

## PLANETS OF OUR SOLAR SYSTEM

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### Summary

When humans noticed that most stars appeared to stay in fixed pattern in the sky, they realized that a few moved against this background. They called these wandering stars, or planets. Over the centuries, our knowledge of these has vastly increased and, in the process, our understanding of the system as a whole has changed. Five hundred years ago it was realized that the Earth was not the center of the Universe, but was a planet that orbited the Sun. Other members of the solar system have been discovered. Two hundred years ago, objects were found orbiting the Sun between Mars and Jupiter, with Ceres being the largest. Initially these were called planet, but when it became evident that they were very numerous, they became minor planets (or asteroids). Originally it was thought that all the planets were physically similar to the Earth. We now know that there are great differences between the various planets.

Fifteen years ago, a second swarm of bodies was discovered beyond Neptune and first became known as the Kuiper Belt, but the general population is now more widely known as trans-Neptunian Objects. It soon became evident that Pluto was part of this swarm. Large objects have been discovered in this region, with one at least, named Eris, being larger than Pluto, while Haumea and Makemake are nearly as large. All of them are smaller than seven of the moons that orbit the planets. With these discoveries it became clear that our terminology relating to planets needed re-visiting and a new category, called dwarf planets was defined. At present, Pluto, Eris, Haumea, Makemake and Ceres are the five dwarf planets. Four of these orbit beyond Neptune and have been given the collective name of Plutoids.

Planets have also been discovered orbiting around many other stars. Hence the story of the planets is a still evolving story with almost certainly many more changes to come.

### 1. Introduction

When humans first studied the heavens, they noticed that most of the points of light in the night sky appeared to be arranged in patterns that stayed constant with the passage of time (the whole pattern moved across the sky each night, but the pattern itself stayed the same). These patterns were regarded as representations of recognizable things, mostly of animals (including humans, fish and reptiles) or inanimate objects. We still recognize these patterns or Constellations today and most of us can easily find Orion and the Great Bear in the Northern night sky or the Southern Cross in the Southern Sky. Studying these constellations was important to ancient civilizations for the position on the horizon of their rising or setting told them the seasons. They also noticed that seven objects did not remain in any pattern, the two great lights of the Sun and the Moon as well as five others which we now call Mercury, Venus, Mars, Jupiter and Saturn. These moving lights were called wandering stars or Planets. Even though they wandered amongst the fixed stars, it was soon realized that they remained within  $9^\circ$  or so of the path of the Sun across the sky (the ecliptic) and this band within which they moved was called the Zodiac.

Other lights appeared in the night sky at random times and also seemed to follow random paths. These lights often had an extended tail and Eastern Astronomers called them 'broom stars'. Western culture called them hairy stars or 'comets'. Because of their unpredictable nature, these were often regarded as bearers of bad news. So, up until about 500 years ago, the heavens had stars which were fixed, planets that moved within the Zodiac and Comets, which were utterly unpredictable.

This chapter deals with the story of our expanding knowledge of what was then called planets, objects that moved in a predictable fashion against the starry background. We discuss not just their motion, but also their physical characteristics.

## **2. The Copernican Revolution**

About five centuries ago, our understanding of the heavens changed completely when in 1543 Copernicus published a book called *De Revolutionibus*. In this book he proposed that the Earth was not the center of the Universe around which everything else, including the fixed stars, revolved but rather that it was only one of a number of bodies that orbited the Sun. The definition of a planet simply as a wandering star was no longer workable and a new definition of a planet as a body that orbited the Sun was accepted. According to this new understanding, the Sun and the Moon both ceased to be Planets while the Earth became one. Thus, the number of planets dropped from seven to six. These, in order of increasing distance from the Sun being, Mercury, Venus, Earth, Mars, Jupiter and Saturn. Though the terms 'ecliptic' and 'Zodiacal Band' remained in use, the meaning behind the terms changed, the ecliptic now being the plane in which the Earth moves around the Sun rather than the actual path of the Sun, while the fact that all the planets moved within the Zodiac implies that the orbits of all of them lie in planes that are close to the ecliptic plane.

A new type of object, namely a Satellite: - the Moon, was also recognized for the first time. This, for the time being at least, made the Earth an anomaly amongst the planets as it was the only planet with a moon.



