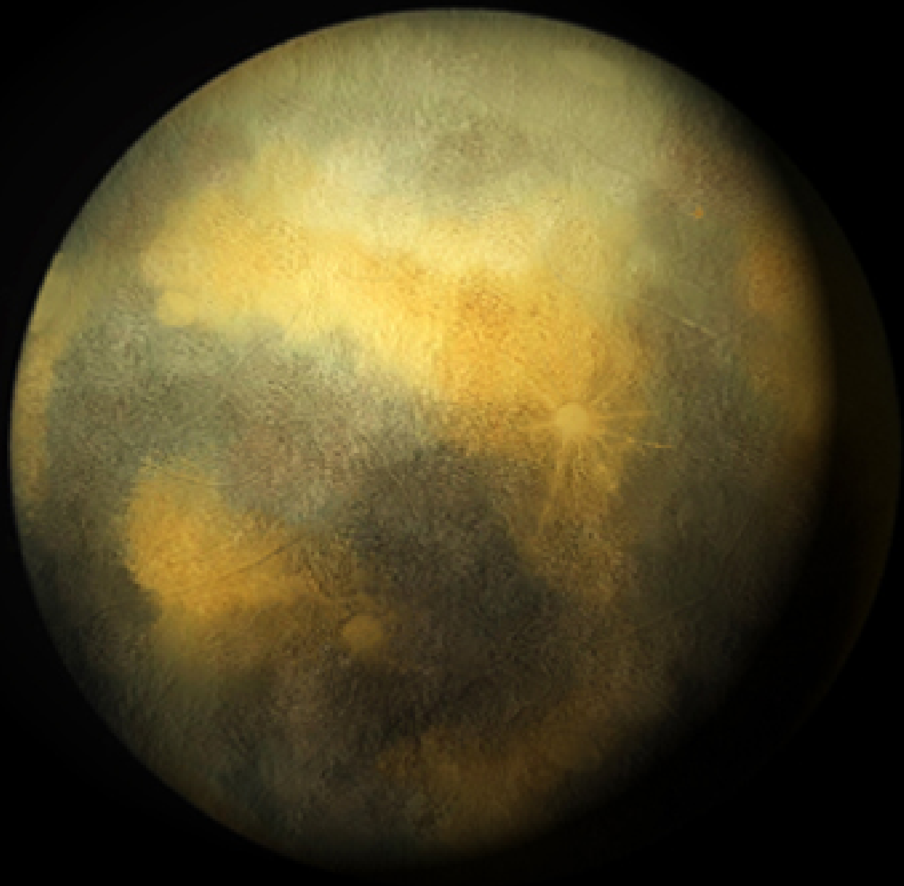
All About

Asteroids and Dwarf Planets



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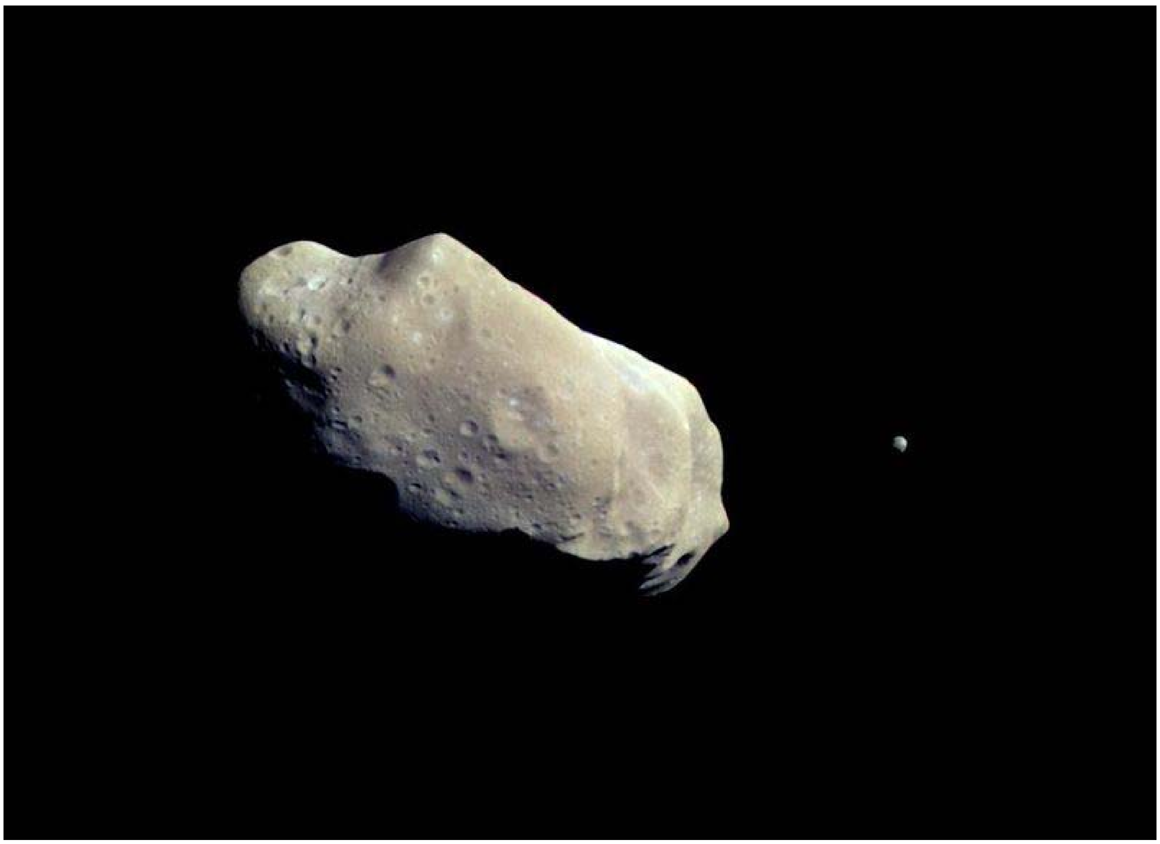
Asteroid

253 Mathilde, a C-type asteroid measuring about 50 kilometres (30 mi) across. Photograph taken in 1997 by the NEAR Shoemaker probe.

Asteroids (from Greek, ἀστήρ ”star” + εἶδος “like”, in form), sometimes grouped with centaurs, Neptune trojans and trans-Neptunian objects into **minor planets** or **planetoids**, are a class of small Solar System bodies in orbit around the Sun. The term "asteroid" was historically applied to any astronomical object orbiting the Sun that was not observed to have the characteristics of an active comet or a planet, but it has increasingly come to particularly refer to the small rocky and metallic bodies of the inner Solar System and out to the orbit of Jupiter. As small objects in the outer Solar System have begun to be discovered their observed composition differs from the objects historically termed asteroids. Harbouring predominantly volatiles-based material similar to comets rather than the more familiar rocky or metallic asteroids, they are often distinguished from them.

There are millions of asteroids, and like most other small Solar System bodies the asteroids are thought to be remnants of planetesimals, material within the young Sun's solar nebula that have not grown large enough to form planets. The large majority of known asteroids orbit in the main asteroid belt between the orbits of Mars and Jupiter, however many different orbital families exist with significant populations including Jupiter Trojans and near-Earth asteroids. Individual asteroids are categorized by their characteristic spectra, with the majority falling into three main groups: C-type, S-type, and M-type. These are generally identified with carbon-rich, stony, and metallic compositions respectively.

Discovery

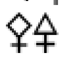
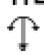
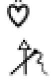


243 Ida and its moon Dactyl. Dactyl is the first satellite of an asteroid to be discovered.

The first named minor planet, Ceres, was discovered in 1801 by Giuseppe Piazzi, and was originally considered a new planet. This was followed by the discovery of other similar bodies, which with the equipment of the time appeared to be points of light, like stars, showing little or no planetary disc (though readily distinguishable from stars due to their apparent motions). This prompted the astronomer Sir William Herschel to propose the term "asteroid", from Greek *αστεροειδής*, *asteroeidēs* = star-like, star-shaped, from ancient Greek *Αστήρ*, *astēr* = star. In the early second half of the nineteenth century, the terms "asteroid" and "planet" (not always qualified as "minor") were still used interchangeably; for example, the *Annual of Scientific Discovery for 1871*, page 316, reads "Professor J. Watson has been awarded by the Paris Academy of Sciences, the astronomical prize, Lalande foundation, for the discovery of 8 new asteroids in one year. The planet Lydia (No. 110), discovered by M. Borelly at the Marseilles Observatory [...] M. Borelly had previously discovered 2 planets bearing the numbers 91 and 99 in the system of asteroids revolving between Mars and Jupiter" (emphasis added).

Symbols

The first few asteroids discovered were assigned symbols like the ones traditionally used to designate Earth, the Moon, the Sun and planets. The symbols quickly became ungainly, hard to draw and recognize. By the end of 1851 there were 15 known asteroids, each (except one) with its own symbol(s).

Asteroid	Symbol
Ceres	
2 Pallas	
3 Juno	
4 Vesta	
5 Astraea	
6 Hebe	
7 Iris	
8 Flora	
9 Metis	
10 Hygiea	
11 Parthenope	
12 Victoria	
13 Egeria	Never assigned.
14 Irene	"A dove carrying an olive-branch, with a star on its head," never drawn.
15 Eunomia	
28 Bellona	
35 Leukothea	
37 Fides	
2060 Chiron	

Johann Franz Encke made a major change in the Berliner Astronomisches Jahrbuch (BAJ, Berlin Astronomical Yearbook) for 1854. He introduced encircled numbers instead of symbols, although his numbering began with Astraea, the first four asteroids continuing to be denoted by their traditional symbols. This symbolic innovation was adopted very quickly by the astronomical community. The following year (1855), Astraea's number was bumped up to 5, but Ceres through Vesta would be listed by their numbers only in the 1867 edition. A few more asteroids (28 Bellona, 35 Leukothea, and 37 Fides) would be given symbols and numbers. The circle would become a pair of parentheses, and the parentheses sometimes omitted altogether over the next few decades.

Naming

A newly discovered asteroid is given a provisional designation (such as 2002 AT_4) consisting of the year of discovery and an alphanumeric code indicating the half-month of discovery and the sequence within that half-month. Once an asteroid's orbit has been confirmed, it is given a number, and later may also be given a name (e.g. 433 Eros). The formal naming convention uses parentheses around the number (e.g. (433) Eros), but dropping the parentheses is quite common. Informally, it is common to drop the number altogether, or to drop it after the first mention when a name is repeated in running text.

Historical methods

Asteroid discovery methods have dramatically improved over the past two centuries.

In the last years of the 18th century, Baron Franz Xaver von Zach organized a group of 24 astronomers to search the sky for the missing planet predicted at about 2.8 AU from the Sun by the Titius-Bode law, partly because of the discovery, by Sir William Herschel in 1781, of the planet Uranus at the distance predicted by the law. This task required that hand-drawn sky charts be prepared for all stars in the zodiacal band down to an agreed-upon limit of faintness. On subsequent nights, the sky would be charted again and any moving object would, hopefully, be spotted. The expected motion of the missing planet was about 30 seconds of arc per hour, readily discernible by observers.

The first asteroid, 1 Ceres, was not discovered by a member of the group, but rather by accident in 1801 by Giuseppe Piazzi, director of the observatory of Palermo in Sicily. He discovered a new star-like object in Taurus and followed the displacement of this object during several nights. His colleague, Carl Friedrich Gauss, used these observations to find the exact distance from this unknown object to the Earth. Gauss' calculations placed the object between the planets Mars and Jupiter. Piazzi named it after Ceres, the Roman goddess of agriculture.

Three other asteroids (2 Pallas, 3 Juno, and 4 Vesta) were discovered over the next few years, with Vesta found in 1807. After eight more years of fruitless searches, most astronomers assumed that there were no more and abandoned any further searches.

However, Karl Ludwig Hencke persisted, and began searching for more asteroids in 1830. Fifteen years later, he found 5 Astraea, the first new asteroid in 38 years. He also found 6 Hebe less than two years later. After this, other astronomers joined in the search and at least one new asteroid was discovered every year after that (except the wartime year 1945). Notable asteroid hunters of this early era were J. R. Hind, Annibale de Gasparis, Robert Luther, H. M. S. Goldschmidt, Jean Chacornac, James Ferguson, Norman Robert Pogson, E. W. Tempel, J. C. Watson, C. H. F. Peters, A. Borrelly, J. Palisa, the Henry brothers and Auguste Charlois.

In 1891, however, Max Wolf pioneered the use of astrophotography to detect asteroids, which appeared as short streaks on long-exposure photographic plates. This dramatically increased the rate of detection compared with earlier visual methods: Wolf alone discovered 248 asteroids, beginning with 323 Brucia, whereas only slightly more than 300 had been discovered up to that point. It was known that there were many more, but most astronomers did not bother with them, calling them "vermin of the skies", a phrase due to Edmund Weiss. Even a century later, only a few thousand asteroids were identified, numbered and named.

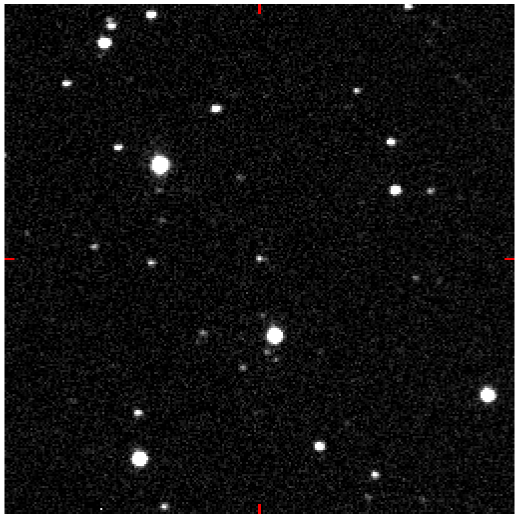
Manual methods of the 1900s and modern reporting

Until 1998, asteroids were discovered by a four-step process. First, a region of the sky was photographed by a wide-field telescope, or Astrograph. Pairs of photographs were taken, typically one hour apart. Multiple pairs could be taken over a series of days. Second, the two films of the same region were viewed under a stereoscope. Any body in orbit around the Sun would move slightly between the pair of films. Under the stereoscope, the image of the body would seem to float slightly above the background of stars. Third, once a moving body was identified, its location would be measured precisely using a digitizing microscope. The location would be measured relative to known star locations.

These first three steps do not constitute asteroid discovery: the observer has only found an apparition, which gets a provisional designation, made up of the year of discovery, a letter representing the half-month of discovery, and finally a letter and a number indicating the discovery's sequential number (example: 1998 FJ_{74}).

The last step of discovery is to send the locations and time of observations to the Minor Planet Center, where computer programs determine whether an apparition ties together earlier apparitions into a single orbit. If so, the object receives a catalogue number and the observer of the first apparition with a calculated orbit is declared the discoverer, and granted the honor of naming the object subject to the approval of the International Astronomical Union.

Computerized methods



2004 FH is the center dot being followed by the sequence; the object that flashes by during the clip is an artificial satellite.

There is increasing interest in identifying asteroids whose orbits cross Earth's, and that could, given enough time, collide with Earth. The three most important groups of near-Earth asteroids are the Apollos, Amors, and Atens. Various asteroid deflection strategies have been proposed, as early as the 1960s.

The near-Earth asteroid 433 Eros had been discovered as long ago as 1898, and the 1930s brought a flurry of similar objects. In order of discovery, these were: 1221 Amor, 1862 Apollo, 2101 Adonis, and finally 69230 Hermes, which approached within 0.005 AU of the Earth in 1937. Astronomers began to realize the possibilities of Earth impact.

Two events in later decades increased the alarm: the increasing acceptance of Walter Alvarez' hypothesis that an impact event resulted in the Cretaceous-Tertiary extinction, and the 1994 observation of Comet Shoemaker-Levy 9 crashing into Jupiter. The U.S. military also declassified the information that its military satellites, built to detect nuclear explosions, had detected hundreds of upper-atmosphere impacts by objects ranging from one to 10 metres across.

All these considerations helped spur the launch of highly efficient automated systems that consist of Charge-Coupled Device (CCD) cameras and computers directly connected to telescopes. Since 1998, a large majority of the asteroids have been discovered by such automated systems. A list of teams using such automated systems includes:

- The Lincoln Near-Earth Asteroid Research (LINEAR) team
- The Near-Earth Asteroid Tracking (NEAT) team
- Spacewatch
- The Lowell Observatory Near-Earth-Object Search (LONEOS) team

- The Catalina Sky Survey (CSS)
- The Campo Imperatore Near-Earth Objects Survey (CINEOS) team
- The Japanese Spaceguard Association
- The Asiago-DLR Asteroid Survey (ADAS)

The LINEAR system alone has discovered 97,470 asteroids, as of September 18, 2008. Among all the automated systems, 4711 near-Earth asteroids have been discovered including over 600 more than 1 km (0.6 mi) in diameter. The rate of discovery peaked in 2000, when 38,679 minor planets were numbered, and has gone down steadily since then (719 minor planets were numbered in 2007).

Terminology

Traditionally, small bodies orbiting the Sun were classified as asteroids, comets or meteoroids, with anything smaller than ten metres across being called a meteoroid. The term "asteroid" is ill-defined. It never had a formal definition, with the broader term minor planet being preferred by the International Astronomical Union from 1853 on. In 2006, the term "small Solar System body" was introduced to cover both most minor planets and comets. Other languages prefer "planetoid" (Greek for "planet-like"), and this term is occasionally used in English for the larger asteroids. The word "planetesimal" has a similar meaning, but refers specifically to the small building blocks of the planets that existed when the Solar System was forming. The term "planetule" was coined by the geologist William Daniel Conybeare to describe minor planets, but is not in common use.

When found, asteroids were seen as a class of objects distinct from comets, and there was no unified term for the two until "small Solar System body" was coined in 2006. The main difference between an asteroid and a comet is that a comet shows a coma due to sublimation of near surface ices by solar radiation. A few objects have ended up being dual-listed because they were first classified as minor planets but later showed evidence of cometary activity. Conversely, some (perhaps all) comets are eventually depleted of their surface volatile ices and become asteroids. A further distinction is that comets typically have more eccentric orbits than most asteroids; most "asteroids" with notably eccentric orbits are probably dormant or extinct comets.

For almost two centuries, from the discovery of the first asteroid, Ceres, in 1801 until the discovery of the first centaur, 2060 Chiron, in 1977, all known asteroids spent most of their time at or within the orbit of Jupiter, though a few such as 944 Hidalgo ventured far beyond Jupiter for part of their orbit. When astronomers started finding more small bodies that permanently resided further out than Jupiter, now called centaurs, they numbered them among the traditional asteroids, though there was debate over whether they should be classified as asteroids or as a new type of object. Then, when the first trans-Neptunian object, 1992 QB1, was discovered in 1992, and especially when large numbers of similar objects started turning up, new terms were invented to sidestep the issue: Kuiper belt object, trans-Neptunian object, scattered-disc object, and so on. These inhabit the cold outer reaches of the Solar System where ices remain solid and comet-like bodies are not expected to exhibit much cometary activity; if centaurs or trans-Neptunian objects were to venture close to the Sun, their volatile ices would sublimate, and traditional approaches would classify them as comets and not asteroids.

The innermost of these are the Kuiper belt objects, called "objects" partly to avoid the need to classify them as asteroids or comets. They are believed to be predominantly comet-like in composition, though some may be more akin to asteroids. Furthermore, most do not have the highly eccentric orbits associated with comets, and the ones so far discovered are larger than traditional comet nuclei. (The much more distant Oort cloud is hypothesized to be the main reservoir of dormant comets.) Other recent observations, such as the analysis of the cometary dust collected by the Stardust probe, are increasingly blurring the distinction between comets and asteroids, suggesting "a continuum between asteroids and comets" rather than a sharp dividing line.

The minor planets beyond Jupiter's orbit are sometimes also called "asteroids", especially in popular presentations. However, it is becoming increasingly common for the term "asteroid" to be restricted to minor planets of the inner Solar System. Therefore, here we will restrict itself for the most part to the classical asteroids: objects of the main asteroid belt, Jupiter trojans, and near-Earth objects.

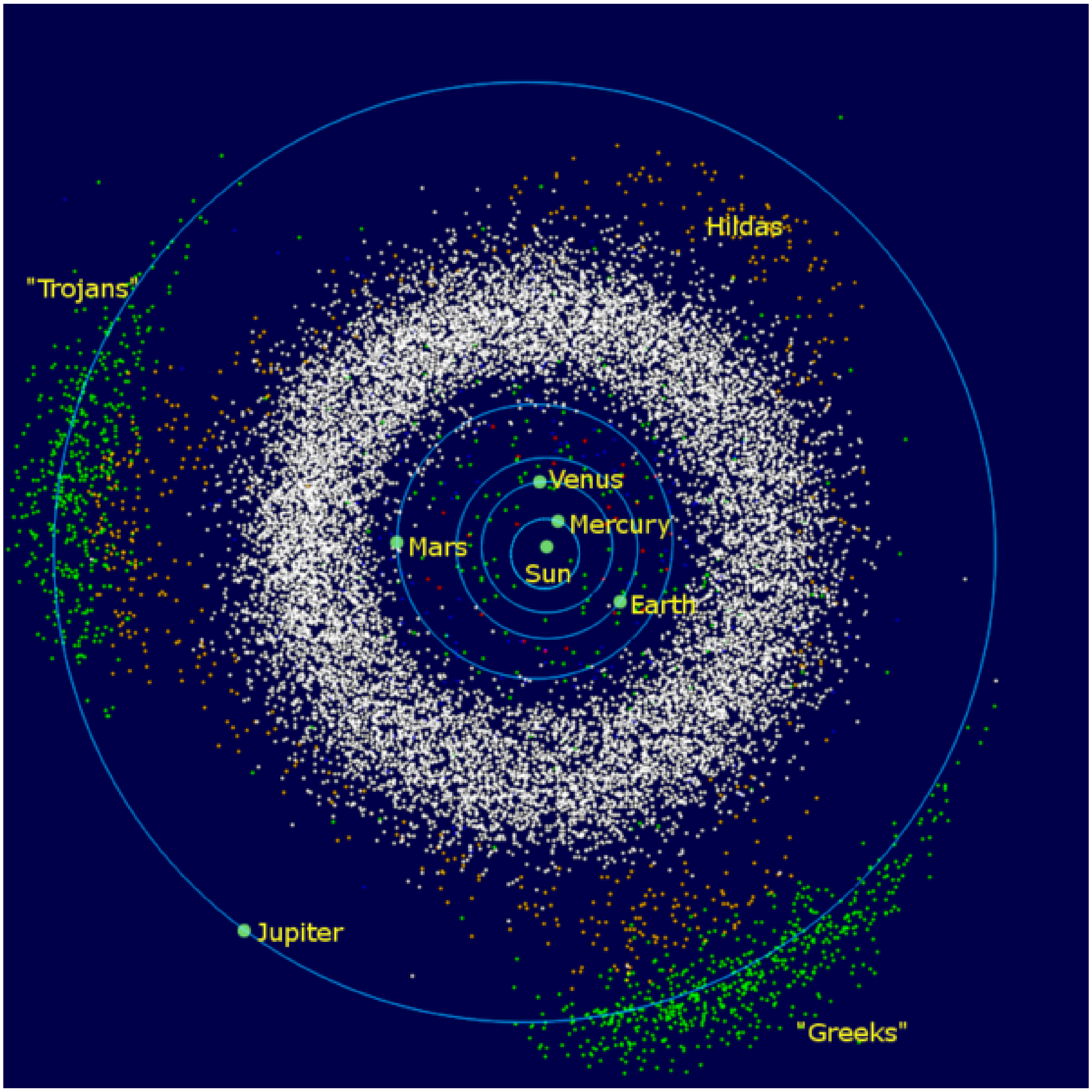
When the IAU introduced the class small solar system bodies in 2006 to include most objects previously classified as minor planets and comets, they created the class of dwarf planets for the largest minor planets—those that have enough mass to have become ellipsoidal under their own gravity. According to the IAU, "the term 'minor planet' may still be used, but generally the term 'small solar system body' will be preferred." Currently only the largest object in the asteroid belt, Ceres, at about 950 km (590 mi) across, has been placed in the dwarf planet category, although there are several large asteroids (Vesta, Pallas, and Hygiea) that may be classified as dwarf planets when their shapes are better known.

Formation

It is believed that planetesimals in the main asteroid belt evolved much like the rest of the solar nebula until Jupiter neared its current mass, at which point excitation from orbital resonances with Jupiter ejected over 99% of planetesimals in the belt. Simulations and a discontinuity in spin rate and spectral properties suggest that asteroids larger than approximately 120 km (75 mi) in diameter accreted during that early era, whereas smaller bodies are fragments from collisions between asteroids during or after the Jovian disruption. At least two asteroids, Ceres and Vesta, grew large enough to melt and differentiate, with heavy metallic elements sinking to the core, leaving rocky minerals in the crust.

