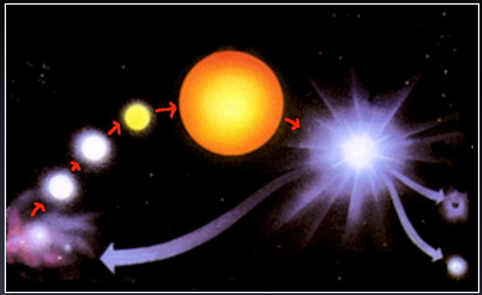
The lives of stars



Koupelis : chapters 14 & 15
OpenStax : chapter 22 & sections 23.1 → 23.4

Suppose star X is twice as far away as star Y. The parallax angle of star X is about

- half that of star Y. 0%
- the same as that of star Y. 0%
- twice that of star Y. 0%
- four times that of star Y. 0%
- [The answer can not be determined from the information given.] 0%

The distances to nearby stars can be measured by

- comparing the apparent magnitude of various stars. 0%
- bouncing radar pulses from their surfaces. 0%
- measuring the time it takes light to get from here to them. 0%
- measuring their shifting motion against background stars through the year. 0%
- [Both b and c above.] 0%

When a star's spectrum is redshifted as the result of the Doppler effect, we know the star is

- much cooler than average. 0%
- slightly cooler than average. 0%
- hotter than average. 0%
- moving away from Earth. 0%

Considering only stars on the main sequence, the most massive stars are

- hottest and brightest. 0%
- hottest and dimmest. 0%
- coolest and brightest. 0%
- coolest and dimmest. 0%
- [No general statement can be made.] 0%

Start the presentation to see live content. For screen share software, share the entire screen. Get help at **pollev.com/app**

Recall: Stars on the Main Sequence

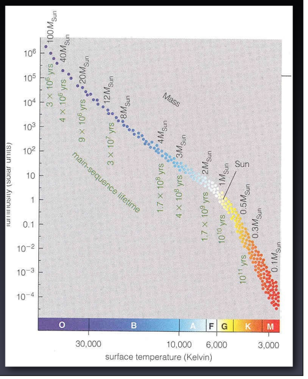
⇒ Stable equilibrium between gravity and gas pressure maintained by nuclear fusion.

A Mass-Luminosity relation for stars on the main sequence:

$L_{\text{Main Sequence}} = C \times M^{3.5}$

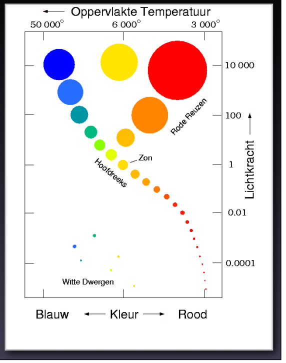
A star 3x more massive than the Sun is 47x brighter!

This has important consequences for their life times!



Stellar evolution : the lives of stars

The mass of a star determines its life time, its internal processes and its ultimate fate.



The Hertzsprung-Russell diagram is a very useful tool to monitor the changes experienced by a star during its life time.

Changes in their internal structure manifest themselves by changes in their temperature, luminosity and size.

Brown Dwarfs

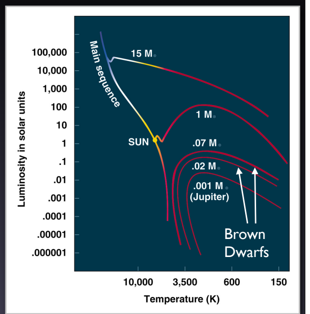
Mass: 0.002 - 0.08 $M_\odot$

A Brown Dwarf is not massive enough to start nuclear fusion.

⇒ it never arrives on the Main Sequence!

