PHAS 1202

3 - Stellar evolution

Key conceptual topics:

- Why are stars not eternal?
- Why is there such a rich diversity of stars?
- How do we know about stellar evolution (over billions of yrs)?

- What are the different stellar life paths?
- What factors do the life paths depend on?

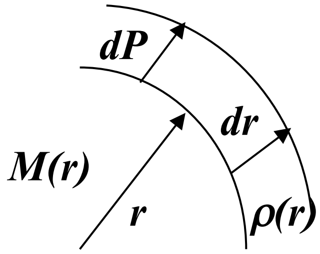
- What are the end-states of evolution?
- What is cosmic recycling?

Stellar energy generation

Stars are generally very stable. Assuming that only the inward gravitational force and the outward (thermal) pressure are at work in the gas, a star is in hydrostatic equilibrium:

Gravitational acceleration

$$\boxed{\frac{dP}{dr} = \frac{-GM(r)\rho(r)}{r^2}} \quad [\mathrm{N\ m^{-3}}]$$



where P: outward pressure (force per unit area)

r: radius from the centre of the star

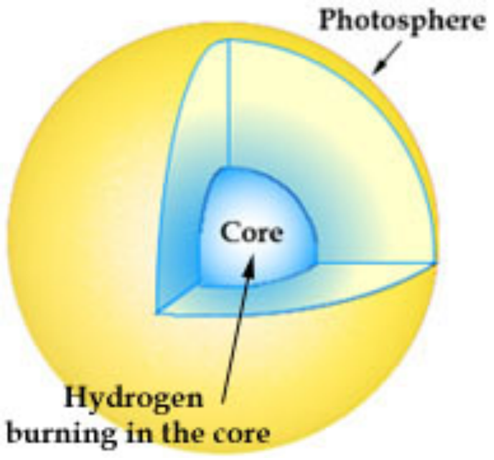
G: gravitational constant

$M(r)$: mass within radius r

$\rho(r)$: density at radius r

Stellar nucleosynthesis

For the Sun: $\langle P \rangle \sim 10^{14}$ Pa = 10^{14} N m^{-2} Sun internal (core) temperature $\langle T \rangle \sim 10^{7}$ K



Nuclear fusion (H ➔ He)

…700 million tons of H into 695 million tons of He every second! ➔ E = mc^2

…but this is a finite fuel supply

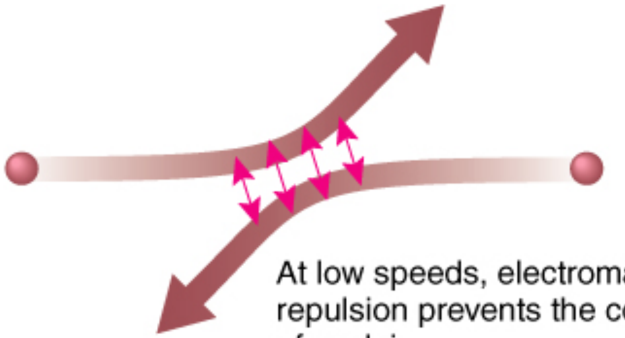
…e.g. the Sun will run out of it 4.6 billion years from now!!

Nuclear fusion reactions

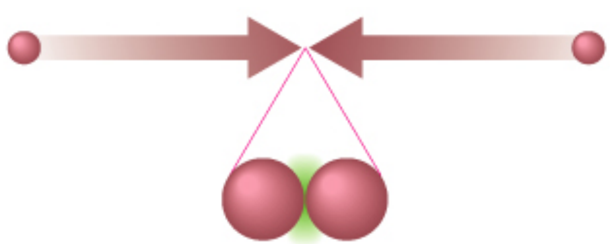
Fusion is the process by which small nuclei of atoms are joined into larger ones → vast energy is generated.

Hydrogen and Helium are the most abundant elements in the Universe, so their fusion is important and they are the most common fuels.

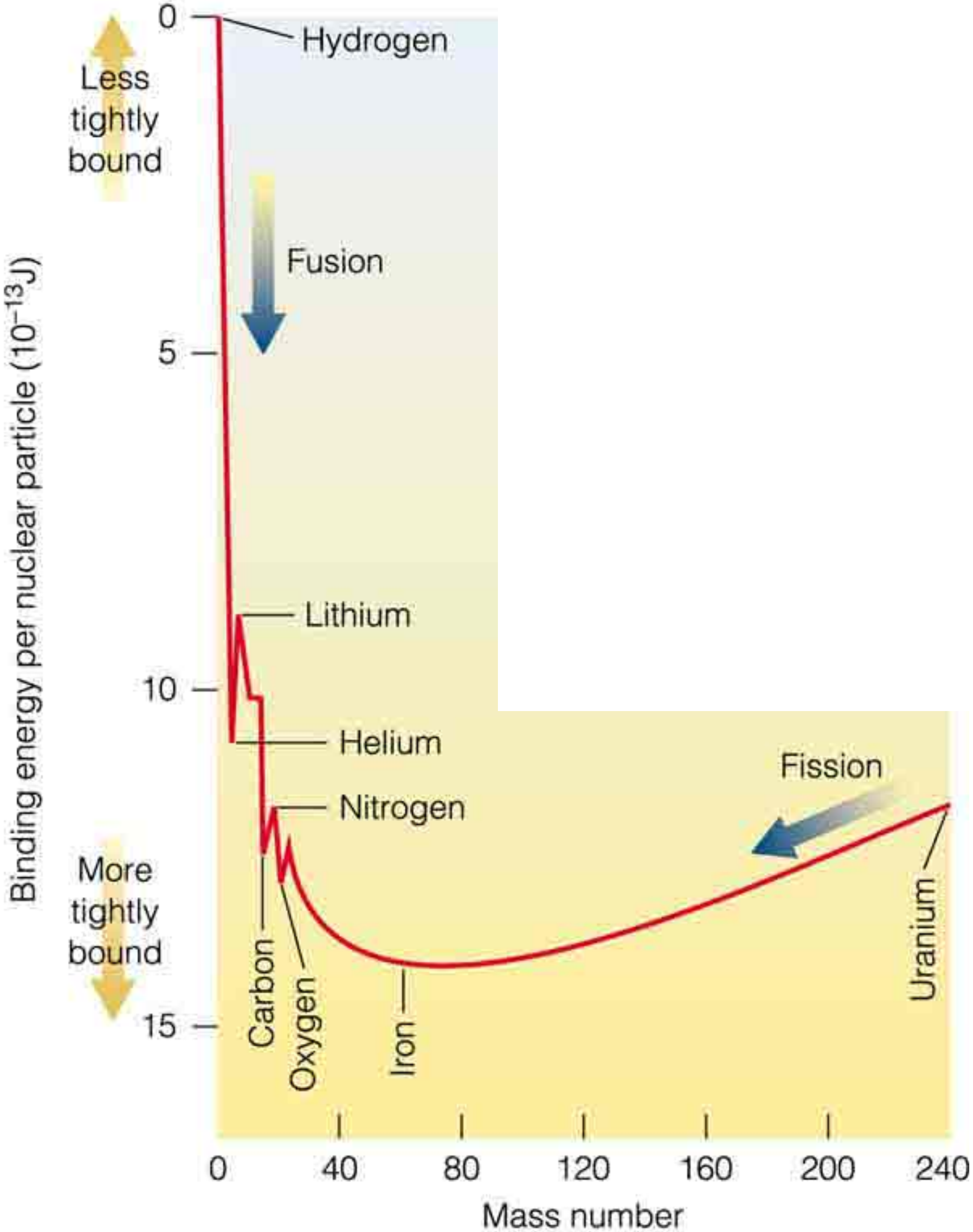
Electromagnetic forces would keep two protons away from each other. However quantum mechanics allows them to 'tunnel' through the repulsion barrier and allows nuclear forces to 'turn on' when they are close enough (~10^{-15} m).



At low speeds, electromagnetic repulsion prevents the collision of nuclei.



At high speeds, nuclei come close enough for the strong nuclear force to bind them together.



Fusion: light bind together to form heavy

Fission: break up heavy to form light

Shown is the energy released per fusion/fission event; this is called the **binding energy**.

Note that a relatively large amount is released from hydrogen to helium.

