International Journal for Multidisciplinary Research (IJFMR)
E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

# Formation and Evolution of Special Stellar Types: A Comprehensive Study of Special Stars.

**Anupam Das[1], Baibhab Ghosh[2]**

Undergrad Students, Department of Physics, Kokrajhar, Government College, Kokrajhar, Assam, India

**Abstract:** This article presents a comprehensive study of the formation, evolution, and distinctive characteristics of special stellar types, including protostars, super-giants, pulsars, red giants, etc. By exploring the life cycles of these stars, we gain a deeper understanding of the nuclear reactions, gravitational influences, and electromagnetic spectra that govern their development and eventual demise. Through a synthesis of observational data, theoretical models, and recent advancements in astrophysics, this research aims to elucidate the intricate processes driving the life cycles of these stellar phenomena. The findings contribute to the broader knowledge of stellar dynamics, offering insights into the mechanisms of stellar evolution and the fundamental forces shaping our universe.

**Index Terms:** [2] Binary Stars, [3] Pulsars, [4] Redgaints, [5] White Dwarfs, [6] Neutron Stars.

## 1. Introduction

### 1.1 HISTORICAL BACKGROUND

The study of stellar formation and evolution has been a central focus of astrophysics for centuries, tracing its origins back to early night sky observations by ancient civilizations. Ancient astronomers, such as the Indus, Babylonians, Greeks, and Chinese, meticulously recorded the positions and movements of stars, laying the groundwork for future astronomical studies. In the early 20th century, the field of astrophysics began to take shape with the advent of modern telescopes and spectroscopy. The pioneering work of astronomers such as Ejnar Hertzsprung and Henry Norris Russell led to the development of the Hertzsprung-Russell (H-R) diagram, a pivotal tool in understanding stellar evolution. The H-R diagram revealed the relationship between a star's luminosity and its temperature, providing insights into the various stages of stellar life cycles.

The mid-20th century saw significant advancements in our understanding of nuclear and thermal processes within stars. The discovery of various stellar types further expanded our knowledge. Protostars[7], identified through infrared observations, represented the early stages of star formation, offering a glimpse into the birth of stars from interstellar gas clouds and ultimately interstellar medium. The identification of super-giants, pulsars[2], and red-giants added to the complexity of stellar classification, each type exhibiting unique characteristics and life cycles.

The discovery of pulsars in the 1960s by Jocelyn Bell Burnell and Antony Hewish marked a significant milestone. These rapidly rotating neutron stars, emitting beams of electromagnetic radiation, provided crucial evidence for the existence of neutron stars and opened a new path of research in high-energy astrophysics. In recent decades, the synthesis of observational data and theoretical advancements has deepened our understanding of stellar dynamics.

### 1.2 WHAT ARE STELLAR OBJECTS AND MASSES?

As there are stars with different luminosities, different masses, and sizes, the Sun is a G-type Dwarf (i.e. yellow dwarf with surface temperatures of 5,000–6,000 K). Many types of stars are bigger than the Sun and also smaller than the Sun. Generally, stars are divided into two categories with their population criteria- Population I type and Population II type. Population I stars are younger stars like our Sun, found in the disk of the galaxy that contain lots of atoms heavier than helium (metals) and Population II stars are older metal-poor stars found in a galaxy's nuclear bulge, halo, and globular clusters. Population I stars are formed from the debris of the explosion of Population II stars. While photographing the Andromeda galaxy, Walter Baade discovered older stars in the core and younger stars in the spiral arms of the galaxy.

## 2. Binary Star System:

As per our understanding, we can say that Binary stars are pairs of stars that orbit around a common centre of mass, gravitationally bound to each other. These systems may seem very simple and common but also critical to our understanding of stellar dynamics, evolution, and the broader mechanics of the universe. The study of binary stars provides crucial insights into the mass, size, and composition of stars, as well as the mechanics of their formation and evolution. Binary stars come in various configurations, ranging from wide pairs with orbits spanning thousands of astronomical units to close pairs where the stars are nearly touching, Yesss!!! Touching. The classification of binary stars includes visual binaries, spectroscopic binaries, and eclipsing binaries. Visual binaries are those that can be resolved into two separate stars through a telescope, i.e. you can see with your telescope and recognize the set of stars is binary. Spectroscopic binaries are identified through their spectral lines, which shift due to the Doppler effect* as the stars move toward or away from the observer (Blue-Shift or Red-Shift, respectively). Eclipsing binaries are complex systems where the orbital plane lies along the line of sight to the observer, causing periodic dimming as one star passes in front of the other.

The study of binary stars has a rich history dating back to the early 19th century when astronomers like William Herschel and Friedrich Bessel began systematic observations. Bessel's analysis of the proper motion of Sirius led to the eventual discovery of its faint companion: Sirius B, a white dwarf which is described in the later chapter by my co-author. This discovery was pivotal in establishing the concept of binary star systems and their importance in astrophysics. Why do we study the Binary system of stars? Well, binary stars play a crucial role in the measurement of stellar masses. By observing the orbital motion of binary stars and applying Kepler's laws of motion, we can determine the masses of the constituent stars with high precision. This information is vital for testing theories of stellar structure and evolution. Furthermore, binary stars are essential for understanding phenomena such as mass transfer, tidal interactions, and the final stages of stellar evolution, including the evolutionary stages of supernovae and the formation of compact objects like white dwarfs, neutron stars, and black holes.

International Journal for Multidisciplinary Research (IJFMR)
E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

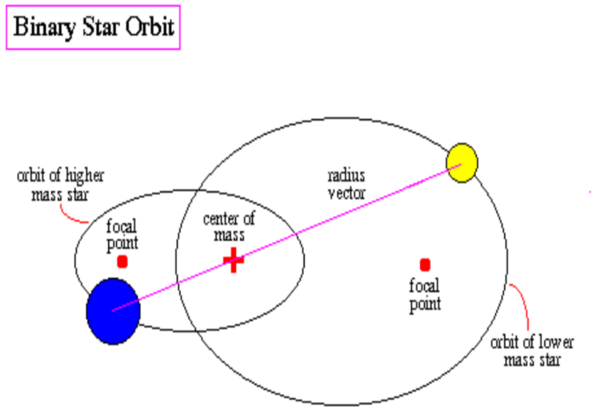



**Fig 2.1: The trajectory of Binary Star system**

**2.1 Formation of Binary System:**

The formation of a binary star system is a complex process that is not yet fully understood by us, but significant progress has been made through observations and simulations through years of research and observations. Binary stars are thought to form through several mechanisms that include fragmentation of a collapsing molecular cloud, capture where the stars form independently and bound together due to Gravitational influence, and disk fragmentation. So, let's discuss in detail about the various processes involved:

**2.1.1. Fragmentation of a Collapsing Molecular Cloud**: This is the most widely accepted mechanism (as of now) for the formation of binary stars. When a molecular cloud collapses under its own gravity, it can fragment into several smaller clumps, like soil. If two clumps form close enough to each other, they can become gravitationally bound and form a binary system. There you go! The turbulence within the molecular cloud and its initial conditions, such as rotation and magnetic fields, are also important in the fragmentation process. Observations of young star-forming regions provide evidence for this mechanism, showing that many stars form in clusters with a high incidence of binary and multiple-star systems.

**2.1.2. Capture**: This mechanism involves two stars that initially form independently and later become gravitationally bound. For capture to occur, the two stars must lose enough kinetic energy to become bound. This can happen through interactions with other stars in a dense stellar cluster or through the influence of a surrounding gas cloud. However, the capture mechanism is considered less efficient than fragmentation, particularly in the early stages of star formation when the stellar densities required for frequent encounters are typically not high.

**2.1.3**. **Disk Fragmentation**: As the name suggests, during the formation of a single star, a circumstellar disk often forms around the protostar due to the conservation of angular momentum. If the disk becomes massive enough, it can become gravitationally unstable and fragment, leading to the formation of a companion star. This process can produce close binary systems and is supported by observations of young stars with circumstellar disks showing evidence of companions.

