UNIT 12 THE MILKY WAY

Structure

12.1 INTRODUCTION

In Unit 11, we discussed the death of stars and its consequences and thereby completed our discussion about stars. You now know how stars are formed, how they live their lives and how and why they die. If you wish to know more about the Universe, you may ask questions like: What is the structure of the Universe? Is it a single entity comprising unrelated and independent stars or does it consist of substructures in which stars are arranged according to a scheme? If stars constitute communities, what is the nature of such communities and what mechanism brings them into existence? **It is now believed that stars arrange themselves into billions of self-contained systems called galaxies**. Our star, the Sun, is one of about 200 billion stars in the galaxy called the Milky Way – our home galaxy. In the present Unit, you will learn about the Milky Way galaxy also called the Galaxy.

On a clear night sky, you can see a broad *white patch* running across the sky. It is seen during winter months in the northern hemisphere. The patch is actually made up of hundreds of billions of stars, so close to each other that they cannot be seen individually. This is a part of our home galaxy, the **Milky Way**. Just as Copernicus discovered that the Earth and the planets revolved around the Sun, astronomers in the early twentieth century discovered that the Milky Way system is indeed a galaxy in which our solar system is situated.

In Sec. 12.2, you will learn the basic structure and properties of the Milky Way. It is found that the Sun revolves once in 200 million years around the centre of this galaxy in a nearly circular orbit. In addition, the Galaxy itself is rotating. You will learn the consequences of the rotation of the Galaxy in Sec. 12.3. You will also discover that the Galaxy is a spiral galaxy with several spiral arms. In Sec. 12.4, you will learn about the various constituents of the galaxy, namely the stars, globular clusters, compact stars and the interstellar medium. At the present time, we know a lot about our Galaxy, its shape and its size. Much of the contemporary focus has been to understand the central region of the galaxy and the activities surrounding it. Today, it is believed that the central region contains a massive black hole of mass $M \sim 2.6 \times 10^6 M_\odot$. In Sec. 12.5, you will learn about the nature and characteristics of the central region of the Milky Way.

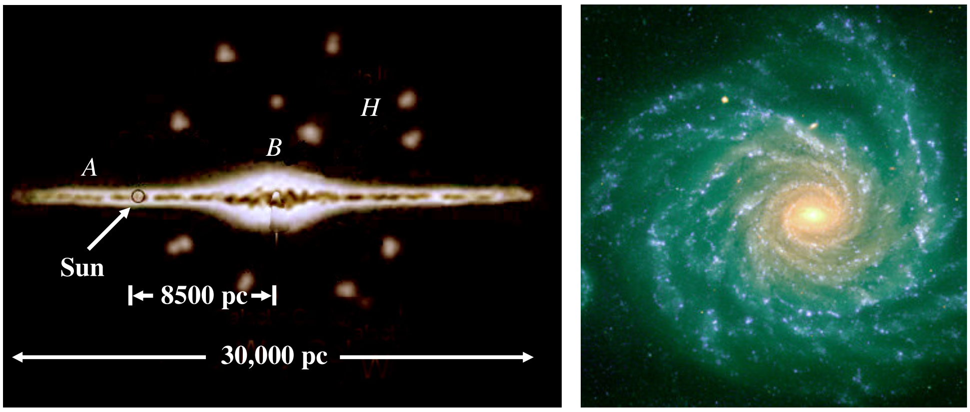
Objectives

After studying this unit, you should be able to:

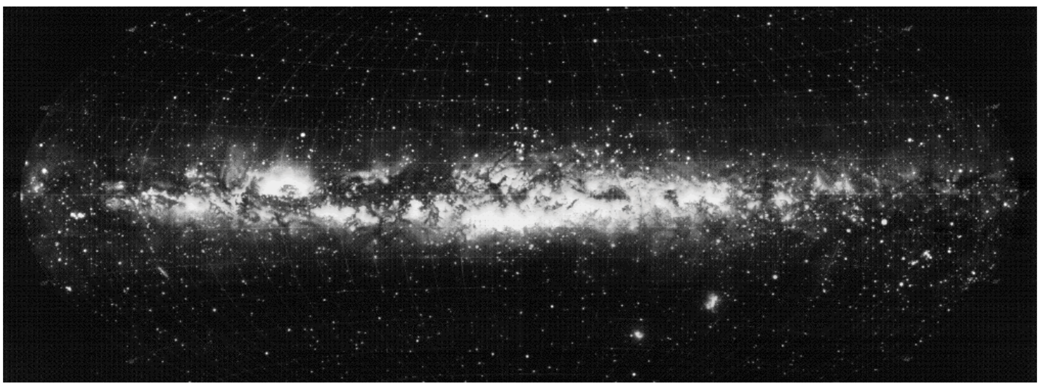
- describe the shape and size of the Milky Way galaxy;
- explain the consequence of rotation of the Galaxy;
- describe the major building blocks of the Galaxy including the stars and star clusters;
- explain the nature and persistence of the spiral arms of the Galaxy; and
- describe the activities taking place near the centre of the Galaxy particularly the nature of the central compact object.

12.2 BASIC STRUCTURE AND PROPERTIES OF THE MILKY WAY

The Milky Way is a highly flattened, disk shaped galaxy comprising about 200 billion (2×10^{11}) stars and other objects like molecular clouds, globular clusters etc. *It is so huge that, to travel from one edge of the Galaxy to the other, light takes about 100,000 years!* Its radius is about 15,000 pc. The solar system is located roughly at a distance of about 8.5 kpc from the centre of the Galaxy. The total mass of Milky Way has been estimated to be about $2 \times 10^{11} M_{\odot}$. Refer to Fig. 12.1 which shows a schematic diagram of the Milky Way Galaxy. You may note that, broadly speaking, the Galaxy can be divided into three distinct parts: a central bulge (B), the flattened galactic disk (A) and a halo (H) which surrounds the Galaxy.



