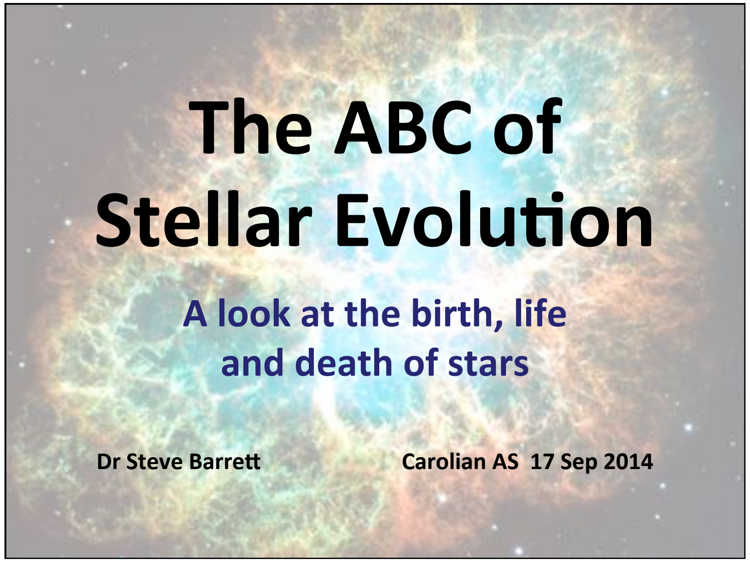


How Stars Tick

Birth

At the Heart of the Matter	Nuclear Fusion
Where Do Stars Come From?	Ignition

Life

A Question of Balance	Radiation v Gravity
Live Fast, Die Young	Star Types
When the Fuel Runs Out	New Elements

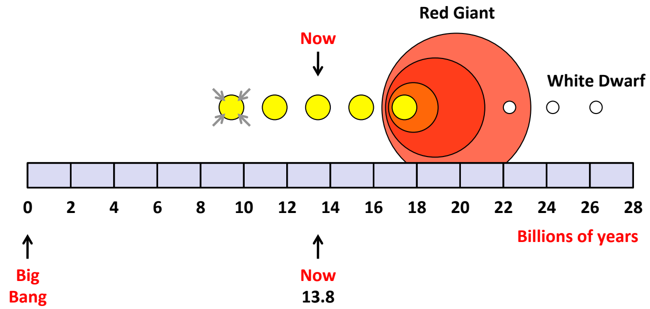
Death

Bang or Whimper?	Supernova
What's Left Afterwards?	Neutron Star
When Gravity Wins	Black Hole

ABC Stellar Evolution / Introduction 2

Life Cycle of the Sun

Our Sun is middle-aged…



[Sizes not to scale]

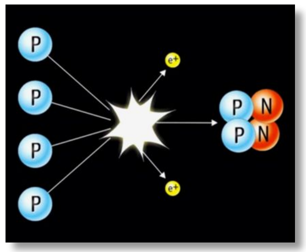
ABC Stellar Evolution / The Sun 3

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

600 M'tons



1 x helium

596 M'tons

ABC Stellar Evolution / Fusion 4

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, and the answer was in the talk on the "The Beginning of Everything"?

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**

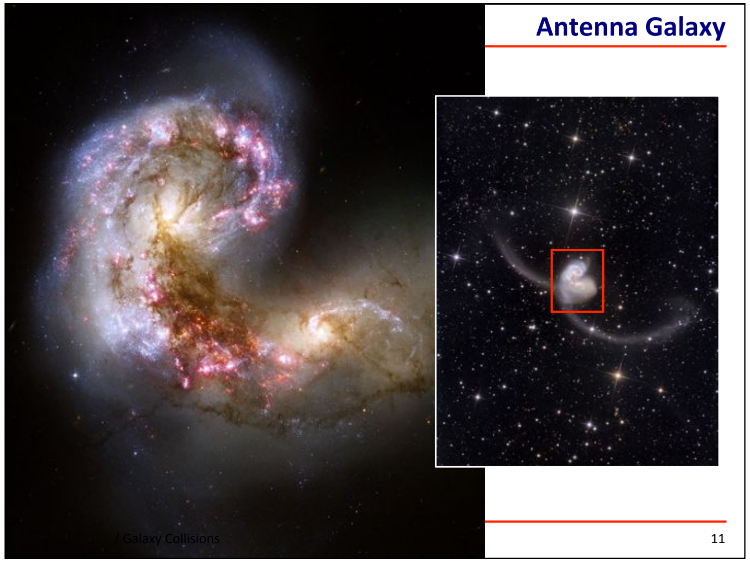
What Triggers Star Formation?