Still, it takes 10^{38} reactions per second to support the sun!

Mass deficit and binding energy

The simplest fusion reaction, becoming significant at T ~ 10^7 K, involves 2 protons (H nuclei) and 2 neutrons combined in the next stable nucleus, ^{4}He (α particle).

Atomic mass of proton: 1.0078 amu
Atomic mass of 4 protons: 4.0312 amu
Atomic mass of ^{4}He nucleus: 4.0026 amu → mass deficit of 0.0286 amu

amu: atomic mass unit (1/12 of the mass of a ^{12}C atom, = 1.66 x 10^{-27} kg)

Mass deficit = nuclear binding energy that holds nucleus together

Mass deficit converted into energy according to Einstein's equation:

$$E = mc^2 = 0.0286 \times (1.66 \times 10^{-27}) \times (9 \times 10^{16}) \text{ Joule}$$
$$= 4.3 \times 10^{-12} \text{ Joule}$$

Total nuclear energy in the Sun

Assume 10% of H in the Sun (temperature and density are high enough only in the core) converts into ^{4}He.

Fraction of mass liberated into energy: $\frac{0.0286}{4.0312} = 0.0071$
(i. e. efficiency ~ 0.7%)

So

$$\boxed{\begin{aligned} E_{\text{total}} &= mc^2 = 0.0071 \times 0.1 \times M_{\text{Sun}} \times c^2 \\ &= 0.0071 \times 0.1 \times (2 \times 10^{30}) \times (9 \times 10^{16}) \text{ Joule} \\ &= 1.3 \times 10^{44} \text{ Joule} \end{aligned}}$$

Then the Sun can continue to radiate for

$$\boxed{\frac{E_{\text{total}}}{L_{\text{Sun}}} = \frac{1.3 \times 10^{44}}{4 \times 10^{26}} \text{ s} = 3 \times 10^{17} \text{ s} = 10^{10} \text{ yr}}$$

Solar system age: 5 x 10^9 years ➔ Sun is ~ halfway through its H-burning phase

Fusion processes for H → He

Simultaneous collision of 4 protons very unlikely!

Two thermonuclear processes lead to conversion H → He:

Proton-proton chain (PP)

Dominates at $T < 2 \times 10^7$ K (Sun-like stars)

Particles involved: Protons, neutrons, electrons,

positrons, e^+ (= electrons, but charge = $+e$)

neutrinos, ν (very small mass, no charge, only energy and spin)

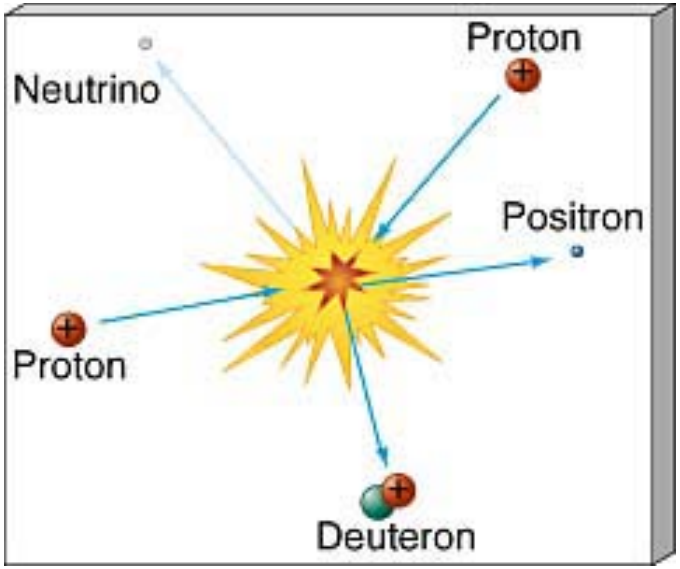
SUMMARY -- Hydrogen burning (1)

The PP Chain

The PP chain has three main branches called the PPI, PPII and PPIII chains.

PPI Chain	PPII Chain	PPIII Chain
1 $p + p \rightarrow d + e^+ + \nu_e$	3' $^3He + {}^4He \rightarrow {}^7Be + \gamma$	4" $^7Be + p \rightarrow {}^8B + \gamma$
2 $d + p \rightarrow {}^3He + \gamma$	4' $^7Be + e^- \rightarrow {}^7Li + \nu_e$	5" $^8B \rightarrow {}^8Be + e^+ + \nu_e$
3 $^3He + {}^3He \rightarrow {}^4He + 2p$	5' $^7Li + p \rightarrow {}^4He + {}^4He$	6" $^8Be \rightarrow 2{}^4He$

What about those **neutrinos**…?



Neutrinos pass right out of the sun… →and provide direct view of sun's core!

<u>About 1,000,000,000,000 neutrinos pass through your body every second</u> and none of them interact!

If we could measure them (count them per unit time), we could test our theory of the nuclear reactions in the sun.

Energy generation in stars → neutrinos

Only energy released as γ-rays will interact with electrons and protons and heat the interior of a star, such as the Sun. This heating supports the star and prevents it from collapsing under its own weight.

Neutrinos do not interact significantly with matter and do not help support the Sun against gravitational collapse. In a few seconds they escape.

The neutrinos in the PP1, PP2 and PP3 chains carry away 2.0%, 4.0% and 28.3% of the energy respectively.

Thus it will be possible to detect the neutrinos on Earth and verify the theory of the thermonuclear reactions occurring in the Sun (Solar Standard Model = SSM).

Three neutrino 'flavours'

Three types of neutrinos are known:

Nuclear fusion in the Sun produces only neutrinos that are associated with electrons ('electron neutrinos', ν_e) .

Laboratory accelerators or exploding stars produce 'muon neutrinos' (ν_μ) and 'tau neutrinos' (ν_τ), which are associated with the muon and tau particles (leptons heavier than the electron).

Solar Neutrino Problem

From H burning in the Sun's core, ~ 2×10^{38} neutrinos s^{-1} expected to be produced ➔ ~ 7×10^{14} neutrinos $m^{-2}\ s^{-1}$ at Earth

Since the 1960s neutrino detectors have been built on the Earth to measure the flux of solar neutrinos and verify the SSM:

Mid -1960s - Raymond Davis, Homestake gold mine (South Dakota, USA) experiment, using a tank of 100,000 gallons of tetrachloroethylene C_2Cl_4 one mile underground:

solar neutrinos transmute $^{37}Cl \rightarrow {}^{37}Ar$ (radioactive)

number of ^{37}Ar atoms ➔ solar neutrino flux

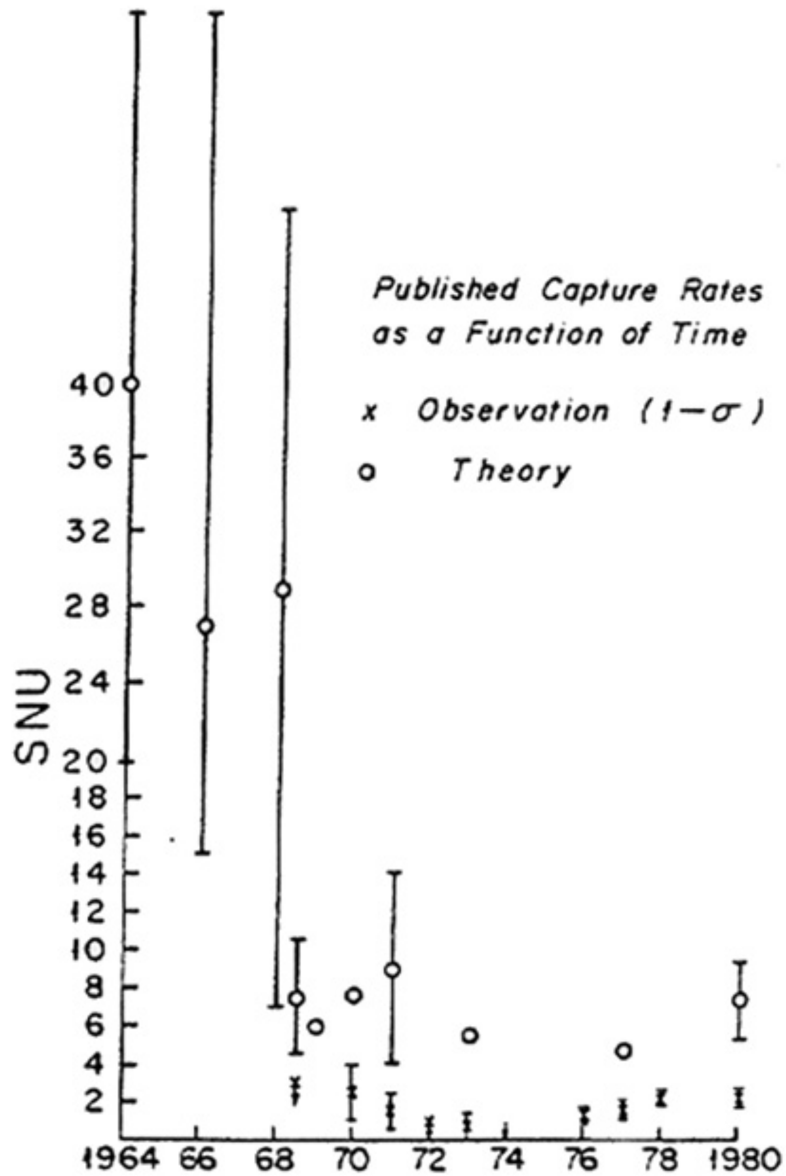
Only 1/3 of expected high-energy (PP3) neutrinos detected