Figure 1. The Earth-Moon system (Credit NEAR Spacecraft team)

However, this anomaly did not last too long, for in 1610 Galileo Galilei discovered that Jupiter had four moons, now called the Galilean satellites of Jupiter and named Io, Europa, Ganymede and Callisto. In 1656, Christan Hugen's found an explanation for the curious changes in appearance of Saturn, where appendages appeared and disappeared. Saturn was surrounded by a very thin flat ring.

So, by this time, a picture of the Solar System was emerging where the Sun was being orbited by a number of planets, all moving in nearly the same plane on near circular orbits and where these planets could in turn have satellites or moons orbiting them. This development is often portrayed as the result of a battle between two theories and the outcome decided by choosing the simplest. This is not really the case; it was as much the result of new technology, namely the glass lens leading to the invention of the refracting telescopes that were capable of observing fainter objects, not visible with the naked eye, producing new facts that were difficult to incorporate into the old theories.

### **3. New Telescopes - New Discoveries**

The development of the refracting telescope was only the start of a new era in observational astronomy, for in 1663 James Gregory proposed a new design, the reflecting telescope. Variations of this were also proposed by Cassegrain and Isaac Newton. The reflecting telescope had two main advantages over a refracting telescope. First, light is reflected off two mirrors rather than passing through a lens before entering the eye-piece thus reducing loss of photons. Second, larger telescopes could be built as the telescope tube needed in a reflecting telescope is much shorter than that required in a refracting telescope since the light passes up and down the tube of a reflecting telescope. In practice, this meant that much fainter celestial objects could now be detected using a reflecting telescope.

### 3.1. The Titius-Bode Law

Aside from the main theme of improving technologies leading to new discoveries, we should briefly discuss a curious theoretical development, leading to an alleged law, the Titius-Bode law, which also played an important part in the motivation for discovering new objects in the Solar system. It should however be stressed that very few astronomers believe that the law actually has any scientific basis. In 1702 Gregory, a professor at Oxford University noted quite correctly that the distances of the known planets from the Sun were roughly proportional to the numbers 4, 7, 10, 15, 52 and 95. In 1766 Titius, a professor at Wittenberg University, slightly altered the set of numbers but also pointed out that they could be written as 4, 4+3, 4+6, 4+12, 4+48 and 4+96. Further, the added part was part of a sequence, 3, 3,  $3 \times 2^2$ ,  $3 \times 2^4$ , and  $3 \times 2^5$ . Note that at this time they were not written in terms of the Astronomical Unit (The mean Sun-Earth distance), but as integers. To get the distance in astronomical units a division by 10 is called for. There is a gap in this sequence at 4+24 (or  $4+3 \times 2^3$ ) or 2.8 AU and Bode stated that a planet lay undiscovered orbiting at this distance from the Sun. The next discovery was not at this distance however, but much further out.

### 3.2. The Discovery of Uranus

In 1781, William Herschel was using his reflecting telescope to examine the brighter stars one by one in order to familiarize himself with the night sky. In the constellation of Gemini he found a 'star' that appeared anomalous, and which he described as *either a nebulous star or perhaps a comet*. This turned out to be a new planet, the first ever discovered since the dawn of time, and is now known as Uranus. This discovery restored the number of planets to seven, the number before the Copernican revolution.

The distance of Uranus from the Sun was, astonishingly, proportional to  $4+3 \times 2^6$ , or 19.6 AU, the next distance in the sequence proposed by Bode. This discovery had two immediate effects, the sequence of Bode was given the status of a law, and efforts were re-doubled to find the missing planet corresponding to  $4+3 \times 2^3$  in the sequence. In response to this, the court astronomer in Gotha, Baron von Zach, organized a team of 24 leading astronomers throughout Europe, to search for the missing planet. Each was assigned a portion of the Zodiac to monitor for any strangers and the team was given the name 'celestial police'. As often happens however, their plans were overtaken by events, the object they were to look for being discovered before they could get going.

