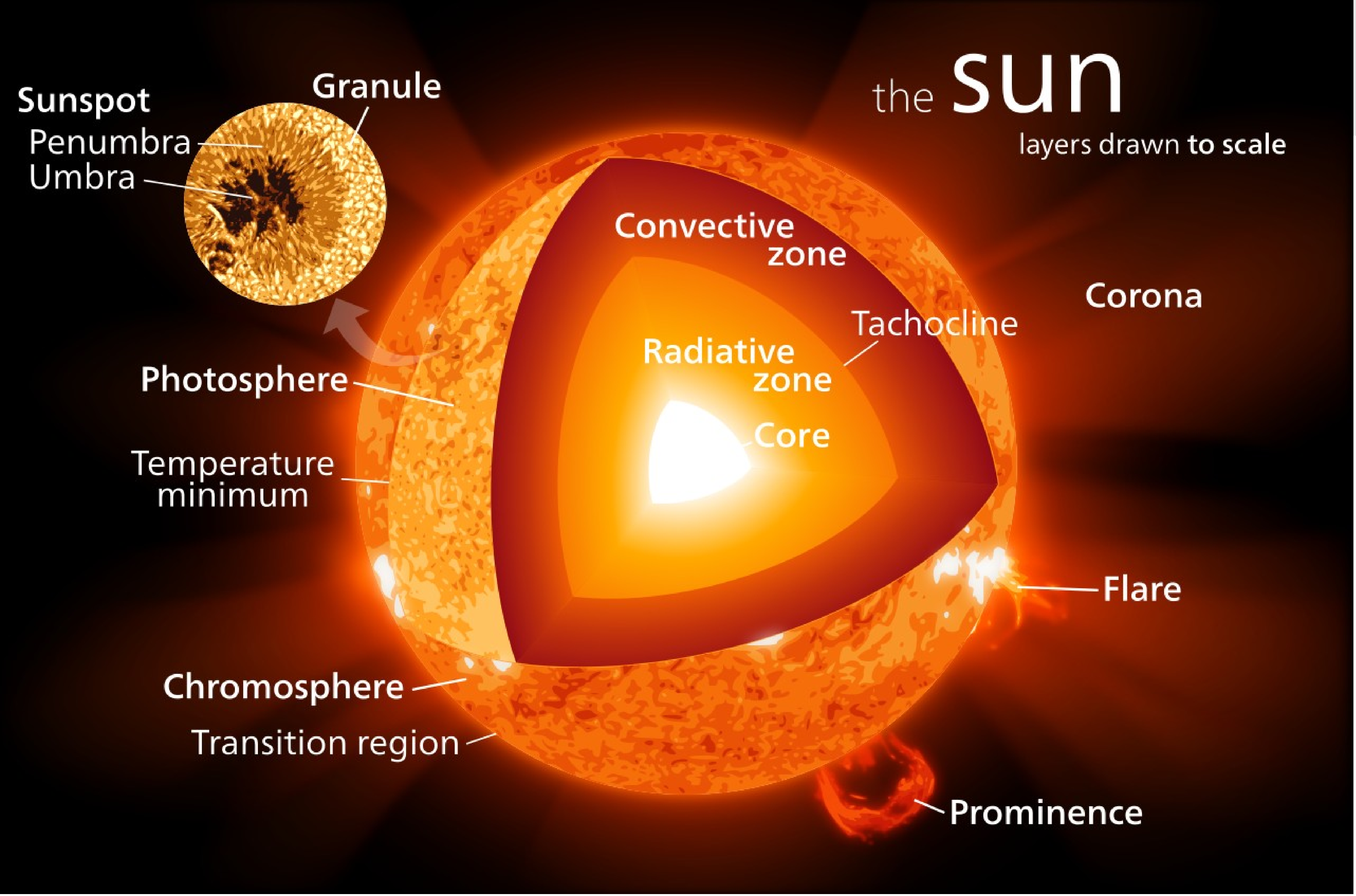
Table 16-1 Sun Data

Distance from the Earth:	Mean: 1 AU = 149,598,000 km
	Maximum: 152,000,000 km
	Minimum: 147,000,000 km
Light travel time to the Earth:	8.32 min
Mean angular diameter:	32 arcmin
Radius:	696,000 km = 109 Earth radii
Mass:	1.9891×10^{30} kg = 3.33×10^{5} Earth masses
Composition (by mass):	74% hydrogen, 25% helium, 1% other elements
Composition (by number of atoms):	92.1% hydrogen, 7.8% helium, 0.1% other elements
Mean density:	1410 kg/m^3
Mean temperatures:	Surface: 5800 K; Center: 1.55×10^{7} K
Luminosity:	3.90×10^{26} W
Distance from center of Galaxy:	8000 pc = 26,000 ly
Orbital period around center of Galaxy:	220 million years
Orbital speed around center of Galaxy:	220 km/s

WEB LINK 16.1

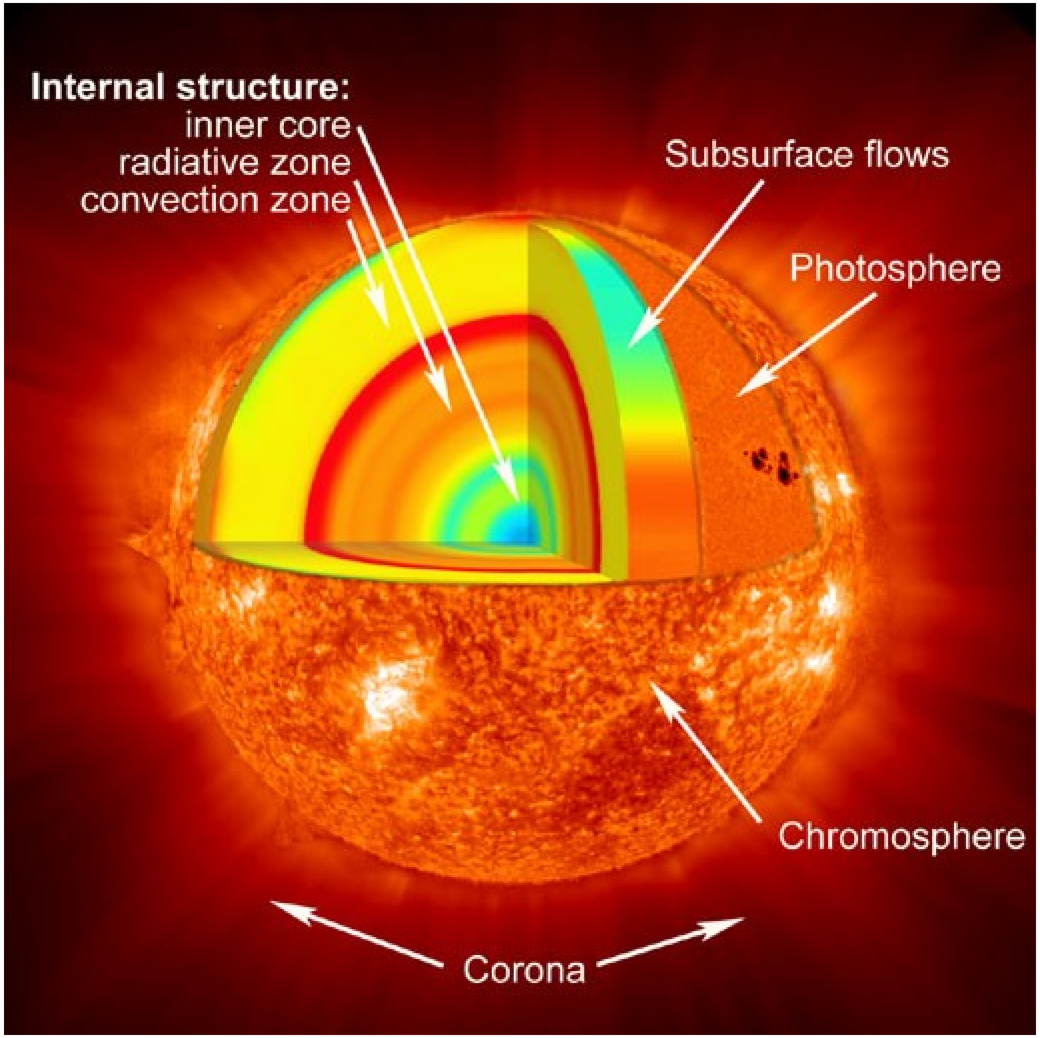
R I V U X G

(NOAO)