In the Nice model, many Kuiper Belt objects are captured in the outer Main Belt, at distances greater than 2.6 AU. Most were later ejected by Jupiter, but those that remained may be the D-type asteroids, and possibly include Ceres.

Distribution within the Solar System



The Main asteroid belt (white) and the Trojan asteroids (green)

Various dynamical groups of asteroids have been discovered orbiting in the inner Solar System. Significant populations include;

Main asteroid belt

The majority of known asteroids orbit within the main asteroid belt between the orbits of Mars and Jupiter, generally in relatively low-eccentricity (i.e., not very elongated) orbits. This belt is now estimated to contain between 1.1 and 1.9 million asteroids larger than 1 km (0.6 mi) in diameter, and millions of smaller ones. These asteroids may be remnants of the protoplanetary disk, and in this region the accretion of planetesimals into planets during the formative period of the solar system was prevented by large gravitational perturbations by Jupiter.

Trojans

Trojan asteroids are a population that share an orbit with a larger planet or moon, but do not collide with it because they orbit in one of the two Lagrangian points of stability, L4 and L5, which lie 60° ahead of and behind the larger body.

The most significant population of Trojan asteroids are the Jupiter Trojans. Although fewer Jupiter Trojans have been discovered as of 2010, it is thought that there are as many as there are asteroids in the main belt.

A couple trojans have also been found orbiting with Mars.

Near-Earth asteroids

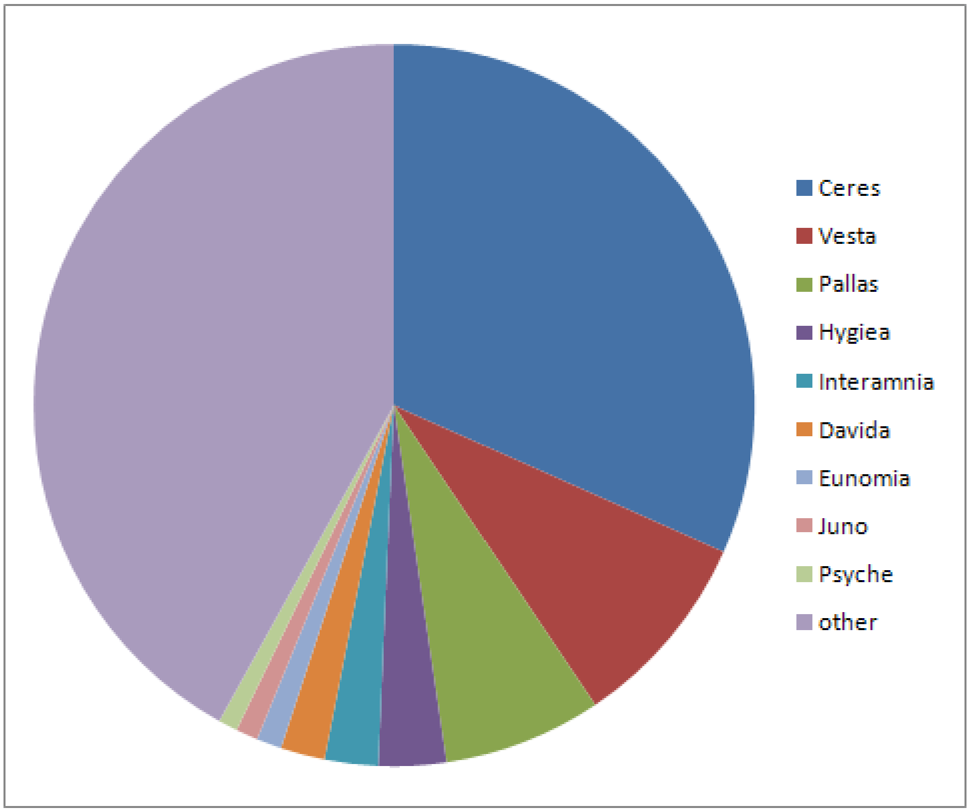
Near-Earth asteroids, or NEA's, are asteroids that have orbits that pass close to that of Earth. Asteroids that actually cross the Earth's orbital path are known as *Earth-crossers*. As of May 2010, 7,075 near-Earth asteroids are known and the number over one kilometre in diameter is estimated to be 500 - 1,000.

Characteristics

Size distribution

Asteroid Vesta (left) and dwarf planet Ceres (center), with Earth's Moon (right) shown to scale

Objects in the main asteroid belt vary greatly in size, from almost 1000 kilometres for the largest down to rocks just tens of metres across. The three largest are very much like miniature planets: they are roughly spherical, have at least partly differentiated interiors, and are thought to be surviving protoplanets. The vast majority, however, are much smaller and are irregularly shaped; they are thought to be either surviving planetesimals or fragments of larger bodies.



The relative masses of the nine largest main-belt asteroids for which precise data is available, compared to the remaining mass of the main belt.

Ceres	511 Davida
4 Vesta	15 Eunomia
2 Pallas	3 Juno
10 Hygiea	16 Psyche
704 Interamnia	All others

The dwarf planet Ceres is the largest object in the asteroid belt, with a diameter of 975 km (610 mi). The next largest are the asteroids 2 Pallas and 4 Vesta, both with diameters of just over 500 km (300 mi). Normally Vesta is the only main belt asteroid that can, on occasion, become visible to the naked eye. However, on some rare occasions, a near-Earth asteroid may briefly become visible without technical aid; 99942 Apophis.

The mass of all the objects of the Main asteroid belt, lying between the orbits of Mars and Jupiter, is estimated to be about $3.0\text{-}3.6\times10^{21}$ kg, or about 4 percent of the mass of the Moon. Of this, Ceres comprises 0.95×10^{21} kg, some 32 percent of the total. Adding in the next three most massive objects, Vesta (9%), Pallas (7%), and Hygiea (3%), brings this figure up to 51%; while the three after that, 511 Davida (1.2%), 704 Interamnia (1.0%), and 52 Europa (0.9%), only add another 3% to the total mass. The number of asteroids then increases rapidly as their individual masses decrease.

The number of asteroids decreases markedly with size. Although this generally follows a power law, there are 'bumps' at 5 km and 100 km, where more asteroids than expected from a logarithmic distribution are found.

Approximate number of asteroids N larger than diameter D

D	100 m	300 m	500 m	1 km	3 km	5 km	10 km	30 km	50 km	100 km	200 km	300 km	500 km	900 km
N	~25,000,000	4,000,000	2,000,000	750,000	200,000	90,000	10,000	1100	600	200	30	5	3	1

Composition

The physical composition of asteroids is varied and in most cases poorly understood. Ceres appears to be composed of a rocky core covered by an icy mantle, where Vesta is thought to have a nickel-iron core, olivine mantle, and basaltic crust. 10 Hygiea, however, which appears to have a uniformly primitive composition of carbonaceous chondrite, is thought to be the largest undifferentiated asteroid. Many, perhaps most, of the smaller asteroids are piles of rubble held together loosely by gravity. Some have moons or are co-orbiting binary asteroids. The rubble piles, moons, binaries, and scattered asteroid families are believed to be the results of collisions that disrupted a parent asteroid.

Asteroids contain traces of amino-acids and other organic compounds, and some speculate that asteroid impacts may have seeded the early Earth with the chemicals necessary to initiate life, or may have even brought life itself to Earth.

Only one asteroid, 4 Vesta, which has a reflective surface, is normally visible to the naked eye, and this only in very dark skies when it is favorably positioned. Rarely, small asteroids passing close to Earth may be naked-eye visible for a short time.

The orbits of asteroids are often influenced by the gravity of other bodies in the solar system or the Yarkovsky effect.

Classification

Asteroids are commonly classified according to two criteria: the characteristics of their orbits, and features of their reflectance spectrum.

Orbital classification

Many asteroids have been placed in groups and families based on their orbital characteristics. Apart from the broadest divisions, it is customary to name a group of asteroids after the first member of that group to be discovered. Groups are relatively loose dynamical associations, whereas families are tighter and result from the catastrophic break-up of a large parent asteroid sometime in the past. Families have only been recognized within the main asteroid belt. They were first recognised by Kiyotsugu Hirayama in 1918 and are often called Hirayama families in his honor.

About 30% to 35% of the bodies in the main belt belong to dynamical families each thought to have a common origin in a past collision between asteroids. A family has also been associated with the plutoid dwarf planet Haumea.

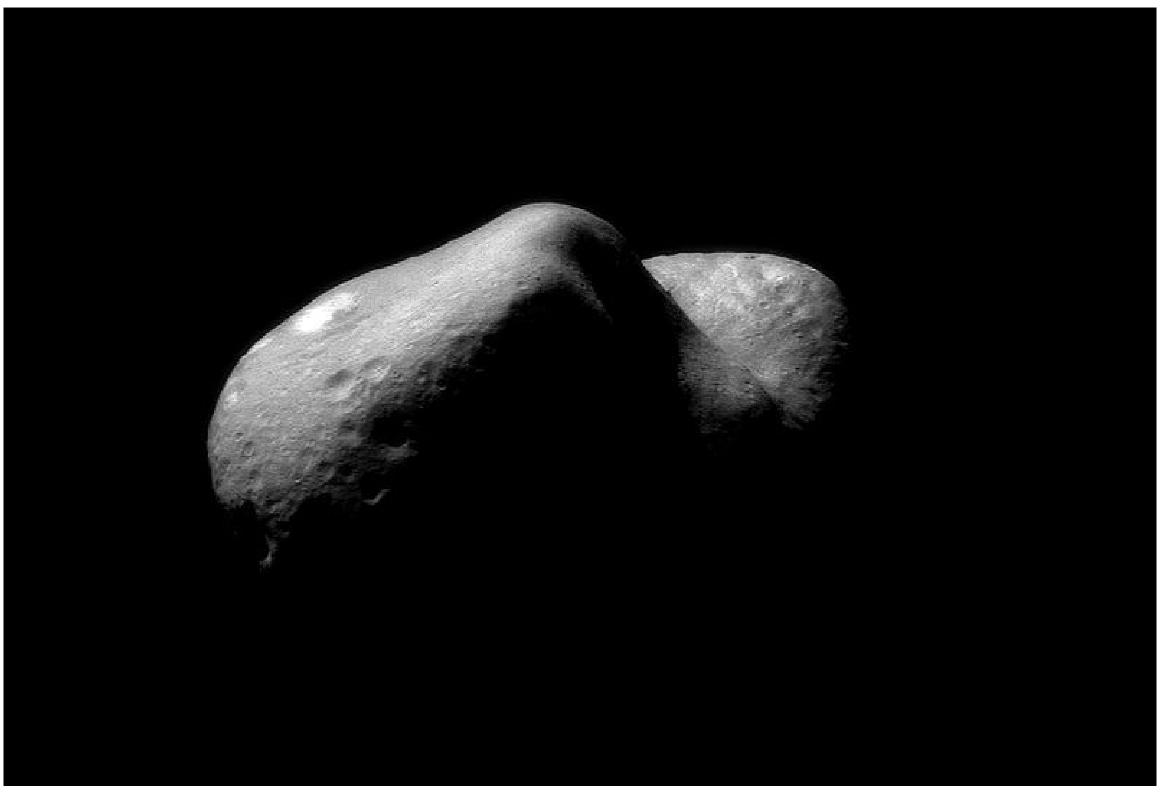
Quasi-satellites and horseshoe objects

Some asteroids have unusual horseshoe orbits that are co-orbital with the Earth or some other planet. Examples are 3753 Cruithne and 2002 AA_{29}. The first instance of this type of orbital arrangement was discovered between Saturn's moons Epimetheus and Janus.

Sometimes these horseshoe objects temporarily become quasi-satellites for a few decades or a few hundred years, before returning to their earlier status. Both Earth and Venus are known to have quasi-satellites.

Such objects, if associated with Earth or Venus or even hypothetically Mercury, are a special class of Aten asteroids. However, such objects could be associated with outer planets as well.

Spectral classification



This picture of 433 Eros shows the view looking from one end of the asteroid across the gouge on its underside and toward the opposite end. Features as small as 35 m (115 ft) across can be seen.

In 1975, an asteroid taxonomic system based on colour, albedo, and spectral shape was developed by Clark R. Chapman, David Morrison, and Ben Zellner. These properties are thought to correspond to the composition of the asteroid's surface material. The original classification system had three categories: C-types for dark carbonaceous objects (75% of known asteroids), S-types for stony (silicaceous) objects (17% of known asteroids) and U for those that did not fit into either C or S. This classification has since been expanded to include many other asteroid types. The number of types continues to grow as more asteroids are studied.

The two most widely used taxonomies now used are the Tholen classification and SMASS classification. The former was proposed in 1984 by David J. Tholen, and was based on data collected from an eight-color asteroid survey performed in the 1980s. This resulted in 14 asteroid categories. In 2002, the Small Main-Belt Asteroid Spectroscopic Survey resulted in a modified version of the Tholen taxonomy with 24 different types. Both systems have three broad categories of C, S, and X asteroids, where X consists of mostly metallic asteroids, such as the M-type. There are also several smaller classes.

Note that the proportion of known asteroids falling into the various spectral types does not necessarily reflect the proportion of all asteroids that are of that type; some types are easier to detect than others, biasing the totals.

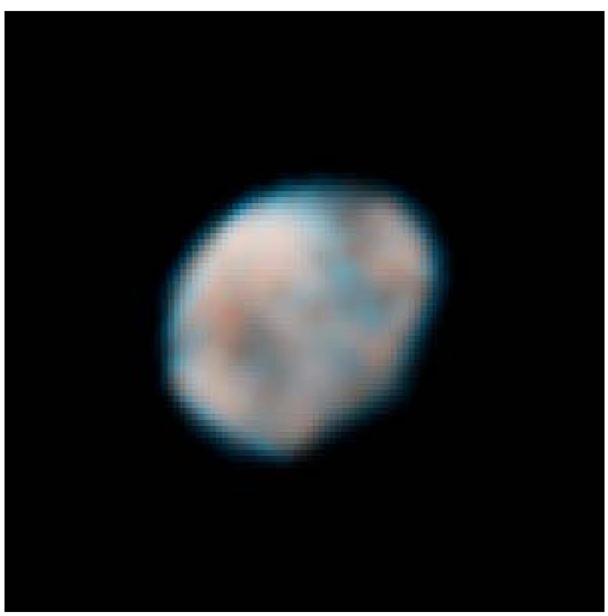
Problems

Originally, spectral designations were based on inferences of an asteroid's composition. However, the correspondence between spectral class and composition is not always very good, and a variety of classifications is in use. This has led to significant confusion. While asteroids of different spectral classifications are likely to be composed of different materials, there are no assurances that asteroids within the same taxonomic class are composed of similar materials.

At present, the spectral classification based on several coarse resolution spectroscopic surveys in the 1990s is still the standard. Scientists cannot agree on a better taxonomic system, largely due to the difficulty of obtaining detailed measurements consistently for a large sample of asteroids (e.g. finer resolution spectra, or non-spectral data such as densities would be very useful).

Exploration

951 Gaspra is the first asteroid to be imaged in close-up



Vesta, imaged by the Hubble Space Telescope

Until the age of space travel, objects in the asteroid belt were merely pinpricks of light in even the largest telescopes and their shapes and terrain remained a mystery. The best modern ground-based telescopes and the Earth-orbiting Hubble Space Telescope can resolve a small amount of detail on the surfaces of the largest asteroids, but even these mostly remain little more than fuzzy blobs. Limited information about the shapes and compositions of asteroids can be inferred from their light curves (their variation in brightness as they rotate) and their spectral properties, and asteroid sizes can be estimated by timing the lengths of star occulations (when an asteroid passes directly in front of a star). Radar imaging can yield good information about asteroid shapes and orbital and rotational parameters, especially for near-Earth asteroids.

The first close-up photographs of asteroid-like objects were taken in 1971 when the Mariner 9 probe imaged Phobos and Deimos, the two small moons of Mars, which are probably captured asteroids. These images revealed the irregular, potato-like shapes of most asteroids, as did later images from the Voyager probes of the small moons of the gas giants.

The first true asteroid to be photographed in close-up was 951 Gaspra in 1991, followed in 1993 by 243 Ida and its moon Dactyl, all of which were imaged by the Galileo probe en route to Jupiter.

The first dedicated asteroid probe was NEAR Shoemaker, which photographed 253 Mathilde in 1997, before entering into orbit around 433 Eros, finally landing on its surface in 2001.

Other asteroids briefly visited by spacecraft en route to other destinations include 9969 Braille (by Deep Space 1 in 1999), and 5535 Annefrank (by Stardust in 2002).

In September 2005, the Japanese Hayabusa probe started studying 25143 Itokawa in detail and was plagued with difficulties, but returned samples of its surface to earth on June 13, 2010.

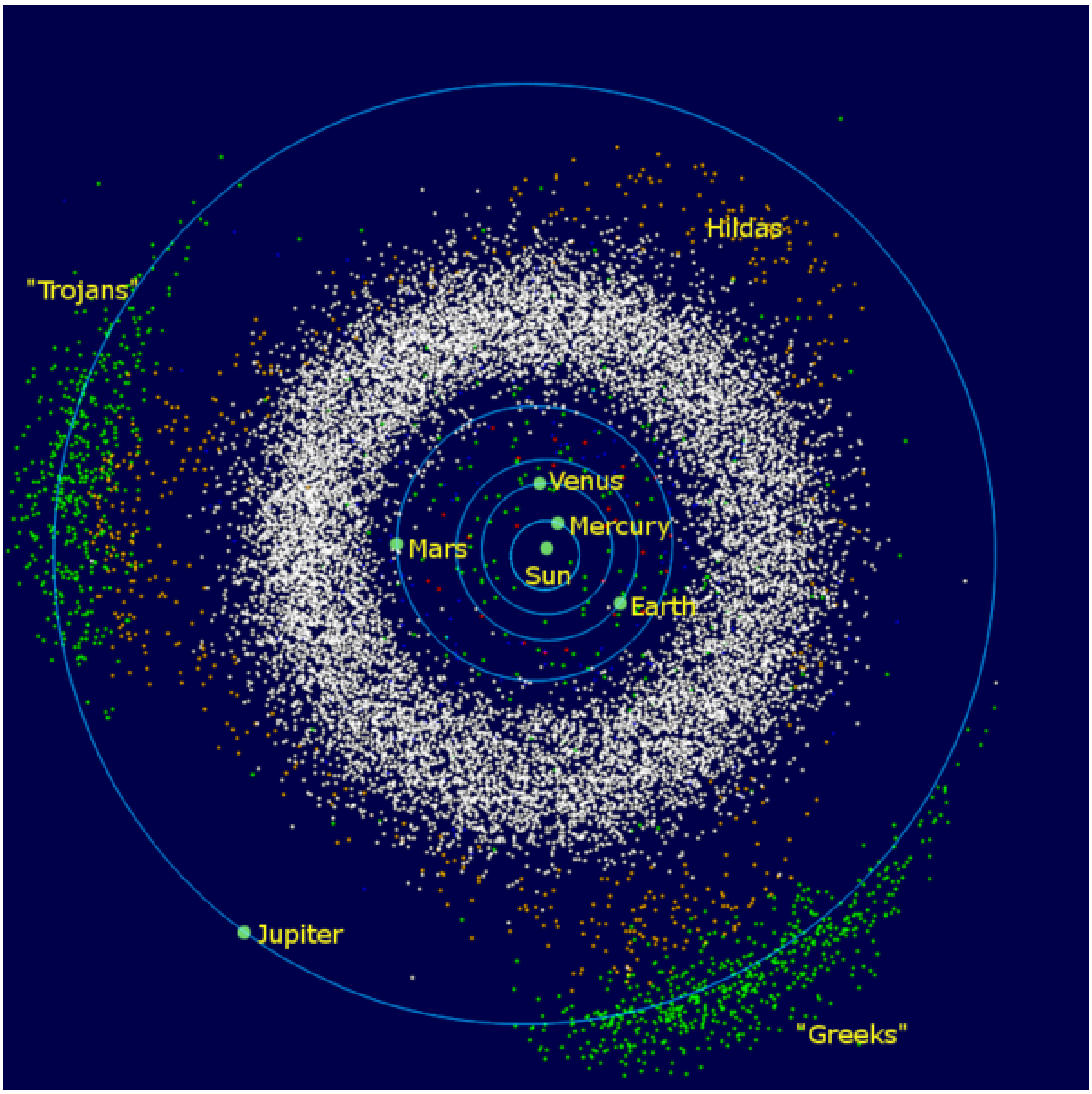
The European Rosetta probe (launched in 2004) flew by 2867 Šteins in 2008 and 21 Lutetia, the largest asteroid visited to date, in 2010.

In September 2007, NASA launched the Dawn Mission, which will orbit the protoplanet 4 Vesta in 2011 and the dwarf planet Ceres in 2015.

It has been suggested that asteroids might be used as a source of materials that may be rare or exhausted on earth (asteroid mining), or materials for constructing space habitats. Materials that are heavy and expensive to launch from earth may someday be mined from asteroids and used for space manufacturing and construction.

Chapter 2

Asteroid Belt



The main asteroid belt (shown in white) is located between the orbits of Mars and Jupiter

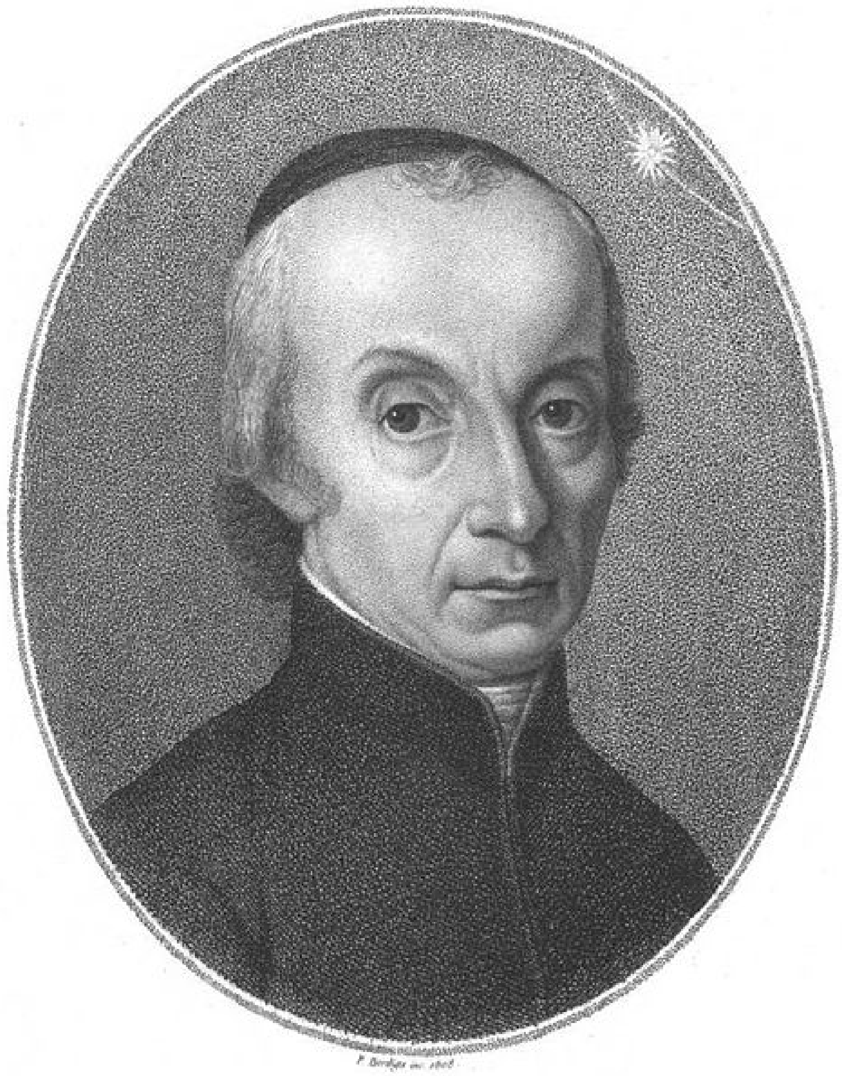
The **asteroid belt** is the region of the Solar System located roughly between the orbits of the planets Mars and Jupiter. It is occupied by numerous irregularly shaped bodies called asteroids or minor planets. The asteroid belt region is also termed the **main asteroid belt** or **main belt** because there are other asteroids in the solar system such as near-Earth asteroids and trojan asteroids.

