

THE SUN

Radius & Temperature

- Mass $M_0 = 1.99 \times 10^{33}$ g.
..... 99.9 % of mass of solar system
- Radius $R_0 = 6.96 \times 10^8$ cm
- Average density 1.4 g/cm^3

The Sun is an 'average' star :

stellar masses range from $0.1 M_0$

to (?) $100 M_0$

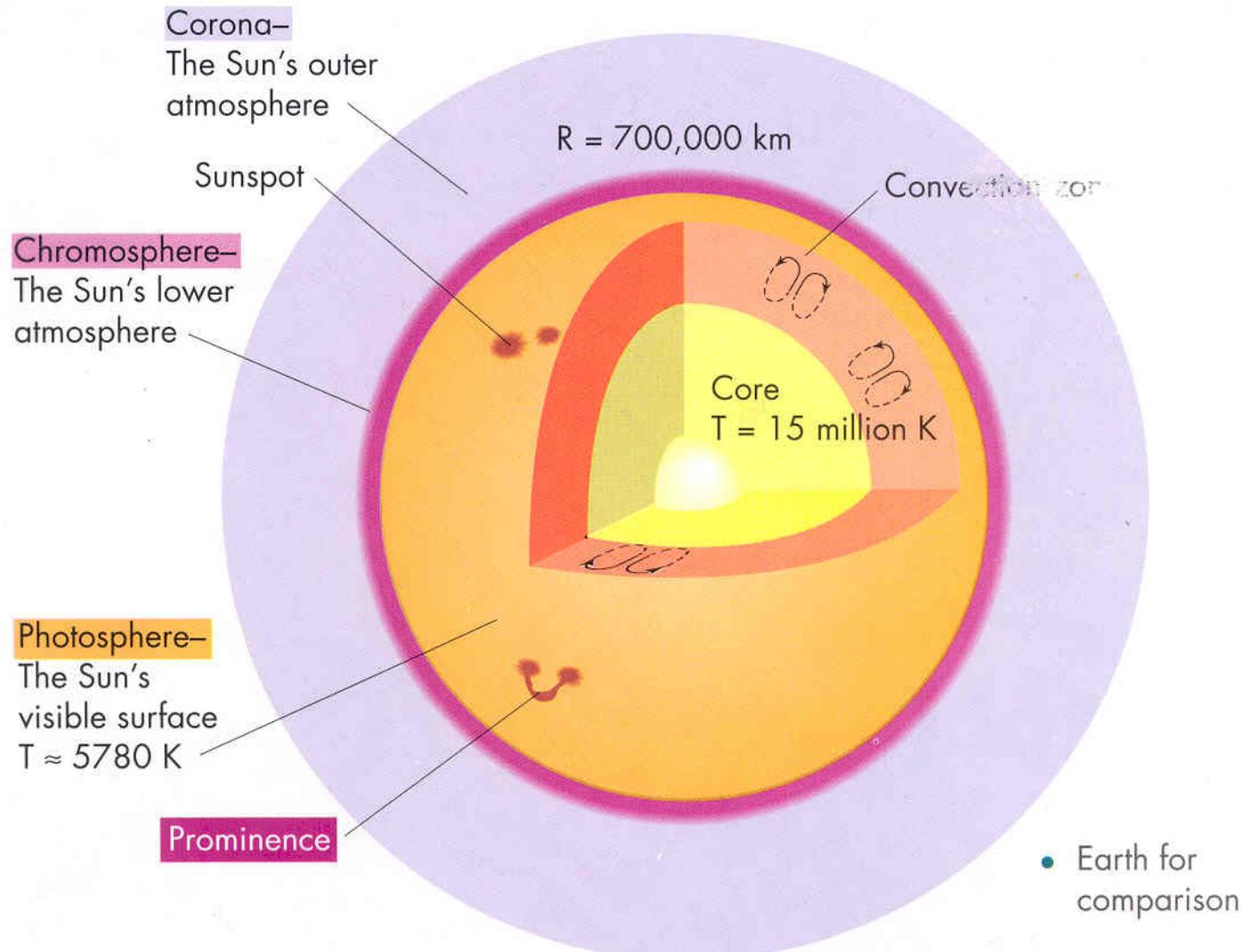
'average' evolutionary state.