They just glow and slowly cool down…

Temp.: 1000 - 3500 K



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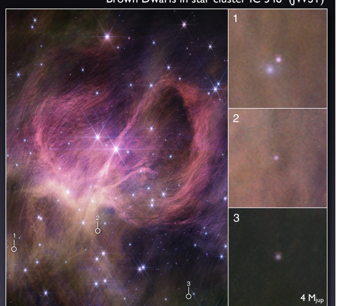
Temp.: 1000 - 3500 K

Brown Dwarfs in star cluster IC 348 (JWST)



Life on the Main Sequence

The mass determines which nuclear fusion process dominates:

lighter than 1.5 $M_\odot$

proton-proton cycle

$$^{1}H + {}^{1}H \rightarrow {}^{2}H + e^{+} + \text{electron neutrino}$$

$$^{1}H + {}^{2}H \rightarrow {}^{3}H + \text{gamma ray photon}$$

$$^{3}H + {}^{3}H \rightarrow {}^{4}He + {}^{1}H + {}^{1}H$$

heavier than 1.5 $M_\odot$

CNO - cycle

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

$$^{13}N \rightarrow {}^{13}C + e^{+} + \text{electron neutrino}$$

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

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

$$^{15}O \rightarrow {}^{15}N + e^{+} + \text{electron neutrino}$$

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

In both cases, the number of particles reduces : four H ⇒ one He

Stellar Thermostat

equilibrium between gravity and gas pressure

Fusion decreases ← Less collisions

↓ ↑

Gas cools down — Atomic nuclei move further apart

↓ ↑

Stellar core shrinks — Stellar core expands

↓ ↑

Atomic nuclei come closer together — Gas heats up

↓ ↑

More collisions → Fusion increases

Life on the Main Sequence

The number of particles in the stellar core slowly reduces

↓

The stellar core shrinks

↓

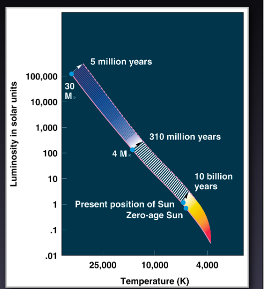
The temperature in the core increases

↓

Fusion becomes more efficient and core produces more energy

↓

The star becomes brighter & the outer layers expand and cool slightly



The end is near...

Life on the Main Sequence ends when Hydrogen is exhausted.

This occurs sooner in massive stars than in low-mass stars.

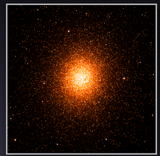
Pleiades

Blue stars are usually massive and therefore evolve fast:

<u>They are always young!</u>

In general, blue stars are found in star forming regions.

Globular cluster M15

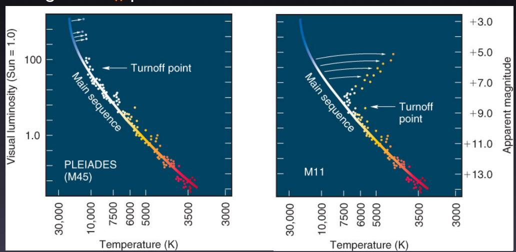


Red stars are usually low-mass and evolve more slowly:

<u>They are usually older.</u>

A young star cluster contains many more massive blue stars on the Main Sequence than an old star cluster.

At the end of their lives on the Main Sequence, the photospheres of stars cool down: they 'evolve' to the upper-right in the HR-diagram, causing a *turn-off* point.



The location of the turn-off point reveals the *age* of the group.

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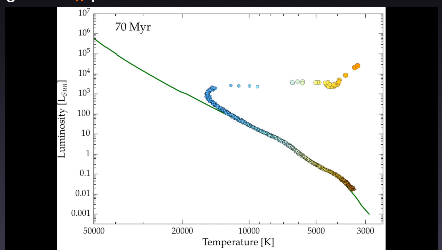
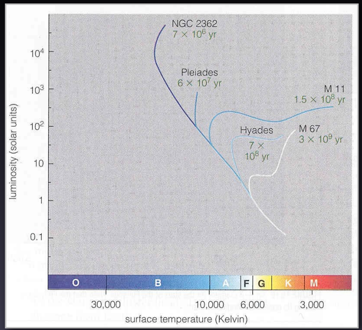


The location of the turn-off point reveals the *age* of the group.

