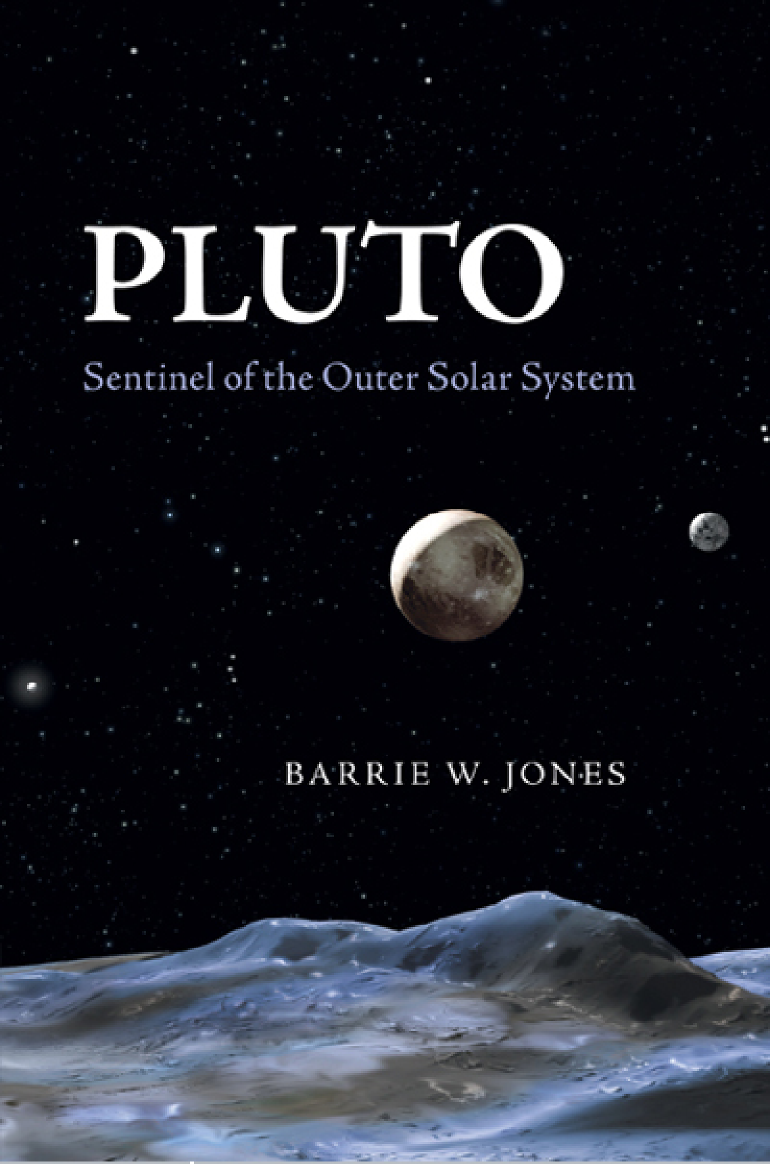

PLUTO

Sentinel of the Outer Solar System

BARRIE W. JONES

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Orbiting at the edge of the outer Solar System, Pluto is an intriguing object in astronomy. Since the fascinating events surrounding its discovery, it has helped increase our understanding of the origin and evolution of the Solar System and has raised questions about the nature and benefits of scientific classification.

This is a timely and exciting account of Pluto and its satellites. The author uses Pluto as a case study to discuss discovery in astronomy and how remote astronomical bodies are investigated. He also examines the role of classification in science by discussing Pluto's recent classification as a dwarf planet. Besides Pluto, the book also explores the rich assortment of bodies that constitute the Edgeworth-Kuiper Belt, of which Pluto is the innermost substantial member.

Richly illustrated and up to date, this book is written for general readers, amateur astronomers and students alike. Boxed text provides more advanced information especially for readers who wish to delve deeper into the subject.

BARRIE W. JONES is Emeritus Professor of Astronomy in the Department of Physics and Astronomy, The Open University. A highly regarded university lecturer, he has an outstanding record in the public understanding of science, particularly in astronomy, through lectures, local and national radio and TV and articles in popular magazines and in the press. His main research area is the habitability of planetary systems.

