Formation and Evolution of a Star

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Why do we need to know about Stars? Origin of all the elements of our body (excluding Hydrogen) is either from an internal explosion or from the final explosion of a star. In other words it is correct to say that the life originated from a star. According to modern theory of Astronomy, Big Bang led to the origin of the Universe. Hydrogen was formed from this explosion and a very small amount of Helium may have formed during the Big Bang. All the other heavy elements were formed from the nuclear fusion reactions which occurred inside a star.

Figure 1: Molecular Cloud

If we want to learn about the formation of a star, it is important to understand about the interstellar medium. Interstellar medium mainly consist of gaseous hydrogen, and the state of hydrogen (atomic/molecular/ionic) depends on the temperature of the interstellar medium. The normal temperature of the interstellar medium is very low and is about 10 ^{0}K. Under normal conditions the density of the interstellar medium is very low.

To identify hydrogen gasses, radio waves with a wave length of 21cm can be used, which is emited during the transitions between the energy states. These radio waves can be observed through a radio telescope.

In some instances the temperature of an interstellar medium is high enough to ionize hydrogen atoms in it. When an interstellar medium shrinks under gravitational forces, temperature may rise due to the conversion of potential energy to kinetic energy. Hot stars emit ultraviolet rays and when an interstellar cloud is situated near a hot star hydrogen atoms may get ionized by the ultraviolet ray emitted by that hot star. The Bamer series of the hydrogen spectrum which contain more red light will be emitted from a ionized interstellar cloud and shine red. This kind of a gaseous cloud is called a Emission Nebula.

The interstellar medium consists of hydrogen; gases such as ammonia, methane, carbon dioxide; other elements; and compounds containing hydrogen, nitrogen, carbon, oxygen, silicon and sulfur and dust particles. Tiny dust particles (0.5 *ìm*) aggregate to form big molecules. Dust particles play a catalytic role in forming big molecules, also play a role in protecting the big molecules from been destroyed by UV rays.

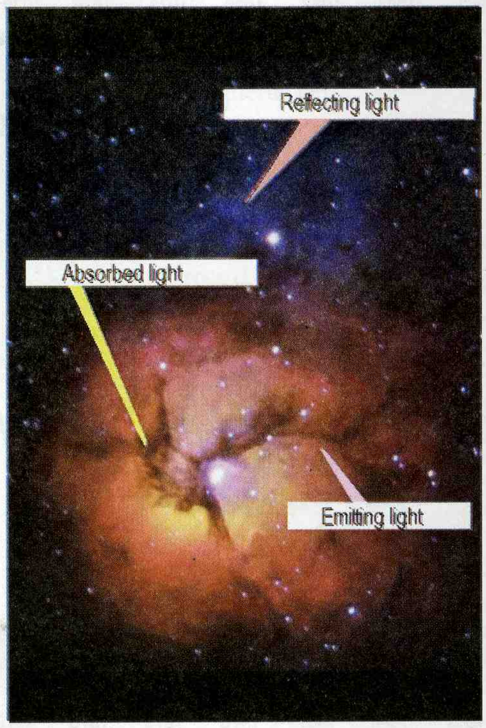

Figure 2: Nebula

Gravitational and electrostatic forces among the small molecules are not large enough to attract each other. However, such forces in between complex and big molecules are strong enough to shrink the molecular cloud. The release of enormous heat and the pressure developed during this shrinking process initiate the nuclear fusion to form new stars.

Dust particles containing nebulae absorb the background light which is emitted by the stars, and as a result dark regions can be seen. In addition these nebulae scatter the light. The blue light which has a lower wave length gets more scattered than the red light. Therefore the stars in those nebula backgrounds shine in red, and the reflected light from the nebula appears in blue. The region from which the light reflects is named as reflection nebulae.

