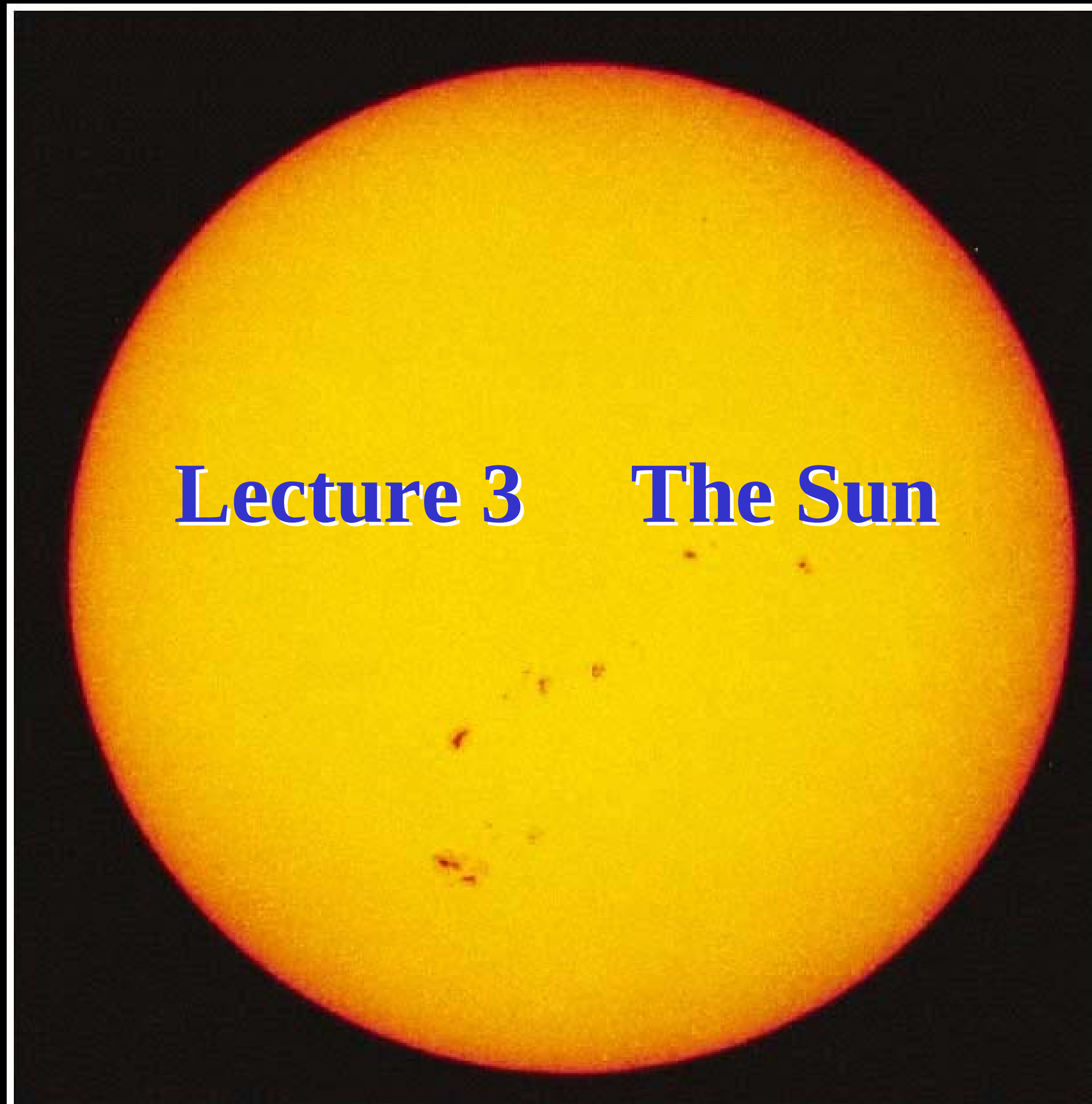
Lecture 3 The Sun



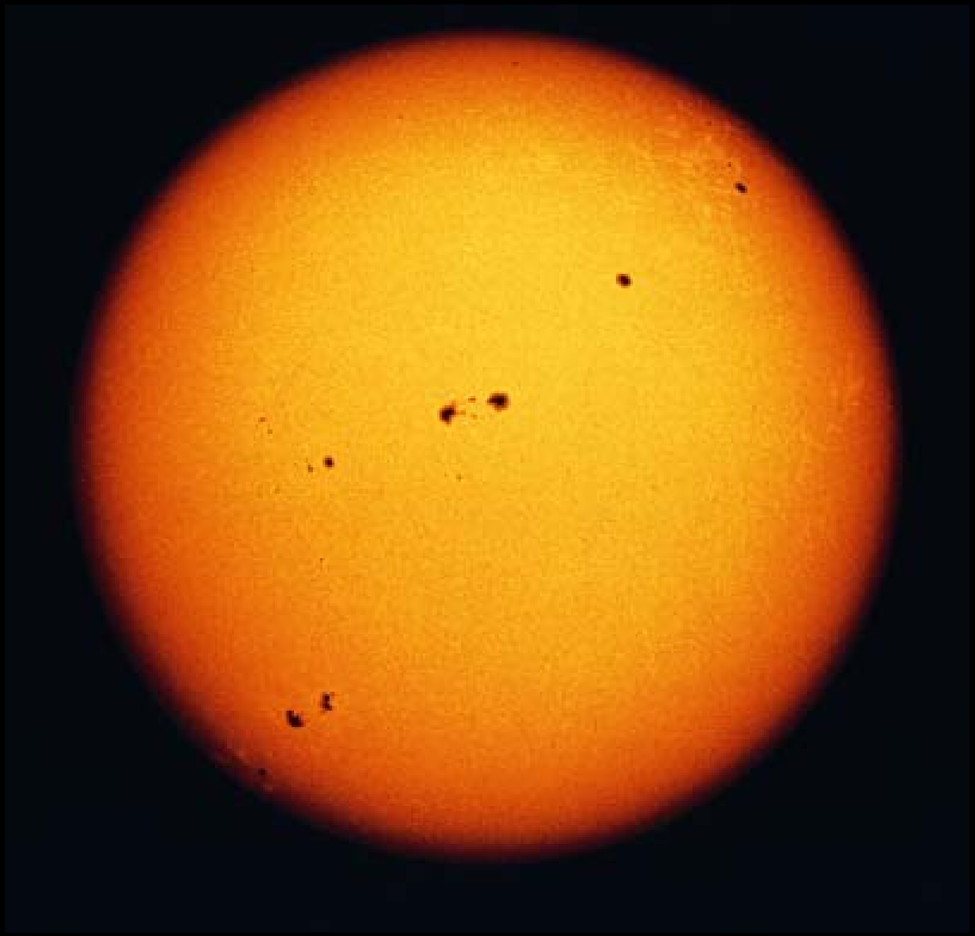
Basic Properties of the Sun

Distance: 1.48 x 10^8 km
= 1 A.U.

Mass: 1.99 x 10^{30} kg

Radius: 6.96 x 10^5 km

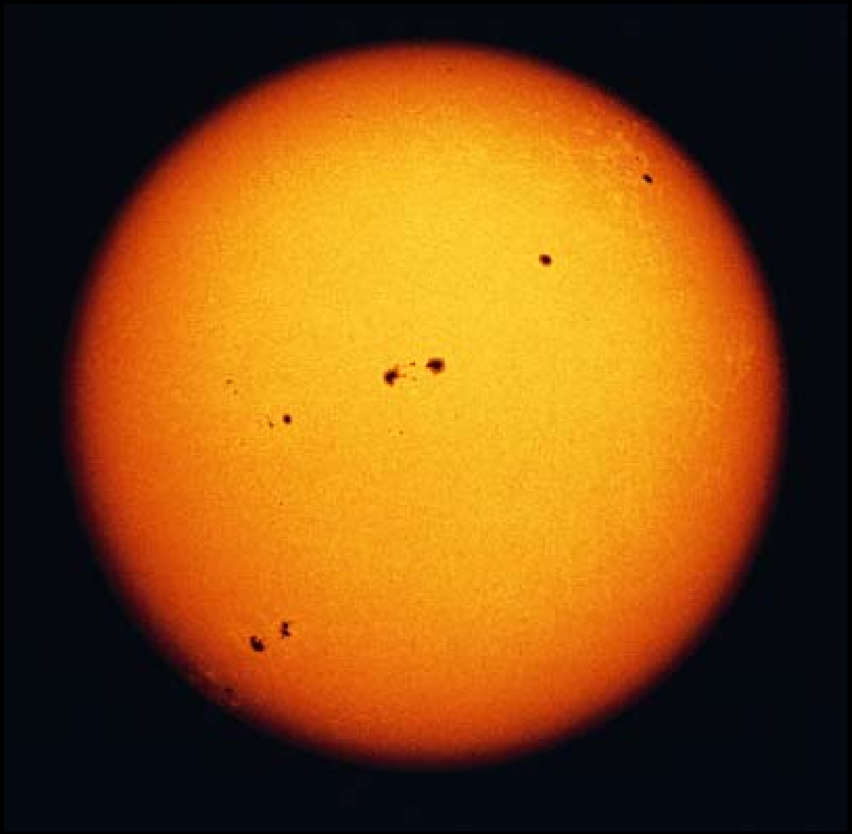
Density: 1.41 g/cm^3



Luminosity: 3.8 x 10^{26} watts

Photosphere

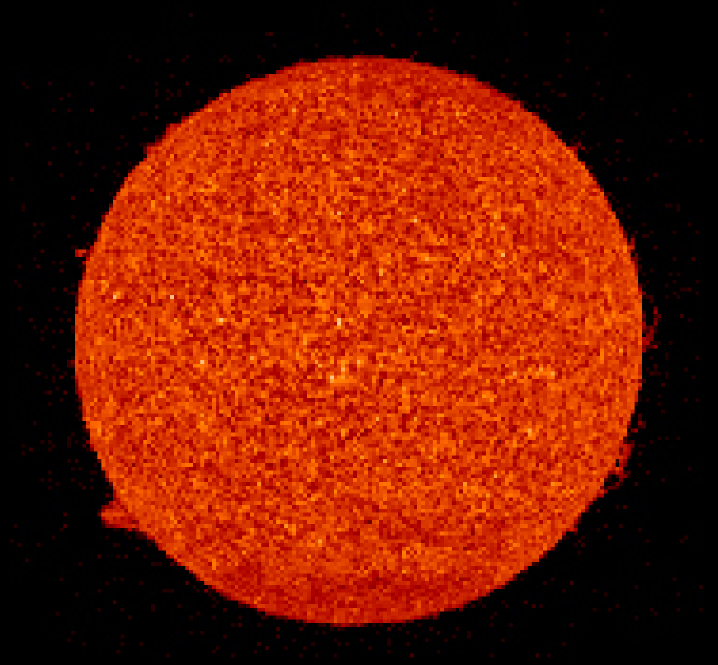
- T = 5,800 K; depth = 400 km
- This is the yellow “surface” that we see.



Chromosphere

- T = 1 – 5 x 10^4 K; depth = 2,500 km
- A thin layer above the photosphere where most of the Sun's UV light is emitted.

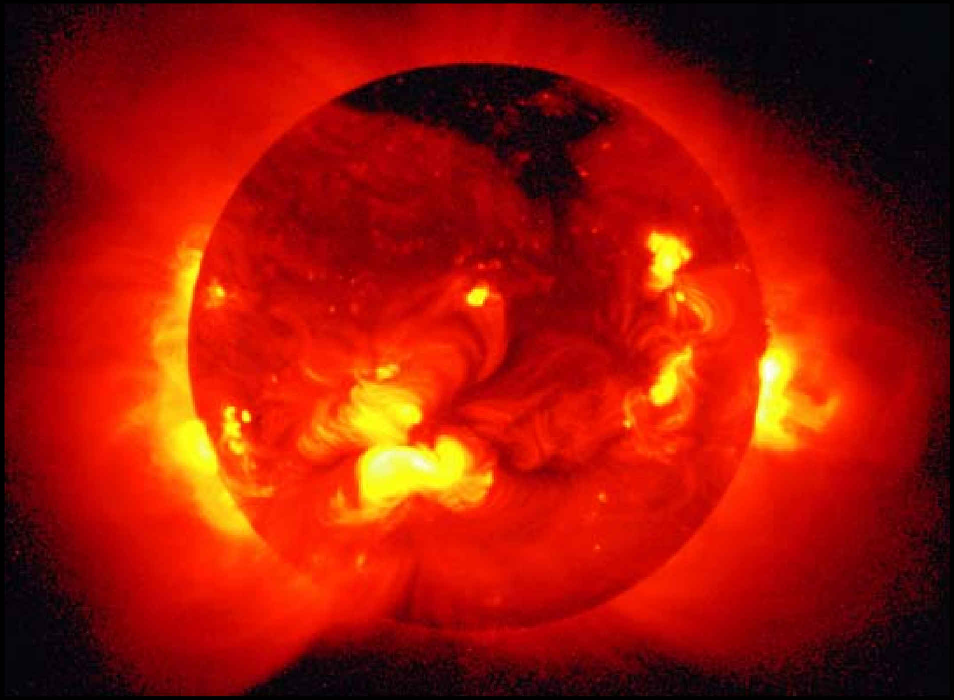
- UV image of the Sun
- light emitted from neutral Helium at 20,000 K



courtesy of SOHO/SUMER consortium
SOHO is a project of ESA and NASA

Corona

- $T = 2 \times 10^6$ K; depth ≈ 600,000 km
- The hot, ionized gas which surrounds the Sun.
  - it emits mostly X-rays
- It can be seen in visible light during an eclipse.

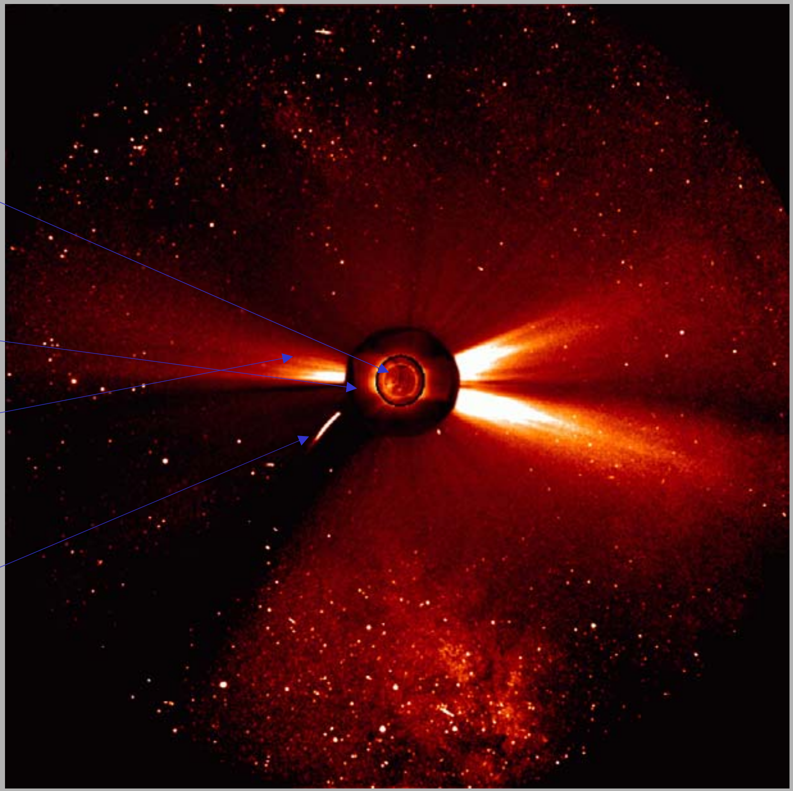


X-ray image (YOHKOH telescope)

Visible image

Solar Wind

- The stream of electrons, protons, Helium nuclei and other ions which flow out from the Sun.
- It extends out beyond Pluto.



