THE SUN

- Mass $M_\odot = 1.99 \times 10^{33}$ g.

  .... 99.9 % of mass of solar system ......

- Radius $R_\odot = 6.96 \times 10^{10}$ cm

- Average density 1.4 g/cm^3

The Sun is an 'average' star :

stellar masses range from $0.1\, M_\odot$

to (?) $100\, M_\odot$

'average' evolutionary state.

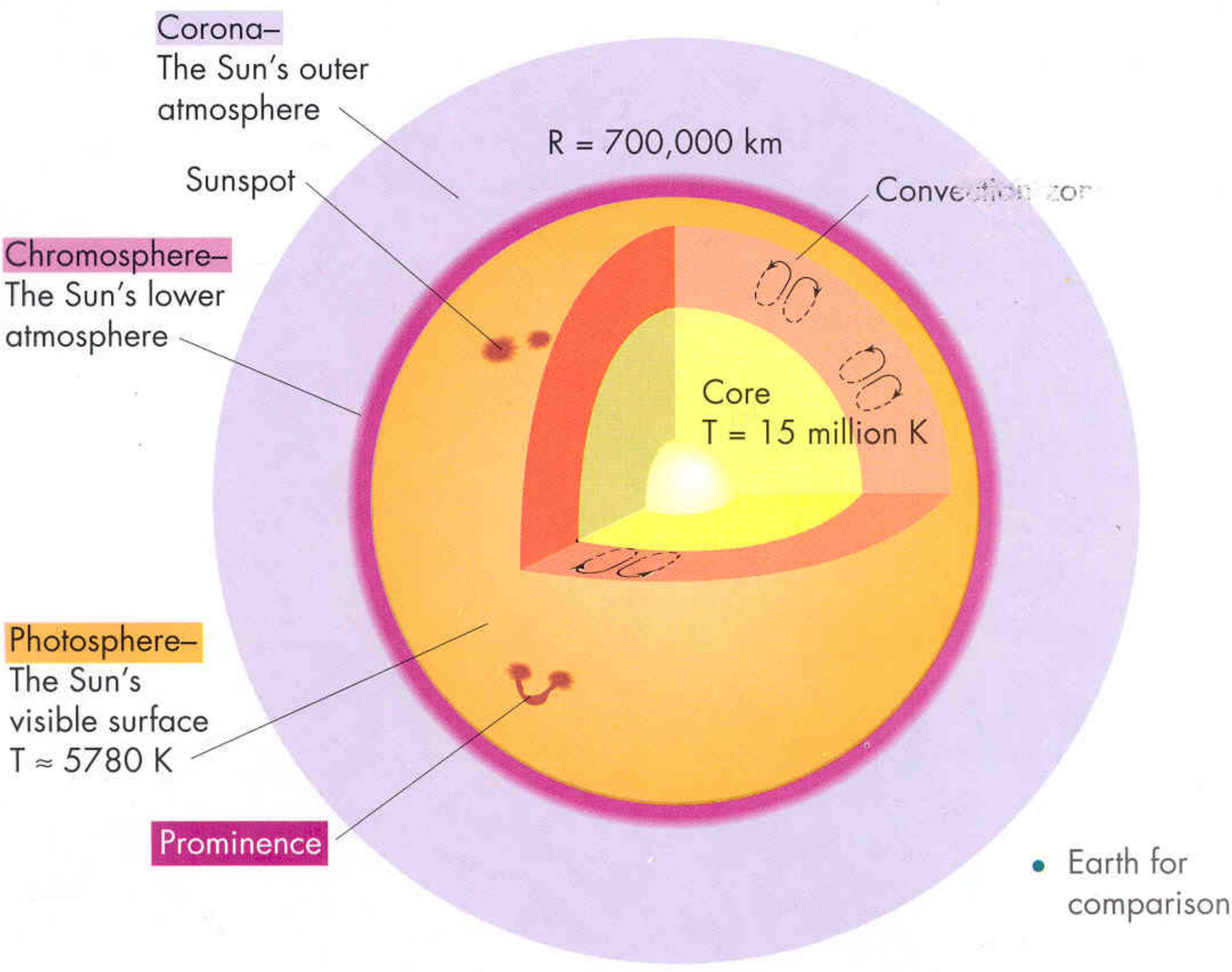
- luminosity : total energy / sec given off by Sun

