UNIT 6 THE SOLAR FAMILY

Structure

6.1 INTRODUCTION

In Unit 5, you have learnt about various features of the Sun such as solar atmosphere, solar activity and energy transportation. You know that the Sun is the only star in our solar system. It is the most massive object in the system and all the planets revolve around it. You have already studied about the solar system in your school science course as well as in Foundation in Science and Technology (FST-1) course. Therefore, you know most of the facts and figures such as mass, density, distance from the Sun, and surface temperature of all the nine planets of the solar system. However, being a student of physics and astronomy, you may not be satisfied only with the facts and figures and would like to know: How did the solar system come into being? Is it possible to explain the observations pertaining to the solar system on the basis of the principles of physics? Do all the stars have planetary systems similar to our solar system? Does life exist on any other planet? In the present unit, we shall address some of these issues.

In Sec. 6.2, you will recapitulate some facts and figures about the solar system. This is necessary because any model for the formation of the solar system must be consistent with these observations. In Sec. 6.3, you will learn the nebular model which is at the core of all the contemporary theories of formation and evolution of the solar system. In this section you will also discover that the nebular model explains most of the dynamic properties of the solar system. Further, it has been argued that the gravitational force gives rise to tides in the oceans on the Earth and planetary rings around the outer planets such as Jupiter and Saturn. The genesis of tidal forces and planetary rings has been discussed in Sec. 6.4. And, in Sec. 6.5, you will learn about the efforts made by astronomers to investigate the existence of extra-solar planets.

Objectives

After studying this unit, you should be able to:

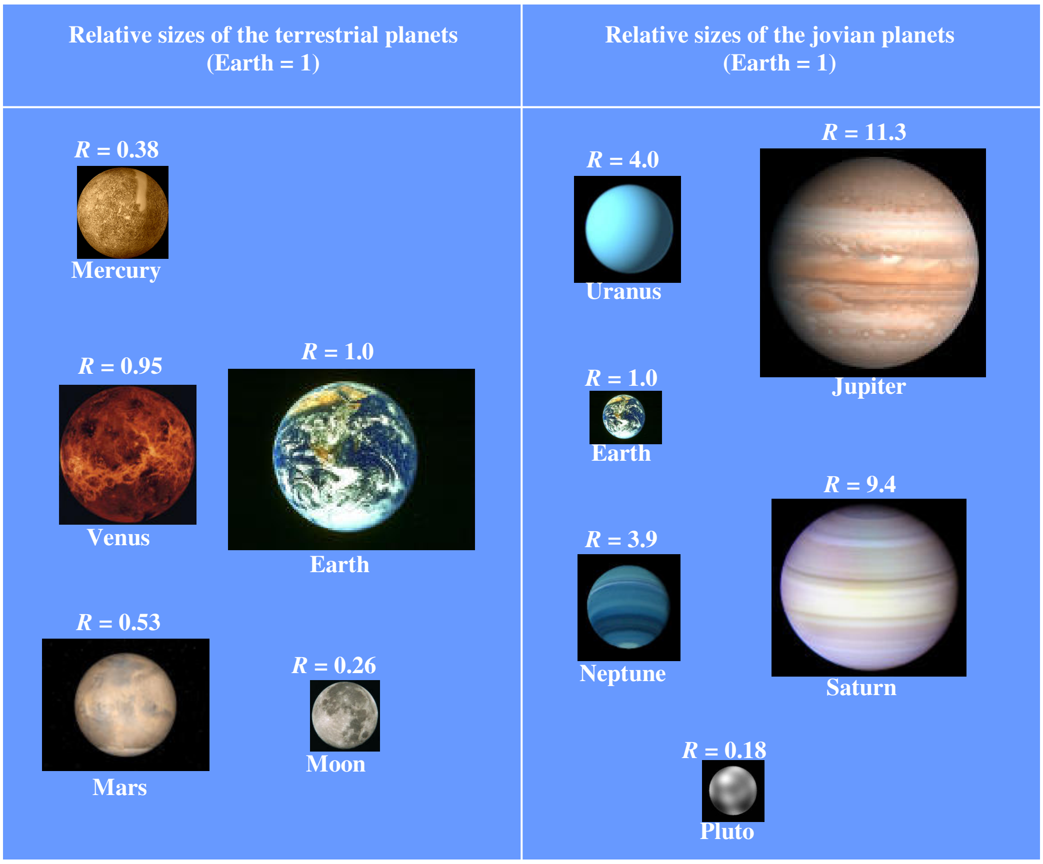
- describe the planets of the solar system;
- understand how the terrestrial planets differ from the jovian planets;
- explain the nebular model of the solar system;
- discuss the role of gravitational forces in generating tides and in the formation of Earth's tidal bulge and planetary rings; and
- discuss the possible existence of extra-solar planets.

6.2 SOLAR SYSTEM: FACTS AND FIGURES

The solar system consists of the Sun, nine planets (*see the margin remarks*), satellites of planets, asteroids and comets. The nine planets, arranged according to their increasing distances from the Sun, are: Mercury (*Buddha*), Venus (*Shukra*), Earth (*Prithvi*), Mars (*Mangal*), Jupiter (*Brihaspati*), Saturn (*Shani*), Uranus (*Arun*), Neptune (*Varun*) and Pluto (*Yama*). The sizes of these planets with respect to the Earth are shown in Fig. (6.1).

In a recent development, the International Astronomical Union (IAU) has decided to remove Pluto from the list of planets in the solar system. So, the solar system now has only eight planets. Pluto has now been categorised as an object of the Kuiper belt, found in the outer region of the solar system. Kuiper belt contains many objects of the size of Pluto. In fact, it was the realisation that many more objects of the size of Pluto could be discovered in future that prompted IAU not to consider Pluto as planet.

Note in Fig. 6.1a that the sizes of the first four planets are similar to that of the Earth and they are called **terrestrial planets**. On the other hand, from Fig. 6.1b, it is obvious that the sizes of the next four planets are bigger than the Earth. They are called **jovian planets**. The status of the ninth planet, Pluto, is somewhere in-between.

