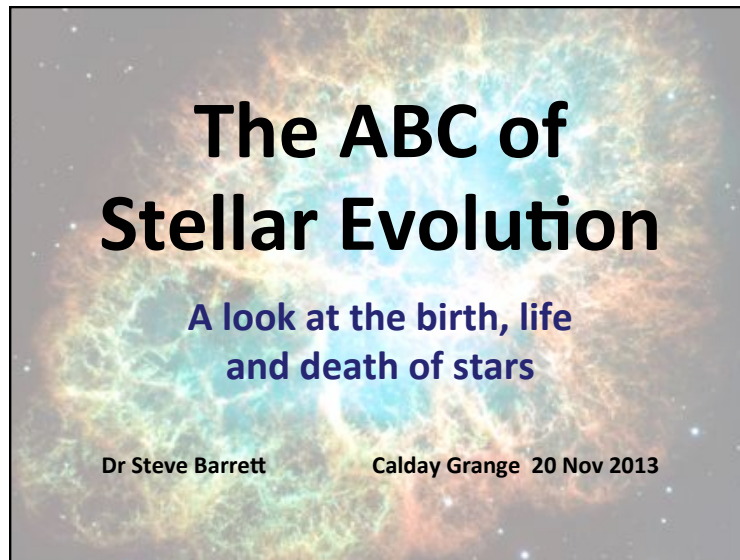
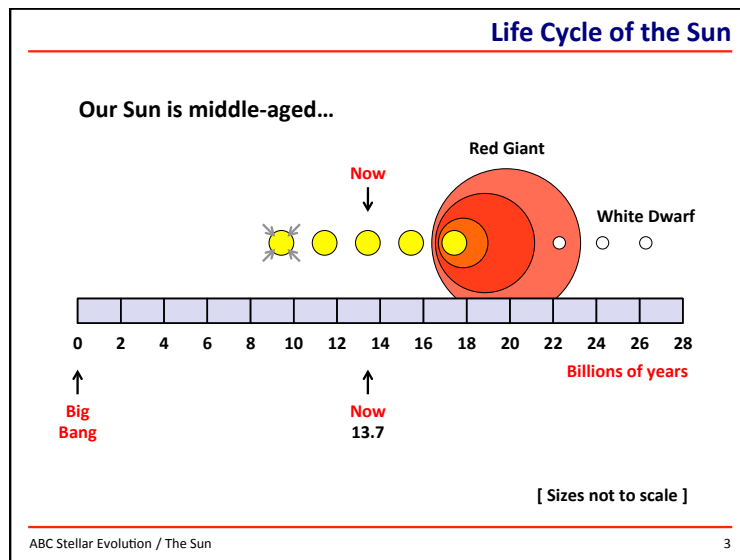


The ABC of Stellar Evolution



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



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

The ABC of Stellar Evolution

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?

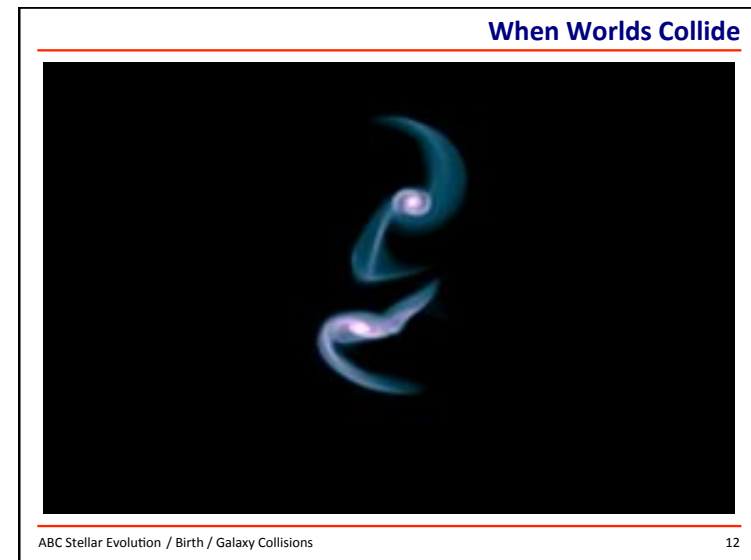
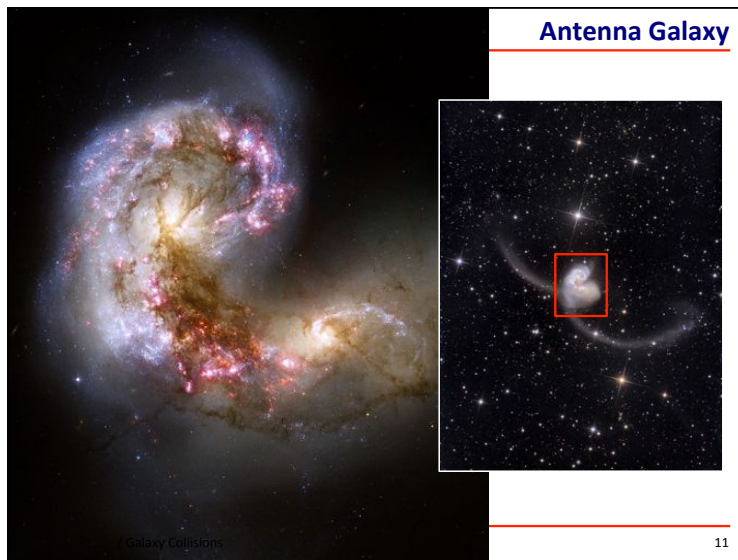
Giant Molecular Clouds float around the galaxy