More than half the mass of the main belt is contained in the four largest objects: Ceres, 4 Vesta, 2 Pallas, and 10 Hygiea. These have mean diameters of more than 400 km, while Ceres, the main belt's only dwarf planet, is about 950 km in diameter. The remaining bodies range down to the size of a dust particle. The asteroid material is so thinly distributed that multiple unmanned spacecraft have traversed it without incident. Nonetheless, collisions between large asteroids do occur, and these can form an asteroid family whose members have similar orbital characteristics and compositions. Collisions also produce a fine dust that forms a major component of the zodiacal light. Individual asteroids within the main belt are categorized by their spectra, with most falling into three basic groups: carbonaceous (C-type), silicate (S-type), and metal-rich (M-type).

The asteroid belt formed from the primordial solar nebula as a group of planetesimals, the smaller precursors of the planets. Between Mars and Jupiter, however, gravitational perturbations from the giant planet imbued the planetesimals with too much orbital energy for them to accrete into a planet. Collisions became too violent, and instead of sticking together, the planetesimals shattered. As a result, most of the main belt's mass has been lost since the formation of the Solar System. Some fragments can eventually find their way into the inner Solar System, leading to meteorite impacts with the inner planets. Asteroid orbits continue to be appreciably perturbed whenever their period of revolution about the Sun forms an orbital resonance with Jupiter. At these orbital distances, a Kirkwood gap occurs as they are swept into other orbits.

Other regions of small solar system bodies include the centaurs, the Kuiper belt and scattered disk, and the Oort cloud.

History of observation



Giuseppe Piazzi, discoverer of Ceres, known as a planet for many years, then as asteroid number 1, and eventually, a dwarf planet

In an anonymous footnote to his 1766 translation of Charles Bonnet's *Contemplation de la Nature*, the astronomer Johann Daniel Titius von Wittenburg noted an apparent pattern in the layout of the planets. If one began a numerical sequence at 0, then included 3, 6, 12, 24, 48, etc., doubling each time, and added four to each number and divided by 10, this produced a remarkably close approximation to the orbits of the known planets as measured in astronomical units. This pattern, now known as the Titius-Bode Law, predicted the semi-major axes of the six planets of the time (Mercury, Venus, Earth, Mars, Jupiter and Saturn) provided one allowed for a "gap" between the orbits of Mars and Jupiter. In his footnote Titius declared, "But should the Lord Architect have left that space empty? Not at all". In 1768, the astronomer Johann Elert Bode made note of Titius's relationship in his *Anleitung zur Kenntniss des gestirnten Himmels* but did not credit Titius, which led many to refer to it as "Bode's law". When William Herschel discovered Uranus in 1781, the planet's position matched the law almost perfectly, leading astronomers to conclude that there had to be a planet between the orbits of Mars and Jupiter.

In 1800, astronomer Baron Franz Xaver von Zach recruited 24 of his fellows into an informal club he dubbed the "Lilienthal Society". Determined to bring the Solar System to order, the group became known as the "Himmelspolizei", or Celestial Police. Notable members included Herschel, British astronomer Royal Nevil Maskelyne, Charles Messier, and Heinrich Olbers. Each astronomer was assigned a 15° region of the zodiac to search for the missing planet.

Only a few months later, a non-member of the Celestial Police confirmed their expectations. On January 1, 1801, Giuseppe Piazzi, Chair of Astronomy at the University of Palermo, Sicily, found a tiny moving object in the exact location predicted by the Titius-Bode Law. He dubbed it Ceres, after the Roman goddess of the harvest and patron of Sicily. Piazzi initially believed it a comet, but its lack of a coma suggested it was a planet. Fifteen months later, Olbers discovered a second object in the same region, Pallas. Unlike the other known planets, the objects remained points of light even under the highest telescope magnifications, rather than resolving into discs. Apart from their rapid movement, they were indistinguishable from stars. Accordingly, in 1802 William Herschel suggested they be placed into a separate category, named *asteroids,* after the Greek *asteroeides*, meaning "star-like". Upon completing a series of observations of Ceres and Pallas, he concluded,

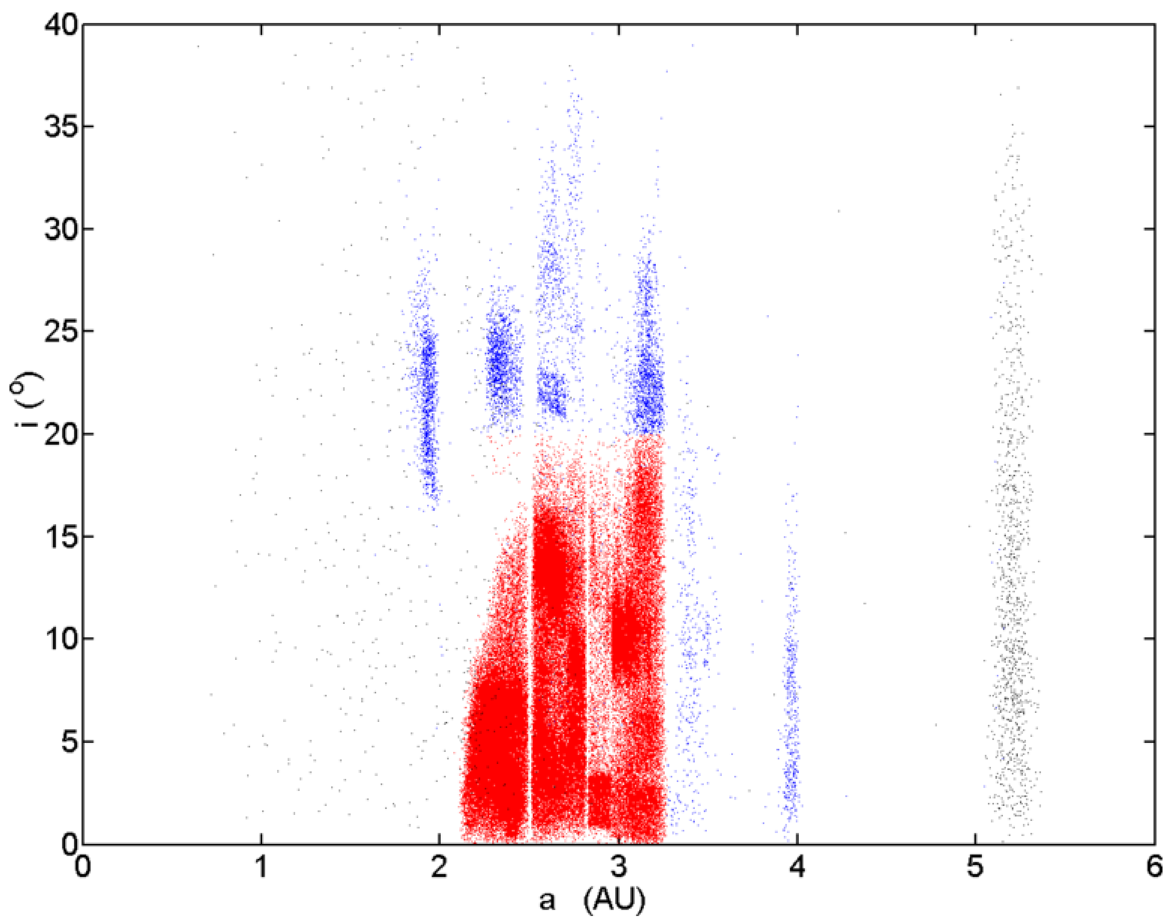
Neither the appellation of planets, nor that of comets, can with any propriety of language be given to these two stars ... They resemble small stars so much as hardly to be distinguished from them. From this, their asteroidal appearance, if I take my name, and call them Asteroids; reserving for myself however the liberty of changing that name, if another, more expressive of their nature, should occur.

Despite Herschel's coinage, for several decades it remained common practice to refer to these objects as planets. By 1807, further investigation revealed two new objects in the region: 3 Juno and 4 Vesta. The Napoleonic wars brought this first period of discovery to a close, and it was not until 1845 that another object (5 Astraea) was discovered. Shortly thereafter new objects were found at an accelerating rate, and counting them among the planets became increasingly cumbersome. Eventually, they were dropped from the planet list as first suggested by Alexander von Humboldt in the early 1850s, and William Herschel's choice of nomenclature, asteroids, gradually came into common use.

The discovery of Neptune in 1846 led to the discrediting of the Titius-Bode Law in the eyes of scientists, as its orbit was nowhere near the predicted position. To date, there is no scientific explanation for the law, and the consensus among astronomers is that it is a coincidence.

The expression "asteroid belt" comes into use in the very early 1850s, although it is hard to pinpoint who coined the term. The first English use seems to be in the 1850 translation (by E. C. Otté) of Alexander von Humboldt's *Cosmos:* "[...] and the regular appearance, about the 13th of November and the 11th of August, of shooting stars, which probably form part of a belt of asteroids intersecting the Earth's orbit and moving with planetary velocity". Other early appearances occur in Robert James Mann's *A Guide to the Knowledge of the Heavens*, "The orbits of the asteroids are placed in a wide belt of space, extending between the extremes of [...]". The American astronomer Benjamin Peirce seems to have adopted that terminology and to have been one of its promoters. One hundred asteroids had been located by mid-1868, and in 1891 the introduction of astrophotography by Max Wolf accelerated the rate of discovery still further. A total of 1,000 asteroids had been found by 1921, 10,000 by 1981, and 100,000 by 2000. Modern asteroid survey systems now use automated means to locate new minor planets in ever-increasing quantities.

Origin



The asteroid belt (showing inclinations), with the main belt in red ("core" region) and blue

Formation

In 1802, shortly after discovering Pallas, Heinrich Olbers suggested to William Herschel that Ceres and Pallas were fragments of a much larger planet that once occupied the Mars-Jupiter region, this planet having suffered an internal explosion or a cometary impact many million years before. Over time, however, this hypothesis has fallen from favor. The large amount of energy that would have been required to destroy a planet, combined with the belt's low combined mass, which is only about 4% of the mass of the Earth's Moon, do not support the hypothesis. Further, the significant chemical differences between the asteroids are difficult to explain if they come from the same planet. Today, most scientists accept that, rather than fragmenting from a progenitor planet, the asteroids never formed a planet at all.

In general in the Solar System, planetary formation is thought to have occurred via a process comparable to the long-standing nebular hypothesis: a cloud of interstellar dust and gas collapsed under the influence of gravity to form a rotating disk of material that then further condensed to form the Sun and planets. During the first few million years of the Solar System's history, an accretion process of sticky collisions caused the clumping of small particles, which gradually increased in size. Once the clumps reached sufficient mass, they could draw in other bodies through gravitational attraction and become planetesimals. This gravitational accretion led to the formation of the rocky planets and the gas giants.

Planetesimals within the region which would become the asteroid belt were too strongly perturbed by Jupiter's gravity to form a planet. Instead they continued to orbit the Sun as before, while occasionally colliding. In regions where the average velocity of the collisions was too high, the shattering of planetesimals tended to dominate over accretion, preventing the formation of planet-sized bodies. Orbital resonances occurred where the orbital period of an object in the belt formed an integer fraction of the orbital period of Jupiter, perturbing the object into a different orbit; the region lying between the orbits of Mars and Jupiter contains many such orbital resonances. As Jupiter migrated inward following its formation, these resonances would have swept across the asteroid belt, dynamically exciting the region's population and increasing their velocities relative to each other.

During the early history of the Solar System, the asteroids melted to some degree, allowing elements within them to be partially or completely differentiated by mass. Some of the progenitor bodies may even have undergone periods of explosive volcanism and formed magma oceans. However, because of the relatively small size of the bodies, the period of melting was necessarily brief (compared to the much larger planets), and had generally ended about 4.5 billion years ago, in the first tens of millions years of formation. In August 2007, a study of zircon crystals in an Antarctic meteorite believed to have originated from 4 Vesta suggested that it, and by extension the rest of the asteroid belt, had formed rather quickly, within ten million years of the Solar System origin.

Evolution

The asteroids are not samples of the primordial Solar System. They have undergone considerable evolution since their formation, including internal heating (in the first few tens of millions of years), surface melting from impacts, space weathering from radiation, and bombardment by micrometeorites. While some scientists refer to the asteroids as residual planetesimals, other scientists consider them distinct.

The current asteroid belt is believed to contain only a small fraction of the mass of the primordial belt. Computer simulations suggest that the original asteroid belt may have contained mass equivalent to the Earth. Primarily because of gravitational perturbations, most of the material was ejected from the belt within about a million years of formation, leaving behind less than 0.1% of the original mass. Since their formation, the size distribution of the asteroid belt has remained relatively stable: there has been no significant increase or decrease in the typical dimensions of the main-belt asteroids.

The 4:1 orbital resonance with Jupiter, at a radius 2.06 AU, can be considered the inner boundary of the main belt. Perturbations by Jupiter send bodies straying there into unstable orbits. Most bodies formed inside the radius of this gap were swept up by Mars (which has an aphelion at 1.67 AU) or ejected by its gravitational perturbations in the early history of the Solar System. The Hungaria asteroids lie closer to the Sun than the 4:1 resonance, but are protected from disruption by their high inclination.

When the main belt was first formed, the temperatures at a distance of 2.7 AU from the Sun formed a "snow line" below the condensation point of water. Planetesimals formed beyond this radius were able to accumulate ice. In 2006 it was announced that a population of comets had been discovered within the asteroid belt beyond the snow line, which may have provided a source of water for Earth's oceans. According to some models, there was insufficient outgassing of water during the Earth's formative period to form the oceans, requiring an external source such as a cometary bombardment.

Characteristics

The asteroid 951 Gaspra, the first ever imaged by a spacecraft, taken by *Galileo* as it passed by it in 1991; the colors are exaggerated

Allende is a carbonaceous chondrite meteorite that fell to Earth in Mexico in 1969

Contrary to popular imagery, the asteroid belt is mostly empty. The asteroids are spread over such a large volume that it would be improbable to reach an asteroid without aiming carefully. Nonetheless, hundreds of thousands of asteroids are currently known, and the total number ranges in the millions or more, depending on the lower size cutoff. Over 200 asteroids are known to be larger than 100 km, while a survey in the infrared wavelengths shows that the main belt has 700,000 to 1.7 million asteroids with a diameter of 1 km or more. The apparent magnitudes of most of the known asteroids are 11–19, with the median at about 16.

The total mass of the asteroid belt is estimated to be 3.0×10^{21} to 3.6×10^{21} kilograms, which is just 4% of the Moon. The four largest objects, Ceres, 4 Vesta, 2 Pallas and 10 Hygiea, account for half of the belt's total mass, with almost one-third accounted for by Ceres alone. Ceres's orbital distance, 2.766 AU, is also very close to the location of the belt's center of mass, 2.8 AU.

Composition

The current belt consists primarily of three categories of asteroids: C-type or carbonaceous asteroids, S-type or silicate asteroids, and M-type or metallic asteroids.

Carbonaceous asteroids, as their name suggests, are carbon-rich and dominate the belt's outer regions. Together they comprise over 75% of the visible asteroids. They are more red in hue than the other asteroids and have a very low albedo. Their surface composition is similar to carbonaceous chondrite meteorites. Chemically, their spectra match the primordial composition of the early Solar System, with only the lighter elements and volatiles removed.

S-type or silicate-rich asteroids are more common toward the inner region of the belt, within 2.5 AU of the Sun. The spectra of their surfaces reveal the presence of silicates and some metal, but no significant carbonaceous compounds. This indicates that their materials have been significantly modified from their primordial composition, probably through melting and reformation. They have a relatively high albedo, and form about 17% of the total asteroid population.

M-type (metal-rich) asteroids form about 10% of the total population; their spectra resemble that of iron-nickel. Some are believed to have formed from the metallic cores of differentiated progenitor bodies that were disrupted through collision. However, there are also some silicate compounds that can produce a similar appearance. For example, the large M-type asteroid 22 Kalliope does not appear to be primarily composed of metal. Within the main belt, the number distribution of M-type asteroids peaks at a semi-major axis of about 2.7 AU. It is not yet clear whether all M-types are compositionally similar, or whether it is a label for several varieties which do not fit neatly into the main C and S classes.

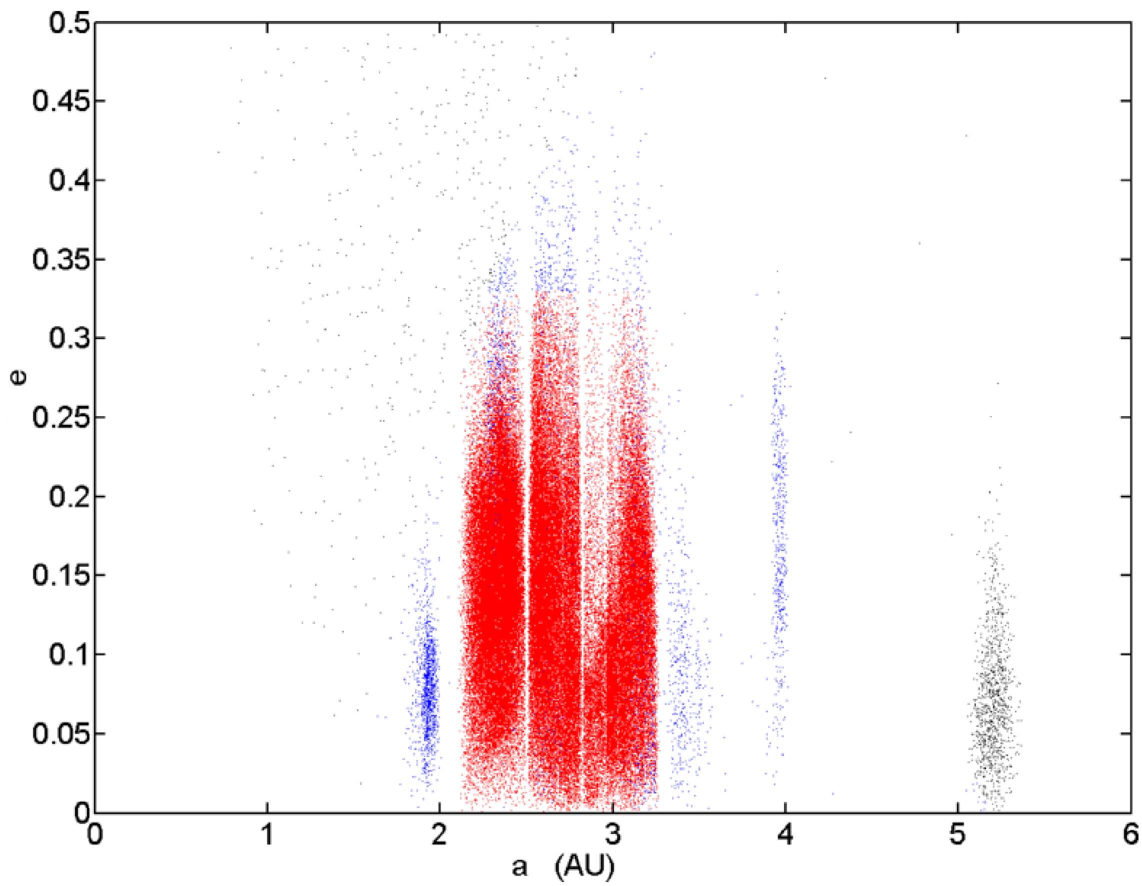
One mystery of the asteroid belt is the relative rarity of V-type, or basaltic asteroids. Theories of asteroid formation predict that objects the size of Vesta or larger should form crusts and mantles, which would be composed mainly of basaltic rock, resulting in more than half of all asteroids being composed either of basalt or olivine. Observations, however, suggest that 99 percent of the predicted basaltic material is missing. Until 2001, most basaltic bodies discovered in the asteroid belt were believed to originate from the asteroid Vesta (hence their name V-type). However, the discovery of the asteroid 1459 Magnya revealed a slightly different chemical composition from the other basaltic asteroids discovered until then, suggesting a different origin. This hypothesis was reinforced by the further discovery in 2007 of two asteroids in the outer belt, 7472 Kumakiri and (10537) 1991 RY_{16}, with differing basaltic composition that could not have originated from Vesta. These latter two are the only V-type asteroids discovered in the outer belt to date.

The temperature of the asteroid belt varies with the distance from the Sun. For dust particles within the belt, typical temperatures range from 200 K (−73 °C) at 2.2 AU down to 165 K (−108 °C) at 3.2 AU However, due to rotation, the surface temperature of an asteroid can vary considerably as the sides are alternately exposed to solar radiation and then to the stellar background.

Main-belt comets

Several otherwise unremarkable bodies in the outer belt show cometary activity. Since their orbits cannot be explained through capture of classical comets, it is thought that many of the outer asteroids may be icy, with the ice occasionally exposed to sublimation through small impacts. Main-belt comets may have been a major source of the Earth's oceans, since the deuterium-hydrogen ratio is too low for classical comets to have been the principal source.

Orbits and rotations



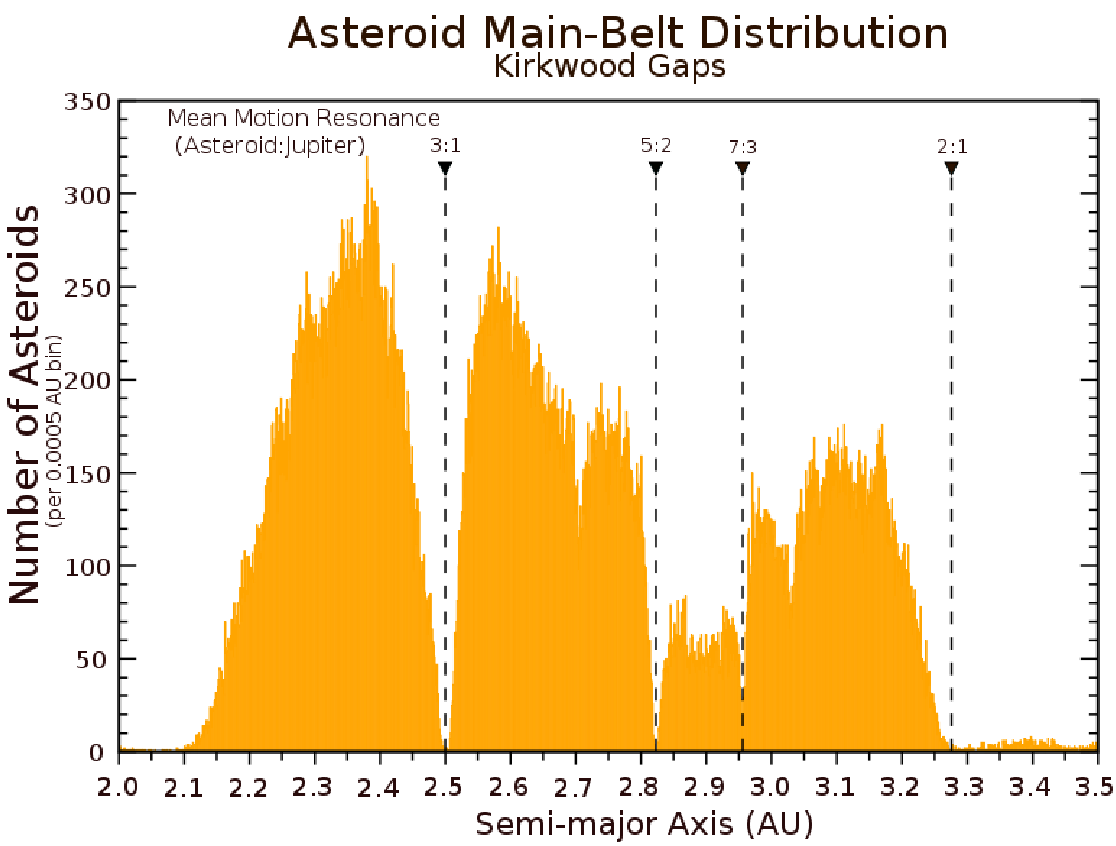
The asteroid belt (showing eccentricities), with the main belt in red and blue ("core" region in red)

Most asteroids within the main belt have orbital eccentricities of less than 0.4, and an inclination of less than 30°. The orbital distribution of the asteroids reaches a maximum at an eccentricity of around 0.07 and an inclination below 4°. Thus while a typical asteroid has a relatively circular orbit and lies near the plane of the ecliptic, some asteroid orbits can be highly eccentric or travel well outside the ecliptic plane.

Sometimes, the term *main belt* is used to refer only to the more compact "core" region where the greatest concentration of bodies is found. This lies between the strong 4:1 and 2:1 Kirkwood gaps at 2.06 and 3.27 AU, and at orbital eccentricities less than roughly 0.33, along with orbital inclinations below about 20°. This "core" region contains approximately 93.4% of all numbered minor planets within the Solar System.

