STAR

An astronomical object – luminous spheroid of plasma held together by its own gravity.

Nearest Star : **SUN**

Like individual : Stars are unique

Like family : Sharing common characters

Human being : 100 years

Stars : million or billions of years.

Stars are born from clouds of interstellar gas and dust.

General features:

Each star begins its life roughly with the same chemical composition.

At birth ¾ of star mass - hydrogen

Roughly ¼ of star mass - He

Note more than 2% elements heavier than He

Same type of balance between inward pull of gravity = outward push of internal pressure.

This governs the rate at which energy generated - Nuclear fusion

Classification:

Before 20th century stars classified based on brightness. Not proper because stars appear bright may be extremely luminous or very nearby. Now classification is based on luminosity and surface temperature.

PROPERTIES OF STARS

Stars are characterized by

1. Luminosity
2. Brightness
3. Surface temperature
4. Spectral type
5. Mass

LUMINOSITY:

The total amount of power a star radiates into space. unit – watt. It is the amount of energy generated in the star and released as Electro Magnetic radiations. We cannot measure stars luminosity directly.

From Stefan's equation, Luminosity of a star is given by

L = $\boldsymbol{\sigma A T^4}$ where **A-**Surface area of the illuminating body

A = $\mathbf{4\pi R^2}$ where **R-**Radius of the illuminating body

L = $\mathbf{4\pi R^2 \sigma T^4}$

For sun $\mathbf{L_S = 4\pi R_S{}^2 \sigma T_S{}^4}$

① ÷ ②

$$L/L_S = (R/R_S)^2 \, (T/T_S)^4$$

Also we can show

$$L/L_S = (M/M_S)^{3.5}$$

M_S - Mass of the sun

From either of above expressions we can determine the luminosity of a star.

BRIGHTNESS

Two types of Brightness: 1) Apparent Brightness

2) Absolute Brightness

Apparent Brightness is the measure of visible brightness from earth which depends on the distance of the star.

Absolute Brightness is the measure of visible brightness at a distance of 10 parsec.

Magnitude of a star is a unit less quantity and it is a log scale of observed visible brightness.

$$M_1 - M_2 = -2.5 log_{10} \frac{L_1}{L_2}$$

SURFACE TEMPERATURE: SPECTRAL TYPE

Measuring surface temperature is somewhat easier than measuring its luminosity. We can measure surface temperature directly from the star's colour or spectrum.

A star's surface temperature determines the color of light it emits. A red color star is cooler than a yellow star which intern is cooler than a blue star.

The emission and absorption in a star's spectrum provide an independent and more accurate way to measure its surface temperature.

Stars displaying spectral lines of highly ionized elements must be fairly hot, while stars displaying spectral lines of molecules must be relatively cool. Astronomers classify stars according to surface temperature by assigning a spectral type determined from the spectral lines presents in a star's spectrum.

Spectral type

O B A F G K M

↓ ↓

hottest coolest

Each type is further divided using numeric digit with 0 (zero) being hottest and 9 being coolest. (Ex. from G_0 to G_9)

Oh Be A Fire Girl/Guy Kiss Me

Ex: Sun is designated spectral type G_2which means it is hotter than a G_3 star and cooler than a G_1 star.

Spectral type	**Temperature (k)**	**Colour**	**Spectra**	**Ex.**
O	>30,000K	Blue	Ionized Helium	Stars of Orion Belt
B	10,000 TO 30,000k	B-W	Neutral He	Rigel
A	7,500 to 10,000k	White	Hydrogen	Sirius
F	6,000 to 7,500k	Y-W	Ionized metal lines(ionized ca)	Polaris
G	5,200 to 6,000k	Yellow	Neutral metal ions (strong lines of ionized ca)	Sun Alpha centauri A
K	3,700 to 5,200k	Orange	Neutral metal ions	Areterus
M	2,400 to 3,700k	Orange-Red	Band spectra of molecules	Betel geuse Proxima centauri

COLOUR INDEX:

Instead of colour we can use colour index (number) to describe a star. Colour index is defined by taking the difference in magnitude at 2 different wavelengths. Using UV, Blue and Visible colour filter, there are 3 possible differences.

B-V colour index (Blue & Visible)

U-B colour index (UV & Blue)

U-V colour index (UV & Visible)

STELLAR MASSES:

Stellar mass is an important property but harder to measure. By using Newton's version of Kepler's third law we can measure stellar masses of binary stars.

Determination of Stellar Masses:

Newton's version of Kepler's law

$$(M_1 + M_2) = \frac{4\pi^2}{G}\frac{a^3}{p^2}$$

G- gravitational constant

a- Semi major axis

p- Period of one orbit

semi major axis can be calculated as follows

Orbital velocity of one star relative to its companion is given by

$$v = \frac{2\pi a}{p} = \frac{distance\ \ travelled\ \ in\ one\ orbit}{period\ \ of\ one\ orbit}$$

$$a = \frac{pv}{2\pi}$$

by knowing a and p we can determine M_1 and M_2.

