

Chapter 2

A Brief History of the Solar System

*This world was once a fluid haze of light,
Till toward the centre set the starry tides,
And eddied into suns, that wheeling cast
The planets: then the monster, then the man.*

—Alfred Tennyson
(In *The Princess*, 1847)

The Solar System: Our Neighborhood

From the year 1930 to the year 2006, nine objects in the solar system were considered as planets. The planets Mercury, Venus, Earth, and Mars are known as terrestrial or rocky planets because they have a solid surface like that of the Earth. The planets Jupiter, Saturn, Uranus, and Neptune are known as Jovian planets. They all are giant gaseous objects. Not much was known about Pluto. Even the mass of this planet was not known until the end of the last century. Now we know that Pluto is a rocky object and it is much smaller than even our Moon. The terrestrial planets are also known as the inner planets and the Jovian planets are known as the outer planets because an asteroid belt between Mars and Jupiter separates them. This asteroid belt has many small objects orbiting around the Sun and some of them are as large as Pluto. All the planets except Pluto are orbiting in the same plane. We also know that the planets are not the only members of the solar system. There are a large number of satellites, comets, asteroids, and planetesimals (small, rocky celestial objects formed during the birth of the solar system). In 2006, the general assembly of the International Astronomical Union, the “Parliament” or “Senate” of astronomers, decided a definition of the planets and resolved that Pluto should no more be considered as a planet. So, if we go by that definition, then the number of planets reduces to eight. Pluto and other objects similar to the size or mass of Pluto are now considered as Dwarf Planets. We shall discuss it later on.

If one is born and brought up in a small town, has never traveled outside it, and doesn't know much about the people outside the town, then the small town becomes one's very own world irrespective of one's knowledge that there exist other towns and cities and even countries. So, in this book we consider the solar system as "our world" because we know the parent of this planetary system, the Sun, and the neighbors of the Earth the best. All the planets and the Sun have mutual influence on each other gravitationally. Also the formation and evolution of the Earth are coupled with the formation and evolution of all the other solar objects. The chemical composition or the elemental abundance of all the solar system objects is also the same because they all were born out of the same molecular cloud called the solar nebula. Even the fate of all the planets in the solar system is almost the same as that of the Earth.

Our present understanding based on several observations also implies how unique the solar system is, at least within our galaxy. However, before we discuss about the individual planets and their discoveries, let us see how a planetary system in general or the solar system in particular was formed.

How the Solar System Was Formed

It is believed that all the solar system objects—the Sun, the planets, the Moon, asteroids, comets, etc.—were formed at the same time and out of the same nebula or interstellar cloud. Therefore, the solar planets and their parent star, the Sun, have almost the same age—about 4.6 billion years. Now, the question is how a star similar to the Sun is usually formed. A star is formed by the gravitational collapse of a huge cloud of molecules and dust in the interstellar medium. The cloud is so large that light takes about 3–4 years or more to travel from one end to the other. It is spherical in shape and is spinning slowly around its own axis of rotation. The outward pressure caused by the heat of the cloud exactly balances the gravitational pull towards its center. This is called hydrostatic equilibrium or hydrostatic balance. Now, imagine that a slight disturbance is given by compressing a certain part of the cloud. This would cause a perturbation in the cloud and the disturbance will travel through the cloud at the speed of sound. This is analogous to the propagation of the disturbance that we observe when we drop a stone in the stagnant water of a pond or a tank. The speed of sound in any medium is directly proportional to the square root of the temperature of that medium. Therefore, the disturbance travels faster if the medium is hotter and it travels slower if the medium is cooler. Suppose this disturbance takes a time t to travel a distance R within the cloud. As this disturbance passes through the cloud, the pressure tends to bring back the medium to its original stable condition. At the same time the gravitational force tries to pull matter towards the center so that there is a tug of war between the outward pressure and the gravitational force in this disturbed or perturbed region. The matter is displaced at a speed called the free fall velocity. What is it? If you throw a stone upwards, it goes up with a certain speed that keeps on decreasing with the height, and at some

point, it comes to the rest and then falls back to the Earth. The motion of the falling stone is directed towards the center of the Earth. The speed at which the stone falls depends on the mass and the radius of the Earth and not on the size or mass of the stone. That is why objects of all kinds, irrespective of their mass or size, fall onto the Earth with the same speed. This phenomenon was demonstrated first by Galileo Galilei. The velocity at which any small object, initially at rest, falls towards a massive object under the influence of its gravitational attraction is called the free fall velocity. So, the adjacent matter within the disturbed region of the cloud would move at the free fall velocity towards the center. Now, if the time taken by the disturbance to travel the distance R is shorter than the time taken by the matter to make a free fall of distance R , then the pressure wins the race and the disturbed region is restored to its initial condition. This means nothing happens to the cloud by the disturbance.

