

Secrets of the Outer Solar System Revealed: Pluto, the Oort Comet Cloud, Centaurs, and the Kuiper Belt

Adapted from *Is Pluto a Planet?* (David A. Weintraub, 2007)

A New View of the Solar System

Astronomical discoveries in the twentieth century completely reshaped our understanding of our solar system, and thus of the likely sets of objects that orbit other stars. Rather than our solar system consisting of the Sun orbited by eight planets, an asteroid belt, and a few comets, we now know about the Kuiper Belt, the Oort Comet Cloud, centaurs in the outer part of the planetary part of the solar system, and of planet-sized objects in the trans-Neptunian zone. This is the story of how our new understanding developed over the last hundred years.

Predictions of the Existence of Planet X

Observations of the position of Uranus extending from 1690 to 1895 should have enabled astronomers to accurately predict its future locations, yet the planet was never quite where it was expected to be. In 1900, Danish astronomer Hans-Emil Lau predicted that the gravitational pulls from two unknown, massive planets in the distant solar system beyond Neptune were influencing the orbit of Uranus. He calculated the precise masses and locations of these two not-yet-observed planets, but Lau's planets were never found and do not exist.

Between 1901 and 1903, the Europeans Gabriel Dallet, Theodore Grigull and Vicomte du Ligondes separately all made similar calculations for the existence of a massive trans-Neptunian planet, the so-called Planet X. In 1902, a Russian, Alexander Garnowsky, predicted the existence of four massive, trans-Neptunian planets. In 1904, the American Thomas Jefferson Jackson See suggested that three massive, trans-Neptunian planets were waiting to be found. All these predictions included precise masses and locations of the planets. None of these planets were ever found. None of them exist.

This game had come to resemble the story of the boy who cried wolf. Predictions regarding trans-Neptunian planets were treated skeptically by most of the astronomy community, and this skepticism was reinforced by the disagreements in predictions between the advocates and the failures of any planet hunters to find any of these planets. Then, in one of the more prescient and underappreciated aspects of this enterprise, the Frenchman Jean Baptiste Aimable Gaillot reviewed the orbital data for Uranus and Neptune and concluded that the orbit of Uranus was well explained by the presence of Neptune, only. No Planet X exists, he said.

Percival Lowell and the Search for Planet X

The work of Gaillot put the issue of the existence of a trans-Neptunian planet to rest for most of the astronomy community, but not for all. Percival Lowell, a rich gentleman from Boston, trained in mathematics and a self-taught astronomer built himself an observatory in Flagstaff, Arizona dedicated to observing Mars and proving that Martians existed. Then he spent much of the last decade of his life, from 1906 through 1916, in a fruitless search for Planet X, taking long exposure photographs of the locations in the heavens where he predicted Planet X should be found. Amazingly, two of the photographic plates he obtained at Lowell Observatory in 1915 contain images of Pluto, but Lowell was looking for a much brighter (i.e., bigger) object and his sought-after Planet X slipped through his fingers.

Clyde Tombaugh discovers Pluto

When Lowell died in 1916, his hypothesized Planet X remained hidden in the darkness of the outer solar system. A decade later, the director of Lowell Observatory decided to launch a new search for Lowell's planet and hired amateur astronomer Clyde Tombaugh to assist in the program.

Tombaugh's work was exceedingly hard and tedious and required extraordinary dedication and patience. He spent his nights in a cold telescope dome, carefully acquiring long exposures on 14-inch x 17-inch photographic plates of carefully selected regions of the sky. Each region of the sky had to be observed multiple times. Then, by comparing the positions of the more than 300,000 stars on each plate with their positions on the same image of the sky obtained a few days later, Tombaugh looked for evidence of a slowly moving object.¹ His examination of only a few square inches of a pair of photographic plates was a full day's work. Nevertheless, on February 18, 1930, Tombaugh found Pluto while examining images obtained a month earlier.

Almost from the date on which the discovery of Pluto was announced, Pluto generated controversy: it was almost ten times fainter than Lowell had predicted for Planet X, and this implied that it was significantly smaller and less massive than predicted by Lowell for Planet X. With a low mass, Pluto could not perturb Uranus's orbit and thus could not generate the problems with the orbit that led Lowell (and others) to predict that Pluto existed!

