BHARATA MATA COLLEGE
THRIKKAKARA, KERALA 682021
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MASTER OF SCIENCE IN SPACE SCIENCE FINAL YEAR PROJECT REVIEW REPORT

FORMATION OF WARM IONIZED GAS PHASE IN INTERSTELLAR MEDIUM OF GALAXIES

SUBMITTED TO THE MAHATHMA GANDHI UNIVERSITY

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This is to certify that Ms. Vismaya P V, 4th semester M Se Space Science student, Bharata Mata College, Thrikkakkara, Ernakulam (Affiliated to Mahatma Gandhi University, Kottayam) has completed her project work under my guidance during April 2023 to June 2023 period.

Her project work is titled **“Formation of Warm Ionized Gas Phase in the Interstellar Medium of Galaxies”**. She attentively worked on the tasks that were given and could reach the expected results.

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CERTIFICATE

Certified that the minor project work titled “FORMATION OF WARM IONIZED GAS PHASE IN INTERSTELLAR MEDIUM IN GALAXIES” is carried out by Ms. Vismaya P V (210011023203) who is a bonafide student of Bharata Mata College, Thrikkakara in partial fulfilment for the award of degree of Master of Science in Space Science of the Mahatma Gandhi University, Kottayam in the year 20202022. It is certified that all corrections indicated for Internal Assessment have been incorporated in the report deposited in the departmental library. The project report has been approved as it satisfies the academic requirement respect of project work prescribed by the institution for the said Degree.

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This is to certify that this project work titled "FORMATION OF WARM IONIZED GAS PHASE IN THE INTERSTELLAR MEDIUM OF GALAXIES" is a record of bonafide work done by VISMAYA P V (Register number: 210011023203) in partial fulfillment of the requirments for the award of the masters degree in space science from MAHATHMA GANDHI UNIVERSITY and no part of this work has been submitted earlier for the award of any degree.

EXTERNAL EXAMINER

CERTIFICATE

I hereby declare that the project work with the title “FORMATION OF WARM IONIZED GAS PHASE IN THE INTERSTELLAR MEDIUM OF GALAXIES”is my own work and that all datas and sources I have used or quoted have been indicated and acknowledged by means of complete references.

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VISMAYA P V

ABSTRACT

Interstellar medium is the region between stars that contain vast diffuse clouds of gases and minute solid particles. The ISM, it exist in multiple temperature and densities, Such as hot ionized medium, warm ionized medium, warm neutral medium, cold neutral medium and molecular gas. Compared to other phases, the hot ionized medium and warm ionized medium are more active and mostly studied.It is widely dependent on the stars around them.The discovery and investigation of faint interstellar emission lines at optical wavelengths has proven to be the primary method for learning about the distribution, kinematics, and other physical characteristics of the Warm Ionized Medium (WIM), despite the fact that the WIM was initially discovered through radio observations. Temperatures in the solar neighbourhood range from 6000 K to 12,000 K, and the average hydrogen ionisation rate there is 4 10^6 s^{-1} in a one cm^2 column that extends perpendicularly through the Galactic disc, which is about 1/8th as fast as what is possible from star ionising photons. Ionisation intensifies as one gets closer to the Galactic centre. The average ionisation rate is found to be roughly half that provided by stars in other galaxies.

The primary goals of this project are about how warm ionized medium are organized, how interstellar gas which is initially cold and atomic transforms into warm ionized medium, what process causes it and what sustains it. The newly born stars are responsible for ionizing the medium. So assuming the temperature of stars of a wide range of masses. We will first generate synthetic blackbody spectrum of these stars and then we will calculate ionizing flux from these stars .The Planck's equation has an enormous role in generatinging the black body spectrum.It's modified structure is also using to find the photon flux per second with the help of integration.Finally we will calculate the ionization region that form around stars of different spectral type. These works are done using python programmes

From this the conclusion can be obtained such as stars of what mass ranges, what surface temperature and what kind of luminosity are capable of producing large cavity of ionized interstellar gas around them. The importance of the temperatures of the star formed in this region also can understand from these methods. This is the overall structure of work.

TABLE OF CONTENT

CHAPTER 1

INTRODUCTION

The enormous, diffuse material that covers the void between stars in a galaxy is known as the interstellar medium (ISM). It is an environment that is both intriguing and intricate, made up of many kinds of gas, dust, and cosmic rays. Stars and planetary systems are formed and evolve as a result of the ISM. The substance that resides there as interstellar matter. From star counts, Sturbe (1847) inferred the existence of this substance. Once more, Baade's (1944) observational findings showed a substantial correlation between young stars and a rather dense concentration of interstellar matter. The evolution of stars and galaxies, the distribution of stellar masses, the formation of binaries, the origin of life, and many other issues of interest to astrophysics and biology are just a few examples of the issues that interstellar matter directly affects. The interstellar medium needs to be studied in order to comprehend the evolution of the universe as a whole, the life cycle of galaxies, and the birth of stars and planetary systems. Researchers look at the dynamics and properties of the interstellar medium using a number of observational methods, such as radio, infrared, and X-ray measurements.

A source of raw elements for future stars and planetary systems, the interstellar medium also serves this purpose. It contains substances that are heavier than hydrogen and helium and are created in stars through nuclear processes. These substances are then expelled into the interstellar medium by stellar processes such stellar winds, supernova explosions, and other stellar occurrences.

One should first be aware of the current level of our understanding of interstellar matter and gather the data that is currently accessible, such as the dust-to-gas ratio, the column density of interstellar molecules, the radius, mass, and temperature of various interstellar clouds.

Again, it is important to understand the composition, absorption, scattering, polarisation, etc. of interstellar granules. As opposed to the 10^{19} molecules/cc near the earth's surface, the number density in interstellar clouds is exceedingly low, on the range of(10^3 - 10^6) molecules/cc. Aside from that, the temperature is barely 80 K, and the clouds are exposed to powerful radiation fields from cosmic rays, star UV rays, etc.

In spiral galaxies, the interstellar medium (ISM) is a complex and varied environment that is essential to the development, evolution, and dynamics of these galaxies. Spiral arms, which are regions of increased star formation and interstellar matter, are what spiral galaxies are known for.

The interstellar medium (ISM) in spiral galaxies is a complex and diverse environment that is vital to the growth, evolution, and dynamics of these galaxies. Spiral galaxies are characterised by their spiral arms, which are regions of enhanced star formation and interstellar matter.Spiral galaxies are permeated with magnetic fields, which affect how the ISM behaves. The ISM-driven motion of galactic dynamos can intensify and sustain these magnetic fields.Material from the ISM is ejected from the galactic disc into the halo or outer regions of the galaxy via processes known as galactic fountains and outflows. These processes, which cycle material between the ISM's many phases, are propelled by supernovae and stellar winds from big stars.

The continuing evolution and star-forming activity in spiral galaxies are both influenced by the ISM, which is a dynamic and linked structure in these galaxies. Deciphering the mechanisms influencing the development and behaviour of spiral galaxies requires an understanding of the ISM.

Figure 1.1 Interstellar Medium

CHAPTER 2

INTERSTELLAR MEDIUM

2.1 PHASES OF INTERSTELLAR MEDIUM:

ISM can be divided into 5 phases depending on the temperatures. These important phases are:

2.1.1 MOLECULAR CLOUDS

The most prevalent molecule in these areas, molecular hydrogen (H2), makes up the majority of molecular clouds. They do, however, also contain other molecules like ammonia (NH3), carbon monoxide (CO), and numerous chemical compounds. These molecules are crucial for cooling the gas and enabling star formation by allowing it to collapse. When compared to other ISM phases, molecular clouds have substantially higher densities, with average values between hundreds and thousands of particles per cubic centimetre. In molecular clouds, the gas is extremely cold, with temperatures frequently falling between 10 and 30 Kelvin (-263 and -243 degrees Celsius). The diameter of molecular clouds can range from a few light-years to tens or hundreds of light-years .They found mostly in the Galactic plane. Carbon monoxide (CO) emission is a molecular cloud tracer that can be picked up by radio telescopes. Astronomers can map the location and characteristics of molecular clouds in our galaxy and other galaxies using these data.

2.1.2 COLD NEUTRAL MEDIUM (CNM)

Temperatures in the Cold Neutral Medium typically range from 10 to 100 Kelvin (-263 to -173 degrees Celsius), making it relatively cold compared to other ISM phases. Due to the gas's low temperature, it can continue to exist mostly in atomic rather than molecule form. In contrast to the ISM's other phases, the CNM has a comparatively high density. The CNM's density might vary, but it normally ranges within 10 to 100 particles per cubic centimetre. Neutral atomic hydrogen (H I) is the main constituent of the CNM. H I is made up of single, un-ionized hydrogen atoms. Radio wave readings can be used to identify and map the H I in the CNM because it emits and absorbs radio waves at a specific wavelength of 21 centimetres. They are observed in the form of sheets or filaments that are present almost everywhere in the galaxy.

2.1.3 WARM NEUTRAL MEDIUM (WNM)

In comparison to the CNM, the Warm Neutral Medium has a somewhat greater temperature. Most commonly, it lies between a few thousand to approximately 10,000 Kelvin (-273 to -263 degrees Celsius). The hydrogen atoms can be energetically stimulated and still maintain their neutrality within this temperature range. In comparison to the CNM, the density of the WNM is lower. The average value is between a few and a few tens of particles per cubic centimetre. While being less dense than the CNM, the WNM is nonetheless denser than the ISM's ionized regions. The main component of the WNM, like the CNM, is neutral atomic hydrogen (H I). It occupies 30- 60% of ISM volume. Using 21 hydrogen line spectrum we can study about WNM.

2.1.4 WARM IONIZED MEDIUM (WIM)

It contains defuse gas with temperature range 6000-12000K.So it is warmer than WNM and CNM but cooler than Hot Ionized Medium. Densities of WIM is in the ranges of approximately 0.1 cm^3. Ionization, or the removal of electrons from their parent atoms, transforms the gas in the WIM into a plasma state. Hydrogen (H II) and helium (He II and He III) are the main ionised elements in the WIM, while additional ionized species may also be present. The recombination of ionized atoms within the WIM causes distinctive emission lines to be produced. The hydrogen emission lines from the Balmer series, such as Hα, Hβ and so forth, are the most noticeable lines that may be seen in the optical spectrum. You may follow the location and characteristics of the WIM using these emission lines. It frequently forms filamentary formations or bubbles.