But, if the region is sufficiently cool so that the disturbance does not propagate fast enough and if R , the size of the region, is sufficiently large, then the time taken by the disturbance to travel across the region becomes longer than the free fall time. In this situation, the gravitational force wins the race and the whole region starts collapsing. The minimum size of a region or the critical length of a region at which this is possible is called the Jeans Length after the name of Sir James Jean who pointed out this during 1940. The phenomenon is called the Jeans instability. The total mass contained in a spherical region of diameter equal to the Jeans Length is called the Jeans Mass. Therefore if the mass of a region is equal to or more than the Jeans Mass, then any external disturbance exerted to this region would initiate gravitational collapse. Of course the Jeans Length depends on the initial temperature of the cloud. Further investigations on Jean's analysis show that if one region of a large cloud starts collapsing, the other regions surrounding it also get disturbed and as a result the whole cloud gets fragmented into several collapsing regions. This triggers the formation of stars with different masses depending on the mass of the different collapsing regions.

Now let us consider one such collapsing spherical cloud which is also spinning around its own axis. As the size of the sphere reduces, the spin velocity increases because the angular momentum of the cloud has to be conserved. Angular momentum of a rotating body is the product of its rotational speed and the moment of inertia. The moment of inertia is determined by the distribution of matter inside the body. For a spherical body, it is proportional to the square of the radius. Hence, if the radius decreases, the moment of inertia also decreases. Therefore, to keep the product—the angular momentum unaltered—the rotational speed increases. Now, the centrifugal force due to the spin acts in the opposite direction to the gravitational attraction and produces an equatorial bulge. As a result, the increase in the rotational speed and hence the increase in the outward centrifugal force slow down the inward flow of matter in the equatorial plane. As the collapse continues, the rotational speed keeps on increasing. At some point the rotational speed of matter in the equatorial plane becomes so high that the outward centrifugal force acting on the matter exactly balances the inward gravitational pull. This is known as the breaking point of the rotation. If the rotational speed exceeds this breaking point,

then matter overcomes the gravitational force and starts escaping from the equator. Therefore, at the breaking point of rotation when the centrifugal force is balanced by the gravitational pull, the matter in the equatorial plane only rotates around the central high-density region called the protostar and does not move towards the center of the system. All the remaining matter falls onto the equatorial plane. Consequently the shape of the cloud becomes ellipsoidal and finally becomes a thick disk rotating around the protostar. This is known as a protostellar disk. At the same time, the central collapsing region, i.e., the protostar which remains spherical, becomes denser and hotter due to the release of gravitational potential energy. If the mass of this protostar is greater than about 8 % of the present mass of the Sun, then it becomes so hot that two hydrogen atoms are fused releasing enormous amount of nuclear energy. If the process of nuclear burning at the core of the region continues, then the protostar becomes a main-sequence star. However, if the mass of the central region is less than the critical mass for nuclear burning, then the heat generated by the gravitational potential energy becomes insufficient to sustain the nuclear process. In that case a Brown Dwarf is produced instead of a star. We shall discuss this situation in Chap. 4.

Is there any upper limit on the mass of the protostar? The answer is yes. If the protostar is about a hundred times more massive than the Sun, the star becomes unstable and cannot survive even a million years. This kind of stars is called Wolf-Rayet stars after their discoverers Charles Wolf and Georges Rayet. Wolf-Rayet stars are at least 20 times heavier than the Sun and are very unstable. Therefore, in order to form a main-sequence star, the mass of the protostar should lie between 0.08 and 100 times the mass of the Sun. Of course this range is slightly different for stars with different chemical composition or elemental abundance. For example, a protostar may be poor in heavy elements such as carbon, oxygen, nitrogen, etc. and composed mainly of hydrogen and helium. Such a protostar needs to be much heavier than 0.08 times the mass of the Sun. Otherwise it cannot become a normal or main-sequence star. All the normal stars are born through the process described above. The disturbance or the perturbation that triggers the fragmentation and collapse of the cloud may originate from the shock wave produced by the explosion of a nearby star (known as supernova) or from the collision between two galaxies or by any other energetic transient phenomenon.

