Chapter 10

Introduction to the Solar System

In this chapter we give a brief overview of the solar system. Its cast of characters includes:

- the Sun;
- the terrestrial (rocky, or Earth-like) planets: Mercury, Venus, Earth, Mars;
- the Jovian (gas giant, or Jupiter-like) planets: Jupiter, Saturn, Uranus and Neptune;
- asteroids and comets;
- the planet Pluto and other Kuiper belt objects, the Oort cloud;
- moons.

In the remainder of the chapter we will look more closely at these ingredients. We will not, however, treat in detail its most important player, the Sun, and we will only touch briefly on planetary geology, as both of these topics are treated in separate courses.

10.1 Planets and their orbits

Table 10.1 gives some basic information on the planets of the solar system. With one exception (Pluto) they divide neatly into two main categories: terrestrial (earth-like) and Jovian (or gas giant). The terrestrial planets are all relatively close to the Sun, and are mainly composed of heavy elements, e.g., Fe, Si, O, Mg, Al. The Jovian planets are further away from the Sun and are much larger than their terrestial counterparts. For example, Jupiter is roughly one eleventh the size of the Sun or around 10 times larger than the Earth. The gas giants are mostly composed of hydrogen and helium. The exception is Pluto, which is smaller than any of the terrestrial planets and yet further from the Sun than the gas giants.

Some of the values from Table 10.1, particularly the distances, are perhaps counter to our intuition. For example, suppose the Sun, with its diameter of 1 400 000 km were the size of a beach ball 60 cm in diameter. On this scale, the Earth would be roughly the size of a pea, orbiting at a distance of 64 m. Jupiter would be the size of a tennis ball, some 360 m away from

Table 10.1: Properties of planets and their orbits (from [29]). (Note Pluto has been reclassified as a *dwarf planet*; see Section 10.5.)

Planet	Diameter (km)	a (AU)	Orbital eccentricity	Inclination of orbital plane (deg.)	Obliquity (tilt of axis, deg.)
Mercury	4 879	0.387	0.206	7.0	0.0
Venus	12 104	0.723	0.007	3.39	178
Earth	12 756	1.0	0.017	0	23.45
Mars	6 787	1.524	0.093	1.85	25
Jupiter	142 800	5.203	0.048	1.3	3.08
Saturn	120 660	9.537	0.056	2.49	26.7
Uranus	51 118	19.19	0.047	0.77	97.9
Neptune	49 528	30.07	0.009	1.77	29.6
Pluto	2 300	39.48	0.248	17.15	122.5

the Sun. The nearest star is Proxima Centauri at a distance of 1.3 pc (1 pc = 206 265 AU). In the imaginary world with the Sun as a beach ball, Proxima Centauri would be sitting at a distance of 35 000 km.

From Table 10.1 we can see that most of the planets have orbits that lie within a few degrees of the ecliptic, with only Pluto having a relatively large inclination angle of 17°. All of the planets orbit in the same direction, and most of the planets revolve about their own axes also in the same direction. Here the exceptions are Uranus and Pluto. Uranus's axis of rotation almost lies in the plane of its orbit. It has been proposed that Uranus suffered a major collision early in the history of the solar system that caused its rotational axis to tip over by more than 90°. Pluto's axis has a tilt angle of 122.5°, which also is presumably related to interactions with other bodies during the formation of the solar system.

10.2 Asteroids and the Titius-Bode Law

From Table 10.1 we also see that the sizes of the orbits show a curious regularity. The semi-major axis values, a, can be approximately described by the forumla

$$a = [0.4 + 0.3 \times 2^n] \text{ AU, with } n = -\infty, 0, 1, 2, 3, \ldots \; . \tag{10.1}$$

This emperical rule is called the Titius-Bode Law, and was found independently by Titius and Bode in the 18th century to describe the six planets known at the time (out to Uranus). Table 10.2 shows the predictions of this rule along with the observed orbital sizes. The agreement is seen to be relatively good, at least out to Uranus, with one important exception: for $n = 3$ one predicts an object orbiting at $a = 2.8$ AU, and this did not appear to correspond to any known planet.