- 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...

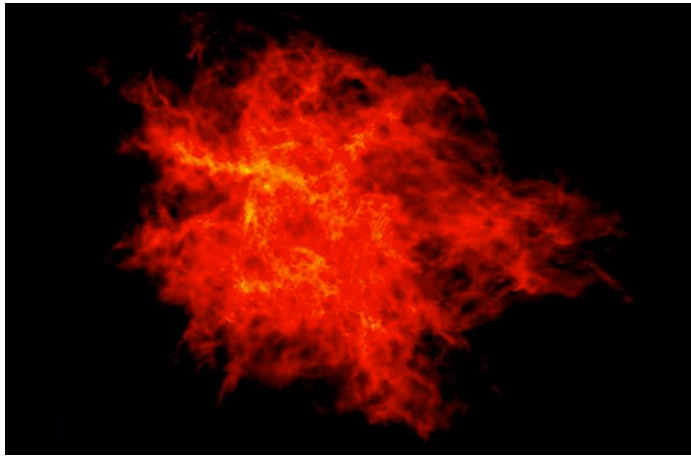
- One cloud colliding with another
- Shock waves rippling through the cloud
- Galaxy collisions (!)

The ABC of Stellar Evolution



The ABC of Stellar Evolution

Collapsing Cloud



ABC Stellar Evolution / Collapsing Cloud

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Star Cluster



ABC Stellar Evolution / Birth / Collapsing Cloud / Reality

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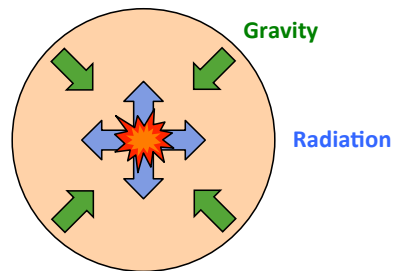
A Question of Balance

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.

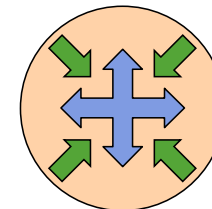


ABC Stellar Evolution / Life / Balance

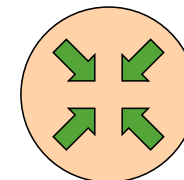
15

The ABC

← ⊕ ⊕ →
Like charges repel so
high T and high P
ACCELERATE fusion



In a star in equilibrium
gravity and radiation
are in **BALANCE**

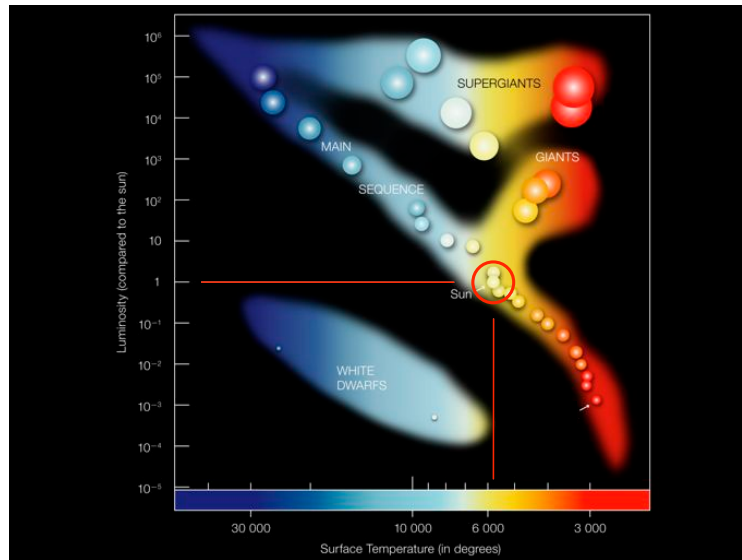


COMPRESSION
produces heat

ABC Stellar Evolution / Life / ABC

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The ABC of Stellar Evolution

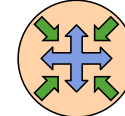


Live Fast, Die Young

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.