2.1.5 HOT IONIZED MEDIUM (HIM)

The Hot Ionized Medium is the hottest phase of the ISM, with temperatures that generally range from tens of thousands to millions of Kelvin. The energetic processes that cause the high temperatures include supernova explosions, star winds, and interactions with energetic phenomena like active galactic nuclei. The gas in the HIM is highly ionized, which means that the electrons have been taken away from their parent atoms, creating a plasma state. The main ionized elements in the HIM are hydrogen (H II) and helium (He II and He III), while additional ionized species may also be present. The Hot Ionized Medium generally has a density of 0.1 to a few particles per cubic centimetre. Due to the rarity of particle collisions, the low density allows the gas to maintain its high level of ionization.

Among these parts of ISM, Warm ionized medium and Hot ionized medium have more importance in studies. In conclusion, the warm ionised medium and hot ionised medium are fundamental elements of the interstellar medium and are crucial to galactic dynamics and feedback processes, as well as star formation and chemical enrichment. We can better understand the intricate interactions between stars, gas, and cosmic structures in the universe by studying these media.

Now let’s focus more on the warm ionized medium.We defined it’s general properties earlier, thse properties are derived from differernt observational methods.

2.2 WARM IONIZED MEDIUM: OBSERVATION METHODS

Due to the unusual properties of the warm ionised medium (WIM), observing it in astrophysics frequently necessitates specialised equipment and methods. Ionised hydrogen (H II regions) and other ionised elements make up the warm ionised medium, which is normally at temperatures between 10,000 and 20,000 Kelvin. Here are some typical observation techniques and tools for studying the warm ionised medium:

1. **Optical Spectroscopy:**

Emission Line Spectroscopy: Optical spectrographs can be used to observe the emission lines that ionised atoms and molecules in the WIM generate. Studying H II areas requires a special focus on the hydrogen Balmer lines (H-alpha, H-beta, etc.).

2. **Using radio spectroscopy:**

Radio Telescopes: Radio telescopes are necessary to observe the WIM's radio emission. An important emission line for examining the WIM is the 21-centimeter hydrogen line (HI). The WIM may be mapped in great resolution using devices like radio interferometers.

3. **Observations in infrared and submillimeter range:**

Infrared and Submillimeter Observations: Telescopes operating in the infrared and submillimeter range can detect the thermal emission of dust and chemicals linked to the WIM. The temperature and density structure of the medium can be studied with the use of these observations.

4. **UV (ultraviolet) Observations:**

WIM observations in the UV region of the electromagnetic spectrum are possible using space-based UV observatories like the Hubble Space Telescope (HST). Ionised species' UV emission lines can tell us a lot about the physical characteristics and chemical make-up of the medium.

5. The Fabry-Perot interferometer:

Ionised gas velocity maps in H II regions are measured with great resolution using Fabry-Perot interferometers. The kinematics and dynamics of the WIM can be revealed by them.

6. Multi-wavelength Surveys:

In order to better understand the distribution, structure, and characteristics of the WIM on both a local and galactic scale, large-scale surveys frequently combine observations from many wavelengths (e.g., optical, radio, IR, and UV).

7. Space-based Observations:

The Earth's atmosphere won't interfere with WIM observations made using space-based telescopes. Our understanding of the WIM has been greatly enhanced by space telescopes like Hubble, Chandra X-ray Observatory, and SOFIA (Stratospheric Observatory for Infrared Astronomy).

8. Adaptive Optics:

Higher-resolution observations of the WIM are possible thanks to the use of adaptive optics systems with ground-based telescopes to eliminate atmospheric distortions.

9. Intuitive Field Spectroscopy:

Researchers can trace the emission line characteristics and kinematics of the WIM in detail using tools like integral field spectrographs, which can concurrently acquire spectra from several spatial locations.

10. **Polarimetry**:

With regard to the dynamics and evolution of the WIM, polarimetry can be employed to investigate the magnetic fields present.

These methods and tools must be used in conjunction to observe the warm ionised medium in order to fully comprehend its characteristics, make-up, and dynamics in various astrophysical environments, from star-forming regions to the interstellar medium of galaxies.

CHAPTER 3

SPECTRAL CLASS OF STARS

3.1 COLOUR AND TEMPERATURE OF STARS

The stars show a multitude of colours, including red, orange, yellow, white, and blue. Stars do not all have the same colour due to differences in temperature, as we have seen. Astronomers have developed quantitative ways for defining the colour of a star and then utilising those colours to calculate stellar temperatures in order to define colour exactly. A star's temperature can be determined by its colour. In contrast to red stars, which are colder, blue-white stars are significantly hotter than the Sun. The field is roughly 13.3 light-years wide and has an average distance between the stars of about 25,000 light-years (or 25,000 years for light to get from them to us).

According to Wien's law, star temperature and colour are related. The visible light output of very hot stars is dominated by the colour blue (with significant extra ultraviolet energy). On the other hand, cold stars produce more infrared radiation than red wavelengths, which account for the majority of their visible light energy. Therefore, a star's colour offers a measurement of its true or intrinsic surface temperature. Colour is independent of proximity to an object. You should be able to relate to this from daily life. For instance, a traffic signal's colour appears the same from any distance. The apparent brightness (magnitude) of a star would vary if we could watch it, transfer it far farther away, and then return to it. But since this variation in brightness is the same across all wavelengths, its colour would not change.

The hottest stars are above 40,000 K in temperature, while the coolest stars are around 2000 K. The peak wavelength colour of our sun is a somewhat greenish-yellow, and its surface temperature is around 6000 K. The Sun would seem white and shine with roughly equal proportions of reddish and bluish light wavelengths in space. From the surface of the Earth, it appears somewhat yellow because the nitrogen molecules on our planet scatter some of the shorter (blue) wavelengths of sunlight, leaving behind more longer wavelength light. The blue sky is a result of sunlight that has been reflected by Earth's atmosphere, which also explains why it is blue.

3.2 COLOUR INDICES

Astronomers typically assess a star's apparent brightness with filters, each of which only transmits light from a certain limited band of wavelengths (colours), in order to precisely determine the colour of a star. When put in front of your eyes, a green plastic soft drink bottle serves as a rudimentary example of a filter because it only allows the green hues of light to pass.

One set of filters that is frequently used in astronomy measures the brightness of stars at three different wavelengths, which correspond to ultraviolet, blue, and yellow light. U (ultraviolet), B (blue), and V (visual, for yellow) are the names of the filters. These filters each transmit light at a wavelength somewhere between 360 nanometers (nm), 420 nm, and 540 nm.

Each filter's brightness measurement is typically represented in magnitudes. A colour index is the difference between any two of these magnitudes, such as the difference between the blue and visual magnitudes (B-V).A star with a surface temperature of roughly 10,000 K, like Vega, is given a colour index of 0 by adjusting the ultraviolet, blue, and visible magnitudes of the UBV system. The bluest stars, with temperatures of around 40,000 K, have a B-V colour index of 0.4, while the reddest stars, with temperatures of around 2000 K, have a B-V colour index of +2.0. The Sun's B-V index is approximately +0.65. The B-V index is always the "bluer" colour less the "redder" colour, as per convention.

Even though a colour index ultimately signifies temperature, we nevertheless use it. Because astronomers actually measure the brightness of stars using filters, and because people always feel more at ease when making claims about quantifiable things.

3.3 CLASSIFICATION OF STARS

Astronomers use a system known as stellar classification to categorise and describe stars based on their observable properties, particularly their spectral features. The categorization is crucial for comprehending the various kinds of stars and offers useful details on their physical characteristics, stages in evolution, and behaviours. The Harvard Spectral Classification (M-K classification) and the Morgan-Keenan (MK classification) systems are the two most widely used methods for categorising stars. Stellar classification is a fundamental tool in astronomy, as it provides insights into a star's temperature, luminosity, size, mass, and evolutionary stage. By studying the properties of stars across the different spectral types, astronomers can better understand the life cycles of stars, the structure of galaxies, and the overall evolution of the universe.

3.3.1 HARVARD SPECTRAL CLASSIFICATION (M-K CLASSIFICATION)

The Harvard Spectral Classification system, sometimes referred to as the M-K classification system, divides stars into spectral classes according to their visible spectrum absorption lines. In decreasing order of temperature, the spectral classes are denoted by the letters O, B, A, F, G, K, and M. The classification within the primary type is further refined by the existence of a numeric subclass (0 to 9) for each letter class. However, this classification scheme does not completely describe the star as it cannot distinguish between stars with the same temperature but different luminosities .In other words, it cannot distinguish between main sequence (dwarf) stars, giant stars and supergiant stars. For this reason, the Morgan-Keenan luminosity class (MK or MKK) was established.

3.3.2 THE MORGAN-KEENAN CLASSIFICATION (MK CLASSIFICATION)

The Morgan-Keenan classification scheme is a developed variant of the Harvard Spectral Classification. For more sorts of stars, especially those with strange or distinctive spectra, it provides extra spectral classes. It was created in the 1940s by Philip C. Keenan and William W. Morgan, and it is still frequently used today.

Based on how a star's spectrum appears, which is discovered by running its light through a spectrograph, the MK classification system is used to categorise stars. By separating the light into its individual wavelengths, a spectrograph can reveal absorption lines and other properties particular to each star's chemical makeup and temperature.

The MK classification system is made up of two parts:

- **(M, K, G, F, A, B, O) Spectral Type:** A letter that represents the distinctive elements in the star's spectrum is used to indicate the spectral type. The different spectral categories are O, B, A, F, G, K, and M in decreasing order of temperature. To express finer temperature differences within the group, each spectral type is further separated into numerical values (e.g., A0, A1, A2).
- **Class of Luminosity (I, II, III, IV, V):** The star's brightness or luminosity in relation to other stars of the same spectral type is indicated by the luminosity class. It offers details on the size and stage of the star's growth. The luminosity classes are denoted by Roman numerals:
  - I (Roman numeral one): Super Giants
  - II (Roman numeral two): Bright Giants
  - III (Roman numeral three): Giants
  - IV (Roman numeral four): Subgiants
  - V (Roman numeral five): Main Sequence (Dwarf) Stars

A classification for a star is produced by combining the two elements, for instance, G2V, which stands for a G-type main-sequence (dwarf) star like the Sun.

