The ABC of Stellar Evolution

A look at the birth, life and death of stars

Dr Steve Barrett

Sandy AS 8 May 2024

Galaxies

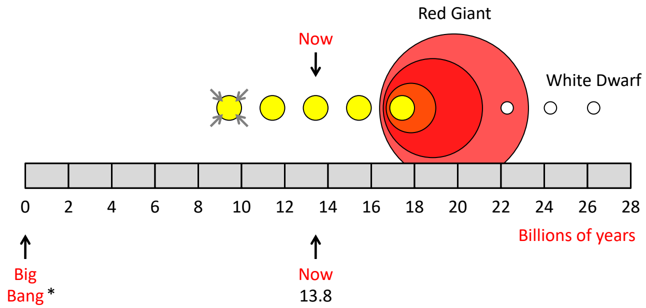
UNIVERSITY OF LIVERPOOL 2

Contents

UNIVERSITY OF LIVERPOOL 3

Life Cycle of the Sun

Our Sun is middle-aged…



[Sizes not to scale]

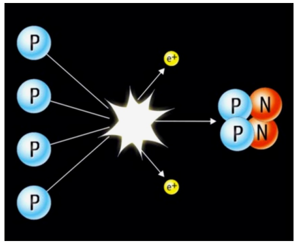
UNIVERSITY OF LIVERPOOL * See "The Beginning of Everything" 4

At the Heart of the Matter

In the core of a star, where the pressure and temperature conditions are right, the fusion of hydrogen into helium releases energy.

4 x hydrogen

620 M'tons



1 x helium

616 M'tons

UNIVERSITY OF LIVERPOOL

5

Fusion

Stars are not just nature's way of lighting up the universe …

they are the "fusion factories" that make the elements heavier than hydrogen.

BUT …

Where does the hydrogen come from in the first place?

That's a very good question, but the answer is a bit too long to cover here and is the subject of a different talk.*

UNIVERSITY OF LIVERPOOL

* See "The Beginning of Everything"

6

Star Formation

Where do stars come from?

Anyone can make a star in 5 easy-to-follow steps …

1. Start with a big cloud of hydrogen
2. Wait …
3. Wait some more …
4. Wait a bit longer …
5. You now have a star

UNIVERSITY OF LIVERPOOL

7

What Triggers Star Formation?

Giant Molecular Clouds float around the galaxy

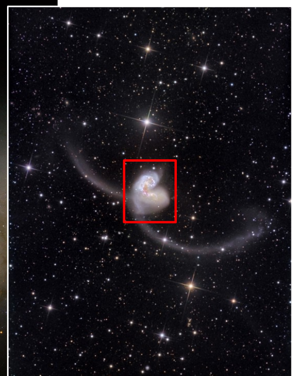
- They look like clouds
- They consist mainly of hydrogen molecules
- They are big (~100 light years across)

What makes a GMC collapse? Triggers may include …

- One cloud colliding with another
- Shock waves rippling through the cloud
- Galaxy collisions (!)

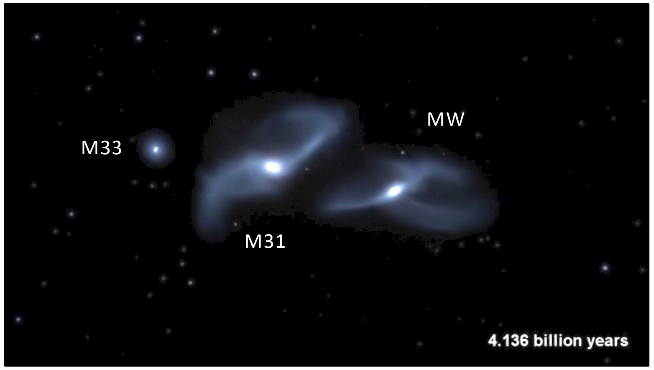
UNIVERSITY OF LIVERPOOL 9

Antenna Galaxy



11

Milky Way–Andromeda Collision



UNIVERSITY OF LIVERPOOL 12

Milky Way–Andromeda Collision

UNIVERSITY OF LIVERPOOL 13

Milky Way–Andromeda Collision

UNIVERSITY OF LIVERPOOL 14

Collapsing Cloud

UNIVERSITY OF LIVERPOOL 15

Star Cluster

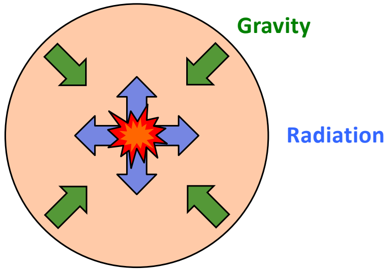
UNIVERSITY OF LIVERPOOL 16

A Question of Balance

All stars are a balance between the opposing forces of gravity and radiation pressure.