In 1801 Giuseppe Piazzi discovered an object orbiting the Sun at a distance very close to 2.8 AU, and this was interpreted by Bode as the missing planet. Piazzi's planet was actually the

Table 10.2: Values of the semi-major axis of planets as observed and as predicted by the Titius-Bode Law.

Planet	n	a predicted (AU)	a observed (AU)
Mercury	$-\infty$	0.4	0.39
Venus	0	0.7	0.72
Earth	1	1.0	1.0
Mars	2	1.6	1.52
Ceres	3	2.8	2.77
Jupiter	4	5.2	5.20
Saturn	5	10.0	9.54
Uranus	6	19.6	19.2
Neptune	7	38.8	30.07
Pluto	8	77.2	39.48

asteroid Ceres, one of thousands of rocky objects found in the *asteroid belt* between the orbits of Mars and Jupiter. Asteroids, also called ‘minor planets’, are small rocky bodies that are left over from the formation of the solar system. They are prevented from fusing together by the gravitational perturbations caused by Jupiter, which is by far the most massive planet in the solar system. Ceres is the largest asteroid, having a diameter of 940 km and containing a third of the mass of the entire asteroid belt. Some properties of some of the larger asteroids are given in Table 10.3.

Table 10.3: Properties of some of the asteroids [30].

Asteroid	Size (km)	Semimajor axis (AU)	Orbital eccentricity
Ceres	960 × 932	2.767	0.0789
Pallas	570 × 525 × 482	2.774	0.2299
Juno	240	2.669	0.2579
Vesta	530	2.362	0.0895
Eugenia	226	2.721	0.0831
Siwa	103	2.734	0.2157
Kleopatra	217 × 94	2.793	0.2535
Ida	58 × 23	2.861	0.0451
Mathilde	66 × 48 × 46	2.646	0.2660
Eros	33 × 13 × 13	1.458	0.2229
Gaspra	19 × 12 × 11	2.209	0.1738

Although the discovery of Ceres appeared to be a stunning victory for the Titius-Bode Law, its success is to a large extent regarded as a coincidence. Simulations of the formation of a planetary system from the collapse of a gas cloud can indeed result in regularities in the spacing of the orbits, but these turn out to be difficult to predict in advance and are highly sensitive to the initial conditions. This is typical of complex systems governed by nonlinear force laws such as gravity.

Asteroids larger than around 500 km diameter contain enough mass to be pulled into a roughly spherical shape. Smaller asteroids such as Kleopatra, Ida, etc., are often irregularly shaped boulders. Figure 10.1 shows images of the asteroids Ida and Eros.

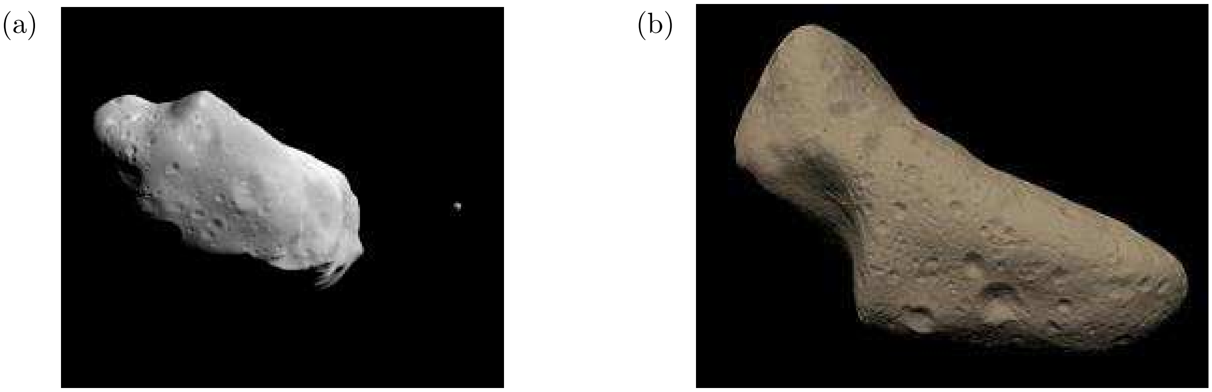

Figure 10.1: (a) Image of the asteroid Ida and its moon Dactyl taken by the Galileo spacecraft in 1993. [31]. (b) Image of the asteroid Eros taken by the NEAR spacecraft in 2001 [32]. NEAR proceeded to land on the surface of Eros returning images from as low as 120 m [33].