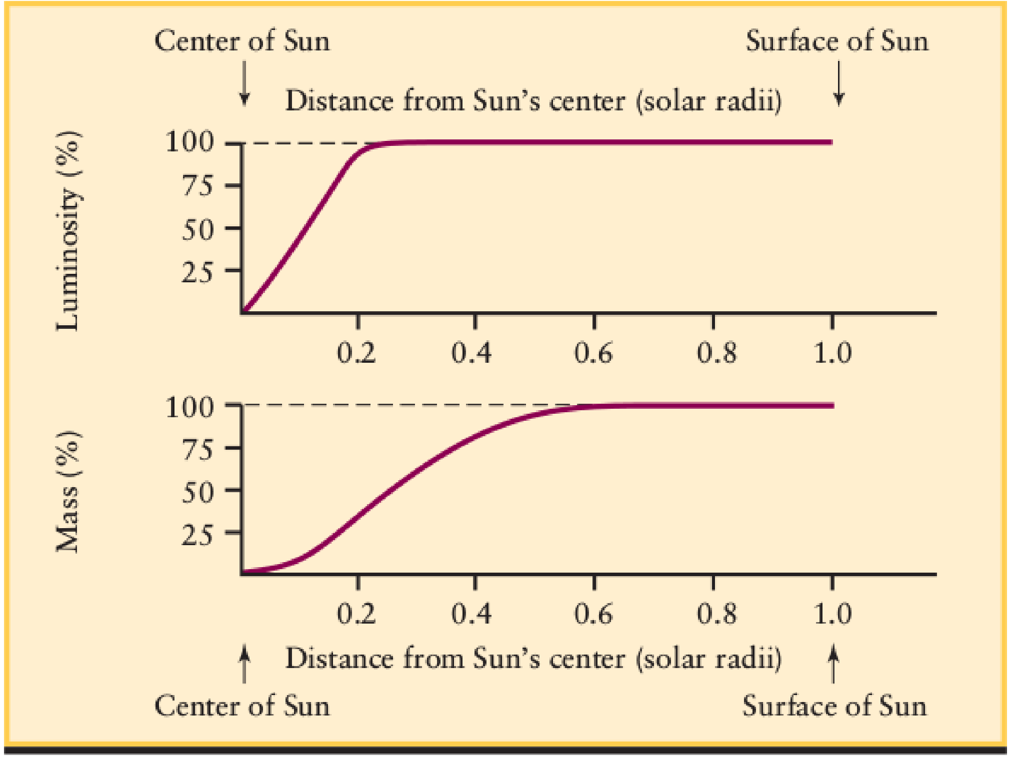

the sun
layers drawn to scale
Sunspot
Granule
Penumbra
Umbra
Convective zone
Corona
Tachocline
Radiative zone
Photosphere
Core
Temperature minimum
Flare
Chromosphere
Transition region
Prominence

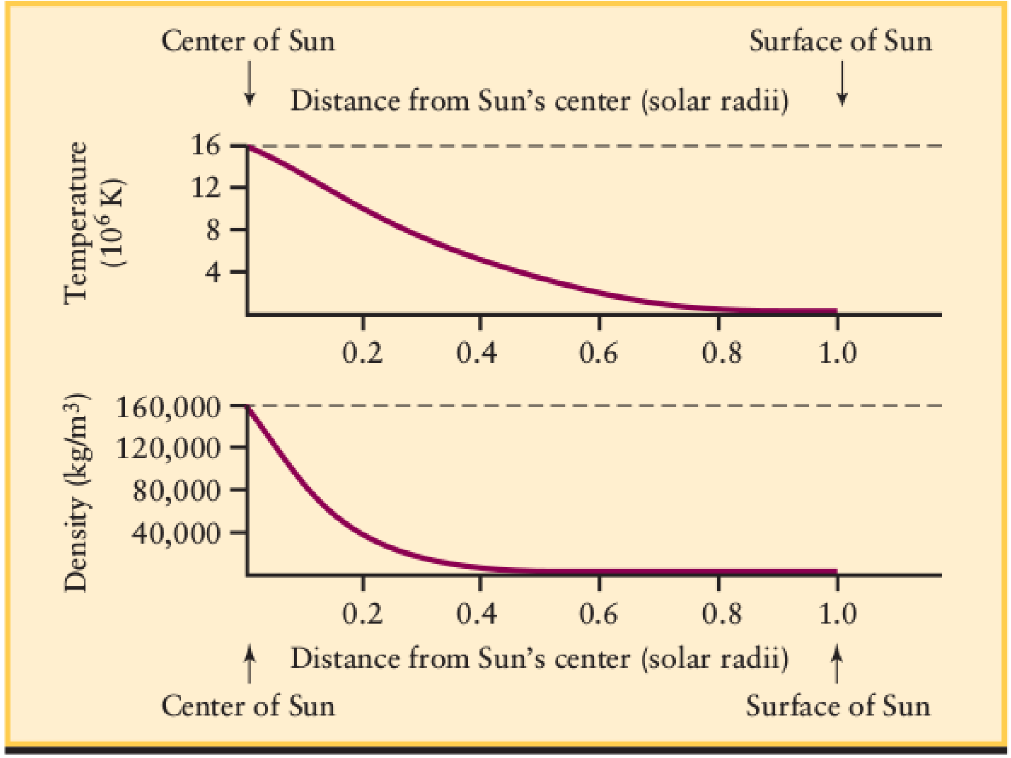
Layers

- **core** -- nuclear burning central part of the Sun
- **radiative zone** -- the layer below convection zone where energy is transported by photons
- **convection zone** -- layer of the Sun just below the photosphere that transports energy by convection
- **photosphere** -- "visible surface"
  - **prominences** -- magnetically driven plumes of hot gas, from chromosphere to corona
  - **sunspots** -- cold spots seen against the photosphere
- **chromosphere** -- lower atmosphere (contains spicules)
- **corona** -- outer atmosphere
- **solar wind** -- outflowing ions and subatomic particles from the solar surface



Models


Center of Sun
Surface of Sun
Distance from Sun's center (solar radii)
Luminosity (%)
100
75
50
25
0.2
0.4
0.6
0.8
1.0
Mass (%)
100
75
50
25
0.2
0.4
0.6
0.8
1.0
Distance from Sun's center (solar radii)
Center of Sun
Surface of Sun

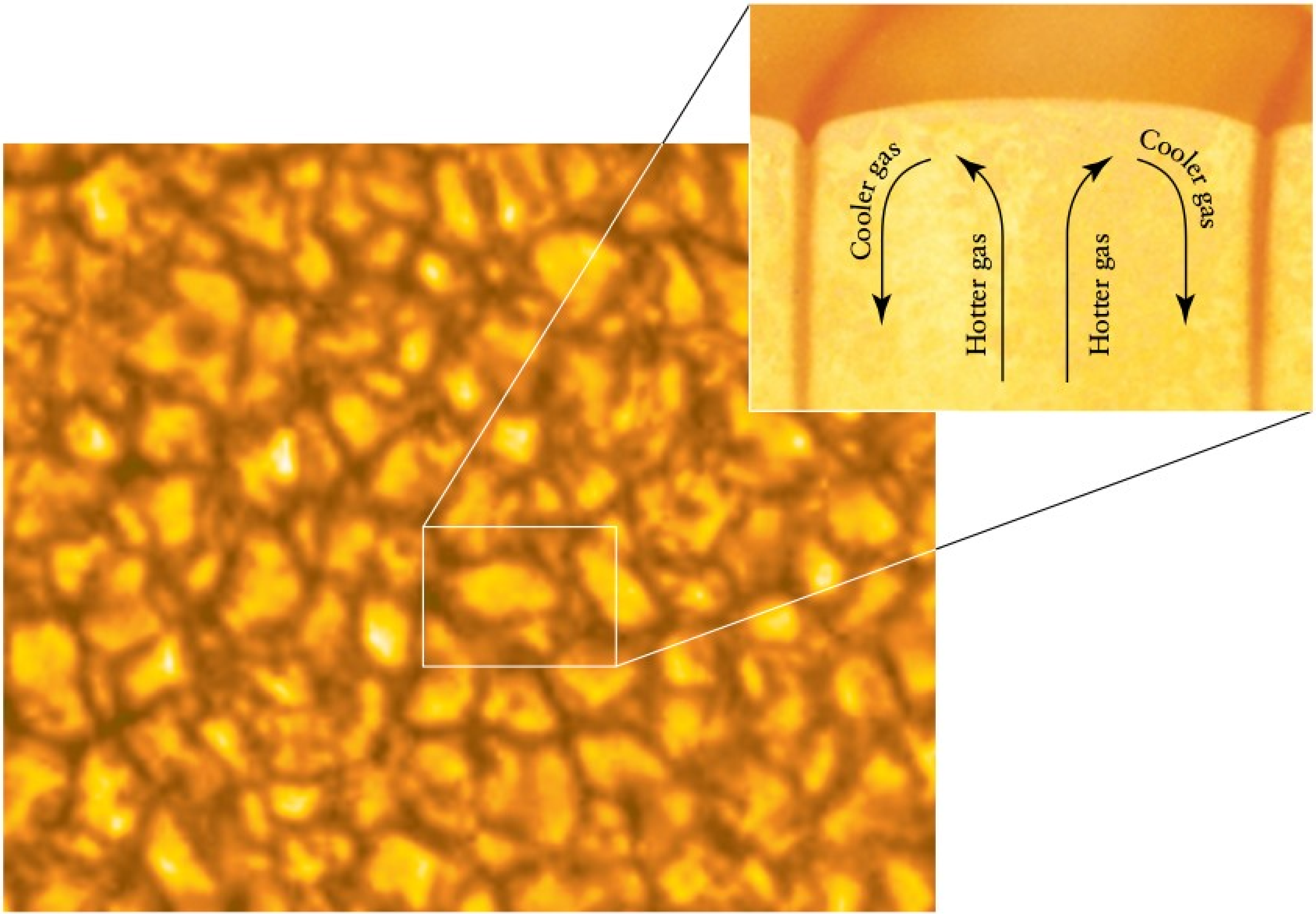

Center of Sun
Surface of Sun
Distance from Sun's center (solar radii)
Temperature (10^6 K)
16
12
8
4
0.2
0.4
0.6
0.8
1.0
Density (kg/m^3)
160,000
120,000
80,000
40,000
0.2
0.4
0.6
0.8
1.0
Distance from Sun's center (solar radii)
Center of Sun
Surface of Sun

Radiative/Convection Zones

- Radiative
  - inner 2/3 of the Sun
  - gas fully ionized in plasma form
  - energy carried outwards by photons
  - very dense, photon takes 100,000 years to exit the Sun