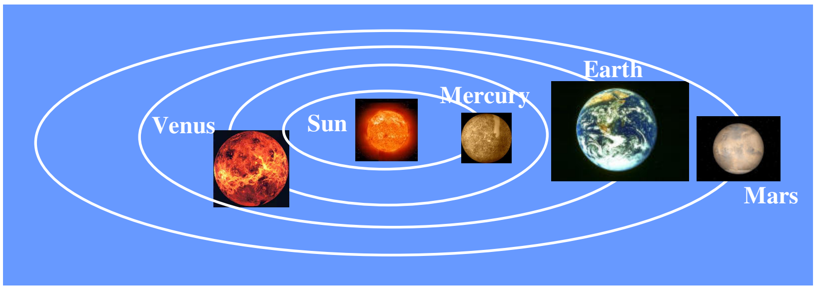


(a) (b)

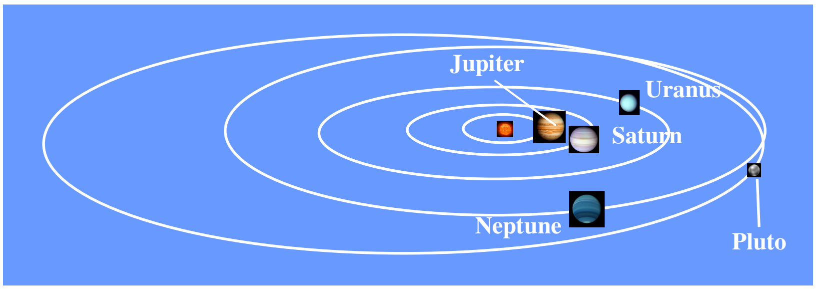
Fig.6.1: Sizes of a) terrestrial; and b) jovian planets relative to the Earth

The properties of the terrestrial and jovian planets are different. For example, terrestrial planets are mainly made of rocks and metals having an average density of 4 or 5 g cm^{-3} whereas jovian planets consist mainly of gas and ice with an average density of 1 or 2 g cm^{-3}.

All these planets revolve around the Sun in elliptical orbits. The planetary orbits are almost in the same plane except that of Pluto which is inclined at an angle of ~ 17° to the common plane (Fig.6.2). **Asteroids** are believed to be the captured objects which were wandering in the solar system. Their orbits are mostly located in between the orbits of Mars and Jupiter. Since all the planets revolve round the Sun, it is considered the 'head' of the solar family. In addition, the Sun contains almost 99.87% of the total mass of the solar system. Among the planets, Jupiter and Saturn are the most massive, accounting for 92% of the mass of all the planets.



(a)



(b)

Fig.6.2: Orbits of the a) terrestrial; and b) jovian planets in the solar system

Table 6.1 summarizes some basic data about these planets and the Moon. Many of these features could directly be attributed to the distance of a planet from the Sun.

Table 6.1: Some basic data of planets and the Moon

Planets	Mass [kg]	Density [g cm^{-3}]	Mean distance from the Sun (km)	Rotation Period (hours or days)	Revolution Period (days)	Inclination of orbit to the plane of the Solar System (deg)	Percentage of light reflected
Mercury	3.30×10^{23}	5.4	5.8×10^{7}	58 d	88	7.0	7
Venus	4.87×10^{24}	5.2	1.1×10^{8}	243 d	245	3.4	76
Earth	5.97×10^{24}	5.5	1.5×10^{8}	23 h 56 min	365.25	0.0	39
Mars	6.42×10^{23}	3.9	2.3×10^{8}	24 h 37 min	687	1.8	18
Jupiter	1.90×10^{27}	1.3	7.7×10^{8}	9 h 55 min	4333	1.3	51
Saturn	5.69×10^{26}	0.7	1.4×10^{9}	10 h 30 min	10743	2.5	50
Uranus	8.70×10^{25}	1.1	2.8×10^{9}	17 h 14 min	30700	0.8	66
Neptune	1.03×10^{26}	1.7	4.5×10^{9}	18 h	60280	1.8	62
Pluto	1.00×10^{22}	2.1	5.9×10^{9}	6 d 09 h 17 min	90130	17.1	15
Moon	7.35×10^{22}	3.3	3.8×10^{5}*	27.33 d	27.33	5.0	

* This is Moon's mean distance from the Earth.

SAQ 1

Spend 5 min.

Using the data given in Table 6.1, verify Kepler's third law:

$$\frac{T^2}{r^3} = \text{Const}.$$

where T is the orbital period of a planet and r is its mean distance from the Sun.

Further, as mentioned above, the division of planets into two groups namely, terrestrial and jovian, is based on the similarity of some major characteristics of the planets in a particular group. Table 6.2 lists these characteristics of terrestrial and jovian planets. Such classification helps in developing theoretical models for their formation and evolution.

Table 6.2: Characteristics of the terrestrial and jovian planets

Characteristics	Terrestrial	Jovian
Basic form	Rocky	Gas/Liquid/Ice
Mean orbital distance (AU)	0.39–1.52	5.2–30.1
Mean surface temperature (K)	200–700	75–170
Mass (relative to the Earth)	0.055–1.0	14.5–318
Equatorial radius (relative to the Earth)	0.38–1.0	3.88–11.2
Mean density (g cm^{-3})	3.96–5.42	0.68–2.30
Sidereal rotation period (equator)	23.9 h – 243 h	9.8 h – 19.2 h
Number of known Moons	0–2	8–20
Ring systems	No	Yes

We present some salient features of the individual planets in Table 6.3.

Table 6.3a: Salient features of the terrestrial planets

Mercury	Venus	Earth	Mars
• It can be seen near the horizon at sunset or sunrise with unaided eyes. • Like the Moon, it has no atmosphere and its surface is full of craters. • It is, at the same time, the coldest and the hottest planet because its periods of revolution and rotation are almost equal which keeps its same surface face the Sun all the time. • Its surface temperature varies between +340°C to −270°C.	• It appears as the third brightest object in the sky after the Sun and the Moon, as it is nearest to the Earth. • Its surface is dry, hot and volcanic. Its atmosphere contains about 96 percent carbon dioxide, 3.5 percent nitrogen and remaining half percent is water vapours, argon, sulphuric acid, hydrochloric acid etc. • The planet is covered by a thick cloud mainly consisting of sulphuric acid droplets. • Its surface temperature is very high (~ 470°C) which is perhaps caused due to the greenhouse effect: the infrared radiation emitted by the planet is not allowed to escape due to the presence of carbon dioxide in its atmosphere thus causing the heat received from the Sun to be trapped and raise its temperature.	• Its crust, extending to 10 km deep under the oceans and up to 40 km under the continents, consists mainly of silicon (27.7%), and oxygen (47.3%). Elements like aluminium, iron, calcium, sodium etc. make the bulk of its matter and less than 2% is made of all other elements. • Its rotation axis is tipped by ~ 23° causing various seasons and polar caps. • Its atmosphere consists of distinct layers called troposphere, stratosphere and ionosphere. Troposphere comprises mainly of 78% nitrogen, 21% oxygen; stratosphere contains ozone which absorbs the harmful ultraviolet radiation from the Sun.	• Though half in size of the Earth, this planet has various similarities with the Earth i) A day on Mars is 24h 40 minutes and a year lasts for 1.88 Earth year, ii) its rotation axis is tipped at 25° and thus has seasons and polar caps. • This is the most extensively probed planet and a few automated laboratories have also been landed. The atmosphere and geology of this planet has many features similar to the Earth. • Martian surface has craters of all sizes and enormous volcanoes. • Martian soil, like the Earth, is mostly made of silicates. However, due to the presence of 16 percent iron oxide in its soil, it has the characteristic red colour. It is also known as the Red Planet.