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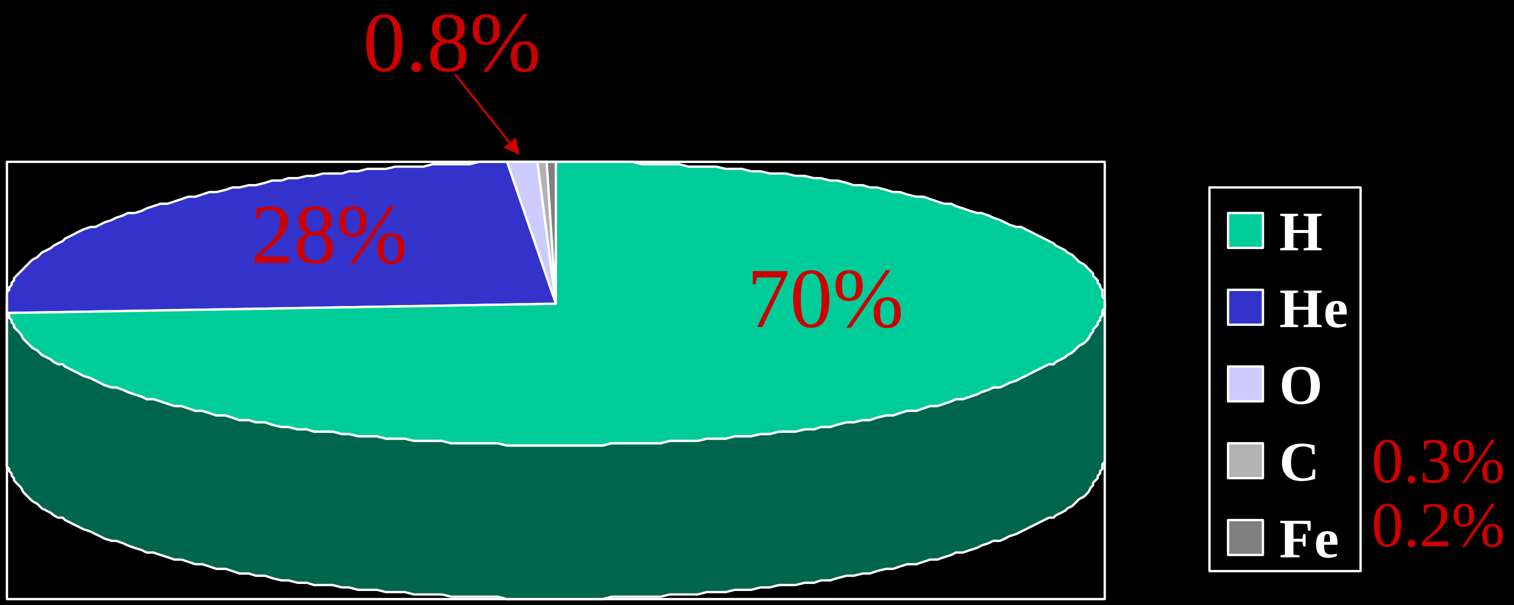
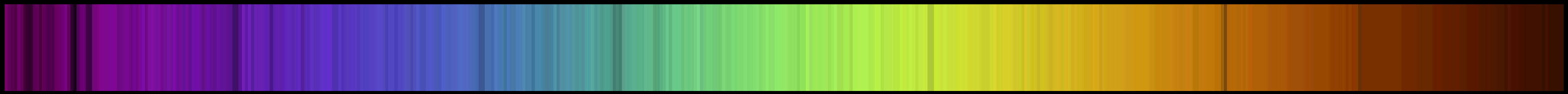
Composition of the Sun



Composition of the Sun

We know this by identifying the **absorption lines** in the Sun’s spectrum.

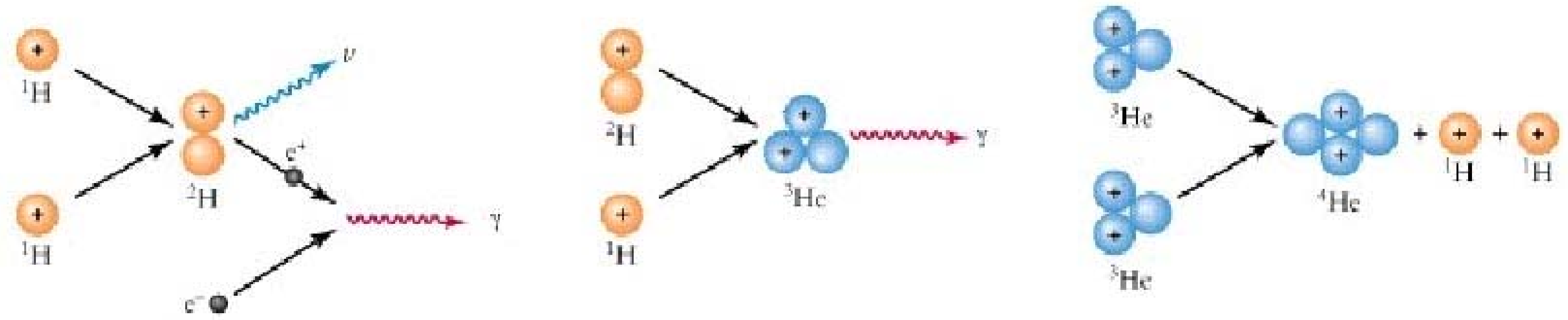


These lines are formed in the photosphere.

The Sun's energy is generated by thermonuclear reactions in its core.

- The Sun's luminosity (energy output) is 3.9 x 10^{26} watts (or joules per second) and written as $L_{\odot}$
- The Sun is powered by thermonuclear fusion reactions in the core where hydrogen is being converted into helium and releasing energy in a process called the *proton-proton-chain*
- Einstein's equation, $E = mc^2$ describes how energy can be created from mass, *m*

The Sun’s energy is generated by thermonuclear reactions in its core.

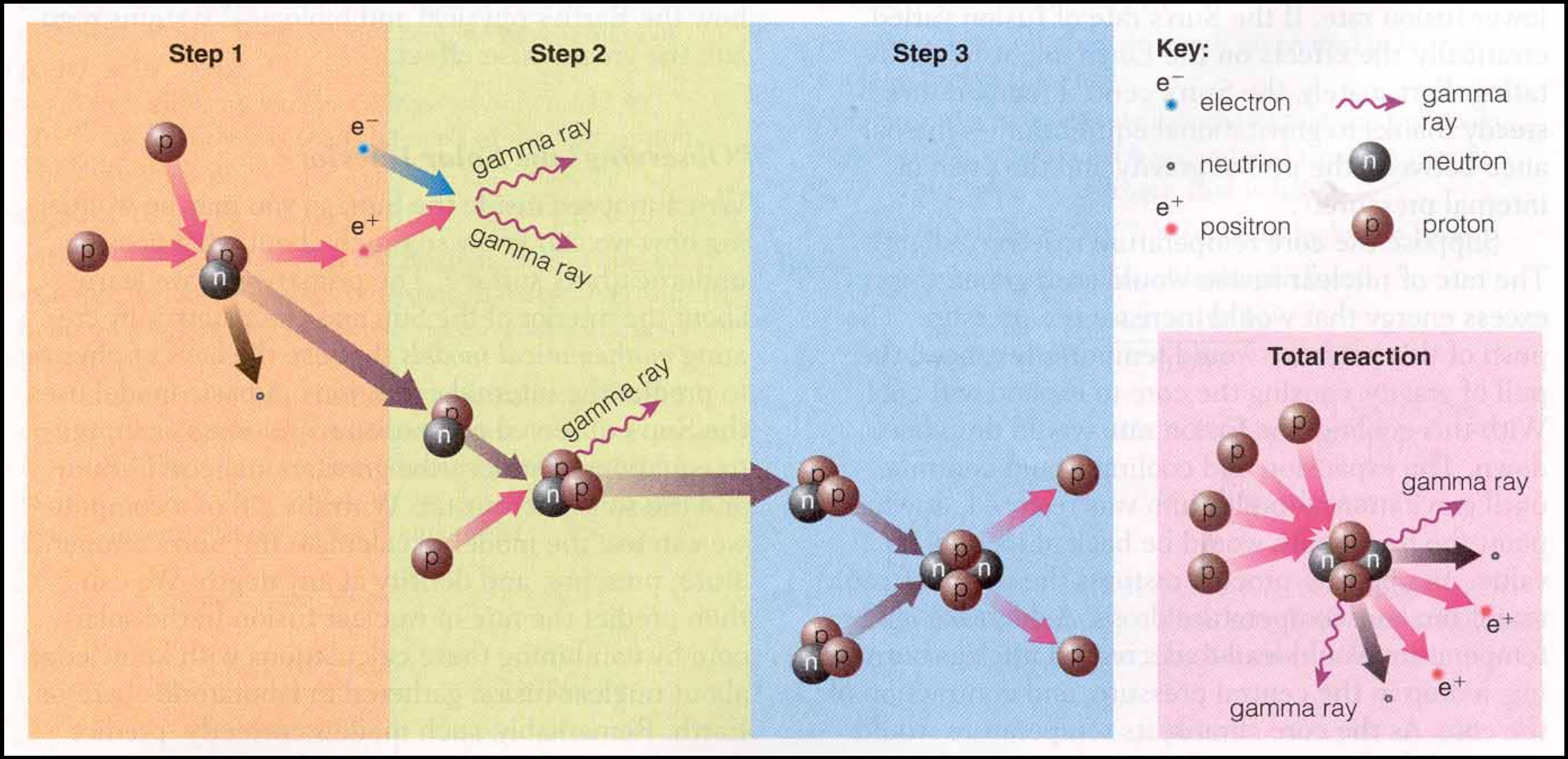


At extremely high temperatures and pressures, 4 Hydrogen atoms can combine to make 1 Helium atom and release energy in the process according to $E = mc^2$

$$4H \longrightarrow He + energy$$

HYDROGEN FUSION

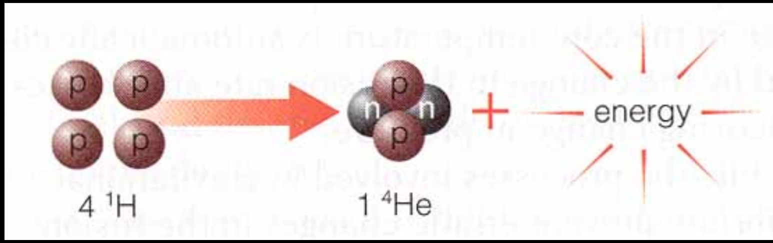
Proton-Proton Chain



IN: 6 H, (2 e^-)

OUT: He, 2 H, 2 ν_e, 4 γ

Effectively 4 H nuclei are converted into 1 He nucleus and energy is released.



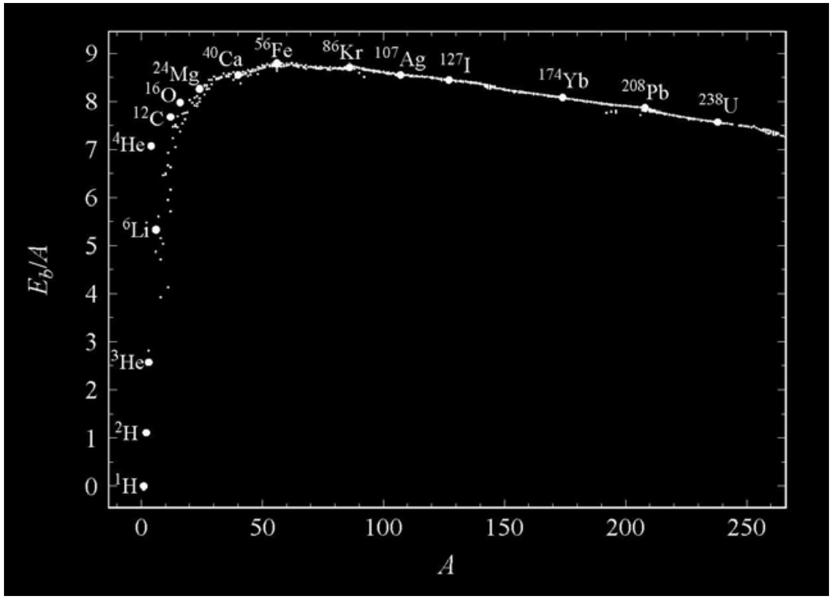
Nucleosynthesis

- At the temperatures conducive to helium burning, other reactions can take place by the capturing of α-particles (He atoms).

$$^{12}_{6}C + ^{4}_{2}He \rightarrow ^{16}_{8}O + \gamma$$

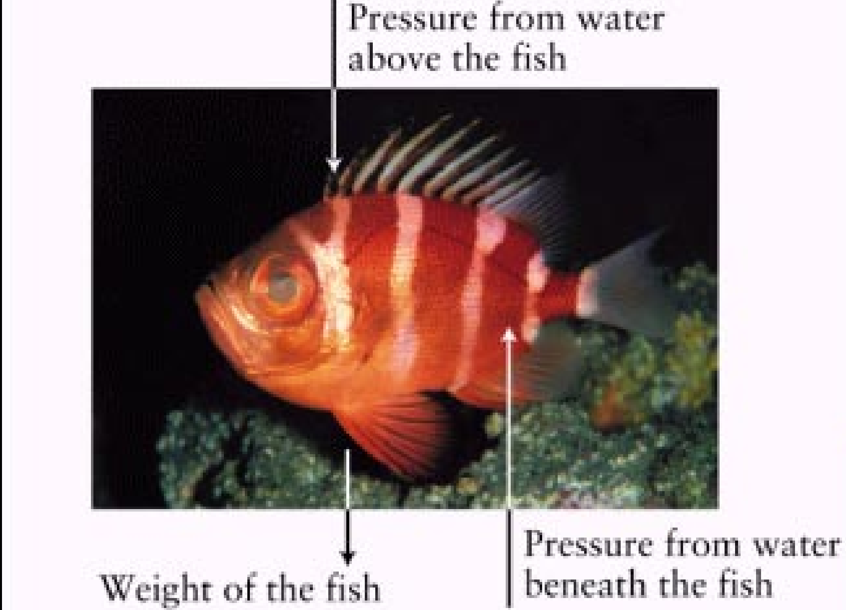
$$^{16}_{8}O + ^{4}_{2}He \rightarrow ^{20}_{10}Ne + \gamma$$

- In more massive stars, the central temperature may be significantly higher, allowing further reactions to occur.
  - Iron is the most stable nucleus. Thus, iron will be the ultimate product of nucleosynthesis, if temperatures are high enough to overcome the Coulomb barrier



