Early Star Formation, Types of Supernovae and Redshifts - A Review

Vibha S Vivek[1], Sunil Joshi[2], Karthik Shastry[3]

[1]National Academy for Learning
Email: *vibhavivek15[at]gmail.com*

[2]Student, Department of Electronics & Communication Engineering, RVCE
Email: *suniljoshi.ec21[at]rvce.edu.in*

[3]Assistant Professor, Department of Physics, RVCE
Email: *karthikshastry[at]rvce.edu.in*

Abstract: ***This paper reviews early star formation (Big Bang Nucleosynthesis and Population I stars) and different types of supernovae. The H-R diagram will direct most of the writing of this paper, by differentiating between different types of stars on the spectral scale. We will also investigate the proof for the expanding universe through cosmological and relativistic redshifts. The paper will also cover important background knowledge to understand the latter further.***

Keywords: supernovae, stellar evolution, cosmology, nucleosynthesis, H-R diagram, redshifts

1. Introduction

Supernovae are explosive and luminous events that occur when a star reaches the end of its life, releasing a vast amount of energy. These phenomena momentarily outshine their galaxy [1], marking a remarkable occurrence where a single star can briefly outshine an entire galaxy, reaching a very high luminosity.

The purpose of this academic study is to explore the various astrophysical phenomena that shape our universe. We will analyse fundamental concepts such as the earliest stages of star formation, as illustrated by Hertzsprung-Russell (H-R) diagrams, and the intricate processes of stellar evolution and nucleosynthesis. We will also examine supernova's typological complexity and its crucial role in cosmic evolution. Additionally, we will explore the cosmological implications of redshifts, focusing on Type Ia supernovae with the help of the Redshift Distance Test. We hope to contribute to a greater scholarly understanding of the universe's workings through our comprehensive exploration of these celestial mechanisms.

2. Historical Significance

The first record of a supernova occurrence dates back to 185 CE by the Chinese civilisations – in particular the 'Song Dynasty'.[2] According to 'Song-Shi' (History of Song), Astronomical Treatise, Chapter 56 says - "on the first year of the Chi-ho reign period, 5th month, chi-chou (day - July 4th, 1054), a "guest star" appeared approximately several inches to the south-east of the Tian-Kuan[3] (also known as the red-giant star, Aldebaran of the Taurus constellation).[4]

In the same century, around the same time as that of the Song Dynasty, in present-day Chaco Canyon in northern New Mexico, United States, Hopi and Navajo tribes painted what appeared to be a "guest star" into a protected rock overhang[5]. The descriptions of this guest star visibly matched that of which was given by the Chinese.[6] The orientation and the phase of the moon and the guest star are exactly what they would have been on that day when the Song Dynasty reported their guest star – suggesting that they are the same[7].

The "guest star" mentioned in the above annals is none other than supernova 'SN 185'[8]. This was the first supernova recorded. It had appeared in the direction of Alpha Centauri between the constellations of Circinus and Centaurus. The remnant of the supernova is known as the 'Crab Nebula Supernova'[9]. It is a supernova pulsar wind remnant in the Taurus constellation. The supernova remnant (SNR) of the guest star – SN 185, is called RCW 86[10]. After the appearance of the "guest star" (SN 185), there have been only two other similar objects seen in our Galaxy. (see Table 1.1 and Table 1.2).

Table 1.1: The two most recent occurrences of supernovae in our history, recorded by Tycho Brake in 1572, and Johannes Kepler in 1604.[11]

The Occurrence of the Supernova	*Description*
1572, in the constellation Cassiopeia.	It was observed by the Danish astronomer Tycho Brake.The "guest star" was bright enough to be visible in broad daylight.
1604, in the constellation Ophiuchus.	It was studied and observed by Tycho's student- Johannes Kepler.The observed "guest star" was not as bright as Tycho's "guest star".However, it was as bright and visible as Jupiter.

With the invention of telescopes in the 1920s, the appearance of supernovas increased and was visible in many galaxies quite often. The brightness levels and amounts of energy being released prompted Fritz Zwicky to label these said guest stars as "supernovae"[12].

Observations of supernovae – especially Type Ia - have also indicated, in recent years, that 70% of the energy in the universe is something never before observed - antimatter, dark matter and energy; with properties that were imagined in the most speculative of our theories of nature[13].

Table 1.2: List of Historical Supernovae visible to the naked human eye, (Joglekar H., Sule A., Vahia M N., 2015, In search of Indian Records of Supernovae, pg 2.)[14]

	Year	Date	Con	Mag	Remnant	Observed/Comments	RA	Dec
1	2241 BC			-10		Dubiously listed in some source		
2	352 BC					Chinese; "first such record"		
3	185 AD		Cen	-2	G315.4-2.3	Chinese	14:43.1	-62:28
4	369 AD					Chinese		
5	386 AD		Sgr		G11.2-0.3?	Chinese		
6	393/ 396 AD		Sco	-3	SNR 393	Chinese	17:14	-39.8
7	1006 AD		Lup	-10	SNR 1006	Arabic; also Chinese, Japanese, European	15:02.8	-41:57
8	1054 AD	4-Jul	Tau	-6	M1	Chinese, North American (?); also Arab, Japan	05:34.5	+22:01
9	1181 AD	6-Aug	Cas	-1	3C 58	Chinese and Japanese	02:05.6	+64:49
10	1572 AD	6-Nov	Cas	-4	Tycho SNR	Tycho Brahe's SN	00:25.3	+64:09
11	1592 AD		Cas			Korean; probably Nova		
12	1604 AD	9-Oct	Oph	-3	Kepler SNR	Johannes Kepler's SN	17:30.6	-21:29

3. Formation of Population I Stars

3.1 Introduction

150 million years ago, the period of the Dark Ages began[15]. The only matter with quantifiable mass available during this era were protons, neutrons, etc. These particles exert gravity as did the dark matter present in the universe[16]. When the universe had cooled further, the traces of hydrogen and helium accumulated in denser regions forming molecular gas clouds, and as the matter was distributed randomly some regions became denser than others. The sizes of the clouds varied greatly and can be scaled to over light years in size[17].

Based on kinetic molecular theory[18], we know that the atoms and molecules present in a gas are always in constant and random motion. These particles in a gas exert equal pressure (outward force) in all directions. However, we know that all matter exerts gravity (inward force). Likewise, in molecular clouds of hydrogen and helium, two forces were acting on the same cloud in opposite directions. Let's assume that **E1** is the kinetic energy of the gas pressure and **E2** is the gravitational potential energy. In mathematically incomplete terms, when **E1 ~ E2**, or when the forces acting on the gas cloud are balanced, the nebula (gas clouds) will remain in hydrostatic equilibrium.

Now if **E1 << E2**,it will become unstable and collapse in itself once the critical mass of the gas cloud is exceeded. This critical mass is known as Jeans' mass and is a function of a gas cloud's temperature and density. As the mass of the cloud increases, along with an increase in the critical radius of the cloud (Jeans' length), the bigger it becomes, and the colder the temperature of the same drops, the cloud will become less stable against gravitational collapse. When a molecular cloud does exceed the threshold of Jeans' mass, a gravitational collapse of the cloud occurs[19]. The cloud starts to spin rapidly as it contracts to conserve angular momentum[20]. Centrifugal force (which is a recombination of the gravitational force as well as the nebula's rotation from the mass of the nebula) increases the spin of the nebula and flattens out the poles[21]. This collapse continued for millions of years.

