Nuclear Fusion
and
The Lives and Deaths of Stars

Failed stars	**Stars**	**Dying stars**	**Dead stars**
Brown dwarfs	normal stars (e.g., Sun) Blue giants (e.g., Rigel) Red dwarfs (e.g., Proxima Centauri)	Red giants (e.g., Betelgeuse) Planetary Nebulae	White dwarfs Neutron stars = pulsars Black holes

$M_\odot$ = 1 solar mass = the mass of the Sun = 2 x 10^{30} kg = 300,000 M_{earth}
M_{earth} = 1 Earth Mass

1

… remember …

mass attracts other mass:

$$F_{gravity} = -G\frac{Mass_A Mass_B}{(Distance)^2}$$

gravitational contraction: a process by which a spherical object squeezes itself harder and harder and harder under the influence of gravity

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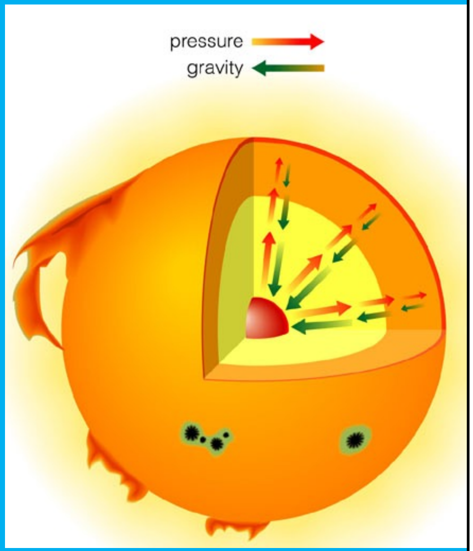
Gravitational contraction:

- Recall: Protostar keeps on shrinking until internal (thermal) pressure can resist gravity
- Balance reached at T = 10^7 K
  - **nuclear fusion reactions begin**
  - balance between gravity and thermal pressure is reached (*hydrostatic equilibrium*)



Star: an object in which the inward force of gravity is balanced by outward pressure generated by nuclear fusion reactions

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Life of a Star

- The life of any star is a contest between two opposing processes:
  - **Gravity (inwards)** vs. **Thermal Pressure (outwards)**
- Pressure resists gravity, pushes outwards.
  - the type of object is defined by what provides the outwards pressure
  - if outwards pressure can't balance gravity: protostar
  - if outwards pressure can balance gravity and is from heat generated by nuclear fusion: a normal star
  - If outwards pressure comes from 'degeneracy pressure,' it's a dead star

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$E = mc^2$

E = energy
M = mass
c = speed of light

1905: Albert Einstein's *Theory of Special Relativity*

Different ways of express the physics expressed by this equation:

– Energy is equivalent to mass
– Mass is a 'storage device' for energy
– Mass can be converted into energy
– Energy can be converted into mass

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1905: Albert Einstein's *Theory of Special Relativity*

Different ways of understanding this equation:

– Energy is equivalent to mass
– Mass is a 'storage device' for energy
– Mass can be converted into energy
– Energy can be converted into mass

Stars are huge, natural machines that are in the business of converting mass into energy and distributing that energy throughout the universe

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$E = mc^2$

- 1926: this could power stars (Arthur Eddington).
  How? Stars convert four hydrogen nuclei (somehow) into one helium nucleus
- 1929: stars are mostly made of hydrogen (Cecilia Payne-Gaposhkin)
  Good news! composition of stars makes Eddington's idea possible
- 1932: neutron discovered (James Chadwick)
  Aha! Composition of helium nucleus now understood (2p, 2n)
- 1938: correct explanation of nuclear fusion found (Hans Bethe)
  the step-by-step process in which 2p are converted to 2n