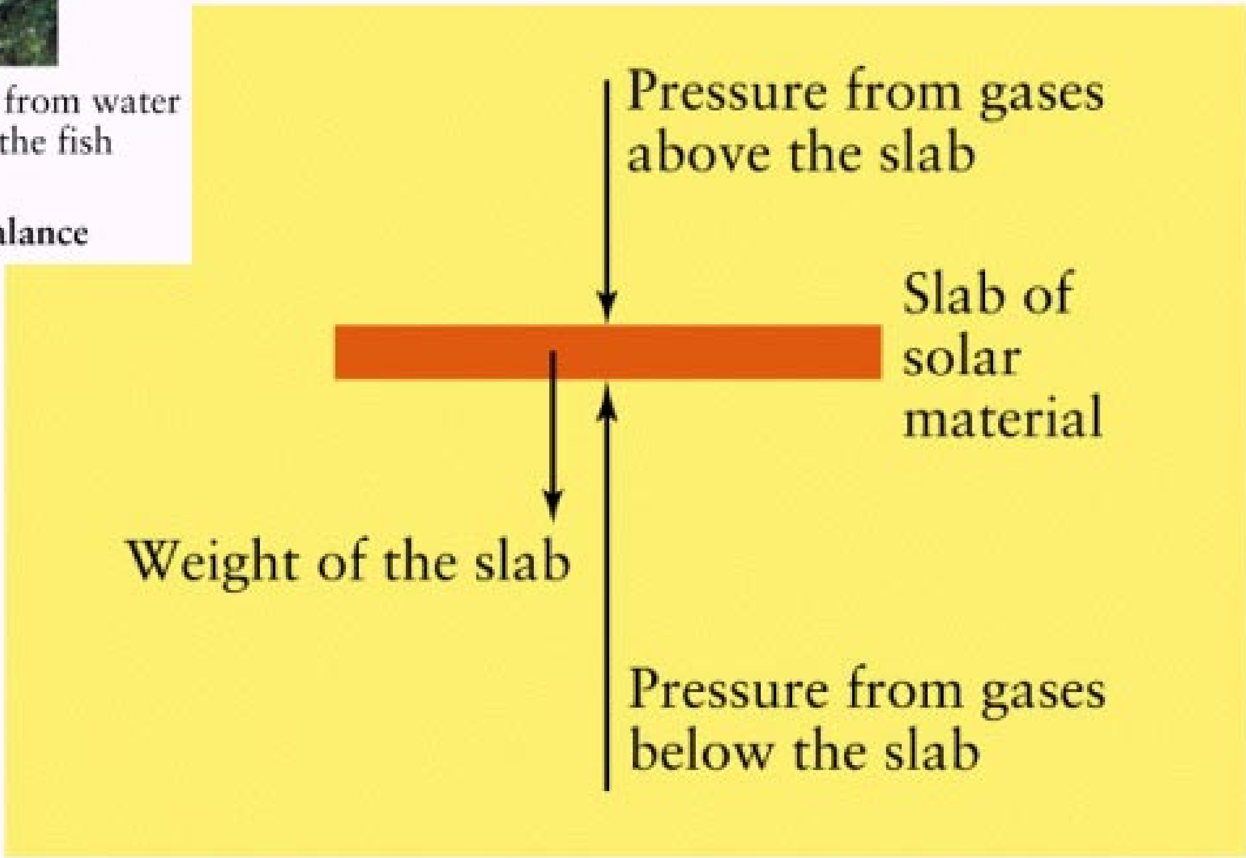
- The binding energy per nucleon describes the stability of a nucleus. It is easier to break up a nucleus with a low binding energy.

Hydrostatic Equilibrium



(b) **In hydrostatic equilibrium, forces balance**

The inward pull of gravity is balanced by the outward push of energy from the core.

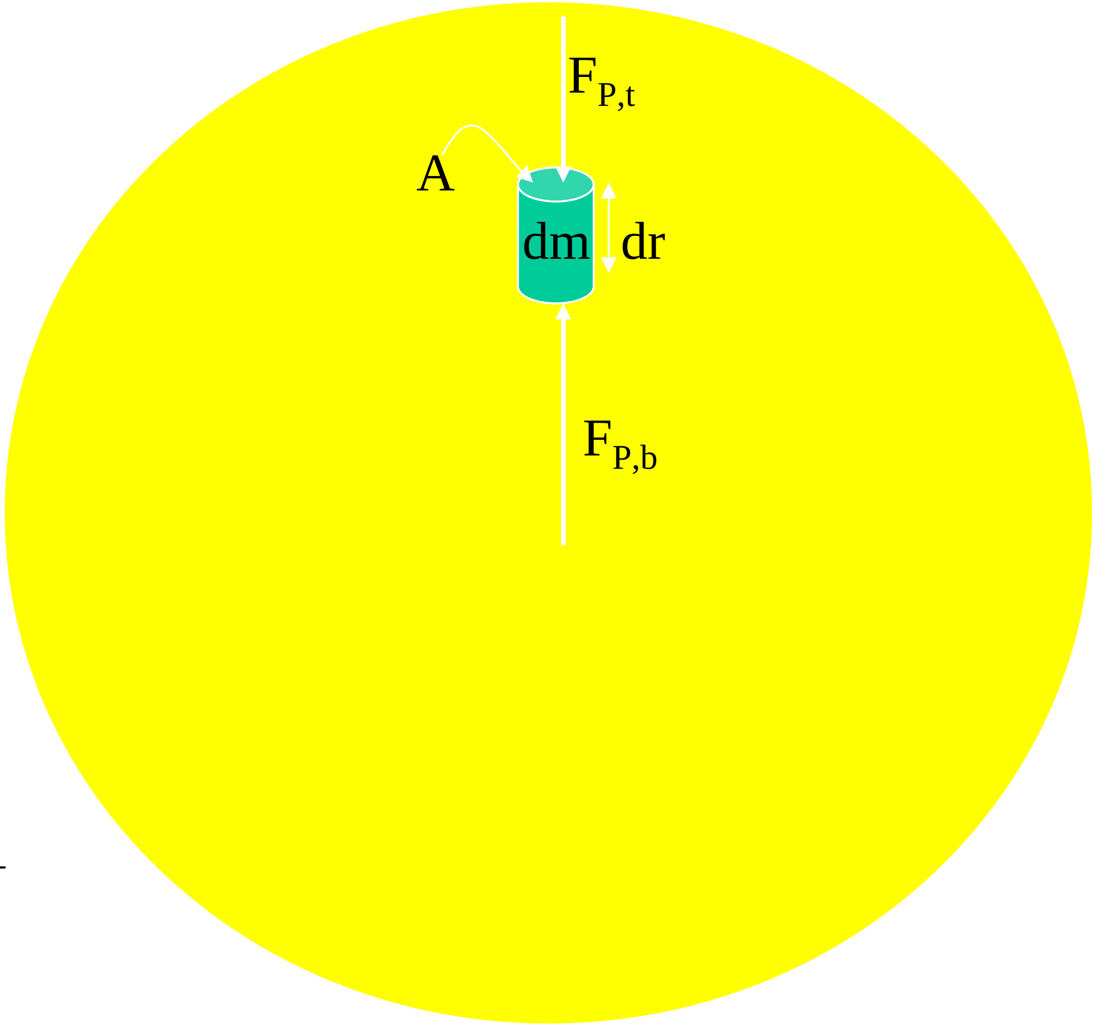


(a) **In hydrostatic equilibrium, forces balance**

Hydrostatic equilibrium

- Consider a small cylinder at distance r from the centre of a spherical star.

- Pressure acts on both the top and bottom of the cylinder.
  - By symmetry the pressure on the sides cancels out



- Apply Newton's law:

$$\vec{F}_{total} = \vec{F}_g + \vec{F}_{P,t} + \vec{F}_{P,b} = dm \frac{d^2 r}{dt^2}$$

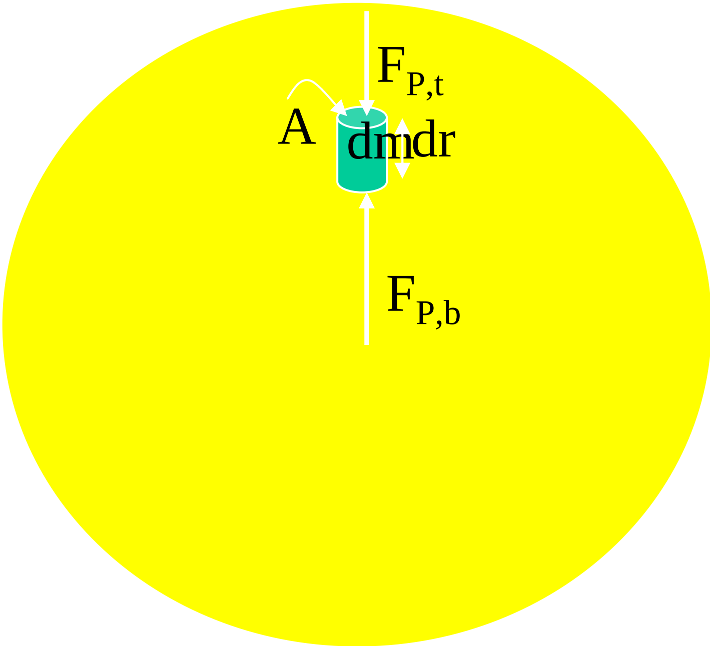
- writing $\vec{F}_{P,t} = -\left(\vec{F}_{P,b} + dF_P\right)$
- we get $\vec{F}_g - d\vec{F}_P = dm \frac{d^2 r}{dt^2}$

Hydrostatic equilibrium

- The force of gravity on the cylinder is just $\vec{F}_g = -\frac{GM_r dm}{r^2}$

- where M_r is the mass enclosed within radius r

- And the force due to pressure can be written in terms of the differential pressure and the area A: $dF_P = AdP$



- Finally $dm = \rho A dr$ so

$$\vec{F}_g - d\vec{F}_P = dm\frac{d^2 r}{dt^2}$$

- gives:

$$-\frac{GM_r A\rho dr}{r^2} - AdP = A\rho dr\frac{d^2 r}{dt^2}$$

$$-\frac{GM_r \rho}{r^2} - \frac{dP}{dr} = \rho\frac{d^2 r}{dt^2}$$

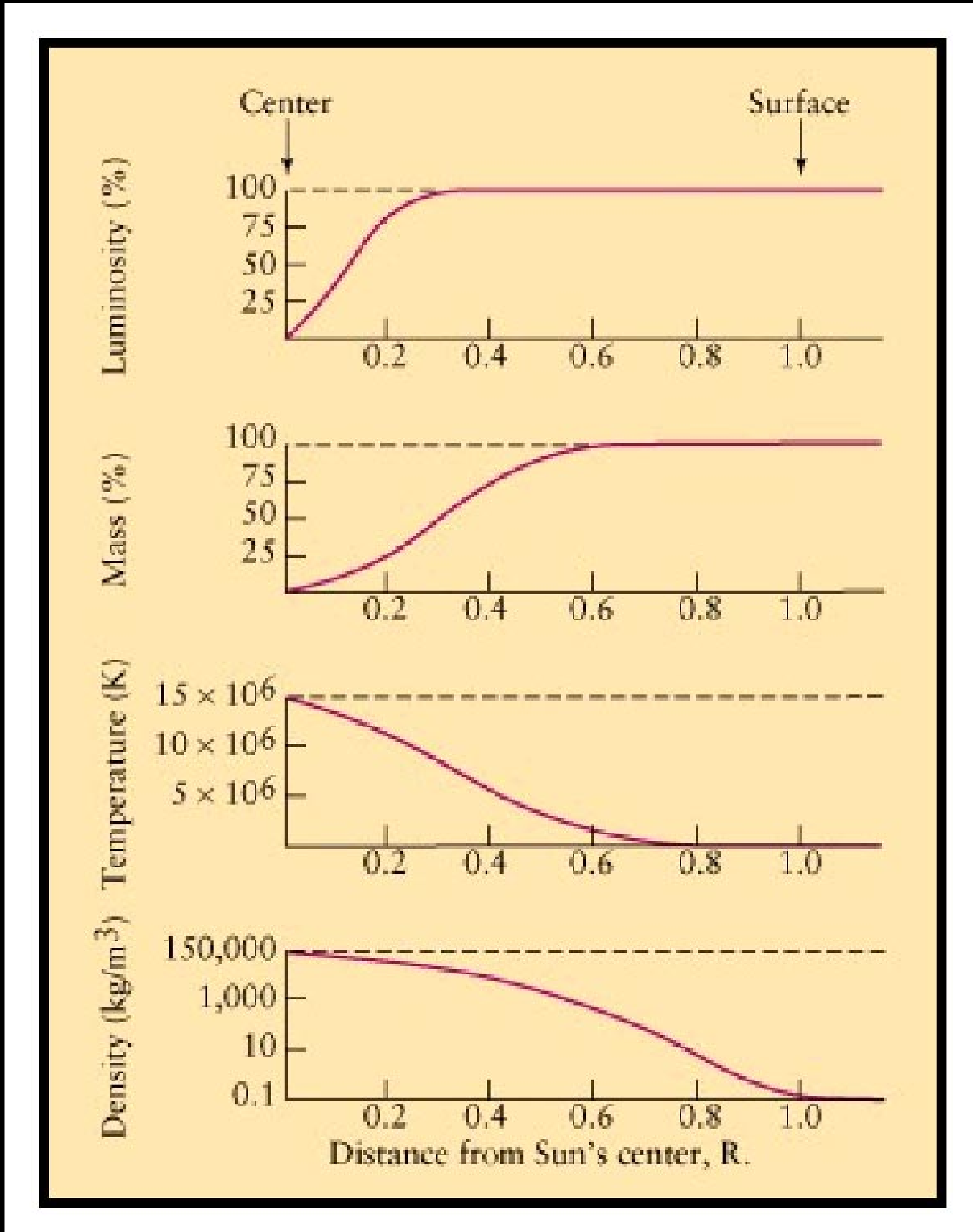
Hydrostatic equilibrium

$$-\frac{GM_r\rho}{r^2}-\frac{dP}{dr}=\rho\frac{d^2r}{dt^2}$$

- If we now assume the gas is static, the acceleration must be zero. This gives us the equation of *hydrostatic equilibrium* (HSE).

