UNIT 9 STAR FORMATION

Structure

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9.1 INTRODUCTION

In Unit 8, you have learnt the basic physical principles governing the processes in the interior of stars. The existence of stars was taken for granted and their coming into being was not discussed. It is, however, logical to ask: Where do the stars come from? How are the stars formed? In general terms, you did study about the formation of the solar system including the Sun (the only star in our solar system) in Unit 6. But the focus of that unit was to understand the formation and characteristics of the planets. In the present unit, you will learn about the formation of stars.

You must have observed stars in the night sky. On a clear dark night away from city lights, you can observe that the space surrounding the bright stars is fairly luminous. This is due to the scattering of light from the star by the gas and dust in its surroundings. Further, astronomical observations suggest that the more luminous and massive stars are younger and have been formed recently. Since these stars are completely surrounded by gas and dust, it is believed that the stars are formed from it. The gas and dust in the interstellar space is called the **I**nter **S**tellar **M**edium **(ISM)** and it is the major constituent of our galaxy – the Milky Way Galaxy. You will learn the basic composition of ISM and methods of its detection in Sec. 9.2. Under suitable conditions, a cloud of gas and dust condenses or collapses due to its own gravity and forms protostars. In Sec. 9.3, you will learn the Jeans criterion which is a rough measure of the mass and size of the interstellar cloud which may collapse and give birth to a star. You will discover that the interstellar cloud must fragment repeatedly to form stars. In Sec. 9.4, you will learn how a protostar evolves into a full fledged star and becomes a member of the main sequence (in the H-R diagram discussed in Unit 7).

It is usual to write our galaxy with the upper case G, that is, as Galaxy.

The various stages from the initial collapse of a cloud of ISM upto the pre-main sequence are collectively considered as birth of a star, that is, the process of its formation. You may ask: What happens afterwards? This issue is addressed in the next Unit on Nucleosynthesis and Stellar Evolution where we discuss the *life* of stars.

Objectives

After studying this unit, you should be able to:

- describe the basic composition of ISM;
- derive Jeans criterion for the stability of a gas cloud;
- explain the necessity of repeated fragmentation of a collapsing cloud; and
- discuss the evolution of an interstellar cloud into a pre-main sequence star.

9.2 BASIC COMPOSITION OF INTERSTELLAR MEDIUM

The interstellar medium (ISM) makes up only 10 to 15 percent of the visible mass of the Milky Way Galaxy. It comprises matter in the form of gas and dust (very tiny solid particles). About 99 percent of ISM is gas and the rest is dust. You may like to know: **Which elements are present in the ISM?** An important clue for investigating the composition of the ISM is the fact that the birth and death of stars is a cyclic process. This is so because a star is born out of ISM, and during its life, much of the material of the star is returned back to the ISM by the process of stellar wind (in case of the Sun, it is solar wind; see Unit 5) and other explosive events such as Nova and Supernova. The material thrown back into the ISM may form the constituents of the next generation of stars and so on. To know the basic composition of ISM, astronomers use photographs and spectra. *In the following discussion, we shall confine ourselves to the composition of the ISM of the Milky Way Galaxy in the neighbourhood of the Sun.* Further, for simplicity, we will first discuss the composition of interstellar gas and then come to interstellar dust.

9.2.1 Interstellar Gas

Hydrogen and helium are the two major constituents of interstellar gas; hydrogen constitutes about 70 percent and the rest is helium. Indeed, other elements are also present but in very small quantities. The analysis of the radiation received from ISM has enabled astronomers to classify the gaseous matter filling the interstellar space into the following four types:

i) H II region,
ii) H I region,
iii) Inter-cloud medium, and
iv) Molecular cloud.

We now briefly describe these regions and their possible roles in the formation of stars.

i) H II region: As the name suggests, these regions of ISM mainly consist of (singly) ionised hydrogen. In addition, these regions contain ions of other elements such as oxygen and nitrogen and free electrons. **Since the ionisation energy of hydrogen atom is very high, such regions can exist only in the vicinity of very hot stars**. H II region can be viewed even with naked eye in the constellation of Orion. If you look carefully at Orion's sword, you will see that one of the objects is a hazy cloud of gas (Fig. 9.1). This bright cloud is called **Orion nebula**. The spectrum of this nebula shows lines of hydrogen and some other elements in its bright line spectrum. Such bright nebulae are also called **emission nebulae**.

It has been discovered that emission nebulae do not shine by their own light. They absorb high energy ultraviolet photons from hot stars. These photons ionise the gas in the nebulae and subsequently, low energy photons are radiated. Since the spectrum of the nebula consists of many emission lines of hydrogen, it indicates that the light must have been emitted by a low-density gas. Further, the emission lines of hydrogen are very strong and the red, blue and violet Balmer lines blend together resulting in the characteristic pink-red colour of the nebula (Fig. 9.1).

Fig.9.1: Orion nebula – a typical bright and diffuse nebula

At this stage, you may ask: **Why are the H II regions always found in the emission nebulae?** Note that only those photons which have wavelengths shorter than 91.2 nm have sufficient energy to ionise hydrogen. Such high energy photons can be produced in sufficiently large numbers by hot (~ 25,000 K) stars only. And stars (such as hot O or B star) having temperature of this order are located in or near the emission nebulae. Further, H II regions have very low density (~ 10^9 particles m^{-3}). They provide observable evidence supporting the existence of matter in interstellar space.

ii) H I region: Although it has been generally believed by astronomers that hydrogen atoms populate interstellar space, they could not detect H I gas till 1951. The reasons are obvious: it is not possible for the neutral hydrogen in ISM to produce emission line as it is in the ground state. However, with the development of radio telescopes, it is now possible to detect H I region. **The detection of H I in the ISM is based on the detection of a unique radiation of wavelength 21 cm.**

SAQ 1

Spend 5 min.

