CHAPTER 1

The edge of the solar system

Like the planets Pluto and Neptune, the existence of what is frequently called the Kuiper Belt was predicted theoretically long before it was actually observed. Probably the first fairly detailed speculation about a cometary ring beyond Neptune was put forward by Kenneth Essex Edgeworth in 1943. Edgeworth was an interesting character who had progressed from soldier and engineer to retired gentleman and amateur theoretical astronomer. He was born on 26th February 1880 in County Westmeath, Ireland, into a classic well to do literary and scientific family of that era. As a young man he joined the Royal Military Academy at Woolwich, England, and attained a commission in the Royal Engineers. He spent his next few years stationed around the world building bridges, barrack blocks and the like. With the outbreak of the First World War he served with the British Army in France as a communications specialist and was decorated with both the Distinguished Service Order and the Military Cross. He remained in the army until 1926 and then took up a position with the Sudanese department of Posts and Telegraphs in Khartoum. Edgeworth remained in the Sudan for five years before retiring to Ireland to live out the remainder of his life.

Although retired, Edgeworth was by no means inactive. During the 1930s he studied economic theory and published several books on this topic. Although never affiliated with a university or other astronomical institution, he also pursued an interest in astronomy which he had acquired in his youth (he had joined the Royal Astronomical Society in 1903). After he retired he wrote a number of articles, mostly theoretical in nature, dealing with the process of star formation and developing ideas about the origin of the solar system. In 1943 he joined the British Astronomical Association, whose journal published his first

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paper on the evolution of the solar system that summer. It was a short note which Edgeworth himself described as containing 'Not so much a theory, but the outline of a theory with many gaps remaining to be filled'. In his paper he described how a cloud of interstellar gas and dust might collapse to form a disc. He speculated that within such a disc numerous local condensations of higher density might then develop and collapse upon themselves. Noting that the real solar system does not comprise a huge number of small objects, but rather a few large planets and moons, Edgeworth suggested that these condensations then coalesced to form the nine known planets and their satellites. Crucially, Edgeworth recognised that there was no obvious reason why the disc of planet-forming material should have been sharply bounded at the orbit of the outermost planet. He suspected that the disc probably extended far beyond this distance and reasoned that, so far from the Sun, the density of material in the disc would be

Figure 1.1 A caricature of Kenneth Edgeworth as a young man. Comparison with photographs of him in later life suggests that it is a good likeness. (Royal Signals Museum Archive.)

very low. So, although individual condensations of reasonable size might form beyond Neptune, there would be little likelihood of them encountering each other frequently enough to form large planets. He suggested instead that these condensations would simply collapse upon themselves to form a large number of small bodies. Echoing then current theories of comets as concentrated swarms of meteoroids he described these distant condensations as astronomical heaps of gravel. He added that perhaps from time to time one of these condensations 'Wanders from its own sphere and appears as an occasional visitor to the inner solar system'. Here was the genesis of the idea of a trans-Neptunian comet belt.

Edgeworth developed his ideas further, writing a longer paper along similar lines a few years later. This second paper was submitted to the *Monthly Notices of the Royal Astronomical Society* in June 1949. Although by today's standards it contained numerous poorly justified assumptions, it was accepted almost immediately and appeared in an issue of the journal dated late 1949. In this paper Edgeworth expanded on his model for the formation of the planets and once again mentioned the likely existence of a vast reservoir of potential comets beyond the orbit of Neptune.

About the same time as Edgeworth's musings, the Dutch-born astronomer Gerard Kuiper was also considering the existence of tiny worlds beyond Pluto. Kuiper was working at the Yerkes Observatory in Chicago and, in 1951, he wrote what became a classic book chapter summarising the state of knowledge about the solar system. Kuiper noted that the distribution of material in the outer solar system seemed to come to an unnaturally sharp edge in the region of the planet Neptune and that there was no obvious reason why this should be so. Perhaps taking a lead from newly published theories about the composition of comets, Kuiper suggested that during the formation of the planets many thousands of kilometre-sized 'snowballs' might have been formed in a disc beyond the planet Neptune. Like Edgeworth, Kuiper reasoned that at such great distances from the Sun, where the relatively tiny snowballs would occupy a huge volume of space, it was unlikely that these snowballs could come together to form large planets. He suggested that instead their orbits were disturbed by the gravitational influence of the planet Pluto† and they were either ejected into deep space or sent in towards the Sun to

† Pluto was then thought to be much more massive than we now know it to be.

appear as comets. However, in a world in which observational astronomy was still dominated by the photographic plate, the detection of such tiny objects remained impracticable.