The individual masses of the two stars can be calculated by using the fact that the relative velocities of the two stars around their common center of mass are inversely proportional to their relative masses.

parsec Unit:

1 Parsec (PC) = Distance to a star with a parallax angle of 1 arc second. d = 1AU / sinp

`If p=1 arcsec then d = 1AU / sin 1”

1 arc sec = 1/3,600

$$d = 1AU / \sin(1/3{,}600)$$

$$= 1AU / 4.84814 \times 10^{-6}$$

$$= 149.6 \text{ million km} / 4.84814 \times 10^{-6}$$

$$= 3.26 \text{ light years}$$

$$1PC = 3.09 \times 10^{13} \text{ km}$$

1 pc = 3.09×10^{16} m
1 pc = 3.26 light years
1 AU = 149.6 Million km
1 LY = 10 trillion km
9.461×10^{12} km

Parsec is a unit of length used to measure the large distances to astronomical objects outside the solar system. Its approximately equal to 31 trillion Km or 3.26 light years.

Distance in parsecs

d (in parsecs) = 1/p (in arc secs)

If parallax angle is ½ arc secs, then distance of the star is 2 parasecs.

Distance of few near by stars.

Sirus	-	2.6 parasecs	-	2.6 x 3.26 light years
Altair	-	5 parasecs	-	5 x 3.26 light years
Vega	-	8 parasecs	-	8 x 3.26 light years

STELLAR EVOLUTION/ LIFE CYCLE OF STARS

Like human, stars have different evolution stages.

Birth ⟶ Maturity ⟶ Ageing ⟶ Death

The star's main goal in life is to achieve stability, or equilibrium, where pressure from fusion within the core is **equal** to the force of gravity pushing down on it (this keeps the star "alive").

Smaller stars have longer live. Larger stars have shorter live. Larger stars have more fuel, but they have to burn (fuse) it faster in order to maintain equilibrium. Because fusion occurs at a faster rate in massive stars, large stars use all their fuel in a shorter length of time. But a smaller star has less fuel, but its rate of fusion is not as fast. Therefore, smaller stars live longer than larger stars because their rate of fuel consumption is not as rapid.

Life Cycle of a Star like our Sun

Nebula(Hydrogen cloud) → Protostar→ Main Sequence Star → Red Giant →White Dwarf

Life Cycle of a Star with Greater Mass than our Sun

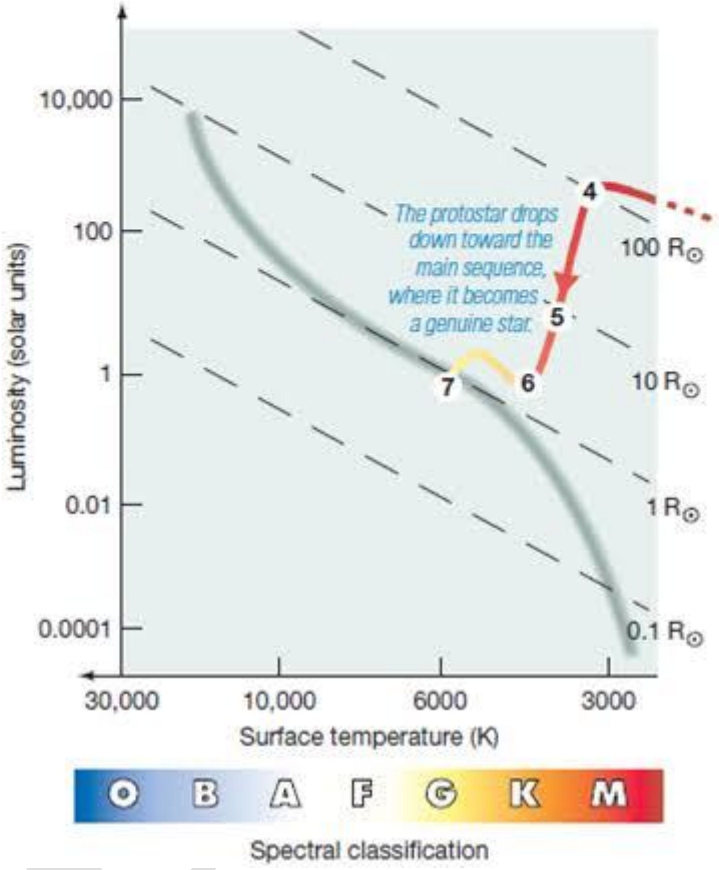
Nebula→ Protostar→ Main Sequence Star → Red Supergiant →Supernova → Neutron Star or Black Hole

Birth of a Star

The cold cloud contains hydrogen of size of the order of light years and mass equals 1000 solar masses contracts due to its own gravity. A cloud of gas and dust, consisting mostly of hydrogen gas and dust begin to clump together to form a **Protostar** (a baby star). A protostar is a young star in the earliest phase in stellar evolution. The evolution of protostar is indicated as Hayashi track on the HR diagram.

In a protostar, every constituent atom is pulled towards the centre of gravity resulting in shrinkage of its size. The temperature increases from about 100 K to about 50,000 K in a year. The high temperature gives rise to violent collisions between the hydrogen atoms dislodging their atomic electrons. Now there are two types of gases electron gas and proton gas. The shrinkage continues and the temperature increases.