Calculate the energy of electromagnetic radiation having wavelength 21-cm.

On solving SAQ 1, you must have found that the value of the energy of radiation corresponding to wavelength 21-cm is very small. You may ask: **What kind of transition produces such a low energy photon?** In a hydrogen atom, an electron revolves around the proton. Since the proton and the electron possess spin, there are two possible ways for their spins to align with respect to each other. The two spins may be parallel (aligned) or anti-parallel (anti-aligned) (Fig. 9.2). *It is known that the parallel spin state of hydrogen atom has slightly more energy than the anti-parallel spin state*. Therefore, if there is a flip from the parallel to the anti-parallel state, there is a loss in energy of the hydrogen atom and it results in the emission of a photon. The frequency and the wavelength of such emissions are 1420 MHz and 21 cm, respectively.

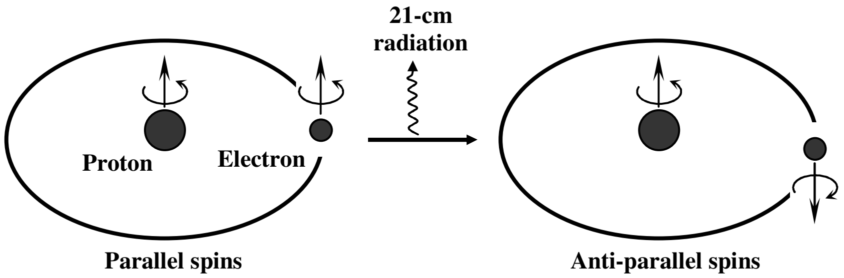

Fig.9.2: Parallel and anti-parallel spin alignments of the electron and proton in a hydrogen atom

Further, the question is: **Can we obtain 21-cm radiation in laboratory conditions?** It is not possible because the best vacuum that can be produced in a laboratory has a much higher density of atoms than that found in the ISM. So, in laboratory conditions, practically all the hydrogen atoms get de-excited due to higher collision rate and we cannot obtain 21-cm line. Thus, the only place where favourable conditions for emission of such radiations can exist is outer space. The 21-cm line was first detected in the year 1951 using a radio telescope even though it was predicted as early as in the 1940s. Since its detection, it has become a common tool in astronomy to map the location and densities of H I regions. This helps in determining the structure of galaxies including our own. Investigations of diffuse interstellar H I clouds suggest that their temperatures are in the range of 30 – 80 K, masses in the range of 1 – 100 solar masses and the number densities in the range of $10^8 - 10^9$ cm^{-3}.

iii) Inter-cloud Medium: Having read about clouds of ionised and neutral hydrogen in ISM, you would like to know: **Is the space between the interstellar clouds empty?** It is not so; the inter-cloud space consists of

a) neutral hydrogen gas with a density of 10^5 atoms m^{-3}, and
b) hot (~ 8000 K) ionised gas with very low density (~ 10^4 ions m^{-3}).

You would further like to know: **Is there any interaction between the H I clouds and the inter-cloud medium?** The H I clouds are very cool and have high densities whereas inter-cloud medium has very low density and high temperature. The pressure of a region, being a function of its density and temperature, in the H I clouds and in the inter-cloud medium is about the same and they are in equilibrium.

iv) Molecular Cloud: Analysis of optical spectra of interstellar medium reveals that matter exists in molecular form in ISM. Since hydrogen is the most abundant matter in ISM, it mainly consists of the hydrogen molecules (H_2). However, molecules of hydrogen do not emit photons of radio wavelength and vast clouds of hydrogen molecules remain undetected by radio spectroscopy. Other molecules, such as CO (carbon monoxide), capable of emitting in radio wavelength, can indeed be detected. In fact, nearly 100 such molecules have been detected. But the basic question is: **How do these molecules form in ISM?** It is believed that the atoms come in the vicinity of each other and bond to form molecules on the surfaces of the dust grains (about which you will learn later in this Section). These molecules are very weakly bonded and can be easily broken by high energy photons. Thus, they can exist only deep inside dense clouds. Also, efficient release of energy by molecules makes these dense clouds very cool. These dense, cold clouds are called **molecular clouds**.

Hydrogen molecules have been detected in the ISM by infrared spectroscopy.

In our Galaxy, the largest of these cool, dense molecular clouds are called **giant molecular clouds** (**GMC**). They are 15 to 60 pc across and may contain 100 to 10^6 solar masses! The internal temperature of GMC is very, very low (~ 10 K). The question is: **Do the giant molecular clouds have any role in the formation of stars?** You know that young stars are surrounded by H II regions. And H II regions are invariably found near giant molecular clouds. This proximity indicates that the GMC plays an important role in the formation of stars. Thousands of GMC exist in the spiral arm of our Galaxy. The association of O and B main sequence stars with GMC suggests that star formation takes place in these regions. We will talk more about it later in this Section.

9.2.2 Interstellar Dust

Interstellar medium also contains dust grains, which constitute about one percent of the interstellar mass. Although the temperature of interstellar dust region is very low (~ 100 K), it can be detected by infrared telescopes. A typical dust grain is made of thin, highly flattened flakes of silicates and graphites coated with ice. Fig. 9.3 shows a typical dust grain, which is of the size of the wavelength of blue light.