Of course, speculation about missing planets is not a new phenomenon. Ever since William Herschel's discovery of Uranus in 1781, astronomers have been fascinated by the possibility that there might be other unknown worlds. On the 1st of January 1801 the Italian astronomer Giuseppe Piazzi made a chance discovery of what was at first thought to be a new planet. The object, which was soon shown to be orbiting between Mars and Jupiter, was named Ceres after the Roman goddess of the harvest. It was soon found that Ceres, even though it was quite close, did not show a detectable disc when viewed through a telescope. This suggested that it was smaller than any of the other known planets. Three similar objects, Pallas, Juno and Vesta, were found in 1802, 1804 and 1807 respectively. All appearing as slow-moving points of light, this group of new objects was referred to as asteroids (star-like) by William Herschel. All went quiet for a while until the mid 1840s when new asteroids began to be found in quite large numbers. By the end of 1851 fifteen of them had been found and we now know that Ceres is just the largest of many small rocky objects in what became known as the asteroid belt.

However, by the middle of the nineteenth century attention had once again swung to the outer solar system. Irregularities in the motion of Uranus hinted that it was being tugged by the gravitational pull of another, more distant world still waiting to be discovered. In a now classic story of astronomical detective work, the mathematicians Urbain Le Verrier of France and John Couch Adams of England independently calculated the position of the unseen planet, making its discovery a relatively simple matter once someone could be persuaded to look in the appropriate direction. In the event, it was Le Verrier whose prediction was first tested. While Adams' calculations lay almost ignored by the English Astronomer Royal, the director of the Berlin Observatory J. G. Galle and his assistants searched the region suggested by Le Verrier. They found the predicted planet on 23rd September 1846. However, the discovery of Neptune was not the end of the issue as far as distant planets were concerned. After a few decades it seemed that Neptune alone could not explain all the problems with the orbit of Uranus. This hinted that there might be yet another planet lurking in the darkness of the outer solar system. Two Americans set out to see if this was the case.

William Pickering was one of these planet hunters, suggesting in 1908 that a planet with twice the mass of the Earth should lie in the direction of the constellation Cancer. His prediction was ignored. Eleven years later he revised his calculations and pointed to a position in nearby Gemini. This time astronomers at the observatory on Mt Wilson, California, responded, using their 24 cm telescope to search around Pickering's predicted coordinates. They failed to find anything. Meanwhile, American millionaire Percival Lowell was also turning his attention to the outer solar system. Lowell, who had earlier convinced himself that intelligent life existed on the planet Mars, firmly believed that deviations from the predicted positions of Uranus meant that there must be another unseen planet remaining to be discovered. He called this distant object 'Planet X' and, like Pickering, he tried to calculate where in the sky it might be found. However, Lowell had an advantage over his rival, for he had the means to pursue his search without relying on the whims of others. Lowell owned a private observatory which he had founded in 1894. It was built on Mars Hill, just outside the town of Flagstaff, Arizona. Unlike modern observatories, which are usually located on barren mountain-tops, Lowell placed his telescopes in a delightful setting. The Lowell observatory was surrounded by pine trees and had a fine view back across the town.

Lowell's Planet X was predicted to be quite large, but very distant, and so was unlikely to show an obvious disc in the eyepiece of a small telescope. The best way to find it would be to detect its daily motion relative to the fixed background of stars and galaxies. In the previous century such searches had been made by laboriously sketching the view through a telescope and then comparing this with sketches of the same region made a few days earlier. However, by Lowell's time, astronomical photography had come on the scene and offered a much faster and more reliable way to survey the sky. Lowell's first search was made between 1905 and 1907 using pairs of photographic plates which he scanned by eye, placing one above the other and examining them with a magnifying glass. He soon realised that this method was not going to work.

Lowell's next step was to order a device known as a blink comparator to assist in the examination of the photographs. The comparator provided a magnified view of a portion of the photographs but, more importantly, it allowed the searcher to switch rapidly between two different images of the same patch of sky. Once the photographs were

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aligned correctly, star images remained stationary as the view flashed from one plate to the other. However, should there be a moving object in the field of view, its image would jump backwards and forwards as the images were interchanged. Naturally enough, the process was known as 'blinking' the plates.

