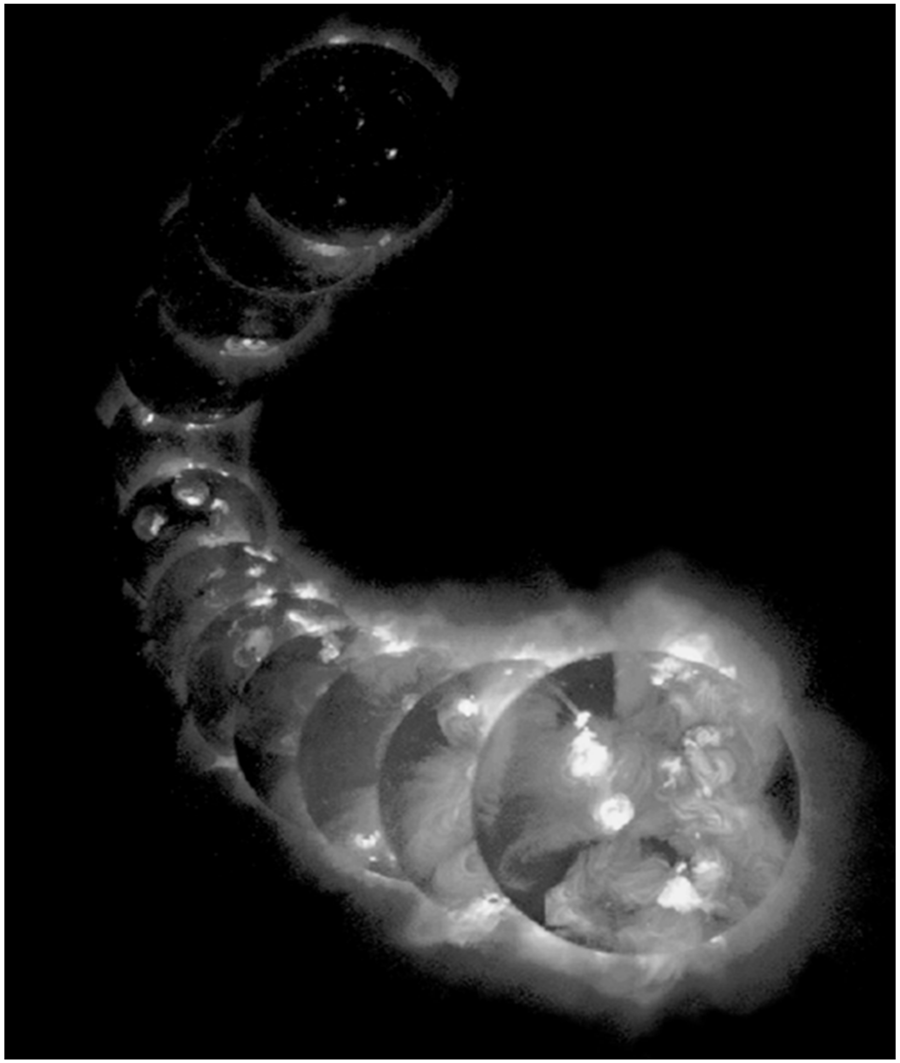
The Sun



The Sun in X-rays over several years

The Sun is a star: a shining ball of gas powered by nuclear fusion.

Mass of Sun $= 2 \times 10^{33}$ g $= 330{,}000\ M_{Earth}$
$= 1\ M_{Sun}$

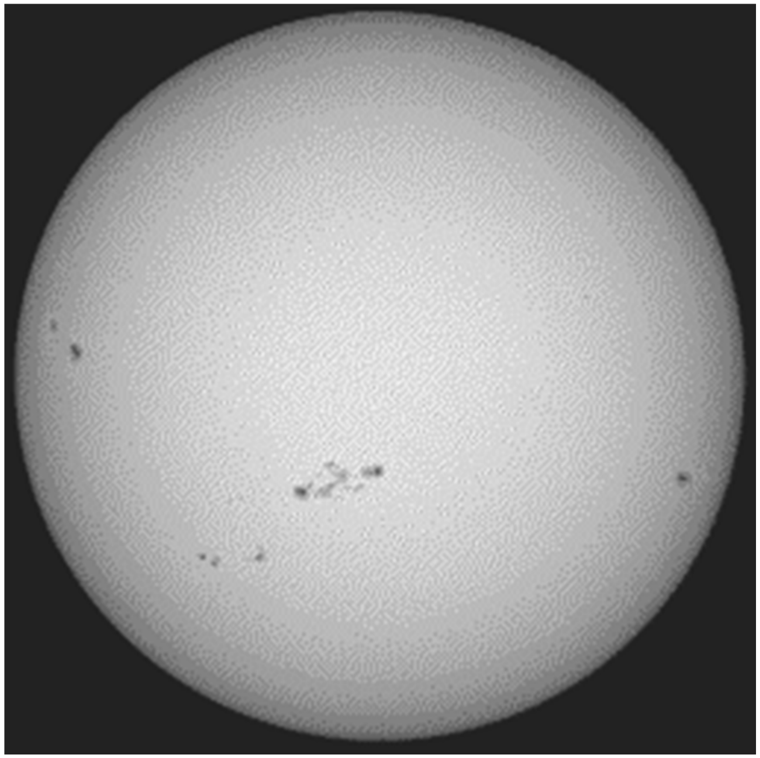
Radius of Sun $= 7 \times 10^{5}$ km $= 109\ R_{Earth}$
$= 1\ R_{Sun}$

Luminosity of Sun $= 4 \times 10^{26}$ Joules/sec or Watts $= 1\ L_{Sun}$

(amount of energy put out each second in form of radiation, $= 10^{25}$ 40W light bulbs)

Temperature at surface = 5800 K => peaks at yellow-green (Wien's Law)