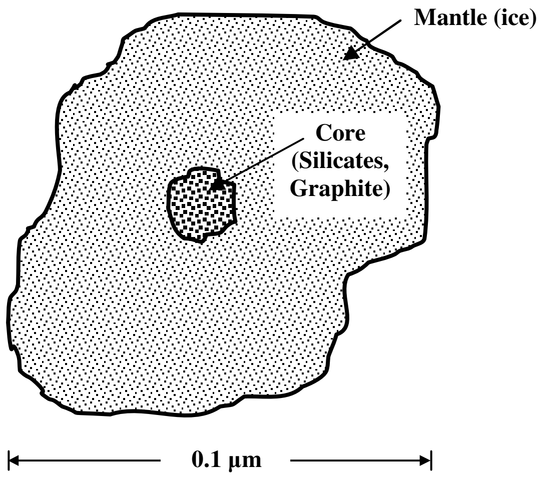

Fig.9.3: A typical dust grain

Now, you may ask: **What is the evidence supporting the existence of dust in ISM?** The two observable effects due to dust are **extinction** and **reddening**. Refer to Fig. 9.4. Note that, besides the brighter gas and dust regions surrounding the stars, there are darker regions as well. You may think that these regions are devoid of stars. It is not so. *In fact, these darker regions are so dense that they completely stop the light emitted by stars behind them and therefore no light is able to pass through.* This phenomenon is known as **interstellar extinction**. The extent to which light is scattered or absorbed in a dust cloud depends on the number density of particles and on its thickness.

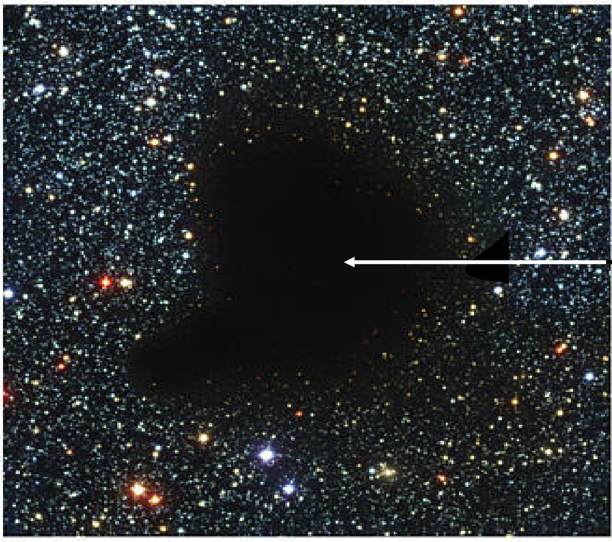

Fig.9.4: Dark interstellar space caused due to extinction

To obtain an expression for the apparent magnitude of a star, located behind the dense cloud of dust, recall (from Unit 1) that the relation between the apparent magnitude (m_λ), the absolute magnitude (M_λ) and the distance d in parsec of a star at wavelength is written as:

$$m_\lambda = M_\lambda + 5\log_{10} d - 5 \qquad (9.1)$$

since the absorption and scattering of light is dependent on the wavelength. For stars suffering extinction, we can write Eq. (9.1) as:

$$m_\lambda = M_\lambda + 5\log_{10} d - 5 + a_\lambda \qquad (9.2)$$

where a_λ *is the magnitude of light scattered or absorbed along the line of sight*. Eq. (9.2) indicates that absorption increases the magnitude of a star. A star which would be visible to the naked eye, for instance, may be invisible due to the large extinction i.e., sufficiently large a_λ. Further, the extinction may be expressed in terms of the optical depth as:

$$a_\lambda = 1.086\ \tau_\lambda \qquad (9.3)$$

Spend 10 *min.*

SAQ 2

The relation between optical depth, τ_λ and intensity I_λ for a star is given by $I_\lambda = I_{\lambda 0} e^{-\tau_\lambda}$.

Show that $a_\lambda = 1.086\ \tau_\lambda$.

(Hint: Remember that apparent magnitude may be written as $m = K - 2.5 \log I$, where K is a constant.)

To appreciate the fact that extinction depends on the density of dust grains, we can express the optical depth τ_λ in terms of the number density of particles, n and scattering cross section σ_λ as:

$$\tau_\lambda = \int_0^s n\ (s)\ \sigma_\lambda\, ds. \qquad (9.4)$$

Assuming that the scattering cross-section σ_λ is constant along the line of sight, we obtain from Eq. (9.4):

$$\tau_\lambda = \sigma_\lambda N_d \qquad (9.5)$$

where N_d is the **column density** of particles, i.e., the number of particles in a cylinder of unit cross section stretching from the star to the observer. Eq. (9.5) shows that extinction depends on the amount of interstellar dust present in the path of light from the star.

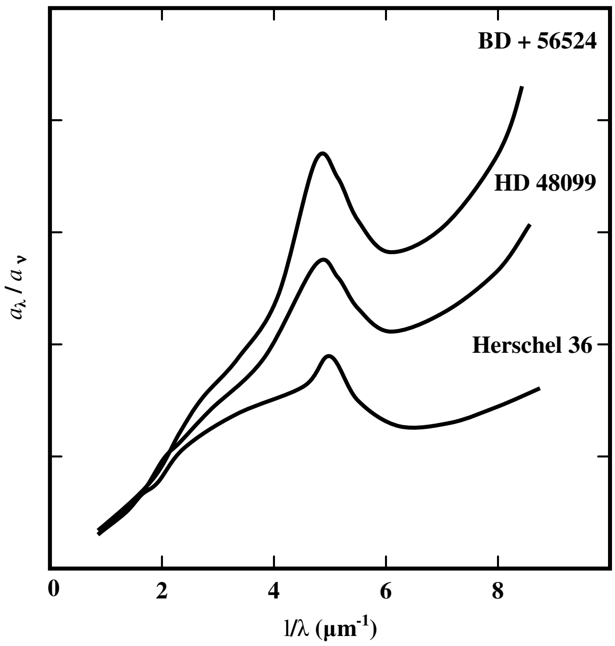

Fig.9.5: Schematic diagram showing the variation of $\frac{a_\lambda}{a_V}$ with $\frac{1}{\lambda}$