- Convection Zone:
  - outer 1/3 of the Sun
  - gas is cooler, and hydrogen atoms begin to form and absorb photons more efficiently
  - energy transported by bulk motion (convection)
  - Granulation (convection cell) = white (hot) in the middle, narrow darker (colder) area around it

Granulation / convection



Convection

- La temperatura di una bolla che sale diminuisce (la bolla si espande) in modo adiabatico ∇T_{ad} (dilatazione termica)
- La temperatura dell'ambiente diminuisce ∇T_{amb}
- La temperatura della bolla deve diminuire piu' lentamente dell'ambiente
  - Bolla calda sale
- $-\nabla T_{ad} < -\nabla T_{amb}$

  ovvero

  $|\nabla T_{ad}| < |\nabla T_{amb}|$

Convection

- La velocita' di convezione e' data dall'equilibrio di Forza di Archimede e Forza di attrito viscoso

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v}\right) = -\nabla p - \mathbf{F}_a + \eta\nabla^2\mathbf{v}$$

$$\Delta V = \alpha V \Delta T$$
$$\Delta\rho = -\alpha\rho\Delta T$$

Dilatazione termica, differenza bolla-ambiente

$$F_A = -g\Delta\rho = g\alpha\rho\Delta T$$

$$\eta\nabla^2\mathbf{v} = \nu\rho\nabla^2\mathbf{v} \simeq \frac{\nu\rho v}{L^2}$$

$$v_{conv} = \frac{g\alpha\Delta T L^2}{\nu}$$

Convection, numero di Rayleigh

$$R_a = \frac{\text{tempo di diffusione}}{\text{tempo di convezione}}$$

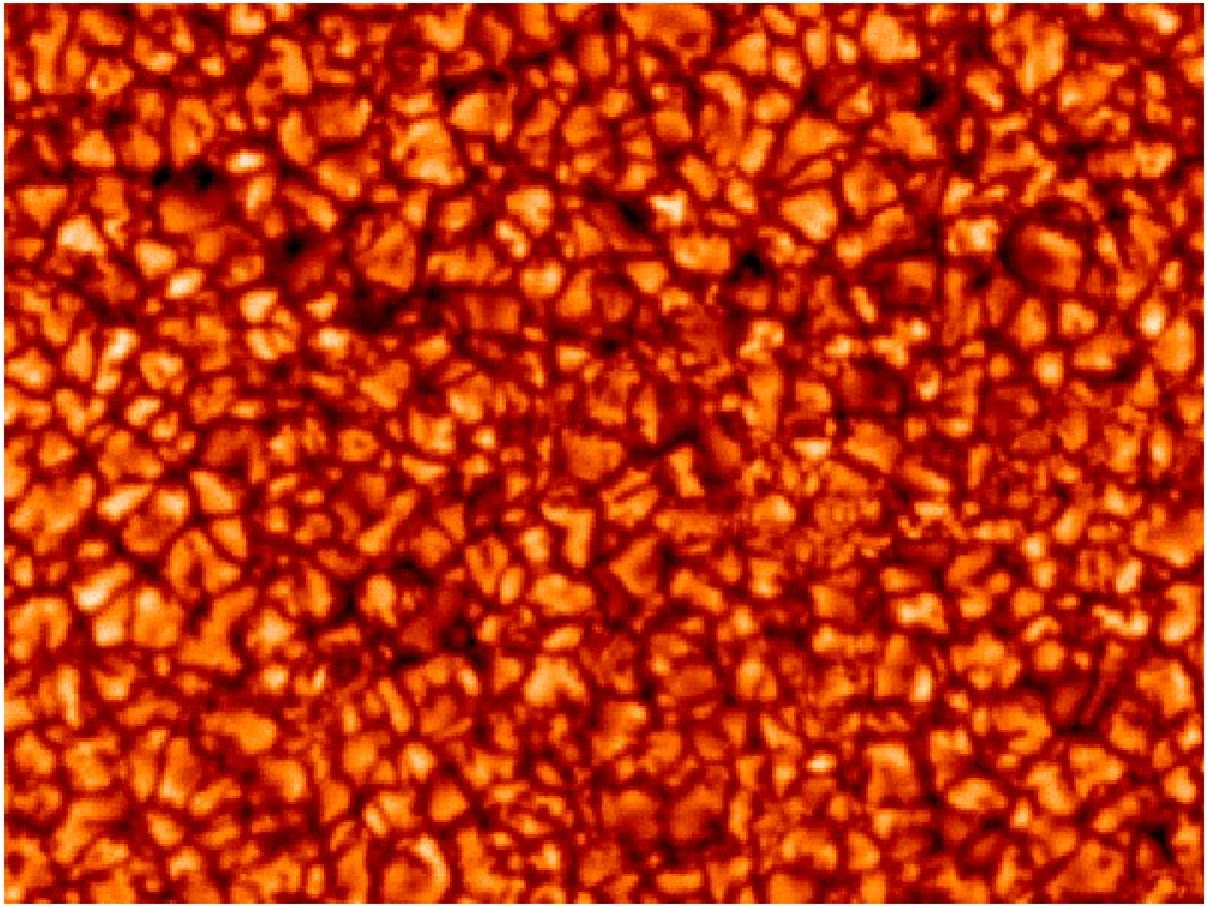
$$\text{tempo di diffusione} = \frac{L^2}{\chi} \qquad \chi = \frac{\rho C_p}{K}$$

$$\text{tempo di convezione} = \frac{L}{v_{conv}}$$

$$R_a = \frac{g\alpha\Delta T L^3}{\nu\chi}$$

Osservazioni

- Ra >> 1
  - convezione
- R >> 1
  - Moto turbolento
- Si osserva la relazione
  - v da Doppler
  - T da corpo nero sole
  - L da granuli



$$v_{conv} = \frac{g\alpha\Delta T L^2}{\nu}$$

Granulazione

CARATTERISTICHE DELLE CELLE CONVETTIVE

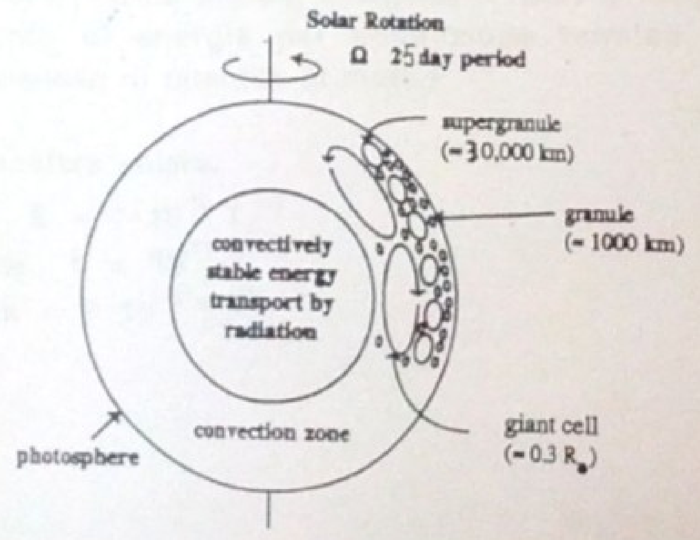
	Dimensioni (km)	Velocità (km/s)	Vita media	Numero
granuli	10^3	1	8 ÷ 10 min	$3 \div 4 \cdot 10^6$
mesogranuli	$5 \div 10 \cdot 10^3$ km	orizz.: 0.5 vert.: 0.05?	1 ÷ 2 h	10^5
supergranuli	$2 \div 3 \cdot 10^4$ km	orizz.: 0.3÷ 0.5 vert.: 0.05÷ 0.1	15 ÷ 30 h	$5 \cdot 10^3$
celle giganti	$1 \div 2 \cdot 10^5$ km	0.05 ?	1 anno ?	?

Granuli, mesogranuli e supergranuli insorgerebbero alle profondità di ionizzazione dei due elementi più abbondanti nel Sole: l'idrogeno e l'elio. Infatti:

granuli ---> H^+ (1000 km)

mesogranuli ---> He^+ (5000 km)

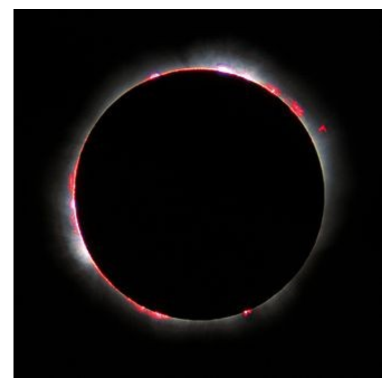
supergranuli ---> He^{++}(15000 km)



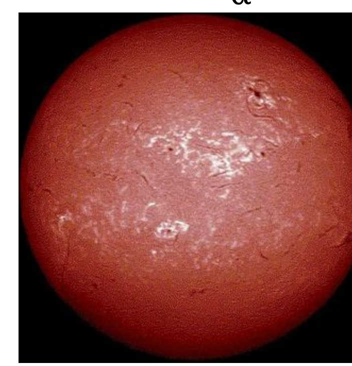
Schematic of interior of Sun and convection cells of various sizes.