Understanding stellar traits, evolution, and star distribution in the universe all depend on the MK classification system. It enables astronomers to classify and organise stars according to their physical attributes, making it simpler to research various stellar populations and acquire understanding of the activities taking place inside them at various phases of their lifespan.

SPECTRL CLASS	EFFECTIVE TEMPERATURE (K)	COLOUR	M/M_{Sun}	R/R_{Sun}	L/L_{Sun}	Main Sequence Lifespan
O	28000 - 50000	Blue	20 - 60	9 - 15	90,000 - 800000	1 - 10 Myr
B	10800 - 28000	Blue – White	3 - 18	3.0 - 8.4	95 - 52,000	11 - 400 Myr
A	7500 - 10800	White	2.0 - 3.0	1.7 - 2.7	8 - 55	400 Myr-3 Gyr
F	6000 - 7500	White – Yellow	1.1 - 1.6	1.2 - 1.6	2.0 - 6.5	3 - 7 Gyr
G	4900 - 6000	Yellow	0.85 - 1.1	0.85 - 1.1	0.66 - 15	7 - 15 Gyr
K	3500 – 4900	Orange	0.65 - 0.85	0.65 - 0.85	0.10 - 0.42	17 Gyr
M	2000 - 3500	Red	0.08 - 0.05	0.17 - 0.63	0.001 - 0.08	56 Gyr

Table 1.1: Spectral class summary

The temperature of a star can be inferred from both colours and spectral classifications. Because detectors must be sensitive enough to detect particular wavelengths and the light must be bright enough to spread out into all the colours of the rainbow, spectra are more difficult to measure. The detectors simply need to react to the several wavelengths that pass concurrently through the selected coloured filters—all blue light, all yellow-green light, etc.—in order to quantify colours.

3.4 LUMINOSITY

The total amount of energy that a star emits over the course of one second is referred to as luminosity, and is commonly expressed in watts (W) or solar luminosities (L⊙). A star's luminosity, which tells us important things about its brightness and energy output, is a crucial attribute .Stars appear in a variety of shapes, temperatures, and luminosities. The brightness of stars is frequently compared to the brightness of the Sun, which is measured as one solar luminosity (1 L⊙). The luminosity of the Sun is roughly 3.81026 watts. For instance, a large, hot star may have a luminosity tens of thousands of times larger than the Sun, but a small, cooler star may have a luminosity thousands of times lower.

The luminosity of a star depends on its size, temperature, and surface area. The relationship between luminosity, temperature, and radius is described by the Stefan-Boltzmann law, which states:

Luminosity (L) = 4π × (Radius)^2 × (Stefan-Boltzmann constant) × (Temperature)^4

OR $$L = 4\pi r^2 \sigma T_{eff}^4 \tag{2.1}$$

In this equation, the Stefan-Boltzmann constant is approximately 5.67×10^{-8} W/($m^2 \cdot K^4$)

This equation gives the total amount of energy radiated perpendicular to the entire surface of the star in one second.

Understanding a star's life cycle, the way it produces energy, and how it interacts with its environment all depend on the magnitude of its brightness it is. The luminosity of a star and other vital information about celestial objects are determined by astronomers using a variety of observational techniques, including as spectroscopy and photometry.

Additionally, luminosity can be expressed using the astronomical magnitude system. Absolute magnitude is a logarithmic measure of luminosity within a particular wavelength range or filter band, whereas absolute bolometric magnitude (Mbol) is a logarithmic measure of an object's total energy emission rate. But in astronomy, the word "brightness" usually refers to an object's perceived brightness, or how bright it looks to the viewer. The apparent brightness of an item is affected by its luminosity, its distance from the observer, any light that is absorbed along the path from the object to the observer, and other factors. A logarithmic representation of apparent brightness is apparent magnitude. It is frequently referred to as the luminosity distance because the distance calculated by luminosity measurements can be a little misleading.

A star's luminosity is a measurably inherent characteristic that is independent of distance. On the other hand, the concept of magnitude takes into account distance. According to the inverse-square law, the apparent magnitude is a measurement of how much the flux of light decreases with increasing distance. Both apparent and absolute magnitudes are measured using the Pogson logarithmic scale, with the latter equivalent to the brightness of a star or other celestial object as observed if it were situated at an interstellar distance of 10 parsecs. In addition to the brightness loss brought on by greater distance, interstellar dust extinction causes an additional loss of brightness.

CHAPTER 4

LYMANN CONTINUUM AND CORRESPONING LAWS

4.1 THE PLANCK’S LAW

A fundamental tenet of physics called Planck's law, commonly referred to as the Planck radiation law, specifies the spectrum of electromagnetic radiation emitted by a perfect black body at a specific temperature. Max Planck, a German physicist, developed it in 1900, which was a crucial turning point in the evolution of quantum mechanics.

The spectral brightness B_ν(T) as a function of frequency and temperature T is another way that Planck's law can be represented in terms of frequency. The speed of light equation, which is defined as c= λν , where c is the speed of light in a vacuum, explains the connection between wavelength and frequency. We use the formula ν= λ/c to translate Planck's law into frequency terms. The result of substituting this into the expression for $B_\lambda(T)$ is:

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{K_B T}}} \tag{4.1}$$

B_v (T) is the black body's spectral radiance (or spectrum radiated power per unit area per frequency) at a particular frequency and temperature T.

- h or 6.626 x 10^{-34} joule-seconds, is the Planck constant.

- 299,792,458 metres per second, or c, is the speed of light in a vacuum.

- The frequency of radiation is measured in hertz (cycles per second).

- The Boltzmann constant, or k_B, has a unit of energy per Kelvin of about 1.380649 x 10^{-23}

  Just like in the wavelength form, Planck's law in terms of frequency shows how the spectral radiance of a black body changes with temperature and frequency. As the temperature of the black body increases, the peak of the spectral distribution shifts to higher frequencies (shorter wavelengths), following Wien's displacement law. This behaviour is essential for understanding the emission spectra of various objects in the universe and has significant implications in astrophysics and cosmology. This historical invention was birthed from the study about the characteristics of black body radiation.

4.2 BLACK BODY RADIATION

In analysing thermal radiation and electromagnetic radiation energy transfer in all wavelength bands, the ideal blackbody is crucial. The blackbody serves as a benchmark against which the absorption of actual bodies is measured because it is the optimum radiation absorber. The blackbody is utilised as a standard for comparison with the radiation of actual physical bodies because it emits the most radiation overall. This idea, first put forth by G. Kirchoff in 1860, is so crucial that it is actively used in research on radiations induced by various physical forces in addition to the intrinsic thermal radiation of natural media. A black body does not reflect or transmit any light and is a perfect absorber and emitter of light at all wavelengths. It is a fundamental idea in physics and is essential to comprehending a variety of phenomena in astrophysics and other scientific disciplines.

The optimum source of blackbody radiation must be obtained in order to investigate blackbody radiation. Consider the radiation coming from a tiny hole in an enclosure that has been heated to a temperature of T as a workable solution to this problem.It is obvious that any radiation striking the hole is almost completely "absorbed," and as a result, the radiation emanating from it is in fact blackbody radiation.

Kirchoff demonstrated that the cavity's radiation must be isotopic in order for the second law of thermodynamics to apply .It may be demonstrated that the energy density U(,T) inside the cavity is related to the emissive power (E), which is defined as the energy emitted per unit area per unit time .The relation is

$$U_{\lambda,T} = \frac{4E_{\lambda,T}}{c} \tag{4.2}$$

Wein derived the law of energy of distribution in the blackbody spectrum (also known as the Wein radiation law) in 1896 using classical notions

$$U_{(\nu,T)} = \nu^2 g \frac{\nu}{T}. \tag{4.3}$$

However, as was made evident, the Wein radiation law calculation was accurate only for short wavelengths.On the presumption that the conventional notion of the uniform distribution of energy is true, Rayleigh (1900) and Jeans (1905) calculated the spectral distribution of thermal radiation. Rayleigh came to the conclusion.

$$U_{(\nu,T)} = \mathrm{KT}\frac{8\pi\nu^2}{c^3} \tag{4.4}$$

Where K stands for the Boltzmann constant.It is known as the ultraviolet catastrophe that the Rayleigh-Jeans law does not agree with experiment at high frequencies.

This situation compelled Planck to focus on harmonic oscillators, which were previously thought of as the sources and absorbers of radiation energy.Finally, Planck produced the empirical equation that was quickly and consistently verified experimentally based on the Wein-Lummer Blackbody Model.

4.3 LYMAN CONTINUUM

The photons released by stars at energies higher than the Lyman limit are referred to as Lyman continuum photons (abbreviated LyC), also known as Ly continuum photons or Lyc photons. Absorbing LyC causes hydrogen to ionise. Theodore Lyman observed between 1906 and 1914 that atomic hydrogen only absorbs light at particular frequencies (or wavelengths), building on Victor Schumann's discovery of ultraviolet light. As a result, the Lyman series is named after him. The ultraviolet band contains the entire spectrum of the Lyman series' wavelengths. The ionisation energy is the energy limit over which this quantized absorption behaviour only occurs. The Lyman limit, where the photon has sufficient energy to completely ionise the atom and produce a free proton and free electron, is the minimal ionisation energy for neutral atomic hydrogen. Any wavelength of light that is above this energy (below this wavelength) may be absorbed. This creates a continuum in the energy spectrum, which is continuous as opposed to being made up of numerous discrete lines as is the case at lower energies.

At a wavelength of 91.2 nm (912 Å), or 3.29 million GHz, with a photon energy of 13.6 eV, the Lyman limit is reached. The electromagnetic spectrum's ultraviolet C region contains the majority of LyC energies (see Lyman series).Although X-rays and gamma rays can also ionise hydrogen atoms, a star's photosphere mostly emits UV-C radiation, which is much more common. An electron and a proton may collide to create atomic hydrogen as a result of the photon absorption process that leads to the ionisation of atomic hydrogen. The photon that an atom theoretically emits when it is created would have a theoretical energy of 13.6 eV if the two particles were moving slowly (kinetic energy could therefore be neglected). However, if the atom is formed in an excited state, the energy will actually be lower. The extra (kinetic) energy is radiated as shorter-wavelength (higher energy) photons at quicker speeds, but momentum must be preserved. As a result, the energetic protons and electrons that combine to create atomic hydrogen and emission from photo-ionized hydrogen both produce photons with energy above 13.6 eV. Applying Planck's function to determine the Lyman continuum,

$$B_\nu(T)d(\nu) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{K_BT}}}\ J\,m^{-2}Hz^{-1}Sr^{-1}s^{-1} \tag{4.5}$$

to avoid the solid angle the equation 3.5 is multiplied by 4π the equation becomes,

$$B_\nu(T)d(\nu) = \frac{8\pi h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{K_BT}}}\ J\,m^{-2}Hz^{-1}s^{-1} \tag{4.6}$$

to find the luminosity of a star the Planck function is multiplied by $4\pi R^2$ where R is the radius of a main sequence star. luminosity of a star is

$$L_\nu = \frac{32\pi^2 h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{K_BT}}}\ JHz^{-1}s^{-1} \tag{4.7}$$

$$The\ photon\ flux = \frac{L_\nu}{h\nu} \tag{4.8}$$

No. of photon per second.