After 10 million years, when the protostar shrinks from its original size of trillion of km to about 2.5 million km in diameter, its internal temperature will be about **10^{7}** K.



As it contracts its temperature reach values of the order of **10^{7}** K and thermonuclear reaction starts. Now the star is said to be born. The gravitational force is compensated by radiation produced due to fusion reaction. The star is in the main sequence. It takes about 1, 00,000 years for a star to reach main sequence from H-track. The surface temperature of the new born star is about 3600 K.

Maturity of a star

Proton – proton cycle or carbon – nitrogen cycle are the two types of thermonuclear reactions taking place in the interior of the stars. The release of nuclear energy by fusion at the centre balances the inward gravitational pull so long the star remains in the main sequence. Hydrogen gets continuously consumed and helium is synthesized continually. The release of nuclear energy raises the temperature of the star; the star becomes more and more luminous. The star stays in main sequence for millions of years. Burning of hydrogen into helium covers 99% of the life of a star of one solar mass.

Ageing of stars

The helium formed is collected at the core where there is no further burning of hydrogen. The outer layer expands the size of the star increases and the energy radiated per unit area of its surface decreases. The surface temperature drops and the colour of the star changes from white to red. The star leaves the main sequence and heads towards the giant stage. This stage is called red giant.

Death of a star

The temperature of the helium core rises to $\mathbf{10^8}$ **K.** The helium nuclei undergo nuclear fusion reaction. Carbon is synthesized through triple α process. When there is no more helium to burnt the core of a low mass star collapses into a **white dwarf**, the outer regions drifting away into space. But in massive stars nucleosynthesis continues and heavier elements upto iron are formed. When all the helium is consumed, a catastrophic collapse of the whole massive structure occurs, resulting in a **supernova** explosion. The burnt out remnants become **neutron stars** and **black holes**.

Final Stage of a Star (or) End Products of Stellar Evolution

If a star exhausted all it fuels, it ends up with one of the following Stage.

White dwarf (or) Neutron star (or) Black hole.

Let Ms-Mass of our sun

if mass of the star is < 1.4 Ms It becomes a **white dwarf**

if mass of the star is in between 1.4-3 Ms It becomes a **Neutron star**

if it is greater than 3Ms It becomes a **Black hole**

where 1.4 Ms is Chandrasekhar limit. Below which the star is white dwarf above which star is neutron star.

i) White dwarf:

Small stars of masses upto 1.4 Ms (***Chandrasekhar limit***) becomes a white dwarf. After exhausting all its fuel, a star contracts gravitationally and becomes a white dwarf. White dwarfs are **degenerated stars** which are very dense and composed mostly of **electron-degenerate matter**. They have masses comparable to that of the Sun, volumes comparable to that of Earth, and are very faint. Some white dwarfs are classified as helium stars as they have very strong helium lines and weak hydrogen lines. Here gravity is balanced by the electron degeneracy pressure. Its density is very high (~ 10^6 g/cm^3). Typical composition: Carbon and/or Oxygen

Example: companion of star Sirius is white dwarf.

ii) Neutron star:

Massive stars go through the same life stages as our sun (just on a larger scale) upto the Main Sequence stage. Then the massive stars expand into a Red Supergiant and explode into a Supernova. Then turn into a Black Hole or a Neutron Star. **Neutron stars** are the equivalent of white dwarfs, but the degeneracy pressure is provided by neutrons, not electrons.A heavier star >1.4 Ms, exhausting its fuel contract strongly. There is no energy to counteract the contraction. As the consequence, the density of the star increases, the electrons are squeezed into the nucleus. The following reaction takes place.

$$p + e^- \rightarrow \mathrm{n} + \nu$$

The neutrino escapes, as neutron only remains. Now the density of the star is 10^{11} Kg/cm^3. If our earth becomes a neutron star, the size of earth will be a lemon fruit. But the whole mass of the earth is in the lemon size earth. Example: In crab nebula, a neutron star is found. It is a pulsar, radiating ratio waves.

iii) Pulsar:

A pulsar is a magnetised spinning neutron star that emits a beam of radiation mostly radio waves and also X rays and visible radiations. As the star spins its beam sweeps around. Anytime the beam sweeps by the earth, telescopes detects a pulse of radiation.

About 1700 pulsars have been discovered. Their periods range from 0.0016 s up to 20 minutes. The origin of the radio pulses can be understood if the magnetic field is tilted at an angle of 45°–90° with respect to the rotation axis. The field is so strong that it drags electrons from the surface and accelerates them to relativistic speeds over the magnetic poles. When the electrons are accelerated along the magnetic field lines, they radiate so called curvature radiation which is related to synchrotron radiation. In the direction of the magnetic poles two thin beams of radio radiation are emitted. The beams sweep around the sky, and if the Earth happens to be in the path of the beam a pulsar is seen. The best-known pulsar is located in the Crab nebula

iv) Black hole:

If star mass is heavier than 3Ms, at the final stage the star contracts due to gravitational pull and collapse. The gravitational force is strong enough so that nothing can escape from it. Even light cannot escape from it. We can’t directly observe a Black hole.