- Luminosity : total energy / sec given off by Sun

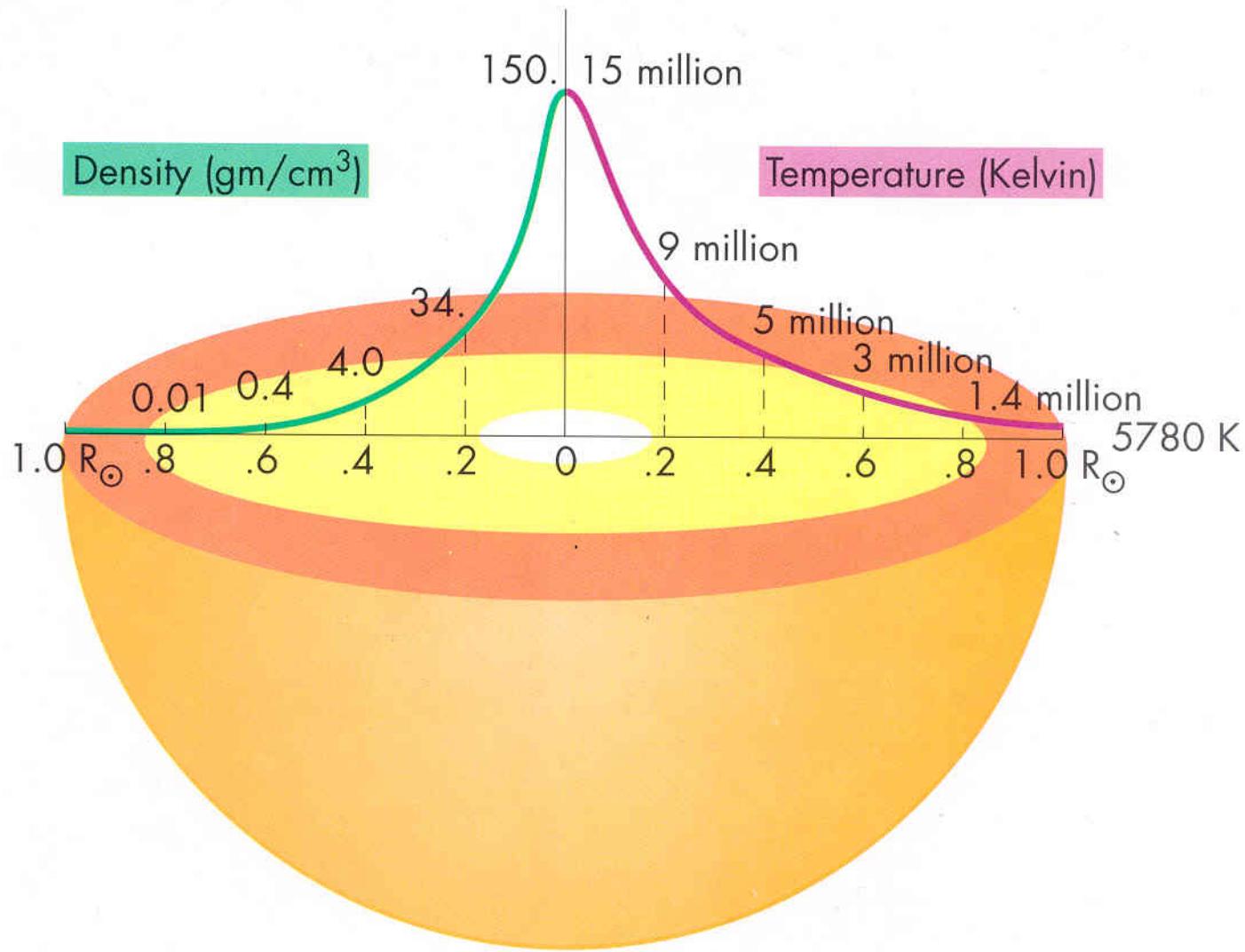
$$L_0 = 3.83 \times 10^{33} \text{ ergs/sec}$$

- 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

- $10^5 \times$ more luminous
- 100 \times more massive
- 4 \times 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



