1
New Frontier

"Ever since celestial mechanics in the skillful hands of Leverrier and Adams led to the world-amazed discovery of Neptune, a belief has existed begotten of that success that still other planets lay beyond, only waiting to be found." – Percival Lowell, 1915

A Planet Hunt

The faint starry image jumped a little – very little, in fact. But the heart of young Clyde Tombaugh, who saw it twitch late that Tuesday afternoon in February of 1930, jumped a good bit more. Tombaugh had been hired by Lowell Observatory, in Flagstaff, Arizona, about a year before. His job: to take up the reins of long-dead Percival Lowell's quest for that romantic denizen of the deep outer solar system: Planet X. Now, only months into the search, 24-year-old Tombaugh had found it.

Who was this cherubic planet finder? He was a Midwestern American, born in Streator, Illinois, in February of 1906, the eldest of the six children his parents Muron and Adella produced.

Clyde had become interested in astronomy early in his childhood. This interest was fanned when he was still a boy by the loan of a 3-inch (7-centimeter) diameter telescope from his uncle Lee. Just after Clyde reached age 16, in mid-1922, his parents moved the family to a rented wheat and corn farm in Burdett, Kansas. In high school there, Clyde played track and field, "dabbled in Latin," and played football with his friends on weekend afternoons. His passion, however, was astronomy, and his classmates knew it. In fact, his fellow Burdett High School seniors of 1925 wrote in their yearbook that Clyde had his head "in the stars."

Too poor to afford college, he took the job at Lowell Observatory equipped with little besides a high school education, and a fire inside himself to become a professional astronomer.

The job at Lowell was young Tombaugh's first experience away from his family. It was, he told us shortly before his death in 1997,

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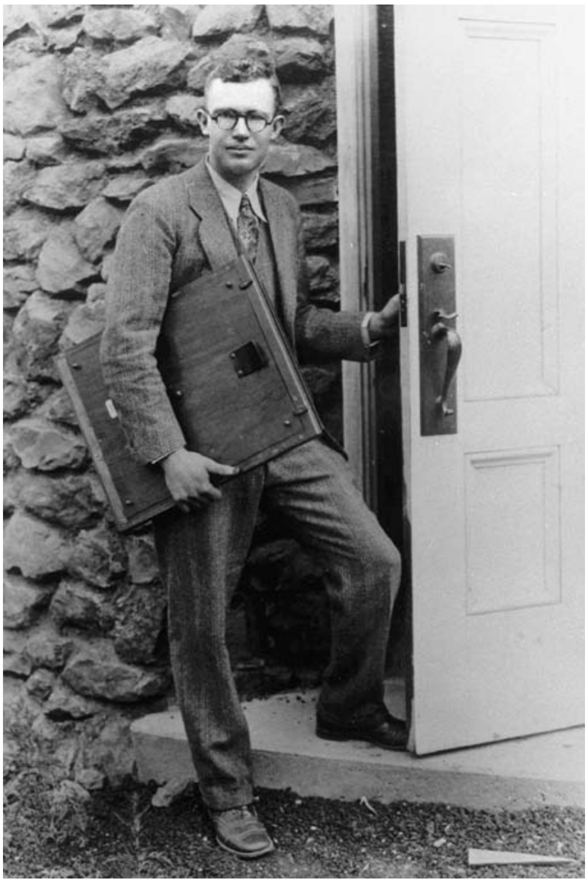

Fig. 1.1: Young Clyde Tombaugh entering the dome of the 13-inch telescope at the Lowell Observatory in the early 1930s. He is carrying one of the large photographic plate-holders for the telescope. (Lowell Observatory photograph)

a little scary to go so far from home. There, far away from friends and family, Clyde was laboriously to photograph the sky and inspect the images in search of astronomer-aristocrat Percival Lowell's last, some thought chimerical, obsession, this Planet X (Figure 1.1). He did not care much that it was tough, almost thankless work. And never mind that there was no assurance of ultimate success. He just dove right in – night after night, week after week, month after month. But his labor *did* pay off, for on a cold February afternoon

Clyde Tombaugh bagged one of the best known astronomical prizes of the young century: a new planet.

The decades-long search for Planet X had been driven by two motivations – one scientific, one more instinctive. First, there had been the mounting observational evidence that some unseen object was tugging at Uranus and Neptune, causing their courses on the sky to differ from predictions. Second, there was the sheer lure of it – the attraction of finding a new world, of making a mark on the immortal annals of discovery, of tilting at Don Quixote's old windmill.

Fig. 1.2: Percival Lowell (1855–1916) in about 1910, founder of the Lowell Observatory at Flagstaff, Arizona. He was the chief motivator behind the observatory's original search for Planet X. (Lowell Observatory photograph)

The search for the ninth planet was largely initiated by Percival Lowell, a wealthy, scientifically literate aristocrat born just before the US Civil War (Figure 1.2). It is a good thing that the instinctive motivation to make the search was so strong in Lowell, because he did not know that the measurements (made by others, mind you), indicating that the positions of Uranus and Neptune were slightly off their predicted tracks, were wrong. Uranus and Neptune were right on course.

But sometimes, ignorance is bliss. And ignorance of the true situation caused Lowell to use the incorrect "residuals" – that is, the difference between the expected course of Uranus and Neptune and what had been measured – to calculate where in the sky the phantom planet should be.

As early as 1905 Lowell organized the first search for his elusive prey, which he called "Planet X." Lowell was not alone in ninth-planet hunting. Several other astronomers pursued the same goal, including MIT-educated William H. Pickering. Dr Pickering called the phantom "Planet O," and organized several searches for it in the early years of the century.

Fig. 1.3: Vesto Slipher (1875–1969) in 1911. After Lowell died in 1916, Slipher became acting director of the Lowell Observatory. Ten years later he was confirmed as director. In 1929 Slipher hired Clyde Tombaugh as an assistant to help in the search for Lowell's predicted ninth planet, then called "Planet X." (Lowell Observatory photograph)

Altogether, at least eight searches were undertaken by Pickering and Lowell between 1905 and 1920. In these attempts, over 1000 photographic images were made – all to no avail. Those were long years of depressingly ill-rewarded work using what now seem depressingly primitive and inefficient tools and techniques. During those long years of fruitless hunting, four presidents passed the American stage, automobiles exploded into the commonplace, the motion picture industry was born, and "The Great War" came (and thankfully went). As the years dragged by, Percival Lowell grew old. Saddened by the world war, exhausted and discouraged, Lowell suffered a stroke and passed away in November 1916. But his dream of discovering a ninth planet would live on.