Now, the evolution of the surrounding disk varies depending on the material of the disk. It also depends on the mass and hence the temperature of the protostar and subsequently on the brightness of the newly born star. If the initial star forming cloud is composed only of primordial light elements—hydrogen, helium, and lithium—most of the matter would be used in the formation of the central star and the remaining matter would blow away or disperse in a short period of time. Therefore, the first-generation stars that were born out of the primordial light elements or the stars which lack sufficient amount of heavy elements (metal-poor stars) cannot have planets around them as there was no residual material available around them to form planets.

On the other hand, if a star forming cloud is composed of heavy elements that were synthesized inside the first generation of stars and during the explosion of the

first generation stars, the protostellar disk may survive even after the star is born. The disk is then called a proto-planetary disk because all the planets, planetesimals, comets, asteroids, etc. are formed out of the material within this disk. However, if the mass of the newly born star is a few times the mass of the Sun, the strong radiation energy emitted by the star blows off the disk. Therefore, formation of planets is not possible around massive and very bright stars even if they are rich in heavy elements or metal rich. Note that the astronomers call all elements heavier than hydrogen and helium as metals. So, if the newly born star is like our Sun or is fainter than it or even a Brown Dwarf that has failed to become a star, the proto-planetary disk formed around it would initiate the planet formation process. At first, the dust particles of size as small as a few centimeters stick to each other by electrostatic force. Once they become sufficiently large, they attract matter through their gravity and several planetesimals of size about a kilometer are produced in this process. These planetesimals collide with each other to form bigger objects that are the embryos of planets.

The next stage of the evolution is governed by the mass of the embryos and their proximity to the stars. The embryos that are very near to the star would get strong illumination over their surface and so become very hot. As a result they lose most of their gaseous components composed of light elements such as hydrogen and helium. This gives rise to rocky planets such as Mercury, Venus, Earth, and Mars. On the other hand, the outer bodies are cooler and so they would retain the gaseous components. These outer bodies are more massive as well and hence their gravitational attraction is also very strong. Therefore, matter cannot escape easily. This gives rise to the Jovian planets such as Jupiter, Saturn, Uranus, and Neptune. Note that the entire planet is made of gas and there is no solid rock inside any Jovian planet. Of course, the pressure near the center of such planets should be so high that the gas becomes liquid at even very high temperature.

The actual mechanism of planet formation involves several stages and many complicated dynamical and radiation processes. Astronomers are still working on it by using sophisticated computer codes. However, the above description provides a basic idea on the formation of any planetary system in general and the formation of the solar system in particular. Interestingly, the other planetary systems discovered so far are all drastically different from the solar system. Contrary to our current understanding, they all have giant gaseous planets very near to their parent stars. This might be caused by the frictional force in the proto-planetary disk and astronomers call the mechanism as “planetary migration.” Under this hypothesis, the giant planets were born far away from the star but then migrated very near to it.

How Many Planets? The History of Controversy

Aristotle's World: Seven Planets for Two Thousand Years

Now we know how a large and massive interstellar cloud gives birth to different types of objects whatever be their names. The name is essential to identify a group of objects with similar nature or physical properties. Out of each collapsing cloud, one central object is born which produces its own energy through nuclear burning. We call it a star. So if we identify an object as a star, we understand that (1) it has its own source of continuous energy, (2) the amount of energy it releases is balanced by the amount of energy it produces, and (3) the outward radiation force is exactly balanced by the inward gravitational force. This is the definition of a normal star.

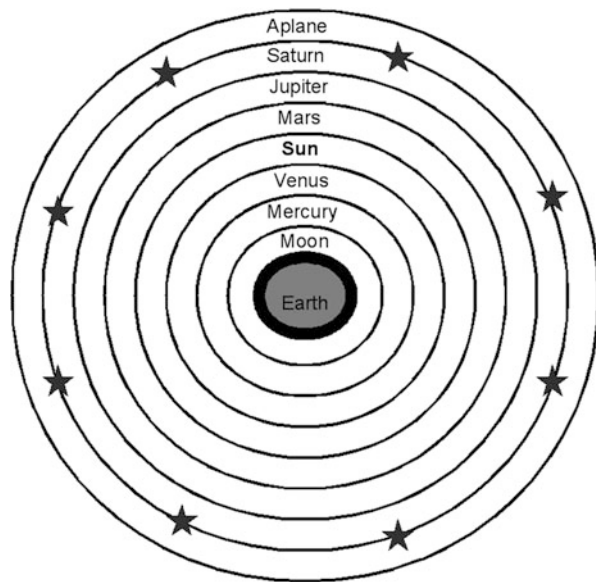
The word “planet” is derived from the Greek word “planetos” means wanderer. Thousands of years ago people of various ancient civilizations noticed that hundreds and thousands of lights moved around the night sky. The Babylonians, the Greeks, the Mayans, the Egyptians, and the Indians noticed that out of the hundreds of wandering lights, seven were very bright and distinct. They knew that human life on the Earth was affected by the two bright light sources, the Sun and the Moon. These two sources were the brightest among all the other light sources in the sky. But they also noticed that five other bright lights, although did not have any impact on life, behaved similar to the Sun and to the Moon in their motion and in their appearance.

