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Study of life cycle of Stars

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ABSTRACT

The objective of this research paper is to explore the life cycle of stars, beginning with their formation and ending with their final stages. The paper describes the various stages of a star's life, including the pre-main sequence, main sequence, red giant, planetary nebula, white dwarf, neutron star, supernova, and black hole phases. The paper also sheds light on the concept of brown dwarfs, planets and star clusters.

The Jeans instability model and the turbulence model, among other mathematical models of star formation, are discussed in the paper as well. The paper discusses the ways in which these models shed light on the physical processes, including gravitational collapse and fragmentation, that result in the formation of stars.

Finally, the paper discusses future prospects for the study of star formation and evolution. It also highlights the importance of ongoing research efforts in understanding the formation and evolution of stars, and how this research can provide insights into fundamental questions in astrophysics. Overall, this research paper provides a comprehensive overview of the life cycle of stars and the mathematical models that are used to study their formation and evolution.

Keywords: pre-main sequence, main sequence, red giant, planetary nebula, white dwarf, neutron star, supernova, black hole, Jeans instability model, turbulence model, gravitational collapse.

1. *STAR FORMATION*

A star is a bright celestial body composed of hot, glowing gases that emits energy, mainly in the form of light and heat. Stars are the fundamental components of galaxies and are essential to the universe. They are enormous plasma spheres that are held together by their own gravity. The process of star formation is a very complex process which involves the collapse of a cloud of gas and dust, known as a molecular cloud, into a dense, hot, and luminous object. The process can be divided into several key stages.

1.1. MOLECULAR CLOUD FORMATION

The process in which a large, cold and dense regions of interstellar gas and dust in galaxies come together to form molecular clouds is known as molecular cloud formation. These clouds consist of molecular hydrogen along with trace amount of carbon dioxide and water molecules and is known to be the birthplace of stars.

The formation of molecular clouds is a complex process which involves various physical mechanisms and environmental variables. Some key aspects of molecular cloud formation are:

- **Density Enhancement:** Molecular clouds tend to form in the regions of high gas density in interstellar medium. Shockwaves from supernova explosions, the compression of gas due to the gravitational pull of surrounding massive objects, or the interaction of gas with spiral density waves in galaxies can all lead to density enhancement.
- **Cooling and Radiative Processes:** With the increase of gas density, radiative cooling becomes more efficient causing the gas to cool and condense. Heavy elements and dust grains absorb and emit specific wavelengths which helps the cooling of gas. With the help of this process, gas attains lower temperatures which further favours the process of formation of molecular hydrogen and other molecules.
- **Feedback Processes:** Feedback from newly formed stars can also impact molecular cloud formation. Stellar winds, radiation pressure, and supernova explosions can scatter and shape the molecular cloud structure by adding energy and momentum to the surrounding gas. These feedback mechanisms can control the rate of star formation and have an impact on the cloud's overall evolution.

In galaxies, the production of molecular clouds is a dynamic, continuing process that takes place at various scales and under varied circumstances. For the study of star formation and the evolution of galaxies, it is essential to comprehend the mechanisms and processes underlying this formation.

1.2.GRAVITATIONAL COLLAPSE

The process by which a dense region within a molecular cloud falls under the influence of gravity, resulting in the development of a protostellar core or a cluster of protostars, is known as gravitational collapse of a molecular cloud. The gravitational attraction between the cloud's gas and dust particles causes this collapse to take place.

1.2.1. CONDITION FOR GRAVITATION COLLAPSE

We can derive the condition for gravitational collapse of a molecular which will form stars using virial theorem.

Statement of virial theorem: Let us consider a system of N interacting particles, that has attained dynamical equilibrium through inverse square central force interactions. For such a system 2T+V=0,

Where T is the total translational Kinetic Energy of such a system and Vis the potential energy [1].

Derivation of the condition:

From virial theorem we know that:

$$2T = -V \text{ -----------(1)}$$

Consider a spherical cloud of gas with mass M, radius R, and uniform density ρ.

The total kinetic energy of the gas cloud is the sum of the kinetic energies of individual gas particles:

$$K = \frac{3}{2} NK_BT \text{ -------- (2)}$$

Where, N is the total number of gas particles,

K_B is the Boltzmann constant,

and T is the temperature of the gas cloud.

The gravitational potential energy of the gas cloud is given by:

$$V = -\frac{3}{5}\frac{GM^2}{R} \text{ ------------ (3)}$$

Where G is the gravitational constant.

Putting (2) and (3) in equation (1) we get

$$3NK_BT = \frac{3}{5}\frac{GM^2}{R} \text{ - ----(4)}$$

From equation (4) we can say that if the equality holds then the system is in virial equilibrium [1]. Moreover, if the LHS is bigger that means the kinetic energy is more than gravitational energy which means the molecular cloud will expand [1].

On the contrary, if the RHS is bigger the cloud will collapse.