Fig. 9.5 shows the variation of $\frac{a_\lambda}{a_V}$ with $\frac{1}{\lambda}$. Here, a_V is the amount of extinction in the visual band of wavelengths centered at 5500 Å. In Fig. 9.5 we observe a peak in the ultraviolet region which indicates that radiations of corresponding wavelengths are strongly absorbed by ISM. Such a peak, therefore, provides a basis for determining the composition of ISM. It is now known that graphite interacts strongly with electromagnetic radiation of wavelength around 2175 Å. Therefore, the occurrence of peak at $\lambda = 2175$ Å in Fig. 9.5 suggests the presence of graphite as one of the constituents of ISM. Further, the presence of absorption bands at 9.7 μm and 18 μm in the observed spectrum (not shown in Fig. 9.5) indicate the presence of silicate grains in the ISM.

Yet another manifestation of interstellar dust is in the form of **interstellar reddening**. You know that an O star should be blue in colour. But, it has been observed that some stars with the spectrum of an O star look much redder. This is caused due to scattering of light from stars by interstellar dust.

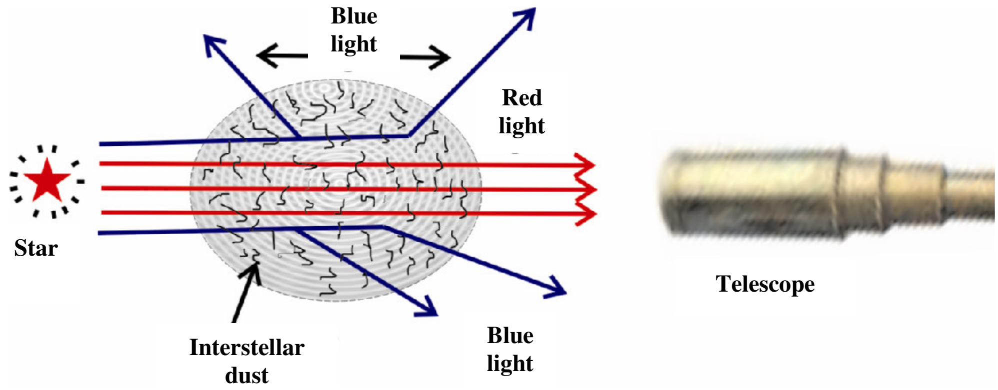

Fig.9.6: Interstellar reddening caused due to the scattering of blue light coming from star

Refer to Fig. 9.6. The light coming from a star behind the dust cloud is scattered. *Since the typical size of dust grains is of the order of the wavelength of blue light, the blue light from star is scattered more than the red light*. As a result, some of the blue light from the star is lost and it appears redder.

You might wonder as to why we discussed ISM in such detail. It is because astronomers suspect that stars are formed from ISM. The most important observation supporting this hypothesis is the association between young stars and clouds of gas: **wherever we find the youngest group of stars, we also find large clouds of gas illuminated by the hottest new stars**. In the following section, you will learn about the processes and principles involved in the formation of stars from ISM.

9.3 FORMATION OF PROTOSTAR

In the previous Section, you learnt that the giant molecular clouds (GMCs) are the likely sites where star formation can take place. However, GMCs are very unlike stars: their typical diameter is 50 pc, typical mass exceeds 10^5 solar masses and their density is 10^{20} times less than a typical star. Thus, the question is: **How do stars form from such molecular clouds?** The simplest answer to this question is that the stars form due to gravity: a cloud of gas contracts due to self-gravity. This contraction increases density and temperature of the core, initiating generation of nuclear energy. You may ask : **How do we reconcile the typical mass of a star with the mass of a GMC (~ 10^5 solar mass)?** This problem was addressed by Jeans who proposed a criterion for the mass of a contracting cloud which may evolve into a star.

9.3.1 Jeans Criterion

Jeans proposed that there are two competing processes in the gravitational collapse of a molecular cloud. On the one hand, the gravitational contraction increases the internal pressure of the cloud which tends to expand the cloud. On the other hand, gravity acts on the cloud and tends to further contract it. *Which of these two processes will dominate is determined by the mass of the cloud*. If the internal pressure is more than the gravitational force, the cloud will break up. A clump of cloud must have a minimum mass to continue collapsing and give birth to a star. This minimum mass is called the **Jeans mass**. It is a function of density and temperature.

To obtain an expression for the Jeans mass, we make the following simplifying assumptions:

i) the cloud is uniform and non-rotating;
ii) the cloud is non-magnetic; and
iii) the gas and dust is confined to a certain region of space by the gravitational force and is in hydrostatic equilibrium.