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To my wife Anne, to all other members of my family, and in memory of my parents

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Preface

Pluto is a very tiny, distant world. It orbits the Sun beyond the giant planet Neptune, the outermost of the other eight planets in the Solar System. In inward order from Neptune these planets are Uranus, Saturn, Jupiter, Mars, Earth, Venus and Mercury. Pluto has a diameter a little less than one fifth of the diameter of our planet, which itself is a long way from being the largest planet in the Solar System. That title belongs to the giant planet Jupiter, with a diameter just over 11 times that of the Earth.

Why should a book be devoted to such a tiddler among the planets? There are three main reasons. First, the discovery of Pluto in 1930 is a fascinating episode in our quest to discover whether the Solar System beyond Neptune is devoid of planetary bodies. Second, ever since its discovery, controversy has been rampant about what sort of body Pluto is. Is it deserving of the status of planet, or is it too small for that? The classification of Pluto is an excellent example of the role of classification in all branches of science: classification not only comes with great advantages but also with difficulties. Third, Pluto is the closest large member of the Edgeworth-Kuiper belt, a great swarm of small bodies that orbit the Sun beyond Neptune. Though the existence of such a belt had been predicted in the 1940s, it was not until the 1990s that discoveries of other trans-Neptunian bodies were made. By learning about Pluto we learn something about the more distant bodies, and therefore learn more about how the Solar System formed and evolved.

A valuable spin-off is that in describing how Pluto has been explored, and will be explored, you will meet techniques in astronomy of wide applicability, not only to other bodies in the Solar System but, in a few instances, to much larger bodies, namely, the stars and to any planets that they might possess. In this respect, Pluto is a case study, but none the worse for that.

I have aimed this book at a wide readership, indeed at anyone interested in the outer reaches of the Solar System and also in tales of discovery and in how we learn about objects far away. I have assumed that you bring to this book no knowledge of astronomy, and almost no mathematics – only a basic ability in arithmetic is required and only in a few places.

To meet the needs of those able and wishing to go deeper I have used boxed text. Nothing that follows afterwards requires that you have studied the text. If you are not familiar with the contents of such boxes, you can read the text to improve your overall understanding. Boxed text is also used to separate from the main story material that would interrupt the flow, and this material is at the general level of the main text. Each box is tagged so that you know what sort it is.

Under *Further reading and other resources* I've listed some of the key papers in the scientific literature. These are to enable you to read about the various topics in this book in greater detail or greater depth. Most of these require some knowledge of astronomy and mathematics. I've also listed a few books about the Solar System, Pluto and the outer Solar System that, like this book, are aimed at a wide readership; other books listed require more background in astronomy and mathematics, and are labelled accordingly. Finally, I've given details of a few magazines and internet links.

Throughout the book you will see how our knowledge and understanding of Pluto and the outer Solar System has changed through the decades. You will also see that many uncertainties remain, and much is unknown. This is the very essence of science, a story that will never be finished, never be finalized. I wish you an enjoyable and informative read.

Acknowledgements

I am grateful to Nick Sleep for commenting on a draft of the whole book, and to William Grundy, David Jewitt, Pedro Lacerda and Alan Stern for commenting on individual chapters. Marc Guie, Dale Cruikshank, James Elliot, Amanda Gulbis, Charles Harding, Jonathan Horner, Brian Marsden, William McKinnon, Olivier Mousis, Jay Pasachoff and Judy Pipher have supplied information and clarification in response to my requests. Peter Hingley has assisted with completing several references to key papers in the scientific literature.

Illustrations have come from a variety of sources, acknowledged wherever possible in the captions. Antoinette Beiser, Christine Colburn, Mark Hurn, Debbie James and Sandrine Marchal have helped me find several photographs.

Simon Mitton was instrumental in getting my proposal for this book accepted by Cambridge University Press, and Vince Higgs and his team at CUP have helped to get it into production.

