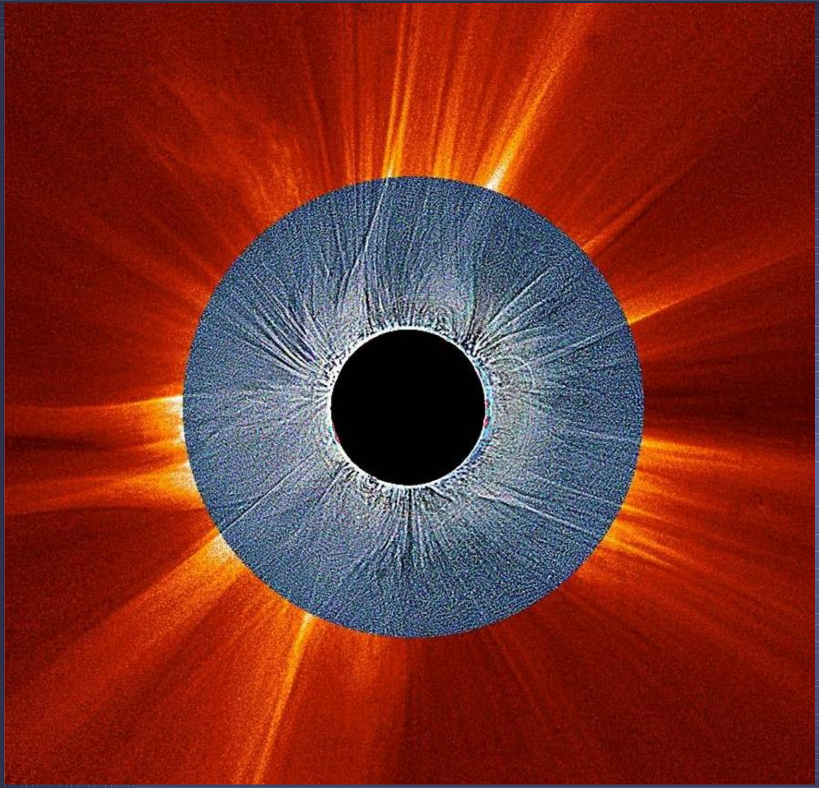
What do we see on the face of the Sun?

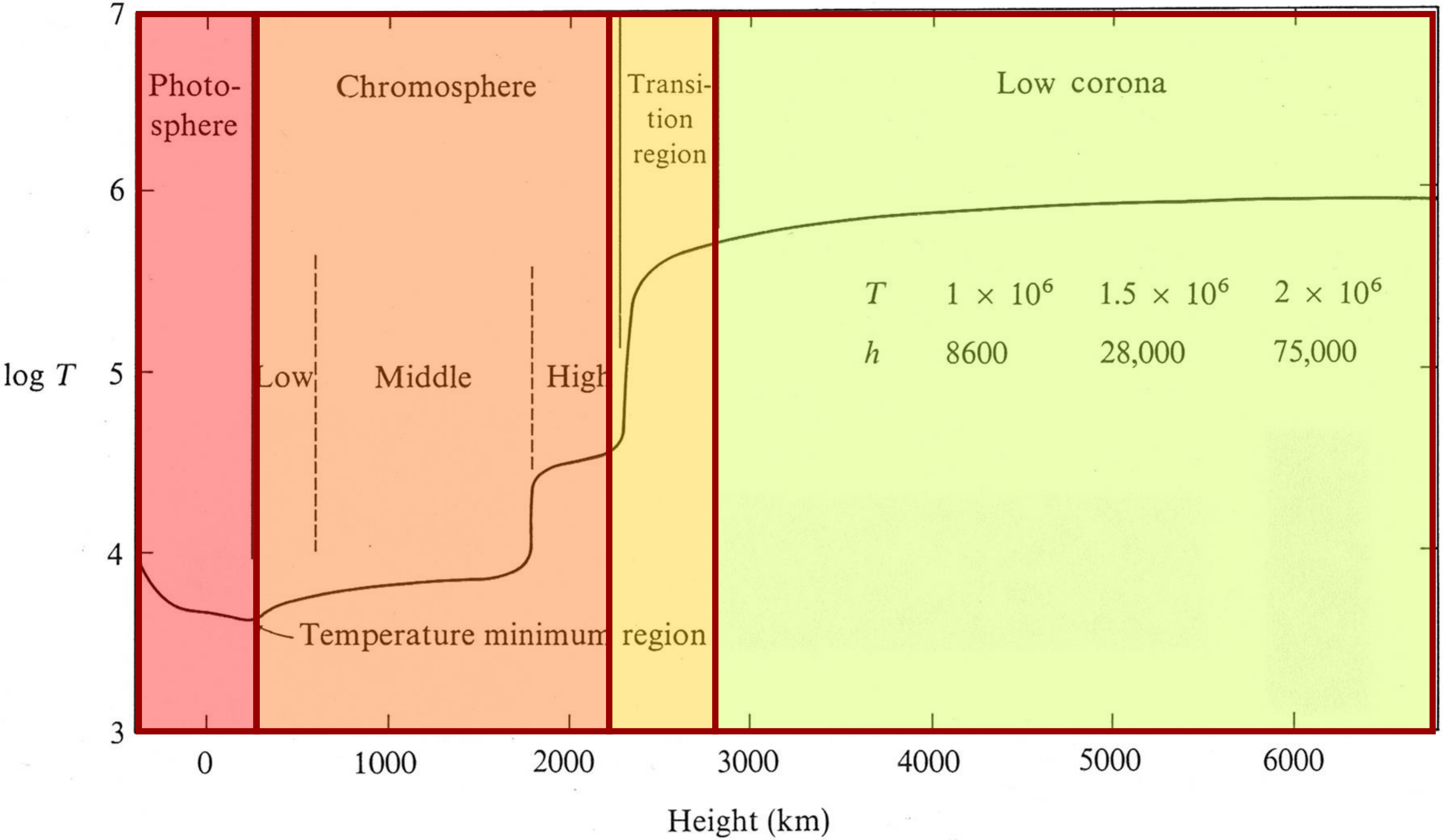
Lecture 3: The solar atmosphere



The Sun's atmosphere

- Solar atmosphere is generally subdivided into multiple layers. From bottom to top: photosphere, chromosphere, transition region, corona, heliosphere
- 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 → $H_\rho \approx 100\mathrm{km}$
- Density of Sun's atmosphere is rather low →
  - Mass of the solar atmosphere ≈ mass of the Indian ocean (≈ mass of the photosphere)
  - Mass of the chromosphere ≈ mass of the Earth's atmosphere

Stratification of average quiet solar atmosphere: 1-D model



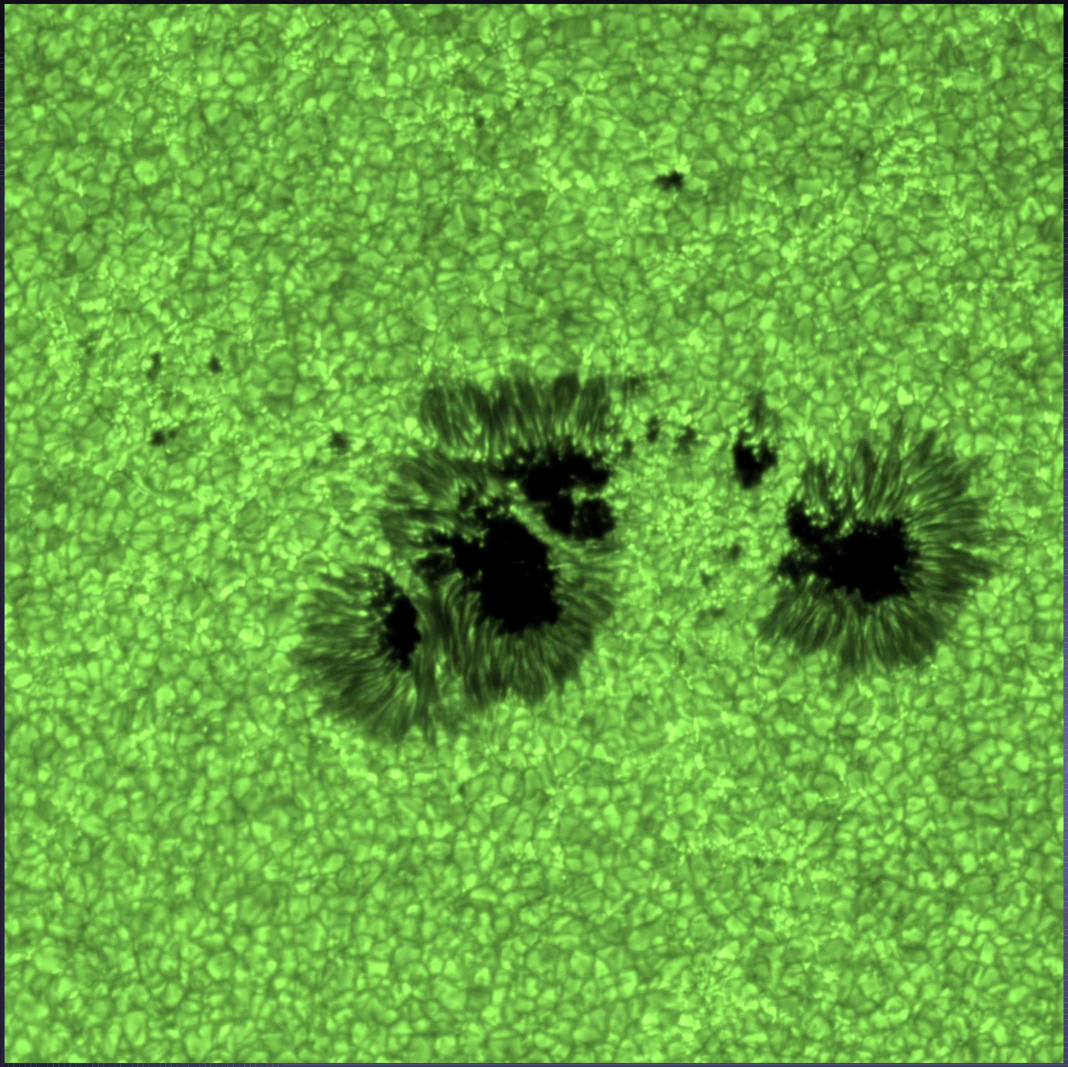
Typical values of physical parameters

	Temperature K	Number Density cm-3	Pressure dyne/cm2
Photosphere	4000 - 6000	1015 – 1017	103 – 105
Chromosphere	6000 – 50000	1011 – 1015	10-1 – 103
Transition region	50000-106	109 – 1011	0.1
Corona	106 – 5 106	107 – 109	<0.1

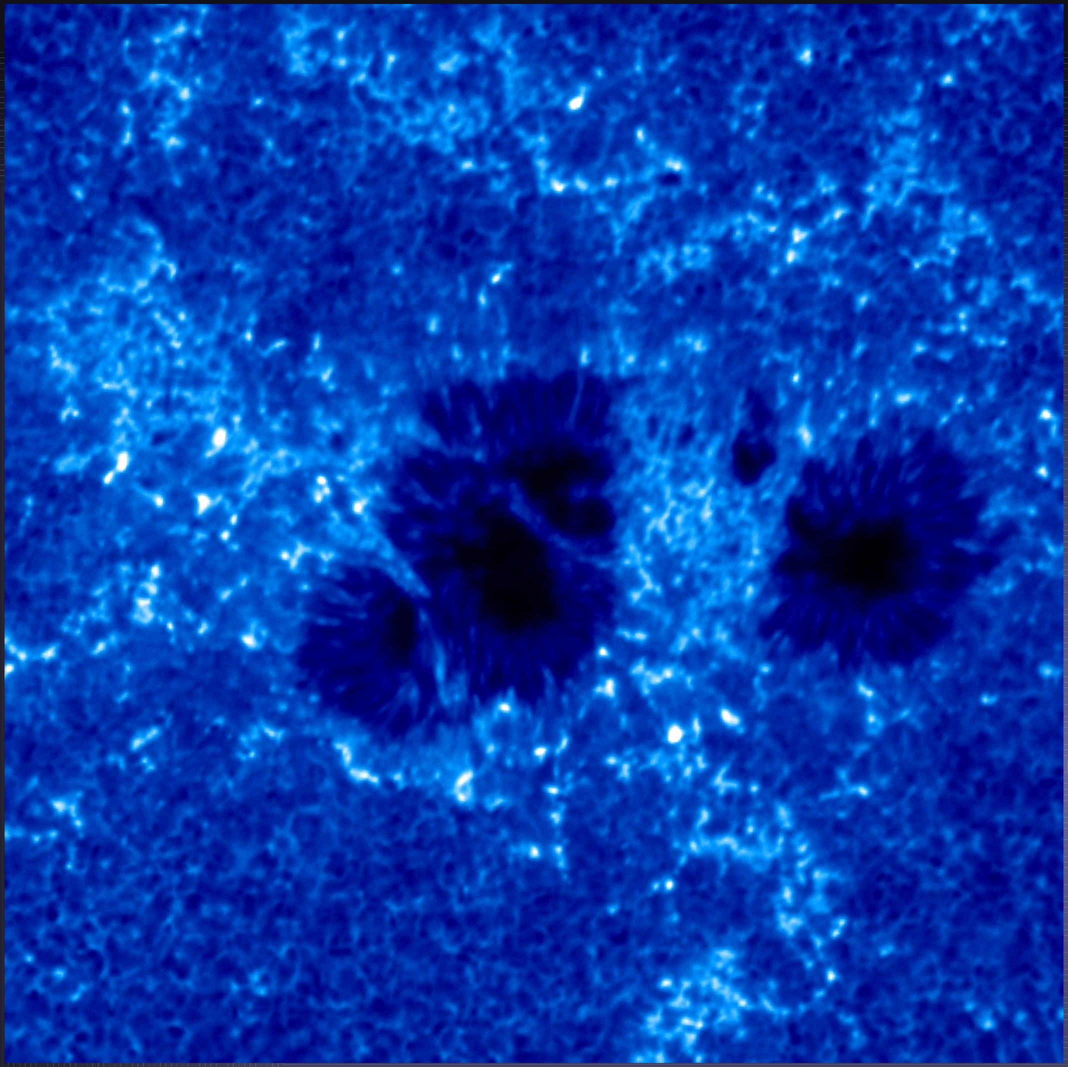
How good is the 1-D approximation?

- 1-D models reproduce extremely well large parts of the spectrum obtained at low spatial resolution
- However, high resolution images of the Sun at basically all wavelengths show that its atmosphere has a complex structure
- Therefore: 1-D models may well describe averaged quantities relatively well, although they probably do not describe any particular part of the real Sun
- The following images illustrate inhomogeneity of the Sun and how the structures change with the wavelength and source of radiation