Solar atmosphere

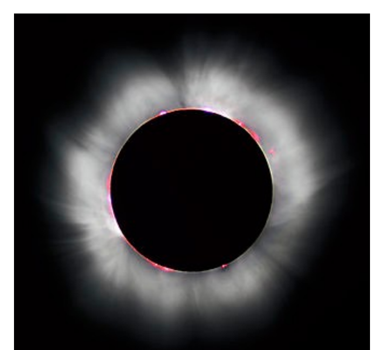
- **photosphere** -- "visible surface"
  - **prominences** -- magnetically driven plumes of hot gas, from chromosphere to corona
  - **sunspots** -- cold spots seen against the photosphere
  - 500 Km thick
  - From tau=1 (T=6400 K) to temperature minimum (T=4100 K)
  - Visible to tau = 2/3 (T=5800K)
  - Density 2 10^{-4} Kg/m^3
  - Absorption lines (T higher in the inner part)



H_α filter



- **chromosphere** -- lower atmosphere (contains spicules)
  - Density 10^{-4} times the photosphere
  - T up to 10000 K
  - Emission lines, in particular H_α (3-2 transition)



- **corona** -- outer atmosphere
  - Extends several solar radii
  - Density $\rho=10^{-12}$ Kg/m^3 $T=10^6K$
  - Variable with solar activity

Corona

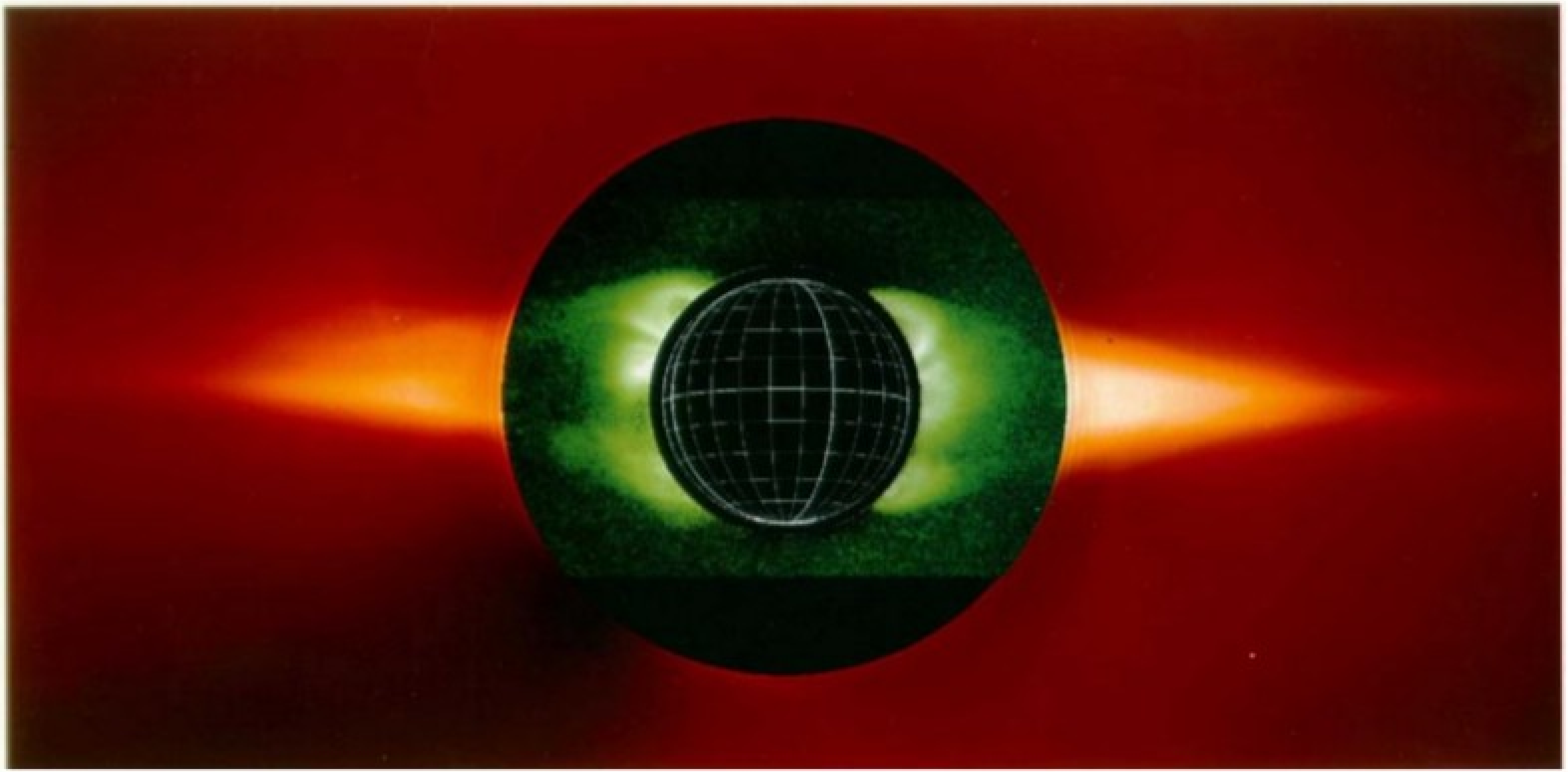
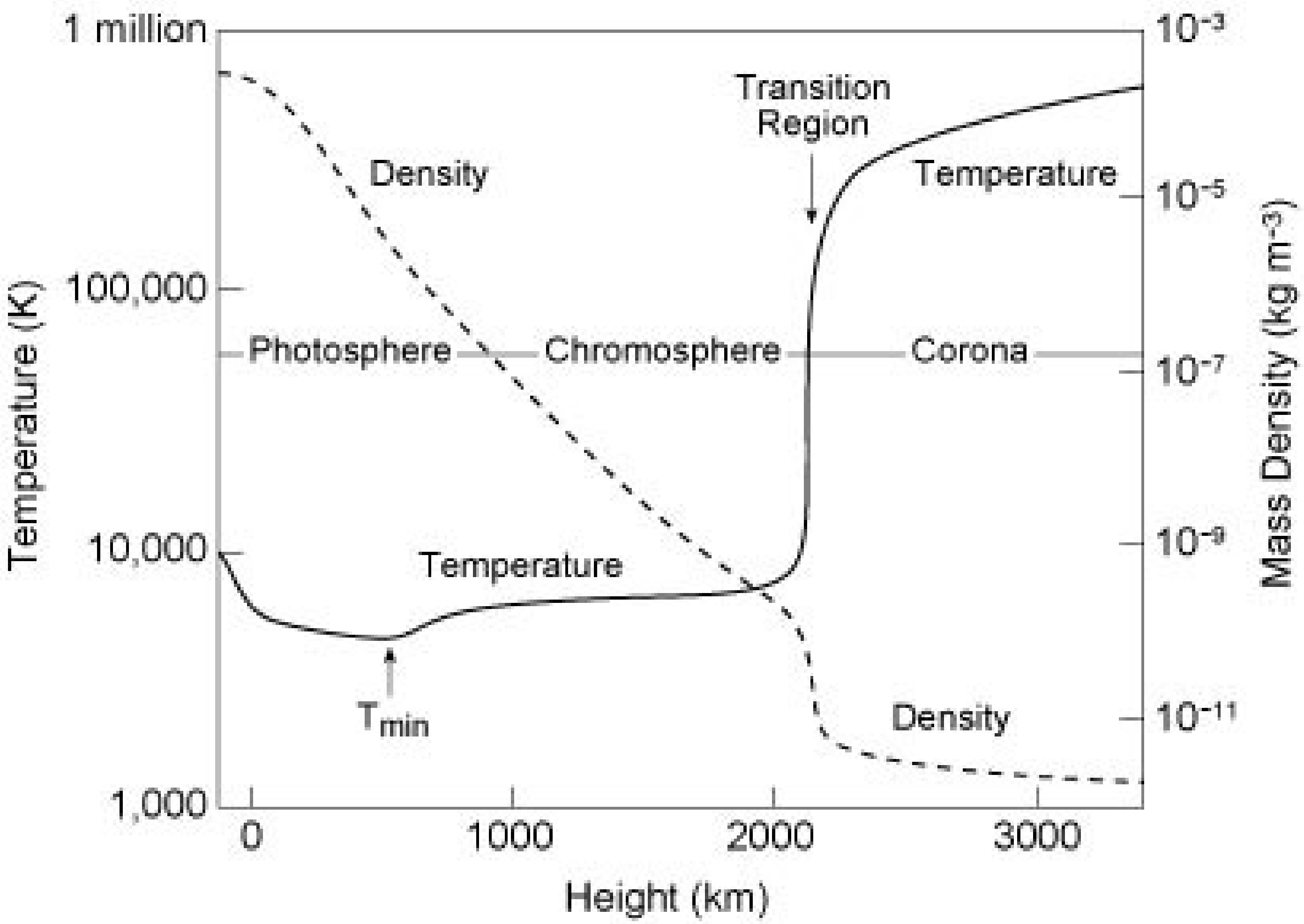


Figure 3. A coronagraph view of the extended minimum corona (on 1st February 1996), composed by a green-line emission image and a white-light image taken by the LASCO coronagraphs on-board SOHO. **This figure is reproduced as Color Plate 54.**

Solar atmosphere

- Temperature:
  - From Doppler lines broadening
  - From lines intensity (ionization level of atoms)



Solar wind

- The most fundamental problem in solar system research is still unsolved:
  - how can the Sun with a surface temperature of only 5800 K heat up its atmosphere to more than a million K?
  - In fact, the solar atmosphere is so hot that not even the Sun’s enormous gravity can contain it. Part of it is continuously evaporating into interplanetary space:

the SOLAR WIND

Solar wind

Table 1. Typical parameters of the slow solar wind at 1 AU.