The total photon flux which is able to ionize hydrogen can be determined as,

$$The\ \ total\ flux = \int_{13.6}^{\infty}\frac{L_\nu}{h\nu}\,d\nu \tag{4.9}$$

If ν_0 is taken as the minimum frequency of radiation required to ionize the hydrogen, then equation will be

$$The\ \ total\ flux = \int_{\nu_0}^{\infty}\frac{L_\nu}{h\nu}d\nu \tag{4.10}$$

Substituting the value of L_ν in equation (3.10)

$$The\ total\ flux = \int_{\nu_0}^{\infty}\frac{\frac{32\pi^2 h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{K_BT}}}}{h\nu}d\nu \tag{4.11}$$

The total Lyman continuum flux can be calculated for each main sequence by integrating the equation 3.11 with appropriate values of temperature T, and radius R.

4.4 HI AND HII REGIONS

4.4.1 HI REGION

In astronomy, a "HI region" is a region of the interstellar medium (ISM) that is rich in neutral hydrogen (HI) gas. The huge area of gas and dust between stars in a galaxy is known as the interstellar medium. It is made up of several substances, such as ionized gas, molecular gas, and neutral gas.

The term "neutral hydrogen" (HI) refers to hydrogen atoms that are in their ground state and are not ionized (i.e., still have their electrons attached). Radio waves with a wavelength of 21 centimeters (about 1.4 GHz frequency) can be emitted and absorbed by these atoms. Radio telescopes can use this characteristic to observe and research HI regions.

For a number of reasons, HI regions are of great interest to astrophysics.

- **Tracing Galactic Structure:** The distribution and kinematics of gas in galaxies can be mapped using HI regions. Astronomers can measure the velocity of gas with respect to Earth by measuring the Doppler changes of the 21 cm emission or absorption lines, and by doing so, investigate the rotation of galaxies.
- **Star Formation:** Neutral hydrogen in dense places can collapse under the force of gravity to create new stars. These regions are frequently connected to molecular clouds, where the HI gas transforms into H2, the main component of star-forming regions.
- **Galactic Dynamics:** Information on the general gravitational potential and mass distribution of galaxies can be gleaned from the distribution of HI in galaxies
- **Gas recycling:** Through events like supernovae or stellar winds, stars can discharge material back into the interstellar medium as they deteriorate. The current HI gas is mixed with this enhanced material, which affects future star formation and the galaxies' chemical history.
- **Evolution of Galaxies:** Astronomers can gain a better understanding of galaxies' evolution over cosmic time by examining the characteristics of HI regions in various types of galaxies.

Radio telescopes are frequently used to observe HI regions because they can pick up on the distinctive emission or absorption lines at 21 cm. Regarding the distribution, velocity, density, and temperature of the neutral hydrogen gas in the interstellar medium, the data gathered from these observations are extremely helpful.

4.4.2 HII REGION

A region of the interstellar medium (ISM) that has a high concentration of ionized hydrogen atoms, specifically hydrogen ions (protons) and free electrons, is known as an HII region (pronounced "H-two region"). The name "HII" is derived from the chemical abbreviation for ionized hydrogen (H) and the Roman numeral "II" signifying that the hydrogen atoms have lost one electron.

In areas of active star formation, where massive, hot, young stars generate intense ultraviolet (UV) radiation, HII zones are frequently seen. The neutral hydrogen atoms in the area are sufficiently ionized by the UV light to lose their electrons, generating a plasma of charged particles (ions and electrons) as a result. It usually consists of a partially ionized cloud of gas that has recently undergone star formation. Its size can range from one to hundreds of light years, and its density can range from a few to approximately a million particles per cubic cm. The first such object was discovered in 1610 by Nicolas-Claude Fabri de Peiresc, who used a telescope to examine the Orion Nebula, now known to be an HII area. Due of the uneven distribution of the stars and gas inside of them, they can have any shape. Over a million years, HII regions may give birth to thousands of stars.

The gases of the HII area will eventually be dispersed, leaving behind a cluster of stars that have formed, thanks to supernova explosions and powerful stellar winds from the most massive stars in the ensuing star cluster.While elliptical galaxies are almost devoid of HII areas, spiral and irregular galaxies have a lot of them. HII areas are concentrated in the spiral arms of spiral galaxies like the Milky Way, but they are dispersed erratically in irregular galaxies. Huge HII zones in some galaxies may contain tens of thousands of stars.

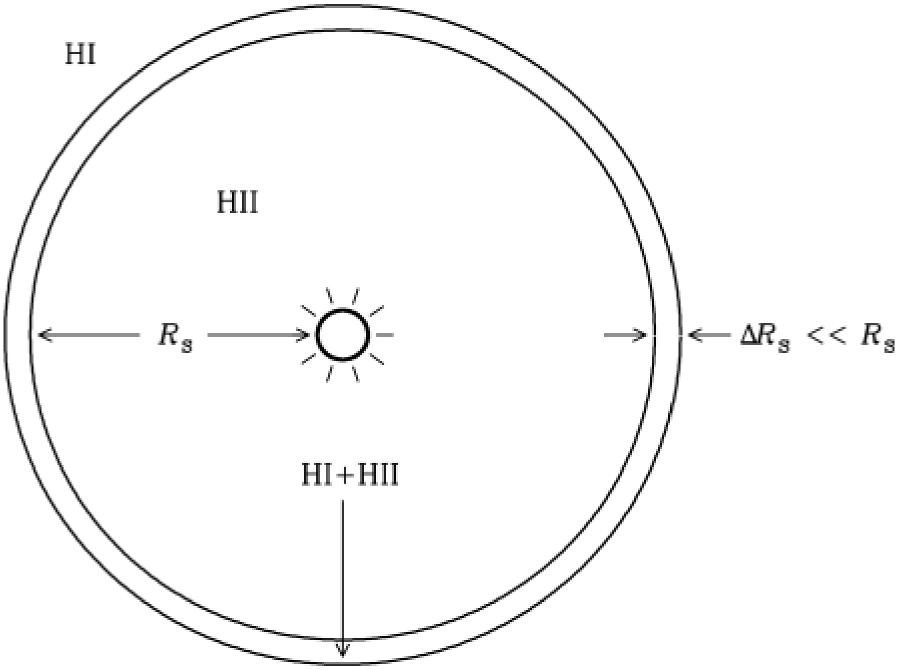


Figure 4.1: Schematic representation of HI and HII region.

Ionised atomic hydrogen regions, also known as HII Regions, are found surrounding main sequence stars and are made up of gas that has been ionised by photons with energies higher than the hydrogen ionisation energy of 13.6 eV. These objects include Planetary Nebulae, the ejected outer envelopes of A, G, and B stars photo-ionized by the hot remnant stellar core, and Classical HII Regions, ionised by hot O or B stars (or clusters of such stars) and associated with regions of recent massive star formation. The physics regulating these many sorts of gaseous nebulae is essentially the same, despite the fact that their physical beginnings are highly different. All of these will collectively be referred to as HII Regions in this section. HII areas have extremely abundant emission lines in their UV, visible, and IR spectra. These lines are largely collisionally excited lines of metal ions and recombination lines of hydrogen and helium. As thermalized electrons and radio recombination lines from highly excited states of H, He, and some metals generate radio waves, HII regions are also visible at radio wavelengths.

Three processes govern the physics of HII regions:

1 Photoionization equilibrium the harmony of recombination and photoionization. This establishes both the nebula's structure and the general geographical distribution of the ionic states of the constituent elements in the ionised zone.

2 The thermal balance between cooling and heating. Photoelectrons with thermal energy of a few eV that are ejected from Hydrogen and Helium are the primary source of heating. Most HII areas cool primarily as a result of metal ion electron-ion impact excitation, followed by emission of forbidden lines from low lying fine structure levels. These cooling lines are responsible for the distinctive spectra of HII regions.

3 Hydrodynamics, which includes winds and outflows from the embedded stars as well as shocks, ionisation and photodissociation fronts. Since neutral hydrogen atoms have an extremely high absorption cross-section to ionising UV photons (10 -17 cm2), each ionising photon that enters an HI region is swiftly absorbed and creates a new ion nearly as soon as it transitions from an HII region to an HI region.

An HII region's forerunner is a giant molecular cloud (GMC).A GMC is a dense, chilly (10–20 K), and primarily hydrogen-containing cloud .Long-lasting stability characterises the GMC scan, although shock waves brought on by supernovae, cloud collisions, and magnetic interactions can cause it to collapse. .Stars are created as a result of this, through the collapse and fragmentation of the cloud (for a more detailed explanation, see stellar evolution).The most massive stars will become hot enough to ionise the surrounding gas as they form within a GMC. Energetic photons produce an ionisation front shortly after the creation of an ionising radiation field, which rips through the surrounding gas at supersonic speeds. The ionisation front slows as the distance from the ionising star increases, but the ionised volume grows due to the pressure of the freshly ionised gas. The shock front produced by the expansion of the material ejected from the nebula eventually overtakes the ionisation front as it slows to subsonic speeds

The HII region is now come to fruition. An HII region has a lifespan of a few million years or less. The majority of the gas will eventually be driven away by radiation pressure from the hot new born stars. Less than 10% of the gas in the HII area forms into stars before the rest is blasted off, making the entire process often exceedingly inefficient. The most massive stars' supernova explosions, which will take place in under 1-2 million years, will contribute to the gas loss. The Orion Nebula, the Tarantula Nebula of the Large Magellanic Cloud, NGC 604 in the spiral galaxy M33, and other notable galactic HII areas are examples. The stunning Orion Nebula is the only HII area observable with the unaided eye. It can be seen as the main "star" in Orion's sword and is part of the constellation that bears the hunter's name from Greek mythology.