So, the condition for the gravitational becomes,

$$3NK_BT < \frac{3}{5}\frac{GM^2}{R} \text{ ---------- (5)}$$

Putting the value of N and R as

$$N = \frac{M}{\mu m_H} \text{--------(6)}, \; R = \left(\frac{3M}{4n}\right)^{\frac{1}{3}} \text{ ----------- (7)}$$

$$3\left(\frac{M}{\mu m_H}\right) K_B T = \frac{3}{5} GM^2 \left(\frac{4\pi\rho}{3M}\right)^{\frac{1}{3}}$$

After solving the above equation, we get:

$$M > \left(\frac{5k_BT}{G\mu m_H}\right)^{\frac{3}{2}} \left(\frac{3}{4\pi\rho}\right)^{\frac{1}{2}}$$

$$M > M_{\square}$$

$$\text{Where } M_J \text{ is } \left(\frac{5\square\square\square}{G\mu m_H}\right)^{\frac{3}{2}} \left(\frac{3}{4n\square}\right)^{\frac{1}{2}}$$

M_J is also known as jeans mass.

Cloud collapse will only take place if the mass of the cloud is greater than Jeans mass.

Jeans mass depends on the temperature and the density of the cloud.

Now, as a molecular cloud breaks up, it heats up, and tiny pockets of gas and dust inside the cloud start to disintegrate due to gravity. These tiny pockets are known as prestellar cores, are the precursors to stars.

1.3.FORMATION OF A PROTO STAR

Proto-stars are the precursors to stars, and their formation occurs through a process known as protostar formation. This process begins when a cloud of gas and dust, called a molecular cloud, becomes dense enough to collapse under its own gravitational pull.

As the cloud collapses, it begins to spin faster and faster, flattening into a disk-like shape. At the centre of this disk, the density increases further, forming a dense core that eventually becomes a protostar.

The protostar begins to grow as more material from the surrounding disk falls onto it, causing it to heat up and become increasingly luminous. At this point, it is not yet a true star, as it is not generating energy through nuclear fusion in its core.

As the protostar continues to accrete material, it eventually reaches a critical point where the temperature and pressure in its core become high enough to initiate nuclear fusion, at which point it becomes a full-fledged star.

The process of protostar formation is a critical stage in the evolution of stars, and understanding it is key to understanding the formation and evolution of galaxies as a whole.

1.4. ACCRETION DISK

An accretion disk is a structure formed around a central object, such as a star or a black hole, when material from its surroundings is pulled in by gravity. In the context of star formation, accretion disks are a crucial component in the process of forming protostars from molecular clouds.

When a molecular cloud collapses, it forms a rotating disk-like structure, with the majority of the mass concentrated in the center. As material falls towards the center of the disk, it gains kinetic energy, causing it to heat up and emit radiation. This radiation is what makes the protostar visible, and it provides the energy needed to counteract the force of gravity and prevent the protostar from collapsing further.

The material in the accretion disk is also thought to play a role in regulating the formation of the protostar, by transporting angular momentum away from the center and allowing material to fall towards the protostar at a steady rate. This is important, as if the material were to fall onto the protostar too quickly, it would overheat and disintegrate before it could form a stable star.

In addition, the accretion disk can also influence the formation of planets around the star, by providing a reservoir of material from which they can form. As the material in the disk coalesces into planetesimals, these objects can collide and stick together to form larger and larger bodies, eventually leading to the formation of planets.

Overall, accretion disks play a critical role in the process of star formation, and studying them can provide valuable insight into the physical processes that govern the formation and evolution of stars and planetary systems.

1.5. MAIN SEQUENCE STARS

A main sequence star is a star that is fusing hydrogen in its core to form helium, and it is the longest and most stable phase of a star's life cycle. In terms of star formation, the main sequence is the final stage in the process of forming a star.

As a protostar continues to accrete material from its surrounding disk, its core temperature and pressure increase until it reaches a point where nuclear fusion reactions can begin. At this point, the protostar becomes a true star and enters the main sequence phase.

The length of time that a star spends on the main sequence is determined by its mass, with more massive stars having shorter main sequence lifetimes. During this phase, a star's energy is primarily generated through the fusion of hydrogen into helium in its core, and the energy produced is what causes the star to shine.

As the star ages and runs out of hydrogen fuel in its core, it will eventually begin to evolve off of the main sequence, entering a new phase of its life cycle. This can result in a wide range of outcomes, depending on the star's mass, and can include the formation of a white dwarf, neutron star, or black hole, among other possibilities.

The study of main sequence stars is important in understanding the formation and evolution of galaxies, as the properties of these stars can be used to determine their ages and distances. By studying the main sequence and other phases of a star's life cycle, astronomers can gain insight into the physical processes that govern the formation and evolution of stars, and ultimately the structure and evolution of the universe as a whole.

1.6. FACTORS INFLUENCING STAR FORMATION

Star formation is a complex process that is influenced by a variety of factors, including:

Gravity: Gravity is the primary force that drives the collapse of molecular clouds and the formation of protostars. As the cloud collapses, its material becomes more densely packed and gravitational forces become stronger, leading to further collapse and the formation of a protostar.

Pressure: As a molecular cloud collapses, it also heats up due to the compression of its material. This increase in temperature causes the gas pressure within the cloud to increase, which can counteract the force of gravity and slow down the collapse process.

Magnetic fields: Magnetic fields can also play a role in regulating the collapse of molecular clouds and the formation of protostars. These fields can help to support the cloud against gravitational collapse, and can also influence the orientation and rotation of the protostar as it forms.

Turbulence: Molecular clouds are often turbulent, with gas and dust swirling around chaotically. This turbulence can create regions of higher density within the cloud, which can then collapse under the influence of gravity to form protostars.