Flow speed v_{P}	$350\ \mathrm{km\ s^{-1}}$
Proton density n_{P}	$9\ \mathrm{cm^{-3}}$
Flux density $n_{\mathrm{P}} v_{\mathrm{P}}$	$3 \times 10^8\ \mathrm{cm^{-2}\ s^{-1}}$
Composition	96% protons, 4% He^+ ions, minor constituents, plus an adequate number of electrons to maintain nearly perfect charge neutrality
Proton temperature T_{P}	4×10^4 K
Electron temperature T_{e}	1.5×10^5 K
Magnetic field B	4 nT

- Bulk velocity >> thermal velocity (peak width)

$$c_s = \left\{ \frac{\gamma p}{\rho} \right\}^{\frac{1}{2}} = \left\{ \frac{\gamma \kappa_B}{m_p + m_e} (T_p + T_e) \right\}^{\frac{1}{2}}$$

$$c_s \sim 60 km/s$$

- Thus, SW is a supersonic flow

Solar wind speed

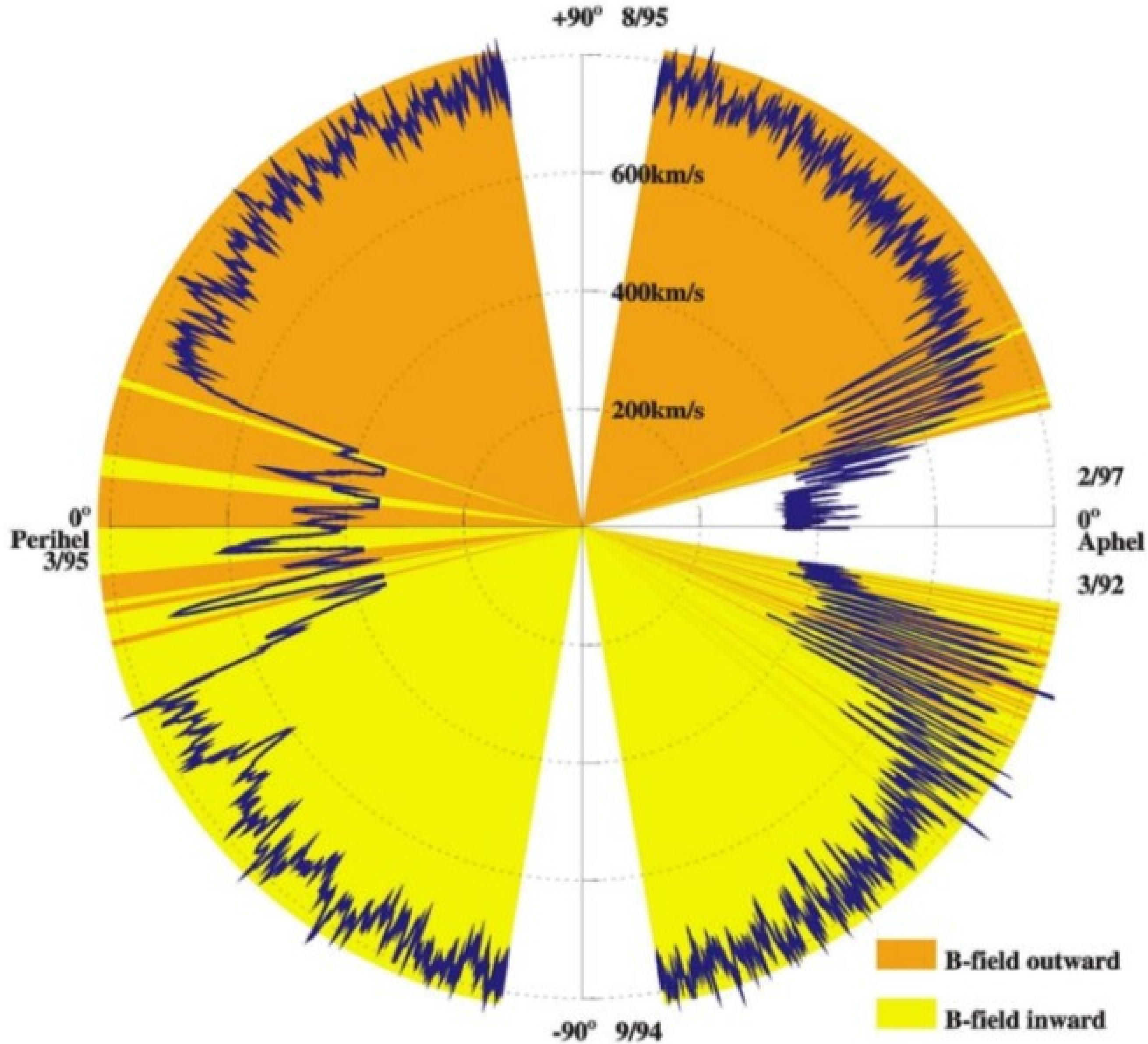


Figure 4. Solar wind and magnetic field polarity observations during the passage of Ulysses across both solar poles. (Courtesy of J Woch, Max-Planck-Institute für Aeronomie.)

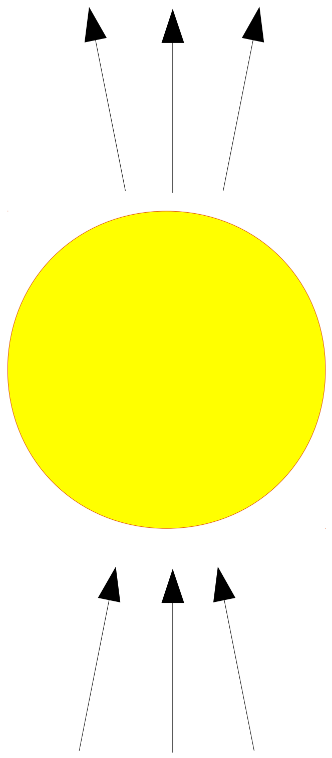
Campo magnetico solare

- Misurato tramite effetto Zeeman
  - Le linee dello spettro di Fraunhofer si separano proporzionalmente alla componente del campo magnetico parallela alla linea di vista

