60

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The satellites of the outer planets

The discovery of the four large satellites of Jupiter by Galileo Galilei in January 1610 was one of the most significant events in the history of science. Galileo's observations of moons appearing to move from one side of the planet to the other provided support for the Copernican view of the Universe by showing that celestial objects did not all orbit the Earth. His claim as the first observer of what he called the 'Medicean planets' was hotly disputed by the German astronomer Simon Marius. Marius claimed to have observed the satellites in November 1609 and there is little doubt that he was using a telescope to study the heavens around the same time as Galileo. However, Galileo published his observations while there is no record of those of Marius. In Galileo's honour, the four large satellites of Jupiter are often now referred to as the Galilean satellites.

While the scientific and philosophical significance of Galileo's discovery cannot be underestimated, the observations also started an enormous expansion in the number of known objects in our Solar System. Prior to Galileo's discovery, eight Solar System objects were known: six planets (Mercury, Venus, Earth, Mars, Jupiter and Saturn), one moon (the Moon) and the Sun. His observations raised the number of known Solar System objects by 50% at a stroke. There are now 61 satellites of the 9 planets known (several other irregular satellites of Saturn await confirmation), 57 of them are satellites of the gas giant planets Jupiter, Saturn, Uranus and Neptune (Figure 1). Many of the satellites have remarkable phenomena associated with them. There are, for example, volcanoes on Io, geysers on Triton and a thick atmosphere on Titan. In some senses, therefore, Galileo's discovery was also the start of a new discipline in planetary sciences – the study of planetary satellites.

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The rest of this chapter is organized as follows. It begins with a historical overview of the discoveries of planetary satellites in the twentieth century. Included are brief anecdotes about some of the astronomers involved in these observations and a short description of the spacecraft that made many of the more recent discoveries. In the following sections the orbits of planetary satellites are discussed in more detail, including a look at the limited amount of information we have about surface composition. This is followed by a description of the atmospheres of planetary satellites which have become a major topic since the early 1980s. The availability of spacecraft imaging of outer Solar System objects has also led to an amazing growth in the field of planetary geology which in turn has given us clues as to the evolution of planetary satellites. The chapter concludes with a brief discussion of what the twenty-first century could hold.

HISTORICAL INTRODUCTION

Status in 1900

By the start of the twentieth century 22 planetary satellites had been discovered. After the discovery of the Galilean satellites, Christiaan Huygens (1629–1695) and Giovanni Domenico Cassini (1625–1712) found most of the larger moons of Saturn in the seventeenth century. The larger satellites of Uranus were found in the eighteenth and nineteenth centuries by William Herschel (1738–1822) and William Lassell (1799–1880) while the largest satellite of Neptune, Triton, was also discovered by Lassell in 1846.

In his introductory chapter to the book *Satellites*, Burns (1986) suggested a means of classifiying planetary satellites. In his classification, regular satellites are large, spherical and