Lowell had predicted a mass for Planet X of 6.6 Earth masses. Pluto, however, was too small for even the biggest telescopes to resolve. That is, it looked like a point of light, just like a star, showing no disk. Its combined smallness and brightness implied a physical mass well below Lowell's predictions. In fact, in 1930 using the measured brightness of Pluto and a value estimated for Pluto's reflectivity, English astronomer A. C. D.

¹ All of the stars remain in exactly the same positions in the sky, relative to each other, from night to night. But a planet would change positions relative to the stars.

Crommelin calculated a mass for Pluto of only 0.11 Earth masses. This created a catch-22 situation: if Pluto's mass was this small it could not exert a significant gravitational tug on Uranus, and if it couldn't tug on Uranus then there would have been no problems with understanding the orbit of Uranus, and if Uranus was always in the right place then Lowell could not have predicted that it existed, and without that prediction no search should have been done and Pluto should not have been found.

Yet not only was Pluto was found, it was found fairly close—only 5.8 degrees away—to one of the two positions predicted for it by Lowell. "Fairly close," like beauty, is in the eye of the beholder. In 1846, Johann Galle had located Neptune only 55 minutes of arc, or just less than one degree, from the position predicted for it a year before by Urbain Le Verrier. In other words, Le Verrier's prediction for the position of Neptune was six times better than the positions predicted for Pluto by Lowell. Given that Lowell predicted two positions for Planet X, on opposite ends of the sky, the part of the sky within six degrees east or west of both of those positions encompasses 24 degrees, or 7%, of the band of the sky called the ecliptic. In fact, Tombaugh had already searched star fields in Aquarius, Pisces, Aries and Taurus, before he found Pluto in Gemini. He had searched more than one third of the zodiac, the set of constellations that enclose the ecliptic, prior to stumbling upon Pluto.

Calculations by P. Baldi and M. Caputo, in 1974, shrunk Pluto further, to between 0.004 to 0.014 Earth masses, making it comparable to or smaller in mass than the Moon (0.012 Earth masses). Then in 1976, Dale Cruikshank, Carl Pilcher and David Morrison, of the University of Hawaii were able to determine that Pluto was better at reflecting light than anyone previously thought; rather than being dark, like coal, Pluto is bright, like freshly made ice. With a surface that efficiently reflects light back to Earth, Pluto could be smaller and still reflect the same total amount of light as would a Pluto with a dark surface. Cruikshank and his colleagues estimated Pluto's mass to be only 0.003 Earth masses, less than one three-hundredths of the mass of the Earth and barely one-quarter the mass of the Moon.

In 1978, James Christy of the U.S. Naval Observatory discovered that Pluto had a moon, which he named Charon. From Kepler's laws, the orbital period of a moon combined with the size of the orbit immediately gives the total mass of the planet plus the mass of the moon. Christy and his colleague Robert Harrington used this method to calculate the total combined system mass; they obtained an answer of 0.0023 Earth masses. Since Charon was much fainter than Pluto, it almost certainly was much smaller and less massive than Pluto. On this basis, Christy and Harrington guessed that ~90% of the total mass of the Pluto-plus-Charon system would be the mass of Pluto. With Charon discovered and its orbit known, Pluto's mass had shrunk to very nearly 0.002 Earth masses. Today, using data collected by the New Horizons spacecraft that flew past Pluto in 2015, we know Pluto's mass with great precision. It is only 0.00219 Earth masses, about 450 times less massive than the Earth and only one-sixth the mass of the Moon.

Pluto never quite disappeared, but it came close. More importantly, by 1978 it was abundantly clear that Pluto was not Planet X. Pluto was not capable of exerting any significant gravitational tugs on Uranus. In fact, despite the great distances between the planets, the Earth has greater perturbative effects on the orbits of both Uranus and Neptune than does Pluto. *The existence of Pluto, and certainly the actual location of Pluto, simply could not have been predicted by Lowell or anyone else. Yet, Pluto was discovered. Why?*

We now know that all the predictions for the existence of Planet X were based on attributing a greater accuracy to the data in-hand than that data merited (all measurements have errors, and those errors were ignored) and in interpreting those data with a subtle bias in which calculations and conclusions were overly influenced by expectations. Some astronomers hoped, too much, for the fame that would accrue to the one who correctly predicted the location of Planet X. The bottom line is that Clyde Tombaugh should never have been hired for the specific project of finding Percival Lowell's planet. Yet, Tombaugh was hired, and within a few months Tombaugh found Pluto. *Simply put, the object Tombaugh found was not the object he was looking for and the object he was looking for does not exist.* So why did Tombaugh find Pluto relatively near the location predicted for Planet X?