- Debole componente radiale poloidale

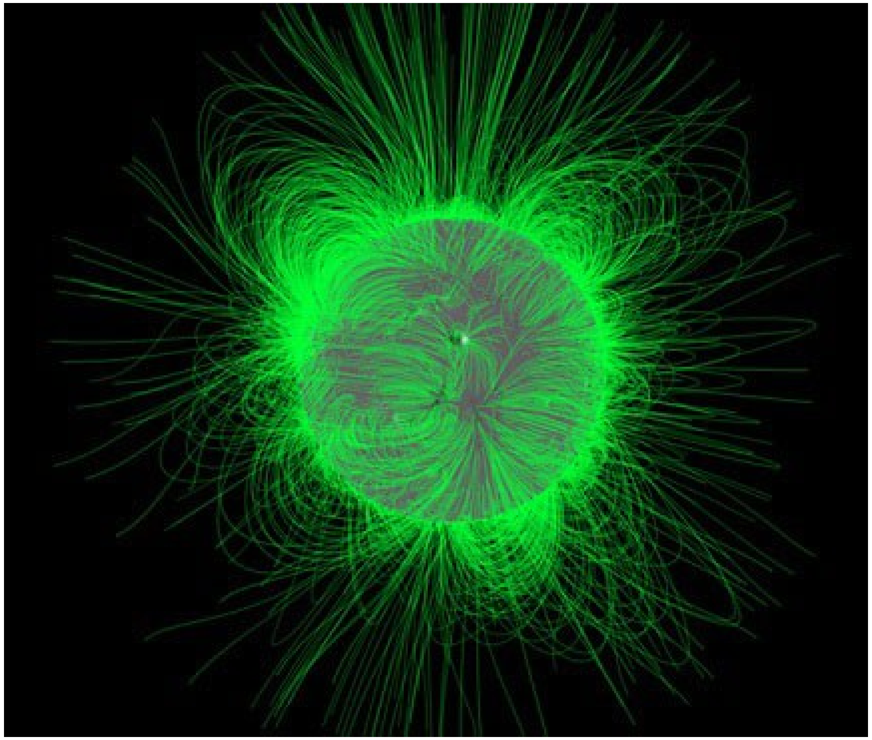
$$B = B_0 \cos^8(\theta)$$

$$B_0 = 11.5 \text{ Gauss}$$



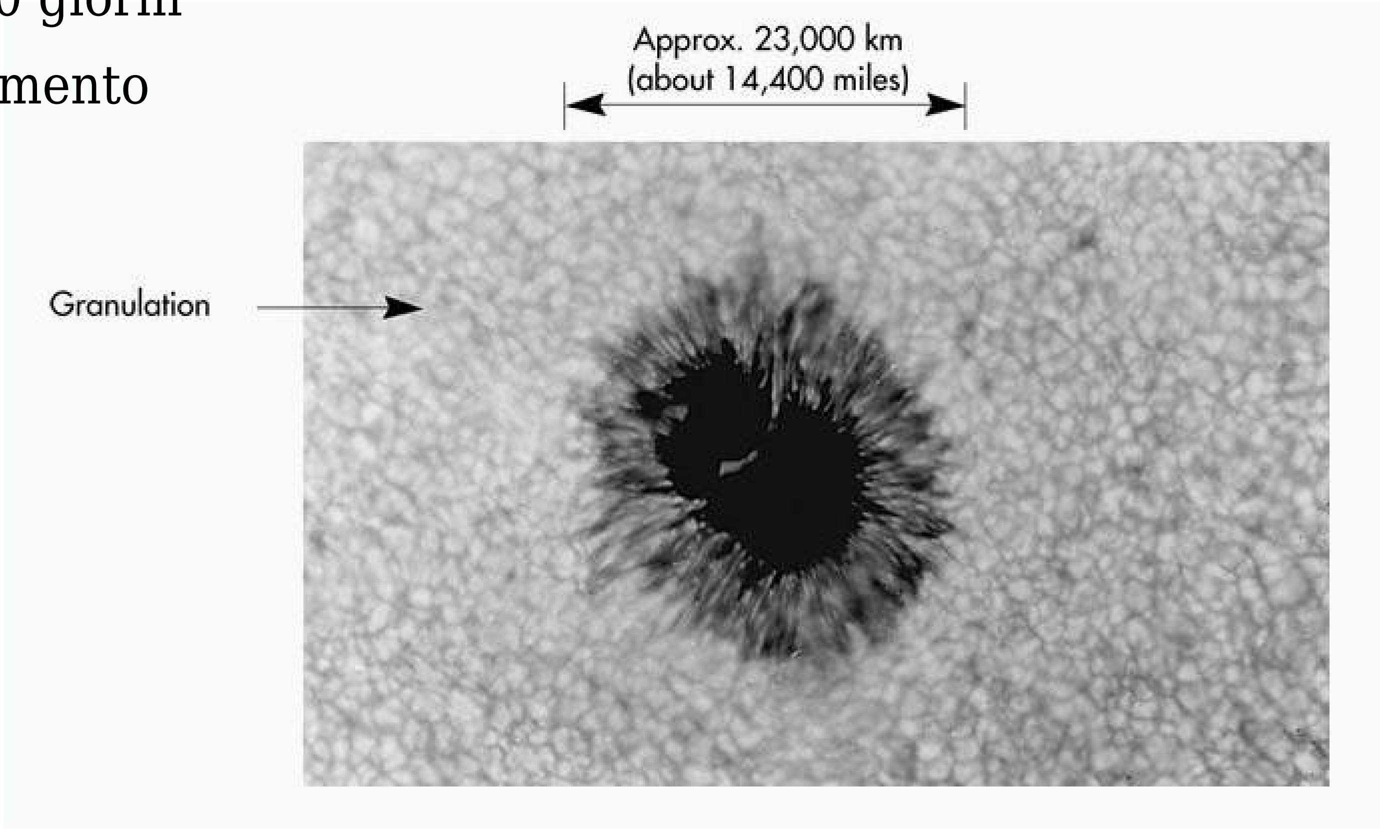
Campo magnetico solare

- Estremamente complicato dalla attivita' solare

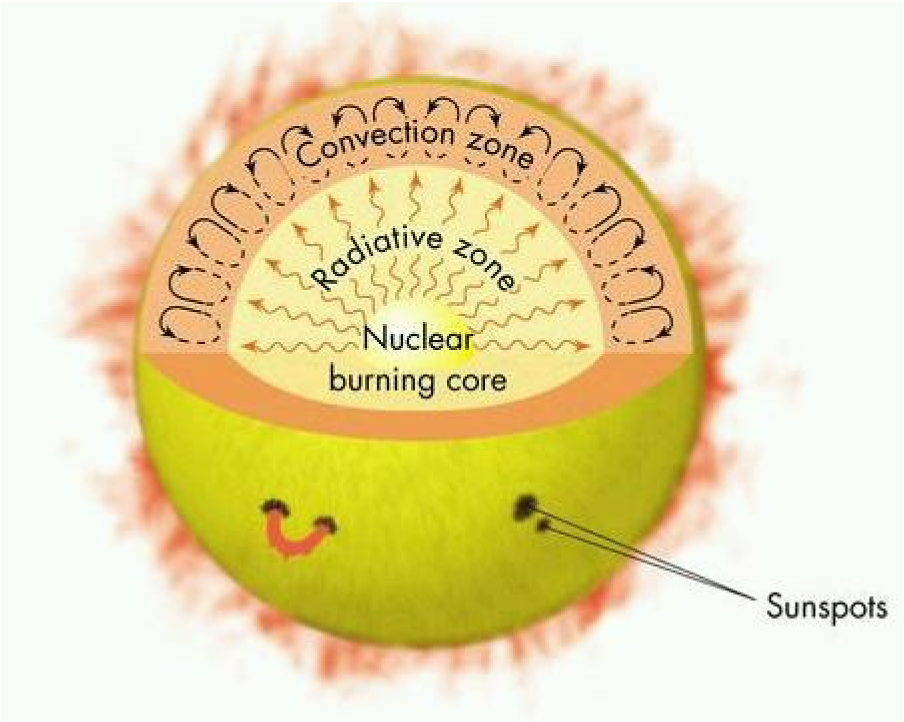


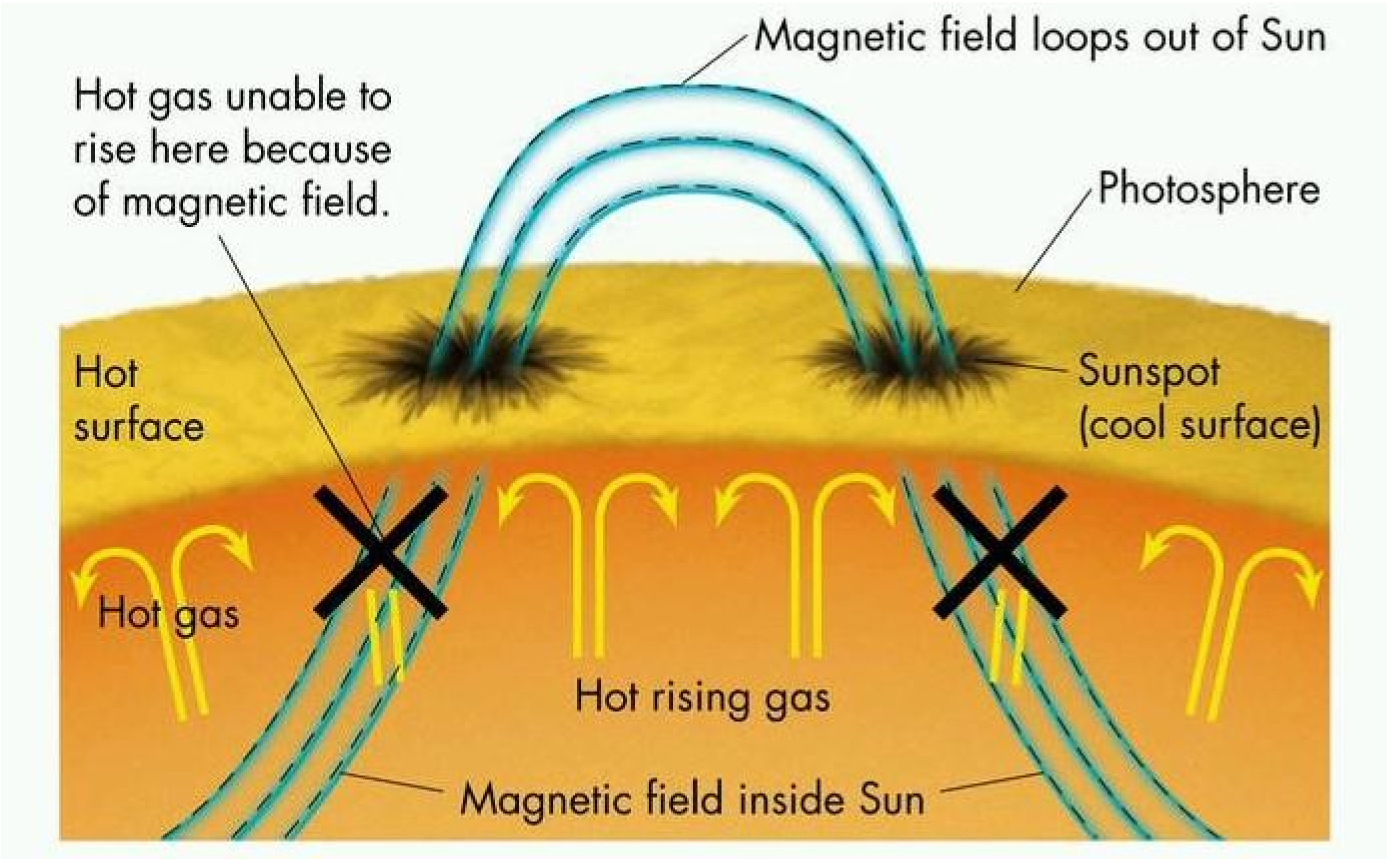
Macchie solari

- Si osservano nella fotosfera
- Ombra, zona centrale,
  - Fredda, T=3900 K (luminosita' 20%)
  - Intenso campo magnetico, B=3000 Gauss
- Penombra, zona periferica, composta da filamenti radiali
- Durata: poche ore – 50 giorni
- → teoria del raffreddamento

