The Mystery of the Solar Core

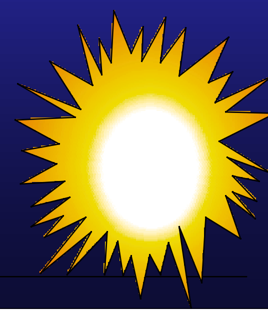
The structure of the sun

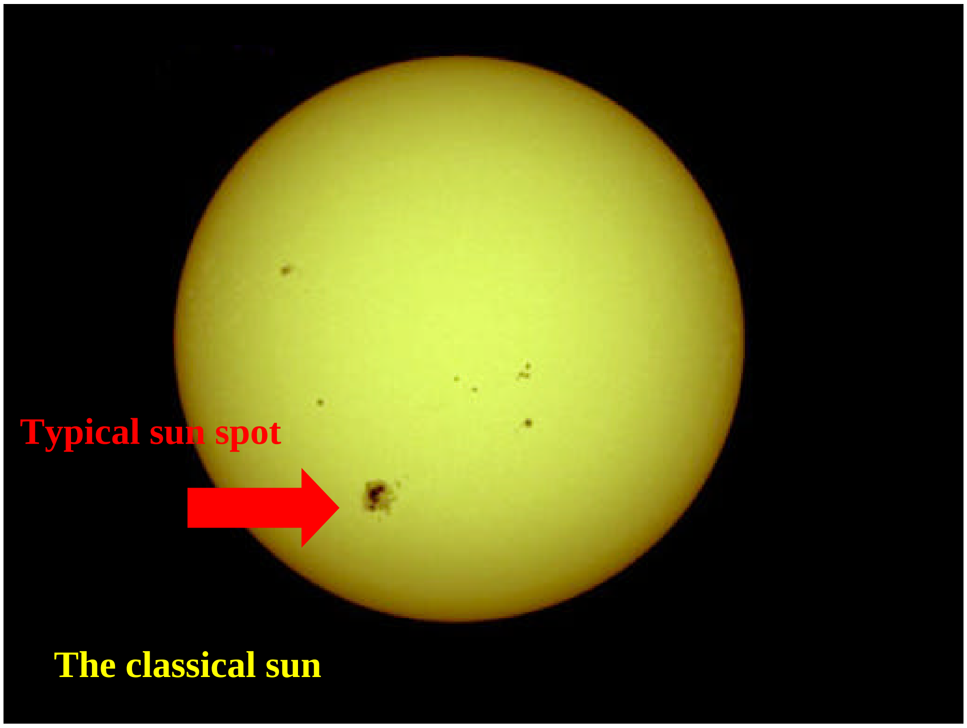
The solar neutrino problem

The evolution of the sun and its future

What will happen to the sun

and the Earth





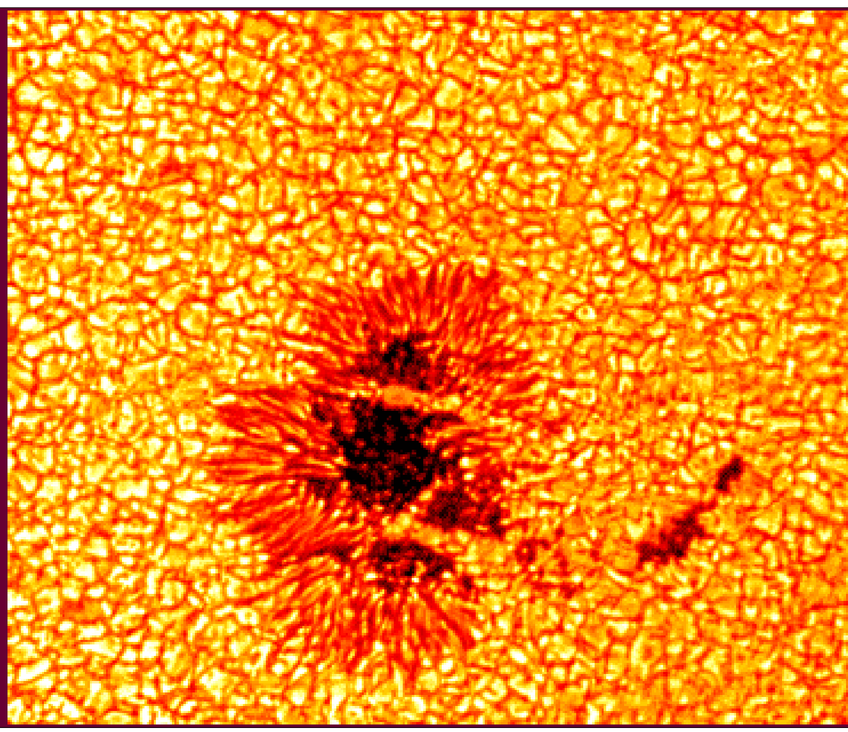
The Sun rotates about its axis.

The period varies with latitude from 25-27 days.

The Sun does not rotate as a rigid body.

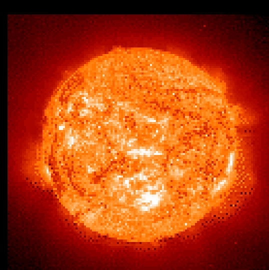
The Sun rotates slowly meaning: the centrifugal force on the equator is negligible (one part in 1000) of the gravitational force.