$$\boxed{\frac{dP}{dr}=-\frac{GM_r\rho}{r^2}}$$

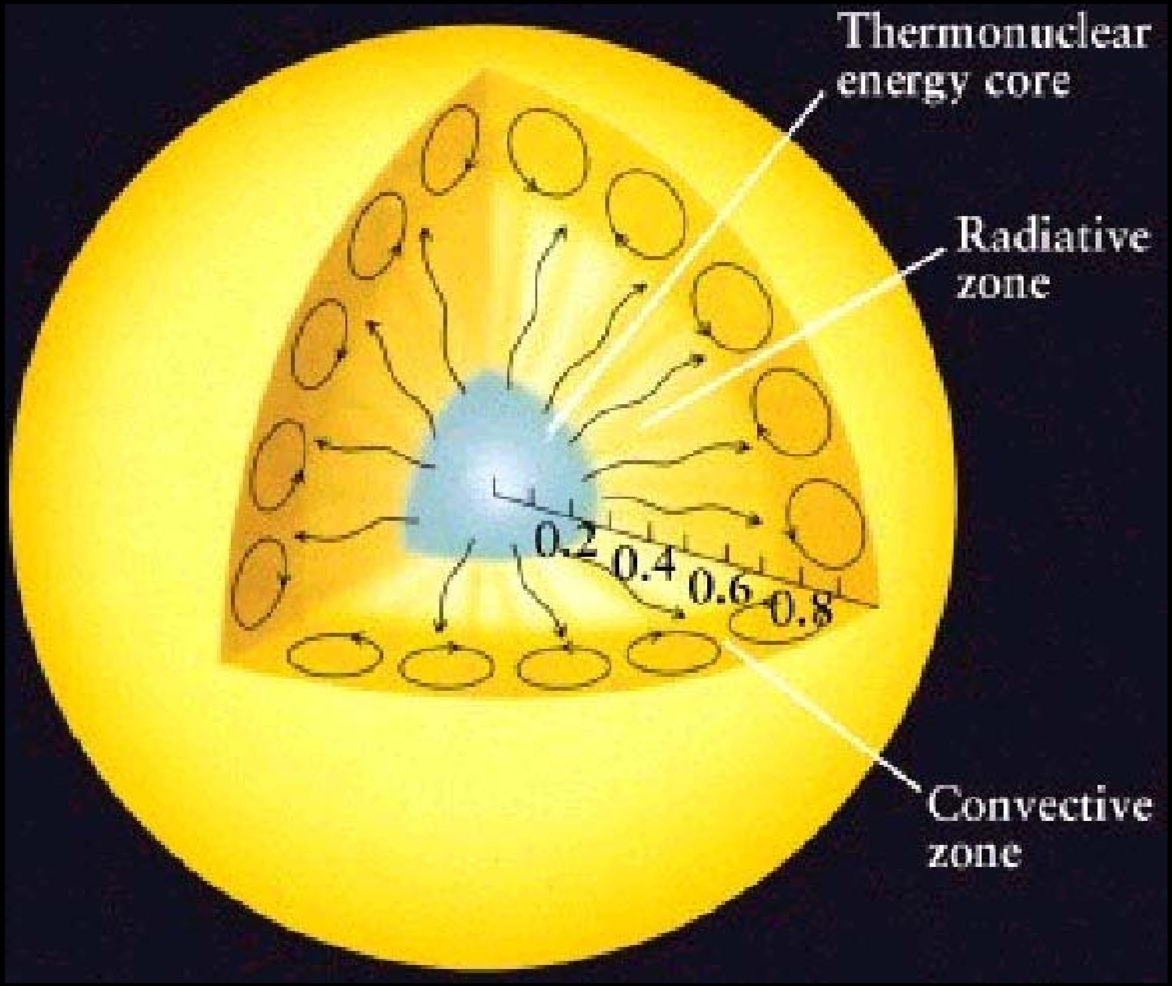
- It is the pressure *gradient* that supports the star against gravity
- The derivative is always negative. Pressure must get stronger toward the centre



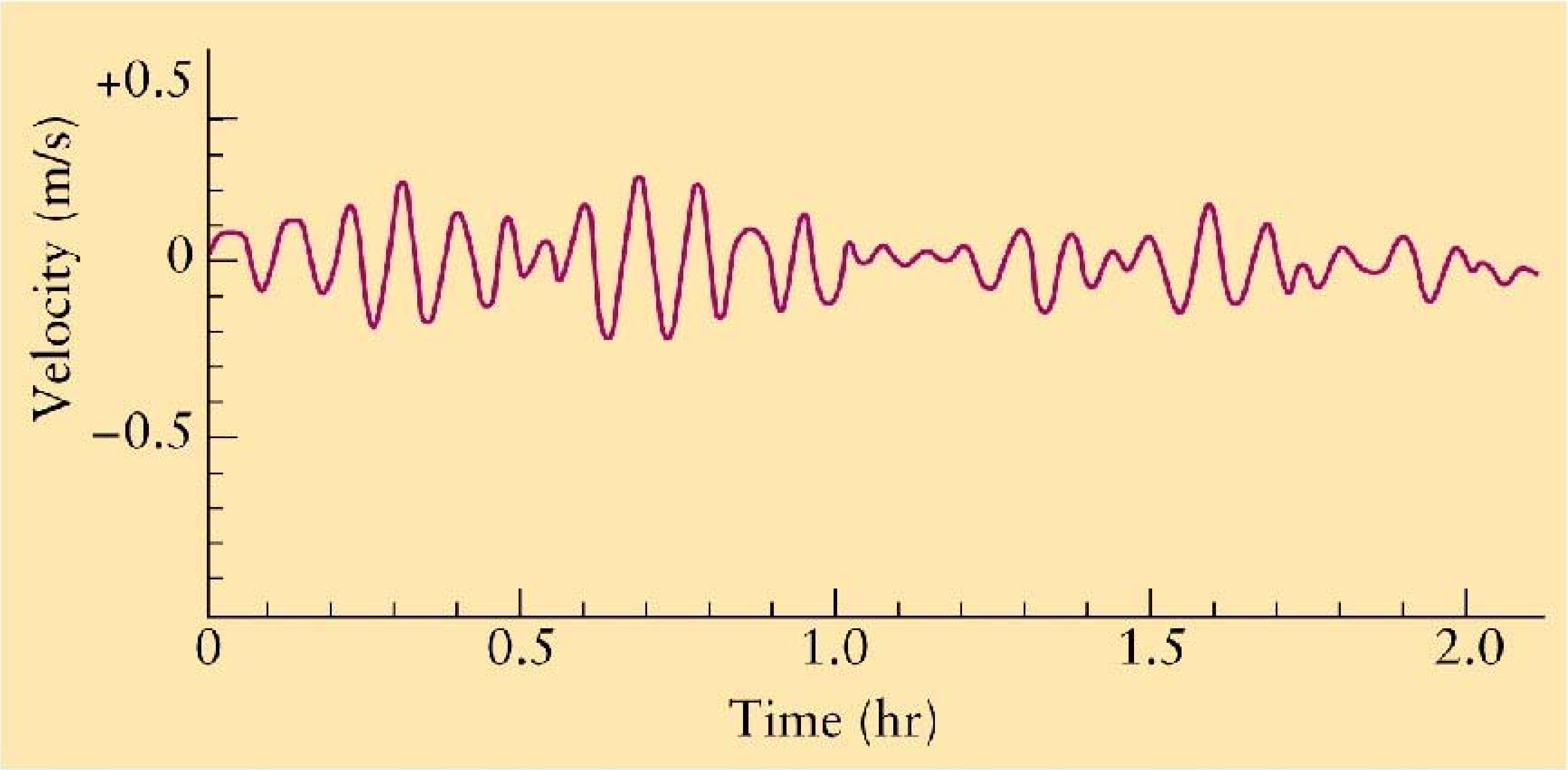
A theoretical model of the Sun shows how energy gets from its center to its surface.

Thermonuclear fusion can only occur at very high temperatures and pressures.

A theoretical model of the Sun shows how energy gets from its center to its surface through the:
(1) core,
(2) radiative zone,
and the (3) convective zone



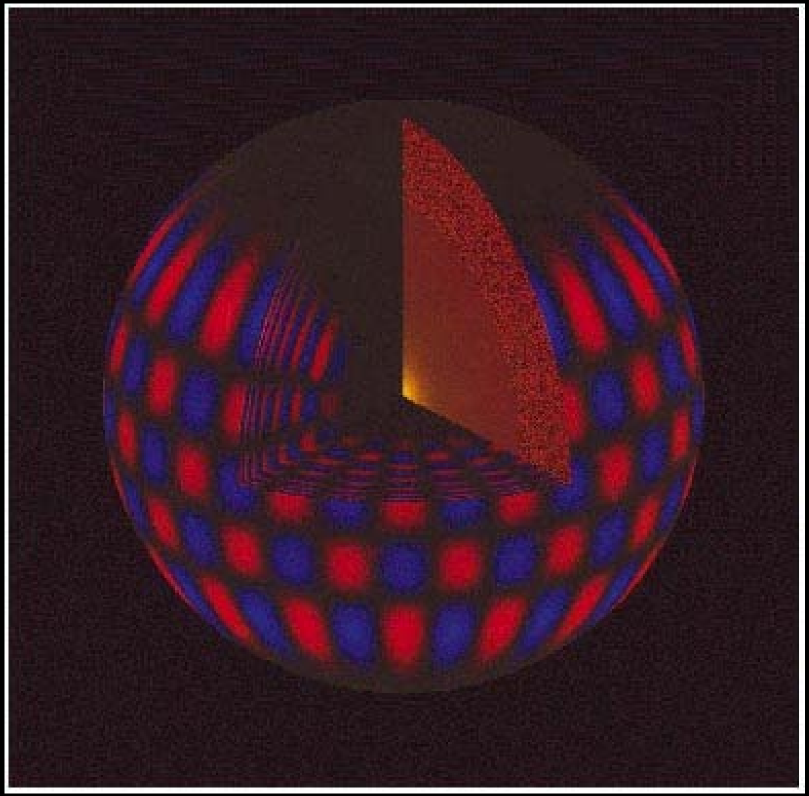
Astronomers probe the solar interior using the Sun's own vibrations.



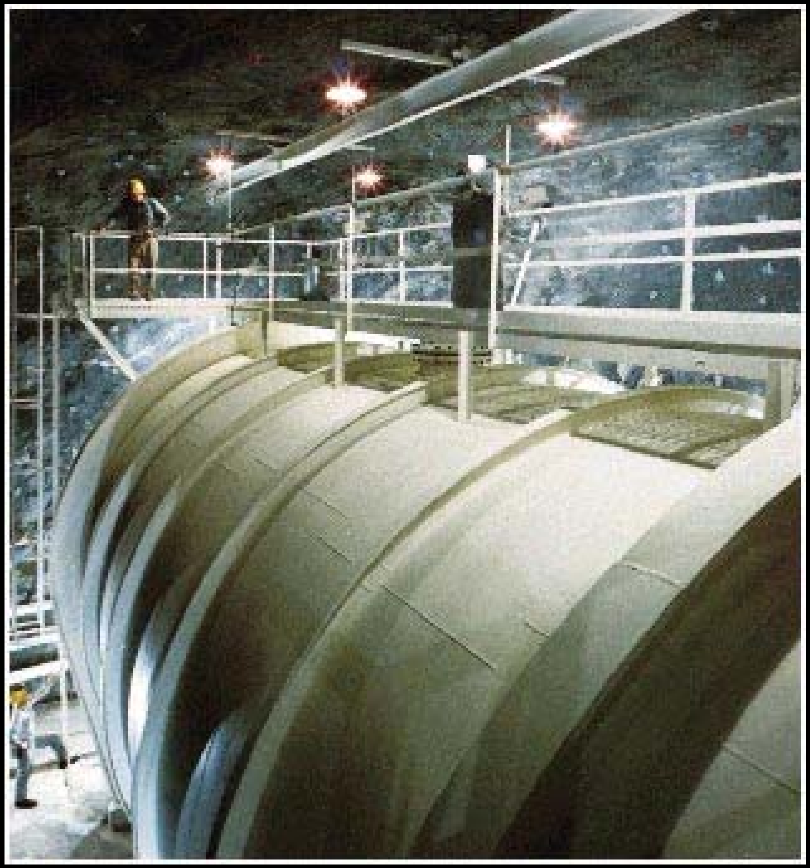
Sections of the Sun's surface quickly oscillate up on down.

Astronomers probe the solar interior using the Sun’s own vibrations.

- Exploring the Sun’s interior by studying its vibrations is called HELIOSEISMOLOGY.
- Because we cannot actually “see” inside the Sun, helioseismology provides theoreticians with a way to check their models of the solar interior.



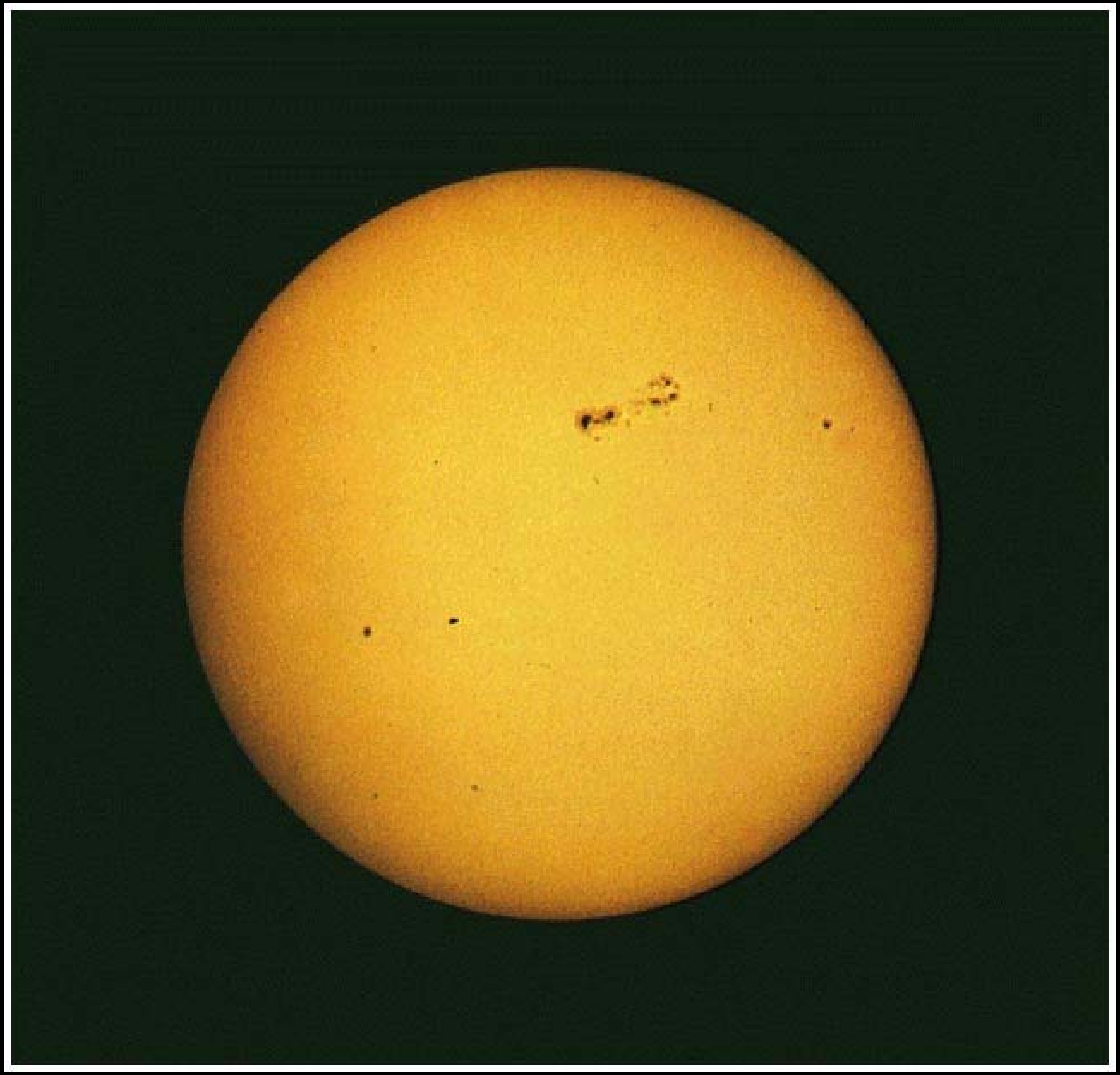
Neutrinos provide information about the Sun's core - and have surprises of their own.