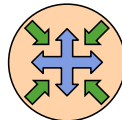
ABC Stellar Evolution / Life / Mass

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!

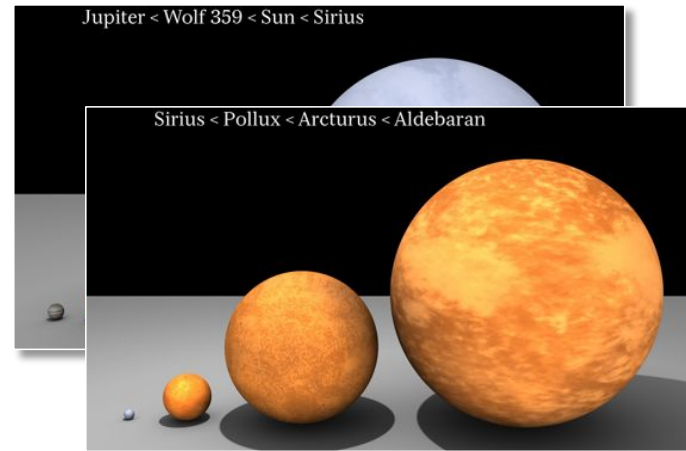
ABC Stellar Evolution / Life / Mass

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How Big is a Star?

Jupiter < Wolf 359 < Sun < Sirius

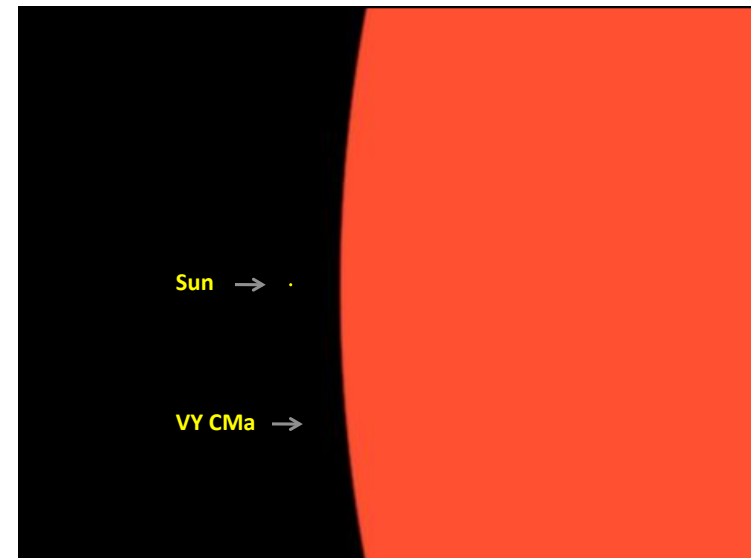
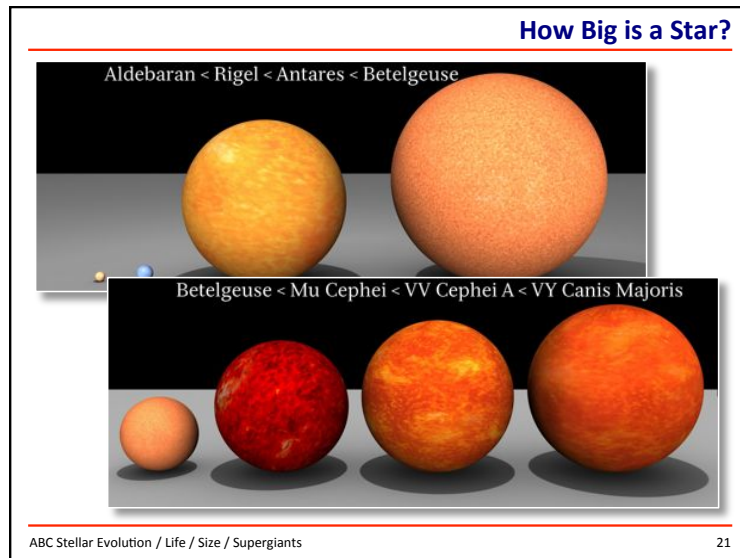
Sirius < Pollux < Arcturus < Aldebaran



ABC Stellar Evolution / Life / Size / Giants

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The ABC of Stellar Evolution



What Happens When the Fuel Runs Out?

