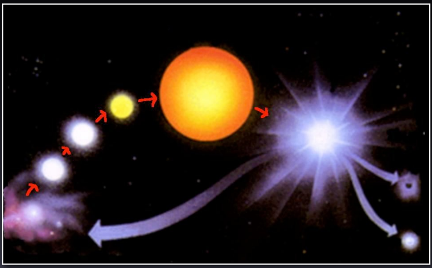
The lives of stars



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

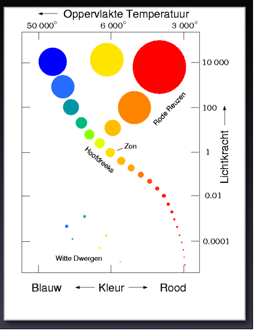
1

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.



2

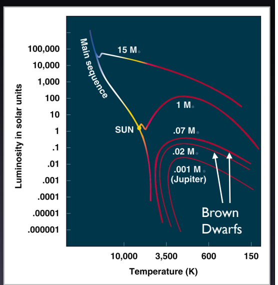
Brown Dwarfs

Mass: 0.002 - 0.08 M⊙

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



3

Brown Dwarfs

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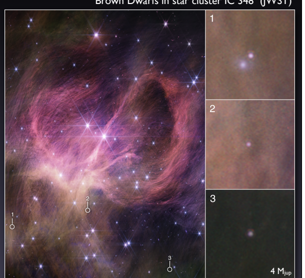
They just glow and slowly cool down…

Temp.: 1000 - 3500 K

Brown Dwarfs in star cluster IC 348 (JWST)

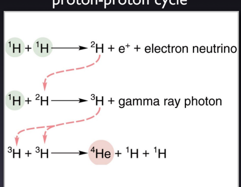


4

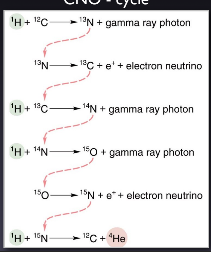
Life on the Main Sequence

The mass determines which nuclear fusion process dominates:

lighter than 1.5 M⊙
proton-proton cycle



heavier than 1.5 M⊙
CNO - cycle



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

5

6

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

7

Life on the Main Sequence

The number of particles in the stellar core slowly reduces

↓

The stellar core shrinks

↓

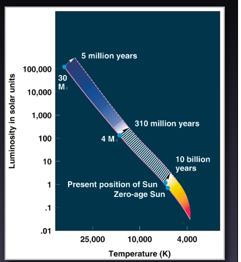
The temperature in the core increases

↓

Fusion becomes more efficient and star produces more energy

↓

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



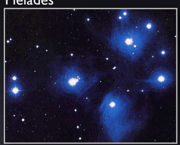
8

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

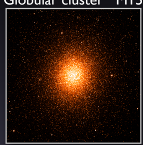


Blue stars are usually massive and therefore evolve fast:

They are always young!

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

Globular cluster M15



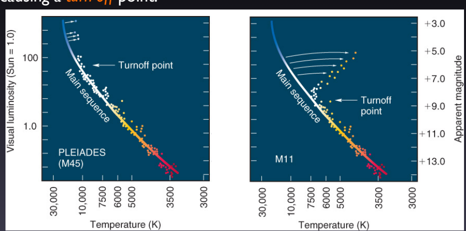
Red stars are usually low-mass and evolve more slowly:

They are usually older.

9

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.

10

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

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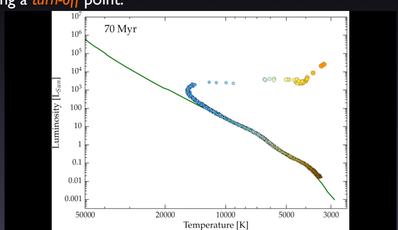
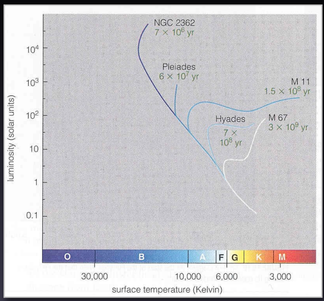


The location of the turn-off point reveals the *age* of the group.

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

NGC 2362 is very young



M67 is very old

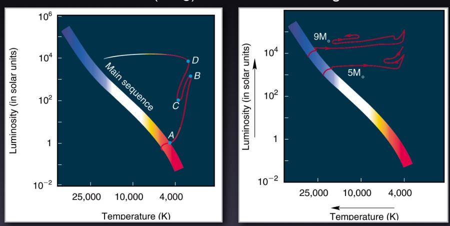
Note the different turn-off points!