Measurements of the rotation rates of large asteroids in the main belt show that there is an upper limit. No asteroid with a diameter larger than 100 meters has a period of rotation faster than 2.2 hours. For asteroids rotating faster than approximately this rate, the inertia at the surface is greater than the gravitational force, so any loose surface material would be flung out. However, a solid object should be able to rotate much more rapidly. This suggests that most asteroids with a diameter over 100 metres are rubble piles formed through accumulation of debris after collisions between asteroids.

Kirkwood gaps



This chart shows the distribution of asteroid semi-major axes in the "core" of the main belt. Black arrows point to the Kirkwood gaps, where orbital resonances with Jupiter destabilize orbits.

The semi-major axis of an asteroid is used to describe the dimensions of its orbit around the Sun, and its value determines the minor planet's orbital period. In 1866, Daniel

Kirkwood announced the discovery of gaps in the distances of these bodies' orbits from the Sun. They were located at positions where their period of revolution about the Sun was an integer fraction of Jupiter's orbital period. Kirkwood proposed that the gravitational perturbations of the planet led to the removal of asteroids from these orbits.

When the mean orbital period of an asteroid is an integer fraction of the orbital period of Jupiter, a mean-motion resonance with the gas giant is created that is sufficient to perturb an asteroid to new orbital elements. Asteroids that become located in the gap orbits (either primordially because of the migration of Jupiter's orbit, or due to prior perturbations or collisions) are gradually nudged into different, random orbits with a larger or smaller semi-major axis.

The gaps are not seen in a simple snapshot of the locations of the asteroids at any one time because asteroid orbits are elliptical, and many asteroids still cross through the radii corresponding to the gaps. The actual spatial density of asteroids in these gaps does not differ significantly from the neighboring regions.

The main gaps occur at the 3:1, 5:2, 7:3, and 2:1 mean-motion resonances with Jupiter. An asteroid in the 3:1 Kirkwood gap would orbit the Sun three times for each Jovian orbit, for instance. Weaker resonances occur at other semi-major axis values, with fewer asteroids found than nearby. (For example, an 8:3 resonance for asteroids with a semi-major axis of 2.71 AU.)

The main or core population of the asteroid belt is sometimes divided into three zones, based on the most prominent Kirkwood gaps. Zone I lies between the 4:1 resonance (2.06 AU) and 3:1 resonance (2.5 AU) Kirkwood gaps. Zone II continues from the end of Zone I out to the 5:2 resonance gap (2.82 AU). Zone III extends from the outer edge of Zone II to the 2:1 resonance gap (3.28 AU).

The main belt may also be divided into the inner and outer belts, with the inner belt formed by asteroids orbiting nearer to Mars than the 3:1 Kirkwood gap (2.5 AU), and the outer belt formed by those asteroids closer to Jupiter's orbit. (Some authors subdivide the inner and outer belts at the 2:1 resonance gap (3.3 AU), while others suggest inner, middle, and outer belts.)

Collisions

The zodiacal light, created in part by dust from collisions in the asteroid belt

The high population of the main belt makes for a very active environment, where collisions between asteroids occur frequently (on astronomical time scales). Collisions between main-belt bodies with a mean radius of 10 km are expected to occur about once every 10 million years. A collision may fragment an asteroid into numerous smaller pieces (leading to the formation of a new asteroid family). Conversely, collisions that occur at low relative speeds may also join two asteroids. After more than 4 billion years of such processes, the members of the asteroid belt now bear little resemblance to the original population.

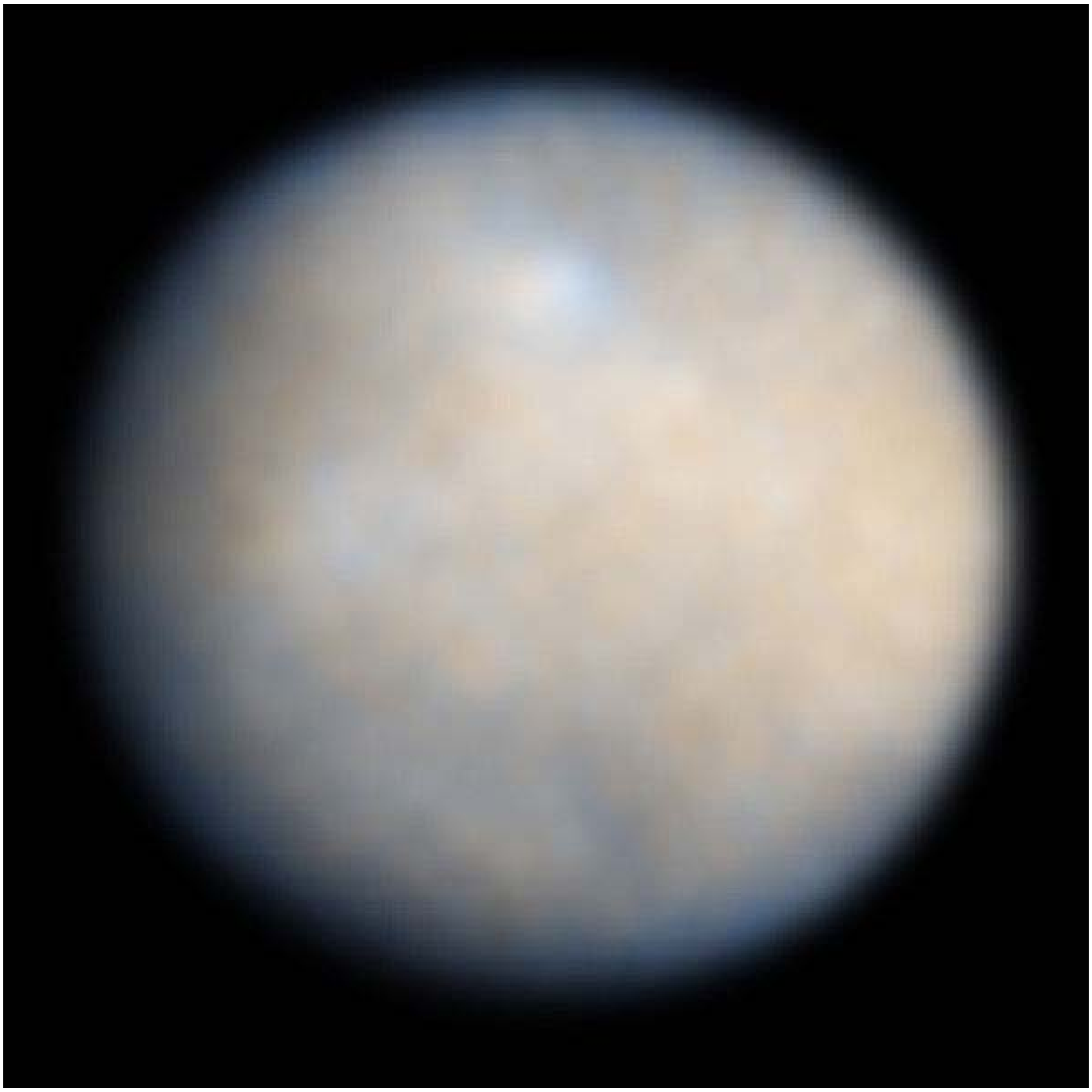
Along with the asteroid bodies, the main belt also contains bands of dust with particle radii of up to a few hundred micrometres. This fine material is produced, at least in part, from collisions between asteroids, and by the impact of micrometeorites upon the asteroids. Due to Poynting-Robertson drag, the pressure of solar radiation causes this dust to slowly spiral inward toward the Sun.

The combination of this fine asteroid dust, as well as ejected cometary material, produces the zodiacal light. This faint auroral glow can be viewed at night extending from the direction of the Sun along the plane of the ecliptic. Particles that produce the visible zodiacal light average about 40 μm in radius. The typical lifetimes of such particles are about 700,000 years. Thus, to maintain the bands of dust, new particles must be steadily produced within the asteroid belt.

Meteorites

Some of the debris from collisions can form meteoroids that enter the Earth's atmosphere. More than 99.8 percent of the 30,000 meteorites found on Earth to date are believed to have originated in the asteroid belt. A September 2007 study by a joint US-Czech team has suggested that a large-body collision undergone by the asteroid 298 Baptistina sent a number of fragments into the inner solar system. The impacts of these fragments are believed to have created both the Tycho crater on the Moon and the Chicxulub crater in Mexico, the remnant of the massive impact which is believed to have triggered the extinction of the dinosaurs 65 million years ago.

Largest asteroids

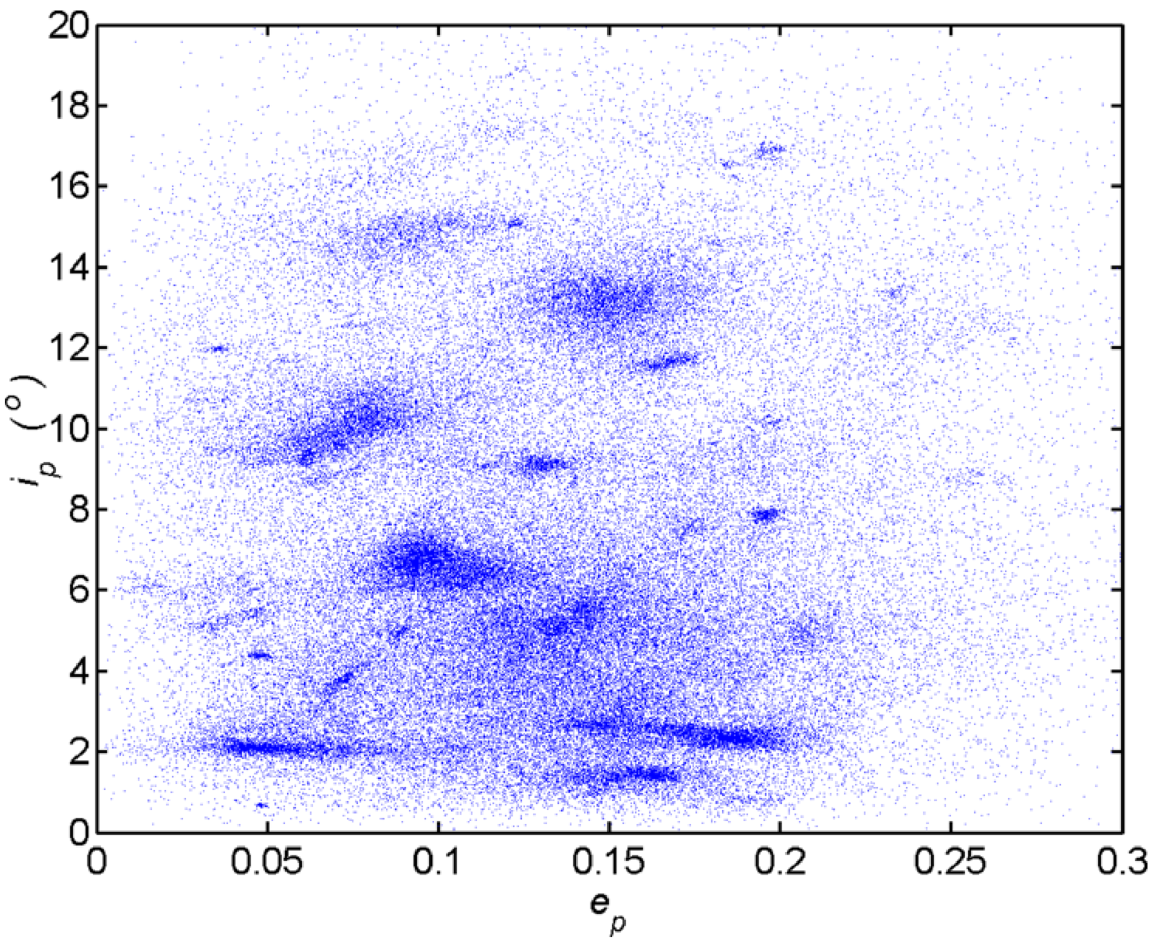


The dwarf planet Ceres

Although their location in the asteroid belt excludes them from planet status, the four largest objects, Ceres, Vesta, Pallas, and Hygiea, hover on the edge of hydrostatic equilibrium, the boundary that separates the small solar system object from the dwarf planet. They share many characteristics common to planets, but also show qualities more akin to rock-like asteroids.

Ceres is the only object in the belt large enough for its gravity to force it into a roughly spherical shape, and so, according to the IAU's 2006 resolution on the definition of a planet, it is now considered a dwarf planet. The other three may also eventually be reclassified as well. Ceres has a much higher absolute magnitude than the other asteroids, of around 3.32, and may possess a surface layer of ice. Like the planets, Ceres is differentiated: it has a crust, a mantle and a core. Vesta, too, has a differentiated interior, though it formed inside the Solar System's "snow line", and so is devoid of water; its composition is mainly of basaltic rock such as olivine. Pallas is unusual in that, like Uranus, it rotates on its side, with one pole regularly facing the Sun and the other facing away. Its composition is similar to that of Ceres: high in carbon and silicon. Hygiea is a carbonaceous asteroid and, unlike the other largest asteroids, lies relatively close to the plane of the ecliptic.

Families and groups



This plot of orbital inclination (i_p) versus eccentricity (e_p) for the numbered main-belt asteroids clearly shows several clumps of asteroid families.

In 1918, the Japanese astronomer Kiyotsugu Hirayama noticed that the orbits of some of the asteroids had similar parameters, forming families or groups.

Approximately one-third of the asteroids in the main belt are members of an asteroid family. These share similar orbital elements, such as semi-major axis, eccentricity, and orbital inclination as well as similar spectral features, all of which indicate a common origin in the breakup of a larger body. Graphical displays of these elements, for members of the main belt, show concentrations indicating the presence of an asteroid family. There are about 20–30 associations that are almost certainly asteroid families. Additional groupings have been found that are less certain. Asteroid families can be confirmed when the members display common spectral features. Smaller associations of asteroids are called groups or clusters.

Some of the most prominent families in the main belt (in order of increasing semi-major axes) are the Flora, Eunoma, Koronis, Eos, and Themis families. The Flora family, one of the largest with more than 800 known members, may have formed from a collision less than a billion years ago. The largest asteroid to be a true member of a family (as opposed to an interloper in the case of Ceres with the Gefion family) is 4 Vesta. The Vesta family is believed to have formed as the result of a crater-forming impact on Vesta. Likewise, the HED meteorites may also have originated from Vesta as a result of this collision.

Three prominent bands of dust have been found within the main belt. These have similar orbital inclinations as the Eos, Koronis, and Themis asteroid families, and so are possibly associated with those groupings.

Periphery

Skirting the inner edge of the belt (ranging between 1.78 and 2.0 AU, with a mean semi-major axis of 1.9 AU) is the Hungaria family of minor planets. They are named after the main member, 434 Hungaria; the group contains at least 52 named asteroids. The Hungaria group is separated from the main body by the 4:1 Kirkwood gap and their orbits have a high inclination. Some members belong to the Mars-crossing category of asteroids, and gravitational perturbations by Mars are likely a factor in reducing the total population of this group.

Another high-inclination group in the inner part of the main belt is the Phocaea family. These are composed primarily of S-type asteroids, whereas the neighboring Hungaria family includes some E-types. The Phocaea family orbit between 2.25 and 2.5 AU from the Sun.

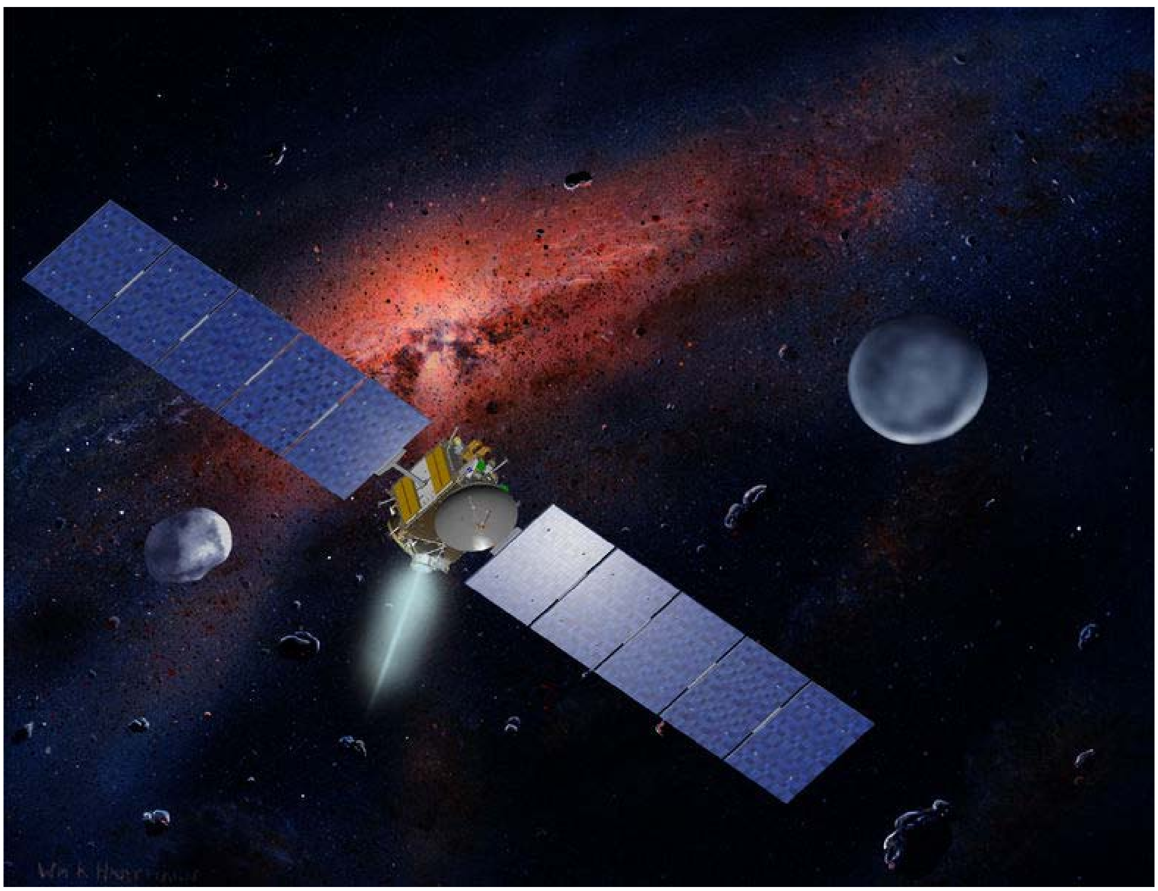
Skirting the outer edge of the main belt is the Cybele group, orbiting between 3.3 and 3.5 AU. These have a 7:4 orbital resonance with Jupiter. The Hilda family orbit between 3.5 and 4.2 AU, and have relatively circular orbits and a stable 3:2 orbital resonance with Jupiter. There are few asteroids beyond 4.2 AU, until Jupiter's orbit. Here the two families of Trojan asteroids can be found, which are approximately as numerous as the asteroids of the main belt.

New families

Some asteroid families have formed recently, in astronomical terms. The Karin Cluster apparently formed about 5.7 million years ago from a collision with a 16 km radius progenitor asteroid. The Veritas family formed about 8.3 million years ago; evidence includes interplanetary dust recovered from ocean sediment.

In the more distant past, the Datura cluster appears to have formed about 450 thousand years ago from a collision with a main-belt asteroid. The age estimate is based on the probability of the members having their current orbits, rather than from any physical evidence. However, this cluster may have been a source for some zodiacal dust material. Other recent cluster formations, such as the Iannini cluster (*circa* 1–5 million years ago), may have provided additional sources of this asteroid dust.

Exploration



Artist's concept of the Dawn Mission spacecraft with Vesta (left) and Ceres (right)

The first spacecraft to traverse the asteroid belt was Pioneer 10, which entered the region on July 16, 1972. At the time there was some concern that the debris in the belt would pose a hazard to the spacecraft, but it has since been safely traversed by 9 Earth-based craft without incident. Pioneer 11, Voyagers 1 and 2 and Ulysses passed through the belt without imaging any asteroids. Galileo imaged the asteroid 951 Gaspra in 1991 and 243 Ida in 1993, NEAR imaged 253 Mathilde in 1997, Cassini imaged 2685 Masursky in 2000, Stardust imaged 5535 Annefrank in 2002, New Horizons imaged 132524 APL in 2006, and Rosetta imaged 2867 Šteins in 2008. Due to the low density of materials within the belt, the odds of a probe running into an asteroid are now estimated at less than one in a billion.

All spacecraft images of belt asteroids to date have come from brief flyby opportunities by probes headed for other targets. Only the NEAR and Hayabusa missions have studied asteroids for a protracted period in orbit and at the surface and these were near-Earth asteroids. However, the Dawn Mission has been dispatched to explore Vesta and Ceres in the main belt. If the probe is still operational after examining these two large bodies, an extended mission is possible that could allow additional exploration.

Chapter 3

Asteroid Groups and Asteroid Family

Asteroid Groups

An **asteroid group** or **minor planet group** is a population of minor planets that have a share broadly similar orbits. Members are generally unrelated to each other, unlike in an asteroid family, which often results from the break-up of a single asteroid. It is customary to name a group of asteroids after the first member of that group to be discovered, which is often the largest.

Groups out to the orbit of Earth

There are relatively few asteroids that orbit close to the Sun. Several of these groups are hypothetical at this point in time, with no members having yet been discovered; as such, the names they have been given are provisional.

- Vulcanoid asteroids are hypothetical asteroids with an aphelion less than 0.4 AU, i.e., they orbit entirely within the orbit of Mercury. A few searches for Vulcanoids have been conducted but there have been none discovered so far.
- Apoheles are asteroids whose aphelion is less than 0.983 AU, meaning they orbit entirely within Earth's orbit. Other proposed names for this group are Inner-Earth Objects or Interior Earth Objects (IEOs) and Anons (as in "Anonymous"). As of March 2008 there are only five known Apoheles with an arc of observations greater than 20 days: (163693) Atira, (164294) 2004 XZ_{130}, 2004 JG_6, 2005 TG_{45} and 2006 WE_4; while there are other four possible candidates, but with a too short arc of observations: 1998 DK_{36}, 2006 KZ_{39}, 2007 EB_{26} and 2008 EA_{32}.
- Mercury-crosser asteroids having a perihelion smaller than Mercury's 0.3075 AU.
- Venus-crosser asteroids having a perihelion smaller than Venus's 0.7184 AU. This group includes the above Mercury-crossers (if their aphelion is greater than Venus's perihelion. All known Mercury crossers satisfy this condition).
- Earth-crosser asteroids having a perihelion smaller than Earth's 0.9833 AU. This group includes the above Mercury- and Venus-crossers, apart from the Apoheles. They are also divided into the
    - Aten asteroids having a semi-major axis less than 1 AU, named after 2062 Aten.

    - Apollo asteroids having a semi-major axis greater than 1 AU, named after 1862 Apollo.
- Arjuna asteroids are somewhat vaguely defined as having orbits similar to Earth's; i.e., with an average orbital radius of around 1 AU and with low eccentricity and inclination. Due to the vagueness of this definition some asteroids belonging to the Apohele, Amor, Apollo or Aten groups can also be classified as Arjunas. The term was introduced by Spacewatch and does not refer to an existing asteroid; examples of Arjunas include 1991 VG.
- Earth Trojans are asteroids located in the Earth-Sun Lagrangian points L_4 and L_5. Their location in the sky as observed from Earth's surface would be fixed at about 60 degrees east and west of the Sun, and as people tend to search for asteroids at much greater elongations few searches have been done in these locations. No Earth trojans are currently known.
- Near-Earth asteroids is a catch-all group for asteroids whose orbit closely approaches that of Earth. It includes almost all of the above groups, as well as the Amor asteroids.

Groups out to the orbit of Mars

- The Amor asteroids, named after 1221 Amor are Near-Earth asteroids that are not Earth-crossers, having a perihelion just outside the Earth's orbit.
- Mars-crosser asteroids have orbits that cross that of Mars, but do not necessarily closely approach the Earth's.
- Mars Trojans follow or lead Mars on its orbit, at either of the two Lagrangian points 60° ahead (L_4) or behind (L_5). As of March 2008, four are known. The largest appears to be 5261 Eureka.
- Many of the Earth- Venus- and Mercury-crosser asteroids have aphelia greater than 1 AU.