The quiet sun and the corona as seen in an eclipse

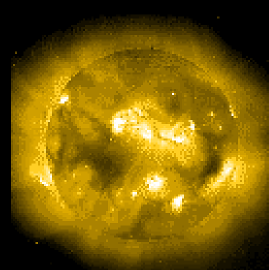


The solar granulation. Elements of the convective

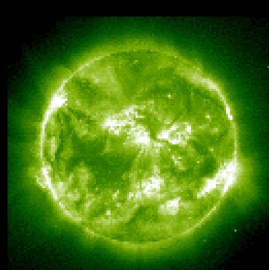
Zone rise and sink in the solar envelope



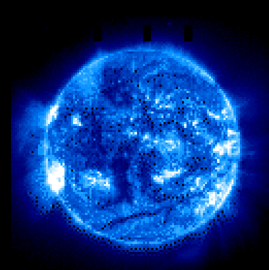
λ=3040A



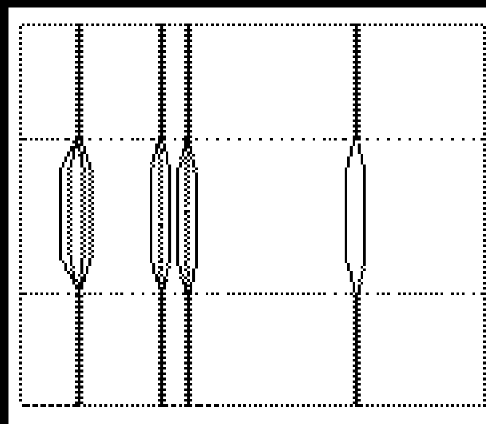
λ=2840A



λ=1950A



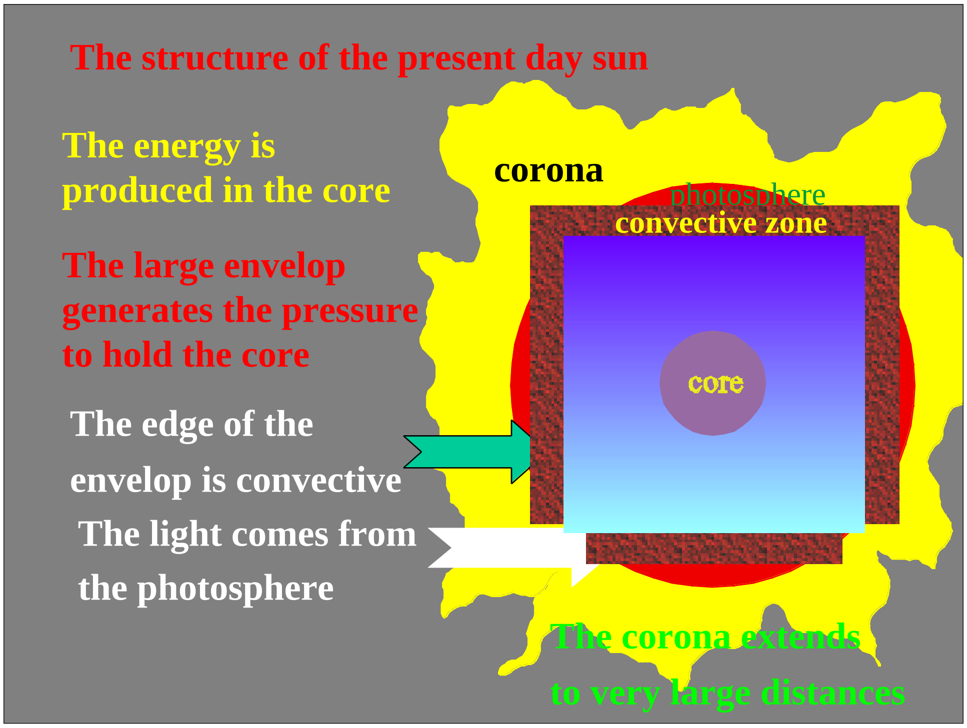
λ=1710A

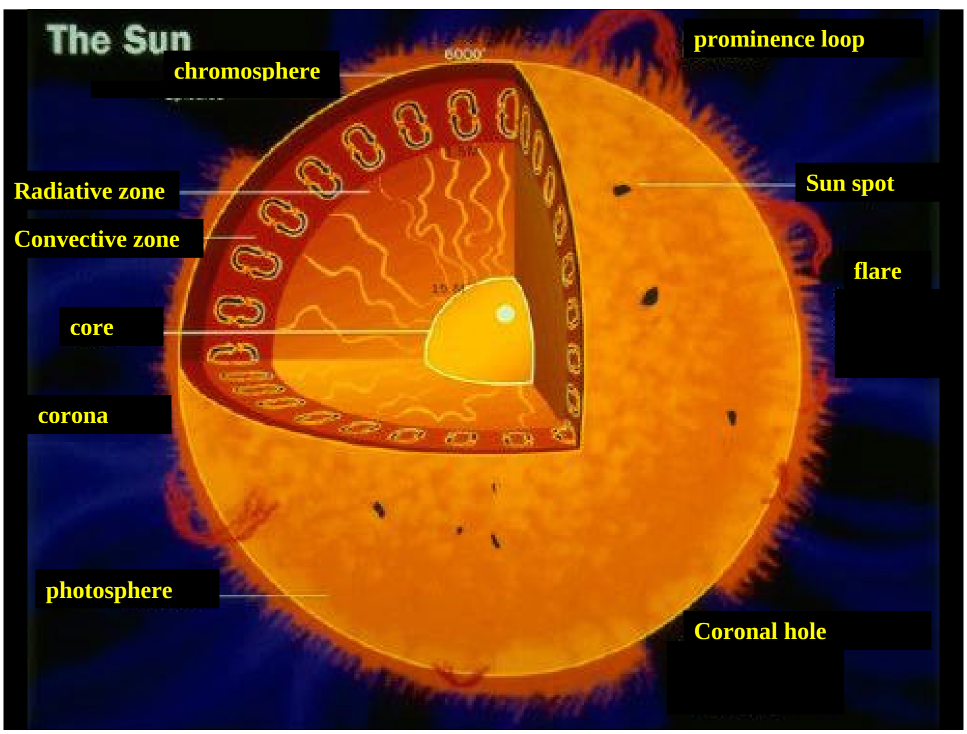


Zeeman splitting of spectral lines inside sun spot is an indication to strong magnetic fields

Inside the Sun Spot the magnetic pressure is of the same order as the gas pressure

