Multi-wavelength Layers of Solar Atmosphere from Photosphere to Corona

General Views

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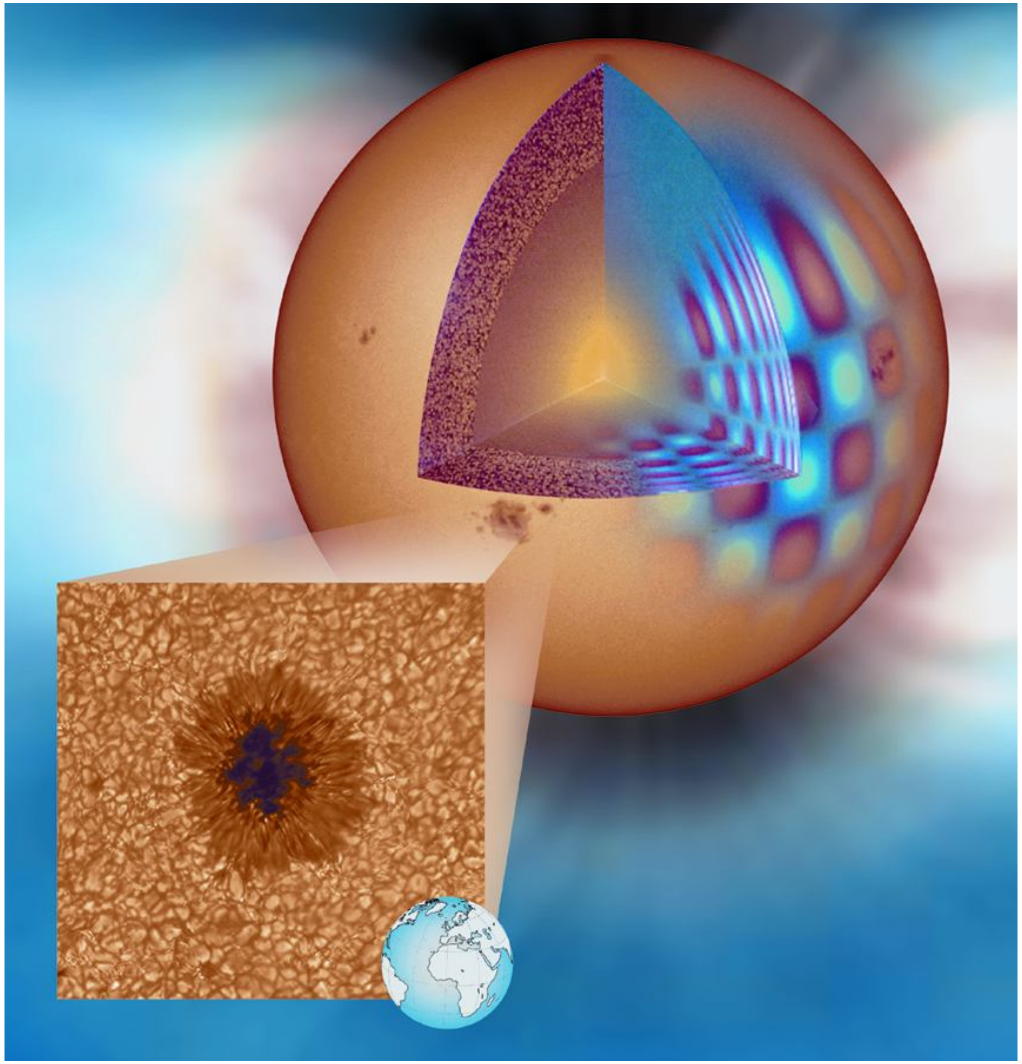
Outline

- Introduction
- Solar radiation and spectrum
  - Kirchoff Law
- Magnetic field
- Photosphere
- Chromosphere
- Corona

The nearest star: The Sun



- Mass = 1.99 1030 kg (= 1 M☉)
- Radius = 6.96 105 km
- Average density = 1.4 g/cm3
- Luminosity = 3.84 1026 W (= 1 L☉)
- Effective temperature = 5777 K (G2 V)
- Core temperature = 15 106 K
- Age = 4.55 109 years (from meteorite isotopes)
- Distance = 1 AU = 1.496 (+/- 0.025) 108 km
- Rotation period = 27 days at equator (sidereal, i.e. as seen from Earth; Carrington rotation)
- Surface gravitational acceleration g = 274 m/s2

The Sun: a normal star

- The Sun is a normal star: with middle aged (4.5 Gyr) as a main sequence star with spectral type G2V
- Special as the nearest star:
  - it is the only star on which we can see full-disk and resolve the spatial-temporal scales on which fundamental processes take place (note: 1 arc sec = 722±12 km on solar surface)
  - It provides almost all the energy to the Earth
  - it provides us with a unique laboratory in which to learn about various branches of physics.

Structures and Layers

Solar interior: (Indirect observation)

- Energy transferred layers into hydrogen-burning core, radiative and convective zones

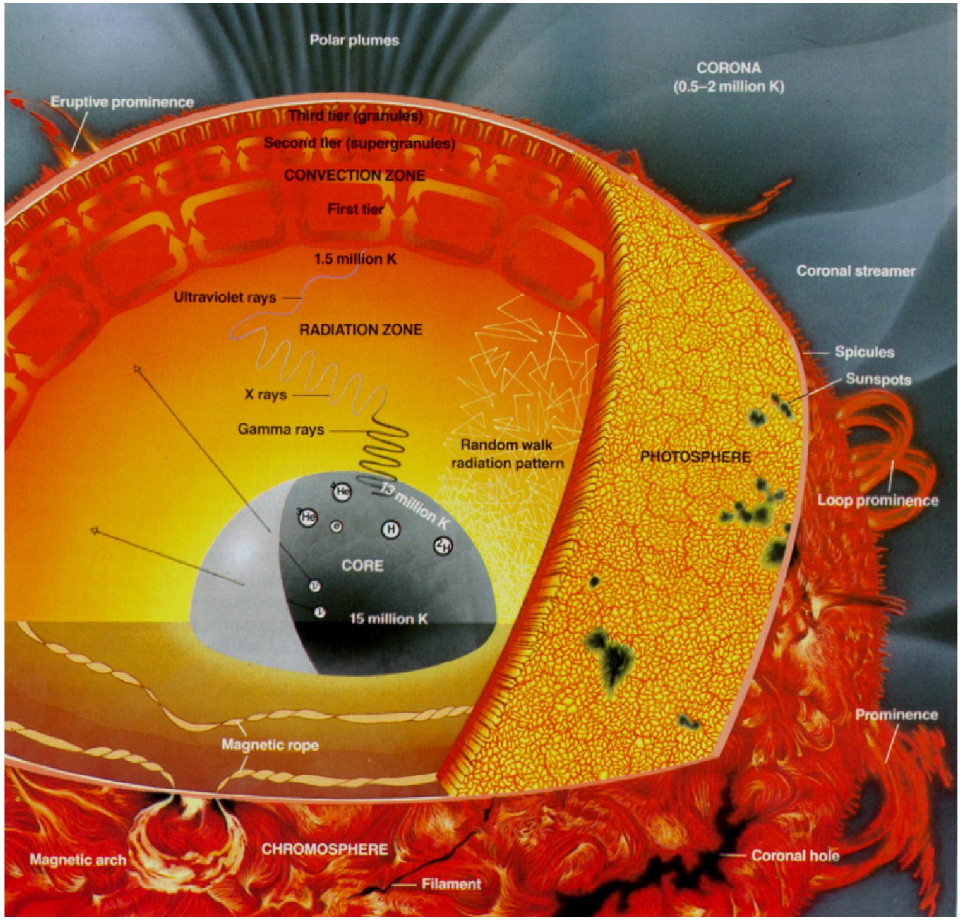
Solar atmosphere: (Direct observation)

- Divided into photosphere, chromosphere, corona and heliosphere

Solar surface

A point is reached where the average mean free path becomes so large that the photons escape from the Sun.

This point is defined as the solar surface. It corresponds to optical depth $\tau = 1$. Its height depends on λ. Often $\tau = 1$ at λ=5000 Å is used as a standard for the solar surface at Photospheric layer.



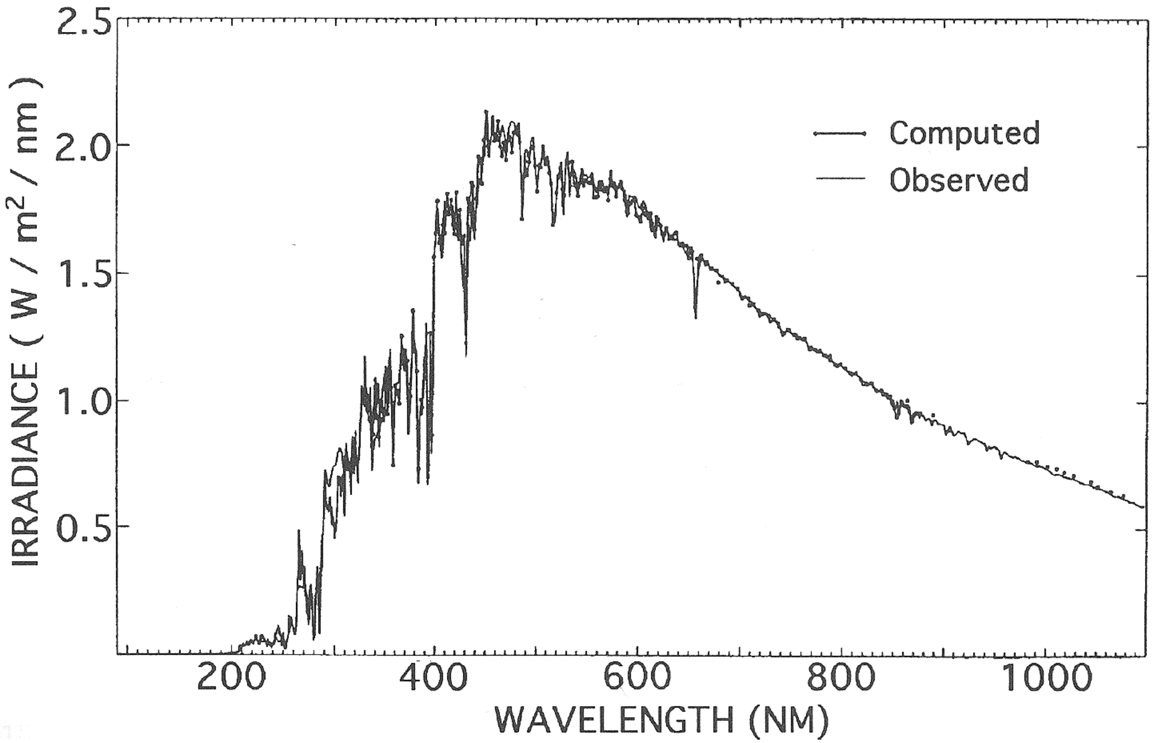
Solar radiation and spectrum

Solar irradiance spectrum

Irradiance = solar flux at 1AU

Spectrum is similar to Planck function

➔ Radiation comes from layers with different temperatures or different wavelength

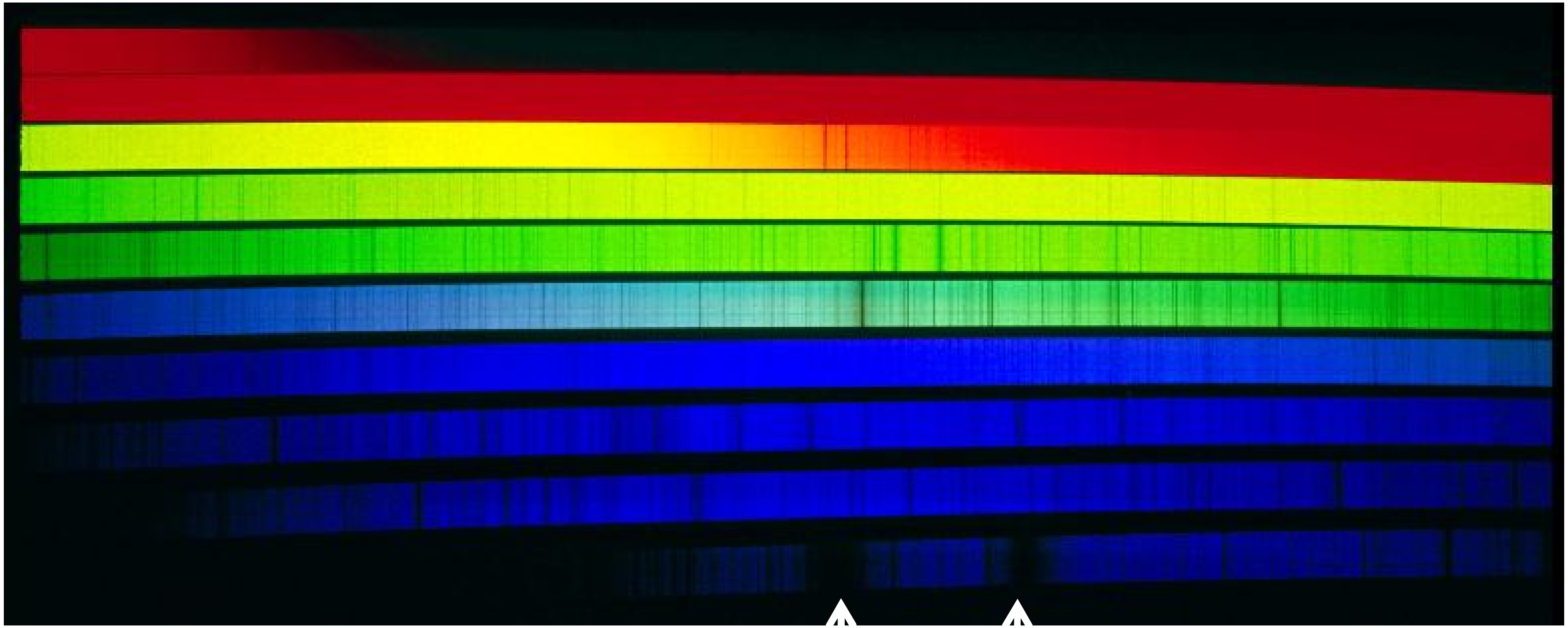


Effective temp: σT^4_{eff} = Area under flux curve

The solar spectrum: continua with absorption and emission lines

- The solar spectrum changes in character at different wavelengths.
  - X-rays: Emission lines of highly ionized species
  - EUV: Emission lines of neutral to multiply ionized species plus recombination continua
  - UV: stronger recombination continua and absorption lines
  - Visible: H^- bound-free continuum with absorption lines
  - FIR: H^- free-free continuum, increasingly cleaner (i.e. less lines, except molecular bands)
  - Radio: thermal and, increasingly, non-thermal continua

The photospheric spectrum



Ca II H, K

Selected Fraunhofer lines

Wavelength (Å)	Spectrum no.	Familiar name	W (Å)
2795	Mg II	k	22
2802	Mg II	h	16
3934	Ca II	K	19
3969	Ca II	H	14
4102	H I	Hδ	3
4341	H I	Hγ	4
4384	Fe I	d	1
4861	H I	Hβ	14
5890,5896	Na I	D	2
6563	H I	Hα	16

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Kirchhoff Law

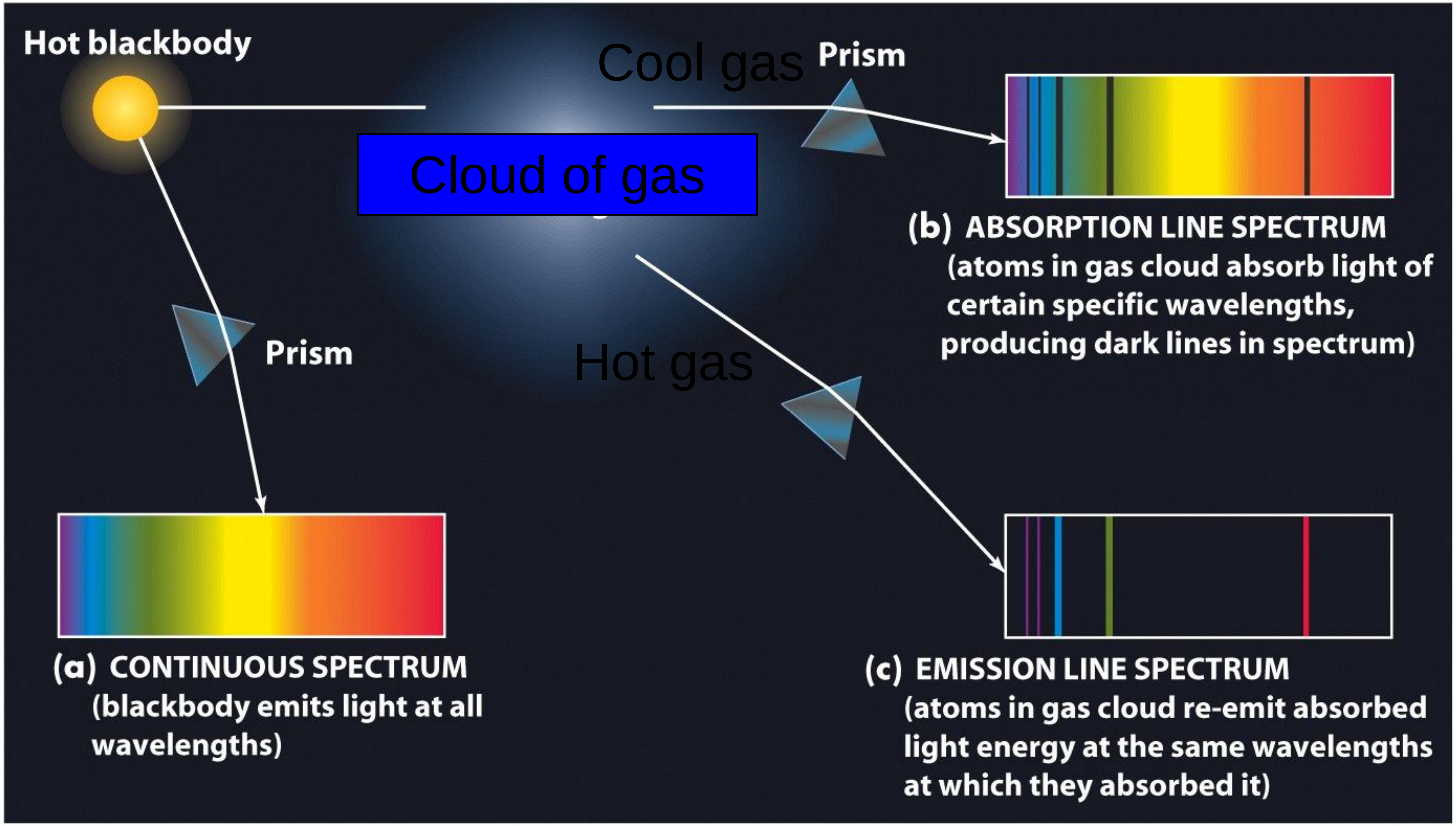
Gustav Robert Kirchhoff
(12 March 1824 – 17 October 1887)

Kirchhoff's Laws on Spectrum

- Law 1- Continuous spectrum: a hot opaque body, such as a perfect blackbody, produce a continuous spectrum – a complete rainbow of colors without any spectral line
- Law 2 – emission line spectrum: a hot, transparent gas produces an emission line spectrum – a series of bright spectral lines against a dark background
- Law 3 – absorption line spectrum: a relatively cool, transparent gas in front of a source of a continuous spectrum produces an absorption line spectrum – a series of dark spectral lines amongst the colors of the continuous spectrum. **Further, the dark lines of a particular gas occur at exactly the same wavelength as the bright lines of that same gas.**

Kirchhoff’s Laws on Spectrum

- Three different spectrum: continuous spectrum, emission-line spectrum, and absorption line spectrum

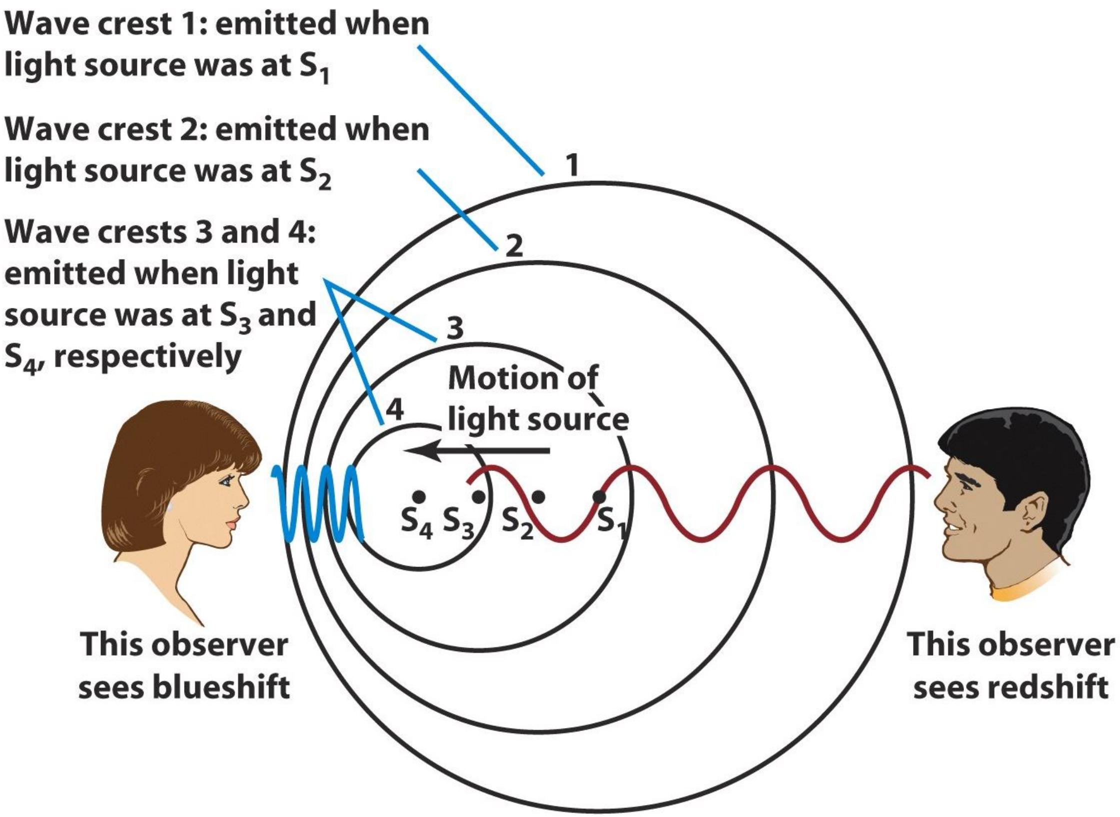


Diagnostic tools of spectral lines

- Doppler shift of line: flows in the Line of Sight direction.
- Line width: temperature and turbulent velocity
- Equivalent width: elemental abundance, temperature (via ionisation and excitation balance)
- Line depth: temperature and temperature gradient
- Line asymmetry: inhomogenities of solar atmosphere.

Doppler Effect

- **Doppler effect: the wavelength of light is affected by motion between the light source and an observer**



- **Red Shift**: The object is moving away from the observer, the line is shifted toward the longer wavelength
- **Blue Shift**: The object is moving towards the observer, the line is shifted toward the shorter wavelength

$$\Delta\lambda/\lambda_o = v/c$$

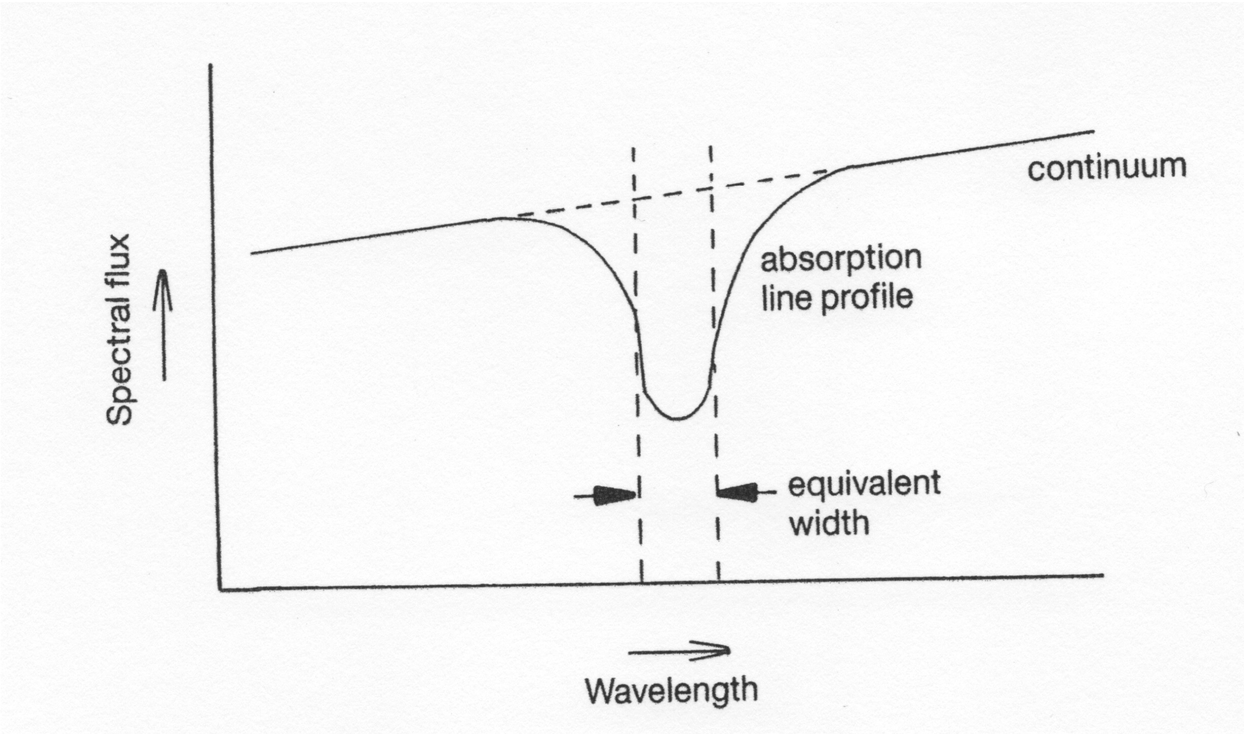
$\Delta\lambda$ = wavelength shift

λ_o = wavelength if source is not moving

v = velocity of source

c = speed of light

Equivalent width of absorption

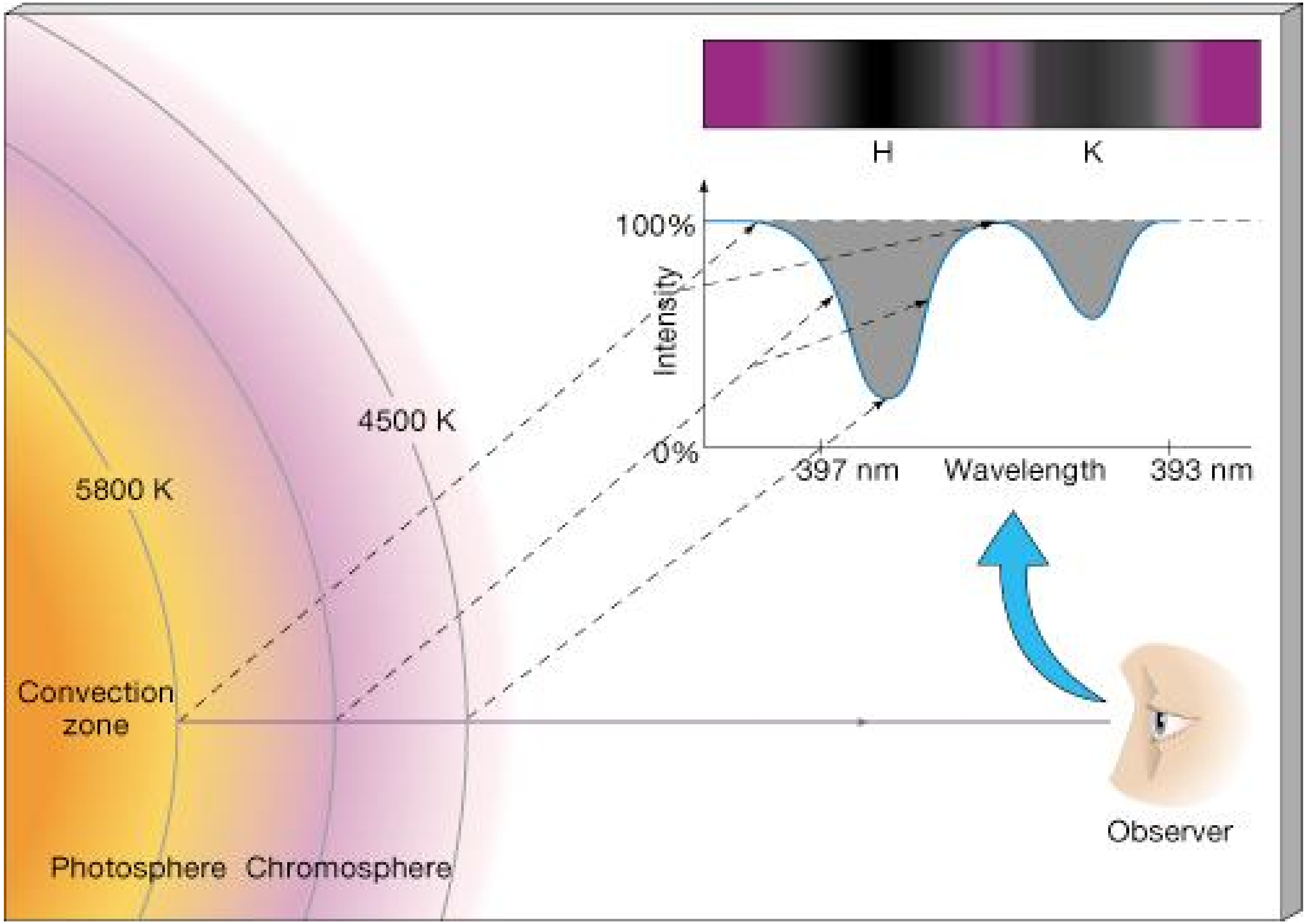


Equivalent width of spectral line is

$$W_\lambda = \int (F_{cont} - F_\lambda)/F_{cont}\, d\lambda$$

Units of equivalent width are Å.

