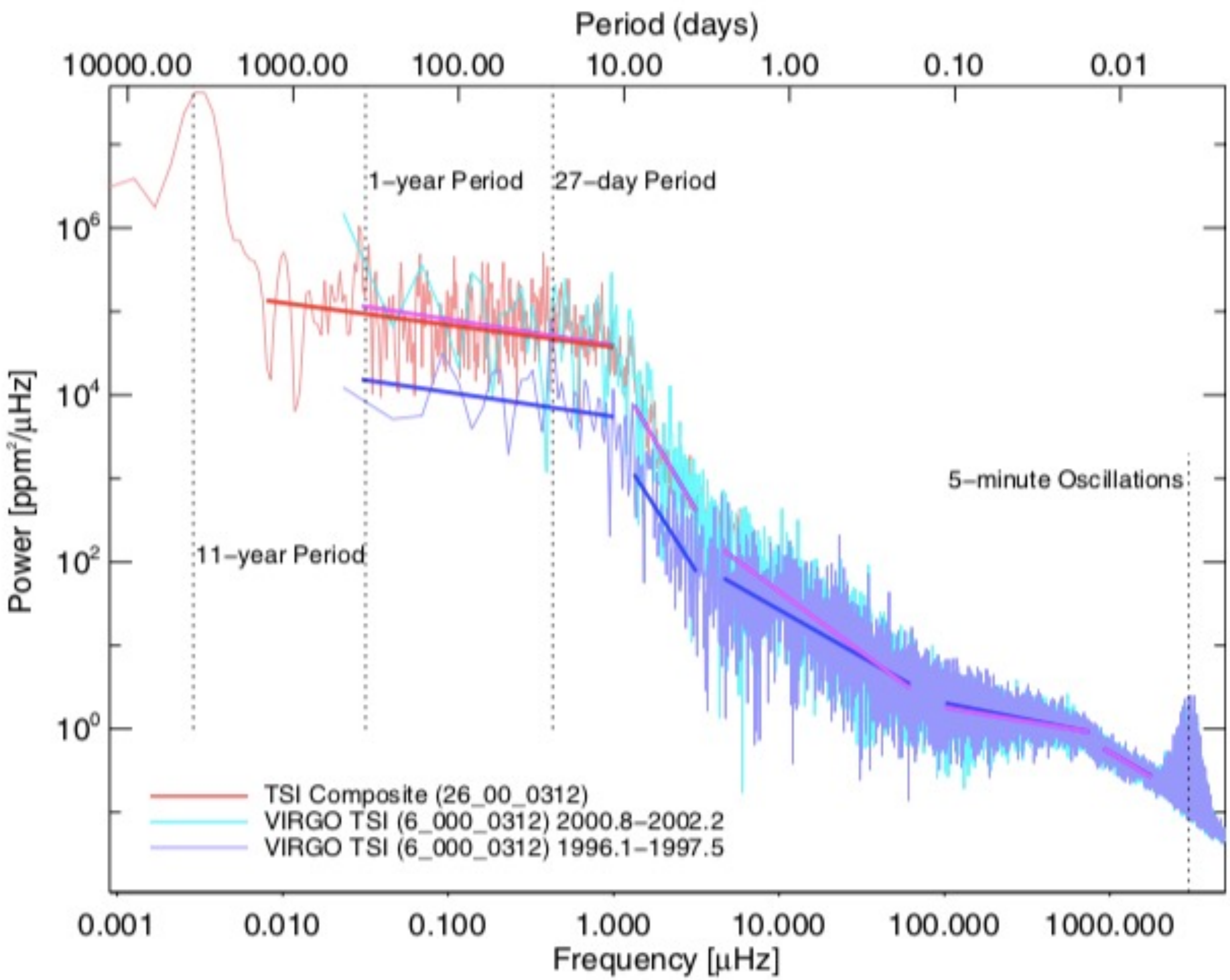
Variability occurs on many scales:

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

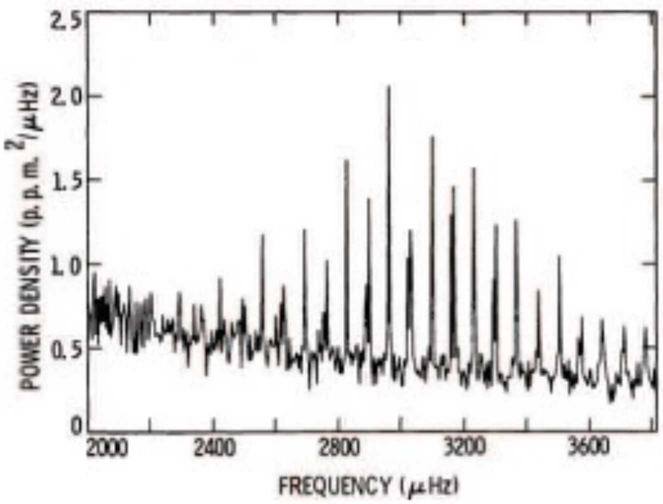
Note the "Maunder minimum" of the 17th century.