Table 6.3b: Salient features of the Jovian planets

Jupiter	Saturn	Uranus	Neptune	Pluto
• It is the largest (having diameter 11.2 times that of the Earth) and the most massive planet (contains 71% of all the planetary mass). • It is like a spinning ball of gas and liquids with no solid surface. In this regard, it is similar to the Sun. It has a large number of satellites. • It is covered by a turbulent, gaseous atmosphere comprising of hydrogen, helium and small traces of water vapour, ammonia, methane etc. • It has a Great Red Spot on its surface which has an oval shape. It is big enough to accommodate two Earths! It is presumed to be due to huge cyclonic disturbance in its atmosphere. • In view of its composition, size and the number of Moons, Jupiter looks like a star having its own 'solar system'! • It has rings and it emits radio waves.	• It is the second largest planet exceeded in size and mass only by Jupiter. Like Jupiter, it consists mainly of hydrogen and helium. • It is the last (sixth) planet visible from the Earth. It has beautiful rings (which can be seen through a telescope). The rings are, in fact, a thousand tightly packed individual ringlets. • The temperature at its cloud tops is – 180°C. It is colder than Jupiter. • This planet is less dense than water and being mostly liquid and rotating rapidly, its shape is flattened. • It has a large number of satellites orbiting at the edge of the rings. These satellites (Moons) are composed of rock and ice and have craters. • Its main satellite, Titan, is very large (diameter 5800 km) and has atmosphere of its own as dense as ours.	• This planet is smaller than Jupiter and four times farther from the Sun. In a telescope, it appears as a green disc with vague markings. • Its axis of rotation is tipped 97.9° from the perpendicular to its orbit. This causes its poles to nearly point towards the Sun and it would seem that the planet is rolling along the orbit like a wheel. • The rings of this planet were discovered as late as 1977 (Voyager 2) and they comprise of very dark material, as black as coal. • It has a large number of Moons.	• This planet was discovered in 1846 and it is so far away that, seen from this planet, the Sun would look like a bright spot! • Its colour is faint blue which is caused due to larger percentage of methane present in it. • Its cloud temperature is about – 237°C. • Like other jovian planets, this planet also has rings. • Two Moons of this planet are visible from the Earth. • Triton is the largest Moon of this planet which is orbiting it in the clockwise direction i.e. opposite to the rotation of the planet. Triton also has atmosphere of its own comprising of nitrogen and methane.	• This planet was predicted to exist theoretically to account for the observed irregularities in the orbits of Uranus and Neptune. • It is a very small (about one-fifth the size of the Earth), cold and dark planet. • Unlike most planetary orbits, Pluto's orbit is quite elliptical and therefore it can come closer to the Sun than Neptune. • Being so far away from the Sun, this planet is cold enough to freeze most compounds. • Its mass is only 0.002 times the Earth mass!

At this stage, you may pause for a moment and think about what have you learnt till now. You have basically recapitulated what you learnt in school about the solar system and have acquainted yourself with the characteristic features of each of its planets. In the next section, you will learn about the origin of the solar system. A model for the origin of the solar system must explain its characteristic features listed below:

i) Most of the mass of the solar system is contained in the Sun.

ii) Except for Mercury and Pluto, the orbital planes of all the planets are more or less in the same plane.

iii) When viewed from above, the planets are found to revolve around the Sun in the anticlockwise direction; the direction of rotation of the Sun is also the same.

iv) Except for Venus, Uranus and Pluto, the direction of rotation of planets is the same as their direction of revolution.

v) The direction of revolution of the satellites of each planet is the same as the direction of rotation of the planet itself.

vi) Total angular momentum of all the planets is more than the angular momentum of the Sun.

vii) Terrestrial planets comprise mainly of rocky material whereas jovian planets comprise mainly of gaseous material.

Spend 3 min.

SAQ 2

List some common features of terrestrial and jovian planets.

6.3 ORIGIN OF THE SOLAR SYSTEM: THE NEBULAR MODEL

The formation of the Earth or, in fact, the entire solar system has been of considerable interest to human being for ages. A variety of speculative ideas were proposed which gave rise to two kinds of theories: **catastrophic** and **gradualistic**. According to the catastrophic theories, the planets were formed out of the material ejected from the Sun when a giant comet collided with it or the planets came into being due to ripping-off of material from the Sun caused by the tides generated by a close by passing star. However, these theories do not explain many features of the solar system. Further, during the 20th century, astronomical evidences have been found which support the gradualistic theories. According to these theories, formation of planets is a gradual process and is a natural by-product of the formation of stars like the Sun.

Contemporary gradualistic theories of the solar system are based on the **nebular hypothesis**. *According to this hypothesis, the Sun as well as the planets formed from an interstellar cloud of gas and dust*. A model of the formation of the solar system based on this hypothesis is called a **nebular model**. The basic principle of physics underlying the nebular model is the Newton's law of gravitation. *According to the nebular model, formation of stars including the Sun, begins when the interstellar cloud with enough mass and low internal pressure, contracts due to its own gravity.*

Can you guess the consequences of gravitational contraction of an interstellar cloud? You are on the right track if you think that it leads to increase in density of the cloud. Simultaneously, the kinetic energy of the particles in the cloud increases which causes increase in its temperature. As a result, the internal pressure of the collapsing cloud increases. Eventually, the gravitational contraction is balanced by the internal pressure of the cloud. The contracting cloud is called a **protostar** and when its internal temperature is high enough to initiate thermonuclear reactions, a full-fledged star (such as the Sun) is born. This is the general picture of the formation of a star according to the nebular model.

Well, you may ask**: How did our solar system come into existence**? According to the nebular model, our solar system formed due to gravitational contraction of the rotating interstellar cloud called the **solar nebula**. Due to rotation, the solar nebula takes the form of a disc (Fig. 6.3). When the Sun formed at the centre of this disc and became luminous enough, the remaining gas and dust was pushed away due to the Sun's radiation pressure. The blown away gas and dust condensed into various planets orbiting the Sun. One of the natural consequences of the solar nebula model is that most stars in the galaxies should have planetary systems!