At about 200 Ma ~ 1 Ga after the first atoms formed, the period of Reionization[22], which is the second of the two major phase transitions of gas in the universe, started. Even though the majority of baryonic matter was in the form of hydrogen and helium, reionization strictly refers to that of the element- hydrogen[23].

A problem faced during this epoch was that unionized material did not emit light.[24]However, due to the quantum-mechanical transition between hyperfine energy levels in hydrogen (spin-flip transition), microwave radio radiation with an approximate wavelength of 21 cm is emitted.[25] This enables the study of the epoch in the Universe, ranging from the period shortly after the Universe became transparent and neutral around 380,000 years ago, through the initiation of hydrogen reionization in stars approximately 400 million years later, to complete reionization around 1 billion years of age.[26]

The gas clouds become denser and their temperatures increase exceedingly high and do not allow for neutral atoms to exist. This process continues until atoms are re-ionised into plasma. Eventually, the inner region of the cloud is so dense and so hot, that the outward pressure increases the gas pressure and prevents further collapse from gravity. This outward pressure also allows for a temporary hydrostatic equilibrium[27]. This object is called a protostar[28]. Furthermore, this protostar continues to accrete mass and increases the gravitational potential energy. When the accretion of mass is sufficient, the collapse then resumes and inward pressure further increases. As a result of the preceding statement, temperatures rise to 10^9 degrees and above, until the temperature is hot enough for a nuclear fusion to occur[29]. These nuclear fusions generate tremendous amounts of energy and create stars.

This is how a star is born. During the Reionization epoch, the earliest stars- Population I- were formed. The most distant observable galaxies and stars date to this era.

2.2 Fundamental Interactions

The four fundamental forces of nature are gravity, electromagnetism, weak interaction, and strong interaction[30]. Gravity was initially derived from the classical field of Newtonian gravitation, but modern physics has revealed that the gravitational field is attributed to the curvature of space-time[31]. The remaining three interactions are discrete quantum fields and are mediated by elementary particles described by the Standard Model.[32]

Magnetic force is carried by photons and creates electric and magnetic fields[33]. Gluons carry strong interaction, responsible for quarks binding to form hadrons and creating nuclear force[34]. The weak interaction is carried by W and Z bosons, mediating radioactive decay[35]. Strong and weak forces are responsible for all nuclear processes.[36]

Electric forces try to break the nucleus while strong nuclear forces try to bind the nucleus and keep them together. This understanding was only possible due to the discovery of the nucleus by Rutherford[37]. Not long after the discovery of a “positive” nucleus and electrons that “revolved” around them, James Chadwick made a significant discovery that increased our understanding of the atomic structure[38]. He discovered a neutral particle known as the “neutron”.

$$Be_4^9 + He_2^4 \rightarrow {}_6^{12}C + n_0^1 \quad (2)$$

Equation 2: Chadwick’s discovery of “neutron” after bombarding beryllium with α-particles[39].

Once this discovery was made, and it was identified that protons and neutrons together formed the nucleus of the atom, a “strange” force (today known as the nuclear force) was needed to overcome the electrostatic repulsion, a manifestation of electromagnetism, of the positively charged particles (proton-proton repulsion)[40]. If this force did not bind the nucleons together, then the nucleus could not exist. This force also had to be strong enough to squeeze the protons into a volume of 10^-15m[41].

2.3 Mass-energy Equivalence and Energy Binding Curve

According to Einstein's theory of special relativity, energy and mass are interrelated[42]. This means that every substance has energy due to its mass, and when energy is lost during chemical reactions, nuclear reactions, and other energy transformations, the system will also lose a corresponding amount of mass. This energy, along with the mass, can be released to the environment as radiant energy, such as light, or as thermal energy. If a substance loses delta m of its mass, an equivalent amount of delta E of energy is produced[43].

$$\Delta E = (\Delta m)c^2 \quad (3)$$

Equation 3: Einstein’s energy-mass relation, depicting the relationship between mass and energy in a rest frame, or relativistic mass and relativistic energy in a moving frame. This equation unifies the law of conservation of energy and mass.

It has been found that the rest mass of the nucleus of a stable atom is always less than the sum of the masses of its constituent nucleons in the free state[44]. Mass defectis the difference between the sum of masses of the nucleons constituting a nucleus and the rest mass of the nucleus[45].

$$\Delta m_d = Zm_p + (A - Z)m_n + m_N$$

(4)Equation 4: Mass defect equation where m_p is the mass of the protons, m_n is the mass of the neutrons, m_N is the mass of the nucleus, Z is the free protons and $(A - Z)$ is the free neutrons which come from infinity[46].

This “disappeared mass” reappears as equivalent energy which is liberated during the formation of the nucleus. This energy is the sole reason for the binding of protons and neutrons in the nucleus. Conversely, an amount of energy is required to break the nucleus into protons and neutrons and this energy is known as the “binding energy”[47] of the nucleus. Electron binding energy is negligible to nucleon binding energy.

$$E_b = [\, Zm_H + (A - Z)m_n + m({}_Z X^A)]\, c^2 \quad (5)$$

Equation 5: Expression for the nuclear binding energy of an atom : ${}_Z X^A$ in terms of atomic and neutron mass[48].

$$E_{bn} = \frac{E_b}{A} = \frac{[Zm_p + (A - Z)m_n - M_N]}{A} \times 931.5\ MeV \quad (6)$$

Equation 6: Expression for binding energy per nucleon (all masses expressed in amu)[49].

An important graph to understand is the Binding Energy Curve. It is a graph where the average binding energy per nucleon is plotted against mass number (A)[50]. Some important inferences from the energy curve -

1) The flat maximum of the curve (A ~ 50 – 80) corresponds to an average BE/nucleon of about 8.5 MeV, indicating these nuclides are the most stable
2) Elements having > A = 80, the average BE/nucleon decreases slowly and drops to ~ 7.6 MeV for U^{238}, these lower values fail to overcome Coulombian repulsion. This accounts for the radioactivity of elements beyond Bi^{209}.
3) H^2 has an average BE/nucleon ~ 1.1 MeV and the nuclei with A < 20 are less stable.
4) O^{16}, C^{12} and He^4 have subsidiary peaks which imply that even-even nuclei are more stable than their immediate neighbours.

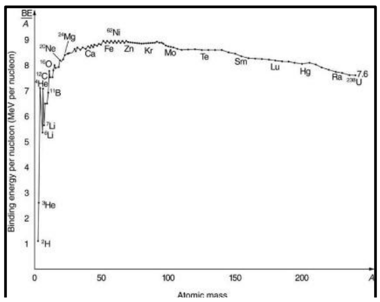


Figure 1: A graph of average binding energy per nucleon (BE/A), (14.5 Binding energy – Radioactivity and Nuclear Physics, Texas Gateway).