$$\frac{H^2}{8\pi} \approx P_{gas} \approx \frac{R}{\mu}\rho T$$

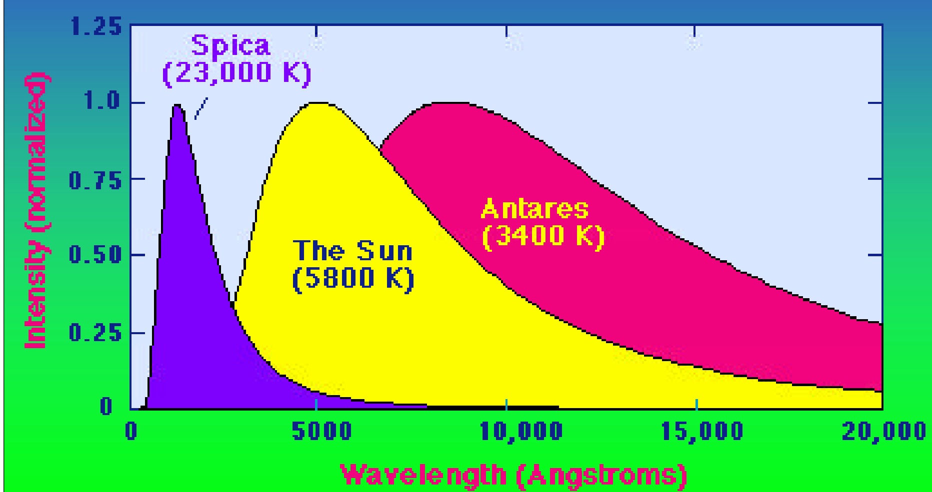

The structure of the present day sun
The energy is produced in the core
The large envelop generates the pressure to hold the core
The edge of the envelop is convective
The light comes from the photosphere
corona
photosphere
convective zone
core
The corona extends to very large distances

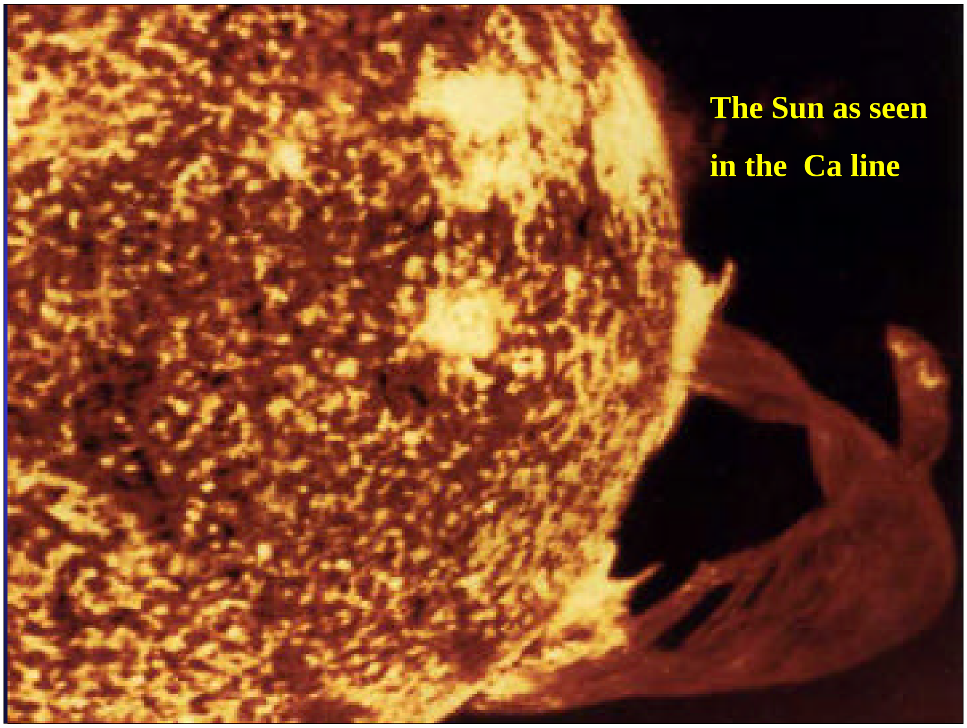

The Sun
chromosphere
prominence loop
Radiative zone
Convective zone
Sun spot
flare
core
corona
photosphere
Coronal hole

