1 The Solar System

Though Pluto, and the far-flung depths of the Solar System, is the focus of this book, it is essential that Pluto is placed in the context of the planetary system that it inhabits – our Solar System. In the first place, this is because Pluto is just one of a large and varied number of bodies that orbit the Sun, and cannot be treated as an isolated body in space. Secondly, much of the material in this chapter is needed to support and enhance your understanding of subsequent chapters.

But before we get to the Solar System, I start by examining its cosmic neighbourhood: a vast assemblage of stars called the Galaxy, which we see in the sky as the Milky Way.

1.1 A JOURNEY INTO OUR GALAXY

The Sun, which is at the centre of the Solar System, is one of about two hundred thousand million stars that make up the Galaxy. From extensive observations made from Earth it is clear that it has a beautiful form that, face-on, is something like that in Figure 1.1.

The stars, of various kinds, plus tenuous interstellar gas and dust, often woven into stunning forms, are concentrated into a disc highlighted by spiral arms (Figure 1.1). In our Galaxy the disc is about 100 000 light years in diameter (see Box 1.1), and most stars are in a thin sheet about 1000 light years thick – roughly the same ratio of diameter to thickness as a CD. This sheet is called the thin disc. It is enclosed in what is called the thick disc, which is about 4000 light years thick, where the space density of stars is less. The spiral arms are delineated by a high space density of particularly luminous stars and luminous interstellar clouds. Elsewhere in the disc the space density of the stars and interstellar clouds is no less; it is just that they are not as bright. At its centre the disc has a bulge called the nuclear bulge,

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FIGURE 1.1 A face-on view of a spiral galaxy rather like ours. This has the galactic catalogue number NGC1232. (European Southern Observatory)

also full of stars and interstellar matter. It is very roughly 10 000 light years across. The bulge is visible as the bright central region of the galaxy in Figure 1.1; it is not quite spherical but slightly flattened. As in our Galaxy it is also slightly elongated in one direction in the plane of the disc. The disc is enveloped in the halo (not visible), a roughly spherical volume in which interstellar matter is particularly tenuous and the space density of stars is low. Throughout the Galaxy there are many groupings of stars, from binaries (two stars orbiting each other) to a variety of much larger groupings, but the Sun is an isolated star.

The Sun is located near the edge of a spiral arm, roughly half way from the centre of the Galaxy to the edge of the disc. Figure 1.2 shows the view we get from Earth of the disc of our Galaxy. This

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BOX 1.1 THE LIGHT YEAR (PLEASE READ)

This is a unit of distance, *not time*. It is the distance that light travels in a vacuum in one year. The speed of light in a vacuum is 299 792.458 kilometres per second (1 kilometre = 0.621371 miles). In a year light travels 9.460536×10^{12} kilometres (10^{12} is 1 000 000 000 000, i.e. 1 followed by 12 zeroes). With space being near enough a vacuum, this immense unit is appropriate for expressing distances in the Galaxy. It is also appropriate for expressing interstellar distances: the nearest star to the Sun, Proxima Centauri, is 4.22 light years from the Sun. However, the Solar System is small compared with interstellar distances – the Sun is 0.0000158 light years from the Earth, which is 8.317 light minutes. The light minute would be an appropriate unit of distance within the Solar System, but as you will see in Section 1.2, a different unit is used instead.

shows part of the Milky Way, and so our Galaxy is often called the Milky Way Galaxy.

Beyond our Galaxy there are many more, some with a spiral form like ours, but there are other configurations too; some have highly irregular forms, others lack any concentration of stars and interstellar matter into a disc. It is estimated that there are tens of billions of galaxies that could be seen by our present telescopes (a billion is a thousand million).

Let's return to our Galaxy, and to that location near the edge of a spiral arm, roughly half way from the centre of the Galaxy to the edge of the disc, where the Solar System resides.