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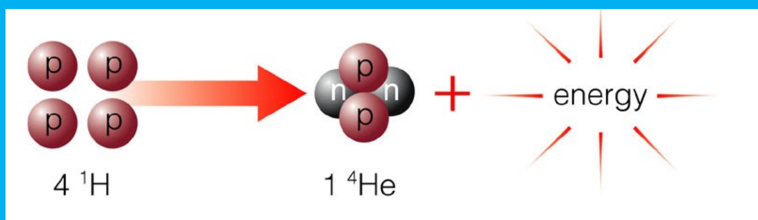
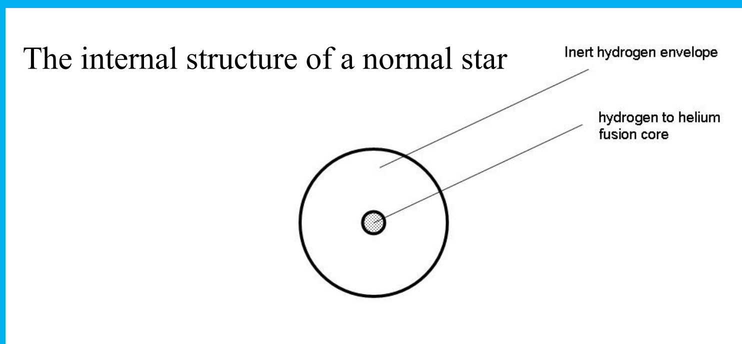
nuclear fusion





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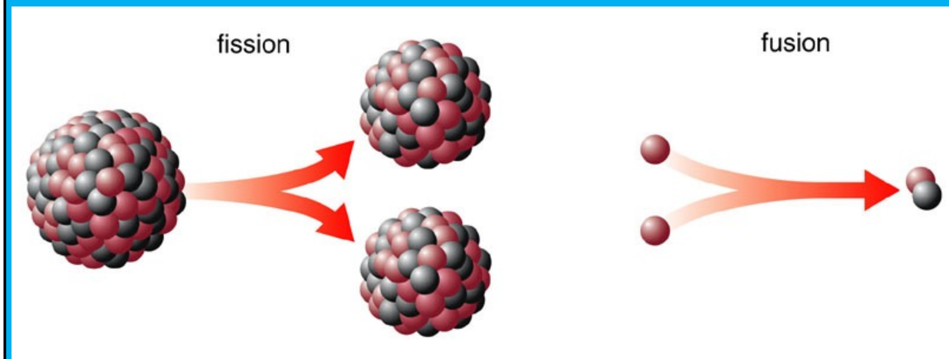

Fission

- Big nucleus splits into smaller pieces
- Radioactivity

Where: nuclear reactors,
atomic bombs, nuclear bombs

Fusion

- Small nuclei stick together to make a bigger one

Where: centers of stars,
nuclear bombs

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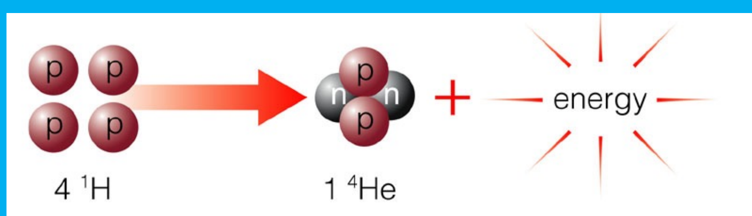
$E = mc^2$



mass of four protons: 6.690×10^{-24} g

mass of helium nucleus: 6.643×10^{-24} g

Δm = lost mass ("delta m")

$\Delta m = (6.690 \times 10^{-24}$ gm$) - (6.643 \times 10^{-24}$ gm$) = 4.700 \times 10^{-26}$ gm

0.7% mass of protons disappears, is turned into energy

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How much energy is this?

$$E = mc^2 = (4.700 \times 10^{-26}\ g) \times \left(3 \times 10^{10}\ \frac{cm}{s}\right)^2$$

$$E = (4.700 \times 10^{-26}\ g) \times \left(9 \times 10^{20}\ \frac{cm^2}{s^2}\right)$$

$$E = 4.2 \times 10^{-5}\ \frac{gm \cdot cm^2}{s^2}$$

$$E = 4.2 \times 10^{-5}\ erg\ \times \left(\frac{1\ calorie}{4.184 \times 10^7\ erg}\right)$$

$$E = 10^{-12}\ calorie$$

Notes : 1 erg = 1 $\frac{gm \cdot cm^2}{s^2}$; 1 calorie = 41,840,000 ergs

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Brown Dwarfs: Failed Stars

- If the protostar has a mass < 0.08 $M_\odot$:
  - It does not contain enough gravitational oomph to reach a core temperature of 10^7 K
  - First step in proton-proton chain cannot happen
  - The object never becomes a normal star
  - But at 10^6 K, deuterium fusion begins (protostars contain a small amount of deuterium when they form)
  - Gravity-pressure balance holds until deuterium is used up