Fig. 1.4: The Mausoleum at the Lowell Observatory where the remains of Percival Lowell are interred. (Richard Oliver; all rights reserved)

When Lowell died, his will entrusted the money to ensure the continued survival of his observatory and its staff in Flagstaff. "Percy's" will further stated that the search for Planet X should continue, and so it did. His dedicated assistants, led by Vesto M. Slipher, took up the task (Figure 1.3). And just in case the faint-hearted might someday hence waver in their search, Lowell had himself interred in an ornate blue-and-white marble mausoleum less than 50 meters from the main administration building of his former observatory (Figure 1.4). It was just a little reminder, for the staff . . .

Entombed reminder or not, the search for Planet X did temporarily cool in Flagstaff after Lowell's death. However, in California, Pickering and his assistant Milton Humason (a man who was to later become one of the most widely respected mid-century astronomical observers) undertook a new search in 1919. But once again nothing was found.

Meanwhile in Arizona, Lowell's widow sued his estate for a significant part of the million dollars he intended for the observatory. The litigation fees drained the operating funds of the observatory, and the search stalled. Nearly a decade passed.

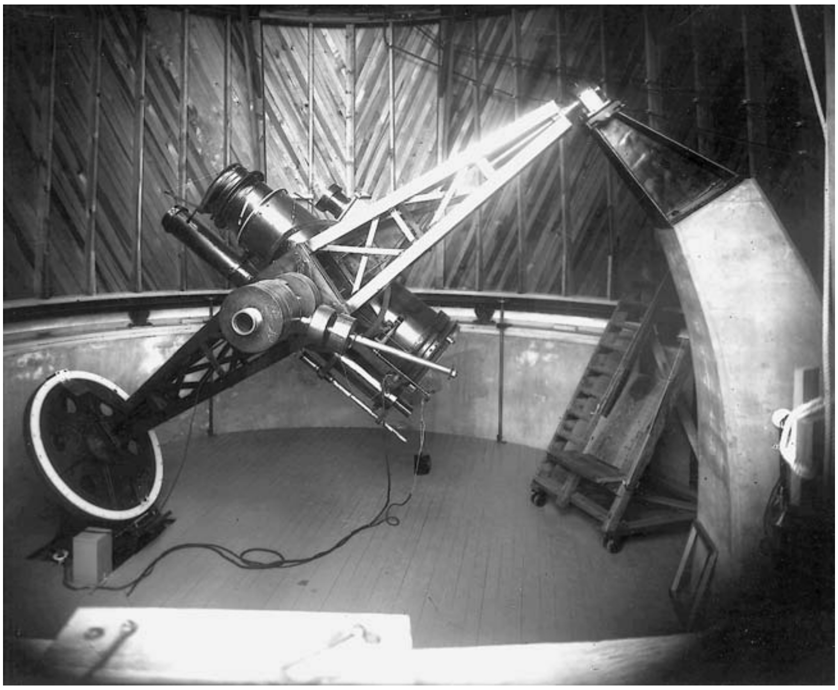

Fig. 1.5: The 13-inch Lawrence Lowell telescope, with which Tombaugh discovered Pluto, as it was originally in its dome at the Lowell Observatory on Mars Hill, Flagstaff. In 1970 the telescope was moved to the Lowell Observatory's site at Anderson Mesa, 12 miles southeast of Flagstaff, but in 1995 it was restored to working order at its original site on Mars Hill. (Lowell Observatory photograph)

Then, in 1925, Lowell's brother Abbott contributed the funds to commission a new tool for hunting Lowell's planet. That tool was a 13-inch (33-centimeter) diameter refracting telescope and camera that together created an unusually large and useful field of view for planet hunting – 164 square degrees. With its combination of broad search swath and good sensitivity, the new telescope would make it worthwhile to renew the search (Figure 1.5).

By 1928, when the new telescope's arrival was imminent, Vesto Slipher had grown older and not so surprisingly had moved into management. His responsibilities had expanded to include the directorship of the observatory. With all the encumbrances that management made on his time, Slipher decided to hire a new technician to assist in the laborious planet search, and he had just the man in mind.

Slipher offered the job to someone who had been enthusiastically corresponding with him and the other astronomers at Lowell for some time. The young man had written to them time after time to share the careful sketches of Mars and Jupiter he had made using a small telescope that he himself had built for $36. His talent and chutzpah together landed him the job. That young man was Clyde W. Tombaugh.

"Young Man, I Am Afraid You Are Wasting Your Time"

Tombaugh arrived in Flagstaff from his Kansas home by train on the wintry afternoon of January 15, 1929. He was away from home for the first time. His father had told him at the station to "work hard, respect his boss, and beware of loose women."

At the station, a graying Vesto Slipher met Clyde Tombaugh for the first time. Tombaugh carried with him a single, heavy trunk, which was laden more heavily with books than clothes. In the letter that offered Tombaugh a job at Lowell, Slipher had not told Tombaugh that he was being brought to Flagstaff to search for Planet X, merely that he would be involved in "photographic work."

It was only on his arrival in Flagstaff that Tombaugh was informed what his job would center on. However, the new planet-finder telescope still was not quite ready. So Tombaugh, astronomer in waiting, was assigned various tasks, ranging from showing visitors around the observatory to shoveling snow and stoking the main building's furnace. It was less than inspiring work, to be sure. Mercifully, however, by early April the new telescope was finally ready, and Tombaugh could begin the search.

Initially, Slipher tutored Tombaugh in observing techniques. Planet X was expected to be at least 15 times fainter than Neptune. They would have to make long, deep exposures of the sky so that the photographs could soak up enough light to detect the prospective planet. Because planets move perceptibly from night to night but stars do not, the key would be to spot a faint, slowly moving target against the fixed backdrop of a myriad stars and galaxies. To do this, each plot of sky would be re-photographed twice over the course of several nights.