Giant Molecular Clouds float around the galaxy

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

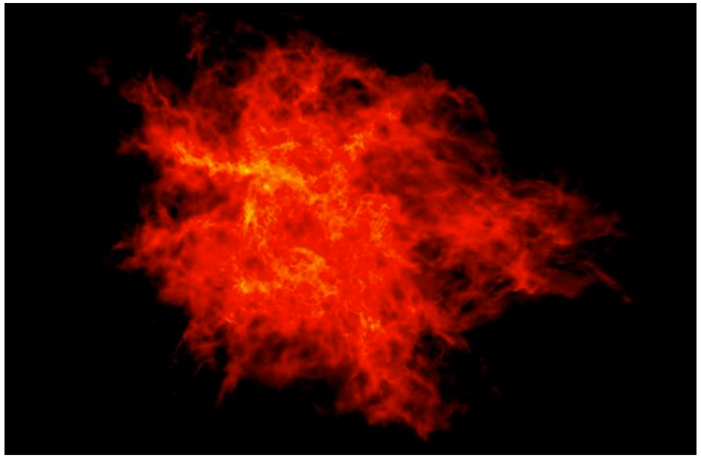
What makes a GMC collapse? Triggers may include…

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


Antenna Galaxy
/ Galaxy Collisions
11


When Worlds Collide
ABC Stellar Evolution / Birth / Galaxy Collisions
12

Collapsing Cloud



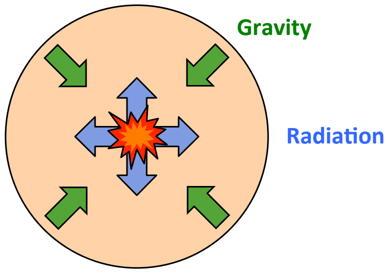
Star Cluster

A Question of Balance

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

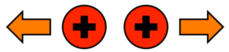
When the opposing forces are balanced, the star is stable.

When out of balance, the star must evolve.

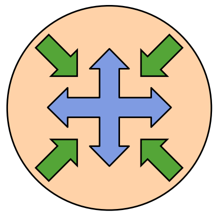


Many aspects of star birth, life and death can be explained in terms of this balance and the ABC of star evolution.

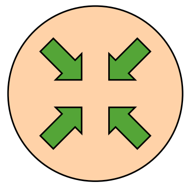
The ABC



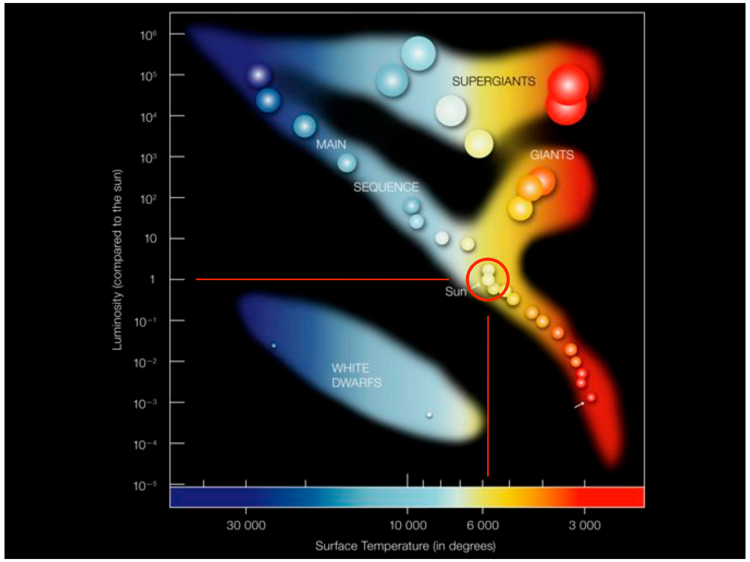
Like charges repel so high T and high P ACCELERATE fusion



In a star in equilibrium gravity and radiation are in BALANCE



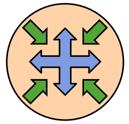
COMPRESSION produces heat



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

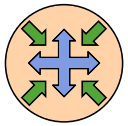
Rather than living for billions of years, like our Sun, high mass stars may live for only a few million years.