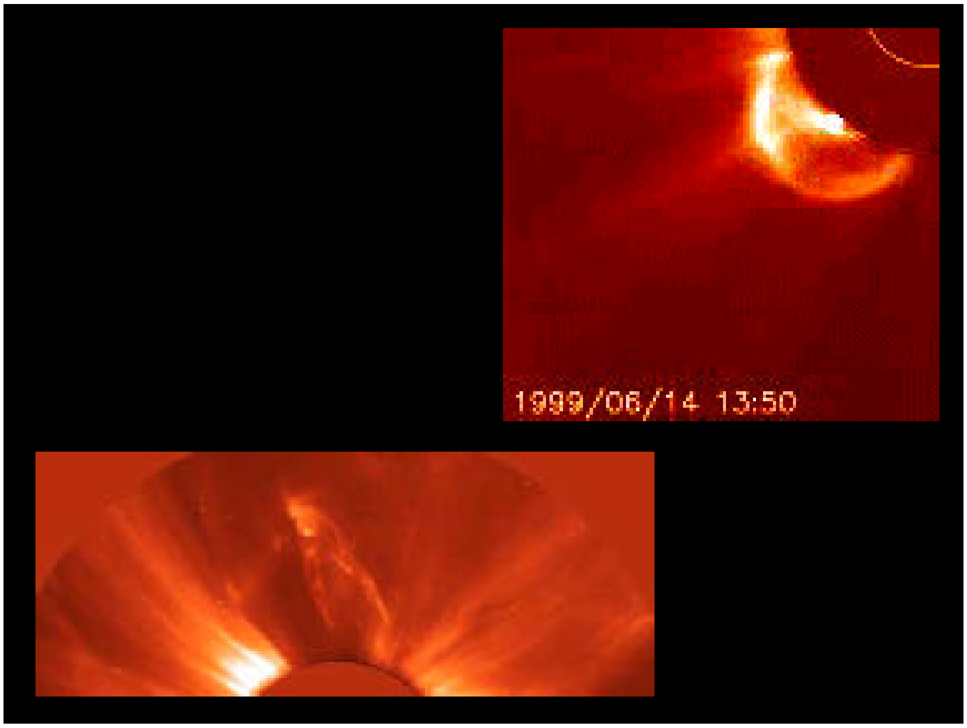
On the surface we see the motion of the convective elements releasing energy and very intense magnetic phenomena releasing energy in flares.

The corona expands and becomes the solar wind which extends throughout the entire solar system and is responsible for the tails of comets