It is the famous Greek scholar and philosopher Aristotle (384–322 BC) who for the first time integrated physics and astronomy by postulating the concept of aether. Aristotle applied arithmetic and mainly geometry to describe the dynamical behavior of these bright lights. According to him, all these bright lights were made of something called aether and they all, including the Sun and the Moon, were rotating around the Earth. The Earth was, however, made of water, fire, air, etc. Aristotle assumed that nature preferred absolute symmetry or perfection and so the orbits of all these seven objects were perfectly circular (Fig. 2.1).

So, Aristotle's world was geocentric. A little after Aristotle, another Greek scholar, Aristarchus (310–230 BC) measured the sizes of the Sun and the Moon and their distances from the Earth in term of the Earth's radius. He derived that the Sun was actually six to seven times larger than the Earth. Considering that smaller objects should rotate around much bigger objects, Aristarchus concluded that the Earth should rotate around the Sun. However, due to the influence of Aristotle's philosophy, there was no taker of his finding. But this was the first attempt to understand that the world is actually heliocentric and not geocentric.

During the second century AD, Klaudios Ptolemaios (85–165 AD), best known as Ptolemy, provided a detailed and complicated mathematical version of Aristotle's geometrical description of the geocentric world. Ptolemy mathematically reproduced the orbits of all the seven celestial “wanderers,” their distances from the Earth and the speed at which each of them rotates around the Earth. According to Ptolemy, there were seven planets, and according to their distances from the

Fig. 2.1 Aristotle's geocentric world. It was visualized as a combination of 55 crystal spheres containing various celestial objects. The sphere after Saturn contains the distant stars (Illustration by the author)



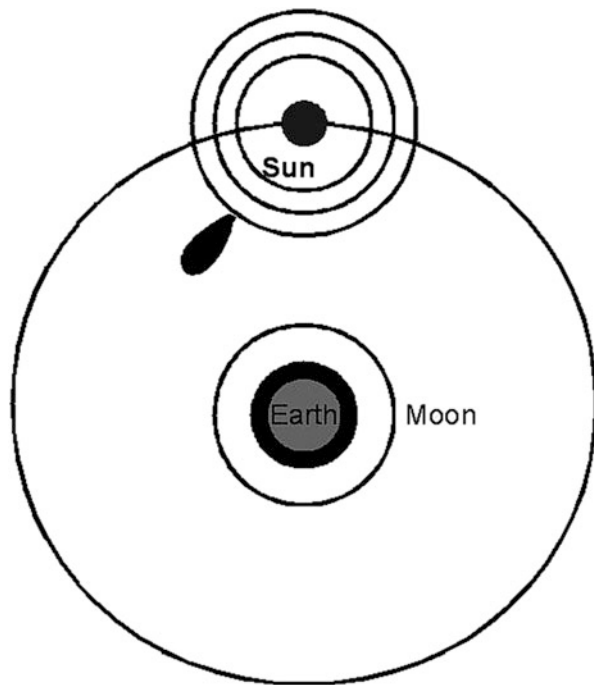
Earth, as he calculated, they were Moon, Venus, Sun, Mars, Jupiter, and Saturn. The names of all these seven wanderers were given after the Greek gods and goddesses. But the subsequent emergence of a strong empire, the Romans, changed the names after their gods and goddesses. The present names of all the planets were derived from the Roman mythology.

During the time of Ptolemy, two strong religions were born, Christianity and Islam. The Roman Catholic Church adopted Ptolemy's concept of a geocentric world and dictated the acceptance of it so widely and strongly that the Ptolemy's view of the world existed for more than a thousand years. Note that the Earth was still not considered as a planet and it carried a special status in the universe.