➔ 'Solar Neutrino Problem' (SNP) !

Solar Neutrino Problem...

At the same time that experiments were improving in sensitivity, theoretical modelling of the energy generation in the Sun was evolving →

more and more accurate calculations (particularly by John Bahcall) were carried out to predict the number of expected neutrinos (very dependent on Sun's core temperature):

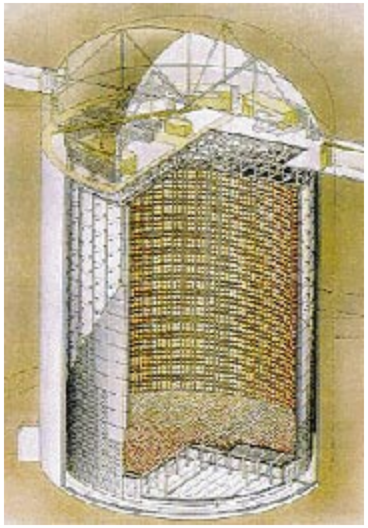


Solar Neutrino Problem...

1989, **Kamiokande** experiment (water detectors) - only 1/2 of expected high-energy PP3 neutrinos

Early 1990s, **GALLEX** (GALLium EXperiment), and **SAGE** (RuSsian American Gallium Experiment) detected just over 1/2 of low-energy neutrinos from PP1 (important because dominant, and calculations more accurate – confirmed PP is the main energy production mechanism in the Sun)

Late 1990s, **Super-Kamiokande** (with some sensitivity to flavours other than electron neutrinos) confirmed high-energy PP3 neutrino deficit by ~50%



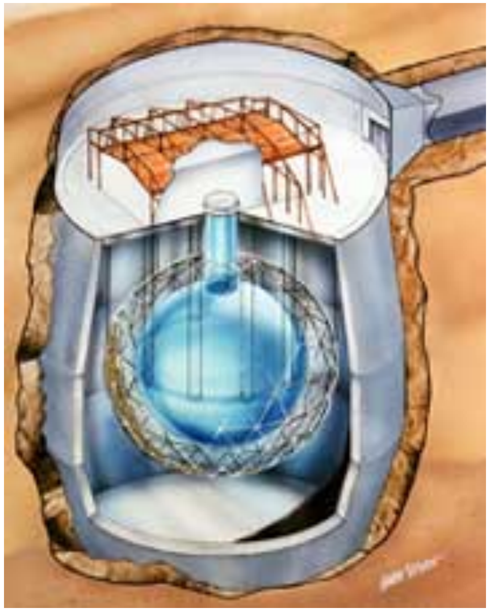
Solar Neutrino Problem

Relative sensitivity of Cl and water experiments to neutrino number and energy suggested **something was happening to neutrinos on their way from Sun to Earth.**

Meanwhile, SSM being tested, and becoming more reliable
➔ Need new neutrino physics? (as suggested by Pontecorvo and Gribov back in 1969) → challenge established Standard Model of Particle Physics!

1999, **SNO** (Sudbury Neutrino Observatory)

heavy water (D_2O) experiment came on-line with similar sensitivity to all three types of neutrinos ➔ detection of ν_μ and ν_τ as well as ν_e



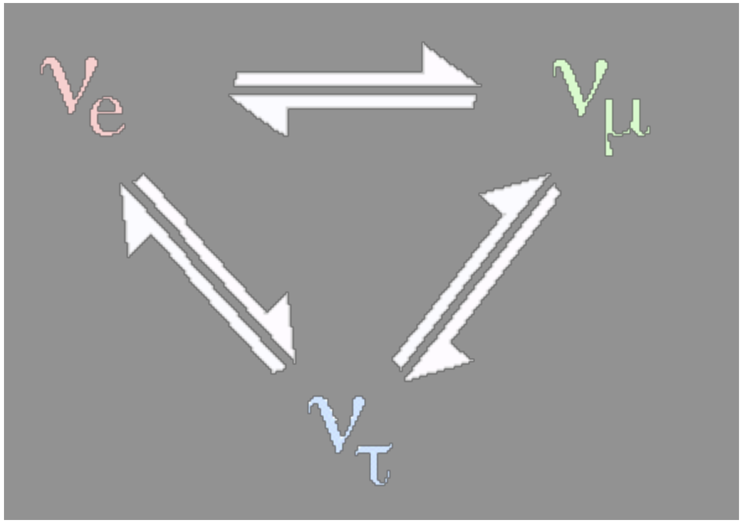
Solution of the Solar Neutrino Problem

18 June 2001, SNO collaboration announced SNP solution:
~2/3 ν_e produced in the Sun transform into ν_μ and ν_τ on their way to Earth

Total number of ν_e, ν_μ, ν_τ is = SSM predictions

Explained by the Mikheyev-Smirnov-Wolfenstein (MSW) effect of 'neutrino oscillations' (enhanced by passage through the Sun)

For neutrino oscillations to occur, neutrinos must have masses (and the Standard Model of Particle Physics has to be revised!)



The mass of neutrinos

Different flavour neutrinos have different masses, with $\boldsymbol{\nu_e}$ being the lightest

From experiments, ν_e mass < 2.2 eV
From cosmology, sum of masses < 1 eV

Among current experiments, MINOS and NEMO3 (with UCL, P&A Dep.t participation) → few 0.1 eV mass sensitivity limit

Future experiments planned may reach mass sensitivity limit ~0.01 eV (SUPERNEMO)

2002, **Nobel Prize in Physics** to Raymond Davis and Masatoshi Koshiba for the detection of cosmic neutrinos

Helium Burning: the triple-α reaction.

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

$$^{8}Be + {}^{4}He \rightarrow {}^{12}C + \gamma$$

Carbon and oxygen burning

$$^{12}C + {}^{12}C \rightarrow {}^{24}Mg + \gamma$$
$$\rightarrow {}^{23}Mg + n$$
$$\rightarrow {}^{23}Na + p$$
$$\rightarrow {}^{20}Ne + \alpha$$
$$\rightarrow {}^{16}O + 2\alpha$$