Decomposition of the solar radiation to different wavelengths

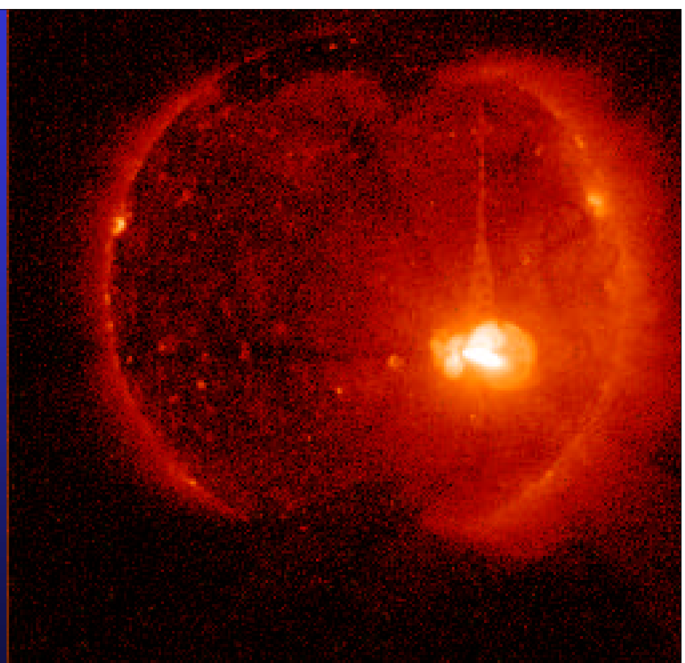


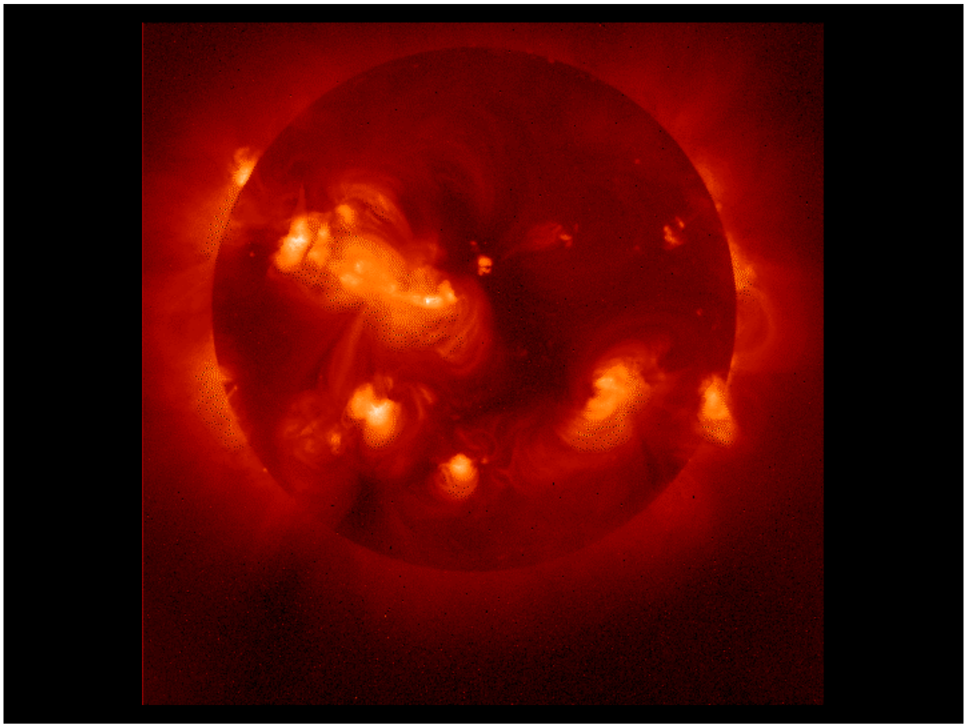

The Sun as seen
in the Ca line



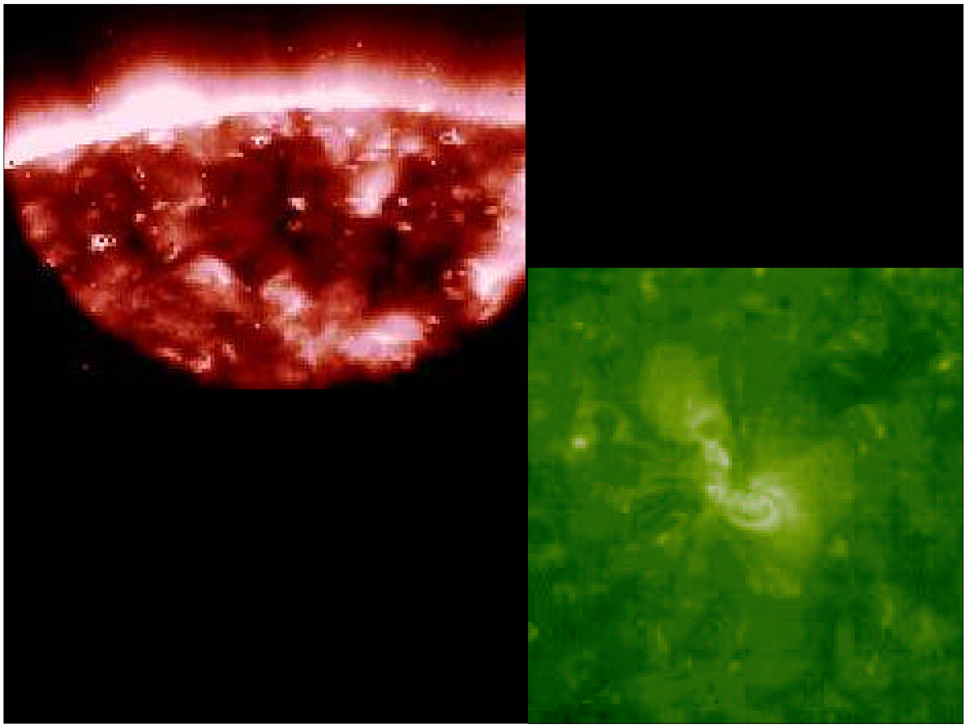
A flare on the surface of the sun observed in

X-rays





The evolution of a flare and the formation of acoustic wave in the surface of the sun



The physics of the photosphere (from where the radiation escapes to space and the star shines),

The corona with its expanding wind

The convection with energy transfer via mass motion

The formation of spectral lines

….

are very complicated problems and will not be discussed here.

What is the energy source of the sun?

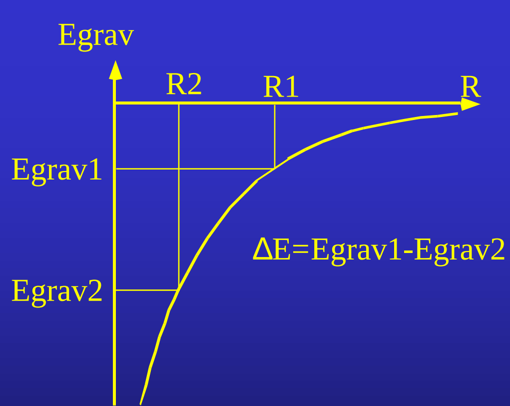
1900 Kelvin & Helmholtz:The stars extract energy from the gravitational well

Stars are bound (inspite of them being hot), the stars are inside a gravitational potential well.

The total gravitational energy is given by:

$$E_{grav} = -G \int_0^M \frac{m(r)dm}{r} = -\alpha \frac{GM^2}{r}$$

$\alpha \sim 1$ **The exact value depends on the density distribution.**



As the star contracts, it sinks deeper into the gravitational potential well and releases the gravitational energy.

Estimate the total energy released by the sun during its lifetime.

$$\int_0^{today} L(t)dt \approx L\tau = \frac{1}{2}\alpha\frac{GM^2}{R}$$

1/2 because the sun heats upon contraction

τ is the present age of the sun

It is safe to assume L(t)=L(today)=const.