  $L_\odot = 3.83 \times 10^{33}$ ergs/sec

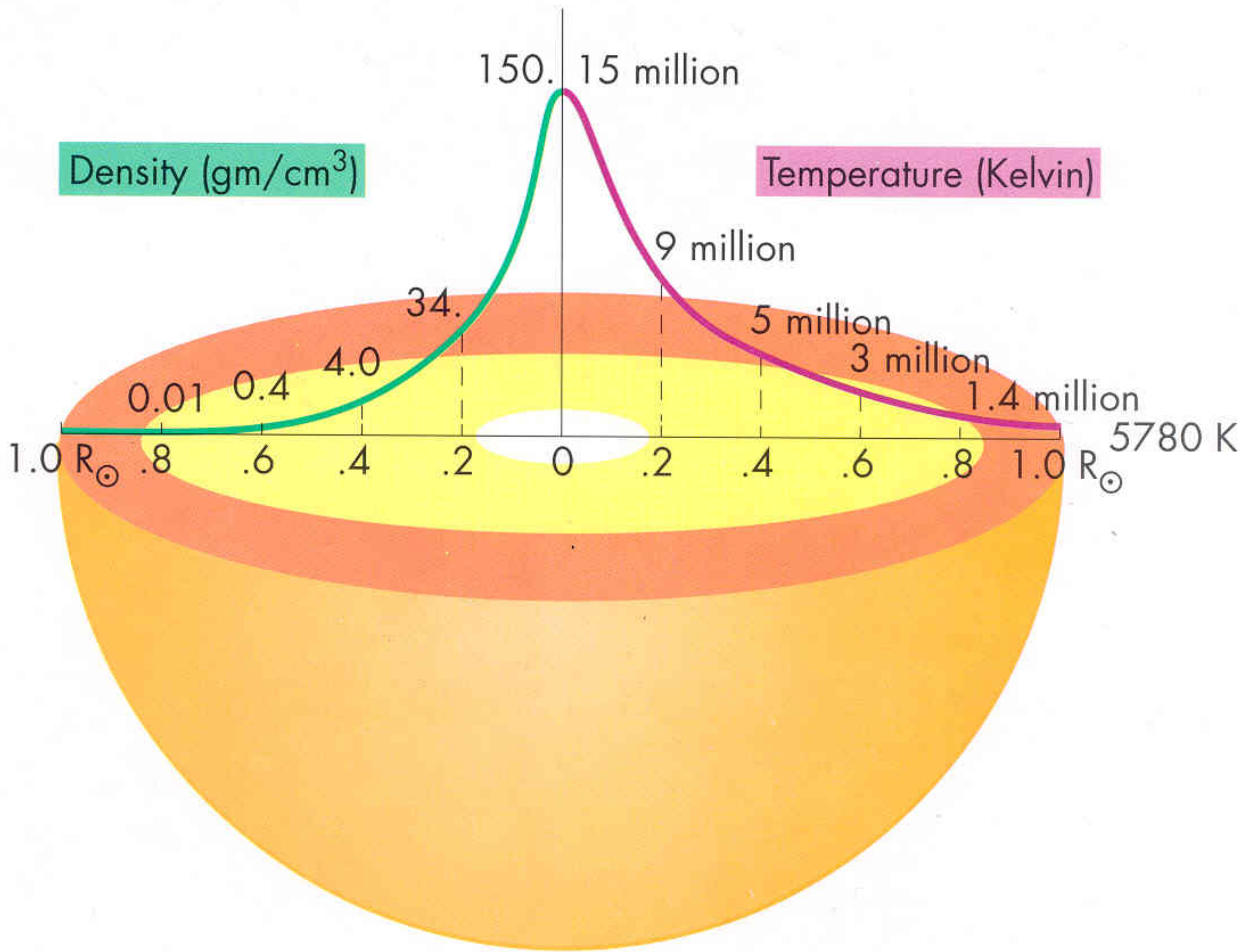
- Temperature at photosphere (surface)

  5800 K

The Sun's interior and atmosphere (Fig. 10-1)



Density and temperature of the Sun (Fig. 10-2)



The Sun as an 'average' star

HR diagram shows there are stars that are

- 10^5 × more luminous
  100 × more massive
  4 × hotter

AND

- 10^4 times less luminous
- 10 times less massive
- 6 times cooler

Fusion reactions

The first nuclear reactions made on Earth were fission ones: splitting apart large nuclei

Q Why is it so difficult to make a fusion reaction work on Earth?