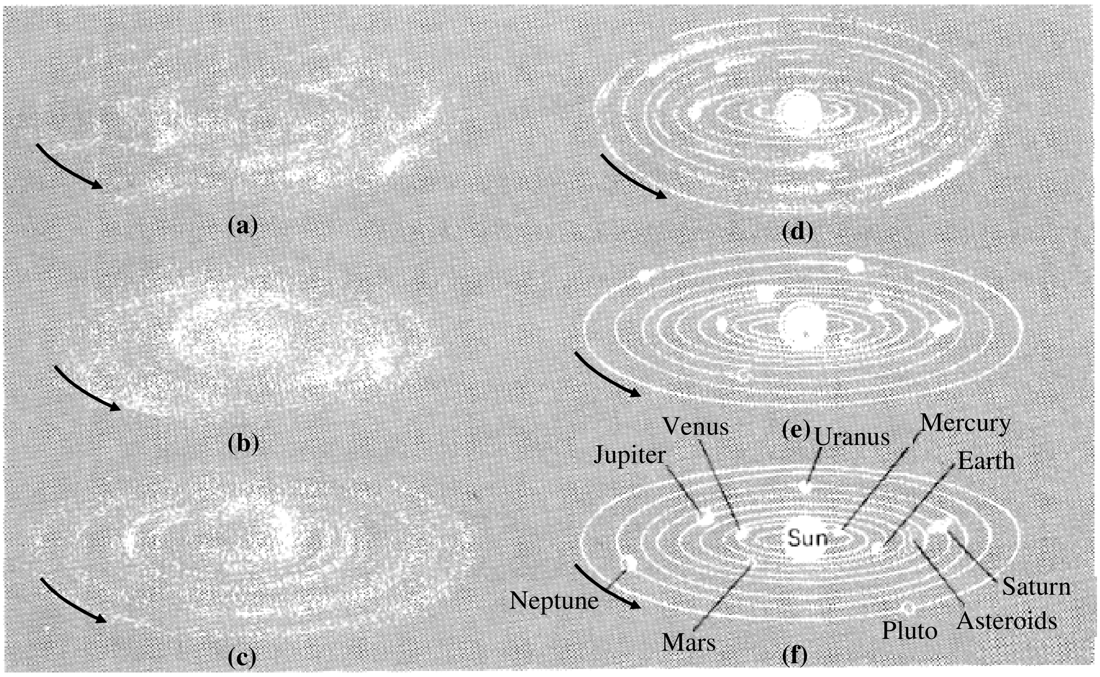


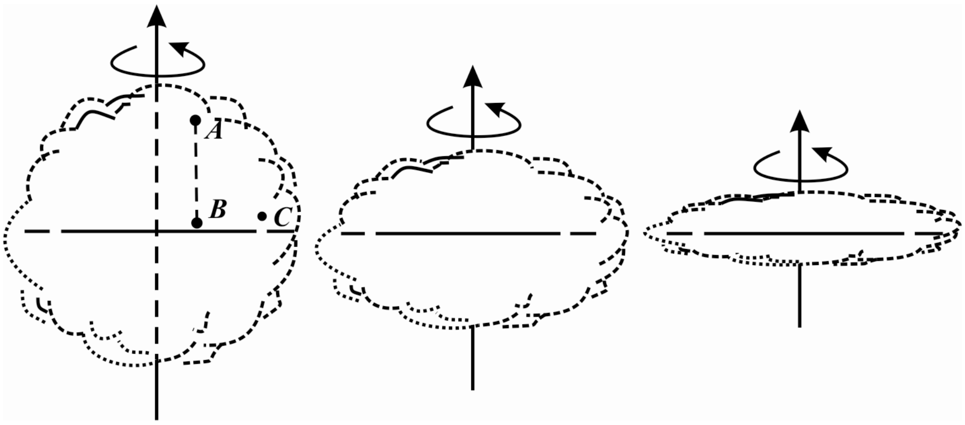
Fig.6.3: Schematic diagram showing different stages (a to f) of the formation of the solar system

Formation of Solar Nebular Disk

You must have noted that one of the significant features of the solar nebular model is the formation of a disk of interstellar cloud around the Sun. You may ask: **Is there any evidence supporting the formation of the disk?** Two facts support this assumption. Firstly, as you know, the orbits of planets, except that of Mercury and Pluto, lie in nearly the same plane. Such coplanar planetary orbits are consistent with the formation of nebular disk. Secondly, the rotation of the Sun and revolution of the planets is along the same direction and their equatorial planes are very close to the plane of the solar system. Thus, the motion of the Sun and the planets are consistent with the disk hypothesis.

Your next logical question could be: **Can we explain the formation of nebular disk on the basis of physical principles?** *It can indeed be done provided we assume that the interstellar cloud, giving rise to the solar system, had some initial rotational motion.* Having assumed this, we can invoke the principle of conservation of angular momentum to explain the formation of a disk. As the cloud contracted due to gravity, each gas and dust particle would come closer to the axis of rotation. To conserve the angular momentum during the contraction, the particles coming nearer to the axis of rotation must revolve faster. At some point, due to the increased speed of revolution, the centripetal acceleration of the particles of the cloud balance the gravitational contraction and equilibrium is attained.

To understand the flattening of the rotating cloud, refer to Fig. 6.4. Particles at points *A* (near the pole) and *B* (near the equator) have the same angular momentum because points *A* and *B* are equidistant from the axis of rotation. Thus, it is energetically more favourable that particle at *A* falls under gravity along the line *AB* and reaches the point *B* (closer to the centre) than say a particle at point *C* to come to point *B*. It is so because, in the first situation, no change in angular momentum is involved. Thus, rotating cloud near the poles contracts more than those near the equator giving rise to the formation of disk.



(a) **(b)** **(c)**

Fig.6.4: a) Interstellar cloud with initial rotational motion; b) due to gravitational attraction, material at the poles contracts along the rotation axis; and c) the final disk shaped solar nebula

The principle of the conservation of angular momentum also explains why most of the planets rotate along the same direction. It is because each planet has retained some of the angular momentum of the solar nebula. Let us discuss the angular momentum of the solar system to appreciate this point better.

Angular Momentum of the Solar System

The present distribution of angular momentum in the solar system seems inconsistent with the basics of the nebular model. The argument goes like this. Since the Sun and the planets are formed from the same spinning interstellar cloud, the angular momentum per unit mass of each of them must be same. The facts are otherwise: the Sun possesses approximately 99.9% of the total mass of the solar system but only 1% of its total angular momentum; orbital angular momentum of Jupiter exceeds the rotational angular momentum of the Sun by a factor of 20; among the planets having 99% of the total angular momentum of the solar system, Jupiter possesses the most of it! To appreciate these facts and figures, you should solve an SAQ.

Spend 5 min.

SAQ 3

Calculate the total angular momentum of the Sun-Jupiter system assuming that Jupiter has a circular orbit of radius 5.2 AU, and its orbital period is 11.86 yr. Assume that the Sun interacts only with Jupiter.

You may ask: **How does the nebular model explain the inconsistency in the distribution of angular momentum**? It is proposed that during the formation of the solar system, the angular momentum is transported from the central part of the nebula to the outer regions. Two possible mechanisms for such a transfer have been suggested. According to the first mechanism, the interaction of the charged particles and the magnetic field of the evolving Sun causes transfer of angular momentum. You know that charged particles spiral along the magnetic field. Thus, the charged particles created by ionisation of solar nebula by the Sun are dragged along by the magnetic field of the rotating Sun (Fig. 6.5). The magnetic field links the outer nebular matter (charged particles) with Sun's rotation. As a result, the nebular material in the outer region gains angular momentum at the expense of the Sun. The other mechanism suggested for transfer of angular momentum is based on viscosity. You know that due to viscosity, motion of fluid in one part is affected by the motion of the fluid in the adjoining part. Thus, it is quite possible that the slow moving particles located at outer edges of the nebula gain in velocity due to their interaction with the fast moving particles in the smaller orbits of the nebula and vice-versa. This may cause transfer of angular momentum from the Sun to the outer planets of the solar system.