Spectrum Formation



Elemental abundances

Photospheric values

- Logarithmic (to base 10) abundances of the 32 lightest elements on a scale on which H has an abundance of 12
- Heavier elements all have low abundances
- Note that in general the solar photospheric abundances are very similar to those of meteorites, with exception of Li, with is depleted by a factor of 100.

Element	Photosphere	Meteorites
1 H	12.00	–
2 He	10.93 ± 0.004	–
3 Li	1.10 ± 0.10	3.31 ± 0.04
4 Be	1.40 ± 0.09	1.42 ± 0.04
5 B	2.55 ± 0.30	2.79 ± 0.05
6 C	8.52 ± 0.06	–
7 N	7.92 ± 0.06	–
8 O	8.83 ± 0.06	–
9 F	4.56 ± 0.3	4.48 ± 0.06
10 Ne	8.08 ± 0.06	–
11 Na	6.33 ± 0.03	6.32 ± 0.02
12 Mg	7.58 ± 0.05	7.58 ± 0.01
13 Al	6.47 ± 0.07	6.49 ± 0.01
14 Si	7.55 ± 0.05	7.56 ± 0.01
15 P	5.45 ± 0.04	5.56 ± 0.06
16 S	7.33 ± 0.11	7.20 ± 0.06
17 Cl	5.5 ± 0.3	5.28 ± 0.06
18 Ar	6.40 ± 0.06	–
19 K	5.12 ± 0.13	5.13 ± 0.02
20 Ca	6.36 ± 0.02	6.35 ± 0.01
21 Sc	3.17 ± 0.10	3.10 ± 0.01
22 Ti	5.02 ± 0.06	4.94 ± 0.02
23 V	4.00 ± 0.02	4.02 ± 0.02
24 Cr	5.67 ± 0.03	5.69 ± 0.01
25 Mn	5.39 ± 0.03	5.53 ± 0.01
26 Fe	7.50 ± 0.05	7.50 ± 0.01
27 Co	4.92 ± 0.04	4.91 ± 0.01
28 Ni	6.25 ± 0.04	6.25 ± 0.01
29 Cu	4.21 ± 0.04	4.29 ± 0.04
30 Zn	4.60 ± 0.08	4.67 ± 0.04
31 Ga	2.88 ± 0.10	3.13 ± 0.02
32 Ge	3.41 ± 0.14	3.63 ± 0.04

Magnetic Field

Methods of magnetic field measurement

- Direct methods:
  - Zeeman effect ➔ polarized radiation
- Indirect methods: Proxies
  - Bright or dark features in photosphere (sunspots, G-band bright points)
  - Ca II H and K plage (Chromosphere)
  - Fibrils seen in chromospheric lines, e.g. Hα (Chromosphere)
  - Coronal loops seen in EUV or X-radiation (Corona)

Zeeman diagnostics

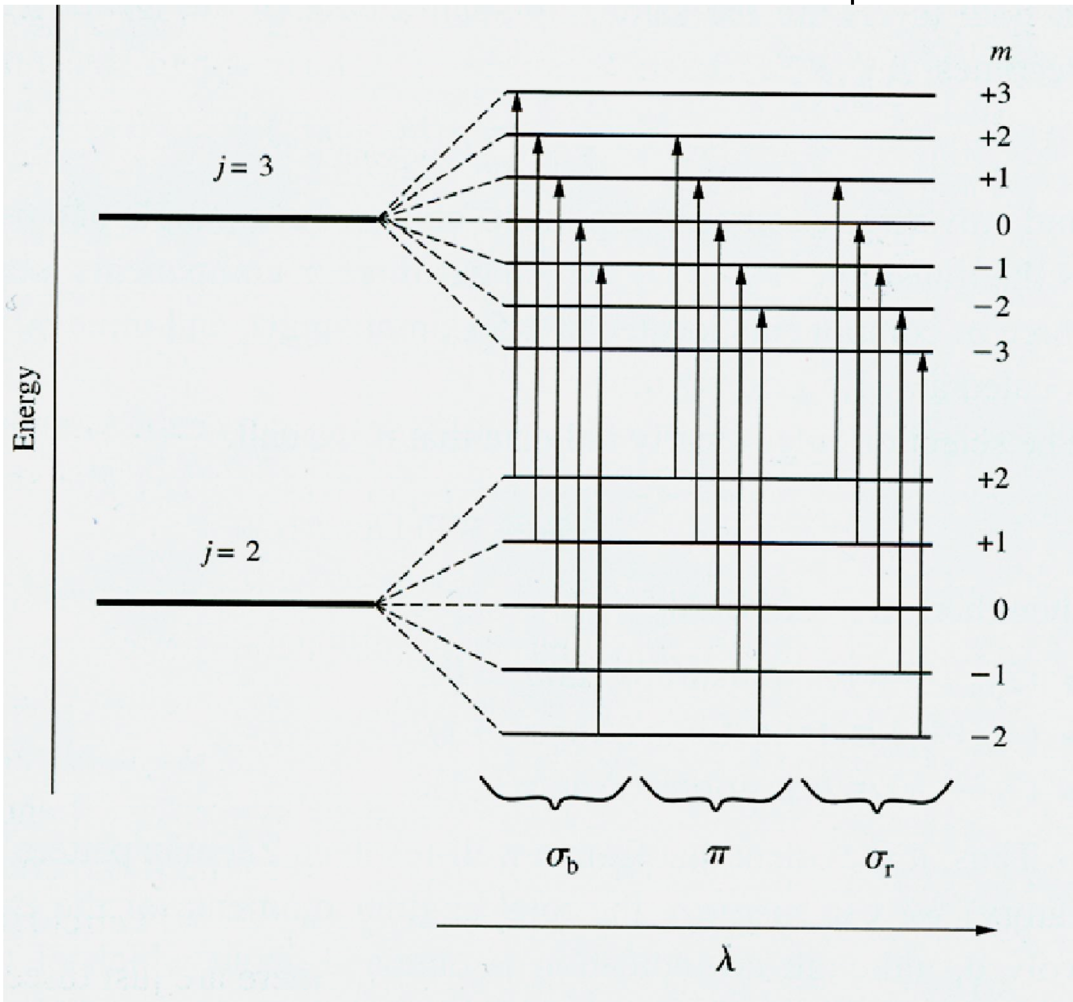
- Direct detection of magnetic field by observation of magnetically induced splitting and polarisation of spectral lines
- Important: Zeeman effect changes not just the spectral shape of a spectral line (often subtle and difficult to measure), but also introduces a unique polarisation signature

→ Measurement of polarization is central to measuring solar magnetic fields.

Zeeman splitting of atomic levels

- In the presence of a B-field a level with total angular moment J will split into $2J+1$ sublevels with different M.
- $E_{J,M} = E_J + \mu_0 g M_J B$
- Transitions are allowed between levels with $\Delta J = 0, \pm 1$ & $\Delta M = 0$ (π), ± 1 (σ_b, σ_r)
- Splitting is determined by Lande factor g :

  $g(J,L,S) = 1 + (J(J+1) + S(S+1) - L(L+1))/2J(J+1)$

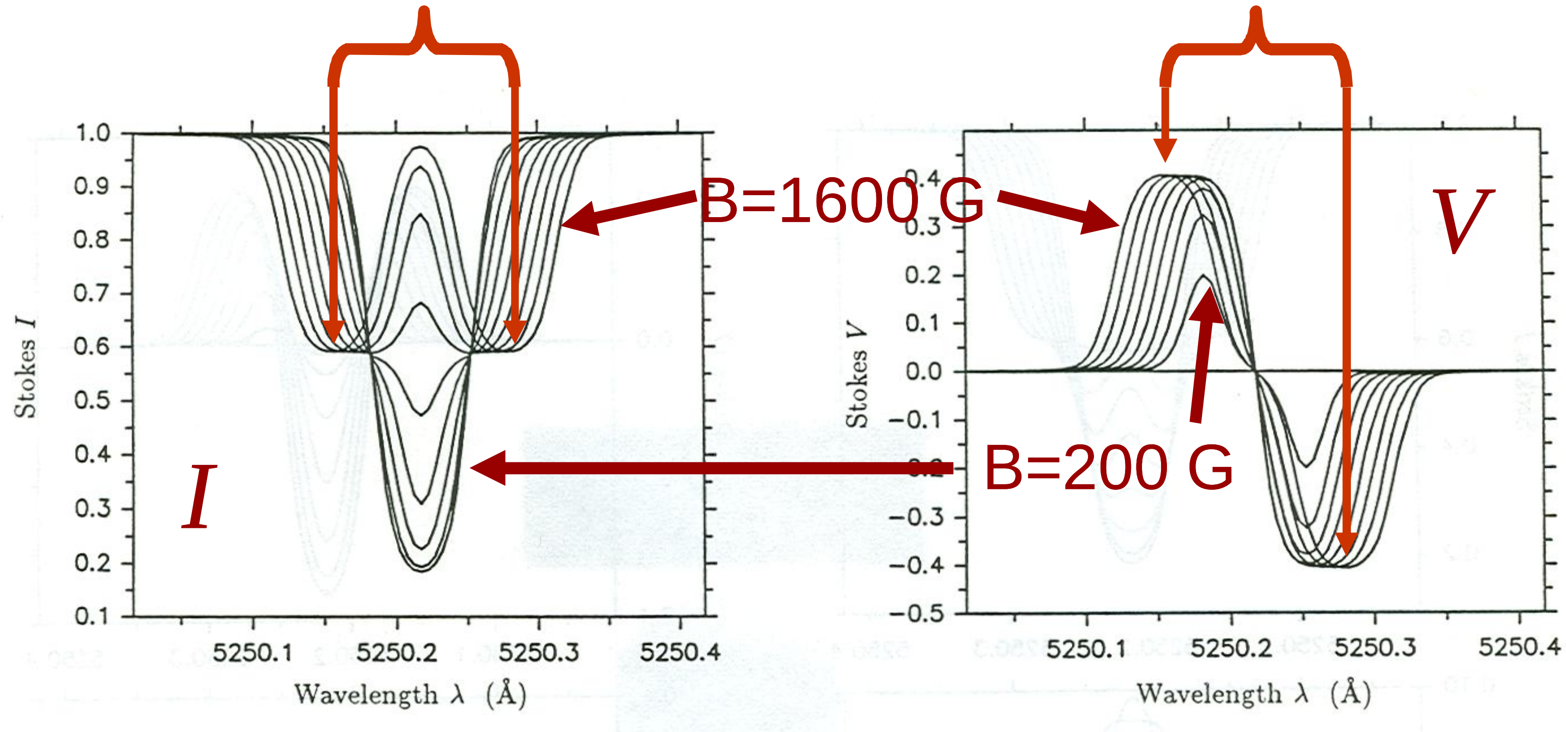


Effect of changing field strength

Formula for Zeeman splitting (for B in G, λ in Å):

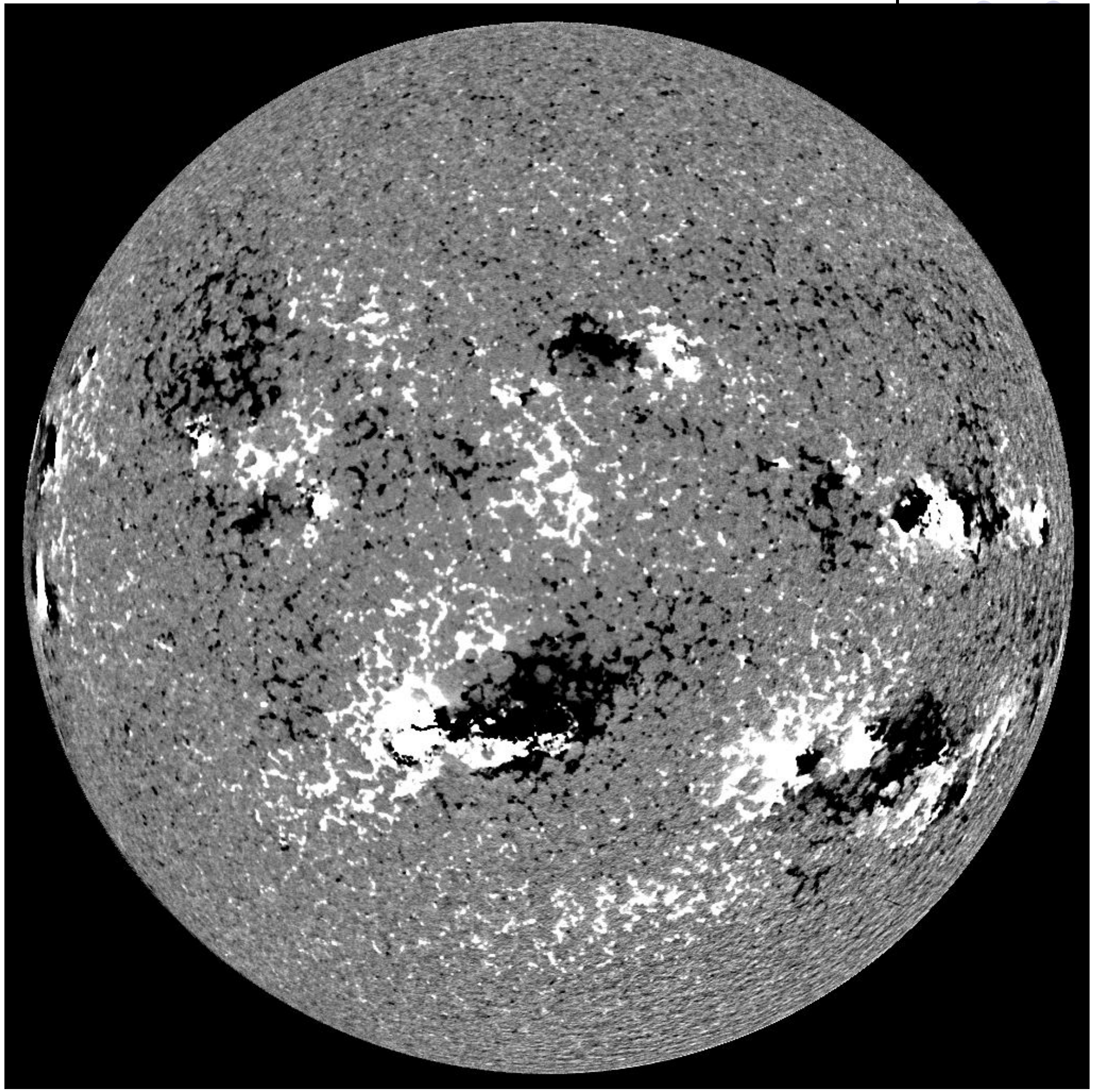
$$\Delta\lambda_H = 4.67\ 10^{-13}\ g_{eff}\, B\, \lambda^2 \quad [\text{Å}]$$

g_{eff}=effective Lande factor of line



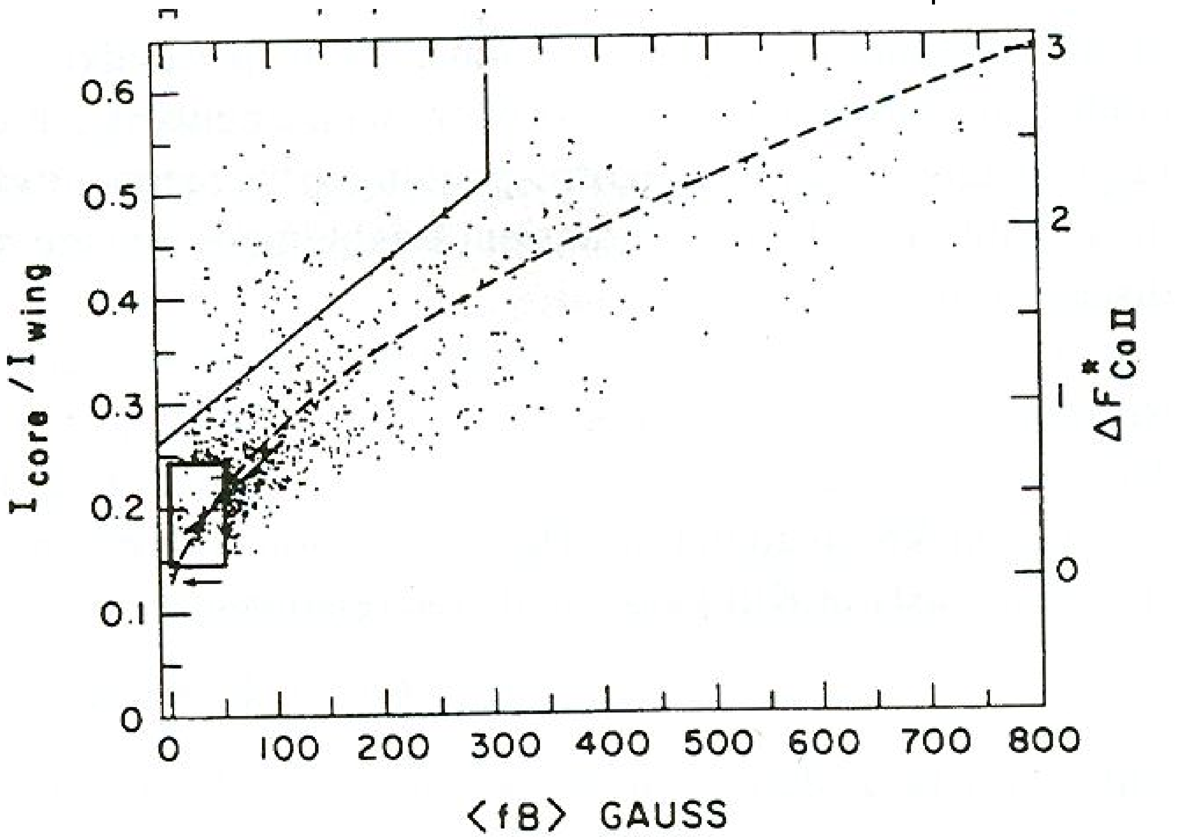
Magnetograms

- Magnetograph: Instrument that makes maps of (net circular) polarization in wing of Zeeman sensitive line.
- Example of magnetogram obtained by MDI
- Conversion of polarization into magnetic field requires a careful calibration.



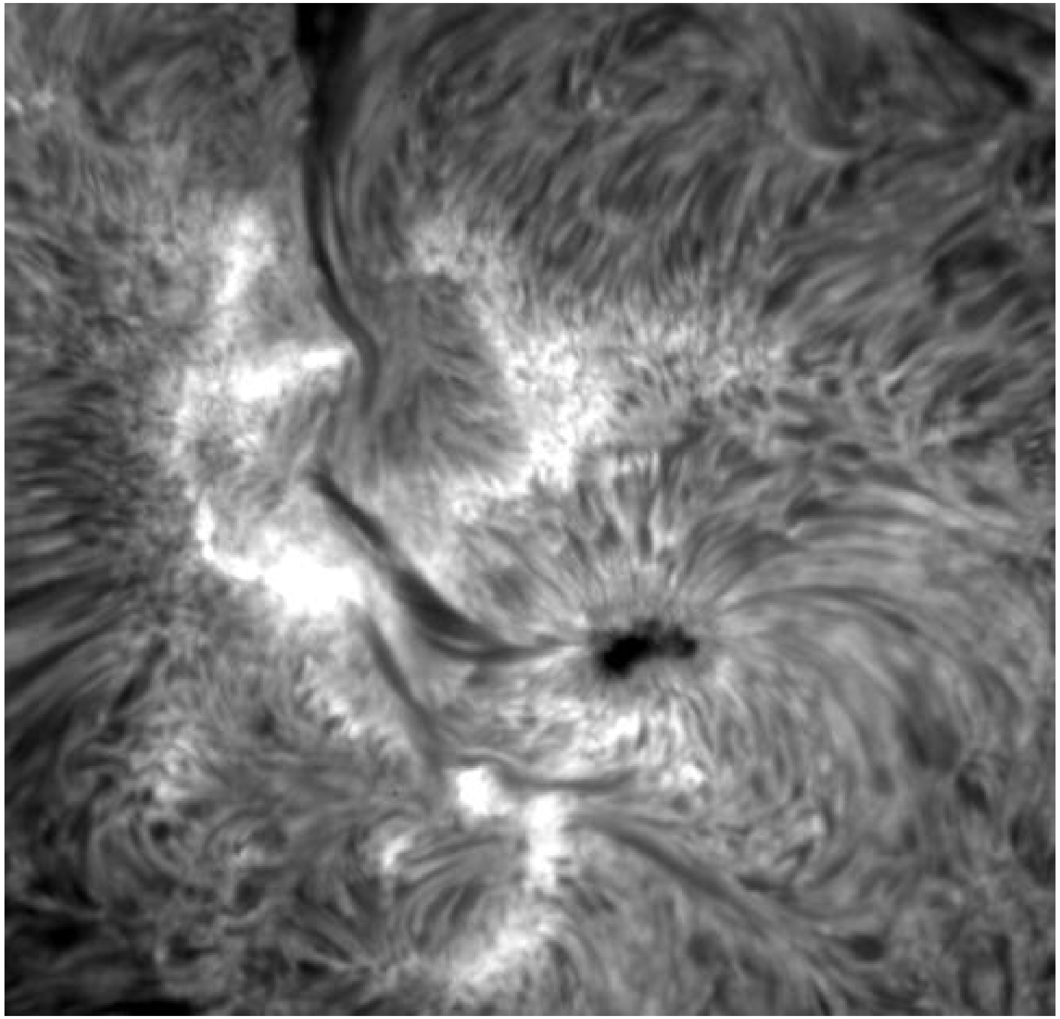
Ca II K as a magnetic field proxy

- Ca II H and K lines, the strongest lines in the visible solar spectrum, show a strongly increasing brightness with non-spot magnetic flux.
- The increase is slower than linear
- Magnetic regions (except sunspots) appear bright in Ca II: Ca plage and network regions



Hα and the chromospheric field

- Hα images of active regions show a structure similar to iron filing around a magnet.
- Relatively horizontal field in chromosphere?
- Note spiral structure around sunspot.

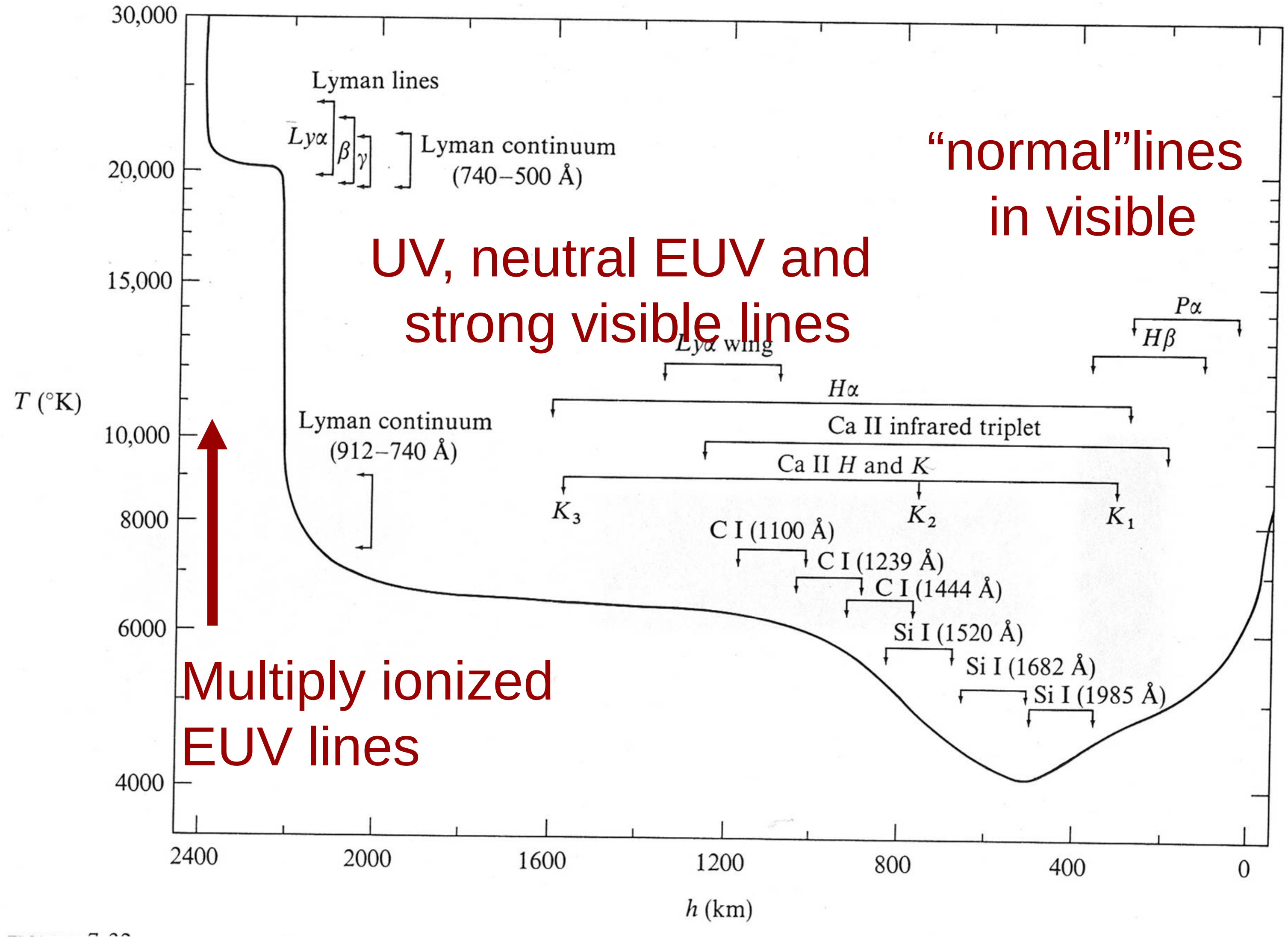


The Solar Atmosphere

The solar atmosphere

- The solar atmosphere is generally described as being composed of multiple layers, with the lowest layer being the photosphere, followed by the chromosphere, the transition region and the corona.
- In its simplest form it is modelled as a single component plane-parallel atmosphere.
- Density drops exponentially: $\rho(z) = \rho_0 \exp(-z/H_\rho)$ (for isothermal atmosphere). T=6000K ➔ $H_\rho \approx 100\mathrm{km}$
- Mass of the solar atmosphere ≈ mass of the Indian ocean (≈ mass of the photosphere)
- Mass of the chromosphere ≈ mass of the Earth's atmosphere