For such a system, we may write the relation between kinetic and potential energies as (see virial theorem, Unit 8):

$$2U + \Omega = 0, \tag{9.6}$$

where U is the internal kinetic energy and Ω is the gravitational potential energy of the cloud. If M and R are the mass and radius of the cloud, respectively, the potential energy of the system can be written as (Eq. (8.14), Unit 8):

$$\Omega = -\frac{3}{5}\frac{GM^2}{R}. \tag{9.7}$$

If the number of particles in the cloud is N and its temperature is T, the internal kinetic energy of the cloud can be written as:

$$U = \frac{3}{2} N k_B T, \tag{9.8}$$

where k_B is the Boltzmann constant. Further, the number of particles $N = \dfrac{M}{\mu\, m}$, where $\mu\, m$ is the mean molecular weight and m is the mass of a hydrogen atom. If the total internal kinetic energy is less than the gravitational potential energy, the cloud will collapse. This condition reduces Eq. (9.6) into

$$2U < |\Omega|$$

Substituting for Ω and U from Eqs. (9.7) and (9.8), respectively, we get:

$$\frac{3k_B TM}{\mu\, m} < \frac{3}{5}\frac{GM^2}{R}.$$

or,

$$M > \frac{5k_B TR}{\mu\, m G} \tag{9.9}$$

On substituting $R = \left(\dfrac{3M}{4\pi\rho}\right)^{\frac{1}{3}}$ in Eq. (9.9), we find that the minimum mass that will initiate a collapse is given by:

$$M \approx M_J = \left[\frac{5k_B T}{\mu\, m G}\right]^{\frac{3}{2}} \left[\frac{3}{4\pi\rho}\right]^{\frac{1}{2}} \tag{9.10}$$

Here M_J is called the **Jeans mass** and Eq. (9.9) is known as **Jeans criterion**. *The Jeans mass is the minimum mass needed for a cloud to balance its internal pressure with self-gravity*; clouds with greater mass will collapse.

Jeans criterion can also be expressed in terms of the **Jeans length**, R_J given by:

$$R_J \approx \left(\frac{15k_B T}{4\pi G \mu\, m \rho}\right)^{\frac{1}{2}} \tag{9.11}$$

which can be obtained by putting $M = \frac{4\pi}{3} R^3 \rho$ in Eq. (9.9). For pure hydrogen, $\mu = 1$.

Spend 5 min.

SAQ 3

A collapsing cloud is made of neutral hydrogen (H I) only. If the temperature of the cloud is 50 K and its number density is 10^5 m^{-3}, calculate its Jeans mass.

In a situation where Jeans criterion is satisfied, the cloud must collapse gravitationally. When the collapsing could attain high density, it becomes gravitationally unstable and breaks up into smaller pieces. Thus, the general picture is that stars form in groups due to fragmentation. You will learn more about it later in this section.

At this stage, you may ask: **How long does it take for a cloud to collapse?** It is a good idea to estimate the minimum time which will be taken if we assume that the cloud collapses only under the influence of self-gravity and there is no other process taking place to slow down the collapse. This assumption is called **free-fall collapse**, and it implies that the pressure gradient in the interior of the clump is negligibly small.

To obtain a rough estimate of the free-fall time, you may recall that a particle on the surface of a star of mass M and radius R experiences an acceleration g given by:

$$g = \frac{GM}{R^2}\,. \tag{9.12}$$

If the time taken by this particle to fall through a distance R is t_{ff} we can write:

$$R = \frac{1}{2} g\, t_{ff}^{\,2}$$

or

$$t_{ff} = \left(\frac{2R}{g}\right)^{\frac{1}{2}} \tag{9.13}$$

Substituting Eq. (9.12) in Eq. (9.13), we get:

$$\begin{aligned} t_{ff} &= \left(\frac{2R^3}{GM}\right)^{\frac{1}{2}} \\ &= \left(\frac{2R^3}{G\frac{4\pi}{3}R^3\rho}\right)^{\frac{1}{2}} \\ &= \left(\frac{3}{2\pi G\rho}\right)^{\frac{1}{2}} \end{aligned} \tag{9.14}$$

Eq. (9.14) shows that the free-fall time, t_{ff} is a function of the cloud's initial density and it does not depend on the initial radius or the initial mass of the cloud. If some part of a collapsing cloud, say in the central region, is denser than its surroundings, the collapse of such a region is likely to be faster than that of the surrounding region.

SAQ 4

Spend 5 min.

Calculate the free-fall time for a molecular cloud whose initial density is 10^{-17} g cm^{-3}.

Now you know that the larger gas clouds collapse if their masses exceed the Jeans mass. In a typical situation of an H I cloud with $T = 100$ K, $\rho = 10^{-24}$ g cm^{-3} and $\mu = 1$, we find that for gravitational collapse, the mass of the cloud must be greater than 10^5 times the solar mass. So, you may be led to believe that the stars could be formed with masses of this order. However, observations suggest that the stars are formed in groups and the masses of the stars are in the range of $0.1 - 120\ M_\Theta$. Thus, the range of stellar mass is much smaller than $10^5\ M_\Theta$. This has led astronomers to propose the *fragmentation of interstellar clouds* during collapse. You will now learn about it.

9.3.2 Fragmentation of Collapsing Clouds

As mentioned earlier, Jeans criterion provides the theoretical justification for fragmentation of a collapsing cloud. Refer to Fig. 9.7 which shows the fragmentation of interstellar cloud of mass M and Jeans mass M_J such that $M > M_J$. Since M is greater than M_J, the interstellar cloud collapses. This results into the increase of the density and temperature of the cloud which may, in turn, change the Jeans mass for the cloud. Let the changed Jeans mass be M'_J ($\neq M_J$).