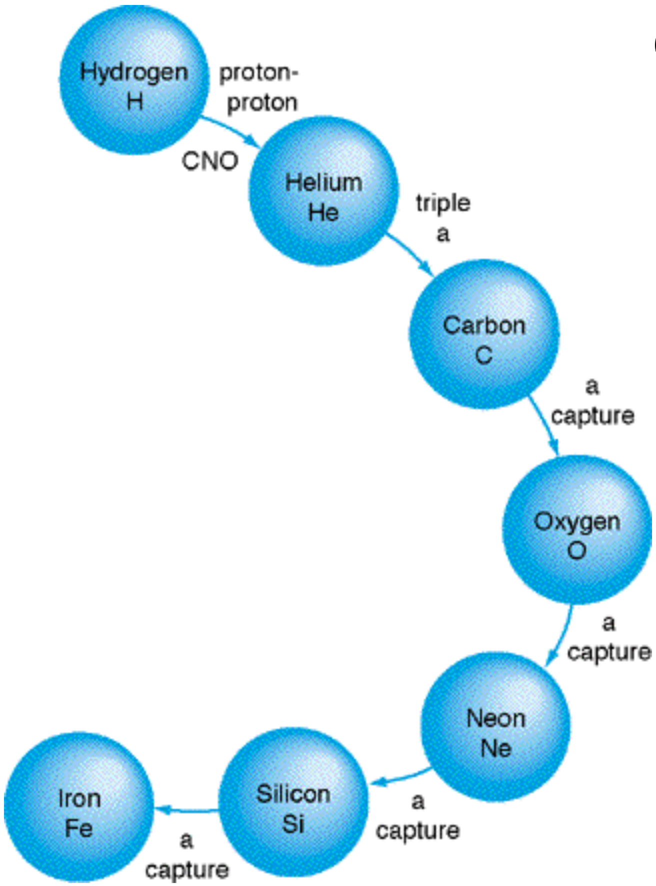
$$^{16}O + {}^{16}O \rightarrow {}^{32}S + \gamma$$
$$\rightarrow {}^{31}S + n$$
$$\rightarrow {}^{31}P + p$$
$$\rightarrow {}^{28}Si + \alpha$$
$$\rightarrow {}^{24}Mg + 2\alpha$$

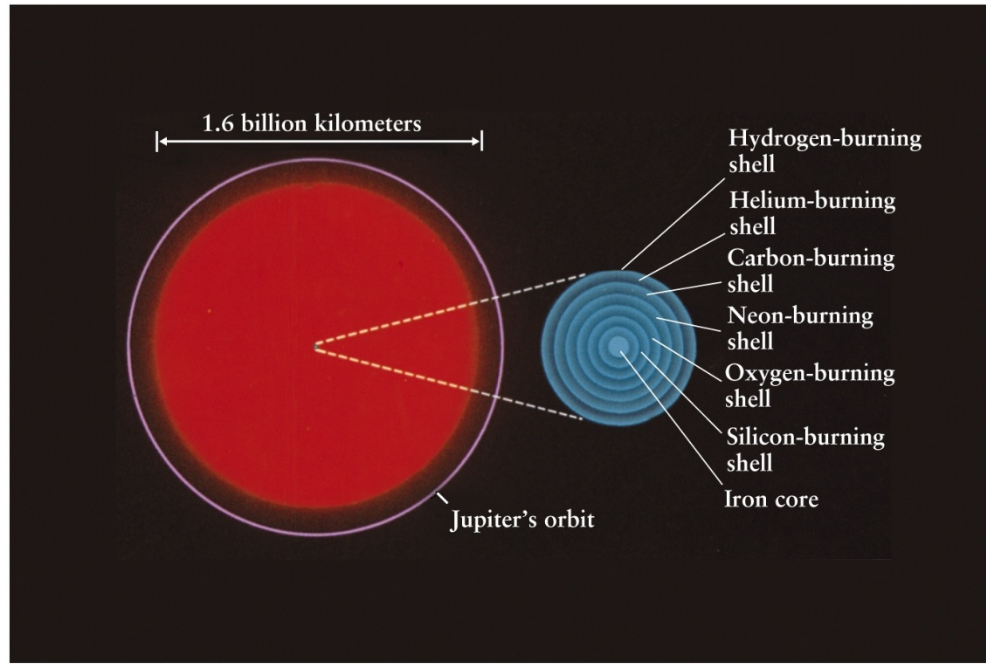
Silicon burning… ➔ Iron

Heavy elements are only manufactured in the cores of <u>massive stars</u>

...including life giving elements!

core temp. > 100 million degrees)





+ rapid nuetron caption in SN ➔ neutron-rich nuclei heavier than Fe

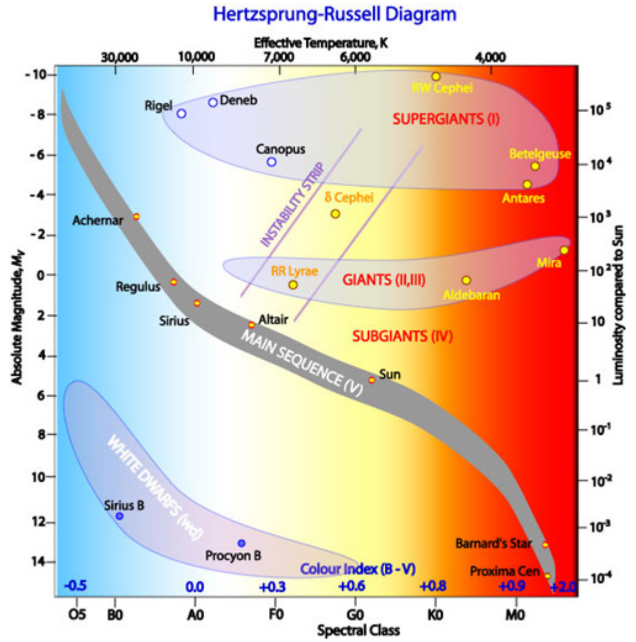
<u>Stellar evolution</u>

Study of physical changes taking place in stars as their composition is altered because of thermonuclear reactions.

General sequence: Protostar → Pre-Main Sequence (PMS) → Main Sequence (MS) → post-Main Sequence

Main physical parameter determining evolution: MASS

Evolutionary track: Plot of points showing <u>time sequence of evolutionary stages</u> of a star on an H-R diagram (which is collection of <u>star snapshots</u>



<u>The birth and evolution of stars</u>

Most (90%) of stars lie on the MS, where stars burning H to He (PP cycles) are in hydrostatic equilibrium.

How do stars get on to the MS, and what happens afterwards?

Stars are born from huge interstellar clouds of gas (mostly in the form of molecular H, i.e. H_2) and dust, which are massive enough to contract gravitationally: <u>collapse starts in free-fall</u> (particles do not collide → no internal pressure): protostar

As density increases, cloud’s core traps (becomes opaque to) IR radiation from dust heated by collisions with molecules, collapse slows down, <u>hydrostatic equilibrium established</u>:

Pre-Main Sequence star

Takes ~ 1 million years to form a PMS star of 1 solar mass

From PMS to MS stars

PMS star shines by slowly contracting, while matter accretes onto its core and the central temperature raises.

Finally, central temperature high enough to start H burning, collapse halts and star is now a real MS star.

Hydrostatic equilibrium maintained by heat from thermonuclear reactions

Takes ~ 20 million years from initial collapse to MS star

Higher mass stars arrive on MS with higher luminosity and temperature.

Main Sequence evolution (1)