Global Solar parameters

$$L_{sun} = 3.86 \times 10^{33} erg/\sec$$

$$M_{sun} = 1.989 \times 10^{33} gm$$

$$\left(\frac{L}{M}\right)_{sun} = 1.94 erg/\sec gm$$

$$R_{sun} = 6.96 \times 10^{10} cm$$

At the present rate of solar luminosity, the gravitational supply will last:

$$\tau = \frac{GM^2}{LR} = 3\times10^7\,yrs$$

τ is known as the Kelvin Helmholtz time scale

$$Solar-age \geq Earth-age = (4.56\pm0.2)\times10^9\,yrs$$

The gravitational energy can supply at most 1% of the total energy released by the sun during its life

The surface composition of all stars observed is quite similar

Composition (in mass fraction) is:

X = 0.70 - 0.73 Hydrogen
Y = 0.25 - 0.28 Helium
Z = 0.03 - 0.001 All the other elements, C,N,O,Ne …

Young stars have Z = 0.02-0.03
Old stars have Z = 0.001
No star was found without any heavy elements`

We cannot see the spectral lines of all elements at the same time (because of different energy levels)

1900 Jeans: The sun is made of U238 and derives its energy from radioactive decay of U238.

Total energy released is radioactive chain

$U^{238} \longrightarrow Pb^{206}$

$$Q = \frac{47\,MeV}{m(\mathrm{U}^{238})} = 1.9 \times 10^{17}\, erg/gm$$

Assume:

$$\text{solar age} \sim 4.5 \times 10^{9}\, yrs \sim \mathrm{U}^{238}\text{half life time}$$

If so, the present sun should be:

50% Uranium and 50% Lead

This is not observed on the surface of the sun

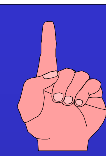
The predicted present day solar luminosity should is:

$$L(today) = \frac{1}{2}\frac{MQ}{\tau(\mathrm{U}^{238})} = 10^{33}\, erg/\sec$$

Jeans hypothesis is nice…but not sufficient!

(See the problem of the surface composition)

1920 Eddington:



The sun converts Hydrogen into Helium.

$$\Delta m(4\mathrm{H} \rightarrow \mathrm{He})c^2 = 4 \times 10^{-5} erg/reaction$$

$$= 6.0 \times 10^{18} erg/gm$$

$$= 30Q(\mathrm{U}^{238} \rightarrow \mathrm{Pb}^{206})$$

How the fusion of Hydrogen occurs? In the early twenties:

Eddington: I don't know

Jeans: impossible because of Coulomb Barrier

Estimate the temperature and the state of the matter

Assume the gas in the sun obeys the ideal gas law:

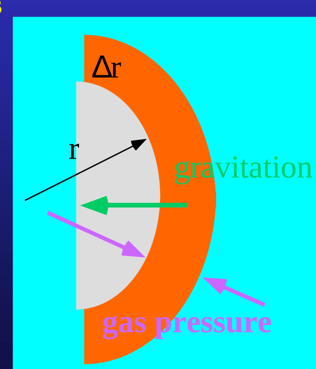
$$P = \frac{k}{m} \rho \; T$$

k - the Boltzmann constant

m - mass of the particles

Assume the sun is in hydrostatic equilibrium:

$$\Delta P = -\frac{GM(r)}{r^2} \rho \Delta r$$



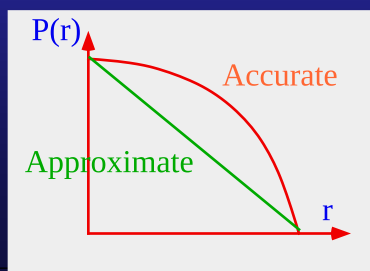
Observed solar composition (by mass):

~0.7H, 0.24 - 0.265 He, 0.0245 heavier elements

At least this is true for the initial (just born) sun

At the surface temperature of the Sun we see no He lines

$$\frac{\Delta P}{\Delta r} \quad \frac{P(r=0)-P(r=R)}{R} \quad \frac{GM}{R^2}\langle\rho\rangle$$



P(r=R)=0

<ρ> mean density

Hence $$P(r=0) \sim \frac{GM}{R}\rho$$

Ideal gas $$\frac{k}{m}\rho\ T \sim \frac{GM}{R}\rho$$

$$T = T_V = \alpha\,\frac{GM}{(k/m)R}$$

Tv is the Virial Temperature of the star.

Tv is an expression of the gravitational potential in units of temperature.

This is the mean gas temperature in the star.

For the thermal pressure of the star to balance gravity, the temperature must be Tv

$$T_V(sun) = \frac{6.67\times10^{-8}\times1.989\times10^{33}}{6.96\times10^{10}\times1.38\times10^{-16}/1.67\times10^{-24}}$$

$$= 2.3\times10^{6}\,\text{K average temperature!}$$

The mean energy of a particles is:

$$E_{kin} = 3/2kT = 1.38\times10^{-16}\times2.3\times10^{6}K$$

$$= 3.2\times10^{-10}erg = 0.2keV$$

$$\langle\rho\rangle = \frac{M}{V} = 1.4gm/cm^{3}$$

What is the state of the matter under the mean solar temperature and density?