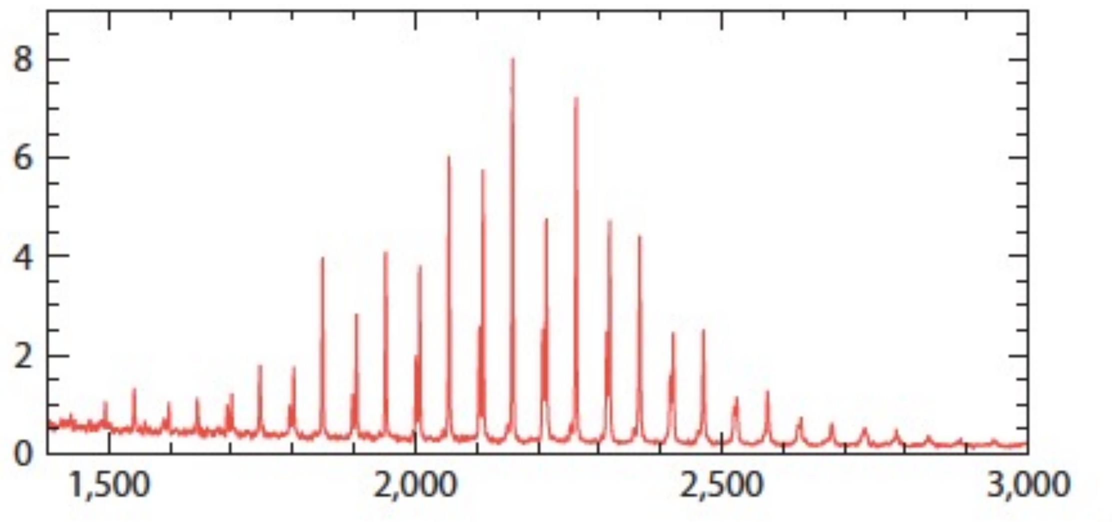


What is the solar power spectrum?



Solar and stellar p-modes

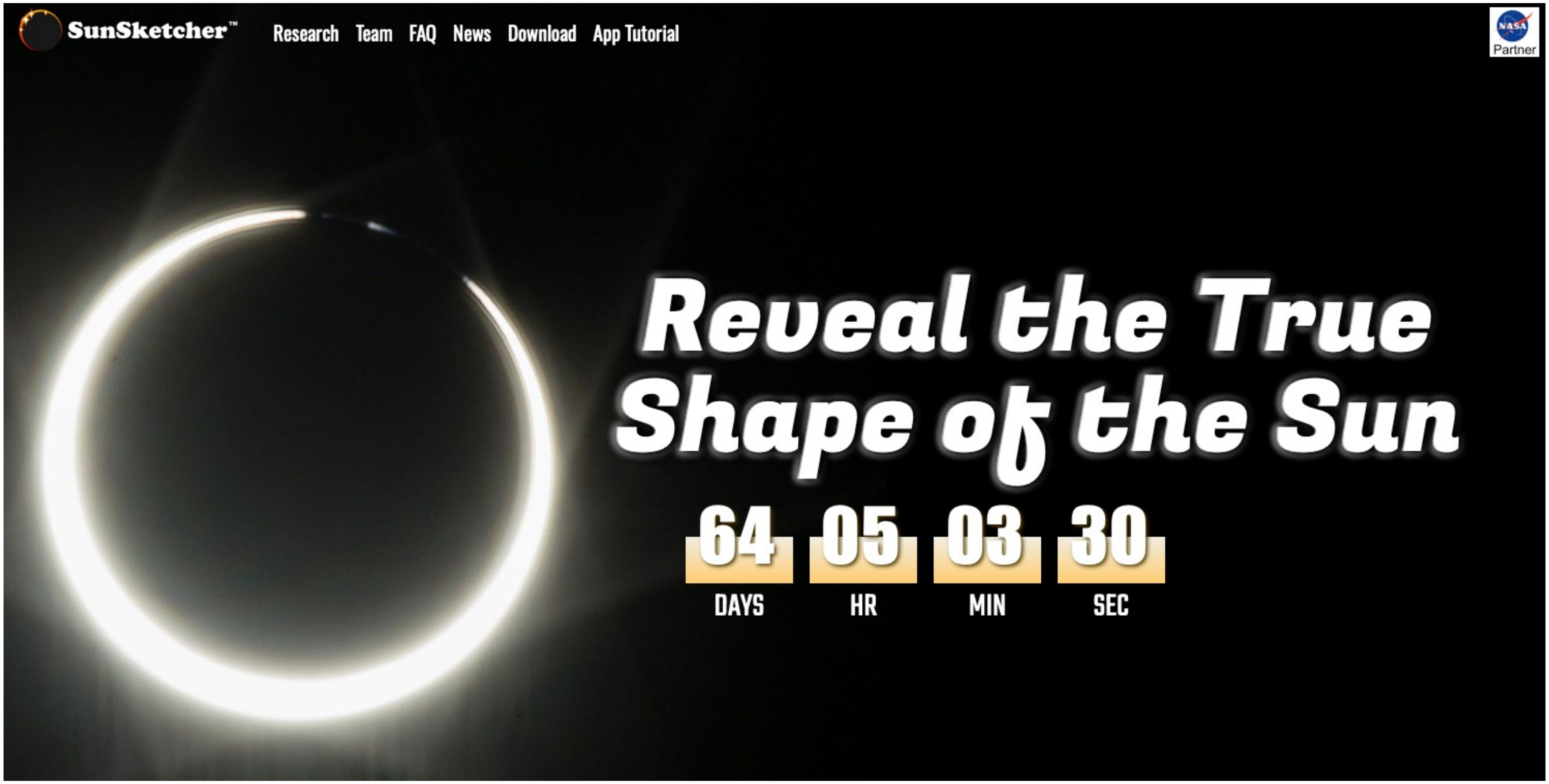




The Sun (Woodard, 1987)
- solar-type
- period ~27 d
- 4.85 x 10^{-6} pc
- m ~ -27

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

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