Classification of Stars and the H-R Diagram

After the first observations of stars in the night sky, astronomers decided to categorize them based on colour classes- white, yellow, red and deep red. This was further refined and broken up into letters- A-D for white, E-L for yellow, M for red and N for deep red. Astronomers then decided to categorize stars based on their surface temperatures, however, the letter system retained as it had eased to process of categorizing the stars.[51] The letters for categorizing stars based on surface temperatures are O- 30,000 K, B- 10,000 - 30,000 K, A- 7,500 - 10,000 K, F- 6,000 - 7,500, G- 5,200 - 6,000 K, K- 3,700 - 5,200, M- 2,400 - 3,700 K. This system was derived from Wien's displacement law which states that black body radiation has different peaks of temperature at different wavelengths inversely proportional to the temperature.[52]

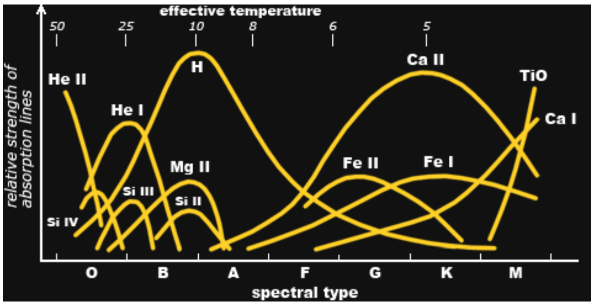


Figure 2: This diagram shows absorption lines of different elements (until Fe II) for different spectral types of stars under their effective temperatures. (2013, MacEvoy Bruce, Astronomical Files from Black Oak Observatory.)

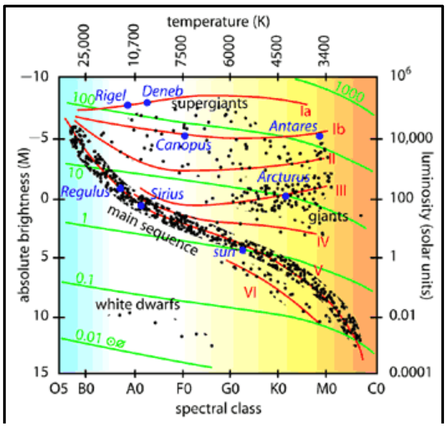


Figure 3: H-R Diagram (2001, BBC – The Guide to Life, Universe and Everything – The Universe / General Astronomy).

This relationship between the stars' absolute magnitudes (measure of a star's luminosity on the inverse logarithmic magnitude scale) versus their effective temperatures (stellar classifications) can be represented through a scatter plot of stars. This diagram is known as the Hertzsprung-Russell Diagram.[53] The original diagram initially plotted stars with the x-axis as the spectral type of stars and the y-axis showed the absolute visual magnitudes. Another form of the H-R diagram is the "theoretical Hertzsprung-Russell Diagram" or the temperature-luminosity diagram. In the latter, the effective temperatures (plotted from high to low) are marked on the x-axis and the luminosity of the stars is marked on the y-axis.

There is significant evidence we can gather from the H-R diagram. The majority of the stars occupy the region along the line called the main sequence. These main sequence stars or dwarf stars are constantly fusing hydrogen in their core. Supergiants occupy a far top-right region of the diagram. They are among the most massive and most luminous stars.[54]

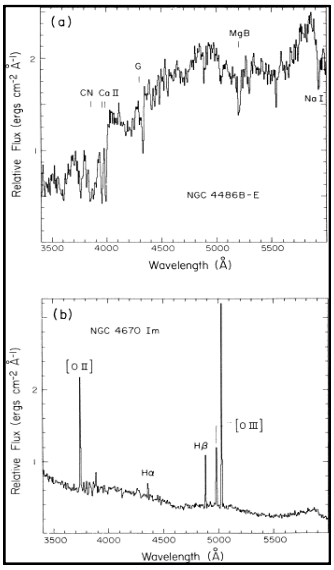


Figure 4: Atomic spectral lines of Population I Stars. (a) – NGC 4486B, with absorption features of Ca, Na, Mg, CN molecule, and G-band blend of Fe and Cr. (b) – NGC 4670, H and O emission lines. (P. Huchra John, 2003, Encyclopaedia of Physical Science and Technology – Third Edition)

Life Cycle of a Star

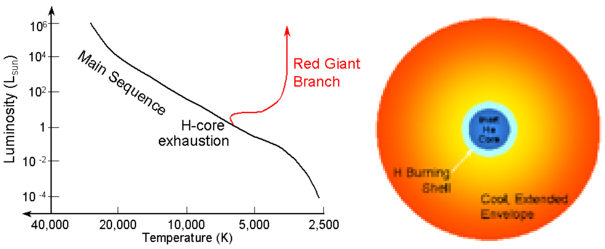
The mass of a star is very crucial in determining the fate of its life. The amount of gas that was collected and coalesced is directly proportional to the size of the star as it serves as the star's fuel. When two light nuclei combine to form a heavier nucleus, the reaction is called nuclear fusion. This adherent understanding of thermonuclear fusion was due to the discovery of the nucleus and the neutron. As we know, when two light nuclei collide together with enough energy (> nucleon binding energy), they form a heavier nucleus- strong nuclear forces bind the two together and a portion of the mass is converted into pure energy. Only by colliding nuclei together and fusing them in its hot core can a star counteract the effects of gravity releasing greater outward energy, relentlessly crushing it inward. This implies that the amount of matter a star has is directly proportional to its fuel. It also signifies the fate of a star. The "fuel" (generated by fusing H into He during the Main Sequence) depends on the total mass and luminosity of the star.[55]

$$\tau_{nuc} = \frac{f \varepsilon M c^2}{L} \quad \textbf{(7)}$$

Equation 7: This function is called the nuclear timescale, (2006, W. Pogge Richard, Astronomy 162 – Introduction to Stars, Galaxies & the Universe). Using the nuclear timescale and the mass-luminosity relation $L \propto M^4$, we can conclude the timeline of a main sequence star, $t_{Ms} \sim \frac{1}{M^3}$.[56]

Fate 1:

A low-mass star or an average star ~ one solar mass. The fusion reactions in a low-mass star begin with two protons fusing, followed by a subsequent beta decay which yields a proton and a deuteron. This thermonuclear fusion occurs for billions of years until all of the Hydrogen has fused to form Helium in its core. During this course, the star maintains a relatively steady temperature, size and luminosity. As H starts to run out, the core simultaneously shrinks in size which causes the remaining H to fuse rapidly. These massive energy radiations generated by the latter will increase the size of a star to produce a red giant.[57]



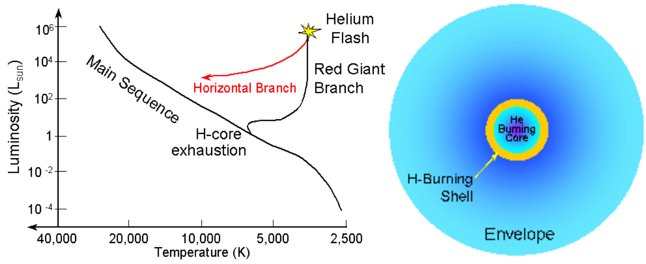
(a) (b)