If a neutron star undergoes gravitational collapse, then since there is no other pressure to balance the gravitational attraction, the gravitational collapse of the star is total. The result is an extraordinary phenomenon ***a black hole***, the term coined by John Mitcell. For a black hole of mass M, the escape velocity reaches the speed of light C at a radius $R_{s.}$ $R_s = 2GM/ C^2$ where R_s is termed as ***Schwarzschild radius*** – the critical radius of the star corresponding to the maximum possible escape velocity. The result implies that even photons from a black hole cannot escape and hence to an observer it appears black. In the black holes powerful X rays and other radiations are generated. Supermassive black holes at the centre of some galaxies are the most powerful source of sustained electro magnetic radiation in the Universe.

v) Super nova:

As a massive star burns its hydrogen, helium is left behind, like ashes in a fireplace. Eventually the temperature climbs enough so that the helium begins to burn, fusing into Carbon. Hydrogen continues to burn in a shell around the helium core. Carbon is left behind until it too starts to fuse into heavier elements. A nested shell-like structure forms. Once iron forms in the core, the end is near. Iron cannot be fused into any heavier element, so it collects at the center of the star. Gravity pulls the core of the star to a size smaller than the Earth's diameter. The core compresses so much that protons and electrons merge into neutrons, taking energy away from the core. The core collapses, and the layers above fall rapidly toward the center, where they collide with the core material and "bounce". The "bounced material collides with the remaining in falling gas, raising temperatures high enough to set off a massive fusion reaction. The star then explodes. This is a ***supernova.*** Gold, uranium and other heavies all originated in a supernova explosion. Supernova leaves behind the collapsed core of neutrons that started the explosion, a ***neutron star***. If the neutron star is massive enough, it can collapse, forming a ***black hole***.

HERTZSPRUNG – RUSSEL DIAGRAM

(HR DIAGRAM)

The HR diagram is the most important classification tool in stellar astronomy. It shows relationships and differences between stars with respect to temperatures, brightness, colors, etc. HR diagram shows stars of different ages and in different stages, all at the same time.

It is a plot between luminosity and surface temperature (spectral type). Luminosity is on the vertical axis and surface temperature on the horizontal axis. Temperature increases from right to left because HR diagram is based on the spectral sequence OBAFGKM.

Each location on the diagram represents a unique combination of spectral type and luminosity. For example, the dot representing the sun in the HR diagrams corresponding to the sun spectral type G_2 and its luminosity 1L sun. the absolute magnitude of our sun is 4.8. The colour index is B-V and temperature is 5780 K.

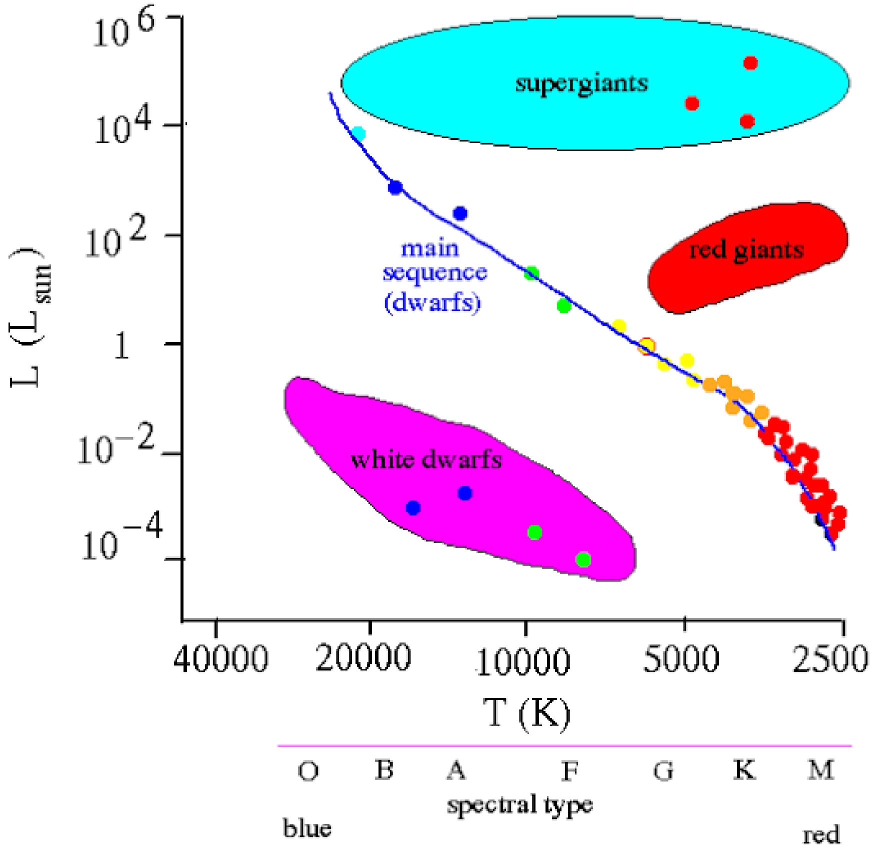
Since luminosity increases upwards and surface temperature increases leftward,