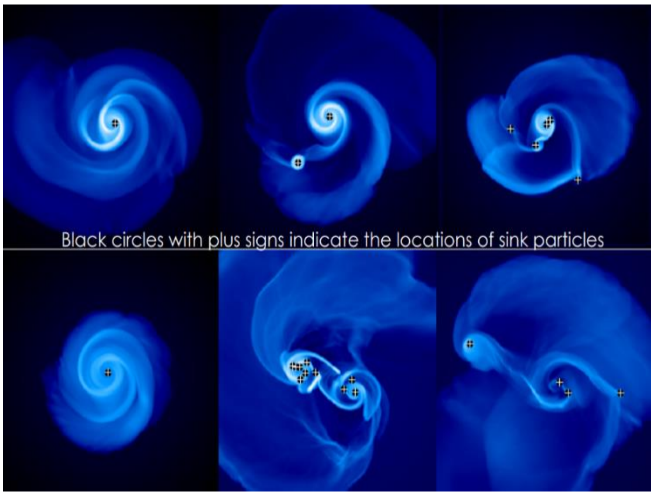



**Fig 2.2: Capture phase of Binary Star system indicating the location of sink particle**

**2.2 Evolutionary trajectory:**

The evolution of binary stars is a fascinating and complex process, isn't it? influenced by the interactions between the component stars. These interactions can significantly alter the evolutionary paths of the stars compared to their solitary counterparts. The evolution of binary stars can also be broadly divided into several stages, including the pre-main sequence, main sequence, post-main sequence, and the final stages involving compact objects:

**2.2.1. Pre-Main Sequence**: During the pre-main sequence phase, binary stars are still in the process of contracting and heating up. The presence of a companion star can influence the accretion disk of material and the circumstellar environment. Close binary systems may experience interactions such as tidal forces, which can lead to synchronization of rotational and orbital periods. In this phase, binary stars are often observed as T Tauri stars or Herbig Ae/Be stars, which are characterized by their variability and strong emission lines due to accretion processes.

**2.2.2. Main Sequence**: Once binary stars reach the main sequence, they begin fusing hydrogen in their cores. The evolution during this phase depends on the masses of the component stars and their separation. In wide binaries, the stars evolve independently, with minimal interaction. However, in close binaries, interactions such as mass transfer can occur when one star expands and fills its Roche lobe, the region around a star where material is gravitationally bound to it. Mass transfer can significantly alter the masses, luminosities, and evolutionary paths of both stars. The accreting star can become revived, appearing younger and more massive, while the donor star loses mass and evolves differently than it would have in isolation.

**2.2.3. Post-Main Sequence**: As the stars evolve off the main sequence, interactions become even more significant. In close binaries, one star may expand into a red giant or supergiant phase, leading to enhanced mass transfer. This can result in phenomena such as novae, where accreted material on the surface of a white dwarf ignites in a thermonuclear explosion, or Type Ia supernovae, which occur when a white dwarf accretes enough mass to exceed the Chandrasekhar limit and undergo a catastrophic explosion (See Section 5.1). Binary interactions can also lead to the formation of exotic objects such as blue stragglers, which are main sequence stars that appear younger and more massive and are also more luminous and bluer than expected, likely due to mass transfer or mergers.

**2.2.4. Final Stages**: The final stages of binary star evolution can produce a variety of outcomes depending on the initial masses and separations of the stars. Common-envelope evolution can occur when a giant star engulfs its companion, leading to the ejection of the envelope and the formation of a close binary consisting of a compact object (white dwarf, neutron star, or black hole) and a main sequence or giant companion. If both stars in a binary evolve into compact objects, such as neutron stars or black holes, they can form a double compact object system. These systems are of great interest as potential sources of gravitational waves, as predicted by general relativity and confirmed by observations from the LIGO and Virgo observatories.

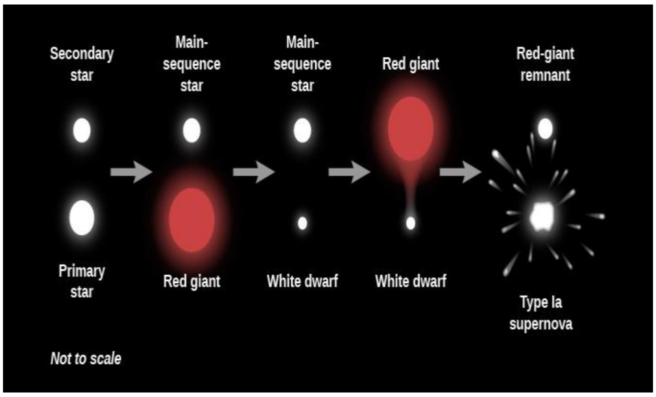



**Fig 2.3: Life Stages of Stars**

**2.3 Gravitational Influence in Binary Star Systems:**

Talking about the Gravitation in binary star systems, two stars are gravitationally bound and orbit a common centre of mass. Simply, we can say that the gravitational forces between the stars govern their orbital motions and significantly impact their physical and dynamic evolution. Understanding these forces is crucial for studying the dynamics, stability, and evolution of binary systems.

The fundamental equation governing the gravitational influence between two stars is the most encountered law: Newton's universal law of gravitation

$$F = \frac{Gm_1m_2}{r^2}$$

where:

- **F** is the gravitational force between the two stars,
- **G** is the gravitational constant **($6.67430\times10^{-11}$ $m^3kg^{-1}s^{-2}$)**
- $m_1$ *and* $m_2$ are the masses of the two stars,
- **r** is the distance between the centres of the two stars.

As we know that this force acts along the line connecting the centres of the two stars and is always attractive.

In a binary system, the stars orbit around a common centre of mass (called barycentre). The positions of the stars relative to the centre of mass ($m_1$ *and* $m_2$) are given by:

$$m_1r_1 = m_2r_2$$

And $r = r_1 + r_2$

The gravitational potential energy **U** of the system is:

$$U = -\frac{Gm_1m_2}{r}$$

Talking about angular momentum, it is a fundamental property in the dynamics of binary star systems, conserved in the absence of external torques. The total angular momentum **L** of a binary system is the sum of the angular momenta of the individual stars:

$$L = M_1 r_1 \times v_1 + M_2 r_2 \times v_2$$

where:

- $r_1$ and $r_2$ are the position vectors of the stars relative to the centre of mass,
- $v_1$ and $v_2$ are the velocity vectors of the stars.

For a circular orbit, the magnitudes of the angular momenta of the stars can be simplified to:

$$L_1 = M_1 r_1 v_1$$
$$L_2 = M_2 r_2 v_2$$

where $v_1$ and $v_2$ are the orbital velocities of the stars. The total angular momentum of the system is then:

$$L = L_1 + L_2$$

Using Kepler's third law, the relationship between the orbital period **T** and the semi-major axis **a** is:

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

The orbital velocities can be related to the semi-major axis and the orbital period:

$$v_1 = \frac{2\pi r_1}{T}$$
$$v_2 = \frac{2\pi r_2}{T}$$

Therefore, the total angular momentum for circular orbits is:

$$L = M_1 \left(\frac{2\pi r_1}{T}\right) r_1 + M_2 \left(\frac{2\pi r_2}{T}\right) r_2$$

Orbital Velocities and Period: For circular orbits, the orbital velocities $v_1$ and $v_2$ of the stars can be derived from the balance of gravitational and centripetal forces:

$$v_1 = \sqrt{\frac{GM_2}{r_1 + r_2}} \quad and \quad v_2 = \sqrt{\frac{GM_1}{r_1 + r_2}}$$

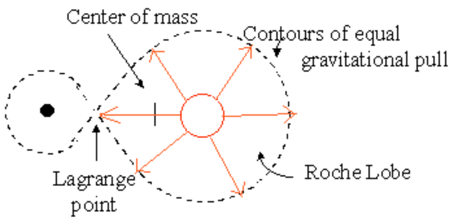
The orbital period **T** is:

$$T = \frac{2\pi \cdot r}{v_1 + v_2}$$

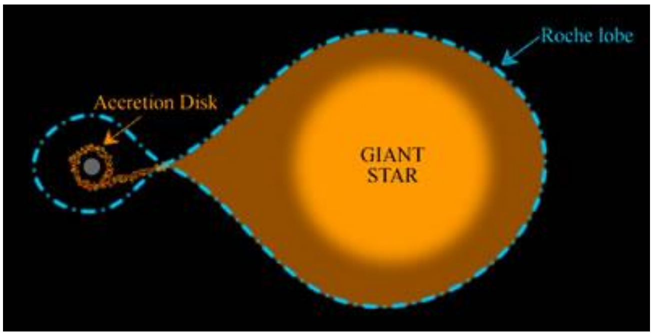
Using Kepler's third law, we can also express the orbital period as:

$$T = \sqrt{\frac{4\pi^2 (r_1 + r_2)^3}{G(M, +M_2)}}$$

In close binary systems, the gravitational influence of each star defines a region known as the Roche lobe. The Roche lobe is the region within which material is gravitationally



bound to a star. If a star expands beyond its Roche lobe, the material can transfer to its companion through the inner Lagrangian point $\boldsymbol{L_1}$.