Feedback: As a protostar forms, it begins to emit radiation and stellar winds that can interact with its surrounding material, heating it up and potentially halting further collapse. This feedback can also trigger the formation of new stars in neighbouring regions of the molecular cloud.

Chemical composition: The chemical composition of the molecular cloud can also influence the formation of stars, as different elements can affect the opacity and cooling of the cloud, as well as the rates of chemical reactions that occur during star formation.

Overall, star formation is a complex and dynamic process that is influenced by a variety of physical and chemical factors, and understanding these factors is crucial for developing a complete picture of how stars form and evolve.

1.7. MATHEMATICAL MODELS OF STAR FORMATION

There are several mathematical models that have been proposed to explain different aspects of star formation. Here is a chronology of some of the key models and their contributions:

- Bonnor-Ebert Model (1956): The Bonnor-Ebert model describes the equilibrium structure of a self-gravitating, isothermal gas sphere. This model is often used to study the stability of molecular clouds and the conditions required for gravitational collapse to occur.

- Shu Model (1977): The Shu model describes the formation of a protostar from a molecular cloud. It proposes that a rotating, collapsing cloud will form a disk-like structure around a central protostar, with material accreting onto the protostar from the disk.
- Larson's Relations (1981): Larson's relations describe empirical relationships between the size, mass, and velocity dispersion of molecular clouds. These relations have been used to study the properties of molecular clouds and their role in star formation.
- McKee & Ostriker Model (2007): The McKee & Ostriker model describes the formation of massive stars in regions of high gas pressure and temperature, such as the centers of molecular clouds. It proposes that these stars form through the rapid accretion of material from a dense, turbulent gas cloud.
- Bate & Bonnell Model (2005): The Bate & Bonnell model describes the formation of multiple stars within a single molecular cloud core. It proposes that these stars form through the fragmentation of the core, with each fragment collapsing and forming a separate protostar.
- Turbulent Core Model (2010): The turbulent core model describes the formation of massive stars in turbulent molecular clouds. It proposes that the turbulent motions within the cloud can create regions of high density that are prone to collapse, leading to the formation of massive stars.

These models represent a sampling of the many different approaches that have been taken to understanding star formation, and each one provides valuable insight into the complex physical processes involved. While there is still much to be learned about the formation and evolution of stars, these models continue to inform our understanding of this fundamental aspect of the universe.

1.8. STAR FORMATION THEORIES

There are several star formation theories that have been proposed to explain the process by which stars are born. Here are some of the main ones:

- Gravitational Collapse Theory: This theory proposes that stars form from the gravitational collapse of a dense cloud of gas and dust, called a molecular cloud. As the cloud collapses under its own gravity, it heats up and becomes denser, eventually forming a protostar at the centre of the cloud.
- Turbulent Fragmentation Theory: This theory proposes that the turbulence within a molecular cloud can cause it to fragment into smaller, dense cores that collapse to form protostars. These cores are held together by a combination of gravity and turbulence, and they can accrete material from the surrounding cloud to grow into full-fledged stars.
- Magnetic Field Theory: This theory proposes that magnetic fields play an important role in the formation of stars. It suggests that magnetic fields can help to regulate the collapse of molecular clouds by providing additional support against gravity. The magnetic fields can also influence the rotation and orientation of the protostar as it forms.
- Competitive Accretion Theory: This theory proposes that protostars

compete for material as they accrete gas and dust from the surrounding cloud. The more massive protostars are able to accrete material more quickly, giving them an advantage in the competition. This can lead to the formation of multiple stars in close proximity to each other.

- Disk Instability Theory: This theory proposes that stars can form directly from the fragmentation of a rotating disk of gas and dust. As the disk becomes more massive and unstable, it can fragment into smaller clumps that collapse to form protostars.
- Colliding Clouds Theory: This theory proposes that stars can form when two or more molecular clouds collide and merge. The shock waves created by the collision can trigger the collapse of dense regions within the clouds, leading to the formation of protostars.

These theories represent some of the main approaches that have been taken to understanding star formation. While each theory has its own strengths and weaknesses, together they provide a comprehensive picture of the complex physical processes involved in the birth of stars.

2. *PLANETARY NEBULA*

Planetary nebulae are not directly related to the formation of stars, but rather represent the final stage in the evolution of certain types of stars. When a star similar in size to our sun runs out of fuel and can no longer maintain fusion reactions in its core, it undergoes a series of transformations that ultimately result in the formation of a planetary nebula.

Figure 1 X-ray/optical composite image of the Cat's Eye Nebula (NGC 6543)

During this transformation, the star sheds its outer layers of gas and dust into space, creating a glowing shell of ionized gas around a small, hot core known as a white dwarf. The ionization of this gas causes it to emit light, which can be observed as the colourful, swirling patterns characteristic of planetary nebulae.

While the formation of planetary nebulae is not directly related to the formation of stars, they do provide important insight into the life cycle of stars and the chemical processes that occur during their evolution. For example, the elements that make up the gas and dust in planetary nebulae are the same elements that are formed inside stars, which are then recycled back into the interstellar medium to form new stars and planetary systems. Therefore, studying planetary nebulae helps us better understand the chemical history of the universe and the processes that govern the formation and evolution of stars and galaxies.

3.0. WHITE DWARF

White dwarfs are stellar remnants that represent the final evolutionary stage of low to intermediate mass stars, including our Sun. They are extremely compact and dense objects, usually the size of the Earth but with masses similar to the Sun. Electron degeneracy pressure protects white dwarfs from gravitational collapse since they are predominantly made of electron-degenerate materials.