Heights of formation

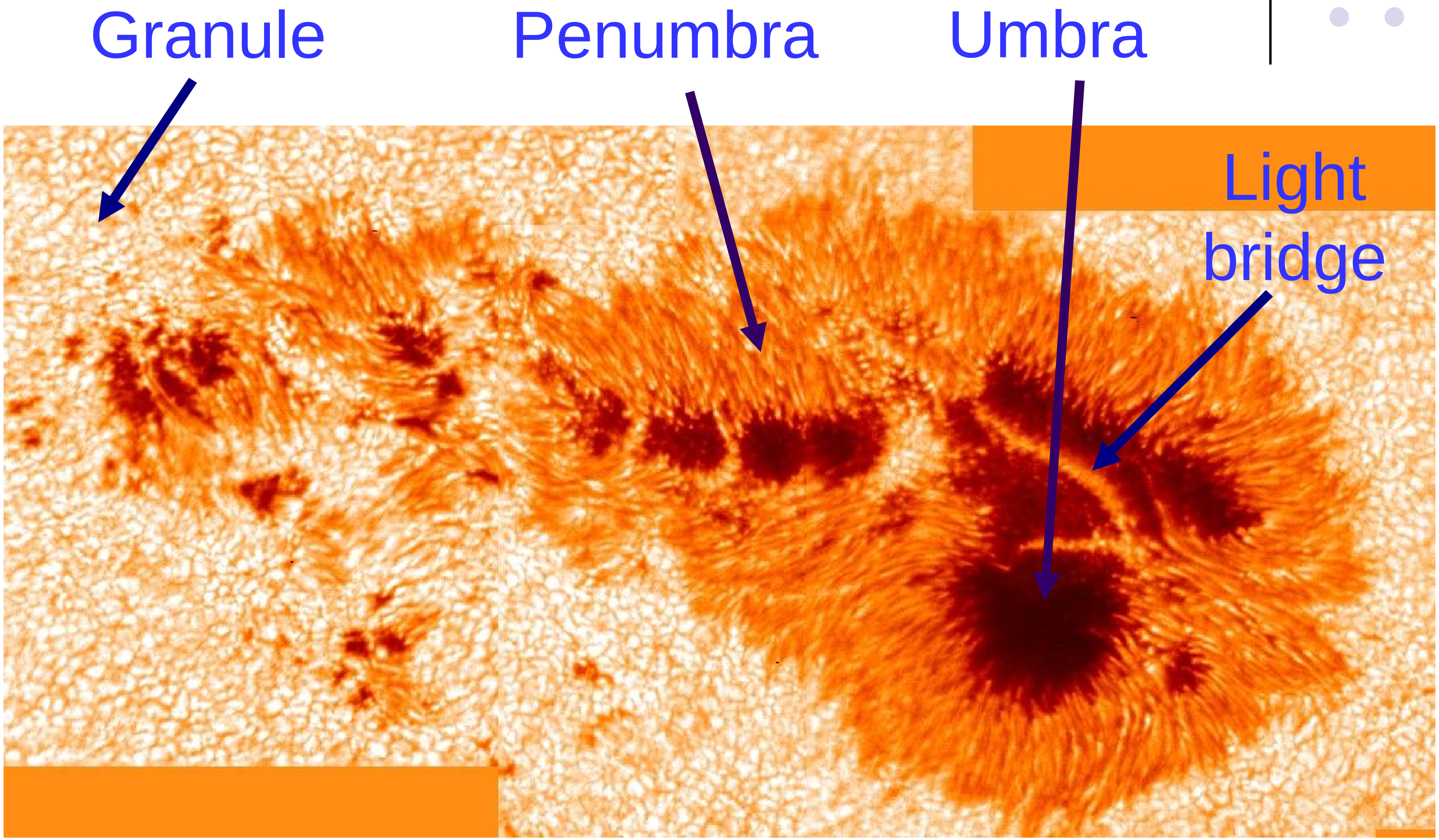


The Photosphere

The photosphere

- The photosphere extends between the solar surface and the temperature minimum, from which most of the solar radiation arises.
- The visible, UV (λ> 1600Å) and IR (< 100μm) radiation comes from the photosphere.
- 4000 K < T(photosphere) < 6000 K
- T decreases outwards ➔ $B_\nu(T)$ decreases outward ➔ absorption spectrum
- LTE is a good approximation
- Energy transport by convection and radiation
- Main structures: Granules, sunspots and faculae

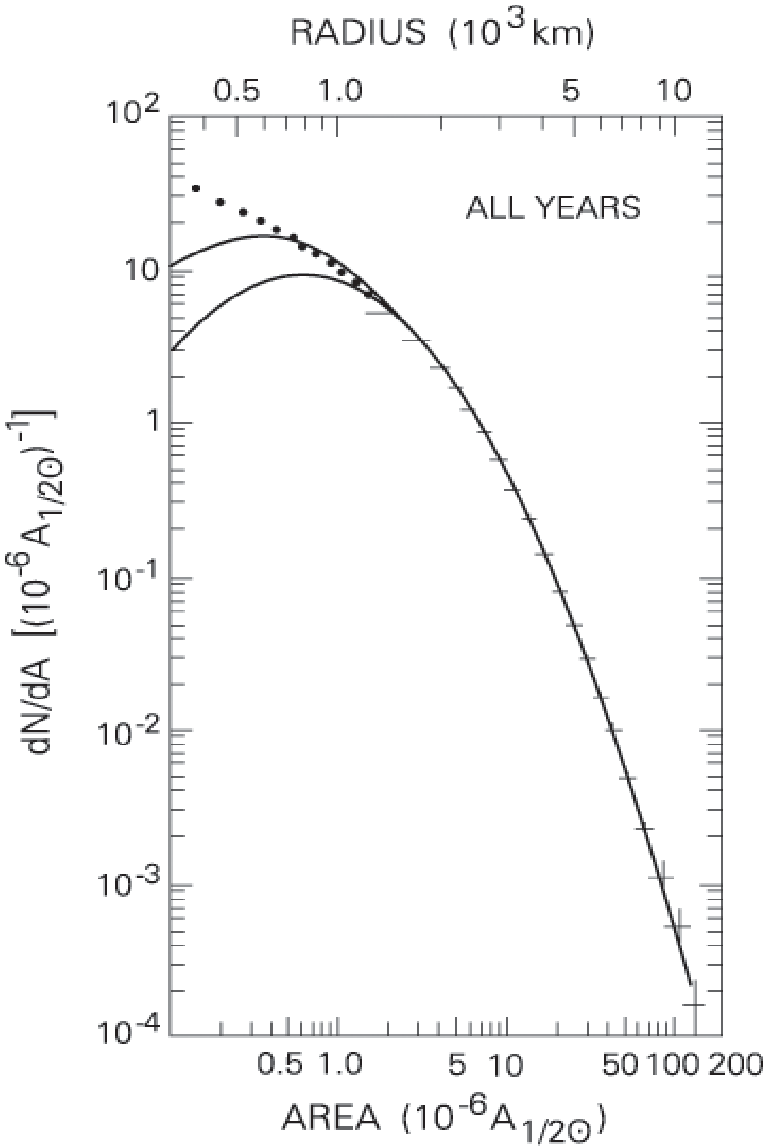
White-light Sun: Sunspots



H. Schleicher, KIS/VTT, Obs. del Teide, Tenerife

Sunspots, morphology

- Sizes: Log-normal size distribution. Overlap with pores (log-normal = Gaussian on a logarithmic scale)
- Lifetimes: T between hours & months: Gnevyshev-Waldmeier rule: $A_{max} \sim T$, where A_{max} = max spot area.
- Brightness: umbra: 20% of quiet Sun, penumbra: 75%

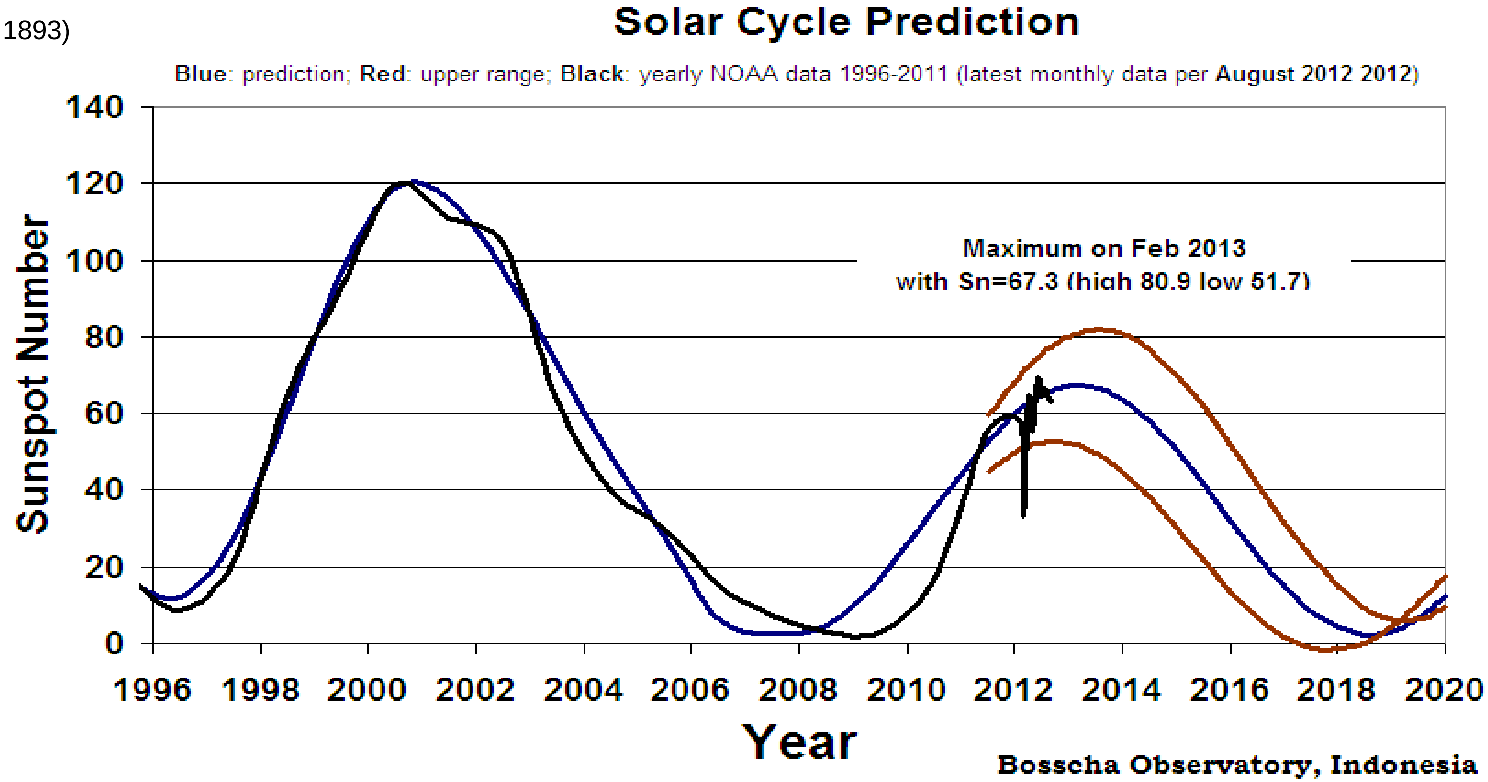


Solar Cycle Prediction

Johann Rudolf Wolf
(7 July 1816 – 6 December 1893)

$$y = y_0 + a * \exp(-0.5 * (\ln(\frac{x}{x_0})/b)^2) + c * \sin(2\pi * (x - x_0)/d + e)^2$$

From 1848, the Wolf number was called. In 1852 Wolf was discovered the link between the cycle and geomagnetic activity on Earth.



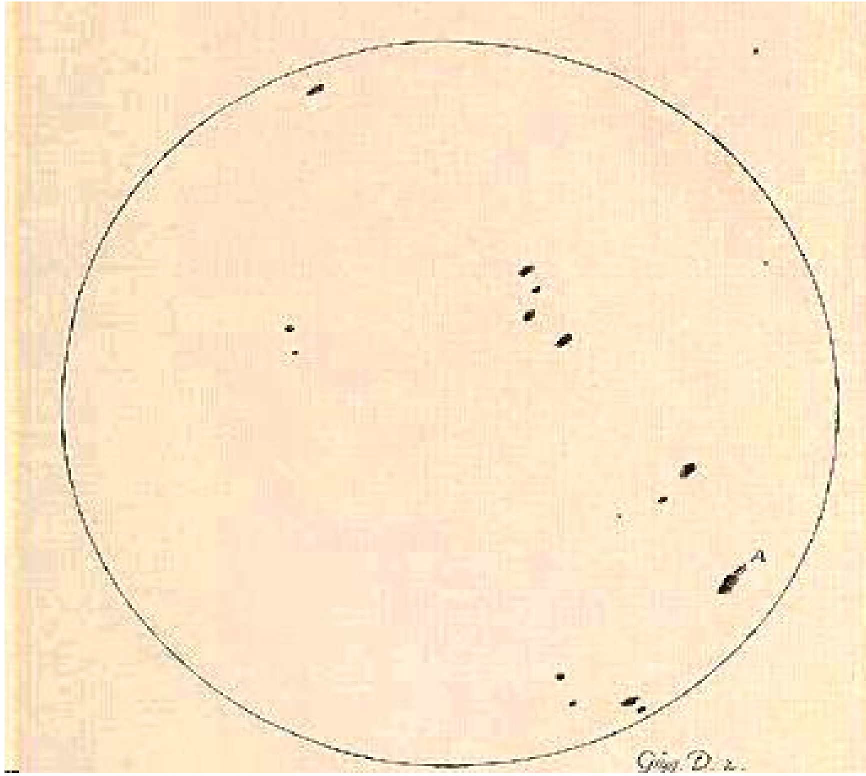
Maximum on Feb 2013
with Sn=67.3 (high 80.9 low 51.7)

(Herdiwijaya, 2004, 2010)

Sunspot Motion: solar rotation

- Galileo Galilei and Christoph Scheiner noticed already that sunspots move across the solar disk in accordance with the rotation of a round body

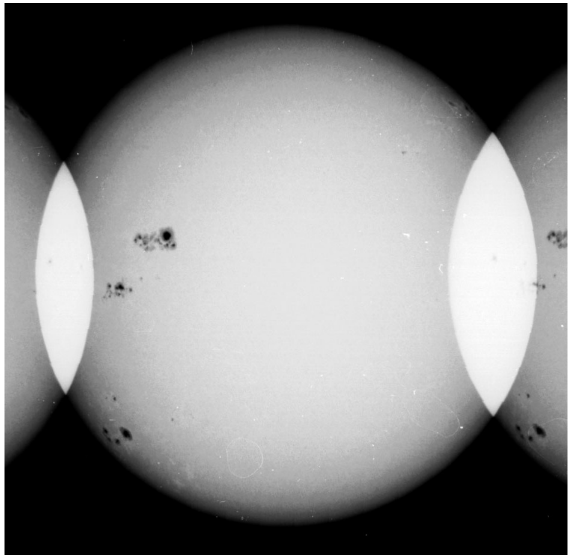
➔ Sun is a rotating sphere



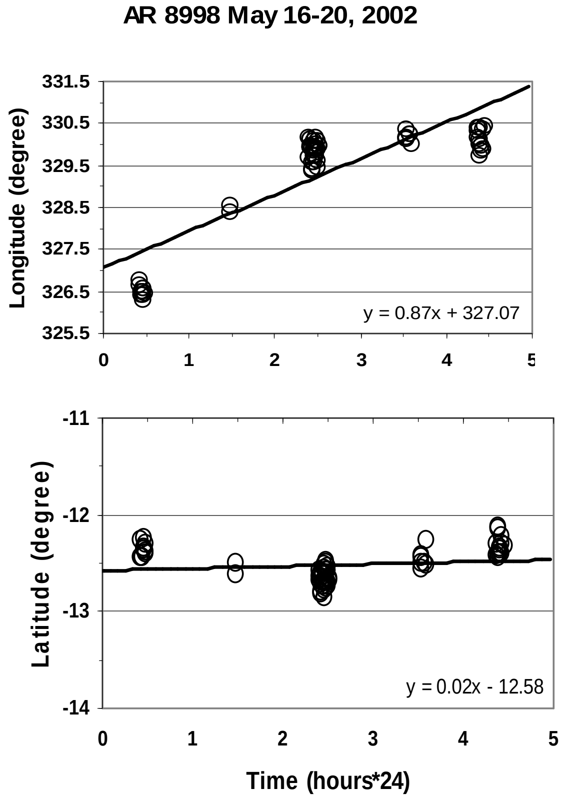
Sunspot Proper Motion

- can trigger magnetic reconnection
- interface/mirror to the interior

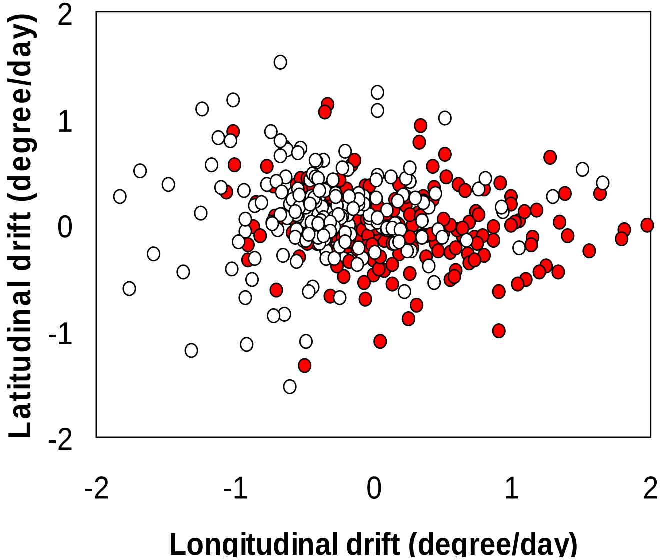
16 May 2000 04:12:05 UT
(Unitron, 10.2 cm/1200 mm)

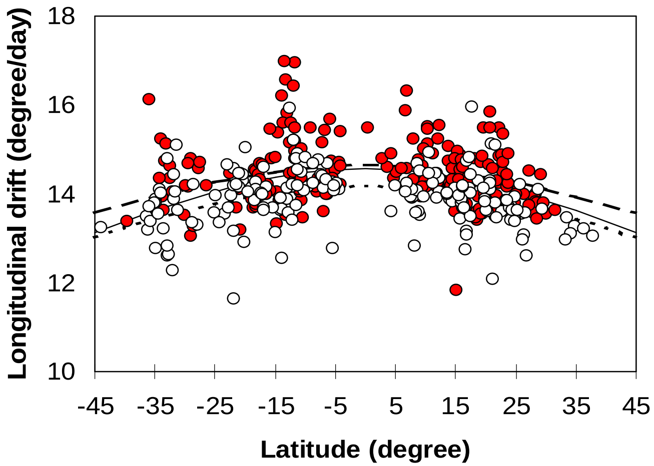


Multi-exposures images were taken with Nikon D3,Fuji film ASA 6



(Black: preceding polarity; White: following polarity)



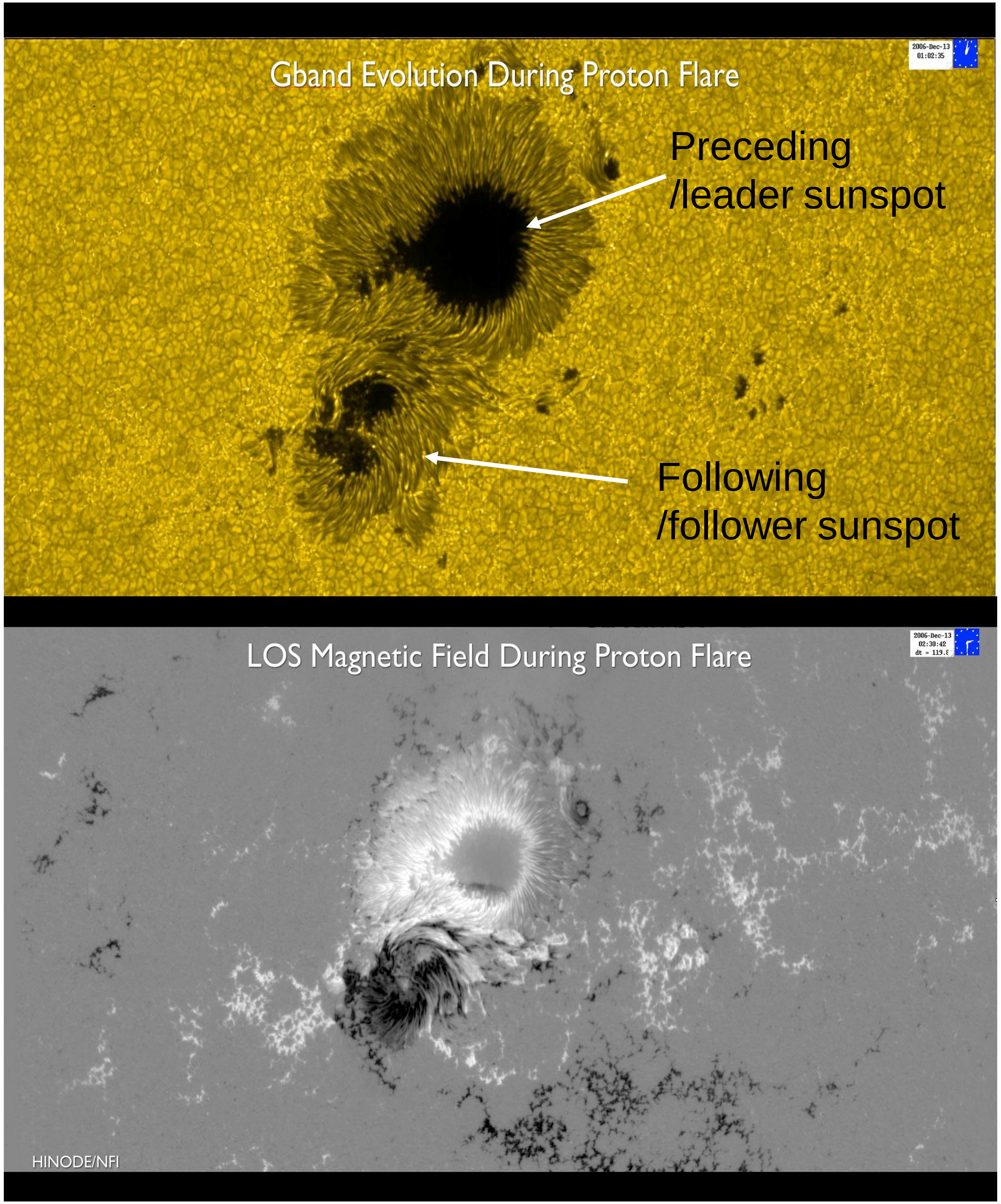


$\omega(B) = 14.5 \pm 0.5 - 2.4 \pm 0.4 \sin^2 B$

Meridional flow ~ 5 m/s (equatorward)

(484 individual sunspot)

(Herdiwijaya et al. 2002)



Hinode white-light and magnetogram images,

13 Dec 2006, 01:02:35 and 02:30:42

Surface differential rotation

- Poles rotate slower than equator.
- Surface differential rotation from measurements of:
  - Tracers, such a sunspots or magnetic field elements (always indicators of the rotation rate of the magnetic field)
  - Doppler shifts of the gas
  - Coronal holes (not plotted) rotate rigidly
- Magnetic tracers rotate faster than gas surrounding

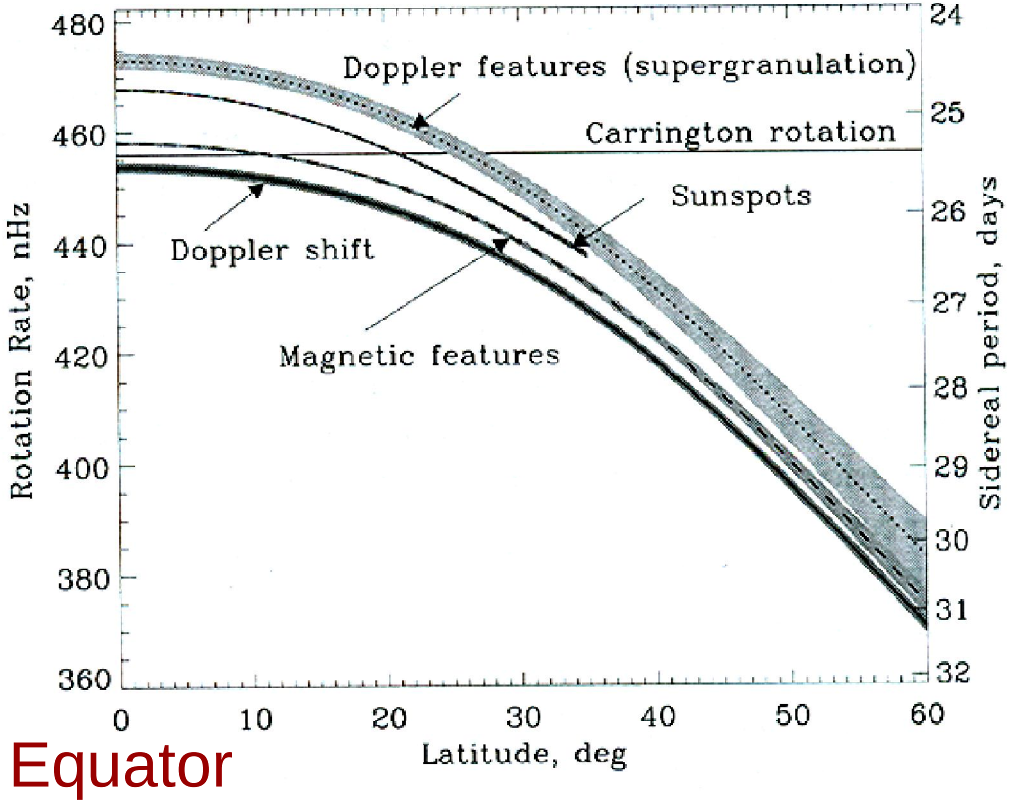
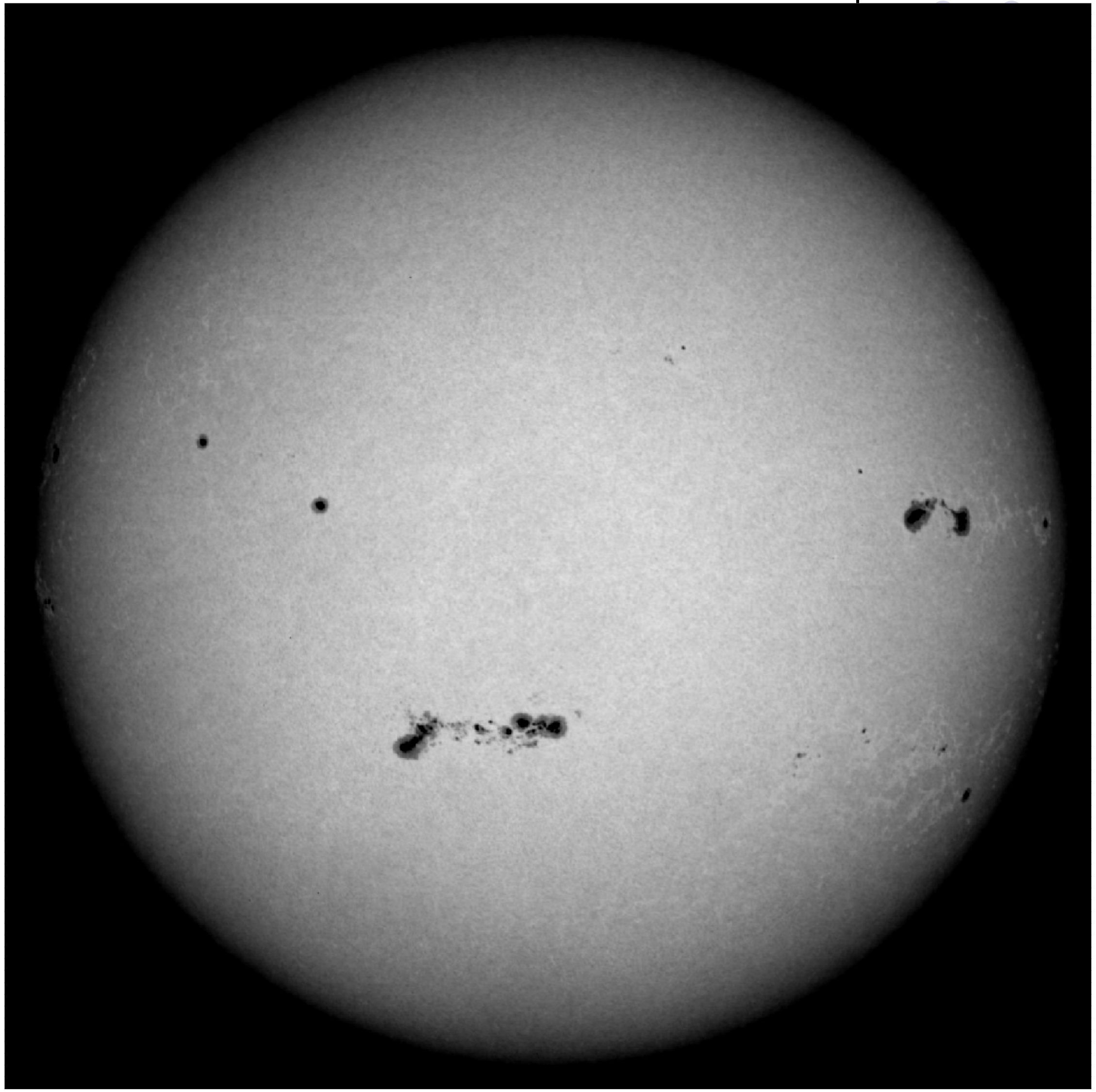