The size of the Roche lobe can be approximated using Eggleton's formula:

$$R_L \approx a\frac{0.49q^{2/3}}{0.6q^{2/3} + ln(1 + q^{1/3})}$$

where $R_L$ is the Roche lobe radius, **a** is the orbital separation, and $q = \frac{M_1}{M_2}$ is the mass ratio.

Mass transfer can lead to the formation of accretion disks, novae, and Type Ia supernovae, profoundly impacting the evolutionary paths of the stars involved.

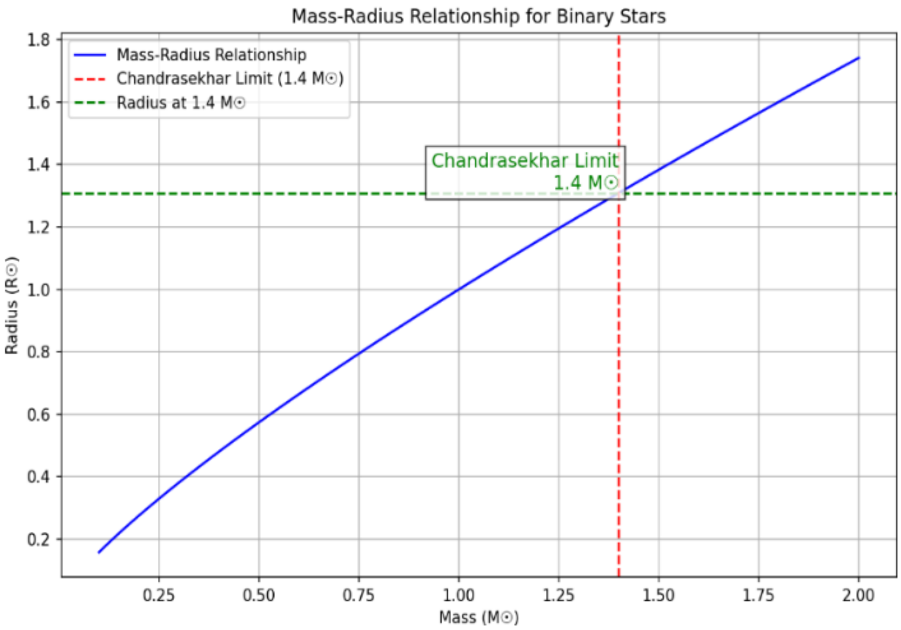



**Fig 2.2: Mass-Radius Relationship curve for Binary stars system**

One of the closest known binary star systems to Earth is **Alpha Centauri**. It is located approximately 4.37 light-years away from our Earth. It consists of two main stars **Alpha Centauri A (Rigil Kentaurus)** and **Alpha Centauri B (Toliman)**. Alpha Centauri A is a G2V spectral type star which is 1.1 times the mass, 1.2 times the Radius, and 1.5 times the luminosity of the Sun (approximate data) while the Alpha Centauri is a K1V spectral type star which is 0.9 times the mass, 0.86 times the Radius, and 0.5 times the luminosity of the Sun (approximate data). The average distance between Alpha Centauri A and B is about 23.6 AU (astronomical units). The orbital period of the stars is approximately 79.91 years.

**3. Pulsars:**

Pulsars are highly magnetized, rotating neutron stars that emit beams of electromagnetic radiation out of their magnetic poles. These beams sweep across space like lighthouse beams, and if they intersect with Earth, we observe them as pulses of radiation, hence the name "pulsar." The period between pulses can range from milliseconds to seconds, and pulsars are known for their incredible regularity, making them some of the most precise clocks in the universe. Pulsars were first discovered in 1967 by Jocelyn Bell Burnell and Antony Hewish. The regularity of the pulses initially led to speculation about extraterrestrial signals, but it was soon realized that pulsars are a natural astrophysical phenomenon. The discovery of pulsars provided critical evidence for the existence of neutron stars, a theoretical prediction made by Fritz Zwicky and Walter Baade in the 1930s.

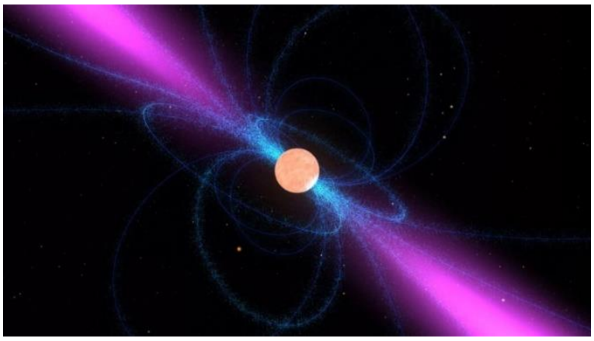


**Fig 3.1: Theoretical Image of how a pulsar should be!**

**3.1 Formation:**

Let’s talk about the formation of pulsars. It involves a complex process. They are as follows:

**3.1.1. Supernova Explosions**

Pulsars are formed from the remnants of massive stars that have ended their life cycles in supernova explosions. When a star with a mass between approximately 8 and 25 times that of the Sun exhausts its nuclear fuel, it undergoes a core-collapse supernova. The core collapses under gravity to form a neutron star, while the outer layers are expelled into space.

**3.1.2. Core Collapse and Neutron Star Formation**

During the core collapse, protons and electrons combine to form neutrons via inverse beta decay:

$$\boldsymbol{p + e^- \rightarrow n + v_e}$$

This results in a dense, compact object primarily composed of neutrons, with densities exceeding $10^{17} kg / m^3$. The conservation of angular momentum causes the newly formed neutron star to spin rapidly, with rotational periods ranging from milliseconds to a few seconds. The collapse also amplifies the magnetic field, resulting in field strengths between $10^{18}$ and $10^{15}$ Gauss.

**3.1.3. Birth Characteristics**

The initial spin period ($P_0$) and magnetic field strength (B) of a neutron star are crucial parameters that determine its subsequent evolution as a pulsar. Newly formed pulsars typically have strong magnetic fields and short spin periods.

$$\boldsymbol{P_0 \approx 10ms}$$

$$\boldsymbol{B \approx 10^{12} gauss}$$

The rotational energy of the neutron star powers the emission of radiation. The loss of rotational energy over time causes the pulsar to slow down, increasing its period.

**3.2 Evolution of Pulsars:**

**3.2.1. Spin-Down and Energy Loss**

Pulsars lose rotational energy primarily through electromagnetic radiation and particle winds. The rate of energy loss ($\dot{E}$) is given by:

$$\dot{E} = -\frac{d}{dt}\left(\frac{1}{2} I\Omega^2\right)$$

where:

- I is the moment of inertia of the neutron star (≈$10^{38} kg\ m^2$),
- Ω is the angular velocity (Ω=2π/P).

Assuming magnetic dipole radiation, the energy loss rate can be approximated as:

$$\dot{E} \approx \frac{B^2 R^2 \Omega^4}{6c^3}$$

where:

- B is the magnetic field strength at the magnetic poles,
- R is the radius of the neutron star (≈10 km),
- c is the speed of light.

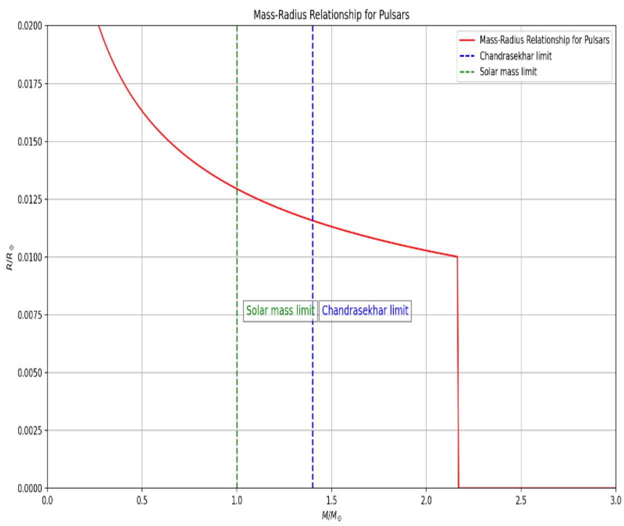



**Fig 3.2: Mass-Radius Relationship for Pulsars**

The spin-down rate ($\dot{P}$) is related to the energy loss rate:

$$\dot{P} \approx \frac{K}{P}$$

where K is a constant that depends on the magnetic field and moment of inertia:

$$K \approx \frac{B^2 R^6}{6Ic^3}$$

Over time, the period P increases, and the pulsar spins down.