3.1. FORMATION

A main sequence star of low to medium mass (0.5-8 Mo) will develop to become a red giant during which time it will fuse helium to carbon and oxygen in its core through the "triple alpha" process once the hydrogen fusing era has ended. A carbon and oxygen inert mass will accumulate at the centre of a red giant if it lacks the mass to create the core temperature of $1*10^9$ K, necessary to fuse carbon. Following that, a star of that type sheds its outer shell and creates a planetary nebula. It leaves behind a core which is remnant white dwarf.

For an understanding of star evolution, as well as their function in cosmology and the study of astrophysical phenomena, it is essential to appreciate the characteristics and formation of white dwarfs.

3.2. PROPERTIES OF WHITE DWARFS

Mass and size: White dwarfs have masses ranging from 0.1 to 1.4 times that of the Sun. Despite their large size, they are extremely compact. A white dwarf's average radius is similar to the size of the Earth, making them incredibly dense.

Composition: White dwarfs are mostly made of carbon and oxygen, which are by-products of nuclear fusion processes that happened during the star's main sequence phase. White dwarfs may contain traces of helium, hydrogen, and heavier elements in certain circumstances.

Surface Temperature: White dwarfs have extremely hot surfaces, with temperatures ranging from 5,000 to 30,000 Kelvin. However, they ultimately cool down over billions of years as they age.

Luminosity: White dwarfs give forth light and heat that they have been holding onto from earlier periods of existence. As they cool, their luminosity diminishes over time. White dwarfs in their youth are still rather bright, but as they age, they get fainter.

Density: White dwarfs have an astronomically high density, with an average density of around 1 ton per cubic centimetre. This high-density results from the star material being compressed during the last stages of stellar evolution.

3.3. MASS AND RADIUS RELATION FOR WHITE DWARFS

The mass-radius relation explains the relationship between a white dwarf's mass and size. White dwarfs are protected against gravitational collapse by electron degeneracy pressure, in accordance with the theory of stellar structure. Accordingly, the Pauli exclusion principle's application prevents electrons from being crushed into the same quantum state, which is where the pressure originates.

As more mass is added to a white dwarf, its radius decreases. This is because the increased mass leads to a stronger gravitational force, which compresses the electrons more tightly. As a result, the white dwarf shrinks in size and becomes denser. Therefore, the mass-radius relation of white dwarfs is inversely related - higher mass corresponds to smaller radius, and vice versa.

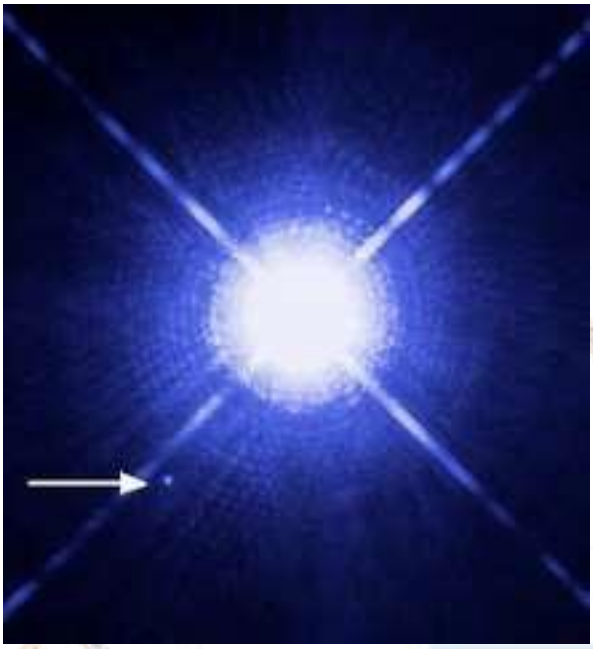

Figure 2 Sirius A and Sirius B by Hubble Telescope where Sirius B is a white dwarf

In order to research the evolution and characteristics of white dwarfs, it is essential to comprehend the mass-radius ratio since it sheds light on their interior structure, chemical composition, and the equation of state guiding their behaviour. It also advances our knowledge of the stellar life cycles by validating and enhancing theoretical models of stellar evolution and white dwarf formation.

Derivation:

$$(\Delta x)(\Delta p) \sim \hbar \text{-----------} (1)$$

Δx is the average distance between electrons.

$$\Delta x \approx n^{-\frac{1}{3}} \text{--------------------} (2)$$

$$(\Delta p) \sim \frac{\hbar}{\text{Llx}} \sim \hbar n \quad ^{1}\ {}_{3}$$

Squaring both sides

$$(\Delta p)^2 \sim \hbar^2 n^{\frac{2}{3}} \text{-------------} (3)$$

Kinetic energy per unit mass is:

$$E_k = \frac{Np^2}{2m} = \frac{N(\text{Llp})^2}{2m}$$

Putting the value of $(\Delta p)^2$ in the above equation

$$E_k \sim \frac{N\square\hbar^2\square^{\frac{2}{3}}\square}{2m} \text{---------} (4)$$

N is the number of electrons per unit mass. In a white dwarf there are N.M electrons.

$$n = \frac{N \cdot M}{R^3} \text{--------} (5) \text{ where } R^3 \text{ is the volume.}$$