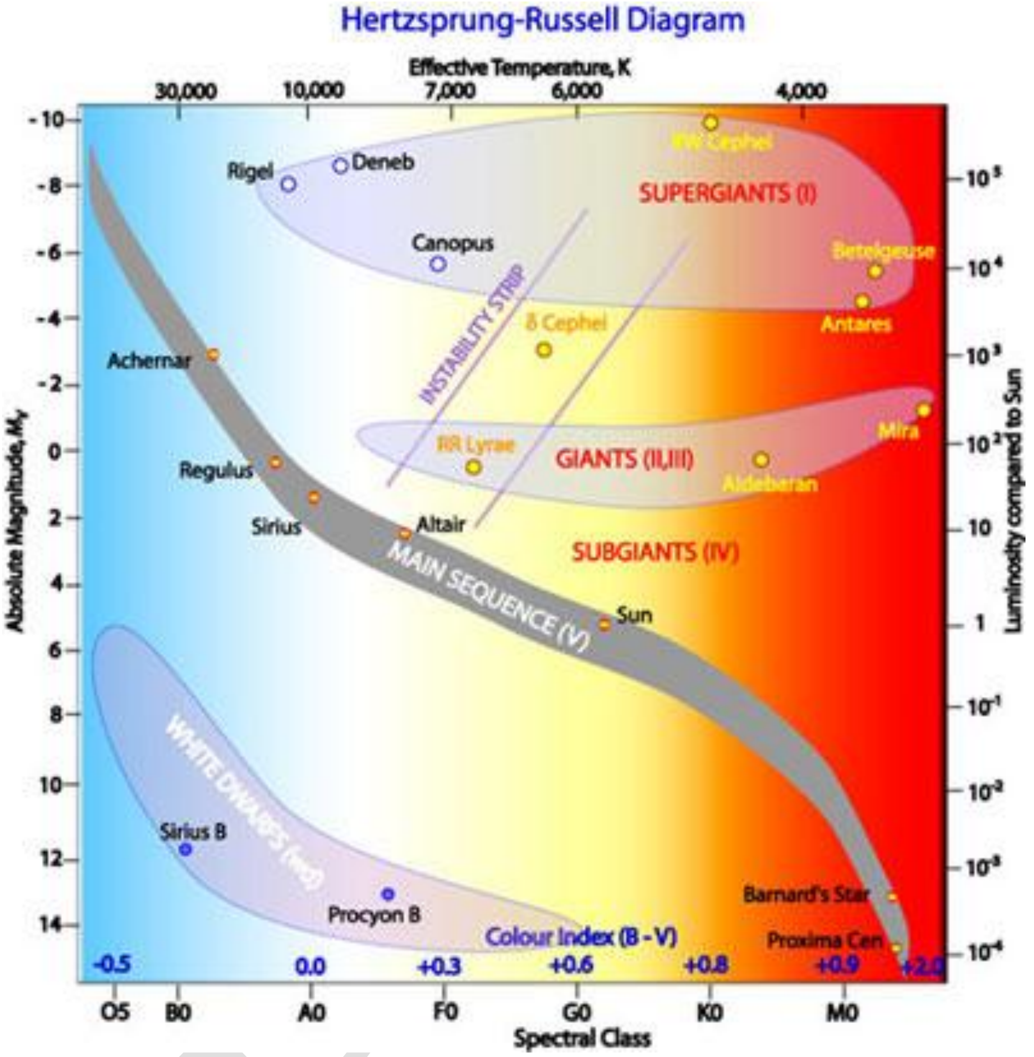
- A star in the upper left corner of the diagram would be hot and bright.
- A star in the upper right corner of the diagram would be cool and bright.
- The Sun rests approximately in the middle of the diagram, and it is the star which we use for comparison.
- A star in the lower left corner of the diagram would be hot and dim.
- A star in the lower right corner of the diagram would be cold and dim.

  - HR diagram also provides direct information about stellar radii. In HR diagram stellar radii increase from the high temperature low luminosity corner (Lower left) to the low temperature high luminosity corner (Upper right).
  - If two stars of same surface temperature and if one is more luminous than the other means that the star is larger in size.
  - Most of the stars fall somewhere along the main sequence the prominent streak running from upper left to the lower right on HR diagram. Our sun is a main sequence star.
  - The stars along the top are super giants because they are very large and very bright.
  - Just below the super giants are the giants somewhat smaller in radius and lower in luminosity.
  - Stars near the lower (below main sequence) are called white dwarfs. They are white in colour and having high temperature.

Importance of HR Diagram

- The H–R diagram is one of the most important tools of astronomers. Much of what we know about stars comes from studying the patterns that appear when we plot stellar surface temperatures and luminosities in an H–R diagram.
- Much of what we know about the universe comes from studies of star clusters. Here again, H–R diagrams play a vital role. For example, H–R diagrams of star clusters allow us to determine their ages.