Theoretically calculated evolution tracks provide so-called isochrones for star clusters.

NGC 2362 is very young

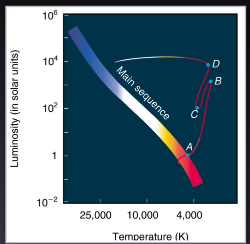


M67 is very old

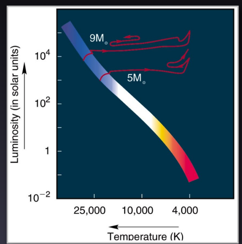
Note the different turn-off points!

What happens after life on the Main Sequence depends again on the mass of a star.

for a low-mass star (1 M☉)



for two high-mass stars



Stars with different masses have different internal structures and very different evolutionary tracks.

Understanding evolutionary tracks after the Main Sequence

Based on theoretical computer models of the internal structure of stars

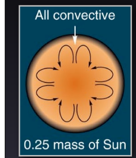
We distinguish four different mass regimes:

- < 0.4 M☉ : very low-mass stars
- 0.4 - 4 M☉ : low-mass stars
- 4 - 8 M☉ : high-mass stars
- >8 M☉ : very high-mass stars

These stars will evolve with a different fate…

The very low-mass stars

< 0.4 $M_\odot$



fully convective

All Hydrogen reaches the core and the newly formed Helium spreads throughout the entire star

↓

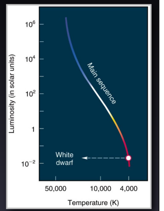
The nuclear fusion and the number of particles slowly decrease

↓

The entire star shrinks and heats up due to gravitational energy

↓

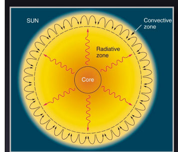
The star moves to the left in the HRD and becomes a cooling White Dwarf



All very low-mass stars ever formed still live on the Main Sequence!

All stars more massive than 0.4$M_\odot$ become Red Giants

Not all Hydrogen reaches the core to become available for fusion



not fully convective

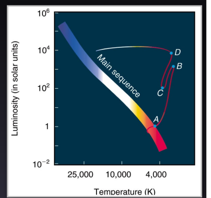
fusion and the number of particles decreases

↓

Helium core shrinks

↓

the core temperature strongly increases (grav. → thermal energy)

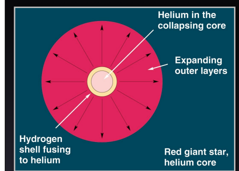


3 consequences:

⇒ Hydrogen fusion continues in a shell around the Helium core
⇒ The amount of radiated energy strongly increases
⇒ The outer layers strongly expand and cool

The low-mass stars

0.4 - 4 $M_\odot$



The Helium core stops shrinking due to pressure from electron-degeneracy.

↓

Hydrogen fusion continues in a shell around the core

↓

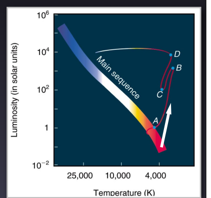
fusion shell dumps new Helium onto the core

↓

the Helium core continues to grow in mass, and to shrink in size

↓

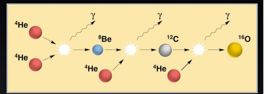
The core increases its temperature and Hydrogen fusion progresses in a shell: A ⇒ B

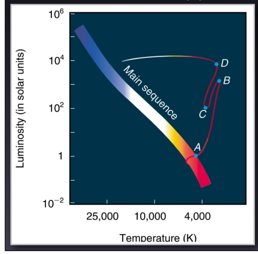


The low-mass stars (2)

0.4 - 4 M⊙

When the Helium core reaches a temperature of 100 million degrees, Helium starts to fuse into Carbon.
If a star is less massive than 2 M⊙ a Helium flash occurs (B).





The core becomes hotter and expands.

↓

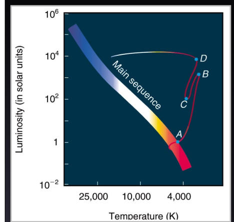
The shell with Hydrogen fusion expands and cools, and the total energy production decreases: B ⇒ C

↓

The outer layers shrink and become slightly hotter.