Putting (5) in (4)

$$E_k \sim \frac{N \cdot \hbar^2}{2m} \cdot \frac{N^{\frac{2}{3}} M^{\frac{2}{3}}}{R^2}$$

$$E_k \sim \frac{N^{\frac{5}{3}} M^{\frac{2}{3}} \hbar^2}{2mR^2} \text{-------} (6)$$

Gravitational energy per unit mass

$$jE_g j \approx \frac{GM}{R} \text{---------} (7)$$

Under equilibrium $E_K = E_g$

$$\frac{GM}{R} \sim \frac{N^{\frac{5}{3}} M^{\frac{2}{3}} \hbar^2}{2mR^2}$$

$$R \sim \frac{N^{\frac{5}{3}} \hbar^2}{2mGM^{\frac{1}{3}}}$$

$$R \propto \frac{1}{M^{\frac{1}{3}}}$$

4.0 SUPERNOVA

Supernovae are an important aspect of star formation as they play a crucial role in shaping the evolution of galaxies and the chemical enrichment of the Universe.

When a massive star, typically at least eight times the mass of the Sun, reaches the end of its life cycle, it will undergo a catastrophic explosion known as a supernova. During this explosion, the star's core collapses under its own gravity, triggering a massive release of energy and ejecting the star's outer layers into space.

The energy released by a supernova can have a profound impact on the surrounding environment, triggering the formation of new stars and shaping the structure of the galaxy. The shockwave from the supernova can compress nearby gas and dust clouds, creating regions of high density that are conducive to the formation of new stars. The heavy elements produced by the supernova explosion are also dispersed into the surrounding interstellar medium, enriching it with new material that can be incorporated into future generations of stars.

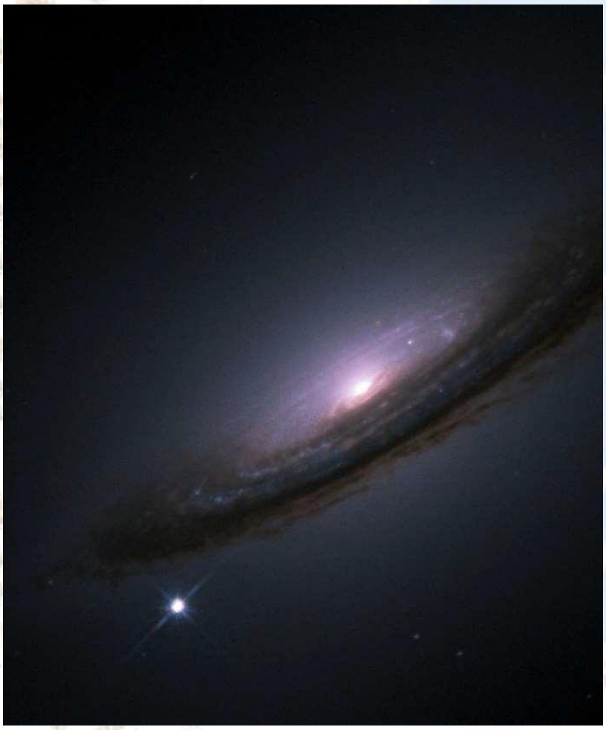

Figure 3 SN 1994D (bright spot on the lower left), a type Ia supernova within its host galaxy, NGC 4526

Supernovae can also have a significant impact on the overall rate of star formation within a galaxy. The energy released by a supernova can heat and disperse the surrounding gas, slowing down the rate of star formation. However, in some cases, the shockwave from a supernova can trigger the collapse of nearby gas clouds, leading to a burst of new star formation.

5.0 NEUTRON STAR

Neutron stars are one of the possible end products of the star formation process. They are extremely dense objects that form when a massive star collapses under its own gravity at the end of its life cycle, typically in a supernova explosion.

During the collapse, the protons and electrons in the star's core are squeezed together so tightly that they combine to form neutrons, which pack together even more tightly. The result is a compact object with a diameter of only about 10-20 kilometers, but a mass that can be up to twice that of the Sun.

The formation of neutron stars is a significant outcome of star formation because they can have a profound impact on their surrounding environment. The intense gravitational fields of neutron stars can cause them to spin rapidly, emitting beams of radiation that can be observed as pulsars. These pulsars can provide important clues about the nature of matter at extremely high densities.

Neutron stars can also have a significant effect on the star formation process itself. The intense gravitational fields of neutron stars can disrupt nearby gas and dust clouds, triggering the formation of new stars. They can also generate powerful winds that sweep away surrounding material, regulating the rate at which stars form.

Figure 4 A computer simulation depicting a neutron star with accretion disk, spewing out X-rays through the magnetic axis. Source: https://images.nasa.gov/details/PIA18845

Moreover, neutron stars can be involved in the formation of black holes. If a neutron star is part of a binary system with another star, it can accrete matter from its companion star, gradually increasing in mass until it reaches a critical point where it collapses to form a black hole.

6.0 BROWN DWARF

Brown dwarfs are objects that form during the star formation process, but are not massive enough to ignite nuclear fusion in their cores and become fully-fledged stars. They are often referred to as "failed stars" because they are too small to sustain the fusion reactions that power stars like the Sun.

Brown dwarfs form in a similar way to stars, from the gravitational collapse of a cloud of gas and dust. However, their mass is limited by the fact that they cannot generate enough heat and pressure in their cores to ignite the nuclear reactions that power stars. Instead, they slowly cool over time, gradually fading away.

