gravitiational potential energy to thermal energy. Brown dwarfs eventually fade out.

Examples of Pre-main sequence objects

i) Bok globules - dense clouds of dust and gas

ii) Infrared stars - R Mon, Orion star forming region

iii) T Tauri stars

Strong stellar wind : 50 - 200 km/s

~0.4 $M_\odot$ blown away

Mass streams away in two jets along the polar axis (Bipolar jets).

Main sequence phase extremely stable. Star self-regulates its structure. If the energy production decreases the core contracts. Presssure and temperature increases and thereby the energy production increases. Hydrostatic equlibrium is maintained.

Post Main Sequence Evolution of 1 $M_\odot$ Star.

Development of degenerate core and evolution to red giant phase :

When H in the core contracts until it is degenerate. H burns in a shell outside the core. Energy production increases causing the outer layers to expand and cool. The star moves from the M-S to the red giant region.

Helium Flash :

The core eventually gets hot enough (~10^8°K) for He to be fused to C by the 3-α process.

$$^{4}He_{2} + {}^{4}He_{2} \rightarrow {}^{8}Be_{4}$$
$$^{8}Be_{4} + {}^{4}He_{2} \rightarrow {}^{12}C_{6}$$

Since the core is degenerate it cannot expand and cool to counteract the new energy source. The reaction takes place rapidly throughout the core (Helium Flash). But so much heat energy is added that the degeneracy is destroyed and the reactions become stable.

Core Helium Burning :

Once stable reactions are taking place in the core (3 He → C) the H shell source becomes less important. The outer layers contract, the surface heats up; star moves to the left on the H-R diagram. [Horizontal Branch Star]

Second Red Giant Phase :

When He in the core is used up, the energy comes from a shell (an inner shell where He → C, and an outer shell where H → He). The outer layers expand again and the star becomes a red giant for a second time.

Variable Star Phase :

There is change in brightness owing to changes in nuclear energy rate or rate of flow of radiation. This change in luminosity is accompanied by changes in the size (R) and surface temperature (T). The star enters the instablility strip.

Hertzsprung Gap : Rapid evolutionary phase during a star's life.

Planetary Nebula Phase :

There is mass loss due to stellar wind. The star loses its outer atmosphere. The core continues to shrink but is never hot again for nuclear reactions. The star has an exposed core and detached atmosphere - planetary nebula.

White Dwarf Phase :

The core becomes degenerate as it contracts. Eventually the outer layers are gone completely leaving a hot, degenerate core that is a white dwarf.

Post Main Sequence Evolution of a 5 $M_\odot$ Star.

First red giant phase :

When H in the core is used up, the core contracts and T increases. H starts burning in a shell around the core at higher T. More energy is produced. The outer layers expand and cool. The star becomes a red giant. The core does not become degenerate because of its high T and there is no He flash.

Subsequent red giant phases :

Each time a nuclear fuel source in the core is used up, the shell source outside the core becomes the dominant energy source. The core then contracts and heats until a new fuel ignites. The star shrinks again and moves back to the left on the H-R diagram. The star may undergo several red giant loops burning in turn helium, carbon, oxygen, and neon by a series of α-capture reactions.

$$H \rightarrow He \rightarrow C \rightarrow O \rightarrow Ne \rightarrow Mg$$

Mass loss :

During each red giant or supergiant phase, mass is lost through stellar winds. Eventually the loss of mass and the requirement for even higher temepratures to start new reaction phases combine to halt all nuclear reactions.

Final stage :

The form of the remnant depends on how much mass is left.

If $M < 1.4\ M_\odot \rightarrow$ white dwarf whose composition will be determined by the number of nuclear reaction stages.