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

→ Coulomb barrier

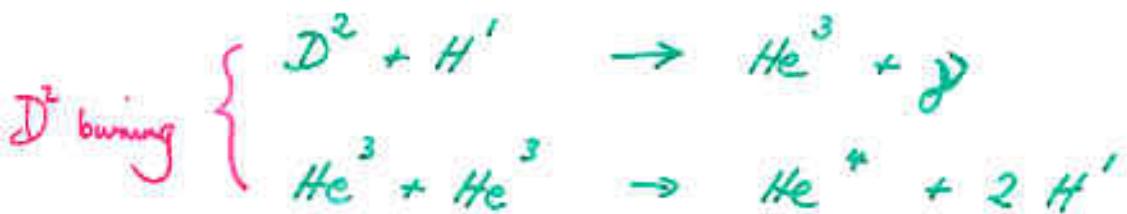
Nucleosynthesis

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

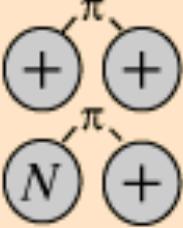
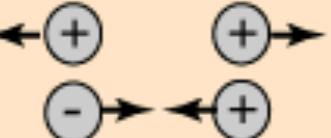
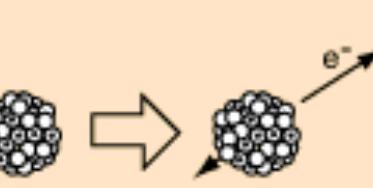
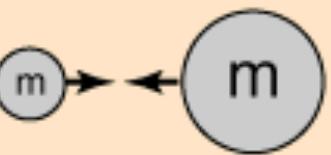
(b) anything heavier than Li was made in stars.

Proton-proton chain:



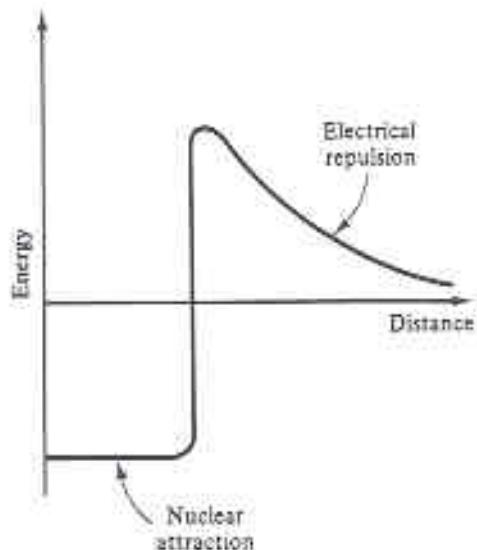
Need very high temperatures to overcome Coulomb barrier

Fundamental Forces

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

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 dist'n:
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:

$$\text{Particle k.e} \quad \frac{1}{2}m\langle v^2 \rangle = \frac{3}{2}kT = \frac{1}{4\pi\epsilon_0} \frac{e^2}{r}$$

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



weak interaction (neutrino produced)
goes very slowly, needs $T \sim 10^7 K$



(more quickly)



(most common)

In total : 4 protons in

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

2 positrons, 2 γ rays, 2 neutrinos

Table 5-1 Reactions of the PP chains

Reaction	Average			$\frac{dS}{dE}$	B	τ_{12} , years†
	Q value, Mev	ν loss, Mev	S_0 , kev barns			
$H^1(p, \beta^+ \nu) D^2$	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
$B^8(\beta^+ \nu) Be^{8*}(\alpha) He^4$						3×10^{-8}
	18.074	7.2				

† 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 ~~the~~ the Sun's core has been converted to ${}^4\text{He}$.

Energy released by converting 4 protons to one ${}^4\text{He}$ atom:

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

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

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

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

$$4m_p - m({}^4\text{He}) = 0.007 m_p \times 4$$

~~(missing is 51, because 1)~~

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

$$\begin{aligned}\text{Total energy} &= 0.007 \times 2 \times 10^{32} \times (3 \times 10^{10})^2 \\ &= 1.3 \times 10^{51} \text{ ergs}\end{aligned}$$

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 $\text{H} \rightarrow \text{He}$:

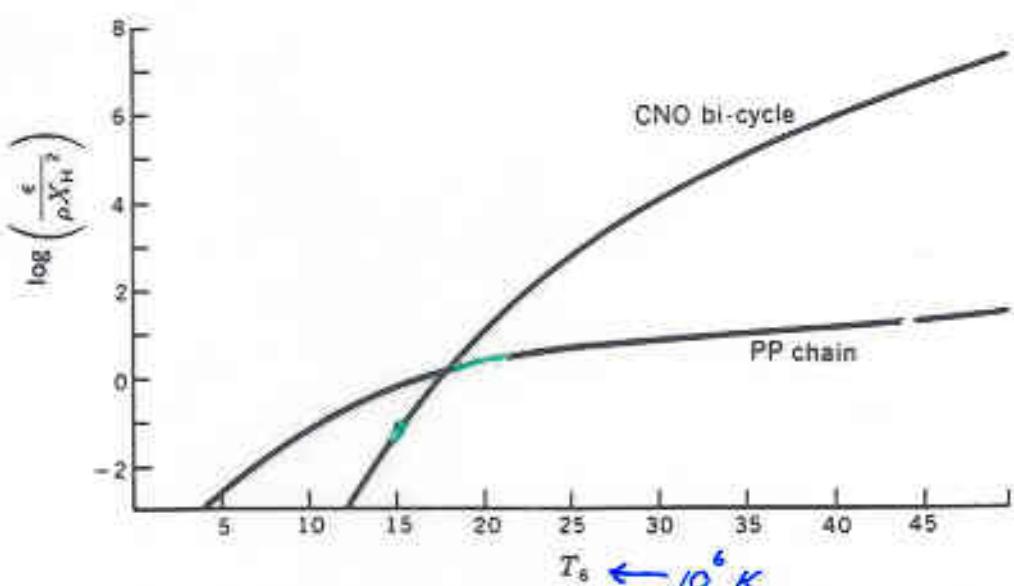


Fig. 5-16 A comparison of thermonuclear power from the PP chains and the CNO cycle. Both chains are assumed to be operating in equilibrium. The calculation was made for the choice $X_{\text{CN}}/X_{\text{H}} = 0.02$, which is representative of population I composition.

OTHER FUSION REACTIONS

(need hotter temperatures than core of Sun)

TRIPLE ALPHA PROCESS



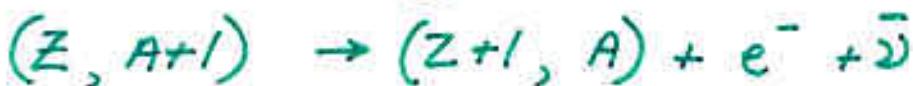
This needs temperature $\sim 10^8 \text{ K}$

NEUTRON CAPTURE

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



- slow w.r.t. beta decay:



"s-process"

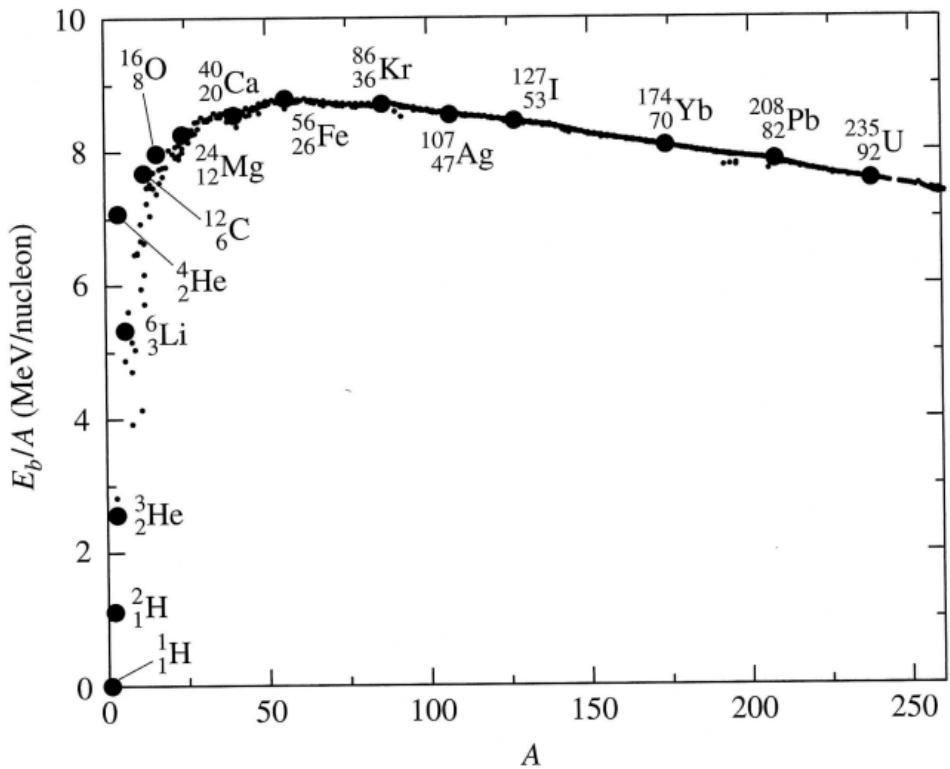


FIGURE 10.9 The binding energy per nucleon, E_b/A , as a function of mass number, A . Note that several nuclei, most notably ^4_2He (see also $^{12}_6\text{C}$ and $^{16}_8\text{O}$), lie well above the general trend of the nuclei, indicating unusual stability. At the peak of the curve is $^{56}_{26}\text{Fe}$, the most stable of all nucl

Binding energy of nucleus : work required to disassemble it.

Higher binding energy \Rightarrow a more stable nucleus.

Question : which ^{isotope} has the most stable nucleus ?