### 3.2.2. Pulsar Death Line

As pulsars spin down, their ability to produce detectable radiation decreases. The pulsar death line is the boundary in the $P - \dot{P}$ diagram (period versus period derivative) beyond which pulsars no longer emit observable radio waves. This occurs when the electric field generated by the rotating magnetic field is insufficient to accelerate particles to relativistic speeds, thus ceasing radio emission.

### 3.3.3. Millisecond Pulsars

Some pulsars are observed with very short periods (1−10 ms), known as millisecond pulsars (MSPs). These are believed to be old neutron stars that have been spun up by accreting matter from a companion star in a binary system. This process transfers angular momentum to the neutron star, reducing its period and increasing its spin rate.

The spin-up process can be described by the accretion torque (N) acting on the neutron star:

$$N \approx \dot{M}(GMR)^{1/2}$$

Where $\dot{M}$ is the mass accretion rate, M is the mass of the neutron star, and R is the radius of the neutron star. The equilibrium spin period ($P_{eq}$) achieved through accretion is given by:

$$P_{eq} \approx \left(\frac{2\pi I}{N}\right)^{1/3}$$

MSPs are highly stable rotators and are often found in binary systems, providing excellent laboratories for studying general relativity and testing fundamental physics.

### 3.3.4. Binary Pulsars and Gravitational Waves

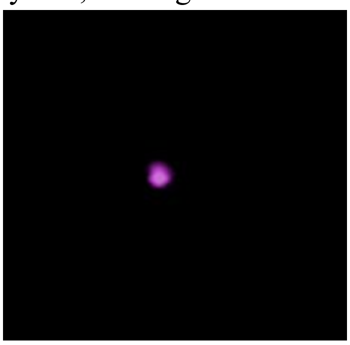
Binary pulsars, where one of the components is a pulsar, provide unique opportunities for studying relativistic effects. The most famous example is the Hulse-Taylor binary pulsar (PSR B1913+16), whose orbital decay due to gravitational wave emission provided the first indirect evidence for gravitational waves.

The rate of orbital period decay ($\dot{P}_b$) due to gravitational wave emission in a binary system with two compact objects is given by:

$$\dot{P}_b = -\frac{192\pi G^{5/3}}{5c^5}\left(\frac{P_b}{2\pi}\right)^{-5/3} \frac{(M_1 M_2)^{5/3}}{(M_1 + M_2)^{\prime\prime 3}}$$

where $P_b$ is the orbital period of the binary system.

The nearest known pulsar is PSR J0108-1431. It's distance from Earth is approximately 130 parsecs (424 light-years) located in the constellation Cetus. It has Spin Period of 0.808 seconds. Approximately 166 million years old. Its Luminosity is very low, making it one of the faintest known pulsars



## 4. Red-Giants:

Red-giants are a fascinating phase in the life cycle of stars, representing a period of transformation and dramatic change. These stars, which are in the latter stages of their evolution, exhibit some of the most striking characteristics in the cosmos. Red giants are stars that have exhausted the supply of hydrogen in their cores, the fuel that powers their nuclear fusion processes. When a star like our Sun depletes its hydrogen, it can no longer maintain the same pressure to counterbalance gravity. As a result, the core contracts and heats up, causing the outer layers to expand enormously and cool down. This expansion gives red giants their characteristic large size and cooler surface temperature, typically between 3,000 to 5,000 Kelvin, which imparts a reddish hue. Stars spend the majority of their lives in the main sequence, where they steadily fuse hydrogen into helium in their cores. For a star with a mass similar to that of the Sun, the main sequence phase lasts about 10 billion years. As the hydrogen in the core is consumed, the star transitions off the main sequence and begins its journey towards becoming a red giant.

### 4.1 Formation of Red Giants:

Let’s talk about the formation of red giants. It involves a complex process that occurs during the late stages of stellar evolution for stars with initial masses between about 0.8 and 8 solar masses. This phase is marked by significant changes in the star's internal structure and energy generation mechanisms. Here is a detailed overview of how red giants form:

#### 4.1.1. Main Sequence Evolution

Stars begin their lives on the main sequence, where they spend the majority of their lifetimes fusing hydrogen into helium in their cores. This process is governed by the proton-proton chain reaction or the CNO cycle, depending on the star's mass. For stars destined to become red giants, this main sequence phase lasts for billions of years. As a star exhausts the hydrogen fuel in its core, the core, now primarily composed of helium, begins to contract under gravity. This contraction leads to an increase in temperature and pressure in the core. Since hydrogen fusion can no longer occur in the

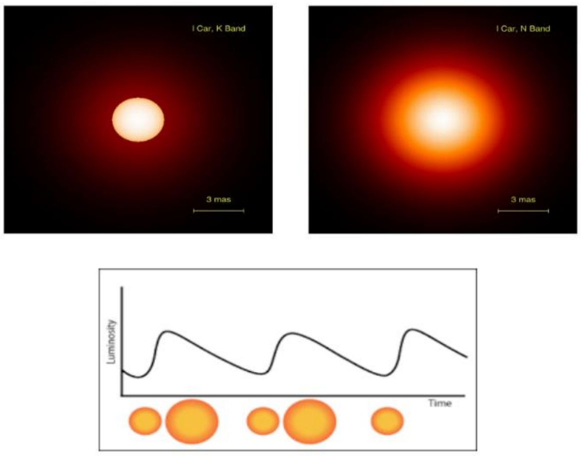



**Fig 4.1: Pulsation Period of Red Giants Stars**

core, the star must find a new energy source to maintain hydrostatic equilibrium.

#### 4.1.2. Hydrogen Shell Burning

With the core contracting and heating up, the temperature in the surrounding shell of hydrogen increases to the point where hydrogen fusion can resume in a shell around the core. This process is known as hydrogen shell burning. The energy produced in this shell causes the outer layers of the star to expand significantly. The expansion of the outer layers leads to a dramatic increase in the star's radius, often by a factor of tens to hundreds. As the outer layers expand, they cool down, resulting in a decrease in surface temperature. This cooling gives the star its characteristic red colour, hence the name "red giant." The expansion and cooling of the outer layers also lead to an increase in the star's luminosity. Despite the lower surface temperature, the much larger surface area of the red giant emits more light overall. The star becomes significantly more luminous than it was in the main sequence.

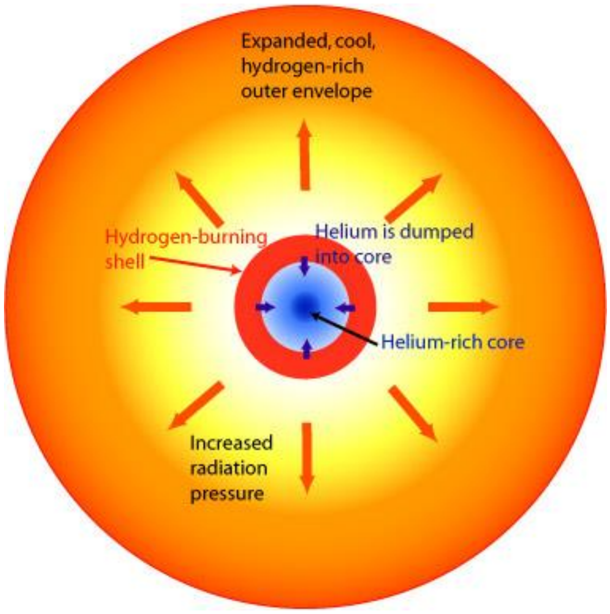



**Fig 4.2: Hydrogen Shell burning photo in Red Giants**

### 4.1.3. Helium Core Contraction

The contracting helium core continues to heat up as it shrinks. If the star has a mass greater than approximately 2.0 solar masses, the core will eventually reach a temperature high enough to ignite helium fusion. This process occurs via the triple-alpha process, where three helium nuclei (alpha particles) fuse to form carbon. For stars with lower masses, the core may become degenerate before helium ignition. In such cases, helium fusion begins in a highly explosive event known as the helium flash. Despite the dramatic nature of the helium flash, it occurs too deep within the star to be observable from the outside.