Temperature at center = 15,000,000 K



Average density = 1.4 g/cm^3

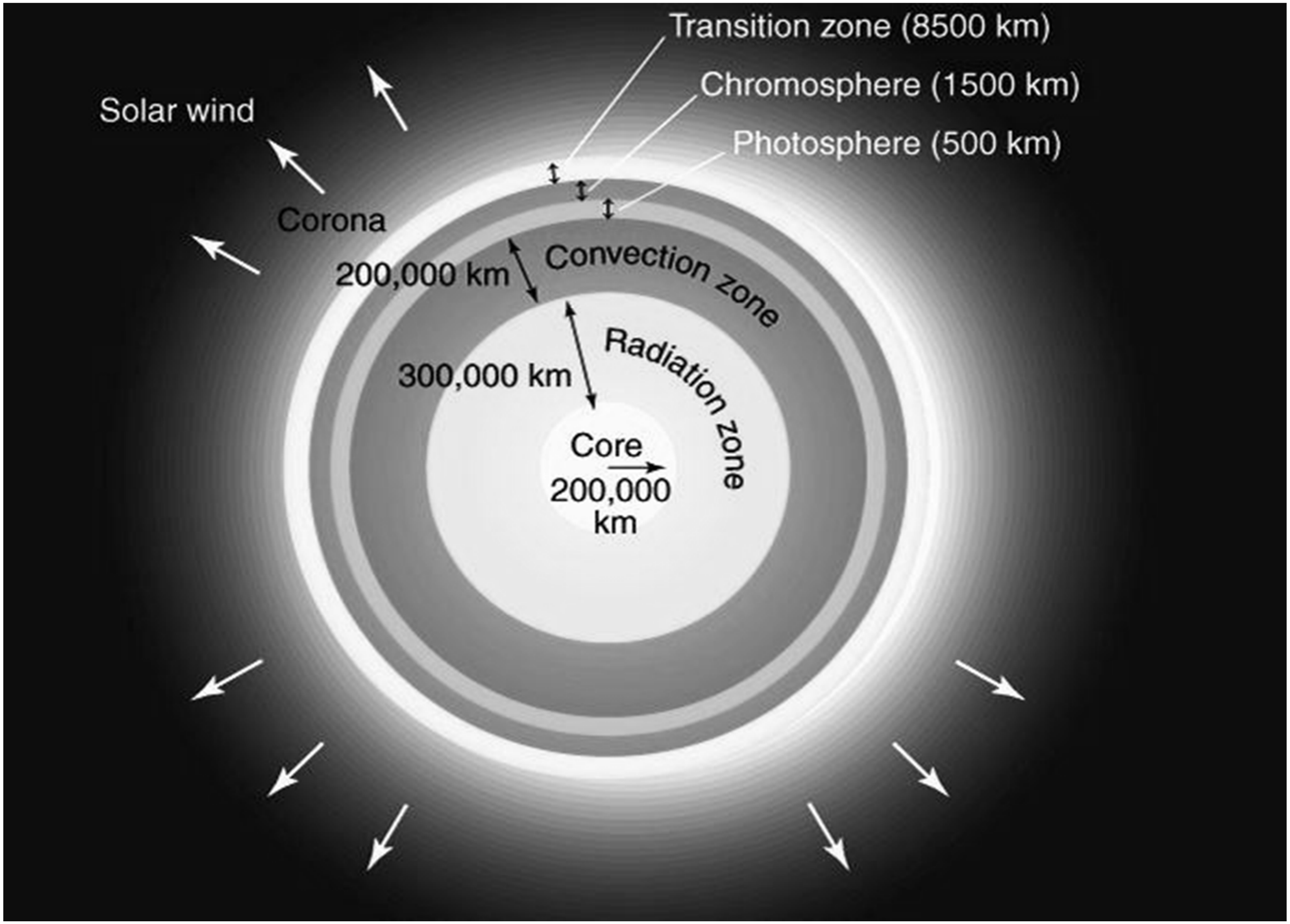
Density at center = 160 g/cm^3

Composition: 74% of mass is H
25% He
1% the rest

Rotation period = 27 days at equator
31 days at poles

The Interior Structure of the Sun

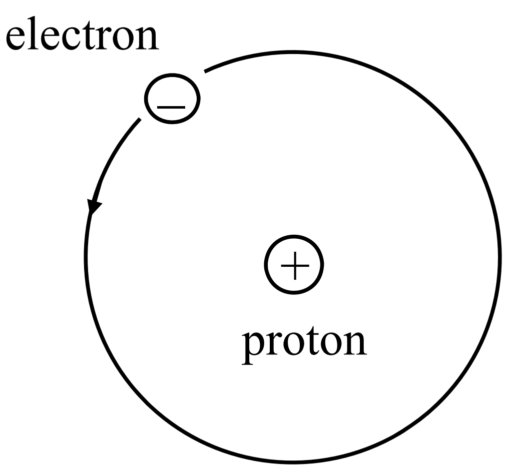
(not to scale)



Let's focus on the core, where the Sun's energy is generated.

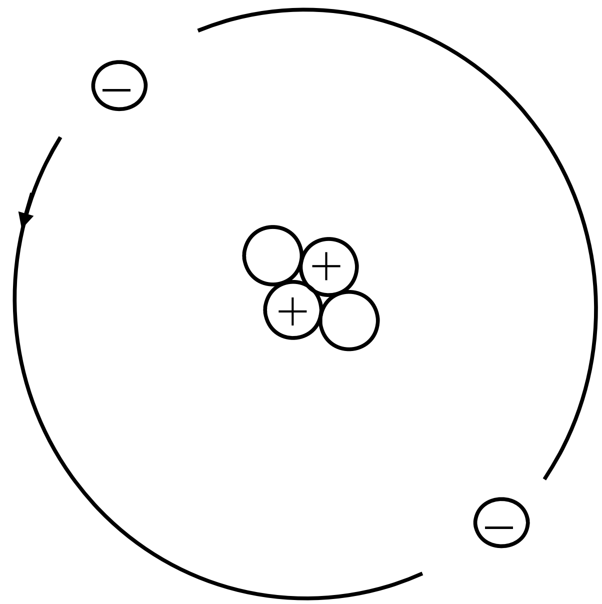
Review of Atoms and Nuclei

Hydrogen atom:



The proton is the nucleus

Helium atom:



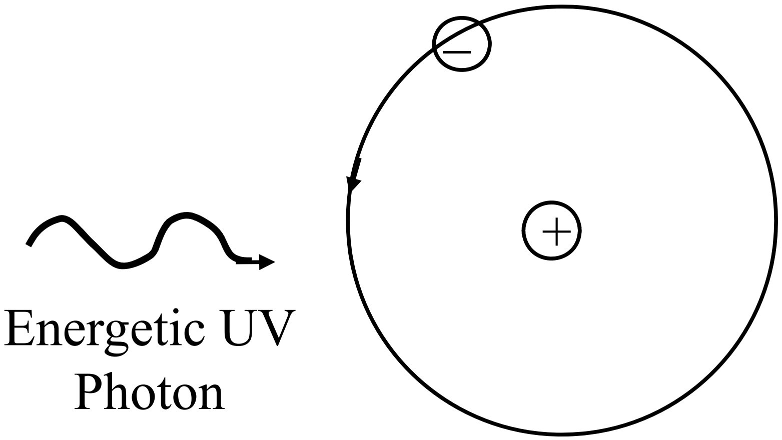
The nucleus is 2 protons + 2 neutrons

What binds the nuclear particles? The "strong" nuclear force.

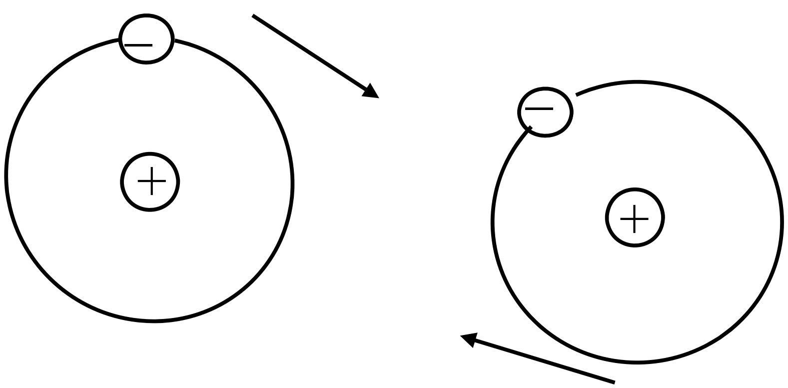
Number of protons uniquely identifies element. Isotopes differ in number of neutrons. Helium example: ^{4}He: 2p + 2n. ^{3}He: 2p + 1n

Review of Ionization

Radiative ionization of H



"Collisional Ionization" of H



Core of Sun is hot: gas is completely ionized by energetic collisions

What Powers the Sun

Nuclear Fusion: An event where nuclei of two atoms join together.

Need high temperatures and densities.