ABC Stellar Evolution / Life / Mass 18

Live Slow, Die Very Old

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

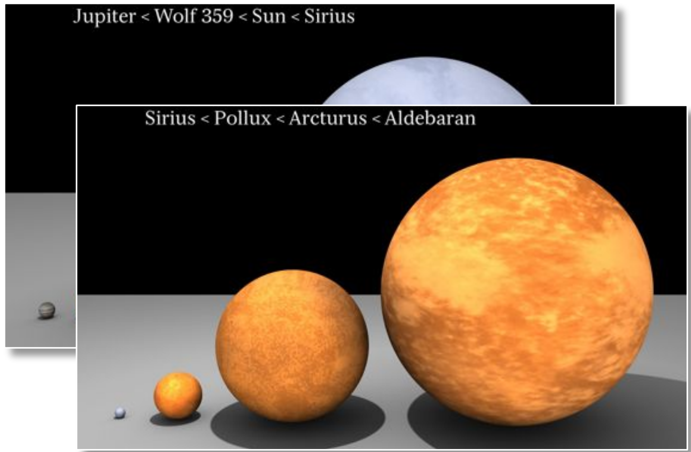
- Gravitational forces are relatively weak
- Hence radiation forces do not have to be high to maintain a balance
- Hence nuclear fuel lasts a long time



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!

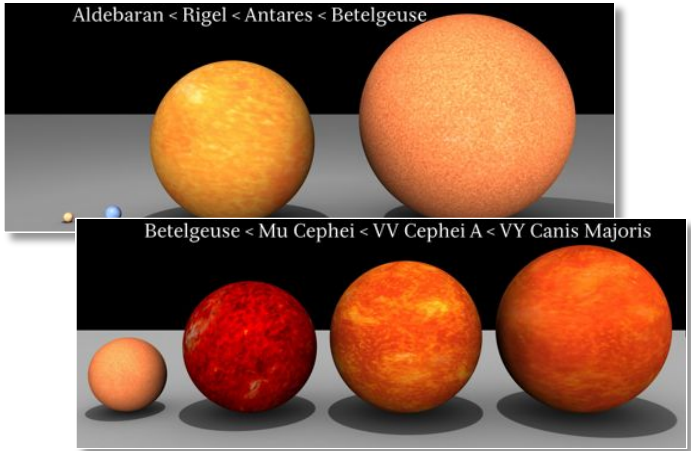
ABC Stellar Evolution / Life / Mass 19

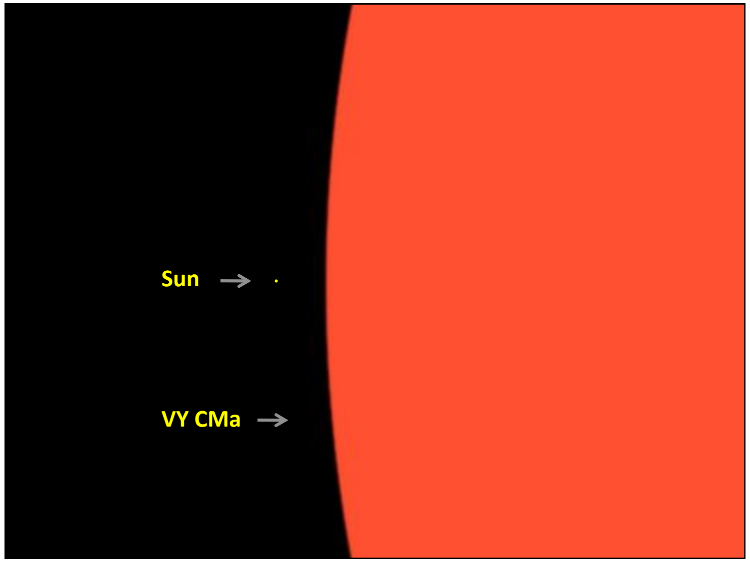
How Big is a Star?