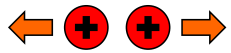
When the opposing forces are balanced, the star is stable.

When out of balance, the star must evolve.

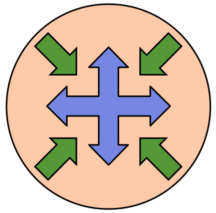


Many aspects of star birth, life and death can be explained in terms of this balance and the ABC of star evolution.

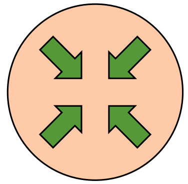
The ABC



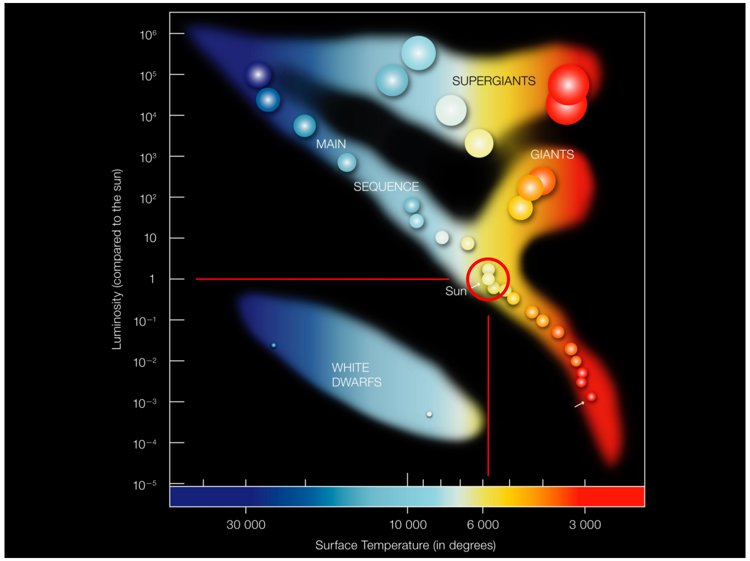
Like charges repel so high T and high P ACCELERATE fusion



In a star in equilibrium gravity and radiation are in BALANCE



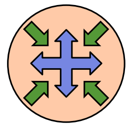
COMPRESSION produces heat



Live Fast, Die Young

Stars of different mass follow quite different lives.

High Mass stars have a lot of fuel, but …



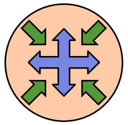
- Gravitational forces are very strong
- Balance requires a lot of radiation to be generated
- Nuclear fuel must be used at a prodigious rate

Rather than living for billions of years, like our Sun, high mass stars may live for only a few million years.

Live Slow, Die Very Old

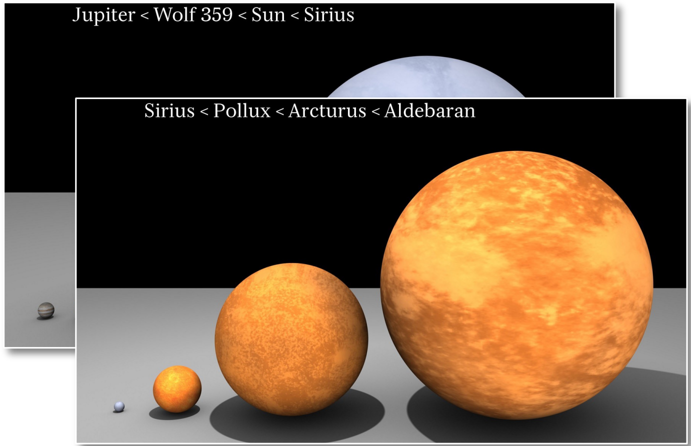
Low Mass stars do not have a lot of fuel, but …