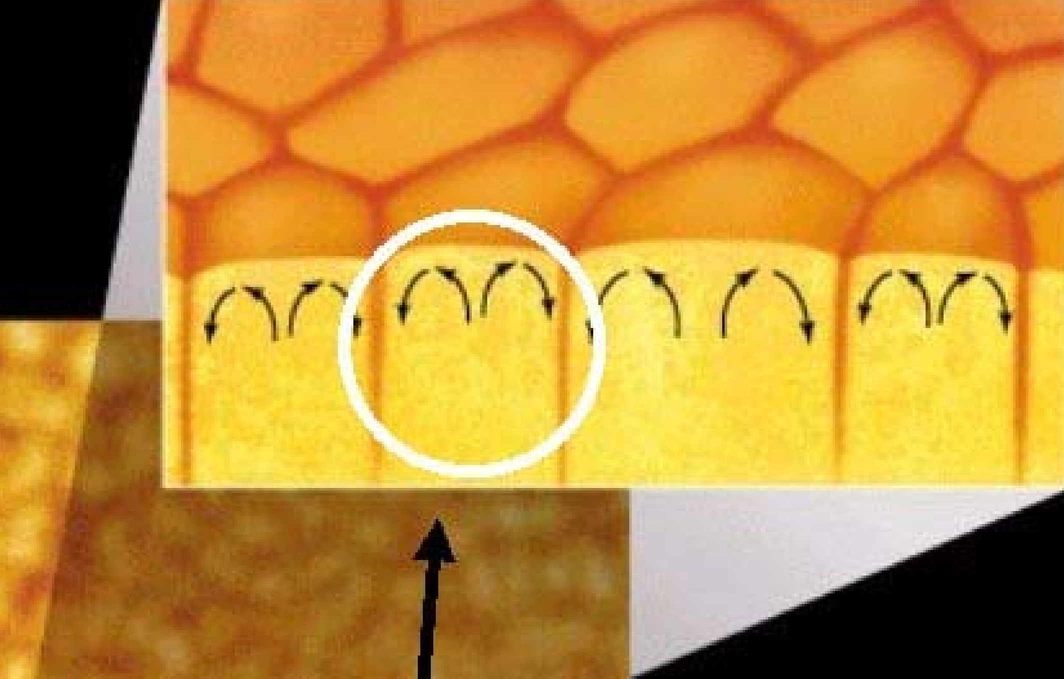
- Current models of the solar interior predict that 10^{38} neutrinos should be released every second if our current theories are correct.
- Solar neutrino detectors on Earth watch for collisions between perchlorethylene cleaning fluid (C_2Cl_4) and neutrinos which produces radioactive argon.
- Only 1/3 of the expected neutrinos from the Sun are being detected.

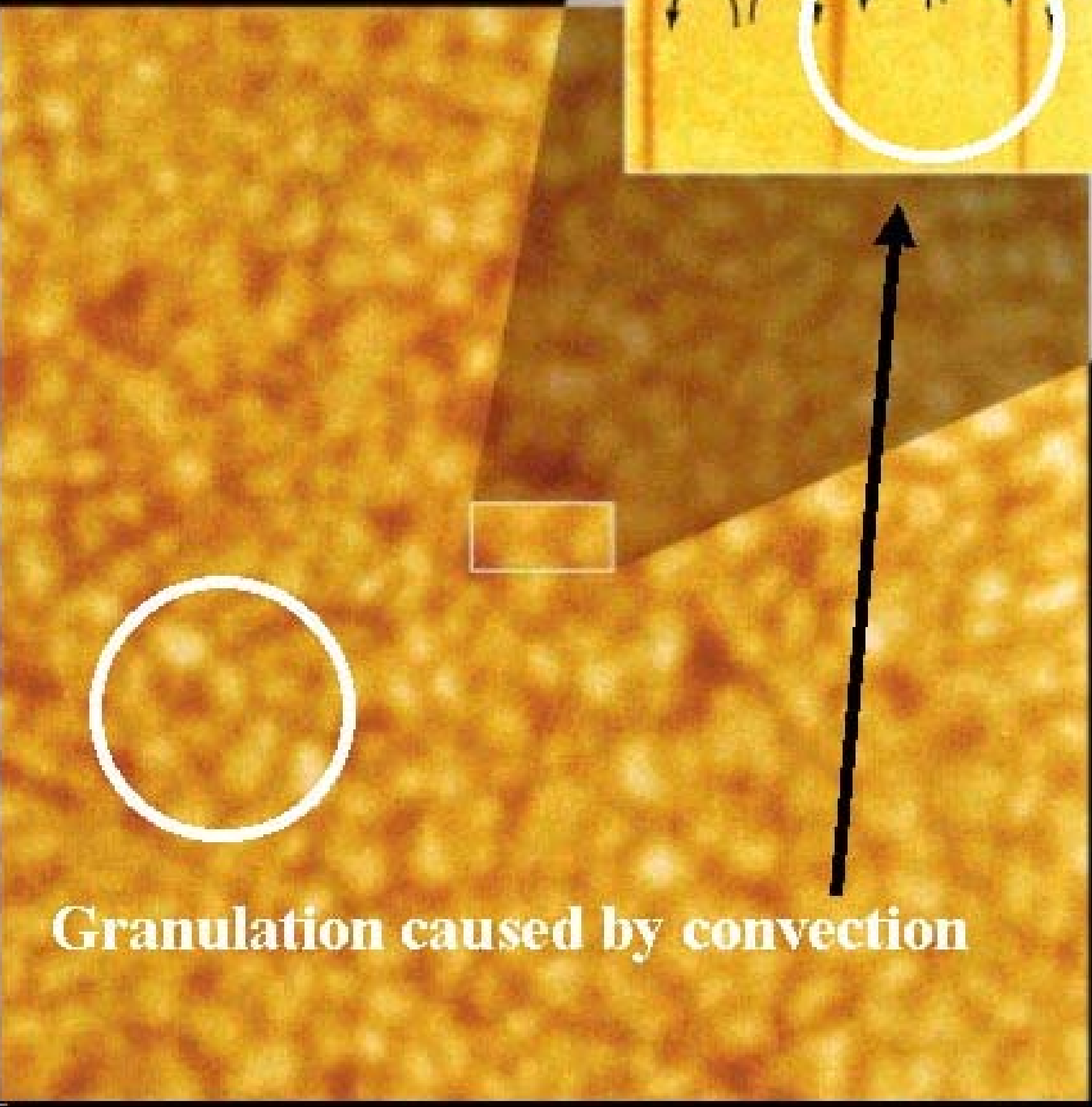
Outer Layers of the Sun's Atmosphere

- ***Photosphere*** - the 5800 K layer we see.
- ***Chromosphere*** - the red layer observed using a hydrogen filter at a million degrees.
- ***Corona*** - the incredibly thin outer atmosphere at millions of degrees.

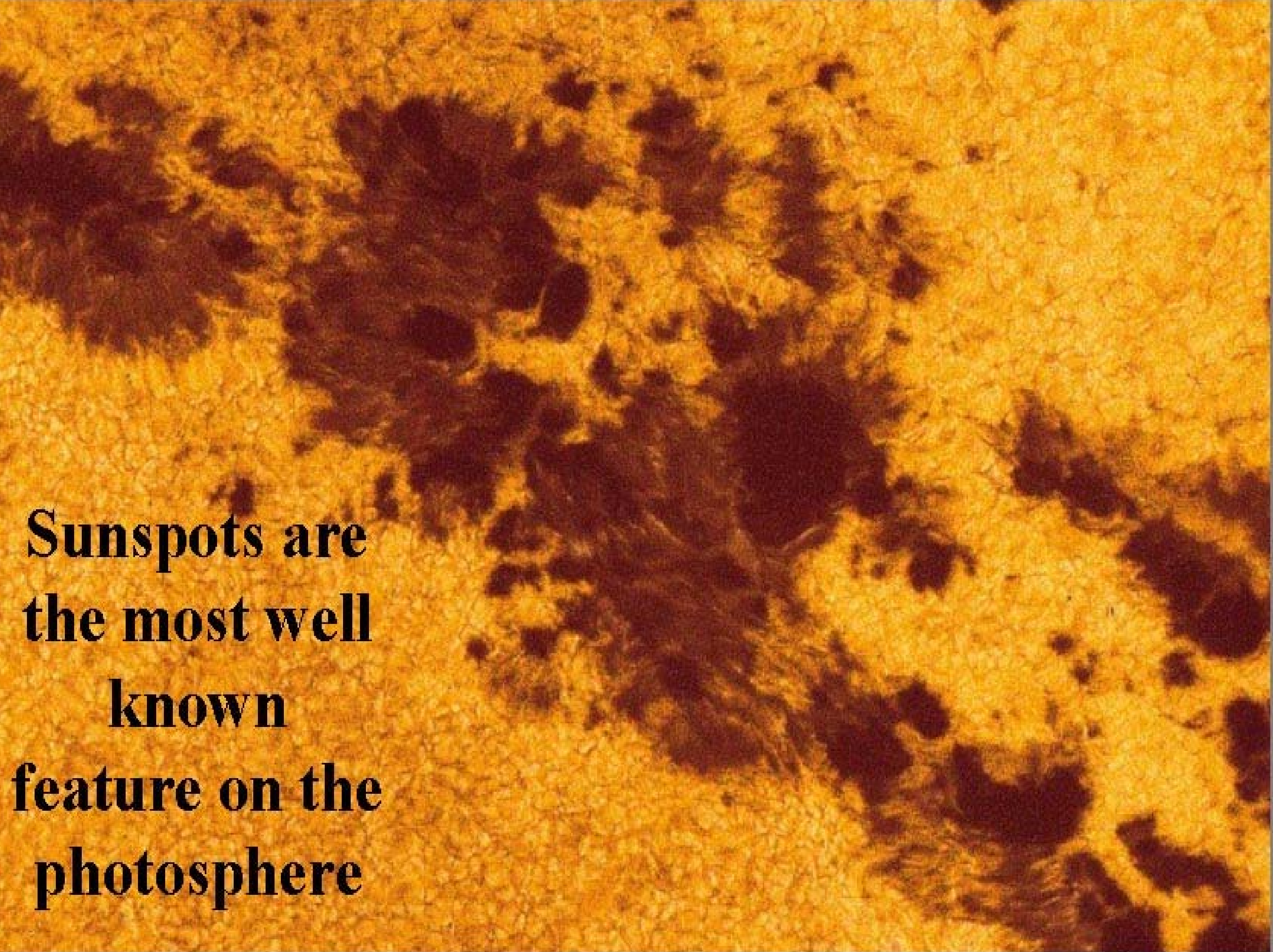


The photosphere is the lowest of three main layers in the Sun's atmosphere.



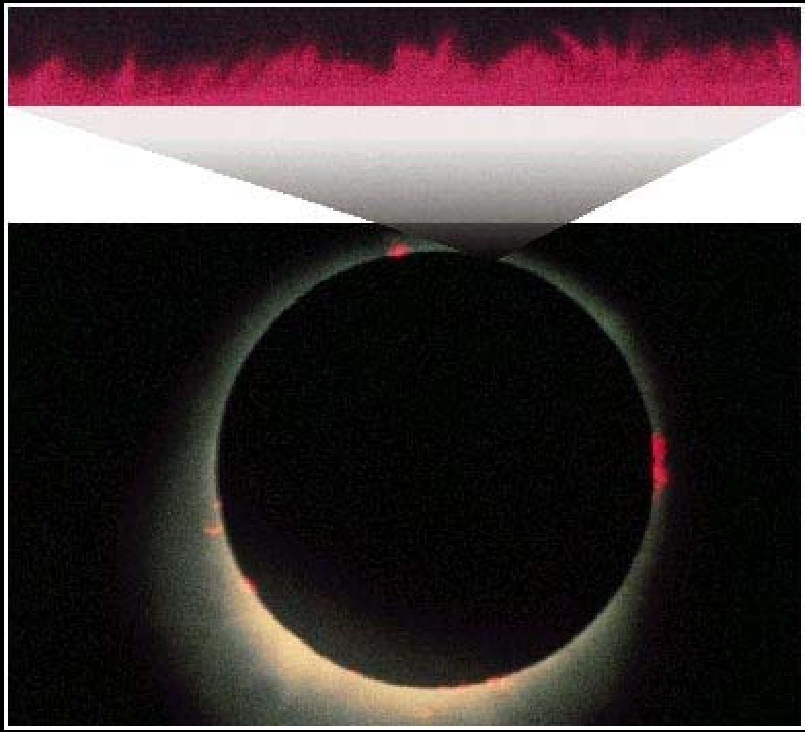


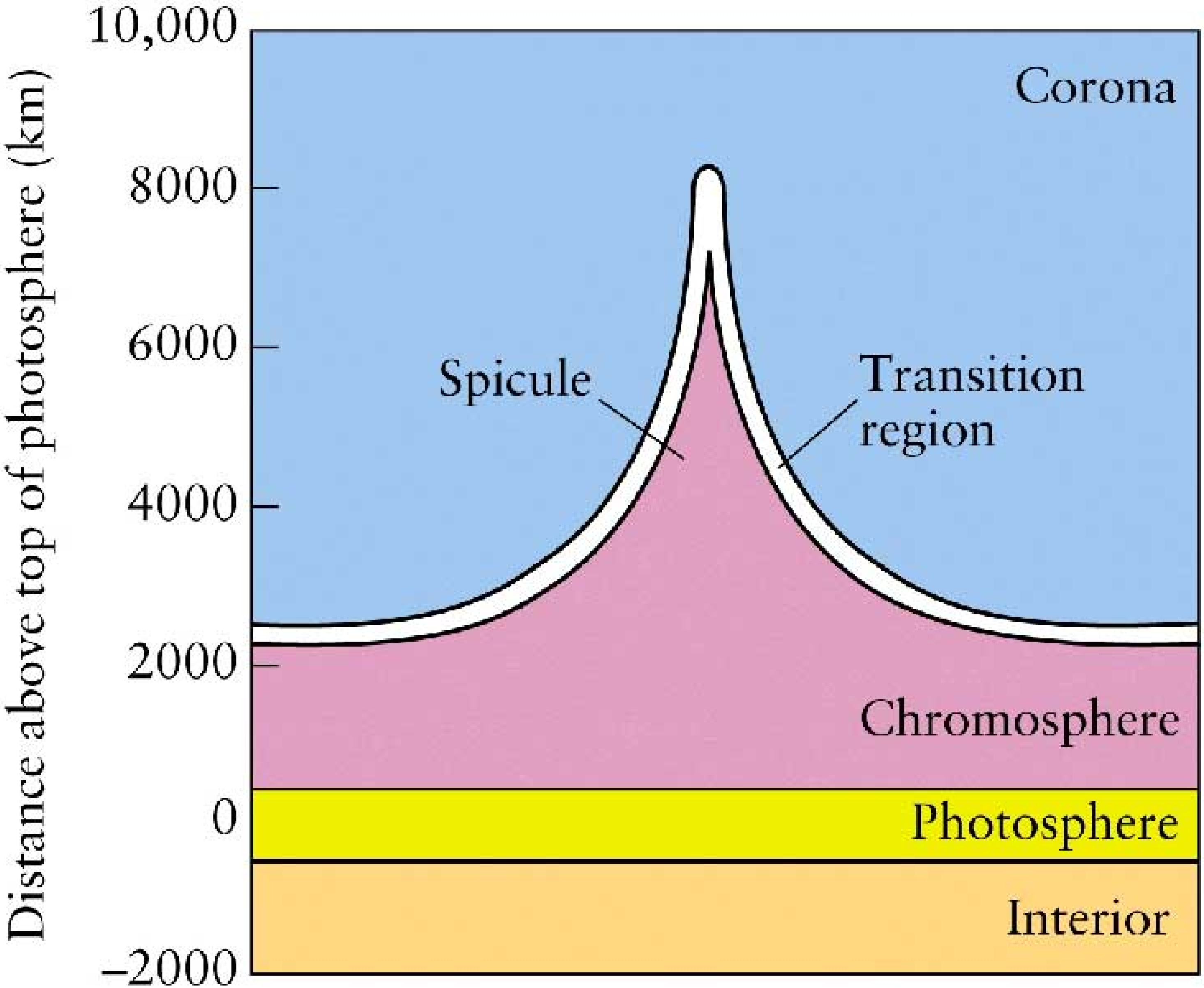
The photosphere is the visible layer of the Sun.