If $1.4\ M_\odot < M < 2$ or $3\ M_\odot \rightarrow$ neutron star

If $M > 3\ M_\odot \rightarrow$ black hole

Post Main Sequence Evolution of Massive Stars (> 10 $M_\odot$)

$T_{surf} \geq 30{,}000$°k $L \sim 10^5$ to $10^6\ L_\odot$

Very short main-sequence lifetime. High mass loss throughout their lives. Some stars have blown away their outer envelope exposing their core. Spectra show strong lines of helium, carbon, and nitrogen. [Wolf-Rayet stars]

They go through the red giant phases very rapidly. They fuse, starting from He, heavier and heavier elements in the core until the core is all Fe. Fe is the most stable of all elements. To fuse Fe into heavier elements requires energy (endothermic process). There is no energy to support the outer layers. When Fe begins to fuse, neutrinos are released which escape freely from the star's interior carrying energy. The outer layers collapse causing an implosion of the core. The outer layers bounce back causing a shock wave which rips the star apart - supernova explosion [Type II].

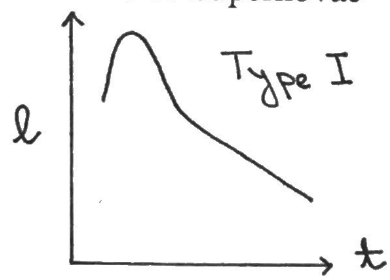
The energy released during the explosion creates elements heavier than iron. The force of the explosion disperses the elements throughout the interstellar medium.

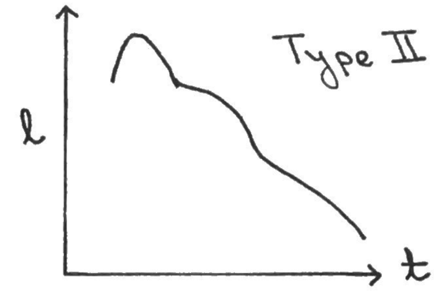
The remnant would be -

i) $1.4 M_\odot < M < 2$ or $3 M_\odot$ - neutron star

ii) $M > 3 M_\odot$ - black hole

Light Curves of Supernovae





Mass Transfer in a Binary System

The evolution of a star in a binary system is complicated by the presence of a companion. In the most general case the two stars in a binary system are of unequal masses.

The more massive star goes through its main-sequence phase faster and becomes a red giant while the less massive star is still on the main-sequence. The red giant spews matter onto the main sequence star through the inner Lagrangian point. The red giant then evolves into a white dwarf.

The main sequence star's evolution is accelerated because of the additional mass. It evolves through its main sequence phase faster than it would normally have. It then becomes a red giant and spews matter through the inner Lagrangian point on to the surface of the white dwarf. Nuclear reactions occur on the surface of the white dwarf and the star suddenly brightens. It is called a nova.

Sometimes the matter from the red giant forms an accretion disk around the white dwarf. If matter falls at regular intervals and the energy released is small the star is called a cataclysmic variable.

If a tremendous amount of matter is dumped on the white dwarf (exceeding the Chandrasekhar limit) the star may explode producing a Type I supernova. Type I supernova occurs in a binary system where one of the members is a carbon-oxygen rich white dwarf and the other is a red giant. Owing to mass loss the red giant deposits mass on the white dwarf. When the mass of the white dwarf gets close to the Chandrasekhar limit carbon starts fusing. Because the core is degenerate carbon burning skyrockets. Supernova explosion follows.

White Dwarfs

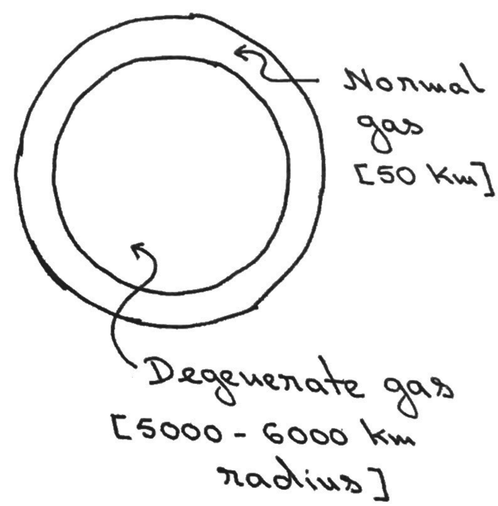
No energy source - supported by electron degeneracy pressure

Maximum mass for white dwarf = 1.4 $M_{\odot}$ (Chandrasekhar Limit)