11

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.

12

Understanding evolutionary tracks after the Main Sequence

Based on theoretical computer models of the internal structure of stars

We distinguish four different mass regimes:

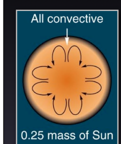
< 0.4 M⊙	:	very low-mass stars
0.4 - 4 M⊙	:	low-mass stars
4 - 8 M⊙	:	high-mass stars
>8 M⊙	:	very high-mass stars

These stars will evolve with a different fate…

13

< 0.4 M⊙

The very low-mass stars



fully convective

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

↓

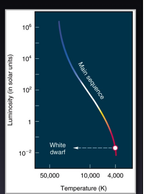
The nuclear fusion and the number of particles slowly decrease

↓

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!

14

All stars more massive than 0.4M⊙ become Red Giants

Not all Hydrogen reaches the core to become available for fusion

↓

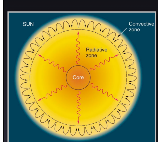
fusion and the number of particles decreases

↓

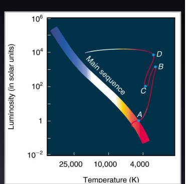
Helium core shrinks

↓

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



not fully convective



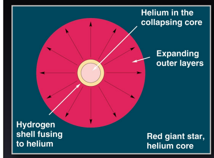
3 consequences:

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

15

The low-mass stars

0.4 - 4 M⊙



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

↓

Hydrogen fusion continues in a shell around the core

↓

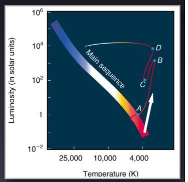
fusion shell dumps new Helium onto the core

↓

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

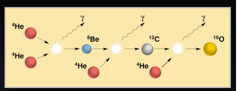


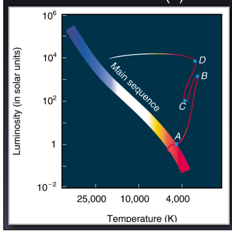
16

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

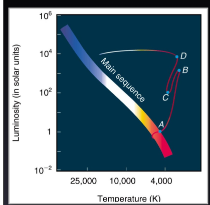
↓

The outer layers shrink and become slightly hotter.

17

The low-mass stars (3)

0.4 - 4 M⊙



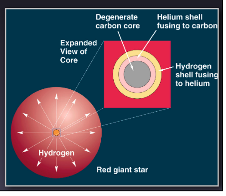
When the Helium is exhausted, the Carbon core shrinks until it is stopped again by the electron degeneracy.

↓

The core continues to heat up.

↓

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



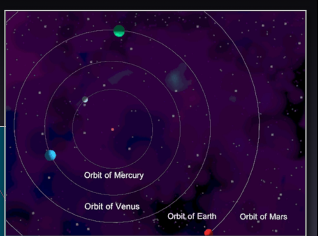
The core of a low-mass star never becomes hot enough to ignite Carbon fusion

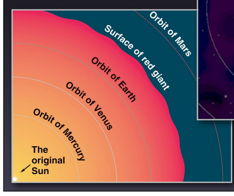
18

Red Giant stars are indeed gigantic!

0.4 - 4 M⊙

Our Sun
6 billion years
from now…





19

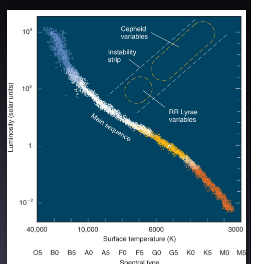
Pulsations and mass-loss

0.4 - 4 M⊙

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.

20

21

0.4 - 4 $M_\odot$

Pulsations and mass-loss

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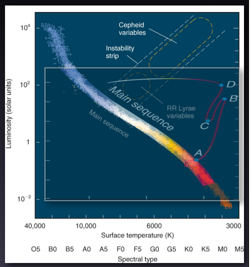
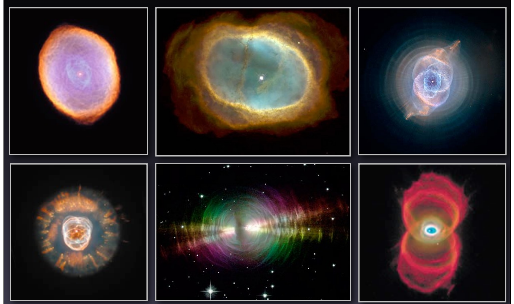


The blown-off outer layers become visible as a so-called Planetary Nebula.