Sunspots are the most well known feature on the photosphere

The chromosphere is characterized by spikes of rising gas.

- The chromosphere is the thin, pinkish layer of SPICULES just above the photosphere.
- Spectrum is dominated by Hα emission lines suggesting it is quite tenuous.
- The temperature is higher in the chromosphere than the photosphere (which is opposite one would expect where it should get cooler with increasing distance).

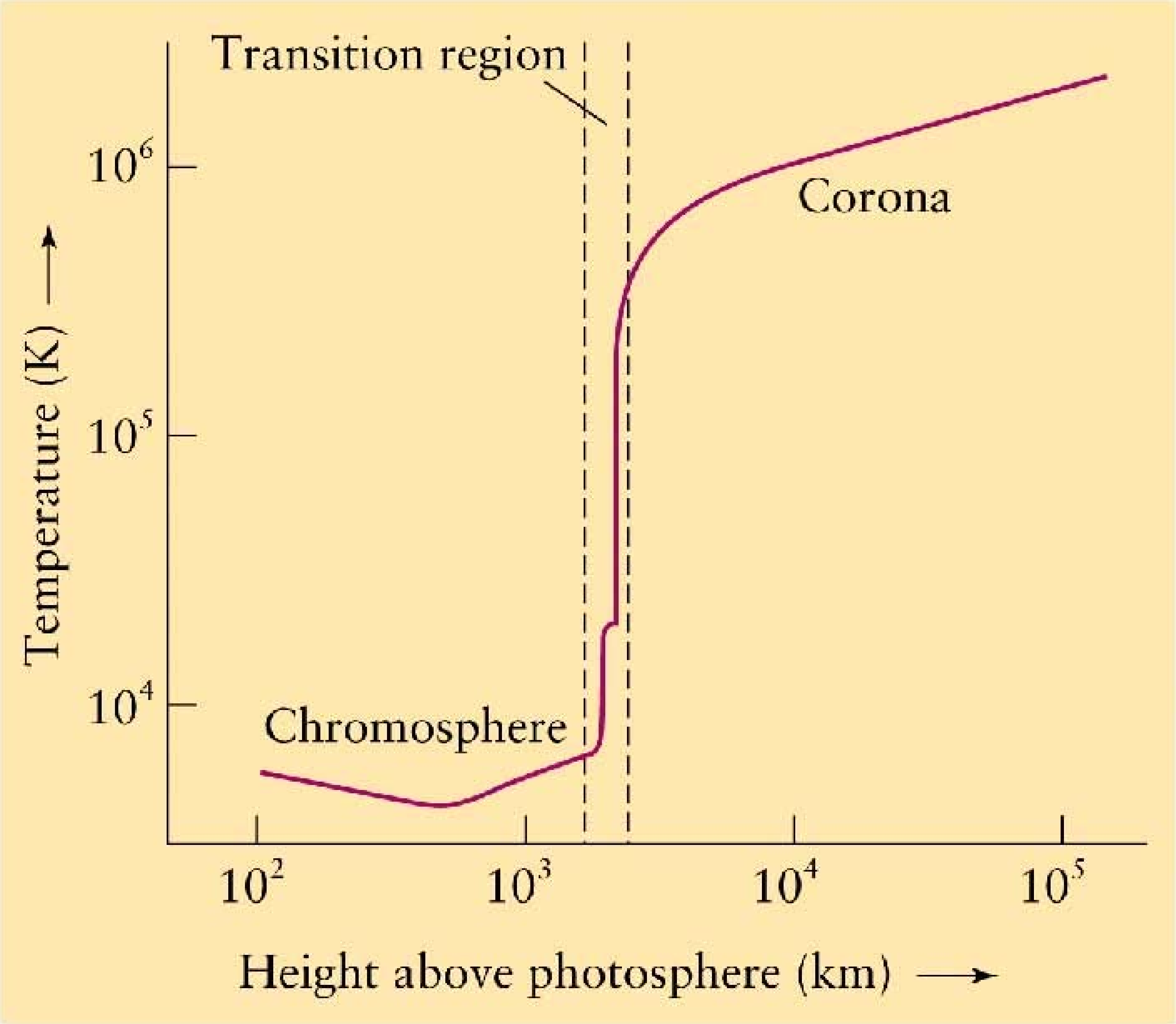




10,000
8000
6000
4000
2000
0
–2000
Distance above top of photosphere (km)
Corona
Spicule
Transition
region
Chromosphere
Photosphere
Interior

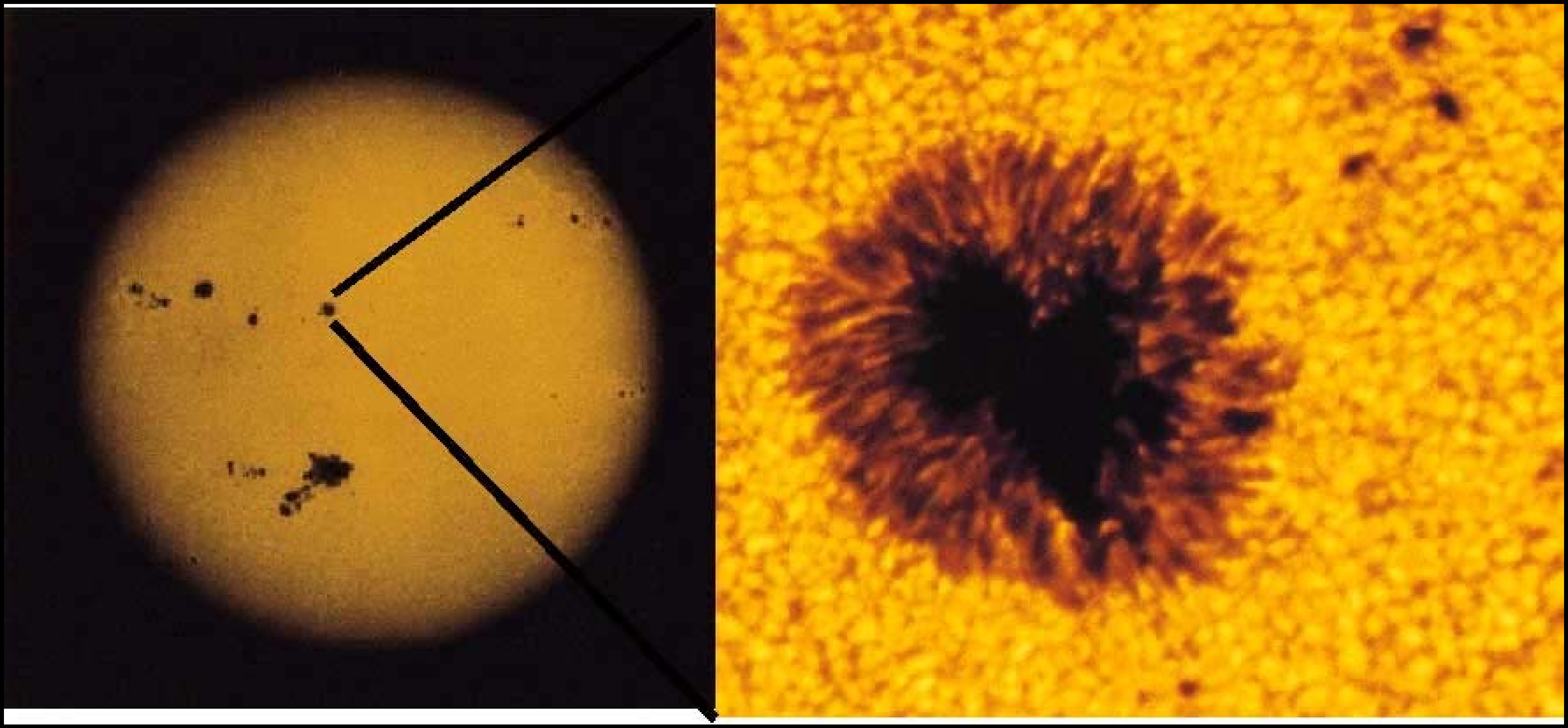
The corona ejects mass into space to form the solar wind.

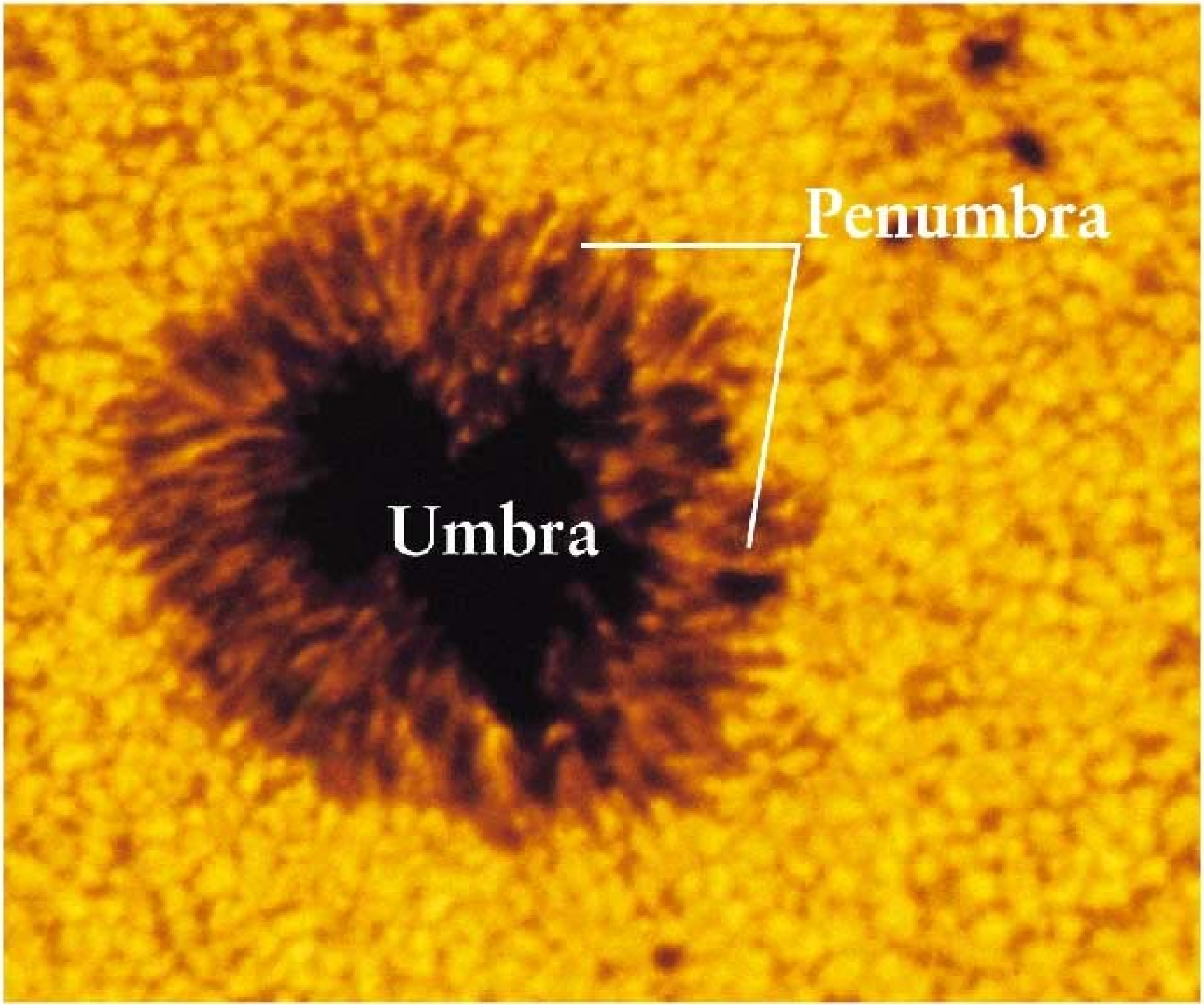
- Most easily seen during an eclipse.
- Thin gas at millions of degrees more than photosphere.
- The outflow of mass from the Sun is called the solar wind.



Transition region
Corona
Chromosphere
10^6
10^5
10^4
Temperature (K)
10^2
10^3
10^4
10^5
Height above photosphere (km)

Sunspots are low-temperature regions in the photosphere.