Figure 5: (a) – H-R diagram depicting a main sequence star entering red giant phase, (b)- a visual representation of Hydrogen exhaustion in a star. (2006, W. Pogge Richard, Astronomy 162 – Introduction to Stars, Galaxies & the Universe)

$$
\begin{aligned}
{}^{4}He + {}^{4}He &\rightleftharpoons {}^{8}Be \\
{}^{8}Be + {}^{4}He &\rightarrow {}^{12}C + \gamma \\
{}^{12}C + {}^{4}He &\rightarrow {}^{16}O + \gamma \\
{}^{16}O + {}^{4}He &\rightarrow {}^{20}Ne + \gamma
\end{aligned} \quad \textbf{(8)}
$$

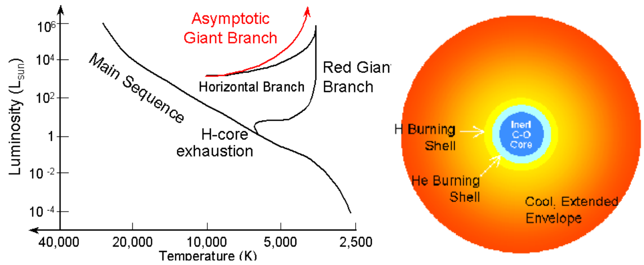
(See Figure 5) A main sequence star of low mass will start to climb the Red Giant Branch and the end-point is ultimately a red giant star. A red giantmaintains the new temperature and luminosity for a time a lot less than the average star ~ 1 billion years. The core continues to burn hydrogen while rapidly shrinking and gaining tremendous heat. When the star reaches the tip of the Red Branch, the temperature of the core is ~ 100 million Kelvin and this triggers He to enter a phase known as the Helium Flash. This ignites the triple-alpha processes (see equation 8).[58]

This Helium now acts as the star's new source of fuel, which helps the star to regain its Hydrostatic and Thermal equilibrium. (See Figure 6) As the star pulsates through its new energy reserve, the stars enter the Horizontal branch. Here, the star continues to increase its temperature yet the size and luminosity of the star decreases. It becomes smaller and bluer. Inside the envelope of the star, H is a burning shell enclosing the burning core of He. The triple-alpha process is very inefficient in producing energy, making it last ~ 100 Myr. Once the core of the star is predominantly Carbon and Oxygen, with thin shells of He and H enclosing it. The C-O core is however too cool to ignite a carbon fusion. When the He is exhausted and triple-alpha processes cannot continue, the C-O core collapses, and the star enters the Asymptotic Giant branch (see Figure 7). The star pulsates due to the consequence of triple-alpha consequences being temperature sensitive, and as a result, small changes in T lead to large changes in fusion energy output.[59]



(a) (b)

Figure 6: H-R diagram depicting a Red Giant entering a horizontal branch, (b)- a visual representation of the Horizontal Branch Phase. (2006, W. Pogge Richard, Astronomy 162 – Introduction to Stars, Galaxies & the Universe)



(a) (b)

Figure 7: H-R diagram depicting an Asymptotic branch, (b)- a visual representation of the Asymptotic branch Phase. (2006, W. Pogge Richard, Astronomy 162 – Introduction to Stars, Galaxies & the Universe)

As the core of a star continues to shrink in size, it eventually becomes as small as the Earth. This causes the star's outer layer to slowly separate due to fast winds in space. If the core is not hot enough, it can't undergo Carbon-Carbon fusion, which usually occurs at a temperature of 650 million K. This creates a separation between the core and outer layer, resulting in an expanding shell of gas called a planetary nebula. This nebula is made up of the remnants of the star's outer layers that have been ionized. Eventually, this material will be used to create new stars. On the H-R diagram, the hot C-O core is exposed and moves quickly to the left at nearly constant luminosity and increasing temperature.[60]

As the contracting C-O core becomes extremely dense, a new gas law is introduced to understand its behaviour. The C-O core consists of electrons, which belong to the category of Fermions. Fermions, like hadrons, follow Pauli's exclusion principle.[61]In general, an ensemble of non-interacting fermions, which is also known as a Fermi gas, can treat each particle independently with a single-fermion energy given by the purely kinetic term.,

$$E = \frac{p^2}{2m} \quad \textbf{(10)}$$

In a fermion gas where thermal effects dominate, most of the electron energy levels are unfilled, allowing for the electrons to move freely into these states. As the particle density increases, the lower energy states are progressively filled by electrons, and at low temperatures, additional electrons are forced to occupy higher energy states. Degenerate gases resist further compression, as the electrons cannot move to already-filled lower energy levels due to the Pauli exclusion principle. Since electrons cannot release energy by moving to lower energy levels, no thermal energy can be extracted. However, the momentum of the fermions in the fermion gas generates pressure, known as "degeneracy pressure".[62]

The following equation gives the electron degeneracy pressure,

$$pisp_x = \frac{2}{5}(3\pi^2)^{\frac{2}{3}}\frac{h^2}{2m_e}\left(\frac{1}{v}\right)^{\frac{5}{3}} \quad \textbf{(10)}$$

When the collapse of the core halts, the star is known as a white dwarf. This electron degeneracy pressure will halt the star from gravitational core collapse if its mass is < Chandrashekar limit (1.41 times solar mass). This pressure prevents the white dwarf star from collapsing further.[63]

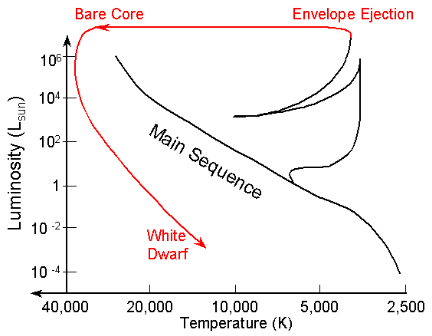


Figure 8: H-R diagram depicting envelope ejection and formation of white dwarfs after star completes asymptotic branch, (2006, W. Pogge Richard, Astronomy 162 – Introduction to Stars, Galaxies & the Universe).

Fate 2:
A high-mass star starts its formation with a much heavier gas cloud. High amounts of mass propel higher inward force towards the core of the star causing the temperatures of the stars to increase its temperature significantly. A hotter star = faster fusion. This generates tremendous outward pressure to counteract the gravitational force. This will result in a main sequence star that is massive and blue. On the alphabet scheme, stars under the O & B category fall into massive stars. On the contrary to low-mass stars, high-mass stars have short spans of life ~ 10 million of years.[64]

In the main sequence phase, the Hydrogen burns to produce Helium via processes called the **'CNO cycle'**.[65] The resulting end is a build-up of a He core (just like average stars) and lasts ~ 10 myr.

$$\begin{aligned} {}^{15}N + {}^{1}H &\rightarrow {}^{16}O + \gamma \\ {}^{16}O + {}^{1}H &\rightarrow {}^{17}F + \gamma \\ {}^{17}F &\rightarrow {}^{17}O + e^{+} + \nu_e \\ {}^{17}O + {}^{1}H &\rightarrow {}^{14}N + {}^{4}He \end{aligned} \quad \textbf{(11)}$$

This CNO cycle can also branch off to this,

$$\begin{aligned} {}^{15}N + {}^{1}H &\rightarrow {}^{16}O + \gamma \\ {}^{16}O + {}^{1}H &\rightarrow {}^{17}F + \gamma \\ {}^{17}F &\rightarrow {}^{17}O + e^{+} + \nu_e \\ {}^{17}O + {}^{1}H &\rightarrow {}^{14}N + {}^{4}He \end{aligned} \quad \textbf{(12)}$$