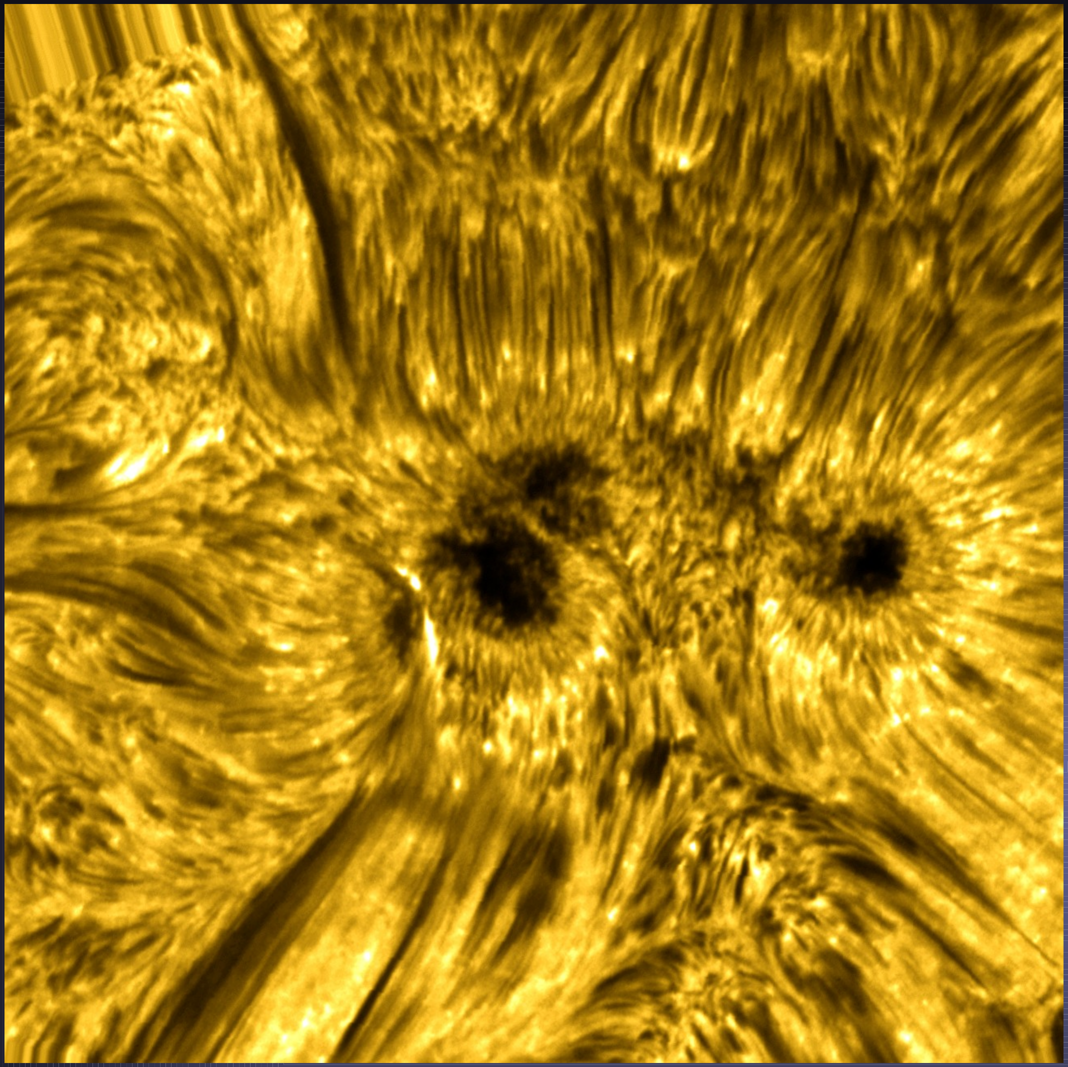
Photosphere



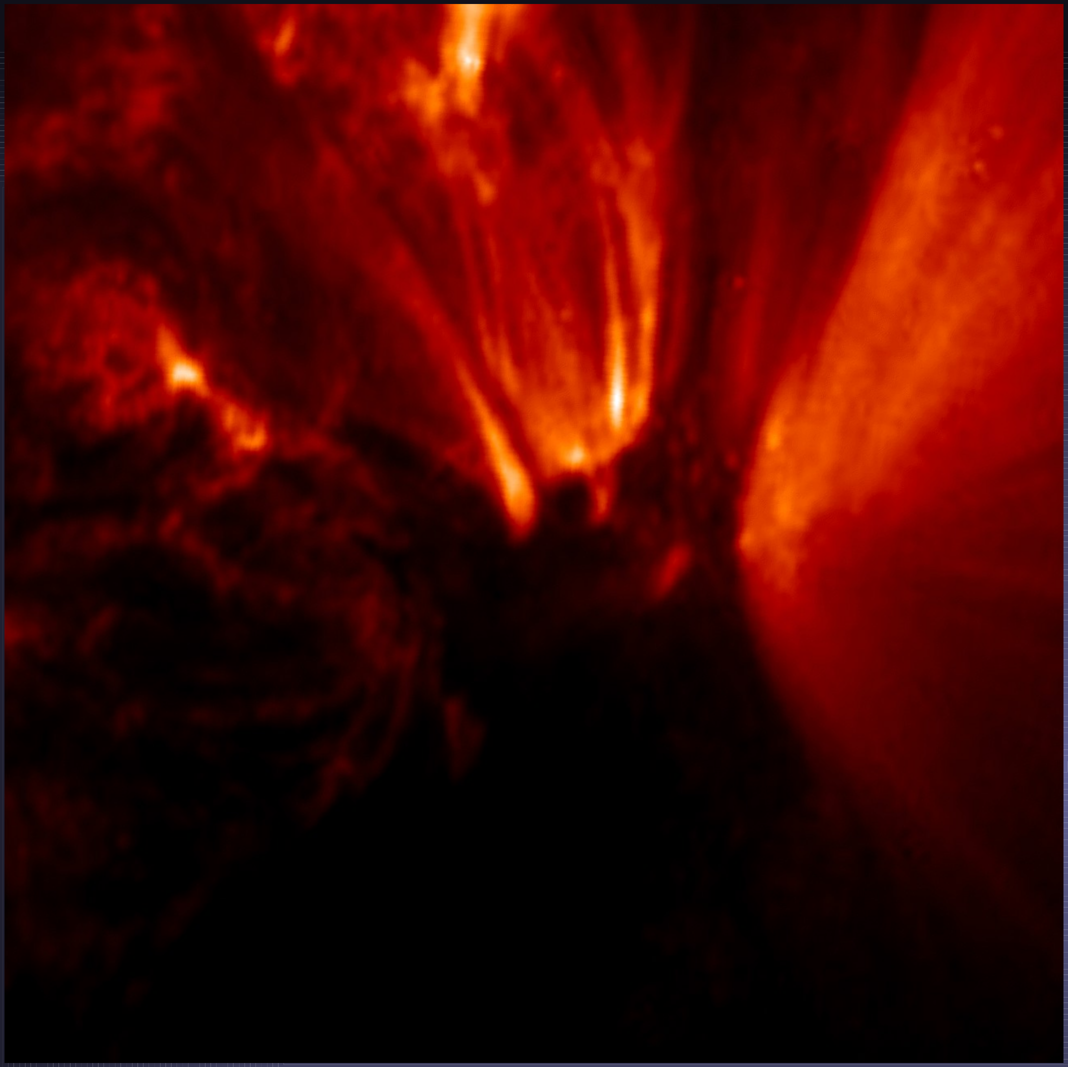
Lower chromosphere



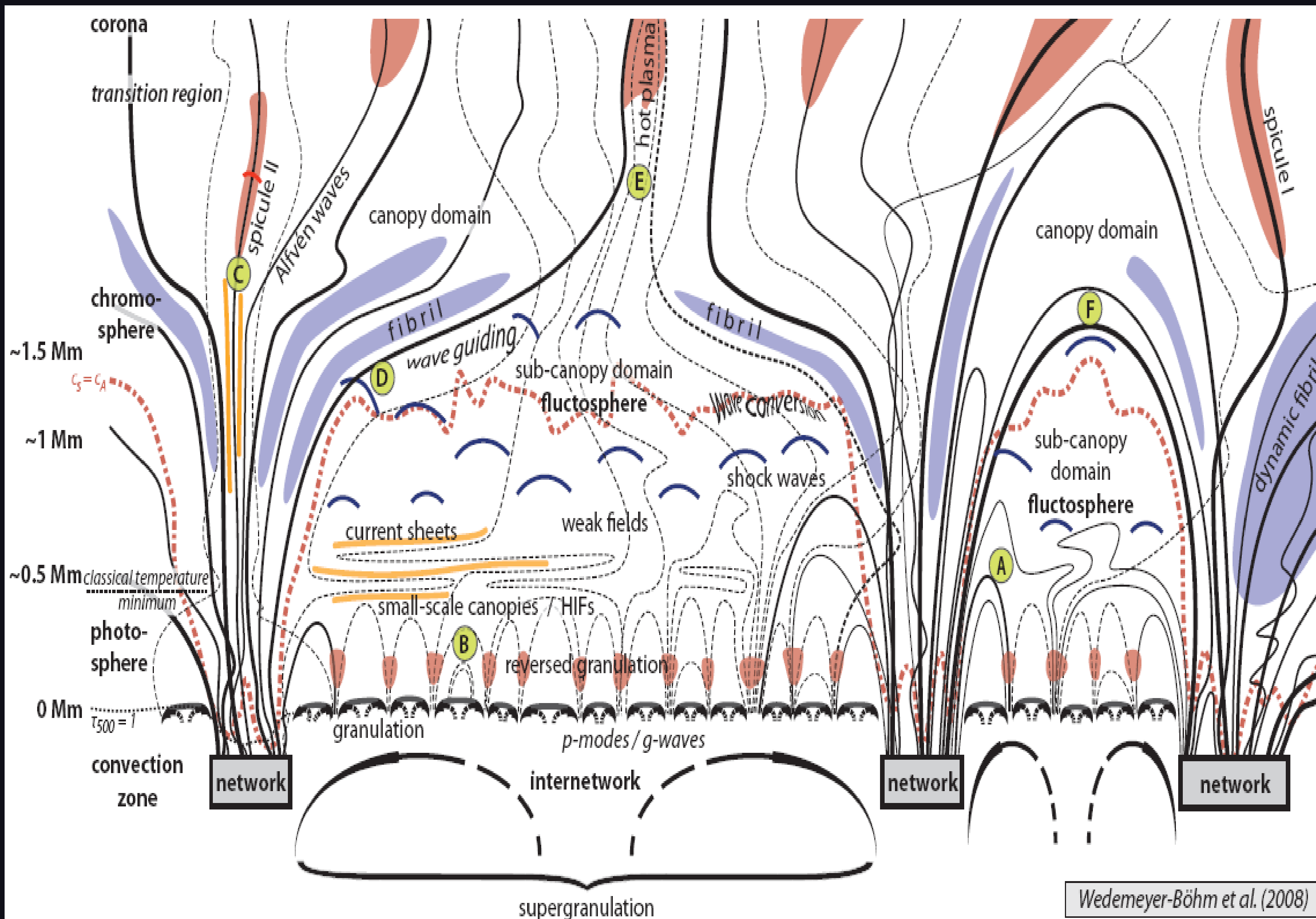
Upper chromosphere



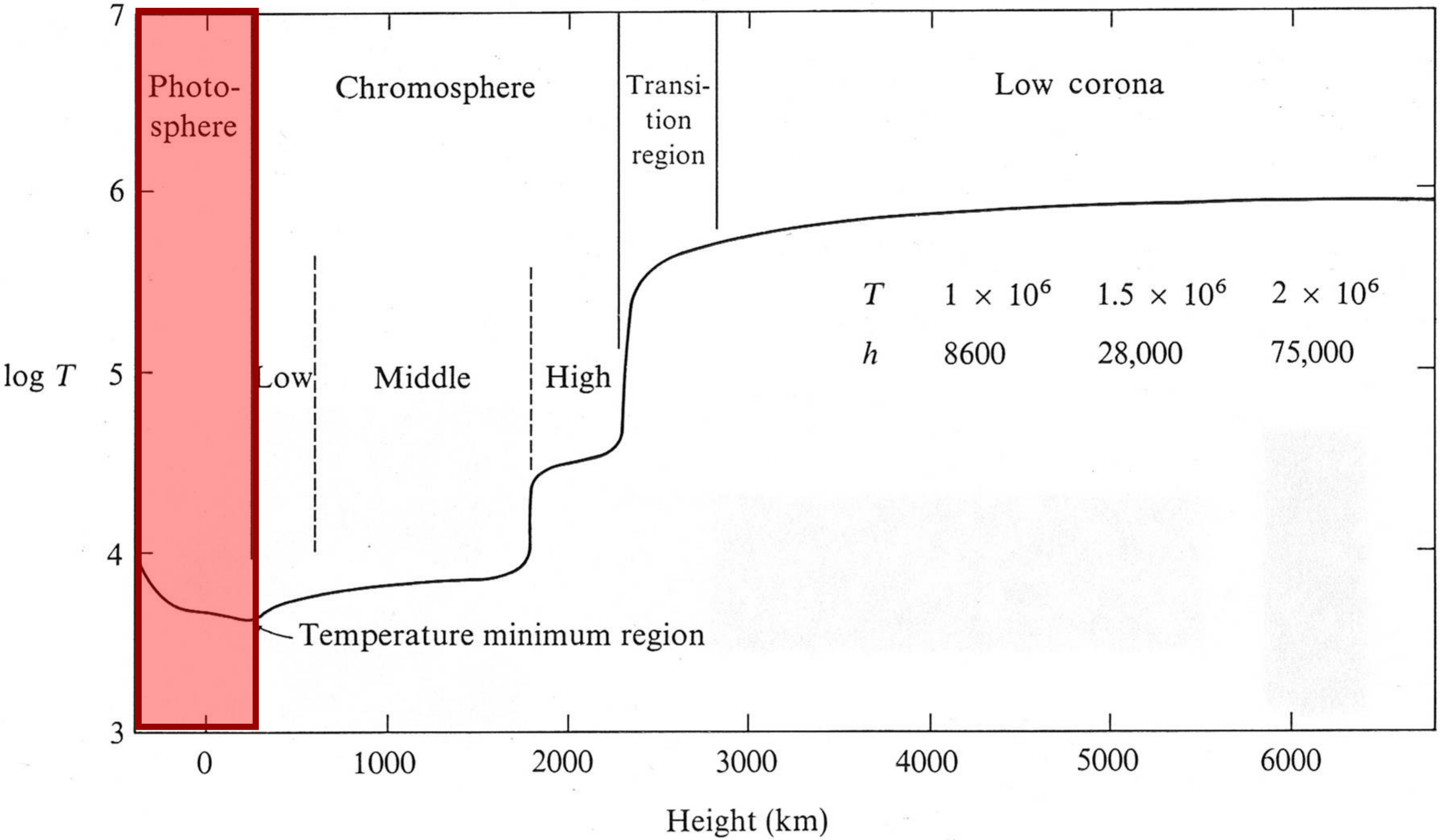
Corona



Cartoon of quiet Sun atmosphere



Photosphere



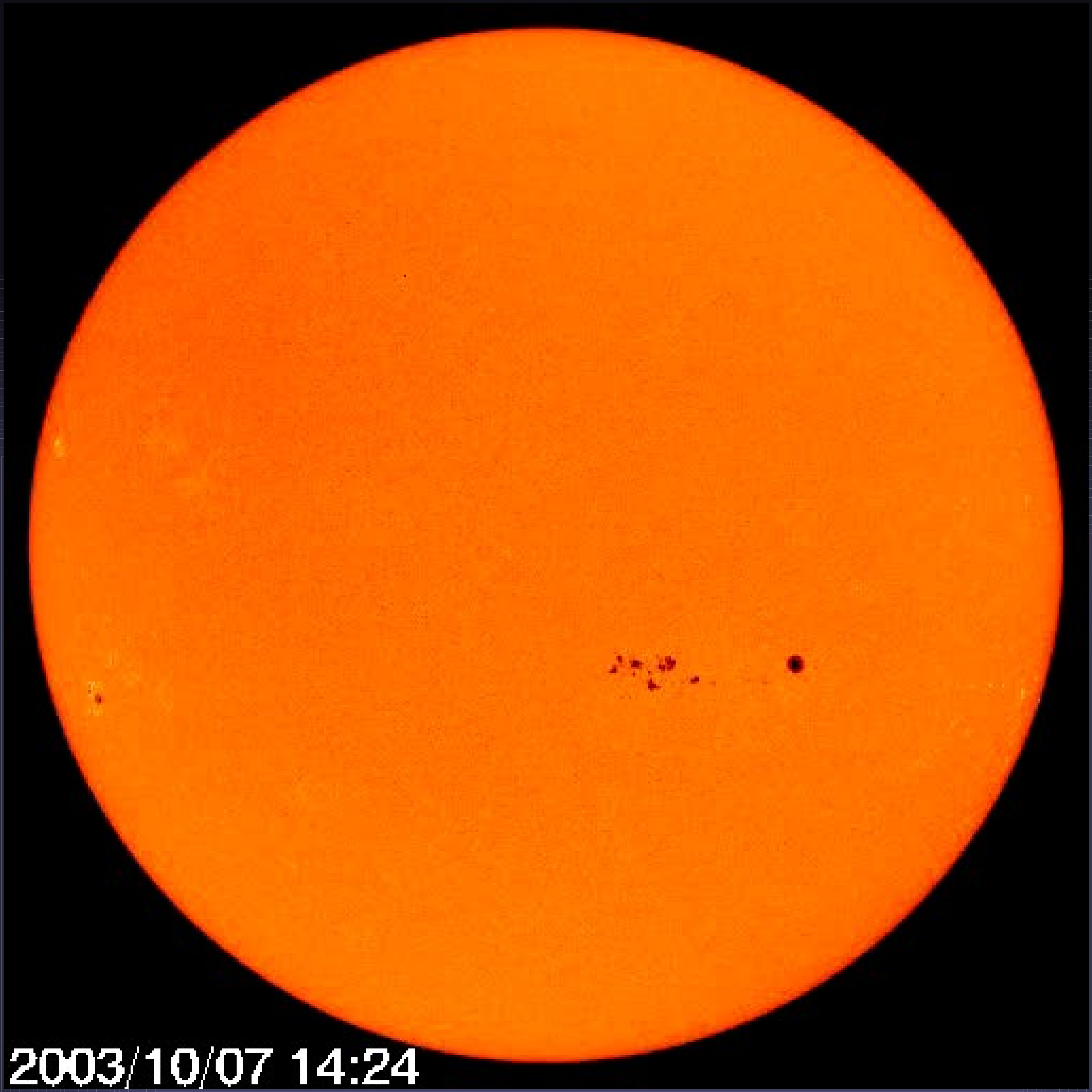
The photosphere

- Photosphere extends between solar surface and temperature minimum (400-600 km)
- It is the source of most of the solar radiation. The visible, UV (λ> 1600Å) and IR (< 300μm) radiation comes from the photosphere.
- 4000 K < T(photosphere) < 6000 K
- T decreases outwards □ *Bν(T)* decreases outward □ photosphere produces an absorption spectrum
- LTE is a good approximation
- Energy transport by radiation (and convection)
- Main structures: Granules, sunspots and faculae

The Sun in White Light

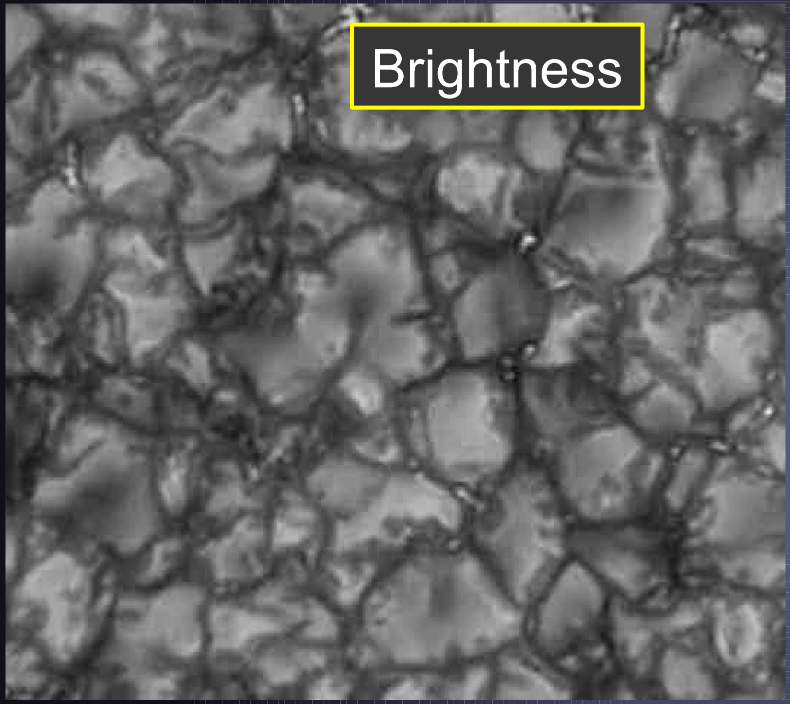
(limb darkening removed)

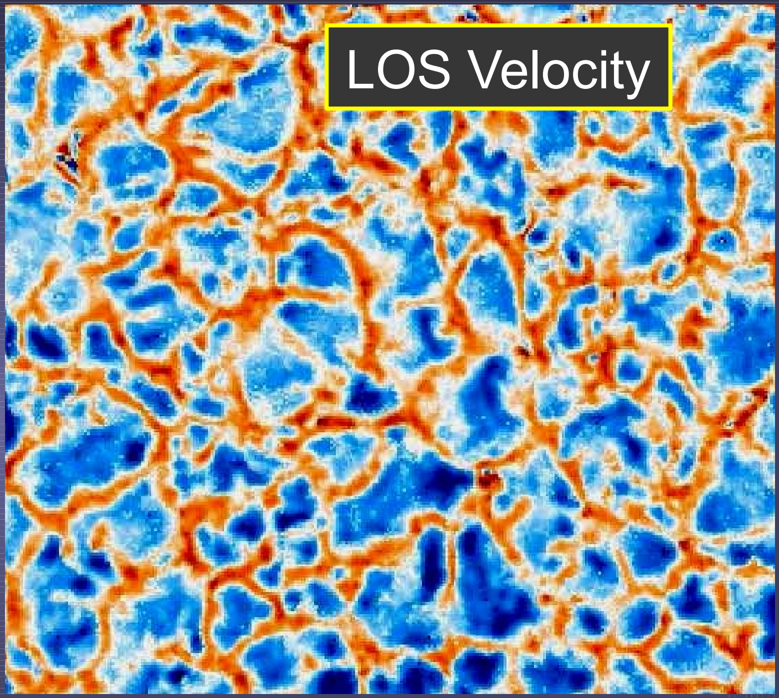
MDI on SOHO



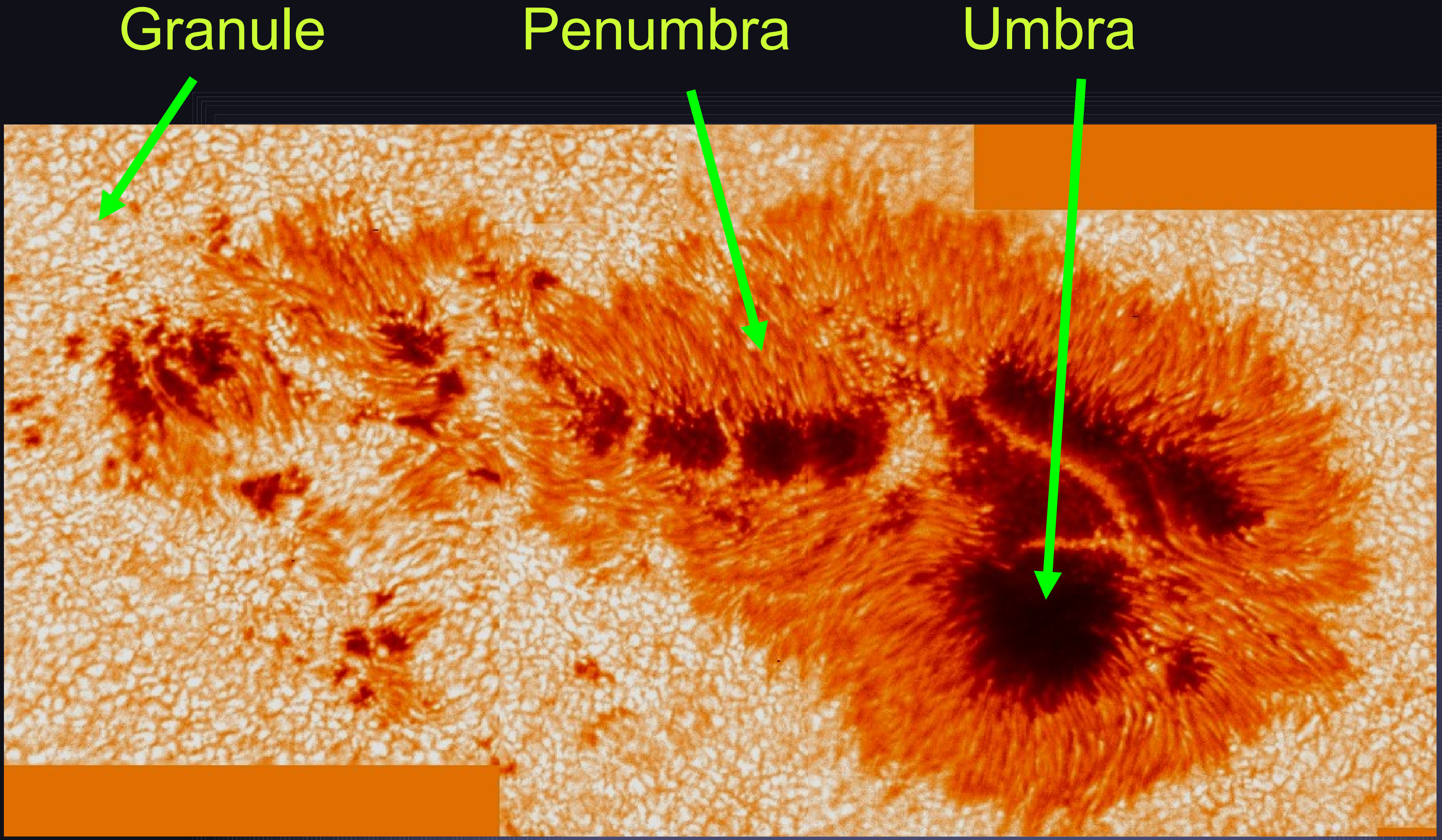
Photospheric structure: Granulation

Physics of convection and the properties of granulation and supergranulation have been discussed in Lecture 2, and can be skipped here





Photospheric structure: Sunspots

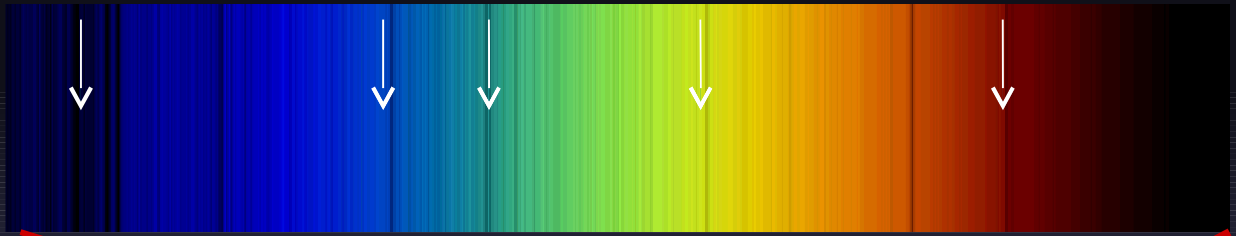


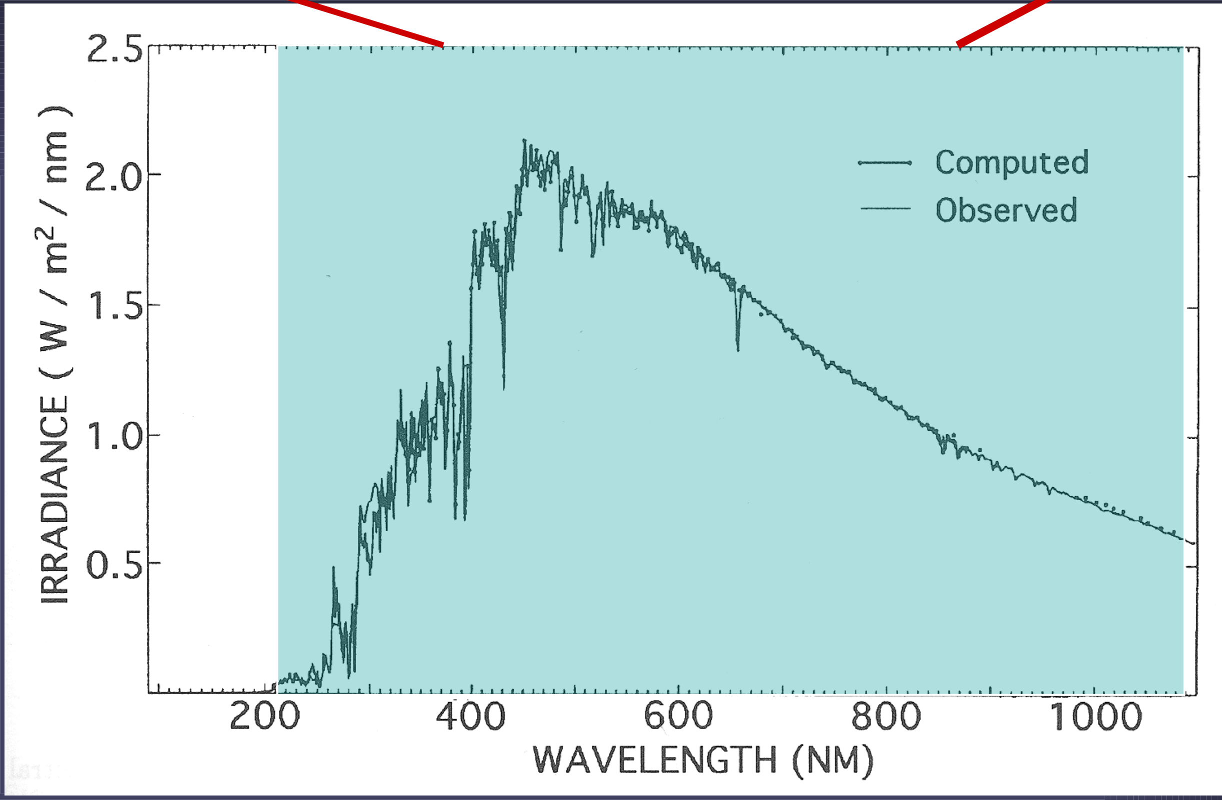
H. Schleicher, KIS/VTT, Obs. del Teide, Tenerife