Figure 4.2: Messier 17 is an HII region in the constellation Sagittarius

Figure 4.3: Orion Nebul

Figure 4.4: Spherical HII region of rosette nebula

Figure 4.5: HII region of Tarantula nebula

Figure 4.6: **NGC 604 is an HII region inside the Triangulum Galaxy**

4.5 VOLUMETRIC RECOMBINATION

In ionised plasmas, such as HII areas, a process known as volumetric recombination takes place when ions and electrons combine to create neutral atoms, resulting in a drop in the plasma's ionisation level. The overall equilibrium between ionisation and recombination in such locations is crucially maintained by this process.

The surrounding hydrogen atoms in an HII zone are ionised by the intense ultraviolet light from young, bright stars, converting them into ions (protons) and free electrons. However, there is a constant process of recombination where ions reclaim free electrons to become neutral atoms once more as a result of collisions and interactions between these charged particles.

The main component of interstellar gas is hydrogen, with traces of helium and heavier elements including carbon, nitrogen, oxygen, iron, and others. Even though many of the heavier elements are not metallic in the conventional sense, astronomers frequently group all of the heavier elements together as metals because they readily form positive ions. The majority of the hydrogen in interstellar space exists as neutral atoms or diatomic molecules (H2), although some of it is also ionized. Singly ionised hydrogen atoms H+ and doubly ionized oxygen atoms O++ are referred to as HII and OIII, respectively.

Bengt Strömgren,, an astronomer, discovered in 1939 that regions of diffuse interstellar gas are either almost entirely ionised (HII much more abundant than HI) or almost entirely neutral, with very thin boundaries separating distinct HI and HII regions. Because of his early theoretical models, Strömgren spheres are occasionally used to refer to the HII zones that surround stars. Assume that at first, HI atoms with a certain number density n_0 are present in a volume of interstellar space. Then, activate a star that is sufficiently hot (T > 3 × 104 K) to produce a large amount of photons with an energy of E ≥ 13.6eV (1 electron Volt ≈ 1.60 × 10^{-12}er g), which is required to ionise a hydrogen atom when it is initially in the ground state. Due to the fact that E = hv = hcλ, these photons have wavelengths λ ≤ 912Å = 912×10^{-10} m, which correspond to ultraviolet (UV) light. These ionising photons will photoionize the hydrogen in a volume V surrounding the star if they are produced at a rate of Nu photons s^{-1}.

Photoionization is the name of the procedure. Since the ionisation potential of helium, which is present in mixtures with hydrogen, is so high $E \approx 24.5$ eV, only extremely hot stars can ionise it. Since neutral hydrogen atoms have an extremely high absorption cross-section to ionising UV photons: $\sigma \approx 1017$ cm^2, each ionising photon that enters an HI region is swiftly absorbed and creates a new ion nearly as soon as it transitions from an HII region to an HI region.

You may think of recombination as the exact opposite of photoionization. Recombination is a term used in cosmology to describe the time period when charged protons and electrons first joined forces to create electrically neutral hydrogen atoms. These hydrogen atoms typically begin with their electrons in a high energy state, and they swiftly transition to their low energy state via emitting photons. This is because direct recombination to the ground state (lowest energy) of hydrogen is exceedingly wasteful.

The HII area is substantially less opaque to ionising photons after becoming ionised from HI into free protons and electrons. Therefore, if we activate an ionising star in a uniform density HI cloud, it will completely ionise a sphere whose Strömgren radius increases with time until equilibrium between ionisation and recombination is attained. The partially ionised boundary of the sphere will be very thin, measuring only approximately 10^{14} cm. It is also known as an ionization-bounded HII area. An ionization-bounded HII region is another name for this area. Electrons and protons occasionally collide and recombine inside the HII zone at a volumetric rate r_r which may be expressed as

$$r_r \approx \alpha_H n_e n_p \tag{3.12}$$

The hydrogen recombination rate is specified by the parameter $\alpha_H \approx 3 \times 10^{-13}\ cm^3 s^{-1}$, and the collision rate per unit volume is proportional to the product of the electron density ne and the proton density np. Here, r_r is the number of recombination per unit time in unit volume. The recombination time is demonstrated to be extremely brief when compared to the life of an ionising star. Thus, we anticipate the development of a steady state in which the rates of total ionisation and recombination in the Strömgren spheres are equal.

In order to control the ionisation state of ionised plasmas like HII zones, volumetric recombination is a crucial process. Temperature, plasma density, and composition, for example, are variables that affect the rate of recombination. The appearance, emission spectra, and general behaviour of HII areas and other ionised nebulae are significantly influenced by how well ionisation and recombination processes are balanced.

4.6 STROMGREN SPHERE

Astrophysics refers to the region around a hot, big star where its strong ultraviolet (UV) radiation has ionised the nearby interstellar hydrogen gas, producing a bubble of ionised gas, as a Strömgren sphere, also known as an ionisation or HII region. The word has the name of Bengt Strömgren, a Swedish astronomer who created the conceptual foundation for comprehending the physical properties of such regions.

The neutral hydrogen (HI) in the surrounding interstellar medium can be ionised by very hot stars of the spectral class O or B, causing hydrogen atoms to lose their solitary electron. This process is known as ionisation. The name HII refers to this hydrogen state. Free electrons eventually rejoin those hydrogen ions. Instead of returning as a single photon, energy is instead reemitted as a sequence of lower-energy photons. As they leave the star's surface, the photons lose energy and are no longer potent enough to contribute to ionisation. If not, the interstellar medium as a whole would become ionised. Theoretically, the ionised regions are described by a Strömgren sphere.

The model, which was developed in its earliest and most basic form by the Danish astronomer Bengt Strömgren in 1939, looks at how electromagnetic radiation from a single star (or a small group of stars that are similar to it) with a certain surface temperature and luminosity affects the interstellar medium that surrounds it. He made two assumptions in order to simplify things.

1. The star brightens quickly and fully.

2. The surrounding medium is uniformly homogeneous.

The link between the temperature and luminosity of the excited star on the one hand, and the density of the surrounding hydrogen gas on the other, is described by Strömgren's formula. Using it, the Strömgren radius can be used to determine the size of the hypothetical ionised zone. Additionally, the edge of the Strömgren sphere exhibits a very sharp cut-off in the degree of ionisation, according to Strömgren's model. This is because, in relation to the size of the Strömgren sphere, the transition region between the highly ionised gas and the neutral hydrogen is extremely small. The HII region has a substantially reduced opacity to ionising photons once it has been ionised from HI into free protons (H+ ions) and electrons. In a uniform density HI cloud, turning on an ionising star will fully ionise a sphere whose Strömgren radius R_S grows over time until equilibrium between ionisation and recombination is reached. The partially ionised boundary of this sphere will be quite thin, only 10^{14} cm thick. It is also known as an ionization-bounded HII area. The HII zone is said to as matter- or density-bounded if the surrounding HI cloud is sufficiently small for the star to completely ionise it. The Strömgren sphere gets bigger as the excited star gets hotter and brighter.

The sphere that has come to be known as Strömgren's sphere in Strömgren's model is formed almost entirely of free protons and electrons. At a density that rises almost exponentially towards the surface, a relatively small number of hydrogen atoms first appear. A thin region where the radiation emitted by the star is strongly absorbed by the atoms, which lose their energy by radiation in all directions, may be seen outside the sphere where radiation of the atoms' frequencies strongly cools the gas. Consequently, a Strömgren system appears as a bright star encircled by a dimly radiating and challenging to notice globe.

The concept of a super brightness and other effects seen using lasers must be explored because excited hydrogen has a low density but potential for long routes. The direction for which the path in excited hydrogen is maximal, i.e., tangential to the sphere, is where a supposedly super radiant Strömgren's shell generates space coherent, time incoherent beams. This concept calculates the Strömgren radius and proposes the Strömgren sphere notion as an explanation for the ionisation and excitation of the interstellar hydrogen. In a steady state, the total flux coming towards the boundary is equal to the recombination rate. In contrast to planetary nebulae, some nebulae's observation spectra revealed that most of the emissions are not focused towards specific bright stars, and that the UV radiation from the O and B stars serves as the necessary energy supply. This emission is produced by the HII area. The Orion Nebula is seen while observing the HII.

The physical characteristics of the star at the centre and the surrounding interstellar medium can be understood using Strömgren spheres. The effective temperature, brightness, and density of the surrounding gas can all be inferred from observations of emission lines from ionised gas within these regions. These areas are crucial for understanding star formation, the interstellar medium, and the interactions between massive stars and their surroundings

Figure 3.7: Strömgren sphere of rosette nebula

CHAPTER 5

PLOTTING AND DATA ANALYSIS

5.1 PLANCK FUNCTION PLOTTING

Using Python programming, the Planck function equation 4.1 (See page 24) is plotted versus frequency v for different main sequence star surface temperatures.