After the core is exhausted from utilising hydrogen as its fuel, the star climbs horizontally on the H-R diagram up the Red Supergiant branch. The star then takes ~ 1 myr to cross the branch on the diagram.[66]

When the star reaches the tip of the Red Supergiant Branch, the temperature of the core is ~ 170 million Kelvin and this triggers He to enter a phase known as the Helium Flash. A C-O core starts to build up in the centre, with shells of H & He surrounding the same. With close reference to the H-R diagram, the star detours to the left of the diagram and enters the branch of a Blue Supergiant. When the star is exhausted, at the core, the C-O core gains tremendous heat and enters into core collapse. As remaining H & He continue to burn in the surrounding shells the star becomes Red Supergiant again. The temperature of the core is now > 600 million Kelvin, with a density > 120,000 g/cc. This temperature is sufficient for the initiation of carbon-carbon fusion (equation 13).[67]

$$\begin{aligned} {}^{12}C + {}^{12}C &\rightarrow {}^{16}O + 2\,{}^{4}He \\ &\rightarrow {}^{20}Ne + {}^{4}He \\ &\rightarrow {}^{23}Na + p^{+} \\ &\rightarrow {}^{23}Mg + n \\ &\rightarrow {}^{24}Mg + \gamma \end{aligned} \quad \textbf{(13)}$$

$$\begin{aligned} {}^{16}O + {}^{16}O &\rightarrow {}^{24}Mg + 2\,{}^{4}He \\ &\rightarrow {}^{28}Si + {}^{4}He \\ &\rightarrow {}^{31}P + p^{+} \\ &\rightarrow {}^{31}S + n \\ &\rightarrow {}^{32}S + \gamma \end{aligned} \quad \textbf{(14)}$$

These reactions form an inert O-Ne-Mg core. However, these thermonuclear fusion reactions are very inefficient as they lose energy through many neutrinos and the entire phase lasts for ~ 1000 years before Carbon is exhausted. Once the O-Ne-Mg core is exhausted, the core then burns the following elements in order- Neon, Oxygen and Silicon. The core of the star is now inert Ni-Fe. However, nuclear fusion stops at the heaviest element inside a star- Iron. Further fusion will no longer produce anything as iron is a relatively stable element (we know about this because of the binding energy curve).[68]

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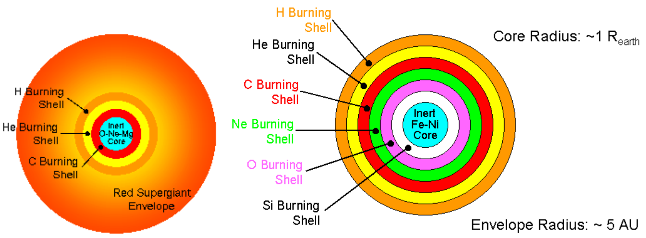
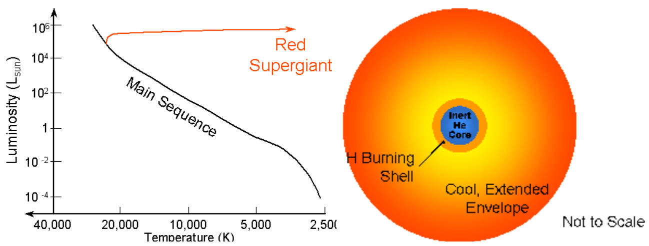


(a) (b)

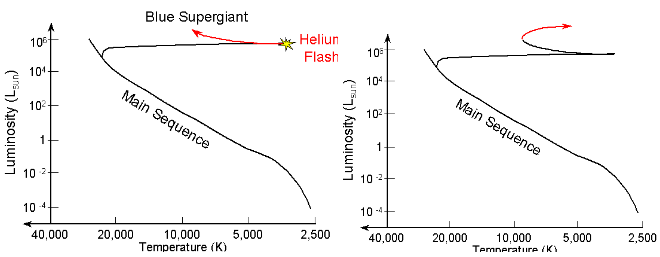
Figure 9: (a) – A diagram showing the initial stages of C-C fusion, (b) – A diagram showing C-C until Silicon is the burning shell surrounding the Inert Fe-Ni core, (2006, W. Pogge Richard, Astronomy 162 – Introduction to Stars, Galaxies & the Universe).

From the energy binding curve, we concur that the fusion of light elements results in the release of nuclear binding energy. Iron has the most tightly bound nucleus and hence, any fusion of nuclei lighter than iron releases energy and any fusion of nuclei heavier than iron absorbs energy. Iron marks a clear distinction between nuclear processes- fusion and fission. This proves that iron is the heaviest element that can sit inside the core of a star. As further fusion does not take place, gravitational forces crush the core of the star and it becomes denser and hotter. The Fe core exceeds a mass of 1.21 times the solar mass and the red supergiant explodes. This explosion releases all the heavy metals into space.[69]



(a) (b)

Figure 10: (a) - H-R diagram showing a main sequence star entering Red Supergiant, (b) – visual depiction of Red Supergiant, (2006, W. Pogge Richard, Astronomy 162 – Introduction to Stars, Galaxies & the Universe).



(a) (b)

Figure1: (a) – H-R diagram showing a Red Supergiant becoming a Blue Supergiant, (b) – H-R diagram for He core exhaustion of a Blue Supergiant, (2006, W. Pogge Richard, Astronomy 162 – Introduction to Stars, Galaxies & the Universe).

Supernovae: Origin and Types

Supernovae are considered to be one of the most violent and energetic phenomena in the universe. The burst of energy produced by these supernovae is so tremendous that elements heavier than iron can be synthesised. The core of Fe will stop growing in size after its mass is 1.2-1.4 * solar mass.[70] The core has an exceedingly high temperature of> 10 billion Kelvin with a high density of ~ 10^7 g/cc.[71] Two important energy processes occur during this phase. Both processes rob the core of energy, hastening its collapse.[72]

Photodisintegration, also known as a photonuclear reaction or photo transmutation, is a nuclear process in which an atomic nucleus absorbs a high-energy gamma ray. As a result, the nucleus enters an excited state and immediately decays by emitting a subatomic particle. The incoming gamma ray forcefully knocks out one or more neutrons, protons, or particles from the nucleus. These reactions are commonly referred to as (γ,n), (γ,p), and (γ,α). This process effectively reverses the previous fusion and drains energy in the form of high-energy photons out of the system.[73]

Neutronization is the process of creating neutrons by combining protons and electrons. This process can occur in various situations. However, the term "neutronization" typically refers to the process that happens during a core collapse, where high density causes nucleons to unbind from nuclei. At this point, protons and electrons quickly combine, leading to a neutronization burst. Each combination also produces a neutrino, which is the source of the large number of neutrinos released by supernovae.[74]