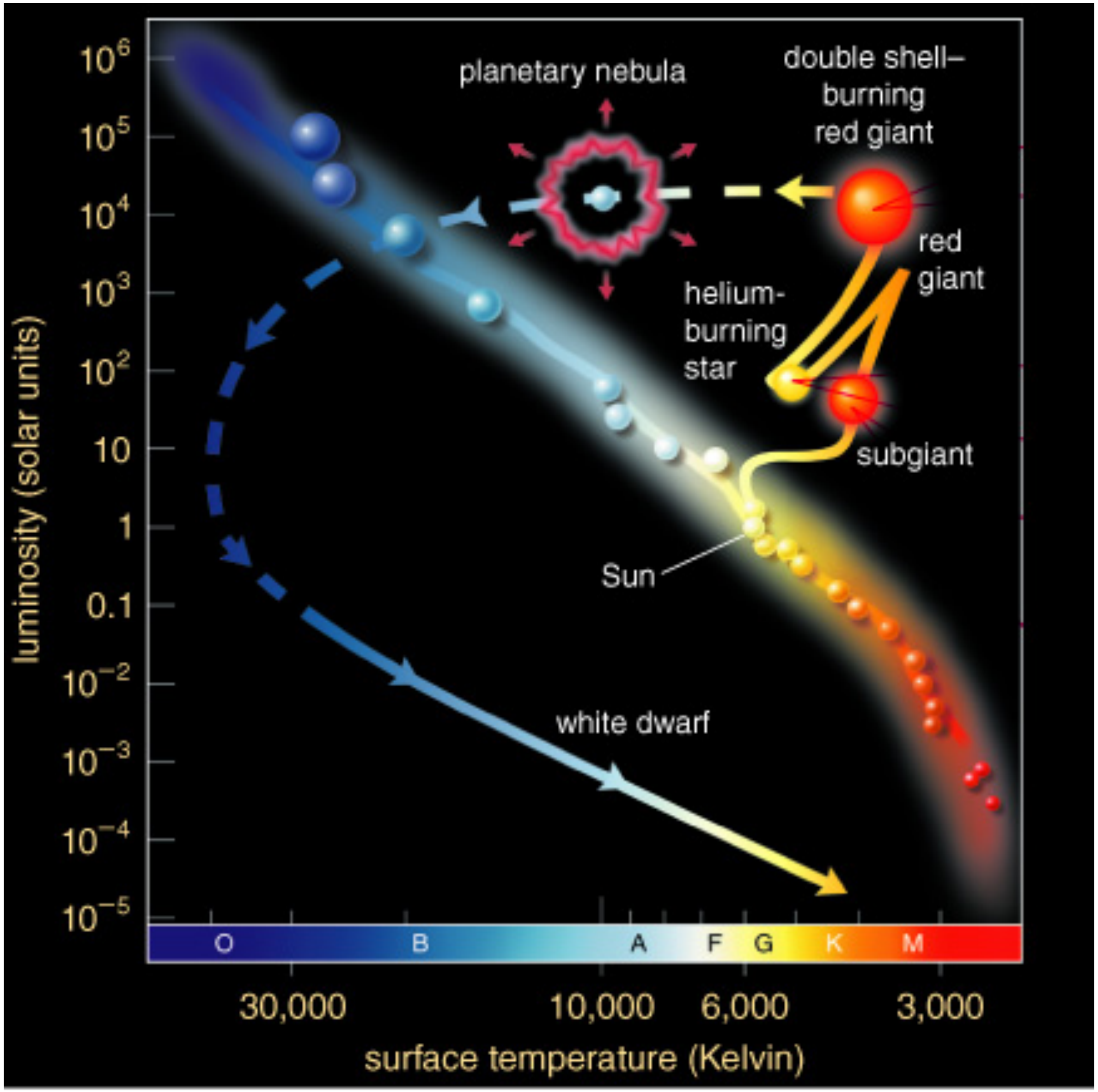
Main Sequence phase: entire phase of H burning in the core (converting H → He mainly via PP)

Duration of MS phase (τ_{MS}) depends on star's store of energy (amount of H, i.e. its mass) and the rate at which energy consumed (luminosity).

Evolution faster for more massive stars: more massive stars have higher central temperatures, thus nuclear reactions occur faster. So:

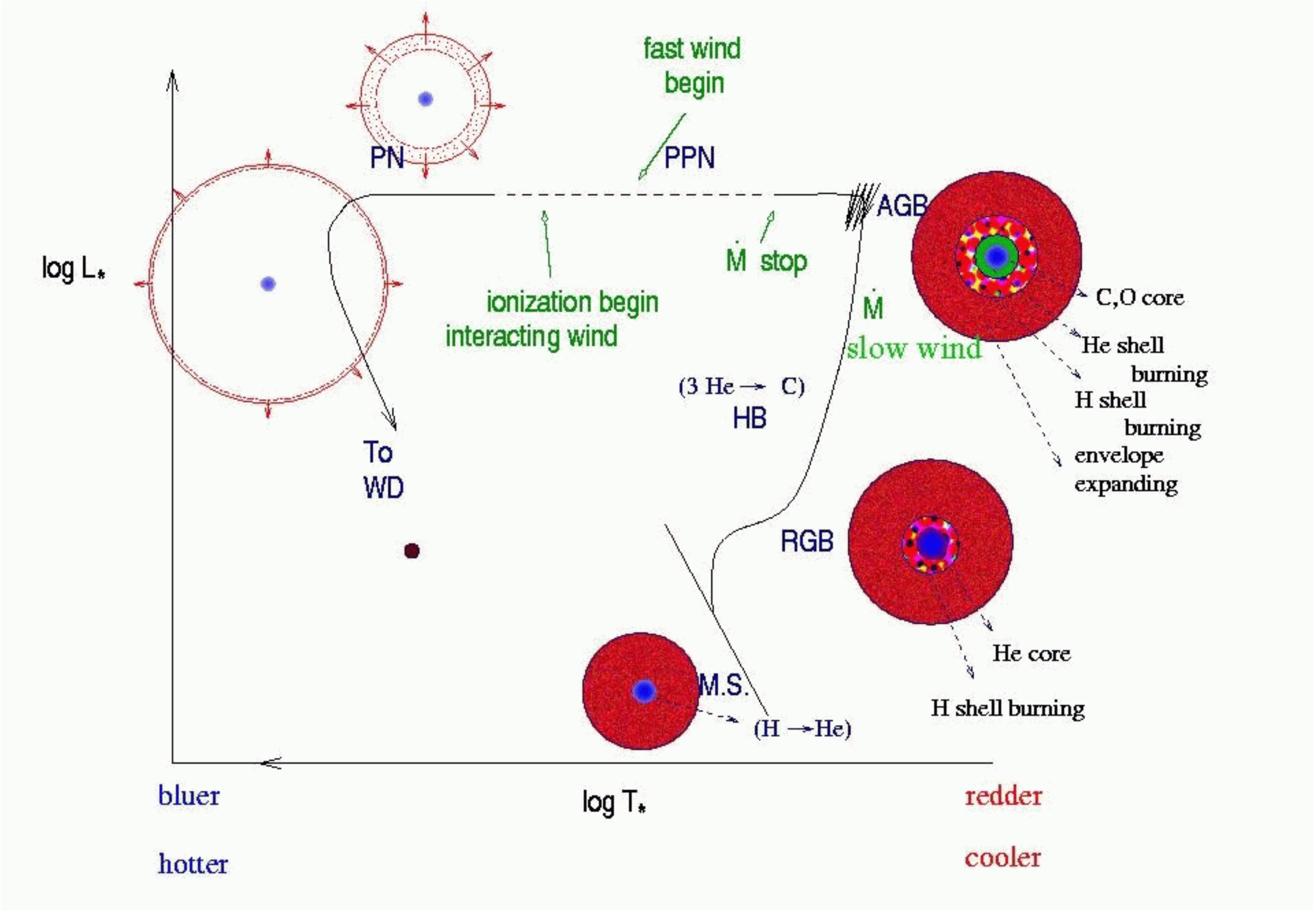
$\tau_{MS} \sim 10^{10}$ yr for a 1 solar mass star
$\tau_{MS} \sim 10^{7}$ yr for a 15 solar mass star

We can plot the trajectory of stellar evolution . . .