22

0.4 - 4 $M_\odot$

examples of Planetary Nebulae



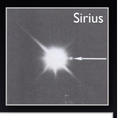
23

0.4 - 4 $M_\odot$

White Dwarfs

the cooling, naked cores of Red Giant stars

No nuclear fusion occurs in White Dwarfs.

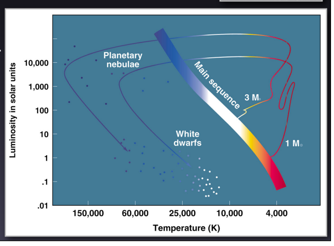


The pressure from electron degeneracy prevents further collapse.

A White Dwarf orbits the star Sirius.

Some 300 White Dwarfs have been discovered.

Our Sun will end as a White Dwarf …



24

Properties of White Dwarfs

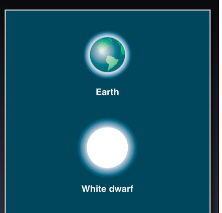
Temperature : 4.000 - 85.000 K

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!

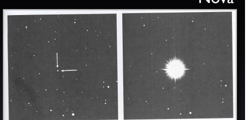


Main Sequence stars that are more massive than 4 $M_\odot$ have a more massive core and don't leave behind a White Dwarf…

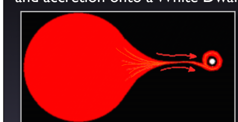
25

A White Dwarf in a double star system

Nova

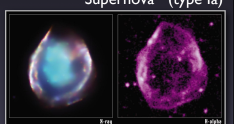


Mass transfer from a Red Giant and accretion onto a White Dwarf



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

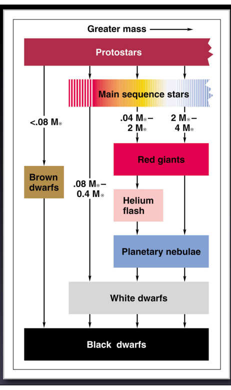
Supernova (type Ia)



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!

0.4 - 4 M☉

Summary: the lives of low-mass stars.



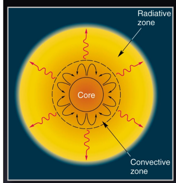
Mass-loss in this phase can be 50% !!

We are made of star dust !

26

> 4 M☉

Stars more massive than 4 M☉



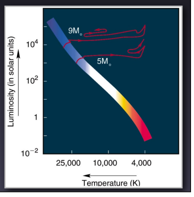
The cores of these stars gradually transform from Hydrogen fusion to Helium fusion with Hydrogen fusion in a shell around the core.

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

⇒ they expand to Red Super-Giants.

convective in core,
radiative in outer parts

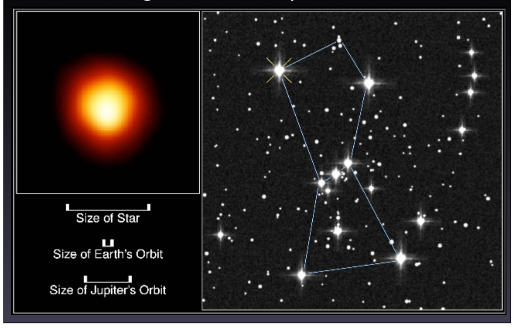
Red Super Giants criss-cross the HR diagram:



27

0.4 - 4 M☉

Betelgeuse : a Red Super-Giant star



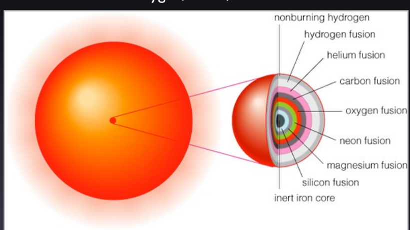
28

> 4 M☉

Nuclear fusion in Red Super Giants

<u>These cores are hot enough for Carbon fusion.</u>

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.

29

> 4 M☉

Nuclear fusion in Red Super Giants

The time scales for fusion in a very high-mass 15 M☉ 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, Sulfer	1	2.000.000.000
Silicon	Iron	few days	3.000.000.000

30

31

> 4 M⊙

The end of a Red Super Giant...

based on theoretical models

The iron core shrinks and becomes extremely hot.