During the process of star death, the Fe core undergoes core collapse until it reaches a density of approximately 2.4x1014 g/cc.[75] As a result, the core bounce creates supersonic shockwaves that blast out into the star. These shock breakouts trigger a massive amount of neutrinos to leave the star system, which in turn triggers a supernova. The remains of a supernova are known as Supernova Remnants. The supernova envelope, which is rich in metals and heavier elements, expands ~ 10,000 km/sec. This expansion heats the interstellar medium, causing it to shine as an ionized nebula. The heavy elements are distributed into space and cosmic rays are accelerated.[76]

Table 8.1 Classification with a description of the types of SNRs observable in the universe.[77]

	Type	*Description*
1	Shell-type	When a star dies and explodes in a supernova, the resulting shockwave travels through space and heats any interstellar material it encounters. This leads to the formation of a hot shell of material in space. In this type of supernova remnant, we observe a ring-like structure due to a phenomenon known as limb brightening. This occurs because there is more hot gas in our line of sight at the edges of the shell than when we look through the middle. Eg: Cassiopeia A
2	Crab-like	These remaining celestial bodies are also known as pulsar wind nebulae or plerions. They are distinct from the shell-like remnants as they appear more like a "blob" than a "ring." The nebulae contain high-energy electrons that are ejected from a pulsar located at the centre. These electrons interact with the magnetic field resulting in a process known as synchrotron radiation, which generates X-rays, visible light, and radio waves. Eg: Crab Nebula
3	Composite	These remnants are a hybrid of shell-type and crab-like remnants, and depending on the part of the electromagnetic spectrum used to observe

		them, they can appear to be shell-like, crab-like, or both. There are two types of composite remnants: thermal and plerionic. Eg: Pulsar wind nebula - G11.2-0.3
4	Thermal composites	These remnants are a hybrid of shell-type and crab-like remnants, and depending on the part of the electromagnetic spectrum used to observe them, they can appear to be shell-like, crab-like, or both. There are two types of composite remnants: thermal and plerionic.
5	Plerionic composites	These supernova remnants (SNRs) have a crab-like shape in both radio and X-ray wavebands, but they also possess shells. The X-ray spectra in the centre of the SNRs do not exhibit spectral lines; however, the X-ray spectra near the shell do have spectral lines.

Classification of Supernova

Supernovae are classified based on their light curves and absorption lines of different chemical elements that appear in their spectra. The first classification of supernovae is based on whether the supernova's spectrum (Minkowski-Zwicky classification) contains the Balmer series. If yes, it is classified as Type II. If no, it is classified as Type I.

Type I:

Type I is further classified into Type Ia, Ib and Ic, based on ionised silicon absorption lines. Type Ia has singly ionised absorption lines of Silicon (Si II). Type Ib and Ic do not. Type Ib shows a non-ionised Helium (He I) line whereas Type Ic does not.[78]

Type Ia supernovae are often associated with binary star systems where one of the stars is a white dwarf. The white dwarf accumulates enough matter from a stellar companion such that the density and pressure increase the core's temperature enough to ignite a thermal runaway process through C-C fusion. The white dwarf accretes matter from its companion until it > the Chandrashekar limit[79] (1.4 * solar mass for a non-rotating star) and will collapse until it can no longer the bulk of its mass through electron degeneracy. Two white dwarfs can also merge, where the combined mass still exceeds the Chandrashekar limit and hence causes an SN type Ia supernova (double-degenerate model). It exhibits a characteristic light curve, with a rapid rise in brightness followed by a slower decline.[80]

Figure 12: A rapid brightening and slower fading of a supernova explosion in the galaxy NGC1365 – SN Type Ia, (2013, Klotz Alain and Hook Richard, ESO)

Type Ib supernovas gradually show lines of oxygen, calcium and magnesium with age. Type Ic follows a similar trend. Both supernovas are produced by the core collapse of massive stars whose outer burning shells of Hydrogen and Helium are lost to interstellar winds or accretion of matter in a companion star. Type Ib progenitors lose most of their Hydrogen envelope whereas Type Ic progenitors lose their Hydrogen and Helium envelope. These supernovas are formed due to rare occurrences of massive stars, hence observations of such supernovas are lesser compared to Type II. Type Ib and Ic (collectively called Type Ibc) are known as stripped core-collapse supernovae. Since they share a similar mechanism to Type II, they are known as core-collapse supernovae.[81]

Type II:

When a star's mass is in the range of 8 – 50 * solar mass[82], the core collapse leads to the production of a Type II supernova. The spectral lines of these supernovae contain hydrogen, and they are the consequences of massive stars. When the iron-nickel inert core of the star produces no outward thermal pressure to counteract gravity, the massive star will collapse. As the inert core's mass goes beyond the Chandrashekar limit of ~ 1.4 * solar mass, electron degeneracy pressure will no longer counteract gravitational pressure. When a star exhausts its fuel, its core implodes due to gravity. However, the collapse is prevented by the repulsive nuclear force and neutron degeneracy, causing the implosion to rebound and expand outward. This expansion generates a powerful shock wave capable of disrupting the overlying stellar material and accelerating it to escape velocity, resulting in a supernova explosion. During the explosion, the extremely high temperatures and pressures that exist for a brief period allow for the production of elements heavier than iron.[83]

Depending on the initial mass of the star, the remnants of the supernova will either form a black hole or a neutron star.[84]

Fusion energy release is limited by the binding energy that holds atomic nuclei. With each step, heavier nuclei are produced, releasing less energy. Carbon burning and onwards cause significant energy loss via neutrino production, leading to a higher reaction rate. Nickel-56 is produced, decaying into cobalt-56 and iron-56.[85] Iron and nickel have the highest binding energy per nucleon, so energy cannot be produced at the core by fusion, causing a nickel-iron core to grow. This core is under immense gravitational pressure, supported only by the degeneracy pressure of electrons due to the Pauli exclusion principle. Fusion energy release is limited by the binding energy that holds atomic nuclei. With each step, heavier nuclei are produced, releasing less energy. Carbon burning and onwards cause significant energy loss via neutrino production, leading to a higher reaction rate. Nickel-56 is produced, decaying into cobalt-56 and iron-56. Iron and nickel have the highest binding energy per nucleon, so energy cannot be produced at the core by fusion, causing a nickel-iron core to grow. This core is under immense gravitational pressure, supported only by the degeneracy pressure of electrons due to the Pauli exclusion principle.[86]

Stars with mass below 20 M⊙[87] result in a neutron star after a core collapse, while those above form a black hole. The maximum mass limit for core collapse is 40-50 M⊙[88]. If a star's mass is greater, it collapses into a black hole without forming a supernova. However, these limits are uncertain due to uncertainties in models of supernova collapse.

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An important thing to note is the Tolman-Oppenheimer-Volkoff limit[89], which is analogous to the Chandrashekar limit. This is the maximum mass of a neutron star ~ 2.2 to 2.9 * solar masses, at which the gravitational pull is balanced with the outward electron degeneracy pressure. Once the limit is exceeded, it will collapse into a denser form which is most likely a black hole.[90]

$$\frac{dP}{dr} = -\frac{Gm}{r^2}\rho\left(1+\frac{P}{\rho C^2}\right)\left(1+\frac{4\pi r^3 P}{mc^2}\right)\left(1-\frac{2Gm}{rc^2}\right)^{-1} \quad \textbf{(15)}$$

Equation 15: r is the radial coordinate, $\rho(r)$ is the density, $P(r)$ is the pressure, $m(r)$ is the mass, G is Gravitational constant and c is thespeed of light.