### 3.3. Four New Planets

On New Year's Day 1801 (the first day of the nineteenth century) Piazzi discovered an eighth magnitude 'star' that appeared to be moving relative to the background stars. Another planet had been discovered and its distance from the Sun (2.77 AU) was, also remarkably, very close to the Bode prediction of 28 or 2.8 AU. The object was named Ceres (and is now one of the dwarf planets - see later). Herschel studied Ceres with his large telescope but he could not detect a planetary disk, suggesting that Ceres was smaller than our Moon. Between 1801 and 1807 three further *planets* were discovered and named Pallas, Juno and Vesta. Herschel could not find a disk for any, they were

star-like in appearance and so Herschel coined a term ‘asteroid’ for these objects. Despite Herschel, they remained as planets for 40 years and in this interval there were consequently eleven planets in the Solar system.

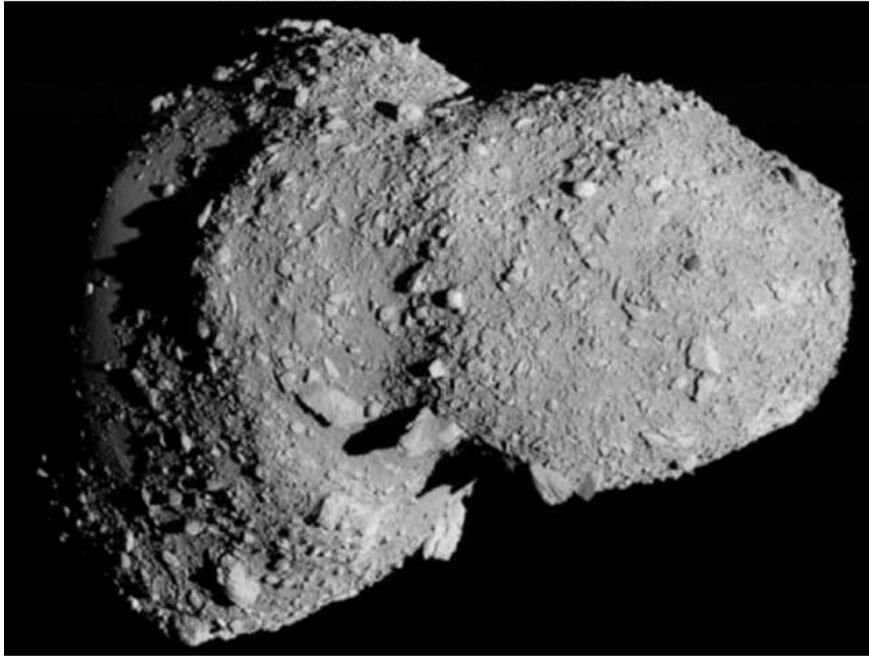


Figure 2. Asteroid Itokawa. (Credit & Copyright: ISAS, JAXA)

### 3.4. The Discovery of Neptune

As has often since proved to be the case, once a discovery is announced, earlier observations of the object comes to light. This was the case for Uranus, both Flamstead in 1690 and Meyer in 1756 had observed the planet but had failed to notice either its motion or its ‘fuzziness’ and recorded it as just another star. Such pre-discovery observations are often useful for they allow a much more accurate orbit to be determined. With observations of Uranus covering a time-span of more than 100 years it became possible to produce a good orbit for it. Using this orbit, predictions were made for the location of Uranus on the sky at given dates. However the observed position of Uranus soon began to diverge from these predicted position, and by the 1830’s Uranus was moving well outside any error bars on the orbit resulting from the observations. In two papers to the Paris Academy of Sciences in 1845 and 1846 Le Verrier presented the hypothesis that the discrepancies were caused by the gravitational perturbations of an additional planet orbiting the sun beyond Uranus. This planet was assumed to be at a distance corresponding to the next space in Bode’s sequence, and Le Verrier concluded that in June 1846 its longitude from the Sun was  $325^\circ$ . Unaware of each other’s work Adams in Cambridge was also working on the same problem with much the same assumptions as Le Verrier. Adams concluded that in September 1845 the longitude of the possible planet was  $323^\circ.34$ . Adams persuaded Challis to search for the planet, a task which he undertook, but with little sense of urgency. In the meantime, Le Verrier had persuaded observers at Berlin observatory to search, a search that proved successful and the twelfth planet, Neptune was discovered. Neptune, according to Bode’s law should have been at a distance proportional to  $4+3 \times 2^7$ , or 38.8 AU. In fact Neptune

was nowhere near this distance being only 30 AU away from the Sun, a fact that was ignored by supporters of Bode.