10^6
10^4
10^2
1
10^{-2}
10^{-4}
L (L_{sun})
supergiants
red giants
main sequence (dwarfs)
white dwarfs
40000
20000
10000
5000
2500
T (K)
O
B
A
F
G
K
M
spectral type
blue
red



MILKY WAY GALAXY: STRUCTURE

On clear, moonless nights a nebulous band of light can be seen stretching across the sky. This is the Milky Way Galaxy. The Milky Way is a lens shaped flat disc in appearance. It is thick at the centre and thin towards the edges. The faint light of distant stars merges into a uniform glow, and therefore the Milky Way appears as a nebulous band to the naked eye. The band of the Milky Way extends round the whole celestial sphere.

Structural Components of the Milky Way

The structure of the MilkyWay can be described by means of an almost spherical halo of old stars and a disk of gas and young and middle-aged stars. Due to its structure the Milky Way belongs to disk galaxies.

Shape: Barred spiral galaxy with 4 arms (bar shaped core surrounded by gas, dwarf & stars)

Mass: 1.5 x10^{12} Ms Ms-sun mass

Number of Stars: 2.5x10^{11} (250 billion stars)

Diameter: 150 kLy (≃ 30 kilo per sec)

Our sun situates at 26.4 kLy from the galactic centre.

At the centre of galaxy much of matter does not emit/absorb electromagnetic radiation. This mass is called “Dark Matter”.

The Milky Way moves through space at a velocity of about 552 km/sec.

The stars, gas and dust of the Milky Way all orbit the centre at the rate of about 220 km/sec.

The Galactic Bar: A large fraction of all disk galaxies are *barred*, with an elongated light distribution at the centre. The first indication that this might also be the case for the Milky Way was found in velocity measurements of neutral hydrogen, which were incompatible with gas moving along circular orbits. **The stellar density is largest near the galactic centre and decreases outwards.**

The structure can be viewed as consisting of **six separate parts**: 1) a nucleus 2) a central bulge 3) a disk both thin and thick 4) a spiral arms 5) a spherical component and 6) a massive halo

The nucleus: At the centre of the Galaxy lies a remarkable object – a massive black hole surrounded by an accretion disk of high temperature gas. Infrared radiations and X rays are emitted from the area and rapidly moving gas clouds can be observed here. The black hole has mass about 4,000,000 times that of Sun. The **stellar halo** forms an almost spherical distribution of stars with ages 12–14 Ga (Ga – billion years; giga annum; Ga = 3.15581x 10^{16} seconds), representing the **oldest part of the Milky Way**.

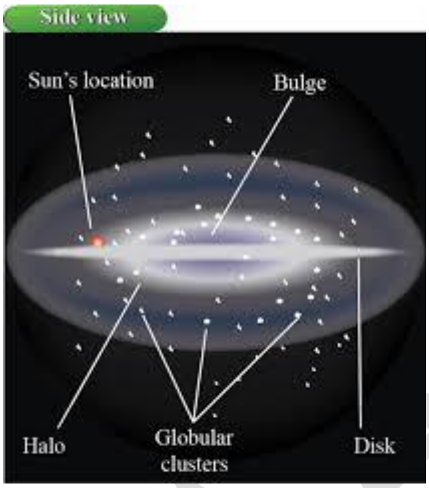
The central Bulge: Surrounding the nucleus an extended bulge spherical in shape primarily consist of Population II stars of ages 7–11 Ga., though they are comparatively rich in heavy elements. Both stars and globular star clusters have nearly radial orbits around the nucleus.

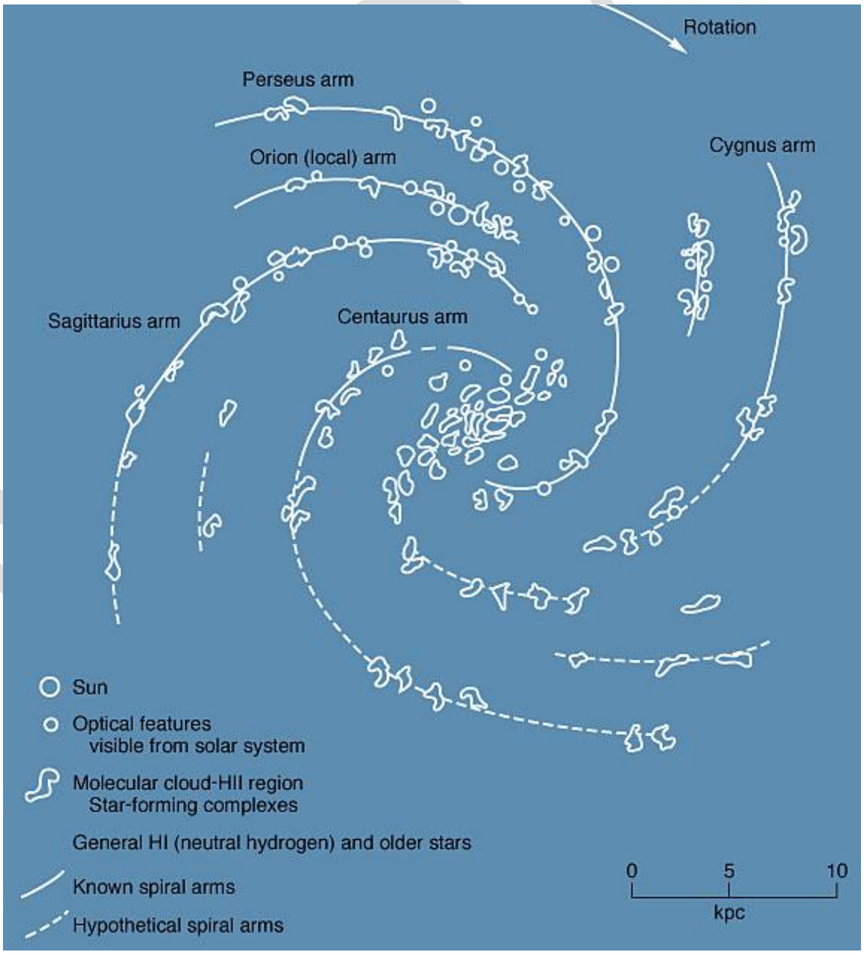
The disk: The most important part of the galaxy- the disk extends from the nucleus out to approximately 75,000 Ly. The thin disk includes the dust and gas and the youngest stars with ages less than 10 Ga while the thick disk includes older stars with an age about 10–12 Ga.