The gravitational binding energy of the star with radius r and total mass$M$ can be computed by equation 16.

$$\delta M = \int_0^R 4\pi r^2 \rho \left(1 - \frac{1}{\sqrt{1-\frac{2Gm}{rc^2}}}\right) dr \quad \textbf{(16)}$$

Type II supernovae can be classified into two different categories based on their light curves. Type II-L supernovae feature a steady decline in brightness following their peak, while Type II-P supernovae have a distinct flat stretch, or plateau, during their decline. During this plateau period, the luminosity decays at a slower rate. The difference in light curve shape is believed to be caused by the expulsion of most of the hydrogen envelope of the progenitor star in the case of Type II-L supernovae.[91]

Type IIn supernovae are denoted by the "n" which signifies the presence of narrow or intermediate-width hydrogen emission lines in their spectra. Two examples of Type IIn supernovae are SN 1998S and SN 2005gl.[92] On the other hand, Type IIb supernovae initially have a weak hydrogen line in their spectra, which is why they are classified as Type II. However, the H emission eventually becomes undetectable, and a second peak in the light curve emerges with a spectrum more closely resembling that of a Type Ib supernova. This is how they got their name, Type IIb. The progenitor of a Type IIb supernova could have been a massive star that expelled most of its outer layers or one that lost most of its hydrogen envelope due to interactions with a companion in a binary system, leaving behind a core consisting almost entirely of helium. Examples of Type IIb supernovae are SN 1993J and SN 1987K.[93]

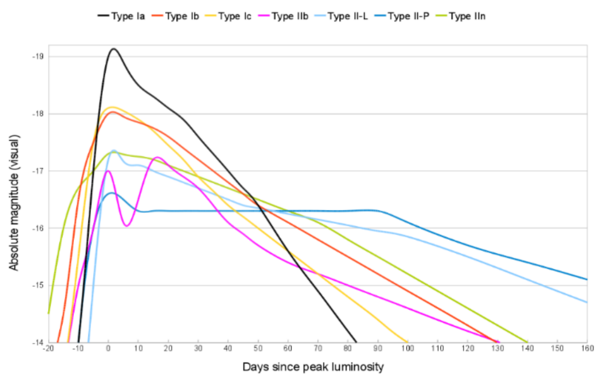


Figure 13: Light curve graph which shows different types of supernovae plotted by their absolute magnitude against time. By Lithopsian - OOCalc chart, CC BY-SA 3.0,

Redshifts

Redshift refers to the increase in wavelength and the corresponding decrease in frequency and photons for electromagnetic radiation. Through the use of a spectrograph, the light emitted by various stars and galaxies in the observable universe can indicate whether they are moving closer or further away from us and at what speed. In astronomy and cosmology, the primary causes of electromagnetic redshift are the relative motions of radiation sources, which give rise to the relativistic It is worth noting that all sufficiently distant light sources exhibit cosmological redshift corresponding to recession speeds proportional to their distances from Earth, a concept known as Hubble's law, which implies that the universe is expanding.[94]

The main reasons for redshift are the Doppler effect, gravitational redshifts and cosmological redshifts.[95]

We use the following equation (17) to compute redshifts in the universe.

$$z = \frac{\lambda_{obs}}{\lambda_{source}} - 1 \ \text{(a)} \quad \text{or} \quad z = \frac{f_{source}}{f_{obs}} - 1 \ \text{(b)} \quad \textbf{(17)}$$

Equation 17: (a) using wavelength and (b) using frequency.

To determine the redshift of an object, we need to know its frequency or wavelength range. To calculate the redshift, we must know the wavelength of the light emitted by the object while it is at rest. This means we need to know the wavelength that would be measured by an observer who is located next to the object and is moving at the same speed as the object. However, since this measurement cannot be done directly, we use the method of analysing spectral lines instead. It is important to note that redshifts cannot be calculated by looking at unidentified features whose rest-frame frequency is unknown, or by using a spectrum that is featureless or shows white noise (random fluctuations in a spectrum).[96]

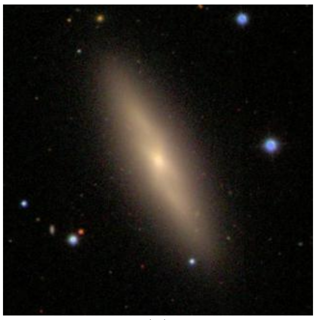
Hubble's Law:

The speed at which a galaxy moves away from us is directly proportional to the distance between us and the galaxy. This relationship is studied in the field of physical cosmology and is commonly referred to as Hubble's Law or Hubble-Lemaitre Law. By using Hubble's Law, we can determine that the universe is expanding and the cosmological principle is being fulfilled. By measuring the shift in light observed from the galaxy, we can determine its distance from us using Hubble's equation after measuring its recession velocity.

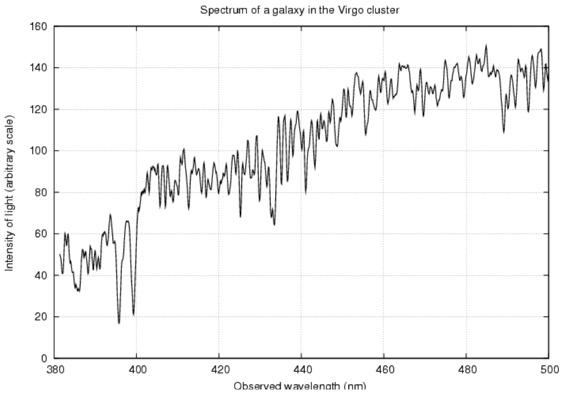
$$v = H_0 d \quad \textbf{(18)}$$

Equation 18: Hubble-Lemaitre law is a function of velocity v and distance d, where H_0 is the Hubble's Constant.

We can observe a trend in the spectra of faint galaxies. They discovered that most of these galaxies were moving away from us, and the farther a galaxy was, the faster it was moving away. This phenomenon was named the "redshift" of a galaxy because the location of spectral features usually shifts towards longer wavelengths, which is towards the red end of the spectrum.



(a)



(b)

Figure 14: (a) – Galaxy present in the Virgo Cluster, (b) – Spectrum of the galaxy in the Virgo Cluster: intensity of light vs observed wavelength, (Richmond Michael, Rochester Institute – Redshift and evidence for an expanding universe).

Special Types of Stars

Pulsars:
Pulsars are highly-magnetized, rotating neutron stars. Neutron stars are remnants of massive stars that have undergone a supernova explosion. Pulsars emit beams of electromagnetic radiation (like light or radio waves) from their magnetic poles. As the neutron star rotates, these beams appear to pulse, giving rise to the name "pulsar." Pulsars are incredibly precise timekeepers, rivalling the accuracy of atomic clocks.[97]

Quasars:
Quasars are extremely bright and energetic sources found at the centres of distant galaxies. They are powered by supermassive black holes, which are millions or billions of times more massive than our Sun. As material falls into the black hole, it forms a hot and glowing accretion disk, emitting intense radiation. Quasars can outshine entire galaxies, making them visible over vast cosmic distances. Studying quasars helps us understand the early universe and the behaviour of supermassive black holes.[98]

Redshift Distance Test[99]
As a function of redshift, the apparent magnitude of distant objects changes under different cosmologies. This is because the shape of space determines how photons spread out as they move outwards (the classic $1/d^2$ effect) and the expansion history determines how the photons are redshifted. This can be worked out under different cosmologies to derive a form akin to our regular magnitude-distance expression (equation 19).[33]

$$m - n = 5\,log\,d_L(z) - 5 \quad \textbf{(19)}$$

Equation 19: $d_L(z)$ is the luminosity distance, and depends on H_0, Ω_M, Ω_L and k. This can be plotted using distance modulus.