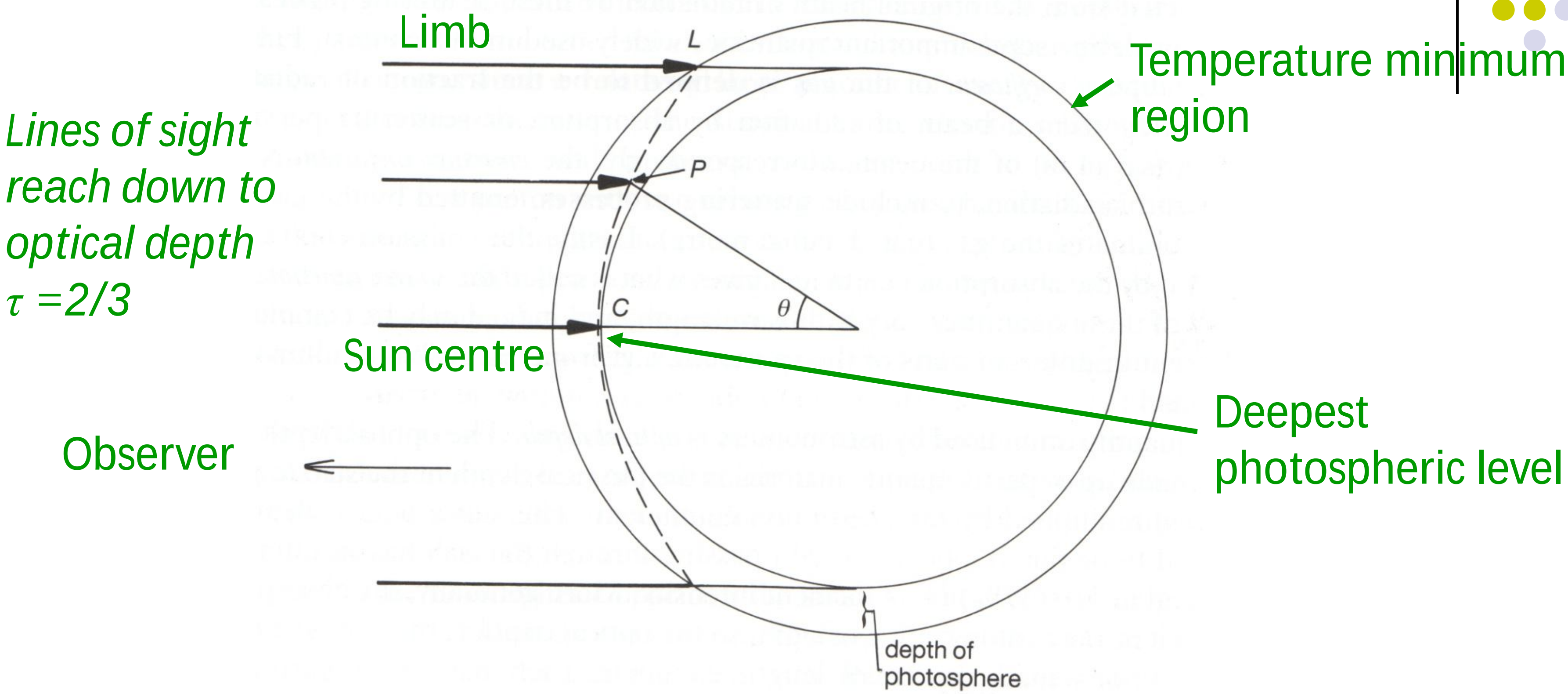
Figure 1. Rotation rate, $\Omega/2\pi$, and period of various tracers on the Sun's surface: recurrent (old) sunspots (dashed curve), magnetic features (dot–dash), and Doppler features (dots). The rotation rate and period determined spectroscopically through the Doppler shift are shown by the full curve. The shaded areas show the 1σ error estimates.

The Sun in white light: Limb darkening

- In the visible, the Sun's limb is darker than the centre of the solar disk (Limb darkening)
- Since intensity ~ Planck function, $B_\nu(T)$, T is lower near limb.
- Due to grazing incidence we see higher near limb: T decreases outward



The Sun's effective and surface temperature

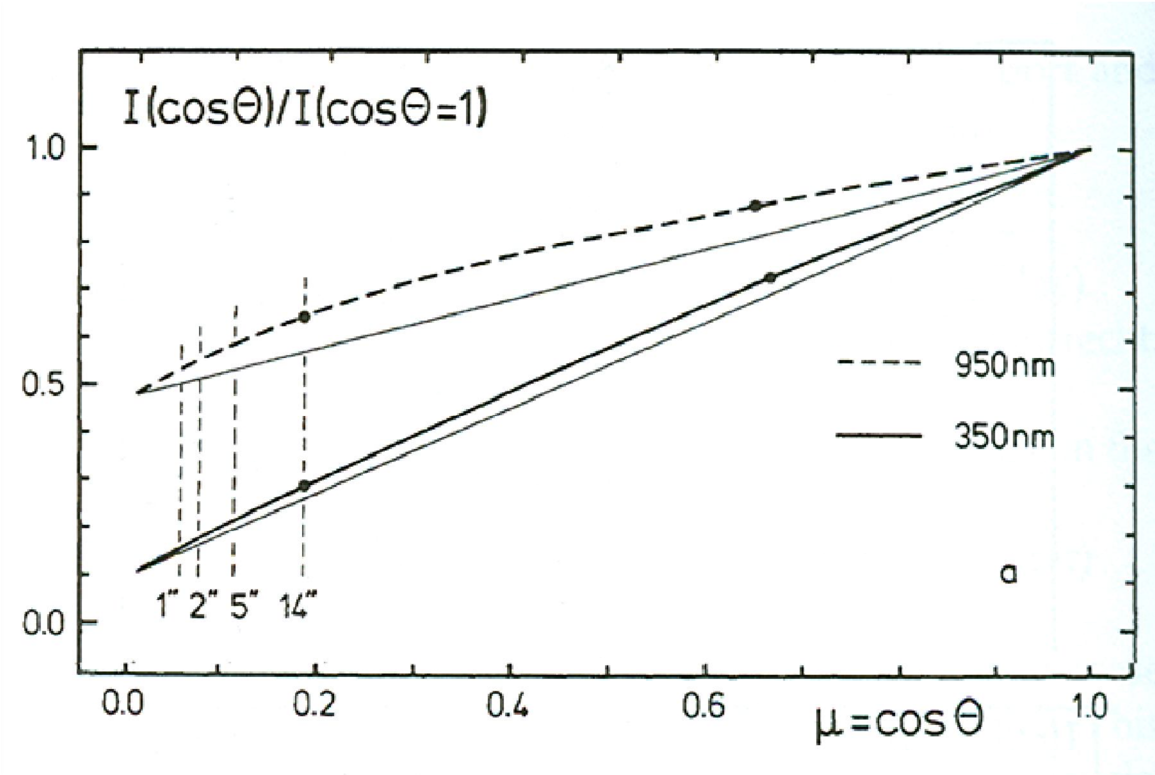


We see radiation from the **deepest photosphere (T = 6400K)** at Sun centre. At the solar limb we see radiation from the **temperature minimum region (T = 4400K).** Thus, there is a **limb darkening**, i.e. a decrease of solar intensity with angle θ.

Note that T_{eff} is a kind of **average of the kinetic temperatures in the photosphere**.

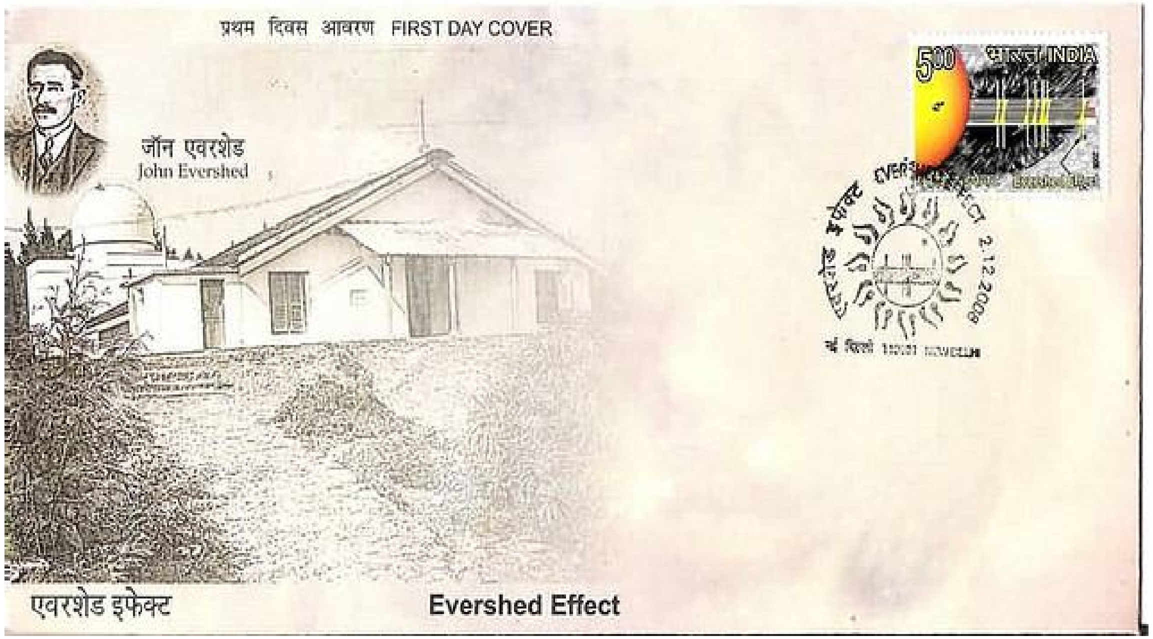
Limb darkening vs. λ

- Between 350 nm and 950 nm
  - short λ: large limb darkening;
  - long λ: small limb darkening
- departure from straight line: limb darkening is more complex than $I(\theta) \sim \cos(\theta)$



Evershed Flow

John Evershed
26 February 1864 – 17 November 1956



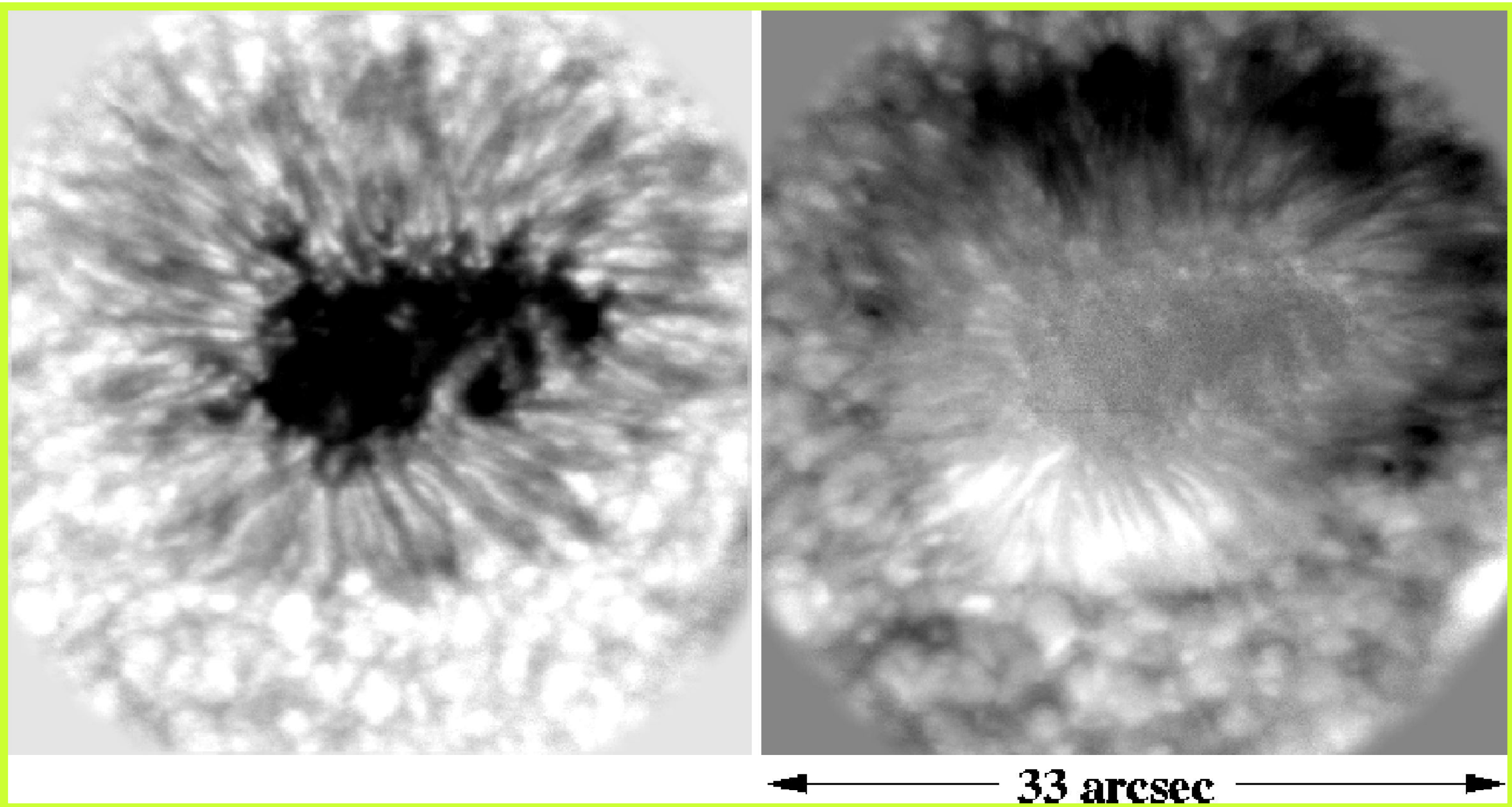
Issued on 2 Dec 2008

The Evershed effect is the radial flow of gas across the photospheric surface of the penumbra of sunspots from the inner border with the umbra towards the outer edge. The speed varies from around 1 km/s at the border between the umbra and the penumbra to a maximum of around double this in the middle of the penumbra and falls off to zero at the outer edge of the penumbra.
Evershed first detected this phenomenon in January 1909, whilst working at the Kodaikanal Solar Observatory in India (1911-1923), when he found that the spectral lines of sunspots showed doppler shift.

Evershed effect

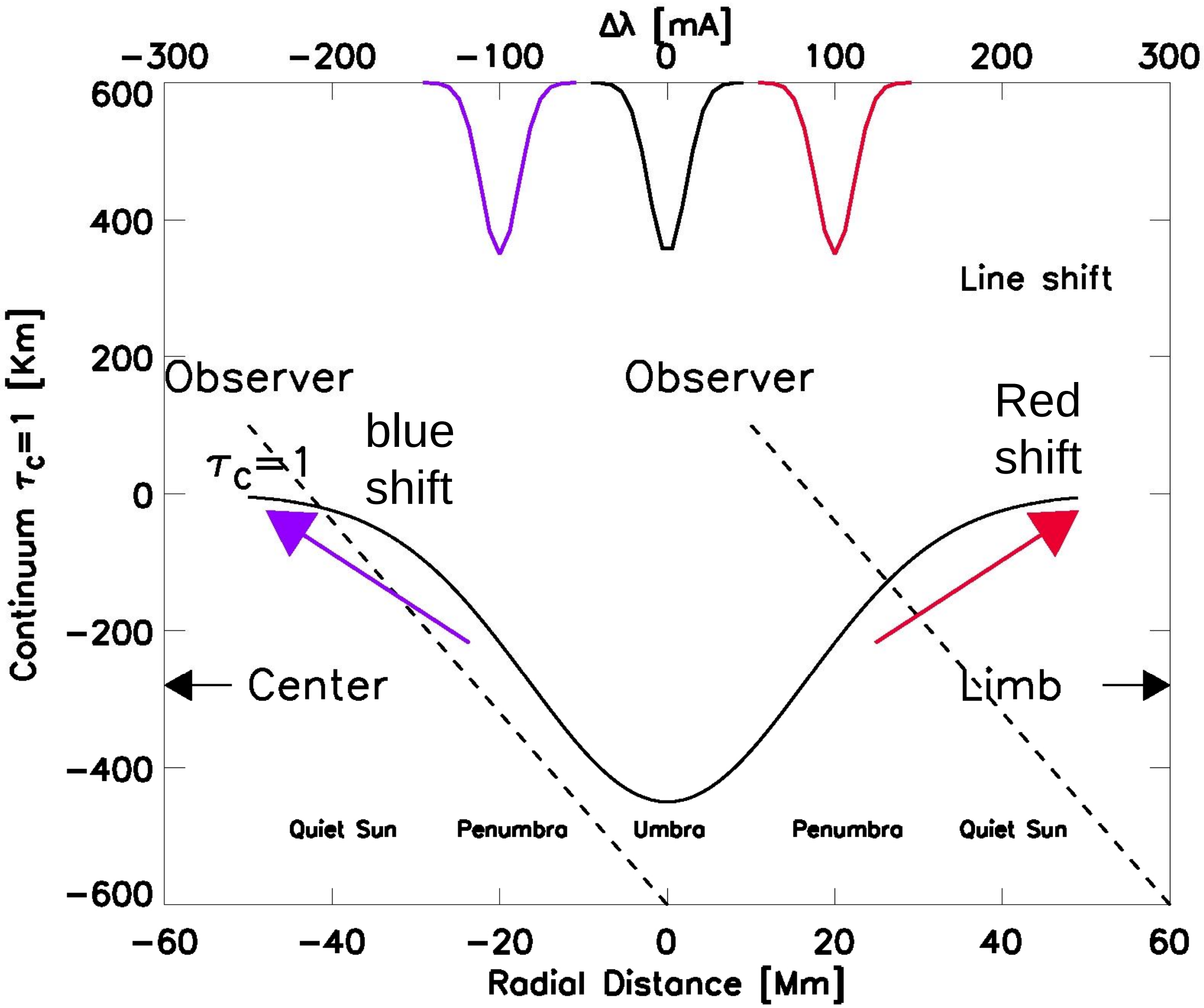
In photospheric layers penumbra shows nearly horizontal outward motion, visible as oppositely directed Doppler shifts (umbra remains at rest). In chromosphere: inward directed flow

Brightness Doppler shift



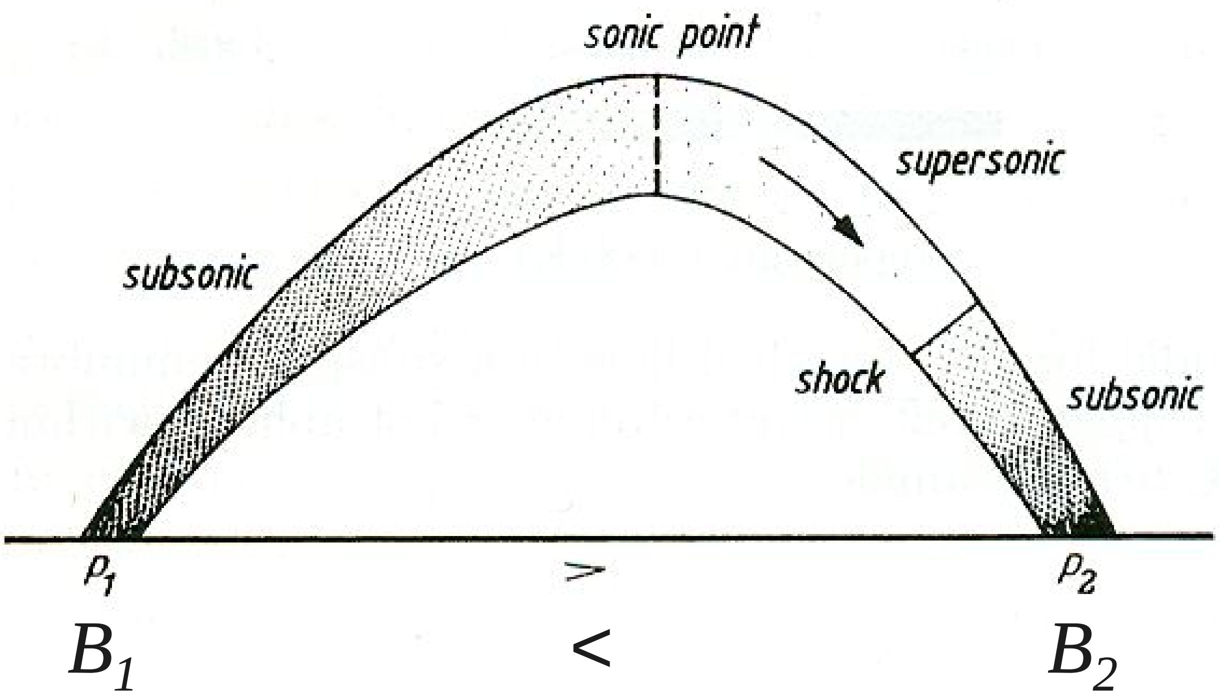
Evershed effect: illustration

- Horizontal outflow of matter.
- Thought to be driven by a siphon flow mechanism



Siphon flow model

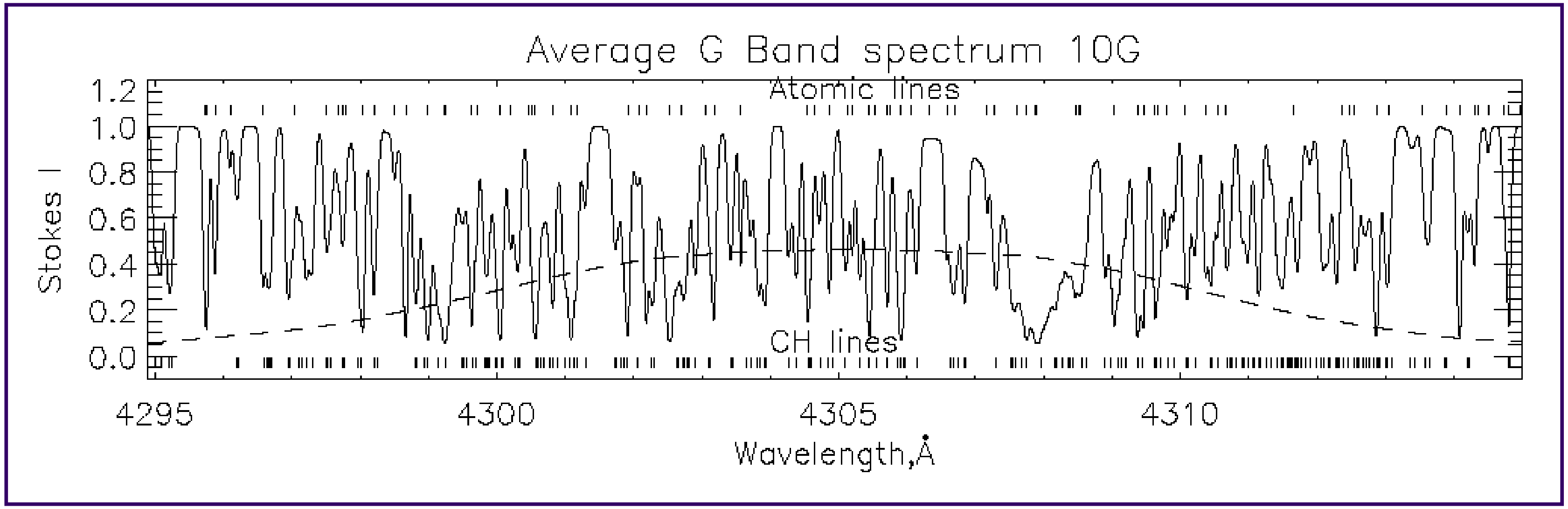
- Proposed by Meyer & Schmidt (1968).
- If there is an imbalance in the field strength of the two footpoints of a loop, then gas will flow from the footpoint with lower B to that with higher B.
- Supersonic flows are possible.



G-band Spectrum Synthesis

G-Band (Fraunhofer): spectral range: 4295-4315 Å

contains many temperature-sensitive molecular lines (CH)