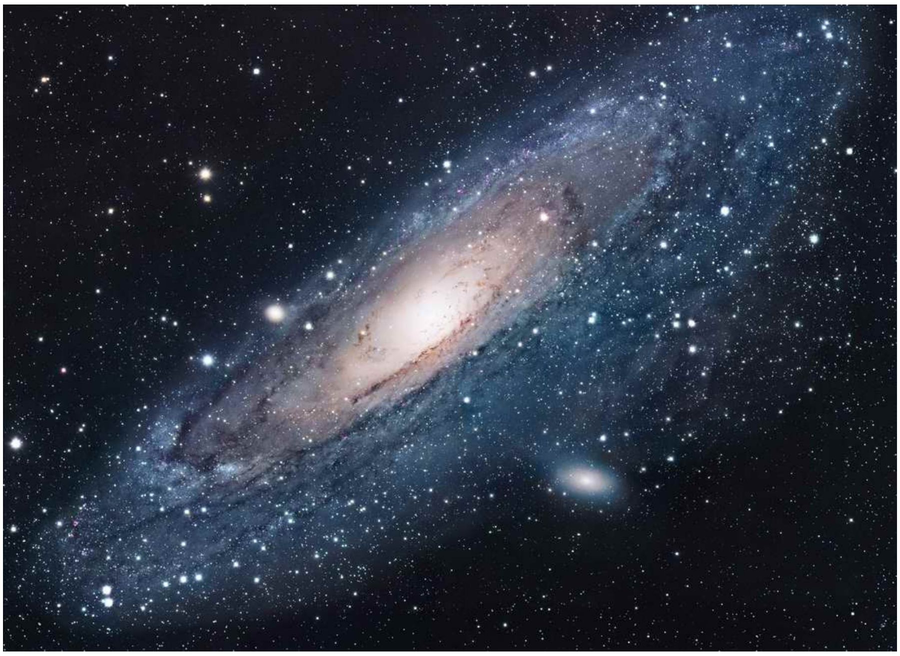
(a) (b)



(c)

Fig. 12.1: a) A schematic diagram of the Milky Way Galaxy viewed edge on, b) view of the Galaxy from the top; and c) part of the Milky Way visible in the sky

The Milky Way belongs to the Local Group, a group of 3 big and 30 odd small galaxies. After the nearby Andromeda galaxy (M31) shown in Fig. 12.2, ours is the largest galaxy in the group. It has a few dwarf galaxies as satellites or companions. Prominent among them are Large and Small Magellanic clouds.



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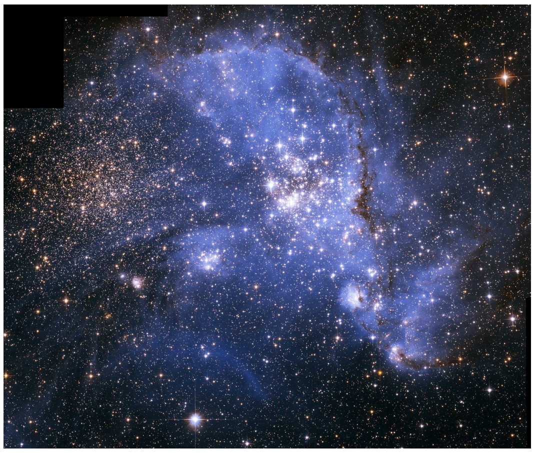

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Fig. 12.2: a) The Andromeda galaxy; b) the Large Magellanic Cloud; and c) the Small Magellanic Cloud

Let us now discuss the nature of the components of Milky Way.

The Central Bulge

The central bulge (Fig. 12.1a) is a more or less spherical cloud of stars. Being located in the disk region of the Galaxy, we cannot see this region in optical wavelengths. It is so because the disk region consists of gas and dust which absorbs optical wavelengths and obstructs our view. The total mass of the bulge is estimated to be about $10^{10} M_{\odot}$. Apart from stars, this region consists of gas in the form of molecular clouds and ionised hydrogen. The motion of the stars and the gas near the centre of the bulge suggests that there could be a massive black hole at the centre.

The Disk Component

The flattened disk component has a radius of about 15,000 pc. But its thickness is very small. Most of the stars are located along the central plane of the disk and as we move away from this plane, the density of stars decreases.

The most significant feature of the disk component is the existence of **spiral arms**. Condensation of stars has been observed along the spiral arms. These arms have very young stars called Population I stars, star-forming nebulae, and star clusters. The arms are named after the constellations in the direction of which a large portion of the arm is situated. Our solar system is located on a Local or Orion arm.

The Halo Component

The bulge and the disk components are surrounded by another, not so well defined, and not so well understood spherical component called the halo component. This is mainly made up of gas and older population of stars. These stars exist in very dense clusters; each cluster having 10^5 to 10^6 stars. These are called **globular clusters**. Stars in these clusters are so densely packed that they cannot be resolved, and clusters appear like a circular patch of light (Fig. 12.3).