→ Coulomb barrier

Nucleosynthesis

Fusion reactions

(a) in Big Bang, Universe was very hot and dense, and some light elements (up to Li^7) were produced. Measurements of 'primordial' abundances of these elements, especially He^4, show very good agreement with predictions — strong confirmation of Big Bang

(b) anything heavier than Li was made in stars.

Proton-proton chain:

$$H^1 + H^1 \rightarrow D^2 + \beta^+ + \nu$$

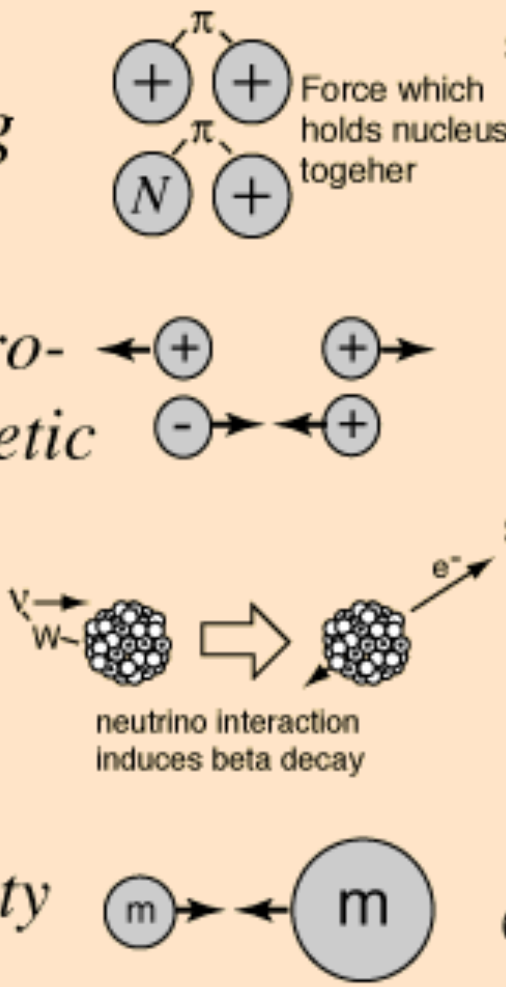
D^2 burning:

$$D^2 + H^1 \rightarrow He^3 + \gamma$$

$$He^3 + He^3 \rightarrow He^4 + 2H^1$$

Need very high temperatures to overcome Coulomb barrier

Fundamental Forces

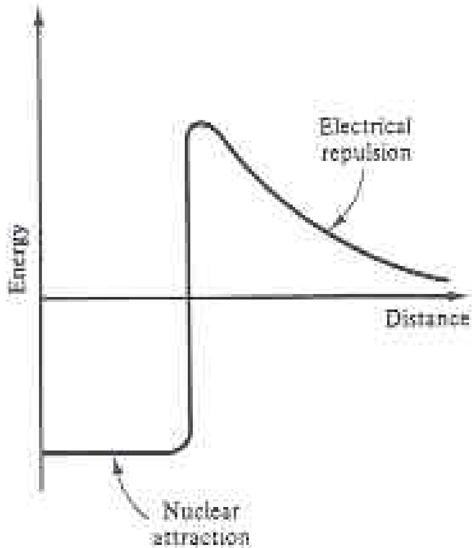


Force	Strength	Range (m)	Particle
Strong	1	10^{-15} (diameter of a medium sized nucleus)	gluons, π(nucleons)
Electro-magnetic	$\frac{1}{137}$	Infinite	photon mass = 0 spin = 1
Weak	10^{-6}	10^{-18} (0.1% of the diameter of a proton)	Intermediate vector bosons W^+, W^-, Z_0, mass > 80 GeV spin =1
Gravity	6×10^{-39}	Infinite	graviton ? mass = 0 spin = 2

http://hyperphysics.phy-astr.gsu.edu/hbase/forces/funfor.html

THE FUSION BARRIER

Figure 9.3 The potential energy for two protons as a function of distance. This includes the electrical force and a model for the nuclear force.