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

If the mass of the core exceeds 1.4 M⊙
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

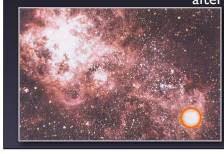
Supernova! (type II)

32

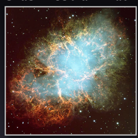
The visible remains of type-II Supernovae

SN1987A before

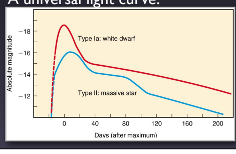
after



The Crab Nebula in Taurus



A universal light curve.



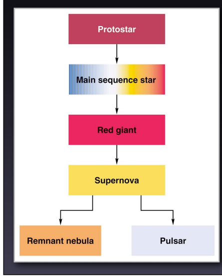
33

> 4 M⊙

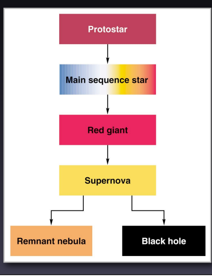
What remains of the core?

again, mass makes the difference:

4 - 8 M⊙ : Neutron star



>8 M⊙ : Black Hole

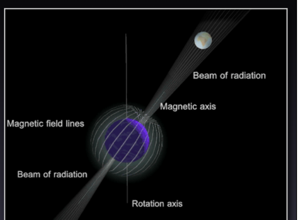


Substantial mass loss!!

34

A neutron star can manifest itself as a Pulsar

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



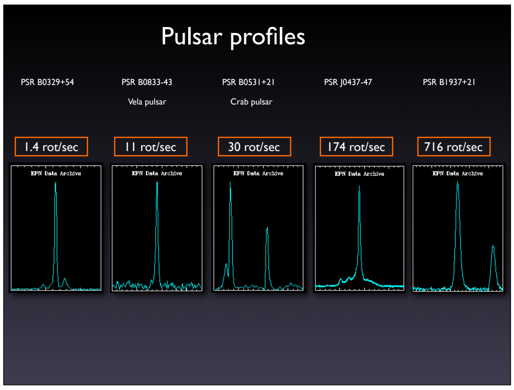
Mass : 1.4 - 3 M⊙
Diam. : 20 km
Temp. : 10.000.000 K

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

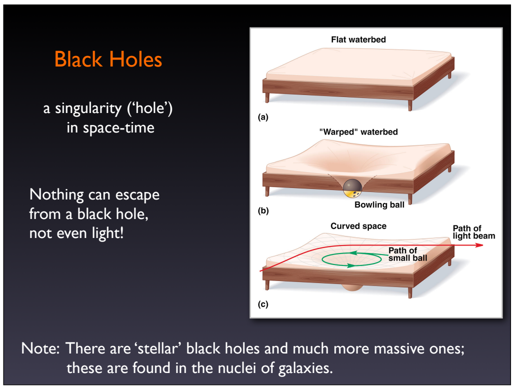
Note: a pulsar is the remains of a star (stellar remnant).

35

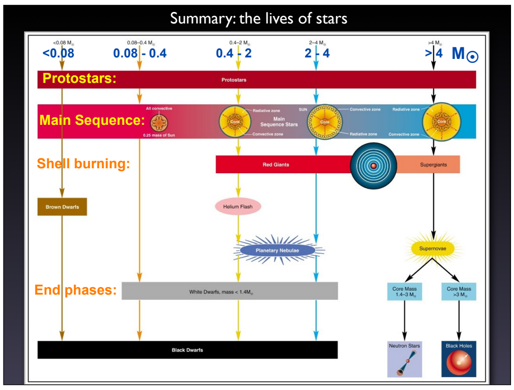
Pulsar profiles


Pulsar profiles
PSR B0329+54
PSR B0833-43
Vela pulsar
PSR B0531+21
Crab pulsar
PSR J0437-47
PSR B1937+21
1.4 rot/sec
11 rot/sec
30 rot/sec
174 rot/sec
716 rot/sec
EPN Data Archive

36


Black Holes
a singularity ('hole')
in space-time
Nothing can escape
from a black hole,
not even light!
Flat waterbed
(a)
"Warped" waterbed
Bowling ball
(b)
Curved space
Path of
light beam
Path of
small ball
(c)
Note: There are 'stellar' black holes and much more massive ones;
these are found in the nuclei of galaxies.

37


Summary: the lives of stars
<0.08
0.08 - 0.4
0.4 - 2
2 - 4
>4
Protostars:
Main Sequence:
Shell burning:
End phases:

38