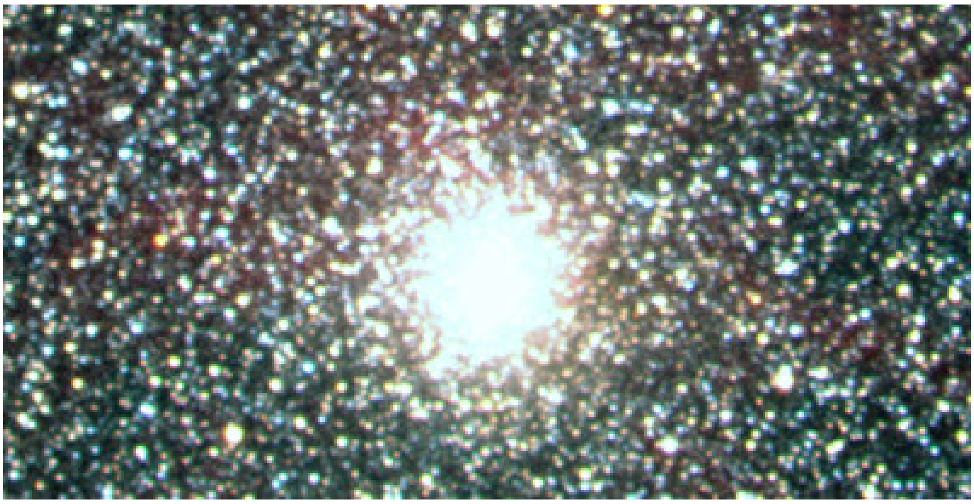


Fig. 12.3: A globular cluster (NGC 1916) containing millions of stars

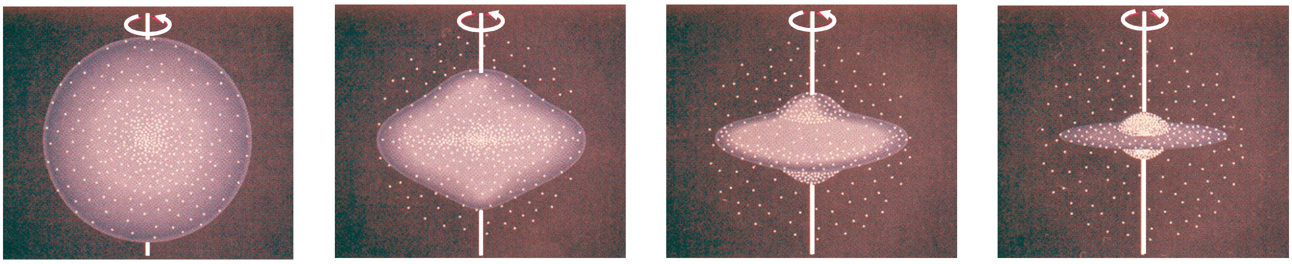
The nature of galactic rotation (about which you will learn later in the Unit) suggests that there is a large amount of matter which is governing the motion of the stars in the disk. This matter is not visible in any wavelengths and scientists call it the **dark matter**. *It is believed that the halo contains at least an equal amount of matter as the disk itself, if not more, in the form of dark matter.* **What could be the nature of this matter?** *We do not know yet.*

12.3 NATURE OF THE ROTATION OF THE MILKY WAY

In the early nineteenth century, Jan Oort and Bertil Lindblad studied the motion of a large number of stars located near the Sun. Their study indicated that stars in the Galaxy constitute a gravitational system. Like many other gravitating systems, our galaxy also rotates, though very slowly. *The rotational velocity enhances the stability of the Galaxy since the outward centrifugal force can counterbalance the inward pull due to gravity.*

The assumption that the Galaxy is a gravitating system is at the core of the traditional hypothesis about how the Galaxy came into being. Since the centrifugal force is only along the equatorial plane, there is no obstacle for matter (other than the pressure) to fall along the vertical direction. As a result, the initially spherical distribution of matter has become, after over 10 billion years, the highly flattened galaxy of today.

Refer to Fig. 12.4 which shows the initially spherical distribution of matter (Fig. 12.4a) gradually evolving into the present day flattened Galaxy (Fig. 12.4d).



(a) (b) (c) d)

Fig. 12.4: Evolution of the Galaxy (from a to d) starting from a spherical cloud of gas and settling into the flattened disk shape of today

The rotational velocity of stars in the Galaxy is very slow compared to what we are familiar with in our solar system. For instance, at a distance of roughly 8 kpc away from the centre, the Sun takes about 240 million years to rotate once around the galactic centre. The question is: **How do we know about this rotation? How do we measure it? What are the consequences of this rotation on the structure and further evolution of the Galaxy?** Let us now learn about these aspects of the Galaxy.

12.3.1 Differential Rotation of the Galaxy and Oort Constants

To appreciate the rotation of stars and other objects in the Galaxy, you need to understand the concept of differential rotation. Let us consider the motion of a star in the Galaxy. Suppose, for the sake of argument, that the whole mass of the galaxy is concentrated at its centre and the stars move like planets round the Sun on orbits called the Keplerian orbits. The angular velocity of a star at a distance r from the centre can, therefore, be written as (Eq. (5.1), Unit 5):

$$\omega_{Kep}(r) = \left[\frac{GM_{Gal}}{r^3}\right]^{1/2}. \tag{12.1}$$

where M_{Gal} is the mass of the Galaxy. We see from Eq. (12.1) that the angular velocity is not a constant. Further, using Eq. (12.1) and the relation $v = \omega r$, we can write the rotational velocity of the star as:

$$v_\phi\,(r) \propto r^{-1/2}. \tag{12.2}$$

Now, if stars in the Galaxy are embedded as particles in a *rigid body*, then the angular velocity, ω of stars would have been constant, independent of its distance from the centre and the rotational velocity $v_\phi\,(r)$ of a star in such a system is given by:

$$v_\phi\,(r) \propto r. \tag{12.3}$$

Comparison of Eqs. (12.2) and (12.3) clearly shows that the nature of the dependence of rotational velocity on the distance from the centre is different in the two cases – the Keplerian motion and rigid body rotation.

When different components of a system rotate independently, the rotation is known as **differential rotation**. On the basis of observations, we can say that the stars indeed have differential rotation. We do see the signature of this differential rotation in astronomical observations.

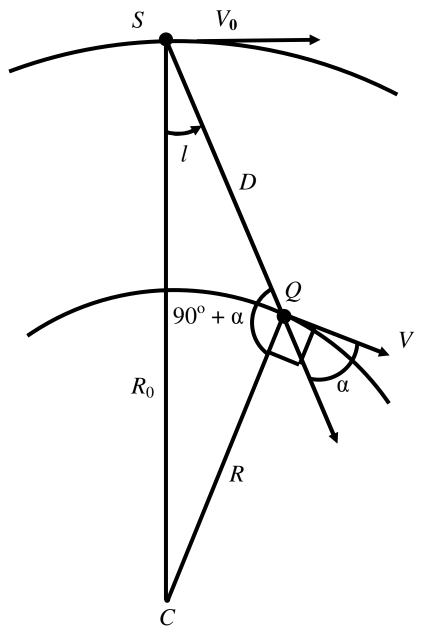


Fig.12.5: Geometry of the differential galactic rotation for stars closer to the Sun

Let us now obtain expression for the velocity of an object in the Galaxy. To do so, refer to Fig. 12.5, which depicts the velocity vectors of the Sun (*S*) and a star (*Q*) with respect to the galactic centre (*C*). Let us assume that the Sun and the star are at a distance of R_0 and R, respectively from *C* and let *D* be the distance between the Sun and the star. Let V_0 be the Sun's rotational speed and *V* be the star's rotational speed; both assumed here to be on circular orbits for simplicity. Let us also assume that *l* is the angle between the direction of the galactic centre and the direction of the star from the Sun.

This is the so-called *galactic longitude* of the star. (Galactic longitude of the centre is $l = 0$ by this definition). The Sun-star direction makes an angle α with the velocity vector of the star. If ω_0 and ω be the angular velocities of the Sun and the star, respectively, we can write:

$$\omega_0 = V_0 / R_0 \qquad (12.4a)$$

and

$$\omega = V / R \qquad (12.4b)$$

We are interested in finding the radial speed of the star with respect to the Sun. The radial velocity is the velocity along the line joining the Sun and the star. We can, therefore, write the star's radial velocity with respect to the Sun, V_r, as:

$$V_r = V \cos\alpha - V_0 \sin l. \qquad (12.5)$$

where the first term on the right hand side is the component of the star's space velocity along the Sun-star direction and the second term is the component of the Sun's own velocity along the Sun-star direction. Thus, radial velocity is essentially the difference between the projected velocities along the Sun-star direction. Substituting Eq. (12.4) in Eq. (12.5), we get:

$$V_r = \omega R \cos\alpha - \omega_0 R_0 \sin l \qquad (12.6)$$

In triangle *QSC* in Fig. 12.5, the angle *SQC* is $90 + \alpha$.