The main asteroid belt

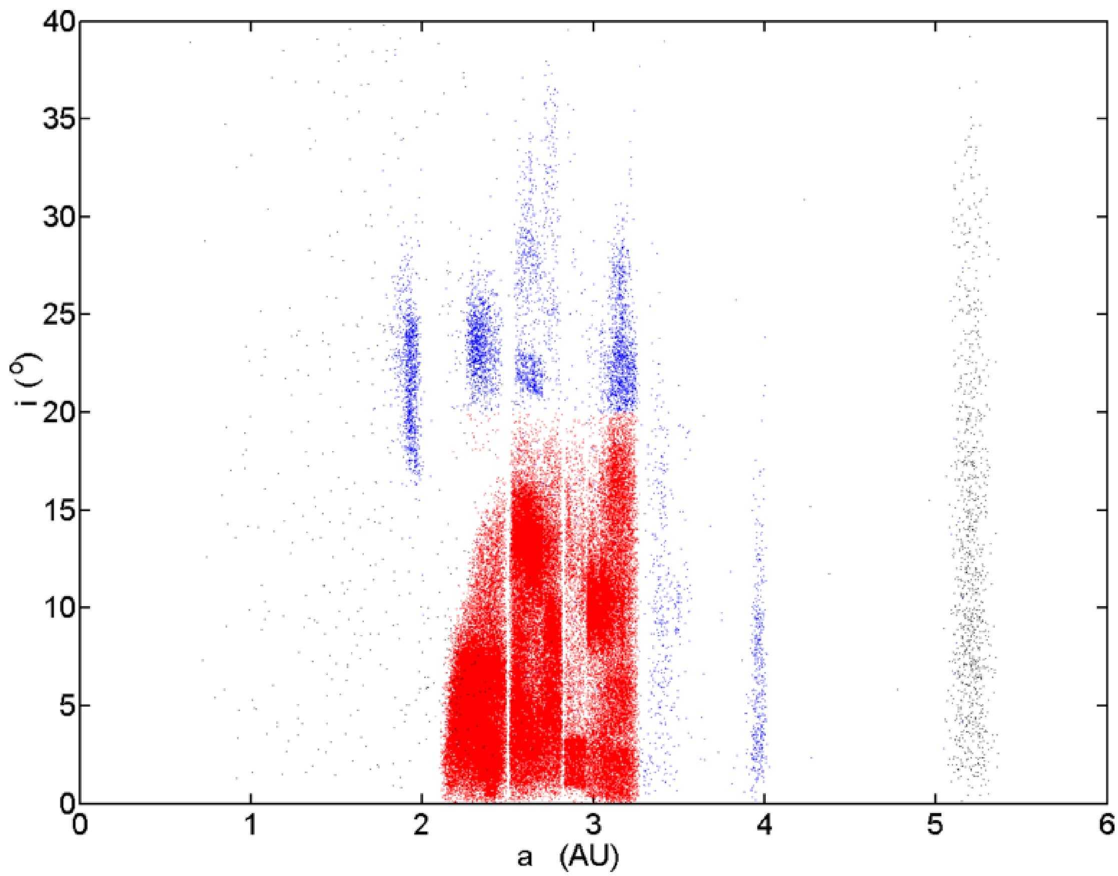
The overwhelming majority of known asteroids have orbits lying between the orbits of Mars and Jupiter, roughly between 2 to 4 AU. These could not form a planet due to the gravitational influence of Jupiter. Jupiter's gravitational influence, through orbital resonance, clears Kirkwood gaps in the asteroid belt, first recognised by Daniel Kirkwood in 1874.

The region with the densest concentration (lying between the Kirkwood gaps at 2.06 and 3.27 AU, with eccentricities below about 0.3, and inclinations smaller than 30°) is often called the Main belt. It can be further subdivided by the Kirkwood Gaps into the:

- **Inner Main Belt**, inside of the strong Kirkwood gap at 2.50 AU due to the 3:1 Jupiter orbital resonance. The largest member is 4 Vesta.

- It apparently also includes a group called the Main Belt I asteroids which have a semi-major axis between 2.3 AU and 2.5 AU and an inclination of less than 18°.

- **Middle** (or intermediate) **Main Belt**, between the 3:1 and 5:2 Jupiter orbital resonances, the latter at 2.82 AU. The largest member is Ceres. This group is apparently split into the:
  - Main Belt IIa asteroids which have a semi-major axis between 2.5 AU and 2.706 AU and an inclination less than 33°.
  - Main Belt IIb asteroids which have a semi-major axis between 2.706 AU and 2.82 AU and an inclination less than 33°.
- **Outer Main Belt** between the 5:2 and 2:1 Jupiter orbital resonances. The largest member is 10 Hygiea. This group is apparently split into the:
  - Main Belt IIIa asteroids which have a semi-major axis between 2.82 AU and 3.03 AU, an eccentricity less than .35, and an inclination less than 30°.
  - Main Belt IIIb asteroids which have a semi-major axis between 3.03 AU and 3.27 AU, an eccentricity less than .35, and an inclination less than 30°.



Asteroid groups out to the orbit of Jupiter. The main belt is shown in red

Other groups out to the orbit of Jupiter

There are a number of more or less distinct asteroid groups outside of the Main Belt, distinguished either by mean distance from the Sun, or particular combinations of several orbital elements:

- Hungaria asteroids, with a mean orbital radius between 1.78 AU and 2 AU, an eccentricity less than 0.18, and inclination between 16° and 34°. Named after 434 Hungaria, these are just outside Mars's orbit, and are possibly attracted by the 9:2 Jupiter resonance or the 3:2 Mars resonance.
- Phocaea asteroids, with a mean orbital radius between 2.25 AU and 2.5 AU, an eccentricity greater than 0.1, and inclination between 18° and 32°. Some sources group the Phocaeas asteroids with the Hungarias, but the division between the two groups is real and caused by the 4:1 resonance with Jupiter. Named after 25 Phocaea.
- Alinda asteroids have a mean orbital radius of 2.5 AU and an eccentricity between 0.4 and 0.65 (approximately). These objects are held by the 3:1 resonance with Jupiter and a 4:1 resonance with Earth. Many Alinda asteroids have perihelia very close to Earth's orbit and can be difficult to observe for this reason. Alinda asteroids are *not* in stable orbits and eventually will collide either with Jupiter or terrestrial planets. Named after 887 Alinda.
- Pallas family asteroids have a mean orbital radius between 2.7 and 2.8 AU and an inclination between 30° and 38°. Named after 2 Pallas.
- Griqua asteroids have an orbital radius between 3.1 AU and 3.27 AU and an eccentricity greater than 0.35. These asteroids are in stable 2:1 libration with Jupiter, in high-inclination orbits. There are about 5 to 10 of these known so far, with 1362 Griqua and 8373 Stephengould the most prominent.
- Cybele asteroids have a mean orbital radius between 3.27 AU and 3.7 AU, an eccentricity less than 0.3, and an inclination less than 25°. This group appears to cluster around the 7:4 resonance with Jupiter. Named after 65 Cybele.
- Hilda asteroids have a mean orbital radius between 3.7 AU and 4.2 AU, an eccentricity greater than 0.07, and an inclination less than 20°. These asteroids are in a 3:2 resonance with Jupiter. Named after 153 Hilda.
- Thule asteroids are in a 4:3 resonance with Jupiter and the group is known to consist of 279 Thule, (186024) 2001 QG_{207}, and (185290) 2006 UB_{219}.
- Trojan asteroids have a mean orbital radius between 5.05 AU and 5.4 AU, and lie in elongated, curved regions around the two Lagrangian points 60° ahead and behind of Jupiter. The leading point, L_4, is called the 'Greek' node and the trailing L_5 point is called the 'Trojan' node, after the two opposing camps of the legendary Trojan War; with one exception apiece, objects in each node are named for members of that side of the conflict. 617 Patroclus in the Trojan node and 624 Hektor in the Greek node are "misplaced" in the enemy camps.

There is a forbidden zone between the Hildas and the Trojans (roughly 4.05 AU to 5.0 AU). Aside from 279 Thule and five objects in unstable-looking orbits, Jupiter's gravity has swept everything out of this region.

Groups beyond the orbit of Jupiter

Most of the minor planets beyond the orbit of Jupiter are believed to be composed of ices and other volatiles. Many are similar to comets, differing only in that the perihelia of their orbits are too distant from the Sun to produce a significant tail.

- Damocloid asteroids, also known as the "Oort cloud group," are named after 5335 Damocles. They are defined to be objects that have "fallen in" from the Oort cloud, so their aphelia are generally still out past Uranus, but their perihelia are in the inner solar system. They have high eccentricities and sometimes high inclinations, including retrograde orbits. The definition of this group is somewhat fuzzy, and may overlap significantly with comets.
- Centaurs have a mean orbital radius roughly between 5.4 AU and 30 AU. They are currently believed to be Trans-Neptunian Objects that "fell in" after encounters with gas giants. The first of these to be discovered was 2060 Chiron.

Groups at or beyond the orbit of Neptune

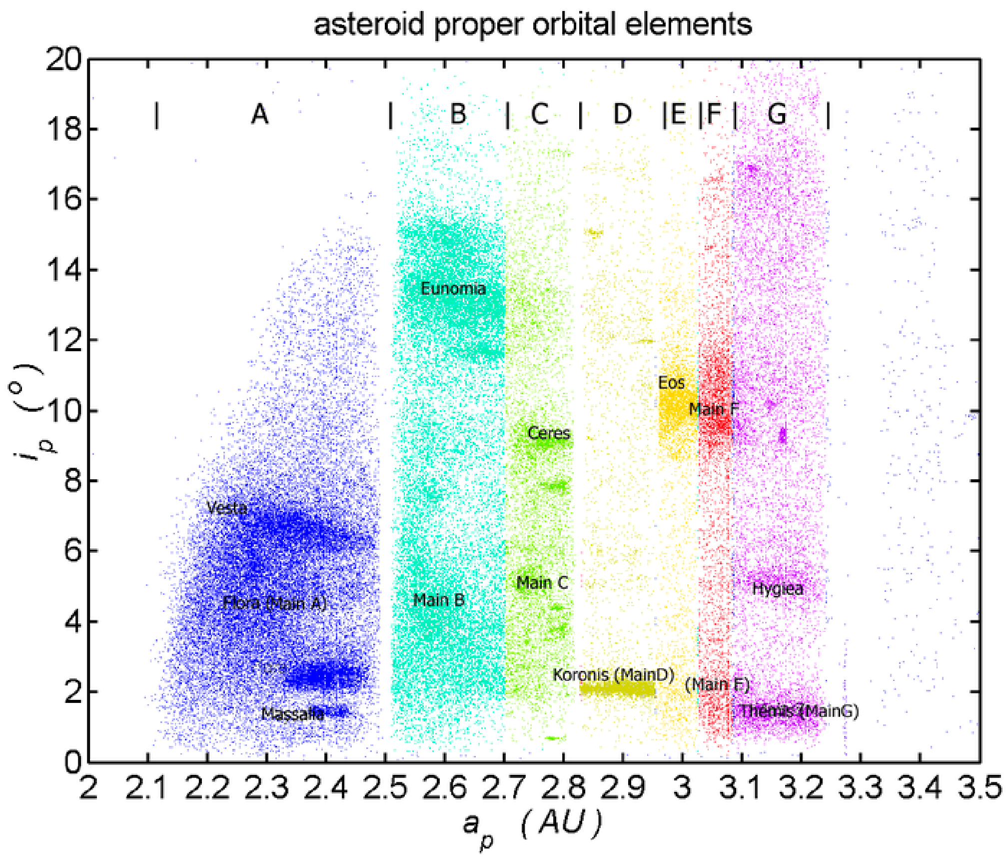
- The Neptune Trojans currently consist of six objects: 2001 QR_{322}, 2004 UP_{10}, 2005 TN_{53}, 2005 TO_{74}, 2006 RJ_{103} and 2007 RW_{10}.
- Trans-Neptunian Objects (TNOs) are anything with a mean orbital radius greater than 30 AU. This classification includes the Kuiper Belt Objects (KBOs) and the Oort cloud.
    - Kuiper Belt Objects extend from roughly 30 AU to 50 AU and are broken into the following subcategories:
        - Plutinos are KBOs in a 2:3 resonance with Neptune, just like Pluto. The perihelion of such an object tends to be close to Neptune's orbit (much as happens with Pluto), but when the object comes to perihelion, Neptune alternates between being 90 degrees ahead of and 90 degrees behind of the object, so there's no chance of a collision. The MPC defines any object with a mean orbital radius between 39 AU and 40.5 AU to be a plutino. 90482 Orcus and 28978 Ixion are among the brightest known.
        - Cubewanos, also known as "classical KBOs". They are named after (15760) 1992 QB_1 and have a mean orbital radius between approximately 40.5 AU and 47 AU. Cubewanos are objects in the Kuiper belt that didn't get scattered and didn't get locked into a resonance with Neptune. Haumea (with two satellites) and Makemake are among the brightest.
        - Additional groups of resonant objects occupy other orbital resonances with Neptune than the 2:3 resonance of the plutinos and the 1:1 resonance of the Neptune Trojans (such as 2001 QR_{322}), but they have not yet been officially named. There are several known objects in the 1:2 resonance, unofficially dubbed *twotinos*, with a mean orbital radius of 47.7 AU and an eccentricity of 0.37. There

are several objects in the 2:5 resonance (mean orbital radius of 55 AU), and objects in the 4:5, 4:7, 3:5, and 3:4 resonances.

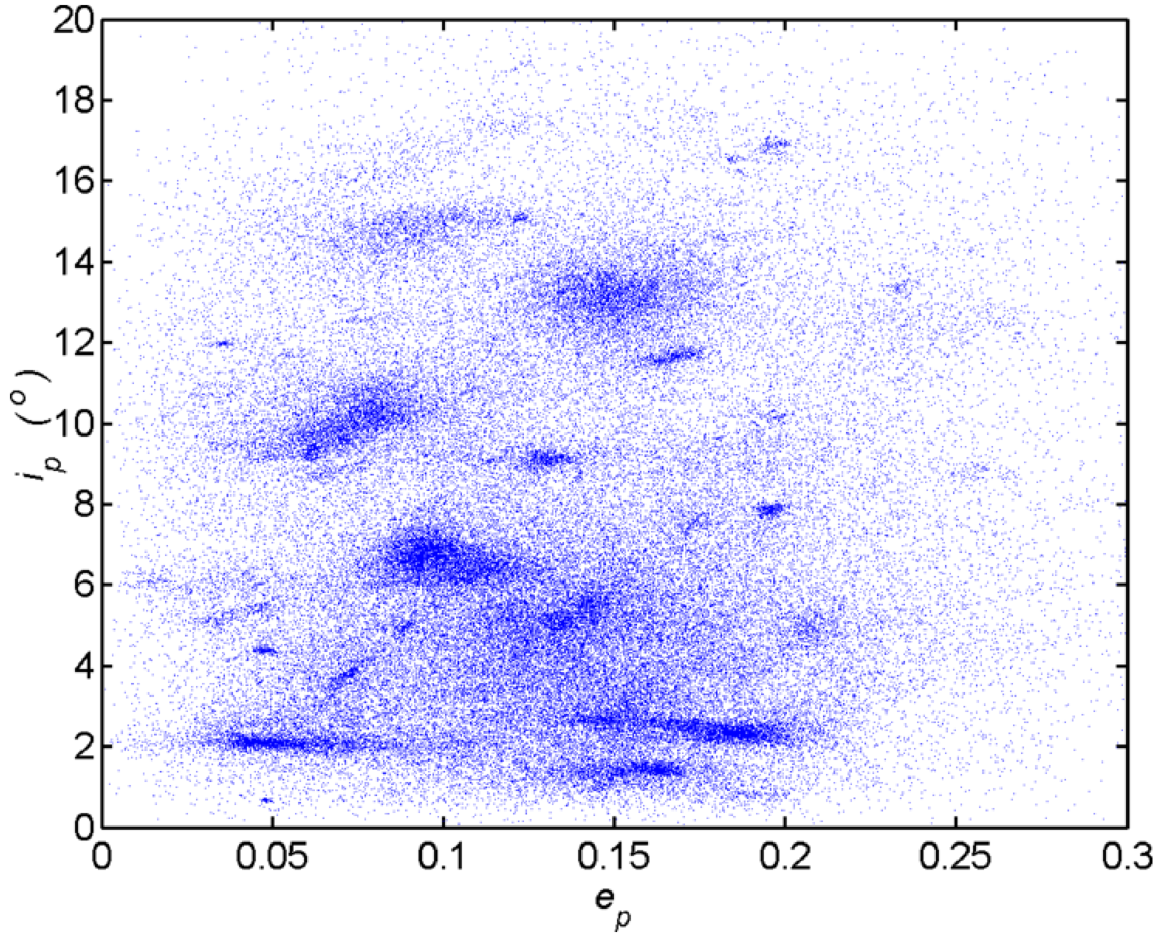
- Scattered Disk Objects (SDOs), unlike cubewanos and resonant objects, typically have highly inclined, high-eccentricity orbits with perihelia that are still not too far from Neptune's orbit.. They are assumed to be objects that encountered Neptune and were "scattered" out of their initial more circular, close to the ecliptic orbits. The recently famous, Pluto-size Eris belongs to this category.
    - Extended Scattered Disk (detached) objects with generally highly elliptical, very large orbits of up to a few hundred AU. Their perihelion is too far away from Neptune for any significant interaction to occur. One typical member of the extended disk is 2000 CR_{105}, while some researchers include Sedna in this class.
- The Oort cloud is a hypothetical cloud of comets with a mean orbital radius between approximately 50,000 AU and 100,000 AU. No Oort cloud objects have been detected, the existence of this classification is only inferred from indirect evidence. Some astronomers have tentatively associated 90377 Sedna with the Oort cloud.

Asteroid family

An **asteroid family** is a population of asteroids that share similar orbital elements, such as semimajor axis, eccentricity, and orbital inclination. The members of the families are thought to be fragments of past asteroid collisions.



Plot of proper inclination vs. semi-major axis for numbered asteroids. Asteroid families are visible as distinct clumps. Prominent Kirkwood gaps divide the core region. (A, B+C, D, E+F+G)



Plot of proper inclination vs. eccentricity for numbered asteroids

General properties

Large prominent families contain several hundred recognized asteroids (and many more smaller objects which may be either not-yet-analyzed, or not-yet-discovered). Small, compact families can have only about ten identified members. About 33% to 35% of asteroids in the main belt are family members.

There are about 20 to 30 reliably recognized families, with several tens of less certain groupings. Most asteroid families are found in the main asteroid belt, although several family-like groups such as the Pallas family, Hungaria family, and the Phocaea family lie at smaller semi-major axis or larger inclination than the main belt.

One family has been identified associated with the dwarf planet Haumea . Some studies have tried to find evidence of collisional families among the trojan asteroids, but at present the evidence is inconclusive.

Origin and evolution

The families are thought to form as a result of collisions between asteroids. In many or most cases the parent body was shattered, but there are also several families which resulted from a large cratering event which did not disrupt the parent body (e.g. the Vesta, Pallas, Hygiea, and Massalia families). Such *cratering families* typically consist of a single large body and a swarm of asteroids that are much smaller. Some families (e.g. the Flora family) have complex internal structures which are not satisfactorily explained at the moment, but may be due to several collisions in the same region at different times.

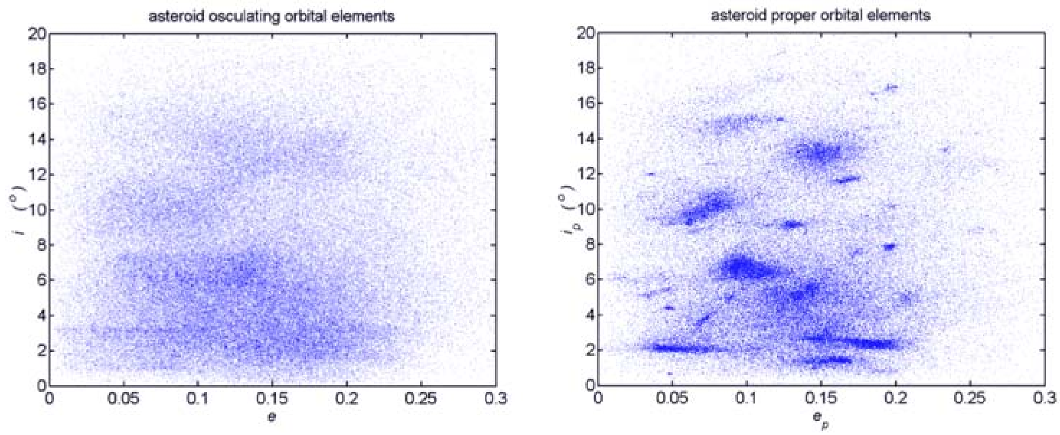
Due to the method of origin, all the members have closely matching compositions for most families. Notable exceptions are those families (such as the Vesta family) which formed from a large differentiated parent body.

Asteroid families are thought to have lifetimes of the order of a billion years, depending on various factors (e.g. smaller asteroids are lost faster). This is significantly shorter than the Solar System's age, so few if any are relics of the early Solar System. Decay of families occurs both because of slow dissipation of the orbits due to perturbations from Jupiter or other large bodies, and because of collisions between asteroids which grind them down to small bodies. Such small asteroids then become subject to perturbations such as the Yarkovsky effect that can push them towards orbital resonances with Jupiter over time. Once there, they are relatively rapidly ejected from the asteroid belt. Tentative age estimates have been obtained for some families, ranging from hundreds of millions of years to less than several million years for e.g. the compact Karin family. Old families are thought to contain few small members, and this is the basis of the age determinations.

It is supposed that many very old families have lost all the smaller and medium-sized members, leaving only a few of the largest intact. A suggested example of such old family remains are the 9 Metis and 113 Amalthea pair. Further evidence for a large number of past families (now dispersed) comes from analysis of chemical ratios in iron meteorites. These show that there must have once been at least 50 to 100 parent bodies large enough to be differentiated, that have since been shattered to expose their cores and produce the actual meteorites (Kelley & Gaffey 2000).

Identification of members and interlopers

When the orbital elements of main belt asteroids are plotted (typically inclination vs. eccentricity, or vs. semi-major axis), a number of distinct concentrations are seen against the rather uniform background distribution of generic asteroids. These concentrations are the asteroid families.



Asteroid orbital elements: standard Keplerian on the left (families indistinguishable) vs. proper elements on the right (families visible).

Strictly speaking, families and their membership are identified by analysing the so-called proper orbital elements rather than the current osculating orbital elements, which regularly fluctuate on timescales of tens of thousands of years. The *proper elements* are related constants of motion that remain almost constant for times of at least tens of millions of years, and perhaps longer.

The Japanese astronomer Kiyotsugu Hirayama (1874–1943) pioneered the estimation of proper elements for asteroids, and first identified several of the most prominent families in 1918. In his honor, asteroid families are sometimes called Hirayama families. This particularly applies to the five prominent groupings discovered by him.

Present day computer-assisted searches have identified several tens of asteroid families. The most prominent algorithms have been the Hierarchical Clustering Method (HCM) which looks for groupings with small nearest-neighbour distances in orbital element space, and the Wavelet Analysis Method (WAM) which builds a density-of-asteroids map in orbital element space, and looks for density peaks.

The boundaries of the families are somewhat vague because at the edges they blend into the background density of asteroids in the main belt. For this reason the number of members even among discovered asteroids is usually only known approximately, and membership is uncertain for asteroids near the edges.

Additionally, some *interlopers* from the heterogeneous background asteroid population are expected even in the central regions of a family. Since the true family members caused by the collision are expected to have similar compositions, most such interlopers can in principle be recognised by spectral properties which do not match those of the bulk of family members. A prominent example is 1 Ceres, the largest asteroid, which is an interloper in the family once named after it (the Ceres family, now the Gefion family).

Spectral characteristics can also be used to determine the membership (or otherwise) of asteroids in the outer regions of a family, as has been used e.g. for the Vesta family, whose members have an unusual composition.

Family types

As previously mentioned, families caused by an impact that did not disrupt the parent body but only ejected fragments are called *cratering families*. Other terminology has been used to distinguish various types of groups which are less distinct or less statistically certain from the most prominent "nominal families" (or *clusters*). The term *cluster* is also used to describe a small asteroid family, such as the Karin Cluster. *Clumps* are groupings which have relatively few members but are clearly distinct from the background (e.g. the Juno clump). *Clans* are groupings which merge very gradually into the background density and/or have a complex internal structure making it difficult to decide whether they are one complex group or several unrelated overlapping groups (e.g. the Flora family has been called a clan). *Tribes* are groups that are less certain to be statistically significant against the background either because of small density or large uncertainty in the orbital parameters of the members.

