Star formation and Evolution

Star formation and Evolution

Stars burn fuel to produce energy and shine so they must evolve and live through a life cycle

In the Milky Way we see stars at every stage of its evolution, some stars as old as the universe, 13 billions, sun with 4.5 billion years, star clusters a few million years old, and stars which are just forming.

At the beginning, shortly after its formation, the Universe was made out of about 92% hydrogen atoms and 8% helium atoms by number (or about 75% hydrogen and 25% helium by mass), with trace amounts of lithium and beryllium, but not much else.

All other elements were formed by nuclear interactions undergoing in stars.

Star formation and Evolution

- Stars are powered by the nuclear reactions in their interior, mostly converting hydrogen into helium.

- Because stars shine by those nuclear reactions, they have a finite life span. The theory of stellar evolution describes how stars form and change during that life span.

- Stars are formed when part of a interstellar gas cloud contracts under its own gravitational force; as it collapses, the center becomes hotter until nuclear fusion begins in the core.

- Interstellar gas and dust, which make up the interstellar medium, are concentrated in the disk of the Galaxy

Gas/dust clouds in the Milky way, appears dark because they block light from stars in the background

A young cluster of stars embedded in the nebula in which they formed.

- At the beginning, shortly after its formation, the Universe was filled with primordial gases
  - about 92% hydrogen atoms and 8% helium atoms by number (or about 75% H and 25% He by mass), with trace amounts of lithium and beryllium, but not much else.
  - all other elements were produced by nuclear interactions undergoing in stars later on.
  - elements produced in stars are ejected into interstellar space as a star blows off its outer layers during its final phases of evolution, enriching the interstellar space with heavier elements.

- Interstellar gas/dust clouds within the interstellar medium are called nebulae,
  - they could span few to hundreds of light years in size and thousands solar masses.
  - They are very thin low-density clouds , $10^2—10^6$ atoms/cm^3. (compared with 2×10^{19} atoms/cm^3 in air, they are better than best produced on Earth)

- A small over density produced by some disturbance (shock wave from an exploding star) in the cloud causes a gravitational pull on the surrounding low-density gas.
- Contraction begins and the over density grows, thus producing a faster contraction.
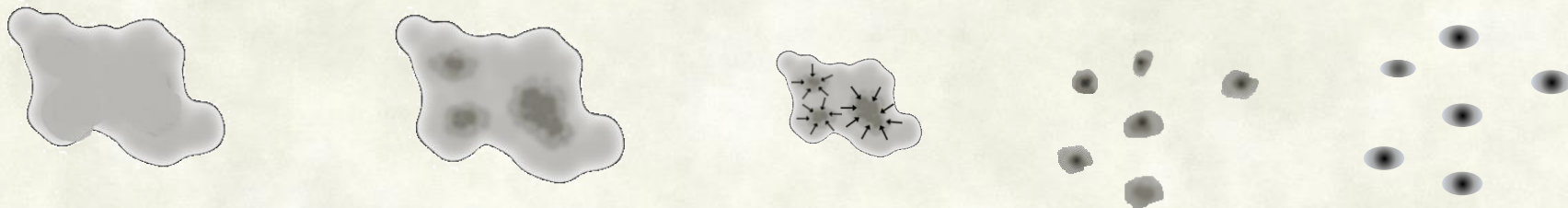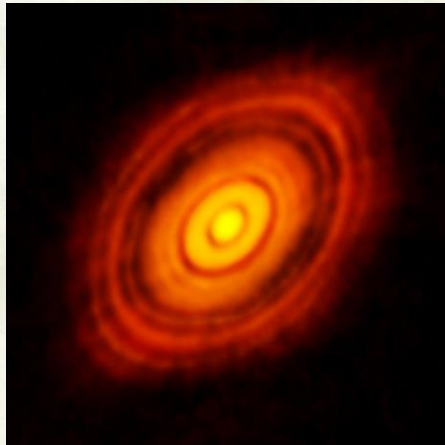

- As the cloud contracts, it subdivides into smaller pieces, each piece will contact and become a star, thus forming a cluster
  - stars are not born in isolation, isolated stars (like our Sun) were born in a cluster and later ejected from it due to gravitational interactions.
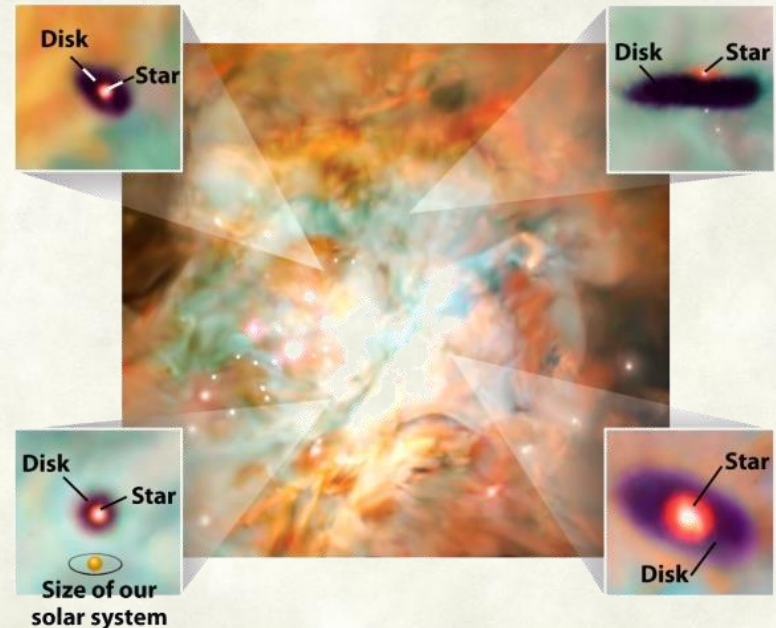