The Spiral arms: As mentioned earlier, the Milky Way appears to be a spiral galaxy. Investigations using a variety of methods, both optical and radio have confirmed that a four-armed pattern gives the best description of the spiral structure in the Sun's vicinity. They are Persecus, Outer (Cygnus) , Centaurus and Sagittarius arms. The spiral arms contain a higher density of interstellar gas and dust as well as greater concentration of star formations. Three of the arms start at the position of the galactic bar.

Spherical Component: The space above and below the disk of galaxy is occupied by a thinly populated extension of the central bulge. Nearly spherical in shape this region is populated by outer globular clusters and also contains many stars of population II.

The massive halo: Outside the plane of the MilkyWay, an almost spherically symmetric ***halo*** extends out to over 50 kpc and even further out there is a ***corona.*** The least understood component of the galaxy is the giant massive halo that is exterior to the entire visible part. The existence of the massive halo is demonstrated by its effect on the outer rotation of the galaxy. The halo extends considerably beyond a distance of 100,000 Ly from the centre and that its mass is several times greater than the mass of the rest of the galaxy taken together.





EXPANDING UNIVERSE OR BIG BANG THEORY OR HUBBLE'S LAW

If universe is expanding then the light coming from distant objects would be red shifted. The red shift would increase with increasing distance to the object. Larger telescopes were being built that were able to accurately measure the spectra, or the intensity of light as a function of wavelength, of distant objects.

Evidence for Expanding Universe / Big Bang:

i) Doppler red shift of Galaxy
ii) Microwave back ground radiation.

Doppler red shift of Galaxy – Hubble's Law

Between 1912 and 1922, astronomer Vesto Slipher discovered that the spectra of light from many of the distant objects was systematically shifted to longer wavelengths, or red shifted. A short time later, other astronomers showed that these nebulous objects were distant galaxies.

Edwin Hubble observed that the all galaxies receding from each other. In 1929 he measured the red shifts of a number of distant galaxies. He also measured their relative distances by measuring the apparent brightness of a class of variable stars. When he plotted red shift against relative distance, he found that the redshift of distant galaxies increased as a linear function of their distance.

The expansion of the universe (or recessional velocities of galaxies) is proportional to their distance i.e the farthest they are, the fastest they move away from us.

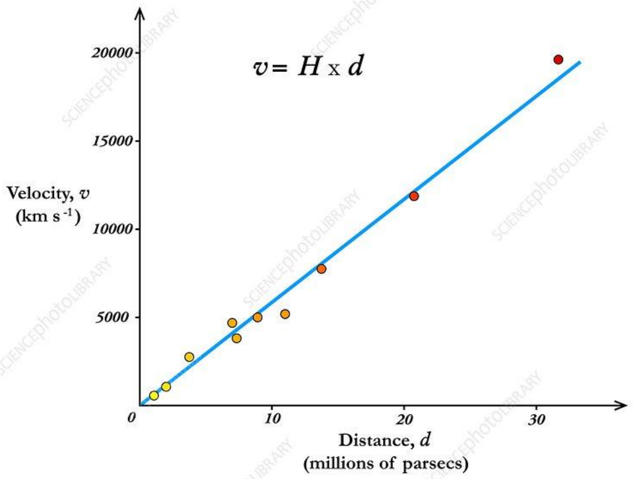
$$\mathbf{V \propto D}$$

$$\mathbf{V = H_oD}$$

H_o- Hubble's constant (km/sec/Mpc)

V – Observed velocities of the galaxy

D – Distance of the galaxy (Mpc) **$H_o \simeq 70$ km/sec/Mpc**



The only explanation for this observation is that the universe was expanding. Since that the distance between galaxies increases, it must mean that in the past, they were close together. A**t some point in the past the entire universe would have been a single point.** This point, later called **the big bang**, was the beginning of the universe as we understand it today. The atoms produces by the Big Bang were Hydrogen. Giant clouds of these primordial elements later collapsed through gravity form stars and galaxy.