The low-mass stars (3)

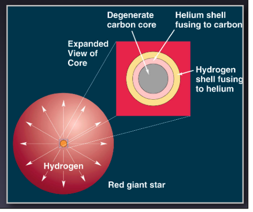
0.4 - 4 M⊙



When the Helium is exhausted, the Carbon core shrinks until it is stopped again by the electron degeneracy.

↓

The core continues to heat up.



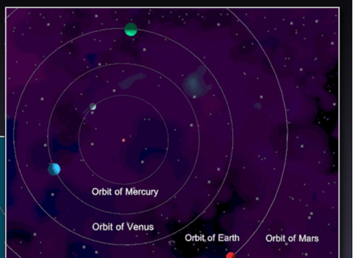
Helium fusion continues in a shell around the Carbon core: C ⇒ D.

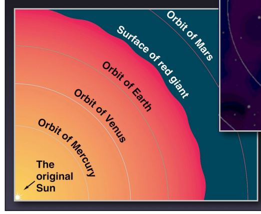
The core of a low-mass star never becomes hot enough to ignite Carbon fusion

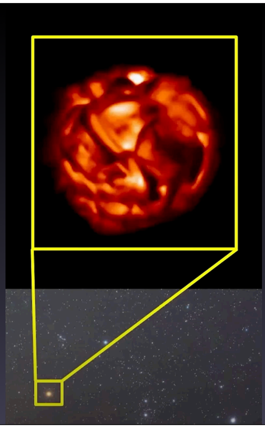
Red Giant stars are indeed gigantic!

0.4 - 4 M⊙

Our Sun
6 billion years
from now…







simulated surface of the red giant star Betelgeuse (alpha Orionis)

0.047 arcsec diameter

~1200 R_{sun}

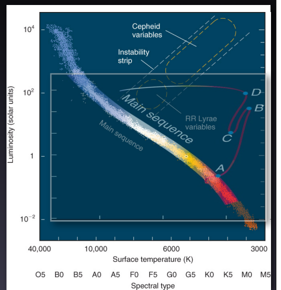
0.4 - 4 $M_\odot$

Pulsations and mass-loss

Stars evolve through the *instability strip*.

The stellar atmosphere becomes unstable and starts to pulsate with periods of 1 − 100 days.

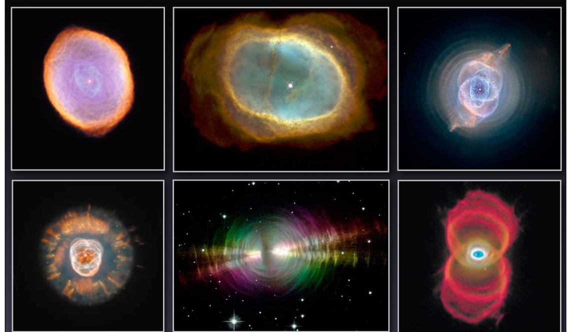
⇒ A lot of mass is then expelled!



The blown-off outer layers become visible as a so-called Planetary Nebula.

0.4 - 4 $M_\odot$

examples of Planetary Nebulae

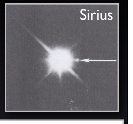


0.4 - 4 $M_\odot$

White Dwarfs

the cooling, naked cores of Red Giant stars

No nuclear fusion occurs in White Dwarfs.

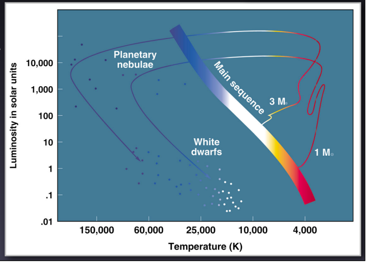


The pressure from electron degeneracy prevents further collapse.

A White Dwarf orbits the star Sirius.

Some 300 White Dwarfs have been discovered.