A young cluster of stars embedded in the nebula in which they formed.

Pleiades star cluster

Proto star HL-Tauri

Protostars in the Orion nebula

- The rotation speed of each cloud gradually increases due to conservation of angular momentum.

- The rotating ball collapses into thin disk with most of the mass concentrated near the center - a protostar

- During contraction, Collisions between infilling gas particles dissipate energy and heat up the protostar. A star like the sun can reach a surface temperature of a few thousand Kelvin and a luminosity of 100x the Sun's present luminosity due to its large size.

- The protostar continue collapse under gravitation and it heats up further. It becomes hottest near the center where much of the mass is collected.

6

- When temperature exceed few thousands kelvins, all the electrons in atoms are dislodged from atoms, most of the matter in the form of a atomic mix of atomic nuclei and free electrons, this state of matter is called plasma (solid → liquid → gas →plasma)

- When the core reaches 10 million K, nuclear fusion of hydrogen begins. The protostar becomes a star.

- Why doesn't nuclear fusion happen at a lower temperature?

Electrical repulsion between two hydrogen nuclei keep them apart

- Hydrogen nucleus (proton) has a positive eclectic charge
- Since same sign electric changes repulse each other according to inverse square law, two protons do not come very close, or need an enormous force to bring them together.

- So two protons won't combine together to form a larger nucleus under normal conditions.

Gas Kinematic

gas atoms   container
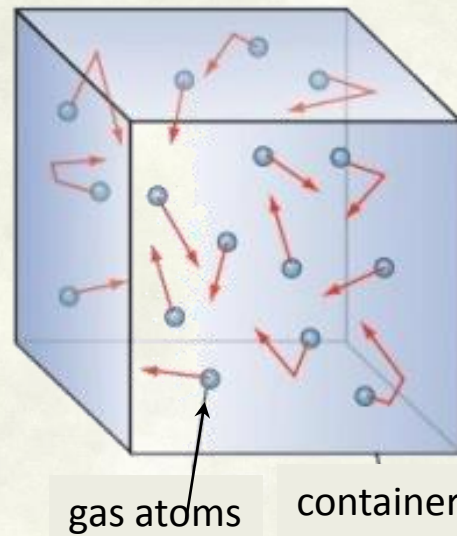
- In a gas, particles (molecules, atoms, or nuclei in case of a plasma) are always moving at random velocities.

- Mean velocity of a gas particle is proportional to the square root of temperature:

$$\text{mean velocity of gas particles,} \quad V_m \propto \sqrt{T}$$

- Thus, when temperature of the gas is increased velocity of gas particles also increases.

- The pressure a gas in a container is the result of continuous collisions of gas molecules on the container wall.

- That is what causing the pressure of a gas to go up when its temperature is increased

8

Hydrogen Nuclear Fusion
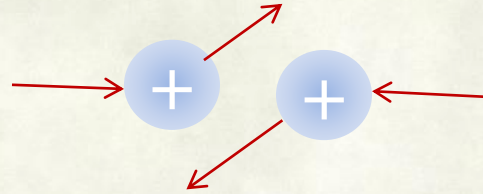
- At lower temperatures two colliding hydrogen nuclei wont touch each other, due to electrical repulsion they are pushed away from each other.

- But when the temperature is high enough (10 million K) nuclei move so fast that when they collide they overcome the electrical repulsion and fuse together.

- There is no stable nucleus with just two protons, so it rearrange to form the a deuterium nucleus ^2H (hydrogen isotope which has a proton and a neutron)

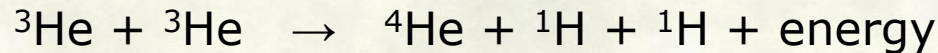$$^1H + {}^1H \rightarrow {}^2H + e^+ + neutrino$$

- $^1H + {}^1H \rightarrow {}^2H + e^+ + $ neutrino

  or in simple terms: $^1H + {}^1H \rightarrow {}^2H + $ energy

- Deuterium thus produced combine with a hydrogen nuclei to from a helium 3 isotope ^3He,