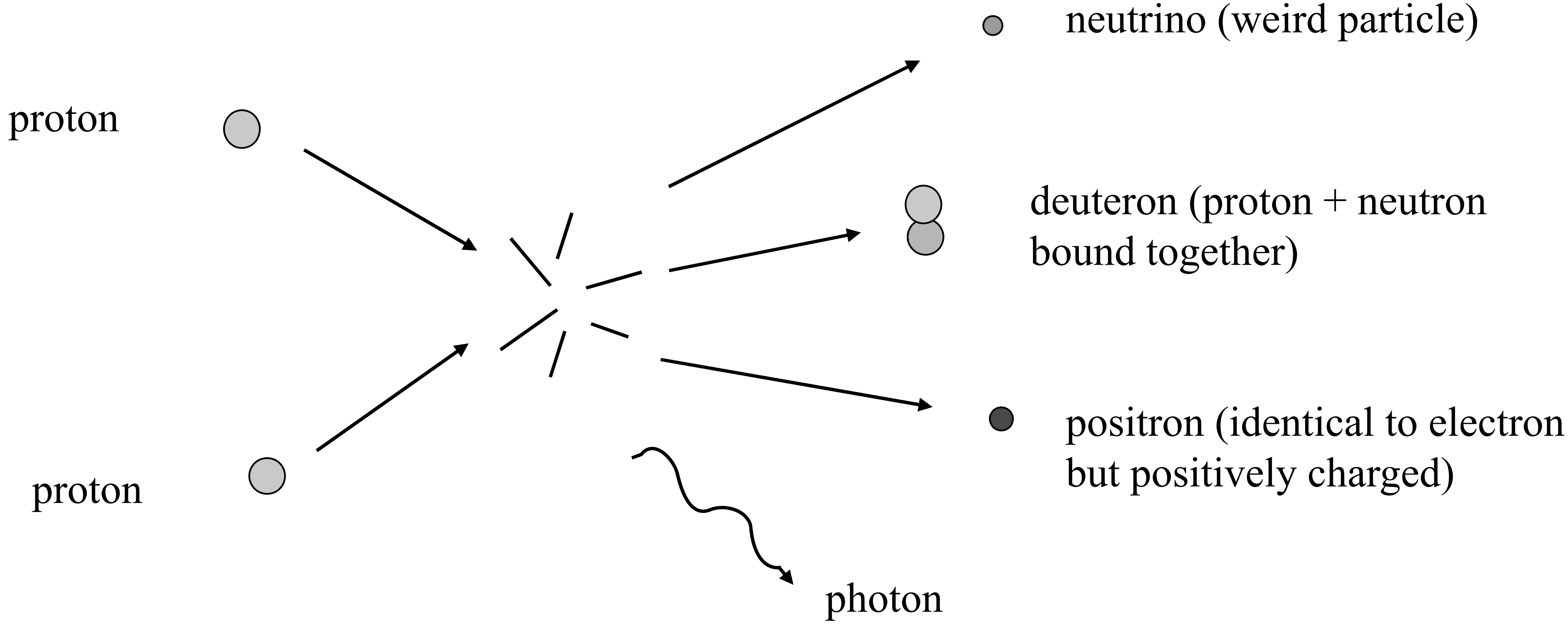
Energy can be produced. Elements can be made.

nuc. 1 + nuc. 2 $\rightarrow$ nuc. 3 + energy (radiation)

Mass of nuc. 3 is often slightly less than mass of (nuc. 1 + nuc. 2). The lost mass is converted to energy. Why? Einstein's conservation of mass and energy, $E = mc^2$. Sum of mass and energy always conserved in reactions. Fusion reactions power stars.

Chain of nuclear reactions called "proton-proton chain" or p-p chain occurs in Sun's core, and powers the Sun.

In the Sun's Core...



1) proton + proton → proton+neutron + neutrino + positron

(deuteron)

+ energy (photon)

2) deuteron + proton $\rightarrow$ ^3He + energy

He nucleus, only 1 neutron

3) ^3He + ^3He $\rightarrow$ ^4He + proton + proton + energy

Net result:

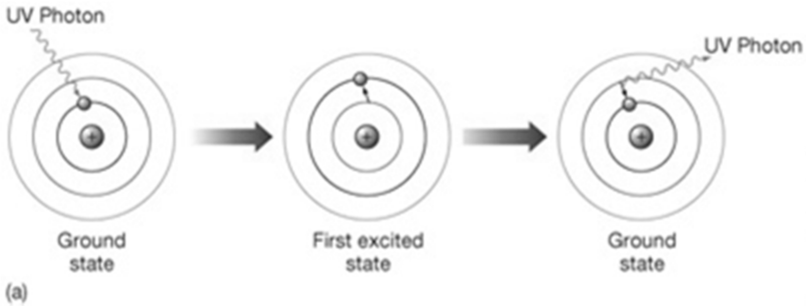
4 protons $\rightarrow$ ^4He + neutrinos + energy

Mass of end products is less than mass of 4 protons by 0.7%.
Mass converted to energy.

600 million tons per second fused. Takes billions of years to convert p's to ^4He in Sun's core. Process sets lifetime of stars.

Hydrostatic Equilibrium: pressure from fusion reactions balances gravity, allows Sun to be stable.

How does energy get from core to surface?



"surface" or "atmosphere" or photosphere: gas density low enough so photons can escape into space.

"radiative zone":

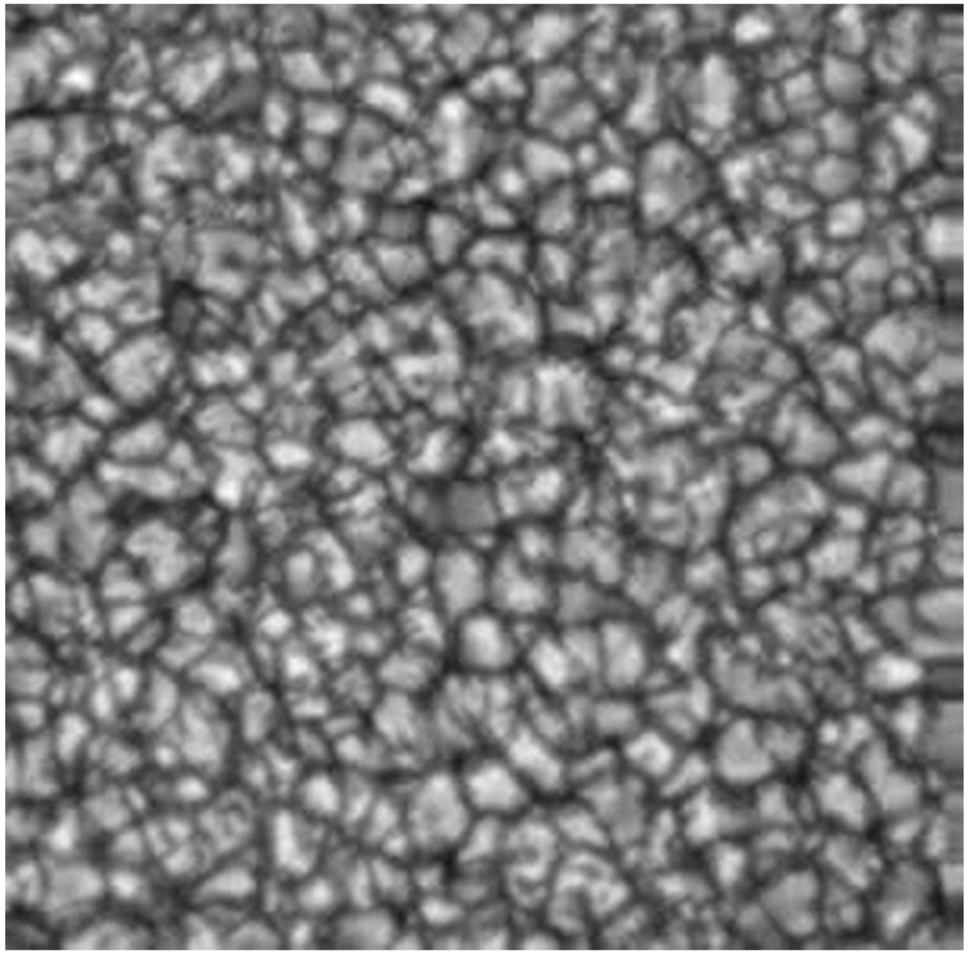
photons scatter off nuclei and electrons, slowly drift outwards: "diffusion".