**4.1.4. Ascent on the Red Giant Branch (RGB)** As the star continues to burn hydrogen in the shell around the helium core, it ascends the red giant branch (RGB) on the Hertzsprung-Russell diagram. This phase is characterized by increasing luminosity and decreasing surface temperature. The star's radius continues to expand, and it becomes more luminous.

### 4.1.5. Helium Burning Phase

Once the core temperature becomes sufficiently high, helium fusion begins in earnest, marking the start of the helium-burning phase. During this phase, the star stabilizes for a while, burning helium in the core and hydrogen in a shell around it. This phase can last for several million years, depending on the star's mass.

### 4.1.6. Late Stages and Planetary Nebula Formation

After helium in the core is exhausted, the star goes through further stages of shell burning, where heavier elements like carbon and oxygen are fused in shells around the inert core. For stars with masses up to about 8 solar masses, the outer layers are eventually expelled into space, forming a planetary nebula. The remaining core becomes a white dwarf.

For more massive stars, the evolution continues with more advanced stages of nuclear burning, ultimately leading to a supernova explosion. However, such stars do not typically pass through the red giant phase as their late stages are dominated by different processes.

### 4.2 Evolutionary Trajectories:

The evolution of red giants is a dynamic and complex process that follows the formation phase. This stage of stellar evolution involves significant changes in the star's structure, nuclear processes, and interactions with its environment. The evolution of red giants can be described mathematically through various aspects, including stellar structure equations, energy balance, and evolutionary models.

#### 4.2.1. Initial Red Giant Phase

After a star exhausts the hydrogen fuel in its core, it enters the red giant phase. The core, now primarily composed of helium, contracts and heats up, while the outer layers expand and cool.

- **Hydrogen Shell Burning:** As the core contracts, a shell of hydrogen surrounding the core reaches temperatures high enough for hydrogen fusion to resume. This hydrogen shell burning provides the energy that causes the outer layers to expand and cool, turning the star into a red giant.

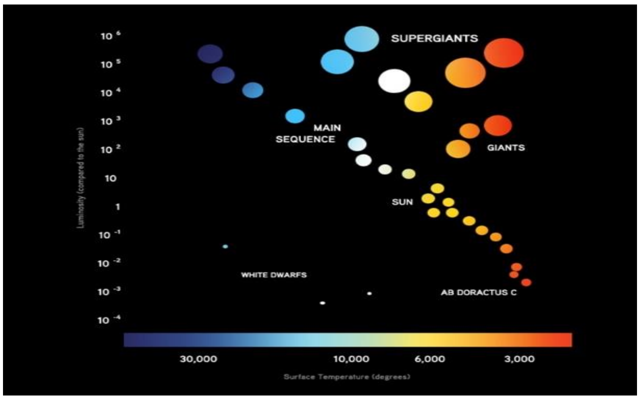



**Fig 4.3: H-R Diagram of Stars and their respective luminosity and ultimate fate**

- **Expansion and Luminosity Increase:** The expansion of the outer layers results in a significant increase in the star's radius, often by a factor of tens to hundreds. Despite the cooling of the outer layers, the increased surface area leads to a substantial rise in luminosity. The star moves up the red giant branch (RGB) on the Hertzsprung-Russell (H-R) diagram, becoming more luminous as it evolves

#### 4.2.2. Asymptotic Giant Branch (AGB) Phase

After the helium in the core is exhausted, the star undergoes further evolution.

- **Double Shell Burning:** The star now has an inert carbon-oxygen core surrounded by shells of helium and hydrogen. Helium shell burning occurs just outside the core, while hydrogen shell burning continues in a shell further out. This double-shell burning phase leads to significant thermal pulsations.
- **Thermal Pulses:** During the AGB phase, the star experiences periodic thermal pulses caused by the unstable helium shell burning. These pulses cause the outer layers to expand and contract, leading to significant changes in luminosity and mass loss. The star loses a considerable amount of mass through

strong stellar winds, enriching the surrounding, interstellar medium with heavy elements.

For main sequence stars:

$$L \propto M^{3.5}$$

For red giants, this relationship becomes more complex due to increased luminosity and expanded radius. During the Asymptotic Giant Branch (AGB) phase, the mass loss rate $\frac{dM}{dt}$ can be modeled as:

$$\frac{dM}{dt} = A \cdot L^{\alpha} \cdot \frac{T_{eff}^2}{M}$$

where A is a constant, α is a fitting parameter, L is the luminosity, $T_{eff}$ is the effective temperature, and M is the mass of the star. The core's temperature $T_{core}$ before and after the helium flash can be estimated using:

$$T(core) \propto \left(\frac{L_{He}}{R(core)^2}\right)^{1/4}$$

Where $L_{He}$ is the luminosity from helium burning, and is $R(core)$ the core radius.

**4.2.3. Post-Red Giant Phase**

The intense mass loss during the AGB phase results in the shedding of the outer layers, creating a planetary nebula. The strong stellar winds expel the outer layers into space, forming a circumstellar envelope. The star loses a significant fraction of its mass, which can be observed as an expanding shell of gas and dust. As the outer layers are ejected, the hot core of the star is exposed. The intense ultraviolet radiation from the hot core ionizes the surrounding expelled material, causing it to glow as a planetary nebula. This phase is relatively short-lived, lasting a few tens of thousands of years. After the planetary nebula phase, the remaining core of the star becomes a white dwarf.

The mass of the ejected planetary nebula can be approximated by:

$$M_{nebula} = M_{initial} - M_{WD}$$

where $M_{initial}$ is the initial mass of the star and $M_{WD}$ is the mass of the white dwarf remnant. As the white dwarf cools, it gradually fades in luminosity, eventually becoming a cold, dark black dwarf. However, the timescale for a white dwarf to cool to such an extent is longer than the current age of the universe, so no black dwarfs are expected to exist yet. The white dwarf's luminosity $L_{WD}$ as it cools is:

$$L_{WD} = L_{initial}\left(\frac{T_{WD}}{T_{initial}}\right)^4$$

where $T_{WD}$ is the temperature of the white dwarf, and $L_{initial}$ is the initial luminosity of the white dwarf.

## 5. White Dwarfs:

White Dwarf are a fascinating and well-studied topic in astronomy & astrophysics. White dwarf is a key way to understanding stellar evolution and the ultimate fate of stars as discussed in the earlier section. Their unique physical properties and evolutionary pathways offer insights into fundamental astrophysical processes and the lifecycle of stars. White Dwarfs are the remnants of low- to intermediate-mass stars that have exhausted the nuclear fuel in their cores. They represent the final evolutionary state of stars with initial masses less than about 8 solar masses. White dwarfs exhibit remarkable density, with masses similar to that of the Sun but volumes equivalent to Earth. Consequently, their densities can exceed 106 grams per cubic centimetre. The high density of White Dwarfs is counteracted by electron degeneracy pressure, a quantum mechanical principle originating from the Pauli Exclusion Principle, to prevent gravitational collapse. The primary composition of most White Dwarfs is carbon and oxygen, but they might also include helium or, less frequently, neon and oxygen, depending on the mass and evolutionary path of the progenitor star. The surface layers of a White Dwarf may consist of hydrogen and helium, frequently creating a thin atmosphere.