Thus, using the law of sines, we can write:

$$\frac{\sin(90+\alpha)}{R_0} = \frac{\sin l}{R}$$

or,

$$\cos\alpha = \frac{R_0}{R}\sin l$$

Substituting this value of cos α in Eq. (12.6), we get:

$$V_r = (\omega - \omega_0)\, R_0 \sin\, l \tag{12.7}$$

Similarly, the tangential component of the velocity of star with respect to the Sun can be written as:

$$V_t = V\sin\alpha - V_0\cos\, l\; = (\omega - \omega_0)\, R_0\cos\, l\; - \omega D. \tag{12.8}$$

In the solar neighbourhood, $D << R_0$, and we can approximate the angular velocity of the star, ω in terms of ω_0 by using the *Taylor series expansion*. Thus, we can write:

$$\omega = \omega_0 + \left(\frac{d\omega}{dR}\right)_{R_0} (R - R_0) \tag{12.9}$$

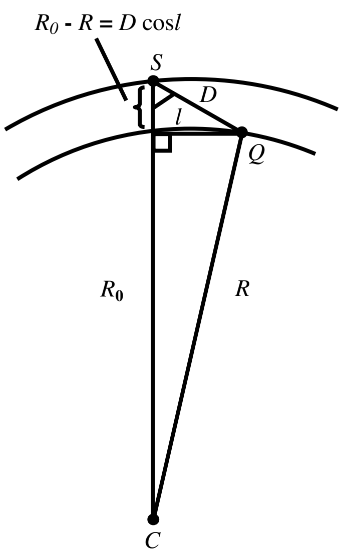


Fig.12.6

If we define a constant A as,

$$A = -\frac{R_0}{2}\left(\frac{d\omega}{dR}\right)_{R_0} = \frac{1}{2}\left[\frac{V_0}{R_0} - \left(\frac{dV}{dR}\right)_{R_0}\right] \tag{12.10}$$

then, the radial component of the velocity of a *nearby* star can be written as:

$$V_r = -\,2A\,(R - R_0)\sin l\; = AD\sin(2\,l\,) \tag{12.11}$$

where, we have made use of the fact that for $D << R_0$, $(R_0 - R) \sim D\cos l$ (Fig. 12.6). Further, using the same procedure and approximations, you can show that the tangential velocity of the star is given by:

$$V_t = D\,[A\cos(2\,l\,) + B] \tag{12.12}$$

where B (= $A - \omega_0$) is another constant given as:

$$B = -\frac{R_0}{2}\left(\frac{d\omega}{dR}\right)_{R_0} - \omega_0 \tag{12.13}$$

Since $V_0 = \omega_0 R_0$, Eq. (12.13) can be written as:

$$B = -\frac{1}{2}\left(\frac{V_0}{R_0} + \left(\frac{dV}{dR}\right)_{R_0}\right) \tag{12.14}$$

The constants A and B are called **Oort constants**. Fig. 12.7 depicts the observed variation of a star's radial velocity as a function of galactic longitude. Note that the variation of radial velocity is periodic in longitude with a period of 180° and this observation is consistent with Eq. (12.11). The value of R_0 is 8.5 kpc. The estimated values of Oort constants are:

$$A = 15 \text{ kms}^{-1} \text{ kpc}^{-1}$$

and

$$B = -10 \text{ kms}^{-1} \text{ kpc}^{-1}$$

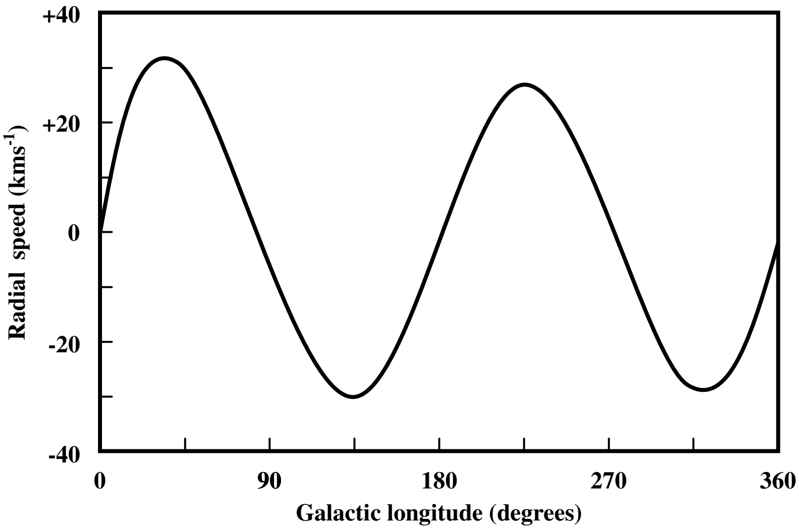


Fig. 12.7: Variation of the radial velocity of stars as seen from the Earth

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SAQ 1

Spend 10 *min.*

a) Derive Eq. (12.12).

b) Show that

$$A = \frac{1}{2}\left[\frac{V_0}{R_0} - \left(\frac{dV}{dR}\right)_{R_0}\right]$$

and

$$B = -\frac{1}{2}\left[\frac{V_0}{R_0} + \left(\frac{dV}{dR}\right)_{R_0}\right]$$

On the basis of the above discussion, you know that the galactic disk *in our neighbourhood* is indeed differentially rotating. You may ask: **Do the stars rotate as if the entire mass is concentrated at the galactic centre?** To answer this question, we must know the rotation velocity of galactic objects as a function of their distances from the centre of the Galaxy. This is known as the *rotation curve* of a galaxy which contains useful information about the mass distribution in a galaxy. Let us learn about it now.

12.3.2 Rotation Curve of the Galaxy and the Dark Matter

The rotation curve of a galaxy is obtained by plotting the rotational velocities of galactic components against their distances from the galactic centre. Refer to Fig. 12.8 which depicts the rotation curve of our galaxy. Note that it is not a smooth curve; rather, it has various ups and downs. This nature of the curve is not understandable in terms of Keplerian motion of stars in the vicinity of the Sun which assumes that the galactic mass is concentrated at the centre and the rotation velocity must be proportional to $R^{-1/2}$ (Eq. (12.2)).