Beginning of Modern Astronomy: Six Planets for a Few Decades

Modern astronomy began its journey during the early sixteenth century. Around the year 1510 AD—nearly 1,800 years after Aristarchus realized that the Earth was not the center of the world—Nicolas Copernicus (1473–1543), a polish astronomer, came out with the revolutionary proposal that the Sun was the center of the world and the Earth revolved around it. In fact Copernicus went a step forward. According to Aristotle's opinion, all objects except the Earth were made of aether and they moved in a perfectly circular orbit around the Earth which was made of air, fire, water, and earth. Copernicus proposed that although the Earth was not made of aether, it moved around the Sun and the Sun did not move although it was made of

Fig. 2.2 Tychonic system of the world. This is partly heliocentric, partly geocentric. The orbits of three planets are shown centered on the Sun. The orbits of the Moon and the Sun are centered on the Earth. The comet appeared in 1577 AD is shown orbiting the Sun (Illustration by the author)



aether. Copernicus proposed that the Sun was the center of motion of the planets and the Earth was the center of motion of the Moon. So, for the first time, the Earth got the status of a planet and the Sun was no more a planet whereas the status of the Moon was undefined. However, the Roman Catholic Church did not accept the Copernican world. No astronomer, except the Italian thinker Giordano Bruno (1548–1600), supported the Copernican concept of a heliocentric world. During the latter half of the sixteenth century, the Danish astronomer Tycho Brahe (1546–1601) gathered a good amount of information through observations. Tycho Brahe proposed a scenario which was sort of a compromise between Aristotle’s world and Copernicus’ world. The “Tychonic” world was partly heliocentric and partly geocentric.

In this world, all the planets—Mercury, Venus, Mars, Jupiter, and Saturn—move around the Sun forming one system. The Moon and the Sun along with this system move around the Earth (see Fig. 2.2). Tycho Brahe also discovered a comet and realized that not all heavenly bodies moved in perfectly circular orbits—a contradiction to Aristotle’s concept. However, Tycho Brahe in his proposal retained Aristotle’s concept of a geocentric world.

So, the number of planets remained the same.

The Kepler's Laws

Finally, the German mathematician Johannes Kepler (1571–1630) who used the observational records of Tycho Brahe and the Italian physicist Galileo Galilei (1564–1642) established the fact that the Earth indeed moves around the Sun. Galileo used the newly invented telescope to observe the sky. This type of telescope uses a convex lens and is known as Galilean telescope. In order to acquire the observational records of Tycho Brahe, Kepler joined Tycho as his assistant. After Tycho passed away, Kepler got access to a large amount of data. By using it, Kepler discovered the three laws of the planetary motion. The first law states that the planets orbit the Sun in elliptical paths—a sharp contradiction with the Aristotelian thought of perfect circular and the geocentric world. The second law states that the straight line joining the Sun and a planet sweeps out equal areas in equal time. The third law states that the square of the period of revolution of any planet is directly proportional to the cube of the semimajor axis. The semimajor axis of an ellipse is the longest distance from the center of the ellipse to its edge. The shortest distance is called semiminor axis. Together, these three laws are known as Kepler's laws. It was Sir Isaac Newton (1642–1727) who explained these laws by his theory of gravitation.

So how many planets are there? We can summarize it. (1) During the ancient civilizations prior to the Greek and the Babylonian civilizations, seven wandering stars—Mercury, Venus, Moon, Sun, Mars, Jupiter and Saturn—were known. (2) For the next 2,000 years, from the Aristotle's era to the middle of the sixteenth century, these seven objects were termed as planets with the Earth as the center of the motion of all the seven planets. The Earth was also thought to be physically quite different from the planets. (3) In the sixteenth century, it was realized that the Earth was also a planet orbiting around the Sun. Kepler demonstrated that there were six planets—Mercury, Venus, Earth, Mars, Jupiter, and Saturn. So the Sun is no more a planet, neither the Moon is. However, the status of the Moon was undefined although it was known that the Moon revolved around the Earth.