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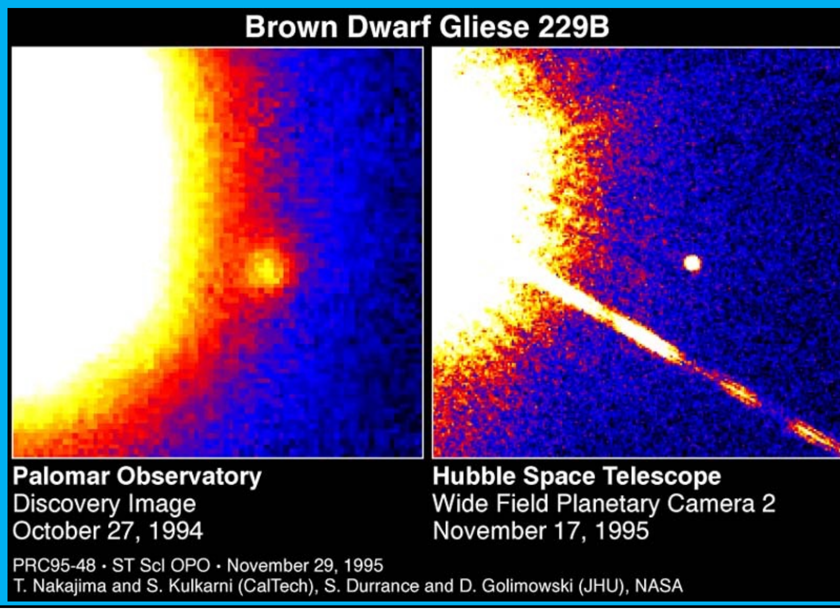
The First Brown Dwarf Discovery



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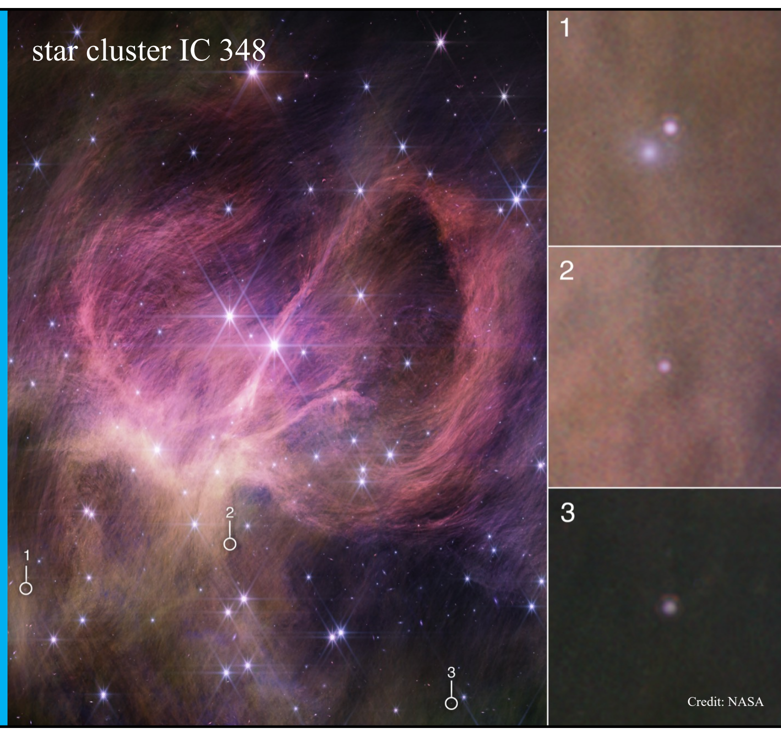