  ($^3He = $ two protons+ a neutron)

  and releasing some energy

  $^2H + {}^1H \rightarrow {}^3He + $ energy
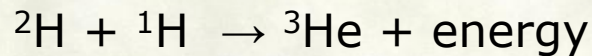
- Two ^3He nuclei combine to form helium 4

  ($^4He = $ 2 protons+2 neutrons)

  $^3He + {}^3He \rightarrow {}^4He + {}^1H + {}^1H + $ energy
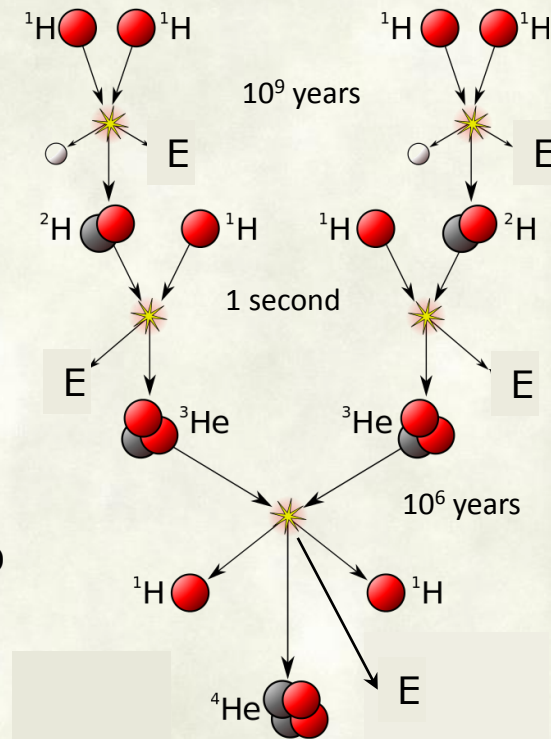
- Overall, net result is four hydrogen nuclei combined to form a Helium nucleus. ^4He nucleus is slightly less massive than four ^1H nuclei

  mass of 4 hydrogen nuclei = 6.693×10^{-27} kg,
  mass of Helium ^4He nucleus = 6.645×10^{-27} kg
  Difference in mass = 0.048×10^{-27} kg, 0.7%,

this lost mass is converted to energy according to $E = mc^2$

^1H ● ● ^1H ^1H ● ● ^1H
10^9 years
○   E   ○   E
^2H ● ● ^1H ^1H ● ● ^2H
1 second
E   E
● ● ^3He ^3He ● ●
10^6 years
^1H ●   ● ^1H
E
^4He ● ●

● proton, ● neutron , E energy

Main Sequence Stars

- Once nuclear fusion sets in, energy production is maintained by hydrogen fusion and the protostar becomes a hydrogen burning star.

- The star continues to contract and increase in temperature, until internal pressure counters gravitational collapse and come to an equilibrium.

gravity

pressure

hydrostatic equilibrium

- The star has reached a stable state called 'main sequence' and will remain there as long as it has hydrogen to burn.

- Sun has been a main sequence star for 4.5 billion years, every second 600 million tons of hydrogen are converted into helium in the Sun's core, generating 4×10^{27} Watts of energy. Sun has enough hydrogen to remain as a main sequence star for another 6-7 billion years.

- A protostar must have more than 0.08 Solar mass (80 times the mass of Jupiter) in order to become dense and hot enough that fusion can begin. Otherwise gradually cool off and become a brown dwarfs.

- They glow in the infrared due to the gravitational energy, and then gradually fade off.

- Brown dwarfs are difficult to observe directly, as they are very dim.

Gliese 229B, about 20-50 times the mass of Jupiter
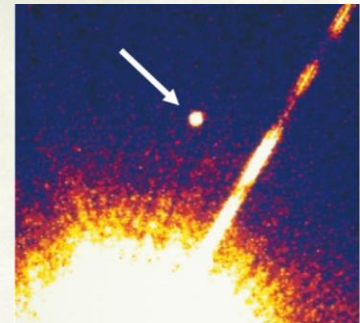
Star life time

- The more massive a star, the higher its core temperature and the faster it consumes the nuclear fuel.
- Approximately luminosity of a star (that is rate it produce and emit energy) is proportional to the third power of its mass

$$L \propto M^3$$

  - The Sun will stay ~10 billion as a main sequence star.
  - a 100 solar mass star has a luminosity of $10^6 L_\odot$ and will stay there only 1 million years.
  - a star with only 0.1 M_o has a luminosity of $10^{-3} L_\odot$ and has a lifetime of 100 billion years.

- A protostar with more than 100 solar masses produces so much energy that the object blows apart after onset of nuclear fusion.

Red Giant stage

- As the hydrogen burning continues, eventually the star runs out of hydrogen and helium accumulate at the center.

- Helium (^{4}He) can not undergo nuclear fusion until the core temperature is extremely high, of order 100 million K.

- So core pressure decreases and inert He core starts contracting and getting hotter.

- Hydrogen nuclear burning moves to shells around the core.

- Higher temperatures around the core increase the hydrogen fusion rate and the energy production.