Assuming ideal gas then:

If Ekin > Ionization potential

the bound electrons are lost in particle collisions.

The nuclei cannot hold the electrons if the collisions with other nuclei are more energetic than the binding energy of the electrons

The Saha equation: how ionized are given species

$$\frac{n_{r+1} n_e}{n_r} = \frac{G_{r+1} g_e}{G_r} \frac{(2\pi m_e kT)^{3/2}}{h^3} e^{-\chi/kT}$$

n_r Number density of specie ionized r times

$$G(T) = 1 + \sum g_r e^{-E_r/kT}$$

$G_r \sim 1$ Partition functions

g_e, g_r Statistical weights (electrons, ions ionized r times)

The dominant factor: $e^{-\chi/kT}$

Since in the sun the mean kinetic energy is much greater then the ionization potential:

The matter in the sun is in a form of a plasma:

Stripped atoms (bare nuclei) and electrons

In the plasma state, all atoms are stripped of all their electrons. So the plasma contains (positively) charged nuclei and (negatively) charged electrons. On the average the plasma is neutral.

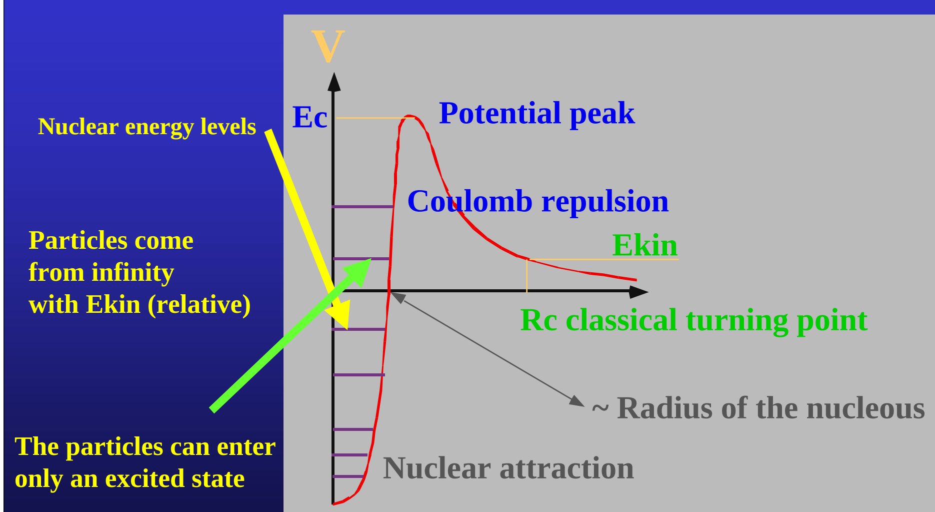
Actually, the plasma state is the most frequent one in astrophysics and in Nature

Nuclear reactions in plasma (stars or Tokomaks)

The reaction takes place in two steps:

- A) The particle penetrates the Coulomb barrier
- B) A compound nucleus is formed and it forgets how it was formed
- C) The compound nucleus is formed in an excited state which can either decay into a more stable nucleus or disintegrate back the way it was formed (or even another way)

The interaction between charged particles in the plasma



The excited state can either decay into a bound state and form a new nucleous
Or decay into the incoming channel and 'nothing happened'

Estimate of the Coulomb barrier: $E_c = \dfrac{(Z_1 e)(Z_2 e)}{R_{nuc}}$

$Z_i e$ **The charge of the colliding particles**

$R_{nuc} = 1.4 A^{1/3} \times 10^{-13} cm$ **Nuclear radius**

A - atomic weight

for Hydrogen plasma $Z_{1,2} = 1, A_{1,2} = 1$

$$E_c = \frac{e^2}{R} = \frac{\left(4.8 \times 10^{-10}\right)^2}{2 \times 1.4 \times 10^{-13}} = 5.1 \times 10^{-5} erg$$

$$= 0.51 MeV$$

$$\sigma(reaction) = P \sigma(nuclear)$$

Potential penetration factor:

$$P \propto \exp\left(-\frac{2\pi Z_1 Z_2 e^2}{\hbar v}\right)$$

$v = \sqrt{2 E_{kin} / m}$ the particle velocity at ∞

Slow particles with low v have a very small probability to penetrate into the nucleous

The Coulomb barrier penetration

The nuclear part is slowly changing with energy

$$\sigma(E) \equiv \frac{S(E)}{E} \exp\left(-\frac{2\pi Z_1 Z_2 e^2}{\hbar v}\right)$$

S(E) nuclear factor not sensitive to E (take it as a constant)

A temperature of $2.3 \times 10^6 K$ is about 0.03keV

The temperature in the center of the Sun is $1.5 \times 10^7 K$

or only 0.2keV

The peak of the Coulomb barrier (for p+p) is 500keV

So even when there is penetration through the barrier it is very very slow

S(E) for the p+p reaction is particularly small!

$$S_{pp}(E) = 4.1 \times 10^{-22}\, keVbarn$$

For example the reaction: $D^2 + p \rightarrow He^3 + \gamma$

$$S_{D+p}(E) = 2.5 \times 10^{-4}\, keVbarn$$

$$1\text{barn} = 10^{-24}\, cm^2$$

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Why is the p+p reaction so slow?