ABC Stellar Evolution / Life / Size / Giants 20

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.

600 million tons of H → 596 million tons of He

every second

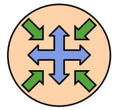
The 4 million tons that is "lost" is converted to energy that is radiated out from the core.

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

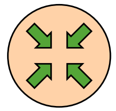
What happens when the hydrogen runs out?

What Happens When the Fuel Runs Out?

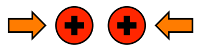
Remember the ABC of stellar evolution?



- When the hydrogen runs out, radiation drops
- The star is out of BALANCE as gravity > radiation

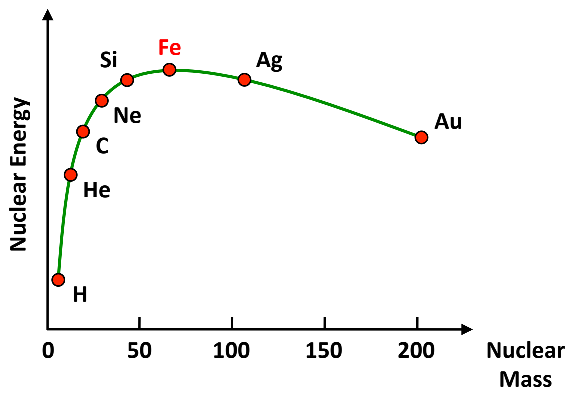


- The star shrinks and COMPRESSION heats the core to a higher temperature
- This forces nuclei together and ACCELERATES the fusion of helium into heavier elements

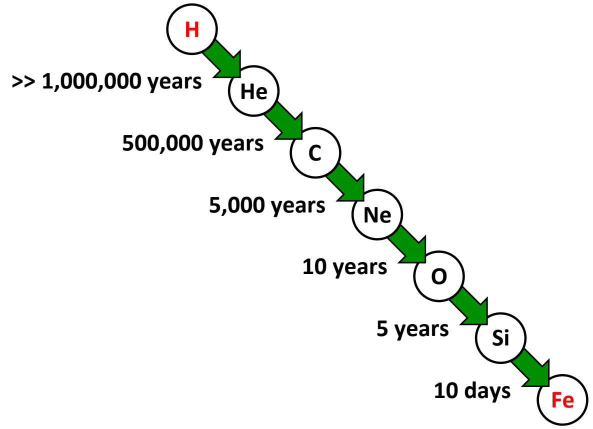


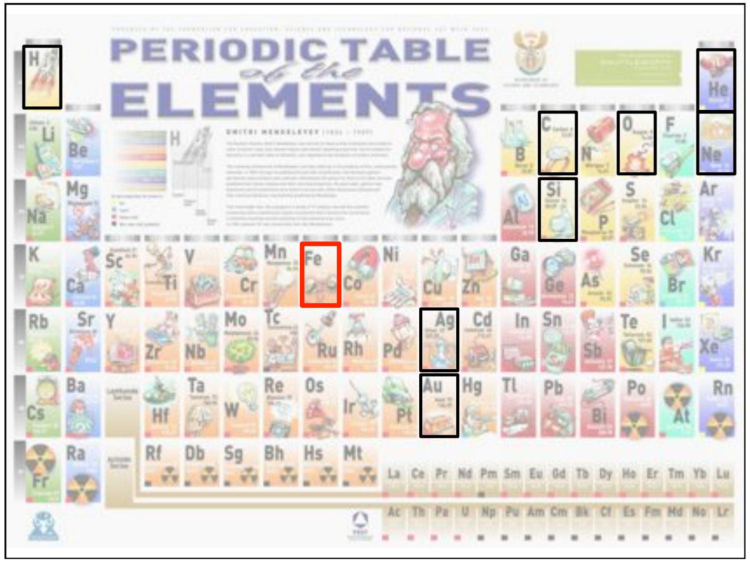
- Radiation increases and BALANCE is restored

What Happens When the Fuel Runs Out?



What Happens When the Fuel Runs Out?



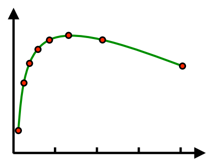


Why Does Gold Exist?