- Gravitational forces are relatively weak
- Hence radiation forces do not have to be high to maintain a balance
- Hence nuclear fuel lasts a long time

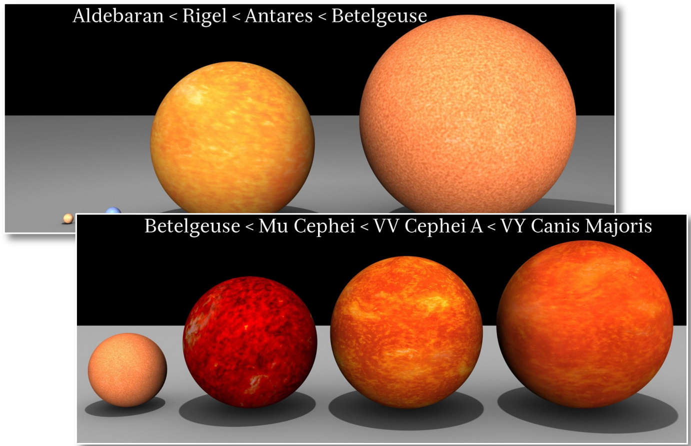


For stars of mass = 10% of the mass of our Sun, we are not even sure what happens when the fuel runs out — it hasn't happened yet in the history of the Universe!

How Big is a Star?



How Big is a Star?



What Happens When the Fuel Runs Out?

Remember than nuclear fusion (or "burning") does not use up much of the star's mass.

620 million tons of H → 616 million tons of He

every second

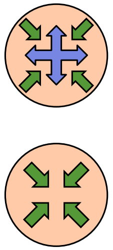
The 4 million tons that is "lost" is converted to energy that is radiated out from the core.

Even after billions of years, 99% of the mass is still there, transmuted from hydrogen into helium.

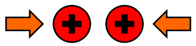
What happens when the hydrogen runs out?

What Happens When the Fuel Runs Out?

Remember the ABC of stellar evolution?

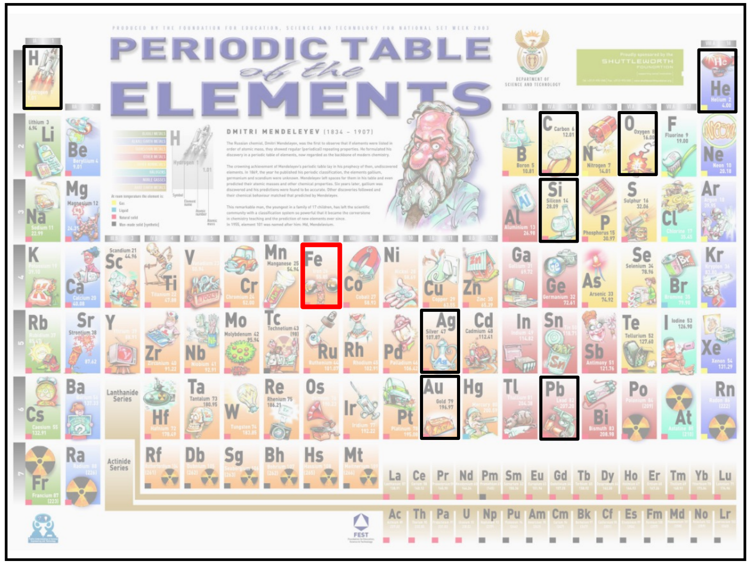


- When the hydrogen runs out, radiation drops
- The star is out of BALANCE as gravity > radiation
- The star shrinks and COMPRESSION heats the core to a higher temperature
- This forces nuclei together and ACCELERATES the fusion of helium into heavier elements



- Radiation increases and BALANCE is restored

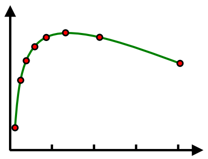
UNIVERSITY OF LIVERPOOL 25



Why Does Gold Exist?

Stars' fusion factories can "burn" H to make He, and then He to make C, and then C to make Ne, and so on, creating all the elements up to Fe.