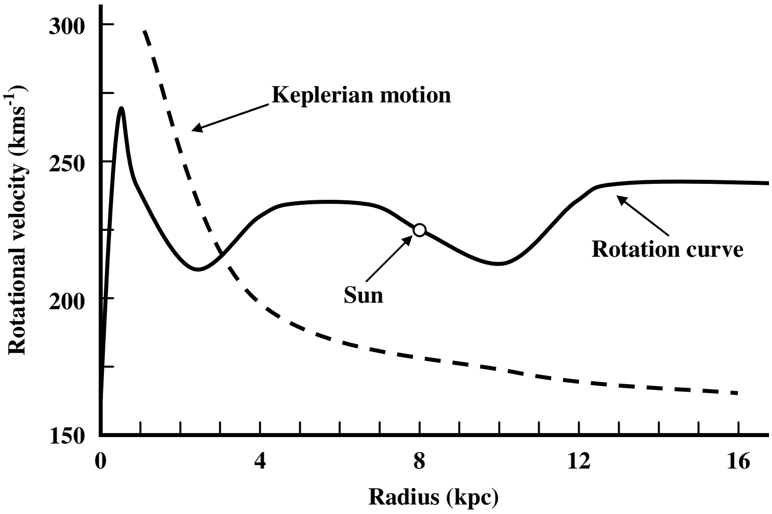

Fig. 12.8: Rotation curve of the Milky Way

Rotation curves, such as the one shown in Fig. 12.8, indicate that the matter is spread out all across the galaxy. This inference is, however, contrary to the concentration of stellar mass around the nucleus of the galaxy. You may ask: **What is the way out of this paradoxical situation?** If the rotation curve flattens out instead of falling monotonically, we can infer that much of the matter in the disk cannot be in the form of stars. How do we infer this? Let us try to understand it using the fact that the centrifugal force V_ϕ^2 / R must balance gravity and we can write:

$$\frac{V_\phi^2}{R} = \frac{GM(R)}{R^2} \qquad (12.15)$$

where, $M(R)$ is the mass of the Galaxy up to radius R and V_ϕ is the rotational velocity of a stellar object at a distance R from the galactic centre. If $V_\phi = V_0$, a constant, we have from Eq. (12.15):

$$M(R) = \frac{V_0^2 R}{G}. \qquad (12.16)$$

Eq. (12.16) indicates that the mass within radius R must increase linearly with R, and not be concentrated entirely at the centre. But we do not observe this spread out mass. This means that sufficient amount of matter in the Galaxy exists in a form which is not detectable. What is this matter made up of ? No one knows. In the field of Astronomy and Astrophysics, this is known as **the missing mass problem.** The matter perhaps exists in a form that does not emit radiation and hence is also called **dark matter**.

12.3.3 Nature of the Spiral Arms

In Fig. 12.1, we showed a sketch of our galaxy as it would be seen by someone situated very high above and outside our galaxy. Note that it consists of spiral arms. The prominent arms are (a) Norma Arm, (b) Scutum-Crux Arm, (c) Sagittarius Arm, (d) Orion Arm, (e) Perseus Arm and (f) Cygnus Arm. The Sun's location is on Orion Arm (see Fig. 12.9). The spiral arms do not form a single entity that was originally present. These are the result of dynamical interaction of the Galaxy with other galaxies and the matter present in the inter-galactic space.

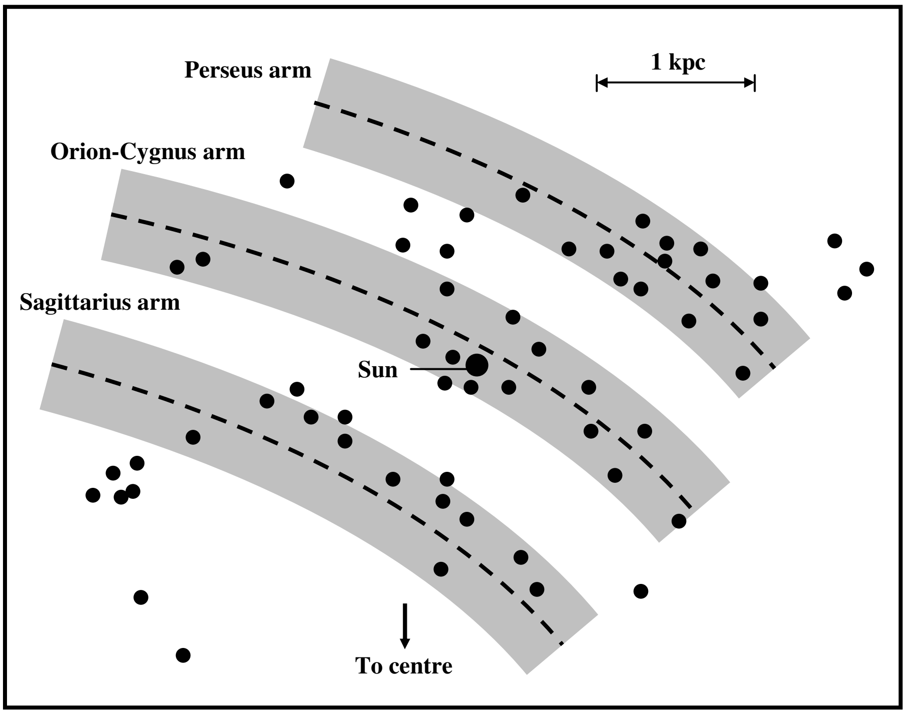

Fig. 12.9: Schematic diagram depicting some of the spiral arm structures of the Galaxy in which dots denote stars

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SAQ 2

Spend 7 min.

How many times would the Sun have revolved around the centre of the Galaxy if it is rotating with a velocity of 250 kms^{-1} at a distance of 8.5 kpc from the galactic centre? Assume the age of the Sun to be 4.6×10^9 years. This age is different from the age of the Galaxy, since the Sun is relatively younger.