Discovery of Jupiter's and Saturn's Moons: 16 Planets

Galileo Galilei, one of the fathers of modern science, was born 21 years after the death of Copernicus. Galileo had regular communication with Johannes Kepler and he too realized the correctness of Copernicus' concept of a heliocentric world. While Kepler was interested in the mathematical formulation of the dynamics of the planets, Galileo devoted most of his life in experimenting on dynamics and optics. During the early seventeenth century, when Kepler had just published his laws of motion for the planets, Galileo constructed his telescope that made any object larger by 20 times. At first this instrument was used by the merchants to track their ships and also by the military. But at some point of time, Galileo started using it to watch

the night sky. The first thing that he observed was the Moon. He immediately realized that the Moon was like the Earth and not made by aether as thought by Aristotle. He discovered the craters and mountains of the Moon. He also found the sunspots and realized that the Sun too was not perfectly spherical. Subsequently, Galileo made his most important discovery, four small objects rotating around Jupiter. Galileo called them the Medicean stars. This discovery made him to understand that the Earth was not the only center of motion as advocated by Aristotle but Jupiter was also a center of motion for some objects. Now, if both the Earth and Jupiter could be the center of motion, then why not the Sun? So, Galileo immediately realized that Copernicus was correct. However, the Catholic Church opposed the concept and forced Galileo to withdraw his support for a heliocentric world. This is now a history and we will not go into that.

Now, what happened to Galileo's four "Medicean stars"? Although Galileo retracted his view under the pressure of the Church, many other people observed these four objects. They were soon considered to be planets. If so, then the Moon should also be a planet. In this way, by the year 1610, we had a total of 11 planets—6 orbiting around the Sun as proposed by Copernicus, 1 orbiting around the Earth, and 4 orbiting around Jupiter. All of them follow Kepler's laws. Of course Kepler's laws were slightly modified by replacing the Earth as the center of motion for the Moon and Jupiter as the center of motion for the Galilean planets. Most probably Kepler realized that the six planets orbiting around the Sun should be different from the five objects orbiting around the Earth and Jupiter. In 1655, about half a century after the discovery of Jupiter's moons, Christiaan Huygens discovered a moon of Saturn called Titan. After 4 years, Huygens reported the presence of the ring around Saturn. During 1671 and 1684, Jean-Dominique Cassini, an astronomer at the Observatory of Paris, discovered four more moons orbiting around Saturn.

So, by the end of the seventeenth century, the number of planets became 16—6 orbiting around the Sun, 1 orbiting around the Earth, 4 orbiting around Jupiter, and 5 orbiting around Saturn. Note that the Sun was no more considered as a planet but the Earth was a planet and all the satellites discovered were also considered as planets. The whole scenario changed within two centuries—from 7 to 6 and then to 11 and finally to 16 planets. If we don't care about the name or the status of the planets and their satellites, then the most important development during these two centuries was the understanding that (1) the Sun is stationary and the planets rotate around the Sun in elliptical orbits, (2) the Earth is also a planet, and (3) the discovery of ten more objects in the solar system—Tycho's Comet, four objects around Jupiter, and five objects around Saturn.

Discovery of Planets Beyond Saturn: Number Changes

Sixteen was the highest number ever considered for the planets. However, Huygens observed that the Moon and the objects orbiting around Jupiter and Saturn were quite different from the six planets revolving the Sun. So he termed the ten objects

rotating around the Earth, Jupiter, and Saturn as secondary planets or moons or satellites. The six objects rotating around the Sun were termed as primary planets. In the mean time some interesting phenomenon was observed. Edmond Halley (1656–1742) observed a comet in 1682 and calculated its orbit by using the laws discovered by Sir Isaac Newton. Halley's calculation was published in 1705. Clearly this was not a planet. In fact Tycho's Comet was also not considered as a planet. In 1758, a comet was spotted and it was identified as the same comet that Halley observed and predicted for its reappearance. It revealed the fact that Halley's Comet orbited the Sun and followed Kepler's laws but it was not a planet. So, not everything that orbits the Sun is a planet. By the second half of the eighteenth century, it became usual to call the objects orbiting around the Earth, Jupiter, and Saturn as moons and consequently the number of planets in the solar system reduced back to six. The ten satellites and all the comets were of course considered as the member of the solar system. Sir Isaac Newton discovered his laws of gravitation as an interpretation of Kepler's laws. In fact it is known that Newton wrote his famous book "Principia" on constant pursuit of Halley. Astronomy plays such an important role in science! So, in less than 300 years, the number of planets changed from 6 to 11, to 16, and back to 6.