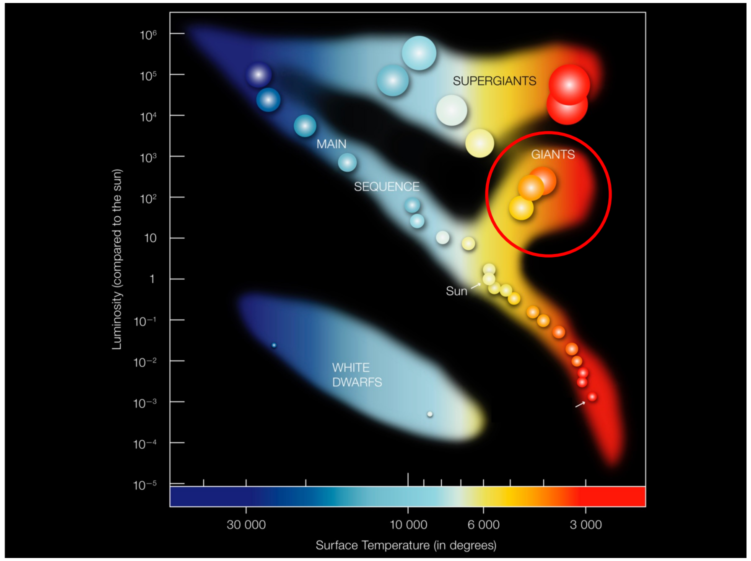
Nuclear physics tells us that fusion of Fe does not release energy.
It needs an input of energy.



So where do all the heavy elements come from?

We have to look beyond star life — at star death.

UNIVERSITY OF LIVERPOOL 27



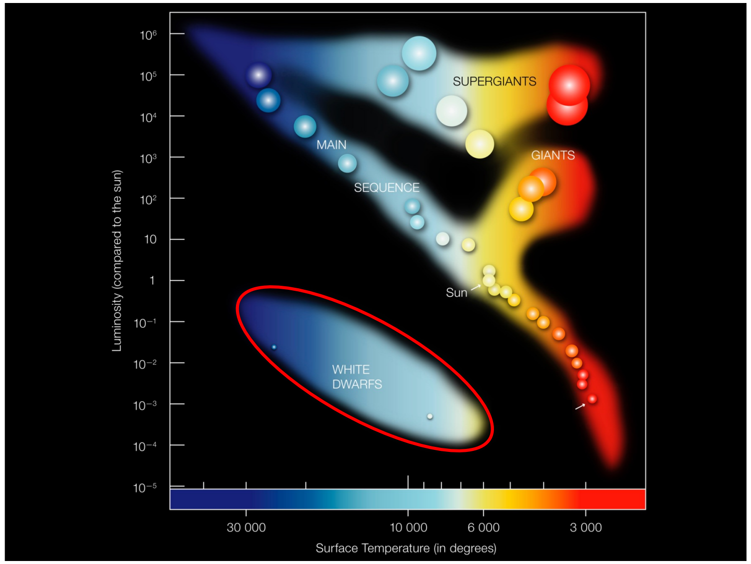
Red Giant or White Dwarf

For Medium Mass stars, gravity may not be strong enough to hold on to the outer layers of the star when He starts to burn in the core.

As the star expands the outer layers cool and redden — the star becomes a Red Giant.

The He burning in the core can become unstable. If the outer layers are given enough energy they can be blown off the star completely, leading to the formation of a Planetary Nebula.

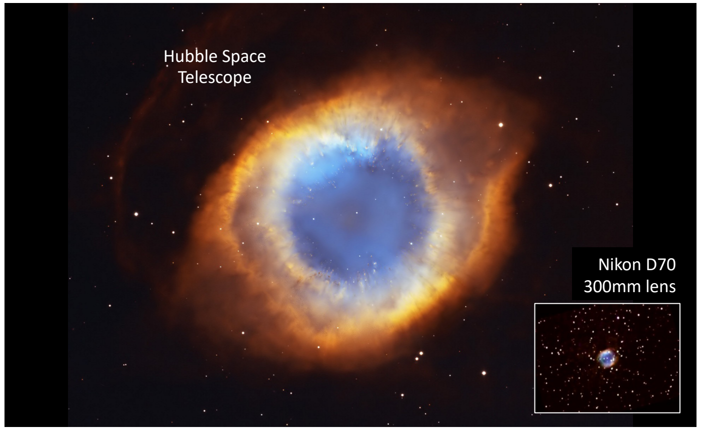
The remaining core becomes a White Dwarf.