To have a qualitative understanding of the spiral arms of the Galaxy, we need to ask ourselves: **How do we determine that the disk of the Galaxy comprises spiral arms? In view of the differential rotation of the galactic disk, how do the spiral structures persist for so long?**

The first evidence of the spiral nature of the Galaxy came from the observations that the distribution of O and B stars is not uniform in the Galaxy. To appreciate the significance of this observation, you should recall from Unit 10 that O and B stars are very massive, bright and short-lived. These massive stars, after their death, return some of the stellar materials back to the interstellar medium. It is observed that these stars occur around the locations where star formation can take place; that is, the interstellar medium containing gas and dust. Therefore, it was suggested that the spiral arms of the Galaxy contain gas and dust in the form of molecular clouds, and young stars like O and B stars. **But the problem was how to detect gas and dust at such distances?** *This could be made possible by radio astronomy, particularly after the discovery of 21 cm radiation.* This enables astronomers to map the Galaxy and probe its spiral nature. Astronomers use the intensity of the neutral hydrogen and carbon monoxide emission lines to trace the spiral arms. Further, the young stars emit ultraviolet light and ionise the gas which surrounds them. These ionised gaseous regions are known as the H II (H II stands for ionised hydrogen) regions. They are very luminous. Simultaneously, due to the recombination process taking place in these H II regions, neutral hydrogen (H I) regions are formed which are detected by their 21-cm radio emission.

Next logical question could be: **How do these spiral structures persist because the differential rotation of the galaxy should have destroyed them?** To answer this question, C.C. Lin and Frank Shu proposed the so called **density wave model**. According to this model, spiral arms are not a simple fixed array of stars; rather, spiral arms are the areas where the density of gas is greater than in other places. *As such, the arms and the space between the arms contain roughly the same number of stars per unit volume. However, the arms contain larger number of brighter (*O *and* B*) stars*. According to Lin and Shu, the high density waves move through the galactic disk which gives rise to the formation of stars. As interstellar clouds approach the density wave, it is compressed, the collapse of interstellar gas is triggered and new stars are formed. Thus, density waves are capable of generating all the constituents of spiral arms. You must note that according to the density wave model, a spiral arm is not a static collection of slow moving gas and stars; rather it is a dynamic entity which always contains the same type of objects.

This brings us to the question: **How does a density wave come into existence?** The density wave model does not provide a satisfactory answer to this question. Astronomers believe that the death of massive stars causing supernovae explosions may produce density waves. It has been found by computer simulation (experiments on the computer) that the supernovae explosions combined with the Keplarian motion can lead to the formation of spiral arms.

So far, you have learnt how the Milky Way looks like from the edge as well as from above and what are its large scale basic components. Now we discuss the nature of the building blocks, namely, the stars and the star-clusters of these components.

12.4 STARS AND STAR CLUSTERS OF THE MILKY WAY

You have learnt in the previous section that the components of the Galaxy consist of stars and star clusters. The question is: **Are the stars in all the regions of the Galaxy similar?** A detailed knowledge about the types of stars in each region can provide valuable information about various aspects of the Galaxy itself.

Types of Stars in our Galaxy

Stars can be classified into the so-called population (I and II) depending on the abundance of the metals (any element heavier than hydrogen and helium is called a *metal* in astronomy) in them. To quantify, let us represent the fraction of hydrogen per unit mass by X, of Helium by Y and of metals (all metals combined) by Z. The stars which are very much metal deficient are called the **population II** stars. For such stars, $Z < 0.001$. *Population II stars are observed far from the galactic plane and are primarily located in the halo.* On the other hand, the metallicity of the stars increases ($Z \to 0.01$) as we approach the disk closer to the plane. These stars constitute the **disk population**. Stars in the plane of the disk and in spiral arms are relatively young, bright and blue in colour. They are called **population I** stars and they are metal rich.

You may ask: **Why do the different regions of the Galaxy have different metallicity?** Actually, when the galaxy was originally formed, there was very little metal in it, since no metal had been produced by that time. Initially, the stars formed from material which had no metal ($Z \sim 0$). But as the density of the initial cloud, from which the Galaxy was formed, increased towards the plane of the disk, massive stars were forming closer to this plane and they evolved more rapidly than the halo stars. They underwent supernova explosions and spewed out metals formed in them (refer to Unit 10) in the interstellar gas. The interstellar gas was thus enriched with metals as it approached the galactic plane. The second generation stars formed from this gas are naturally more metal rich. The population I stars, therefore have higher metallicity ($Z \geq 0.01$).

Further, the globular clusters (consisting of roughly 10^4 to 10^5 population II stars each) which formed a spherical halo around the Galaxy are found throughout the Milky Way and other galaxies. Like the stars, the globular clusters also display a high degree of gradient in their metal content depending upon their location in the Galaxy. They are found in almost every component of the Galaxy: from galactic centre to very far away in the halo. There are a few hundreds of these objects in our galaxy. Fig. 12.3 shows one such globular cluster. The typical size of a globular cluster is about 5 pc. It has been found that the majority of stars in the globular clusters are the main sequence stars while other stars in them belong to the red-giant branch, sub-giant branch and the horizontal branch.

Since our galactic centre is about hundred times closer to us than the nearest well-known galaxy **Andromeda**, we may assume that the astronomers would be most excited to know the nature of the galactic centre. *However, as we said earlier, we reside on the plane of the Galaxy, and millions of stars and dust obscure our direct view of the centre in optical, ultraviolet and soft X-rays.* In infrared and radio waves, the observation becomes easier. Given that the galactic centres are usually bright and contain many stars, you may naturally be curious to know as to what may be going on in and around the galactic centre of the Galaxy. In the next section, we shall describe the motion of matter and gas within about 100pc of the galactic centre including the properties of the possible black hole at the centre of the Galaxy and how it can be detected.

12.5 PROPERTIES OF AND AROUND THE GALACTIC NUCLEUS

Astronomers believe that at the very centre of the Galaxy, there exists a black hole of mass $2.6 \times 10^6 M_\odot$. Modern radio telescopes using very large baseline arrays have been able to resolve features of the galactic centre in great detail. It has been estimated that about 10% of the entire mass of the galactic interstellar matter (that is, about $10^8 M_\odot$) resides within a 100pc of the centre of the Galaxy. The number density of hydrogen is about $10^2\,\text{cm}^{-3}$ which is about a hundred times greater than the average density in the entire Galaxy. This interstellar gas is mostly concentrated in giant molecular clouds (GMCs), of few parsec size, which are very hot (40-200K) compared to the average gas in the galaxy.