- This increased outflow of energy expand and cool the outer layers of the star, extending it over100 times. The star becomes a red giant.

  - Lower temperature of outer layers make it look red,

  - Despite its cooler temperature, its luminosity increases enormously due to its large size .

  - When the Sun becomes a red giant in about 7-8 billion years its will extend beyond the orbit of Mercury.

H burning shell

inert He core

cool extended envelope
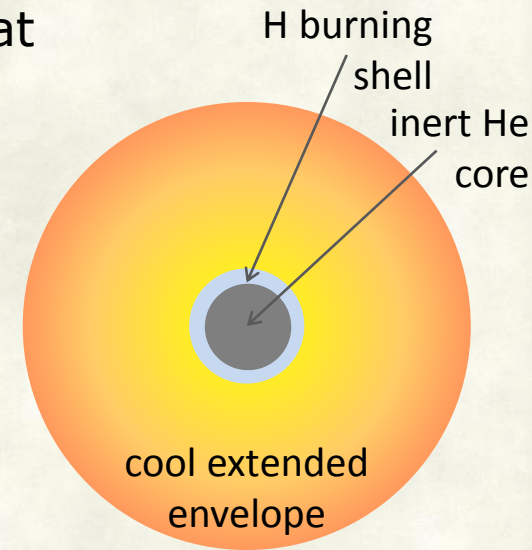
Helium Fusion

- Meanwhile, He core continues contracting until reaching 100 million K. Once the core temperature has risen to 100M K, the helium in the core starts to fuse, through the three-alpha process:

  - $^4He + {}^4He \rightarrow {}^8Be + energy$

  - $^8Be + {}^4He \rightarrow {}^{12}C + energy$

  (^4He nucleus is call an alpha particle, hence the name)

- This reaction produces carbon in the star's core.

- Now there are two shells, hydrogen burning outer and Helium burning inner and an inert carbon core.

- As the helium in the core fuses to carbon, the core becomes hotter and hotter, and the helium burns faster and faster, which causes further expansion of the outer layers

- Low escape velocity from giant star causes the gas of the outer layers to blow out in a stellar wind.

- The ejected envelope expands into interstellar space, forming a planetary nebula.
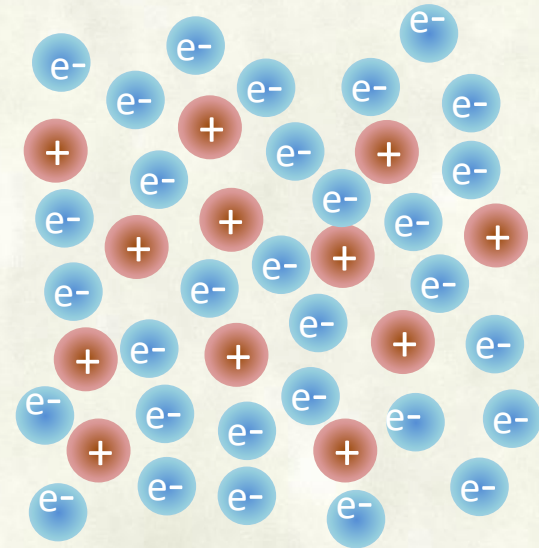
- The light from the central star causes the wind to glow in a planetary nebula.
  - through a small telescope the expanded gas envelope looks line a planetry disk, so early astronomers viewing the fuzzy envelope called   planetary nebula, though they have nothing to do with planets.