"convection zone"

some electrons bound to nuclei
=> radiation can't get through
=> heats gas, hot gas rises,
cool gas falls

Can see rising and falling convection cells in photosphere => granulation. Bright regions hotter and rising, dark ones cooler and falling. (Remember convection in Earth's atmosphere, interior and Jupiter).

Granules about 1000 km across



link if movie doesn't work

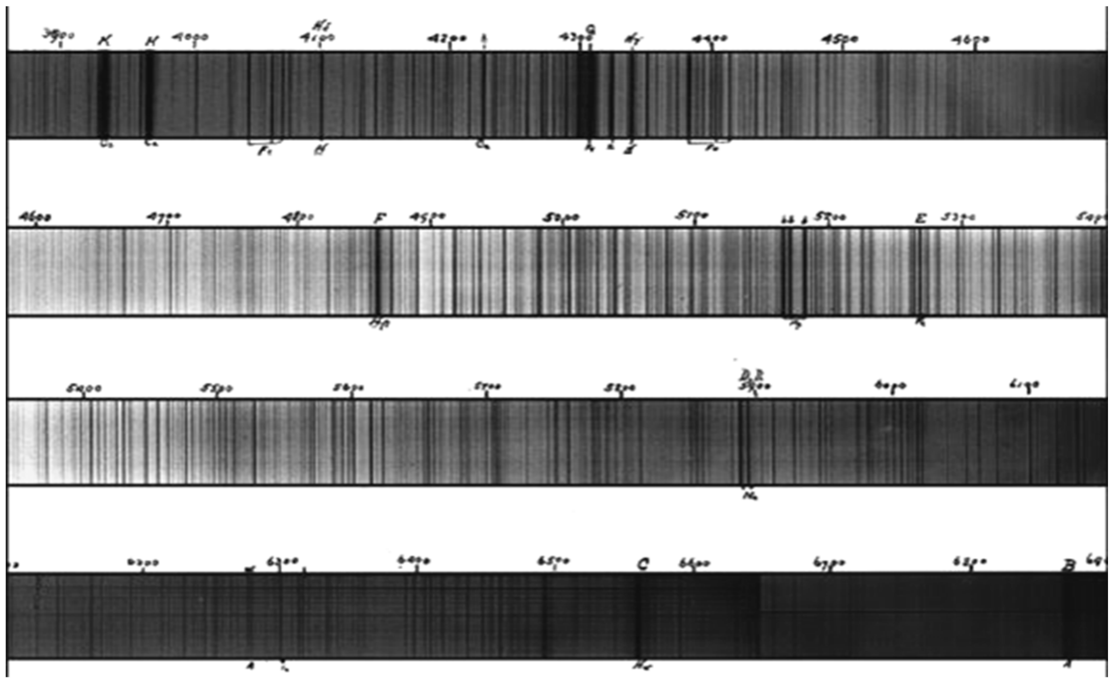
Why are cooler regions dark? Stefan's Law: brightness α T^4

The (Visible) Solar Spectrum

Spectrum of the Sun shows:

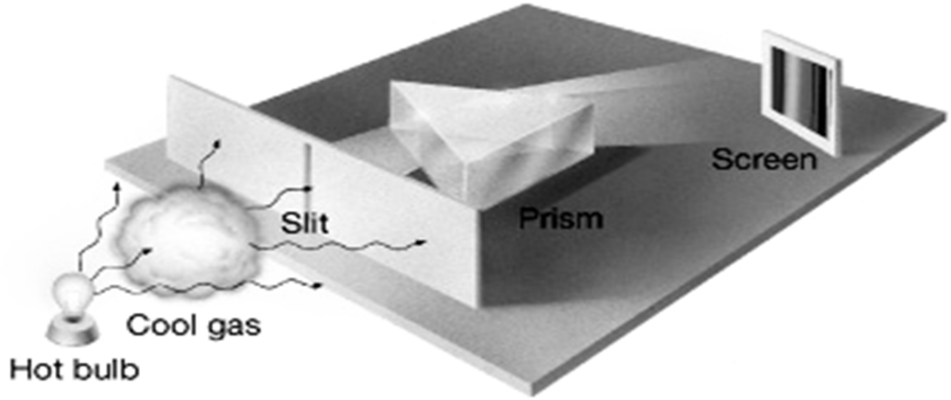
1) The Black-body radiation

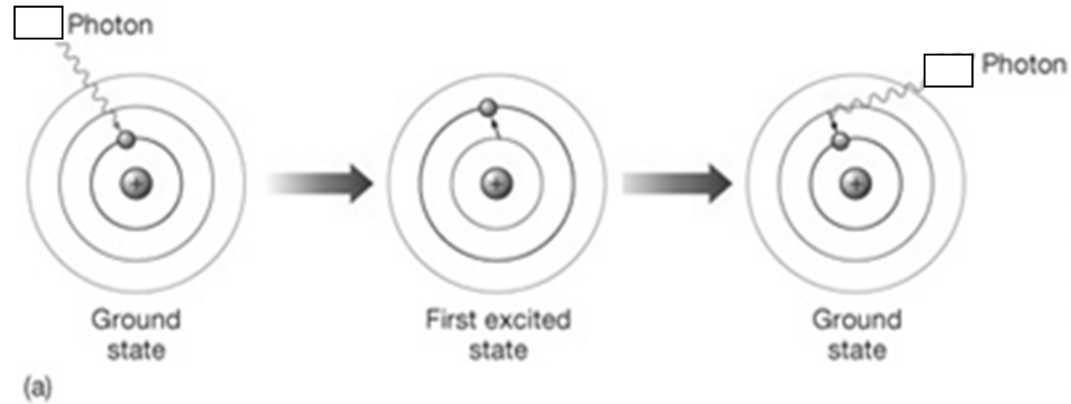
2) Absorption lines (atoms/ions absorbing photons at specific wavelengths).