### **3.5. The Asteroid Belt is discovered**

At nearly the same time as the discovery of Neptune, a further 'planet' was discovered orbiting between Mars and Jupiter. This marked the beginning of an explosion in the number of bodies discovered in this location. One hundred years after the discovery of the first (Ceres), more than 450 were known and the invention of photography allowed the discovery rate to increase even more. By 1960, the known number was well over 2000 and at the present time the number has reached an astonishing total of more than 150000. These are the objects which Herschel wanted to call Asteroids and indeed the belt in which they are located is commonly called the asteroid belt. However, the international astronomical community decided that the official name for them would be minor planets, a name that survives still. Eventually bodies were discovered that were not between the orbits of Mars and Jupiter. Basically there were two groups, those that crossed the orbits of Mars and hence could become close to the Earth and those on the same orbit as Jupiter. All of these are also minor planets and are popularly called Near Earth Asteroids and Trojan Asteroids.

Thus, early in the twentieth century there were eight planets, Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus and Neptune together with nearly 500 minor planets. There was no well defined boundary between the two, and indeed it was probably not necessary as Mercury, the smallest planet with a diameter of 4879km was very much larger than Ceres, the largest minor planet (asteroid) with a diameter of 940 km.

### **3.6. The Discovery of Pluto**

As more observations of Uranus came in, it appeared that the inclusion of Neptune as an additional perturber did not completely remove the discrepancy between the predicted position of Uranus based on its calculated orbit and its observed position. This naturally led to the speculation that another planet was present somewhere beyond Neptune, with believers in Bode's law thinking that it should be at  $4 + 3 \times 2^8$  or around 77 AU.

Tombaugh at Lowell Observatory conducted a systematic search for this planet using a blink comparator (a device that allowed him to flick between two images to make the finding of moving object easier). He spent 14 years on the task, observing some 90 million objects. Most were of course normal stars, but nearly 4000 were moving. All but one of these was moving so fast that they were undoubtedly objects in the main asteroid belt. But one, observed in 1930, was moving very much slower than Neptune and so must be beyond Neptune. This object was assumed to be responsible for the additional perturbations on the orbit of Uranus and so must be large, several times larger than Earth, and thus a proper planet. It was given the name Pluto. So the number of planets increased to 9 and, with Pluto assumed to be larger than the Earth, no thought was given to the distinction between planet and minor planet. Pluto however did not move within the Zodiaic.

### **3.7. The True Size of Pluto**

With additional observations, the mean distance of Pluto from the Sun at about 40 AU was established. (Note that this is very far from the distance predicted by the Bode sequence). Some astronomers had doubts about the assumed large size of Pluto. It was very faint for a large object at a distance of only 40 AU, but even in the 1950, in standard books giving the sizes of objects, Pluto was recorded as being larger than the Earth. Through the 60's and 70's as more observations became available, the quoted mass of Pluto was slowly decreasing, but it was not until a moon of Pluto, now called Charon, was discovered that the true size of Pluto became clear. It was actually only one sixth ( $1/6$ ) the mass of our Moon and having a diameter of 2300 km, very much smaller than the next smallest planet, Mercury (diameter 4879 km). It was however still larger than the next largest known object in the Solar System, Ceres the then largest minor planet (or asteroid) with a diameter of 940 km. Consequently the problem of the distinction between minor planet and planet was not re-visited at this time.