The study of brown dwarfs is important for our understanding of the star formation process because they represent an intermediate stage between planets and stars. They are typically much more massive than planets, but much less massive than stars, and have properties that bridge the gap between the two.

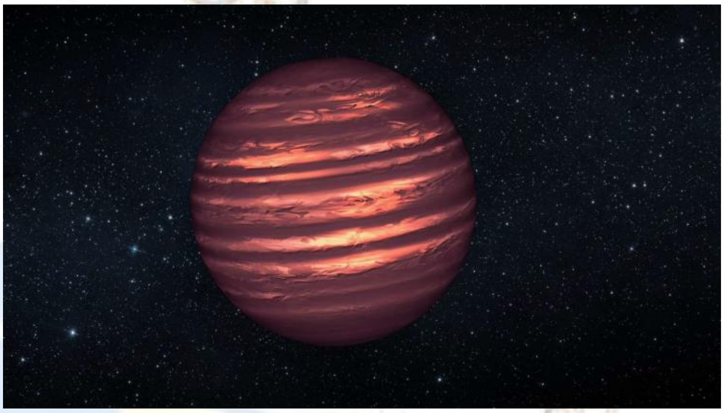

Figure 5 Artist's concept of a T-type brown dwarf. Source: http://planetquest.jpl.nasa.gov/image/114

Brown dwarfs can also have a significant impact on the surrounding environment. Like stars, they can generate powerful winds and magnetic fields that can shape their surroundings. They can also be involved in the formation of planetary systems, either as companions to stars or as isolated objects.

The discovery of brown dwarfs has also provided new insights into the distribution of matter in the Universe. It is estimated that brown dwarfs may be as numerous as stars, but because they are much fainter and harder to detect, they have only been discovered relatively recently.

7.0 H-R DIAGRAM

The Hertzsprung-Russell (HR) diagram is a graphical representation of stars that plots their luminosity (or absolute magnitude) versus their temperature (or color index). It was first developed by the Danish astronomer Ejnar Hertzsprung and the American astronomer Henry Norris Russell in the early 20th century. The HR diagram is a powerful tool for understanding the properties and evolution of stars.

The vertical axis of the HR diagram represents the luminosity of a star, which is a measure of the total amount of energy it emits per second. The luminosity is typically expressed in terms of the absolute magnitude, which is the magnitude a star would have if it were placed at a distance of 10 parsecs (about 32.6 light-years) from Earth. The more luminous a star, the higher it is on the vertical axis.

The horizontal axis of the HR diagram represents the temperature of a star, which is a measure of the surface temperature of the star. The temperature is typically expressed in terms of the color index, which is the difference in magnitude between a star in the visual (V) band and a star in the ultraviolet (U) band. The hotter a star, the more to the right it is on the horizontal axis.

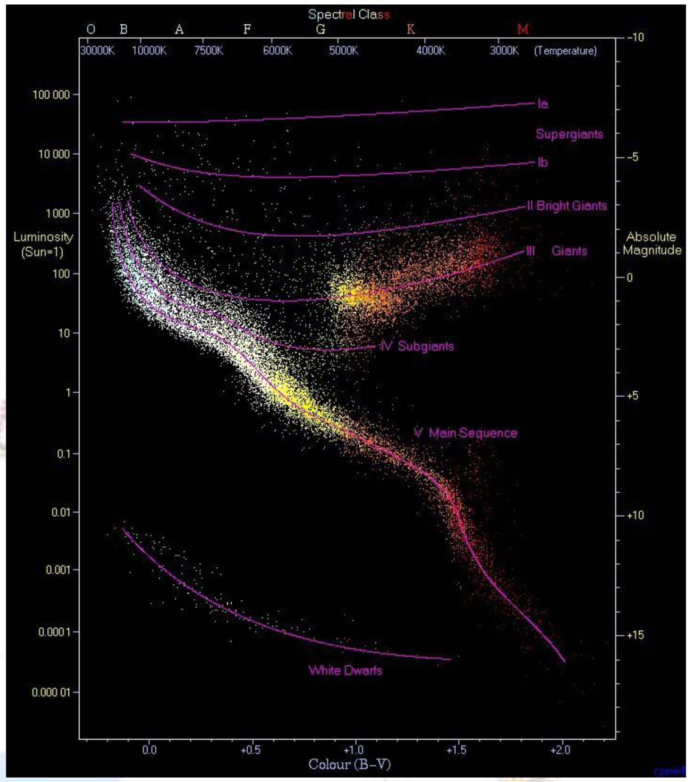

Figure 6 An observational Hertzsprung–Russell diagram with 22,000 stars plotted from the Hipparcos Catalogue and 1,000 from the Gliese Catalogue of nearby stars. Source: http://www.atlasoftheuniverse.com/hr.html

The HR diagram can be used to understand the properties and evolution of stars. When stars are plotted on the HR diagram, they form a distinct pattern that is divided into several regions. The main regions of the HR diagram include:

1. The Main Sequence: The main sequence is a diagonal band that runs from the upper left corner of the HR diagram to the lower right corner. It represents stars that are in the process of burning hydrogen in their cores to form helium. The majority of stars in the universe are located in the main sequence, and their luminosity and temperature are determined by their mass.
2. Giants and Supergiants: These are stars that have exhausted the hydrogen in their cores and have begun to fuse helium. They have expanded and cooled, causing their

surface temperatures to decrease while their luminosities increase. Giants and supergiants are found in the upper right corner of the HR diagram.