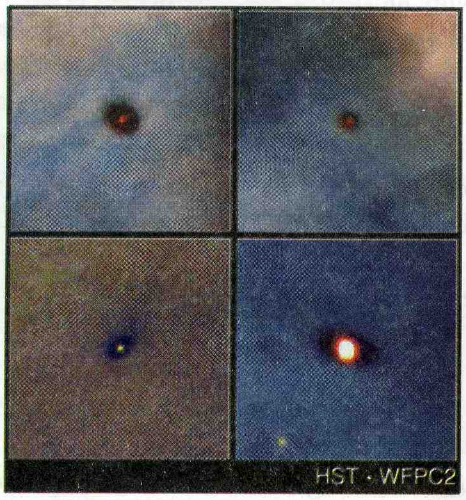

Figure 3: Protoplanetary disks

Essential factors for star formation

Low and medium weight stars: Molecular cloud should shrink under gravitational force to form stars. In this case pressure of gasses in the cloud act as the opposing forces and if the mass of the cloud can withstand these opposing forces the clouds starts to shrink. In addition, the centrifugal force and the magnetic force (due to the motion of charged particles) too act as opposing forces. The stars formed only with gravitation forces like our sun, are of medium weight.

Heavy weight big stars: High dense heavy molecular clouds can create heavy weight big stars. There are several ways for formation of high dense clouds. Big explosions (like Super nova) in the universe generates shock waves. When this shock wave travels through a galaxy, it creates a dense cloud. When molecular clouds colloid with each other they get disturbed. Even when a nearby star emits hot hydrogen during an explosion it can increase the density of a molecular cloud.

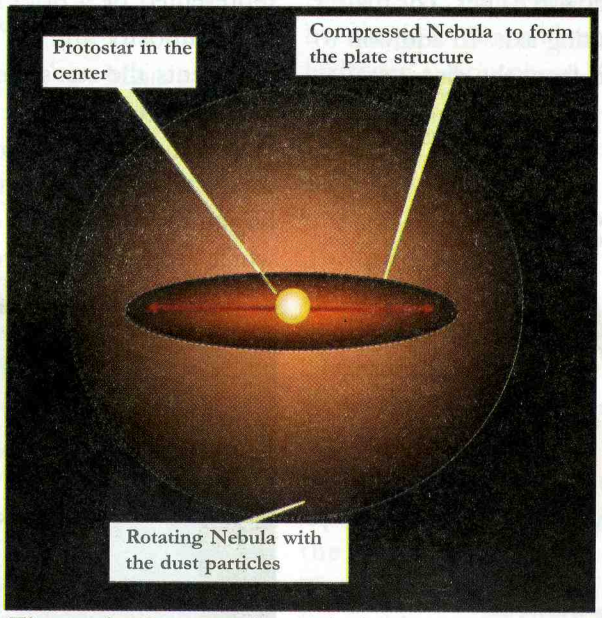

Figure 4: Compressing Nebula

Stellar wind (contains mainly ionized hydrogen and other elements, wind speed is around hundreds of kilometers per second) from the newly formed star tends to push the nearby molecular clouds. Therefore the edges of the molecular clouds get compressed. The compressed high dense cloud regions give birth to new stars. This type of a star formation occurs in the famous Orion nebula. A compressed molecular cloud which contains a new star with a planetary system is called a protoplanetary disk or proplyds. Lots of proplyds can be found in Orion nebula.

When a molecular cloud or a nebula is compressed to a certain level it will form a rotating disk with a proto star in the center. Potential energy of the molecular star will decrease when the cloud compresses and the kinetic energy of the cloud should increase according to the law of energy conservation. This happens by the increase of the angular momentum of the cloud/nebula, and the direction of rotation will remain the same as that of the cloud as when it was rotating previously.

When a nebula is compressed under gravity it takes the shape of a ball, and the rotation speed is high near the equator. The angular momentum of the nebula near the equator is so high that it will not fall on the protostar. But the angular momentums near the poles are low and hence the matter in this area will fall on the protostar, and accordingly the middle of the nebula will get the shape of a round plate. The nebula which gets compressed under these conditions will have high temperature and pressure. These conditions can lead to nuclear reactions at any moment. Then we can say that a Young Stellar Object has formed.