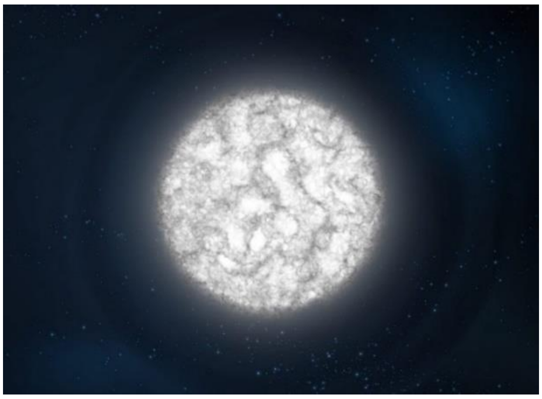


**Fig 5.1: Theoretical Picture of White Dwarfs**

**5.1 Formation Process of White Dwarfs:**

The formation of White Dwarfs involves several phases. They are as follows:

**5.1.1. Red Giant Phase:** As discussed earlier, a star possessing a mass of less than roughly 8 solar masses will expand into a red giant during its late evolutionary phases. As White Dwarfs exhaust the hydrogen fuel in their cores, nuclear fusion slows down, and the core begins to contract under gravity. The outer layers of the star expand due to the heat generated by the core contraction, and the star swells into a red giant. The surface temperature drops, giving the star its characteristic reddish colour. In the core of a red giant, Helium fusion takes place, culminating in the formation of carbon and oxygen once the core temperature reaches about 100 million Kelvin(K). This process is known as the "Helium Flash". The core stabilizes temporarily, but eventually, it begins to contract again when helium is depleted. As the core contracts, hydrogen fusion continues in a shell around the core, contributing to the luminosity of the star. Additional shells may form, leading to the star shedding its outer layers.

**5.1.2. Planetary Nebula Phase:** We have seen in the evolutionary process of red giants, at the last stage the outer layers of the star are ejected, leading to the formation of a planetary nebula, while the core shrinks into a White Dwarf. The core emits intense ultraviolet radiation, which ionizes the ejected material, causing it to glow brightly. This glowing shell is basically a shell of ionized gas which is known as a planetary nebula. A planetary nebula typically stretches a few light-years in diameter and can last for tens of thousands of years, which is relatively short in astronomical terms. Eventually, the nebula disperses into the Interstellar Medium (ISM). The vivid colours seen in planetary nebulae come from the ionized gases, primarily hydrogen (Red), oxygen (Green), and nitrogen (Blue). The specific colours depend on the temperature of the central White Dwarf and the composition of the ejected material. The Helix Nebula (NGC 7293): Often referred to as the "Eye of God", this nebula in Aquarius in one of the closest planetary nebulae to Earth. The Ring Nebula(M57): One of the most famous planetary nebulae, located in the constellation Lyra. It appears as a bright ring with a central White Dwarf. The Cat's Eye Nebula (NGC 6543): Located in the constellation Draco, it is known for its intricate and symmetric structure.

**5.1.3. Cooling:** Upon formation, White Dwarfs are extremely hot, with surface temperatures exceeding 100,000 kelvins(K). They radiate their residual heat into space and begin to cool. The young White Dwarf initiates a cooling process over billions of years, progressively fading as it radiates its accumulated thermal energy. The initial cooling is relatively fast because of the high-temperature gradient between the White Dwarf and the surrounding space. As the White Dwarf cools, the matter inside begins to crystallize, starting in the core. This process releases additional energy, temporarily slowing the cooling process. The crystallization is a phase transition where the ions in the core form a more ordered structure, releasing latent heat. This phase can last for billions of years, and the energy released during crystallization slightly delays the White Dwarf's cooling.

### 5.2 Evolutionary Trajectories:

#### 5.2.1. Chandrasekhar Limit:

The Chandrasekhar limit is approximately 1.4 times the mass of the Sun (1.4 Solar masses). It was first calculated by Indian Astrophysicist Subrahmanyan Chandrasekhar in 1930 when he was only 19 years old. This limit defines the maximum mass a White Dwarf can have before it can no longer support itself against its own gravity through electron degeneracy pressure. The Mass-Radius relationship for white Dwarf stars is shown below. In a white dwarf, the pressure that counteracts gravitational collapse is provided by electron degeneracy pressure, a quantum mechanical effect. This pressure arises from the Pauli Exclusion Principle, which states that no two electrons can occupy the same quantum state. As a result, the densely packed electrons in a White Dwarf create a repulsive force that balances the gravitational pull. With an increase in the White Dwarf's mass, the gravitational pull strengthens, compressing the electrons more tightly and elevating the electron degeneracy pressure. If the mass goes beyond the Chandrasekhar limit, the electron degeneracy pressure is insufficient to counterbalance gravity, causing a collapse.

#### 5.2.2. Consequences of exceeding the Chandrasekhar Limit:

As discussed by my colleague n Binary Star systems, when a White Dwarf absorbs enough matter from a neighbouring star and its mass approaches the Chandrasekhar Limit, it can initiate a rapid thermonuclear explosion, leading to a Type Ia Supernova. These Supernovae captivate astronomers because their steady peak brightness enables them to be used as 'standard candles' for calculating cosmic distances. NASA's Hubble Space Telescope (HST) has been essential in tracking these Supernovae through enormous distances, facilitating the calculation of the Universe's Expansion Rate. In a binary system, if a White Dwarf surpasses the Chandrasekhar Limit without exploding as a supernova, it could collapse into a neutron star, an even denser body sustained by neutron degeneracy pressure.

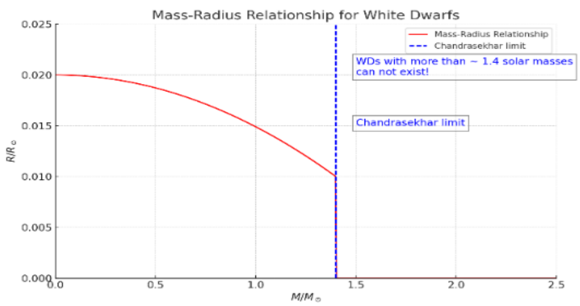



**Fig 5.1: Mass- Radius relationship curve for White Dwarfs**

#### 5.2.3. Cooling and Fading:

White Dwarfs gradually lose heat and diminish in brightness over time, transitioning from a hot, luminous state to a cooler, dimmer condition. Over time, the rate of cooling decreases, and the White Dwarf gradually dims. The cooling follows a predictable path, with the White Dwarf eventually reaching temperatures where it emits only infrared radiation or faint visible light, becoming what is known as a "Black Dwarf". However, the universe is not old enough for any White Dwarfs to have cooled into Black Dwarfs yet. The cooling timescale is extremely long, on the order of billions of years. It means that White Dwarfs from the early stages of the galaxy's formation are still observable. NASA's observations, particularly from the Hubble Space Telescope, have been crucial in studying White Dwarfs and their cooling rates. These observations help astronomers determine the ages of star clusters by comparing the observed White Dwarf's cooling curves to theoretical models.

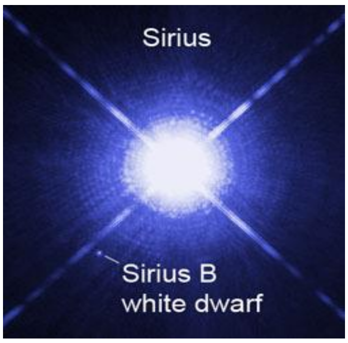
White Dwarfs generally exhibit surface temperatures ranging from about 5,000 to 40,000 Kelvin(K). In their initial stages, White Dwarfs can be intensely hot, with temperatures climbing up to 100,000 Kelvin(K), however, they gradually cool as they age. The luminosity of White dwarfs is usually much lower than that of main-sequence stars. It typically varies from around 0.001 to 0.1 times the Sun's luminosity. The specific luminosity is influenced by the White Dwarf's, temperature, and cooling age. Younger and Hotter White Dwarfs are more radiant, whereas older and cooler ones produce less light.

Sirius B is the closest White Dwarf to Earth about 8.6 Light-years away, part of the Sirius star system, alongside Sirius A, the brightest star in our night sky. It is located in the Canis Major constellation. Despite its brightness, Sirius B is much fainter than Sirius A, making it difficult to observe without a telescope. It is a typical White Dwarf, primarily composed of carbon and oxygen.

## 6. Neutron Stars:

Neutron stars are one of the most fascinating and extreme objects in the Universe, formed as a result of the gravitational collapse of massive stars. Neutron stars are the remnants of colossal stars that have experienced a supernova event. When a star with a mass roughly 8 to 20 times that of the Sun depletes its nuclear fuel, it can no longer resist gravitational collapse. The star's core implodes under gravity, causing protons and electrons to merge into neutrons, leading to a dense core made predominantly of neutrons.

Neutron stars are extremely dense, with an average radius of around 10 kilometres, yet their mass can reach up to 1.4 times that of the Sun (the Chandrasekhar limit for White Dwarfs). The density of a neutron star is exceptionally high, ranging from approximately 1014 to 1015 g/cm3, so a sugar-cube-sized piece of neutron star material would weigh roughly about 4 billion tons on Earth.