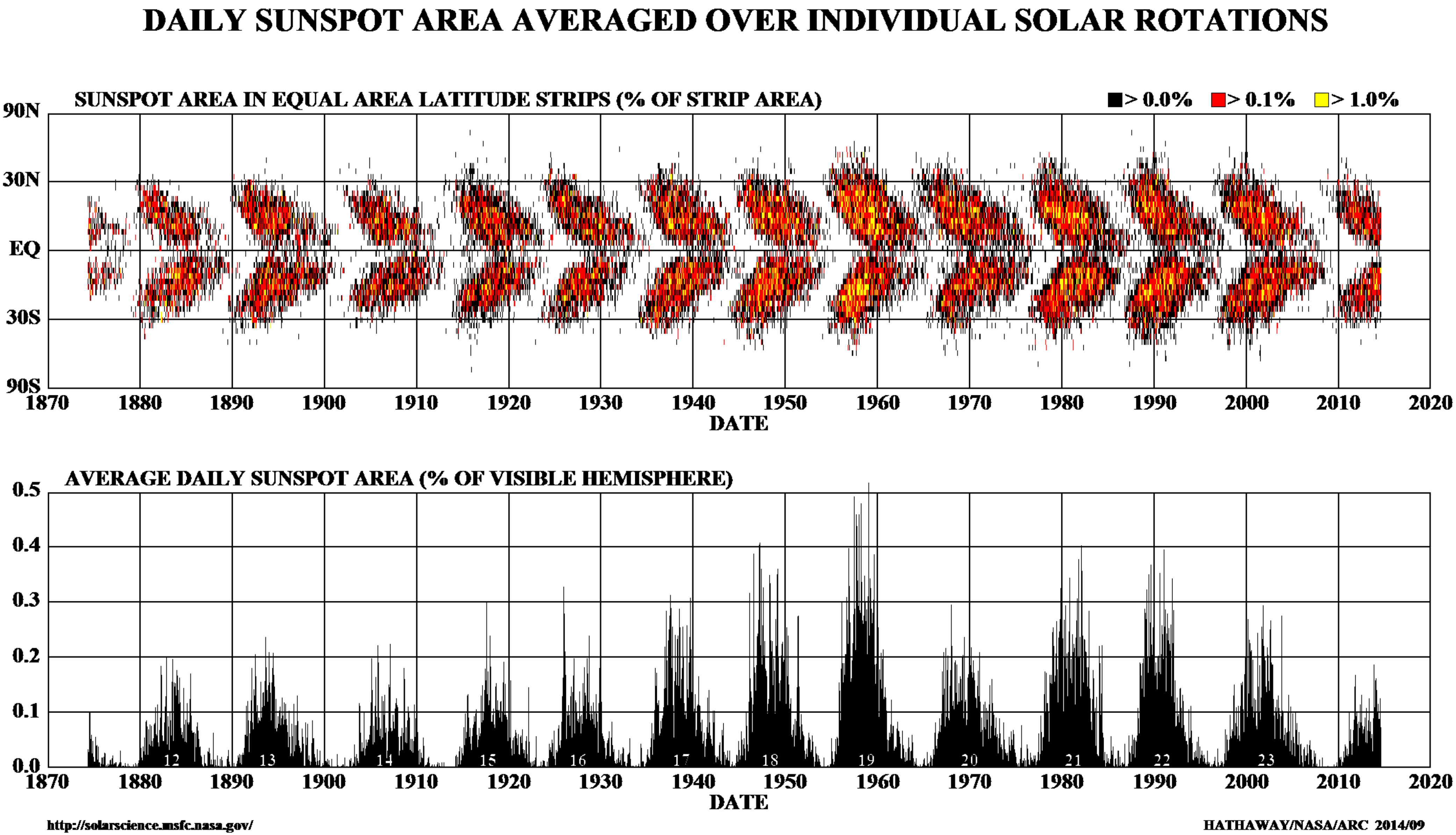


- Le macchie solari si presentano in regioni bipolari
  - P preceding
  - F following



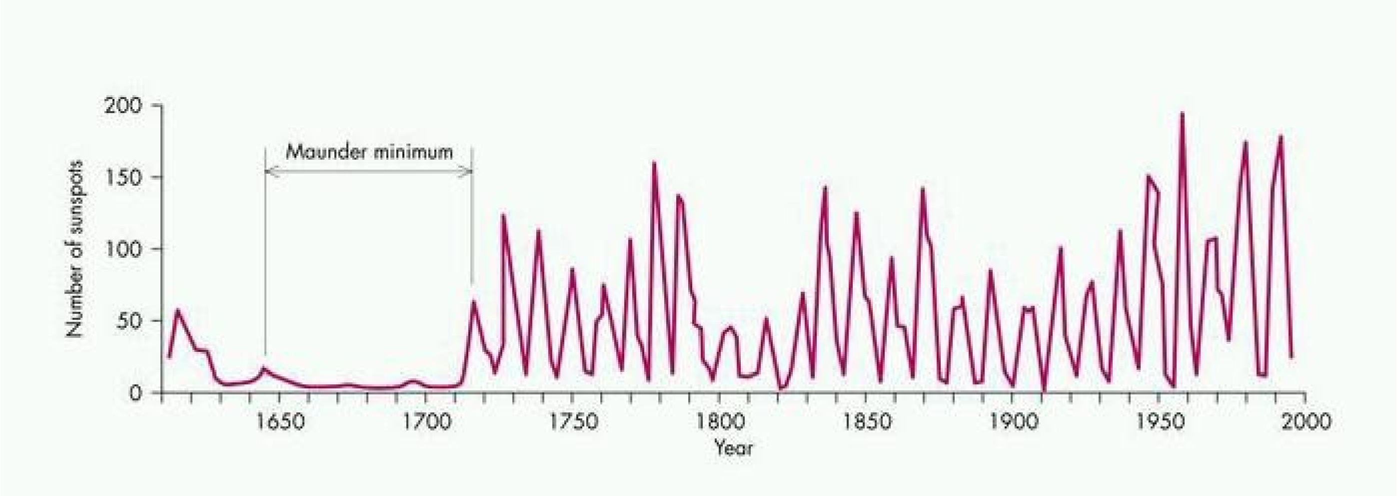

Magnetic field loops out of Sun
Hot gas unable to rise here because of magnetic field.
Photosphere
Hot surface
Sunspot (cool surface)
Hot gas
Hot rising gas
Magnetic field inside Sun

Conteggio delle macchie

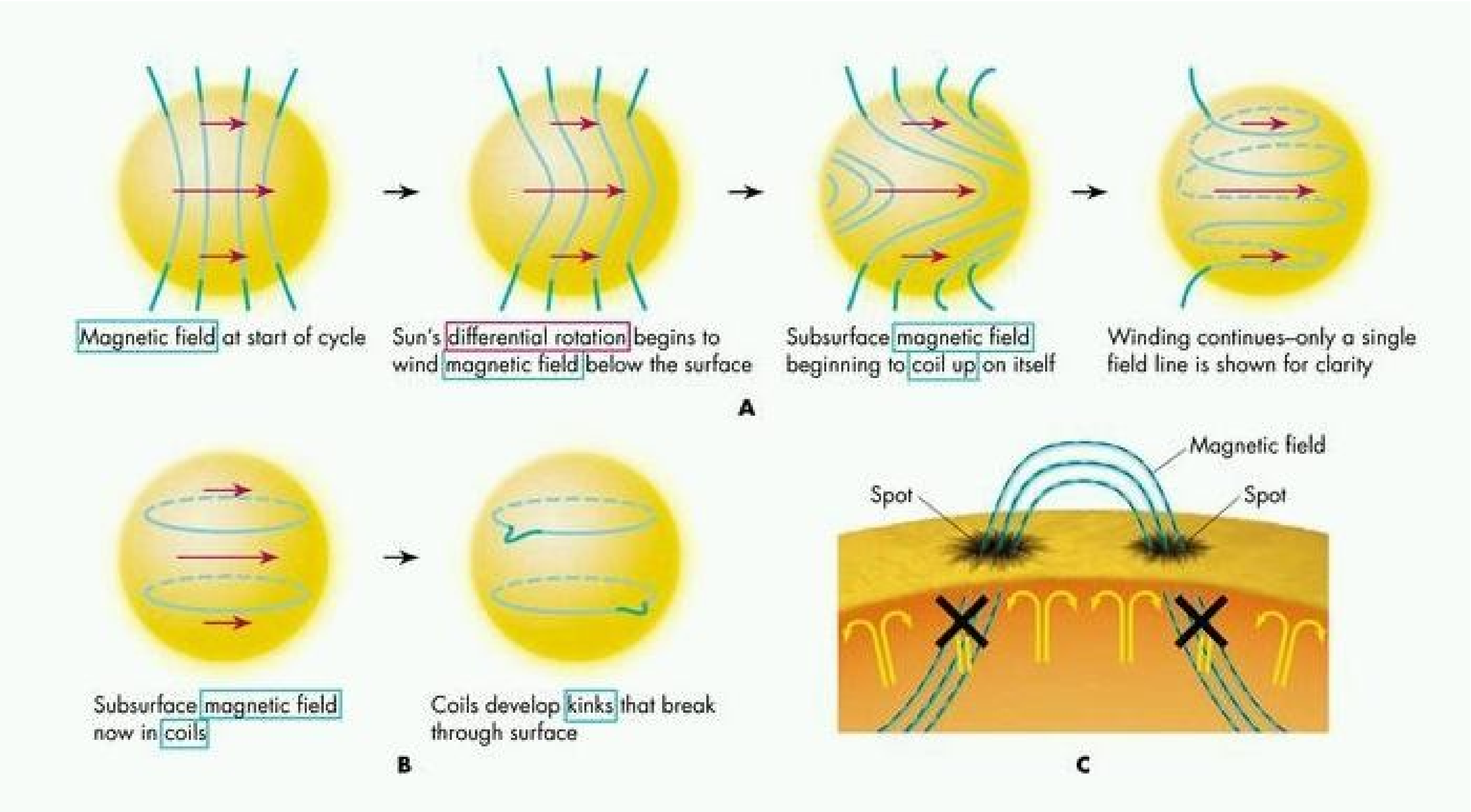


Solar cycle

- Periodicita' 11 anni
- Ogni 11 anni si ha inversiione della polarita'
- Dati storici



Solar cycle



Magnetic field at start of cycle
Sun's differential rotation begins to wind magnetic field below the surface
Subsurface magnetic field beginning to coil up on itself
Winding continues–only a single field line is shown for clarity
A
Subsurface magnetic field now in coils
Coils develop kinks that break through surface
B
Magnetic field
Spot
Spot
C

Solar cycle

- Cause of the Solar Cycle:
- close link between gas and magnetic field
- "11 year cycle" (22 year cycle?)
- differential rotation of the Sun
- winding of magnetic field lines
- quenched when wound too tightly?