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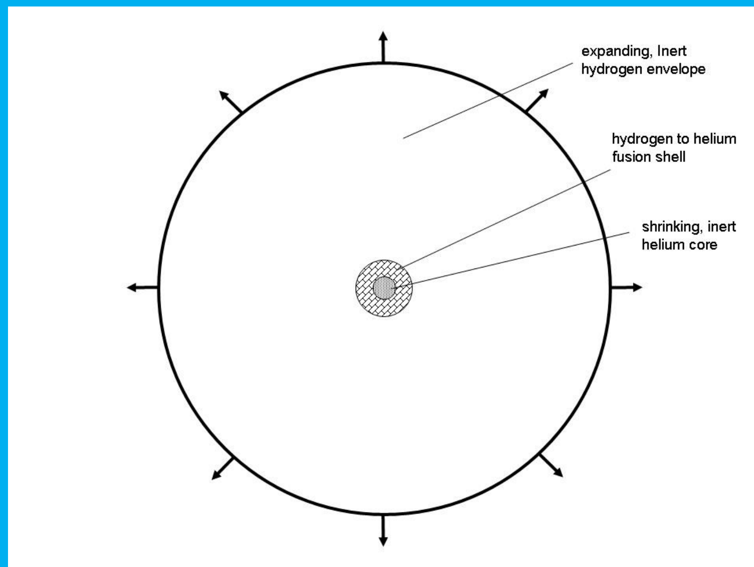
Red giants: stars after they run out of fuel in core for fusion

Fusion in their outer layers makes them expand



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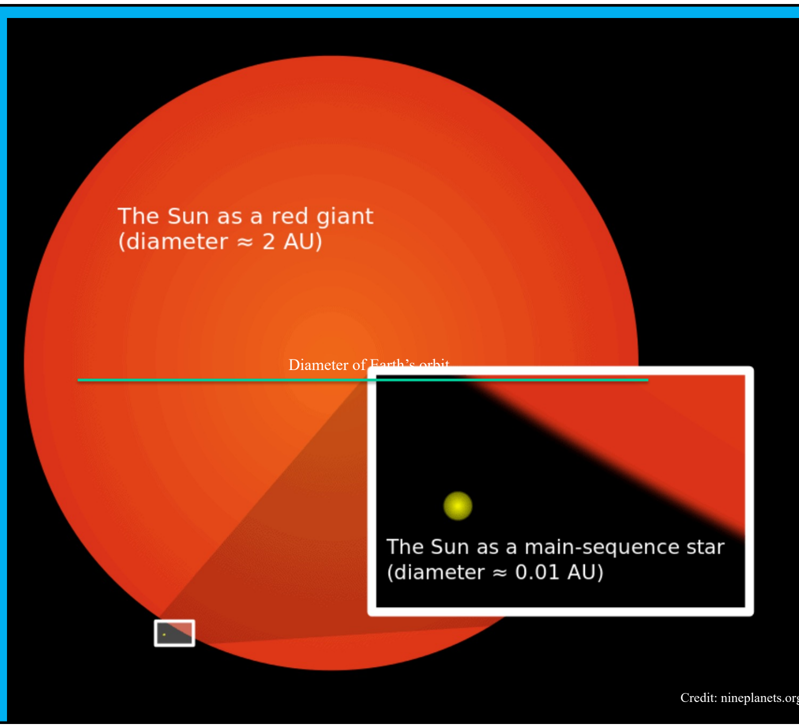