Photospheric spectrum

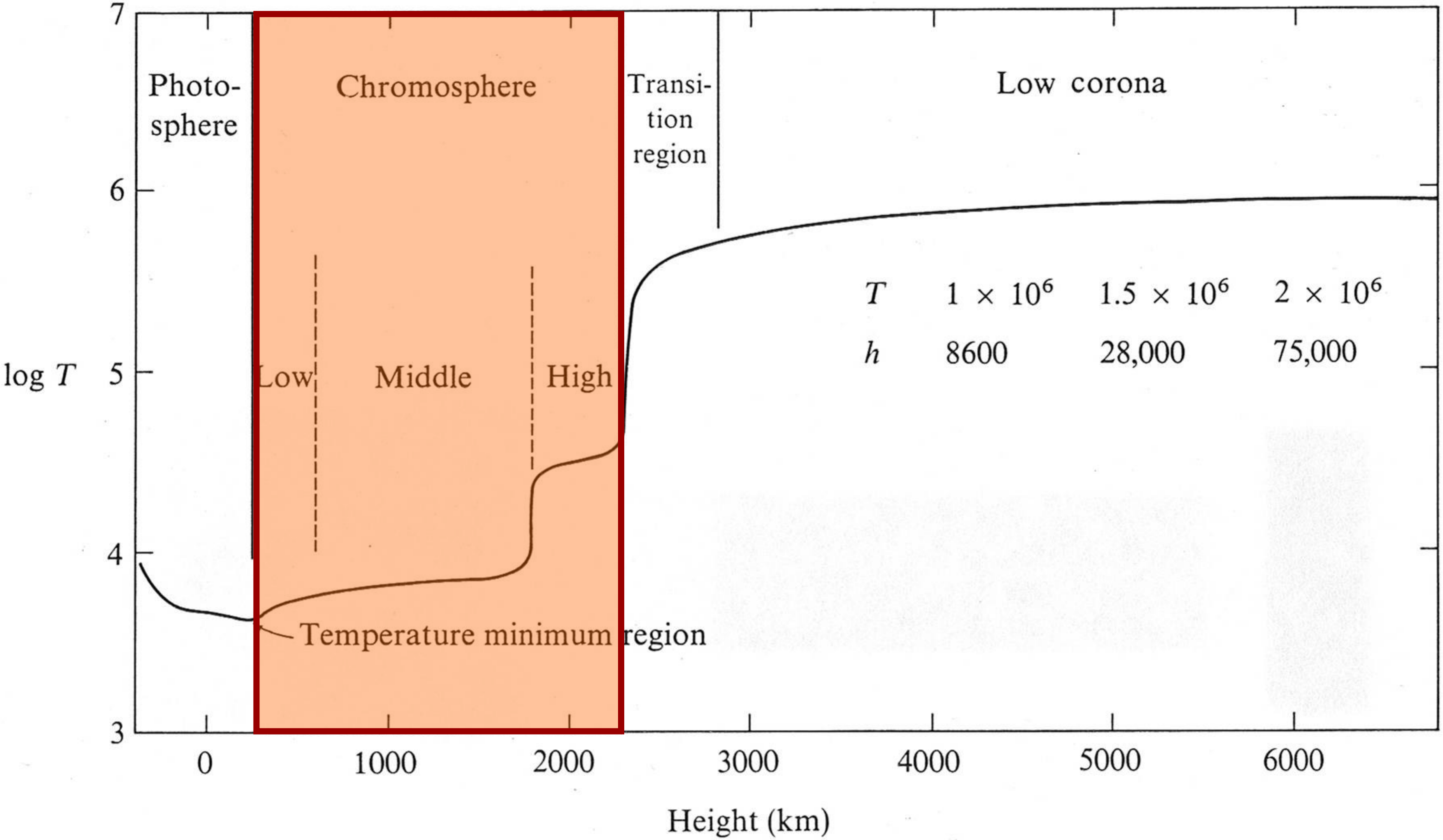
- Most of the visible, near UV (> 160 nm) and near IR (<300 μm) solar spectrum arises in the photosphere
- Chromospheric lines are marked by arrows in the upper spectrum (visible part of solar spectrum)

Arrows mark chromospheric spectral lines





Chromosphere



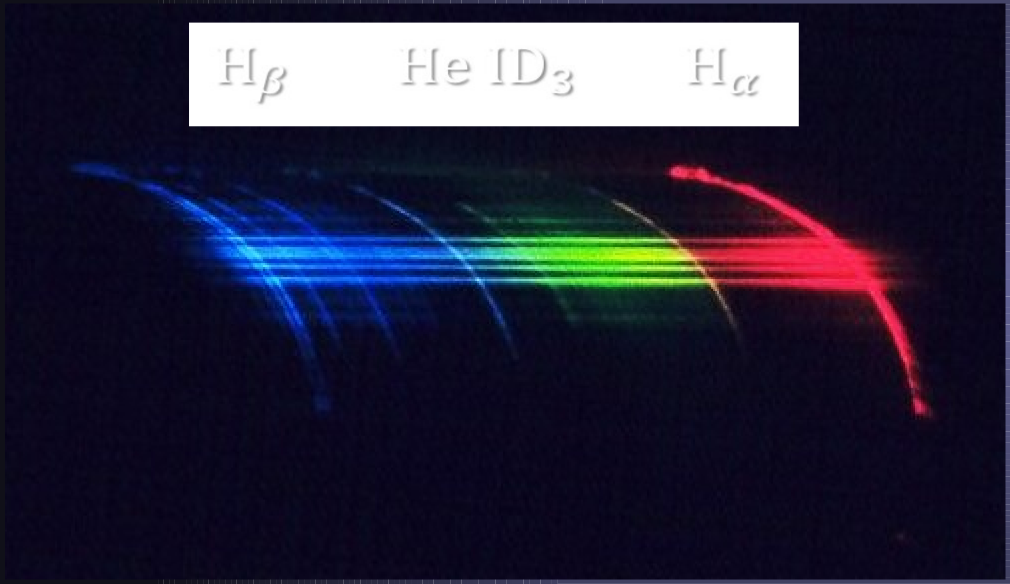
Chromosphere

- Layer just above photosphere, at which temperature appears to increase outwards (classically forming a temperature plateau at around 7000 K)
- Strong evidence for a spatially and temporally inhomogeneous chromosphere (gas at $T<4000$K is present beside gas with $T>8000$ K)
- Assumption of LTE breaks down
- Assumption of plane parallel atmosphere breaks down (i.e. radiative transfer in 3-D important)
- Energy transport mainly by radiation and waves

Discovery of Chromosphere

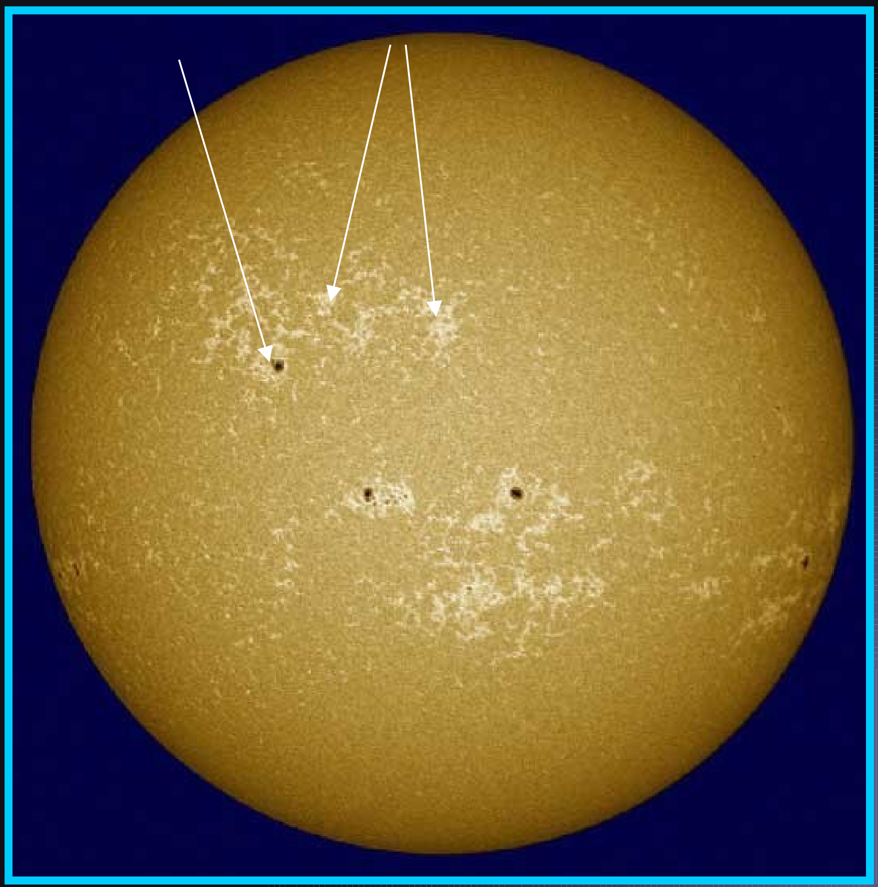
- Red ring seen for seconds at start and end of totality (second and third contact): chromosphere in Hα

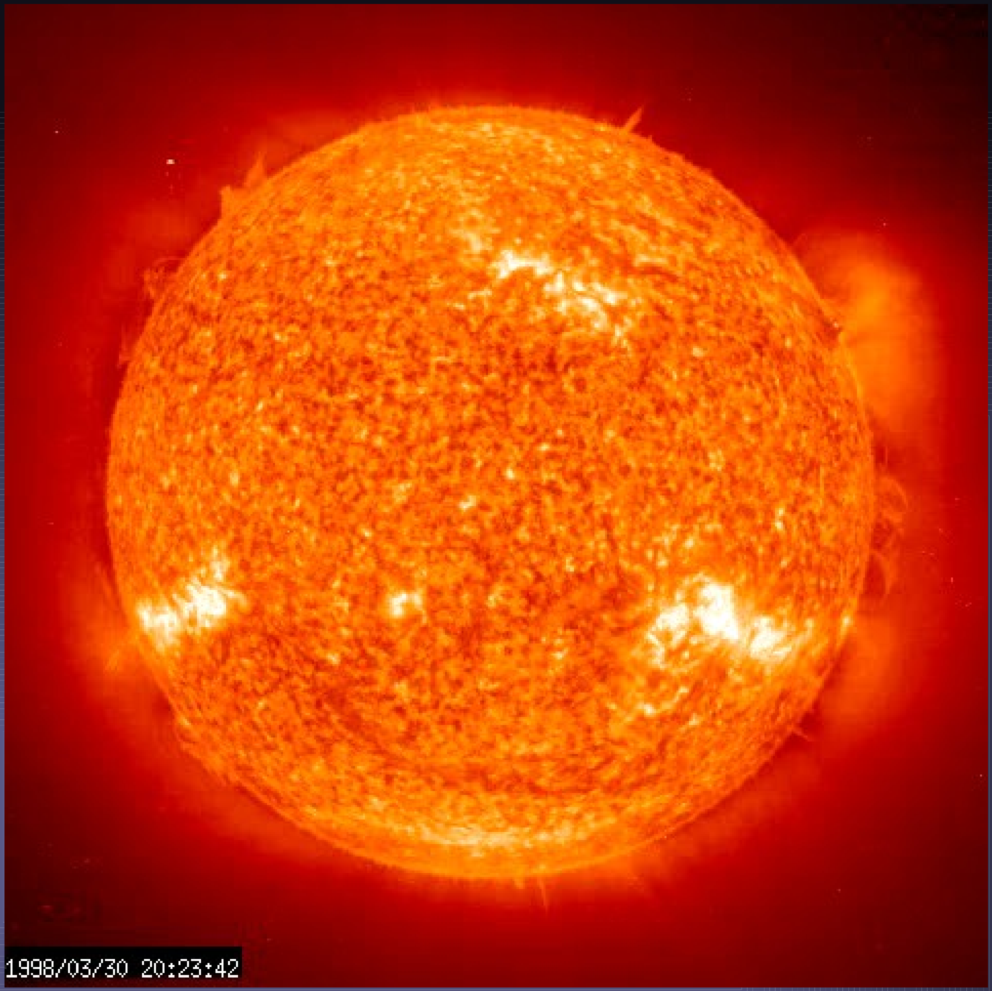
- Spectra taken at second and third contact show the flash spectrum coming entirely from chromosphere



Chromospheric structure & dynamics

Spots plages



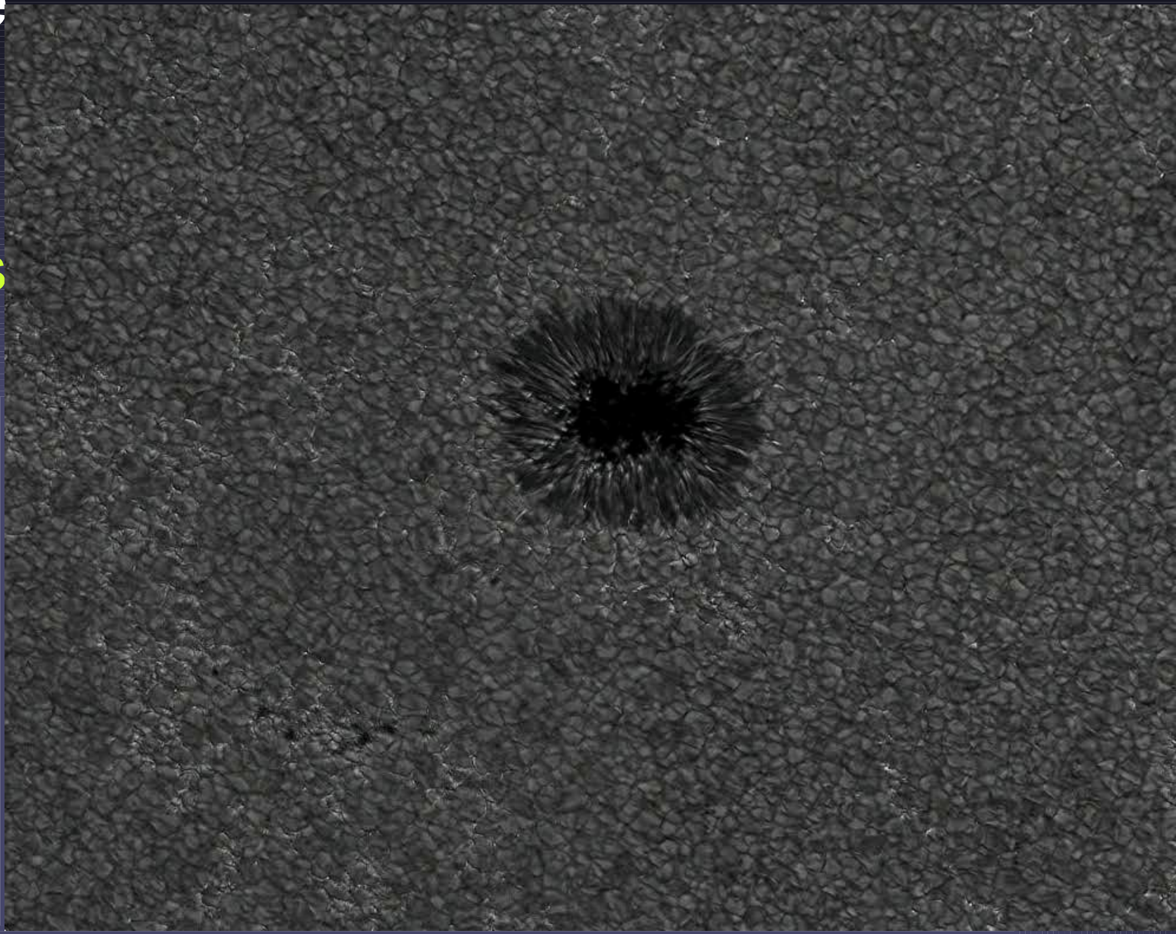


7000 K gas Ca II K

5 104 K gas (EIT He 304 Å)

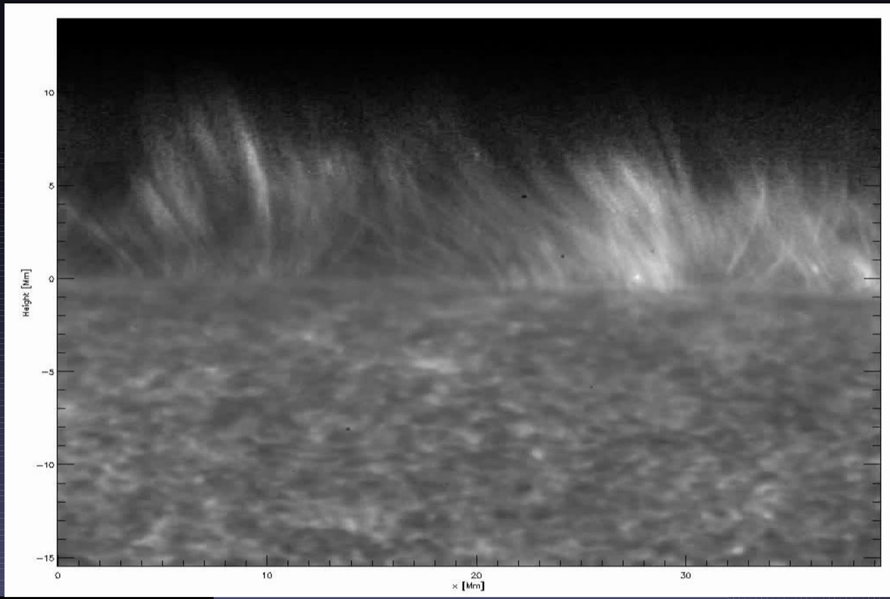
Chromospheric structure

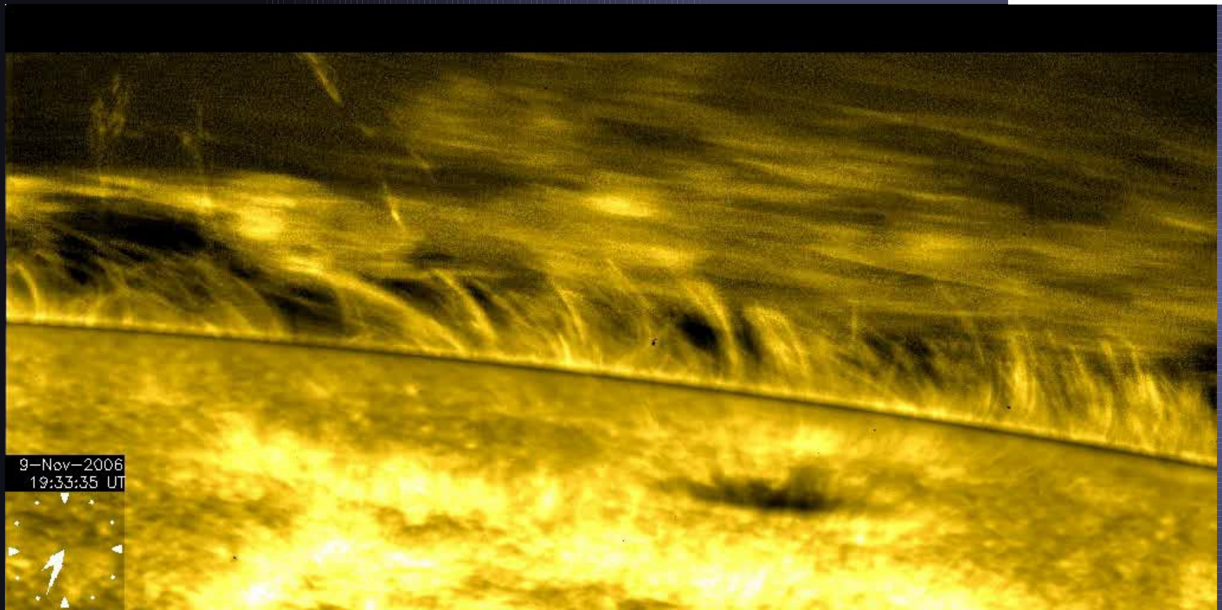
- The chromosphere exhibits a very wide variety of structures. E.g.,
  - Sunspots and Plages
  - Network and internetwork
  - Spicules
  - Prominences and filaments
  - Flares and eruptions