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.

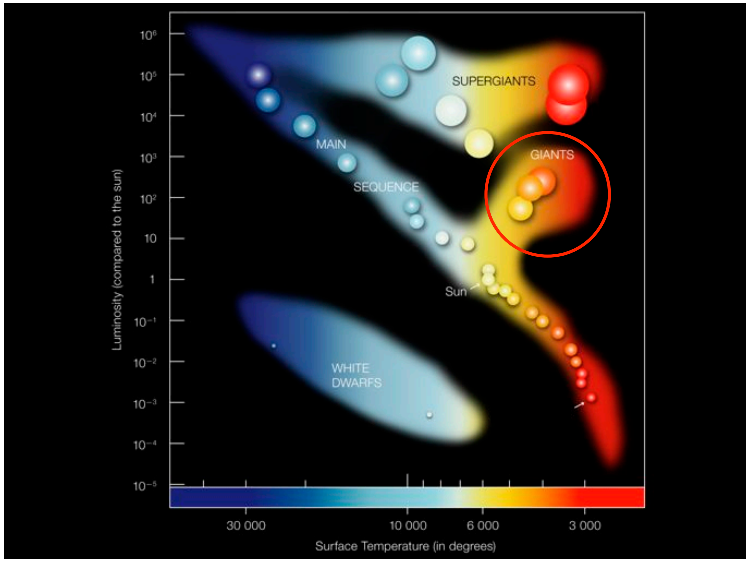
Fusion of Fe does not release energy.

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.



Red Giant or White Dwarf

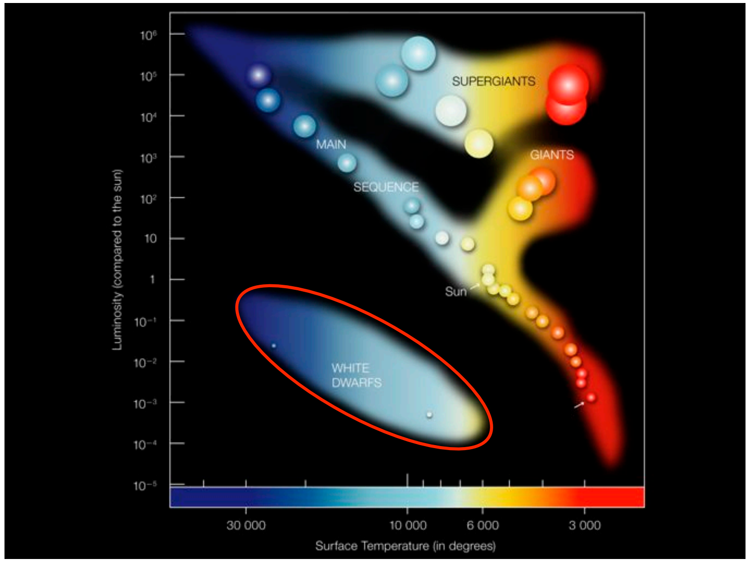
For **Medium Mass** stars, gravity may not be strong enough to hold on to the outer layers of the star when He starts to burn in the core.

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**.