A search of the constellation Libra was made in 1911, but was abandoned after a year when nothing was found. Undeterred by this failure, Lowell began another search in 1914. Between then and 1916 over 1000 photographic plates were taken, but once again nothing was found.† Lowell died suddenly from a stroke on the 16th of November 1916, his planet-finding ambition unfulfilled. He was buried in a small mausoleum, shaped to resemble the planet Saturn, in the grounds of his observatory on Mars Hill. For a time the search for Planet X was halted as Lowell's widow tried to break the provisions of his will. Mrs Lowell wanted to remove funds from the operation of the observatory and preserve the site as a museum in her late husband's memory. The resulting litigation siphoned off funds from the observatory for a decade.

Eventually, under the directorship of Vesto Slipher, the Lowell Observatory returned to the problem of the missing planet. Slipher recruited a young amateur astronomer named Clyde Tombaugh, a farmboy from Kansas, as an observing assistant. Tombaugh arrived in Flagstaff during January 1929 and was set the task of taking photographs which could be searched for Lowell's Planet X. It took a while to get the new 31 cm telescope, built especially for the search, into full operation, but by April all was ready. Tombaugh took a number of photographic plates covering the region around the constellation of Gemini, the latest predicted location of Planet X. The plates were 33.5 cm by 40 cm in size and covered nearly 150 square degrees of sky. Each contained many thousands of star images. Vesto Slipher and his brother blinked the plates over the next couple of weeks, but they failed to find anything. In the meantime, Tombaugh continued to photograph the sky and soon a large backlog of unexamined plates had built up. Slipher then asked Tombaugh to blink the plates as well as taking them, explaining that the more senior observatory staff were too busy to devote much time to the onerous and time-consuming blinking process.

† In fact the missing planet did appear on two of these images, but it was much fainter than expected and its presence was missed.

Figure 1.2 Clyde Tombaugh entering the dome of the Lowell Observatory's 33 cm telescope. He is carrying a holder for one of the photographic plates. After exposing the plate he had to search it millimetre by millimetre for Planet X. Few astronomers now go to their telescopes so formally dressed, as can be seen by comparison with figures 4.1 and 5.7. (Lowell Observatory archives.)

Tombaugh regarded the prospects of his new assignment as 'grim', but he dutifully continued with his programme. Night after night he made a systematic photographic survey of the sky. He concentrated on regions close to the ecliptic, an imaginary line across the sky which marks the path traced out by the Sun across the constellations of the zodiac during the course of a year. The ecliptic is not the precise plane of the solar system, which is better defined by taking account of all the planets and not just of the Earth. When this is done the result is known as the invariable plane. However, when projected onto the sky, the ecliptic and the invariable plane are not much different and it is common, if careless, to use the two terms interchangeably. Since the orbit of Planet X would presumably be close to the invariable plane, the ecliptic was the obvious region around which to search.

Tombaugh's method was to take three photographs of each region of sky at intervals of two or three days. Each photograph was exposed for several hours. During each exposure Tombaugh painstakingly guided the telescope to make sure that the images of the stars were sharp, with all their light concentrated onto as small an area of the photographic emulsion as possible. Only then would his plate reveal the very faintest objects and give him the best chance of success. At dawn he developed the plates, careful lest a tiny mistake ruin them and waste his hours of work in the telescope dome. Later he examined the plates for anything which might have moved between the two exposures.

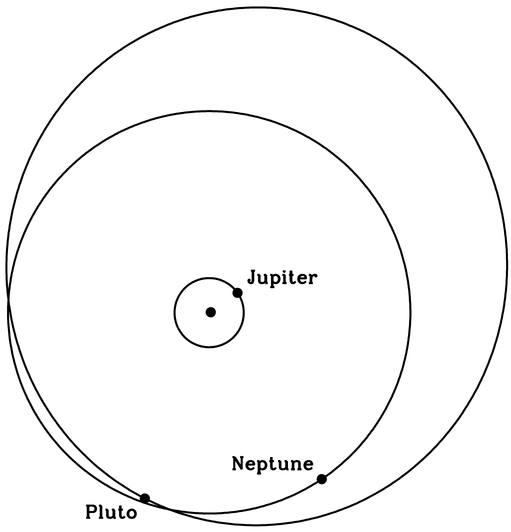

Figure 1.3 The orbits of Jupiter, Neptune and Pluto. Pluto's eccentric orbit crosses that of Neptune, although the significance of this was not realised at the time of its discovery. (Chad Trujillo.)