Python code of Black Body spectrum

```
#!/usr/bin/env python
# Import necessary libraries
import numpy as np
import matplotlib
# Choose backend for LaTeX plot export
# Comment out the line for interactive display
#matplotlib.use(’pgf’)
# Define necessary constants
k = 1.38064852e-23
h = 6.626070040e-34
c = 299792458
def bnu(nu,T):
 ans = 2*h*(nu**3)/(c**2)
 ans /= np.expm1((h*nu)/(k*T))
 return ans
#Prepare the graph for plotting
import matplotlib.pyplot as plt
fig = plt.figure( )
ax = fig.add_subplot(111)
#Set x and y axis on log scale
ax.set_xscale(’log’)
ax.set_yscale(’log’)
ax.set_ylim(1e-15,1e5)
ax.set_xlabel(’Frequency(Hz)’)
ax.set_ylabel(r’$B_\nu(T)[Js^{-1}m^{-2} Hz^{-1}sr^{-1}]$’)
ax.set_title(’Black Body Spectrum: Plank Function’)
#Define values of parameter T(in K)
T = [3e2,1e3,3e3,1e4,3e4,1e5, 3e5,1e6,3e6,1e7]
#Define frequency range of graphs. Geometric progression
#is used since x axis is logarithmic
nu = np.geomspace(1e8,1e20,200)
#Plot Plank function for each value of parameter T
for t in T:
  #Plot the curve here
  curve = ax.plot(nu,bnu(nu,t))
  #Extract color from the curve so that it can be applied to annotation
```

```
  color = curve[0].get_color()
  #Calculate position for an notation using Wien’s displacement law
  x_ann = c*t/2.89e-3
  y_ann = bnu(x_ann,t)
  #Convert temperature into a nicely formatted string (texstring)35
  exponent = int(np.floor(np.log10 (t)))
  mantissa = t/(10**exponent)
  texstring = r’$\{:.0f}\times10^{{{:d}}}K$’.format(mantissa,exponent)
  #Annotate the curve here
  ax.annotate(texstring,xy=(x_ann,y_ann),color=color ,size=8)
#Export figure for LaTeX.Comment out for interactive display
#fig.savefig(’plank.pgf’)
#Uncomment the following line for interactive display
#plt.axvline(x=328846539734623,color=’r’)
plt.show()
```

The resulted graph is given

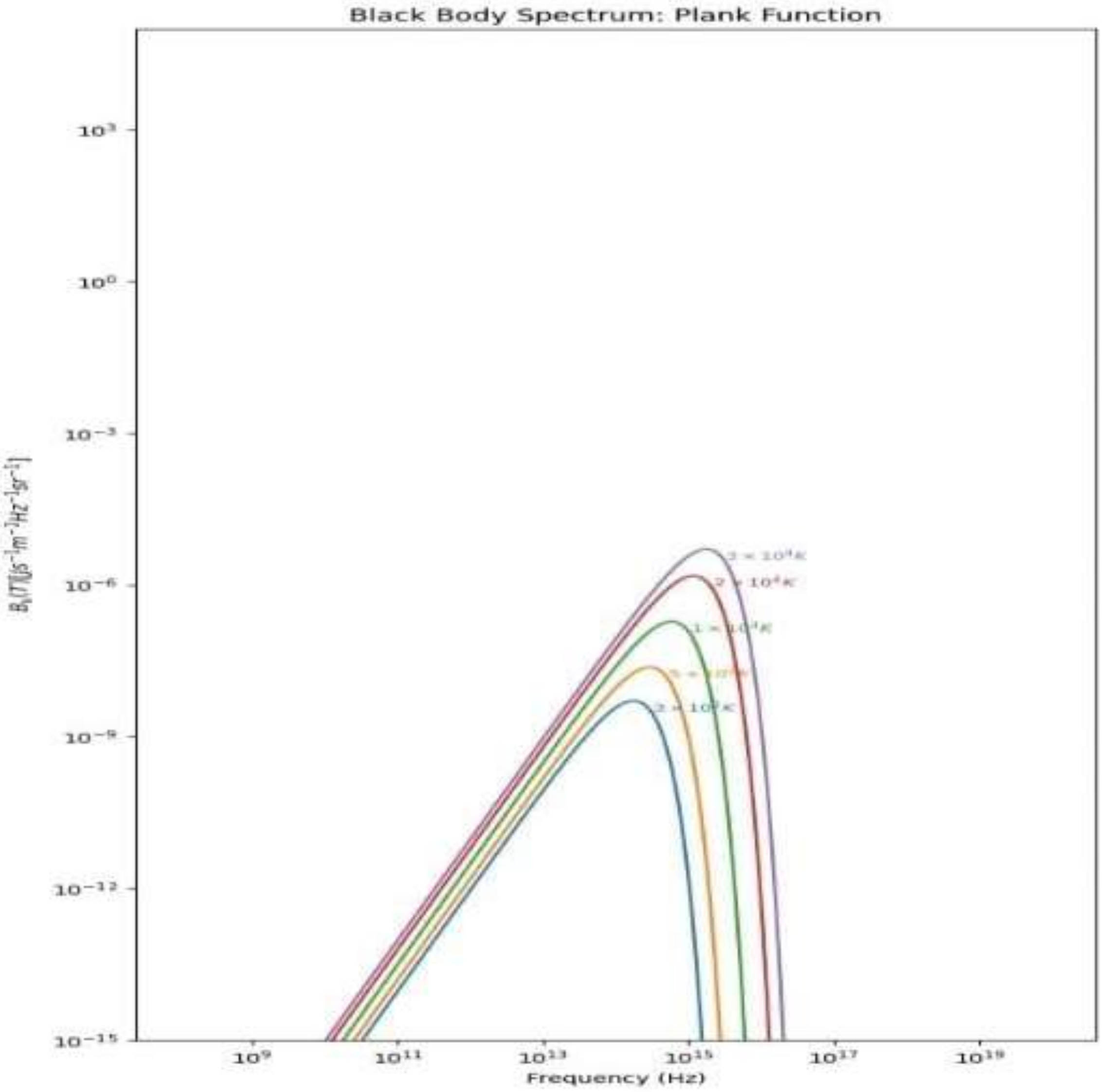


Figure 4.1: Blackbody spectrum of spectral class stars

If we plot a vertical line for the value 3.28 x 10^{15} which is equal to the ionization energy of the hydrogen molecule. Those stars having frequency higher than 3.28 x 10^{15} Hz can ionize hydrogen molecules. So we can conclude from the graph that stars having temperature higher than 10000K can ionize the hydrogen molecule in their near by surrounding (because they have frequency ranges higher than 10^{15} Hz

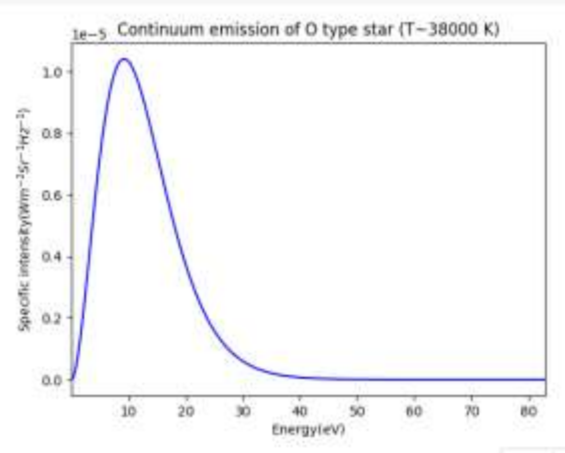
5.2 THE CONTINUUM EMISSION MODELS OF STARS

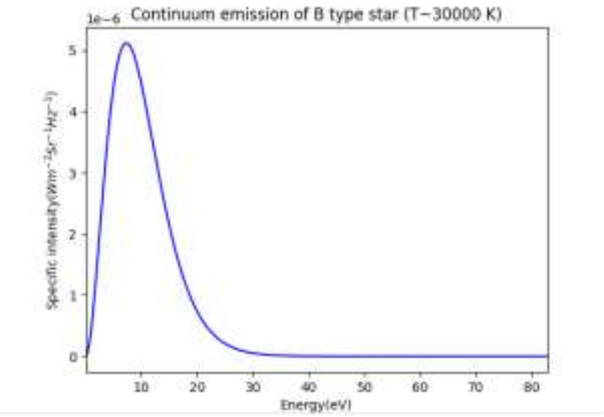
Code

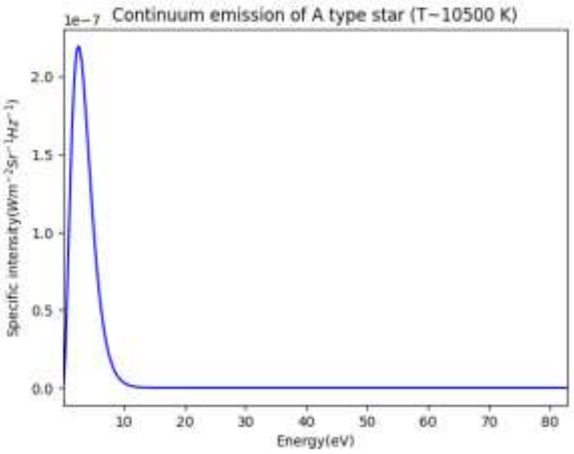
```
import numpy as np
import matplotlib.pyplot as plt
import scipy.constants as sc
import astropy.constants as astr

#defining the constants
c=sc.c
h=sc.h
k=sc.k
T=38000
R0= (astr.R_sun).value
R=10*R0
delta =0.01
ev_J=1.6*10**-19
f_mult =10**15
nu=np.arange (0.01,20,delta)
#nu is in units of 10^15
en=h*nu*f_mult
#en is in Joules
I_nu =(2*h*(nu* f_mult)**3/(c**2))*(1/(np.exp(h*nu*f_mult/(k*T))-1))
#I_nu is in SI units (specific intensity)
F_nu=4*np.pi*I_nu
L_nu=4*np.pi*F_nu*R**2
for i in range ( 1 , len ( en ) ):
    if (en[i]/ev_J)>13.6:
       j=i
       break
 N=0
for i in range ( j , len ( nu ) ):
    N=N+(L_nu[i]*delta/(h*nu[i]))
print (N)
plt.clf()
```

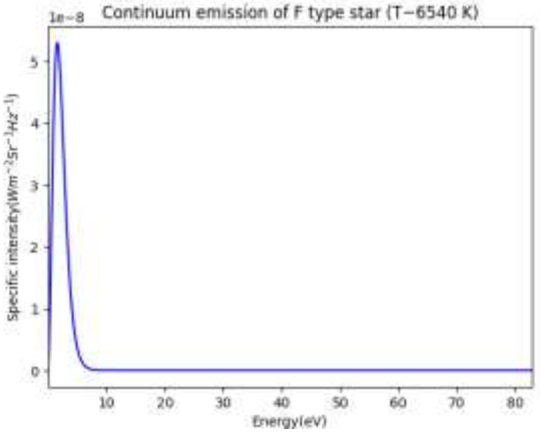
```
     plt.plot(en/ev_J,I_nu,color='b')
     plt.xlim(np.min(en/ev_J),np.max(en/ev_J))
     plt.xlabel('Energy(eV)')
     plt.ylabel(r'Specific intensity($Wm^{-2}Sr^{-1}Hz^{-1}$)')
     plt.title('Continuum emission of O type star (T~%d K)'%T)
     plt.show ()
     #plt.save fig('o.png ')
```