Since the observed X-rays and γ-rays have energies $\geq$ keV, the gas must be very hot ($\sim 10^7$K or more). At least a dozen, very compact and energetic sources have been detected by satellites such as EINSTEIN and ROSAT (sensitive to X-rays/γ-rays) within the central region. Many of these compact objects have been identified to be black holes and neutron stars. At the centre, Sgr A* itself is not very strong in X-rays, and it is believed that this is due to the fact that not much matter is falling on it.

As we go closer to the centre, the activity increases and there is evidence of very high rates of star formation. But since the disk does not contain enough mass supply to continuously carry on star formation, the matter has to come from outside the region. It is believed that interstellar gas accumulates at a rate of about $10^{-2} M_\odot$ for some time (say 10^7 years) and the accumulated mass then collapses and a fresh star formation event is triggered due to density waves. This is probably what is happening from time to time close to the centre of our galaxy.

One can easily compute the mass of the central compact object by using the well known virial theorem:

$$2U + \Omega = 0, \qquad (12.17)$$

where U is the total kinetic energy and Ω is the total potential energy. That is,

$$M < v^2 > + \Omega = 0, \tag{12.18}$$

where $< v^2 >$ is the mean square velocity and

$$\Omega = -G\int_0^R \frac{M(R)}{R}\, dM(R) \tag{12.19}$$

Using Eqs. (12.18) and (12.19), we can determine the *enclosed mass* at a given radius if we know the stellar velocities data.

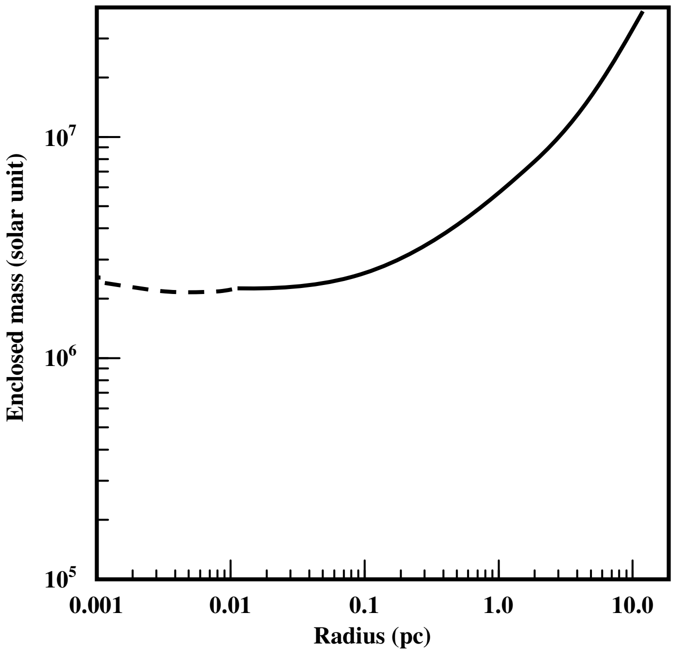

Fig. 12.10: Graph showing variation of the enclosed mass as a function of the radial distance close to the galactic centre

In Fig. 12.10, we show the enclosed mass as a function of distance from the centre of the Galaxy. It is clear that even though there are no measurements below $R < 0.015$pc, the enclosed mass seems to have converged to a fixed number. The mass can be read out from the plot itself: it is $2.6 \times 10^6 M_\odot$. The only acceptable solution seems to be that a massive black hole of this mass resides at the centre. For a spiral galaxy this is not very small, but probably in the lower end. Generally, in the centres of spiral galaxies, black holes of mass $M \sim 10^7 M_\odot$ are quite common.

Spend 5 min.

SAQ 3

What is the mass density of the region around the galactic centre in units of ($M_\odot$ pc^{-3}) below $r = 0.015$ pc?

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

12.6 SUMMARY

- The Universe comprises billions of self contained systems called **galaxies**. The Sun – only star in our solar system – is one of about 200 billion stars in the galaxy called the Milky Way, our home galaxy.

- The **Milky Way** is a highly flattened, disk shaped galaxy. Its radius is 15,000 pc and its total mass is estimated to be about $2\times10^{11} M_\odot$.

- Broadly, the Milky Way can be divided into **three distinct portions**: a **central bulge**, the flattened galactic **disk**, and a **halo**.
- The **central bulge** is a spherical cloud of stars and most of the mass ($\sim 10^{10} M_{\Theta}$) of the Galaxy is contained in it.
- The **disk component** consists of spiral arms; most of the stars are located along the central plane of the disk.
- The **halo** is made up of gas and older population stars; these stars exist in very dense clusters called **globular clusters**. The halo contains an equal amount of matter as the disk itself in the form of **dark matter**.
- Like many gravitational systems, our **galaxy also rotates**. The rotational velocity of stars in the Galaxy is very slow compared to what we are familiar with in our solar system. The stars in the Galaxy undergo **differential rotation**.
- **Rotation curve** of a galaxy contains useful information about the distribution of mass in it and it helps us understand whether or not most of the mass of the galaxy is concentrated at the galactic centre.
- The **spiral arms** of the Galaxy do not form a single entity that was originally present; rather, they result from the dynamical interaction of the Galaxy with other galaxies and the matter present in the inter-galactic space.
- The persistence of spiral arms, despite differential rotation, is explained on the basis of **density wave model**. According to this model, spiral arms are the areas where density of gas is greater than other places. The arms and the space between them contain roughly the same number of stars per unit volume. However, the arms contain larger number of brighter (O and B) stars.
- Investigations indicate that a **massive black hole**, having mass $2.6 \times 10^6 M_{\Theta}$, resides at the centre of the Milky Way.

12.7 TERMINAL QUESTIONS

Spend 30 *min.*

1. Suppose the contribution of the stellar disk to the mass of our galaxy is negligible and the mass of the entire Galaxy is concentrated at the centre located at a distance of 8.5kpc. What would be the mass you need to put at the galactic centre in order that the estimated Oort constants agree roughly with those observed?
2. Describe the spiral arms of the Galaxy. Explain how they can persist for a long time.
3. Distinguish between stars of population I and II. Where are they found in the Galaxy?
4. It is believed that, in its early phase, the universe was very hot. The average energy of particles at that time was ~ 15 GeV. What was the temperature in degree Kelvin?