Although the technique sounds simple in principle, Tombaugh's task was a huge one. The long nights of observing were tiring and the blinking of the frames was tedious in the extreme. Many false detections appeared, caused by things such as variable stars, chance alignments of main belt asteroids and photographic defects which mimicked moving objects. To eliminate these false detections, Tombaugh used his third plate to check if any of the candidate objects were visible again. Usually, of course, they were not. Tombaugh's patience was finally rewarded on the 18th of February 1930 when he was examining a pair of plates he had taken a few weeks earlier. Blinking them, he found a moving object that was clearly not a star, a nearby asteroid or a flaw in the photographic emulsion. What was more, the object's slow motion across the sky suggested that it must be well beyond Neptune. After a few more weeks of observations had been made to define the object's motion more accurately, the discovery was announced on 13th March. The date was chosen since it would have been Lowell's 75th birthday if only he had lived to see the day. After a certain amount of debate, to which we shall return later, the new object was named Pluto, after the god of the underworld.

Clyde Tombaugh continued his search for another 13 years. He estimates that in this time he covered about 70% of the heavens and blinked plates covering some 90 000 square degrees of sky.† All in all he spent some 7000 hours scanning every square millimetre of about 75 square metres of plate surface. Although he marked 3969 asteroids, 1807 variable stars and discovered a comet, he never found another object as distant as Pluto. This was a little odd since it gradually became clear that the new planet was rather smaller than predicted. The first clue that Pluto was small came from its faintness, which suggested it could not be any larger than the Earth. Worse still, even the largest telescopes of the day could not resolve Pluto and show it as a disc. Under even the highest magnifications, the planet remained a tiny point of light, devoid of any features. This was worrying since if Pluto was very small it could not affect the orbit of Uranus to any significant extent. None the less, the intensity of Tombaugh's efforts seemed to rule out any chance that any other massive planet could exist near Neptune's orbit.

It was not until much later that theoretical work, notably by

† The total area of the sky is less than this, but some regions were examined more than once.

American E. Myles Standish in 1993, explained the apparent deviations in the motion of Uranus. Standish based his calculations on improved estimates of the masses of the giant planets which had been determined during the flybys of the Voyager spacecraft. Using these he showed that any remaining errors in the measurements of Uranus' position were tiny and could be explained by systematic observational uncertainties. There was no need to invoke the gravitational influence of a missing planet, massive or otherwise. Lowell's hypothesis of a Planet X had been completely wrong. The discovery of Pluto was a consequence of the thoroughness of Tombaugh's systematic search and the fact that Pluto was fairly close to Lowell's predicted position was just a coincidence.

It was well into the 1970s before the true nature of Pluto was revealed. The planet's orbit was quite well defined within a year of its discovery, but Pluto's faintness made determining details of its physical make-up almost impossible for decades. In the mid 1950s it was established that Pluto has a rotation period of 6.39 days and in 1976 methane frost was detected on its surface. Since methane frost is quite reflective, this implied that Pluto was even smaller than at first thought. Pluto soon shrank again. In 1977 James Christy was examining images of Pluto when he noticed that the planet seemed to be elongated some of the time and not others. He soon realised that this was due to the presence of a large satellite going around the planet every 6.39 days, the same as Pluto's rotation period. As its discoverer, Christy had to name the new moon and he chose Charon, the name of the ferryman who transported souls to the underworld. Strictly speaking Charon should be pronounced Kharon, but it is often enunciated as Sharon since Christy's wife, Sharlene, is known to her friends as Shar. Once the details of Charon's orbit had been established, it was possible to determine the combined mass of Pluto and Charon. This turned out to be no more than 0.0024 times the mass of the Earth. Pluto was a small and icy world. Although the true size of Pluto was unclear in the 1940s, it may have been the realisation that there was no massive Planet X that made Edgeworth and Kuiper speculate about the edge of the solar system. Certainly the existence of small icy worlds at the fringe of the planetary region seemed a natural conclusion from theories of how the solar system formed.

It had once been suggested that the solar system was produced when a close encounter between our Sun and another star pulled out a filament of material which condensed into planets. However, it was