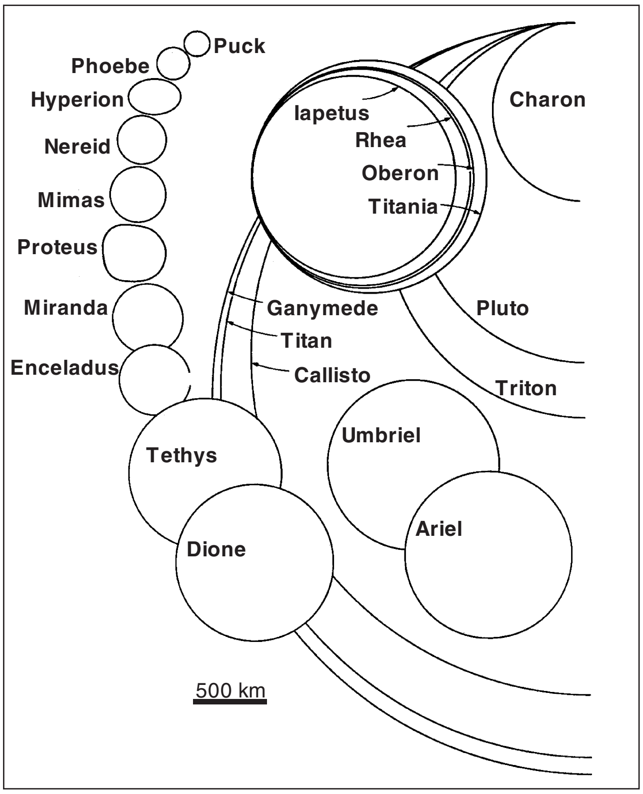

Figure 1 A montage of the relative sizes and shapes of some of the larger planetary satellites in the Solar System. (From Croft and Soderblom 1991, courtesy of University of Arizona Press).

relatively close to the parent planet. They are in prograde orbits with low inclination and eccentricity and are often in synchronous rotation (that is, the same hemisphere always faces the parent). Their masses are small compared to the parent. Collisional shards are small, irregularly shaped objects, extremely close to the planet or co-orbital with a regular satellite. They have prograde orbits with essentially zero inclination and eccentricity. They are thought to be the 'debris' left over after planet and regular satellite formation. Irregular satellites are far from the parent and have substantial inclination, eccentricity, or both. They are small. They are thought to have been captured into their present orbits (although it has to be said that a reasonable mechanism for this process remains to be demonstrated). A fourth group of unusual satellites, which do not fall into any of the above categories, was also suggested (Table 1).

By around 1850 all the regular satellites had been discovered. Two of the three satellites we now categorize as unusual (the Moon and Triton) had also been found (the third, Charon, would not be found until 1978). Shortly before the beginning of the twentieth century, telescopes became powerful enough to find some of the smaller collisional shards. Hyperion, which might be considered to be intermediate between a regular satellite and a collisional shard, was discovered in 1848. Phobos and Deimos were discovered by Asaph Hall (1829–1907) in 1877 and Edward Emerson Barnard (1857–1923) observed Amalthea, a satellite inside the orbit of Io, from the Lick Observatory in 1892 during a systematic search for new Jovian satellites.

Up to this point the discovered satellites were all relatively close to the parent (within 60 planetary radii of the centre of mass). However, the discovery of the irregular satellite Phoebe, in a retrograde orbit, 215 planetary radii from Saturn by William Henry Pickering (1858–1938) in April 1899 (on a plate obtained seven months previously) indicated that many objects at hundreds of planetary radii away from the parent planet could exist.

Initial discoveries

The first significant event of the twentieth century was the discovery in 1904 of the irregular satellite of Jupiter, Himalia, by the American astronomer Charles Dillon Perrine (1878–1951). Perrine worked at the Lick Observatory on Mount Hamilton in northern California and later became director of the Argentinian National Observatory in Cordoba. An 86 km diameter crater on the Moon (at 42.5°N, 127.8°W) is named after him.

Philibert J. Melotte (1880–1961) discovered the eighth moon of Jupiter, Pasiphaë, in 1908. While photographing Pasiphaë with the 36-inch (0.9 m) Crossley reflector at the Lick Observatory, Seth Barnes Nicholson (1891–1963) discovered a ninth moon which was named Sinope. Nicholson was born in Springfield, Illinois, and became interested in astronomy as an undergraduate at Drake University in Iowa. He graduated in 1911 and became a graduate student at the University of California from which he gained his doctorate in 1915. His dissertation was based on his discovery and orbit computation of Sinope.

Nicholson subsequently moved to the Mount Wilson Observatory near Pasadena, California, where he spent the rest of his career. His main job was to observe the Sun with the 150-foot (46 m) solar tower telescope. He produced annual reports on sunspot activity (with Hale and St John) and magnetism for decades. During this period, however, he also discovered three more Jovian satellites (Lysithea, Ananke and Carme) and a Trojan asteroid (Menelaus) as well as computing the orbits of several comets. He also worked with Edison Pettit to produce a vacuum thermocouple which was used to measure the temperatures of the Moon and planets in the early 1920s. He was twice president of the Astronomical Society of the Pacific and became the 56th winner of the Catherine Wolfe Bruce medal, awarded by the society, shortly before he died.