Each photographic plate would have to be exposed for an hour or more to detect the faint pinpoint of light for which they were searching, and Clyde would have to adjust precisely the telescope to keep pace with the turning sky throughout each exposure. To ensure the darkest possible sky as an aid to spotting the faint wanderer, the images were to be made around the time of the new Moon.

According to Tombaugh's own account, after a few nights of lessons, Slipher said, "You're doing all right. You're on your own." And so from then on Tombaugh did the photography. Within a few weeks, Slipher also gave Tombaugh the responsibility for inspecting the photographs for evidence of the hoped-for planet. In effect, the search for Planet X now rested entirely with one young man.

Tombaugh told us in 1996 that few people, even astronomers, "have any concept of the grim (plate-to-plate comparison) job that V. M. Slipher gave to me." We agree. Today no one would stand for such a job – a computer would make the comparisons. But the late 1920s was another time, with a wholly different set of technologies to accomplish things. It was a time when the ocean was crossed by steamship, phone connections were made by human operators moving cables across a board, and most iceboxes actually used ice delivered from distant frozen lakes. So too, the 1920s technology for comparing the images with one another for slowly moving points of light was by today's standards frighteningly primitive. Tombaugh's image comparison technology consisted of a machine called a "blink comparator" that allowed him manually to switch viewing back and forth between any two images (Figure 1.6). Stars, which of course remained motionless, could be distinguished from planets and other moving objects because the moving bodies would seem to jump from frame to frame.

When Tombaugh was not up nights photographing the sky, he was at work during the day, developing the plates[1] and inspecting them

Fig. 1.6: Clyde Tombaugh in 1938 at the Zeiss blink comparator, which he used to examine pairs of photographic plates from the 13-inch telescope during his Pluto search. Following the discovery of Pluto, Tombaugh continued this dedicated but ultimately fruitless work in an attempt to find more distant planets. No discoveries were made. The large glass plates Tombaugh used each measured 14 by 17 inches (36 by 43 centimeters). (Lowell Observatory photograph)

for moving objects. It was not easy. It was not glamorous. It was not even very interesting.

Fortunately, Tombaugh's commitment was monumental – and so was his concentration, which he needed in order to combat the sheer drudgery of methodically inspecting hundreds of photographic images. *Each* contained 50 000 to 900 000 stars. Tombaugh was looking to see if one of the faint points of light might move just the right amount from night to night.

Tombaugh would blink plates slowly, methodically, for hours on end. He set out to be a perfectionist about the task, something that demanded nearly Herculean concentration. He later said that he had to take frequent breaks to clear his mind so he could continue concentrating. Tombaugh knew that the penalty for missing the suspected prey was too great to permit his mind to become dulled by the tedium.

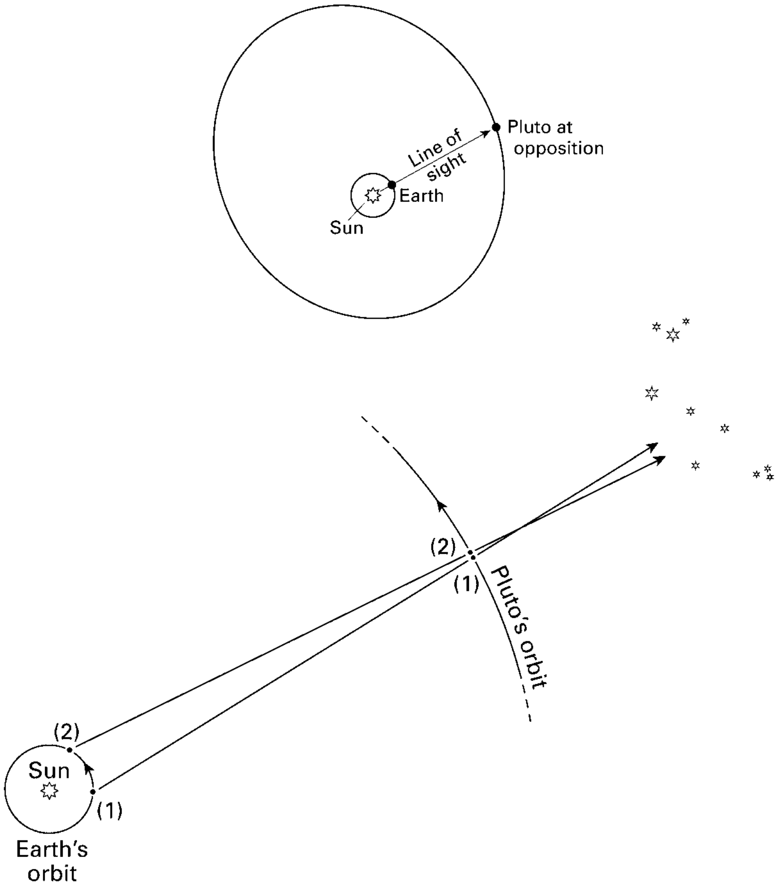

Fig. 1.7: Top: A planet is "at opposition" when it lies in the part of the sky directly away from the Sun as seen from Earth. This occurs when the Sun, Earth, and the planet are in a line in space, as shown here schematically. This is the optimum time for making discovery observations for a number of reasons. One is that the planet reaches its highest point in the sky at midnight, so potential observing time is a maximum. It is also at one of its nearest points of approach to Earth. Another key factor is that a planet's distance can be directly measured at opposition by its rate of travel across the sky. Bottom: Earth travels farther than Pluto does in the time between two observations, (1) and (2). Traveling in its orbit six times faster than Pluto, Earth rapidly overtakes the more distant planet. As a result, Pluto's position in the sky changes relative to the starry background. The change in position over a given period of time is greatest near opposition. The stars themselves do not appear to change their positions between images taken a few days apart because they are more than 10 000 times farther away than Pluto.