10.3 Comets and trans-Neptunian objects

Comets are small bodies composed of dust and ices (mainly water, but also C0 and $C0_2$) that reside in the outer solar system. According to Kepler's laws, bodies orbiting at a very large radius move very slowly, and thus it does not take a very large perturbation to bring their angular motion to a halt. If this happens, they then fall in toward the inner solar system, often falling into the Sun but also possibly passing around it in a highly eccentric orbit. As a comet approaches the Sun its ices sublimate giving its nucleus an atmosphere of gas and dust called the *coma*.

The coma is swept by the Sun's light into a visible *tail*, which can be up to an AU in length. Often comets have two distinct tails, one from ionized gas and one from dust. The ion tail extends opposite the direction of the Sun and often appears blue, since the most commonly found ion, $C0^+$, preferentially scatters blue light. The dust tail also extends away from the Sun as dust particles are pushed away from the Sun's radiation pressure. As the comet swings around the Sun, the particles find themselves in orbits slightly further away, and therefore with slower orbital speeds. The dust tail is therefore bent into a curved shape that lags behind the gas tail. Figure 10.2(a) shows the comet Hale-Bopp, which was clearly visible in the spring of 1997. The lower tail is from ionized gas, and the upper one from dust.

Comets can be classified as either *short-period* or *long-period*. The long-period comets (period greater than 200 years) enter the solar system isotropically and have orbits that originate around 50 000 AU from the Sun. It has been postulated that at this distance there is a spherical

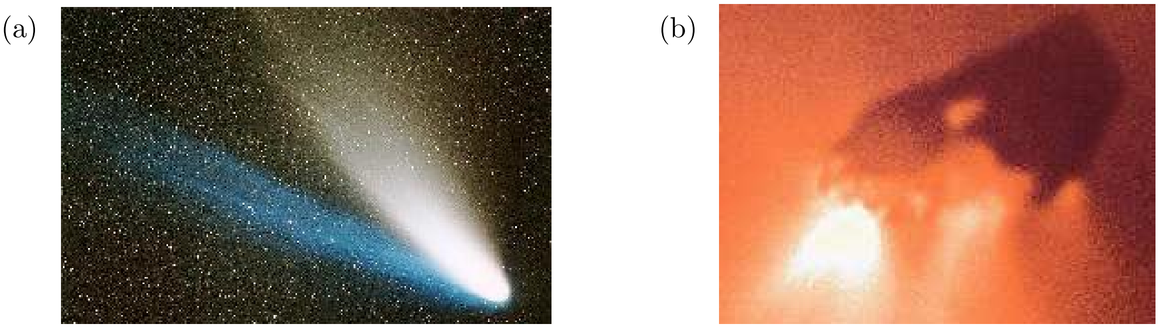

Figure 10.2: (a) Image of Comet Hale-Bopp, showing the ion and dust tails [34]. In the spring of 1997 this comet was clearly visible to the unaided eye. (b) Nucleus of Comet Halley, approximately 15 km long by 8 km wide, imaged in 1986 by the Giotto spacecraft [35].

distribution of cometary nuclei called the *Oort Cloud*. The gravitational perturbation that causes an Oort Cloud object to fall in toward the Sun could come from a nearby star.

The short-period comets (period less than around 200 years) come from a reservoir called the *Kuiper Belt*, which starts roughly at the orbit of Neptune (30 AU) and extends out to 50 AU or more. The Kuiper Belt lies in the ecliptic plane and contains more than 70 000 objects with diameters larger than 100 km. The short-period comets therefore also have orbits close to the ecliptic and move around the Sun in the same direction do the rest of the planets. Comet Halley, having a period of 76 years, falls into this category.

Cometary nuclei are believed to be objects left over from the formation of the solar system. The Kuiper Belt objects were never accreted into planets, but their orbits still lie roughly in the plane of the solar system. Any such objects that were at smaller radii near the orbits of Neptune and Uranus would have undergone close encounters with these planets whereby they were ejected out to much further distances and in random directions; these are the present Oort Cloud objects. Cometary nuclei that had close encounters with Jupiter or Saturn would most likely be ejected from the solar system entirely.