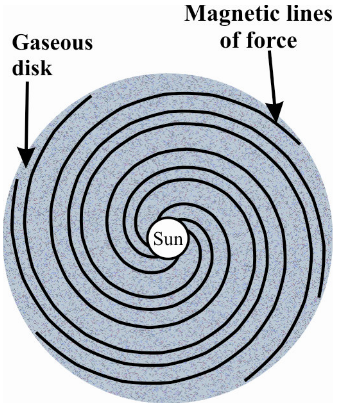


Fig.6.5: Magnetic lines of force of the rotating Sun

Now, you will learn about formation and evolution of planets according to the nebular model.

Formation of Planets

You know that the solar nebula consisted of gas and dust. As the solar nebula contracted, it became hot enough and most of the dust particles evaporated. So, the solar nebula consisted mainly of gaseous matter. The question is**: How did the planets form from the solar nebula?** The formation of planets is a two-stage process: firstly, small solid particles are formed from the gaseous matter and then these particles stick together and grow into planets.

Depending upon the temperature of the nebular region, the nebular gas condensed into solid matter of different types. In the inner region, the temperature was very high and materials with very high melting points were formed. The sequence of condensation of gas into different types of materials, from the centre of the nebula (the Sun) to its periphery, is called the **condensation sequence** and is given in Table 6.4.

Table 6.4: The condensation sequence

Temperature (K)	Material(s) formed	Planet (Temperature of formation)
1500	Metal oxides	Mercury (1400 K)
1300	Metallic Iron and Nickel	
1200	Silicates	
1000	Feldspars	Venus (900 K)
680	Troilites (FeS)	Earth (600 K) Mars (450 K)
175	H_2O, Ice	Jovian (175 K)
65	Argon-neon Ice	Pluto (65 K)

With the help of computers, it is possible to study the behaviour of a large number of particles when they interact in the manner as in the process of accretion. Such computer experiments are called simulation. The results of such simulation studies suggest that there could be as many as 100 planetesimals of the size of the Moon along with a large number of smaller objects in the region of inner planets. In addition, there could be about 10 bodies with masses comparable with the planet Mercury and many other objects of the size of the planet Mars.

From Table 6.4, it is evident that terrestrial planets formed from high density materials and jovian planets formed from low density materials.

Having discussed the general chemical composition of planets, we now focus on the evolution of planets. **The evolution of planets involves three stages**:

a) The first stage involves the growth of macroscopic grains of solid matter from the interstellar cloud. The size of these grains range from a few cm to a few km and they are called **planetesimals**. Planetesimals can grow through two processes: **condensation** and **accretion**. In the condensation process, grains grow by adding one atom at a time to a 'nucleus' atom, from the surrounding gaseous cloud. This is similar to the growth of snowflakes in the Earth's atmosphere. In the accretion process, solid particles stick together. Further, the planetesimals would tend to rotate in the plane of the solar nebula.

b) In the second stage, planetesimals coalesce and form **protoplanets** – objects having planetary sizes and masses. You may ask: **How do the protoplanets form?** Since all the planetesimals are moving along the same direction in the nebula, they collide with each other at a low relative velocity and stick together to form protoplanets. Further, growth of protoplanets is helped by gravity because the nebular matter is attracted by the protoplanets.

c) At the third stage, when a protoplanet grows into a stable planet, a large amount of heat is generated in its core due to the decay of short-lived radioactive elements. Heat is also generated due to collision of these planets with other objects. Due to high temperature, the planets melt and facilitate the process of gravitational separation in which materials in the planet segregate themselves according to their density. Therefore, the inner regions of the planets hold heavier elements and compounds and lighter elements are pushed to the surface.

This, in the nutshell, is the 'story' of planet building! You must have noted that there are many unanswered questions and many ifs and buts in the mechanism described above. To understand the details of formation of planets is still an active area of research in astronomy and astrophysics. We will, however, not go into those details and close our discussion with a few words about the success of the nebular model.

The creation of a massive object, like Jupiter, influences the orbits of nearby planetesimals. Most of the objects present in the asteroid belt today had their orbits changed gradually into more eccentric orbits till they were sucked in by Jupiter. It is also likely that they either left the solar system or crashed into the Sun. This process might in fact have resulted in the smaller mass left in the asteroid belt and also a smaller planet Mars.

The solar nebular model successfully accounts for the following three important features of the solar system:

i) *Disk shape of the solar system*: The model suggests that the rotating solar nebula ultimately evolves into disk shape due to gravitational contraction and conservation of angular momentum.

ii) *The orbits of most of the planets are coplanar:* As per the model, this situation exists because of the disk shape of the solar nebula from which planets are formed.

iii) *The direction of rotation of the Sun and the directions of revolution of most of the planets are the same*: It is so because the Sun and the planets formed from the same rotating nebula.

As we go further from Jupiter and beyond in the nebula, the material density becomes very low. So, the accretion process for the formation of a planet-like object takes much longer time. Saturn perhaps took twice as long to form as Jupiter, while the planet Uranus took an even longer time. The planet Neptune is estimated to have taken twice the time it took to form Uranus.

You have also learnt that the condensation sequence of the solar nebula explains why terrestrial planets comprise of compounds having high melting point and jovian planets comprise of ices and gases.

The nebular model has some very obvious limitations. You know that the Moon's surface is not smooth; it has craters of varied sizes, small and large. Also, its surface composition is extremely poor in hydrogen, helium etc. These observations suggest the continued collisions of bigger planetesimals with the Moon's surface even after its formation. It is quite likely that other objects (planets) in the solar system experienced similar collisions with planetesimals. Thus, the theory of solar system formation must account for massive encounters endured by planets in the early stages of their formation. These massive collisions or encounters are possibly responsible for different orientation of the spin axis of the planets in the solar system. It is now known that Venus, Uranus and Pluto have retrograde rotations.

The cause for tipping of rotation axis, retrograde rotation etc. of planets cannot be understood as such by gradualistic models like the nebular model. We need to consider catastrophic events. During the formation of the solar system, the wandering planetesimals did perhaps collide with other planets such as Mercury, Venus, Earth etc. The collision with Mercury ripped off its low density mantle while such a collision with Venus flipped its rotation axis. A collision with Earth led to the formation of the Earth-Moon system. Further, massive planetesimals crashed into Mars as well as other outer planets changing orientation of their rotation axes. It is also possible that some of these planetesimals were captured by planets as their Moons.

Now, before you proceed further, how about answering an SAQ?

SAQ 4

Spend 7 min.

a) List two evidences supporting the assumption that a disk shaped solar nebula existed during the evolution of the solar system.

b) Why do terrestrial planets comprise mainly of materials having high melting points?

c) What is the difference between the condensation and accretion processes?