Remember that 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?

ABC Stellar Evolution / Life / Heavy Elements

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What Happens When the Fuel Runs Out?

Remember the **ABC** of stellar evolution?

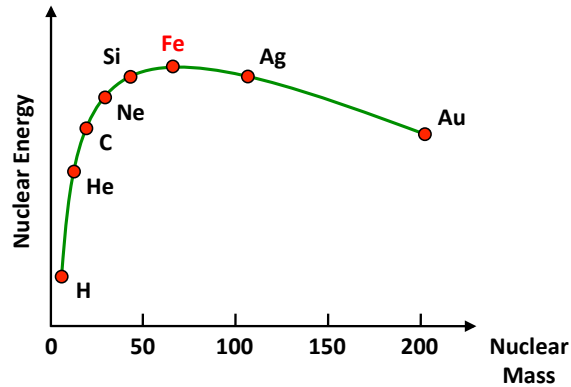
- When the hydrogen runs out, radiation drops
- The star is out of **BALANCE** as gravity > radiation
- The star shrinks and **COMPRESSION** heats the core to a higher temperature
- This forces nuclei together and **ACCELERATES** the fusion of helium into heavier elements
- Radiation increases and **BALANCE**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

ABC Stellar Evolution / Life / Heavy Elements

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The ABC of Stellar Evolution

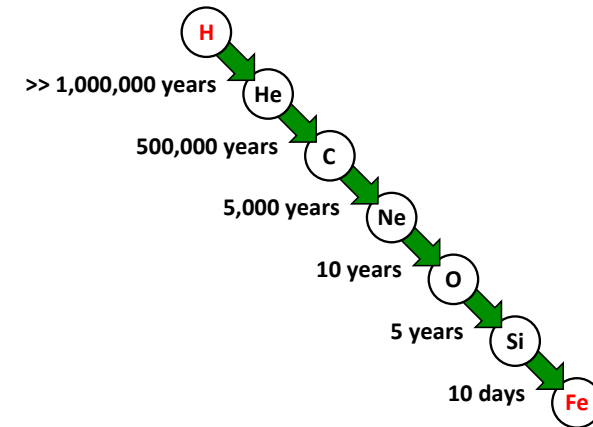
What Happens When the Fuel Runs Out?



ABC Stellar Evolution / Life / Heavy Elements

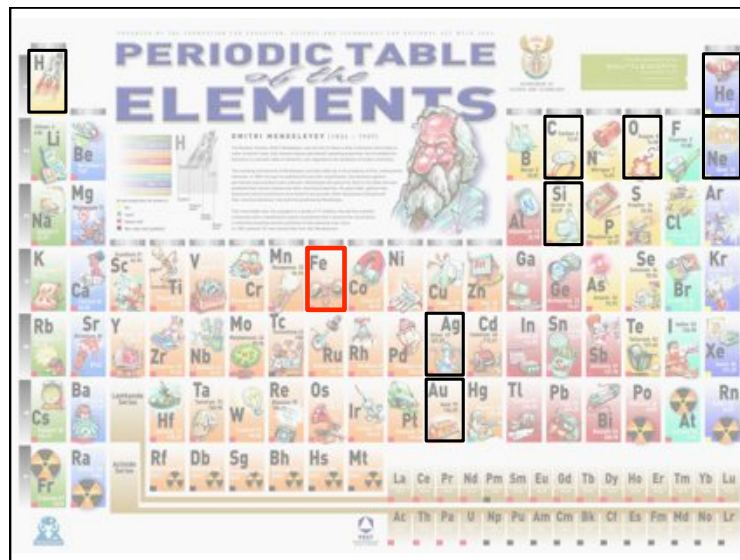
25

What Happens When the Fuel Runs Out?



ABC Stellar Evolution / Life / Heavy Elements / Timescales

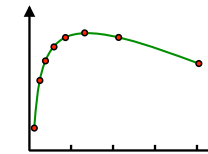
26



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.