The planet Pluto has an orbital semi-major axis of 39.5 AU. Although its diameter of 1200 km perhaps gives it a certain similarity to the terrestrial planets, its orbit puts it in the middle of the Kuiper Belt. One therefore expects Pluto's origin to be more directly connected to that of comets than to the inner planets. It is perhaps best classified as a large Kuiper Belt object.

Recently a 10th 'planet' has been discovered at an orbital radius of 97 AU, placing it in the outer reaches of the Kuiper Belt [36]. From its apparent brightness we can infer that it must be at least as large as Pluto. The object's provisional name is 2003 UB 313, based on the date of the first recorded images. Three of these images, taken 90 minutes apart, are shown in Fig. 10.3. The planet, indicated by the circle, is clearly moving relative to the background stars. Further images have even shown that this body is orbited by a smaller moon.

10.4 Moons

Many of the planets in the solar system have in orbit around them smaller bodies or moons. Mercury and Venus do not have moons, the Earth of course has a relatively large moon, (usually

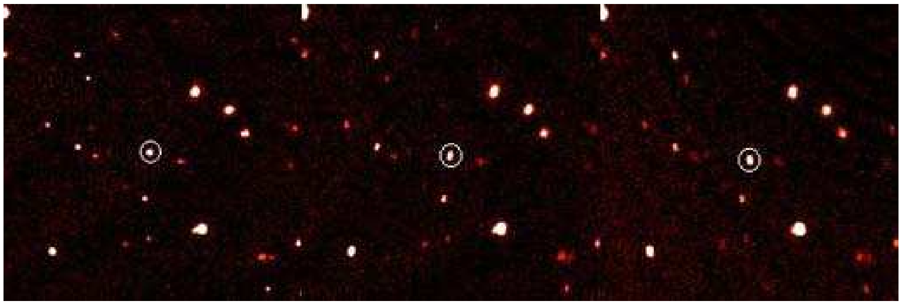

Figure 10.3: The tenth planet, 2003 UB 313, now renamed the dwarf planet Eris [36].

written with a capital letter, the *Moon*). Mars has two small moons (~ 10 km diameter), Phobos and Deimos, which may be captured asteroids. All of the Gas Giants have many moons. Jupiter, for example, has more than 60, the largest four of which are called the Galilean moons, having been seen by Galileo in 1610. His discovery counts as one of the earliest to be made with a telescope and revealed the first example of celestial motion not apparently centred about the Earth [37]. Figure 10.4 shows the four Galilean moons: Io, Europa, Ganymede and Callisto.

Figure 10.4: A composite image of Jupiter and its four largest moons, from top to bottom (also in order of increasing distance from Jupiter): Io, Europa, Ganymede and Callisto [38].

The moons of the Jovian planets have sizes typically smaller than but roughly the same order of magnitude as the terrestrial planets. The largest moon, Ganymede has a diameter of 5 262 km and is actually larger than Mercury or Pluto. The moons of the Jovian planets differ significantly from the inner planets in composition, however, with significantly greater quantities of ices (water, $C0_2$, amonia, methane).

10.5 2006 update: Pluto demoted to dwarf

In August 2006 the International Astronomical Union voted at its 26th General Assembly Meeting in Prague on a new classification of the members of the solar system. The outcome was the creation of a new type of celestial body called *dwarf planet*. Pluto was reclassified as a dwarf planet along with the asteroid Ceres and the previously mentioned '10th planet', 2003 UB 313. Several weeks later, 2003 UB 313 was renamed (136199) Eris (pronounced ee′-ris, the Greek goddess of discord and strife), or Eris for short. Its moon, formerly known as S/2005 (2003 UB 313) 1 and now known technically as (136199) Eris I, has been named Dysnomia (the daughter of Eris).

The new classification scheme defines a planet to be a body that orbits the Sun and is massive enough so that its gravity pulls it into an approximately spherical shape. Furthermore it must be massive enough to have ejected or accreted other objects in its path. To be a dwarf planet, it is sufficient to orbit the Sun and be roughly round; it is not required that the body clear away other nearby objects. Both of these categories exclude moons, which are bound to planets or dwarf planets that are themselves orbiting around the Sun.