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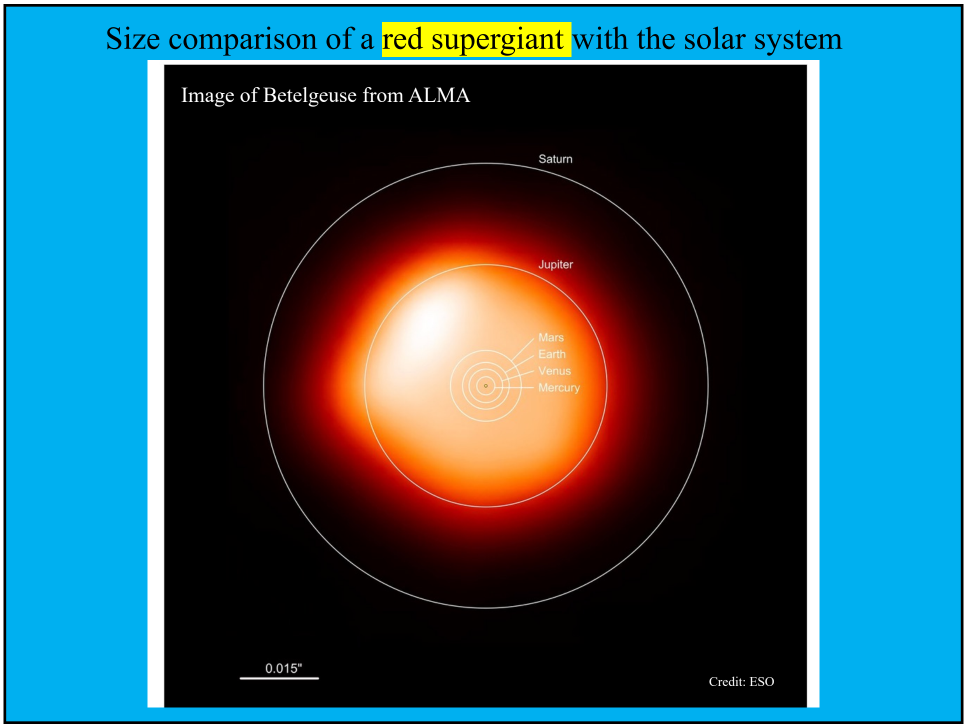
Size comparison of a red supergiant with the solar system
Image of Betelgeuse from ALMA
Saturn
Jupiter
Mars
Earth
Venus
Mercury
0.015"
Credit: ESO

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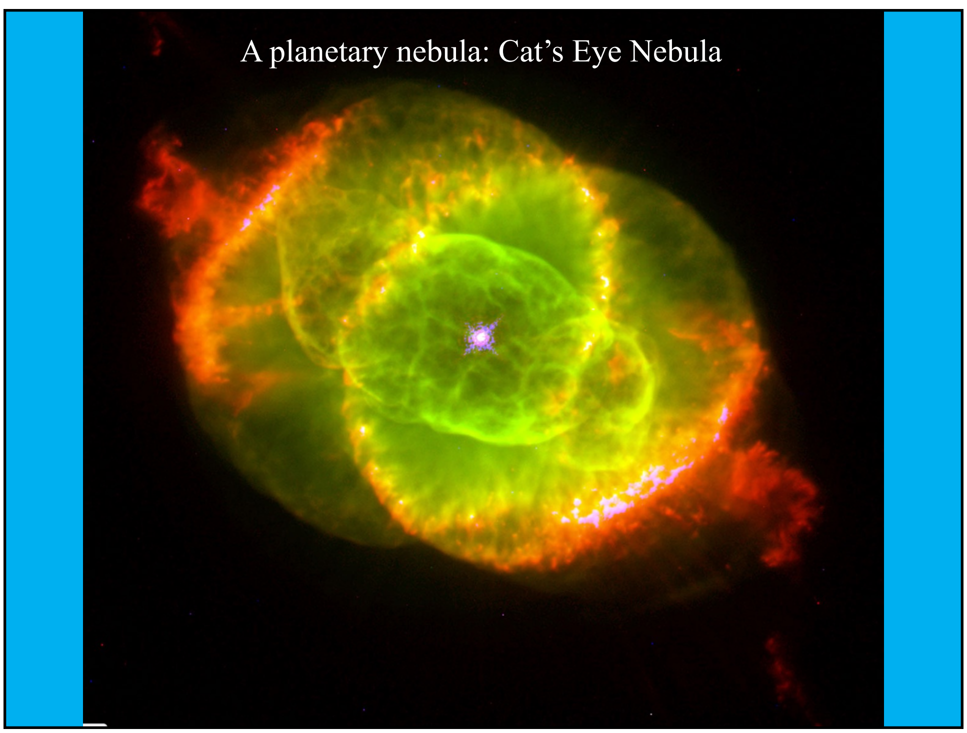
A planetary nebula: Cat's Eye Nebula