An astronomical object with known absolute magnitude is known as a standard candle. Standard candles can be used to measure the apparent magnitude of the object (see equation 19). Hence, standard candles are important and can be used in the RedShift Distance Test. Type Ia supernovae are approximated and classed as standard candles, even though they do not all have the same peaks of brightness. They can be made into perfect standard candles by correcting the differences in their peak luminosities which are correlated with how quickly the light curve declines after maximum light via the luminosity-decline rate relation.[100]

General Relativity
To understand more about redshifts, Einstein's general relativity is discussed. After many years of believing that the universe obeyed Euclidean geometry, Einstein's theory of general relativity changed those preconceived views. According to general relativity, space-time warps around objects with mass- meaning that three spatial dimensions curve around a fourth (x-axis, y-axis and z-axis are the spatial dimensions while time is the fourth dimension they curve around. This is extremely difficult to visualize.) This concluded that the shape of the universe is non-Euclidean. These objects with mass which warp space-time, induce a curvature that attracts all massive objects to each other. These "objects" don't necessarily have to be physical or quantifiable. Matter, radiation, momentum, pressure, energy, and particles along with the fabric of space-time, obey a set of equations known as the Einstein Field Equations. General relativity can be defined as a pseudo-Riemannian manifold with a Lorenztian signature representing spacetime, and an energy-momentum tensor representing all matter and radiation, which combine to obey the Einstein field equation[101],

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = kT_{\mu\nu} \quad \textbf{(1)}$$

Equation 1: Einstein Field Equation is a tensor equation where $\boldsymbol{R_{\mu\nu}}$is the Ricci curvature tensor, $\boldsymbol{g_{\mu\nu}}$ is the metric tensor, $\boldsymbol{T_{\mu\nu}}$is the stress-energy tensor, $\boldsymbol{\Lambda}$is the cosmological constant, and $\boldsymbol{k}$is the Einstein gravitational constant.

General relativity is essential in the context of redshifts. Let's look at both cosmological and gravitational:

- Gravitational redshifts[102]: It is anticipated that the wavelength of electromagnetic radiation undergoes elongation when ascending from a gravitational well. Photons, while endeavouring to escape, need to expend energy. However, since photons always maintain a constant speed of light, the energy loss occurs through a modification in frequency rather than velocity. When the photon's energy diminishes, there is a concurrent

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decrease in frequency. This translates to an expansion of the photon's wavelength, leading to a shift towards the red end of the electromagnetic spectrum.

- Cosmological redshifts[103]: These are also consequences of space-time warp. As galaxies move away from each other due to this expansion, the light they emit undergoes a stretching of its wavelength during its journey through space. This stretching results in a redshift, where the observed light appears more toward the red end of the electromagnetic spectrum. The concept is akin to the Doppler effect for light, with higher redshift values indicating greater cosmic distances and faster rates of recession. This fundamental principle provides astronomers with a crucial tool to estimate distances to distant galaxies and study the large-scale structure and dynamics of the universe.

4. Conclusion

Extensive research on the production of population I stars has provided us with a deeper insight into early star formation and Big Bang nucleosynthesis, which produced the observable clusters visible at night and the heavier elements much of what we see every day. Every phase transformation of a star using H-R diagrams was analysed.

This research has led to explorations of supernovae, including detailed discussions on historical evidence, the various types of supernovae, and their remnants. Moreover, redshifts have been introduced as evidence for the expanding and accelerating universe, and type Ia supernovae have been meticulously examined to provide further evidence for redshifts. All of these findings combined have brought us closer to understanding the expanding universe.

5. Future Scope

Stellar evolution is the process by which a star changes over its lifetime, transitioning through various stages dictated by its mass. This fascinating journey involves the interplay of gravitational forces, nuclear reactions, and the delicate balance between pressure and gravity within a star. Nucleosynthesis, a key aspect of stellar evolution, refers to the synthesis of elements within stars through nuclear reactions. This process not only shapes the composition of stars but also influences the cosmic abundance of elements in the universe.

Supernovae, explosive events marking the end of a massive star's life, play a pivotal role in the dissemination of heavier elements into space. These cataclysmic explosions release an enormous amount of energy, outshining entire galaxies for a brief period and contributing to the formation of new celestial bodies. The study of redshifts, a phenomenon where light from distant galaxies shifts towards longer wavelengths due to the expansion of the universe, has revolutionized our understanding of cosmic distances and the vastness of the cosmos.

Firstly, despite the comprehensive understanding of stellar evolution, certain limitations persist. Thermal runaway, a phenomenon where a star's core temperature increases uncontrollably, remains a challenge to predict accurately. This process can lead to unexpected outcomes, such as the premature depletion of a star's fuel, altering its evolutionary path. Population III stars, hypothesized as the first stars formed in the universe, are currently only theoretical. The lack of observational evidence makes it challenging to validate their existence and understand their impact on early cosmic structures.

Secondly, a very popular star, Betelgeuse – belonging to the M-12 category and a part of Population I stars, had a strange occurrence in the fall of 2019. The star being a red-supergiant, began to drastically dip in brightness. Within months, 60% of the star's luminosity had dipped. This is known as the Great Dimming. Scientists are still debating about this effect, which they initially had concurred it to be a 'pre-supernova'. Understanding stellar populations and formations, certain puzzle pieces can be solved such as this one.[104]

Thirdly, the redshift distance test, while a powerful tool for estimating distances in the vastness of the universe, has its limitations. Gravitational interactions between galaxies, peculiar velocities, and the influence of local structures can introduce uncertainties in the redshift-distance relationship. These factors may affect the accuracy of distance measurements, impacting our understanding of cosmic structures and the rate of the universe's expansion.

Advancements in studying supernovae types could potentially reshape our understanding of stellar evolution. Different types of supernovae may exhibit unique characteristics that challenge existing models and alter our perception of the Hertzsprung-Russell (H-R) diagrams, fundamental tools for classifying and understanding stellar properties. Further discoveries may open new avenues to explore the intricacies of stellar evolution, prompting revisions in established theories and enhancing our ability to unravel the mysteries of the cosmos.

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Author Profile

Vibha S Vivek is a student at the National Academy for Learning. Her research interests and passions lie in the disciplines of astronomy and biology, more inclined to astrophysics. She wishes to continue understanding the history, present, and future of the universe, particularly in the areas of dark matter, alien life, and black holes. In addition to her academic pursuits, she is also an avid footballer, with a keen interest in sports science. Vibha enjoys reviewing movies and playing the piano in her spare time. She also spends her free time writing screenplays or reading books.