Surface Temperature ≈ 10,000 °K

Diameter ≈ 5 x 10^5 gm / cm^3

Surface gravity ≈ 1.3 x 10^5 $g_{\oplus}$



Observationally they appear as
- Low luminosity objects ≈ 0.005 $L_{\odot}$
- Broad lines in its spectra due to
  - pressure broadening
  - splitting of lines due to Zeeman Effect
- Lines are red-shifted (gravitational redshift)

[Aside : The gas inside a star is completely ionized and the electrons move around freely. There are discrete energy levels that an electron can occupy. In a low density gas there are plenty of empty energy levels. As the star contracts the gas becomes more and more dense and te energy levels start filling up. When the electrons are occupying all the lower energy levels the gas is said to be degenerate. According to quantum mechanical principles no two electrons can occupy the same energy level.

If the gas is compressed there are no lower energy levels that the electrons can fall to and the gas resists compression. This ability of the electrons to resist compression creates a pressure called electron degeneracy pressure which can support a star against collapsing provided the mass of the star does not exceed $1.4 M_\odot$.]

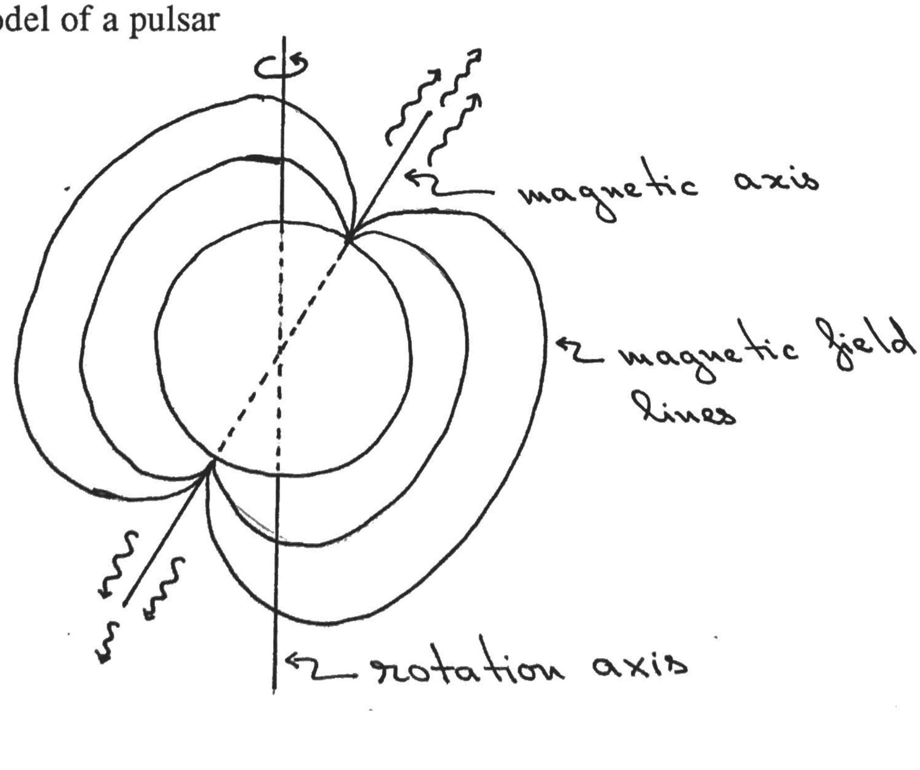
Neutron Stars

- Properties
  - Mass : $1.4 < M \;\; 3 M_\odot$
  - Radius : ~10 km
  - Surface Gravity : $7\text{x}10^9 \; g_\oplus$
  - Magnetic field : 10^{12} x earth's mag. fld
  - Rotation Period : 0.001 to 100 sec

- Discovery
  - Regular pulses (in radio) discovered by Jocelyn Bell in Nov 1967.
  - By 1973 about 100 pulsars discovered.

- Model of a pulsar
  - Rotating neutron star [High rotation due to conservation of angular momentum]
  - Intense magnetic field

- Light house model of a pulsar



- Radiation emitted is synchrotron radiation.
  Synchrotron radiation is produced by relativistic electrons spiralling around intense magnetic field lines.
  Relativistic electrons are high energy electrons travelling close to the speed of light.