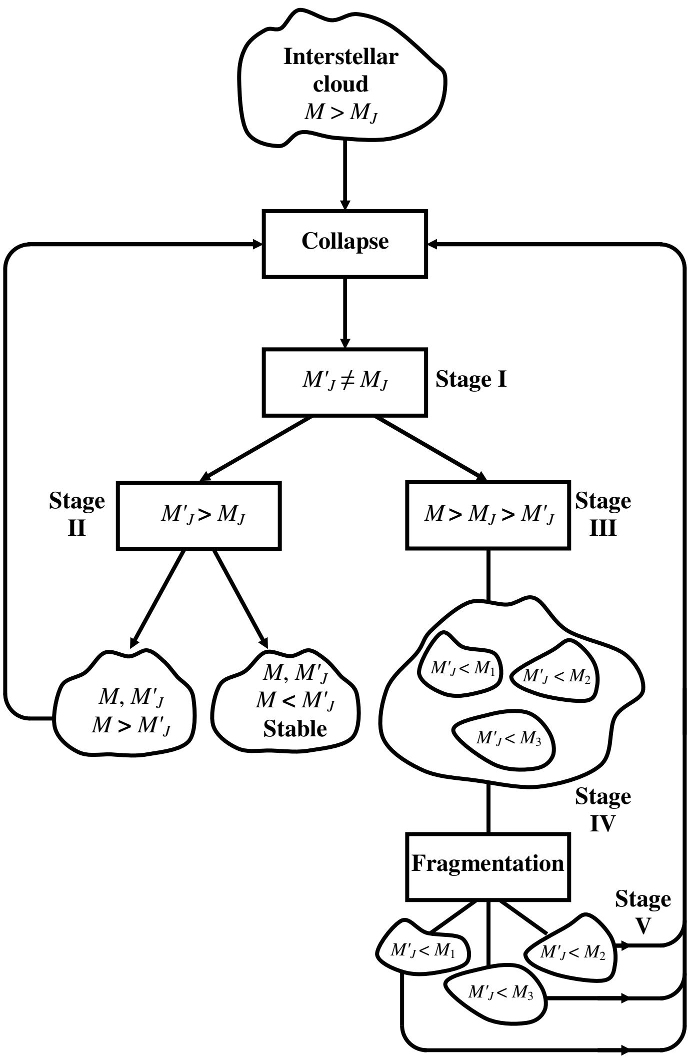

Fig.9.7: Fragmentation of interstellar cloud

Further, from Eq. (9.10) it is evident that, if the cooling of this cloud is not efficient, the Jeans mass will increase (stage II in Fig. 9.7). If the mass of the cloud is less than the new (increased) value of the Jeans mass, the collapse will stop and if $M > M'_J$, the cloud will collapse further. On the other hand, if the cooling of the collapsing cloud is efficient, the temperature of the cloud will fall and the Jeans mass would decrease (stage III in Fig. 9.7). *In such a situation, it is possible that the mass in certain regions of the cloud is more than the reduced Jeans mass* (stage IV in Fig. 9.7). This may trigger further collapse of such regions resulting into fragmentation of the cloud (stage V in Fig.9.7). Fragmentation of clouds continues until clouds of still smaller masses, which are gravitationally stable, are created. These fragments of molecular clouds are the birth places of the stars in the mass range of $0.1 - 120\ M_\odot$.

You must note that for the scenario discussed above to be true, the *Jeans mass should not be a constant during collapse*. It must decrease with increase in density in a local region during collapse. This would lead to further gravitational instabilities which may lead to separate individual collapsing regions.

Further, while discussing the collapse of interstellar clouds, *we assumed that the collapse process is isothermal*. This can be considered to be a valid assumption as far as the initial stages of collapse are concerned. As the collapse begins, the cloud is likely to be optically thin due to its low density. Therefore, the gravitational energy released during collapse is radiated away completely, keeping the temperature of the cloud unchanged.

You may ask: **What happens if the collapse is adiabatic instead of isothermal?** In that case, the energy released during the collapse is used up in raising the internal energy of the cloud and its temperature increases. The increase in temperature thus affects the Jeans mass. Let us now obtain an expression for the Jeans mass for adiabatic collapse.

You may recall from the course entitled Thermodynamics and Statistical Mechanics (PHE-06) that, for an adiabatic process, the relation between temperature T and density ρ of a system is given by:

$$T = K_1\, \rho^{\gamma-1} \tag{9.15}$$

where K_1 is a constant and γ is the ratio of heat capacities. Using this relation in the expression for the Jeans mass (Eq. (9.10)) we can write:

$$M_J = \left[\frac{5k_B T}{\mu m G}\right]^{\frac{3}{2}} \left[\frac{3}{4\pi\rho}\right]^{\frac{1}{2}}$$

$$= \left[\frac{5k_B K_1}{\mu m G}\right]^{\frac{3}{2}} \left[\frac{3}{4\pi}\right]^{\frac{1}{2}} \rho^{(3\gamma-4)/2}$$

Thus

$$M_J \propto \rho^{(3\gamma-4)/2} \tag{9.16}$$

For the cloud comprising only atomic hydrogen, we have $\gamma = 5/3$. Therefore, for adiabatic collapse of the cloud, we get:

$$M_J \propto \rho^{1/2} \tag{9.17}$$

Eq. (9.17) shows that Jeans mass increases with increase in density. However, the relation between the Jeans mass and density for the isothermal collapse is given as $M_J \propto \rho^{-1/2}$. Comparison of these two results indicates that in a switchover from isothermal to adiabatic collapse, the Jeans mass reaches a minimum for the fragments of molecular clouds.

The gravitational collapse is a complex process. It is difficult to ascertain exactly when a switchover from isothermal to adiabatic collapse takes place. Moreover, the transition is neither instantaneous nor complete. The minimum Jeans mass has been estimated to be ~ 0.5 $M_\odot$. This is the right order of magnitude for the mass of the fragments of clouds which become stars.