After a few months of this work, Tombaugh realized that there is an optimal place on the sky to search for a distant planet. This is around the spot where its motion, as seen from Earth, would be both fastest and most noticeable. At this place on the sky, called the opposition point, a remote planet seems to move westward (i.e., backwards) against the stars (Figure 1.7). Over the course of a year the opposition point[2] sweeps out a great circle on the celestial sphere. This circle is called the ecliptic by astronomers and it passes through the constellations that comprise the zodiac.

A second important advantage of working at the opposition point, Tombaugh realized, was that the amount of motion a faraway planet displays there is inversely proportional to its distance from the Sun. So the farther away an object orbits the Sun, the more slowly it appears to move. Thus, by working at the opposition point Tombaugh could easily distinguish a distant, slowly moving planet from the numerous, nearby, faster moving asteroids that also peppered the images. Tombaugh's realization that the opposition point was the optimal place to focus the search was a crucial advance because it made the detection of truly distant objects so much more straightforward.

Tombaugh presented the opposition-point search plan to Slipher, who approved it. With this new technique in hand, Tombaugh went back to the telescope. Night after night he imaged the sky. He calculated that 30 plates would have to be taken each month to cover the opposition region of the sky as it swept eastward, and he knew that he could only work during those nights each month when the Moon was new or nearly so.

By the time Tombaugh had blinked a month's worth of newly developed plates, the opposition point would have moved on. So he would photograph the next opposition point region when there was no Moon, develop the photographs in the observatory's darkroom, and blink these too. And so forth.

Oftentimes the plates contained microscopic flaws that appeared to create a little jumping point of light when two plates were intercompared, as if to mock him – "Just testing." Almost every plate also contained a handful of those pesky asteroids, which taunted him with false alarms. Fortunately, however, their motion at the opposition point was so large that Tombaugh could tell they were too close to be Planet X itself. After all, he was looking for something that would move just a few millimeters between two plates; the asteroids moved ten times that, or more.

In the course of his searches of the outer solar system, Tombaugh counted over 29 000 galaxies on his plates, plus 1800 variable stars, and discovered two new comets. Months passed, but there was still no sign of Planet X.

By February of 1930, over a year after his arrival in Flagstaff, Tombaugh had worked his way around the sky to the constellation Gemini. He had made a few test plates in this region in early 1929 when the 13-inch telescope was first being set up, but at that time he had not hit upon the idea of using the opposition point to make distant planet detections easier and more systematic. This time as he carefully plowed through Gemini there would be no escape for a stealthy little world. This time Tombaugh ran right into his prey, and caught it.

"That's It!"

It was February 18 when Tombaugh examined his photographs of the star field around Delta Geminorum, the fourth brightest star in the constellation Gemini. These plates had been taken between January 21 and 29. There, a pinprick of light equivalent in brightness to a candle seen from a distance of 300 miles (480 kilometers) jumped ever so slightly from image to image (Figure 1.8).

In the sky there are 15 million stars brighter than the pinprick Tombaugh spied hopping across some of his images in a corner of Gemini, but by blink comparing the position of the anonymous little pinpoint between the various plates, he could see it jumping ever so little!

It did not jump far – only three or four millimeters – but the fact that the jump was so small was the exciting part, for that itself indicated that if the object was real then it surely lay beyond Neptune. "That's it!" he said to himself. But in his logbook, his very own X files, Tombaugh simply wrote, "planet suspect" and the coordinates of the tantalizing speck of light. It was 4 p.m.,[3] and then and there a new planet lost its four-billion-year-old anonymity.

After he finished inspecting the other Gemini plates, good soldier he, Tombaugh set out to confirm whether the faint little nomad was

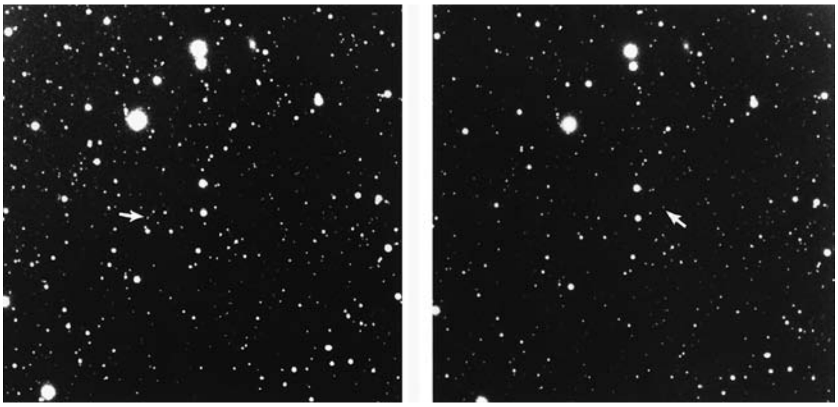

Fig. 1.8: Portions of the original photographic plates on which Tombaugh first detected Pluto by noticing its change in position against the background star pattern. On each plate, the image of Pluto is arrowed. The left plate was taken on January 23, 1930 and the right one six days later, on January 29. (Lowell Observatory photograph)

real. The test he applied was deceptively simple, but stunningly powerful: Tombaugh had taken three other plates of the same region on the same nights, using the smaller, 5-inch telescope that he had bore-sighted onto the 13-inch as a kind of finder scope. Tombaugh's planet-suspect had to appear in the same place on these plates as well if it was real, rather than just an unfortunate artifact of the 13-inch telescope and its camera. And it *was* there.

Bingo! The little wanderer appeared right where it should on all three of these check plates. For nearly three quarters of an hour as he checked and cross-checked the moving pinpoint among the various plates taken, Clyde Tombaugh was the only person in the world to know that Planet X had very likely been found.

Then, sure of himself but trembling with excitement, Tombaugh went to see his boss. Slipher was with Lowell Observatory's assistant director, Carl Lampland. Standing at the door of Slipher's office, Tombaugh knocked and announced directly, "I have found your Planet X."

Tombaugh had never before come to Slipher to make such a statement. He had never set off a false alarm, and both men knew it. On hearing Tombaugh's words, Slipher and Lampland rushed to the blink comparator to check Tombaugh's plates. The two older men confirmed Tombaugh's findings. "Don't tell anyone until we follow it for a few weeks. This could be very hot news," ordered Slipher. Excited, but cautious, Slipher wanted more evidence before going public.