The answer would become apparent with the discovery of a previously unknown structure in the solar system, the Kuiper Belt, of which Pluto is the biggest (so far) known member. Pluto was found because anyone who looked hard enough in enough directions would eventually have found a Pluto-sized object in the outer solar system.

The Oort Comet Cloud

On November 1, 1977, Charles Kowal, working with a pair of images obtained on October 18 and 19 with the 1.22 m telescope on Palomar Mountain in southern California, discovered a heretofore unknown object in the outer solar system. Using the same technique as that employed in 1930 by Clyde Tombaugh to discover Pluto, Kowal saw that his object, Chiron, moved about three minutes of arc through the background stars over the course of 24 hours. An additional observation obtained by Tom Gehrels on the same telescope a week *before* Kowal obtained his data, and other predisccovery photographs dating back to 1895, permitted Brian Marsden, Director of the Minor Planet Center in Cambridge, Massachusetts, to calculate the orbit of this new object. Kowal's object has a semi-major axis of 13.7 AU and an orbital eccentricity of 0.38, making it an odd and extraordinary find^{2,3}. This semi-major axis placed the newly discovered object far beyond the outer edge of the asteroid belt, which lies between the orbits of Mars (beyond 3 AU) and Jupiter (inside of 5 AU), but well inside the Oort Comet Cloud, the

² Planets orbit in ellipses (not circles). The semi-major axis is half of the long axis of the ellipse. The eccentricity measures how close to (or far from) round the ellipse is.

³ 1AU (astronomical unit), or 149.6 million kilometers, is approximately the average distance of the Earth from the Sun.

reservoir for comets that lies well outside of the orbit of Pluto. This netherland between the Oort Cloud and the asteroid belt was thought to be empty except for the giant planets and Pluto; yet, Kowal had found an object in that vast emptiness.

Chiron is an icy, cometlike body but with a diameter of ~210 km is far bigger than any known normal comet⁴. Given its high eccentricity, Chiron is on an unstable orbit. At perihelion⁵, Chiron reaches 8.4 AU while at aphelion⁶, it moves as far from the Sun as 18.8 AU. Such an orbit is extremely unstable against perturbations caused by the gravitational influences of the giant planets: Chiron can come as close as 0.4 AU to Uranus and as close as 3.2 AU to Jupiter, and it *crosses* Saturn's orbit and thus could collide with Saturn or an object in the Saturn moon or ring system. Such near encounters allow the giant planets to tug at Chiron and continually change its orbit; eventually, these small changes will almost certainly cause Chiron to come so close to a giant planet that it will experience one or more dramatic, close encounters. In the not-too-distant future, one of these close gravitational encounters undoubtedly will toss Chiron out of its current orbit. Chiron's new orbit may guide it into the inner solar system, perhaps directly into the Sun or onto a collision course with Earth or Jupiter or Saturn, or the new orbit may cast Chiron right out of the solar system into interstellar space. Chiron's future is nearly a mirror image of its past: it must have experienced a series of close gravitational encounters that tossed it into its current orbit. Clearly, Chiron must have come from somewhere else prior to finding itself in its current location in the solar system. But from where could Chiron have come?

The first hint of "from where?" had emerged three decades earlier, in the work of the Irishman Kenneth Edgeworth and the Dutchman Gerard Kuiper. Edgeworth speculated that at great distances from the Sun, the processes that would contribute toward making planets would operate much more slowly and likely would fail, prior to completion, leaving many small planets rather than one large planet in the trans-Neptune zone of the solar system. In a 1949 paper, he suggested the possibility that such a reservoir might still exist and might be the nearly stable home of the *short-period comets*, prior to those objects being perturbed into the inner solar system where we see them. Kuiper, using different arguments, came to a similar conclusion. Edgeworth's and Kuiper's work was largely ignored and then forgotten for many decades.