The fragmentation of collapsing clouds leads to the formation of protostars – **pre-stellar objects which are hot enough to radiate infrared radiation but not hot enough to generate energy by nuclear fusion**. Due to gravitational collapse, the fragmented clumps of cloud contract and at the core of each of them, high-density region develops which is surrounded by a low-density envelope. Matter continues to flow inward from the outer parts of the clumps. The protostar begins to take shape deep inside the enveloping cloud of cold, dusty gas. These clouds are called *cocoons* because they hide the forming protostar from our view. So, these are the initial stages of the formation of stars. Let us now discuss this further.

9.4 FROM PROTOSTAR TO PRE-MAIN SEQUENCE

We have seen above that initially a cloud collapses, perhaps isothermally, and with the passage of time the cloud collapse tends to become adiabatic. As a result, increased pressure inside tends to slow the time scale of collapse particularly near the centre of the cloud. Further, fragmentation of collapsing cloud leads to a stage when a **protostar** is formed and its interior attains hydrostatic equilibrium. The interior of the protostar at this stage becomes almost convective, that is, the temperature gradient inside becomes larger than the adiabatic gradient. The stellar object so formed is called a **pre-main sequence star**. To understand the evolution of a pre-main sequence star, its position on the HR diagram and changes in its interior during evolution, you must study the concept of a **Hayashi line**.

9.4.1 Hayashi Line

In the HR diagram, Hayashi line or track runs almost vertically in the temperature range of 3000 to 5000 K as shown in Fig. 9.8. This line is important in the discussion of pre-main sequence evolution of stars because of the following features:

i) When a protostar is formed, the interior of the cloud attains hydrostatic equilibrium. At this stage, it is fully convective. The position of such an object must fall on this line.

ii) For a given mass and chemical composition, this line represents a boundary in the HR diagram. It separates the HR diagram into *allowed* and *forbidden* regions. The *forbidden* region occurs to the right of this line and the stars in this region cannot attain hydrostatic equilibrium. For stars falling to the left of this line, energy transport due to convection/radiation or both is possible.

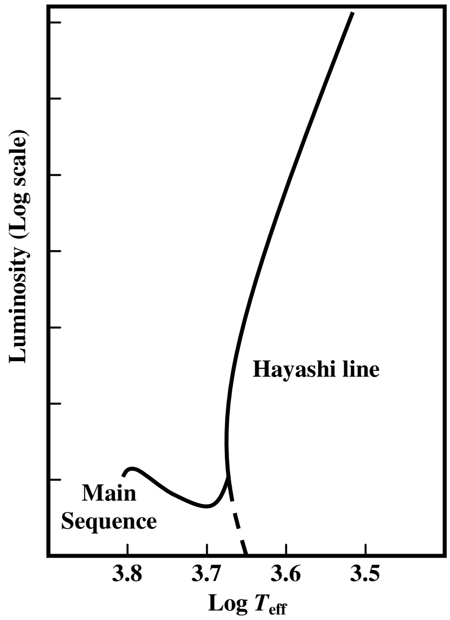

Fig.9.8: The Hayashi line

The internal temperature of pre-main sequence stars is quite low and cannot ignite thermonuclear reactions. To compensate for the loss of energy through radiation, a protostar must contract and this leads to increase in its thermal energy. Because of increase in temperature and pressure in the interior of the protostar, its collapse slows down. **In other words, we expect longer evolution time in the pre-main sequence stage for smaller mass protostars**. For more massive stars, the pre-main sequence evolution is faster and their pre-main sequence lifetime is shorter.

Now, let us sum up what you have learnt in this unit.

9.5 SUMMARY

- The space between the stars, called the **interstellar medium (ISM)**, is not empty. It contains gas and dust, and the gas is mostly hydrogen.
- The interstellar gas is not uniformly distributed. At places, it is highly concentrated. These regions are called **gas clouds**. It is in these gas clouds that new stars are formed.
- The gaseous matter in the interstellar space is classified into four types, namely, **HI region, H II region, inter-cloud medium** and **molecular clouds**.
- The interstellar dust, which constitutes about one percent of the interstellar mass, gives rise to **extinction** and **reddening**. Extinction depends on the density of dust grains and reddening is caused due to scattering of light from stars by interstellar dust.
- Jeans proposed that a molecular cloud must have certain minimum mass, called **Jeans mass**, for its collapse due to self-gravity. The expression for the Jeans mass is:

$$M_J = \left(\frac{5k_BT}{\mu mG}\right)^{\frac{3}{2}}\left(\frac{3}{4\pi\rho}\right)^{\frac{1}{2}}$$

- In terms of the size, the Jeans criterion implies that if a gas cloud becomes larger than a certain size, called **Jeans length**, it collapses under the gravitational force. The expression for the Jeans length is:

$$R_J = \left(\frac{15k_B T}{4\pi G\mu\, m\rho}\right)^{\frac{1}{2}}$$

- The expression for the **free-fall time** taken by a cloud to collapse under the assumption of **free-fall collapse** is:

$$t_{ff} = \left(\frac{3}{2\pi G\rho}\right)^{\frac{1}{2}}$$

- Repeated fragmentation of collapsing clouds leads to the formation of protostars. A protostar contracts due to gravitational force and its temperature and density increases to such an extent that the nuclear reaction at its core becomes feasible. A star is then said to be born. Such stars are called **pre-main sequence stars**.

9.6 TERMINAL QUESTIONS

Spend 25 *min.*

1. What is the origin of the 21 cm line of hydrogen? Why can we not obtain this line in a terrestrial laboratory? Explain the importance of this line in astronomy.