He burning shell

inert C core

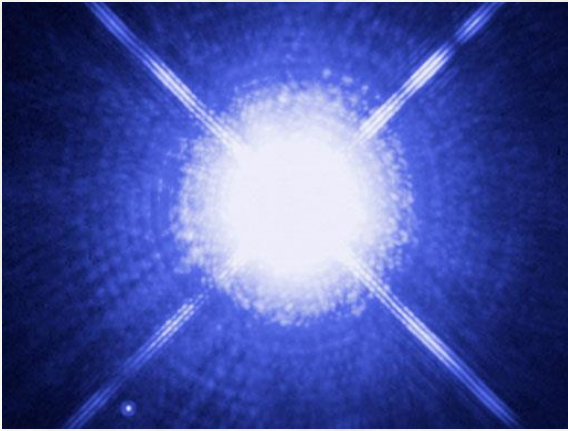cool extended envelope

H burning shell

14
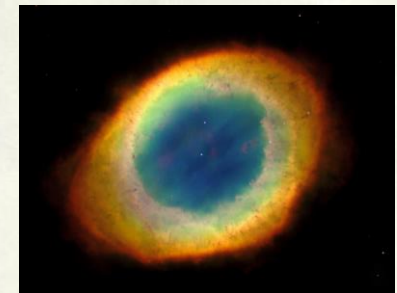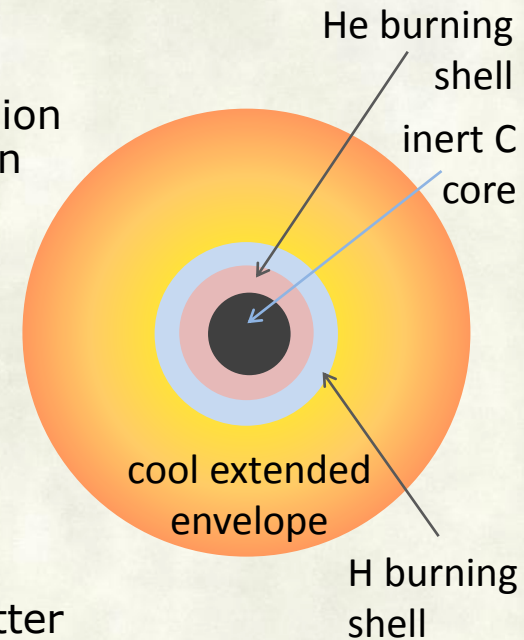
Degenerate Pressure

- The star now has two parts:

- A small, extremely dense carbon core
- An envelope about the size of our solar system
- As the dead core of the star cools, the nebula continues to expand and dissipates into the surroundings.

- If the star has a mass less than 8 solar masses the core cannot get hot enough for C fusion.

- Without pressure generated by nuclear reactions, the core contracts up to the point where electrons resist further packing.

  – Like electrons has no more room to move around, all available energy states elections can occupy are filled, which create what is called **electron degenerate pressure**

  – No further contraction of the core is possible.

  – This state of a star core which had contacted to about the size of the Earth and held by electron deaerate pressure is called a white dwarf.

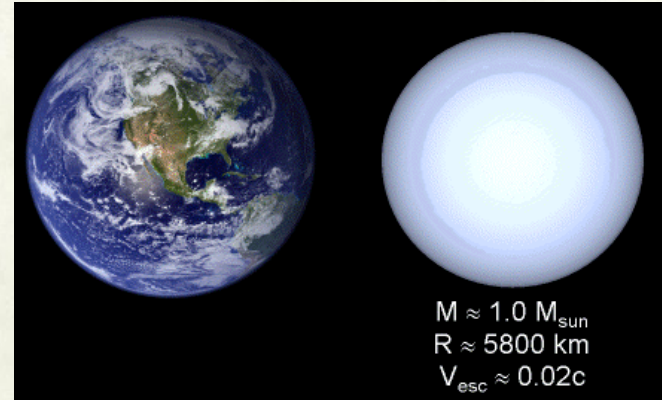 – **Densities of 10^8 to 10^{11} kg/m³**

White Dwarfs

Comparison of a White Dwarf Star and the Earth.

$M \approx 1.0\ M_{sun}$
$R \approx 5800\ km$
$V_{esc} \approx 0.02c$

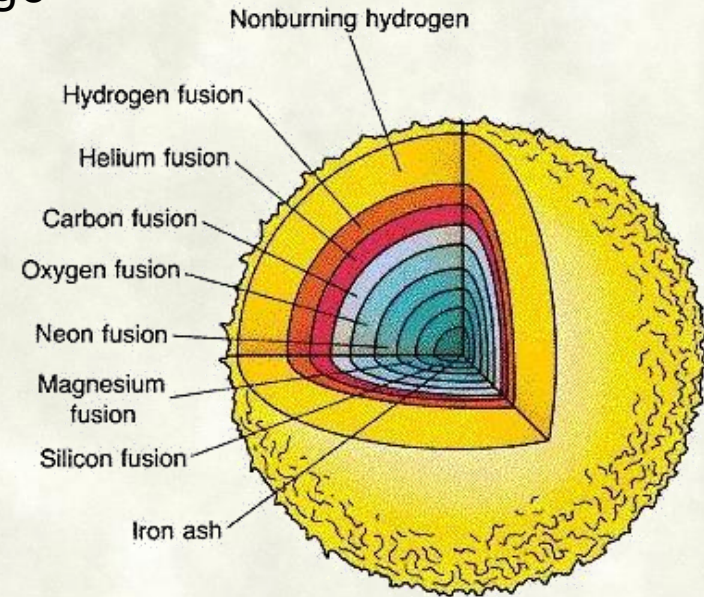Sirius and its white dwarf companion Serius B

- Initially the white dwarf is very hot and cools down slowly (in billion year time scale). White dwarf surface temperatures extend from over 150,000 K to barely under 4,000 K.

- Densities of ~ 10^9 kg/m^3 (a teaspoon of white dwarf matter on would weight over a ton).

- Due to their small size, white dwarfs have low luminosities even when they are initial hot stage. (down to 10^{-4} solar luminosities).

- The Sun will become a red giant, then lose about 40% of its mass and finally become a white dwarf of 0.6 solar masses.

- white dwarfs are unstable for core masses larger than 1.4 solar masses (**Chandrasekhar limit**), beyond that the electron degenerate pressure is not sufficient to counter gravity, and the core further collapses.

- A white dwarf is the end product for low and intermediate mass stars (0.08 < M < 8 solar masses).