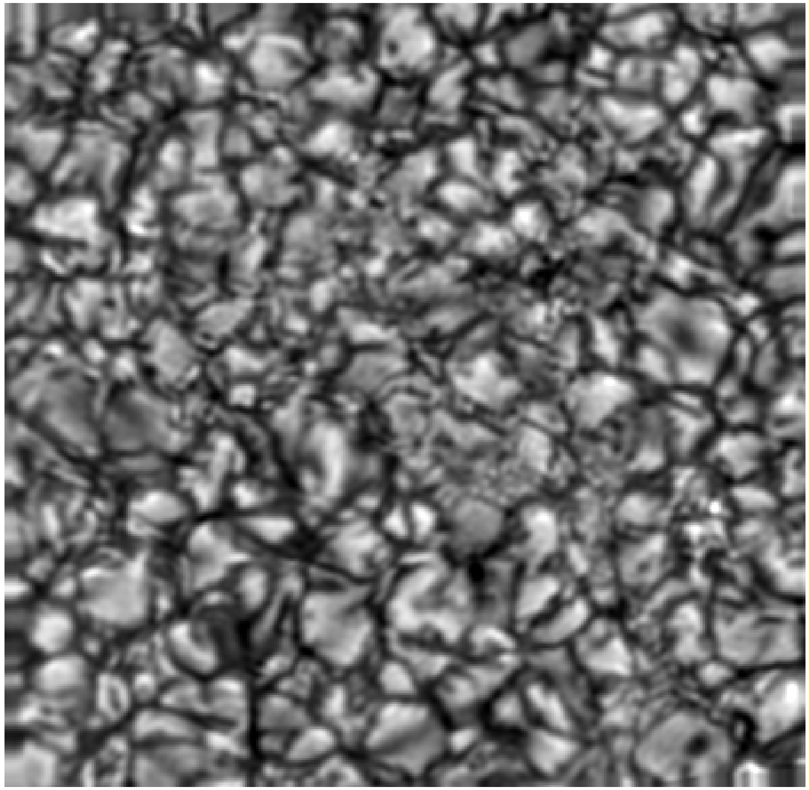


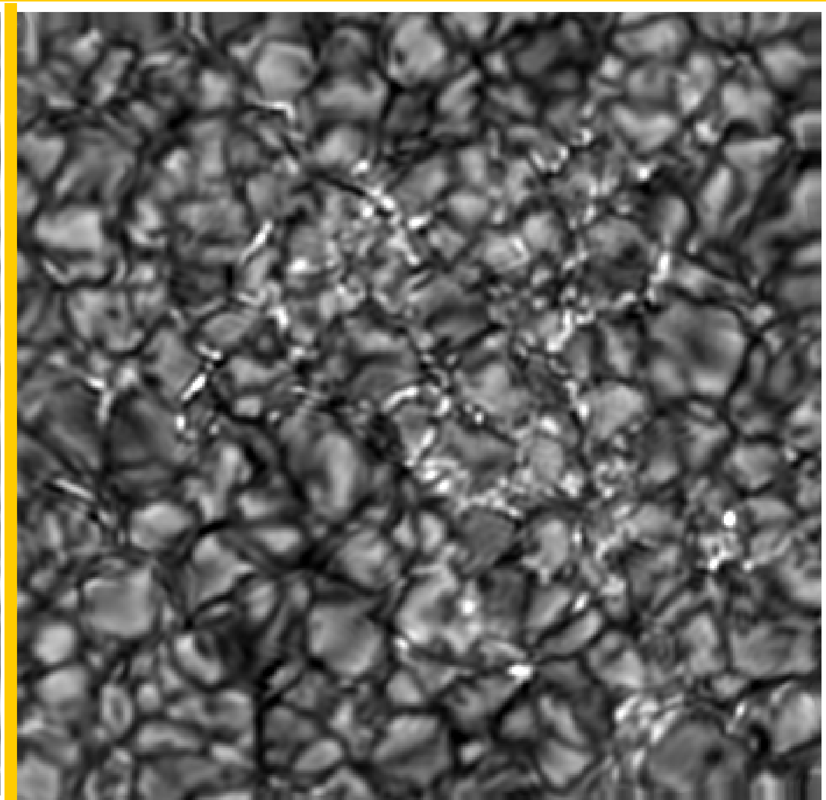
For comparison with observations, we define as G-band intensity the integral of the spectrum obtained from the simulation data:

$$I_G = \int_{4295A}^{4315A} I(\lambda) d\lambda$$

Shelyag et al. 2004

Continuum vs. G-band



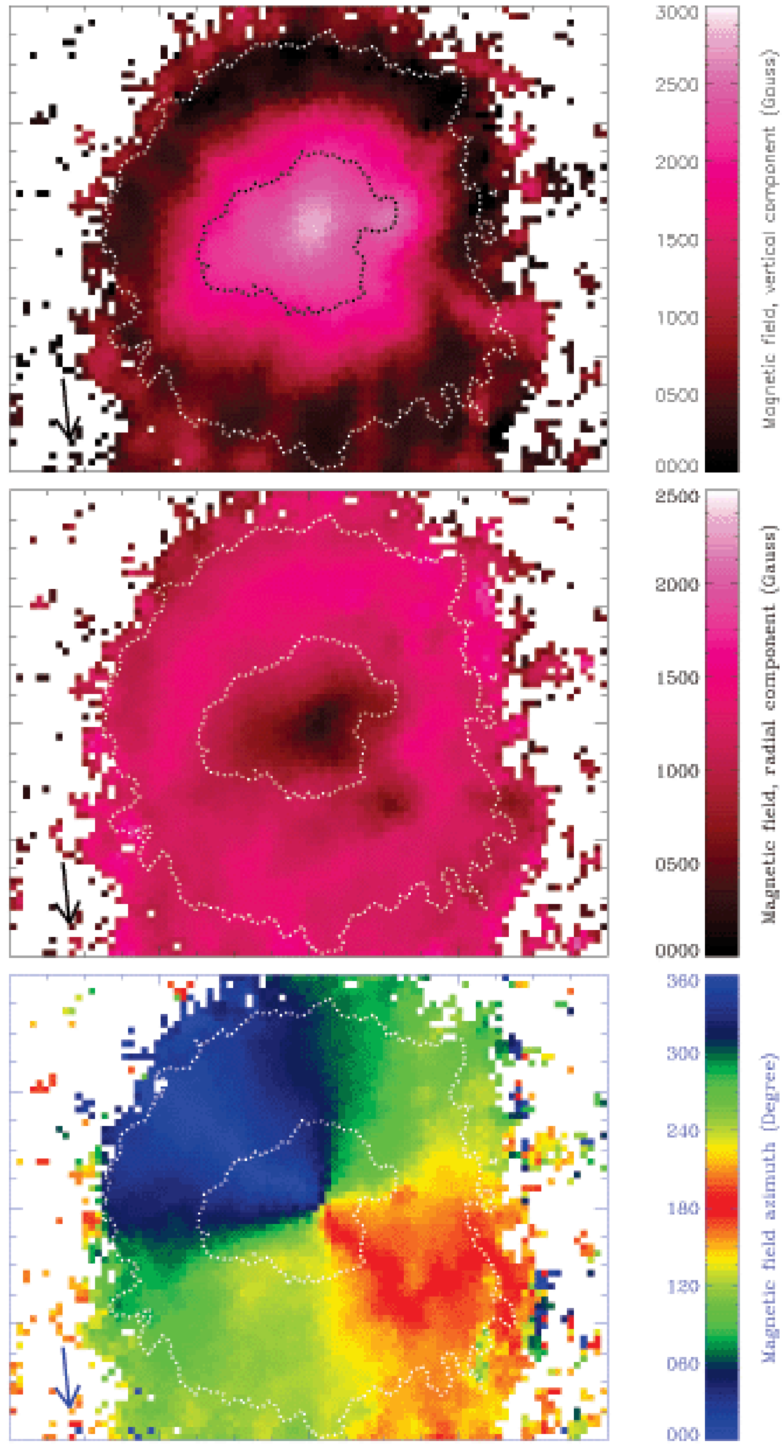


Continuum

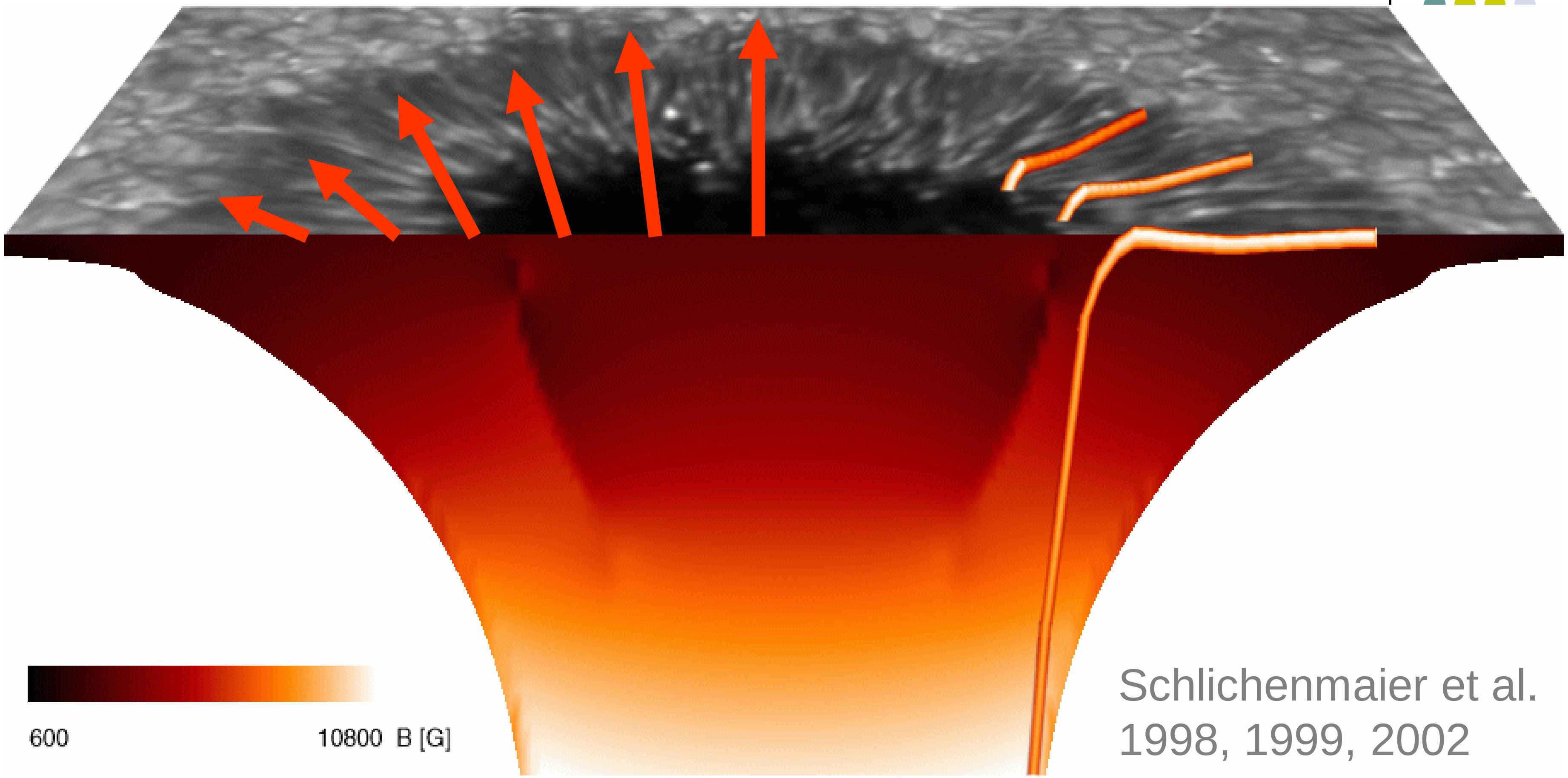
G-band

Magnetic structure of sunspots

- Peak field strength ≈ 2000 – 3500 G (usually in darkest, central part of umbra)
- B drops steadily towards boundary, $B(R_{\mathrm{spot}}) \approx 1000$ G
- At centre, field is vertical, becoming almost horizontal near R_{spot} .
- Regular spots have a field structure similar to a buried dipole



Magnetic structure of sunspots



- Regular on large scales (≈ dipole, B_{max} ≈ 2500 G, for simple spots)
- Extremely complex on small scales (penumbra, subsurface)

Why are sunspots dark?

- Where does the energy blocked by sunspots go?
- Spruit (1982) showed: both heat capacity and thermal conductivity of convection zone (CZ) gas is very large

  ➔High thermal conductivity: blocked heat is redistributed throughout CZ (no bright rings around sunspots)

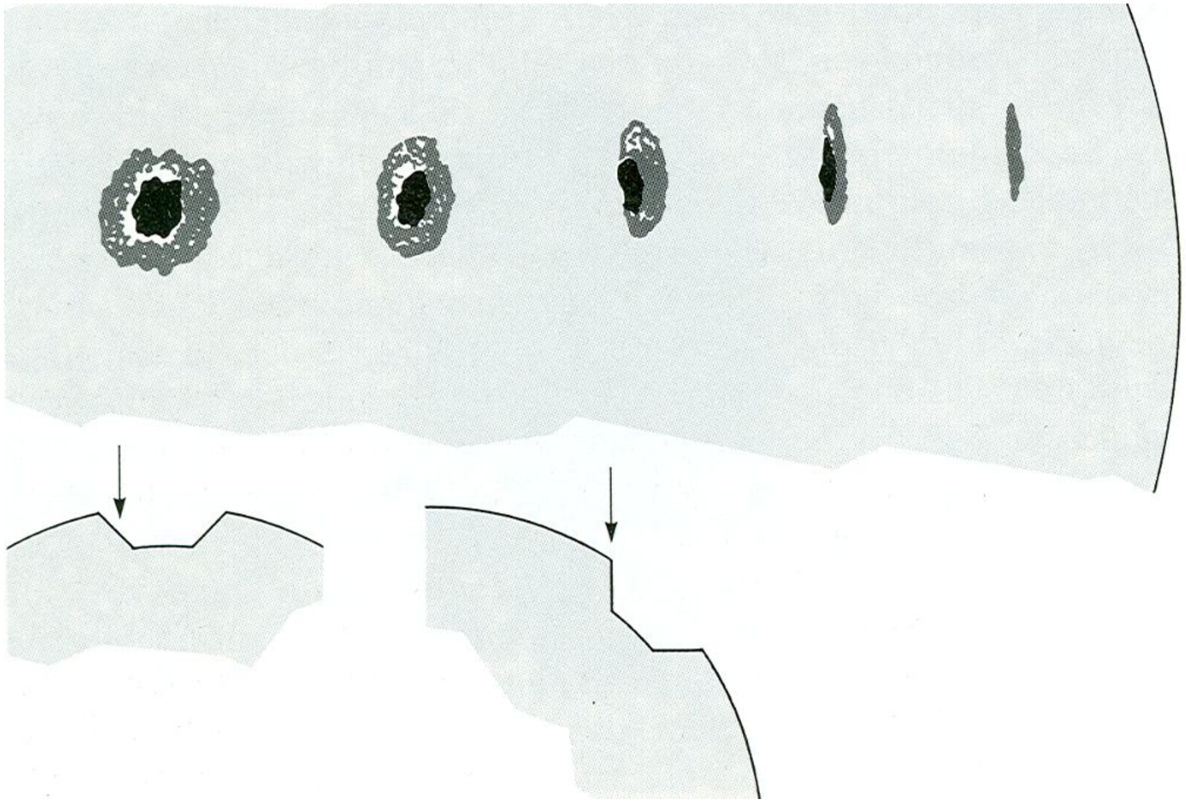
  High heat capacity: the additional heat does not lead to a measurable increase in temperature
- In addition: time scale for thermal relaxation of the CZ is long, 10^5 years: excess energy is released almost imperceptibly.

The Wilson effect

- Near the solar limb the umbra and centre-side penumbra disappear

➔ We see 400-800 km deeper into sunspots than in photosphere

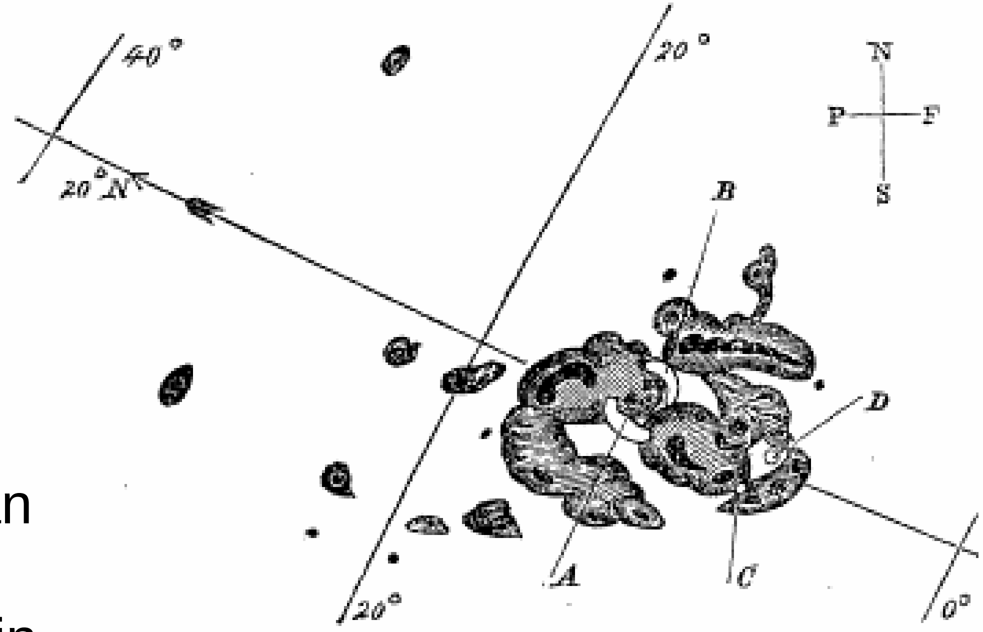
- Correct interpretation by Wilson (18th century).



B square/8 pi means gas pressure lower in spot than outside i.e. density also lower, i.e. fewer atoms to absorb, i.e. opacity also lower, we see deeper into spot

Discovery of a White-light Solar Flare

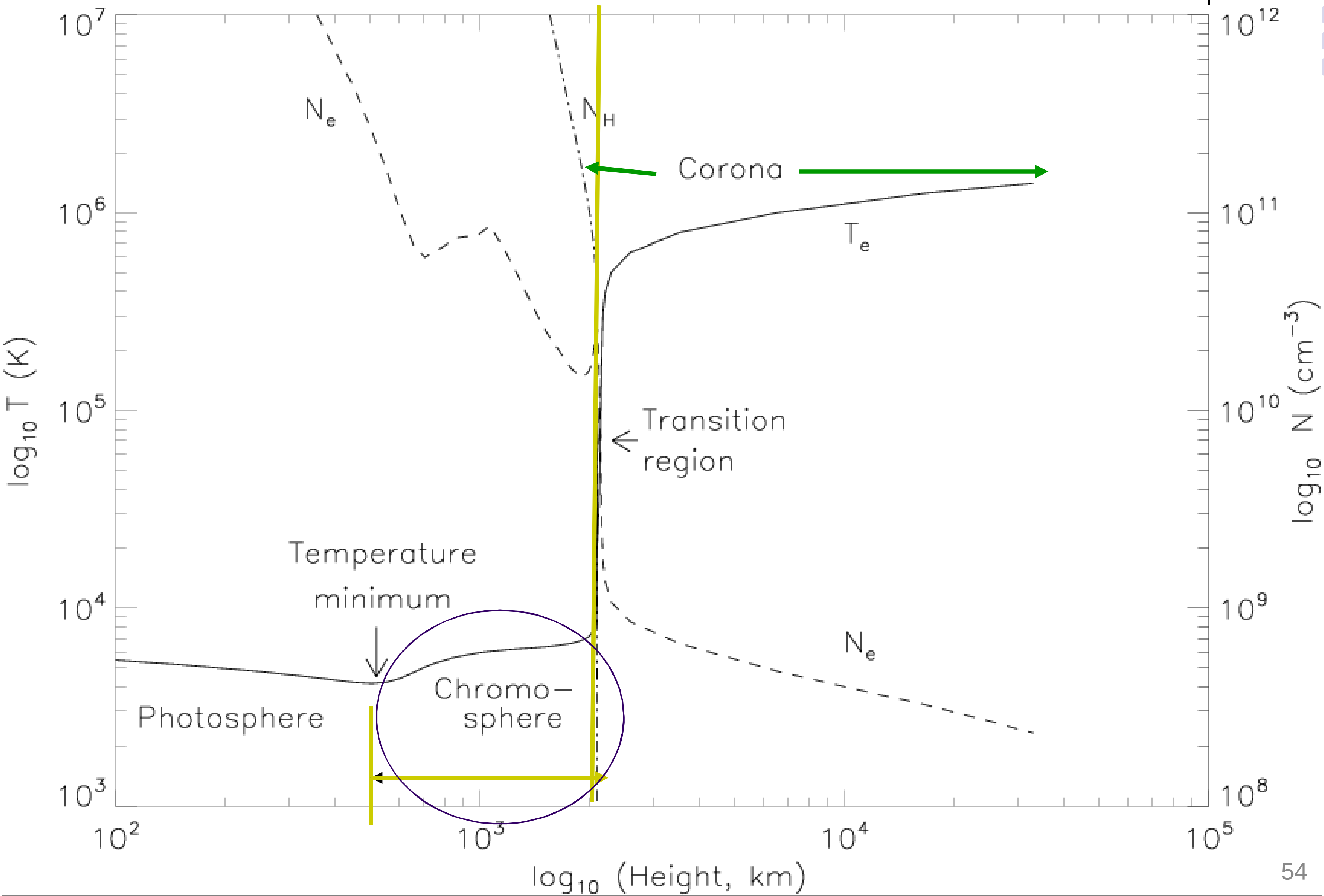
- September 1, 1859
- Independently observed by R. C. Carrington and R. Hodgson
- Magnetic storm commenced early on September 2
- At most 50% brighter than the solar disk
- Typical energy released in a large flare: 10^{32} erg



Drawing by Carrington

The Chromosphere

Chromosphere: Temperature Profile



Chromosphere

- Layer lying just above the photosphere, at which the temperature appears to be increasing outwards (classically forming a temperature plateau at around 7000 K)
- Assumption of LTE breaks down
- Energy transport mainly by radiation and waves
- Assumption of plane parallel atmosphere is very likely to break down as well.
- Strong evidence for a spatially and temporally inhomogeneous chromosphere (gas at $T<4000K$ is present beside gas with $T>8000$ K)

Chromospheric Fraunhofer lines

At the core of the optically thick Hα and the Ca II H and K lines, $\tau_\nu = 2/3$ corresponds to high up in the **chromosphere**.

So when we view the Sun at the **cores** of these lines, we see features in the **chromosphere**.

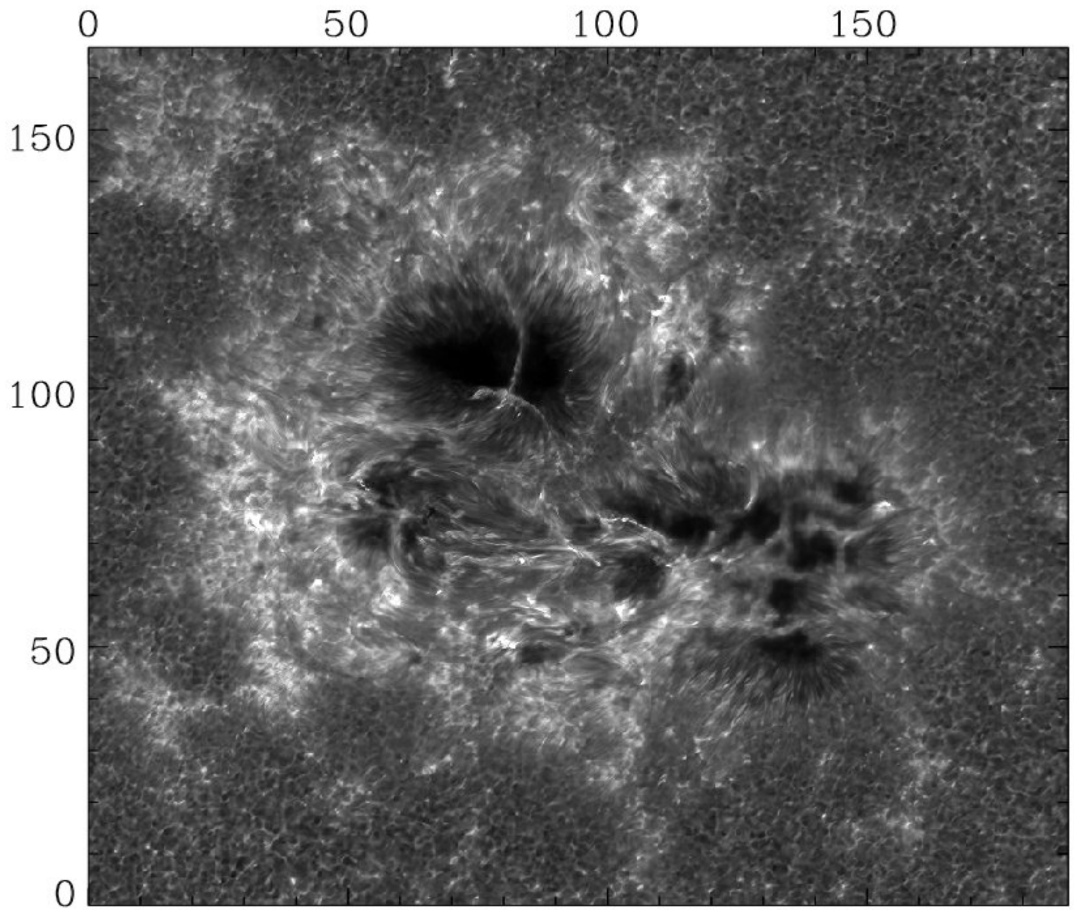
Towards the **line wings**, the $\tau_\nu = 2/3$ level is nearer the **photosphere**.

Chromospheric structure

The chromosphere structures e.g.,

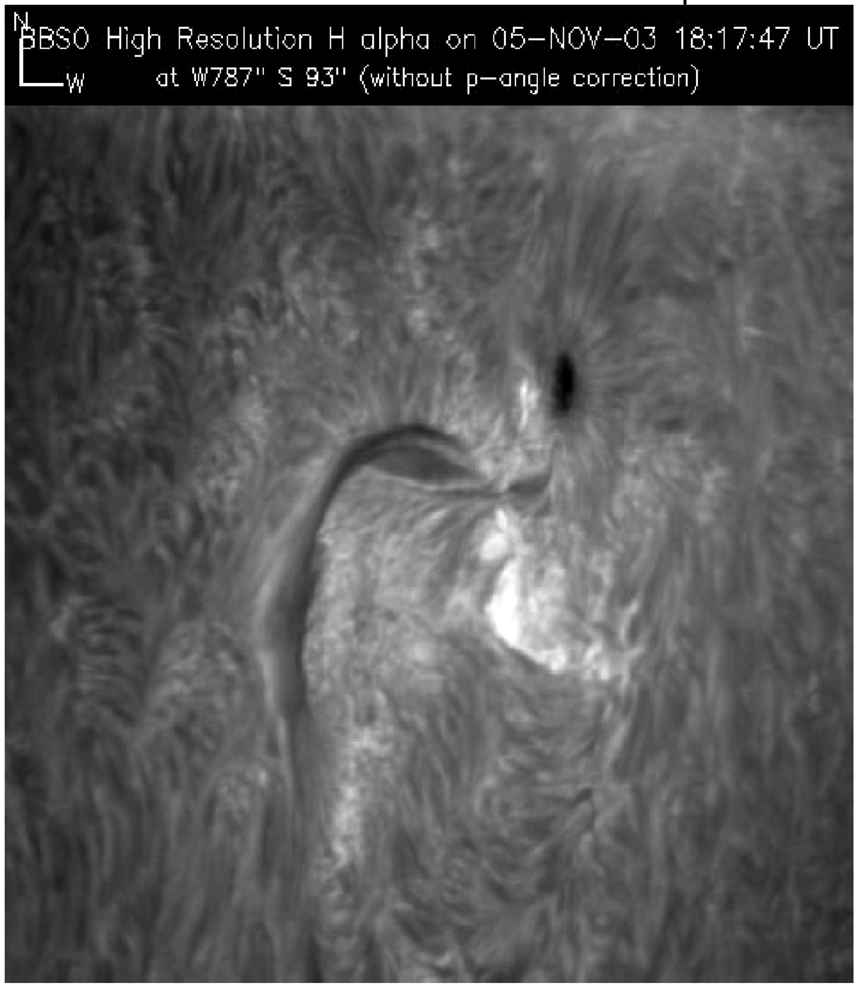
- Sunspots and Plages
- Network and internetwork (grains)
- Spicules
- Prominences and filaments
- Flares and eruptions

DOT Ca II K core: chromosphere



DOT G-band: photosphere

White-light vs Hα

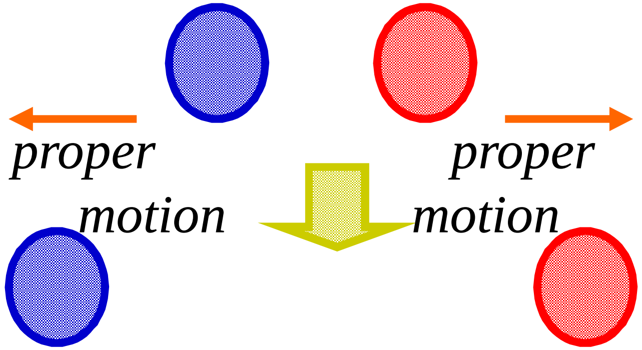


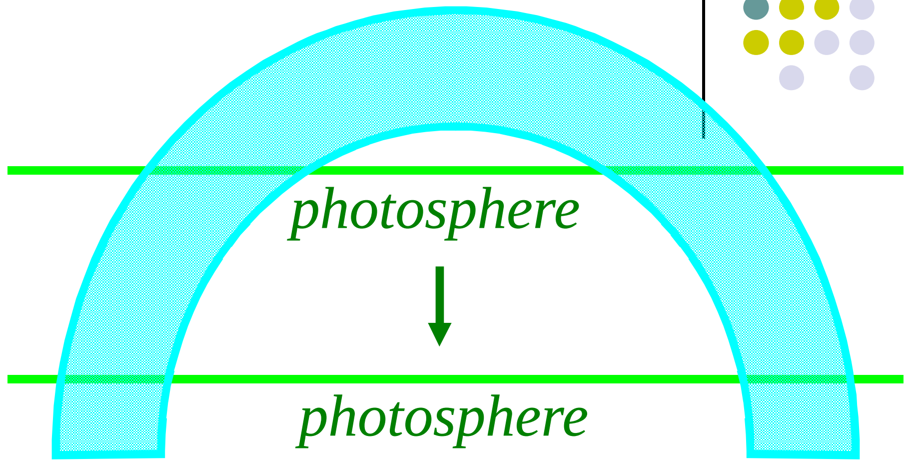
Photosphere 5 Nov. 2003 BBSO Chromosphere