2. What is interstellar reddening? What does it tell us about the composition of interstellar matter?

3. Derive Eq. (9.11). For the data given in SAQ 3, calculate the Jeans length.

9.7 SOLUTIONS AND ANSWERS

Self Assessment Questions (SAQs)

1. You know that the energy of electromagnetic radiation of frequency ν and wavelength λ is given by:

$$E = h\nu$$

$$= h\frac{c}{\lambda}$$

where h is the Planck's constant and c is the velocity of light. Substituting the values of h, c and λwe can write.

$$E = \frac{(6.63\times10^{-34}\,\text{Js})(3\times10^{8}\,\text{ms}^{-1})}{(0.21\text{m})}$$

$$= \frac{6.63\times3}{21}\times10^{-24}\ \text{J}$$

$$\approx\ 10^{-24}\times\frac{1}{1.6\times10^{-19}}\,\text{eV}$$

$$\approx\ 6.25\times10^{-6}\ \text{eV}$$

2. As per the problem,

$$I_\lambda = I_{\lambda 0}\, e^{-\tau_\lambda}$$

Taking logarithm on both sides and multiplying by 2.5, we get :

$$2.5 \log I_\lambda = 2.5 \log I_{\lambda 0} - 2.5\tau_\lambda \log_{10} e$$

If m_0 is the original magnitude and m is the increased magnitude because of extinction, we have:

$$K - m = K - m_0 - 2.5 \times 0.4343\tau_\lambda$$

or,

$$m - m_0 = 1.086\tau_\lambda$$

because we can write the apparent magnitude as:

$$m = K - 2.5 \log I\ .$$

Further, the magnitude of light scattered or absorbed along the line of sight can be written as:

$$a_\lambda = m - m_0 = 1.086\,\tau_\lambda$$

3. From Eq. (9.10), we have the expression for Jeans mass:

$$M_J = \left(\frac{5k_B T}{\mu m G}\right)^{\frac{3}{2}} \left[\frac{3}{4\pi\rho}\right]^{\frac{1}{2}}$$

For pure hydrogen, $\mu = 1$. So, we have:

$$M_J = \left[\frac{5 \times (1.38 \times 10^{-23}\,\mathrm{JK^{-1}}) \times (50\,\mathrm{K})}{(1.67 \times 10^{-27}\,\mathrm{kg}) \times (6.67 \times 10^{-11}\,\mathrm{m^3 kg^{-1} s^{-2}})}\right]^{\frac{3}{2}}$$

$$\times \left[\frac{3}{4\pi \times (10^5 \times 1.67 \times 10^{-27}\,\mathrm{kgm^{-3}})}\right]^{\frac{1}{2}}$$

$$= 10^{24} \left(\frac{5 \times 1.38 \times 5}{1.67 \times 6.67}\right)^{\frac{3}{2}} \times 10^{10} \left(\frac{300}{4\pi \times 1.67}\right)^{\frac{1}{2}} \mathrm{kg}$$

$$= \frac{10^{34} \times 5.45 \times 3.75 \times 10^3}{2 \times 10^{33}}\, M_\Theta$$

$$\approx 10^5 M_\Theta$$

4. From Eq. (9.14), we have the expression for the free-fall time for a collapsing cloud as:

$$t_{ff} = \left(\frac{3}{2\pi G\rho}\right)^{\frac{1}{2}}$$

Substituting the values of G and ρ, we get:

$$t_{ff} = \left(\frac{3}{2\pi \times \left(6.67 \times 10^{-11}\ \text{m}^3\text{kg}^{-1}\text{s}^{-2}\right) \times \left(10^{-14}\ \text{kgm}^{-3}\right)} \right)^{\frac{1}{2}}$$

$$= \left(\frac{30}{2\pi \times 6.67} \right)^{\frac{1}{2}} \times 10^{12}\ \text{s}$$

$$\approx \frac{10^{12}}{3 \times 10^7}\ \text{yr} \qquad \approx 3 \times 10^4\ \text{yr}$$

Terminal Questions

1. See text.

2. See text.

3. The expression for Jeans mass is given by (Eq. (9.10)):

$$M_J = \left[\frac{5k_B T}{\mu m G} \right]^{\frac{3}{2}} \left[\frac{3}{4\pi\rho} \right]^{\frac{1}{2}}$$

Now, for a spherical cloud of mass M and radius R, we have:

$$M = \left(\frac{4}{3} \pi R^3 \right) \times \rho$$

So, we can write:

$$M_J = \left(\frac{4}{3} \pi R_J^3 \right) \times \rho$$

Substituting the above expression for M_J in Eq. (9.10), we can write:

$$\left(\frac{4}{3} \pi R_J^3 \right) \times \rho = \left[\frac{5k_B T}{\mu m G} \right]^{\frac{3}{2}} \left[\frac{3}{4\pi\rho} \right]^{\frac{1}{2}}$$

or,

$$R_J = \left(\frac{15k_B T}{4\pi G \mu m \rho} \right)^{\frac{1}{2}}$$

As per the data given in SAQ 3, we have $T = 50$K and the number density $10^5\ \text{m}^{-3}$. Further, for pure hydrogen, $\mu = 1$. Substituting these values in the expression for R_J, we get:

$$R_J = \left(\frac{15 \times (1.38 \times 10^{-23}\,\mathrm{JK^{-1}}) \times (50\,\mathrm{K})}{4\pi \times (6.67 \times 10^{-11}\,\mathrm{m^3 kg^{-1} s^{-2}}) \times (10^5 \times 1.67 \times 10^{-27}\,\mathrm{kg\,m^{-3}}) \times (1.67 \times 10^{-27}\,\mathrm{kg\,m^{-3}})} \right)^{\frac{1}{2}}$$

$$\approx 10^{19}\ \mathrm{m} \sim 300\,\mathrm{pc}$$