In the 1940s, Dutch astronomer Jan Oort recognized that many comets came from vast distances (tens of thousands of AU) from the Sun. We recognize two types of comets, long-period comets and short-period comets. Long-period comets are seen once in human history; they have orbital periods of thousands of years or longer and therefore have semi-major axes of many hundreds, thousands or even tens of thousands of AU. These enormous orbits explain why, to astronomers in the seventeenth century, most comets appeared to move in parabolic arcs. Short-period comets are those like Comet Halley,

⁴ Most comets are only a few kilometers across.

⁵ The closest approach to the Sun of an object in an elliptical orbit.

⁶ The furthest point from the Sun of an object in an elliptical orbit.

objects that have orbits small enough and orbital periods short enough to make possible multiple returns to the inner solar system in recorded history, or even in a single human lifetime.

Oort concluded that the Sun was surrounded by a vast, spherical cloud of comets—the reservoir of *long-period comets*—that we now call the **Oort Cloud**. These comets orbit at distances of tens of thousands of AU from the Sun, in fairly circular orbits, preserved in the freezer of cold space far from the Sun. The outer edge of the Oort Cloud may extend as far as 50,000 AU from the Sun, nearly halfway to the nearest star. Over long periods of time, the gravitational influences of passing stars kick comets out of their huge orbits into new orbits. Some of those new orbits will bring comets into the inner solar system where we see them. After an Oort Cloud comet is kicked inwards toward the Sun and passes into the inner solar system, it will warm up. Surface ices will sublime—that is, the ices pass directly from solids into gases—and the comet will develop the distinctive coma and tail appearance we associate with them; then, following their highly elliptical orbits, many of these long-period comets will return to the Oort Cloud, where they can hide for thousands of years, in frozen hibernation at the distant edge of the solar system while others will pass right through the Oort Cloud and into interstellar space, escaping the Sun’s gravity completely and forever.

Centaurs

Short-period comets have orbital properties that are different from those of long-period comets. With orbital periods comparable to the orbital period of Jupiter (12 years), short-period comets not only must cross the orbits of the inner planets but also must have close encounters with Jupiter. With each passage into the inner solar system, a comet’s icy surface heats up and the ices sublime into a coma and tail. The material that enters the coma or tail is lost by the comet. As a comet loses mass, its orbit changes. In addition, after enough orbits, unavoidable, close gravitational encounters with Jupiter and the inner planets doom such objects to short lives as short-period comets. Eventually, such an object will shrivel to a tiny remnant of its original size, crash into one of the planets or the Sun, or get slingshot by Jupiter out of the solar system. Since short-period comets have short lives, like long-period comets they must have a home, a freezer compartment within the bounds of the solar system from which they emerge. And where is that freezer?

In contrast to long-period comets, almost all short-period comets have prograde orbits (the same direction as all the planets)—Comet Halley is the most notable exception—with low inclinations to the ecliptic plane⁷. Edgar Everhart, in 1972, suggested that these orbital properties of short-period comets demand that they do not come from the spherical Oort Cloud. Instead, they had to come from a reservoir confined to a flattened volume of space near the plane of the planetary system. Julio Fernandez, of Uruguay, suggested that the gravitational pull of Neptune pulls comets out of a comet reservoir

⁷ The plane in which the major planets orbit the Sun.

located in the ecliptic plane just beyond Neptune, in the trans-Neptunian zone. With the work of Fernandez, Edgeworth's and Kuiper's idea of what became known as the **Kuiper Belt** was reborn.

Just five years later, Chiron was found. Was Chiron an object recently ejected from the Kuiper Belt? If so, more such objects must exist, and soon more of them were found. On the ninth of January 1992, David Rabinowitz of Spacewatch discovered an outer solar system object he named Pholus, Chiron's mythological brother. Like Chiron, Pholus is fairly large, with a diameter of about 190 km. Also like Chiron, Pholus has a very eccentric and unstable orbit. Pholus' closest approach to the Sun is at a distance of only 8.7 AU, inside of Saturn's orbit; at its most distant orbital point, Pholus crosses the orbits of both Uranus and Neptune, reaching a distance of 31.9 AU. Thus, Pholus is a Saturn crosser, a Uranus crosser and a Neptune crosser and is in a dramatically unstable orbit. Now, in addition to planets, moons, asteroids and comets, we can add to the census of solar system objects the **centaurs**, of which there were now two known⁸. Furthermore, we know that the centaurs represent objects ripped by the gravitational pull of Neptune inwards from the not-yet-found Kuiper Belt; so, even though no Kuiper Belt objects had yet been found within the confines of the belt, the presence of two centaurs was a strong hint that another population of objects, **Kuiper Belt objects**, or KBOs, must exist but had simply escaped detection, thus far.