1.2 THE SOLAR SYSTEM: SIZES AND ORBITS

Sizes

The Solar System consists of a variety of bodies orbiting the Sun, plus a variety of natural satellites ('moons') orbiting most of the planets. Figure 1.3 shows the radii of bodies in the Solar System that are large enough to be spherical, and also have well known radii. You

FIGURE 1.2 The Milky Way – our view of the disc of our Galaxy. (Naoyuki Kurita, by permission) (See plate section for colour version.)

can see, for example, that the Sun is nearly 10 times the radius of the largest planet Jupiter. This means that it has nearly $10 \times 10 \times 10 = 1000$ times Jupiter's volume. When comparing bodies, relative volumes give a better impression of relative sizes than relative radii. The radius of the Earth is 6378 kilometres (km), so its diameter is

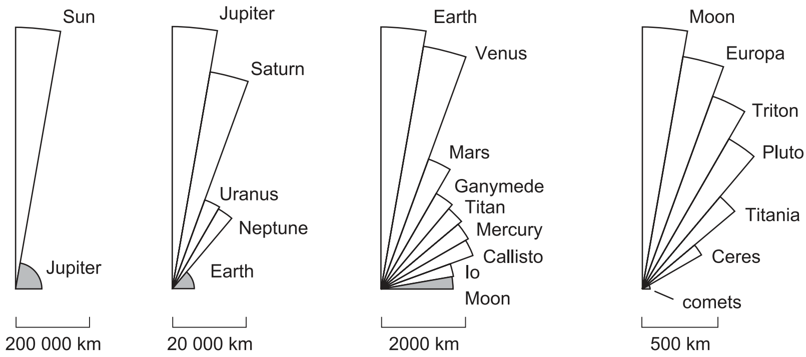

FIGURE 1.3 Radii of bodies in the Solar System large enough to be spherical and with well known radii. (The relative size of comets is also indicated.) Note the scales.

twice this, 12 756 km. More precisely these are the equatorial values. The Earth's rotation around its polar axis slightly flattens it, so the radius pole to pole is 6357 km and the diameter 12 714 km. All the planets are slightly flattened by rotation, the amount depending on the rate of rotation and the composition of the planet.

Orbits

Figure 1.4 shows, to scale, the orbits of the planets Mercury, Venus, the Earth, Mars, Jupiter, Saturn, Uranus, Neptune and Pluto. The remaining bodies in Figure 1.3 are the large planetary satellites and the largest asteroid Ceres, which orbits between Mars and Jupiter. The upper scale in Figure 1.4, 150 million km, is very nearly the same as the *average* distance of the Earth from the Sun, which is always *very* close to 149.6 million kilometres (93.0 million miles). This distance used to define what is called the astronomical unit (AU), but because the value varies very slightly the AU is now nailed down as 149.5978715 million km (what precision!). It is an appropriate unit of distance within the Solar System. Note that 1 AU is nearly 24 000 times the radius of the Earth, or nearly 12 000 times its diameter, exemplifying how small the planets are compared with the distances that separate them.