The nuclear reaction is as follows.

$6\,^1H^+ \rightarrow \,^4He^{++} + 2e^+ + 2\nu + 2\gamma + 2\,^1H^+$

$4\,^1H^+ \rightarrow \,^4He^{++} + 2e^+ + 2\nu + 2\gamma \longrightarrow$ (A)

(A) Weight of reactants(left side of the reaction)
$= 6.693X10^{-27}Kg$

(A) Weight of products (right side of the reaction)
$= 6.645X10^{-27}Kg$

Weight difference of the reaction
$= 6.645X10^{-27} - 6.693X10^{-27} = 0.048X10^{-27}$ Kg

According to $E = mc^2$

Energy corresponding to the weight difference

$E = 0.048X10^{-27}$ Kg X 3 X 10^8 ms^{-1}

$E = 0.43X10^{-11}$ Js^{-1}

When the nuclear reactions begin we cannot see the star because the temperature of surrounding dust and air is not hot enough to emit visible light. But these can be seen under the electro-magnetic range, and hence visible through a radio telescope.

Star driven wind and star jet:

A large magnetic field is created due to the motion of the charged particles in the star. This field is strong near the poles of the star. Ionized hydrogen gushes out from the star as a jet along the magnetic force lines. The matter in the core drives along the rotating axis. In addition to gasses, dust and rays are emitted from the disc.

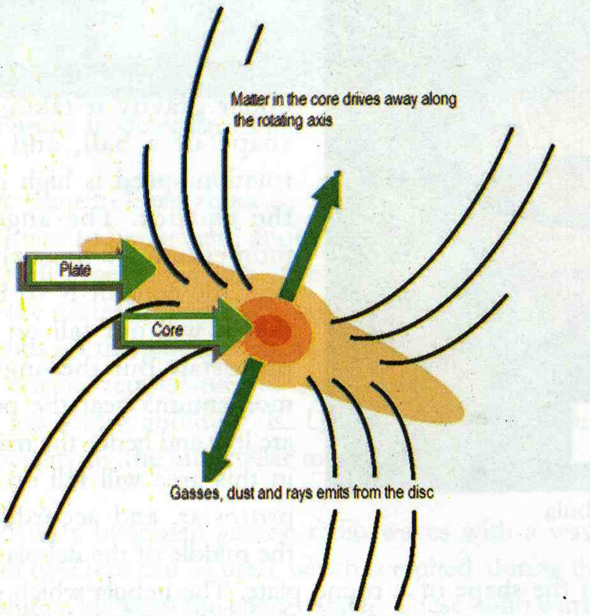

Figure 5: Star driven wind and star jet

Spectroscopy series , luminosity and the size of a star

According to the spectrum of the star, astronomers have categorized the stars. Initially they categorized the stars according to the hydrogen absorption spectrum. They name them as A,B,C,D,E,F,G,H,I,J,K,L,M,N,O, and P according to the strength of the spectrum lines. Later this was modified considering the relative strengths of all spectrum lines, and the stars were categorized as O,B,A,F,G,K,M. Further for fine categorizing, sub groups were included by introducing 1-9 for each group. Warmest stars were categorized as O. The warmest stars are blue in colour while cold stars are red in colour. Luminosity (total amount of emitted light) was also used to categorized the stars using the magnitude scale. This can be expressed as follows:

$$m_1 - m_2 = -2.5\log\left(\frac{f_1}{f_2}\right) \quad \text{where m= magnitude}$$

Magnitude of the star named Vega is considered to be zero. According to this scale brighter stars have a lower magnitude while less bright stars have a higher magnitude.

Hertzsprung-Russell diagram

In the Hertzsprung-Russell (HR) Diagram, each star is represented by a dot. The position of each dot shows its luminosity and its temperature. The vertical axis represents the star's luminosity which is technically the amount of energy a star radiates in one second. **Luminosity** is a common term, as is **absolute magnitude**. Absolute magnitude is the intrinsic brightness of a star. In either case, it is a "ratio scale" in which stars are compared against a reference (our sun).