ABC Stellar Evolution / Death / Red Giant or White Dwarf 30

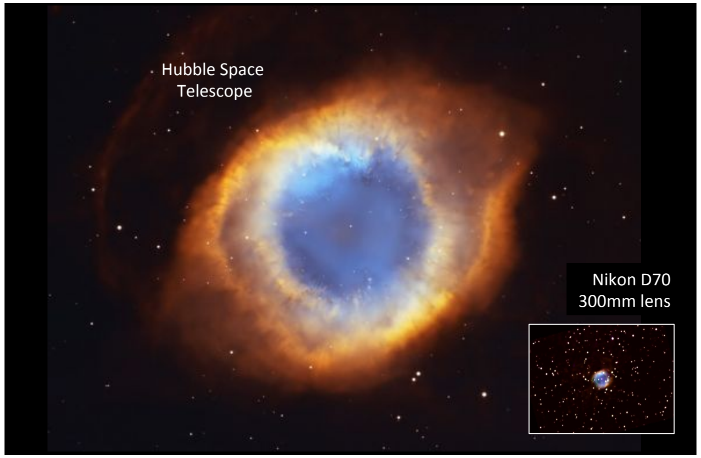


Planetary Nebula

ABC Stellar Evolution / Death / Planetary Nebula 32

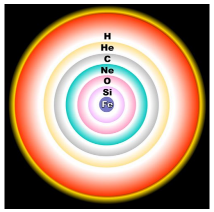
Planetary Nebula

Planetary Nebula



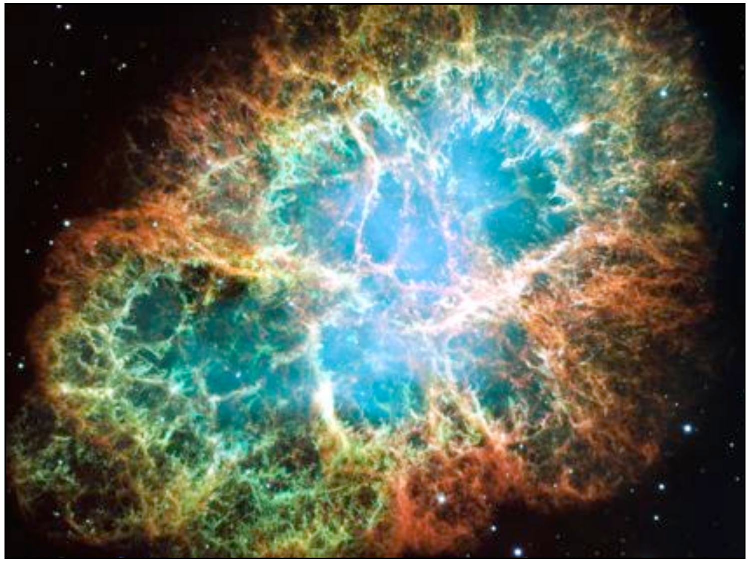
Supernova

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 mêlée of the 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.

All the heavy metals found on Earth must have been made in a supernova.

This means that the Sun must be "second generation". An unkown 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.

Supernova

Think about it for a minute…

We are just the custodians of 'our' atoms.

They were made in a star that died in a supernova explosion and redistributed the atoms into space.

We will use them for a while.

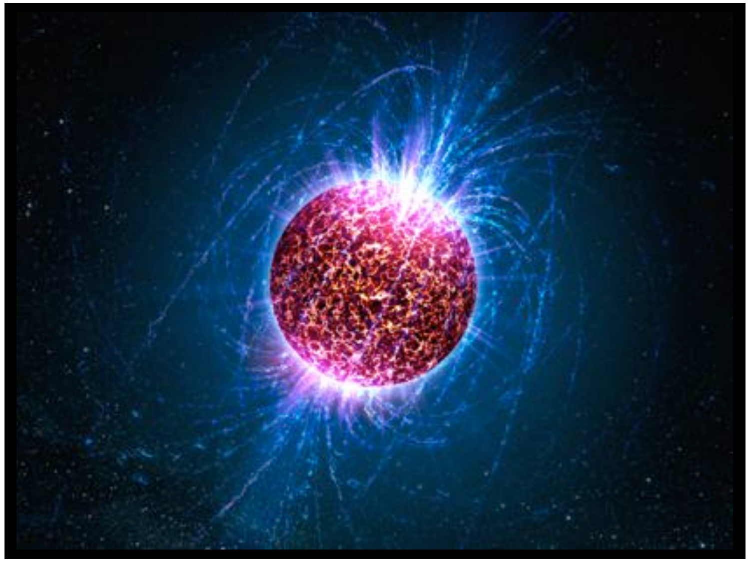
In a few billion years our Sun will die and many of those atoms will be recycled back into space for another generation to use.