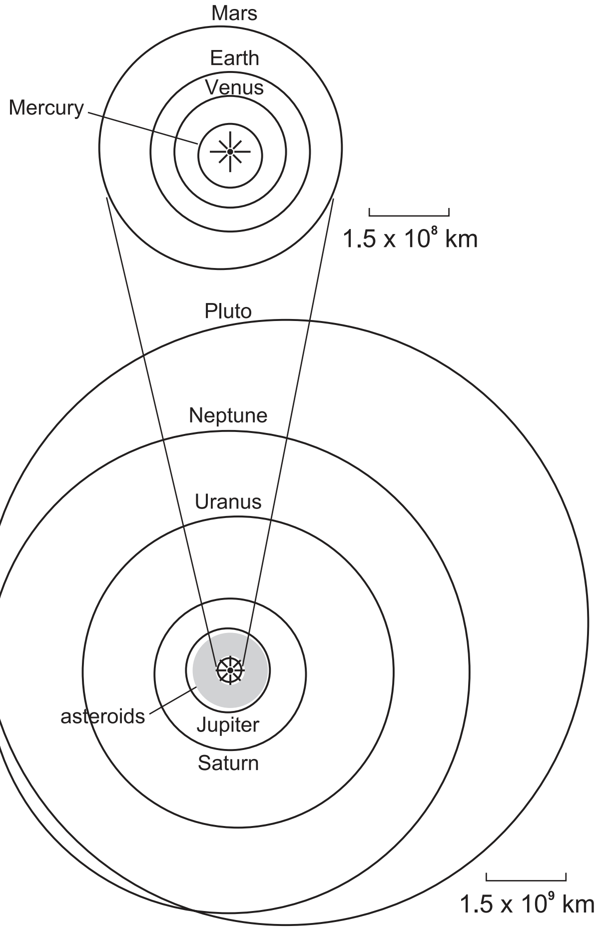

FIGURE 1.4 The Solar System; a face-on view of the planetary orbits. Though the orbits are not quite in the same plane, this makes no difference to the view on the scale here except for the orbit of Pluto, which would look slightly less circular in a face-on view (see Figure 1.5). The planets move around their orbits in an anticlockwise direction when viewed from above the Earth's North Pole.

The orbits of the planets are not quite circular; they are ellipses, which have the shape of a circle when it is viewed at an angle. The non-circular shape is not apparent on the scale of Figure 1.4. What *is* apparent, particularly for Mercury, Mars and Pluto, is that the Sun

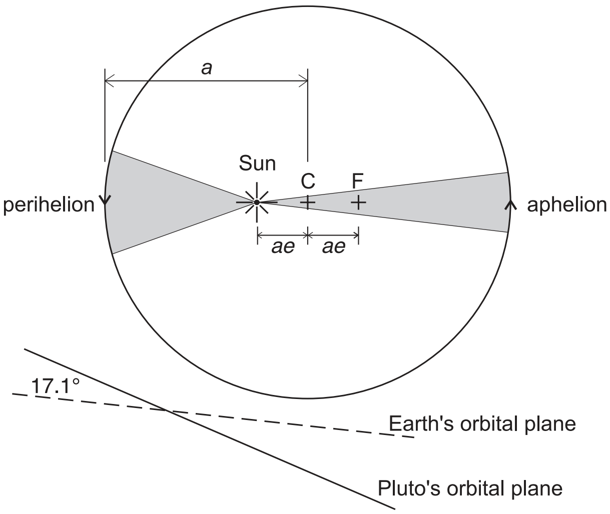

FIGURE 1.5 The orbit of Pluto, here face-on, to show what is meant by the semimajor axis, a, of an orbit and its eccentricity, e. C is the centre of the orbit. For Pluto $e = 0.251$. If e were zero the orbit would be a circle centred on the Sun which would be at C. The Sun is at one of the two points called the focuses of the ellipse. The other focus F is empty.

is not quite at the centre of the orbit. This is a consequence of their larger orbital ellipticity. To take a most pertinent example, Figure 1.5 shows the orbit of Pluto. Perihelion and aphelion are, respectively, the nearest and furthest points of the orbit from the Sun. Two quantities are shown that will be important in subsequent chapters. These are the size of the orbit as measured by its semimajor axis, a, and the non-circularity (ellipticity) of the orbit as measured by its eccentricity, e (a times e is shown in Figure 1.5). For Pluto $e = 0.251$, greater than for all the other planetary orbits. For a circle $e = 0$ and the Sun would lie exactly at the centre of such an orbit. (Note that the average distance of the Earth from the Sun that I referred to above, is the semimajor axis of the Earth's orbit.)