### 6.1 Formation Process of White Dwarfs:

The formation of Neutron stars is a very complex mechanism consists of several phases as follows:

#### 6.1.1. Nuclear Fusion:

In these massive stars, nuclear fusion takes place, transforming hydrogen into helium, followed by the formation of heavier elements such as carbon, oxygen, and ultimately iron. Iron is the heaviest element that can be synthesized through fusion within a star's core. When neutron stars merge, the extreme conditions lead to rapid neutron capture(r-process), producing heavy elements beyond iron. The r-process nucleosynthesis can be represented by a series of reactions where a seed nucleus Z captures neutrons:

$$(n, \gamma) \rightarrow (Z, A + 1)$$

where $(n, \gamma)$ represents neutron capture followed by gamma-ray emission, leading to a heavier nucleus A + 1.

The abundance of elements produced can be calculated using reaction rates $\lambda_n$:

$$\frac{dY_z}{dt} = -\lambda_n Y_z + \lambda_n Y_{z-1}$$

where $Y_z$ is the abundance of elements Z, and $\lambda_n$ is the neutron capture.

**6.1.2. Core Collapse:**

The core of a neutron star is composed of superfluid neutrons, possibly with some protons and electrons. The exact composition and structure of the core are still subjects of research, with possibilities including exotic states of matter such as Quark-Gluon Plasma or Hyperon-rich matter. Surrounding the core is a solid crust, which is composed of a lattice of atomic nuclei, mostly iron, and a sea of degenerate electrons. The crust is extremely thin compared to the overall size of the neutron star but contains a significant portion of its mass. Neutron stars frequently have incredibly intense magnetic fields, from $10^{12}$ to $10^{15}$ Gauss. These fields can affect the radiation emitted by the star, resulting in phenomena such as Pulsars. When iron builds up in the core, it cannot participate in fusion to generate energy. The absence of outward pressure from fusion causes the core to collapse under its gravitational pull. As the core collapses, now approximately 1.4 to 2 times the mass of the Sun but with a diameter of just around 20 kilometres, experiences intense compression. Protons and electrons are forced together to create neutrons, a process called neutronization. This leads to the formation of a neutron star.

**6.2 Gravitational Influence in Binary Star Systems:**

Gravitational waves are ripples in spacetime caused by massive objects accelerating, such as during the merger of neutron stars. These waves were first predicted by Einstein's General Theory of Relativity in 1915. Collisions between neutron stars are one of the origins of gravitational waves, distortions in spacetime first detected directly by the LIGO (Laser Interferometer Gravitational-Wave Observatory) in 2015. These mergers also help to understand the equation of state of dense matter and are essential in the synthesis of heavy elements in the Universe through the r-process. Neutron star collisions rank as some of the most potent generators of gravitational waves. As two neutron stars revolve around one another, they slowly spiral inward, driven by the emission of gravitational waves, which causes them to lose energy. As the stars draw nearer, the frequency of the gravitational waves rises until they finally collide, emitting a burst of gravitational waves that can be detected on Earth. The gravitational waves generated by colliding neutron stars exhibit a distinctive 'Chirp' waveform, with both frequency and amplitude rising progressively until the point of merger.

The energy released during a neutron star merger in the form of gravitational waves is enormous, often equivalent to several solar masses being converted directly into energy as per Einstein's equation:

$$E = mc^2$$

In the weak-field approximation, far from the source, gravitational waves are described by a perturbation of the spacetime metric $h_{\mu v}$

$$h_{\mu v}(t, \vec{x}) = \frac{4G}{c^4} \frac{1}{r} \frac{d^2 Q_{\mu v}}{dt^2}$$

Here

- G represents gravitational constant.
- c is the velocity of light.
- r is the distance from the source.
- $Q_{\mu\nu}$ is the mass quadrupole moment tensor, which characterizes the mass distribution and its changes as the system evolves.

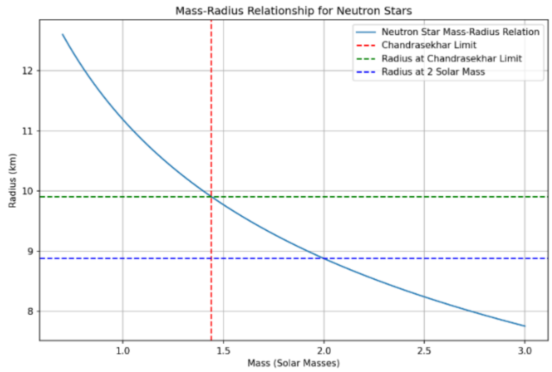



**Fig 6.1: Mass – Radius relationship for Neutron Stars**

The LIGO and Virgo observatories have identified multiple neutron star collisions, including the GW170817 event observed in August 2017. This event not only verified the presence of gravitational waves but also enabled scientists to detect the electromagnetic counterpart of the merger, known as a kilo-nova.

Calvera (1RXS J141256.0+792204): - It is found in the Ursa Minor constellation. Calvera is an isolated neutron star located between 250 and 1,000 light-years away, making it one of the closest neutron stars to Earth. It is notable for not being associated with any supernova remnant or binary companion.

**7. Protostars:**

A protostar is a nascent star that originates from the gravitational collapse of a concentrated zone within a molecular cloud. The study of Protostars is very important for understanding the creation of stars and the initial framework of planetary systems. It indicates the primary stage in the development of a star before nuclear fusion commences in its core. Protostars originates in the dense, shadowy parts of molecular clouds where gravitational forces overcome thermal pressures, triggering the collapse of the cloud fragment. As this collapse advances, the centre of the fragment becomes hotter, producing a dense, hot core called Protostar. This phase in the stellar evolution characterizes a complex interaction of physical processes, involving the accretion of matters from the surrounding envelope, and the launch of powerful jets and outflows. The gas and dust from which protostars originates, often obscure them, making it challenging for direct observation, particularly in visible light. By scrutinizing the characteristics and behaviour of protostars, astronomers acquire insights into the mechanisms involving star formation and the factors contributing to the range of stellar masses and lifetimes.

**7.1. Formation of Protostars:**

**7.1.1. Core and Envelope:** The central core takes shape, surrounded by a descending envelope. The mass of the core expands as additional material from the envelope accumulates onto it. The free-fall time $t_{ff}$, describes this process and is calculated using the equation:

$$t_{ff} = \sqrt{\frac{3\pi}{32G \cdot \rho}}$$

The envelope keeps accreting onto the core until it attains Hydrostatic Equilibrium, balancing the thermal pressure with gravitational forces.

**7.1.2. Accretion Shock:** As material accumulates onto the protostar, it generates an accretion shock at the surface of the protostar's core, contributing to the heating and enlargement of the core. The rapid deceleration of infalling material causes a shock wave, known as the accretion shock. This shock wave is responsible for the conversion of kinetic energy into the heat and radiation of the falling material. The shock heats the material to temperatures that can reach several thousand degrees Kelvin. This heating contributes to the overall temperature increase of the protostar, affecting its thermal balance and subsequent growth.

Hubble Space Telescope (HST) has captured detailed images and spectra of protostars in nearby star-forming regions. These observations have helped scientists analyse the accretion disks and the resulting shocks.

Spitzer Space Telescope (SST) has provided infrared data that reveal the heat signatures associated with accretion shocks. Infrared observations are crucial as they penetrate the dense clouds surrounding protostars, offering insights into the otherwise hidden processes.

Chandra's X-ray Observatory have detected emissions from protostars, indicating high-energy processes, including those associated with accretion shocks. X-ray data provide information on the temperature and composition of the accreting material.

Stratospheric Observatory for Infrared Astronomy (SOFIA) has been used to observe protostars at infrared wavelengths, offering data on the chemical composition and dynamics of the accretion process.

**7.2. Characteristics of protostars:**

Gravitational Collapse: External events like Supernova explosions or collisions with other clouds often trigger gravitational instability in small regions within these clouds, resulting in their collapse. Gravity pulls material inward in regions within molecular clouds, causing them to collapse and form protostars with a dense, hot core. The gravitational instability occurs due to various factors such as density fluctuations, cooling processes or external forces.

What are the initial conditions for Gravitational Collapse?

I. Density and Temperature:- The zones within molecular clouds that collapse into protostars generally have densities between 10 and 1000 particles per cubic centimetre and temperatures as low as 10-20 Kelvin(K). These low temperatures are crucial for the collapse, as thermal pressure is minimized, allowing gravitational forces to dominate.