3. White Dwarfs: These are the remnants of stars that have exhausted their nuclear fuel and have shed their outer layers. They are small and extremely dense, with surface temperatures that can exceed 100,000 K. White dwarfs are located in the lower left corner of the HR diagram.
4. Subgiants: These are stars that are transitioning from the main sequence to the giant phase. They have begun to exhaust the hydrogen in their cores and have expanded slightly, causing their luminosities to increase while their surface temperatures decrease.
5. T Tauri Stars: These are very young, low-mass stars that have not yet reached the main sequence. They are located in the lower right corner of the HR diagram, and are characterized by their strong magnetic fields and intense stellar winds.

The different regions of the HR diagram are important because they provide information about the physical properties and evolutionary stages of stars. By studying the positions of stars in the HR diagram, astronomers can learn about their ages, masses, chemical compositions, and other important properties.

8.0 STELLAR CLASSIFICATION

The most commonly used system for stellar classification is the Morgan-Keenan (MK) system, which uses a combination of spectral type and luminosity class to categorize stars. Spectral type is determined by the star's surface temperature and the resulting colors and spectral lines that are observed in its spectrum, while luminosity class is determined by the star's brightness and size.

The MK system classifies stars into seven main spectral types, labeled with the letters O, B, A, F, G, K, and M. These spectral types are further divided into subtypes based on the presence and strength of specific spectral lines, with the subtypes labeled with numbers from 0 to 9.

Luminosity class is denoted by a Roman numeral, ranging from I to V, with I indicating a supergiant star, II indicating a bright giant star, III indicating a giant star, IV indicating a subgiant star, and V indicating a main-sequence star. There are also additional luminosity classes for stars that are in transition between these stages or have unusual characteristics.

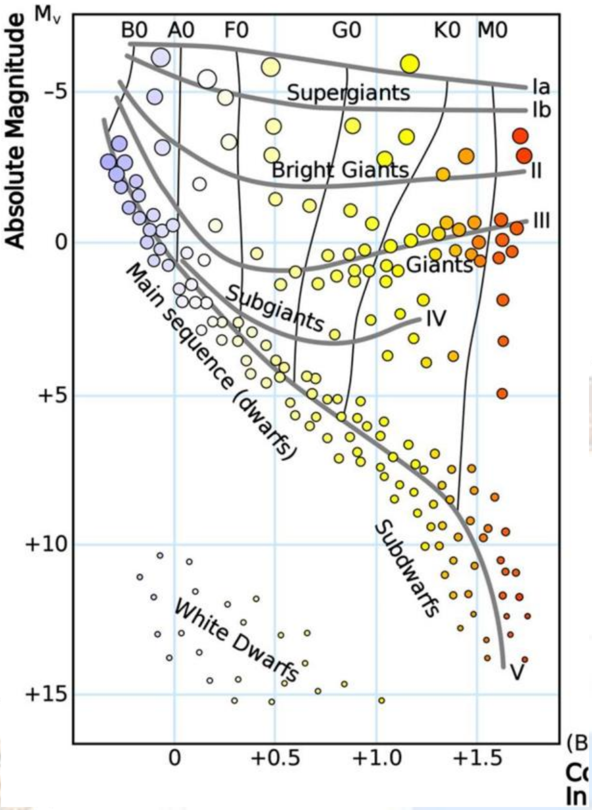

Figure 7 The Hertzsprung–Russell diagram relates stellar classification with absolute magnitude, luminosity, and surface temperature. Source: RurSus/Wiki

Stellar classification is important for understanding the properties and behavior of stars, as well as their evolution and the processes that occur within them. By categorizing stars based on their observed characteristics, astronomers can study their physical properties and compare them to theoretical models, allowing them to gain insights into the workings of the Universe.

CLASSIFICATION	**TEFF (K)**
O	≥30,000
B	10,000-30,000
A	7,500-10,000
F	6,000-7,500
G	5,200-6,000
K	3,700-5,200
M	2,400-3,700

Table 01 Effective temperature of stars according to their classification.

9.0 CURRENT RESEARCH PROJECTS ON STAR FORMATION

1. The establishment of the National Centre for Radio Astrophysics (NCRA) in Pune, India. NCRA is a premier research institution that focuses on the study of radio astronomy, including the study of star-forming regions.
2. The Indian Giant Metrewave Radio Telescope (GMRT) is one of the largest radio telescopes in the world and is used to study the properties of star-forming regions. It is operated by the NCRA and the Tata Institute of Fundamental Research.
3. The Indian Institute of Astrophysics (IIA) in Bangalore is a premier research institution that focuses on the study of astronomy and astrophysics. Research at the IIA includes the study of star formation, including the properties of prestellar cores, protostars, and protoplanetary disks.
4. Max Planck Institute for Astronomy (MPIA) in Germany: The MPIA conducts research on a wide range of topics related to star formation, including the properties of prestellar cores, the formation of protoplanetary disks, and the mechanisms of outflow and jet formation.
5. Harvard-Smithsonian Center for Astrophysics (CfA) in the United States: The CfA conducts research on the formation and evolution of stars, including the study of protostars and T Tauri stars, the properties of protoplanetary disks, and the formation of planetary systems.