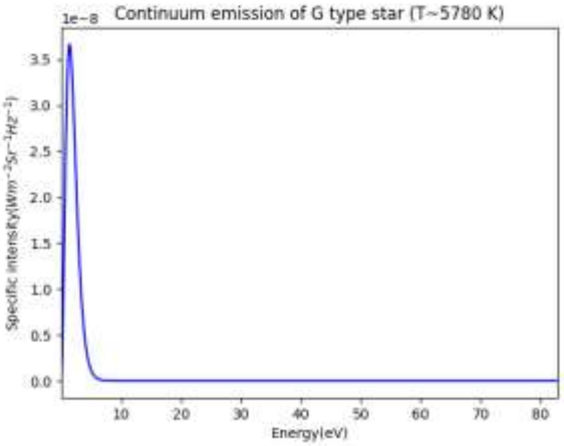
Plots of intensity vs photon energies

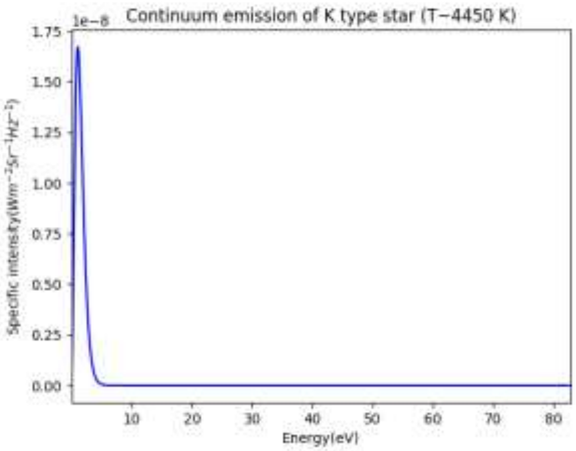


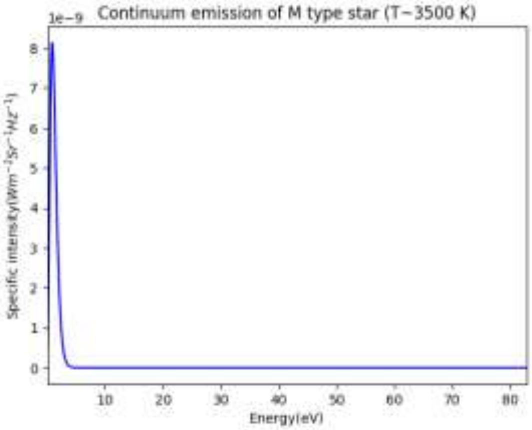



Continuum emission of A type star (T~10500 K)
1e−7
Specific intensity($Wm^{-2}Sr^{-1}Hz^{-1}$)
0.0
0.5
1.0
1.5
2.0
10
20
30
40
50
60
70
80
Energy(eV)


Continuum emission of F type star (T~6540 K)
1e−8
Specific intensity($Wm^{-2}Sr^{-1}Hz^{-1}$)
0
1
2
3
4
5
10
20
30
40
50
60
70
80
Energy(eV)


Continuum emission of G type star (T~5780 K)
1e−8
Specific intensity($Wm^{-2}Sr^{-1}Hz^{-1}$)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
10
20
30
40
50
60
70
80
Energy(eV)





These are the outcome of the corresponding python program for the continuum emission model of each stars. By analyzing these graphs we get the conclusion as O and B types stars (stars earlier than B1 spectral type) are capable of producing HII regions. UV output of these massive stars can 48onize the surrounding ISM and give rise to HII regions.

5.3 FINDING LYMAN CONTINUUM

The Planck function is used to compute the Lyman Continuum equation (see page 28).

$$The\ total\ flux = \int_{\nu_0}^{\infty} \frac{\frac{32\pi^2 h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{K_B T}}}}{h\nu}\, d\nu \tag{5.1}$$

The surface temperature and radius of the main sequence stars are shown below, along with the Lyman

Continuum flux determined for the main sequence stars O, B, A, and F.

SPECTTRAL CLASS	**TEMPERATURE (K)**	**RADIUS(SOLAR RADIUS)**
O	380000	18
B	300000	7
A	10500	2.2
F	6540	1.2
G	5780	
K	4450	0.75
M	3500	0.4

Table 5.1: Radius and Surface Temperature of Main Sequence Stars

This information is used to determine the Lyman continuum and the stromgren radius, respectively.Without changing the programme, the data can be changed by adding information on each star's spectral class. With regard to the provided information, the outcome is obtained.

The LyC (Lyman Continuum) for each star is calculated by python program:

5.3.1 PYTHON CODE TO FIND LYMAN CONTINUUM

```
import numpy as np
import matplotlib as plt
import scipy.constants as sc
import astropy.constants as astr
#Defining the constants
k = sc.k
h = sc.h
c = sc.c
T = 380000
#Change T,S_type values for diff spectral class of stars
S_type ='F'
Ro =(astr.R_sun).value
R =0.4*Ro
delta = 0.01
ev_J = 1.6*10**-19
f_mult = 10**15
nu = np.arange (0.01,20,delta)
#nu is in units of 10^15
en = h*nu*f_mult
#en is in Joules
I_nu=(2*h*(nu*f_mult)**3/(c**2))*(1/(np.exp(h*nu*f_mult/(k*T))-1))
#I_nu is in S I units(specific intensities)
#Numerical integration to find the photon flux
F_nu = 4*np.pi*I_nu
L_nu = 4*np.pi*F_nu*R**2
for i in range (1,len(en)):
   if (en[i]/ev_J)>13.6:
         j = i
```

```
        break
N=0
for i in range(j,len(nu)):
    N = N+(L_nu[i]*delta/(h*nu[i]))
print(N)
```

Here by giving temperature of each stars we can find the corresponding Lymann Continuum. The value of total flux emitting per second by each star is given below.

Spectral class	**Lyman continuum flux (photons per sec)**
O	1.6521279714928235 X10 ^{50}
B	1.0079228856155097 X 10^{50}
A	2.211521776656036 X 10^{41}
F	1.4754685989886885 X 10^{37}
G	5.4262872172581915 X 10^{35}
K	1.1833411769049534 X 10^{32}
M	6.126363520130434 X 10^{27}

.

Table 5.2: LyC value of Spectral Class Stars

5.4 DETERMINATION OF STROMGREN RADIUS

The Stromgren sphere's total ionisation and recombination rates will eventually reach equilibrium.Let NL y represent the quantity of Lyman continuum photons (ionising hydrogen-capable photons with frequencies higher than 3.284×10^{15}) that are released every second.In equilibrium,

$$N_{Ly} = r_r \mathrm{V} \tag{4.2}$$

$$N_{Ly} = \alpha_H n_e n_p \frac{3}{4} \pi R_s^3 \tag{4.3}$$

$$R_S^3 = \left(\frac{3N_{Ly}}{4\pi\alpha_H n_e^2}\right) \tag{4.5}$$

Python programming is used to determine the value of the Stromgren radius for various temperatures, and a graph is displayed based on the spectral classes of the stars.For main sequence stars, the stromgren radius and Lyman continuum are plotted using a combination of python code.

5.4.1 PYTHON CODE FOR STROMGREN RADIUS

```
import numpy as np
import matplotlib as plt
import scipy.constants as sc
import astropy.constants as astr
from astropy import units as u
c=sc.c
h=sc.h
k=sc.k
R0=(astr.R_sun).value
N_Ly=[1.6521279714928235*10**(50),1.0079228856155097
*10**(50),2.211521776656036                  *10**(41),1.4754685989886885
*10**(37),5.4262872172581915                 *10**(35),1.1833411769049534
*10**(32),6.126363520130434 *10**(27)]
```

```
N_Ly[0]
alpha_h=3*10**(-13)
n_e=10**3
Rs=[]
Rs_par=[]
def s_rad(N):
  R_s=(((3*N)/(4*np.pi*alpha_h*n_e**2))**( 1 / 3 ))*10**(-2)
  return R_s
for i in N_Ly:
  Rs=Rs+[s_rad(i)]
#converstion to parsec
Rs=Rs*u.m
Rs_par=Rs.to(u.parsec)
```

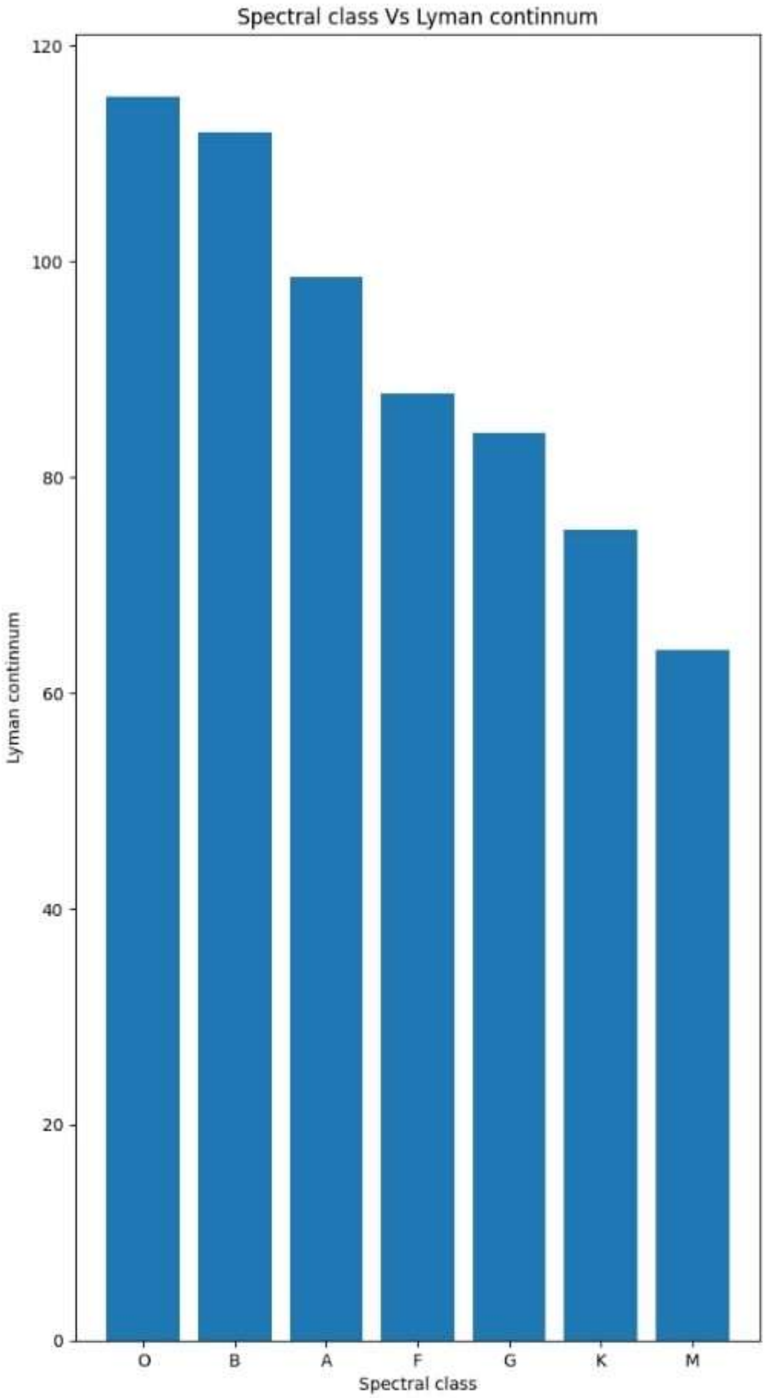
The resultant value of Stromgren radius is given below.