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,

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

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 × 10 × 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

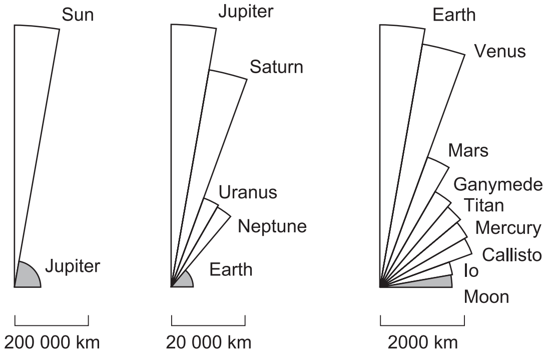

FIGURE 1.3 Radii of bodies in the Solar System large enough to be spherical and with well known radii. (The relative size of comets is also indicated.) Note the scales.

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.

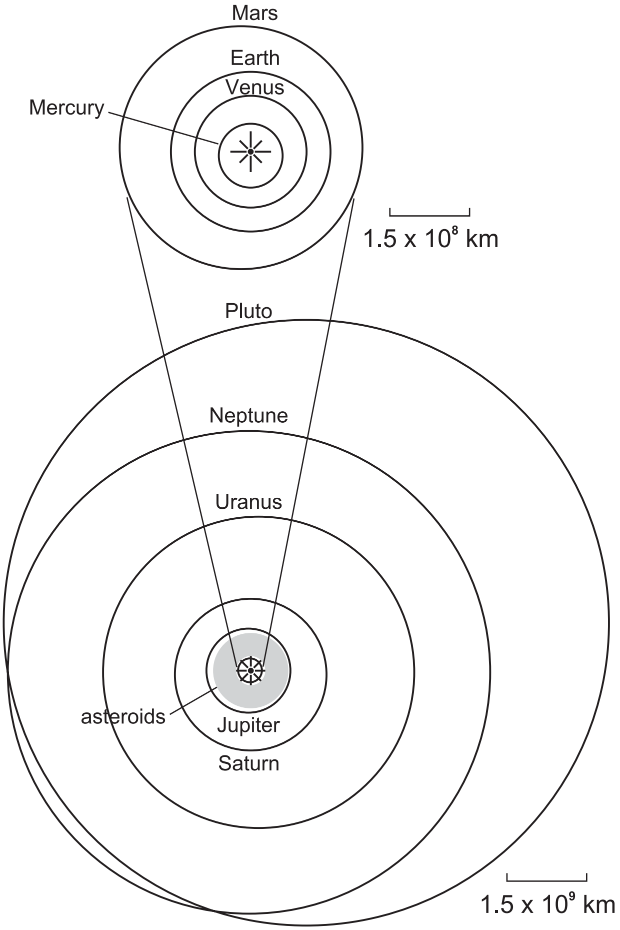

FIGURE 1.4 The Solar System; a face-on view of the planetary orbits. Though the orbits are not quite in the same plane, this makes no difference to the view on the scale here except for the orbit of Pluto, which would look slightly less circular in a face-on view (see Figure 1.5). The planets move around 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

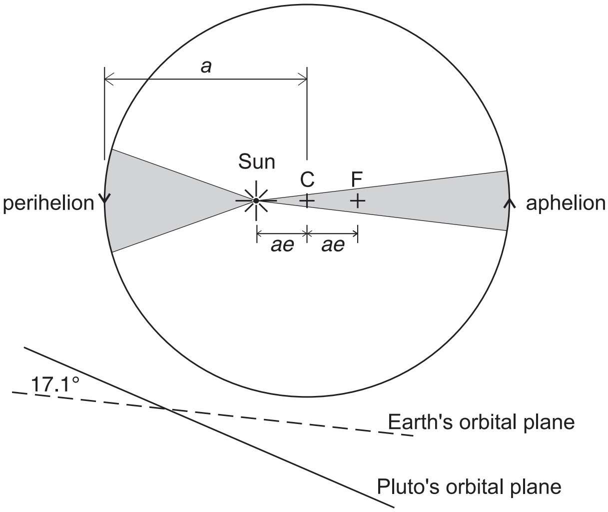

FIGURE 1.5 The orbit of Pluto, here face-on, to show what is meant by the semimajor axis, *a*, of an orbit and its eccentricity, *e*. C is the centre of the orbit. For Pluto $e = 0.251$. If *e* were zero the orbit would be a circle centred on the Sun which would be at C. The Sun is at one of the two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