In 1766, Johann Daniel Titius discovered a relationship among the distances of various planets from the Sun. The distance between the Earth and the Sun is called one Astronomical Unit or AU. One AU is equal to 149.6 million km. Titius found that the distances of the planets followed an arithmetical pattern. From the Sun, the distances to the planets can be expressed as $0.4 + (0 \times 0.3) = 0.4$ AU, $0.4 + (1 \times 0.3) = 0.7$ AU, $0.4 + (2 \times 0.3) = 1$ AU, $0.4 + (4 \times 0.3) = 1.6$ AU, $0.4 + (8 \times 0.3) = 2.8$ AU, $0.4 + (16 \times 0.3) = 5.2$ AU, and $0.4 + (32 \times 0.3) = 10$ AU. This means the distance to Mercury from the Sun is 0.4 AU, the distance to Venus from the Sun is 0.7 AU, and so on. Note that the first and the last numbers remain unchanged while the middle one changes in a specific way (0 for Mercury and power of 2 for other planets). However, it was found that the planet Mars was at a distance of 1.6 AU, but Jupiter was at a distance of 5.2 AU from the Sun. There was no planet at a distance of 2.8 AU from the Sun. Six years after Titius published his formula, Johann Elert Bode realized that there should be another planet at a distance of 2.8 AU from the Sun, i.e., between Mars and Jupiter.

So the Titius–Bode formula predicted a planet between Mars and Jupiter. Extrapolation of the formula beyond Saturn also predicts the presence of a planet at a distance of $0.4 + (64 \times 0.3) = 19.6$ AU. In 1781, William Herschel discovered a planet which was at a distance of 19.18 AU from the Sun, very closed to the predicted distance. Historically, this object was observed first by John Flamsteed in 1690 but he could not realize that it was a planet. Bode suggested the name of the planet as Uranus. So the number of planets was back to seven, as it was before the sixteenth century.

By the beginning of the nineteenth century, astronomers had two powerful theoretical tools, one was the Titius–Bode empirical formula that gives the distance of the solar planets and another was the Kepler's law which gives the orbital motion of a planet. With these two tools, astronomers could predict the presence of new

planets. During the early nineteenth century, it was obvious that the planet Uranus was not exactly following Kepler's law. It was also found that Halley's Comet was delayed in appearing to its predetermined position. All these observations made people to hypothesize another planet, planet X whose gravitational field was considered to be responsible for the deviation in the motions of Uranus and Halley's Comet. Finally, in 1846, after more than half a century of the discovery of Uranus, the hypothetical planet X was discovered and was named as Neptune. Neptune remained the farthest planet in the solar system for almost a century until the discovery of Pluto in 1930.

Eleven Planets for Four Decades

Was Neptune the eighth planet in the solar system? No, Neptune was the thirteenth planet at the time of its discovery! As mentioned earlier, the Titius–Bode formula predicted a planet between Mars and Jupiter, at 2.8 AU from the Sun. Hectic attempts were made to locate it. In 1801, 20 years after the discovery of Uranus and 45 years before the discovery of Neptune, Giuseppe Piazzi discovered a planet located at about 2.7 AU from the Sun, almost exactly at a distance that the Titius–Bode formula predicted. But the size of the object was estimated to be very small as compared to even Mercury. It was named as Ceres after the Roman goddess of harvests. William Herschel, the discoverer of Uranus, and a few other astronomers were reluctant to consider Ceres as a planet because of its small size. Herschel called it an asteroid, a new class of objects in the solar system. But most of the astronomers at that time considered it to be a planet. So Ceres was the eighth planet in the solar system. Next year, in 1802, Heinrich Olbers discovered another object, even smaller than Ceres, located at a distance of about 2.6 AU from the Sun, very near to the orbit of Ceres. It was named as Pallas and was considered to be the ninth planet in the solar system. Just after 2 years of the discovery of Pallas, Karl Harding discovered another planet, Juno, in the vicinity of Ceres and Pallas. This was the tenth planet in the solar system. But the number ten lasted for just a few years. In 1807, Olbers discovered another planet Vesta at the same vicinity. So the number of planets increased from 7 to 11 within a span of 6 years. For the next four decades, 11 planets were known, and according to their distances from the Sun, they were (1) Mercury, (2) Venus, (3) Earth, (4) Mars, (5) Vesta, (6) Juno, (7) Pallas, (8) Ceres, (9) Jupiter, (10) Saturn, and (11) Uranus.

Thirteen Planets for a Year and Eight Planets for Eight Decades

At the end of 1845, just few months before the discovery of Neptune, Karl Ludwig discovered another planet located at a distance of 2.7 AU from the Sun, in the vicinity of Juno, Vesta, Ceres, and Pallas. This was named as Astraca and it was the fifth member of such small objects orbiting very near to each other. So with the discovery of Neptune in 1846, the total number of planets in the solar system increased to 13. But the size of Neptune as compared to the smaller planets Ceres, Pallas, etc. again initiated debate regarding the status of these small objects. So, by 1847, these five smaller objects Ceres, Pallas, Juno, Vesta, and Astraca lost their status as planets and were termed as minor planets or asteroids or planetoids. As a consequence the number of planets went back to seven plus Neptune, that is, a total of eight.