Our Sun will end as a White Dwarf …



Properties of White Dwarfs

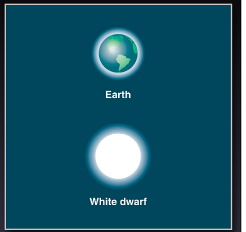
Temperature : 4.000 - 85.000 K

Mass : 0.02 - 1.4 $M_\odot$
(1.4 $M_\odot$ = critical mass)
Chandrasekhar limit

Diameter : comparable to Earth

Density : 2.000 kilo per tea spoon

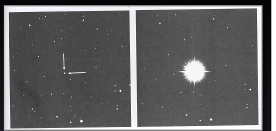
At the surface, you weigh about 400.000 times more than on Earth!



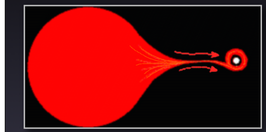
Main Sequence stars that are more massive than 4 $M_\odot$ have a more massive core and don't leave behind a White Dwarf…

A White Dwarf in a double star system

Nova

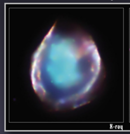


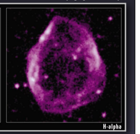
Mass transfer from a Red Giant and accretion onto a White Dwarf



Gas collects on the surface and detonates in a nuclear explosion.

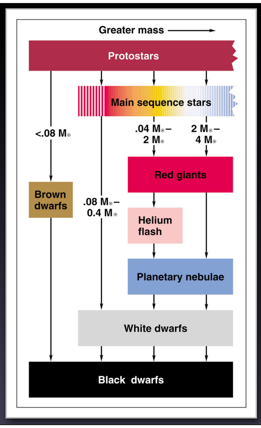
Supernova (type Ia)





If too much gas is dumped onto the White Dwarf, its mass will exceed 1.4 $M_\odot$ ⇒ The entire White Dwarf explodes and nothing remains!

Summary: the lives of low-mass stars.



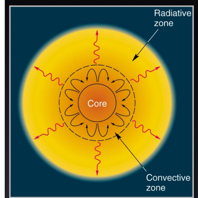
0.4 - 4 M⊙

Mass-loss in this phase can be 50% !!

We are made of star dust !

> 4 M⊙

Stars more massive than 4 M⊙



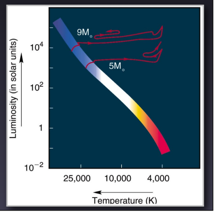
convective in core, radiative in outer parts

The cores of these stars gradually transform from Hydrogen fusion to Helium fusion with Hydrogen fusion in a shell around the core.

The cores are more massive and produce more energy than the cores of Red Giant stars.

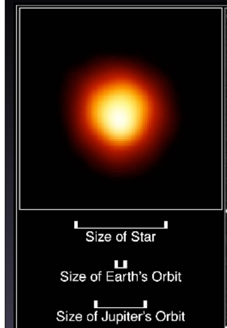
⇒ they expand to Red Super-Giants.

Red Super Giants criss-cross the HR diagram:



0.4 - 4 M⊙

Betelgeuse : a Red Super-Giant star

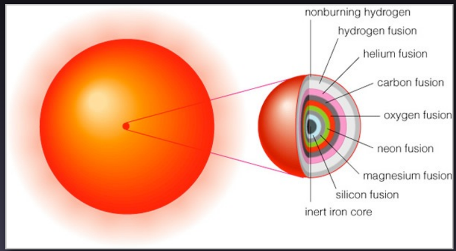


> 4 $M_\odot$

Nuclear fusion in Red Super Giants

These cores are hot enough for Carbon fusion.

Every fusion product serves as 'fuel' for fusion to even heavier elements like Oxygen, Neon, Silicon and even Iron.



These fusions occur in shells around the stellar core.