The Uranian satellite Miranda was discovered in 1948 by the Dutch-born astronomer Gerrit Pieter Kuiper (1905–1973).

Table 1 Classification of planetary satellites

	Earth	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Regular			Io (Galileo 1610) Europa (Galileo 1610) Ganymede (Galileo 1610) Callisto (Galileo 1610)	Mimas (Herschel 1789) Enceladus (Herschel 1789) Tethys (Cassini 1684) Dione (Cassini 1684) Rhea (Cassini 1672) Titan (Huygens 1655) Iapetus (Cassini 1671)	Miranda (Kuiper 1948) Ariel (Lassell 1851) Umbriel (Lassell 1851) Titania (Herschel 1787) Oberon (Herschel 1787)		
Shards		Phobos (Hall 1877) Deimos (Hall 1877)	Metis (Synnott 1979) Andrastea (Jewitt) Amalthea (Barnard 1892) Thebe (Synnott 1979)	Atlas (Terrile 1980) Prometheus (Danielson 1979) Pandora (Collins *et al*. 1980) Epimetheus (Fountain, Larson/Walker 1966/1980) Janus (Dollfus 1966) Telesto (Yoyager 2, 1980) Calypso (Pascu *et al*.1980) Helene (Lecacheux, Laques 1980) Hyperion (W. and G. Bond/Lassell 1848)	Cordelia (Voyager 2, 1986) Ophelia (Voyager 2, 1986) Bianca (Voyager 2, 1986) Cressida (Voyager 2, 1986) Desdemona (Voyager 2, 1986) Juliet (Voyager 2 ,1986) Portia (Voyager 2 ,1986) Rosalind (Voyager 2, 1986) Belinda (Voyager 2, 1986) Puck (Voyager 2, 1986)	Naiad (Voyager 2, 1989) Thalassa (Voyager 2, 1989) Despina (Voyager 2, 1989) Galatea (Voyager 2, 1989) Larissa (Reitsema *et al*. 1981) Proteus (Voyager 2, 1989)	
Irregular			Leda (Kowal 1974) Himalia (Perrine 1904) Lysithea (Nicholson, 1938) Elara (Perrine 1905) Ananke (Nicholson, 1951) Carme (Nicholson, 1938) Pasiphaë (Melotte 1908) Sinope (Nicholson, 1914) S/1999 J1 (Scotti *et al*. 1999)	Phoebe (Pickering 1898) Several others await confirmation	Caliban (Gladman *et al*. 1997) Sycorax (Gladman *et al.* 1997)	Nereid (Kuiper 1949)	
Unusual	Moon					Triton (Lassel 1846)	Charon (Christy 1978)

Kuiper, who is better known by his Americanized name, Gerard Peter, turned to studies of the Solar System shortly before the end of World War II. He discovered the methane atmosphere of Titan in 1944 (see below), the presence of CO_2 in the atmosphere of Mars and the small satellite of Neptune, Nereid, in 1949 at the McDonald Observatory. He was also instrumental in setting up the first institute dedicated to the study of the Solar System. The Lunar and Planetary Laboratory (LPL) of the University of Arizona, at Tucson, remains one of the leading planetary research institutes in the world.

Kuiper not only made ground-based observations. He also pioneered the use of telescopes in high-altitude aircraft for infrared observations. The absorption by the Earth's atmosphere of infrared radiation often prevents the investigation of the compositions of gaseous planets and satellites, the interstellar medium and molecular clouds. Kuiper's idea led to a C-141 StarLifter jet aircraft being used as a flying observatory. The Kuiper Airborne Observatory (KAO) was put into service in 1975 and is operated by NASA from its Ames Research Center at Moffett Field near San Jose. It is expected to be replaced by a flying observatory called SOFIA, which is based upon a Boeing 747, being built in a collaboration between the USA and Germany. Kuiper was also involved in spaceflight and became chief experimenter for the Ranger series of missions to the Moon. He also assisted in the selection of Cerro Tololo in Chile and Mauna Kea in Hawaii as sites for new high-altitude observatories. His name is associated with craters on Mercury, the Moon and Mars. The most prestigious prize of the Division of Planetary Sciences of the American Astronomical Society is also named after him.