Evolution of a high-mass star

- A star of more than 8 solar masses can undergo further core contraction, and reach higher temperatures and fuse heavier elements.

- $^{12}C + {}^{4}He \longrightarrow {}^{16}O$ + photon (for 500M K)
- $^{16}O + {}^{4}He \longrightarrow {}^{20}Ne$ + photon (for 500M K)
- $^{16}O + {}^{16}O \longrightarrow {}^{32}S$ + photon (for 1 billion K)
- And so on until iron is produced,
- Reactions to heavier elements go faster and faster : creating oxygen , Neon, Magnesium takes 1000 years, production of sulfur takes few days.

Nonburning hydrogen
Hydrogen fusion
Helium fusion
Carbon fusion
Oxygen fusion
Neon fusion
Magnesium fusion
Silicon fusion
Iron ash

- Fusion reactions undergo like an onion skin structure with more heavy elements concentrated toward the center of the star.

- Iron has the most stable nuclear structure, it does not release energy when undergo nuclear fusion, instead absorb energy. So once iron is formed fusion chain stops.

- This process is called **Steller Nucleosynthesis** most elements other than hydrogen and helium in the universe (and the Earth made of) is produced in this manner, in a star**.**
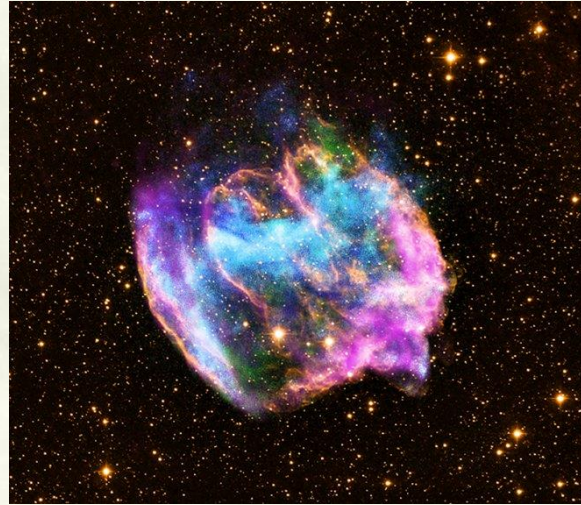
Supernova

- A star initially more massive than   8 solar masses, will form a core more massive than1.4 solar mass Chandrasekhar limit.
    - too big for a white dwarf, electron degenerate pressure can not overcome gravity

- When the size of the degenerate core exceed the Chandrasekhar limit it collapses in a fraction of a second to a radius about 50 km.
    - Protons and electrons in the core fuse together producing neutrons and neutrinos

      proton + electron → neutron + neutrino   ($p + e^- \rightarrow n + v$)