II. Jeans Instability:- The distribution of stellar masses at birth, known as the Initial Mass Function (IMF), is shaped by the Jeans Instability, as it determines which regions form stars of various masses. According to the Jeans Criterion, a region will collapse if its mass exceeds the Jeans mass, a principle often used to describe the collapse. This criterion is a balance between gravitational forces and internal pressure, given by the Jeans mass, as denoted by $M_J$, is calculated using the formula:

$$M_J = \frac{5k_B T}{G\mu m_H}\sqrt{{}^{3}/_{4\pi\rho}}$$

Where,

- $k_B$ is the Boltzmann Constant

- $T$ is the temperature of the cloud
- $G$ is the Gravitational constant
- $\mu$ is the mean molecular weight of the gas
- $m_H$ is the mass of hydrogen atom
- $\rho$ is the density of the cloud

The Jeans Length $(\lambda_J)$ is the critical size scale of a region above which the cloud becomes unstable. It is given by:

$$\lambda_J = \left(\frac{15k_BT}{4\pi G\rho\mu m_H}\right)^{1/2}$$

What are the phases of Gravitational collapse?

I. Isothermal Collapse Phase:- During the first phase of collapse, the gas stays roughly isothermal (i.e. maintains an almost constant temperature), because of effective radiative cooling. Gravity draws the gas inward, leading to an increase in the core's density. This process persists until the central regions become optically dense to their own radiation, which means they can no longer cool effectively.

II. Adiabatic Collapse Phase:- With the rise in the core's density, the material becomes opaque, resulting in an adiabatic collapse that triggers a temperature increase. This temperature rise indicates the transition from a gravity-dominated state to one where pressure plays a significant role. The core develops into a dense and heated protostar.

**7.2.1. Accretion Disk:** As matter is deposited onto the protostar, it often develops into a spinning disk, which is key to angular momentum distribution and the formation of planets. Accretion disks are typically composed of gas and dust, with the inner regions. The disk's structure is governed by several factors, including temperature, density, and magnetic fields. Observational studies using telescopes like the Atacama Large Millimetre/submillimetre Array (ALMA) have delivered insights into the sizes and structures of these disks, revealing a diverse range of disk radii and characteristics. The size of proto-stellar accretion disks can vary significantly, but they generally have radii ranging from a few tens to a few hundred Astronomical Units (AU).

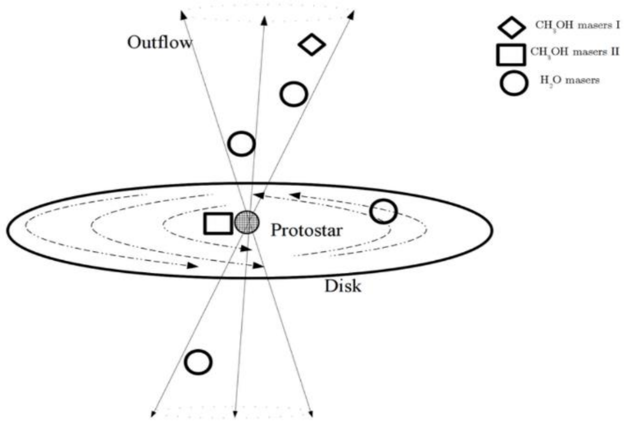



**Fig 7.1: Structure of Accretion Disk of Protostar.**

**7.2.2. Jets and Outflows:** Bipolar jets and outflows are commonly seen in protostars, which assist in distributing angular momentum and the clearing of adjacent material. By clearing away surrounding gas and dust, jets and outflows prevent further accretion and facilitate the emergence of the star from its natal cocoon.

Hubble's observations of the jet from the protostar HH 24 show a highly collimated beam stretching over light-years, highlighting the powerful nature of these jets. Chandra X-ray Observatory on X-ray data revealed how high-energy processes in the jets contribute to heating and ionizing the surrounding material. Observations of protostar HH 154, a jet from a young star, show bright X-ray emissions, indicating powerful shocks where the jet impacts the interstellar medium.

**7.2.3. Temperature and Luminosity:** In the proto-stellar stage, the object emits light mainly due to the conversion of gravitational energy rather than nuclear fusion. Protostars have surface temperatures typically ranging from 2000 to 3000 kelvin(K). This temperature range is cooler than main-sequence stars, which have temperatures between 2500 to 10,000 kelvins (K). As the protostars evolve, the core temperature of protostars gradually increases due to gravitational contraction. This increase eventually leads to the initiation of nuclear fusion when the core temperature reaches around 10 million Kelvin. The protostar HL Tau, observed by ALMA and NASA's Hubble Space Telescope (HST), has a surface temperature of approximately 3000 kelvins (K).

The luminosity of protostars varies widely, from less than 0.1 solar luminosities to several hundred times the solar luminosity, depending on the protostar's mass and stage of development. During the proto-stellar phase, the primary source of luminosity is the release of gravitational energy as the protostar contracts. This process, known as the Kelvin-Helmholtz mechanism, is distinct from the nuclear fusion that powers main-sequence stars. The protostar L1527 IRS, observed by NASA's Spitzer, exhibits a luminosity of about 2.75 solar luminosities, primarily due to gravitational energy release.

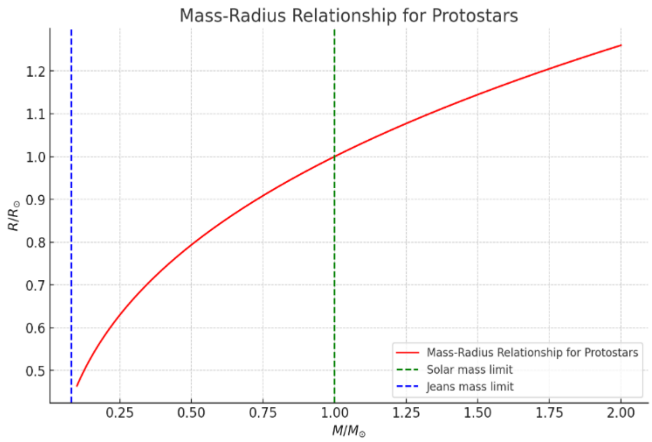



**Fig 7.2: Mass – Radius relationship for Proto-Stars**

T Tauri Stars:- T Tauri stars are located in several constellations like Taurus Constellation, Chamaeleon Constellation, Perseus Constellation, Rho Ophiuchi Constellation, Orion Constellation. These stars are young stars that have recently emerged from the proto-stellar phase and are often used as examples of late-stage protostars. T Tauri stars are typically less than 10 million years old. These stars evolve from protostars as they accumulate mass and energy, transitioning into more stable, hydrogen-fusing stars. This stars generally have masses between 0.2 and 3 solar masses.

## 8. References:

1. Astronomy and Astrophysics by Mohit Kumar Sharma & Suresh Chandra.
2. Introduction to Astrophysics by Hiralal Duorah & Kalpana Duorah.
3. Astrophysics is Easy: An introduction for the Amateur Astronomers by Mike Inglis.
4. Astrophysics For Non-mathematicians: How to picture this universe at Bizarre spacetime curvatures

by Hiten Shelar.
5. Foundations of Astrophysics by Barbara Ryden.
6. Astrophysics for Physicists, by Arnab Rai Choudhuri.
7. Fundamental Astronomy by Hannu Karttunen.
8. Cosmic Queries: StarTalk's Guide to Who We Are, How We Got Here, and Where We're Going by James Trefil.
9. Cosmos by Carl Sagan.
10. Handbook of Pulsar Nora Roberts; D. R. Lorimer; M. Kramer.
11. Narlikar, Jayant V. (1996). Elements of Cosmology. Universities Press. ISBN 81-7371-043-0.
12. "Binary and Multiple Star Systems". Lawrence Hall of Science at the University of California.
13. Haensel, Paweł; Potekhin, Alexander Y.; Yakovlev, Dmitry G. (2007). Neutron Stars. Springer. ISBN 978-0-387-33543-8.
14. EPJ Web of Conferences 43, 05001 (2013) DOI: 10.1051/epjconf/20134305001C 2013, An overview of white dwarf stars by G. Fontaine, P. Brassard, S. Charpinet, S.K. Randall and V. Van Grootel.
15. Evry L. Schatzman (1958). White Dwarfs. North-Holland Publishing Company. ISBN 978-0-598-58212-6.