Table 1.1 *The orbital elements a, e, i and P of the planets and the largest asteroid, Ceres (as of mid 2009).*

	Mercury	Venus	Earth	Mars	Ceres	Jupiter	Saturn	Uranus	Neptune	Pluto
a (AU)	0.387	0.723	1.000	1.524	2.766	5.203	9.515	19.24	30.20	39.64
e	0.206	0.0068	0.0167	0.0934	0.0793	0.0489	0.0534	0.0449	0.0095	0.251
i (°)	7.004	3.395	0.001	1.849	10.59	1.304	2.488	0.7719	1.769	17.14
P (years)	0.241	0.615	1.000	1.881	4.601	11.86	29.33	84.31	165.8	249.4

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

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

Kepler (1571–1630), who announced the first two in 1609 and the third in 1619. They are based on accurate observations of the motions of the planets. The laws are as follows:

First law: Each planet moves around the Sun in an ellipse, with the Sun at one of the two focuses of the ellipse (Figure 1.5).

Second law: As the planet moves around its orbit, the straight line from the planet to the Sun sweeps out equal areas in equal intervals of time (Figure 1.5).

Third law: P increases with a more rapidly than being proportional to a. (See Box 1.2 for the algebraic relationship.)

After their discovery, it was shown that these laws can be accounted for by fundamental physical theory, specifically Newton's laws of motion and law of gravity, developed in the second half of the seventeenth century by the English scientist Isaac Newton (1643–1727), but it would take us too far afield to go into details.

Small bodies in the Solar System: asteroids and comets

As well as planets, the Solar System also contains smaller bodies orbiting the Sun. More than a hundred thousand asteroids are known, mainly between the orbits of Mars and Jupiter. The asteroids are rocky or mixtures of rocky materials and iron, and up to several hundred kilometres in radius, but mostly much smaller. The largest asteroid is Ceres (Figure 1.3).

There are also two populations of bodies with a size range comparable to that of the asteroids but consisting of mixtures of rocky materials (including carbon-rich materials) and ices, mainly water ice. One population constitutes the Edgeworth-Kuiper belt, icy-rocky bodies in orbits of fairly low inclination, the semimajor axes of the great majority being between about 40 AU and 50 AU. The belt is also known as the Kuiper belt, and the members of the belt are known as Kuiper belt objects (KBOs). About 2000 Kuiper belt objects are known, with a steady flow of new discoveries. Chapter 6 is devoted to the Edgeworth-Kuiper belt.

The other population is the Oort cloud. The outer Oort cloud is a thick spherical shell of icy-rocky bodies, surrounding the Solar System, and extending from about 1000 AU (perhaps 10 000 AU) to the very edge of the Solar System at about 100 000 AU. The inner Oort cloud is more belt-like, and extends inwards from the outer Oort cloud towards the Edgeworth-Kuiper belt, perhaps coming as close as a few hundred AU from the Sun. Estimates of the total number of bodies in the Oort cloud range from about a million million (1 000 000 000 000), to ten million million (10 000 000 000 000).

Whereas the larger KBOs are close enough to be seen with telescopes, as tiny dots, Oort objects are much too far away. The existence of the Oort cloud is inferred from those of its members whose orbits are perturbed so that they travel through the inner Solar System, where they initially become fuzzy, and go on to develop huge, spectacular tails (Figure 1.6). They become comets.

Comets are divided into two main classes, the long-period comets, defined as having orbital periods greater than 200 years, and short-period comets which, it won't surprise you to learn, are defined as having orbital periods less than 200 years. As well as occupying different ranges of orbital period, the two classes differ in other ways. Long-period comets have orbital inclinations covering the full range, and thus bombard the Solar System from all directions. The short-period comets have no more than modest inclinations. In both classes, the fuzziness and the tails consist of gases evaporated from the icy component by the heat of the Sun, and of dust particles entrained in this gas flow.

Most of the short-period comets originate in the Edgeworth-Kuiper belt, from where they have had their orbits gravitationally perturbed so that they pass through the inner Solar System. A transitory population between the short-period comets and Kuiper belt objects constitute the Centaurs, which occupy unstable orbits with perihelia between Jupiter and Neptune. The remaining short-period comets, and all of the long-period comets come from the Oort cloud,