- At such high densities neutrinos interact with the matter and push the star envelope outward at high velocity (~5% the speed of light).
- As a result the whole star blow apart in an explosion called **supernova.**
- A supernova momentarily outshines the Sun by 10 billion times, as bright as an entire galaxy
- During the explosion atoms heavier than iron (nickel, silver, lead….) are formed and thrown into the interstellar space along with other elements produced in the star over its life time.
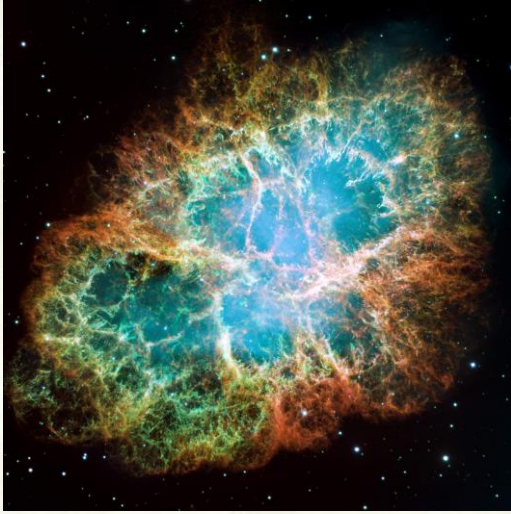
Crab nebula 1000 years   W49B 1000 years   Veil nebula 6000 years
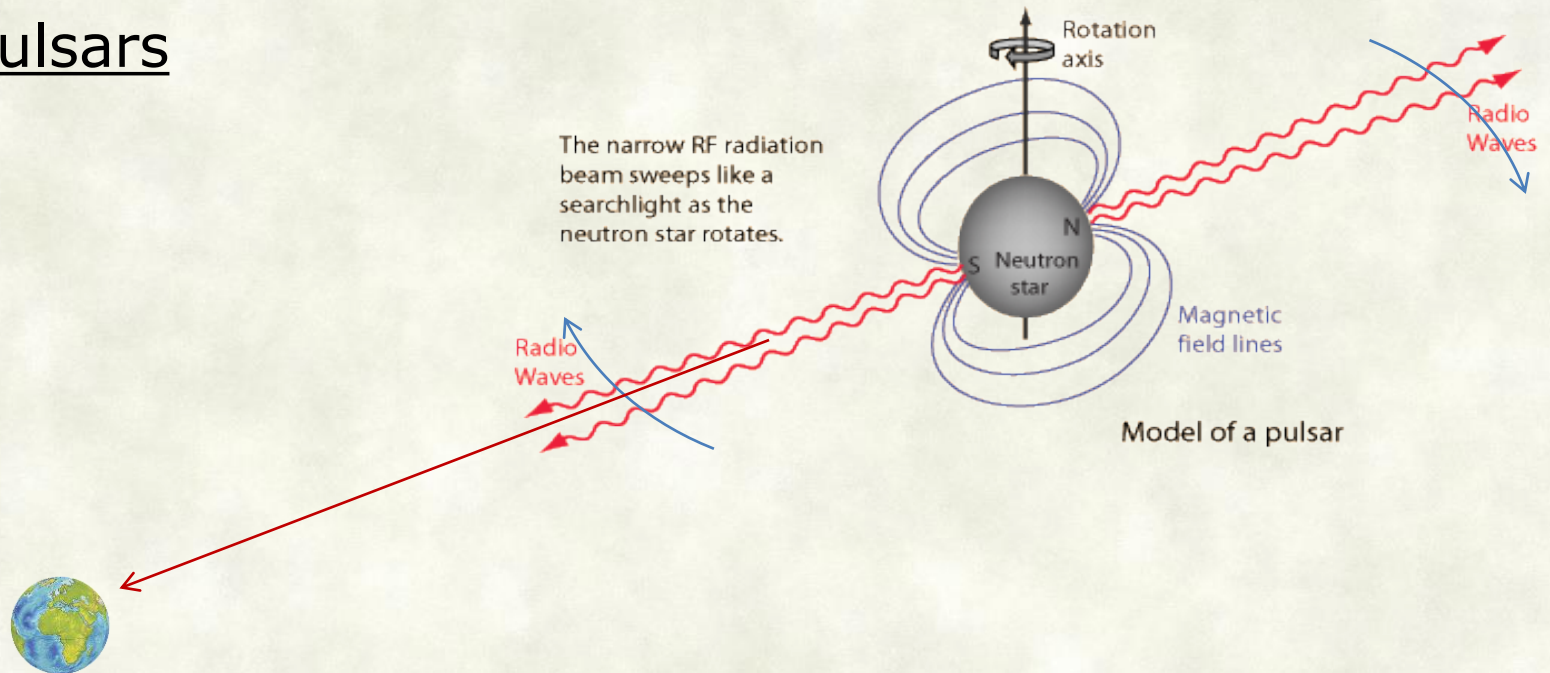
Few supernova remnants

- Supernova are rare events, once every 50 years in a galaxy like ours. The last one was in 1604 (observed by Kepler). There was on in the Large Magellanic Cloud in 1987.

- The ejected gas is rich in heavy elements. Chemically enriched interstellar material becomes the raw material for a new generation of stars and the cycle of stellar birth and death begins again.

- The Sun is a second-generation star. Each of the heavy elements in the solar system, earth, and people of were produced in the core another star that flew away in a supernova explosion

Neutron stars
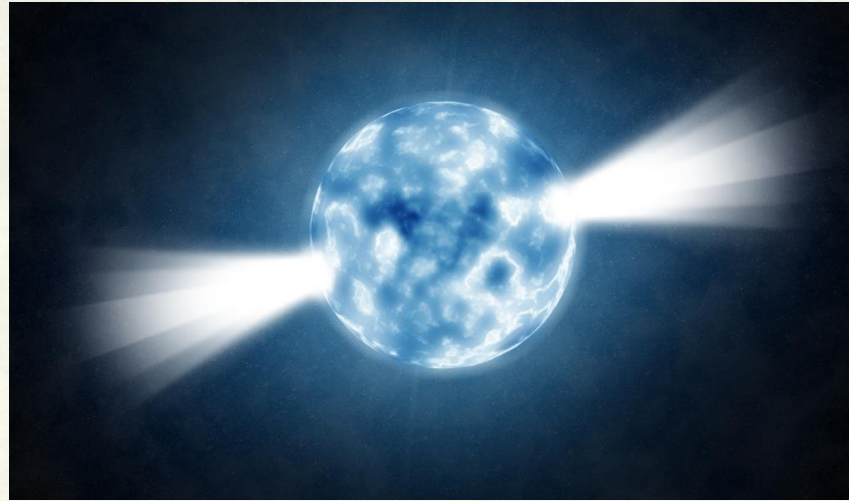
- If the core is less than 3 solar masses, gravity can be balanced by the degenerate pressure,
  - Like tightly packed neutrons almost touching each other.
  - Neutrons stop the collapse and form a stable system called a neutron star.
- Mass ranges between 1.4-3 solar masses, Typical radius ~ 10 to 20 km!
- This is the densest form of matter in the observable universe: 10^{17} kg/m^3 (a teaspoon of neutron star matter would be 100 million tons).
- Due to conservation of angular momentum, it is spinning fast, up to thousands time a second (angular momentum of the star now carried by a small object, thousands times smaller in size)
- They also have extremely strong magnetic field, when material (left over from star) from nearby space fall to the neutron star, they are accelerated and taken to the poles along magnetic filed.