Chromospheric structure

- Spicules
- Prominences and filaments





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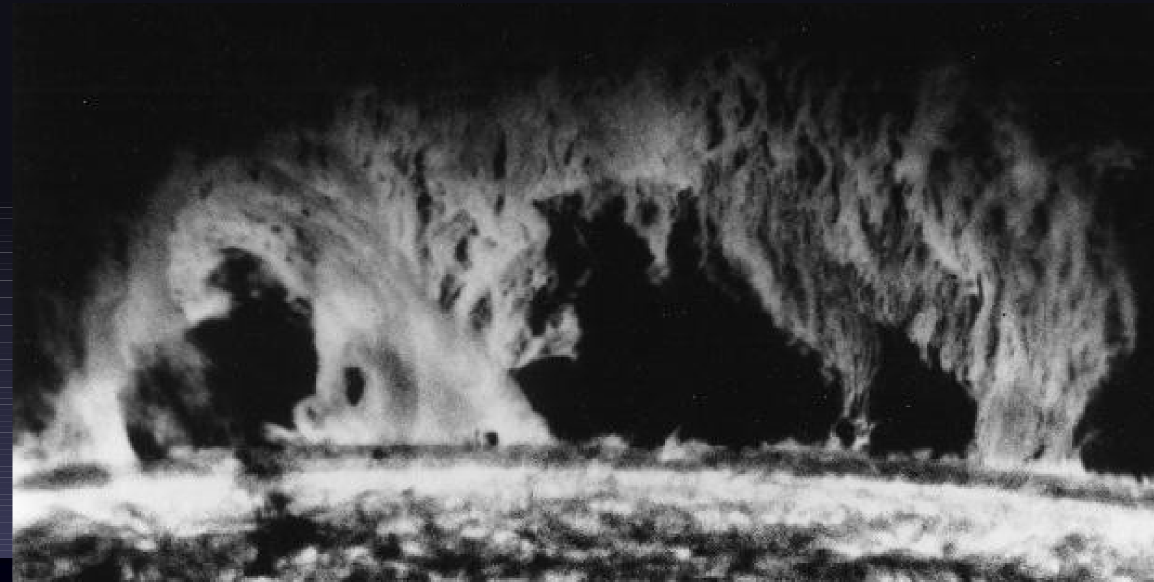
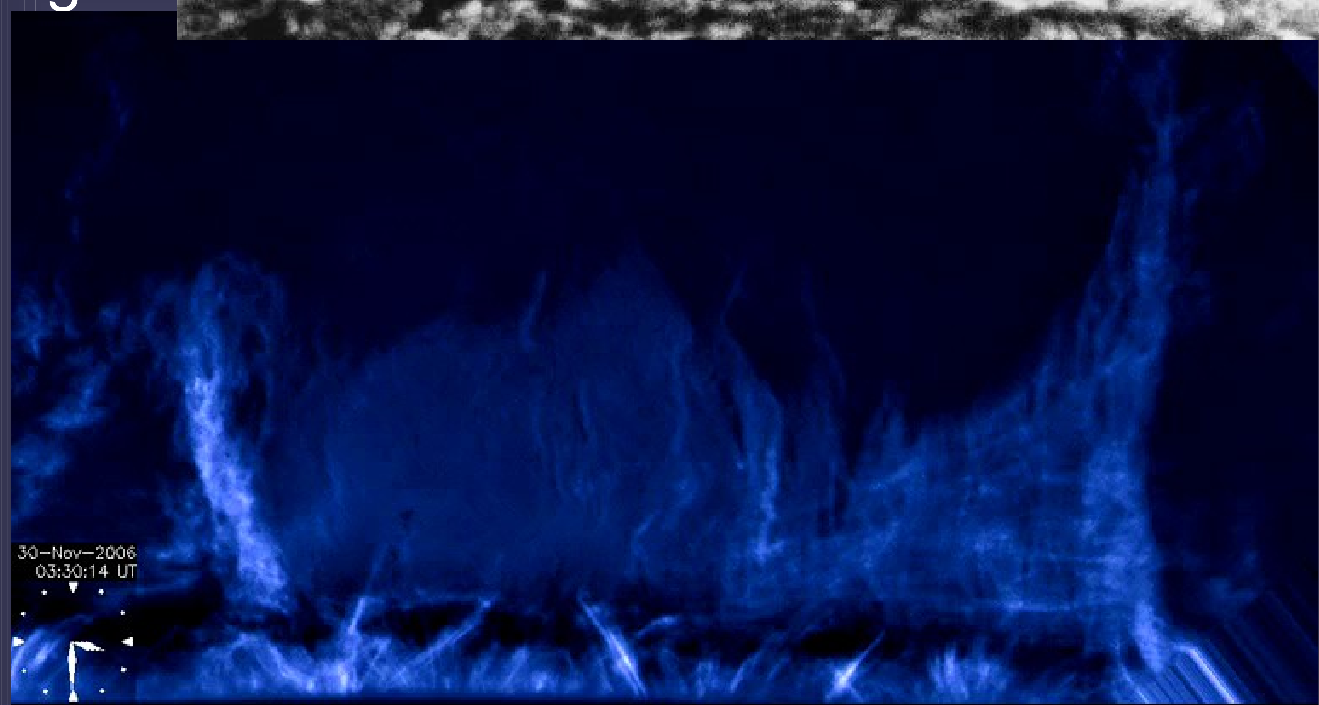
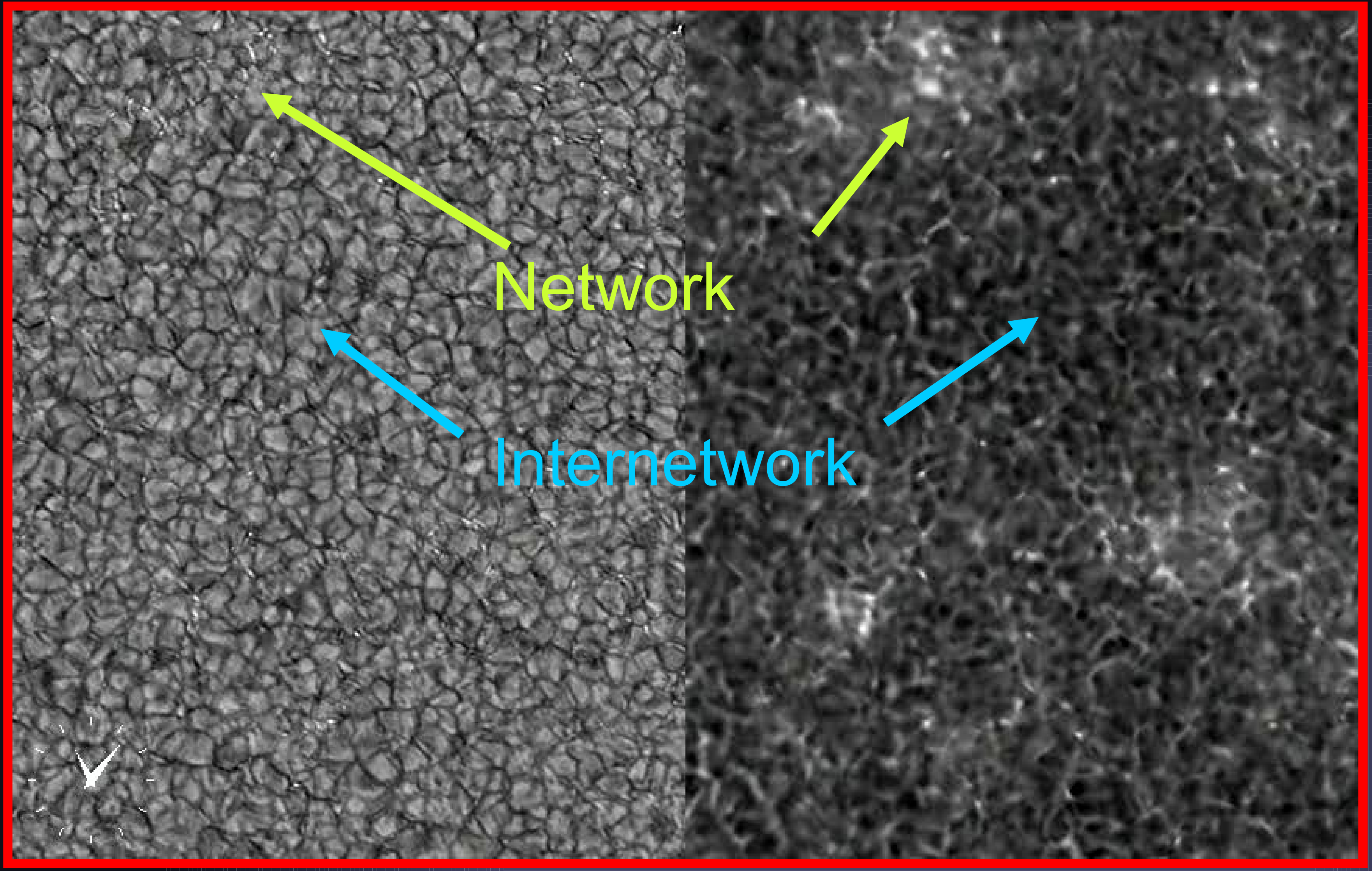


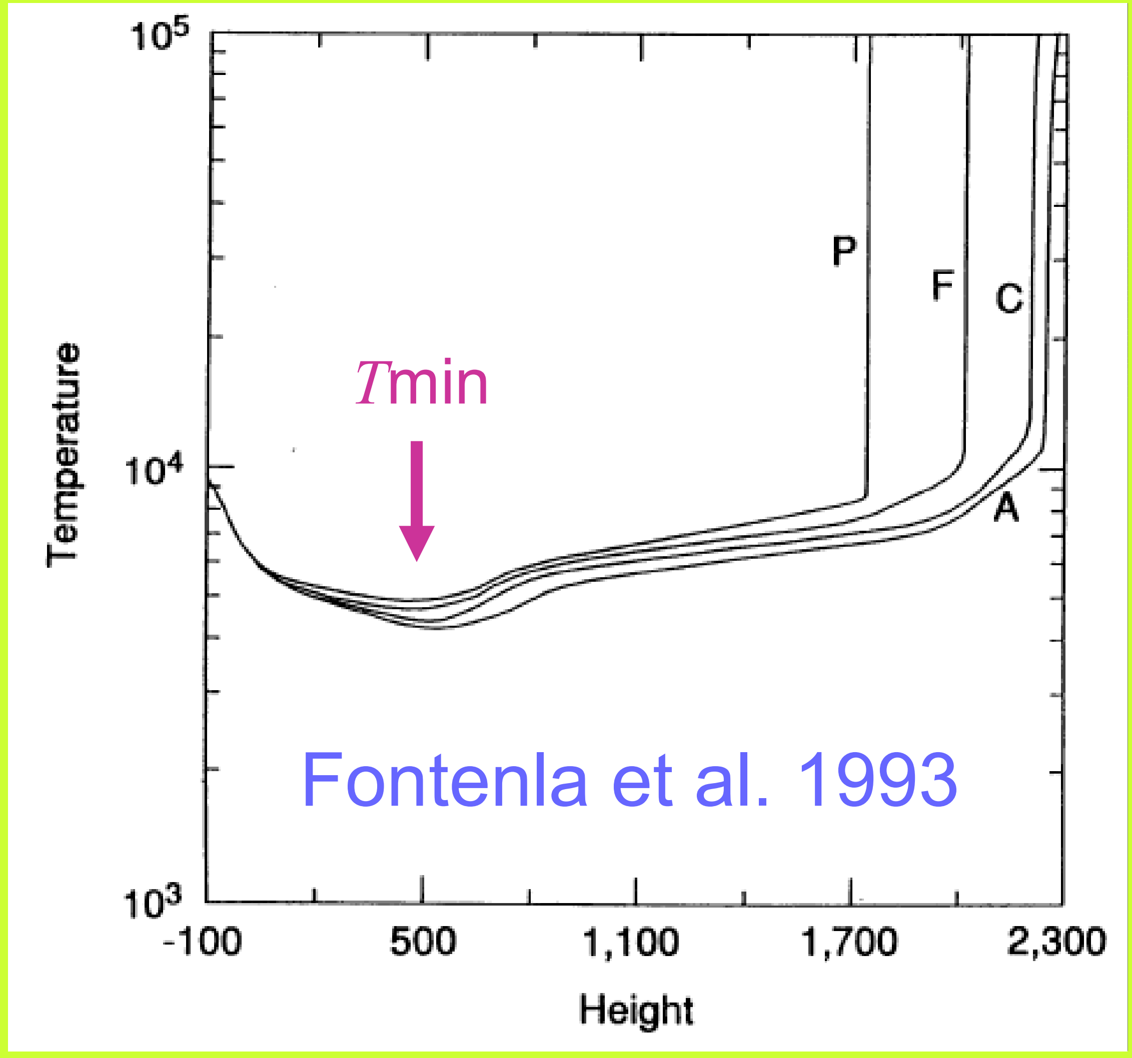


Chromospheric dynamics



Models: the classical chromosphere

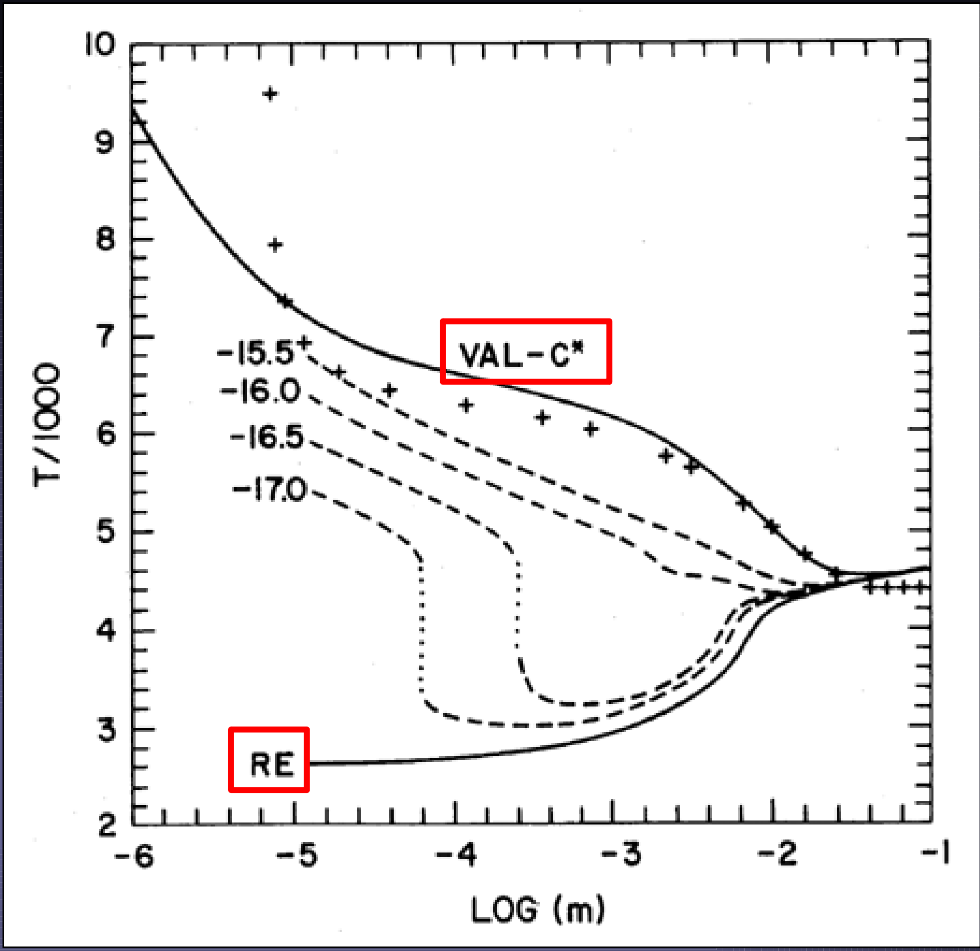
- Classical picture: plane parallel, multi-component atmospheres
- Chromosphere is composed of a gentle rise in temperature between *T*min and transition region.



Need to heat the chromosphere

- 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 obs.

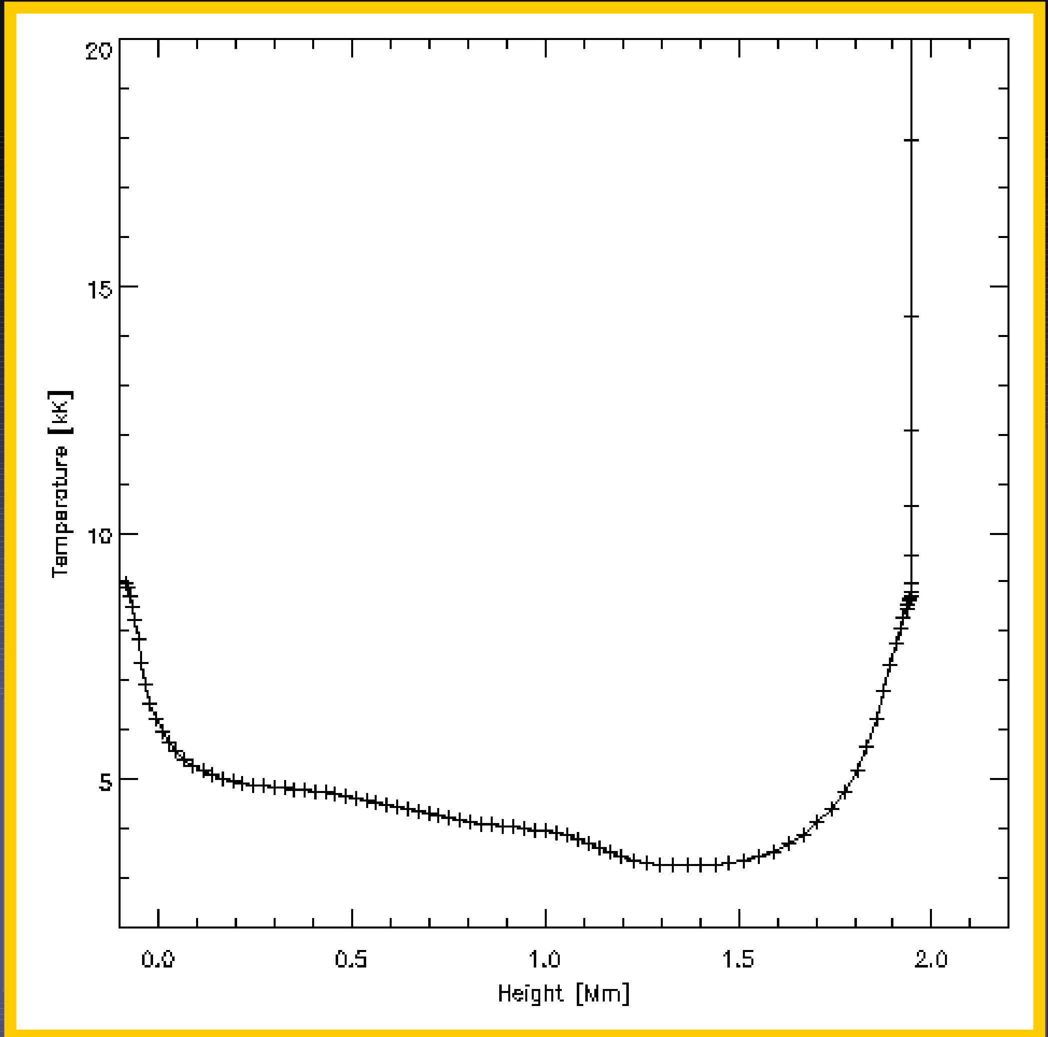


Anderson & Athay 1993

Dynamic models

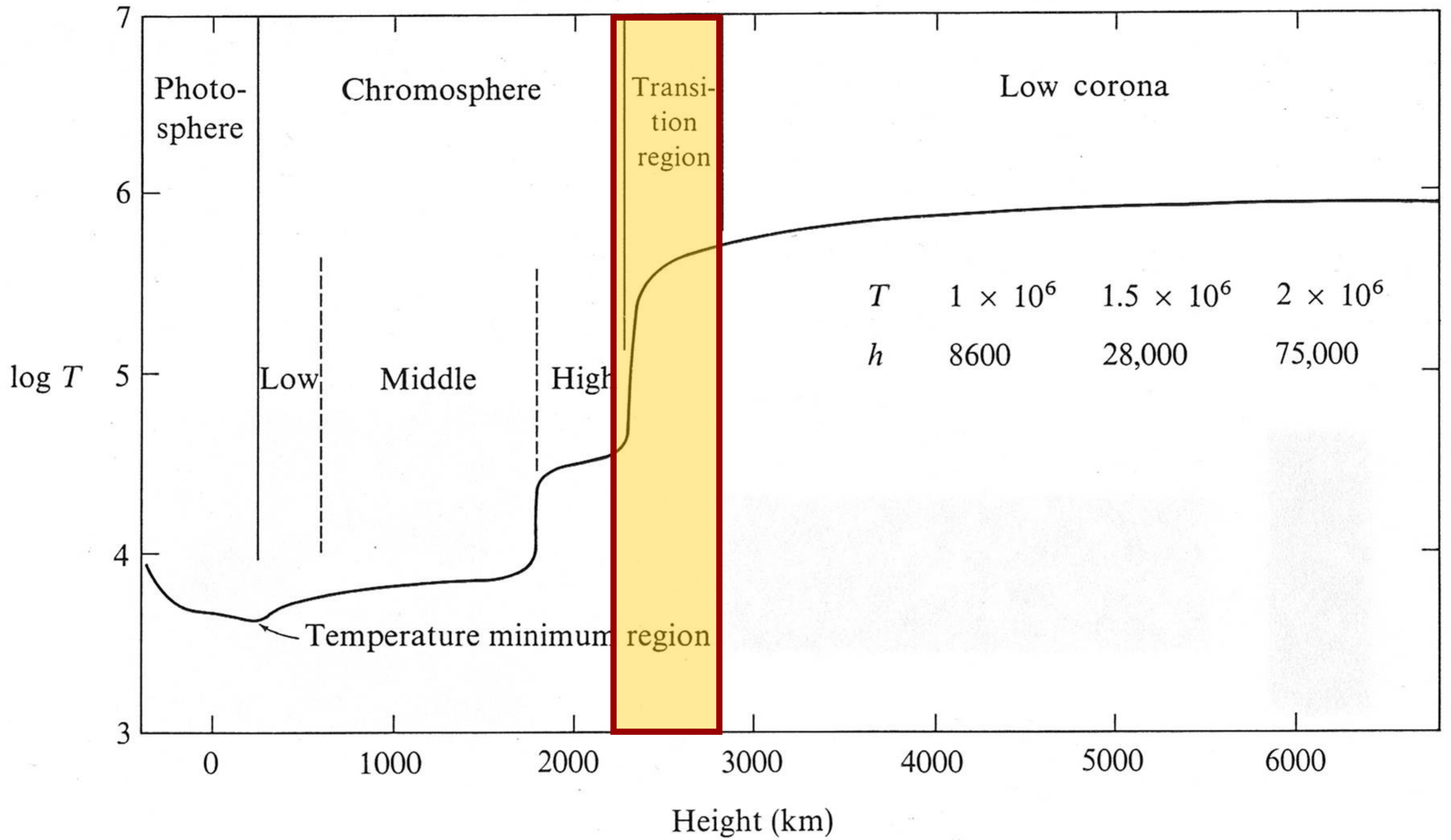
- Start with piston in convection zone, consistent with obs. of photospheric oscillations
- Waves with periods of ≤3min propagate into chromosphere
- Energy conservation (ρv2/2 = const.) & strong ρ decrease □ wave amplitudes increase with height: waves steepen and shock