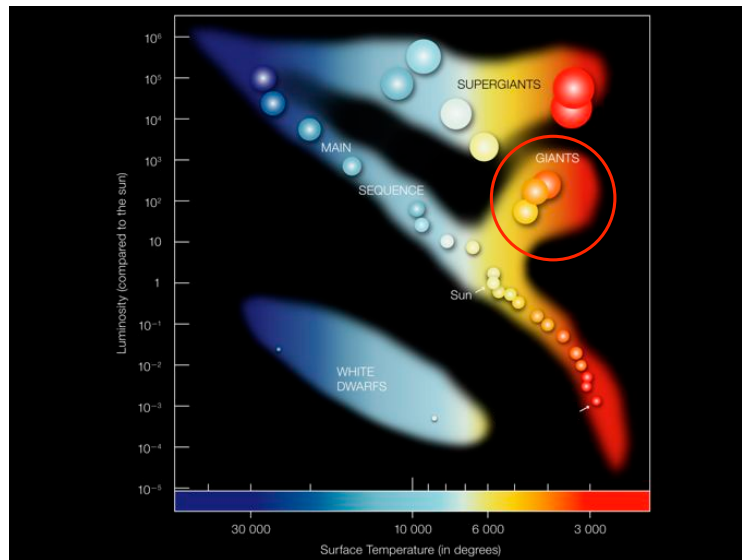
So where do all the heavy elements come from?

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

ABC Stellar Evolution / Death

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The ABC of Stellar Evolution