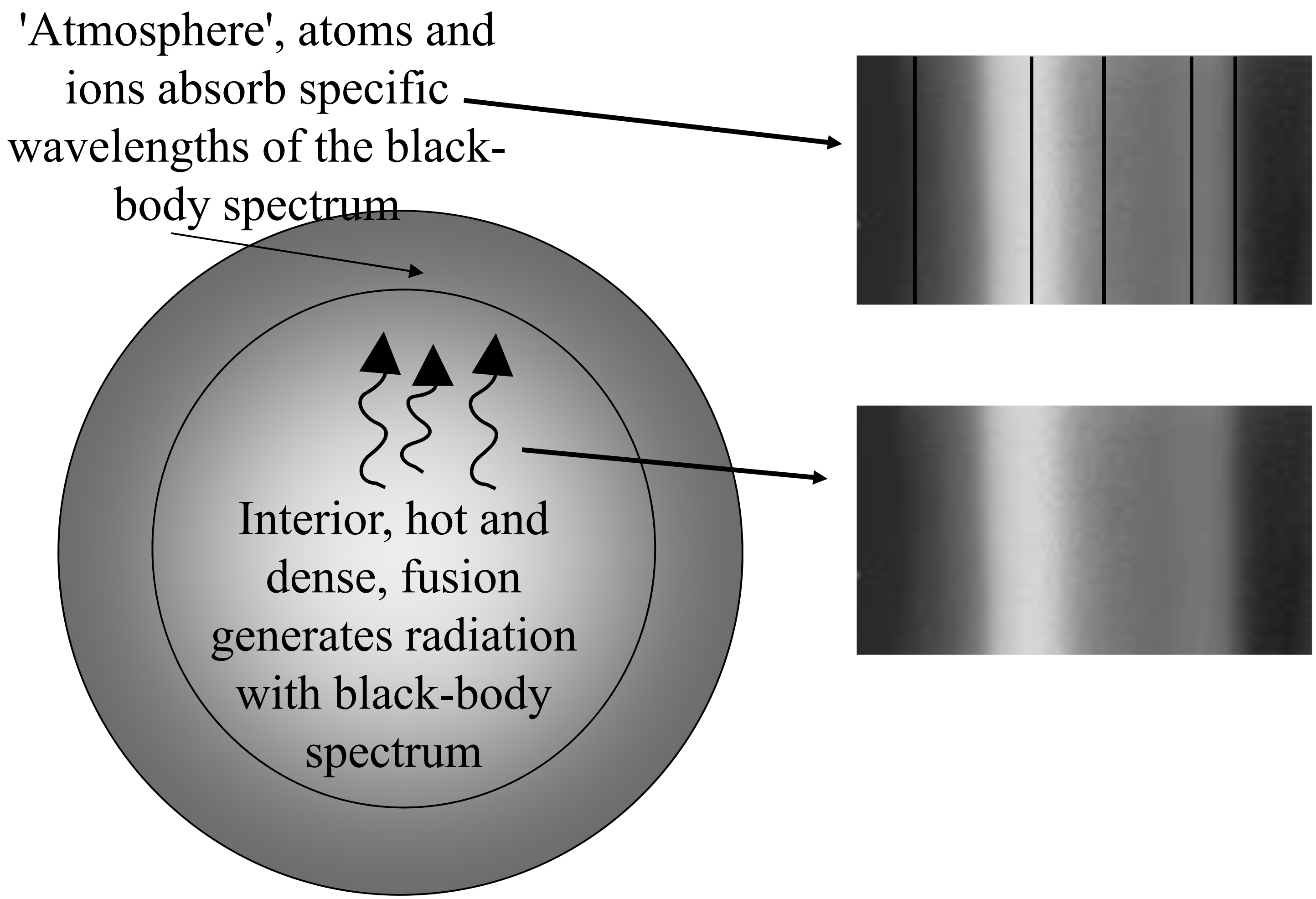


10,000's of lines from 67 elements, in various excited or ionized states.

This radiation comes from photosphere, the visible surface of the Sun.
Elements weren’t made in Sun, but in previous stellar generations.

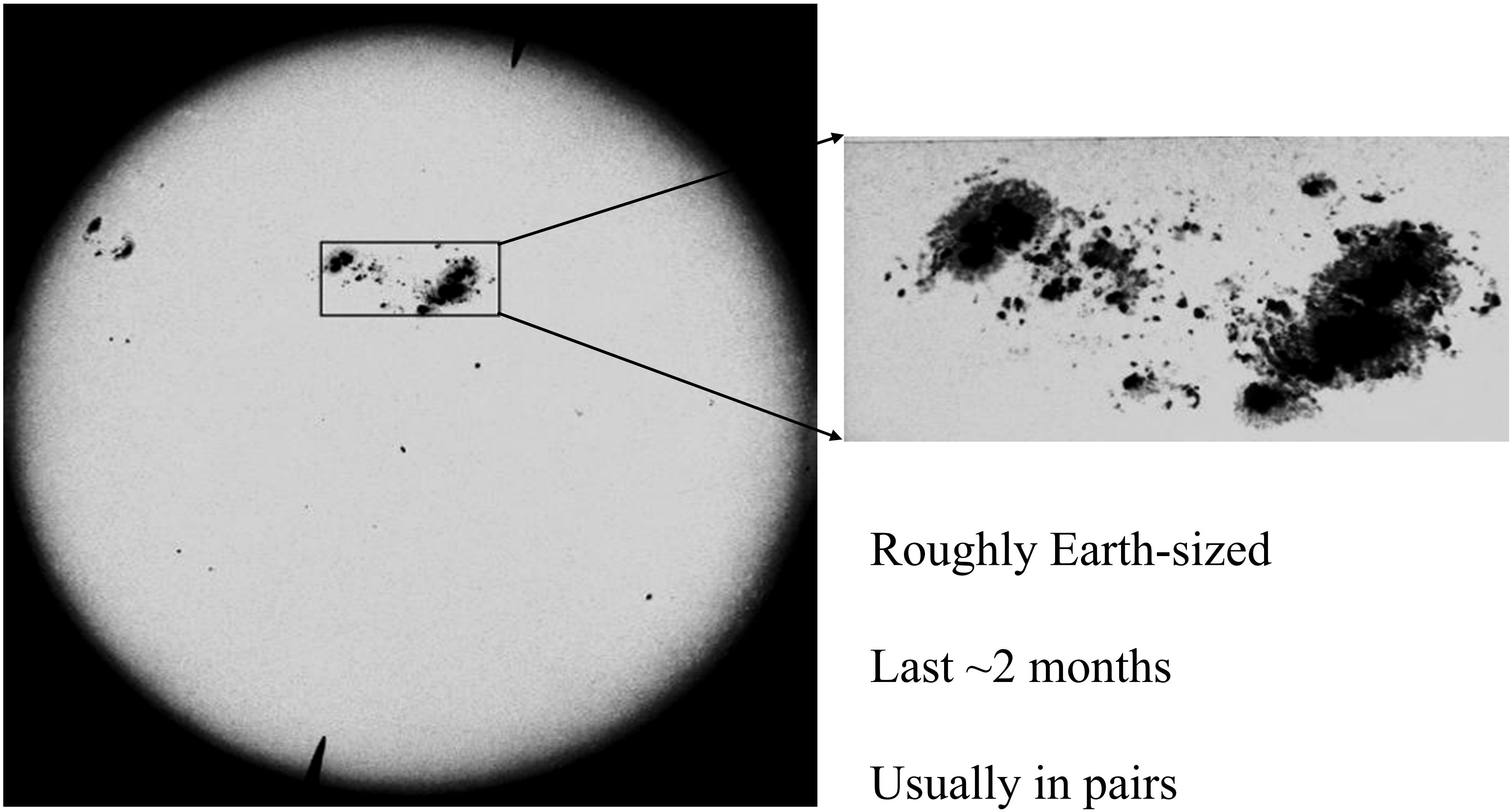

Screen
Slit
Prism
Cool gas
Hot bulb


Photon
Photon
Ground state
First excited state
Ground state
(a)


'Atmosphere', atoms and ions absorb specific wavelengths of the black-body spectrum
Interior, hot and dense, fusion generates radiation with black-body spectrum