- Synchrotron radiation is non-thermal radiation. The intensity of the synchrotron radiation does not depend upon the temperature of the source. There is more energy at long wavelengths compared to thermal radiation. Besides synchrotron radiation is polarized.

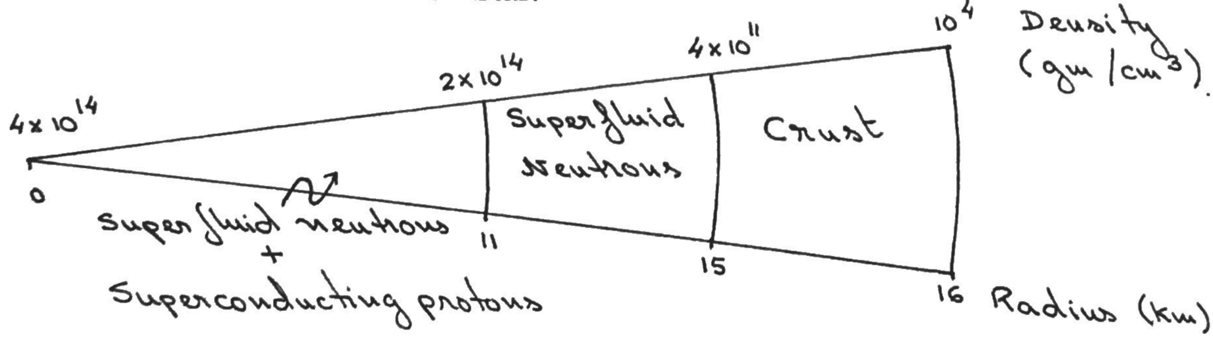
- Neutron star is supported by neutron degeneracy pressure.

- Energy output from the Crab Nebula is $3x10^{38}$ erg/sec. Source of the energy is a rotating neutron star. As the neutron star loses energy, it slows down, and the period of the pulsar increases.

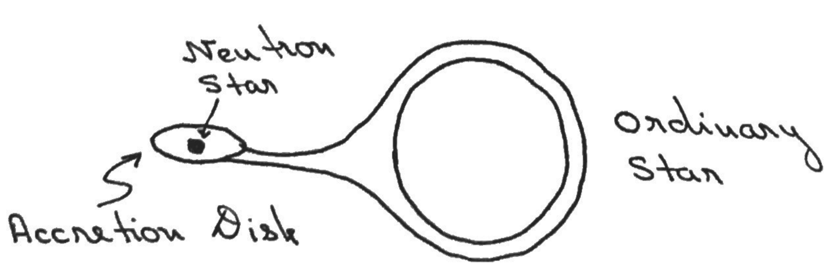
- Occasionally pulsars momentarily speed up. There is a slight decrease in period called a glitch.

- The speeding up is due to the star contracting. The crust must crack and settle (as little as 1 mm). This starquake measures 23 to 25 on the Richter scale. The surface of the neutron star is quite brittle.

- Internal Structure of a Neutron Star:



- Neutron star in a binary system



The gas in the accretion disk loses gravitational potential energy which is transformed to heat energy. As temperatures increase to 10^6 to 10^8 °k x-rays are produced. The neutron star manifests itself as an x-ray source.

Black Holes

- The location in space where the escape velocity from the black hole equals the speed of light is called the event horizon.

- Singularity corresponds to the center of a black hole.

- Distance between the singularity and the event horizon is called the Schwarzschild radius or simply the radius of the black hole.

- Radius of a Black Hole

$$R_{BH} = (2\,G\,M) / c^2 = 3 \text{ km } (M* / M_{\odot})$$

- The law of cosmic censorship : Thou shalt not have naked singularities.

- "Black holes have no hair" theorem : A black hole's structure is completely specified by only three numbers : its mass, its charge, and its angular momentum (spin).

- Detecting black holes : Possible only if the black hole is the unseen component in a binary system. One can measure the mass of the unseen component from Kepler's 3rd law. If the mass turns out to be greater than the mass of a white dwarf or neutron star then it is possibly a black hole. One such possible candidate is the x-ray source Cygnus X-1.