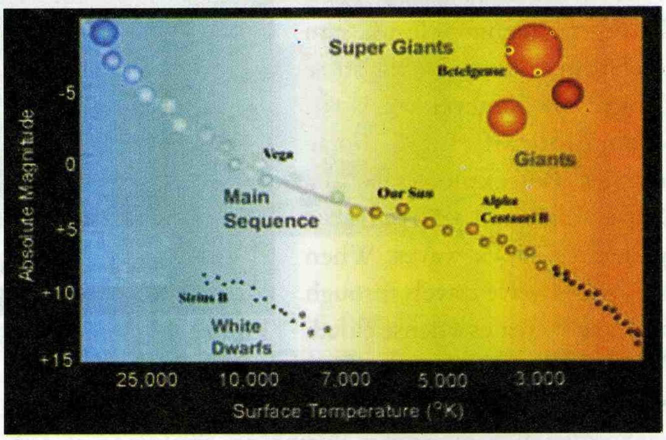

Figure 6: Hertzsprung-Russell diagram

The horizontal axis represents the star's surface temperature not the star's core temperature. Usually this is labeled using the Kelvin temperature scale. *But notice*: In most graphs and diagrams, zero (or the smaller numbers) exists to the left on the diagram. *This is not the case here.* In this diagram the higher (hotter) temperatures are on the left and the lower (cooler) temperatures are on the right. Some HR diagrams include the color of stars which is also a "ratio scale."

So how can one read the HR diagram? A star in the upper left corner of the diagram would be hot and bright while a star in the upper right would be cool and bright. The Sun rests approximately in the middle of the diagram, and can be used for comparison. A star in the lower left corner would be hot and dim, while a star in the lower right corner would be cold and dim.

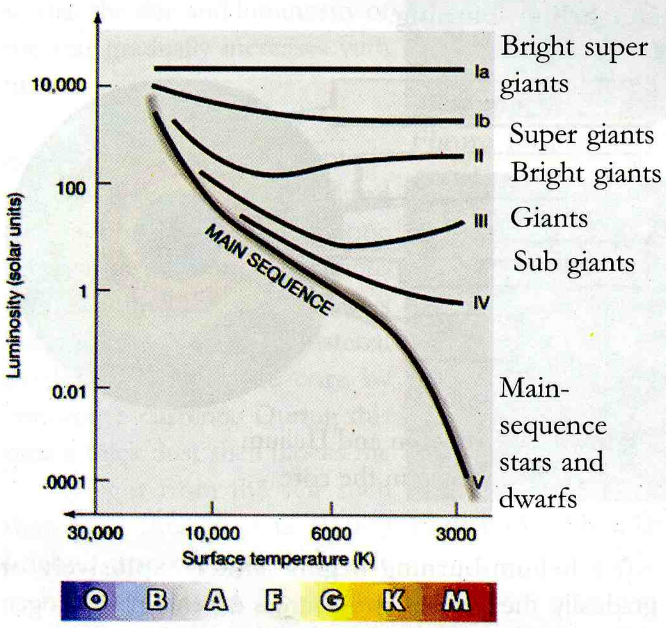

Figure 7: Luminosity Series

Deviations from H-R diagram main sequence line: Protostars which are 0.08 times less in mass than our sun will never start a nuclear reaction. It is not hot enough and dense enough for fusion. These objects are called brown dwarf stars which are not real stars that can reach the main sequence line of the H-R diagram.

Temperature of the core of the stars with higher mass than the sun (100 times) have very high temperatures, and the radian pressure that originates from the nuclear reactions are very high. This leads to instability of the star releasing hot gasses and dust with an explosion. Eta Carian is an example of a star with heavy mass that cannot reach the main sequence line of the H-R diagram.