The first satellite of Saturn to be discovered in the twentieth century was first observed by Andouin Dollfus in 1966 from the Pic du Midi Observatory in France. Dollfus has had a long and distinguished career as a ground-based observer of planets and comets. Much of his more recent work has concerned the investigation of the polarization of light reflected by dust grains ejected from comets. The satellite of Saturn he observed is called Janus. However, there was considerable uncertainty about the orbit of the new satellite. In 1978 John Fountain and Stephen Larson clarified the uncertainty by re-analysing the results of Dollfus's observations and demonstrating that there were two objects in the same orbit about Saturn. The smaller of the two co-orbital objects was subsequently called Epimetheus. In March 1980, just prior to the arrival of Voyager 1 at Saturn, Lecacheux and Lacques who, like Dollfus, worked at the Pic du Midi Observatory detected a small satellite (Helene) in the same orbit as Dione. Hence, prior to the arrival of the Voyager spacecraft, Saturn was known to have at least 12 satellites.

In 1974 Charles Kowal discovered the 13th satellite of Jupiter (Leda). Kowal worked at the Lowell Observatory in Flagstaff, Arizona. This privately endowed observatory was founded by Percival Lowell (1855–1916) in 1894. In subsequent years, Lowell studied the orbit of Uranus and predicted that the perturbations in the orbit could be explained by a large planet outside the orbit of Neptune. According to Lowell, this planet, called Planet X, needed to be approximately seven Earth masses to fit his observations. The discovery of Pluto by Clyde W. Tombaugh (1906–1997) in 1930 merely ignited the controversy because Pluto appeared to be much fainter than would be expected of such a large object. In 1977 Kowal started a photographic search for other objects outside the orbit of Neptune. He studied a region 15° on either side of the ecliptic. He found nothing attributable to an object beyond Neptune but did discover the first Centaur, 2060 Chiron, which may indicate a link between asteroidal debris in the outer Solar System and short-period comets.

In astronomy, the United States Naval Observatory (USNO) is probably best known for being the organization that, together with the Royal Greenwich Observatory, produces the Astronomical Almanac. However, in 1978, while measuring the positions of Pluto on a series of images, the USNO's James W. Christy made an immensely important discovery. Christy saw that the image of Pluto was extended to one side. On examining other plates, he saw that the extension had moved to the opposite side of Pluto. Christy realized that he was observing a very close satellite of Pluto. By viewing a series of older plates he noticed that the extension seemed to move with a period of about a week. After being reminded by a colleague that Pluto had a light-curve with a period of 6.387 days, he concluded that the orbital period was identical to the period of the light-curve. His colleague Robert Harrington computed the orbit the next day from the detailed analysis of the observations and found excellent agreement with a 6.387-day period. This discovery was important because it allowed a determination of the mass of Pluto that demonstrated that Pluto's mass was very much less than that of the Earth and therefore could not be the Planet X predicted by Percival Lowell. Interestingly, Seth Nicholson was also involved these studies. He and others had investigated perturbations in Neptune's orbit and concluded that the mass of Pluto should be only 0.8–0.9 Earth masses. Although this was moving in the right direction, Christy's discovery led to a mass estimate of only 1/400th of the Earth's mass.

The space age

By the time of Christy's discovery the exploration of the outer Solar System with robotic spacecraft was already in full swing. On 3 March 1972 Pioneer 10 became the first probe to be launched to Jupiter. It made its closest approach to Jupiter (132 000 km) on 3 December 1973. Pioneer 11 was launched on 5 April 1973 and passed Jupiter (42 800 km) on

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