6.4 TIDAL FORCES AND PLANETARY RINGS

You must be aware of tides occurring on the Earth's surface. In fact, those of you who live in the coastal areas must be quite familiar with tides. Two high tides occur once in every ~ 24 hours depending on the local features of the coastal area and its latitude. However, generally people are not familiar with the tidal bulge of the Earth along the equator which measures around 10 cm. **Do you know what causes tides or tidal bulge of the Earth?** *It is caused due to the difference between gravitational force of the Moon at different locations, say points A and B, on the Earth* (Fig. 6.6). Due to similar reasons, tidal bulge (as large as 20 m) caused by the Earth has also been observed on the Moon. The larger value of the bulge of the Moon is because the Earth is more massive than the Moon.

Tidal effects play an important role in astronomy, particularly in understanding the creation of large number of satellites and ring systems in the jovian planets. We now derive an expression for the tidal force for the Earth-Moon system. Then we shall use this concept for a qualitative explanation of the formation of planetary rings.

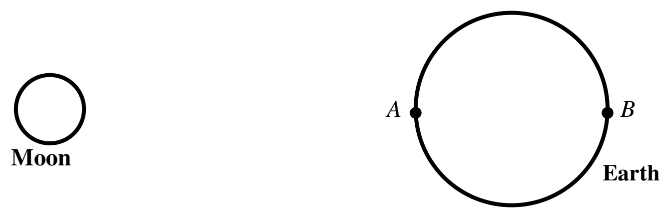


Fig.6.6: Tidal bulge of the Earth is due to the difference in gravitational force of the Moon experienced by mass elements at, say points *A* and *B*, on the Earth.

Let a mass *m* on the Earth be located at a distance *r* from the centre of mass of the Moon (Fig. 6.7). If the mass of the Moon be *M*, the magnitude of the gravitational force acting on *m*, in the direction shown, is given by:

$$F = G\frac{Mm}{r^2}, \qquad (6.1)$$

where *G* is the gravitational constant.

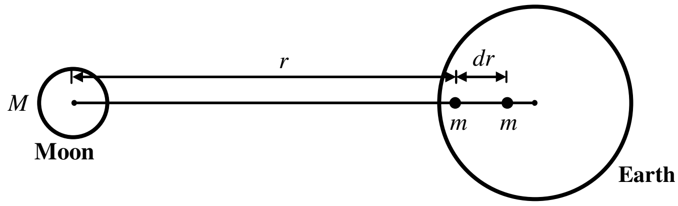


Fig.6.7: Gravitational force on an element of mass *m* located on the Earth at a distance *r* from the centre of mass of the Moon

Now consider a similar mass located at a distance *dr* from the earlier mass element along the same line. The difference between the gravitational forces experienced by these two mass elements can be obtained by differentiating *F* in Eq. (6.1):

$$dF = -2G\frac{Mm}{r^3}dr \qquad (6.2)$$

Note that the difference in the gravitational forces on the two equal masses separated by a distance *dr* will cause them to move with different accelerations. The differential force given by Eq. (6.2) is called the tidal force. The r^3 term in the denominator of Eq. (6.2) clearly shows that the tidal force has a stronger dependence on distance compared to the gravitational force (which varies as $1/r^2$). Further, in case of the Earth-Moon system, the tidal force becomes more pronounced if the mass element is closer to the Moon.

Now to appreciate the effect of the tidal force of the Moon on mass elements located at different points on the Earth, e.g., at the equator and at the poles, let us obtain a general expression for the tidal force considering the Earth as a two-dimensional object. Let us consider an element of mass *m* located at the centre (*C*) of the Earth and another element of mass *m* located at an arbitrary point (*P*) at latitude ϕ on the surface of the Earth (Fig. 6.8). By assuming that the Moon lies along the *x*-direction, the components of gravitational force at points *C* and *P* can be written as:

$$F_{C,x} = G\frac{Mm}{r^2},$$

$$F_{C,y} = 0,$$

and

$$F_{P,x} = G\frac{Mm}{s^2}\cos\theta,$$

$$F_{P,y} = -G\frac{Mm}{s^2}\sin\theta. \qquad (6.3)$$

where s is the distance between points P and the centre of mass of the Moon.

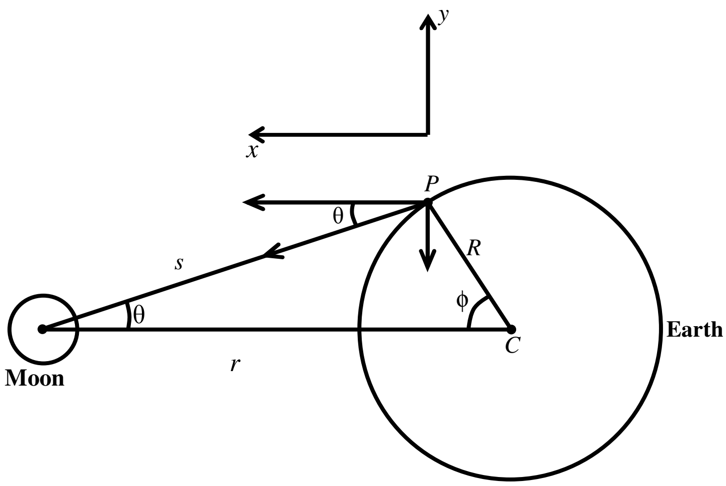


Fig.6.8: The schematic diagram of the tidal force on an arbitrary point on the Earth due to Moon

Let the unit vectors along the x- and y-directions be $\hat{\mathbf{i}}$ and $\hat{\mathbf{j}}$, respectively. Thus, from Eq. (6.3), the difference between the magnitudes of gravitational forces at the points P and C can be written as:

$$\Delta\mathbf{F} = \mathbf{F}_P - \mathbf{F}_C$$

$$= GMm\left(\frac{\cos\theta}{s^2} - \frac{1}{r^2}\right)\hat{\mathbf{i}} - GMm\left(\frac{\sin\theta}{s^2}\right)\hat{\mathbf{j}} \qquad (6.4)$$

Further, s can be expressed in terms of r, R and ϕ as:

$$s^2 = (r - R\cos\phi)^2 + R^2\sin^2\phi$$

$$\approx r^2\left(1 - \frac{2R}{r}\cos\phi\right)$$

Substituting for s^2 in Eq. (6.4) using the small angle approximations, $\cos\theta \approx 1$ and $\sin\theta \approx \frac{R}{r}\sin\phi$, and using binomial expansion we obtain:

$$\Delta\mathbf{F} \approx \frac{GMmR}{r^3}(2\cos\phi\,\hat{\mathbf{i}} - \sin\phi\,\hat{\mathbf{j}}) \qquad (6.5)$$

SAQ 5

Spend 6 min.

Derive Eq. (6.5).