#### 4. Trans Neptunian Objects

The next set of discoveries in the Solar system arose from the study of comets. Edmund Halley showed that comets were members of the Solar System family orbiting the Sun but moving on eccentric orbits. Consequently, as bodies on such orbits move very slowly when far away from the Sun, most comets spend most of their lives in the more distant parts of the Solar System as inactive objects. However, when comets venture into the inner Solar System they have tails, sometimes very spectacular ones. These tails are formed because the comet nucleus becomes heated by solar radiation as it approaches the Sun causing the ices to sublime with the resulting released dust and gas escaping to form the tail. This implies that the comet nucleus loses mass and comets generally have a loss rate in the general region of  $10^{29}$  atoms per second, mostly as water. This converts to a mass loss rate of about  $3000 \text{ kg s}^{-1}$ . Of course, this mass loss only takes place when the nucleus is near enough to the Sun for Solar heating to cause sublimation. Thus on average a comet is only active for about two months and so the total mass loss per orbit is about  $10^{10} \text{ kg}$ . Since the typical mass of a comet nucleus is about  $10^{14} \text{ kg}$ , a comet nucleus can not last for more than 10000 returns, and in many cases may be much less. With a typical period of a few hundred years, comets that penetrate into the inner solar system can only last for a fraction of the age of the Solar System. Hence all the comets we know of at present are fairly new to the inner solar system, and, if they formed at the same time as the remainder of the system, must have been stored somewhere away from solar heating for most of their lives. In 1950, Jan Oort postulated that they were stored in what is now termed the Oort cloud at 40 000 AU or more from the Sun. The distribution of the orbital element, in particular the inclination, of the long period comets match what is expected for objects originating in the Oort cloud, but the distribution of the short period comets does not, all essentially being in the ecliptic. This discrepancy was known for a long time and was usually attributed to the fact that short period comets experience large perturbations from Jupiter and Saturn, causing them to essentially orbit within the ecliptic plane. This effect is real, but when large scale numerical simulations became possible in the late 1980's it became apparent that the numbers of short period comets in the ecliptic was far greater than the number that could be accounted for by these perturbations and an additional source for short period comets was required. At about the same time as Jan Oort had



postulated his cloud, Edgeworth and Kuiper had postulated that a belt of objects could exist somewhere beyond Neptune, but until the short period comet problem emerged, little attention had been paid to their postulates by most astronomers.

#### 4.1. The Edgeworth-Kuiper Belt is discovered

By the 1990s telescope technology had advanced to a stage where it was possible to detect objects down to 22nd and 23rd magnitude, which represent bodies of a few hundred km across at around 40 AU. Hence, it had become possible to detect potential members of the Edgeworth-Kuiper belt and the first member was discovered in 1992 by David Jewitt and Jane Luu and is now best known as 1992QB1, though it actually now has a permanent designation.

After the first discovery, others soon followed and it was not long before the first surprise emerged. 1993SC was shown to be moving in an orbit that was in a 3:2 resonance with Neptune and moving on an orbit with a semi-major axis almost identical to that of Pluto.