Because three weeks had passed since the Gemini plates had been taken, an even more solid test thus presented itself. Based on the direction and degree of motion from January 21 to 29, a precise prediction of the suspected new position of the X prize could be made. If Tombaugh's target was truly a distant planet, it should show up on new plates about a centimeter from where it had been in late January. This kind of prediction check is a hallmark of careful observational astronomy. It had to be done – and done before any announcement could even be contemplated. It had to be done in part because it was in their own interest, but also, more importantly, because it was in their very bones as astronomers to check, and recheck their discovery so as not to set off a false alarm that could damage reputations.

However, as the sky darkened that evening, clouds covered northern Arizona, preventing planet hunting. The suspense must have been hard, but Tombaugh had no way to settle the matter! He would have to wait until the next night to try again. Frustrated and bored, Tombaugh went into Flagstaff to watch a movie. *The Virginian*, with Gary Cooper, was showing. Word was it was going to be a hit.

Fortunately, the sky was clear on the 19th, and Tombaugh was able to capture another photograph of the little spot of light placed against the pregnant star field. By the next morning, Tombaugh had developed the new plate. Then he, Slipher, and Lampland examined it together. Slipher also brought his brother, Earl, along.

The scene must have been a classic, with four pairs of eyes jockeying for position at the blink comparator. Lo and behold their little IT was there! And IT was exactly where the motion in the earlier images had predicted it would be.

Tombaugh's notebook records the reaction: "Each of the group took a look. There it was, a most unimportant-looking, dim, star-like object which had moved perceptibly ... but no disk could be made out."

No disk? Every planet ever seen by human eyes had showed a disk. Like its motion, this was something that distinguished the appearance of a planet from the stars. But maybe this one should not show a disk. It was, after all, very, very faint. Planet X had been predicted to be ten or twenty times fainter than Neptune, but this thing (maybe they should have written it as x, rather than X) was 250 times dimmer than Neptune.

Brother Earl reasoned that it might be small enough, and faint enough, and far enough away just to be a pinpoint, without detectable dimension in their tiny telescopes. To prove his point, Earl built a box with a disk-like hole in one side and a light within, and carried the box a mile from the observatory to convince the group that a faint and far away enough disk would look star-like. As Earl disappeared into the night, ever more distantly, the little disk grew smaller, and smaller, and smaller, until it finally became a pinpoint, just like X! It was a low-tech *tour de force* demonstration that convinced the others: if this new object was sufficiently small and sufficiently far away, it would move but not show a disk.

Now there was beginning to be a feeling that X was really a planet, though perhaps not the large one that Lowell and others had searched for and expected. Ever cautious, Slipher wanted to be even more sure. So, three further weeks of monitoring the motion of the new planet followed, verifying its rate of motion again and again. Amazingly, during all this time, no one breathed a word of it beyond Lowell Observatory.

Then, finally, on the evening of March 12 in Flagstaff,[4] Slipher released the news. After having followed Planet X for seven full weeks, Slipher officially announced the discovery on behalf of Lowell Observatory.

Slipher had selected the official date of March 13 to make the announcement because it held special significance: it was both the 149th anniversary of the date on which Uranus, the first planet[5] to have been discovered telescopically, was initially spotted in 1781, and it would have been Percival Lowell's 75th birthday.

Slipher's first announcement was in the form of a telegram sent via the observatory's trustee (Lowell's grandson, R. L. Putnam) to the Harvard College Observatory, which was the official clearinghouse for discoveries of new asteroids, comets, and novae. Telegrams were typically terse in those days and relatively expensive – one was charged for every word. Slipher's short missive read:

> "Systematic search begun years ago supplementing Lowell's investigations for Trans-Neptunian planet has revealed object which since seven weeks had in rate of mo-

tion and path consistently conformed to Trans-Neptunian body at approximate distance he assigned."

The honor of a second announcement was given to Lowell's widow, Constance. With Mrs Lowell's announcement the circle was complete.

It was done. The world now knew X existed. And the world responded. By 1930, the global village was already a real (if comparatively quaint) electronic construction. Headlines echoed the news: "Ninth planet Found at Edge of Solar System." "9th Planet, X, Is Found by US Scientists." Tombaugh's parents found out from a reporter! Muron's boy had become the hero of the story and a celebrity.

Within days, Tombaugh and company at Lowell were famous. Today the discovery would probably net the standard Warhol allotment of 15 minutes of fame. But in 1930 fame lasted a little longer. The media rush following the discovery went on for months.

But What to Call It?

Something deep-seated in human nature calls on us to name things. It is almost as if a thing is not real, or whole, until we name it. And so of course X *had* to have a name.

Suggestions flooded in: "Zeus," "Cronos," "Minerva." Widow Lowell herself first liked "Zeus," but then suggested "Percival," then "Lowell," and even "Constance," her own name, as candidates.

Soon dozens of other well-meaning suggestions poured in as well. There were hundreds, then thousands. But when all was said and done, the name that the Lowell staff preferred was the one suggested by 11-year-old Venetia Burney[6] of Oxford, England (Figure 1.9) – "Pluto," the Greek god of the Underworld, the brother of Jupiter, Neptune, and Juno, and third son of Saturn, who was able when he wished to render himself invisible.[7]

On May 1, 1930 Lowell Observatory's director, Vesto Slipher, lent his support to naming the new world Pluto; that clinched it. Both the American Astronomical Society and the UK's Royal Astronomical Society later that month adopted Pluto as the official name and ♇ as the official symbol for the new world. ♇, we note, was Percival

Fig. 1.9: Venetia Burney, who as an 11-year-old English schoolgirl suggested the name "Pluto" for the planet newly discovered by Clyde Tombaugh. (Courtesy Mrs Venetia Phair, née Burney)

Lowell's monogram, something that was not lost on those making the naming decision.

Pathways of the Gods

While the international press heralded the discovery of Pluto, astronomers around the world rushed to work out the orbit of the new planet. This was the natural first order of business. Without an orbit the ninth planet's ever-changing position could not be predicted, and the new world could become lost. Worse, its context among its eight more familiar sisters could not be even crudely judged until its orbit was known.