12.8 SOLUTIONS AND ANSWERS

Self Assessment Questions (SAQs)

1. a) From Eq. (12.8), we have the expression for the tangential component of the velocity of star as:

$$V_t = (\omega - \omega_0)\, R_0 \cos l - \omega D$$

And, from Eq. (12.9) we have

$$\omega - \omega_0 = \left(\frac{d\omega}{dR}\right)_{R_0} (R - R_0)$$

$$= -D\cos l \left(\frac{d\omega}{dR}\right)_{R_0}$$

because $(R_0 - R) \sim D\cos l$. Thus, we can write:

$$V_t = -2D\cos^2 l \; \frac{R_0}{2}\left(\frac{d\omega}{dR}\right)_{R_0} - \omega_0 D$$

because we can approximate, $\omega \approx \omega_0$. Thus, we get

$$V_t = D\left[-2\cos^2 l \; \frac{R_0}{2}\left(\frac{d\omega}{dR}\right)_{R_0} - \omega_0\right]$$

$$= D\left[(1+\cos 2l)\; \frac{-R_0}{2}\left(\frac{d\omega}{dR}\right)_{R_0} - \omega_0\right]$$

$$= D\left[\; -\frac{R_0}{2}\left(\frac{d\omega}{dR}\right)_{R_0} - \cos 2l\; \frac{R_0}{2}\left(\frac{d\omega}{dR}\right)_{R_0} - \omega_0\right]$$

$$= D\left[\; -\frac{R_0}{2}\left(\frac{d\omega}{dR}\right)_{R_0} \cos 2l - \frac{R_0}{2}\left(\frac{d\omega}{dR}\right)_{R_0} - \omega_0\right]$$

$$= D\left[A\cos 2l + B\right]$$

b) We can write:

$$\left(\frac{d\omega}{dR}\right)_{R_0} = \left[\frac{d}{dR}\left(\frac{V}{R}\right)\right]_{R_0}$$

$$= \frac{1}{R_0}\left(\frac{dV}{dR}\right)_{R_0} - \frac{V_0}{R_0^{\,2}}$$

where ω and V, respectively, are the angular velocity and radial velocity of a star. Thus, we can write:

$$A = \frac{1}{2}\left[\frac{V_0}{R_0} - \left(\frac{dV}{dR}\right)_{R_0}\right]$$

and

$$B = -\frac{1}{2}\left[\frac{V_0}{R_0} + \left(\frac{dV}{dR}\right)_{R_0}\right]$$

2. We can write the time period of the Sun's rotation as:

$$T = \frac{2\pi R_0}{V_0}$$

Since the age of the Sun is 4.6×10^9 yrs, the number of times (n) it would have revolved around the galactic centre can be written as:

$$n = \frac{4.6\times10^9 \times 3\times10^7}{T}\,\text{s} \qquad (\because \quad 1\text{ yr} = 3\times10^7)$$

$$= \frac{(4.6\times3\times10^{16}\,\text{s})\times(250\times10^3\,\text{ms}^{-1})}{2\pi\times(8.5\times10^3\times3.1\times10^{16}\,\text{m})}$$

$$= \frac{4.6\times3\times250}{2\pi\times8.5\times3.1}$$

$$\approx 21$$

3. Assuming that the mass of the galactic centre is ~ $2.6\times10^6\, M_\Theta$, we can write:

$$\text{Mass density} \quad = \frac{2.6\times10^6 M_\Theta}{\frac{4\pi}{3}\times(0.015\,\text{pc})^3}$$

if we take the mass enclosed within $r \approx 0.015\,\text{pc}$ to be $2.6\times10^6 M_\Theta$. So, we have:

$$\text{mass density} = \frac{2.6\times10^6 M_\Theta}{\frac{4\pi}{3}\times(0.15\,\text{pc})^3\times10^{-3}}$$

$$= \frac{3\times2.6}{4\pi\times(0.15)^3}\times10^9\, M_\Theta\,\text{pc}^{-3}$$

$$\approx 1.8\times10^{11} M_\Theta\,\text{pc}^{-3}$$

Terminal Questions

1. From Eqs. (12.10) and (12.14), we have:

$$\frac{V_0}{R_0} = A - B$$

$$= (15+10)\ \text{kms}^{-1}.\ \text{kpc}^{-1}$$

$$= 25\ \text{kms}^{-1}.\text{kpc}^{-1}$$

substituting the values of Oort's constants A and B. Thus,

$$V_0 = 25\,\text{kms}^{-1}.\text{kpc}^{-1}\times(8.5\,\text{kpc})$$

$$= 212.5\ \text{kms}^{-1}$$

So, for the given values of Oort's constant A and B, the value of the star's (the Sun) rotational speed (V_0) is 212.5 kms^{-1}. Now, to determine the mass, M_G at the galactic centre whose gravitational force needs to be counter balanced by the centrifugal force experienced by the Sun rotating with speed V_0, we can write:

$$\frac{G M_G}{R_0^2} = \frac{V_0^2}{R_0}$$

$$M_G = \frac{V_0^2 R_0}{G}$$

$$= \frac{(212.5\,\text{ms}^{-1})^2 \times 10^6 \times (8.5\times10^3 \times 3.1\times10^{16}\,\text{m})}{6.7\times10^{-11}\,\text{m}^3\text{kg}^{-1}\text{s}^{-2}}$$

$$(\because\ 1\ \text{pc} = 3.1\times10^{16}\ \text{m})$$

$$= \frac{(212.5)^2 \times 10^6 \times 8.5\times10^3 \times 3.1\times10^{16}}{6.7\times10^{-11}\times 2\times10^{30}} M_\Theta$$

$$= \frac{(2.125)^2 \times 10^4 \times 10^6 \times 8.5\times10^3 \times 3.1\times10^{16}}{6.7\times10^{-11}\times 2\times10^{30}} M_\Theta$$

$$(\because\ M_\Theta = 2\times10^{30}\,\text{kg})$$

$$= 10^{10}\ .\ \frac{(2.125)^2 \times 8.5\times 3.1}{6.7\times 2} M_\Theta$$

$$\approx 10^{11} M_\Theta$$

2. See text.
3. See text.
4. You know from the kinetic theory of gases that, the average energy of the particles at temperature T is given by:

$$E = \frac{3}{2} k_B T$$

As per the problem, average energy

$$E = 15\,\text{GeV}$$

$$= 15\times10^9 \times 1.6\times10^{19}\ \text{J}$$

Thus, we have:

$$15\times10^9 \times 1.6\times10^{-19}\ \text{J} = \frac{3}{2} k_B T$$

or,

$$T = \frac{(1.5\times1.6\times10^{-9}\times 2\,\text{J})}{3\times(1.38\times10^{-23}\,\text{JK}^{-1})}$$

$$\approx 10^{14}\ \text{K}$$