List of families

Family Name	Named After	orbital elements *a* (AU)	e	*i* (°)	Size approx. % of asteroids	members in Zappalà HCM analysis[A]	Alternate Names
The most prominent families within the main belt are:							
Eos	221 Eos	2.99 to 3.03	0.01 to 0.13	8 to 12		480	
Eunomia	15 Eunomia	2.53 to 2.72	0.08 to 0.22	11.1 to 15.8	5%	370	
Flora	8 Flora	2.15 to 2.35	0.03 to 0.23	1.5 to 8.0	4-5%	590	Ariadne family after 43 Ariadne
Hygiea	10 Hygiea	3.06 to 3.24	0.09 to 0.19	3.5 to 6.8	1%	105	
Koronis	158 Koronis	2.83 to 2.91	0 to 0.11	0 to 3.5		310	
Maria	170 Maria	2.5 to		12 to		80	

		2.706		17			
Nysa	44 Nysa	2.41 to 2.5	0.12 to 0.21	1.5 to 4.3		380	Hertha family after 135 Hertha
Themis	24 Themis	3.08 to 3.24	0.09 to 0.22	0 to 3		530	
Vesta	4 Vesta	2.26 to 2.48	0.03 to 0.16	5.0 to 8.3	6%	240	
Other notable main belt families:[C]							
Adeona	145 Adeona					65	
Astrid	1128 Astrid					11	
Bower	1639 Bower					13	Endymion family after 342 Endymion
Brasilia	293 Brasilia					14	
Gefion	1272 Gefion	2.74 to 2.82	0.08 to 0.18	7.4 to 10.5	0.8%	89	Ceres family after 1 Ceres and Minerva family after 93 Minerva
Chloris	410 Chloris					24	
Dora	668 Dora					78	
Erigone	163 Erigone					47	
Hilda	153 Hilda	3.7 to 4.2	>0.07	<20°	-		
Karin	832 Karin					39[B]	
Lydia	110 Lydia					38	
Massalia	20 Massalia	2.37 to 2.45	0.12 to 0.21	0.4 to 2.4	0.8%	47	
Meliboea	137 Meliboea					15	
Merxia	808					28	

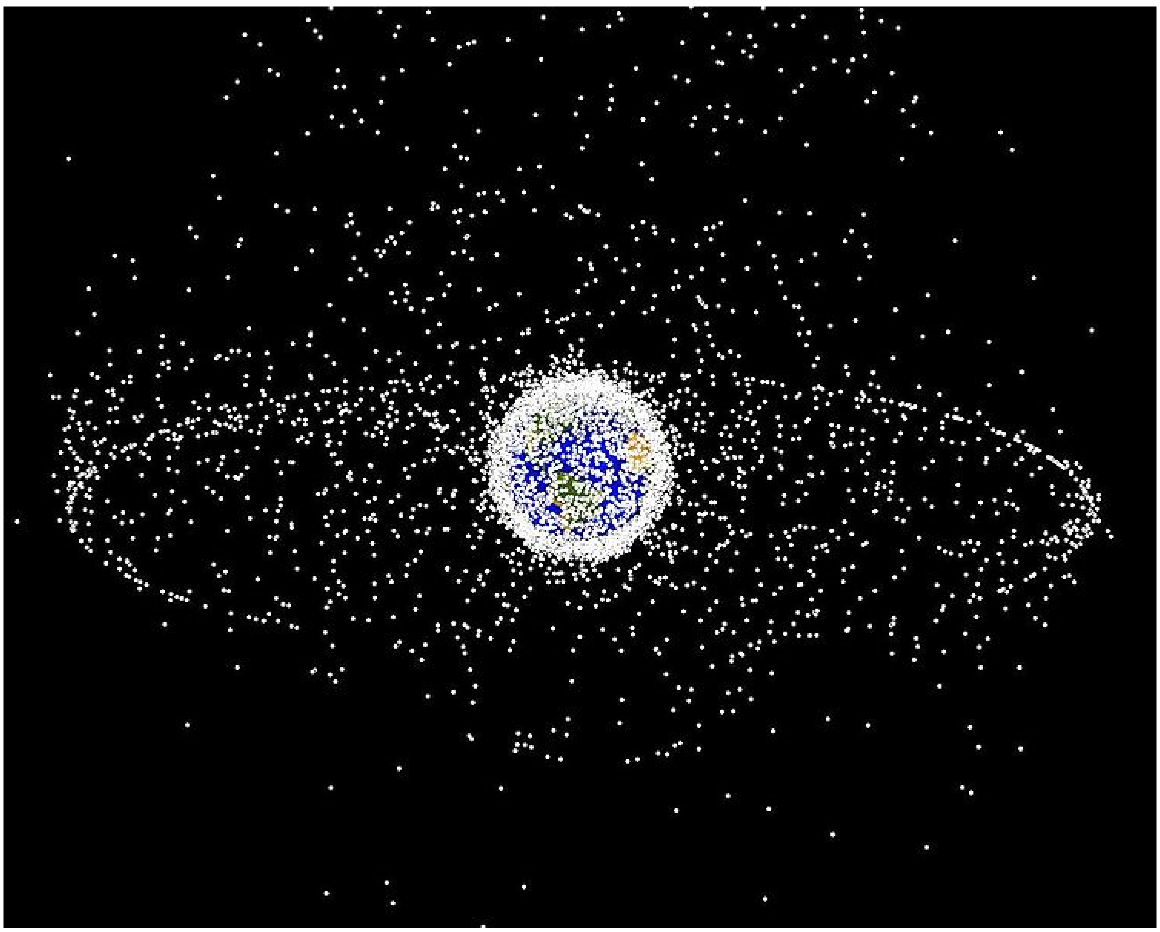
	Merxia					
Misa	569 Misa				26	
Naëma	845 Naëma				7	
Nemesis	128 Nemesis				29	Concordia family after 58 Concordia
Rafita	1644 Rafita				22	
Veritas	490 Veritas				29	Undina family after 92 Undina
Theobalda	778 Theobalda	3.16 to 3.19	0.24 to 0.27	14 to 15		
TNO families: [D]						
Haumea	136108 Haumea	~43	~0.19	~28		

Notes for table:

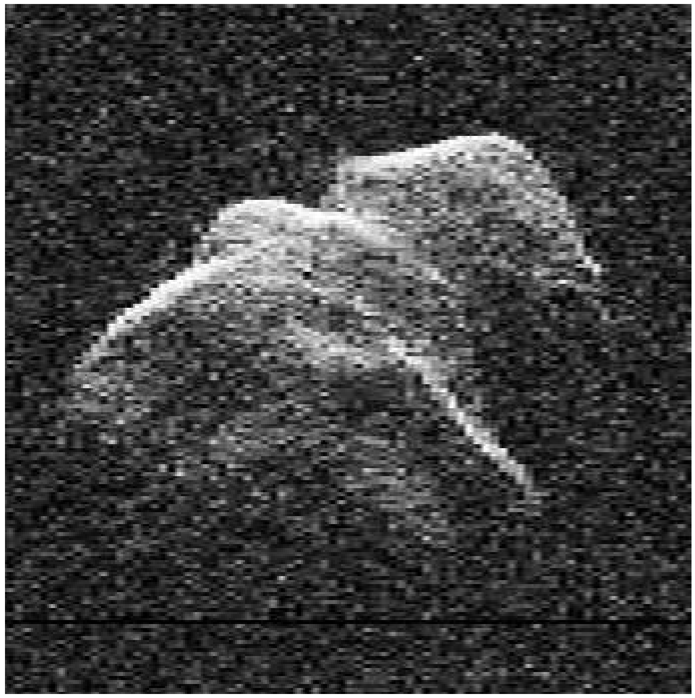
- [A]: Mean of the "core" members found in HCM and WAM analyses by Zappala et al. (1995), rounded to 2 significant digits. That analysis considered 12487 asteroids, but currently over 300,000 are known (an increase by a factor of over 25). Hence, the number of currently catalogued asteroids that are members of a given family is likely to be greater than the value in this column by a similar factor of roughly 25.
- [B]: Reference elsewhere.
- [C]: Most of these are families listed as "robustly" identified in Bendjoya and Zappala (2002). Exception: Karin family.
- [D]: TNOs are not considered asteroids, but are included here for completeness.

Chapter 4

Near-Earth Object



Earth's artificial satellites form a halo of space debris



Asteroid 4179 Toutatis is a potentially hazardous object that has passed within 2.3 lunar distances.

A **near-Earth object** (**NEO**) is a Solar System object whose orbit brings it into close proximity with the Earth. All NEOs have a perihelion distance less than 1.3 AU. They include a few thousand near-Earth asteroids (NEAs), near-Earth comets, a number of solar-orbiting spacecraft, and meteoroids large enough to be tracked in space before striking the Earth. It is now widely accepted that collisions in the past have had a significant role in shaping the geological and biological history of the planet. NEOs have become of increased interest since the 1980s because of increased awareness of the potential danger some of the asteroids or comets pose to the Earth, and active mitigations are being researched. A study showed that the United States and China are the nations most vulnerable to a meteor strike.

Those NEOs that are asteroids (NEA) have orbits that lie partly between 0.983 and 1.3 astronomical units away from the Sun. When an NEA is detected it is submitted to the Harvard Minor Planet Center for cataloging. Some near-Earth asteroids' orbits intersect that of Earth's so they pose a collision danger. The United States, European Union and other nations are currently scanning for NEOs in an effort called Spaceguard. In the United States, NASA has a congressional mandate to catalogue all NEOs that are at least 1 kilometer wide, as the impact of such an object would be expected to produce severe to catastrophic effects. As of October 2008, 982 of these mandated NEOs have been detected. It was estimated in 2006 that 20% of the mandated objects have not yet been found. Efforts are under way to use an existing telescope in Australia to cover the ~30% of the sky that has not yet been surveyed.

Potentially hazardous objects (PHOs) are currently defined based on parameters that measure the object's potential to make threatening close approaches to the Earth. Mostly objects with an Earth minimum orbit intersection distance (MOID) of 0.05 AU or less and an absolute magnitude (H) of 22.0 or less (a rough indicator of large size) are considered PHOs. Objects that cannot approach closer to the Earth (i. e. MOID) than 0.05 AU (roughly 7,480,000 km or 4,650,000 mi), or are smaller than about 150 m (500 ft) in diameter (i. e. H = 22.0 with assumed albedo of 13%), are not considered PHOs. The NASA Near Earth Object Catalog also includes the approach distances of asteroids and comets measured in Lunar Distances, and this usage has become the more usual unit of measure used by the press and mainstream media in discussing these objects.

Some NEOs are of high interest because they can be physically explored with lower mission velocity even than the Moon, due to their combination of low velocity with respect to Earth (ΔV) and small gravity, so they may present interesting scientific opportunities both for direct geochemical and astronomical investigation, and as potentially economical sources of extraterrestrial materials for human exploitation. This makes them an attractive target for exploration. As of 2008, two near-Earth objects have been visited by spacecraft: 433 Eros, by NASA's Near Earth Asteroid Rendezvous probe, and 25143 Itokawa, by the JAXA Hayabusa mission.

Risk scales

There are two schemes for classification of impact hazards:

- the simple Torino Scale, and
- the more complex Palermo Technical Impact Hazard Scale

The annual background frequency used in the Palermo scale for impacts of energy greater than *E* megatonnes is estimated as:

$$f_B = 0.03E^{-0.81}$$

For instance, this formula implies that the expected value of the time from now till the next impact greater than 1 megatonne is 33 years, and that when it occurs, there is a 50% chance that it will be above 2.4 megatonnes. This formula is only valid over a certain range of *E*.

However, another paper published in 2002 – the same year as the paper on which the Palermo scale is based – found a power law with different constants:

$$f_B = 0.00737E^{-0.9}$$

This formula gives considerably lower rates for a given *E*. For instance, it gives the rate for bolides of 10 megatonnes or more (like the Tunguska explosion) as 1 per thousand years, rather than 1 per 210 years as in the Palermo formula. However, the authors give a rather large uncertainty (once in 400 to 1800 years for 10 megatonnes), due in part to uncertainties in determining the energies of the atmospheric impacts that they used in their determination.

On 25 December 2004, minor planet 2004 MN_4 was assigned a 4 on the Torino scale, the highest rating so far. On 27 December 2004 there was a 2.7% chance of Earth impact on 13 April 2029. However, on 28 December 2004, the risk of impact dropped to zero for 2029, but, due to a resonant return possibility the Torino rating for an April 2036 impact rose to 4 in early 2005, and (as of October 2009) has dropped gradually to a Torino rating of 0 (zero). The Palermo rating (October 2009) is −3.08.

Currently, the only known NEO with a Palermo scale value greater than zero is (29075) 1950 DA, which is predicted to pass very close to or collide with the Earth ($p \leq 0.003$) in the year 2880. Depending on the orientation of its axis of rotation, it will either miss the earth by tens of millions of kilometres, or have a 1 in 300 chance of hitting the earth. However, humanity has over 800 years to refine its estimates of the orbit of (29075) 1950 DA, and to deflect it, if necessary.

The Apollo asteroid 2007 TU_{24} approached Earth on January 29, 2008 with a distance of 1.4 LD (lunar distance), or 450,000 km, with an estimated size between 300–600 meters. It may be the closest asteroid to pass Earth until 2027.

NASA maintains a continuously updated web page of the most significant NEO threats in the next 100 years. All or nearly all of the items on this page are highly likely to drop off the list eventually as more data comes in enabling more accurate predictions. (The page does not include 1950 DA, because that will not strike for at least 800 years.)

Number and classification of near-Earth objects

While orbiting the sun, most potential impactors can be classified as meteoroids, asteroids, or comets depending on size and composition. Asteroids can also be members of an asteroid family, and comets can leave debris in their orbits.

As of May 2010, 7,075 NEOs have been discovered: 84 near-Earth comets and 6,991 near-Earth Asteroids. Of those there are 568 Aten asteroids, 2,617 Amor asteroids, and 3,796 Apollo asteroids. There are 1,125 NEOs that are classified as Potentially Hazardous Asteroids (PHAs). Currently, 147 PHAs and 809 NEAs have an absolute magnitude of 17.75 or brighter, which roughly corresponds to at least 1 km in size.

As of May 2010, there are 290 NEAs on the impact risk page at the NASA website. A significant number of these NEAs – 215 as of May 2010 – are equal to or smaller than 50 meters in diameter and none of the listed objects are placed even in the "yellow zone" (Torino Scale 2), meaning that none warrant the attention of general public. As of May 2010, only one asteroid 2007 VK_{184} is listed as having Torino Scale score 1.

Near-Earth meteoroids

Near Earth Meteoroids are objects with orbits in the vicinity of Earth's orbit having a diameter less than 50 metres.

Near-Earth asteroids

Computer model of the object 6489 Golevka, an Apollo asteroid

These are objects that have a near-Earth orbit, yet far enough from the Sun so that the surface material never evaporates, having a diameter over 50 metres. As of May 2010, 7,075 near-Earth asteroids are known, ranging in size up to ~32 kilometers (1036 Ganymed). The number of near-Earth asteroids over one kilometer in diameter is estimated to be 500 - 1,000. The composition of near-Earth asteroids is comparable to that of asteroids from the main asteroid belt, reflecting a variety of asteroid spectral types.

NEAs survive in their orbits for just a few million years. They are eventually eliminated by orbital decay and accretion by the Sun, collisions with the inner planets, or by being ejected from the solar system by close approaches with the planets. With orbital lifetimes short compared to the age of the solar system, new asteroids must be constantly moved into near-Earth orbits to explain the observed asteroids. The accepted origin of these asteroids is that main belt asteroids are moved into the inner solar system through orbital resonances with Jupiter. The interaction with Jupiter through the resonance perturbs the asteroid's orbit and it comes into the inner solar system. The asteroid belt has gaps, known as Kirkwood gaps, where these resonances occur as the asteroids in these resonances have been moved onto other orbits. New asteroids migrate into these resonances, due to the Yarkovsky effect that provides a continuing supply of near-Earth asteroids.

A small number of NEOs are extinct comets that have lost their volatile surface materials, although having a faint or intermittent comet-like tail does not necessarily result in a classification as a near-Earth comet, making the boundaries somewhat fuzzy. The rest of the near-Earth asteroids are driven out of the asteroid belt by gravitational interactions with Jupiter.

There are three families of near-Earth asteroids:

- The *Atens*, which have average orbital radii less than one AU and aphelia of more than Earth's perihelion (0.983 AU), placing them usually inside the orbit of Earth.
- The *Apollos*, which have average orbital radii more than that of the Earth and perihelia less than Earth's aphelion (1.017 AU).
- The *Amors*, which have average orbital radii in between the orbits of Earth and Mars and perihelia slightly outside Earth's orbit (1.017 - 1.3 AU). Amors often cross the orbit of Mars, but they do not cross the orbit of Earth.

Many Atens and all Apollos have orbits that cross (though not necessarily intersect) that of the Earth, so they are a threat to impact the Earth on their current orbits. Amors do not cross the Earth's orbit and are not immediate impact threats. However, their orbits may evolve into Earth-crossing orbits in the future.

Also sometimes used is the Arjuna asteroid classification, for asteroids with extremely Earth-like orbits.

Near-Earth comets

As of May 2010, 84 near-Earth comets have been discovered. Although no impact of a comet in earth history has been conclusively confirmed, the Tunguska event may have been caused by a fragment of Comet Encke. Cometary fragmenting may also be responsible for some impacts from near earth objects.

These near-Earth objects were probably derived from the Kuiper belt, a repository of comets residing beyond the orbit of Neptune.

Impact rate

Objects with diameters of 5-10 m impact the Earth's atmosphere approximately once per year, with as much energy as the atomic bomb dropped on Hiroshima, approximately 15 kilotonnes of TNT. These ordinarily explode in the upper atmosphere, and most or all of the solids are vaporized. Every 2000-3000 years NEA's produce explosions comparable to the one observed at Tunguska in 1908. Objects with a diameter of one kilometer hit the Earth an average of twice every million year interval. Large collisions with five kilometer objects happen approximately once every ten million years.

The rate of impacts of objects of at least 1 km in diameter is estimated as 2 per million years. Assuming that this rate will continue for the next billion years, there exist at least 2,000 objects of diameter greater than 1 km that will eventually hit Earth. However, most of these are not yet considered Potentially Hazardous Objects because they are currently orbiting between Mars and Jupiter. Eventually they will change orbits and become NEOs. Objects spend on average a few million years as NEOs before hitting the Sun, being ejected from the Solar System, or (for a small proportion) hitting a planet.

Historic impacts

Illustration of the impact of an asteroid a few kilometers across. Such impacts are expected to occur less often than every 100 million years.

The general acceptance of the Alvarez hypothesis, explaining the Cretaceous–Tertiary extinction event as the result of a large object impact event, raised the awareness of the possibility of future Earth impacts with other objects that cross the Earth's orbit.

1908 Tunguska Event

It is now commonly believed that on 30 June 1908 a stony asteroid exploded over Tunguska with the energy of the explosion of 10 megatons of TNT. The explosion occurred at a height of 8.5 kilometers. The object that caused the explosion has been estimated to have had a diameter of 45–70 meters.

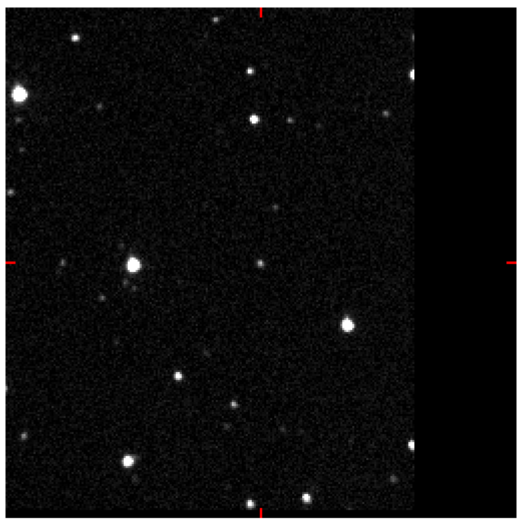
2002 Eastern Mediterranean event

On June 6, 2002 an object with an estimated diameter of 10 meters collided with Earth. The collision occurred over the Mediterranean Sea, between Greece and Libya, at approximately 34°N 21°E and the object exploded in mid-air. The energy released was estimated (from infrasound measurements) to be equivalent to 26 kilotons of TNT, comparable to a small nuclear weapon.

2008 Sudan event

On 6 October 2008, scientists calculated that a small Near-Earth asteroid 2008 TC_3 just sighted that night should impact the Earth on 7 October over Sudan, at 0246 UTC, 5:46 local time. The asteroid arrived as predicted. This is the first time that an asteroid impact on Earth has been accurately predicted. However, no reports of the actual impact have so far been published since it occurred in a very sparsely populated area. A systematic search for fragments found a total of 600 fragments, with a mass of 10.5 kilograms. The object is confirmed to have entered Earth's atmosphere as a meteor above northern Sudan at a velocity of 12.8 kilometres per second (29,000 mph).

Close approaches



Flyby of Asteroid 2004 FH. The other object that flashes by is an artificial satellite.

On August 10, 1972 a meteor that became known as The Great Daylight 1972 Fireball was witnessed by many people moving north over the Rocky Mountains from the U.S. Southwest to Canada. It was an Earth-grazing meteoroid that passed within 57 kilometres (about 34 miles) of the Earth's surface. It was filmed by a tourist at the Grand Teton National Park in Wyoming with an 8-millimeter color movie camera.

On March 23, 1989 the 300 meter (1,000-foot) diameter Apollo asteroid 4581 Asclepius (1989 FC) missed the Earth by 700,000 kilometers (400,000 miles) passing through the exact position where the Earth was only 6 hours before. If the asteroid had impacted it would have created the largest explosion in recorded history, thousands of times more powerful than the Tsar Bomba, the most powerful nuclear bomb ever exploded by man. It attracted widespread attention as early calculations had its passage being as close as 64,000 km (40,000 miles) from the Earth, with large uncertainties that allowed for the possibility of it striking the Earth.

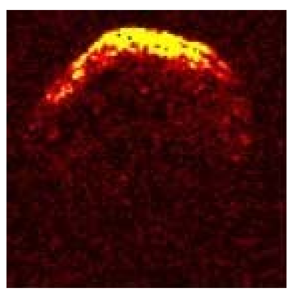
On March 18, 2004, LINEAR announced a 30 meter asteroid 2004 FH, which would pass the Earth that day at only 42,600 km (26,500 miles), about one-tenth the distance to the moon, and the closest miss ever noticed. They estimated that similar sized asteroids come as close about every two years.

On March 31, 2004, two weeks after 2004 FH, meteoroid 2004 FU_{162} set a new record for closest recorded approach, passing Earth only 6,500 km (4,000 miles) away (about one-sixtieth of the distance to the Moon). Because it was very small (6 meters/20 feet), FU_{162} was detected only hours before its closest approach. If it had collided with Earth, it probably would have harmlessly disintegrated in the atmosphere.

On March 2, 2009, near-Earth asteroid 2009 DD45 flew by Earth at about 13:40 UT. The estimated distance from Earth was 72,000 km (44,740 miles), approximately twice the height of a geostationary communications satellite. The estimated size of the space rock was about 35 meters (115 feet) wide.

On January 13, 2010 at 12:46 UT, near-Earth asteroid 2010 AL30 passed at about 122,000 km (76,000 mi). It was approximately 10–15 m (33–49 ft) wide. If 2010 AL30 had entered the Earth's atmosphere, it would have created an air burst equivalent to between 50 kT and 100 kT (kilotons of TNT). The Hiroshima "Little Boy" atom bomb had a yield between 13-18kT.

Future impacts



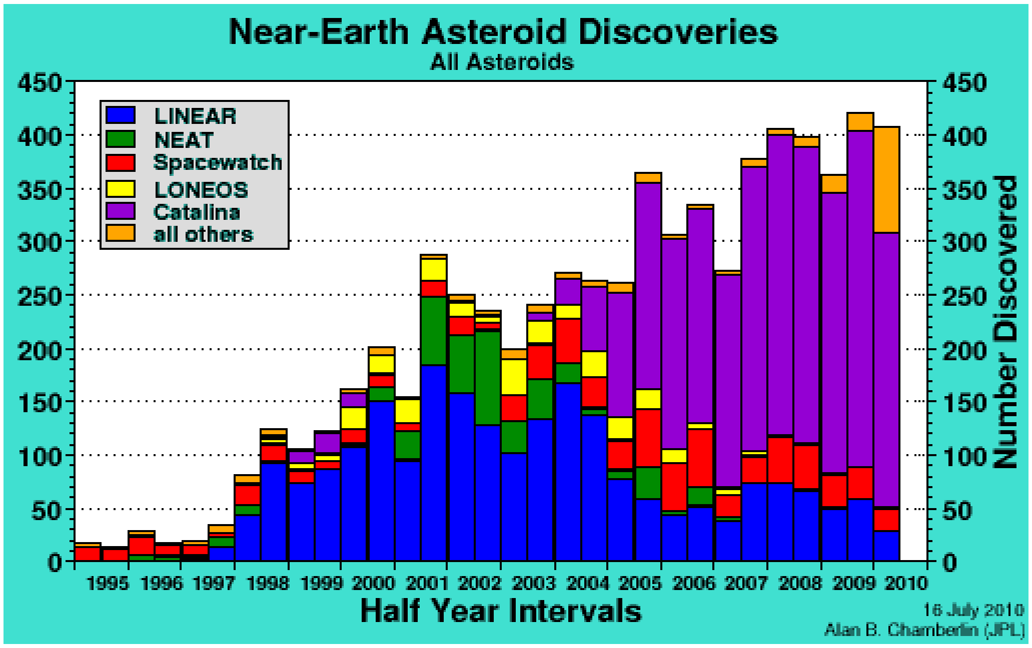
Radar image of Asteroid 1950 DA

Although there have been a few false alarms, a number of objects have been known to be threats to the Earth. (89959) 2002 NT7 was the first asteroid with a positive rating on the Palermo Technical Impact Hazard Scale, with approximately one in a million on a potential impact date of February 1, 2019.