> 4 $M_\odot$

Nuclear fusion in Red Super Giants

The time scales for fusion in a very high-mass 15 $M_\odot$ star:

Fuel	Fusion product	Time scale (years)	Temperature (K)
Hydrogen	Helium	10.000.000	4.000.000
Helium	Carbon	>1.000.000	100.000.000
Carbon	Oxygen, Neon, Magnesium	1.000	600.000.000
Neon	Oxygen, Magnesium	5	1.000.000.000
Oxygen	Silicon, Sulphur	1	2.000.000.000
Silicon	Iron	few days	3.000.000.000

> 4 $M_\odot$

The end of a Red Super Giant...

based on theoretical models

The iron core shrinks and becomes extremely hot.

Iron cannot fuse into heavier elements.
(iron fusion requires more energy than it provides)

If the mass of the core exceeds 1.4 $M_\odot$
it collapses catastrophically within a second.
⇒ Protons and electrons are pushed together and combine to form neutrons and massive amounts of neutrino's.

An enormous shock wave originates and travels outwards, causing:
- the fusion of iron into even heavier elements (lead etc)
- the shock wave blows apart the entire star

Supernova! (type II)

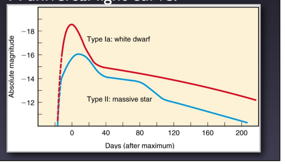
The visible remains of type-II Supernovae

SN1987A before

The Crab Nebula in Taurus

after

A universal light curve.

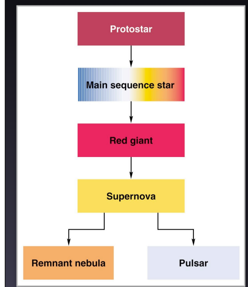


What remains of the core?

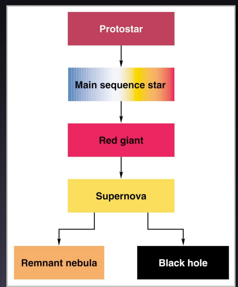
> 4 M$_\odot$

again, mass makes the difference:

4 - 8 M$_\odot$: Neutron star



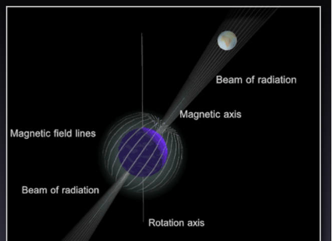
>8 M$_\odot$: Black Hole



Substantial mass loss!!

A neutron star can manifest itself as a Pulsar

Pulsars are
cosmic 'light houses'
(with radio beams)



Mass : 1.4 - 3 M$_\odot$
Diam. : 20 km
Temp. : 10.000.000 K

A paperclip of neutron star material
weighs as much as Mount Everest!

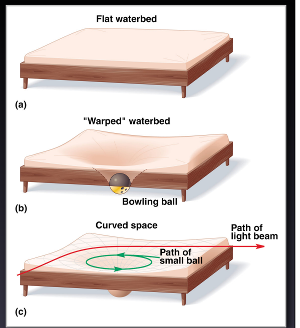
Note: a pulsar is the remains of a star (stellar remnant).

Pulsar profiles

Black Holes

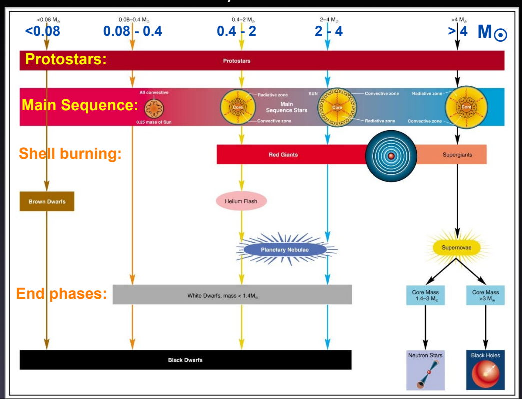
a singularity ('hole') in space-time

Nothing can escape from a black hole, not even light!



Note: There are 'stellar' black holes and much more massive ones; these are found in the nuclei of galaxies.

Summary: the lives of stars



Next lecture

The Milky Way:

- star clusters
- galactic structure (bulge, halo, spiral arms)
- stellar populations
- the galactic center