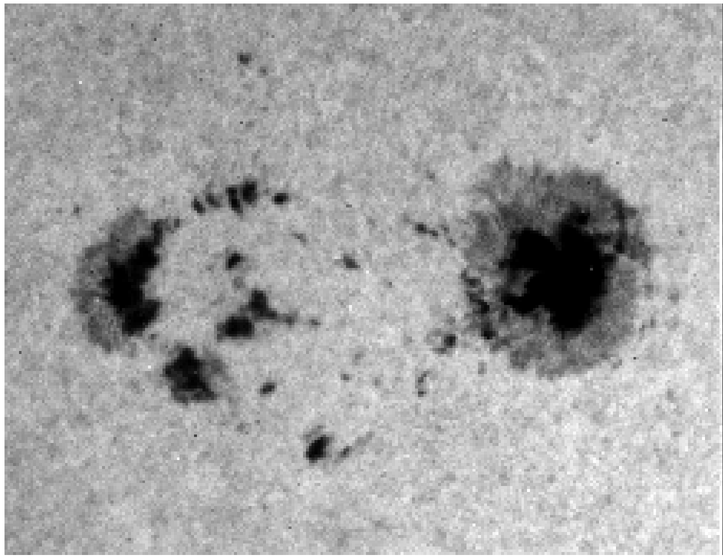
Photosphere-Chromosphere

Emerging magnetic flux tube

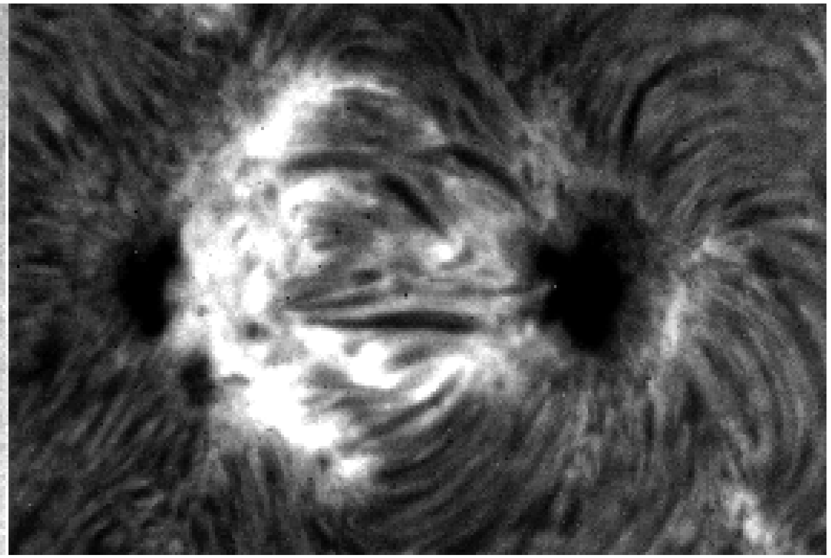
Bipolar pair of sunspots







Photosphere



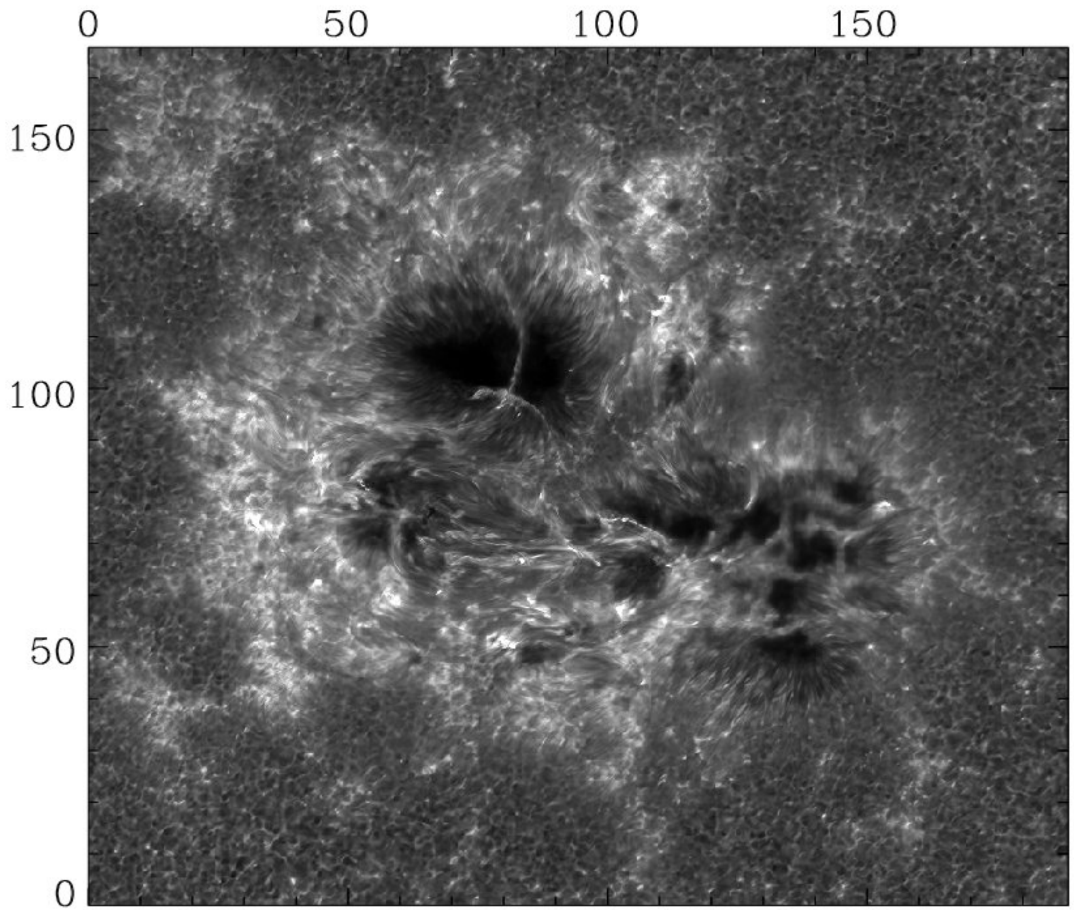
Chromosphere (H-alpha center)

Chromospheric structure

DOT Ca II K core: chromosphere

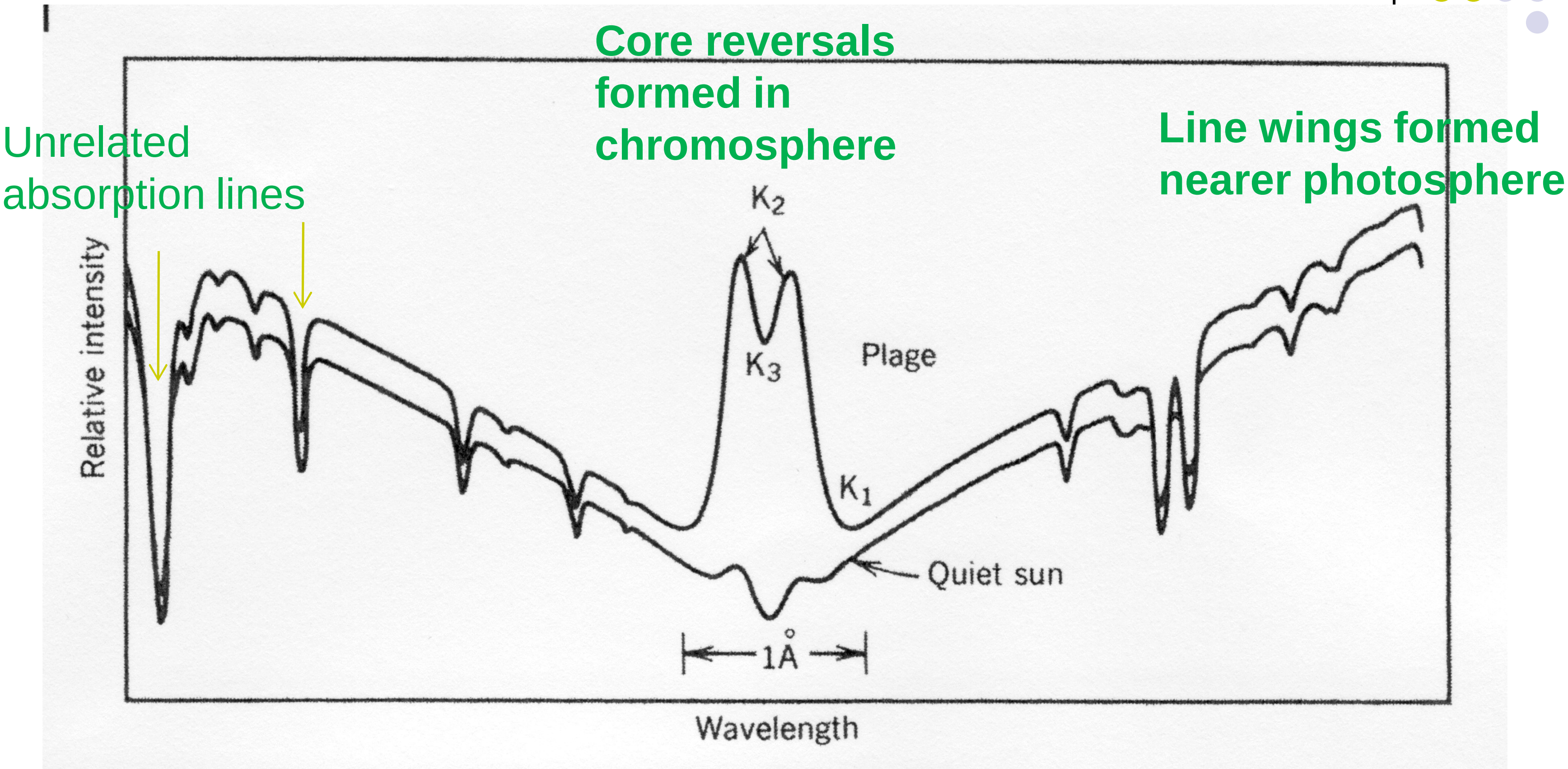
The chromosphere structures e.g.,

- Sunspots and Plages
- Network and internetwork (grains)

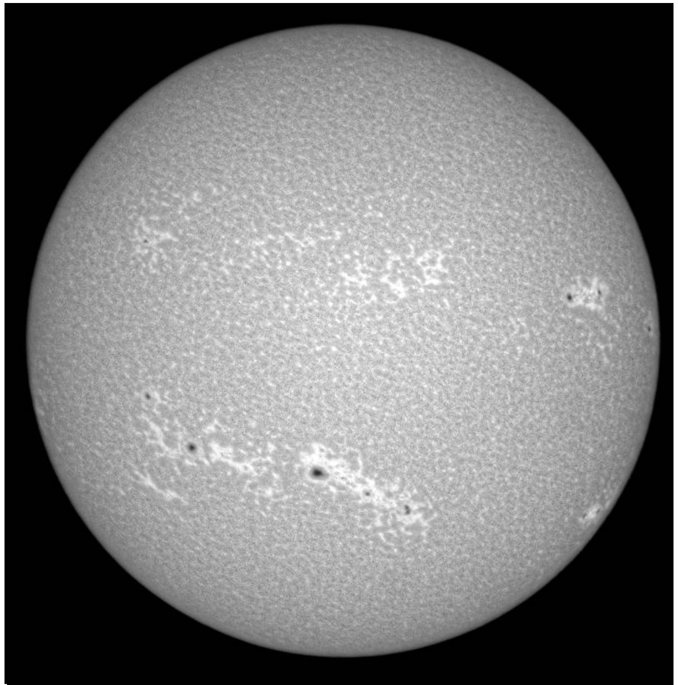


DOT G-band: photosphere

Ca II K (3934 A) line profiles

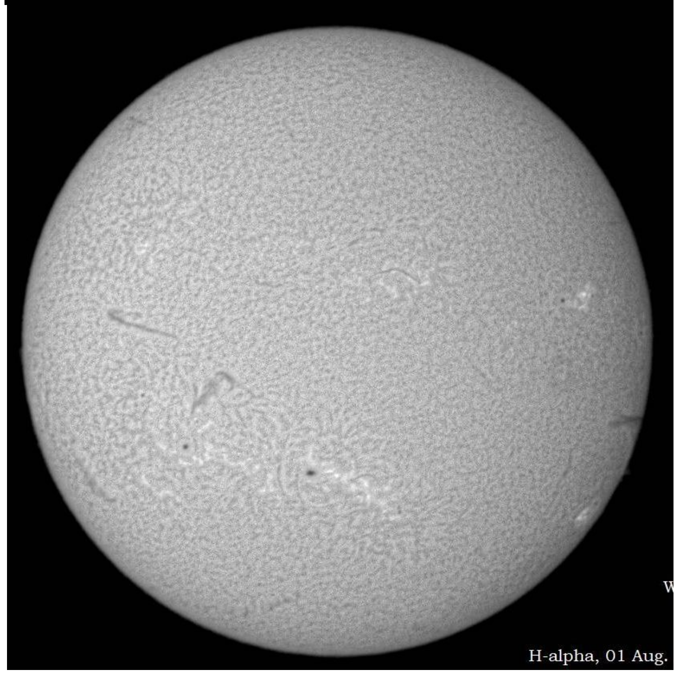


Ca II H and K line profiles depend on activity – plage regions have strong central reversals, quiet regions have hardly any.



Ca II K line (3934 Å),
0.7 A passband

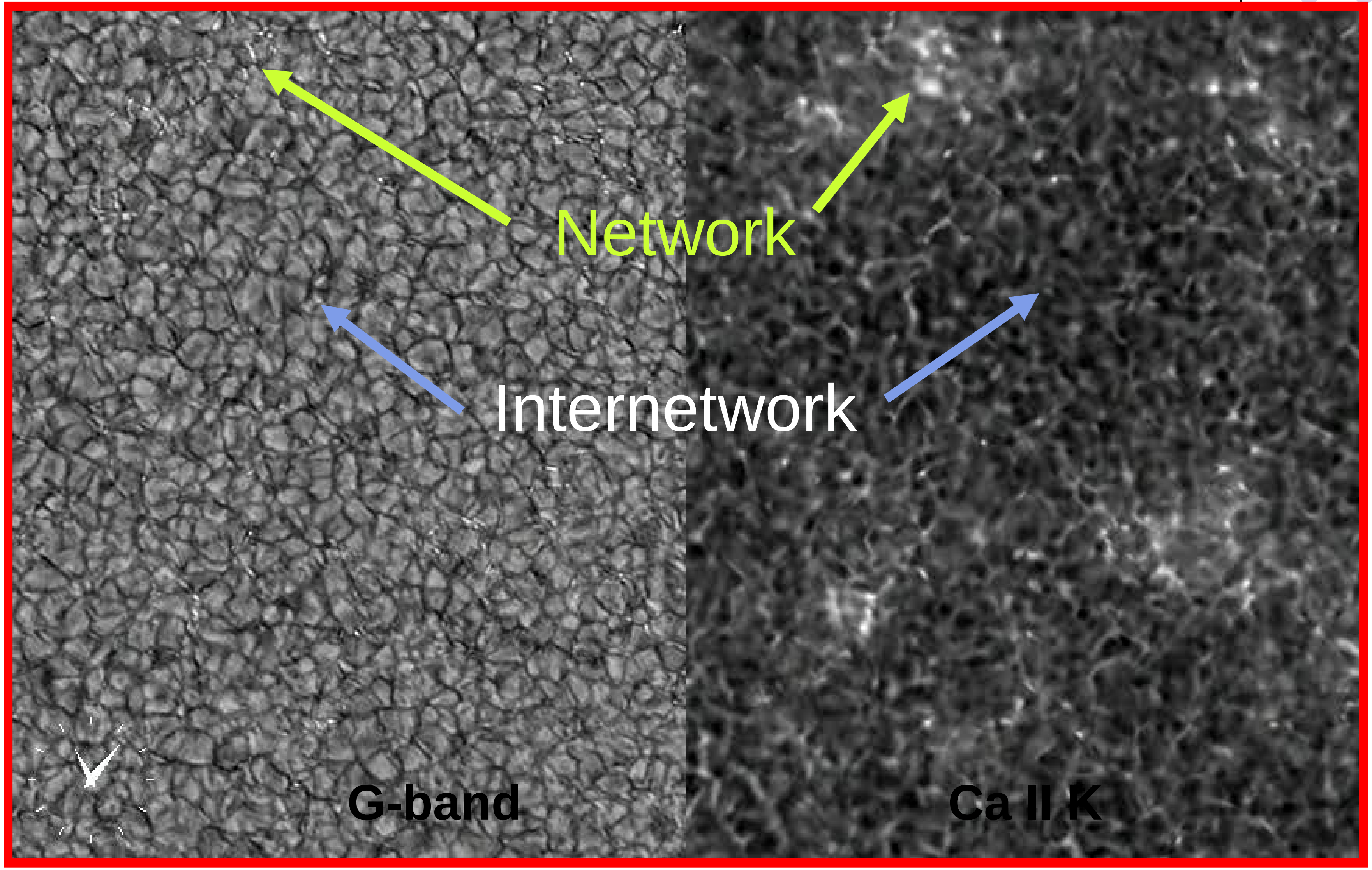
Network regions are bright areas.



H-alpha line (6563 Å),
0.7 A passband

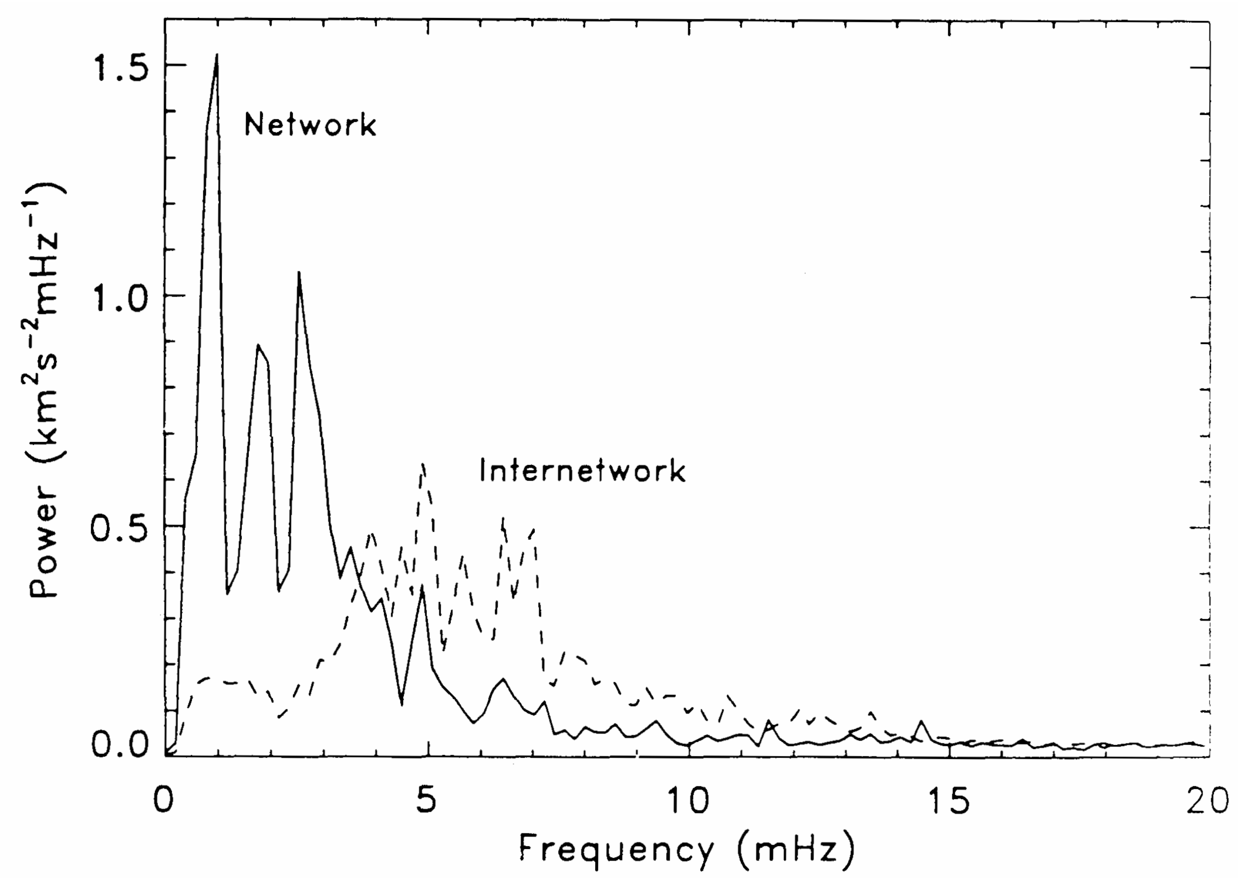
1 Aug 2012,Bosscha
Observatory

Chromospheric dynamics (DOT)



Chromospheric dynamics

- Oscillations, seen in cores of strong lines
- Power at 3 min in Inter-network
- Power at 5-7 min in Network

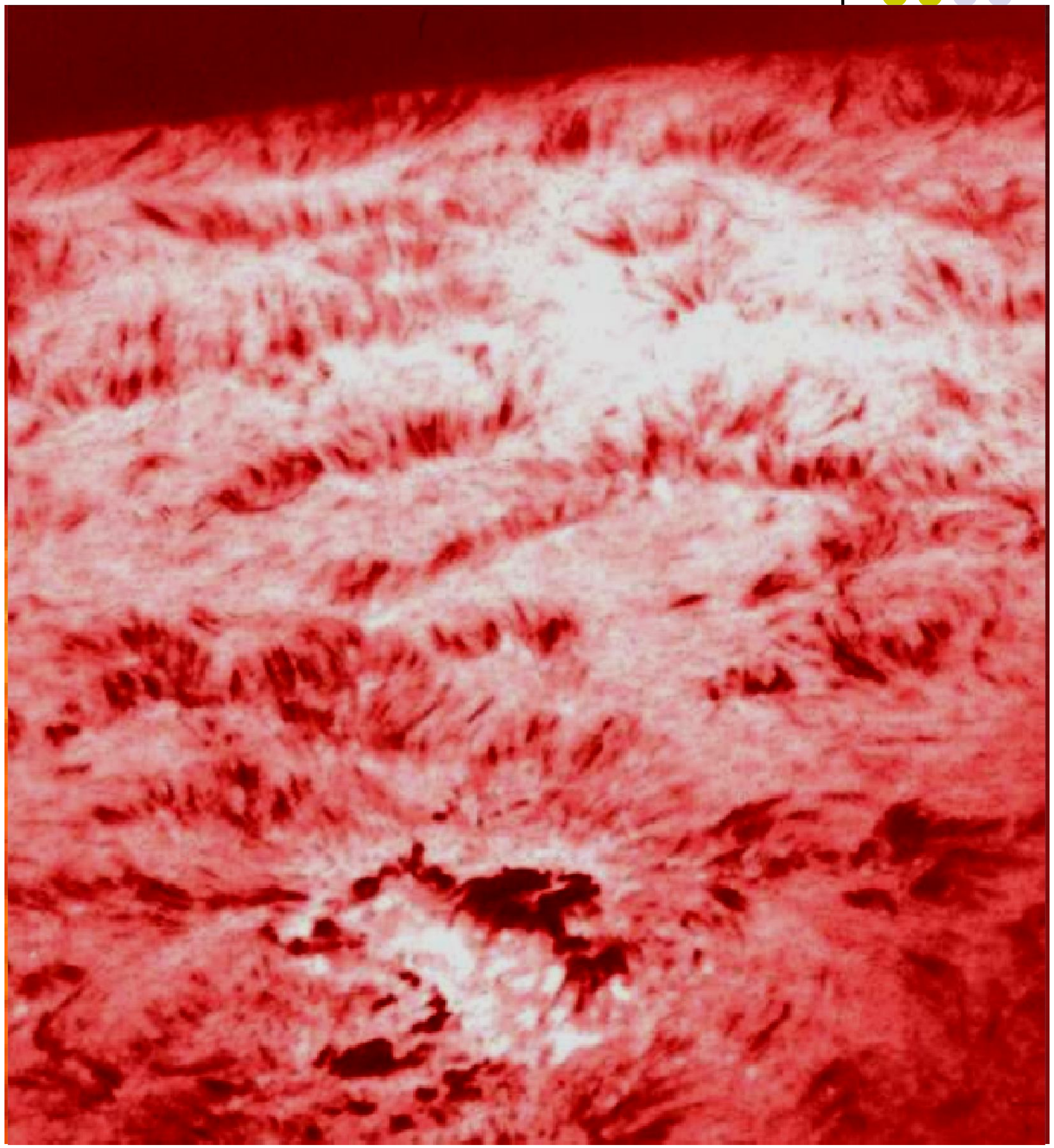


Lites et al. 2002

Chromospheric structure

The chromosphere structures,

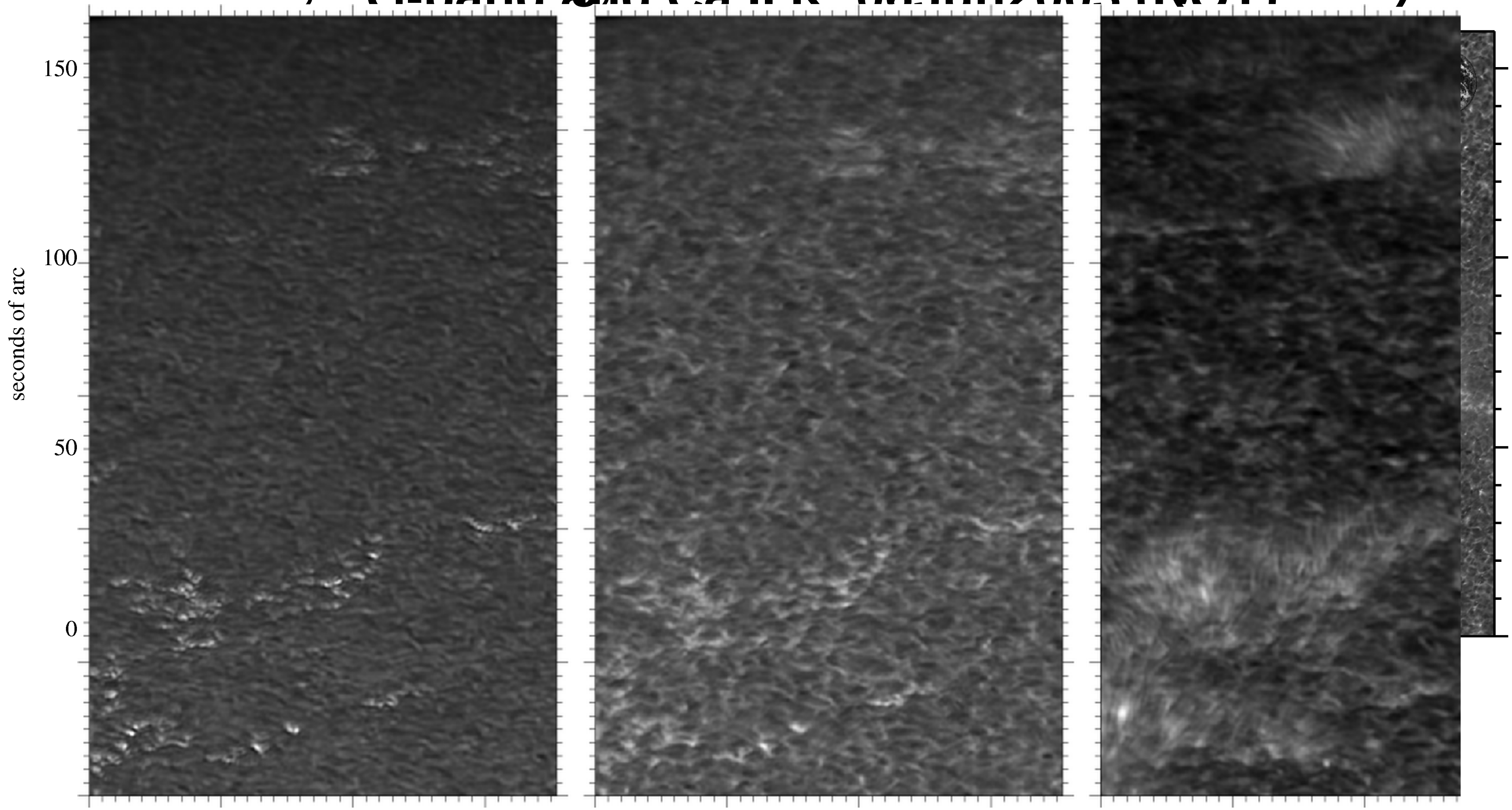
- Sunspots and Plages
- Network and internetwork
- Spicules, Surge (mov)



It moves upwards at about 20 km/s from the photosphere. They were discovered in 1877 by Father Angelo Secchi of the Vatican Observatory in Rome.