During the nineteenth century, a few astronomers suggested the existence of the ninth planet—a planet between Mercury and the Sun. It was named as Vulcan. The suggestion was put forward to explain the excess orbital precession of Mercury (known as perihelion precession). Subsequently, a few professional as well as amateur astronomers claimed to have observed transits of the Sun by this hypothetical planet. But it was never confirmed. Most probably a sunspot was mistaken as the shadow of the planet on the Sun. The excess orbital precession of Mercury was later on explained by Albert Einstein's famous "General Theory of Relativity."

It is interesting to note that from 1847 to 1930, the number of solar planets were eight, just the same to what it has become after 2006. Pluto was discovered by Clyde Tombaugh on 18 February 1930, and it enjoyed the status of the ninth planet in the solar system for the next 76 years. So, there were eight planets for about eight decades and there were nine planets for another eight decades.

Finally Pluto Is Not a Planet: End of Controversy?

So, the number of planets changes depending on the change in our knowledge about them. The planet Pluto was discovered in 1930. However, its mass was not known for more than four decades. It was thought that Pluto was as massive as the Earth. Pluto's main satellite Charon was discovered only in 1978. During the late 1970s, it has been realized that Pluto is about six times lighter and 1.5 times smaller than the Moon. On the other hand, Jupiter, the largest planet in the solar system, is about 146,000 times heavier than Pluto. The debate whether or not Pluto should belong to the group of celestial objects known as planets arises during the late 1990s after the discovery of a large number of planets outside the solar system. Some of these planets orbiting other stars are ten times heavier than Jupiter. Subsequently, the debate intensified when many small objects were discovered beyond the orbit of Neptune and at the extreme edge of the solar system. This region is known as the

Kuiper belt. All these objects have masses comparable to or even more than the mass of Pluto. Importantly, Pluto is also a Kuiper belt object. In 2003, two such objects—2003 UB313 (initially named as Xena) and Sedna—were discovered by Michael Brown and his group. It is estimated that 2003 UB313 is at least 25 % larger than Pluto and Sedna is about half the size of 2003 UB313. The situation became similar to the discoveries of Ceres, Pallas and other asteroids during the early seventeenth century. So, if Pluto is considered to be a planet, then all of these newly discovered objects should also be planets and the number of solar planets could continue to increase with the new discoveries in future.

Under this situation, the International Astronomical Union was compelled to form a committee consisting of eminent scientists from several fields to determine an appropriate definition of planets. Finally, on 24 August 2006, the 26th General Assembly of the International Astronomical Union passed resolution 5A by voting which states the following:

The IAU therefore resolves that planets and other bodies in the *solar system* except the *satellites*, be defined into three distinct categories in the following way:

1. A “*planet*” is a celestial body that (a) is in orbit around the Sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a *hydrostatic equilibrium* (nearly round) shape, and (c) has *cleared the neighborhood* around its orbit.
2. A “dwarf planet” is a celestial body that (a) is in orbit around the Sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, (c) has not cleared the neighborhood around its orbit, and (d) is not a satellite.
3. All other objects except satellites orbiting the Sun shall be referred to collectively as “*small solar system bodies*.”

In the footnote of the resolution, Pluto is mentioned as a dwarf planet which is different from other planets.

Quite obviously, the above resolution generated controversies. Nevertheless, IAU has been very careful in the scope of the definition and emphasizes that the above definition applies to the solar system planets only. The extension of the definition of the solar planets to the planets outside the solar system would have generated further controversy and confusion. This will be clear in the subsequent chapters of this book.

So, right now we have a total of eight solar planets. According to their distances from the Sun, they are Mercury, Venus, Earth, Mars, Jupiter, Uranus, and Neptune. There are five recognized dwarf planets—Ceres, Pluto, Eris, Makemake, and Haumea. The dwarf planets that orbit beyond the orbit of Neptune are called trans-Neptunian objects or plutoids. Except Ceres, all other dwarf planets are plutoids. Ceres, first considered as a planet and then an asteroid, is now considered as a dwarf planet and it is located in the asteroid belt, between Mars and Jupiter. The number of dwarf planets will certainly increase with new discoveries. But the confusion, controversy, doubt, and debate will continue.

Worlds Beyond Our Own

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