Planetary Nebula

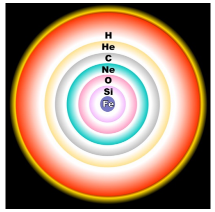
Planetary Nebula

Planetary Nebula



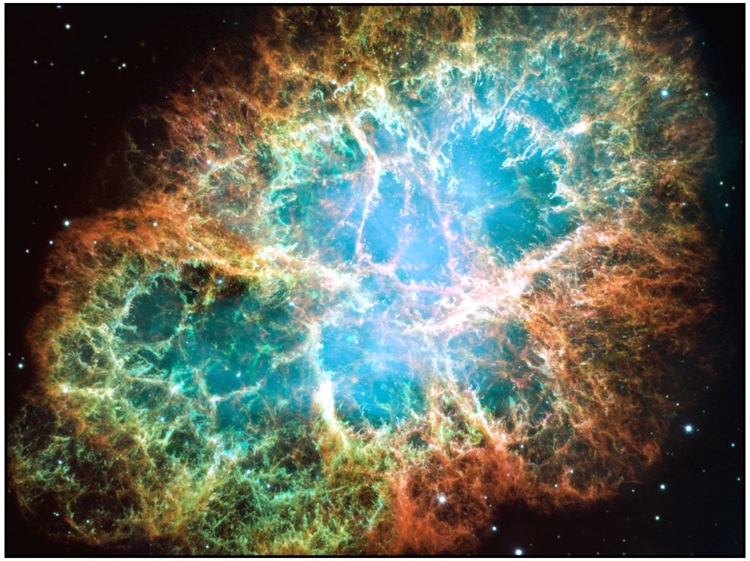
Supernova

For High Mass stars the strong gravity holds the star together through all the stages of nuclear burning.



At the end of its life, when the Fe core can no longer provide the energy to support the star, the core undergoes a catastrophic collapse.

The collapse crushes the core to a size of a few kilometres. A shockwave rebounds from the core and ejects the rest of the star's material into interstellar space.



Supernova

The energy of a supernova explosion is incredible. A back-of-the-envelope calculation shows that to rip a star apart you need an energy of

10^{44} Joules

Imagine the total energy output of the Sun (not just the tiny fraction that falls on the Earth) in each and every second of its 10-billion-year lifetime.

Now imagine all that energy released in just a few seconds.

The word "explosion" just isn't big enough.

Supernova

In the chaos of a supernova explosion nuclei fuse together to create elements heavier than Fe.

All the elements generated during the star's life, and its spectacular death, are ejected into interstellar space.

The heavy metals found on Earth were made in a supernova ...

... so this means that the Sun must be at least a "second generation" star. An unknown star was born, lived and died billions of years ago to seed our region of space with the heavy elements that we see around us today.

UNIVERSITY OF LIVERPOOL 37

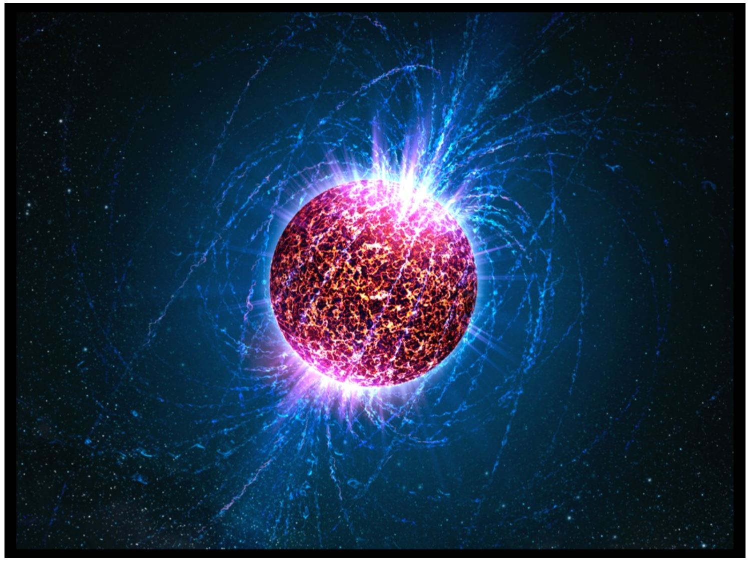
Supernova

After a supernova has crushed the star's core and ripped apart all of the star's outer regions, what is left behind?