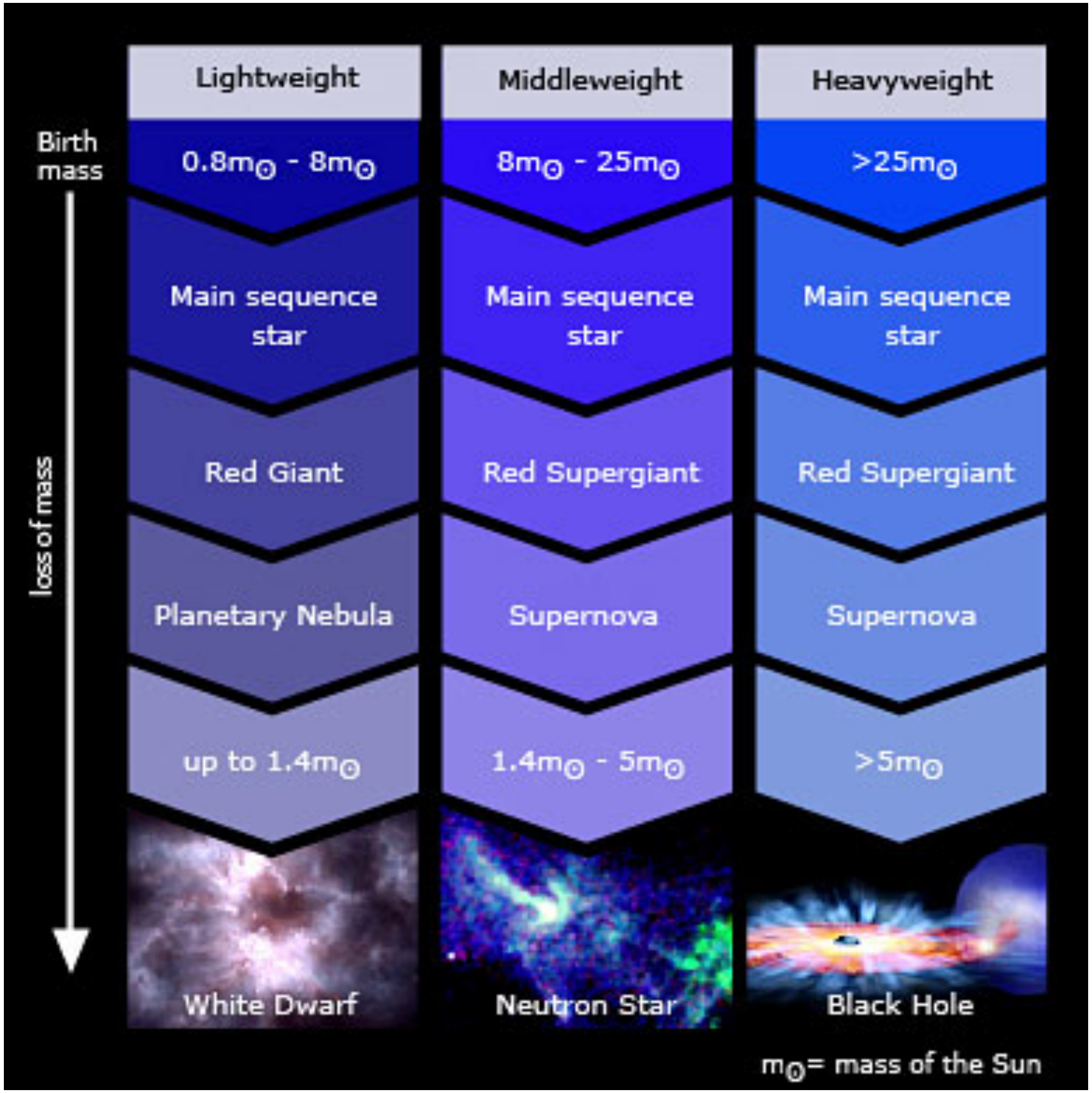


Life and times of the Sun!

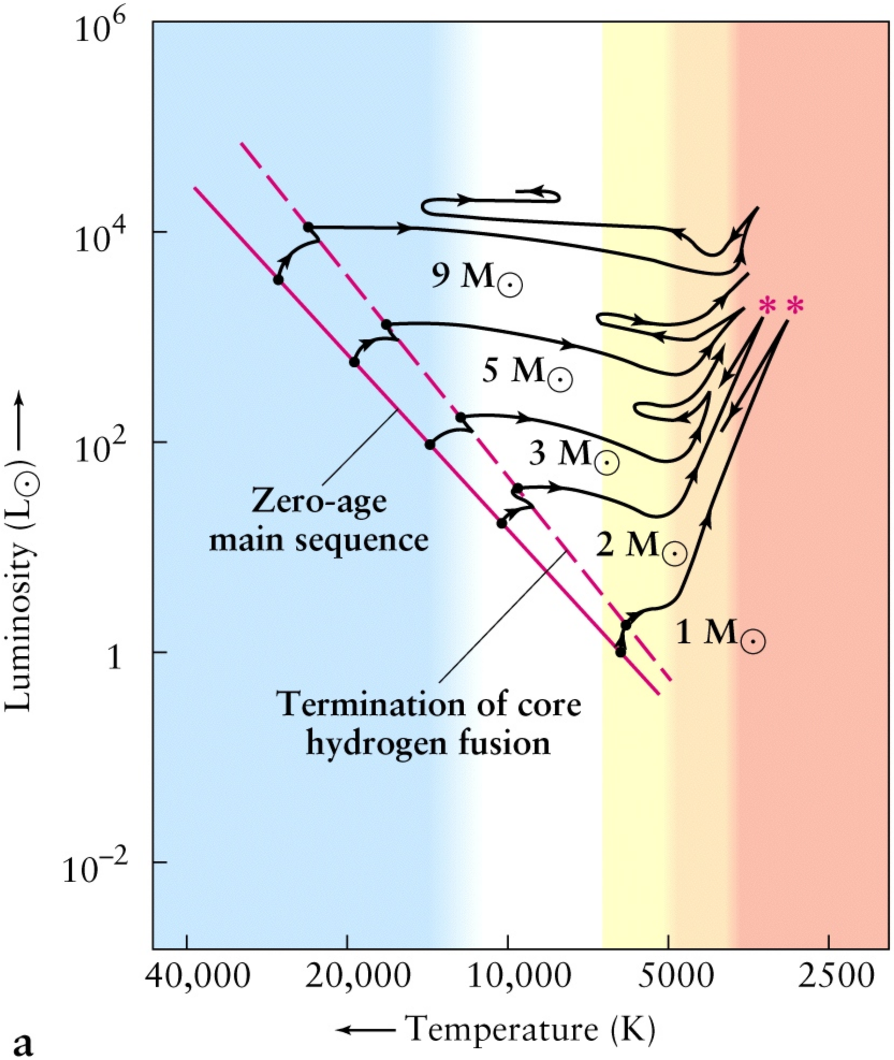
The Hertzsprung-Russell Diagram

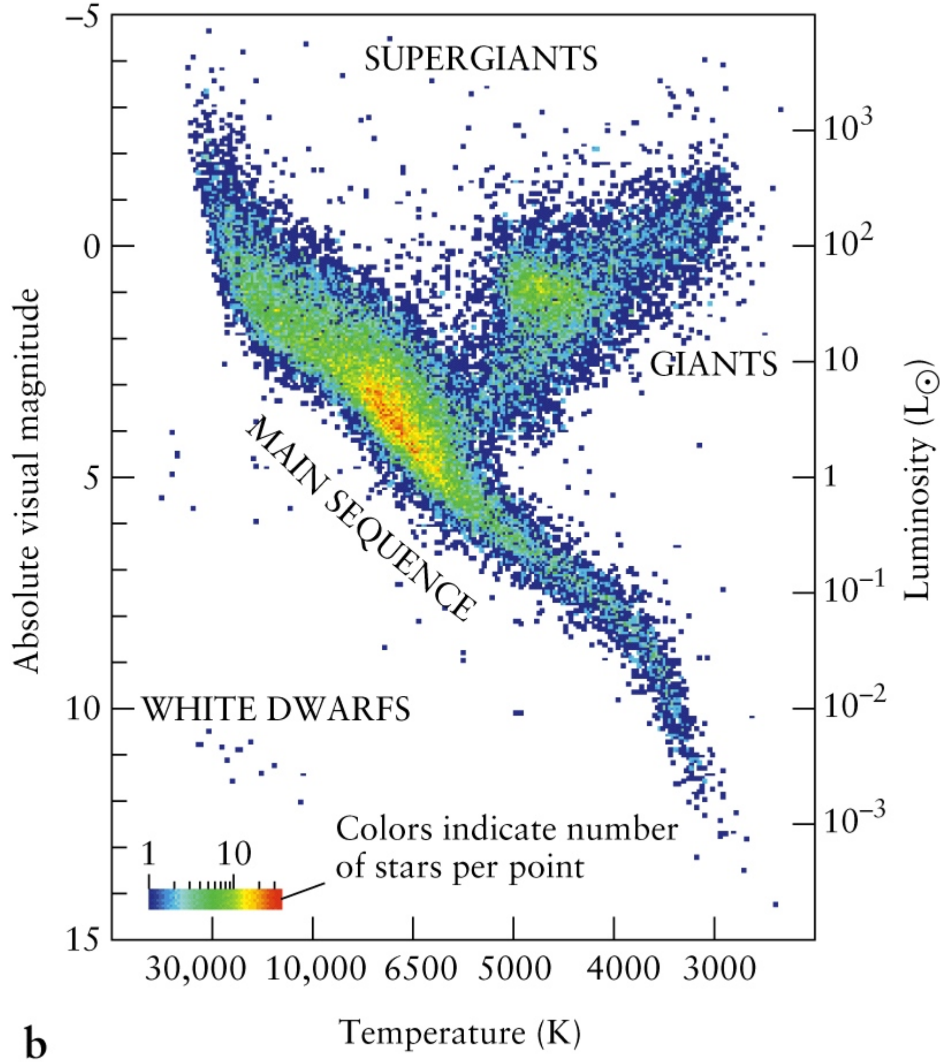


...birth mass matters!