What exactly is a planetary orbit? The orbits of the planets are, simply put, their tracks around the Sun. Each orbit a planet makes is a lap on this repetitive course, and takes a period of time called the planet's "year."

The basic framework for understanding orbits was laid down in the sixteenth century by the Renaissance astronomer Johannes Kepler. Kepler's discoveries resulted from the mental sweat equity he invested to distil patterns from the motion of the six planets originally known to the ancients (Mercury, Venus, Earth, Mars, Jupiter, and Saturn). His three discoveries are so fundamental that they are remembered today, in his honor, as Kepler's laws. They are so powerful, and so utilitarian, that barring some disaster that sets humankind back to a medieval world, Kepler's laws will continue to be used by astronomers, navigators, and space pilots as long as our species endures.

Kepler's first law states that the orbit of a planet about the Sun is an ellipse (Figure 1.10). Kepler's second law states that the line joining a planet to the Sun sweeps out a constant area per unit of time. Sounds a little thick, perhaps, but from a pragmatic standpoint, rule number two means that planets move around the Sun more slowly when they are far from the Sun, and more rapidly when they are closer to it. Kepler's third law describes a simple equation, a numerical recipe, for calculating the length of a planet's "year" almost exactly, using just two observable quantities: the mass of the Sun and the planet's average distance from it.

In the three and a half centuries between the discovery of Kepler's laws and their application to Pluto, a considerable body of theory and observation had accumulated concerning the inner workings of orbits and the architecture of the solar system. By the late eighteenth century, for example, it had become possible to calculate the orbit of a planet from a few well-separated measurements of its position against the stars, and to then use the orbit solution so obtained to predict with high accuracy where the planet would be on any future date. This is not hard for silicon circuits, but it is not a trivial affair for computers made of flesh and blood. Why? Because in addition to the force exerted by the Sun's gravity, each planet's gravity also slightly affects the motion of the others. These other planetary tugs explain why Kepler's calculations were almost – but not quite – exact.

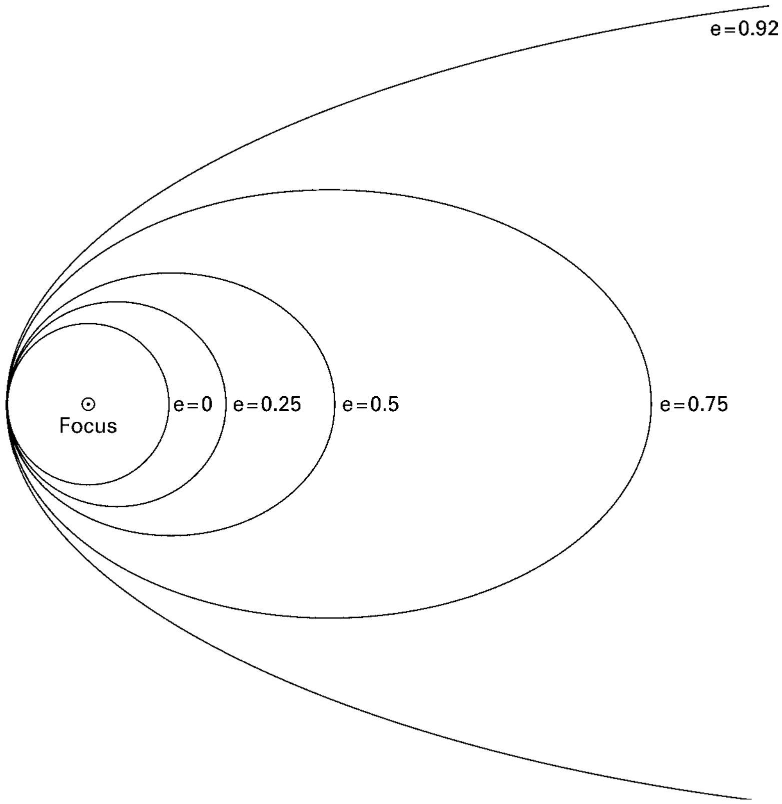

Fig. 1.10: As Johannes Kepler discovered, the orbits of the planets are ellipses, not perfect circles. This diagram shows a circle (zero eccentricity) and four ellipses of different eccentricity. The more elongated an ellipse, the greater its eccentricity, e. The point labeled "Focus" is the center of the circle and also one of the two foci of each ellipse. When a planet travels around the Sun in an elliptical orbit, the Sun is at one focus of the ellipse, which is not the center point (unless the orbit is perfectly circular). The ellipse with eccentricity 0.25 is about the same shape as Pluto's orbit. The ellipse with eccentricity 0.92 is so stretched out that only part of it can be shown. It is similar in size and shape to the very elongated orbits followed by comets such Halley, with periods of many decades or longer.

Against this background, many of the world's astronomers set out in 1930 to learn Pluto's orbit and compute its future path. Before revealing the surprises that they found, however, it is worthwhile to take a little detour to see the forest of the solar system as a whole, before we focus on the solitary sapling called Pluto.

Empty of Empties

In overview, the solar system is laid out with the Sun at its center, and the orbits of the widely spaced planets concentrically arranged outward, from Mercury to Neptune. The four innermost planets – the smaller, rocky ones – move in tight orbits close to the Sun. These so-called "terrestrial" planets share broadly similar qualities of size and rockiness. Apart from Mercury, each has a substantial but razor thin atmosphere surrounding it. Mercury's atmosphere is but a gossamer corona.

The smallest, Mercury, has a diameter of 3050 miles (4880 kilometers); the largest, Earth, has a diameter of 7970 miles (12 753 kilometers). The closer a planet is to the Sun, the more rapidly it completes its orbit. Mercury, for example, lying only about 40% as far from the Sun as the Earth does, completes each circuit in just 88 days.[8] Venus, which is 70% as far out as Earth requires 225 days to make each lap, and the Earth, of course, takes 365 days. Moving farther out, Mars takes about 1.9 Earth years to complete each orbit.