You may ask: **What does Eq. (6.5) signify physically?** This expression clearly indicates that the magnitude of the tidal force is dependent on the latitude. For mass element located at the equator of the Earth, that is, for $\phi = 0$, the magnitude of tidal force is maximum. And, at the poles, where $\phi = \pi/2$, the magnitude of the tidal force is minimum. This is the cause of tidal bulge around the equator and also causes tides in the oceans.

In the above discussion, we have considered the Earth-Moon system to be an isolated one. In fact, we must also consider the tidal forces due to the Sun. When the Sun, Earth and the Moon are all aligned in a straight line, the differential forces discussed above add up to produce large tides on the Earth. These tides are called **spring tides**. When the Sun, Earth and the Moon form a right angle, the differential forces due to the Sun and the Moon are directed opposite to each other and the tides on the Earth (known as **neap tides**) are very small.

Yet another effect of tidal force is that the Earth's speed of rotation is slowed down. This results in longer days at present compared to many years ago. Further, just as the Moon causes tides on the Earth, the Earth also gives rise to tides on the Moon. You know that on the Earth we see the same side of the Moon which implies that its rotation and revolution periods are the same. It is quite likely that earlier the Moon's rotation period was shorter than its orbital period. As time progressed, because of the tidal friction, the rotation period of the Moon increased and has become equal to its orbital period (also called **one-to-one synchronous rotation**). We find such synchronous motion to be quite a common phenomenon in the solar system. For instance, the two Moons of Mars and four Moons of Jupiter and majority of Saturn's Moons are in synchronous rotation. Many moons of the outer planets behave in a similar manner.

You know that most outer planets of the solar system have rings around them comprising of small (~ 10 μm to 10^{-5}m) particles. The concept of tidal forces can be invoked to understand these ring systems. There are two possible scenarios. Since the jovian planets are massive, tidal gravitational force of the planets on their satellites must be very strong. Thus, if a satellite comes very close to, say, Jupiter, it experiences a strong tidal force and breaks up into pieces. The particles formed during such a process revolve around the planet in ring formation. According to the second scenario, during the formation of jovian planets, the tidal forces restrained the particles from condensing into a satellite.

You may argue: **The tidal forces must ultimately disrupt the ring system; what maintains the ring system**? It is suggested that the Moons associated with these planets play an important role in preserving the rings. The particles in the rings are restrained from moving out of their orbit due to the combined gravitational forces of these Moons.

Human beings have always wondered about the existence of planets around other stars. Only in recent times there has been a confirmation that planets do exist outside the solar system. These planets are called **extra-solar planets**. You will learn about them now.

6.5 EXTRA SOLAR PLANETS

Fig.6.9: Photograph of an extra solar planet taken by Hubble telescope

On August 4, 1997, the Hubble Space telescope took the first image of an extra-solar planet around another star (Fig. 6.9). The picture shows a double star located at about 450 light years away towards the constellation of Taurus. It was the first direct look at a planet outside our solar system. It is now believed that this planet is a "runaway" object, thrown out of the binary system, as indicated by the filament tracing. The planet is located at about 1500 times the Earth-Sun distance from its parent. The binary system is believed to be 300,000 years old and the planet seems to be quite similar to Jupiter with a mass of around 2-3 times that of Jupiter. This discovery led to careful investigation by several groups of astrophysicists and by now more than 100 such extra solar planets have been found.

Young planets in the new systems are difficult to detect as the parent stars overshadow their feeble glow. Since it is difficult to detect a planet orbiting a distant star, we look for alternative methods of detection, such as the influence of the planets on their parent stars. You may like to know: **What are these influences**? It is easy to think of gravitational influence. As the planet orbits the star, it will tug at it from different sides causing it to **wobble** back and forth. The gravitational influence gives rise to the following methods for detection of the planet:

a) Astrometric Detection
b) Radial Velocity Detection

The first method is based on measuring the position of a star relative to its background stars. If the star is accompanied by an orbiting planet, it gets a tug from the planet and its position changes a little. This change in the position of the star is measured which would show a periodic change (back and forth) indicating the presence of an orbiting object.

The second method is based on Doppler effect. As an orbiting planet tugs on to its companion star, the light from the star experiences a Doppler shift. If the planet pulls the star slightly away from us, the light emitted by star would shift towards red end of the electromagnetic spectrum while if it tends to pull the star towards the Earth, the light would be shifted towards the blue end of the spectrum. To measure the Doppler shift, we choose a particular spectral line and observe its shift from red to blue and back.

In 1995, Michel Mayor and Didier Qucloz of the Geneva Observatory observed that the Sun-like star, 51 *Pegasi* is wobbling back and forth at the rate of 56 ms^{-1}. The only valid explanation for this observation was the presence of a planet like object orbiting the parent star. The mass of the planet was estimated to be half the mass of Jupiter with a radius of about 0.05 AU. Subsequently, Mayor also detected a planet of about 0.16 times the mass of Jupiter orbiting the star HD 83443 in the constellation of Vela about 141 light years away from the Earth.

Recently David Charbonneau, Timothy Brown and Robert Gilliland used the Hubble spectrometer and made the first direct detection and chemical analysis of the atmosphere of the planet HD 209458b orbiting a yellow, Sun-like star, HD 209458, in the constellation of Pegasus. The mass of the planet is estimated to be 70% of the mass of Jupiter. It passes in front of its star every 3.5 days and contains sodium in its outer layers. The extremely short period of the planet suggests its very close proximity to the star and therefore its atmosphere getting heated to around 1100 degrees Celsius.

Many new results are pouring in and are compelling astronomers to have a re-look on the theories of solar system formation. The search for extra-solar planets is going hand in hand with the search for life in the Universe. Exploration of the solar system has so far not revealed any signs of even primitive life on any of the planets or their satellites. Scientists strongly believe that there must be a large number of extra-solar planets where conditions are suitable for the existence of life. Indeed, some of these planets could be hosting life more advanced than our own. It is possible that some of these intelligent beings are trying to contact us just as we are looking for them. It must be remembered that any message from any of these beings would be coded in radio waves. That is why SETI, an organisation searching for Extra Terrestrial Intelligence, is looking for such signals in the radiation at radio frequencies coming from outside the solar system. Scientists are hopeful that someday they would be able to detect extra-solar intelligence.