Discovery of the Kuiper Belt

On August 30, 1992, David Jewitt and Jane Luu discovered Albion, the first object known *within* the expected confines of the Kuiper Belt, which extends from just beyond the orbit of Neptune (about 30 AU) out to about 50 AU from the Sun. Albion has a semi-major axis of 44.0 AU, a fairly low eccentricity of 0.07, and a diameter of 280 km.

Six months after the initial discovery of Albion, Jewitt and Luu found another Kuiper Belt candidate, 1993 FW, with an orbit slightly greater than that of Pluto and a diameter of 290 km. The Kuiper Belt now had a known population of two objects. Another six months later, on two consecutive days, September 14 and 15, 1993, Jewitt and Luu rounded up two more Kuiper Belt candidates, 1993 RO (diameter = 140 km) and 1993 RP (diameter unknown). Only days after Jewitt and Luu's September 1993 discoveries, the observing team of Iwan Williams, Alan Fitzsimmons, and Donal O'Ceallaigh discovered 1993 SB (diameter = 190 km) and 1993 SC (diameter = 320 km). In the span of just 12 months, Jewitt, Luu Williams, Fitzsimmons, and O'Ceallaigh had populated the hypothesized Kuiper Belt with six objects⁹.

The Giants of the Kuiper Belt

⁸ A few hundred centaurs have been discovered. Astronomers estimate the population of centaurs to be in the millions.

⁹ Astronomers estimate that the Kuiper Belt contains hundreds of thousands of objects larger than 100 km across, and trillions of smaller objects.

The biggest such objects among these newly discovered outer solar system objects include 2002 TC₃₀₂ (diameter >500 km), Varuna (diameter ~700 km), Ixion (diameter ~710 km), Aya (diameter ~700-800 km), Orcus (diameter ~900 km), Sedna (diameter ~900 km), Quaoar (diameter ~1100 km), Haumea (diameter = 1200-1500 km), Makemake (diameter ~1600 km), and Eris (diameter = 2326 km). In comparison, the diameter of Pluto is 2377 km. Thus, Pluto is the largest, though not by much, of the large, currently known trans-Neptunian objects. And all of these objects likely are massive enough for their own gravitational pulls to shape them into nearly spherical objects.

Beginning with that of Albion, with the rapid discovery, of hundreds of objects in the trans-Neptunian region, the Kuiper Belt has become a known part of the solar system and a more distant, colder analog of the asteroid belt. Many of these objects are comparable in size to, and several are larger in diameter than the largest asteroid, Ceres, which has a diameter of about 925 km.

Post-facto, early nineteenth-century astronomers realized that Ceres, the largest of the asteroids, was fortuitously (but not surprisingly) the first-discovered member of a whole population of objects that collectively comprise the asteroid belt. When discovered, astronomers recognized it as a planet. Within a few decades, and after the discovery of dozens of other objects in the asteroid belt, Ceres was reclassified as an asteroid¹⁰. Similarly, the largest known object in the Kuiper Belt, Pluto, was discovered before astronomers knew that the Kuiper Belt existed.

Is Pluto a Planet?

At the end of the twentieth century, the debate over the answer to the question *Is Pluto a planet?* spilled into the public domain because large objects in the Kuiper Belt comparable in size to Pluto had been found. Either Pluto and some of these other objects are all planets, or none of them are. What, exactly, is a planet, and is Pluto one?