Temp. at chromospheric heights varies between 3000 K and 10000 K

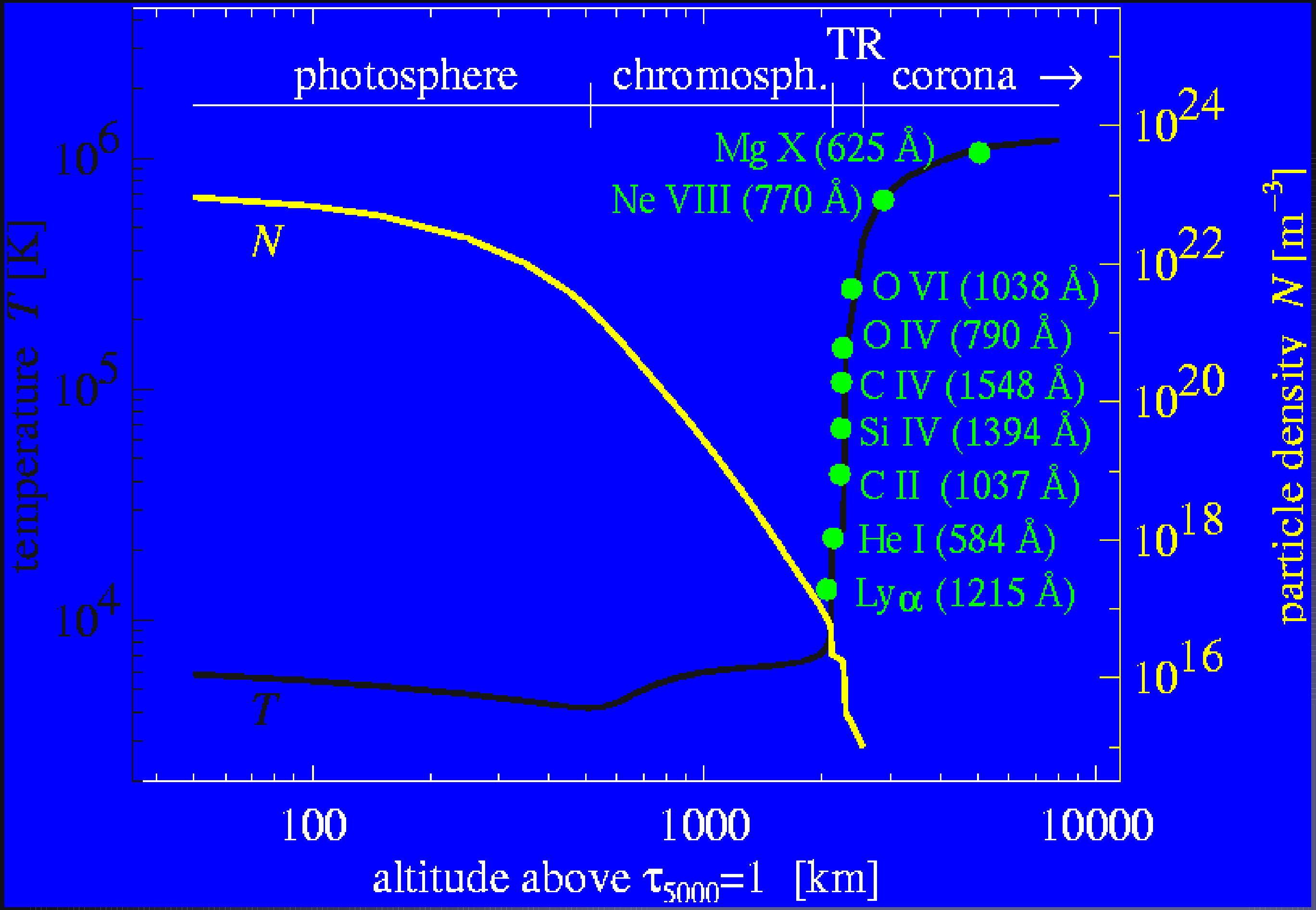


Carlsson & Stein

Transition Region



Transition Region



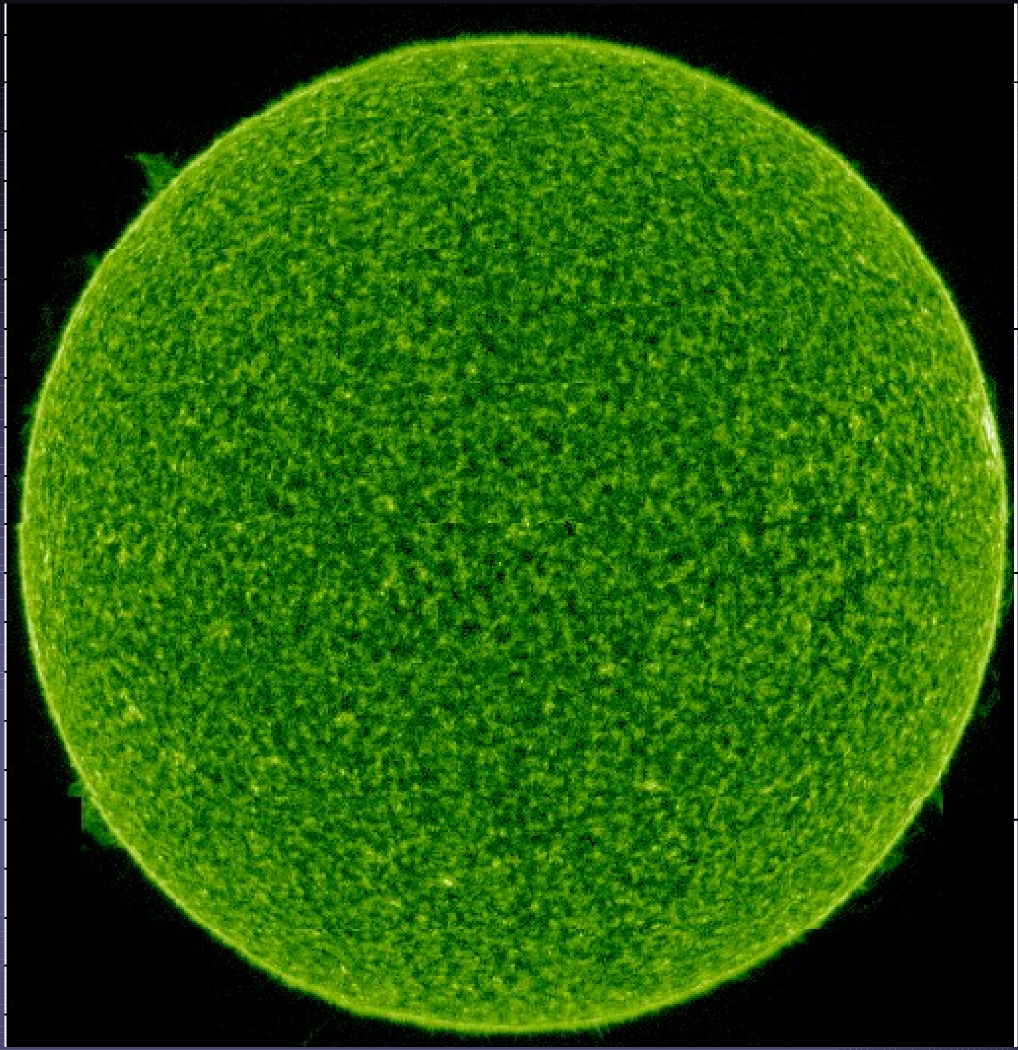
Semi-empirical 1D-models of solar atmosphere: steep increase of T in transition region (TR): < 100 km thick

Transition region properties

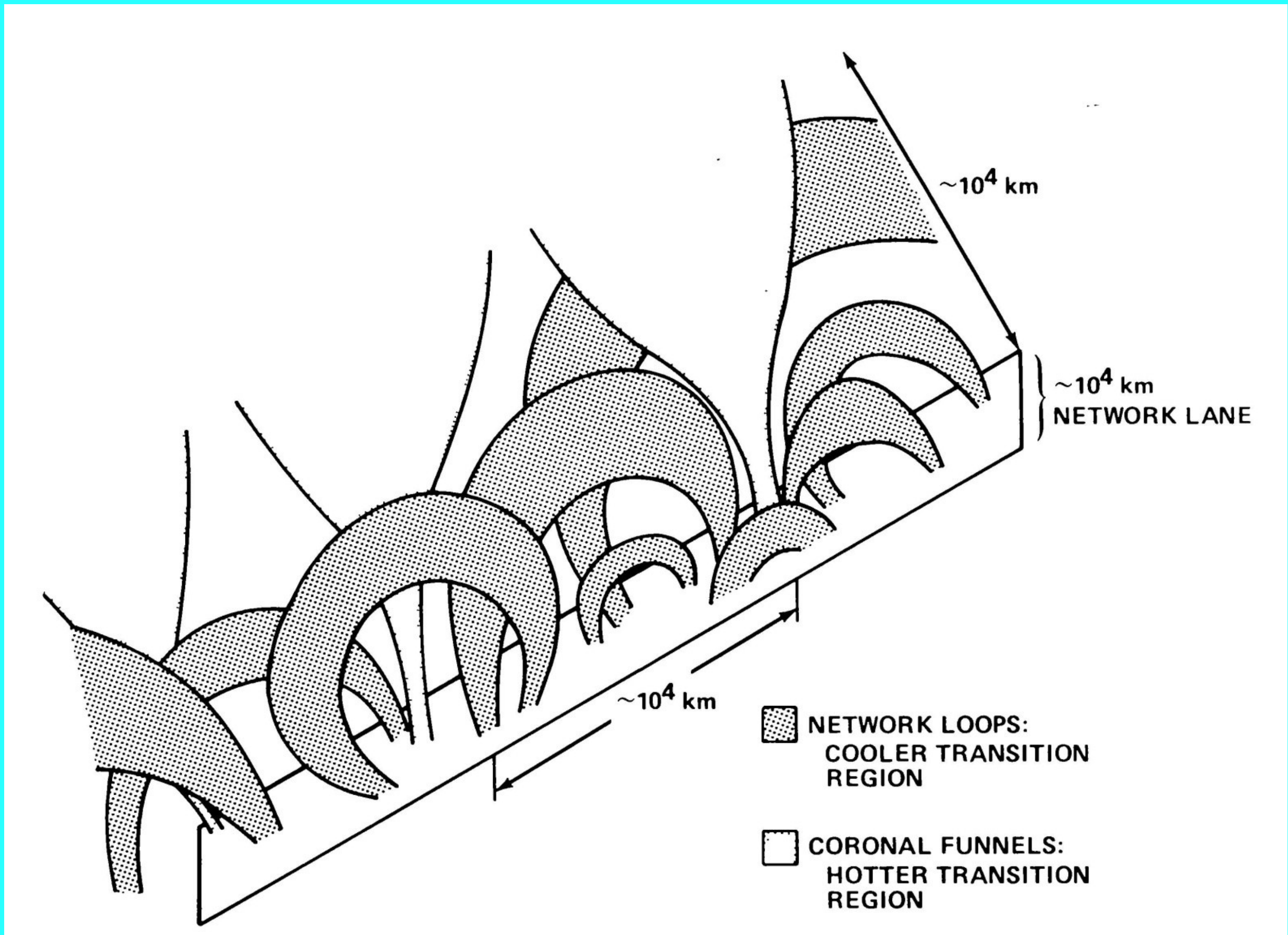
- Temperature increases from 5 104 K to 1 MK
- Density drops dramatically □ Pg remains almost constant
- Divided into
    - lower transition region: T< 5 105 K. Shows network structure, similar to Chromosphere
    - upper transition region: T> 5 105 K. Shows loop structures, similar to Corona
- Populated by 3 types of structures: footpoints of coronal loops, footpoints of open field lines, cool transition region loops.
- Heating thought to be mainly by heat conduction from corona (for those parts magnetically connected to corona), in classical picture.

Transition Region spatial structure

- Lower transition region (T<5 105 K) shows structure very similar to chromosphere, with network, plage etc.
- C IV (105 K) imaged by SUMER
- In upper transition region structures are more similar to corona



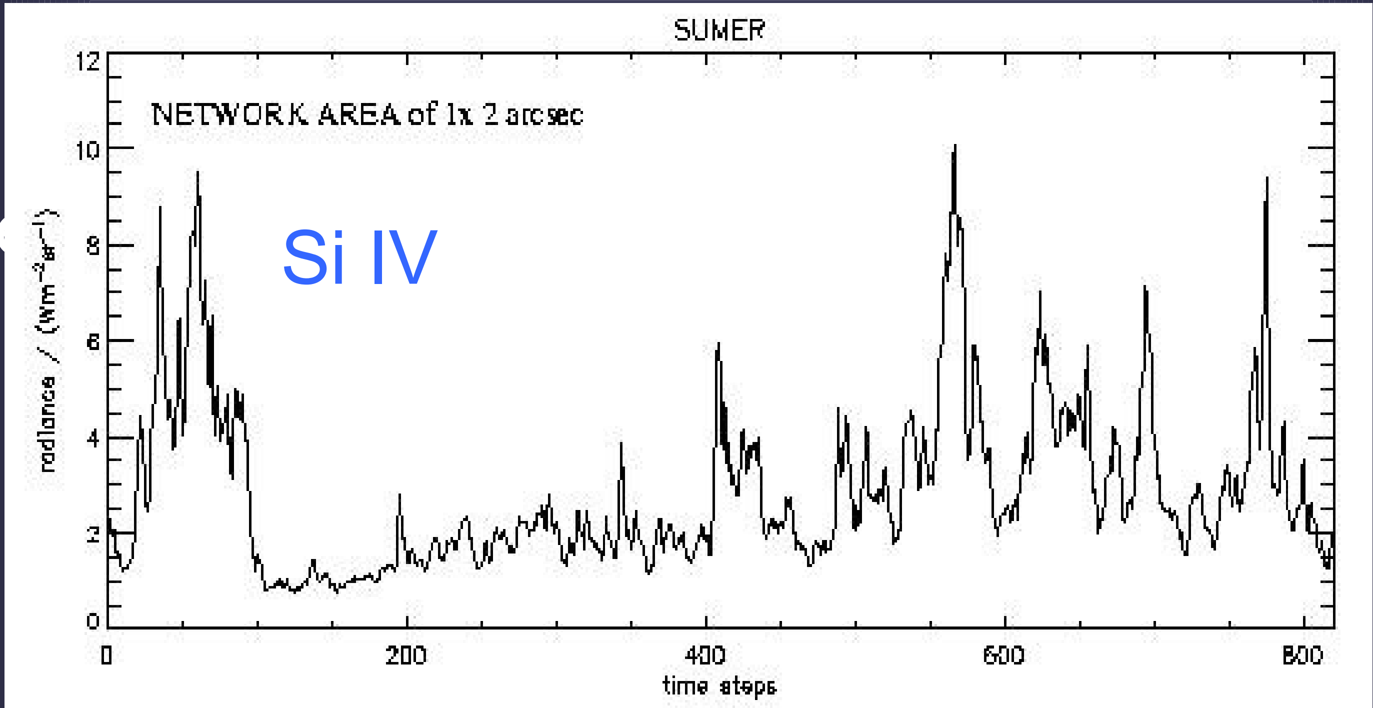
Sketch of the transition region



Dowdy et al. (1986)

TR dynamic phenomena: blinkers

- Brightness variability in Quiet-sun transition region is larger than in any other layer of solar atmosphere
- Typical brightening: blinkers
- Occur everywhere, all the time. Last for minutes to hours. How much of the brightening is du[e to] overlapping blinkers?



- 1 time step ≈ 1 minute

Corona

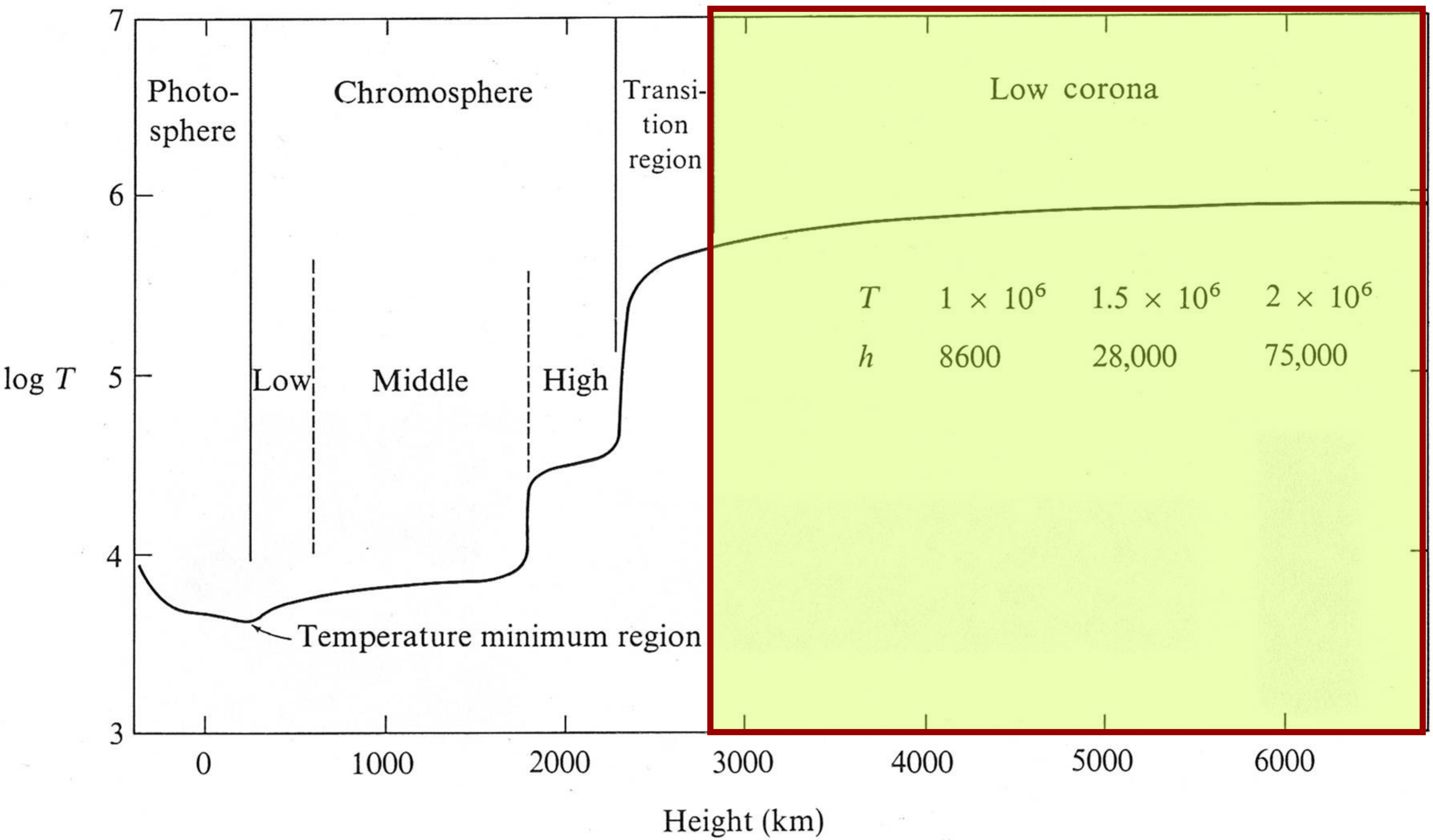
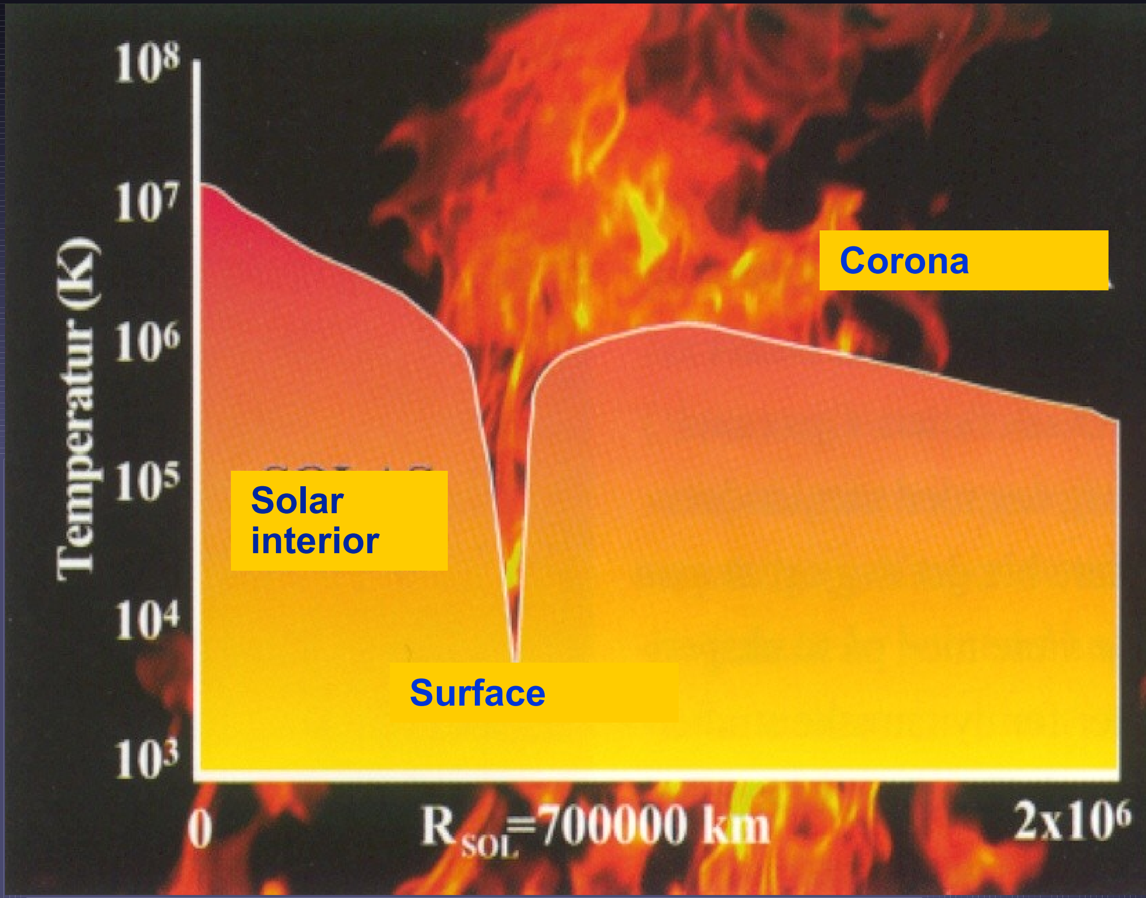