STARS	STM.RADIUS (PC)
O	1.6478869
B	1.3976184
A	0.0018161146
F	7.3658492×10^{-5}
G	2.4495168×10^{-5}
K	1.4744028×10^{-6}
M	5.495161×10^{-8}

Table 4.3: LyC value of Spectral Class Stars

Plotting the values of lymann continuum and stromgren radius versus spectral class stars of various temperatures The graph is displayed below.

These 2 graphs gives the



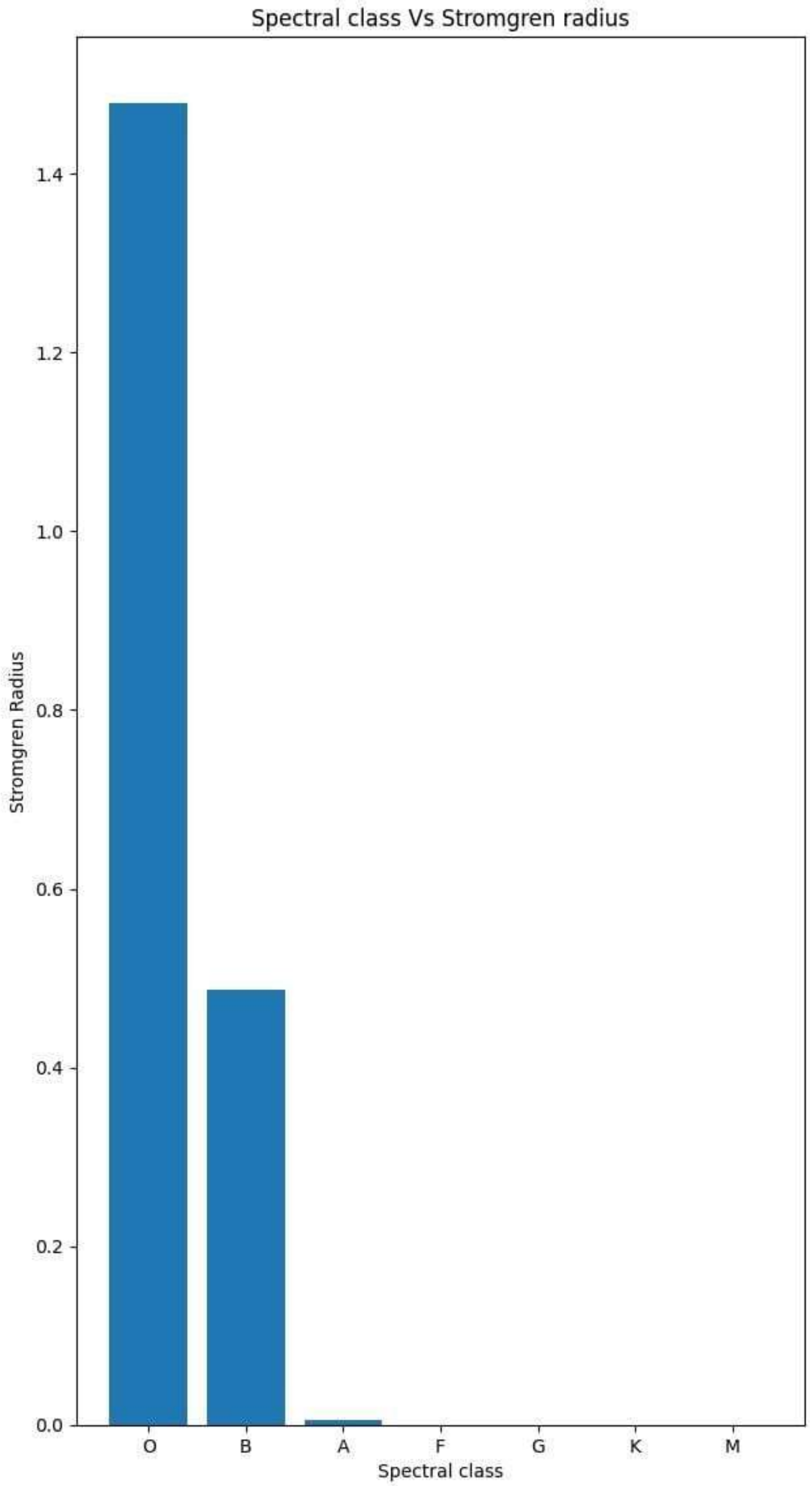


Figure 4.3: The first graph is plotted lyman continuum against spectral class stars.The second graph is plotted with stromgren radius against spectral class stars.

Only enormous stars can generate a greater HII area, according to the graph.and it demonstrates that the huge star's stromgren sphere has a very large radius.The HII region's range is rather broad.

These ideas are connected by the fact that O-type stars—among the hottest and most massive stars—are noted for their potent Lyman continuum radiation and are frequently linked to the ionisation of neighbouring interstellar hydrogen. As for figure 4.2, these areconnected because large stars of various spectrum classes emit the UV light required to ionise the interstellar hydrogen gas around them, which eventually results in the development of Strömgren spheres or HII regions. The characteristics of the ionising star and its surroundings can affect how large the Strömgren radius is.

CHAPTER 6

CONCLUSION AND FUTURE WORKS

6.1 CONCLUSION

There are five phases of the interstellar medium's (ISM) gas composition.Ionised gases are present in the phases known as Warm Ionised Medium (WIM) and Hot Ionised Medium (HIM).The ionisation of a neutral gaseous medium by energy from a supernova event produces the HIM.The area there is the warmest.Massive O and B stars in a galaxy ionise neutral and cold medium, creating the WIM.WIM is responsible for the HII zone that formed around the big stars. The stromgren radius graph demonstrates that the HII region's range expands over a few lightyears around a big star, such as O or B, which are young stars.Additionally, it demonstrates that the occurrence of HII regions is a key indicator of star production in galaxies.

Around the powerful O and B stars, HII zones develop. The gaseous medium was neutral and frigid prior to the creation of stars. But as star formation progresses, the medium surrounding the star's phase changes.The neutral hydrogen atoms become singly ionised hydrogen ions (HII) when high surface temperature stars generate UV photons with enough energy to ionise hydrogen atoms.The formation of the HII region is based on this fundamental idea. A typical HII region is a cloud of gas that is somewhat ionised and has just undergone star formation. Its size can range from one to hundreds of light years.HII regions can be seen throughout the cosmos at great distances, and extra-galactic HII region research is crucial for understanding the chemical makeup of galaxies.The Stromgren Radius refers to the HII region's size.An HII zone may contain several thousand stars, depending on its size.

The relationship between the Lyman Continuum and recombination at the boundary region yields the range of the HII region (Stromgren radius). HII regions generated around O and B stars, which are massive and have high surface temperatures, are found to be more visible than those formed around other stellar classes, according to the graph of Stromgren values for various spectral classes.The H line, produced by recombination at the boundary area, is used to observe the HII region.

The spectral classification of star is also co-related with the masses of stars.The more massive the stars, the more hotter and luminous they will be. So spectral classification is a proxy measure of stellar mass. Stars have different life time, comparatively OB stars have shorter life span. The presence of WIM indirectly indicates that there is a presence of massive OB stars.Since they have shorter life span, the presents of WIM also indicate the ongoing star formation, the last episode of star formation that happened a few million years ago .

Mapping the WIM in external galaxy is one of the ways in which astronomers assess whether these galaxies are actively star forming at the present or not.So the presence of WIM is an indicator of star formation rate.

Due to the transitions of ionised hydrogen atoms, the warm ionised medium exhibits distinctive spectral lines, such as the H-alpha line (656.3 nanometers). Astronomers utilise these visible emission lines to locate and investigate HII areas in galaxies. The surrounding ISM may experience feedback effects as a result of the ionisation and heating the WIM produces. By heating and spreading the gas, for instance, the ionisation of surrounding gas might affect star formation. This feedback is crucial to the evolution of the galaxy.

While massive stars are the main producers of ionising UV radiation for the WIM, it's vital to keep in mind that other processes, such shocks from supernova explosions, can also cause ionisation in some areas of the ISM. Additionally, the star formation rate, metallicity, and overall structure of a galaxy, as well as other factors, can all have an impact on the WIM's formation and evolution. Understanding the interaction between big stars and the ISM in galaxies as well as their overall evolution depends on research into the WIM.

6.2 FUTURE WORKS

Here we concluded that the WIM is mostly produced and sustained by massive young stars. However, we may carry on with our investigation into how the mass and temperature of stars differ between the O and B Star groupings. As a result, we can do more research on how the features of WIM alter depending on the various stars in the O and B groups. The life cycle of the gas in the ISM can be revealed by determining the impact of big stars there.

The star creation in external galaxies is the other area in which we may be interested.Further research will make it possible to track the star formation in the far-off universe and make in-depth comparisons between the Milky Way and other galaxies.

According to several recent studies, the creation and maintenance of WIM can both be attributed to low energy cosmic rays (LECR). We can also keep researching the potential other causes for the production of WIM.

Other feeble nebular emission from this phase was found as a result of the discovery of Hα emission from the WIM. This allows us to find other detectable nebulae and explore more of their characteristics. In comparison to other ionised gas tracers, Hα emission is the best option for WIM research, yet it is interstellar extinction that limits its use. Fine structure lines in the far infrared (FIR), which are effective probes unaffected by interstellar extinction. Finding the other, more effective problems is therefore advantageous.

There is difference in ionization rates of WIM ond HII region , even they both are from massive stars.We can analyse the cause for this riddle also.

CHAPTER 7

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