Time taken to reach the main sequence line of the H-R diagram;

A young protostar becomes hot enough (2,000 to 3,000 K) to glow red, but is obscured by a thick cocoon of gas and dust that allows only infrared and microwaves to pass through. At some point, the central temperature of the protostar climbs high enough for deuterium, to undergo fusion, which temporarily halts the object's gravitational contraction. When deuterium is used up, the embryonic star continues its gravitational infall as a pre-main-sequence object, until its core temperature reaches the point at which normal hydrogen burning can take place, and the star joins the main sequence.

Mass	Time(Years)
0.5 M_Q	$100X10^6$
1.0 M_Q	$30X10^6$
2 M_Q	$8X10^6$
5 M_Q	$0.7X10^6$
15 M_Q	$0.16X10^6$

A star arrives on the main sequence after it starts hydrogen burning in its core and remains there throughout its core-hydrogen-fusion phase. A star's position and length of stay on the main sequence depends critically on mass. Length of stay on the main sequence $\propto$ 1/ (mass of the star)^3

The most massive stars – the hot, blue-white,O stars and B stars – stand at the upper left and have main-sequence lifetimes of only a few million, or tens of millions years. The least massive hydrogen-burning stars, the red dwarfs, sit to the lower right and may remain on the main sequence for hundreds of billions of years. When a star remains on the main sequence, it stays in a hydrostatic equilibrium. That is the gravitational force towards and the outward radiation pressure is in equilibrium. Therefore the star remains unchanged. Here it remains in a stable condition for about 90% of its lifetime.

Mass (relative to the Sun's mass)	Spectral Class	Length of stay on the main sequence (years)
0.4	M	$200,000 X10^6$
1	G2	$10,000 X10^6$
3,3	A	$500 X10^6$
40	05	$1 X10^6$

Nuclear reactions in the core of a star:
Nuclear fusion reactions depend on the temperature of the core.

Nuclear reaction		Temperature
I.	Proton-Proton chain	8 $X10^6$ °K
II.	Carbon-Nitrogen Oxygen Chain	$20X10^6$ °K
III.	Triple-alpha process	$100X10^6$ °K
IV.	Carbon burning	$600X10^6$ °K

When the star exhausts its central hydrogen supply, the core deprived of outward radiation pressure, begins to shrink; meanwhile fusion starts in a shell around the core. This phase is relatively rapid and sees the star's outer layers swell and cool through the sub-giant stage to yield a red giant, or in the case of a very massive star, a red super-giant.

A star's subsequent career continues to hinge on its mass. For stars heavier than one solar mass, the hydrogen-burning shell eats its way outward leaving more and more helium behind. As the helium piles up the core becomes massive, and so it contracts becoming denser and hotter. Eventually, the core becomes so dense that the electrons inside it enter the state of an electron degenerate gas – a condition in which they resist further contraction or expansion(A form of degenerate matter in which the weight of overlying material tries to force all of the electrons surrounding the atomic nucleus into the lowest energy quantum state. The electrons resist because of the Paul Exclusion Principle, and so exert a pressure known as degenerate electron pressure or *electron degeneracy pressure*, that halts further collapse.).

Helium flash
The helium flash happens in the hydrogen-exhausted core of a star that has become a red giant. When gravitational pressure has raised the temperature of the dormant helium core to a temperature of about 100 million K, the helium nuclei undergo thermonuclear reactions. Once the helium burning has started, the temperature climbs rapidly and the extreme sensitivity of the nuclear reaction rate to temperature causes the helium-burning process to accelerate. This in turn raises the temperature, which further accelerates the helium burning, until a point is reached at which the thermal pressure expands the core and thereby limits the flash. The helium flash can only occur when the helium core is less than the 1.4-solar-mass Chandrasekhar limit, and thus it is restricted to fairly low-mass stars.

Helium flash lasts only a few minutes, and the star generates energy at 100 times the rate of the rest of the Galaxy put together. However, this huge surge of energy never reaches the surface, but instead goes into removing the degeneracy of the electrons and expanding the core. For stars more than 2 solar masses, the triple-alpha process starts before the electrons become degenerate, and so there is no helium flash – just a gradual shift to a core-**helium-burning**.