Sun

Sunspots



Roughly Earth-sized

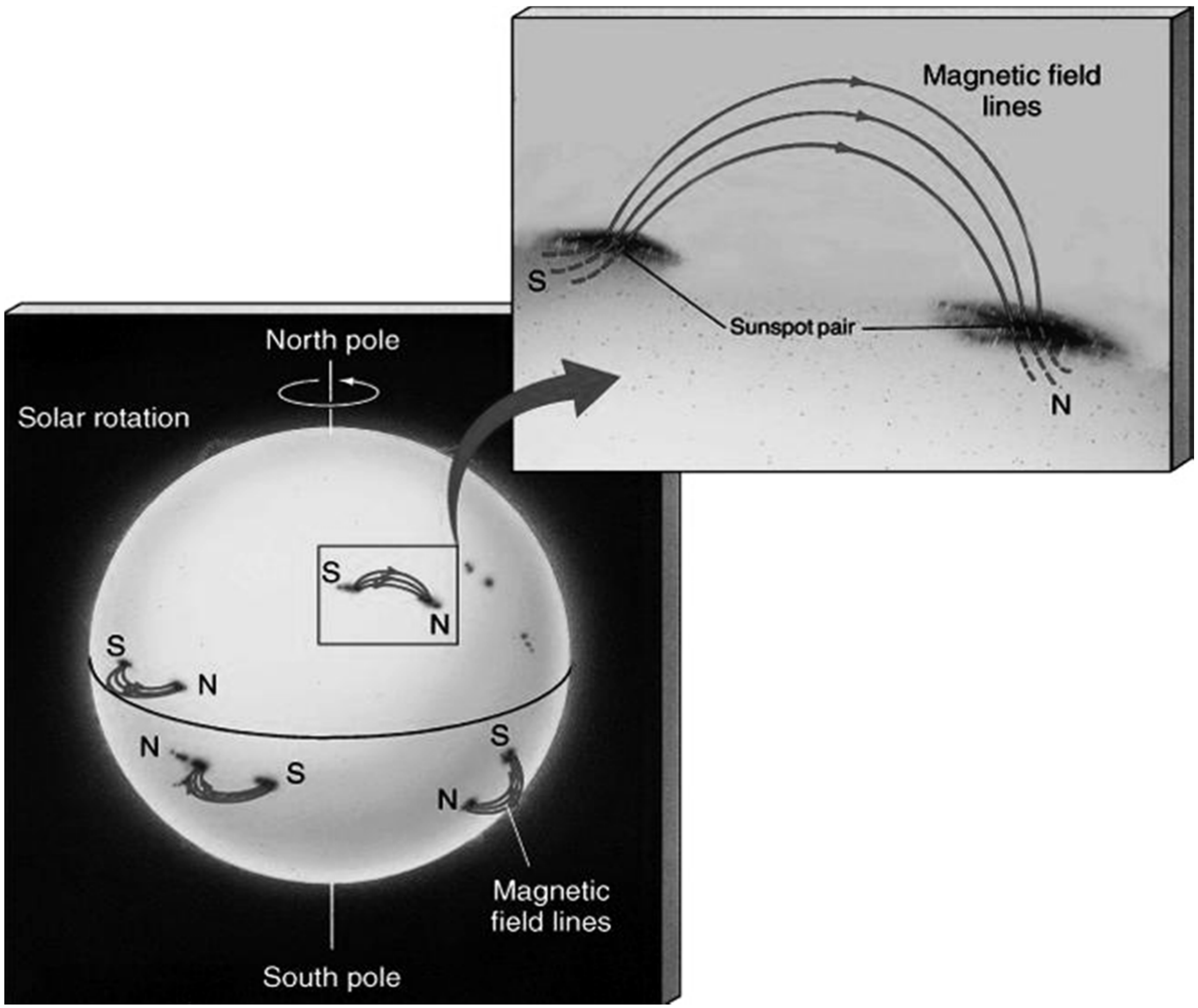
Last ~2 months

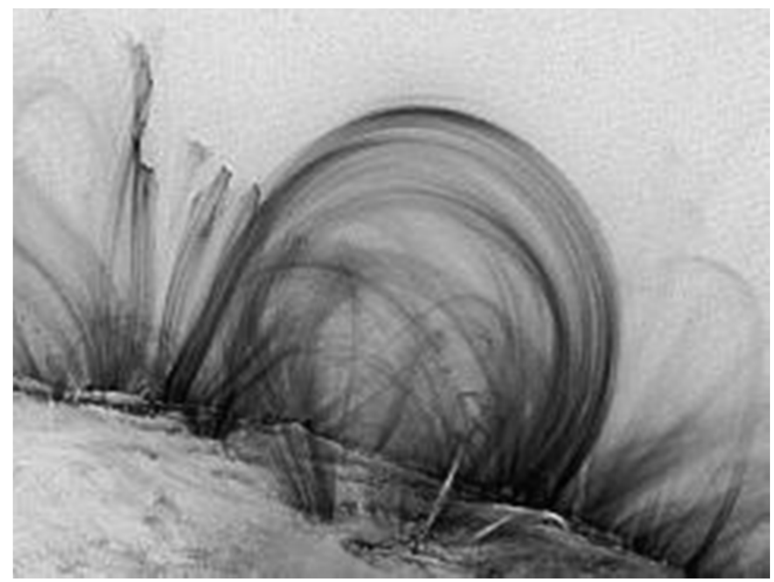
Usually in pairs

Follow solar rotation

Sunspots are darker because they are cooler (4500 K vs. 5800 K).

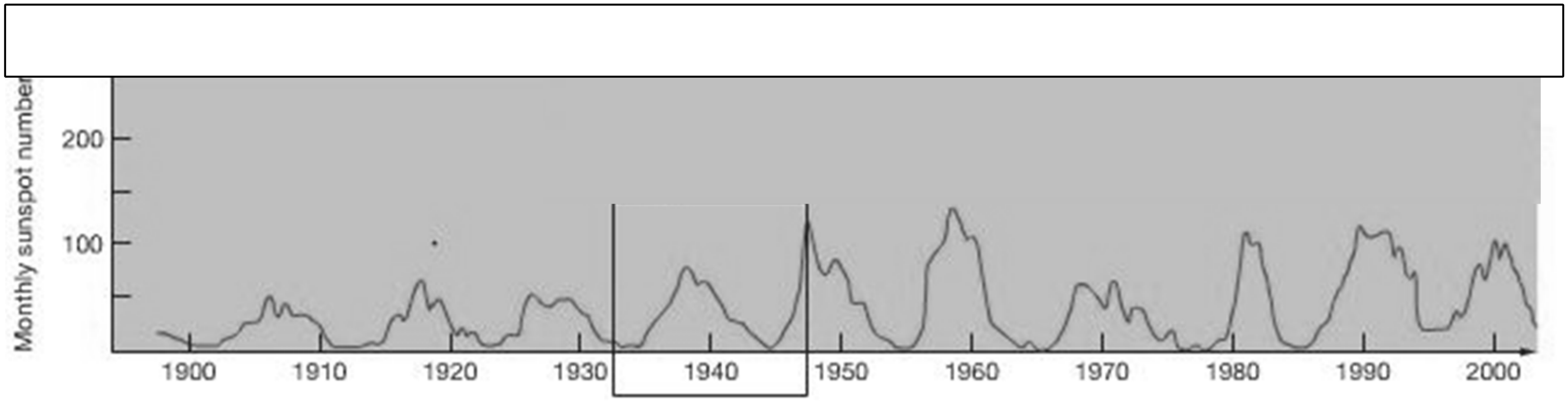
Related to loops of the Sun's magnetic field.