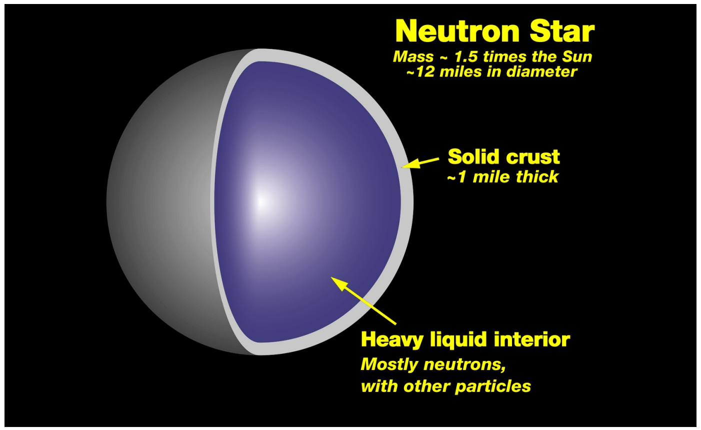
A tiny star a few kilometres in diameter.

A Neutron Star.

UNIVERSITY OF LIVERPOOL 38



Inside a Neutron Star



UNIVERSITY OF LIVERPOOL 40

Ticking Pulsars

Pulsar name	Period
B0329	814 ms
Vela Pulsar	89 ms
Crab Pulsar	33 ms
J0437	5.7 ms
B1937	1.5 ms
	1.55780644887275 ms

When Gravity Wins

Neutron stars formed in supernova explosions have a size of a few kilometres because this is the point at which neutrons are forced to "touch" each other.

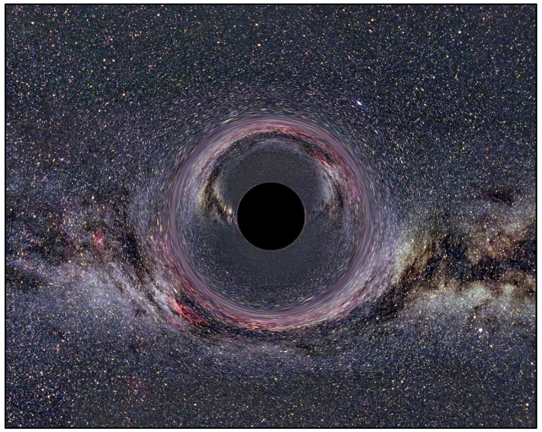
Getting them any closer means that they would have to overlap each other, which they really do not want to do.

If the star has enough mass, then gravity wins and the neutrons are forced together despite their objections. Nothing can stop the collapse continuing.

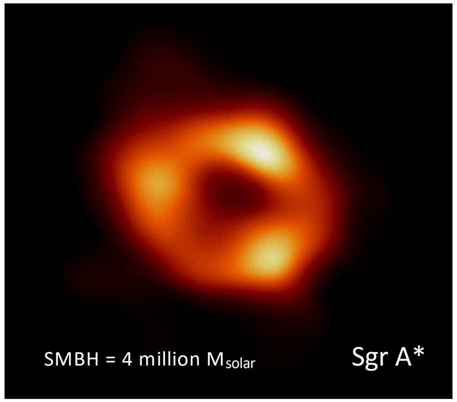
The result is the stuff of science fiction … a Black Hole.*

* See "Warping Space and Time"

Black Hole



Black Holes



Black Hole

* See "Warping Space and Time"

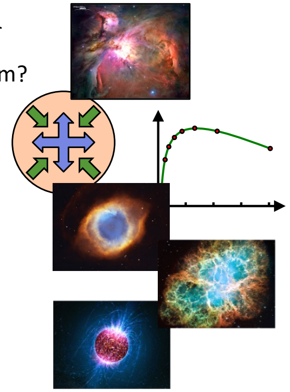
45

The ABC of Stellar Evolution

Birth
- At the Heart of the Matter
- Where Do Stars Come From?

Life
- A Question of Balance
- Live Fast, Die Young
- When the Fuel Runs Out

Death
- Bang or Whimper?
- What's Left Afterwards?
- When Gravity Wins



46