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White Dwarfs: red giants after they run out of fuel for fusion and puff off their outer layers (if $M_{star} < 1.4\ M_{\odot}$)

Dead stars (no fusion anywhere)

Gravity squeezes them until they are so dense that another pressure (electron degeneracy pressure) pushes back against gravity

White dwarfs are hot objects that will spend all of eternity cooling off

Credit: northwestern.edu

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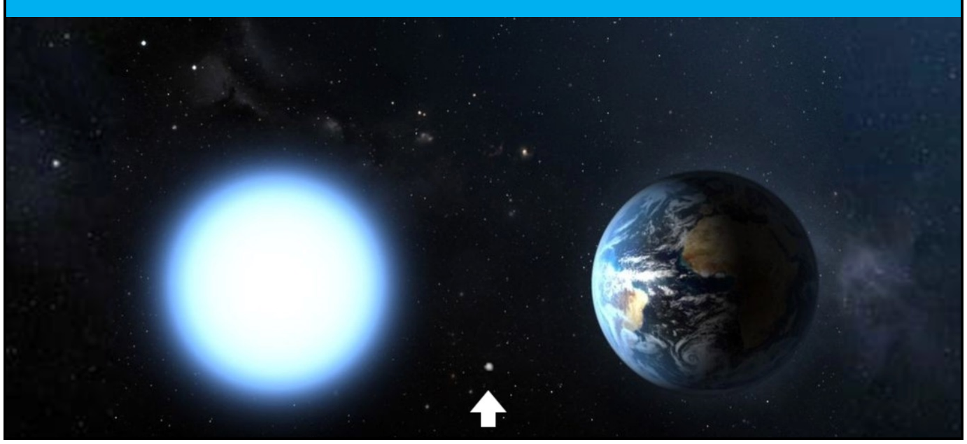
Neutron stars: red giants after they run out of fuel for fusion in their outer layers and collapse if $3\ M_{\odot} > M_{star} > 1.4\ M_{\odot}$

Dead stars (no fusion anywhere)
Even electron degeneracy pressure can't stop gravity if mass > $1.4\ M_{\odot}$
Dead star collapses to size of small city (10 km in diameter)
Gravity stopped by neutron degeneracy pressure (if $M_{star} < 3\ M_{\odot}$)



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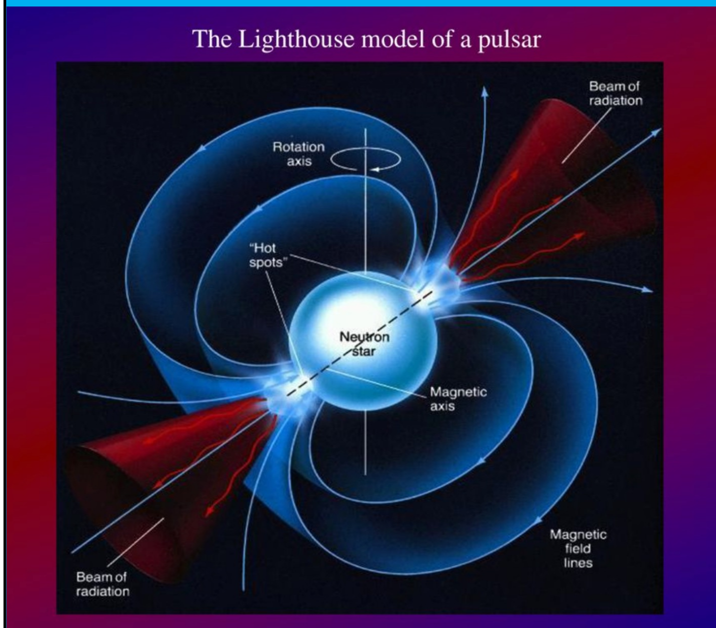
Pulsars: spinning neutron stars