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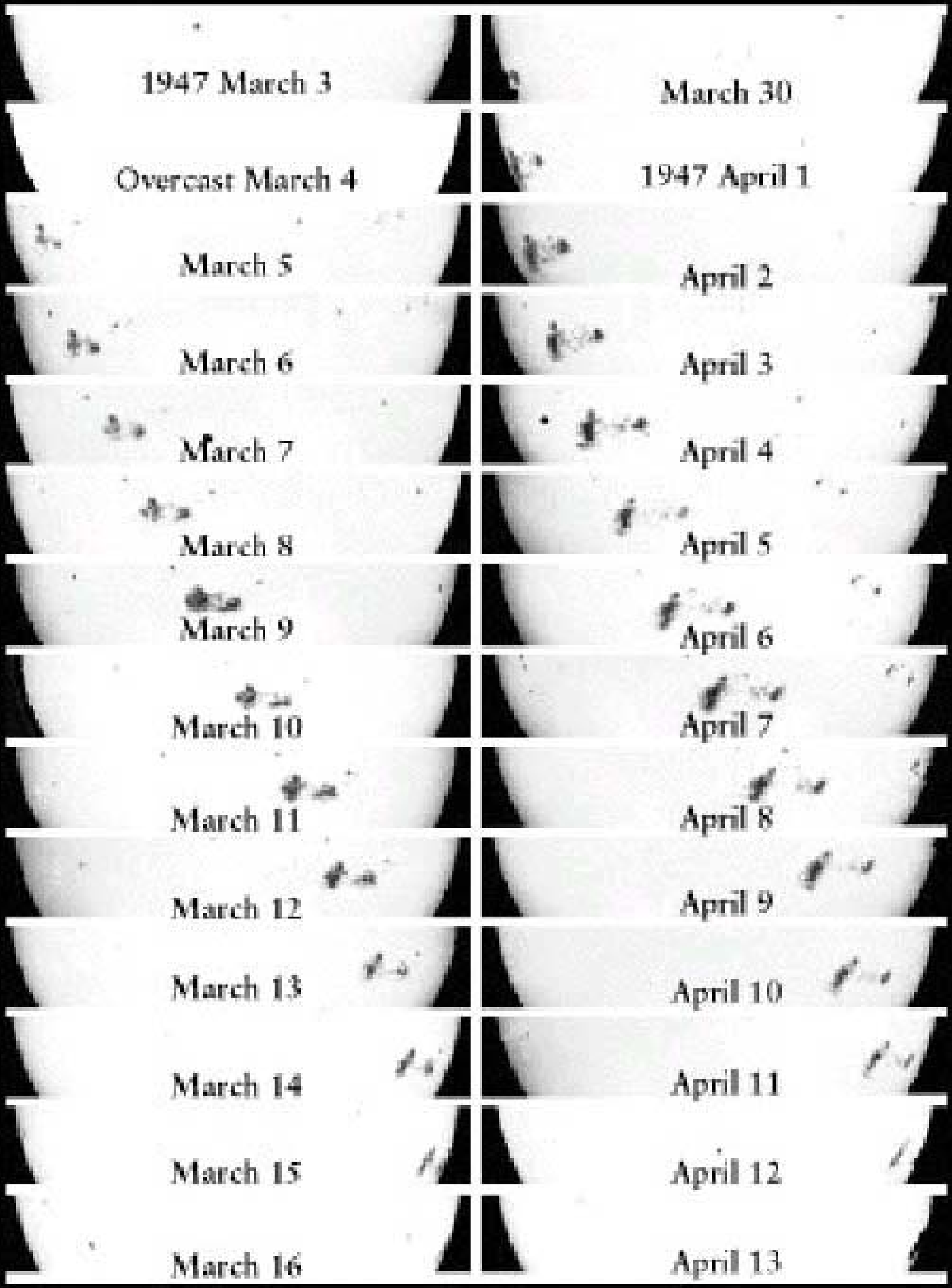
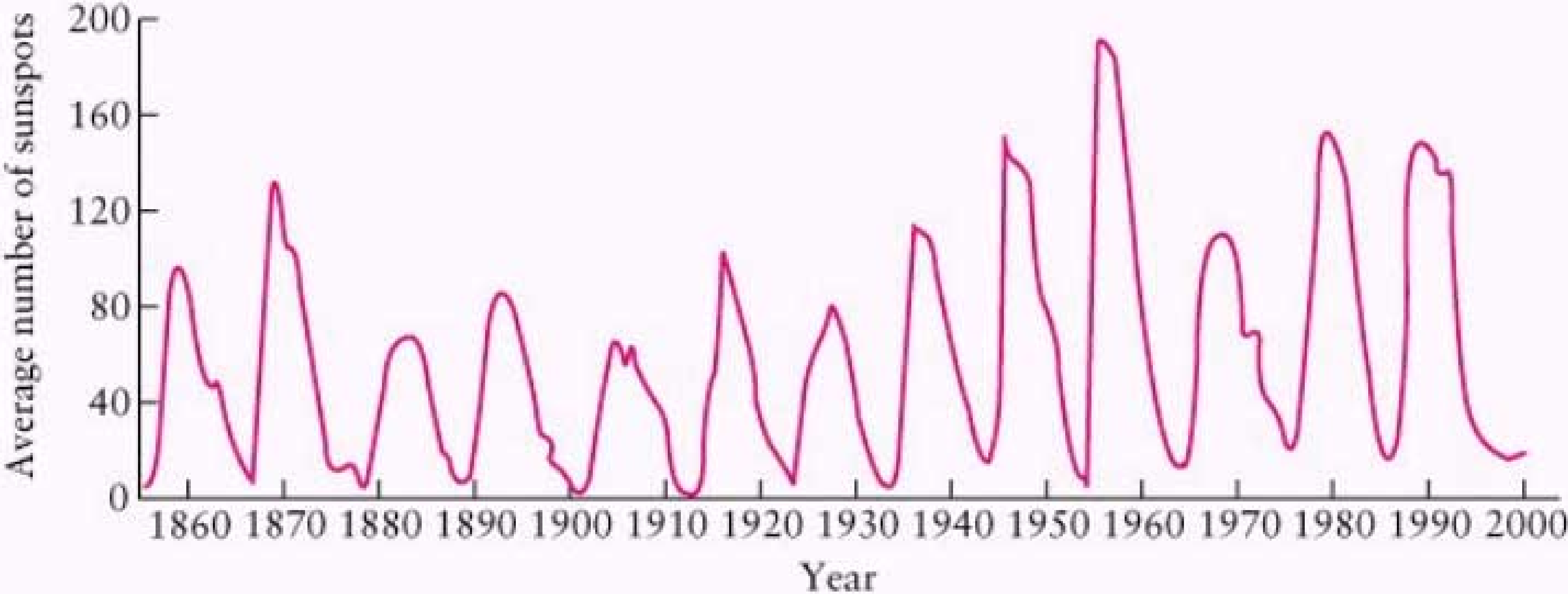
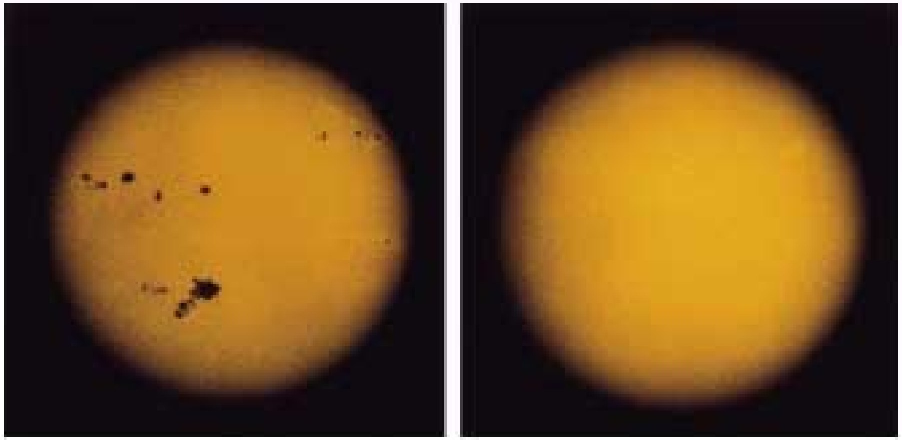


The daily movement of **sunspots** reveals that the Sun’s rotation takes about 4 weeks.

The annual change in numbers of **sunspots** reveals that the Sun experiences an 11-year solar cycle.