Stellar evolution for various stellar masses





Nucleosynthesis

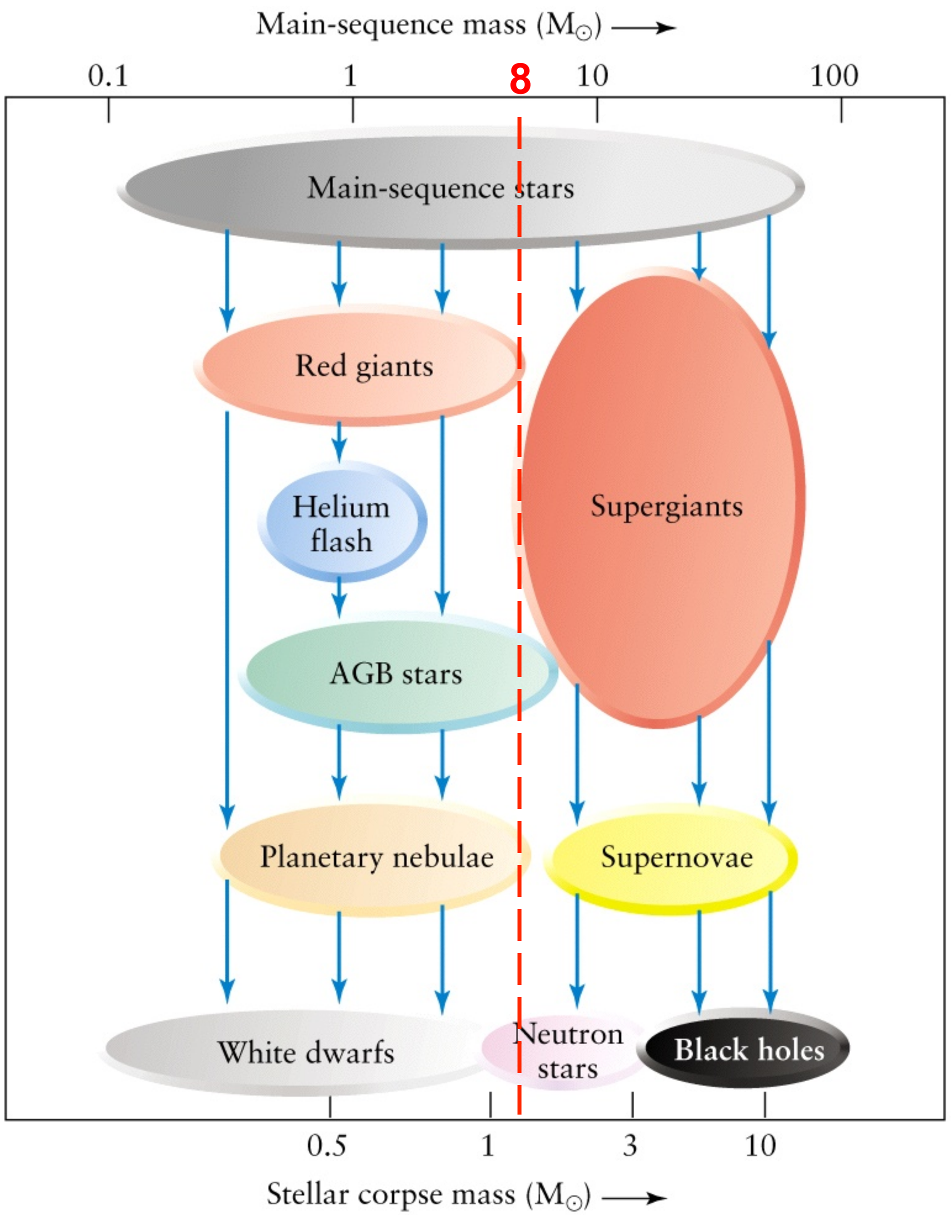
At > 8 solar mass, Ne burning (~10^9 K), then
O burning (2 x 10^9 K)
Si burning (3 x 10^9 K) → S → Fe (Ni)
Faster and faster!! (C: few hundred years; Si, a day)

Massive stars are rare, but most important: they fuse heavy elements and spread them back into the interstellar medium via Supernovae.

End points of stellar evolution

Kind of stellar remnant left over after post-MS evolution depends on the core mass at death (which is less than star's MS mass, because of mass lost in RG phase, PN or SN):

Remnant	Core mass at death (in solar mass)
White dwarf	< 1.4
Neutron star	> 1.4 but < 3
Black hole	> 3



Chandrasekhar limit

White dwarfs have peculiar properties, e.g.
as mass increases, radius decreases (mass-radius relation)

➔Ultimate mass limit for white dwarfs:
Chandrasekhar limit of ~ 1.44 solar mass = 3 x 10^{30} kg

In a contracting stellar remnant with > 1.44 solar mass,
degenerate electron gas pressure cannot hold gravity off
→ Matter crushed to such high densities that

$$p + e^- \rightarrow n + \nu$$

Protons and electrons squeezed into neutrons →
Degenerate neutron gas, which halts the collapse →

neutron star

This process is generally associated with the evolutionary end of massive stars and Type II SN

The path to Supernova

So called 'Type II Supernovae' arise from evolved stars of > 8 solar mass (O and B spectral type), and occur only in spiral galaxies, especially in spiral arms (regions of strong star formation).

Such massive stars can fuse elements up to Fe

→ Fe core grows (Fe cannot fuse and release energy), supported by electron degeneracy pressure

→ when core size reaches the Chandrasekhar limit (1.44 solar mass, or 3×10^{30} kg) degeneracy pressure no longer sustains it

→ core contracts and gets hotter

➔ Catastrophic collapse ('core collapse' supernova)

Core collapse Supernova (Type II)

At ~ 6×10^9 K, photodissociation of Fe (in ¼ second):

$^{56}Fe + \gamma \rightarrow 13\ {}^4He + 4n$ (absorbs 100 MeV, core collapses faster)

$^4He \rightarrow 2p + 2n$

$p + e^- \rightarrow n + \nu$

Proton and electrons 'squeezed' together to form neutrons, emitting pulse of neutrinos (which carry energy away, accelerate core collapse, are absorbed by outer layers, and accelerate their expulsion) in milliseconds!

Collapse eventually halted by short-range repulsive neutron-neutron interactions involving degenerate neutron gas pressure as well as the strong nuclear force → neutron star forms

SN1987A

In the Large Magellanic Cloud, at 51.4 kpc from Earth, on 23 Feb. 1987 (but really ~168,000 yrs before …)

Brightest SN for 400 yrs

Most intensely studied Supernova!