The orbits are also not quite in the same plane. Pluto's is the most inclined, at 17.1° with respect to the orbital plane of the Earth (Figure 1.5). The next most inclined planetary orbit is that of Mercury, at 7.0°. Inclinations are given the symbol i. The reference plane in the

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Table 1.1 *The orbital elements a, e, i and P of the planets and the larges*

	Mercury	Venus	Earth	Mars	Ceres	Jupiter	Satu
a (AU)	0.387	0.723	1.000	1.524	2.766	5.203	9.5
e	0.206	0.0068	0.0167	0.0934	0.0793	0.0489	0.0
i (°)	7.004	3.395	0.001	1.849	10.59	1.304	2.4
P (years)	0.241	0.615	1.000	1.881	4.601	11.86	29.3

Data from the *Observer's Handbook 2009*. (The Royal Astronomical Society

Solar System is called the ecliptic plane. At one time this was the orbital plane of the Earth, but as this plane tilts up and down *very* slightly with respect to the distant stars, the reference plane is now fixed in space.

From Figure 1.4 you might think that Pluto's orbit intersects that of Neptune, in which case they could collide! But the orbital inclination of Neptune is only 1.77°, so the orbits do not actually intersect. More on this in Chapter 2.

Table 1.1 gives the orbital elements a, e and i, and the orbital period, P, of each planet and of the largest asteroid (Ceres). There are slow, periodic variations in these elements, hence the 'as of mid 2009' in the table heading. They are caused mainly by the gravity of the bodies in the Solar System other than the Sun and the body in question. The excursions are small, except for the somewhat larger excursions of the values of e and i of Pluto. The slight variation in the Earth's inclination is apparent in Table 1.1: the value in mid 2009 was 0.001° rather than 0°.

The planets move around their orbits in the same direction, anticlockwise as viewed from above the Earth's North Pole; this is called the prograde direction. They move fastest near to perihelion because the gravitational pull of the Sun is greatest there, and they move slowest at aphelion, where the gravitational pull is least. More precisely, the line from the planet to the Sun sweeps out equal areas in equal time intervals, as illustrated by the two equal areas shaded in Figure 1.5. The time to go around an orbit once is called the orbital period, P. For the Earth it is one year (with respect to the distant stars), whereas for Pluto it is 249 years. Note that though the Sun pulls a body towards itself, the sideways motion of the body, dating back to the birth of the Solar System, turns what otherwise would have been an inward fall and an early demise, into orbital motion.

What is the relationship between the period, P, and the semi-major axis, a? As a increases, the distance around the orbit increases. For a circular orbit this distance is proportional to a, and so, if, for example, the value of a is doubled the distance around the circle is

BOX 1.2 KEPLER'S THIRD LAW OF PLANETARY MOTION (FOR THOSE WISHING TO GO DEEPER)

In 1619 the German astronomer Johannes Kepler (1571–1630), announced that P is proportional to $a^{3/2}$ i.e.

$$P = ka^{3/2}$$

where k is the constant of proportionality. This applies to circular and to elliptical orbits. That P increases as a increases is not surprising – the orbit is bigger. However, this alone would make P proportional to a. The extra sensitivity to a is because the speed of the planet in its orbit decreases as a increases.

In the Solar System, if P is measured in years and a in AU then the constant of proportionality has the value 1 exactly and so $P = a^{3/2}$. For the Earth $a = 1$ AU and so the equation with $k = 1$ gives $P = 1$ year, which is correct! For Pluto, $a = 39.6$ AU and so the equation gives $P = (39.6)^{3/2}$ years, which is 249 years, also correct.

also doubled. If the speed of the planet in each orbit were the same, then the period of the more distant planet would also be doubled. However, because the force of the Sun's gravity decreases with distance, the speed in orbit also decreases, so that in doubling the value of a, P more than doubles, in fact increasing by a factor of $2 \times \sqrt{2}$, which is 2.828 . . . (to four figures). If a is increased three-fold then P increases by $3 \times \sqrt{3}$, which is 5.196, and so on. Though I started with circular orbits, these numerical results apply to elliptical orbits too. The algebraic relationship between P and a constitutes Kepler's third law of planetary motion, and for those of you wishing to go a bit deeper please see Box 1.2.

Kepler's laws of planetary motion

We have now encountered three important laws of planetary motion. These are called Kepler's laws after the German astronomer Johannes