Credit: https://cosmosatyourdoorstep.com

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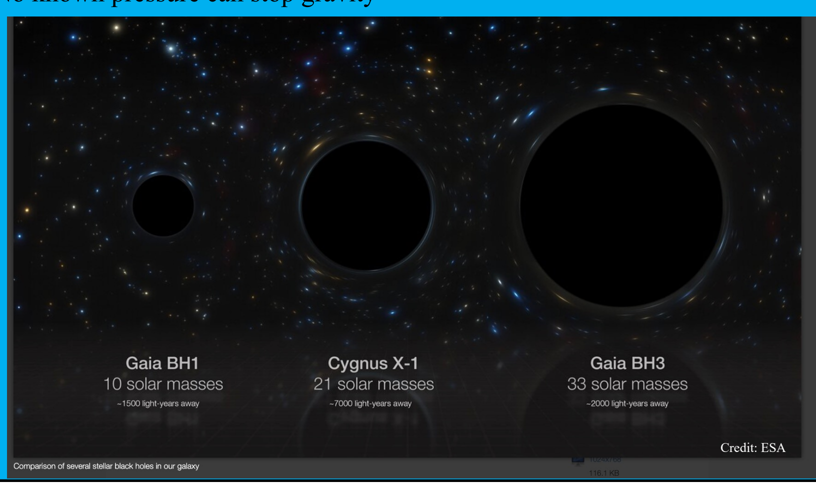
Black holes

Dead stars (no fusion anywhere)
If mass > 3 $M_\odot$, even neutron degeneracy pressure can't stop gravity
Dead star collapses to less than Schwarzschild radius (a few km)
Gravity at 'surface' is so strong that light cannot escape
No known pressure can stop gravity



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OPTIONAL MATERIAL!

The material on the following two slides are optional. This material corresponds to the material in the optional appendix in the reading for Lecture 3.

These slides provide more detail about the nuclear fusion reactions (the proton-proton chain) that takes place in the cores of stars.

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OPTIONAL MATERIAL!

proton-proton cycle

- $^1H + ^1H \rightarrow ^2H + e^+ + \nu$ — T = 10^7 K
- $^2H + ^1H \rightarrow ^3He + \gamma$ — T = 10^6 K
- $^3He + ^3He \rightarrow ^4He + ^1H + ^1H$ — T = 10^6 K

^1H = proton (nucleus of a hydrogen atom)
^2H = deuteron (nucleus of a heavy hydrogen atom; one proton plus one neutron)
^3He = helium nucleus (2 protons, 1 neutron)
^4He = helium nucleus (2 protons, 2 neutrons)
e^+ = positron/antielectron (electron with positive charge)
ν = neutrino (uncharged particle, very low mass)
γ = gamma ray = high energy form of light

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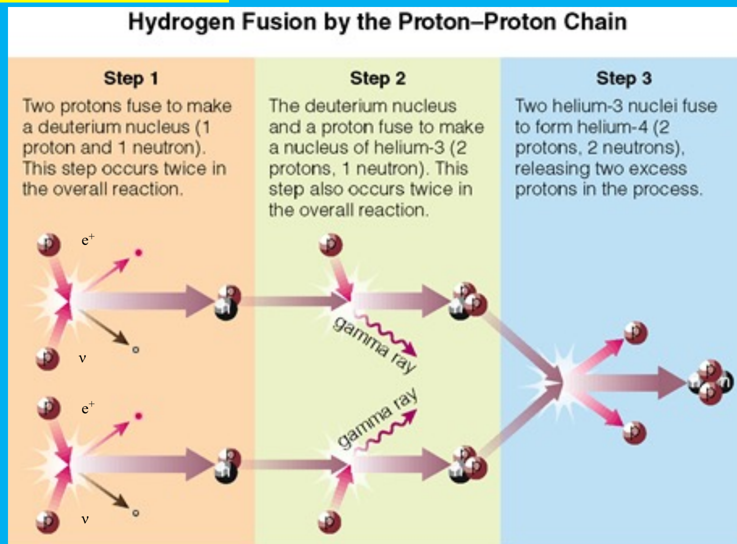
OPTIONAL MATERIAL!



Positron (e^+) will collide with an electron (e^-):

This “anti-particle” collision results in annihilation (all mass is turned into pure energy, i.e., a photon)

Photons (including gamma ray) absorbed by protons, thus heating up the protons

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