Progenitor: presumed 18 solar mass blue supergiant

'Bounceback'

Once collapse stops, innermost core bounces back somewhat, infalling outer layers rebound, producing shock wave (crossing star in a few hours) that blows off the rest of the star's material (at speeds of 5000 – 30000 km s^{-1})

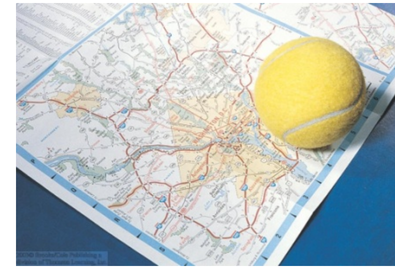
Total energy released ~ 10^{46} Joule (ν), 10^{44} Joule (kinetic = energy Sun will produce over 10^{10} yrs)

➔ Supernova Remnant (SNR)

Neutron star properties

Typical properties:

Mass = 1.5 solar mass
Radius = 10 km
Average density = 10^{17} kg m^{-3}
Escape velocity ~ 0.8 c



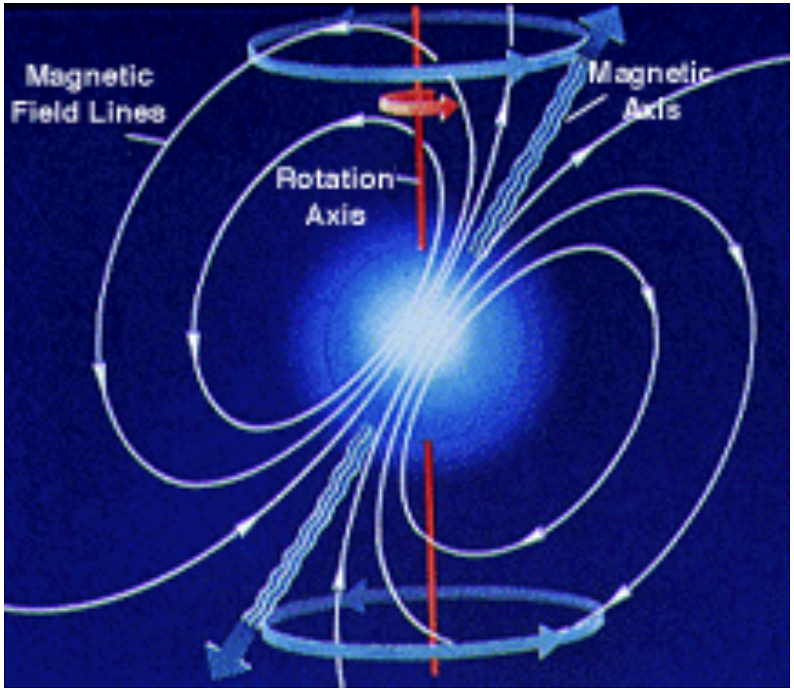
Neutron stars have very low intrinsic luminosities
→ hard to see isolated neutron stars, except in special circumstances … like as pulsars

Pulsar is a rotating, magnetic neutron star (i.e. the star itself <u>does not pulse</u>)

When star collapses, <u>angular momentum</u> and <u>magnetic field</u> strength are conserved → neutron star rotates very rapidly and has strong magnetic field (~ 10^8 Tesla)

‘Lighthouse’ model for pulsars

As pulsar spins, magnetic field induces huge electric field which rips electrons off its surface and accelerates them to <u>relativistic speeds</u> → electrons spiral around magnetic field lines → synchrotron radiation in a tight beam from the magnetic poles



If magnetic and rotation axes are not aligned, and rotation axis is roughly aligned with the Earth, we see bursts of radiation every rotation

→ lighthouse effect

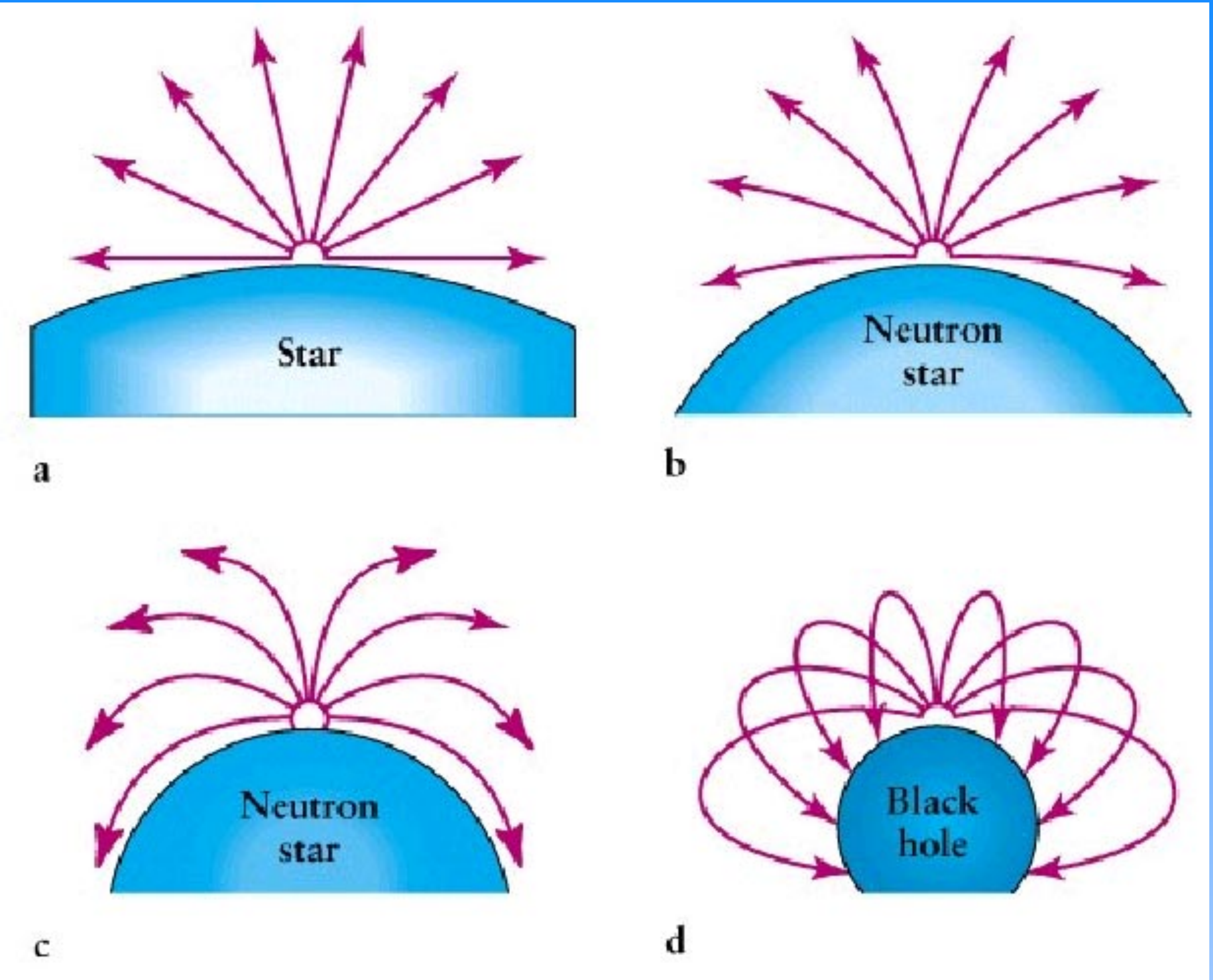
Pulsar’s rotational energy is radiated away →
pulsar must spin down

Core collapse to a black hole

Neutron stars of > 3 solar mass are unstable against further collapse to a black hole (object predicted by Einstein's General Relativity with a gravitational field so strong that nothing can escape from it - not even light)

→ Collapse of 25 - 50 solar mass stars
with a core size > 3 solar mass
can lead to formation of black holes

Gravity bends the path of light



Star collapse to a black hole

Similar physics applies to the collapse of neutron stars as it does to that of white dwarfs → neutron stars also obey a mass-radius relation and the upper limit to the mass is 3 solar mass →

Collapse of stars of > 3 solar mass (MS star > 20 solar mass) cannot be halted at the neutron star stage, but will go all the way to a black hole: volume decreases to zero, density becomes infinite to form a singularity.

A critical radius exists, called the Schwarzschild radius, where the escape velocity equals the speed of light (*G*: gravitational constant; *M*: black hole mass; *c*: speed of light)

$$\boxed{R_{\mathrm{Sch}} = \frac{2GM}{c^2}}$$

Also called the event horizon → nothing can escape!

Black hole: Body that is all contained within its Schwarzschild radius

Observing black holes

An isolated black hole cannot be observed; we can only detect its influence on material around it: matter falling onto a black hole gains kinetic energy and heats up → ionised → radiates

If temperature reaches few million K → X-rays

Most efficient if black hole has plenty of gas supply around, like in a binary system where the companion star fills its 'Roche lobe' (volume controlled by the gravity of the star)
→ Black hole's strong gravity draws gas
from the companion → accretion

If accreted material has some angular momentum, it will form an accretion disk around the black hole; viscosity in the disk heats it up → X-rays