Venus and Earth orbit on ellipses barely distinguishable from circles, but Mercury and Mars follow more exaggerated ellipses that range farther afield. The deviation of an elliptical orbit from a circle is called its orbital eccentricity. (It might also be called the orbit's "eggyness," but this would sound less scientific.) The eccentricity of Earth's orbit is a little under 2%. Venus's orbital eccentricity is less than 1%, but Mars's is near 10% and Mercury's is almost 20%.

Beyond Mars, the final outpost of the terrestrial planets, lies the rocky asteroid belt, and then the vast and unabashedly bizarre wilderness inhabited by the four giant, outer planets: Jupiter, Saturn, Uranus, and Neptune. These Goliaths are enormous, cold worlds with poisonous atmospheres a thousand times deeper than Earth's thin but refreshing blue and breathable shell. Jupiter, the largest of the giants, could fit some 1400 Earths within itself! Even Neptune, the smallest of these giants, could swallow over 60 Earths (Figure 1.11).

The four giant planets travel in orbits that are all circular to within 5%. Their orbital periods (i.e., their own years) range from 12 Earth years for Jupiter to 167 years for Neptune. Jupiter and Saturn are bright enough to see easily by eye, and were known to the ancients as special "stars" that moved across the sky, like Mercury, Venus, and Mars. By contrast, Uranus and Neptune are much fainter, and were

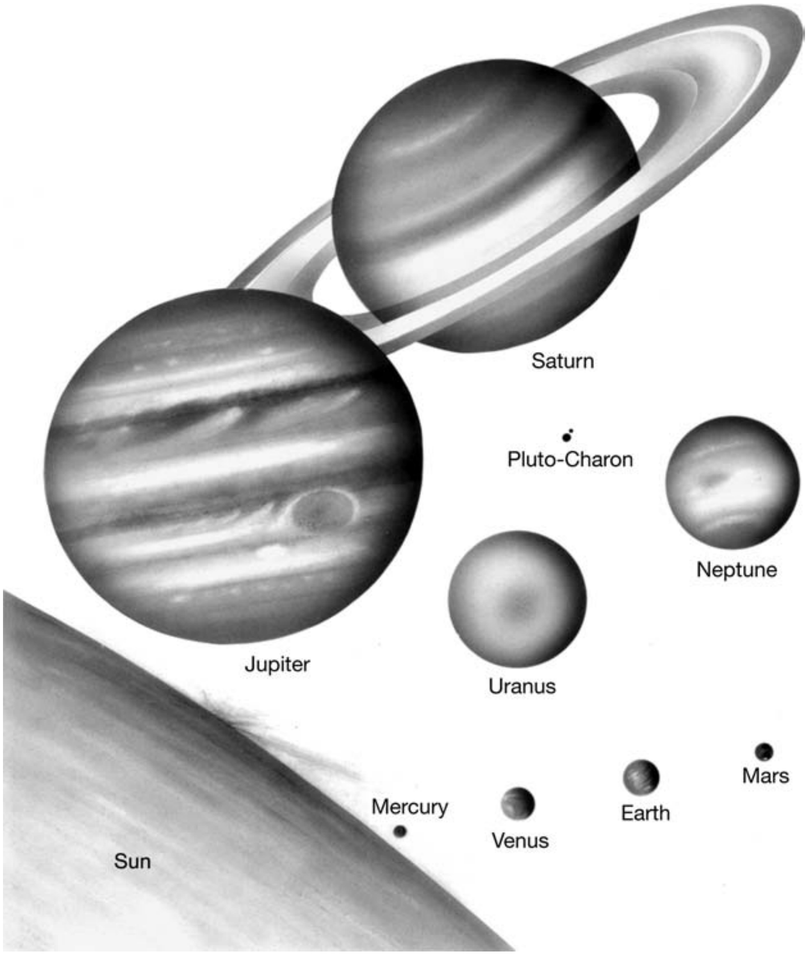

Fig. 1.11: The relative sizes of the nine major planets and the Sun are shown here to scale.

discovered only after the invention of the telescope and its application to astronomy.

The orbits of all eight planets from Mercury to Neptune lie close to a mathematical plane, an imaginary flat sheet extending out into space near the Sun's equator, which astronomers call the "invariable plane." The four inner planets all orbit within 6 degrees of the invariable plane. The four giant planets orbit even closer to this plane – none strays from it by more than 2 degrees.

Now consider the accompaniments of the planets: their rings and moons. Here, there is another major difference between the inner and the outer planets. The inner planets are not encircled with rings, and have *in toto* just one large satellite (our Luna) and two tiny moons hardly larger than a respectable county (Mars's Phobos and Deimos). In contrast, each of the giant planets displays a system of rings, and each possesses dozens of moons. Among the more than 100 moons discovered around the giant planets to date, five are larger than our own moon, and three are larger than Mercury itself. Most, however, are tiny, like Phobos and Deimos.

When we step back from these details, these trees that form our solar system's forest, something even more fundamental emerges. The central, overarching aspect of the planetary system that we all so commonly casually overlook is that it is almost completely empty.

The planets themselves are but specks, spaced across millions and even billions of miles of nothingness. If the Earth were reduced in size to a simple, blue basketball, the Sun itself thus illustrated would be just 100 feet (30 meters) in diameter. In this scale model, the Sun would lie almost 2.5 miles (4 kilometers) away from basketball Earth, with nothing but the little basketball Venus and baseball Mercury occupying the space between the two. In this miniature solar system, Jupiter, about 12 feet (3.7 meters) in diameter, would circle the Sun 10 miles (16 kilometers) away, followed by Saturn 20 miles (30 kilometers) out, Uranus some 40 miles (64 kilometers) out, and lonely Neptune 60 miles (97 kilometers) distant from the tiny yellow hearth, glowing down below. Thus, within the 80 miles (129 kilometers) corralled inside Neptune's orbit in our Tinker-toy™ model, there is nothing but the eight planets known prior to Pluto, their tinier-still retinue of satellites, together with a few thousand scale model asteroids (most no larger than sand grains), and perhaps a few hundred comets, each, like the asteroids, barely a grit of sand.

Empty of Empties! The magnitude of the solar system's emptiness is the essence of the place. Indeed it is almost but not quite, nothing but emptiness. This, of course, is why we call it "space."

It's a Rogue!