Photo-
sphere
Chromosphere
Transi-
tion
region
Low corona
Low
Middle
High
Temperature minimum region
T 1 × 10^6 1.5 × 10^6 2 × 10^6
h 8600 28,000 75,000
log T
7
6
5
4
3
0
1000
2000
3000
4000
5000
6000
Height (km)

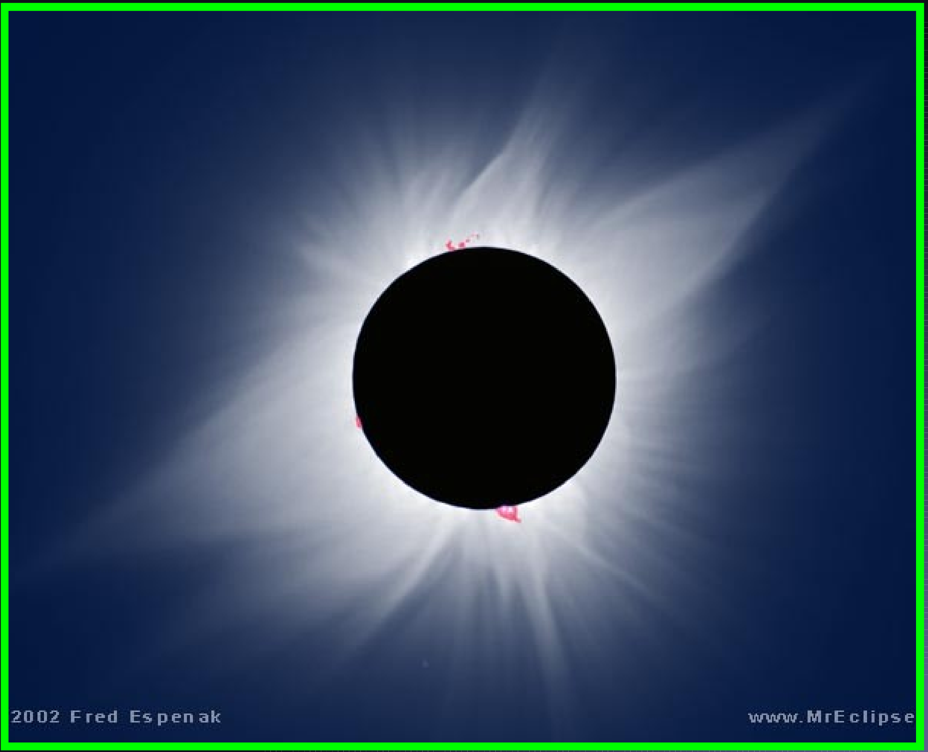
The Solar Corona

While the solar surface is about 6,000 K, the quiet corona reaches ~2 10^6 K (more in active regions)

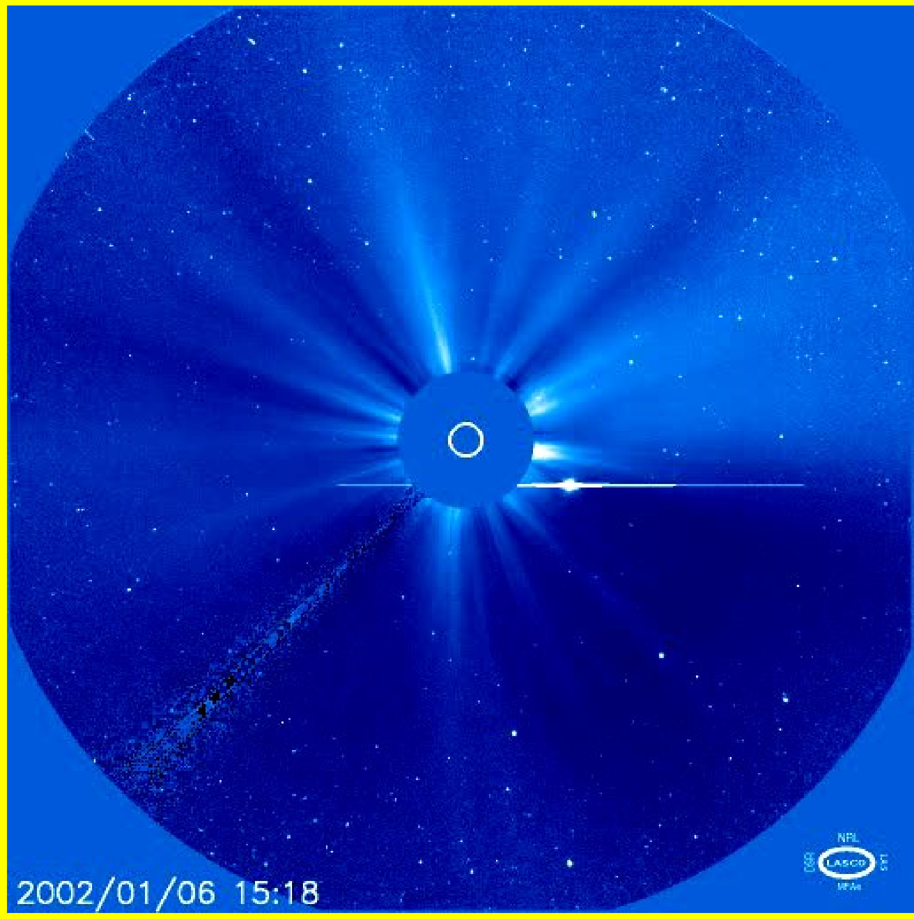
What causes this rapid temperature rise is one of the big mysteries in solar physics



The Hot and Dynamic Corona

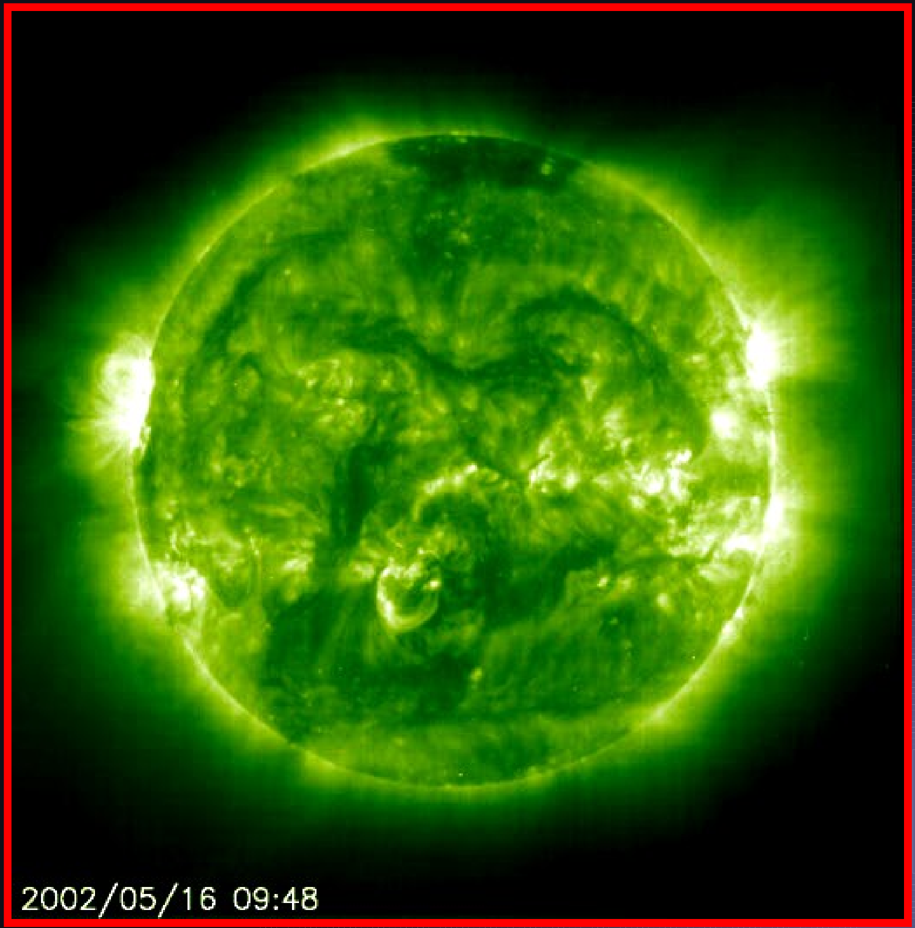


Corona during an Eclipse

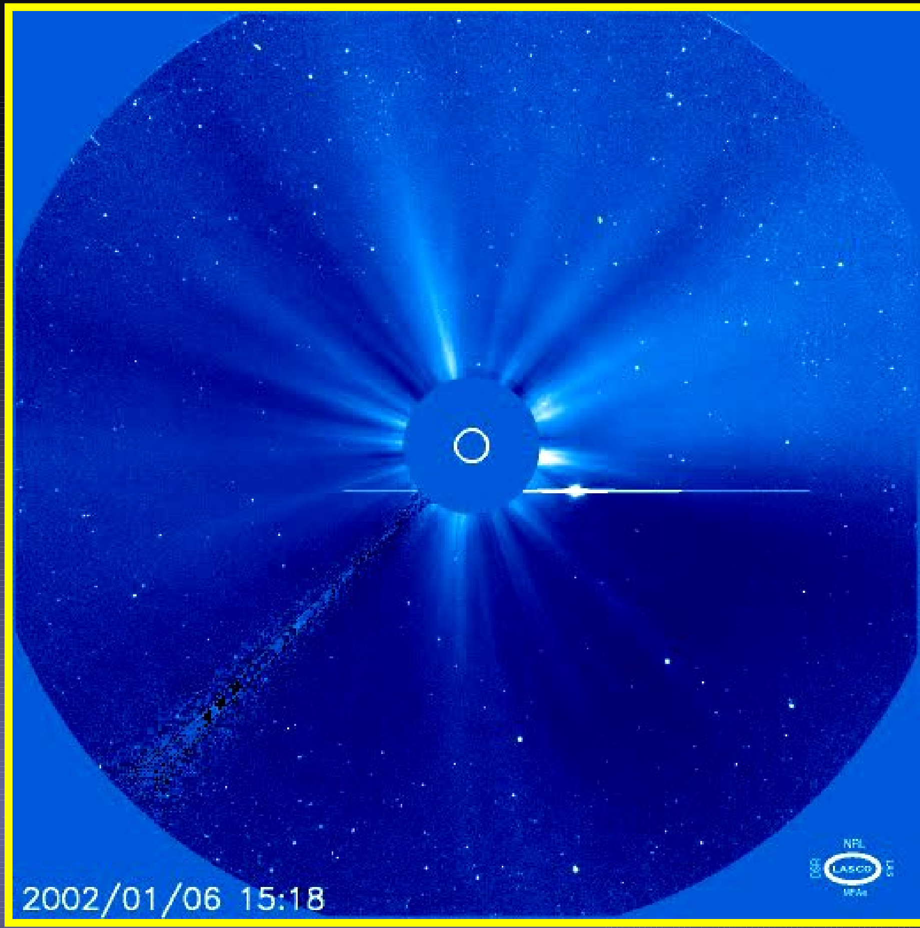


Artificial eclipse
(LASCO C3 / SOHO, MPS)

The Hot and Dynamic Corona

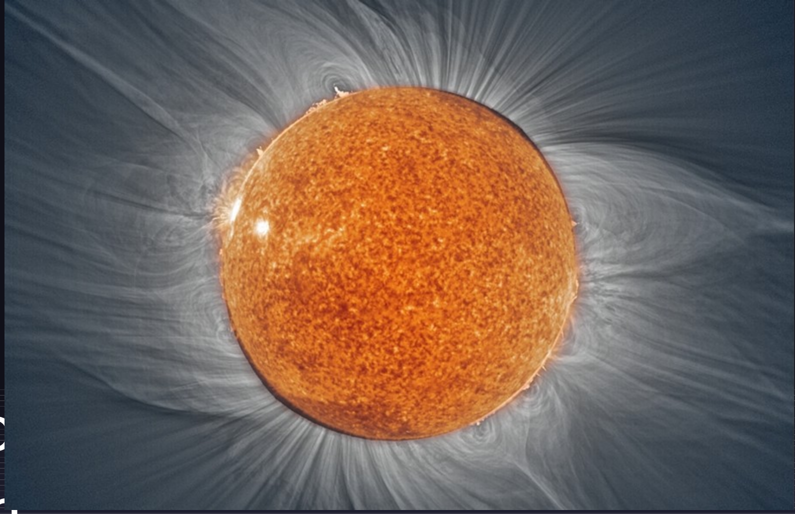


EUV Corona: Plasma at >1 Mio K (EIT 195 Å)



Artificial eclipse (LASCO C3 / SOHO, MPS)

Eclipse corona



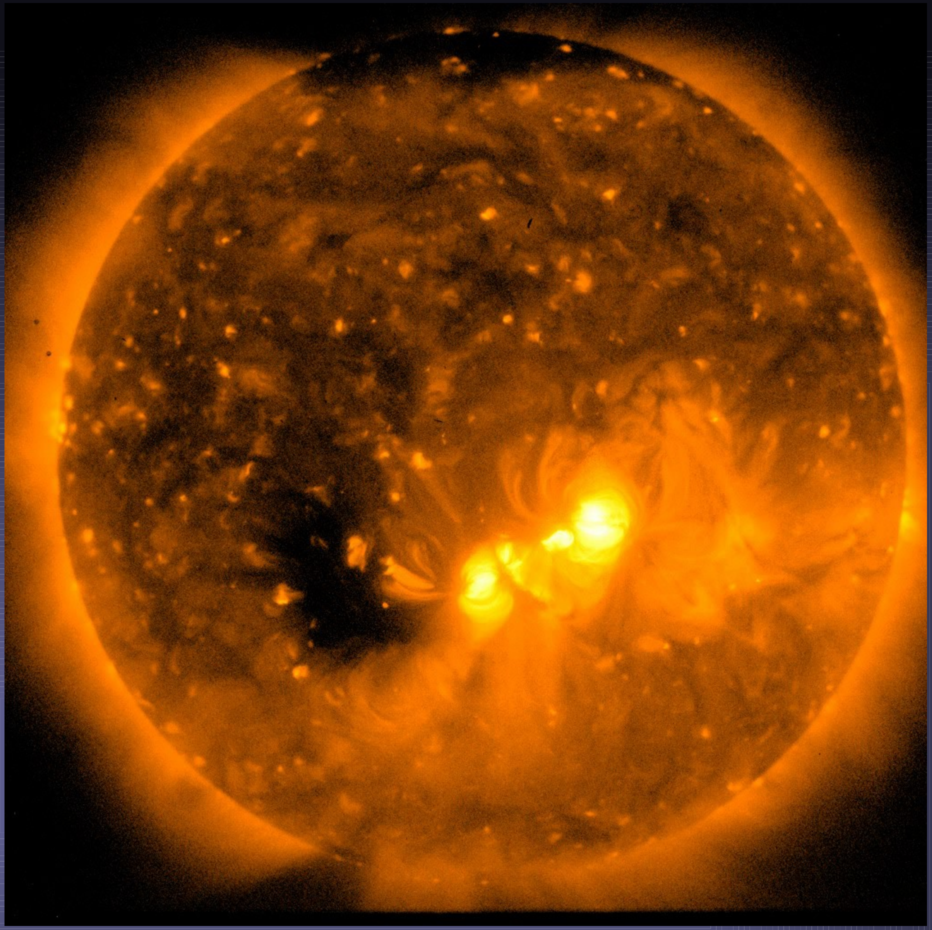
- Total visible flux from corona
  - Act max: 1.5 10-6 F□ = 0.66 Moo
  - Act min: 0.6 10-6 F□ = 0.26 Moon
- Eclipse corona is typically visible for 4 solar radii
- K corona: Inner portion of sun's corona, continuous spectrum due to e- scattering (Thomson scattering)
- F corona: Outer portion of solar corona: scattering on interplanetary dust between sun and earth. Shows Fraunhofer lines (F = Fraunhofer corona)
- L corona: Emission line corona (forbidden lines). Negligible contribution to coronal brightness

Coronal temperature

- Different temperatures & densities co-exist in the corona
- Range of temperatures:
  <1 MK (Coronal hole) to 10 MK (active region)
- Range of e- densities (inner corona):