To combine two protons, they need to have sufficient k.e. to get close enough to overcome repulsive force

Maxwell-Boltzmann distⁿ:

particle energies distributed like $e^{-E/kT}$

Tunneling thru the Coulomb barrier

We can calculate what temperature is required to simply slam those two protons thru the Coulomb barrier, for a Maxwell-Boltzmann distribution of particle velocities:

Particle k.e $$\frac{1}{2}m\langle v^2\rangle = \frac{3}{2}kT = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r}$$

Evaluating, we find T of order 10^{10} K;

(but the Sun's central temp is only 10^7 K …)

Quantum mechanics helps out

Heisenberg uncertainty principle says it's never possible to know a particle's position and momentum exactly:

$$\Delta x \Delta p \sim \hbar$$

Thus there is a finite probability that two protons will be close enough to surmount the Coulomb barrier

Doing a similar calculation but setting the particle separation equal to one proton wavelength ($\lambda = h/p$) and solving for the temperature, we find that the temperature is of order 10^7 K

So, quantum mechanical tunneling is important for nuclear fusion to occur in the Sun, as well as the high kinetic energy of the protons

PROTON - PROTON CHAIN

① $p + p \rightarrow d + e^+ + \nu$

weak interaction (neutrino produced)

goes very slowly, needs $T \sim 10^7$ K

② $d + p \rightarrow {}^3He + \gamma$

(more quickly)

③ ${}^3He + {}^3He \rightarrow {}^4He + p + p$

(most common)

In total: 4 protons in

1 ${}^4He$ nucleus out, plus

2 positrons, 2 γ rays, 2 neutrinos

Table 5-1 Reactions of the PP chains

Reaction	*Q value, Mev*	*Average ν loss, Mev*	*S_0, kev barns*	*$\frac{dS}{dE}$, barns*	*B*	*τ_{12}, years*†
$H^1(p,\beta^+\nu)D^2$	1.442	0.263	3.78×10^{-22}	4.2×10^{-24}	33.81	7.9×10^9
$D^2(p,\gamma)He^3$	5.493		2.5×10^{-4}	7.9×10^{-6}	37.21	4.4×10^{-8}
$He^3(He^3,2p)He^4$	12.859		5.0×10^3		122.77	2.4×10^5
$He^3(\alpha,\gamma)Be^7$	1.586		4.7×10^{-1}	-2.8×10^{-4}	122.28	9.7×10^5
$Be^7(e^-,\nu)Li^7$	0.861	0.80				3.9×10^{-1}
$Li^7(p,\alpha)He^4$	17.347		1.2×10^2		84.73	1.8×10^{-5}
$Be^7(p,\gamma)B^8$	0.135		4.0×10^{-2}		102.65	6.6×10^1
$B^8(\beta^+\nu)Be^{8*}(\alpha)He^4$	18.074	7.2				3×10^{-8}

† Computed for $X = Y = 0.5$, $\rho = 100$, $T_6 = 15$ (sun).

Proton-proton chain is basic energy source of Sun.

Nuclear fusion will continue until [redacted]

[redacted] the Sun's core has been converted to ^4He.

Energy released by converting 4 protons to one ^4He atom:

Since $E = mc^2$, can work this out by comparing masses

$m_p = 1.6726 \times 10^{-24}$ g

mass of ^4He nucleus $= 6.6464 \times 10^{-24}$ g

$4m_p = 6.6904 \times 10^{-24}$ g

$4m_p - m(^4He) = 0.007\, m_p$

~~(misprint [illegible])~~

Assume most of Sun is protons, and 10% will participate in fusion

Available mass = $0.1\ M_\odot$.

Available energy = $0.007\, m_p . c^2$ per proton

Total energy = $0.007 \times 2 \times 10^{32} \times (3 \times 10^{10})^2$

= 1.3×10^{51} ergs

Problem : what is the lifetime of the Sun with this energy production ?

(c) In massive stars with temperature > Sun's, another fusion process, needing ^{12}C as catalyst, operates to convert $H \rightarrow He$:

$$^{12}C + {^1H} \rightarrow {^{13}N} + \gamma$$

$$^{13}N \rightarrow {^{13}C} + e^+ + \nu \quad (\beta \text{ decay})$$

$$^{13}C + {^1H} \rightarrow {^{14}N} + \gamma$$

$$^{14}N + {^1H} \rightarrow {^{15}O} + \gamma$$

$$^{15}O \rightarrow {^{15}N} + e^+ + \nu \quad (\beta \text{ decay})$$

$$^{15}N + {^1H} \rightarrow {^{12}C} + {^4He}$$

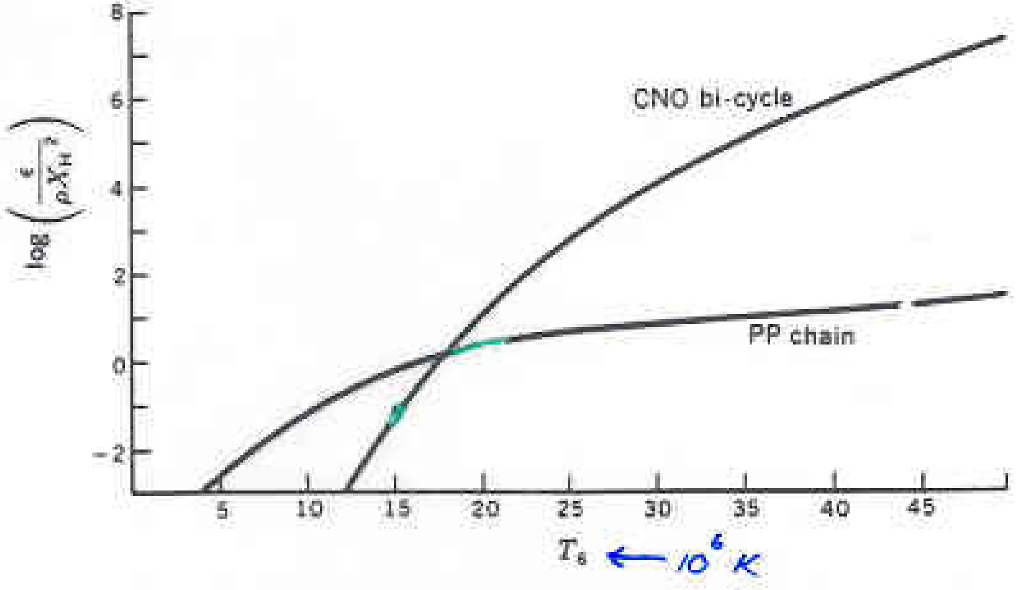


Fig. 5-16 A comparison of thermonuclear power from the PP chains and the CNO cycle. Both chains are assumed to be operating in equilibrium. The calculation was made for the choice $X_{CN}/X_H = 0.02$, which is representative of population I composition.

OTHER FUSION REACTIONS

(need hotter temperatures than core of Sun)

TRIPLE ALPHA PROCESS

$$^4He + {}^4He \rightarrow {}^8Be + \gamma$$

(before ^8Be decays) $^4He + {}^8Be \rightarrow {}^{12}C + \gamma$

This needs temperature $\sim 10^8$ K

NEUTRON CAPTURE

For high atomic number nuclei, electrical repulsion too high for fusion with charged particles. Use neutrons.

$$(Z, A) + n \rightarrow (Z, A+1)$$

- slow w.r.t. beta decay:

$$(Z, A+1) \rightarrow (Z+1, A) + e^- + \bar{\nu}$$

"s-process"

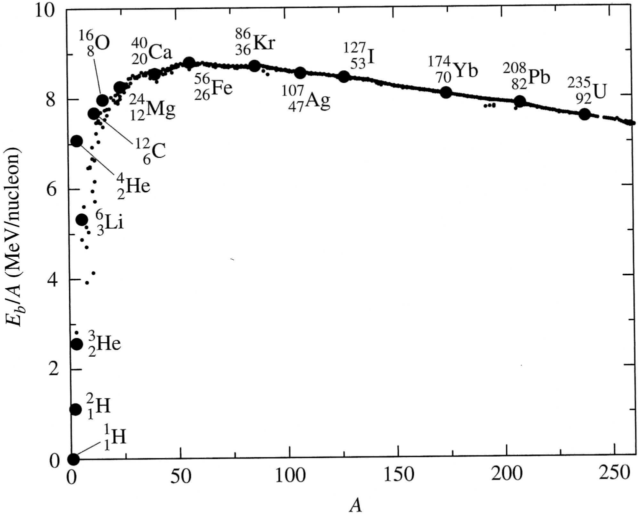


FIGURE 10.9 The binding energy per nucleon, E_b/A, as a function of mass number, A. Not several nuclei, most notably $^{4}_{2}$He (see also $^{12}_{6}$C and $^{16}_{8}$O), lie well above the general trend of th nuclei, indicating unusual stability. At the peak of the curve is $^{56}_{26}$Fe, the most stable of all nuc

Binding energy of nucleus : work required to disassemble it.

Higher binding energy ⇒ a more stable nucleus.

Question : which isotope has the most stable nucleus?