The word ‘planet’ is derived from the Greek word for wandering star, *planetos*. To the ancient Greeks, ‘wandering stars’ were heavenly bodies they distinguished from the ‘fixed stars.’ Planets changed positions in the sky, relative to the stars, while the stars themselves appear fixed in place relative to each other. The seven planets, in the order of their accepted distance from the Earth—which they believed was the center of the universe—were the Moon, Mercury, Venus, the Sun, Mars, Jupiter, and Saturn. And so, to the ancient Greeks *both the Sun and the Moon were planets, but the Earth was not!* Four centuries ago, at the time when Copernicus, Kepler and Galileo made their discoveries, did the Sun change from a planet into a star? Did the Earth change from the center of the universe into a planet? Of course not. Apparently, though, new discoveries changed *our understanding* of what is meant by *planet*; hence, at the moment when our understanding changed, we reclassified the Sun as a star, the Moon as a satellite of a

¹⁰ Asteroids are also known as minor planets.

planet, and the Earth as a planet and discarded the previous meaning of the word ‘planet.’

In the twentieth century, the discovery of the Kuiper Belt and at least one Pluto-sized object in the Kuiper Belt led the International Astronomical Union, in the first decade of the twenty-first century, to attempt to update our definition of the word ‘planet.’ And while a new definition was approved (barely), the definition is extremely flawed and eventually we will, once again, need to revisit the meaning of the word ‘planet.’

In Prague, on August 24, 2006, the 26th General Assembly of the International Astronomical Union (IAU)—an organization of just under 10,000 members—by a simple majority vote of only the 424 members present, passed resolutions redefining *planet* and establishing a new class of objects in the solar system to be called “dwarf planets.” The new definition of *planet* was carefully crafted to exclude Pluto. Here is the exact text of those resolutions:

IAU Resolution: Definition of a “Planet” in the Solar System

Contemporary observations are changing our understanding of planetary systems, and it is important that our nomenclature for objects reflect our current understanding. This applies, in particular, to the designation “planets.” The word “planet” originally described “wanderers” that were known only as moving lights in the sky. Recent discoveries lead us to create a new definition, which we can make using currently available scientific information.

RESOLUTION 5A

The IAU therefore resolves that planets and other bodies in our Solar System, except satellites, be defined into three distinct categories in the following way:

- (1) A “planet”¹ is a celestial body that
 - a. is in orbit around the Sun,
 - b. has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and
 - c. has cleared the neighbourhood around its orbit.
- (2) A “dwarf planet” is a celestial body that
 - a. is in orbit around the Sun,
 - b. has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape,
 - c. has not cleared the neighbourhood around its orbit, and
 - d. is not a satellite.
- (3) All other objects, except satellites, orbiting the Sun shall be referred to collectively as “Small Solar System Bodies.”

¹ The eight planets are: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune.

IAU Resolution: Pluto

RESOLUTION 6A

The IAU further resolves:

Pluto is a “dwarf planet” by the above definition and is recognized as the prototype of a new category of trans-Neptunian objects.

The IAU members present for this vote agreed that, as a part of Resolution 6A, the IAU should create a process to establish a name for this category of objects. As a final step, the IAU approved an amendment to the above definition that requires that the words “dwarf planets” be used with inverted commas¹¹.

These resolutions were hastily put together and not carefully reviewed by the international astronomy community, and many members of the professional community find them problematic, at best. For example,

- What criteria determine whether a planet has ‘cleared the neighborhood around its orbit’? Pluto crosses Neptune’s orbit, and so Neptune also crosses Pluto’s orbit. Does this mean that neither has cleared its neighborhood? So isn’t Neptune a “dwarf planet”?
- The planet-sized objects that orbit other stars are not planets since the IAU resolution defines planets as objects that are “in orbit around the Sun.” So the only planets that exist in the universe (according to this definition) orbit the Sun. This makes no sense.
- The upper mass limit for a planet is undefined.
- The shape of an object depends on what it is made of (iron? rock? ice?), not just on how massive it is, so two objects might have the same mass (and the same ability to clear the neighborhood), but only one might be nearly round.
- The use of “dwarf planet” always inside inverted commas reflects disquiet about using the term directly. And in 2025 virtually no one—whether professionals, lay writers, or teachers—say or write *dwarf planet* rather than *quote unquote dwarf planet*. If no one uses the inverted commas, then is a dwarf planet simply a planet, albeit one that is small?

¹¹ Inverted commas is the European term for quotation marks.