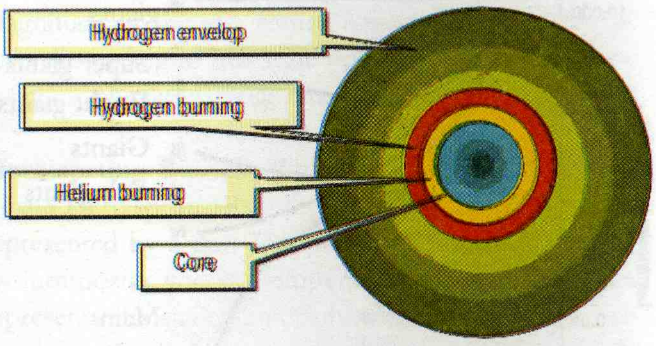

Figure 11: Hydrogen and Helium burning in the core

After helium-burning begins either explosively or gradually, the star has two sources of energy: hydrogen fusion in a shell around the core and helium fusion in the core itself. Helium fuses to give carbon, and some of this carbon combines with helium to yield oxygen. At the same time as the core of the star becomes rich in carbon and oxygen nuclei, the surface temperature climbs until the star reaches a part of the HR diagram known as the horizontal branch. Stars with masses greater than or equal to one solar mass, become smaller and hotter at a constant luminosity. They evolve to the horizontal branch by moving across the HR diagram at constant brightness – low mass stars at about 10 L_{sun}, high mass stars (10 M_{sun}) at about 200 L_{sun}.

After existing as horizontal branch stars for a few million years, the helium in the core of the star is exhausted (now being mostly carbon and oxygen nuclei) and a helium burning shell develops below the hydrogen burning shell. The electrons and nuclei in the core again become degenerate and the star expands and cools to become an **asymptotic giant branch star (AGB stars).** Most of the energy comes from the hydrogen burning shell; the helium burning shell is small at this time. However, the hydrogen shell dumps helium ash onto the helium shell. After some time, enough helium is built up so that the helium shell undergoes an explosive event called a ***thermal pulse.*** Although this pulse is barely noticed at the surface of the star, it serves to increase the mass of the carbon/oxygen core, so that the size and luminosity of the star gradually increases with time.