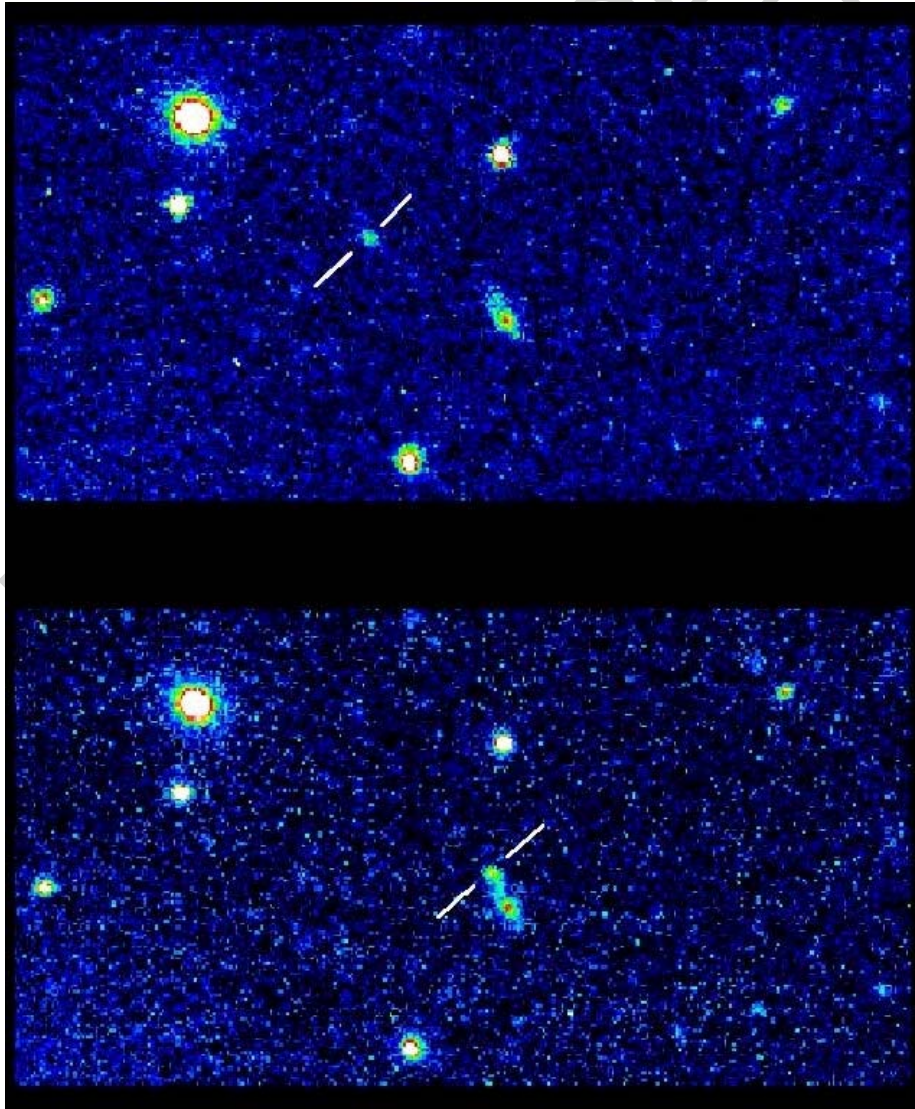


Figure 3. Trans Neptunian object 1993 Sc. (Credit Williams Fitzsimmons O'Ceallaigh)

Again, with the passage of time, the numbers of known objects captured in resonance with Neptune has increased significantly, and the group members are known colloquially as Plutinos for obvious reasons. Their discovery did however imply that Pluto is moving as part of a family of fairly similar objects, thus making it different from the eight planets Mercury to Neptune. Members of the trans-Neptunian population that move roughly as predicted by Edgeworth and Kuiper, that is moving on near circular orbits close to the ecliptic plane between 40 and 50 AU are sometimes called the classical belt members, or more colloquially as cubiwanos (after QB1). More recently, a new class of objects has been found moving on orbits with large semi-major axis and eccentricity as well as possibly having high inclinations. These are called the scattered disk objects since it was initially believed that their orbits had become excited as a consequence of close encounter with Neptune. This last group has proved to be very interesting because most of the larger objects found in the region belong to this group. Further, some of these are comparable in size to Pluto and at least one discovered by Mike Brown and now named Eris is larger.

## 5. Planets and Dwarf Planets

These discoveries brought the distinction between planets and minor planets into sharp focus. Pluto is a member of a population of objects moving on similar orbits, just like Ceres in the asteroidal belt. Pluto is much smaller than Mercury and is smaller than Eris.

Faced with this, the astronomical community has two logical choices, either add Eris (and possibly others) to the list of planets, or recognize that Pluto and Eris are different from the eight planets. Even though they are different, they are still very interesting objects and so the International Astronomical Union decided in 2006 that a new category should be defined, namely dwarf planets, being essentially the larger members of the minor planet population. The formal definition of a dwarf planet is an object that is large enough for its own gravity to be able to overcome solid body forces and make it take up a hydrostatic equilibrium shape (near spherical in most cases). A planet must in addition be large enough to have cleared its own neighborhood of other significant objects and thus not be members of a swarm. Ceres belongs to the asteroidal belt while Pluto and Eris are part of the Edgeworth-Kuiper population. Any planet, dwarf planet and minor planet in the Solar system must also orbit the Sun. At the present time, following this decision, there are 8 planets, Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus and Neptune and so far 5 dwarf planets (though the number is expected to increase), Ceres, Pluto, Eris, Haumea and Makemake. In 2008, a further term was introduced, namely a Plutoid. A Plutoid is any dwarf planets that orbits beyond Neptune. Thus Pluto, Eris, Haumea and Makemake are Plutoids.