6. Institute of Astrophysics and Space Sciences (IA) in Portugal: The IA conducts research on the formation and evolution of stars and planetary systems, with a focus on the study of protostars and T Tauri stars, the properties of protoplanetary disks, and the formation of planetary systems.
7. Centre de Recherche Astrophysique de Lyon (CRAL) in France: CRAL conducts research on the formation and evolution of stars and planetary systems, with a focus on the study of protostars and T Tauri stars, the properties of protoplanetary disks, and the formation of planetary systems.
8. Australian National University (ANU) in Australia: ANU conducts research on the formation and evolution of stars, including the study of protostars, the properties of protoplanetary disks, and the formation of planetary systems.
9. The University of Arizona's Steward Observatory in the United States: The Steward Observatory conducts research on the formation and evolution of stars, including the study of protostars, the properties of protoplanetary disks, and the formation of planetary systems.

10.0 *FUTURE PROSPECTS IN THE AREA*

i. **The study of low-mass star formation:** While much is known about the formation of high-mass stars, relatively little is known about the formation of low-mass stars. Future research in this area is likely to focus on understanding the properties of prestellar cores and the physical processes that lead to the formation of low-mass protostars.

ii. **The study of the initial mass function:** The initial mass function (IMF) describes the distribution of masses of stars that form in a given region. Understanding the IMF is important for understanding the properties of star-forming regions and the formation of planetary systems. Future research in this area is likely to focus on understanding the physical processes that shape the IMF and how the IMF varies in different types of star-forming regions.

iii. **The study of protoplanetary disks:** Protoplanetary disks are the sites of planet formation, and understanding their properties and the processes that lead to the formation of planets is a key area of research. Future research in this area is likely to focus on understanding the properties of disks around low-mass stars, the mechanisms of planet formation, and the properties of exoplanets.

iv. **The study of the role of magnetic fields in star formation:** Magnetic fields are known to play an important role in the formation of stars, but the details of how they regulate the accretion of material onto protostars and the formation of outflows and jets are not well understood. Future research in this area is likely to focus on understanding the properties of magnetic fields in star-forming regions and how they influence the star formation process.

v. **The study of high-redshift star formation:** The study of star formation in the early universe is important for understanding the formation and evolution of galaxies. Future research in this area is likely to focus on using the next generation of telescopes and instruments to study the properties of high-redshift star-forming regions and the mechanisms of star formation in the early universe.

vi. **The study of the impact of nearby supernovae on star formation:** Supernovae are known to have a significant impact on the formation of stars, by triggering the collapse of molecular clouds, and creating new stars. Future research in this area is likely to focus on understanding the physical processes that lead to the formation of stars in the wake of a supernova.

11.0 *KEY TERMS AND COMMON DATA POINTS USED FOR STAR FORMATION*

i. *Interstellar medium (ISM):* The gas and dust that exists between the stars in a galaxy. The ISM is the material from which stars form.

ii. *Molecular cloud:* A dense region of the ISM where molecules such as CO, H2, NH3 are observed. These clouds are the sites of active star formation.

iii. *Prestellar core:* A dense and cold region of a molecular cloud that is on the verge of collapsing to form a new star.

iv. *Protostar:* A young star that is still in the process of forming. A protostar is surrounded by a protoplanetary disk, which is a disk of gas and dust that will eventually form planets.

v. *Accretion:* The process of material falling onto a protostar and adding to its mass. Accretion is a key process in the formation of a star.

vi. *Outflow:* The material that is being expelled from a protostar. Outflows play an important role in the regulation of the accretion process and the regulation of the angular momentum of the protostar.

vii. *T Tauri star:* A type of young star that is still in the process of contracting to become a main-sequence star. T Tauri stars are characterized by their strong magnetic fields, variable luminosity, and high levels of accretion.

viii. *Protoplanetary disk:* A disk of gas and dust that surrounds protostars, it is thought to be the birthplace of planets.

ix. *Jeans instability:* A physical instability that leads to the collapse of dense regions of gas and dust to form new stars.

x. *Magnetic fields:* The presence of magnetic fields play a crucial role in the star formation process, by influencing the dynamics and stability of the molecular cloud, the collimation of outflows and the angular momentum of the protostars.

xi. *Hertzsprung-Russell diagram:* A graph that plots the luminosity of stars versus their surface temperature, it is used to study the properties of stars and understand their evolution.

xii. *Star formation rate (SFR):* The rate at which new stars are forming in a galaxy or a specific region of a galaxy.

xiii. *Spectral line data:* This data is used to measure the properties of the gas and dust in star-forming regions, including the density, temperature, and chemical composition of the material.

xiv. *Continuum data:* This data is used to measure the properties of the dust in star-forming regions, including the temperature and density of the dust.

xv. I*maging data:* This data is used to study the distribution and properties of the gas and dust in star-forming regions, as well as the properties of the young stars themselves.

xvi. *Polarization data:* This data is used to study the magnetic fields in star-forming regions and the role that these fields play in the star formation process.

xvii. *Kinematic data:* This data is used to study the motions of the gas and dust in star-forming regions, including the velocities and accelerations of the material.

xviii. *Light curve data:* This data is used to study the variability of young stars, including the properties of their outflows and jets.

xix. *Photometric data:* This data is used to study the properties of the young stars, including their luminosity, temperature, and colour.

REFERENCES:

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