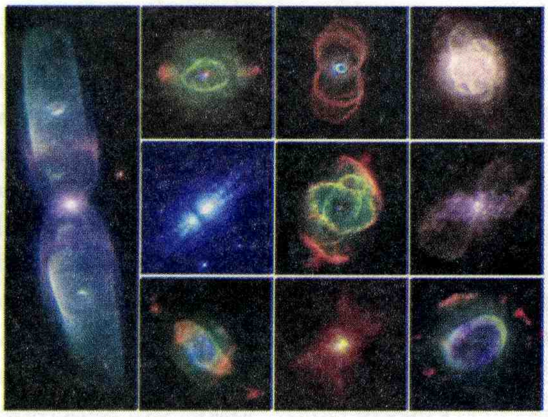

Figure 12: Planetary Nebulae

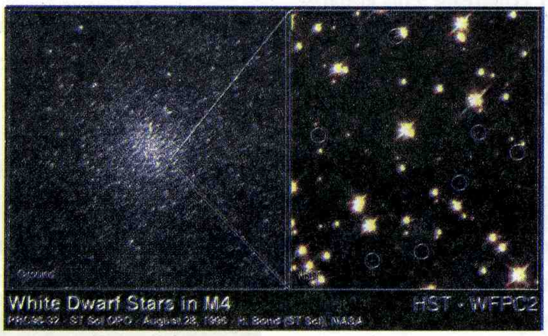

Figure 13: White Dwarf stars

As the star climbs the asymptotic giant branch, a stellar wind develops in the star's envelope that blows the outer layers into space. In this wind, dust particles are formed from carbon material dredged up from the core by convective currents. During this time a thick dust shell blocks the visible light from the star such that even though it is 10,000 brighter than the Sun, it is only seen in the infrared. The stellar wind causes mass loss for AGB stars. This loss is around 10^{-4} solar mass per year, which means that in 10,000 years the typical star will dissolve leaving the central hot core (the central star in a planetary nebula). If the star is larger than 8 solar masses, then the core continues to heat. Carbon and oxygen fuse to form neon, then magnesium, and then silicon. Silicon will fuse to form an iron ash core. Iron is extremely stable and resistant to fusion. The temperature of an iron core can reach 3 billion degrees. When the iron core reaches a critical mass, it collapses suddenly to become a **neutron star** or possibly even a **black hole,** while the outer layers are violently expelled in a supernova explosion.

End of a star, planetary nebulae and white dwarf:

A planetary nebula forms when a star can no longer support itself by fusion reactions in its center. The gravity from the material in the outer part of the star takes its inevitable toll on the structure of the star, and forces the inner parts to condense and heat up. The high temperature in central regions drive the outer half of the star away in a brisk stellar wind, lasting a few thousand years. When the process is complete the remaining core remnant is uncovered and heats the now distant gases and causes them to glow. Despite the name, these objects are totally unrelated to "planets". It is commonly thought that they may represent the final episode of the Sun's existence as a star. This concept has been questioned recently, wherein evidence from globular cluster stars indicates that stars must be about 20% heavier than the Sun to form a Planetary nebula. Planetary nebulae have a lot of shapes. It is believed that the environment of the dying star, distribution of the envelop of the star, and the rotating speed of the star would be the effective factors to determine the shape of the stars.

For stellar masses less than about 1.44 solar masses, the energy from the gravitational collapse is not sufficient to produce the neutrons of a neutron star, so the collapse is halted by electron degeneracy to form white dwarfs. This maximum mass for a white dwarf is called the Chandrasekhar limit. As the star contracts all the lowest electron energy levels are filled and the electrons are forced into higher and higher energy levels, filling the lowest unoccupied energy levels. This creates an effective pressure which prevents further gravitational collapse.

When the white draft does not have the energy source it will become a black dwarf.

Evolution of stars with different masses:

$<0.07\ M_Q$ - Not enough mass for hydrogen burning

$0.07\text{-}0.5\ M_Q$ - Hydrogen burning occurs in this star and it will come to the giant branch. Not enough mass for helium burning.

$0.5\text{-}2.2\ M_Q$ - Star will lie on the main sequence and later it will become a white dwarf.

2.2 – 8.0 M_Q - No helium degeneracy and therefore no helium flushing. But later carbon degeneracy may occur. If the core gets burnt it will end-up with a Super Nova. But so far there is no evidence for such explosions. Astronomers believed that these stars would form star winds but temperature and pressures are not high enough for carbon fusions. Some of the stars end up as planetary nebulae.

8.0 – 10 M_Q - Not enough mass to burn the carbon core. No carbon degeneracy, therefore no explosions. Carbon fuse to form oxygen. But temperature and pressures are not high enough for oxygen fusion.

10- 15 M_Q - Can fuse oxygen and has the oxygen degeneracy. Therefore eventually the star dies in a Super Nova.

15-100 M_Q - Very soon (perhaps 150 million years), helium runs out in the core. The core collapses. This time the mass and gravity are high enough for further nuclear reactions to begin. Carbon can be changed to oxygen and silicon. The carbon in the core runs out after perhaps 40 million years. The core collapses again. Higher core temperatures are reached. More nuclear reactions occur, this time using oxygen. Each time a nuclear fuel runs out in the core, the core collapses. This collapse raises the temperature, which in turn triggers off more nuclear reactions. Each subsequent set of reactions lasts for a shorter period than the previous. This can continue through the elements until iron is reached. Iron nuclei cannot react to produce energy. When the core is made up totally of Iron, gravity finally takes over. The core collapses again. Any nuclear reactions that occur now consume energy so that gravity cannot be held at bay. The core collapses catastrophically. In an instant it shrinks uncontrollably to almost nothing. The huge amount of shrinking heats up the core so dramatically that the power produced blows the outer layers of the star away in a huge explosion.