Asteroid (29075) 1950 DA was lost after its discovery in 1950 since not enough observations were made to allow plotting of its orbit, and then rediscovered on December 31, 2000. The chance it will impact Earth on March 16, 2880 during its close approach has been estimated as 1 in 300. This chance of impact for such a large object is roughly 50% greater than that for all other such objects combined between now and 2880. It has a diameter of about a kilometer (0.6 miles).

The asteroids 99942 Apophis (provisionally known as 2004 MN4), 2007 VK184, and 2008 AF4 have had above-normal rankings on the Torino Scale.

Projects to minimize the threat



Number of NEOs detected by various projects

Several surveys have undertaken "Spaceguard" activities (an umbrella term), including Lincoln Near-Earth Asteroid Research (LINEAR), Spacewatch, Near-Earth Asteroid Tracking (NEAT), Lowell Observatory Near-Earth-Object Search (LONEOS), Catalina Sky Survey, Campo Imperatore Near-Earth Objects Survey (CINEOS), Japanese Spaceguard Association, and Asiago-DLR Asteroid Survey. In 1998, the United States Congress mandated the Spaceguard Survey - detection of 90% of near-earth asteroids over 1 km diameter (which threaten global devastation) by 2008. This could be extended by the George E. Brown, Jr. Near-Earth Object Survey Act, which calls for NASA to detect 90 percent of NEOs with diameters of 140 meters or greater by 2020. But this act has not yet become a law in the U.S.

Chapter 5

99942 Apophis

99942 Apophis

Discovery	
Discovered by	Roy A. Tucker David J. Tholen Fabrizio Bernardi
Discovery site	Kitt Peak
Discovery date	June 19, 2004
Designations	
Named after	Apep
Alternate name(s)	2004 MN_4
Minor planet category	Aten
Orbital characteristics	
Epoch January 4, 2010 (JD 2455200.5)	
Aphelion	1.0987 AU
Perihelion	0.74604 AU
Semi-major axis	0.92241 AU
Eccentricity	0.19121
Orbital period	323.58 d (0.89 a)
Average orbital speed	30.728 km/s
Mean anomaly	339.94°
Inclination	3.3315°
Longitude of ascending node	204.43°
Argument of perihelion	126.42°
Physical characteristics	
Dimensions	~270 m
Mass	2.7×10^{10} kg

Mean density	? g/cm³
Equatorial surface gravity	?
Escape velocity	~0.52 km/h
Rotation period	30.4 h
Albedo	0.33
Temperature	270 K
Spectral type	Sq
Absolute magnitude *(H)*	19.7

99942 Apophis is a near-Earth asteroid that caused a brief period of concern in December 2004 because initial observations indicated a small probability (up to 2.7%) that it would strike the Earth in 2029. Additional observations provided improved predictions that eliminated the possibility of an impact on Earth or the Moon in 2029. However, a possibility remained that during the 2029 close encounter with Earth, Apophis would pass through a gravitational keyhole, a precise region in space no more than about 600 meters across, that would set up a future impact on April 13, 2036. This possibility kept the asteroid at Level 1 on the Torino impact hazard scale until August 2006, when the probability that Apophis will pass through the keyhole was determined to be very small. Apophis broke the record for the highest level on the Torino Scale, being, for only a short time, a level 4, before it was lowered. Its diameter is approximately 270 meters (885 ft).

Keyhole

Additional observations of the trajectory of Apophis revealed the keyhole will probably be missed. On August 5, 2006, Apophis was lowered to a Level 0 on the Torino Scale. As of October 7, 2009, the impact probability for April 13, 2036, is calculated as 1 in 250,000. An additional impact date in 2068 was also identified; the impact probability for that encounter is calculated as 3 in a million.

Space probe

Many scientists agree that Apophis warrants closer scrutiny. To that end, in February 2008 the Planetary Society awarded $50,000 in prize money to companies and students who submitted designs for space probes that would put a tracking device on or near the asteroid. Several other groups have studied or plan to study missions to Apophis.

Basic data

Based upon the observed brightness, Apophis' length was estimated at 450 metres (1,480 ft); a more refined estimate based on spectroscopic observations at NASA's Infrared Telescope Facility in Hawaii by Binzel, Rivkin, Bus, and Tokunaga (2005) is 350 metres (1,150 ft).

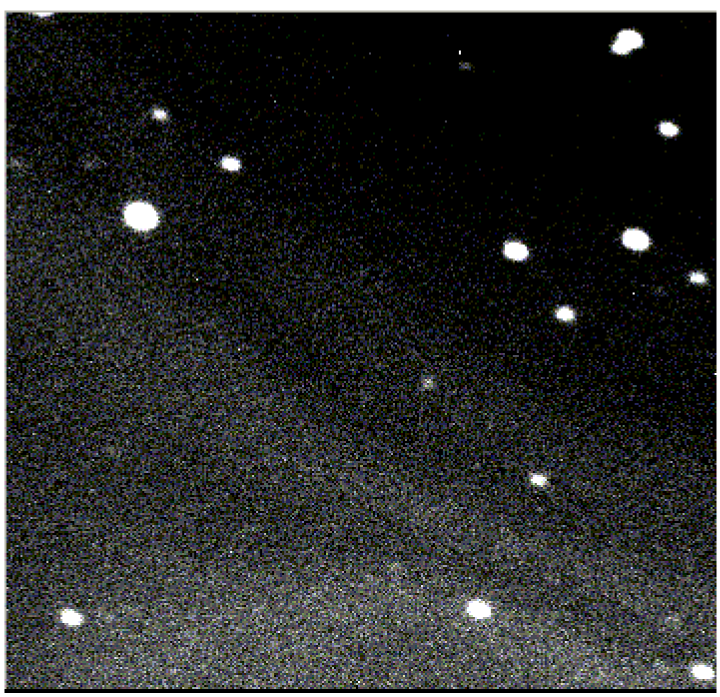
In October 2005 it was predicted that the asteroid will pass just below the altitude of geosynchronous satellites, which are at 35,786 kilometres (22,236 mi). Such a close approach by an asteroid of this size is expected to occur only every 1,300 years or so. Apophis' brightness will peak at magnitude 3.3, with a maximum angular speed of 42° per hour. The maximum apparent angular diameter will be ~2 arcseconds, so that it will be barely resolved by telescopes not equipped with adaptive optics.

Naming

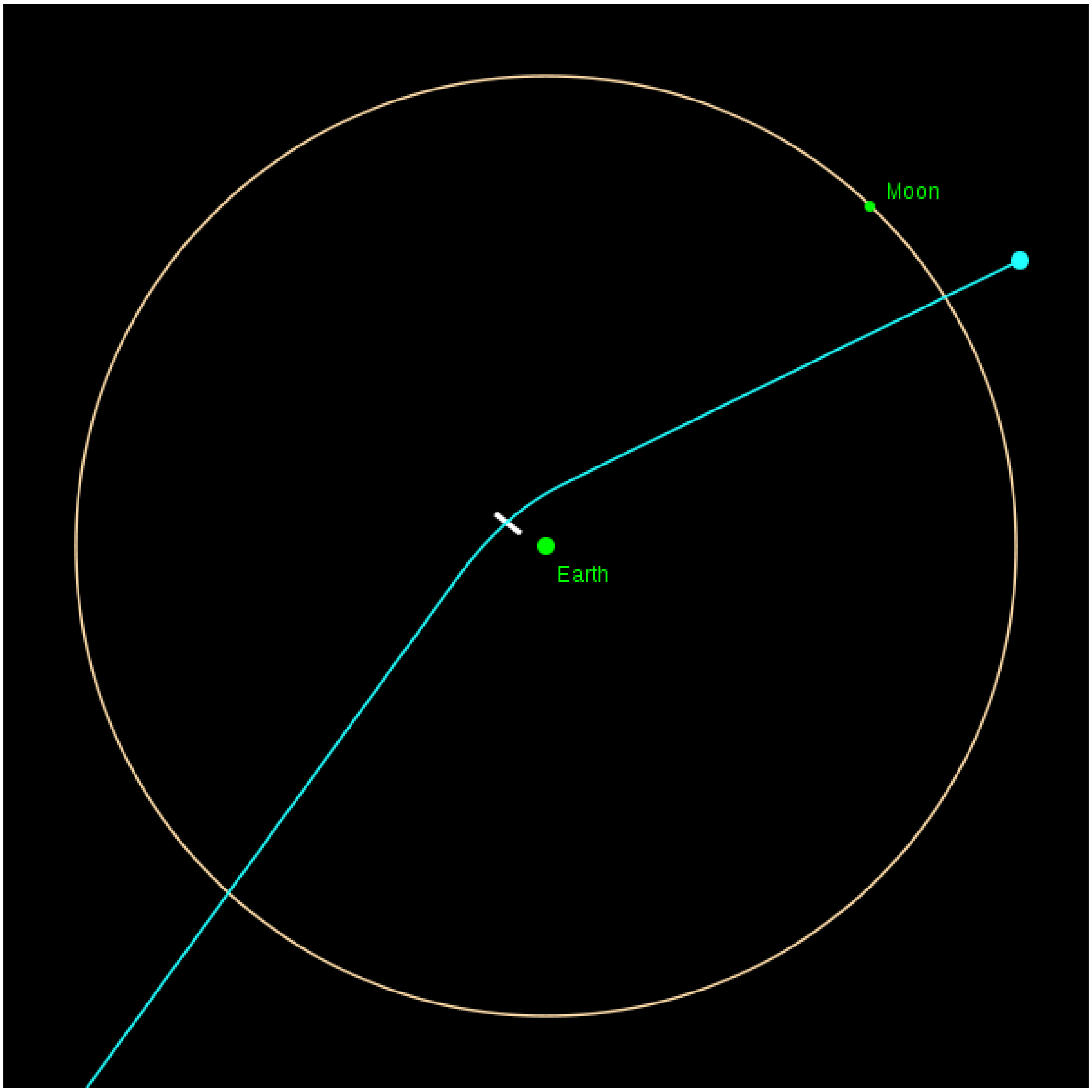
When first discovered, the object received the provisional designation 2004 MN_4 (sometimes written 2004 MN4), and news and scientific articles about it referred to it by that name. When its orbit was sufficiently well calculated, it received the permanent number 99942 (on June 24, 2005). Receiving a permanent number made it eligible for naming, and it received the name "Apophis" on July 19, 2005. Apophis is the Greek name of the Ancient Egyptian enemy of Ra: Apep, the Uncreator, a serpent that dwells in the eternal darkness of the Duat (earth's middle) and tries to swallow Ra during His nightly passage. Apep is held at bay by Set, the Ancient Egyptian god of Chaos.

Although the Greek name for the Egyptian god may be appropriate, Tholen and Tucker — two of the co-discoverers of the asteroid — are reportedly fans of the TV series *Stargate SG-1*. One of the show's persistent villains is an alien also named for the Egyptian god.

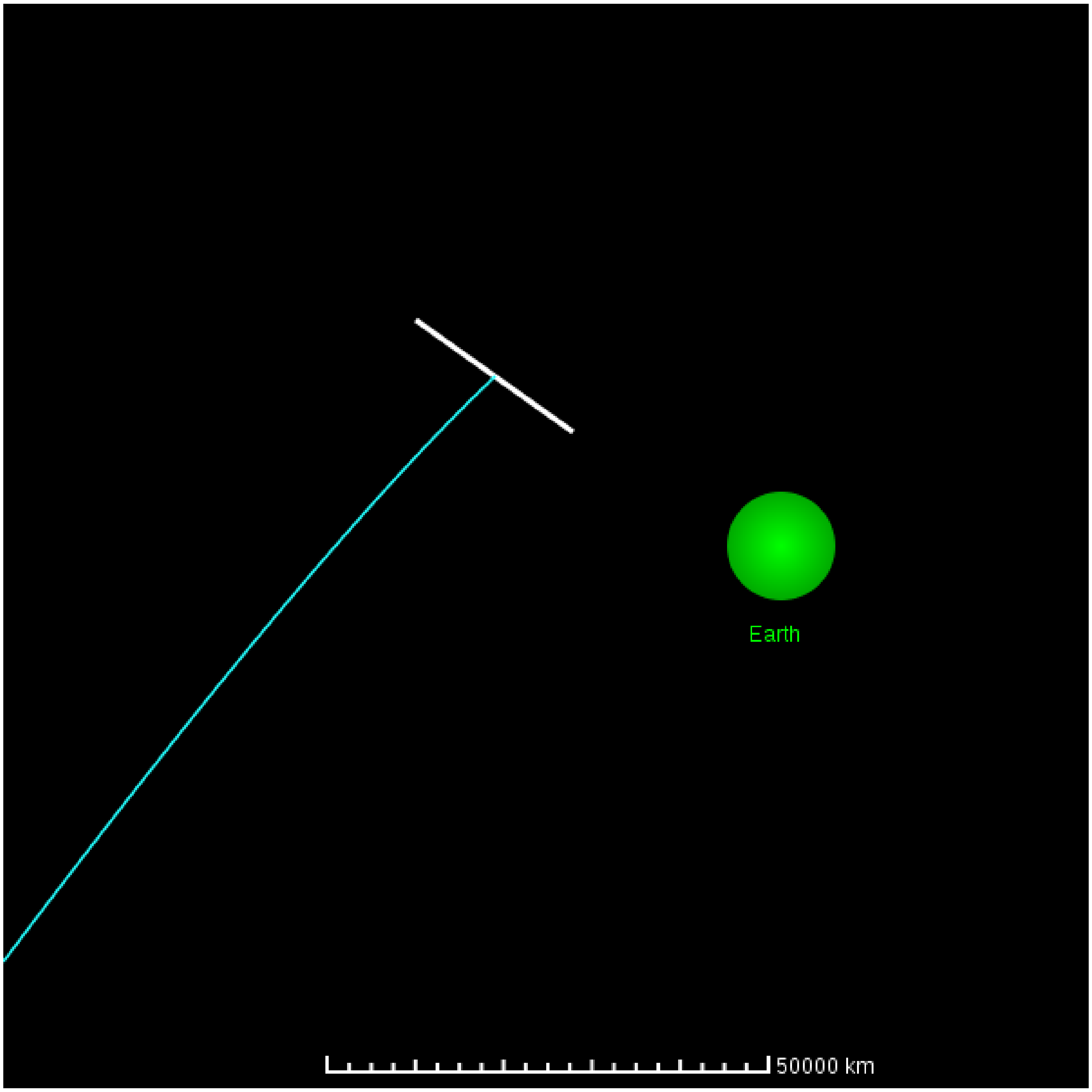
Close approaches



99942 Apophis



Close approach of Apophis on April 13, 2029



The white bar indicates uncertainty in the range of positions

After the Minor Planet Center confirmed the June discovery of Apophis, an April 13, 2029 close approach was flagged by NASA's automatic Sentry system and NEODyS, a similar automatic program run by the University of Pisa and the University of Valladolid. On that date, it will become as bright as magnitude 3.3 (visible to the naked eye from rural as well as darker suburban areas, visible with binoculars from most locations). This close approach will be visible from Europe, Africa, and western Asia. As a result of its close passage, it will move from the Aten to the Apollo class.

After Sentry and NEODyS announced the possible impact, additional observations decreased the uncertainty in Apophis' trajectory. As they did, the probability of an impact event temporarily climbed, peaking at 2.7% (1 in 37). Combined with its size, this caused Apophis to be assessed at level 4 on the Torino Scale and 1.10 on the Palermo scale, scales scientists use to represent the danger of an asteroid hitting Earth. These are the highest values for which any object has been rated on either scale.

On Friday, April 13, 2029, Apophis will pass Earth within the orbits of geosynchronous communication satellites. It will return for another close Earth approach in 2036.

Precovery observations from March 15, 2004, were identified on December 27, and an improved orbit was computed. Radar astrometry further refined the orbit. The 2029 pass will actually be much closer than the first predictions, but the uncertainty is such that an impact is ruled out. Similarly, the pass on April 13, 2036 carries little risk of an impact.

2013 refinement

The close approach in 2029 will substantially alter the object's orbit, making predictions uncertain without more data. "If we get radar ranging in 2013 [the next good opportunity], we should be able to predict the location of 2004 MN_4 out to at least 2070." said Jon Giorgini of JPL. Apophis will pass within 0.09666 AU (14.4 million km) of the Earth in 2013 allowing astronomers to refine the trajectory for future close passes.

In July 2005, former Apollo astronaut Rusty Schweickart, as chairman of the B612 Foundation, formally asked NASA to investigate the possibility that the asteroid's post-2029 orbit could be in orbital resonance with Earth, which would increase the probability of future impacts. Schweickart asked for an investigation of the necessity of placing a transponder on the asteroid for more accurate tracking of how its orbit is affected by the Yarkovsky effect.

History of impact estimates

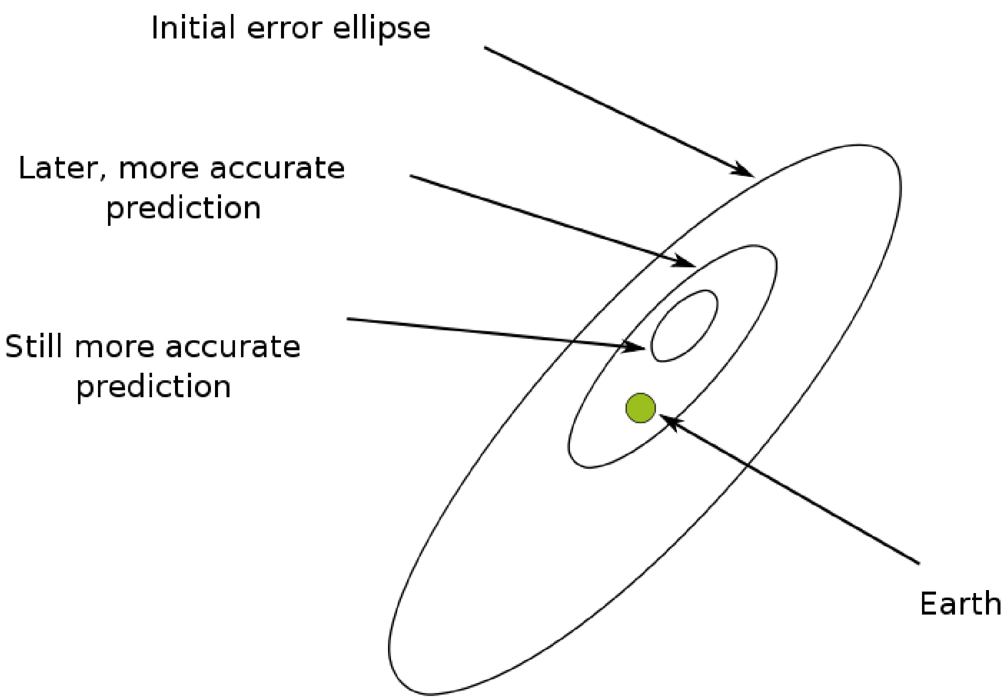


Illustration of a common trend where progressively reduced uncertainty regions result in an asteroid impact probability increasing followed by a sharp decrease.

- The original NASA report on December 23, 2004, mentioned impact chances of "around 1 in 300" in 2029, which was widely reported in the media. The actual NASA estimates at the time were 1 in 233; they resulted in the Torino scale rating of 2, the first time any asteroid had received a rating above 1.
- Later that day, based on a total of 64 observations, the estimates were changed to 1 in 62 (1.6%), resulting in an update to the initial report and an upgrade to a Torino scale rating of 4.
- On December 25, 2004, the chances were first reported as 1 in 42 (2.4%) and later that day (based on 101 observations) as 1 in 45 (2.2%). At the same time, the asteroid's estimated diameter was lowered from 440 m to 390 m and its mass from 1.2×10^{11} kg to 8.3×10^{10} kg.
- On December 26, 2004 (based on a total of 169 observations), the impact probability was still estimated as 1 in 45 (2.2%), the estimates for diameter and mass were lowered to 380 m and 7.5×10^{10} kg, respectively.
- On December 27, 2004 (based on a total of 176 observations), the impact probability was raised to 1 in 37 (2.7%); diameter was increased to 390 m, and mass to 7.9×10^{10} kg.

- On December 27, 2004, in the afternoon, a precovery increased the span of observations to 287 days and allowed more accurate calculations to re-rate the asteroid's 2029 approach as level zero on the Torino scale (no threat). The cumulative impact probability was estimated to be around 0.004%, a lower risk than asteroid 2004 VD_{17}, which once again became the greatest risk object. A 2053 approach to Earth still poses a minor risk of impact, and Apophis was still rated at level one on the Torino scale for this orbit, and thus remains that way.
- On December 28, 2004 at 12:23 GMT and (based on a total of 139 observations), produced a value of one on the Torino scale for 2044-04-13.29 and 2053-04-13.51.
- By 01:10 GMT on December 29, 2004 the only pass rated 1 on the Torino scale was for 2053-04-13.51 based on 139 observations spanning 287.71 days (2004-Mar-15.1104 to 2004-Dec-27.8243). (As of 2010, the 2053 is now a 2056-04-13 risk of 1 in 10 million.)
- By 19:18 GMT on December 29, 2004 this was still the case based upon 147 observations spanning 288.92 days (2004-Mar-15.1104 to 2004-Dec-29.02821), though the close encounters have changed and been reduced to 4 in total.
- By 13:46 GMT on December 30, 2004 no passes were rated above 0, based upon 157 observations spanning 289.33 days (2004-Mar-15.1104 to 2004-Dec-29.44434). The most dangerous pass was rated at 1 in 7,143,000.
- By 22:34 GMT on December 30, 2004, 157 observations spanning 289.33 days (2004-Mar-15.1104 to 2004-Dec-29.44434). One pass at 1 (Torino scale) 3 other passes.
- By 03:57 GMT on January 2, 2005, 182 observations spanning 290.97 days (2004-Mar-15.1104 to 2004-Dec-31.07992) One pass at 1 (Torino scale) 19 other passes.
- By 14:49 GMT on January 3, 2005, observations spanning 292.72 days (2004-Mar-15.1104 to 2005-Jan-01.82787) One pass at 1 (Torino scale) 15 other passes.
- Extremely precise radar observations at Arecibo Observatory on January 27, 28, and 30 refine the orbit further and show that the April, 2029 close approach will occur at only 5.6 Earth radii, approximately one-half the distance previously estimated.
- A radar observation on August 7, 2005, refines the orbit further and eliminates the possibility of an impact in 2035. Only the pass in 2036 remains at Torino Scale 1.
- A new radar observation at Arecibo Observatory on May 6, 2006, slightly lowered the Palermo scale rating, but the pass in 2036 remained at Torino Scale 1 despite the impact probability dropping by a factor of four.
- Additional observations through 2006 resulted in Apophis being lowered to Torino Scale 0 on August 6, 2006. Around this time, the impact probability was lowered to 1 in 45,000.
- As of October 7, 2009, refinements to the precovery images of Apophis by the University of Hawaii's Institute for Astronomy, the 90-inch Bok Telescope, and the Arecibo Observatory have generated a refined path that reduces the odds of a April 13, 2036 impact to about 1 in 250,000.

Possible impact effects

NASA initially estimated the energy that Apophis would have released if it struck Earth as the equivalent of 1480 megatons of TNT. A later, more refined NASA estimate was 880 megatons, then revised to 510 megatons. The impacts which created the Barringer Crater or the Tunguska event are estimated to be in the 3–10 megaton range The 1883 eruption of Krakatoa was the equivalent of roughly 200 megatons. In comparison, the Chicxulub impact, believed by many to be a significant factor in the extinction of the dinosaurs, has been estimated to have released about as much energy as 100,000,000 megatons.

Path of risk where 99942 Apophis may impact Earth in 2036

The exact effects of any impact would vary based on the asteroid's composition, and the location and angle of impact. Any impact would be extremely detrimental to an area of thousands of square kilometres, but would be unlikely to have long-lasting global effects, such as the initiation of an impact winter.