Let us now summarise what you have learnt in this Unit:

6.6 SUMMARY

- The first four planets of the solar system namely Mercury, Venus, Earth and Mars are called **terrestrial planets** and they mainly comprise of solid matter. The next five planets, namely Jupiter, Saturn, Uranus, Neptune and Pluto are called **jovian planets** and they mainly comprise of ices and gases.
- One of the significant features of jovian planets is the **ring system**.
- Some of the **characteristic properties** of the **solar system** are:

  i) Most of the mass of the solar system is contained in the Sun.

  ii) Orbital planes of all the planets except Mercury and Pluto are coplanar.

  iii) The direction of rotation of the Sun and direction of revolution of the planets is the same.

  iv) Total angular momentum of all the planets is more than the angular momentum of the Sun.
- According to the **nebular hypothesis** of the origin of solar system, the Sun as well as the planets formed from an interstellar cloud of gas and dust. A model based on this hypothesis is called **nebular model**.
- According to the nebular model, formation of stars including the Sun takes place when the interstellar cloud contracts due to its own gravity.
- The contracting interstellar cloud takes a disk shape due to its rotational motion. Formation of nebular disk causes coplanar planetary orbits.
- The present distribution of angular momentum in the solar system seems inconsistent with the basics of the nebular model.
- The angular momentum problem is addressed by proposing that there is a transfer of angular momentum from the inner to outer regions of the solar system during its evolution.
- The formation of planets results due to condensation of nebular gas as per the **condensation sequence**.
- The formation of planets involves three stages:

  i) Formation of **planetesimals,**
  ii) Formation of **protoplanets,** and
  iii) **Stabilisation** of the planet.
- Tidal forces result due to the difference in gravitational force at two points on the Earth. For the Earth, tidal forces due to the Moon have a significant effect. Tidal force at the equator is maximum and at the poles, its value is minimum. The general expression for the tidal force is given by

$$\Delta \mathbf{F} \cong \frac{GMmR}{r^3}(2\cos\phi\,\hat{\mathbf{i}} - \sin\phi\,\hat{\mathbf{j}})$$

- In the recent past, a few extra-solar planets have been detected.

6.7 TERMINAL QUESTIONS

Spend 20 *min.*

1. Explain, in your own words, the theory of the solar system formation based on nebular hypothesis.
2. Explain how angular momentum can be transferred from the Sun to the outer planets of the solar system.
3. Is it possible that the Earth also suffered collisions with other bodies of the solar system and its surface also had craters like those on the surface of Mercury? Can you guess what happened to those craters?
4. Explain how extra-solar planets can be detected. Why can they not be seen directly?

6.8 SOLUTIONS AND ANSWERS

Self Assessment Questions (SAQs)

1. To verify Kepler's third law, let us calculate (T^2/r^3) for three representative planets, say the Mercury, the Earth and the Saturn. From Table 6.1, we have

$$T_{Mercury} = 88 \text{ days} = 88\times24\times60\times60 \text{ s} = 7.6\times10^6 \text{s}$$

and

$$r_{Mercury} = 5.8\times10^7 \text{ km} = 5.8\times10^{10} \text{ m}$$

So,

$$\frac{(T_{Mercury})^2}{(r_{Mercury})^3} = \frac{(7.6\times10^6 \text{ s})^2}{(5.8\times10^{10} \text{ m})^3}$$
$$= 2.9\times10^{19} \text{ m}^{-3}\text{s}^2$$

Similarly, using data from Table 6.1, you can easily show that:

$$\frac{(T_{Earth})^2}{(r_{Earth})^3} = 2.9\times10^{19} \text{ m}^{-3} \text{ s}^2$$

and

$$\frac{(T_{Saturn})^2}{(r_{Saturn})^3} = 2.9\times10^{19} \text{ m}^{-3}\text{s}^2$$

Since the ratio (T^2/r^3) for all the three planets has the same value $2.9\times10^{19} \text{ m}^{-3}\text{s}^2$, Kepler's third law is true.

2. See text.

3. For two bodies of mass M_1 and M_2 moving around their centre of mass, the reduced mass is given by:

$$\mu = \frac{M_1 M_2}{M_1 + M_2}$$

So, for the Sun-Jupiter system, we can write:

$$\mu = \frac{M_\Theta M_J}{M_\Theta + M_J}$$
$$\approx M_J$$

Using Kepler's third law, it can be readily shown that the angular momentum L and the period T of the orbiting mass are related as:

$$L = \frac{2\pi ab\mu}{T}.$$

where a, and b respectively are the semi-major and semi-minor axes of the elliptical orbit of the planet. As per the problem, the orbit of Jupiter is to be considered circular. Thus, we can write:

$$a = b = 5.2\,\text{AU}$$

$$= 5.2 \times 2.279 \times 10^{11}\text{m}$$

Substituting the values of $M_J = 2 \times 10^{27}$ kg and $T = 11.86$ yr, we get:

$$L = \frac{2\times 3.14\times (5.2\times 2.279\times 10^{11}\text{ m})^2 \times \left(2\times 10^{27}\text{ kg}\right)}{(11.86\times 365\times 24\times 3600\,\text{s})}$$

$$= \frac{17.63\times 10^{51}\text{ kg m}^2}{4.44\times 10^9\text{ s}}$$

$$= 3.9\times 10^{42}\text{ kg m}^2\text{ s}^{-1}$$

4. See text.

5. Refer to Fig. 6.8. From Eq. (6.4), we have the difference between the magnitudes of gravitational force at points P and C as:

$$\Delta\mathbf{F} = \mathbf{F}_P - \mathbf{F}_C$$

$$= GMm\left(\frac{\cos\theta}{s^2} - \frac{1}{r^2}\right)\hat{\mathbf{i}} - GMm\left(\frac{\sin\theta}{s^2}\right)\hat{\mathbf{j}}$$

$$s^2 = r^2 + R'^2$$
$$= r^2 + R^2 \sin^2\phi$$
$$= (r - R\cos\phi)^2 + R^2 \sin^2\phi$$
$$\simeq r^2 - 2rR\cos\phi + R^2\cos^2\phi + R^2\sin^2\phi$$
$$= r^2 - 2rR\cos\phi + R^2$$
$$\approx r^2\left(1 - \frac{2R}{r}\cos\phi\right) \qquad \text{(neglecting higher order terms in } R\text{)}$$

Substituting for s^2 and making small angle approximations, $\cos\theta \approx 1$ and $\sin\theta \approx \frac{R}{r}\sin\phi$, we can write:

$$\Delta\mathbf{F} = GMm\left(\frac{1}{r^2\left(1-\frac{2R}{r}\cos\phi\right)} - \frac{1}{r^2}\right)\hat{\mathbf{i}} - GMm\left(\frac{\frac{R}{r}\sin\phi}{r^2\left(1-\frac{2R}{r}\cos\phi\right)}\right)\hat{\mathbf{j}}$$

$$= \frac{GMm}{r^2}\left[\left(\frac{r}{r-2R\cos\phi} - 1\right)\hat{\mathbf{i}} - \left(\frac{R\sin\phi}{r-2R\cos\phi}\right)\hat{\mathbf{j}}\right]$$

$$= \frac{GMm}{r^2}\left[\left(\frac{2R\cos\phi}{r-2R\cos\phi}\right)\hat{\mathbf{i}} - \left(\frac{R\sin\phi}{r-2R\cos\phi}\right)\hat{\mathbf{j}}\right]$$

$$\cong \frac{GMmR}{r^3}\left(2\cos\phi\,\hat{\mathbf{i}} - \sin\phi\,\hat{\mathbf{j}}\right) \qquad \text{(because } r >> 2R\cos\phi\text{).}$$

Terminal Questions

1. See text.
2. See text.
3. See text.
4. See text.