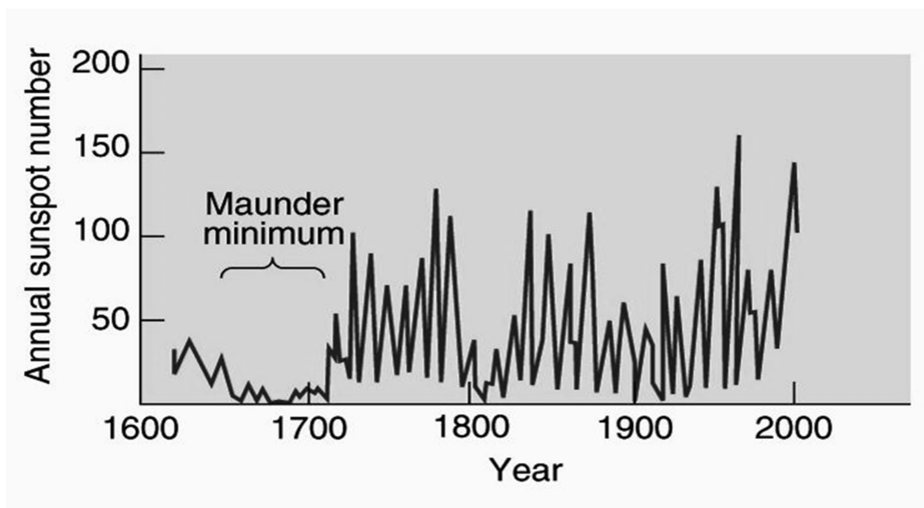




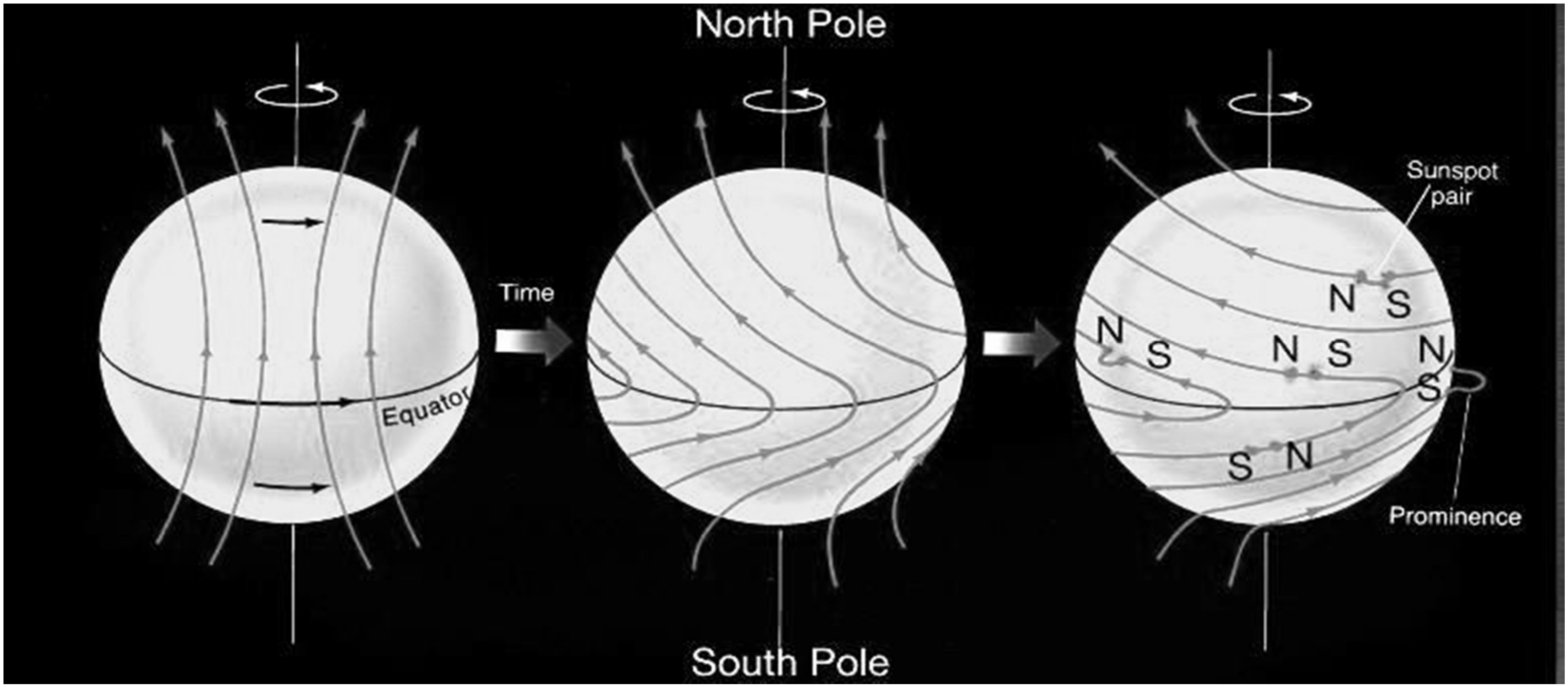
radiation from hot gas flowing along magnetic field loop at limb of Sun.

Sunspot numbers vary on a 11 year cycle.



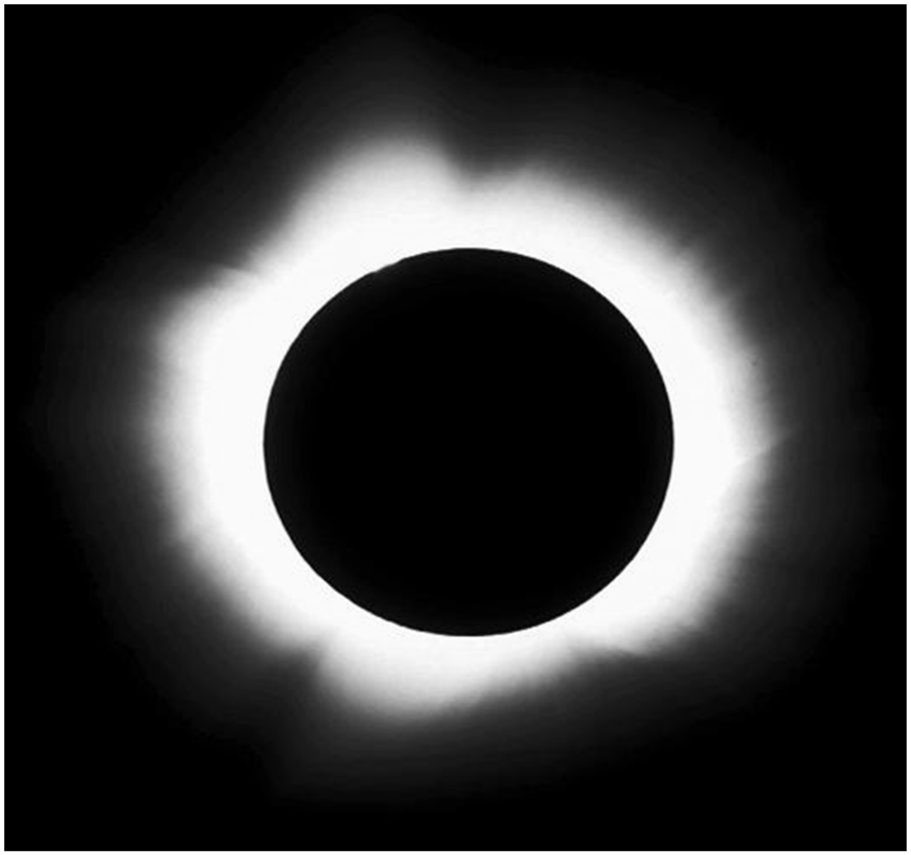


Sun's magnetic field changes direction every 11 years. Maximum sunspot activity occurs about halfway between reversals.