Supernovae come in two main types: Type I, which lack hydrogen lines in their spectra, and type II, which have hydrogen lines. These types are further subdivided. Types Ia, Ib, and Ic are distinguished by other details of their spectra. Types II-L and II-P are distinguished on the basis of their light curves: type II-Ls showing a linear ("L") decline, while type II-Ps remains on a plateau ("P") for a few weeks before falling off. Type Ia supernovae are the brightest of all, reaching a maximum absolute magnitude of -19. Types Ib and Ic tend to be a couple of magnitudes fainter, while Type II supernovae vary widely in their peak output. Type Ia supernovae occur in older populations of stars, such as those making up elliptical galaxies and the halos of spiral galaxies. Types Ib, Ic, and II are largely confined to the younger populations of stars found in the disks of spirals.

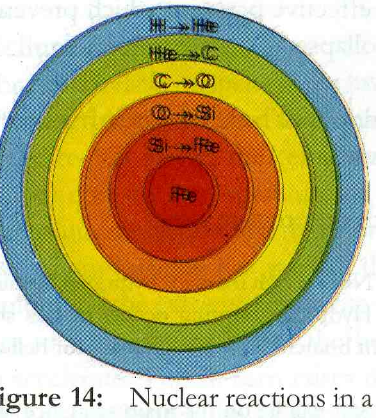

Figure 14: Nuclear reactions in a high dense star

In terms of the underlying mechanism of the explosion, types Ib, Ic, and II have more in common with each other than they do with type Ia. The latter is thought to occur exclusively in binary systems in which a white dwarf has acquired a large amount of material from its companion. When the white dwarf's mass exceeds the Chandrasekhar limit of about 1.4 solar masses, runaway carbon burning is triggered, which results in the incineration of the dwarf and the violent disruption of its contents. The other varieties of supernova are all thought to be due to the core collapse of massive stars. Types Ia and Ib involve stars that have lost their hydrogen envelopes, either through a powerful stellar wind or the transfer of material to a companion. Wolf-Rayet stars are considered likely progenitors of these kinds of supernovae, the slight chemical differences between types Ia and Ib arising from different degrees of stripping of the Wolf-Rayet's outer layers prior to the explosion.

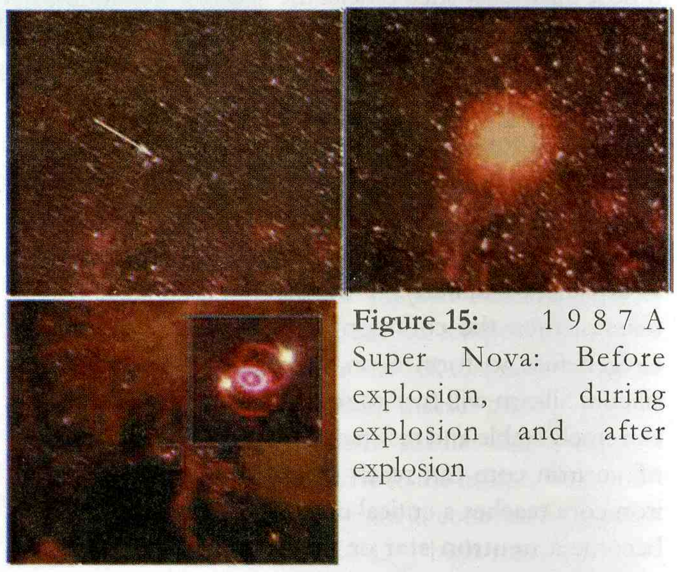

Figure 15: 1987A Super Nova: Before explosion, during explosion and after explosion

Stars come to life, they live over a very long period of time - and finally they die. The life of the stars can vary; the same applies to their death.

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