Photosphere-Chromosphere

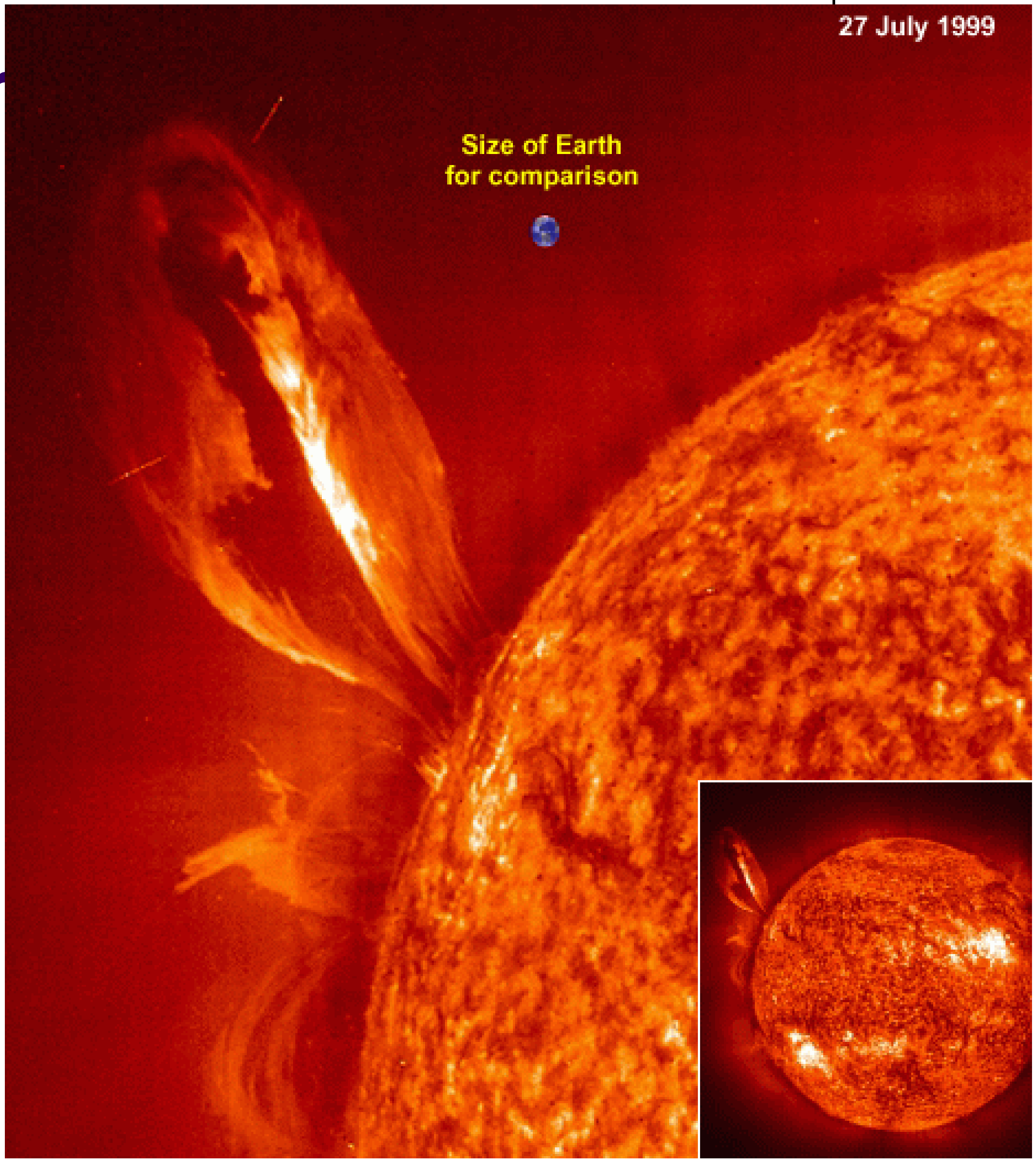
G-band, Ca II K wing, Ca II K core, 18Jun2003 (near limb)



See also DOT movie

Chromospher

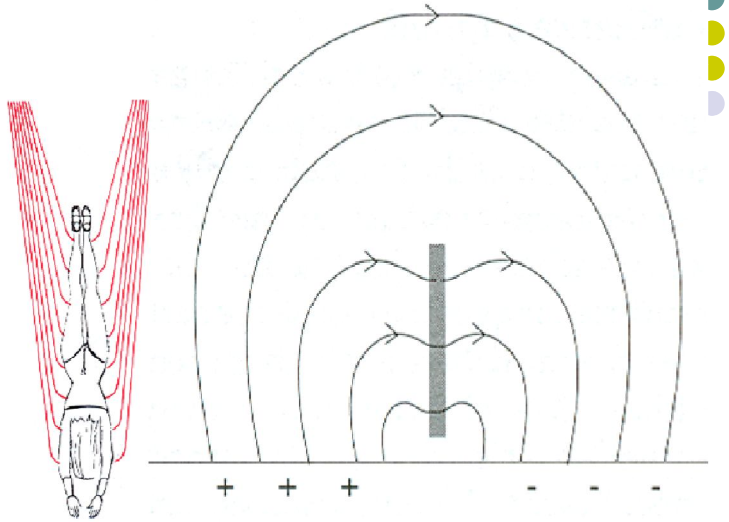
- The chromosphere structures. e.g.,
  - Sunspots and Plages
  - Network and internetwork
  - Spicules
  - Prominences and filaments



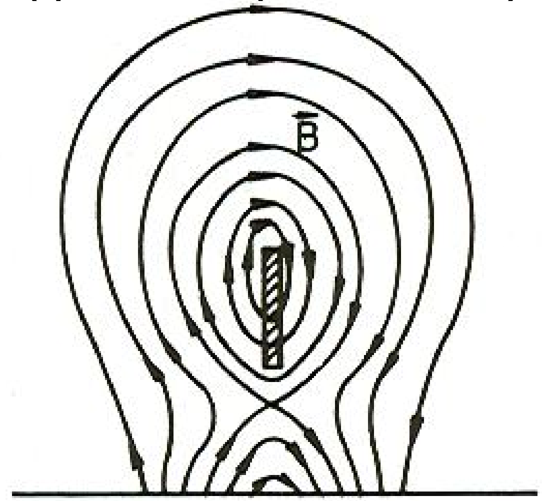
One of solar energetic particle source

Kippenhahn’s magnetic circus

- What if we were like plasma, frozen into the field?
- Trapeze artist as a model for a prominence
- she is hanging quite stably, although much denser than the surrounding air.



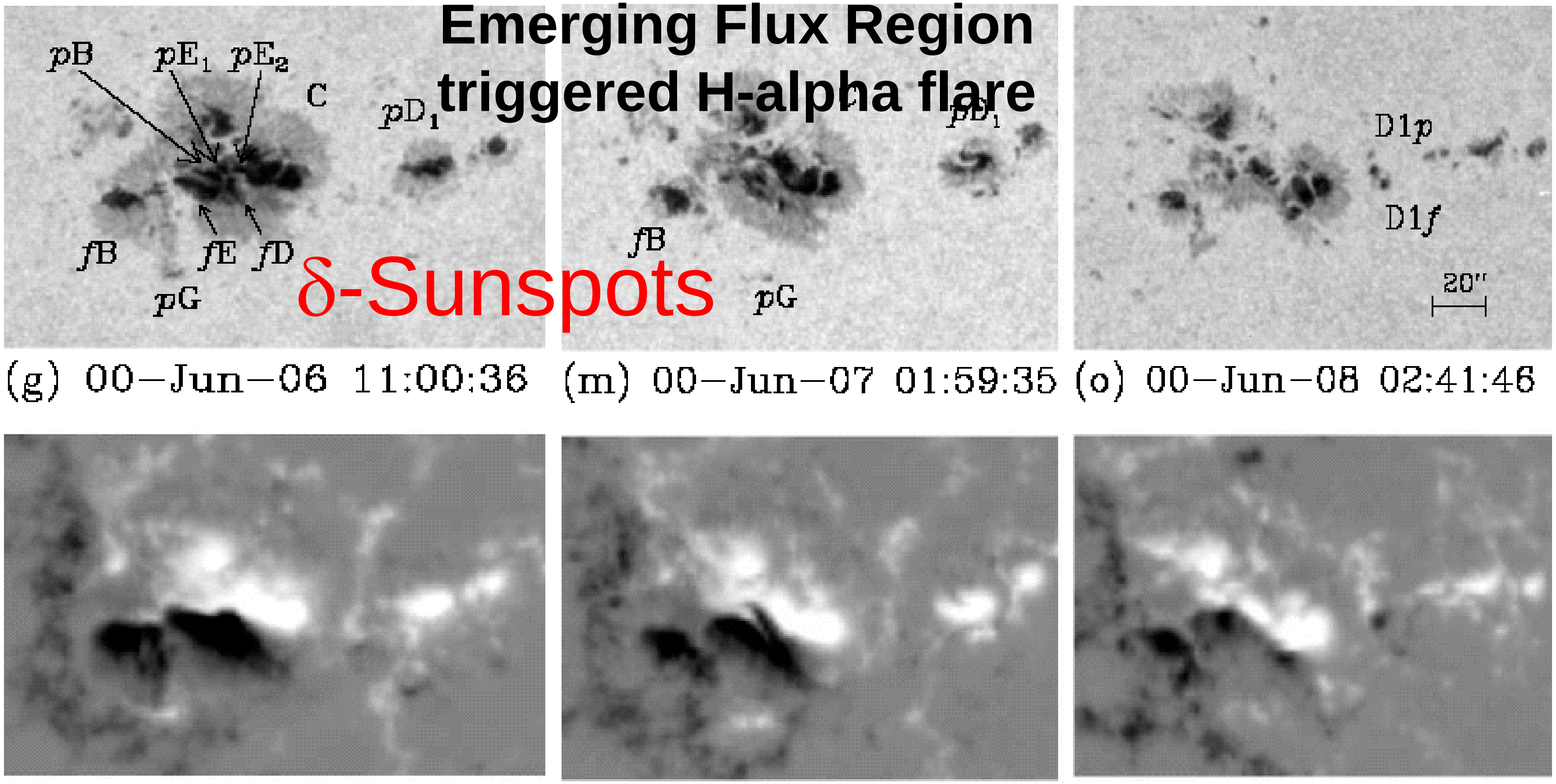
Kippenhahn-Schlüter
(quiescent prominence)

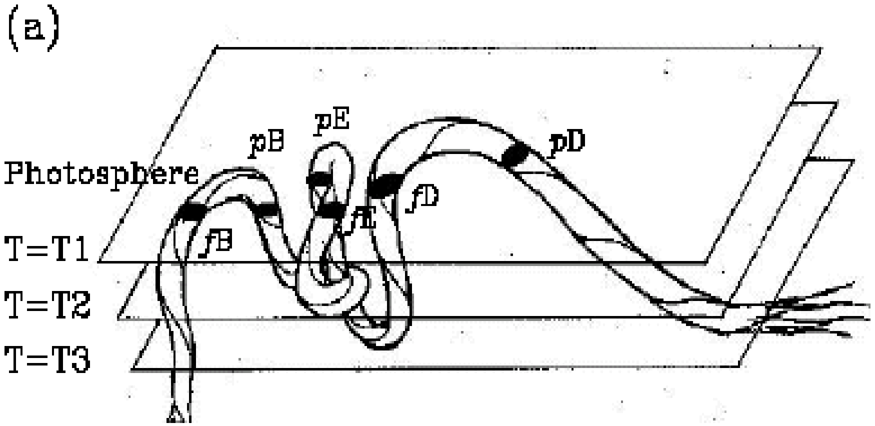


Kuperus-Raadu
(eruptive prominence)

Emerging Flux Region triggered H-alpha flare

δ-Sunspots



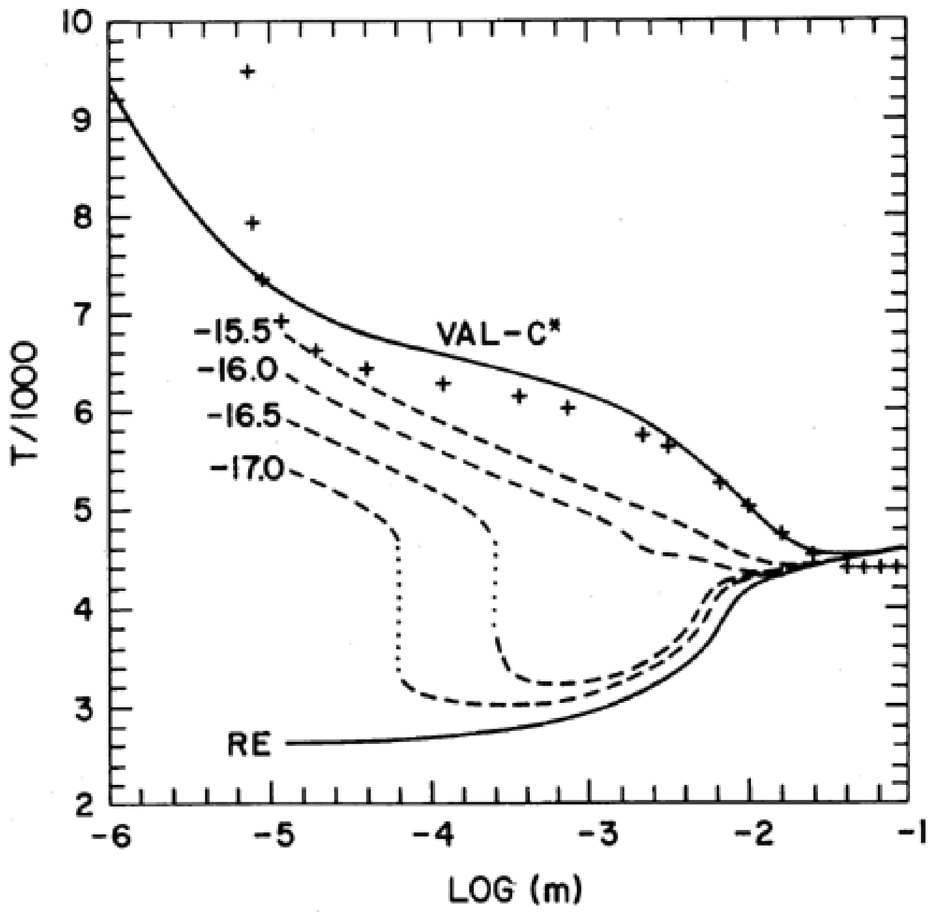


Emergence & Rapid breakdown of twisted flux rope model for strong flare (Kurokawa et al. 2002)

Chromospheric Heating

- Radiative equilibrium, RE: only form of energy transport is radiation & atmosphere is in thermal equilibrium.
- VAL-C: empirical model
- Dashed curves: temp. stratifications for increasing amount of heating (from bottom to top).

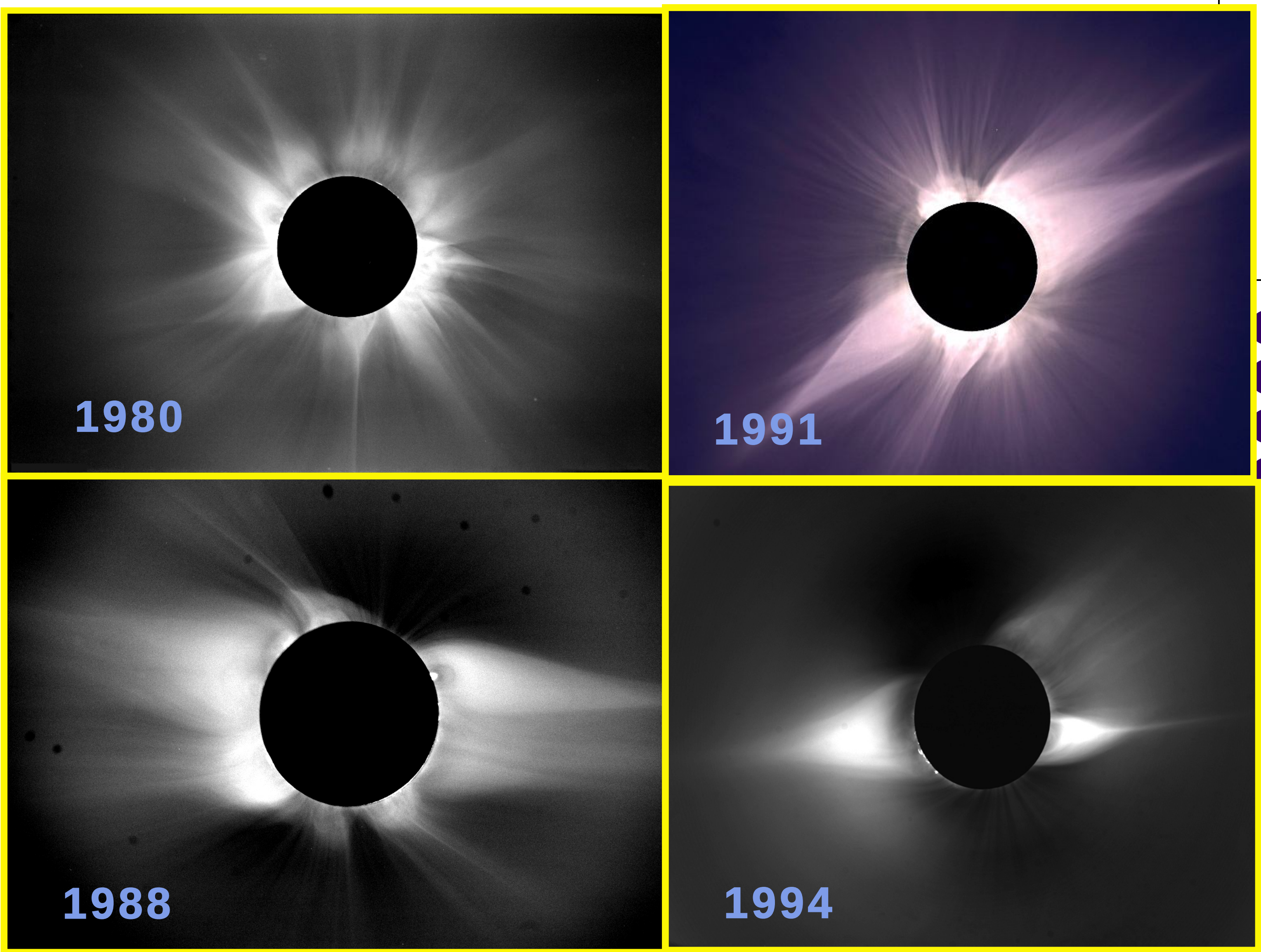
➔ Mechanical heating needed to reproduce observation



Anderson & Athay 1993

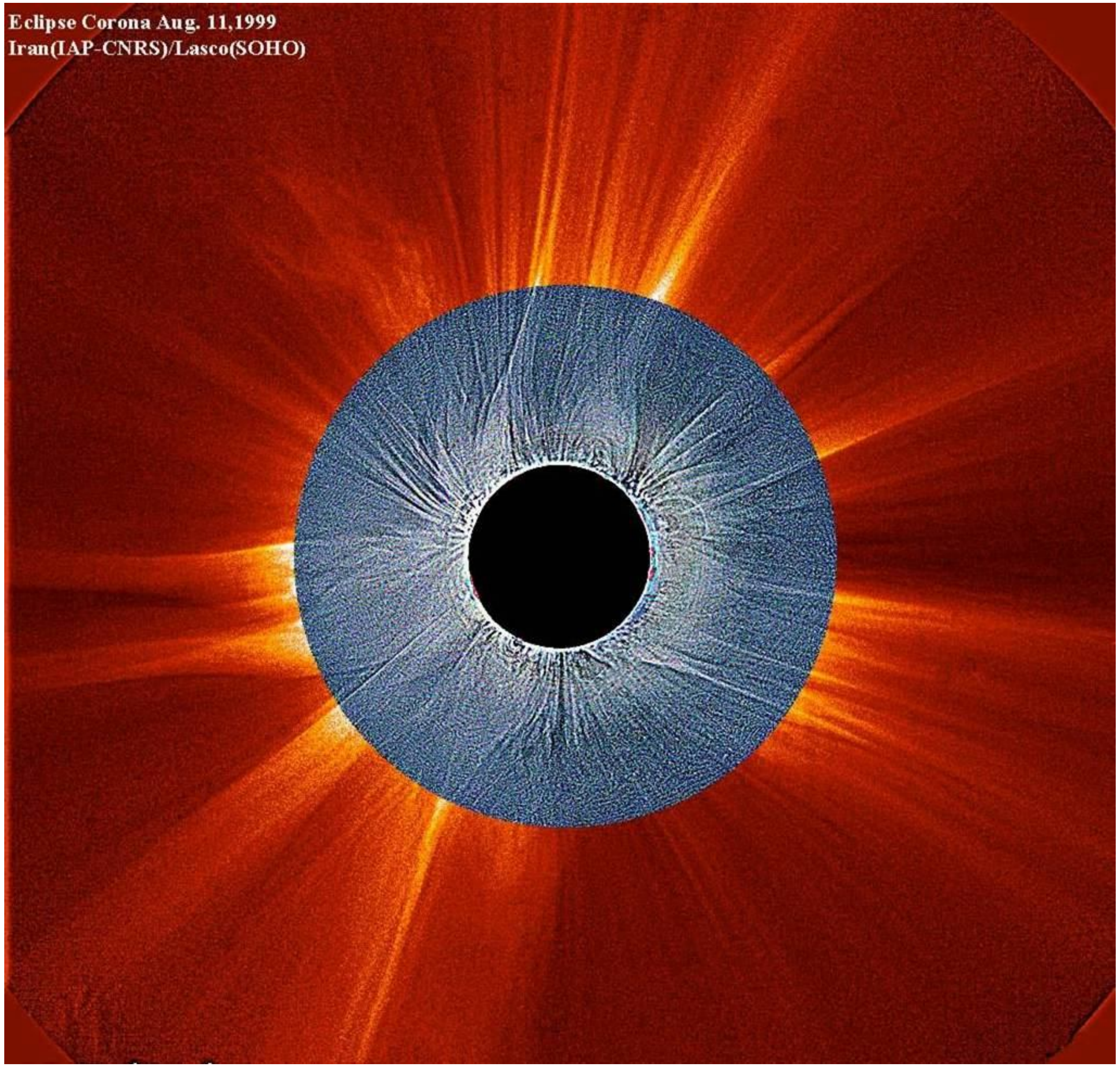
The Corona

Solar corona during Total Solar eclipses



Coronal streamer

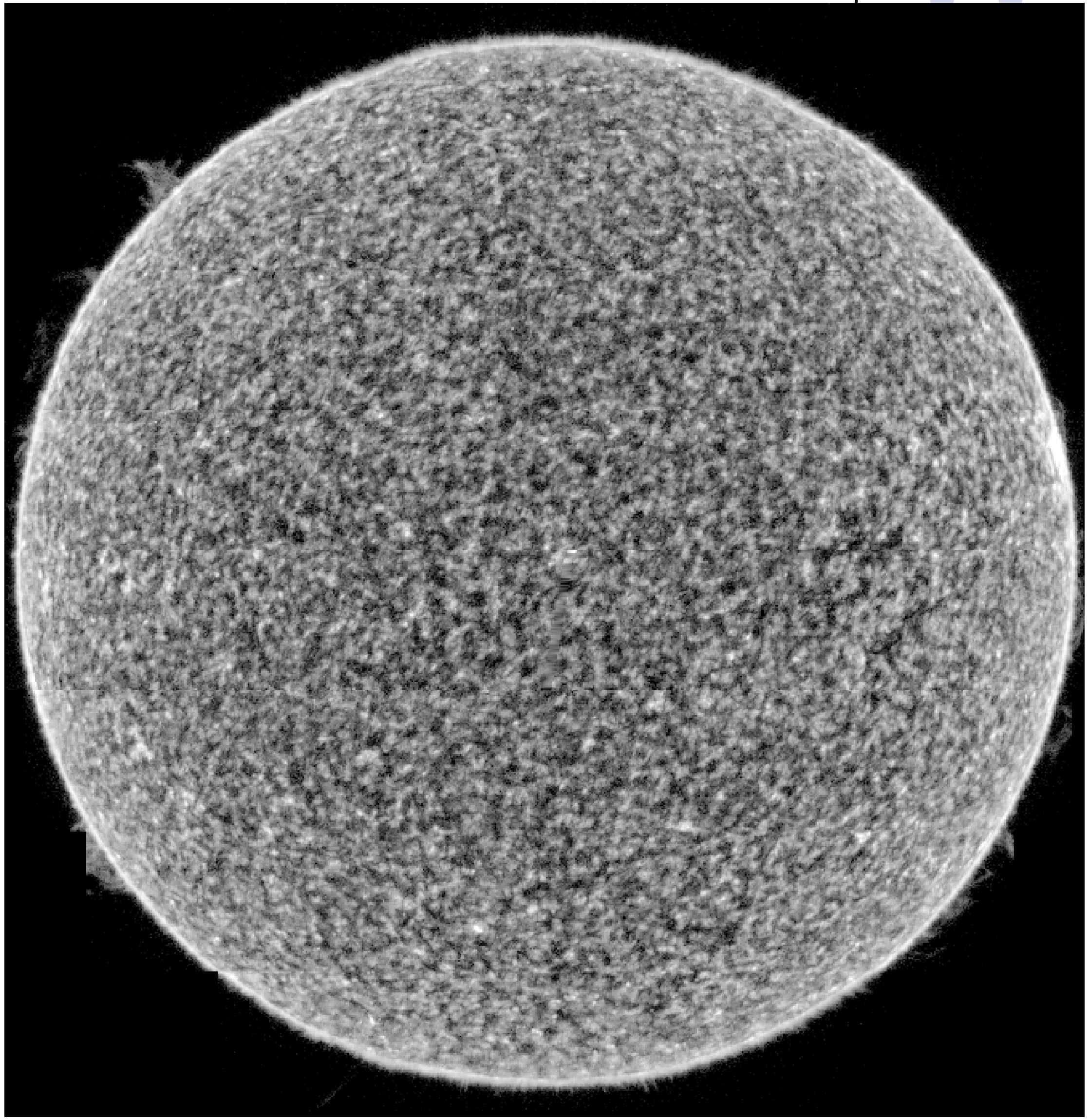
Coronal structure: streamers



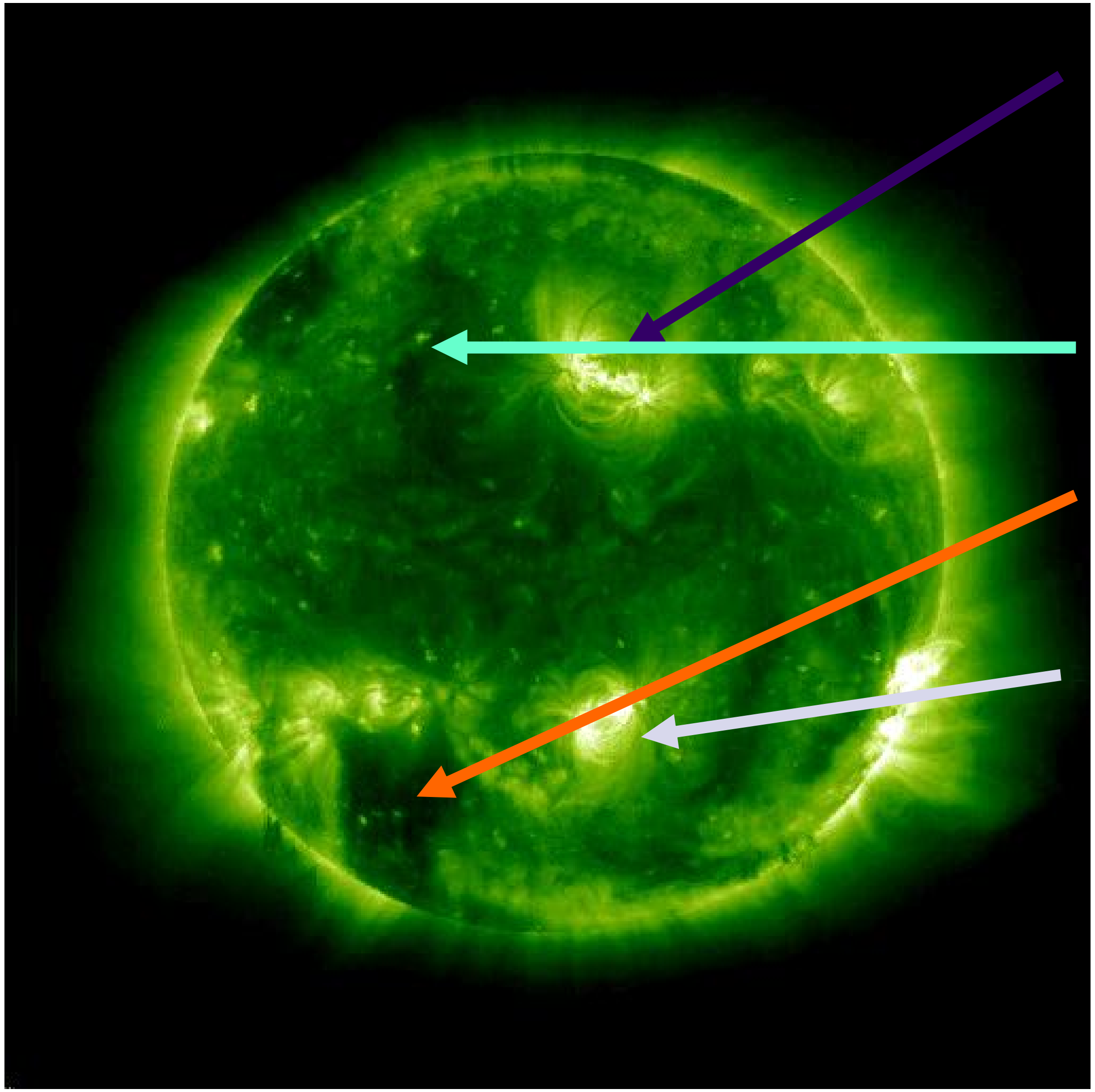
Using Coronagraph

The Sun in the EUV: Limb brightening

- In the EUV, the Sun's limb is brighter than the centre of the solar disk (Limb brightening)
- Since the solar atmosphere is optically thin at these wavelengths, intensity ~ thickness of layer contributing to it. Due to geometrical effects this layer appears thicker near limb (radiation comes from roughly the same height everywhere).