Above the photosphere, there is the chromosphere and...

The Corona

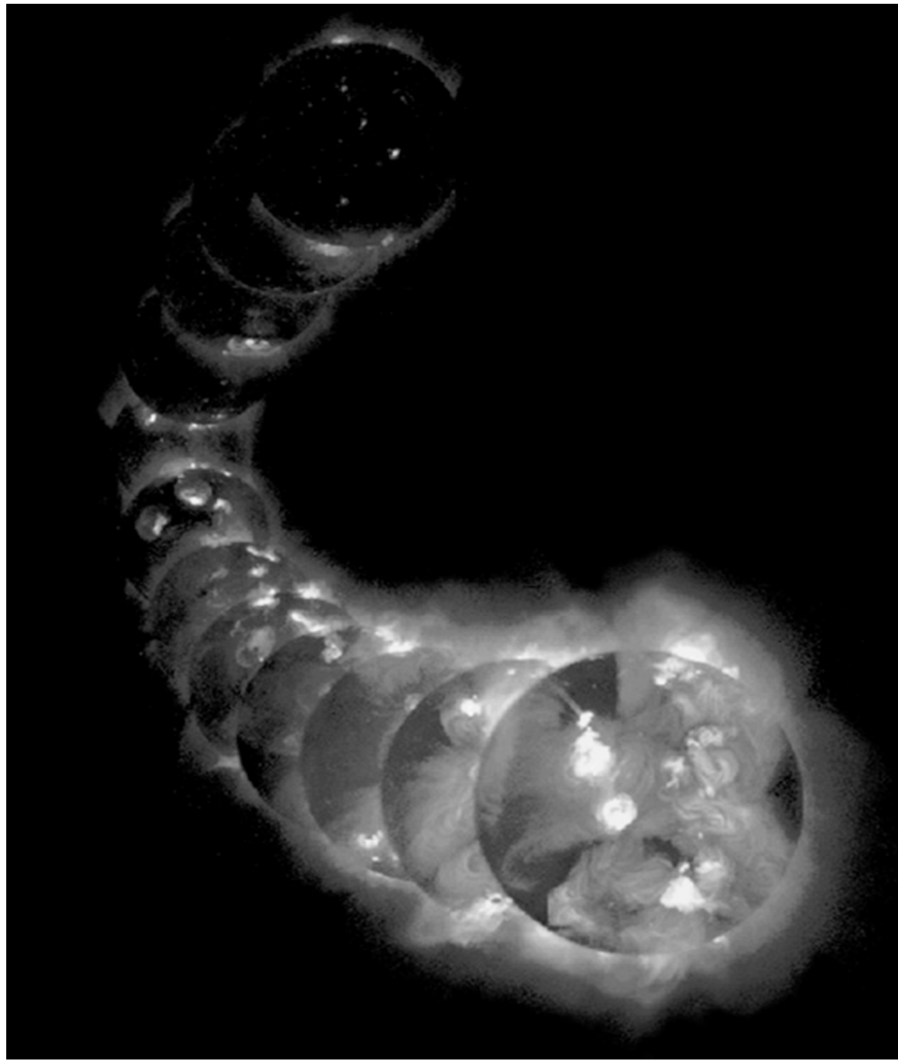


Best viewed during eclipses.

$T = 10^6$ K

Density = 10^{-15} g/cm^3 only!

We expect X-rays from gas at this temperature.



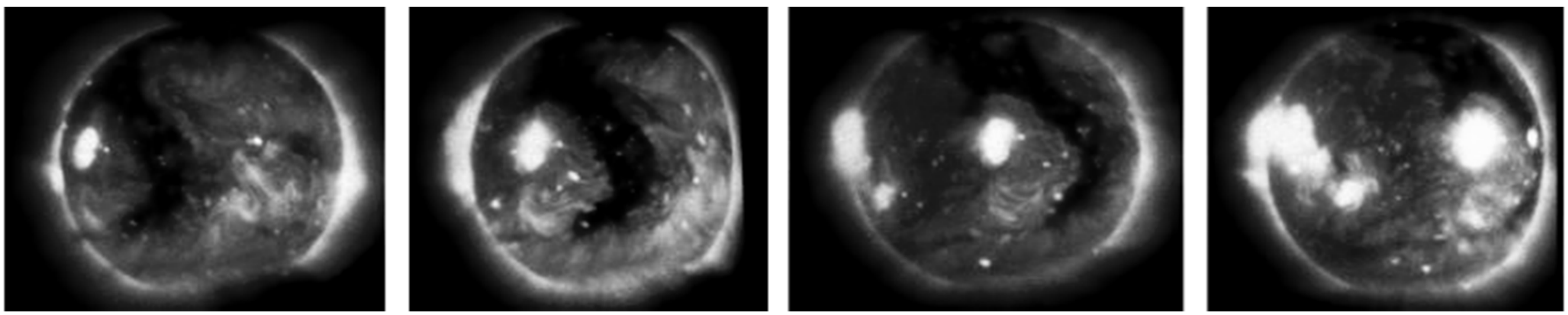
Yohkoh X-ray satellite

X-ray brightness varies over 11-year Solar Cycle: coronal activity and sunspot activity go together.

The Solar Wind

At top of corona, typical gas speeds are close to escape speed => Sun losing gas in a solar wind.

Wind escapes from "coronal holes", seen in X-ray images.



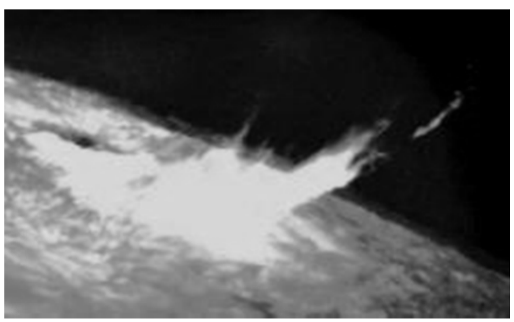
Wind speed 500 km/sec (takes a few days to reach Earth).

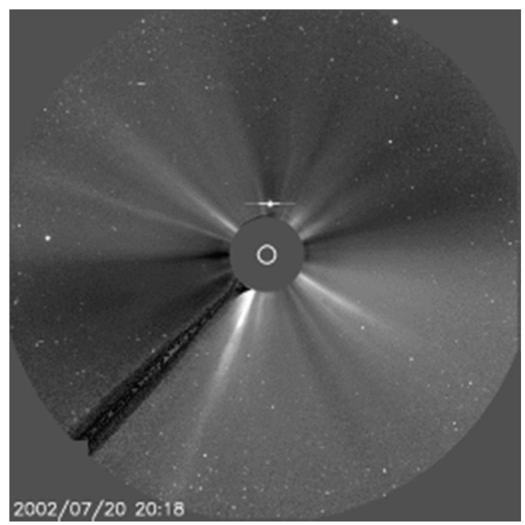
10^6 tons/s lost. But Sun has lost only 0.1% of its mass from solar wind.

Active Regions

Prominences: Loops of gas ejected from surface. Anchored in sunspot pairs. Last for hours to weeks.

Flares: A more energetic eruption. Lasts for minutes. Less well understood.





Solar Flare Video

Prominences and flares occur most often at maximum of Solar Cycle.