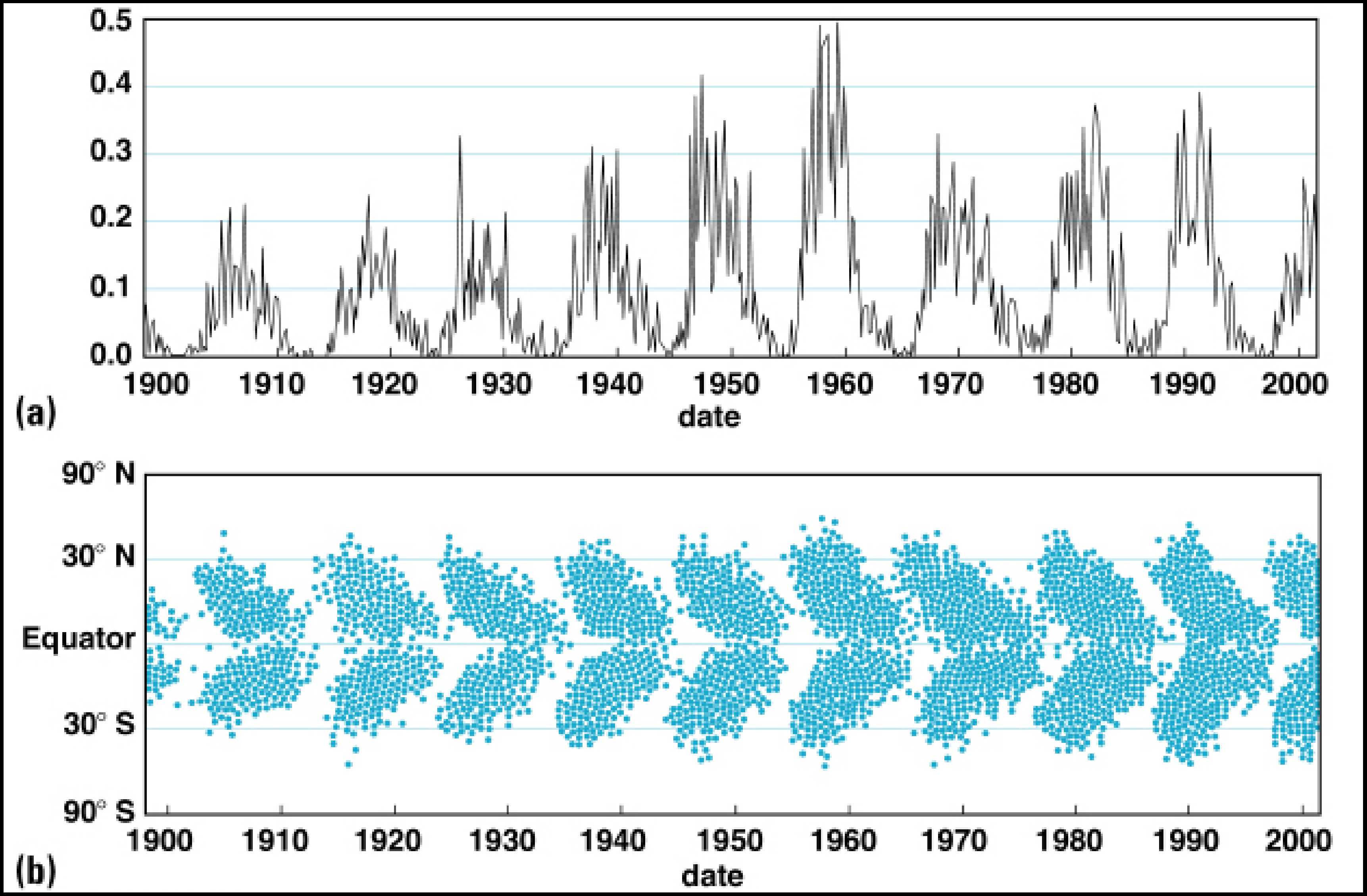


Maximum number

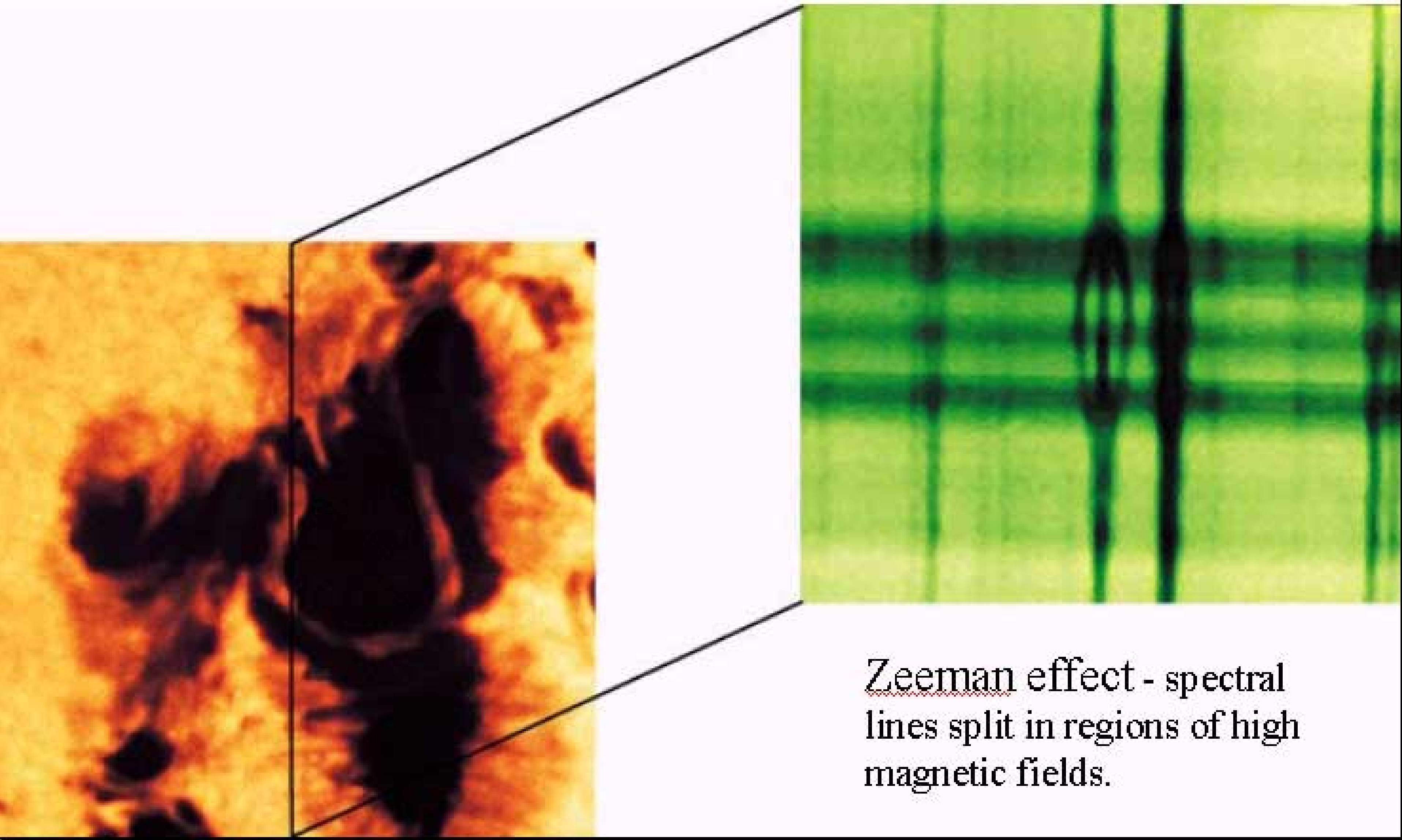


Minimum number

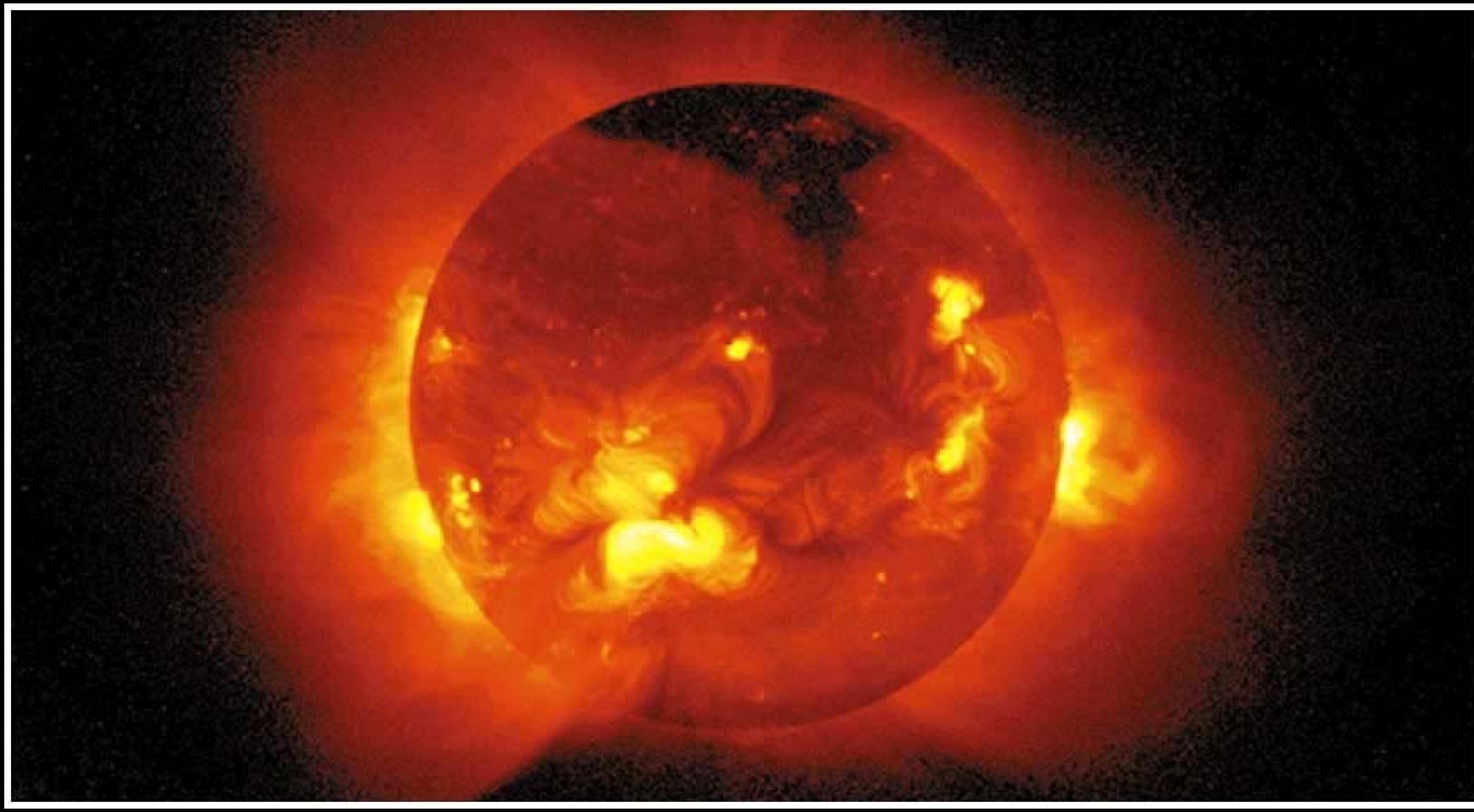
Sunspot Cycle



The Sun's magnetic fields create sunspots

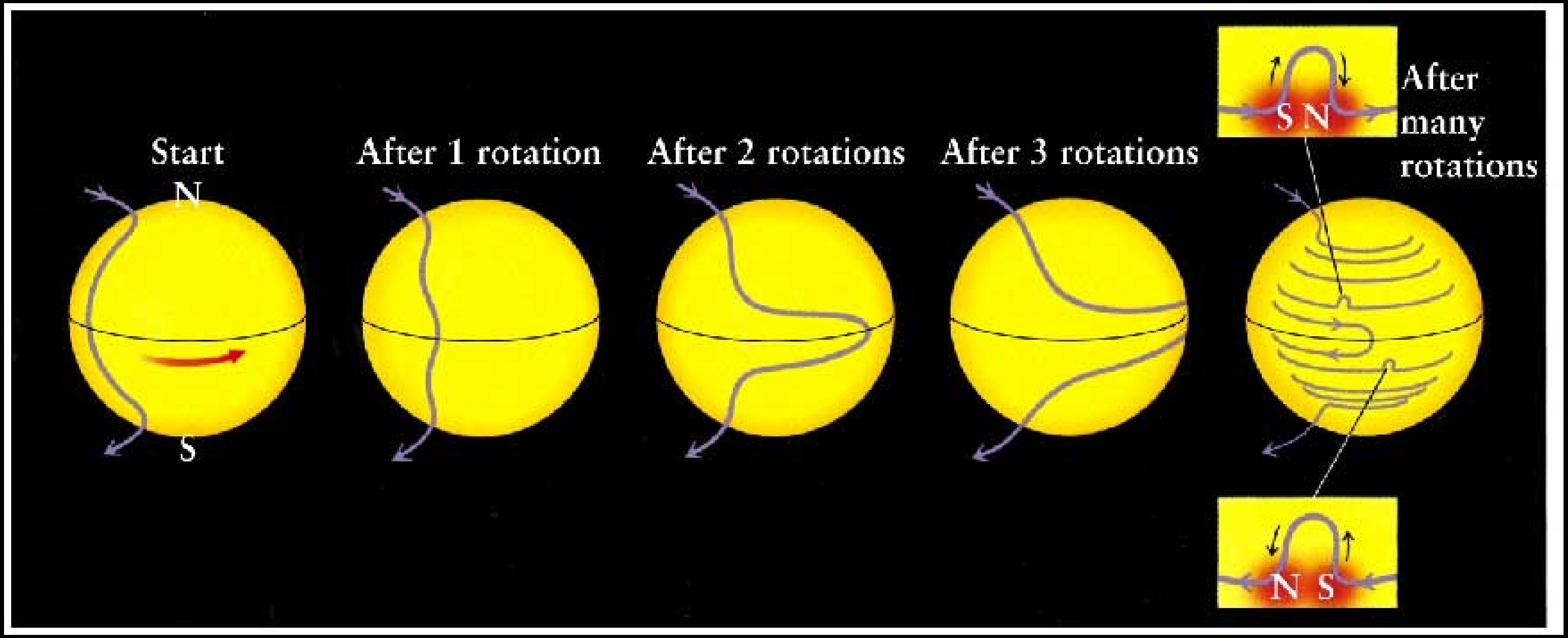


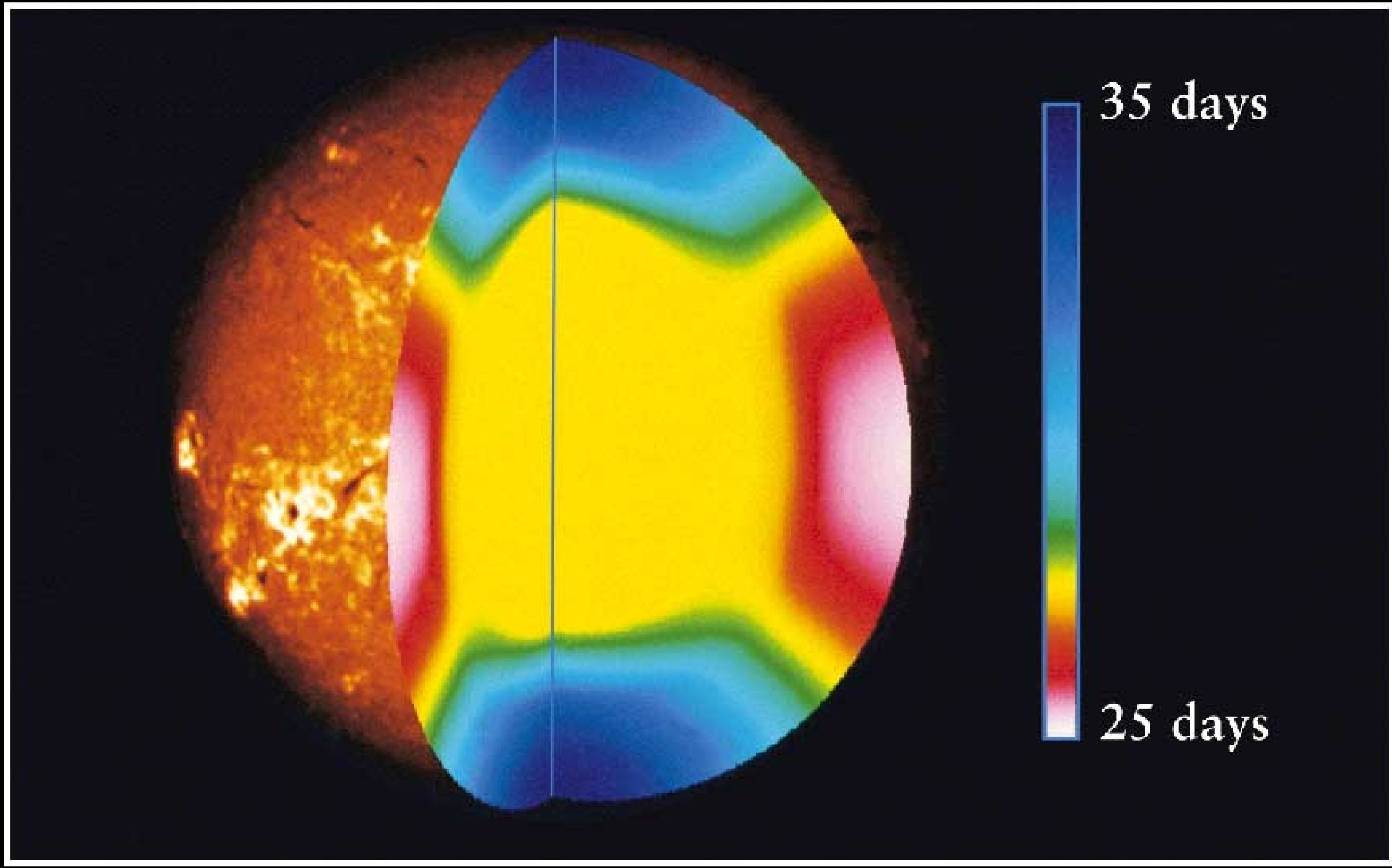
Zeeman effect - spectral lines split in regions of high magnetic fields.



This X-ray image of the Sun shows bright regions where gas is moving along magnetic field lines.

The sunspot cycle may be due in part to the Sun's differential rotation which might cause the magnetic fields to wrap, intensify, then become chaotic and cancel itself.





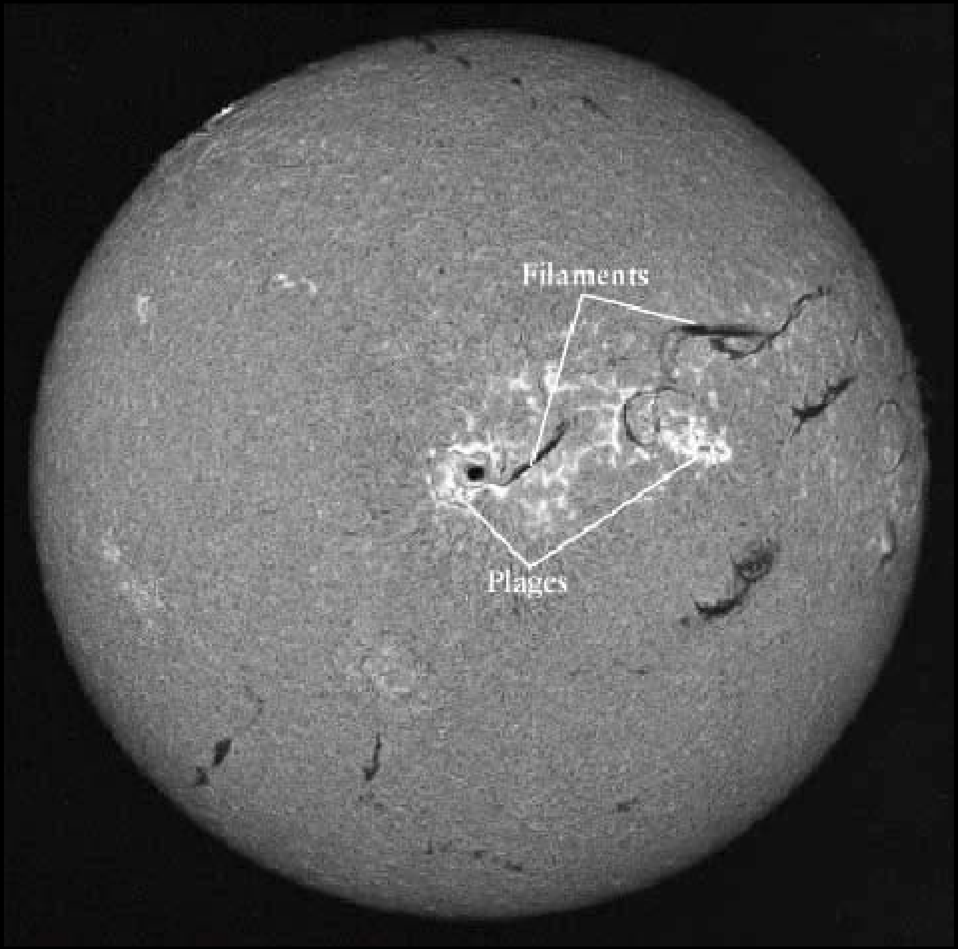
The interior of the Sun rotates at different rates than the exterior as well as differentially at various latitudes. The radiative zone seems to rotate as a rigid sphere.

The Sun's magnetic field also produces other forms of solar activity.

- The highly charged gases in the Sun's outer atmosphere, follow loops in the Sun's magnetic field.

The Sun's magnetic field also produces other forms of solar activity.

- plages
- filaments

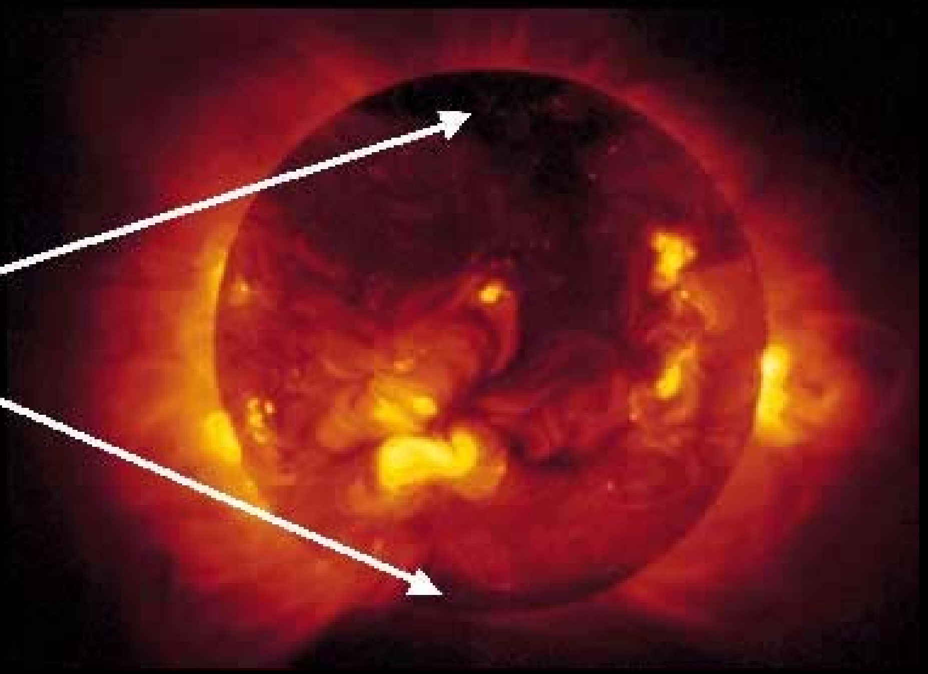


Solar magnetic fields also create other atmospheric phenomena.

- plages
- filaments
- prominences

Solar magnetic fields also create other atmospheric phenomena.

- plages
- filaments
- prominences
- solar flares
- coronal holes



Solar magnetic fields also create other atmospheric phenomena.

- plages
- filaments
- prominences
- solar flares
- coronal holes
- coronal mass ejections (CMEs)