Pulsars

The narrow RF radiation beam sweeps like a searchlight as the neutron star rotates.

Rotation axis

Radio Waves

N
S Neutron star

Radio Waves

Magnetic field lines

Model of a pulsar

- This result in strong beams of electromagnetic radiation emitted at the magnetic poles.

- If the rotation axis is not the same as the magnetic axis, the two beams will sweep out circular paths.

- If the Earth lies in one of those paths, the beams of radiation from the jets sweep around as the pulsar rotates, just as the light beam from a lighthouse does.

- So from earth we see regular flashes of radiation from the neutron star, at the frequency equal to its rotation rate.

- Neutron stars for which we see such pulses are called "pulsars"

Crab nebula in visible light. It is at the same location there was a supernova in 1054
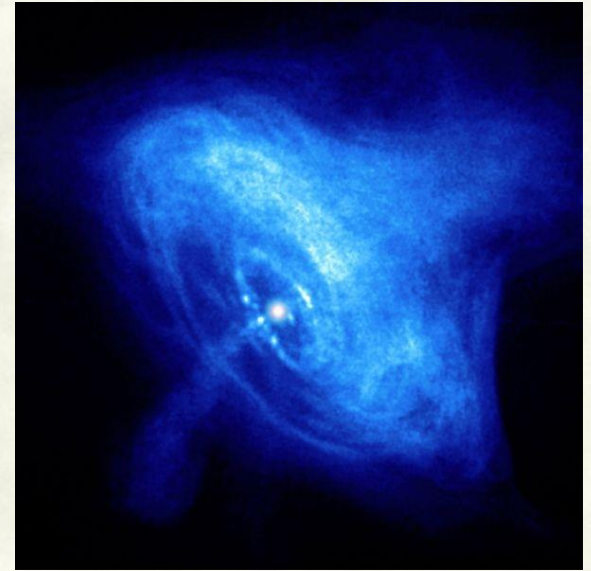
X ray image of the crab nebula, showing jets at the pole and radiation form matter accreting around it
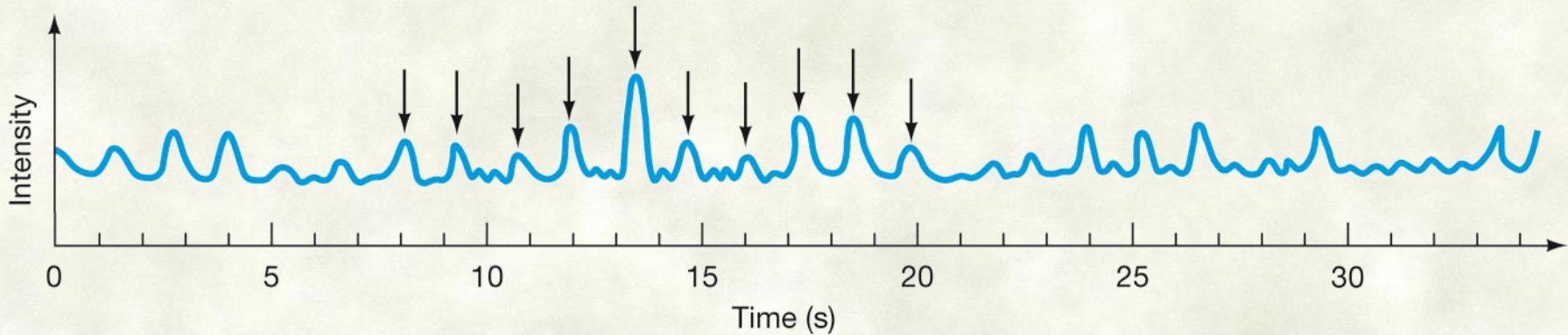
- The first pulsar was discovered in 1967. It emitted extraordinarily regular radio pulses (every 1.33733 seconds**)**; nothing like it had ever been seen before.

- Soon it was realized that this was a neutron star, spinning very rapidly.

- Typical period few seconds, some are milliseconds

Black holes

- If the core has more than 3 solar masses, neutron degenerate pressure cannot stop the collapse, gravity wins, and the core collapse to a space-time singularity state called **black hole.**
- At some distance the distance required to escape the BH would be the speed of light. This is an imaginary sphere around the BH called the event horizon. Nothing (not even light) can escape this region, reason they are called black holes.

- Escape velocity = $\sqrt{\dfrac{2GM}{r}}$ where M is the mass within a sphere of radius r

- So if r can be make small for a given mass there is a stage where escape velocity is equal to speed of light, of if ab object can be compressed to such stage even light cannot escape from it.
- For the earth that to happen Earth has to be compressed to 1 cm.
- For the Sun 3km.
- For a star core 3 solar masses it is 9 km.