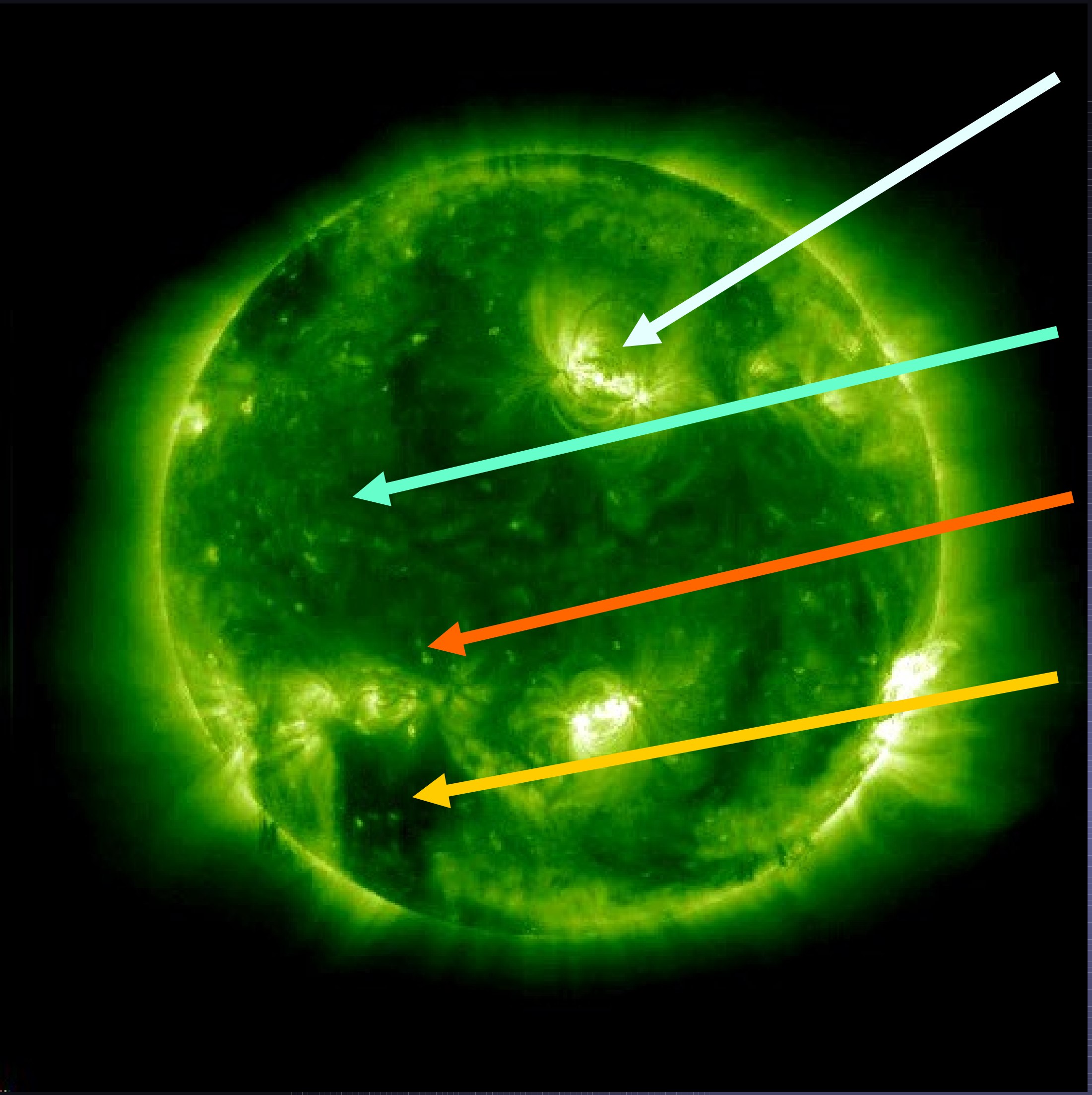
  Loop: 1010 particles/cm3

  coronal hole: 107 particles/cm3



Hinode XRT: 2-5MK gas

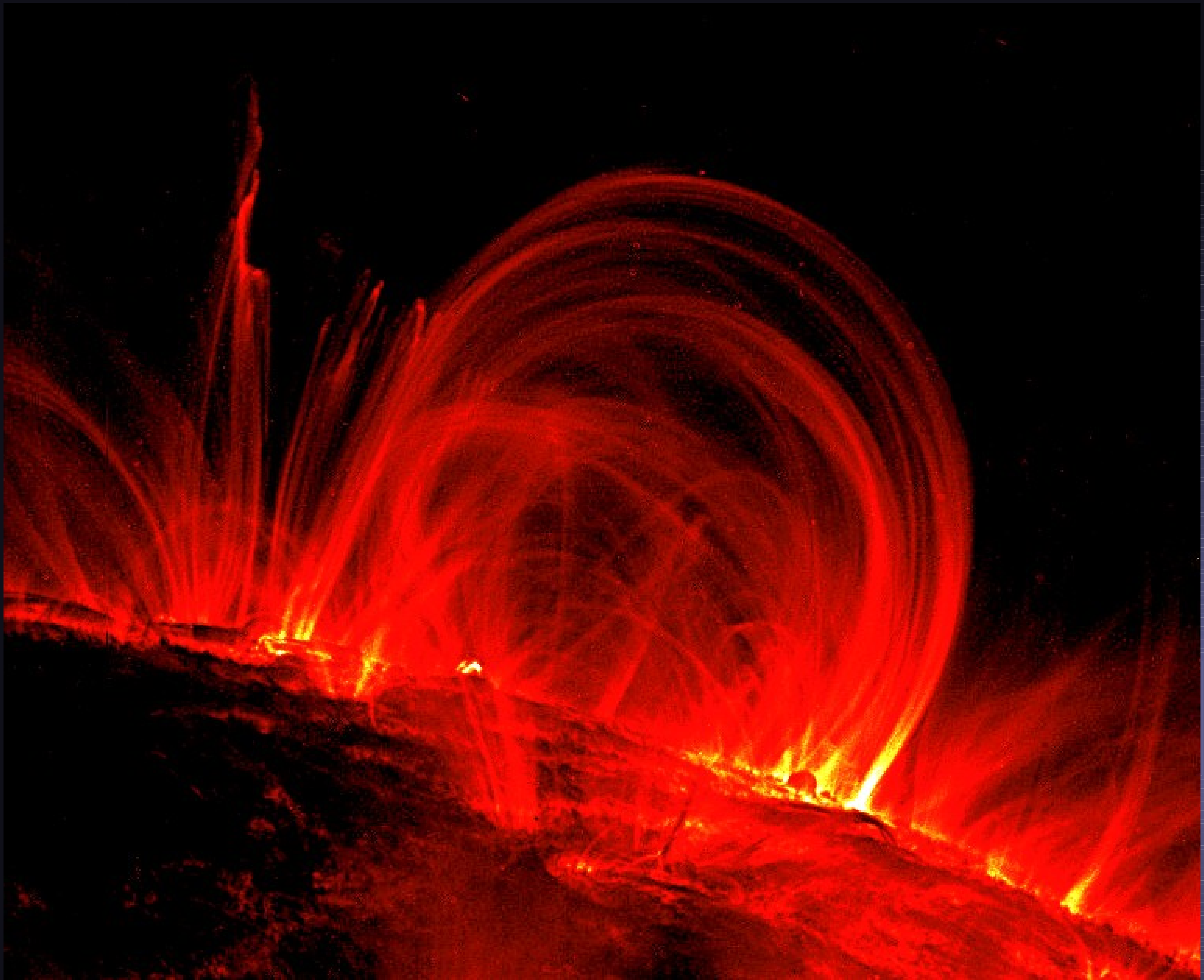
Coronal structures



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

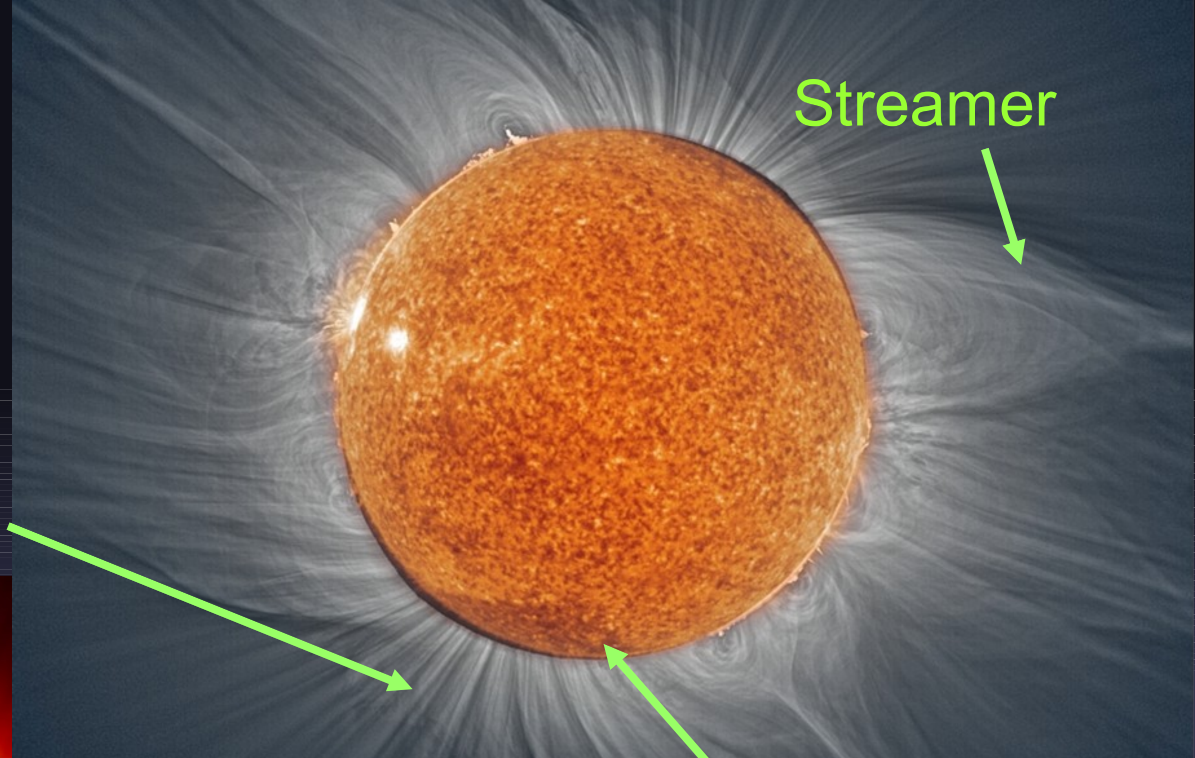
Fe XII 195 Å
(1.500.000 K)
17 May - 8 June 1998

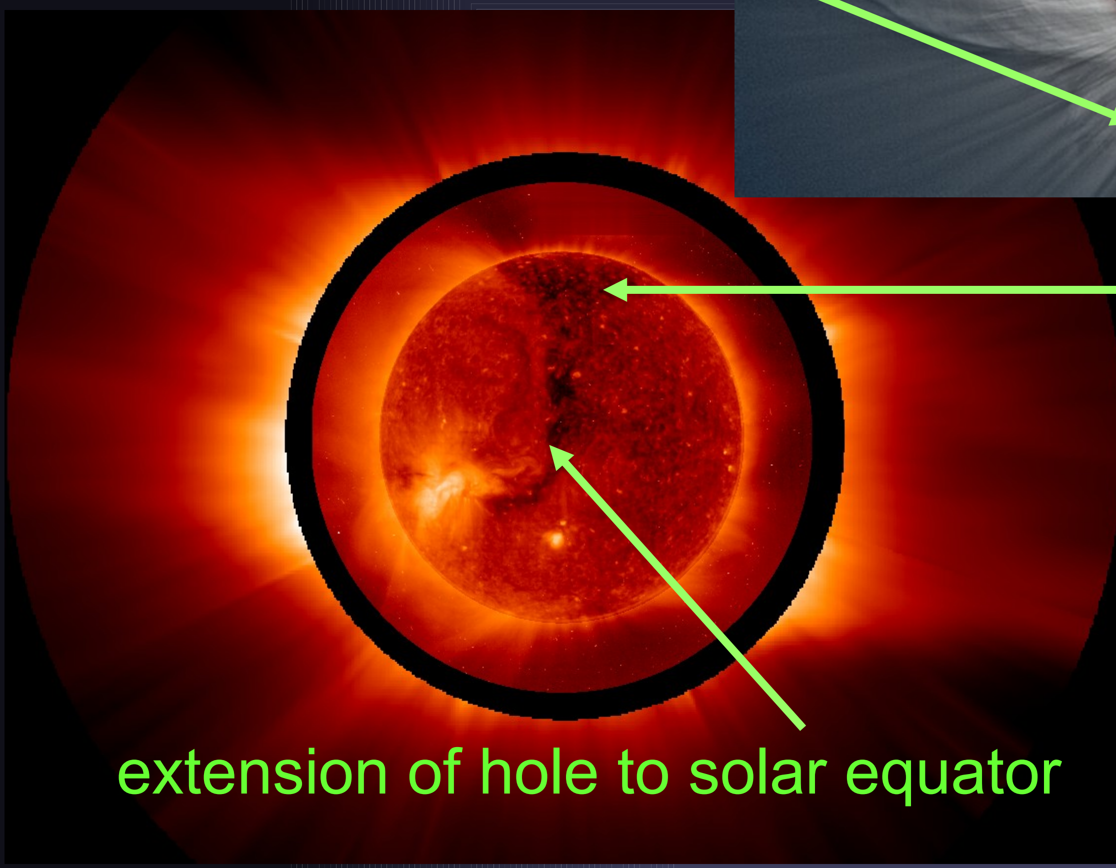
Coronal structure: active region loops

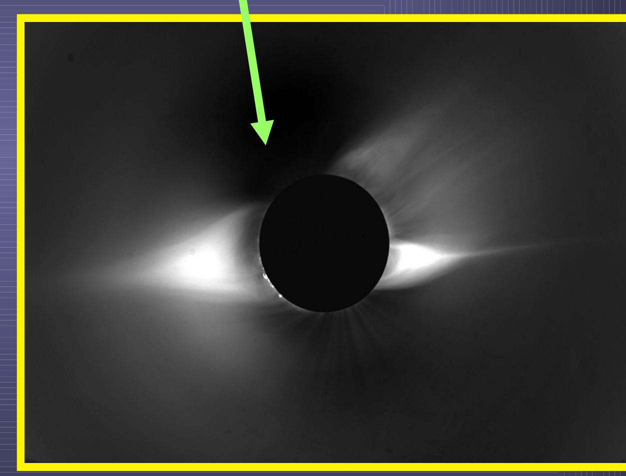


TRACE, 1999

Coronal structures: streamers & coronal holes



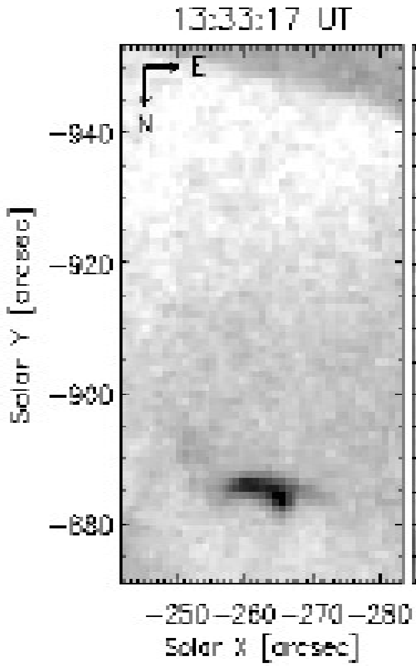


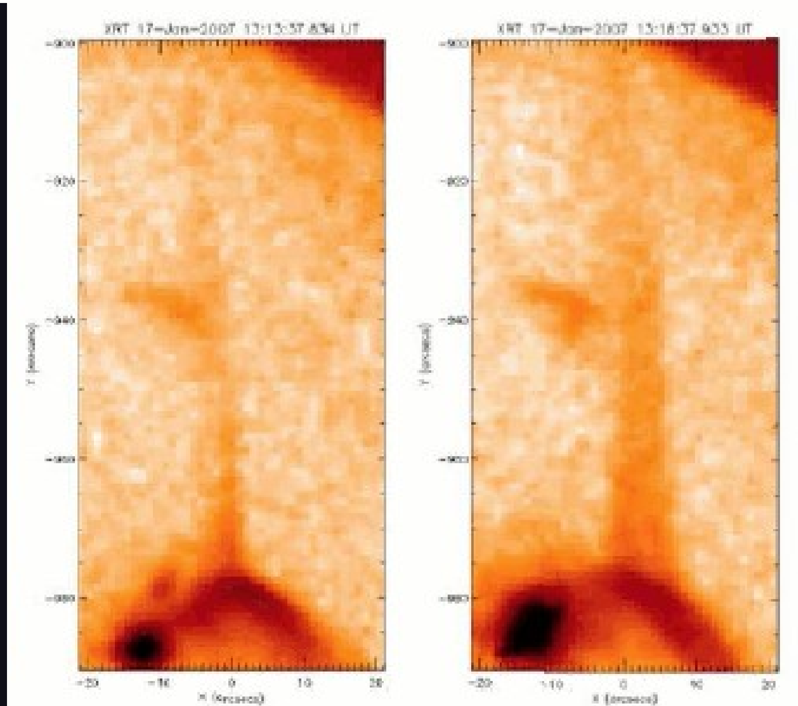


X-ray jets

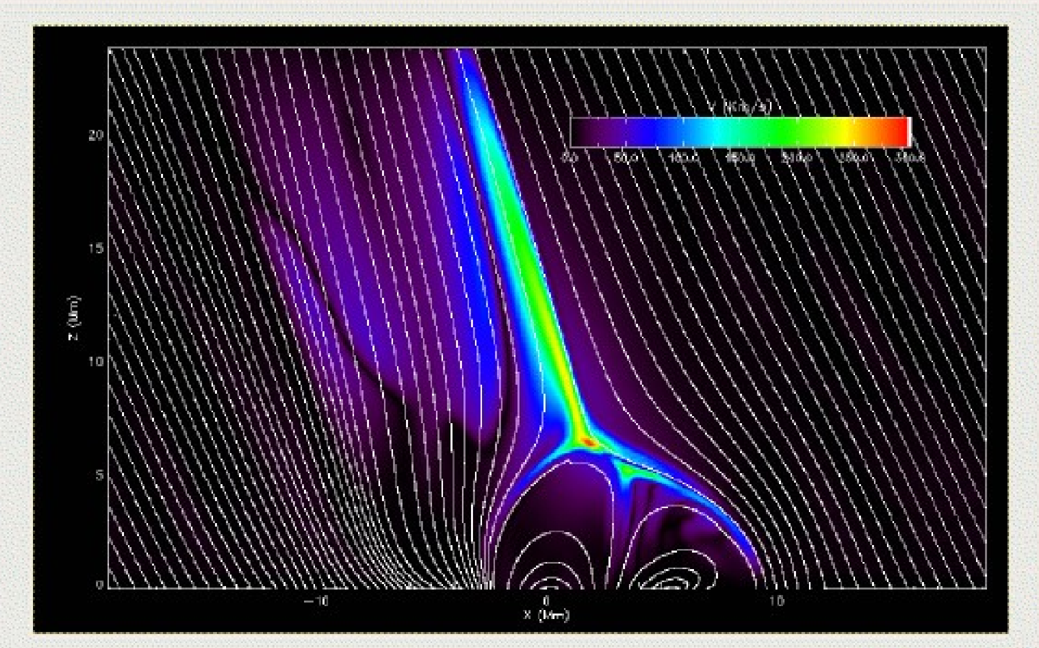
Coronal structures: coronal jets

XRT observations
Model (Moreno Insertis et al.





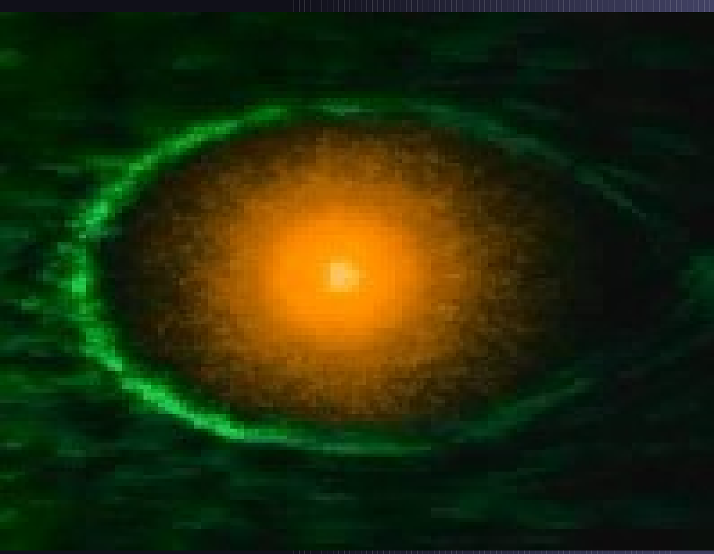
Velocity map

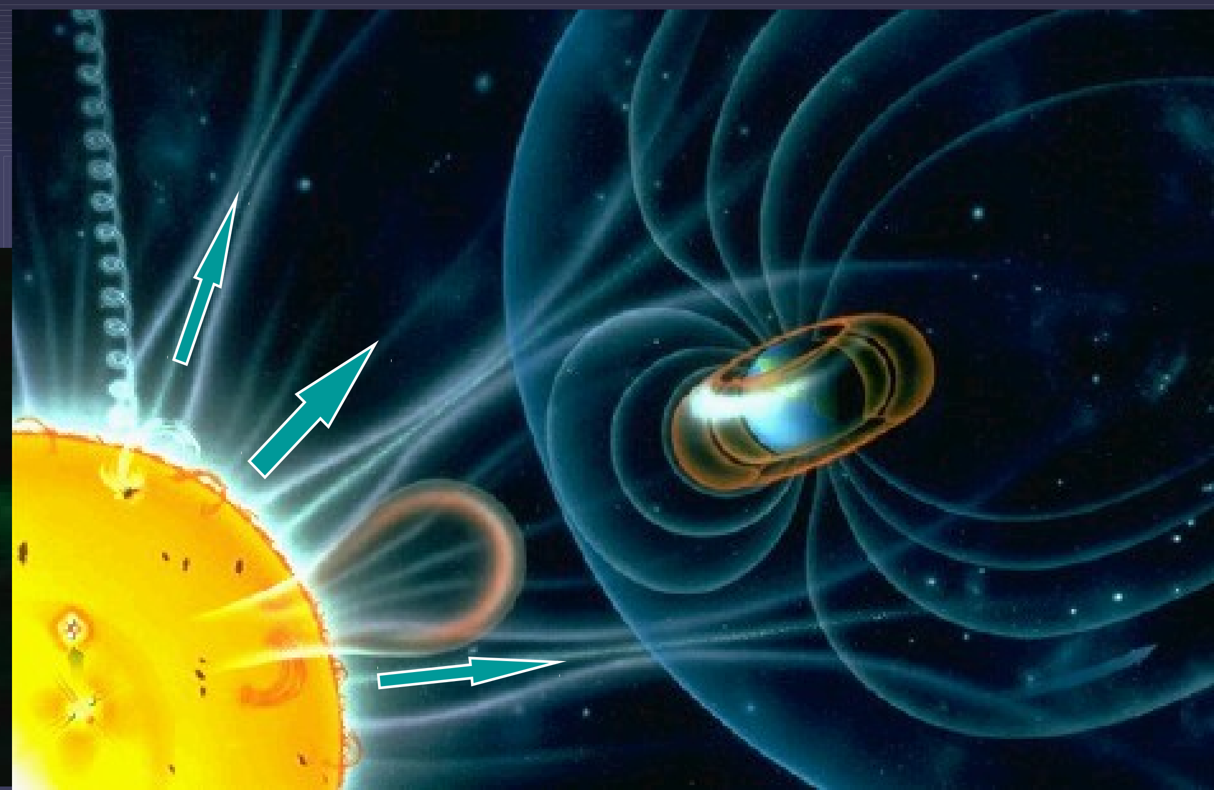


(t=22 min)

The solar wind

A constant stream of particles flowing from the Sun’s corona, with a temperature of 105 – 106 K and with a velocity of 300-1000 km/s. Solar wind reaches to well beyond Pluto's orbit, with the heliopause located at ≈ 100-120 AU





Discovery of the solar wind

- Ludwig Biermann at MPI für Physik und Astrophysik noticed in 1940s that the tails of comets always pointed away from the Sun. Solar radiation pressure was insufficient to explain this.

Postulated a solar wind

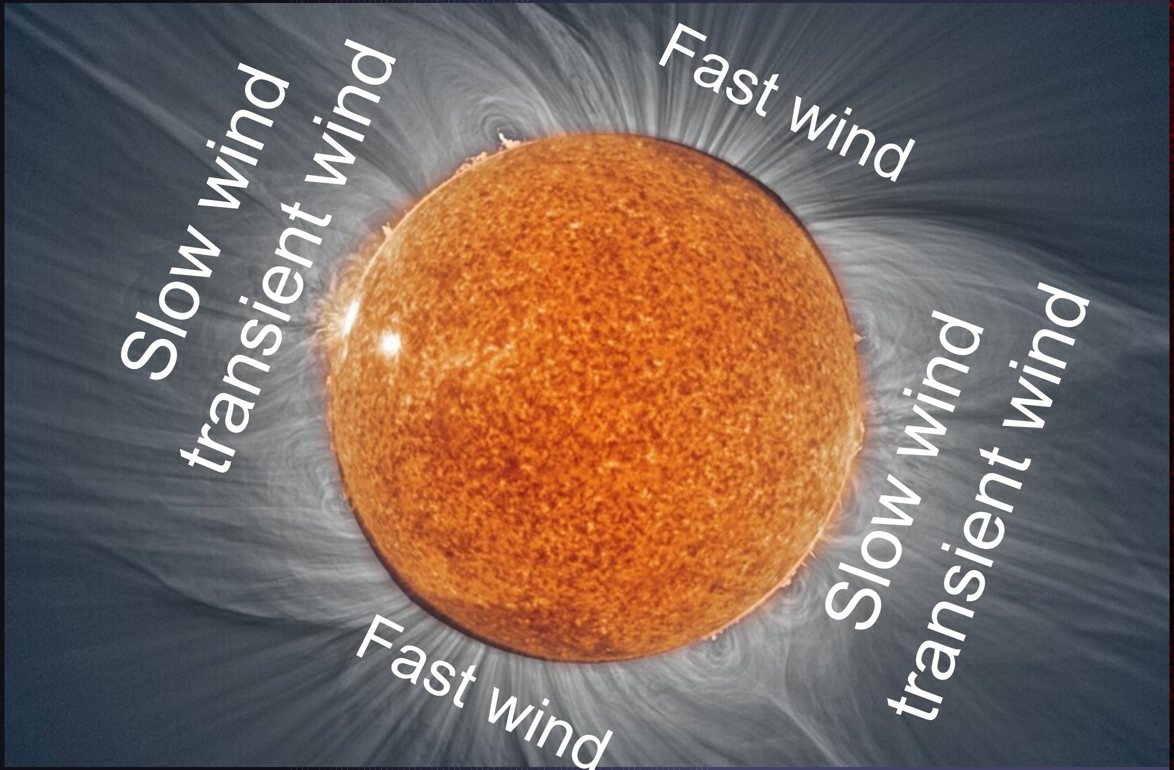
- Independently, Parker (1958) realized that a hot corona must expand if it was to be in equilibrium with the interstellar medium. Only a supersonic solar wind was compatible with theory and observations.