Solar Magnetic Activity

- Solar magnetic fields: thousands of times stronger than on Earth
- **Solar Flare**: brief, bright eruptions of hot gas in the chromosphere. Shower/wind of charged particles and causes Aurora.
- **Prominence**: plumes of glowing gas that jut from the chromosphere to corona.
- **Solar Storm**: a burst of outflowing charged particles from the Sun, as a more immediate outcome of the flares and prominences.
- **Solar Wind**: Solar flares and prominences heats up the chromosphere and corona (e.g. a whip) to temperatures high enough to accelerate gas to escape Sun's gravity.

Atmosphere

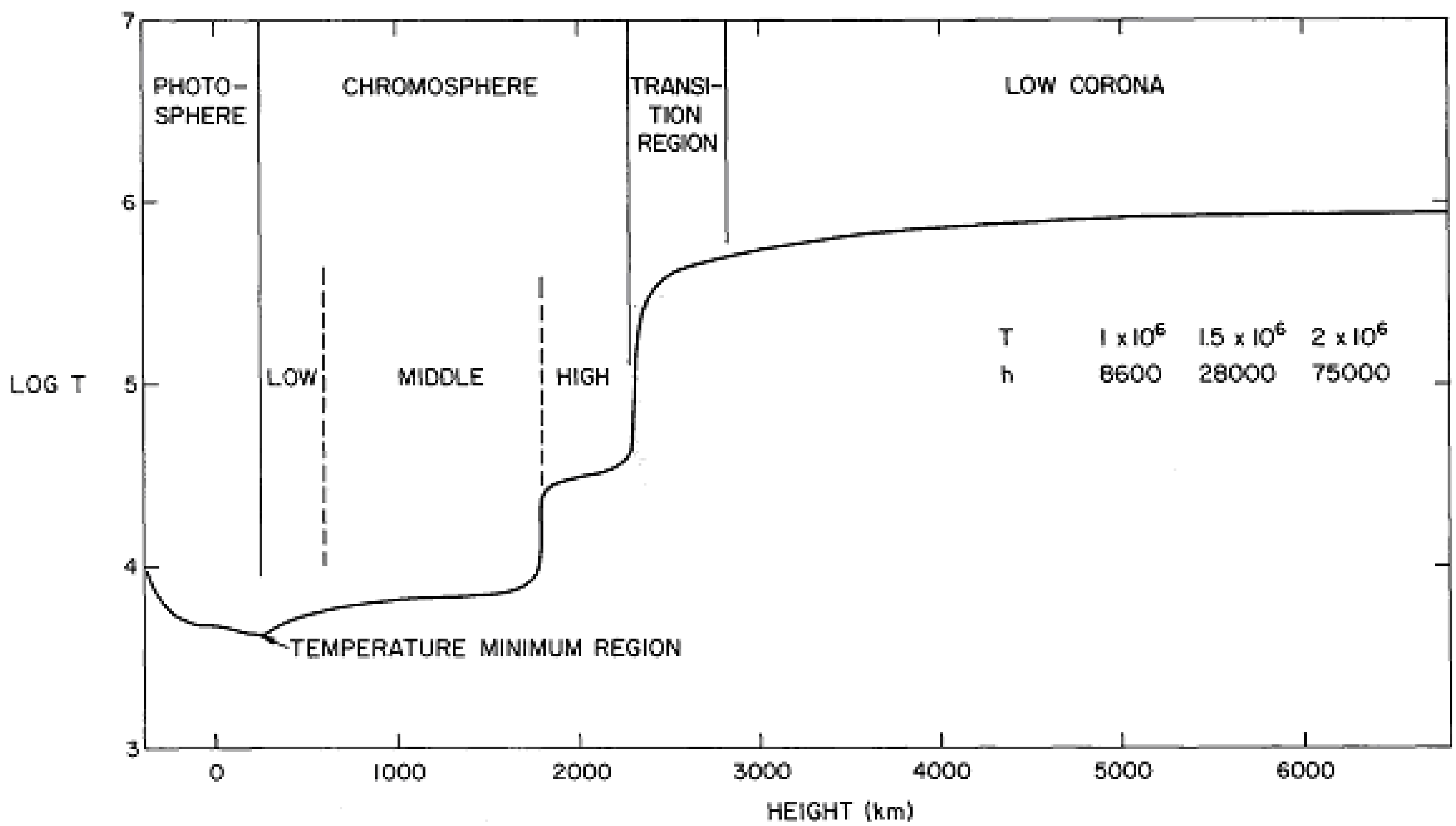
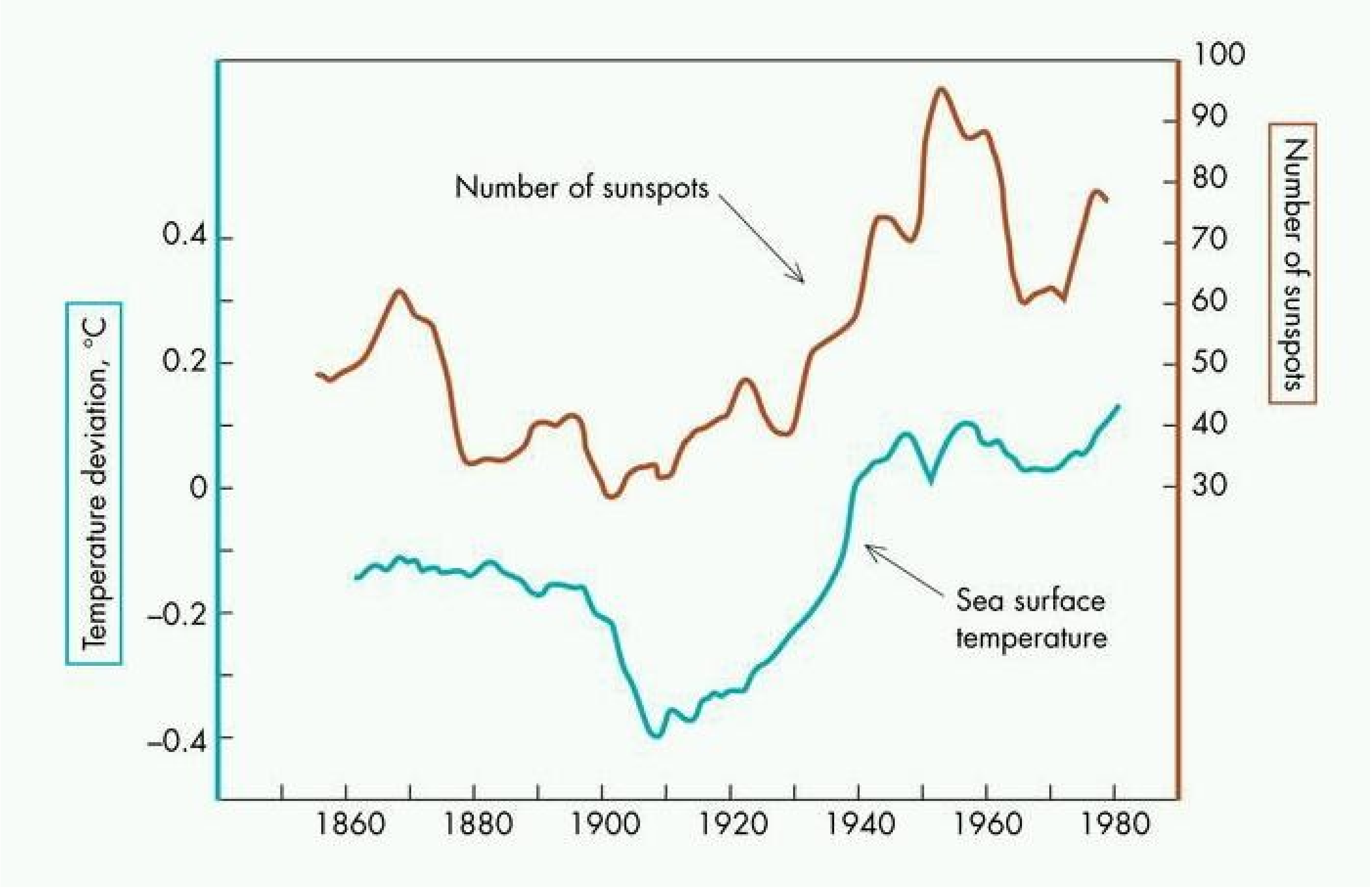


PHOTO-SPHERE
CHROMOSPHERE
TRANSI-TION REGION
LOW CORONA
LOW
MIDDLE
HIGH
T 1 x 10^6 1.5 x 10^6 2 x 10^6
h 8600 28000 75000
TEMPERATURE MINIMUM REGION
LOG T
7
6
5
4
3
0
1000
2000
3000
4000
5000
6000
HEIGHT (km)

Solar Cycle and Climatic Changes

- correlation between the solar cycle and earth temperature
- hypothesis: solar wind changes Earth's upper atmosphere, its temperature structure, and this in turn changes the atmosphere's circulation
- Maunder minimum: few sunspots were observed between 1645 and 1715, coincident with abnormally cold winters in Europe and North America ("mini ice age").
- Greenhouse effect or increased solar activity?



Number of sunspots
Sea surface temperature
Temperature deviation, °C
Number of sunspots
0.4
0.2
0
–0.2
–0.4
100
90
80
70
60
50
40
30
1860
1880
1900
1920
1940
1960
1980