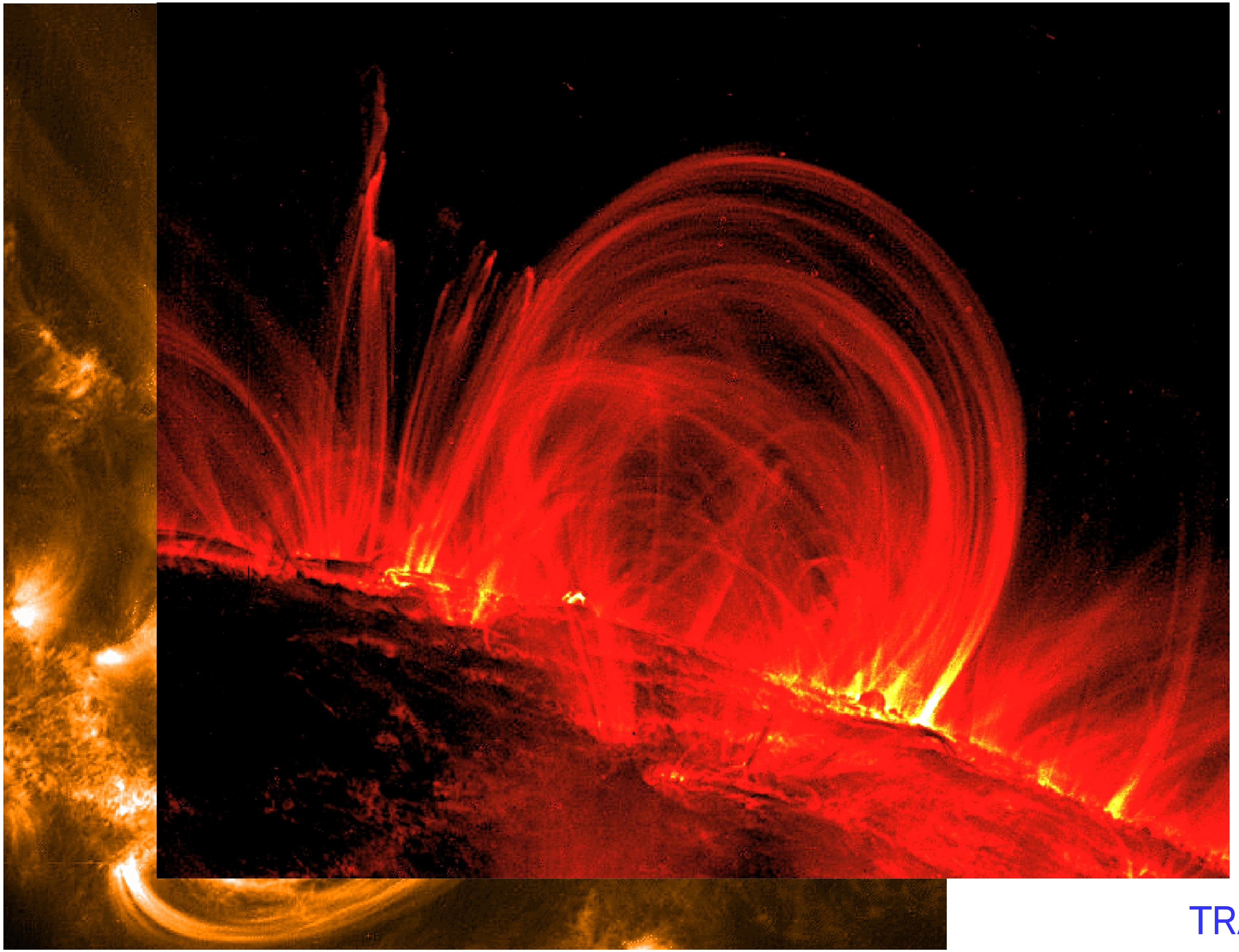
Coronal structures



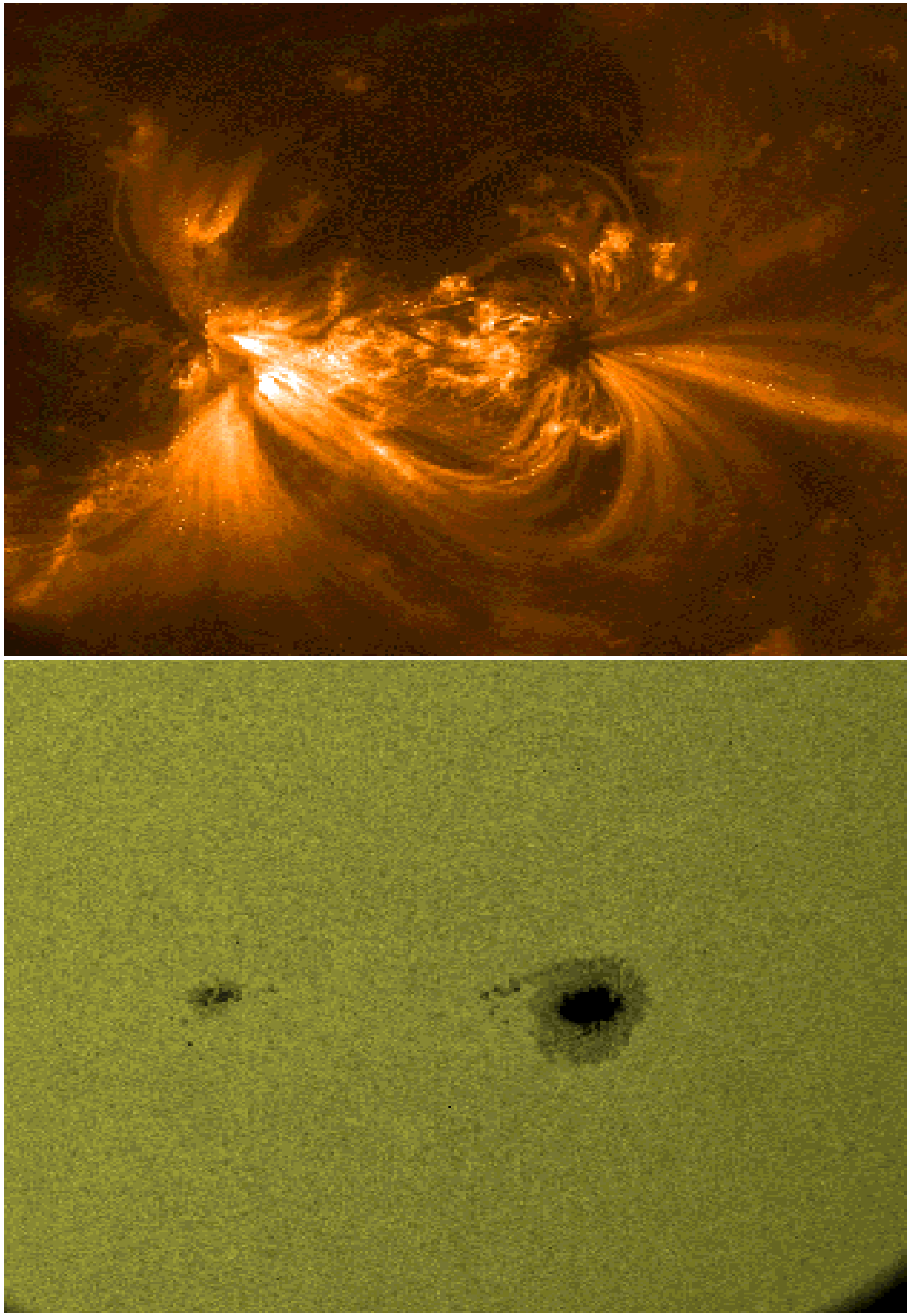
- Active regions (loops)
- Quiet Sun
- X-ray bright points
- Coronal holes
- Arcades

Fe XII 195 Å
(1.500.000 K)
8 June 1998

Coronal active region loops



TRACE, 1999



Photosphere - Corona

EUV and visual images from TRACE

Sunspot proper motion can increased magnetic stress along neutral lines and triggered reconnection

(Courtesy of Lockheed Martin Solar and Astrophysics Laboratory)

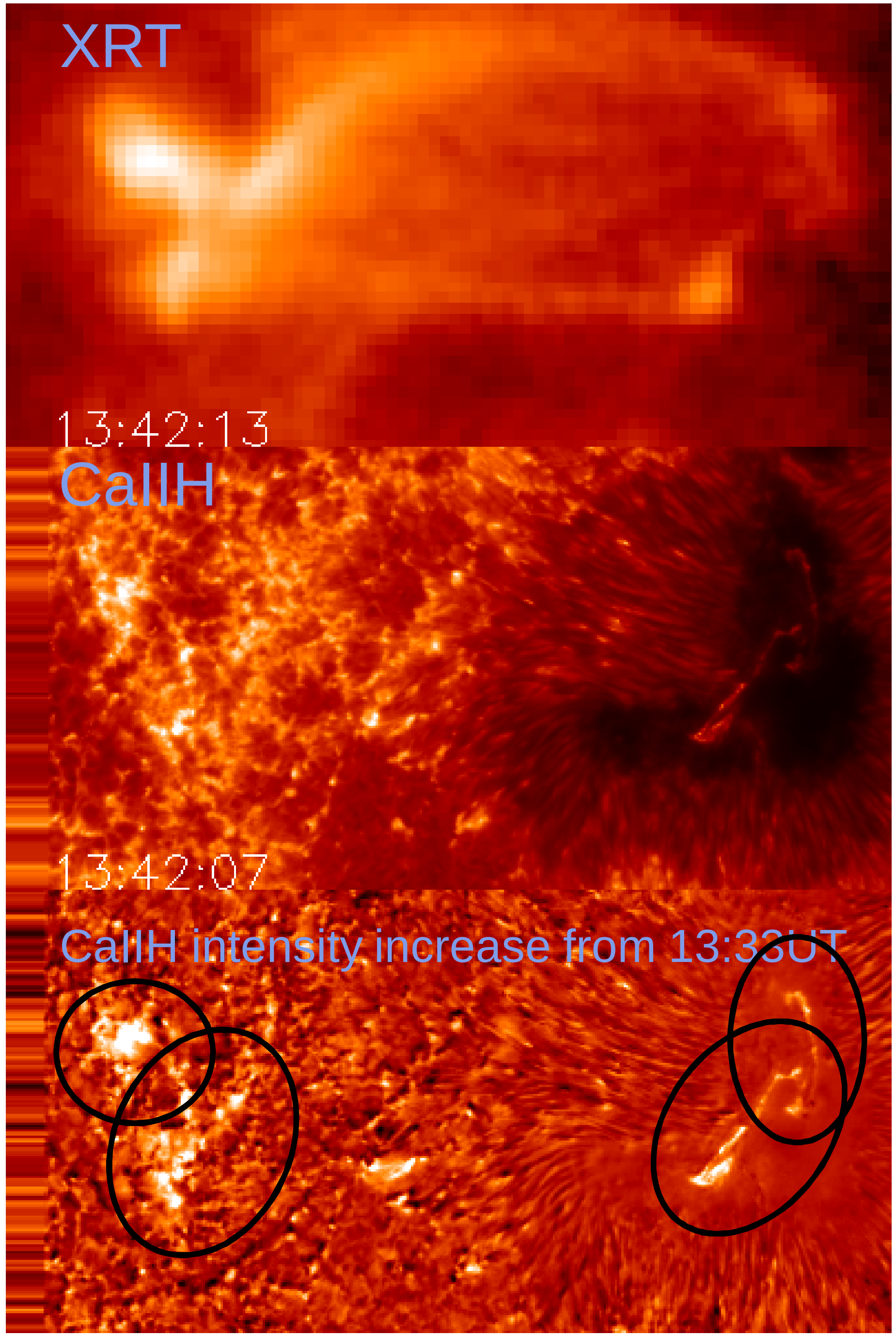
See also DOT movie

Chromosphere - Corona

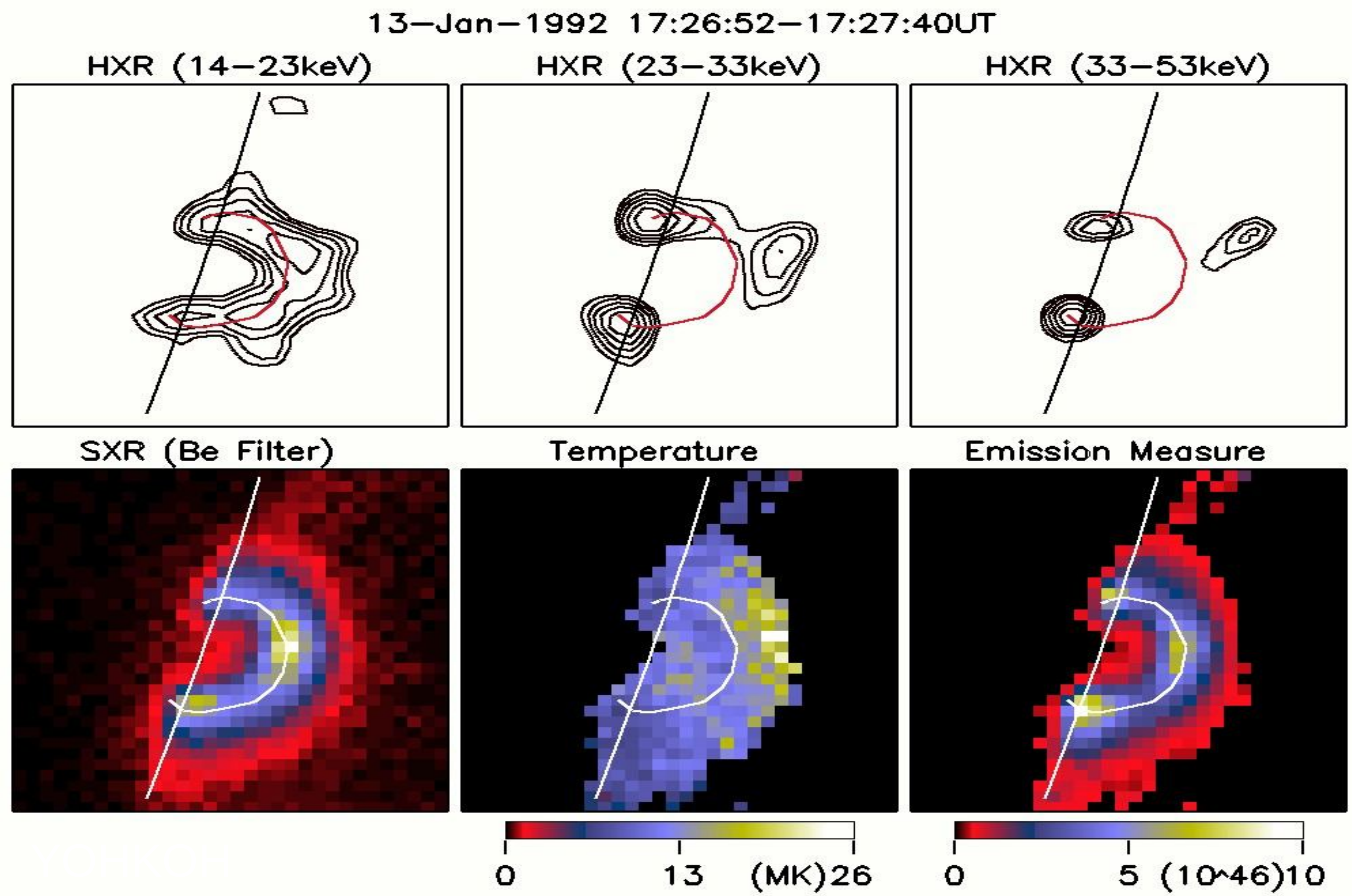
Morphological evolution of X-ray emission is rather complicated.

Similar to flare ribbon, tiny two ribbon brightenings can be observed in chromospheric Ca IIH line images, giving the exact position of the footpoints of brightening loops.

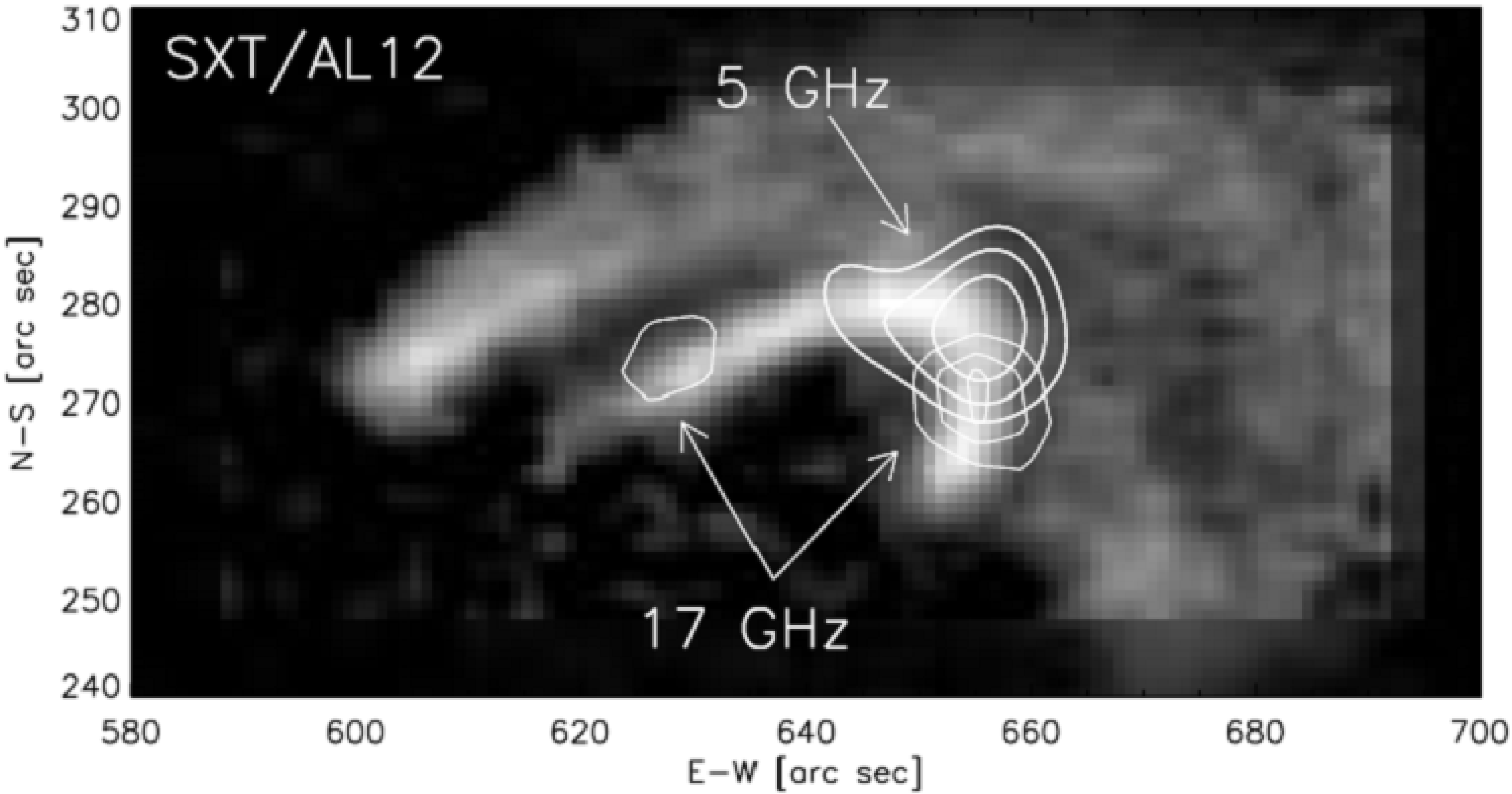
One end is located well inside the sunspot umbra. The ribbon consists of two groups (loop-loop interaction).



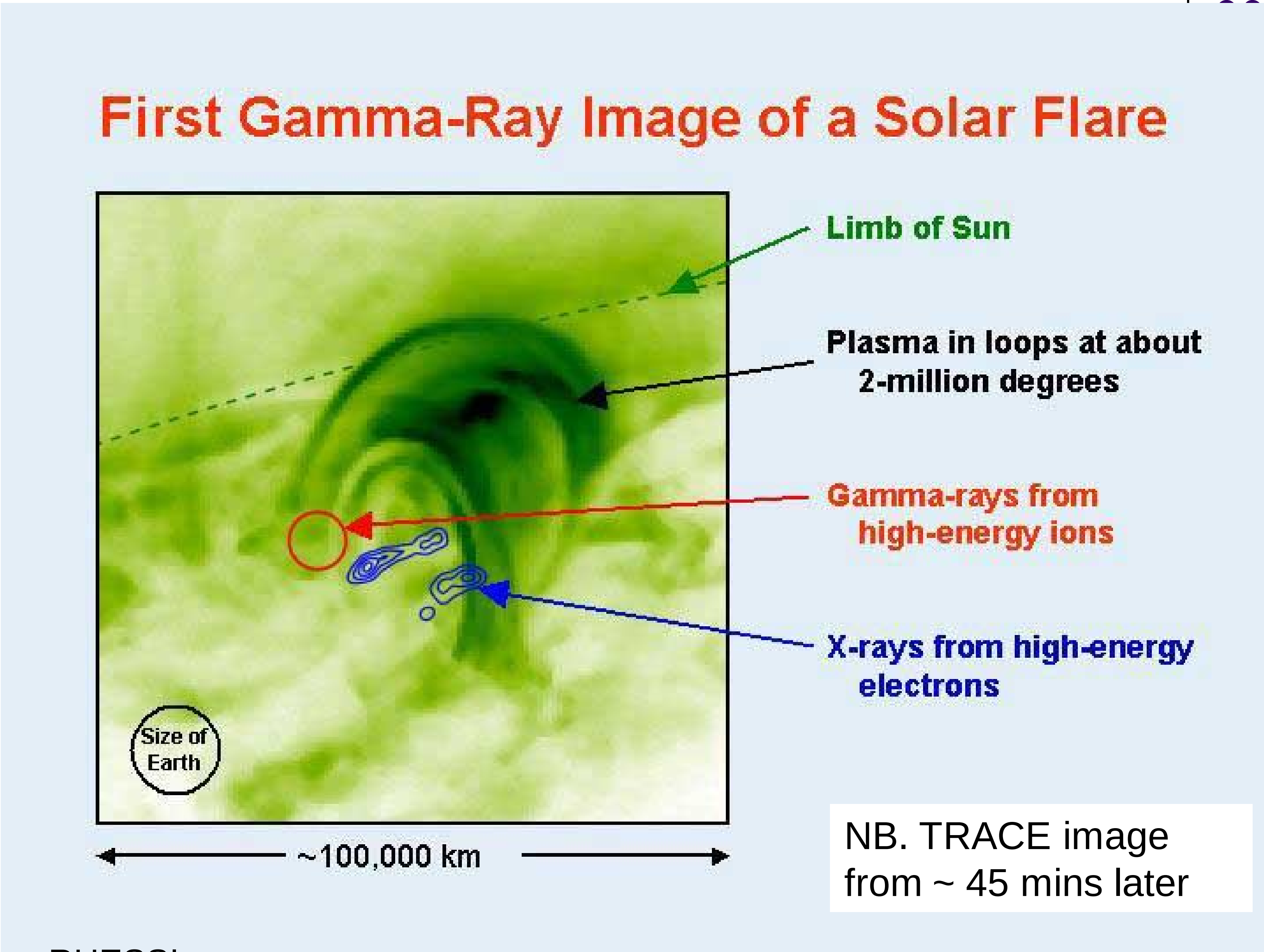
Masuda flare: hard X-ray source above the loop top (Masuda et al. 1994)



A Flare in Soft X-rays & Microwaves



Lee & Gary, *The Astrophysical Journal*, 2000

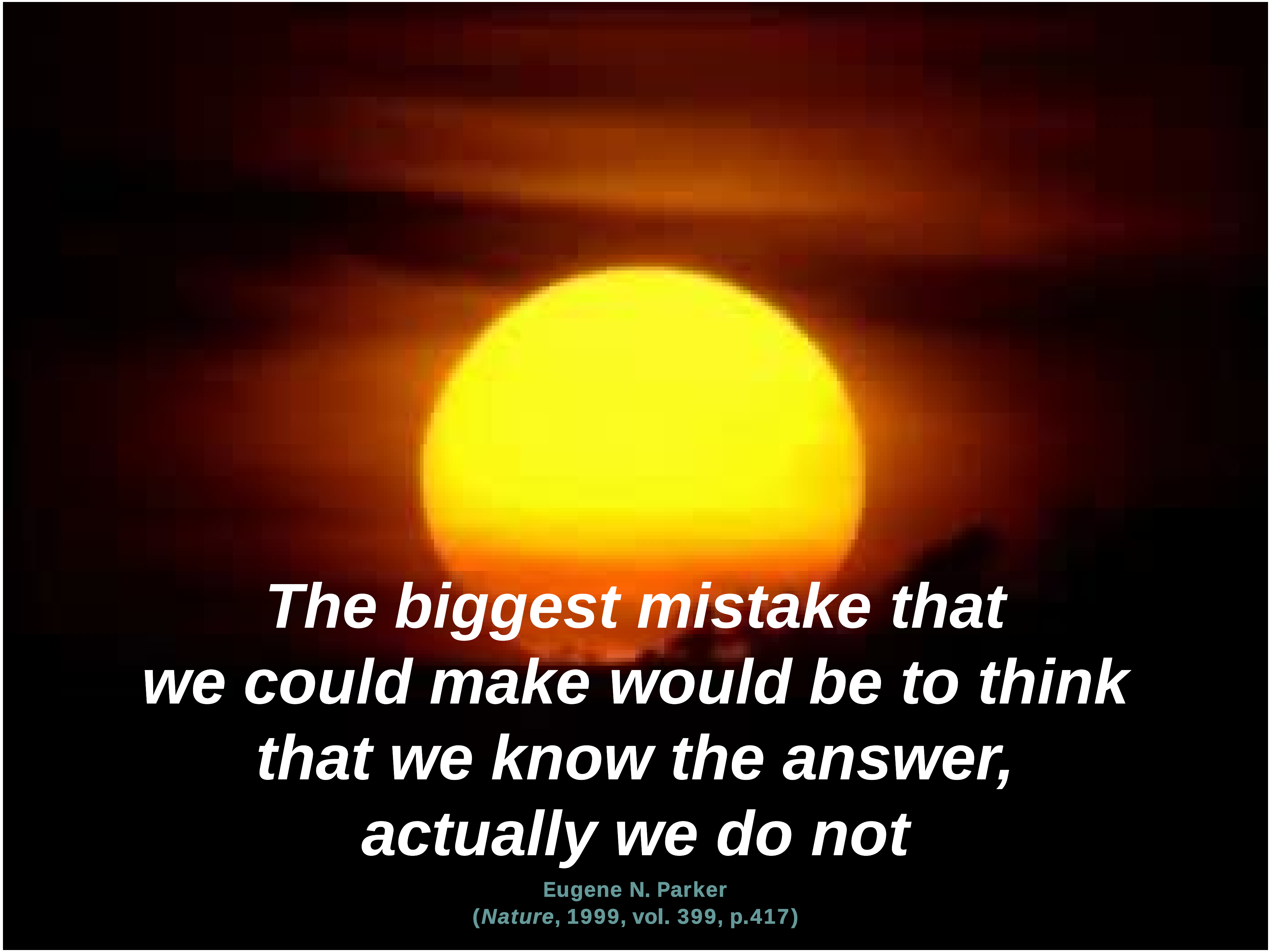


NB. TRACE image from ~ 45 mins later

RHESSI

Take a look

Lecture notes from Max Planck Institute for Solar System Research (http://www.mps.mpg.de)


The biggest mistake that
we could make would be to think
that we know the answer,
actually we do not
Eugene N. Parker
(Nature, 1999, vol. 399, p.417)

Exercise:
Compute Coronal Temperature

In place of the strong Calcium (Ca+) H and K lines (wavelengths λ = 400 nm) rather shallow and broad dips (width $d\lambda$ = 20 nm) can be noticed in the spectrum of K corona. Assume that the dips are in fact the Doppler broadening of the line spectrum and derive a temperature of particles. Note that Thomson scattering (photon-electron scattering) is one of the major processes in the K corona. In this way Grotrian (1931) first concluded that the corona might be hot. Hint: Use the electron mass mc^2 = 511 keV