The continuous expansion of the universe implies that the **universe was denser and hotter in the past.** The expanding universe is finite in both time and space. The reason that the universe did not collapse is that it had been expanding from the moment of its creation. The universe is in a constant state of change.

The Cosmic Microwave Background Radiation

Gamow, Herman, and Alpher, predicted that if the universe were hotter and denser in the past, radiation should still be left over from the early universe.

When the universe was young, it was hot enough for gas to be ionized. The many free electrons were very effective at scattering light, so the gas was optically thick and photons were tightly coupled to matter. As the universe expanded and cooled, the electrons and ions were able to come together to form neutral atoms. Suddenly the photons were liberated, free to travel great distances through the universe. Those photons are still around and visible as the cosmic microwave background (CMB).

In 1963, Arno Penzias and Robert Wilson, found mysterious microwaves coming equally from all directions. This radiation called the Cosmic Microwave Background Radiation, convinced most astronomers that the Big Bang theory was correct. For discovering the Cosmic Microwave Background Radiation, Penzias and Wilson were awarded the 1978 Nobel Prize in Physics.

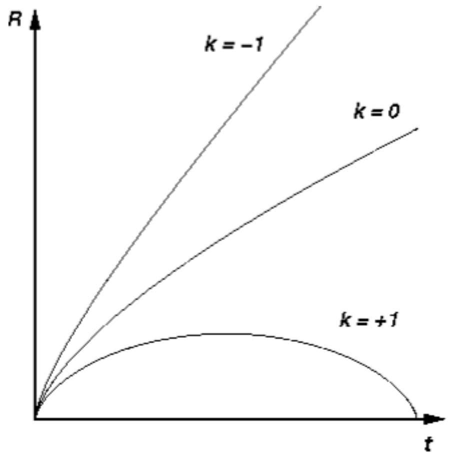
FUTURE PROSPECTS: THE FUTURE OF THE UNIVERSE

Properties of the Expanding Universe

The equations of the expanding universe have three possible solutions. The three possible types of expanding universes are called open, flat, and closed universes.

If the universe were **open**, it would expand forever. If the universe were it **flat**, it would also expand forever, but the expansion rate would slow to zero after an infinite amount of time. The density of the universe seems to be at the critical density; that is, the universe is neither open nor closed but “flat.”

If the universe were **closed**, it would eventually stop expanding and recollapse on itself, possibly leading to another big bang. The final collapse of such a contracting universe is sometimes termed the “big crunch.”In all three cases, the expansion slows, and the force that causes the slowing is gravity.



X axis represents time and Y axis represents separation between the galaxies

When ρ < ρcrit, $k = -1$ Open negative curvature expands for ever

ρ = ρcrit, $k = 0$ Flat expands for ever

ρ > ρcrit, $k = +1$ Closed positive curvature collapses

where ρ - density

However the standard models allow two alternative prospects for the future development of the Universe – open or closed universe. If the universe were open, it would expand forever. If the universe were closed, it would eventually stop expanding and recollapse on itself, possibly leading to another big bang.

In the final squeeze, the early history of the Universe would be repeated backwards: in turn, galaxies, stars, atoms and nucleons would be broken up. However, according to the current observations, this is not the fate of the Universe. Instead, the expansion will continue forever, even at an accelerating pace.

Astronomers have been making increasingly accurate measurements of two important cosmological parameters: Ho - the rate at which the universe expands - and ω - the average density of matter in the universe. Knowledge of both of these parameters will tell which of the two models describes the universe we live in, and thus the ultimate fate of our universe.

The **evolution of the stars** may lead to one of four end results: a white dwarf, a neutron star or a black hole may be formed, or the star may be completely disrupted. After about 10^{11} years, all present stars will have used up their nuclear fuel and reached one of these four final states. Some of the stars will be ejected from their galaxies; others will form a dense cluster at the centre. In about 10^{27} years the central star clusters will become so dense that a black hole is formed.

Similarly the galaxies in large clusters will collide and form very massive black holes. Not even black holes last forever. By a quantum mechanical tunneling process, mass can cross the event horizon and escape to infinity—the black hole is said to "evaporate". The rate of this phenomenon, known as the Hawking process, is inversely proportional to the mass of the hole. For a galactic-mass black hole, the evaporation time is roughly 10^{98} years. After this time, almost all black holes will have disappeared. The ever expanding space now contains black dwarfs, neutron stars and planet-size bodies. The temperature of the cosmic background radiation will have dropped to 10^{-20}K.

Even further in the future, other quantum phenomena come into play. By a tunneling process, black dwarfs can change into neutron stars and these, in turn, into black holes. In this way, all stars are turned into black holes, which will then evaporate. The time required has been estimated to be $10^{10^{26}}$ years! At the end, only radiation cooling towards absolute zero will remain. It is of course highly doubtful whether our current cosmological theories really are secure enough to allow such far reaching predictions.

Finally the state of the Universe could no longer be treated by present-day physics. It is not known whether the collapse would continue to a single point or would the Universe avoid the singularity and start a new expansion.

However new theories and observations **may completely change** our present cosmological ideas.