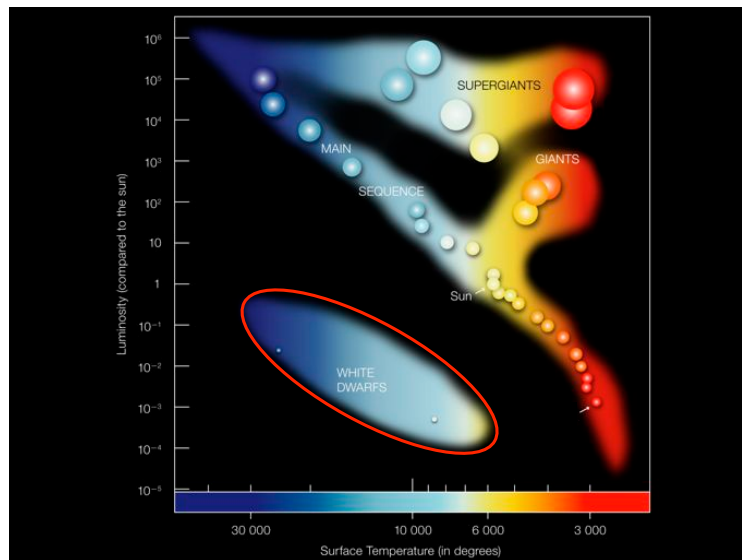
Red Giant or White Dwarf

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



The ABC of Stellar Evolution

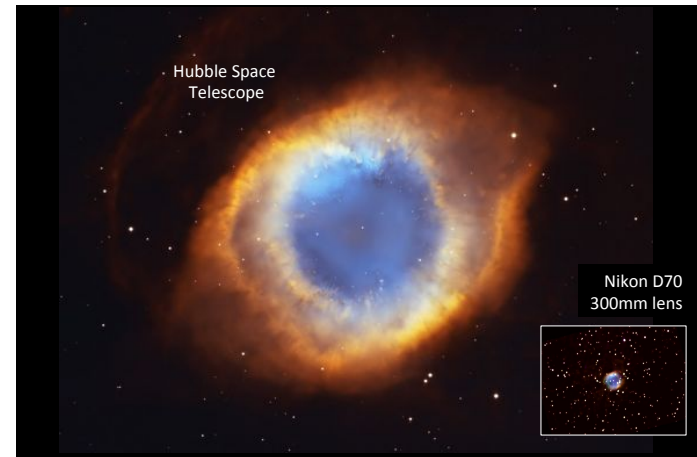
Planetary Nebula



ABC Stellar Evolution / Death / Planetary Nebula / Cat's Eye Nebula

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Planetary Nebula



ABC Stellar Evolution / Death / Planetary Nebula / Helix Nebula

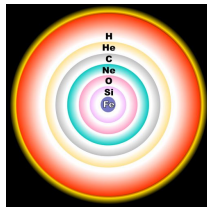
34

Supernova

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

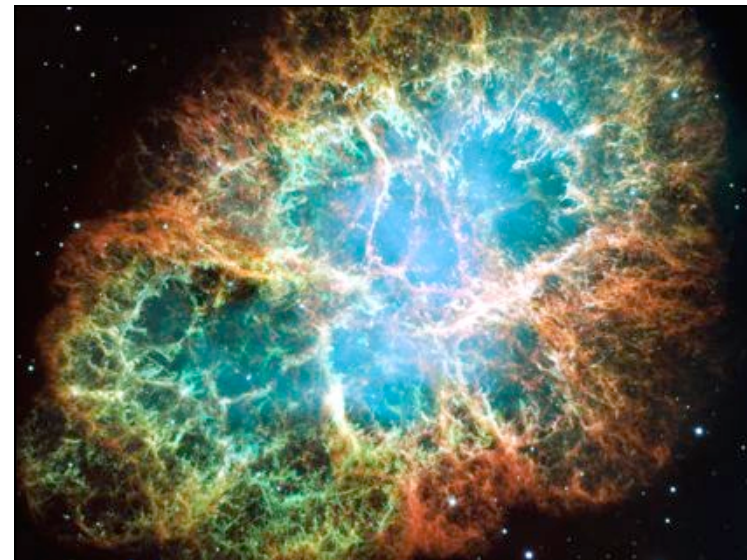
At the end of its life, when the Fe core can no longer provide the energy to support the star, the core undergoes a catastrophic collapse.

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.



ABC Stellar Evolution / Death / Supernova

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The ABC of Stellar Evolution

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.

ABC Stellar Evolution / Death / Supernova

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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 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.

ABC Stellar Evolution / Death / Supernova / Heavy Elements

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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.

ABC Stellar Evolution / Death / Supernova / Heavy Elements

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Supernova

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

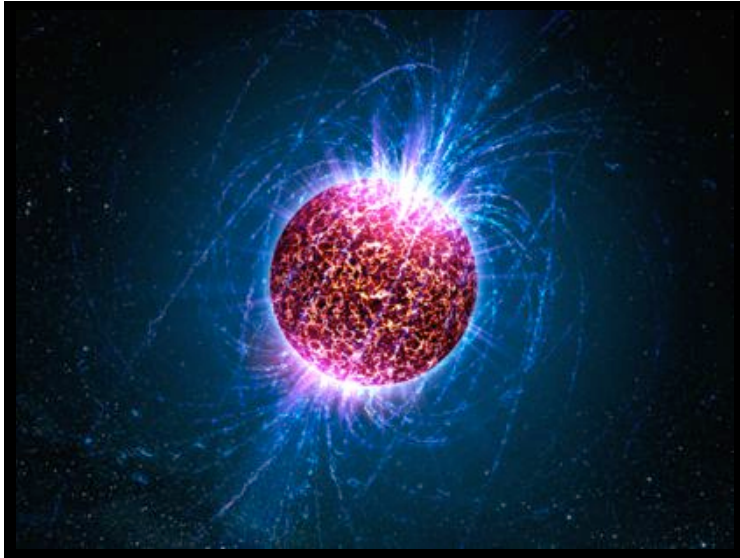
A **tiny** star a few kilometres in diameter.

A **Neutron Star**.

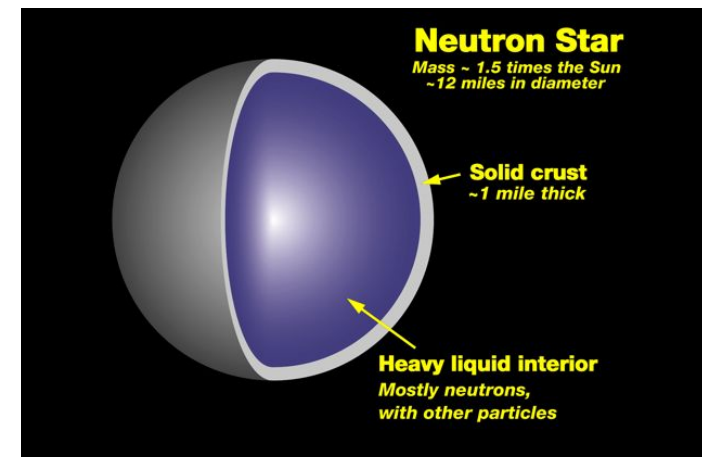
ABC Stellar Evolution / Death / Supernova / Neutron Star

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The ABC of Stellar Evolution



Inside a Neutron Star



ABC Stellar Evolution / Death / Neutron Star

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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

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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

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The ABC of Stellar Evolution