## 6. The Larger Members of the Solar System

The larger bodies are very interesting objects irrespective of the way that they are classified. They may be able to retain an atmosphere and some internal activity and evolution in their structure can take place. In the next section we give a brief description of each of the known larger bodies in the Solar system. Since Ceres (mean diameter 940 km) is defined as a dwarf planet, all objects orbiting the Sun that have a diameter in

excess of 900 km have been included in this category. In addition, we have included in this section also a description of the large moons, including all the moons that are larger than Pluto. The smallest such moon is Triton with a diameter of 2700 km. The next largest moons are Titania (diameter 1580 km), Rhea (diameter 1530 km), Oberon (diameter 1520 km) and Iapetus (diameter 1440 km). Note the substantial gap between the sizes of Triton and Titania. There are further five moons (Tethys, Dione, Ariel, Umbriel and Charon) that are larger than Ceres, but have not been included.

In the discussion below, the semi-major axis, or mean distance from the Sun is given. These values change slowly with time due to mutual gravitational perturbations. The values we give are the instantaneous (or osculating) elements for the epoch of J200, namely 12.00 UT on 1 January 2000 (Julian date 2451545.0). Note also that where a planet has a substantial moon, the motion of the center of the planet is slightly different from that of the barycenter of the system, though this difference may be less than the number of significant figures we quote. Where this is not the case, we quote the barycenter value.

The increase in our knowledge of these larger bodies has been achieved largely through space missions. Space missions have flown by all eight planets, while a mission to Pluto is under way. A number of extended missions have visited Venus, Mars, Jupiter and Saturn. In addition Earth-orbiting telescopes and the general increase in telescope aperture size over the last decade have also contributed significantly. What follows is a short summary of our present day knowledge of each of these larger objects.

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### Biographical Sketch

**Iwan Williams** was born near Prestatyn in North East Wales in 1939, but moved to Dinorwig in the foothills of Snowdon when four years old. He was educated in the local primary school and then at Bryn'r Efail Grammar School until the final year when the family moved to Cyffylliog in Denbighshire and Iwan finished his A-levels at Denbigh Grammar School. He then studied Mathematics at the then University College of North Wales at Bangor, graduating with first class honors. He gained his PhD in Astrophysics in 1963 from Royal Holloway College, University of London, under the supervision of Sir William McCrea.

On completion of his PhD, he was appointed a Lecturer at READING University in 1963 followed by a Readership at Queen Mary College in 1971. He was promoted to Professor of Maths and Astronomy in 1987, becoming Dean for Research 1991 and Dean of the Faculty of Engineering and Mathematical Sciences in 1999.

He has been Vice-President of the Royal Astronomical Society and Chairman of the Comet Halley UK Coordinating Committee and member of the International Halley Watch steering group.

He has also been President of the Society for Popular Astronomy, Commission 22 of the international Astronomical Union and President of Division III Planetary Systems Sciences of the International Astronomical Union. Minor planet number 3634 is named IWAN after him.

After a few years working on problems regarding Stellar Evolution, Iwan Williams worked on the formation of planetary systems and then, towards the end of the 1970's became interested in the dynamical aspects of solar system evolution, producing for example the first models of meteor streams that contained a realistic number of meteoroids. A number of features of meteor streams were explained and this work is continuing. In 1985 the opportunity of observing Halley's Comet could not be missed and this started a long series of Photometric observations of comets which has evolved into a program to observe the nuclei of comets and determine their spin properties. At about the same time it became apparent that the Meridian circle on La Palma was producing photometric as well as astrometric data on asteroids, admittedly at a rate of only one point per night. However, this is ideal for determining the phase dependence of asteroids since a wide variation in phase angle is obtained and so again a series of papers on this topic has emerged. The morphology of asteroids can be carried out by spectrography and this has been a topic investigated using the 4.2m telescope on La Palma. The value of spectrum was also evident for investigating the impact of S-L9 with Jupiter and both a spectrum and CCD imaging were obtained on several nights. The discovery of an object beyond Pluto led to the start of a program to discover and follow Kuiper belt objects, resulting in three new objects being discovered, 1993 SB, 1993 SC and 1994 KV8. In consequence, Prof Williams is a Co-I on a number of observations given time on ISO. This observational work led Iwan Williams into obtaining astrometric data on the satellites of Saturn that was vital for the successful completion of the Cassini mission. Observational work has continued, with current interests being in the Trojan Asteroids, but the main thrust of research is now into the origin of meteor streams and meteorites and their relationship to comets and asteroids. In connection with this, Iwan Williams is a Co Investigator on the CONSERT experiment on the Rosetta ESA mission to study the interior of a comet.