Supernova

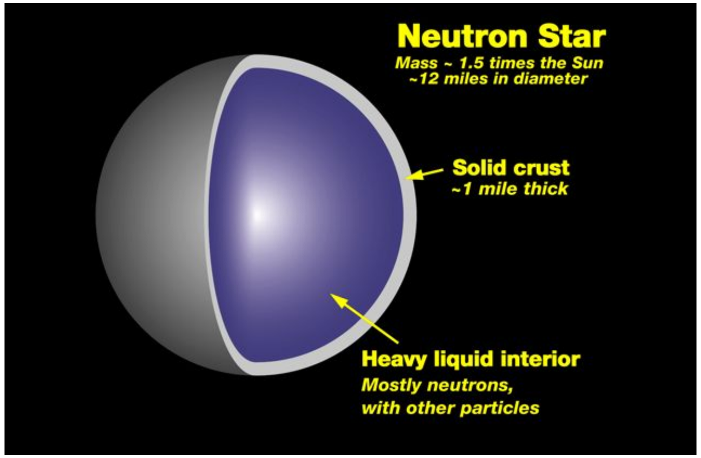
After a supernova has crushed the star's core and ripped apart all of the star's outer regions, what is left behind?

A tiny star a few kilometres in diameter.

A Neutron Star.



Inside a Neutron Star



ABC Stellar Evolution / Death / Neutron Star 42

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

ABC Stellar Evolution / Death / Neutron Star / Pulsars 43

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.

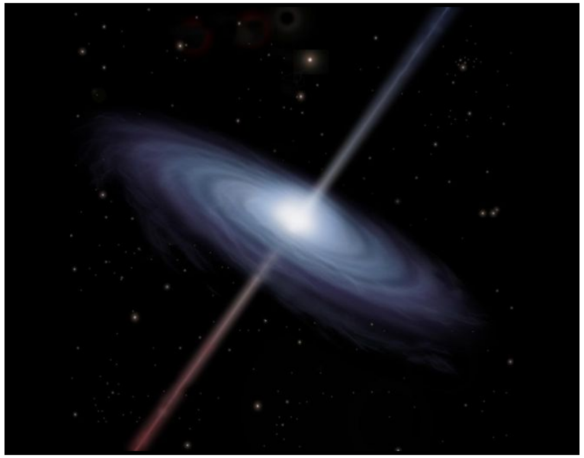
Getting them any closer means that they would have to overlap each other, which they really do not want to do.

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.

ABC Stellar Evolution / Death / Black Hole 44

Black Hole



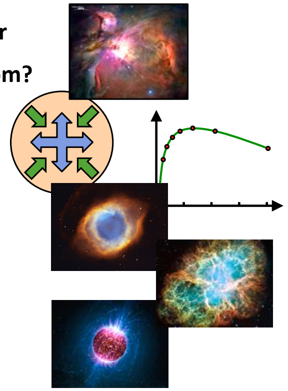
ABC Stellar Evolution / Death / Black Hole 45

How Stars Tick

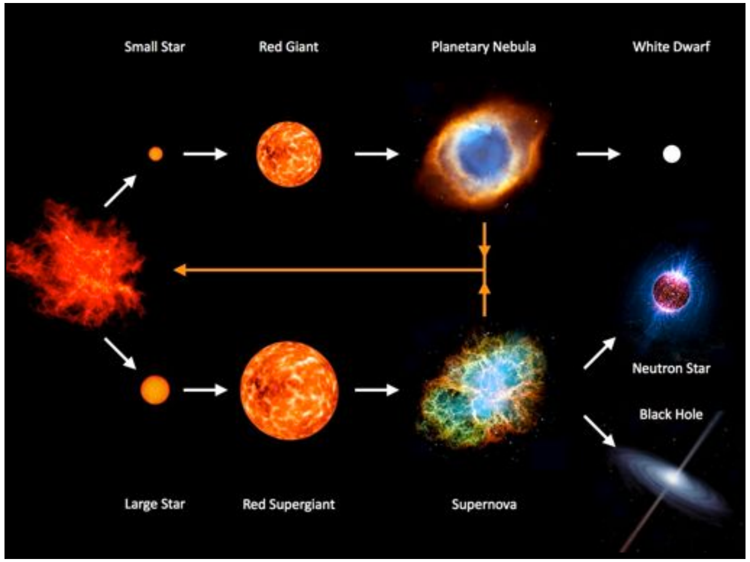
Birth
- At the Heart of the Matter
- Where Do Stars Come From?

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



ABC Stellar Evolution / Summary 46



The ABC of Stellar Evolution

http://www.liv.ac.uk/~sdb/Talks

Dr Steve Barrett

Carolian AS 17 Sep 2014