Supersonic solar wind

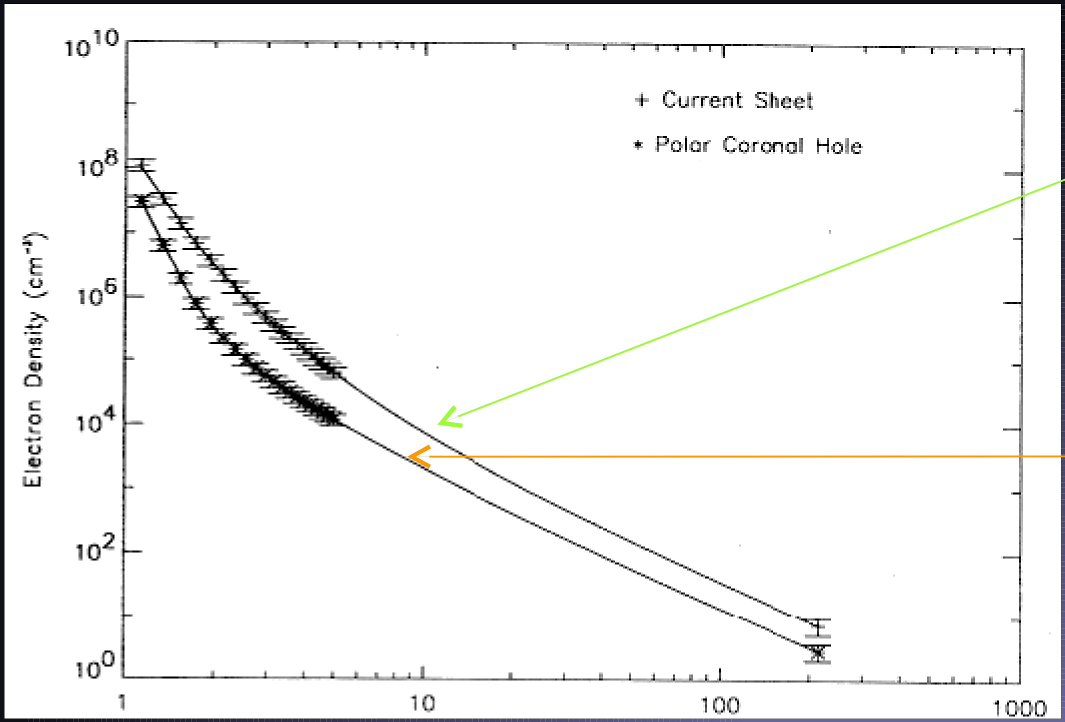
Types of solar wind

- Fast solar wind:
  - emerges from coronal holes
  - has speeds up to 800 km/s at 1 AU
  - is steady, with Alfvenic fluctuations
- Slow solar wind:
  - emerges from normal quiet Sun (and active regions)
  - has speeds around 300-400 km/s at 1 AU
  - Has high variability, with density fluctuations
- Transient solar wind:
  - originates from Coronal Mass Ejections
  - has speeds of 300 – 2000 km/s at 1AU
  - is highly variable, associated with interplanetary shock waves

Distribution of sources of different types of wind



Coronal hole vs. normal corona (outer corona)



Current sheet and streamer belt, closed magnetic field

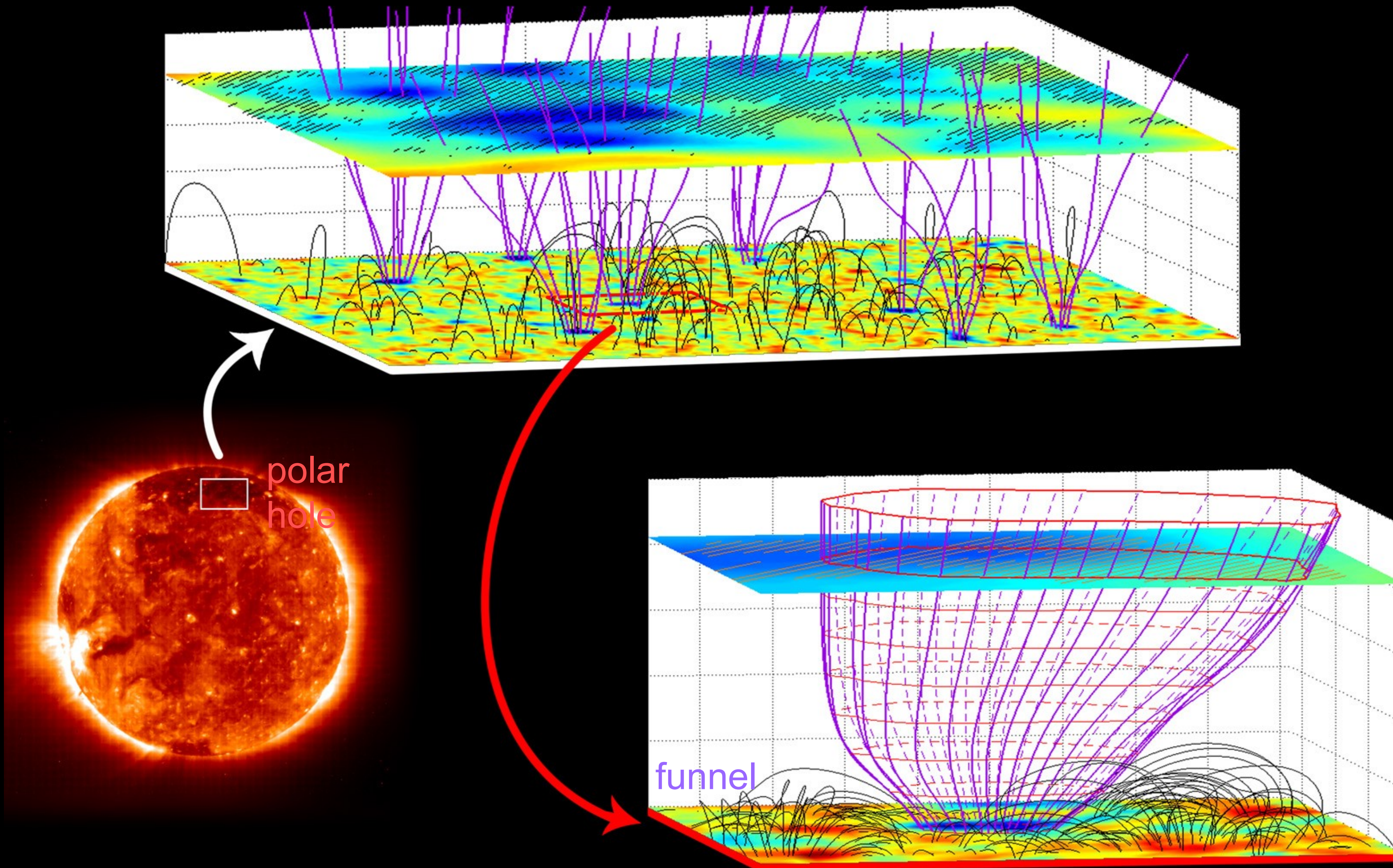
Polar coronal hole, “open” magnetic field

Heliocentric distance [R]

Guhathakurta and Sittler, 1999, Ap.J., **523, 812**

Skylab coronagraph/Ulysses in-situ

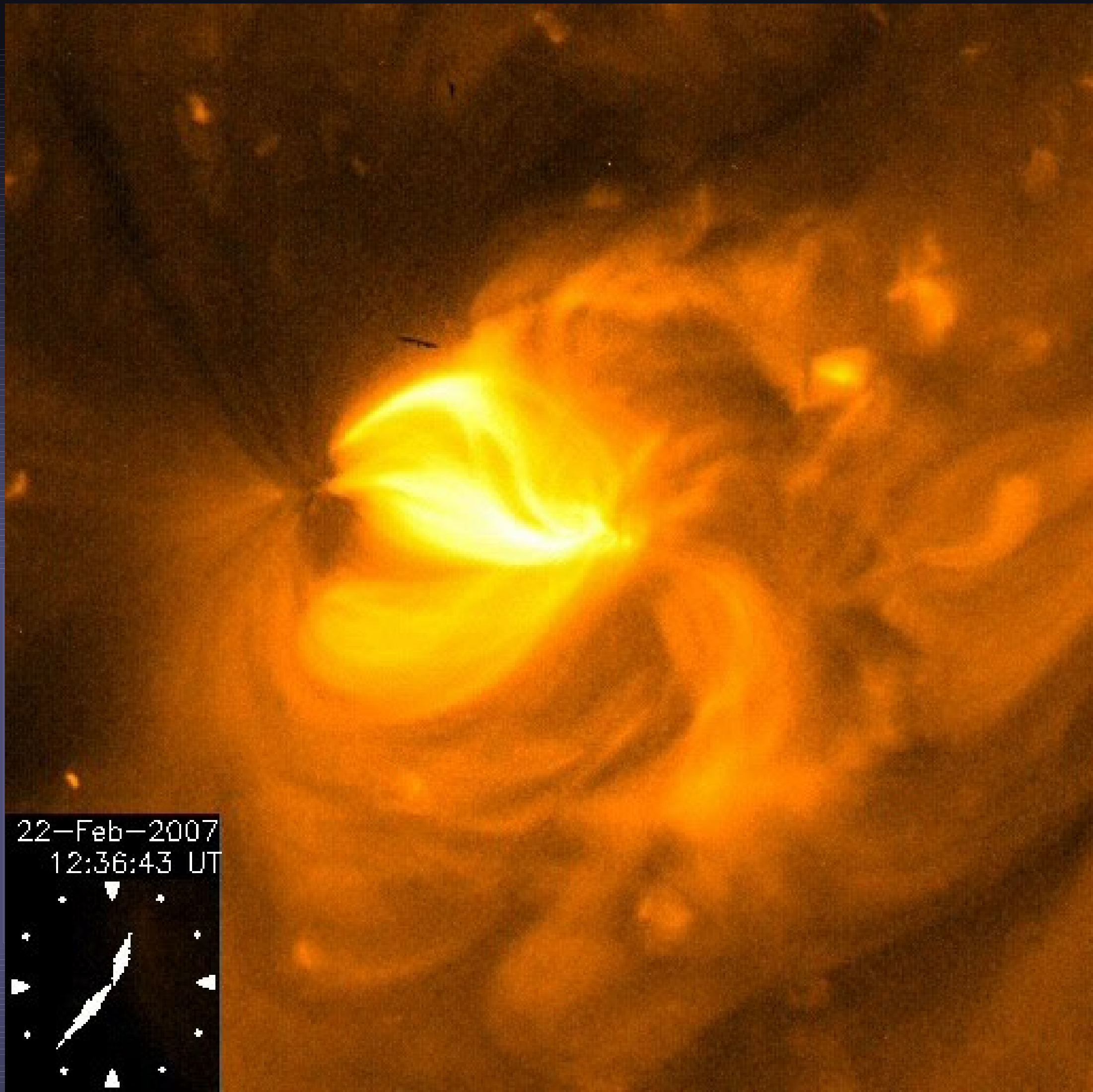
Sources of solar wind: fast wind



Tu, Marsch et al., 2005

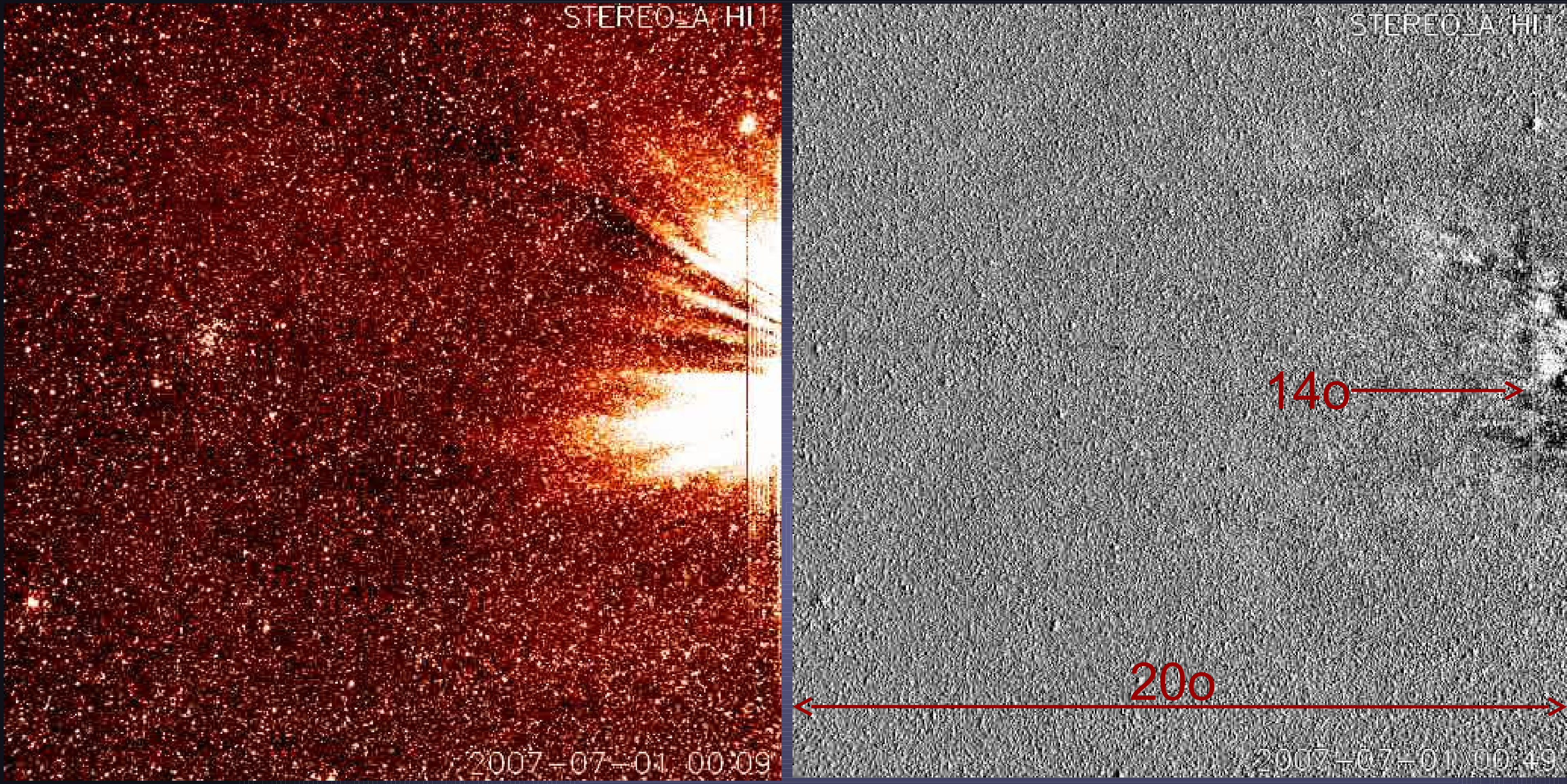
Source regions of solar wind: slow wind

- Possible very early phase of slow solar wind
- Appears to be fed from within an active region
- Not clear in this movie if the field lines along which these features move are open.

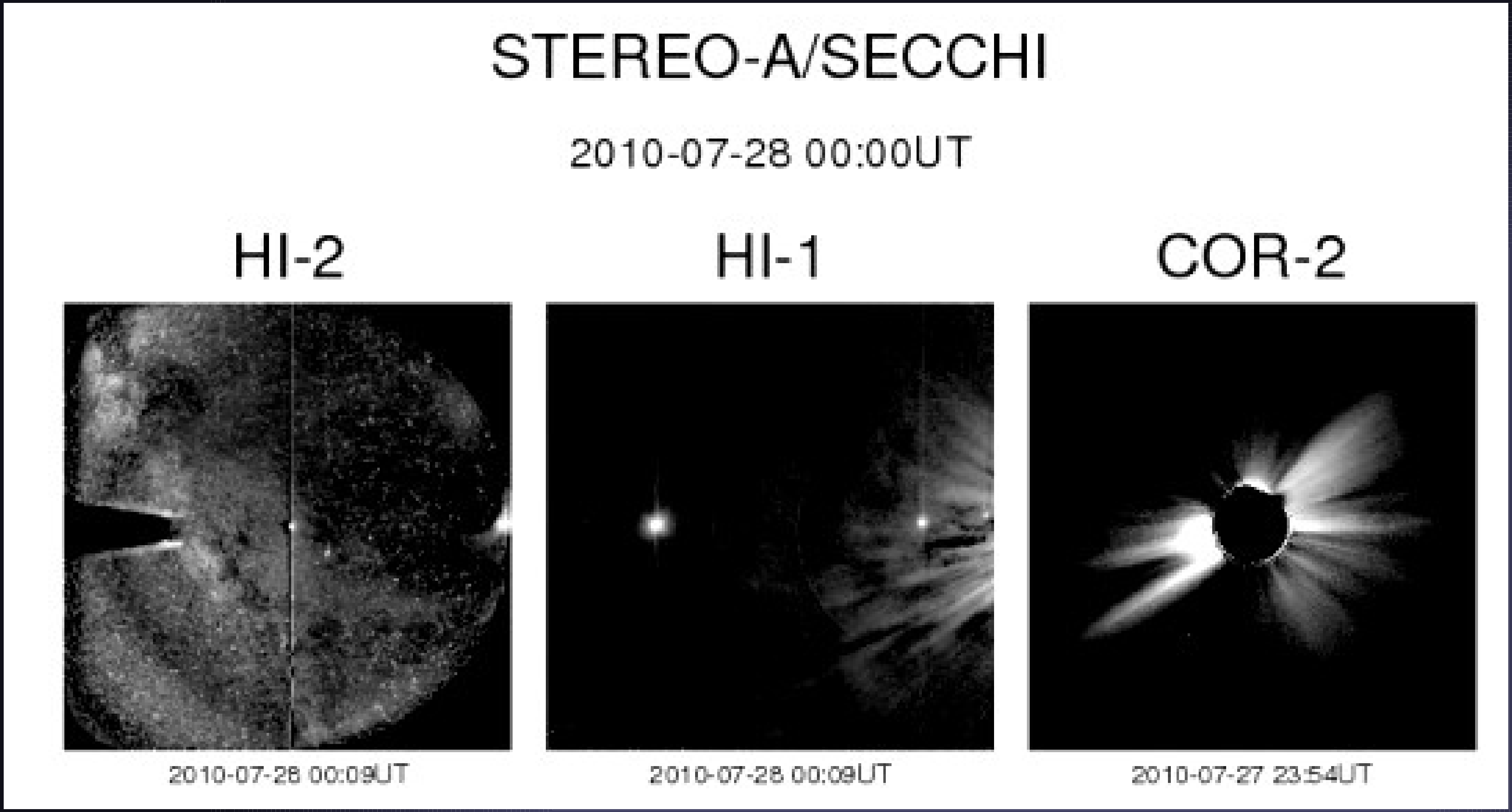


Making the slow and transient winds visible at larger distances

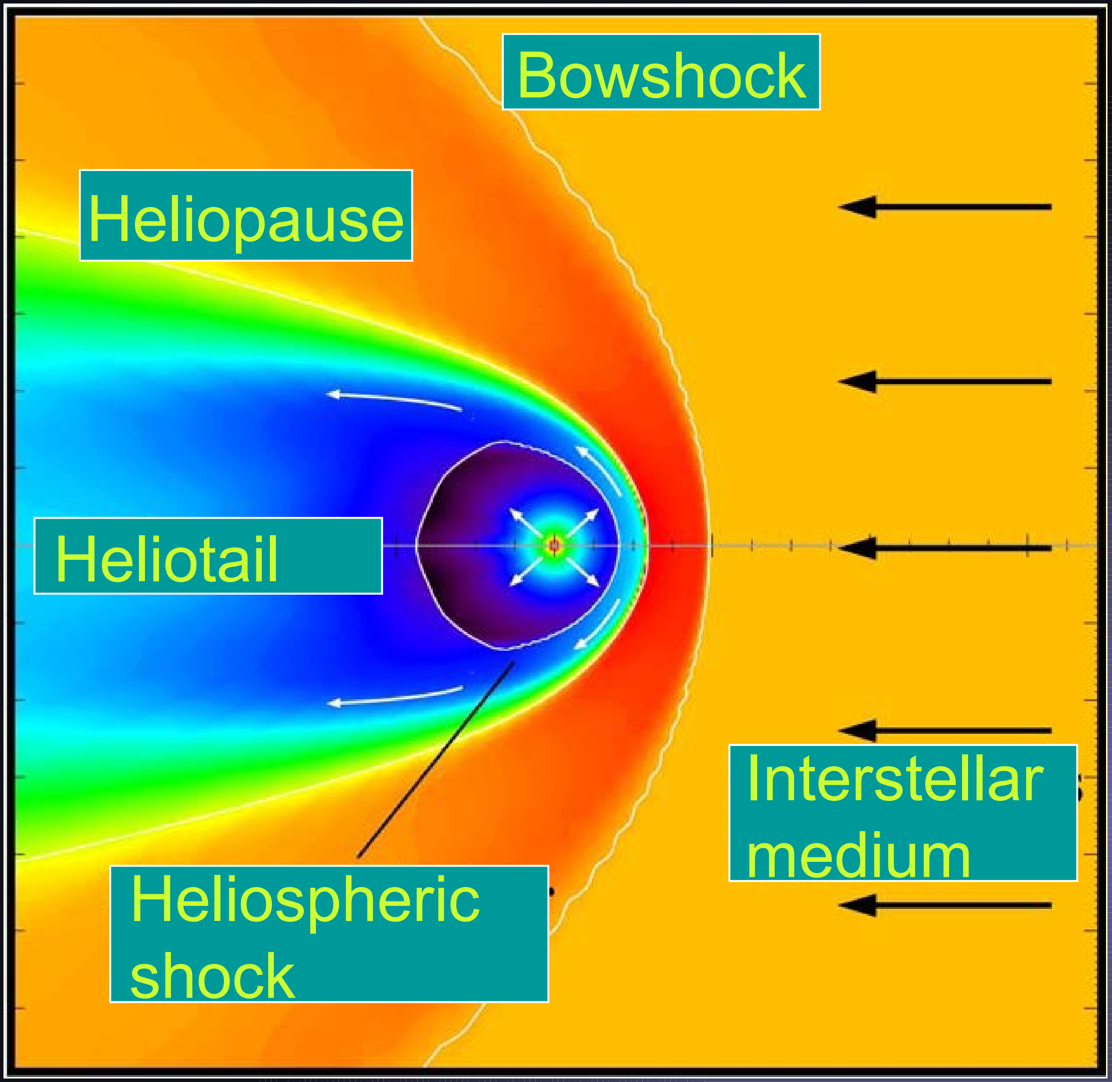
Intensity STEREO Heliospheric Imager 1A Difference



Making the slow and transient winds visible at larger distances



The Heliosphere



- Heliosphere = region of space in which the solar wind and solar magnetic field dominate over the interstellar medium and the galactic magnetic field.
- Bowshock: where the interstellar medium is slowed relative to the Sun.
- Heliospheric shock: where the solar wind is decelerated relative to Sun
- Heliopause: boundary of the heliosphere