When Hydroen fuses into Helium two protons must convert into neutrons. This conversion is carried out by the weak force (which controls the β decay).

All β decays are slow. In this case two protons must meet inside the nucleous and one of them must decay into a neutron during the stay together.

The most frequent process is simple scattering of the two protons.

simple scattering

$p + p \rightarrow p' + p''$

$p + p \rightarrow D^2 + e^+ + \nu + 0.42\,\text{MeV}$

desired reaction

e^+ **- positron, ends it life in annihilation with** e^-

ν - neutrino, a particle with a very weak interaction that escapes from the sun

What is the life time of a proton in the sun?

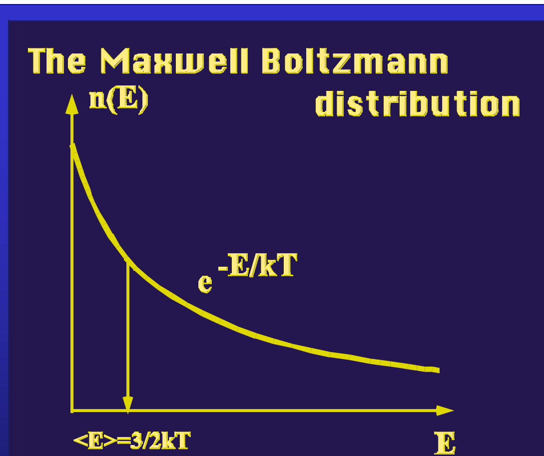
Or

For how long will the hydrogen supply last?

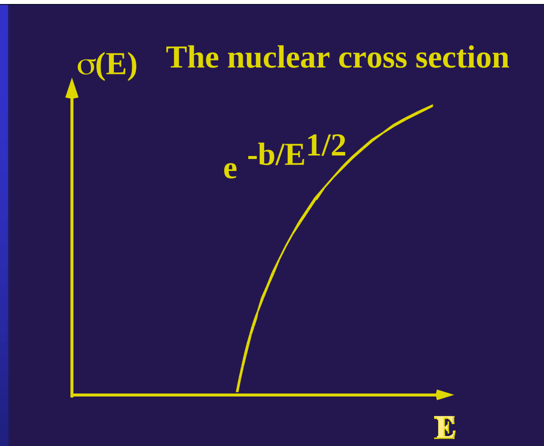
$$l(mean - free - path) = \frac{1}{\sigma n}$$

$$\tau \ (life - time) = \frac{1}{\sigma \ nv}$$

As s is a sensitive function of the energy (because of the penetration) so is the life time of the protons.

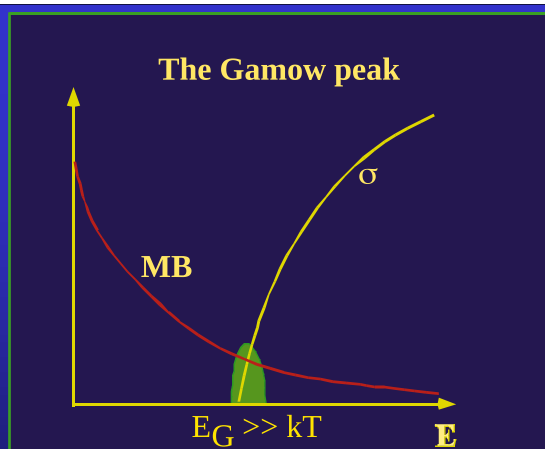


The protons in the sun can be treated as classical particles



The nuclear cross section rises quickly with energy while the number of particles decreases quickly with energy

This is essentially the penetration which causes the fast change in E



Only particles in the Gamow peak have a contribution to the reaction rate.

The energy of the Gamow peak is given by:

The age of the sun is determined by the following condition:

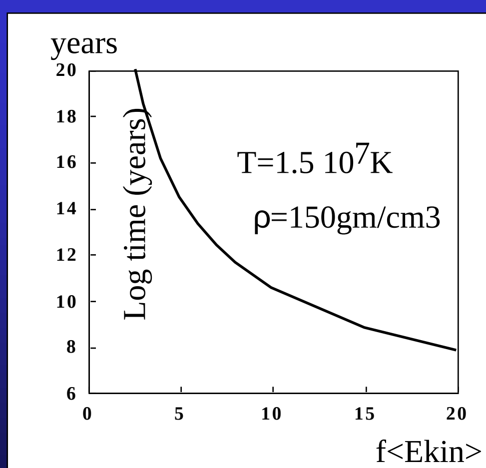
The nuclear reactions in the core must generate the luminosity which comes out from the surface

The luminosity from the surface is determined by the physical conditions on the surface of the Sun. This is atomic physics.

As the kinetic energy of the protons increases so does the reaction rate

The rate of the nuclear reactions will determine the temperature in the core. This is nuclear physics.

The proton life time (against proton capture) in the Sun



The life-time is extremely sensitive to Tc

As the energy released per nuclear reaction is very large, even slow reactions can supply the luminosity of the Sun.

The extreme slowness of the nuclear reactions with the large energy release per reaction, give the sun a long life-time.

In a self gravitating sphere of the mass of the sun the reaction rate is such that the total luminosity is Lsun and the lifetime about 10 billion years.

It is the long lifetime of the sun (due to its dimensions and the physics) which provide the required setup on the Earth for the development of life and advanced civilization.

End of

The structure of