Engulfed within the wild, black emptiness, yet another billion miles in the distance beyond Neptune (20 miles (32 kilometers) in our scale model), Clyde Tombaugh had discovered Lowell's planet; our little *dyevoshka*, our Pluto.

Once Pluto's discovery and position became public knowledge, astronomers across the Americas, and Europe, and Asia, and Africa began to collect frequent observations of its position, so that an accurate orbit could be determined.

Two types of positional data came in. Most came in the form of measurements from new photographs, but some also came from the astronomical archives of the world, as various groups recognized that they had unwittingly photographed patches of sky containing Pluto over the 15 or so years prior to 1930. This kind of research is now common in astronomy, thanks to computer databases, but in the 1930s it was relatively novel since computers did not exist.

The pre-discovery observations of Pluto found in astronomical libraries were particularly useful, because they greatly extended the timebase over which accurate positions were known. Once located, they rapidly gave rise to an accurate orbit.

By the early summer of 1930, some 136 archival images of Pluto had been located on old plates taken before Tombaugh's discovery. Ironically, Seth Nicholson found that Milton Humason's old 1919 search for Pickering's Planet O had in fact netted four images in which Pluto faintly appeared! But Humason had not recognized the planet, in part because he had imaged it away from the opposition point, where planet detection is easiest and least ambiguous.[9]

Armed with accurate positions stretching back as far as 1914, several astronomers calculated and published similar solutions for Pluto's orbit in 1930 and 1931 (Figure 1.12). As a result, within about a year after Pluto had been found, its orbit had been reliably established. This is what was found:

- Pluto takes 248 years to complete an orbit – a record among the known planets. When Pluto was discovered it was heading toward its closest approach to the Sun, called perihelion, which it later reached in 1989. Its previous two perihelia occurred in 1741, when George Washington was only a boy, and in 1493,

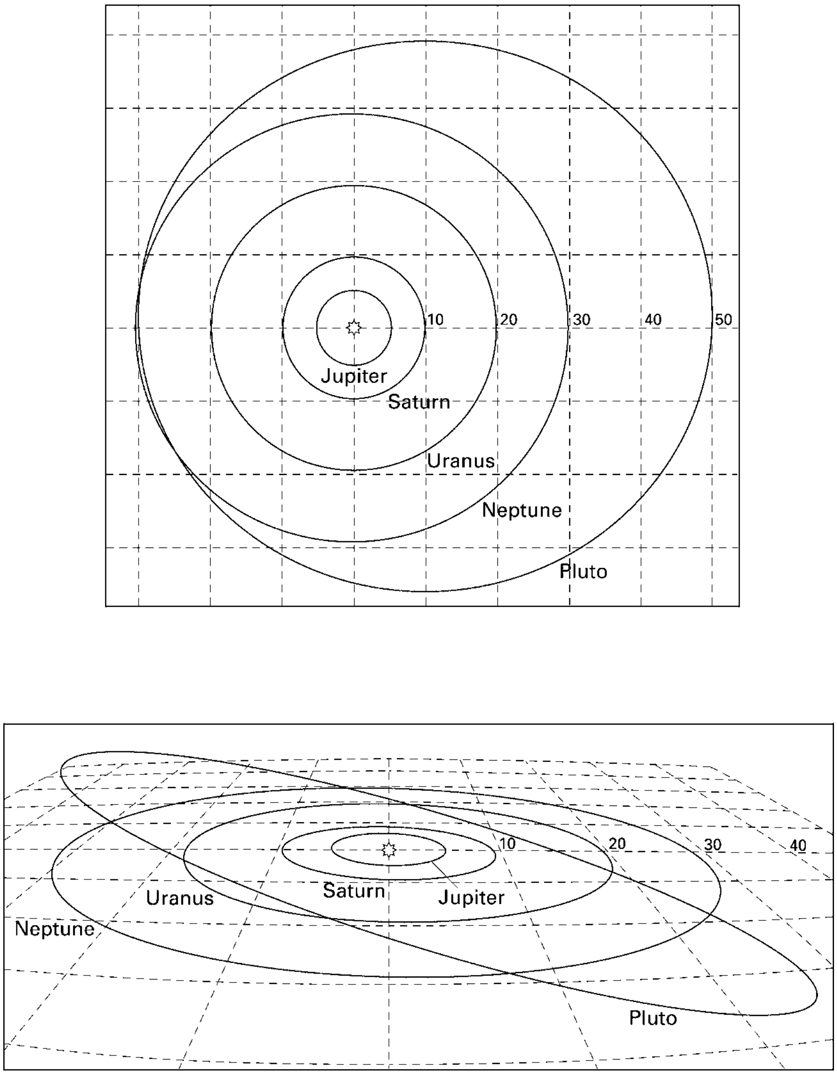

Fig. 1.12: The layout of planetary orbits in the outer solar system. The grids are labeled in astronomical units. Looking down on the plane of the solar system (top) shows how Pluto's strongly elliptical orbit crosses inside Neptune's. The foreshortened perspective view (bottom) shows the inclination of Pluto's orbit relative to the orbits of the other outer planets. The orbits of the inner planets, including Earth, are not shown here.

just months after Columbus had reported his explorations to the Reyes Catolicos. Pluto follows a long orbit indeed!

- While the other planets of the outer solar system follow ellipses that are typically eccentric by only 1% or 2%, Pluto's orbit stretches ellipticity to a new record among all the known planets – 25%! Each orbit Pluto wanders over a range of heliocentric (i.e., solar-centered) distances – from 3 to 5 billion miles (5 to 8 billion kilometers).
- Whereas all the other planets orbit within a few degrees of the invariable plane, Pluto's orbit is tipped away 16 degrees, far askew from the others.

Together, these findings painted a picture of a nearly fantastical orbit, unlike that of any other planet. Pluto's path is so strange, in fact, that near perihelion it actually crosses the orbit of Neptune, making it temporarily planet eight (not nine!) for a few decades every two centuries.

No other planet crosses inside another's orbit. How dare planet Pluto do that! Why? What kind of thing was this rogue roaming the frigid outback of the planetary system? It would take the remainder of the twentieth century to find out.