The B612 Foundation made estimates of Apophis' path if a 2036 Earth impact were to occur as part of an effort to develop viable deflection strategies. The result is a narrow corridor a few miles wide, called the "path of risk", extending across southern Russia, across the north Pacific (relatively close to the coastlines of California and Mexico), then right between Nicaragua and Costa Rica, crossing northern Colombia and Venezuela, ending in the Atlantic, just before reaching Africa. Using the computer simulation tool NEOSim, it was estimated that the hypothetical impact of Apophis in countries such as Colombia and Venezuela, which are in the path of risk, could have more than 10 million casualties. An impact several thousand miles off the West Coast of the US would produce a devastating tsunami.

Potential space missions

Planetary Society competition

In 2008, The Planetary Society, a California-based space advocacy group, organized a $50,000 competition to design an unmanned space probe that would 'shadow' Apophis for almost a year, taking measurements that would "determine whether it will impact Earth, thus helping governments decide whether to mount a deflection mission to alter its orbit." The society received 37 entries from 20 countries on 6 continents.

The commercial competition was won by a design called 'Foresight' created by SpaceWorks Engineering. SpaceWorks proposes a simple orbiter with only two instruments and a radio beacon at a cost of ~140 million USD, launched aboard a Minotaur IV between 2012 and 2014, to arrive at Apophis five to ten months later. It would then rendezvous with, observe, and track the asteroid.

Foresight would orbit the asteroid to gather data with a multi-spectral imager for one month. It would then leave orbit and fly in formation with Apophis around the Sun at a range of two kilometers (1.2 miles). The spacecraft would use laser ranging to the asteroid and radio tracking from Earth for ten months to accurately determine the asteroid's orbit and how it might change.

Pharos, the winning student entry, would be an orbiter with four science instruments (a multi-spectral imager, near-infrared spectrometer, laser rangefinder, and magnetometer) that would rendezvous with and track Apophis. Earth-based tracking of the spacecraft would then allow precise tracking of the asteroid. The Pharos spacecraft would also carry four instrumented probes that it would launch individually over the course of two weeks. Accelerometers and temperature sensors on the probes would measure the seismic effects of successive probe impacts, a creative way to explore the interior structure and dynamics of the asteroid.

Second place, for $10,000, went to a European team led by Deimos Space S.L. of Madrid, Spain, in cooperation with EADS Astrium, Friedrichshafen, Germany; University of Stuttgart, Germany; and Università di Pisa, Italy. Juan L. Cano was Principal Investigator.

Another European team took home $5,000 for third place. Their team lead was EADS Astrium Ltd, United Kingdom, in conjunction with EADS Astrium SAS, France; IASF-Roma, INAF, Rome, Italy; Open University, UK; Rheinisches Institut für Umweltforschung, Germany; Royal Observatory of Belgium; and Telespazio, Italy. The Principal Investigator was Paolo D'Arrigo.

Two teams tied for second place in the Student Category: Monash University, Clayton Campus, Australia, with Dilani Kahawala as Principal Investigator; and University of Michigan, with Jeremy Hollander as Principal Investigator. Each second place team won $2,000. A team from Hong Kong Polytechnic University and Hong Kong University of

Science and Technology, under the leadership of Peter Weiss, received an honorable mention and $1,000 for the most innovative student proposal.

Proposed deflection strategies

Studies by NASA, ESA, and various research groups in addition to the Planetary Society contest teams, have described a number of proposals for deflecting Apophis or similar objects, including gravitational tractor, kinetic impact, and nuclear bomb methods.

On December 30, 2009, Anatoly Perminov, the director of the Russian Federal Space Agency, said in an interview that Roscosmos will also study designs for a possible deflection mission to Apophis.

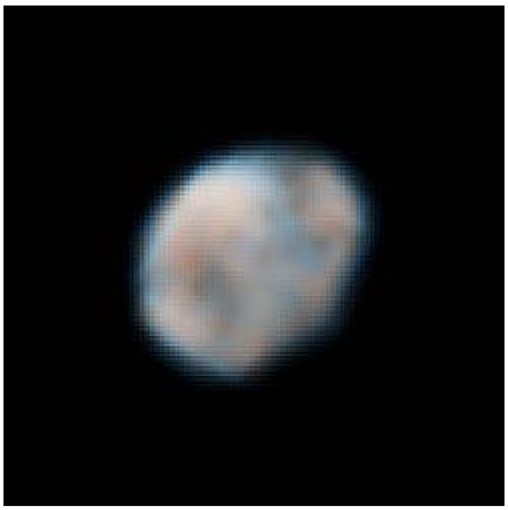
Don Quijote mission

Apophis is one of two asteroids under consideration by the European Space Agency as the target of its Don Quijote mission to study the effects of impacting an asteroid.

Chapter 6

4 Vesta

4 Vesta

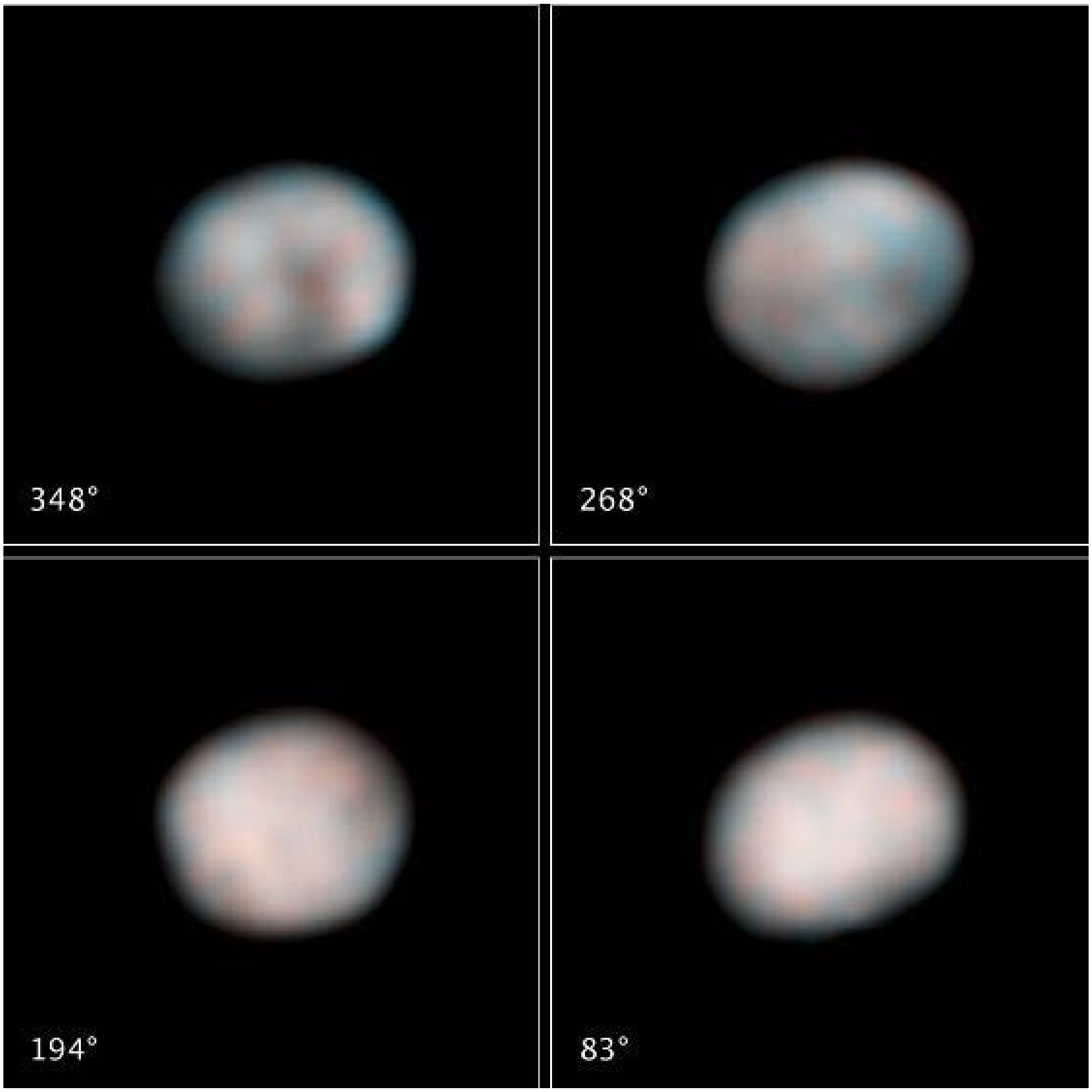


Discovery	
Discovered by	Heinrich Wilhelm Olbers
Discovery date	March 29, 1807

Designations	
Named after	Vesta
Minor planet category	Main belt (Vesta family)
Adjective	Vestian

Orbital characteristics	
Epoch May 14, 2008 (JD 2454600.5)	
Aphelion	384.72 Gm (2.572 AU)
Perihelion	321.82 Gm (2.151 AU)
Semi-major axis	353.268 Gm (2.361 AU)

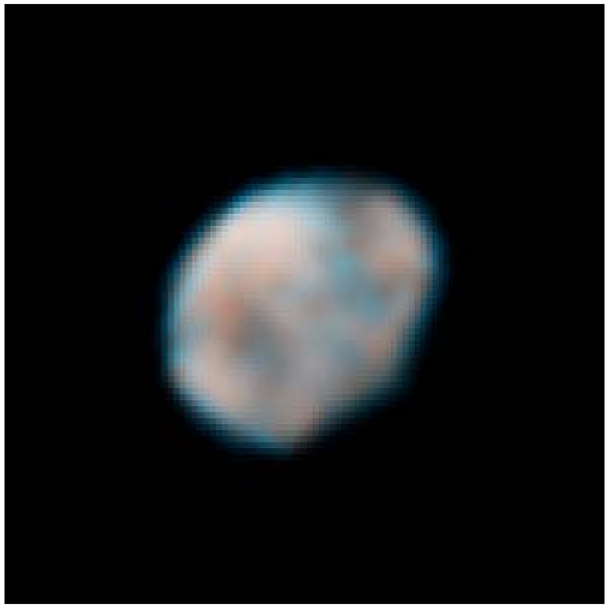
Eccentricity	0.089 17
Orbital period	1325.15 d (3.63 a)
Average orbital speed	19.34 km/s
Mean anomaly	90.53°
Inclination	7.135° to Ecliptic 5.56° to Invariable plane
Longitude of ascending node	103.91°
Argument of perihelion	149.83°
Physical characteristics	
Dimensions	578×560×458 km 529 km (mean)
Mass	$(2.67 \pm 0.02)\times10^{20}$ kg
Mean density	3.42 g/cm³
Equatorial surface gravity	0.22 m/s²
Escape velocity	0.35 km/s
Rotation period	0.222 6 d (5.342 h)
Albedo	0.423 (geometric)
Temperature	*min:* 85 K (−188 °C) *max:* 255 K (−18 °C)
Spectral type	V-type asteroid
Apparent magnitude	5.1 to 8.48
Absolute magnitude *(H)*	3.20
Angular diameter	0.64" to 0.20"



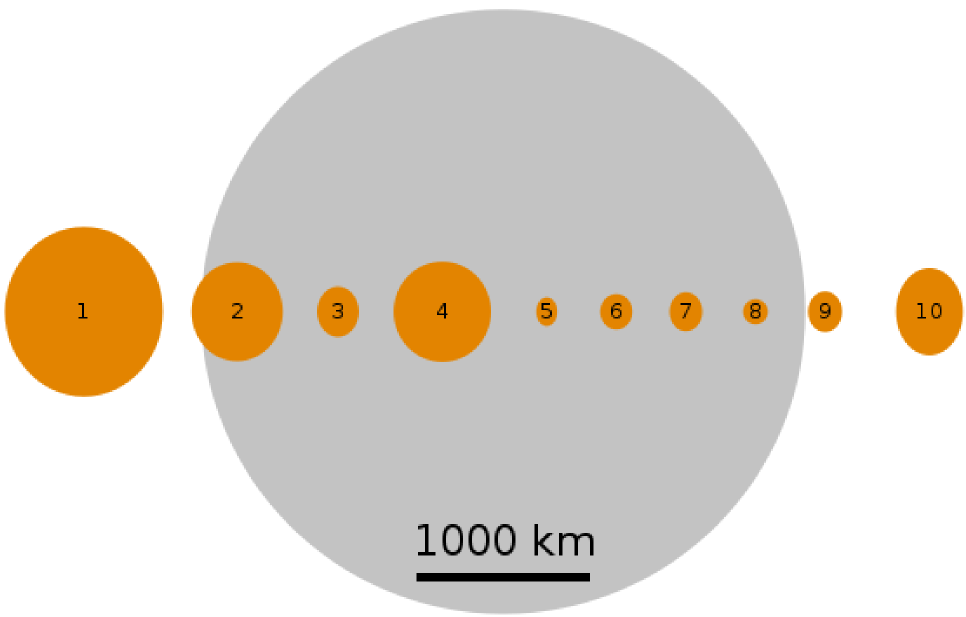
Four views of Vesta as it rotates. The dark patch in the center of the upper-left image is believed to be a lava flow. Orange areas are thought to be impacts.

Vesta, formal designation **4 Vesta**, is an asteroid, thought to be a remnant protoplanet with a differentiated interior, and a mean diameter of about 530 km. Comprising an estimated 9% of the mass of the entire asteroid belt, it is the second most massive object in the belt (the largest being the dwarf planet Ceres). It was discovered by the German astronomer Heinrich Wilhelm Olbers on March 29, 1807 and named after the Roman virgin goddess of home and hearth, Vesta.

Vesta is the brightest asteroid. Its greatest distance from the Sun is slightly more than the minimum distance of Ceres from the Sun, and its orbit is entirely within the orbit of Ceres. Vesta lost some 1% of its mass in a collision less than one billion years ago. Many fragments of this event have fallen to Earth as Howardite-Eucrite-Diogenite (HED) meteorites, a rich source of evidence about the asteroid.



Discovery



Size comparison: the first 10 asteroids profiled against Earth's Moon. Vesta is fourth from the left. (The leftmost object, 1 Ceres, is now classified as a dwarf planet)

The discovery of Ceres in 1801 and Pallas in 1802 led German astronomer Heinrich Wilhelm Olbers to propose that the two objects were the remnants of a destroyed planet. In 1802 he sent a letter with his proposal to the English astronomer William Herschel, suggesting that a search near the locations where the orbits of Ceres and Pallas intersected might reveal more fragments. These orbital intersections were located in the constellations of Cetus and Virgo.

Olbers commenced his search in 1802, and on March 29, 1807 he coincidentally discovered Vesta in the constellation Virgo. As the asteroid Juno had been discovered in 1804, this made Vesta the fourth object to be identified in the region that is now known as the main asteroid belt. This discovery was announced in a letter addressed to German astronomer Johann H. Schröter dated March 31. Olbers allowed the prominent mathematician Carl Friedrich Gauss to name the asteroid after the Roman virgin goddess of home and hearth, Vesta. The mathematician manually computed the first orbit for Vesta in the remarkably short time of 10 hours.

After the discovery of Vesta, no further objects were discovered for 38 years. During this time Ceres, Pallas, Juno and Vesta were classified as planets and each had its own planetary symbol. Vesta was normally represented by a stylized hearth (, □). Other symbols are and . All are simplifications of the original .

Photometric observations of the asteroid Vesta were made at the Harvard College Observatory between 1880–82 and at the Observatoire de Toulouse in 1909. These and other observations allowed the rotation rate of the asteroid to be determined by the 1950s. However, the early estimates of the rotation rate came into question because the light curve included variations in both shape and albedo.

Early estimates of the diameter of Vesta ranged from 383 (in 1825) to 444 km. William H. Pickering produced a estimated diameter of 513 ± 17 km in 1879, which is close to the modern value for the mean diameter, but the subsequent estimates ranged from a low of 390 km up to a high of 602 km during the next century. The measured estimates were based on photometry. In 1989, speckle interferometery was used to measure a dimension that varied between 498 and 548 km during the rotational period. In 1991, an occultation of the star SAO 93228 by Vesta was observed from multiple locations in the eastern US and Canada. Based on observations from 14 different sites, the best fit to the data is an elliptical profile with dimensions of about 550 km × 462 km.

Vesta became the first asteroid to have its mass determined. Every 18 years, the asteroid 197 Arete approaches within 0.04 AU of Vesta. In 1966, based upon observations of Vesta's gravitational perturbations of Arete, Hans G. Hertz estimated the mass of Vesta as $(1.20 \pm 0.08) \times 10^{-10}$ solar masses. More refined estimates followed, and in 2001 the perturbations of 17 Thetis were used to estimate the mass of Vesta as $(1.31 \pm 0.02) \times 10^{-10}$ solar masses.

Physical characteristics

The IAU 2006 draft proposal on the definition of a planet listed Vesta as a candidate. Vesta is shown fourth from the left along the bottom row.

Vesta is the second-most massive body in the asteroid belt, though only 28% as massive as Ceres. It lies in the Inner Main Belt interior to the Kirkwood gap at 2.50 AU. It has a differentiated interior, and is similar to 2 Pallas in volume (to within uncertainty) but about 25% more massive.

Vesta's shape is relatively close to a gravitationally relaxed oblate spheroid, but the large concavity and protrusion at the pole combined with a mass less than 5×10^{20} kg precluded Vesta from automatically being considered a dwarf planet under International Astronomical Union (IAU) Resolution XXVI 5. Vesta may be listed as a dwarf planet in the future, if it is convincingly determined that its shape, other than the large impact basin at the southern pole, is due to hydrostatic equilibrium, as currently believed.

Its rotation is relatively fast for an asteroid (5.342 h) and prograde, with the north pole pointing in the direction of right ascension 20 h 32 min, declination +48° (in the constellation Cygnus) with an uncertainty of about 10°. This gives an axial tilt of 29°.

Temperatures on the surface have been estimated to lie between about −20 °C with the Sun overhead, dropping to about −190 °C at the winter pole. Typical day-time and night-time temperatures are −60 °C and −130 °C, respectively. This estimate is for May 6, 1996, very close to perihelion, while details vary somewhat with the seasons.

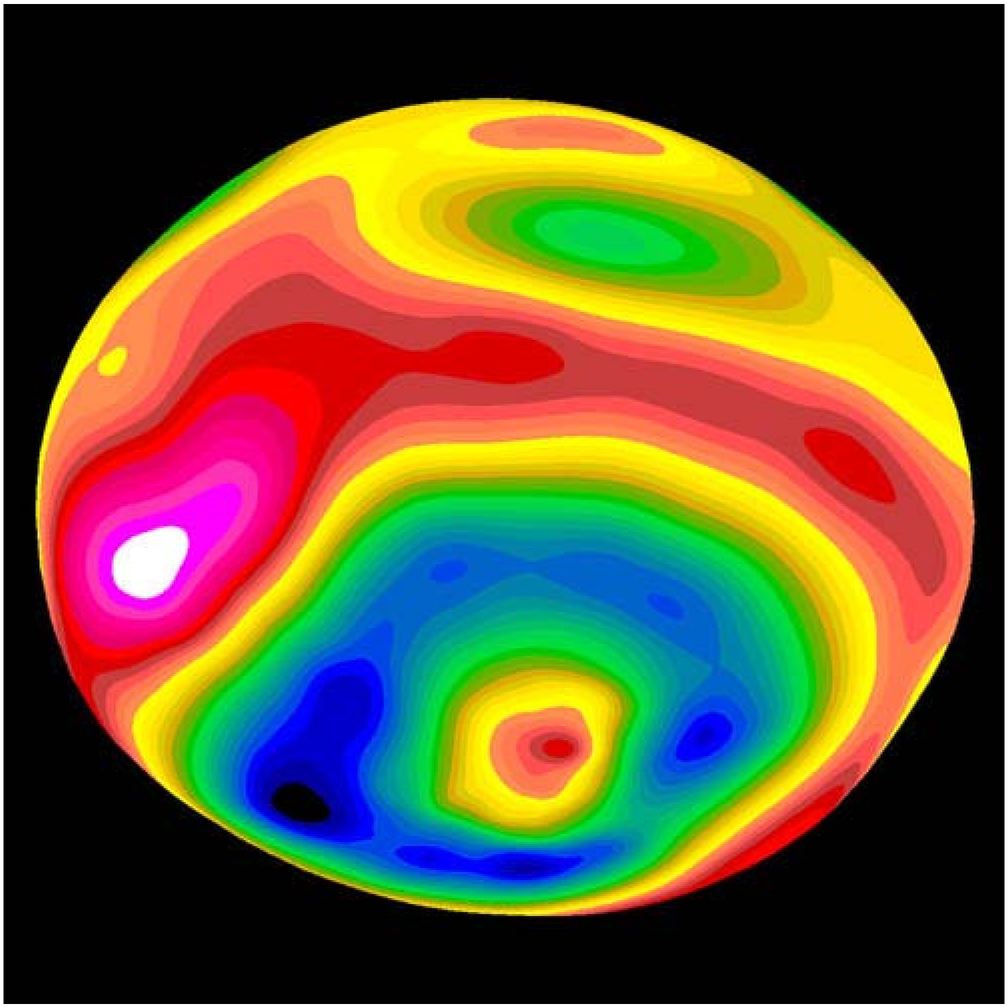
Geology

There is a large collection of potential samples from Vesta accessible to scientists, in the form of over 200 HED meteorites, giving insight into Vesta's geologic history and structure. NASA Infrared Telescope Facility (NASA IRTF) studies of asteroid (237442) 1999 TA_{10} suggest that it originated from the interior of Vesta.

Vesta is thought to consist of a metallic iron–nickel core, an overlying rocky olivine mantle, with a surface crust. From the first appearance of Ca-Al-rich inclusions (the first solid matter in the Solar System, forming about 4,567 million years ago), a likely time line is as follows:

Timeline of the evolution of Vesta

2–3 million years	Accretion completed
4–5 million years	Complete or almost complete melting due to radioactive decay of ^{26}Al, leading to separation of the metal core
6–7 million years	Progressive crystallization of a convecting molten mantle. Convection stopped when about 80% of the material had crystallized
	Extrusion of the remaining molten material to form the crust, either as basaltic lavas in progressive eruptions, or possibly forming a short-lived magma ocean.
	The deeper layers of the crust crystallize to form plutonic rocks, while older basalts are metamorphosed due to the pressure of newer surface layers.
	Slow cooling of the interior



Elevation diagram of 4 Vesta (as determined from Hubble Space Telescope images of May 1996) viewed from the south-east, showing the south pole crater.

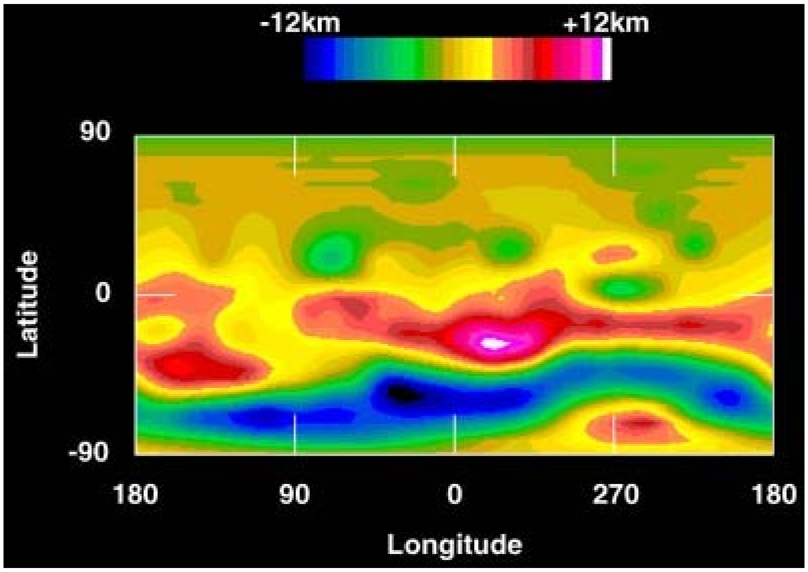
Vesta is the only known intact asteroid that has been resurfaced in this manner. However, the presence of iron meteorites and achondritic meteorite classes without identified parent bodies indicates that there once were other differentiated planetesimals with igneous histories, which have since been shattered by impacts.

Composition of the Vestan crust (in order of increasing depth)

- A lithified regolith, the source of howardites and brecciated eucrites.
- Basaltic lava flows, a source of non-cumulate eucrites.
- Plutonic rocks consisting of pyroxene, pigeonite and plagioclase, the source of cumulate eucrites.
- Plutonic rocks rich in orthopyroxene with large grain sizes, the source of diogenites.

On the basis of the sizes of V-type asteroids (thought to be pieces of Vesta's crust ejected during large impacts), and the depth of the south polar crater (see below), the crust is thought to be roughly 10 kilometres (6 mi) thick.

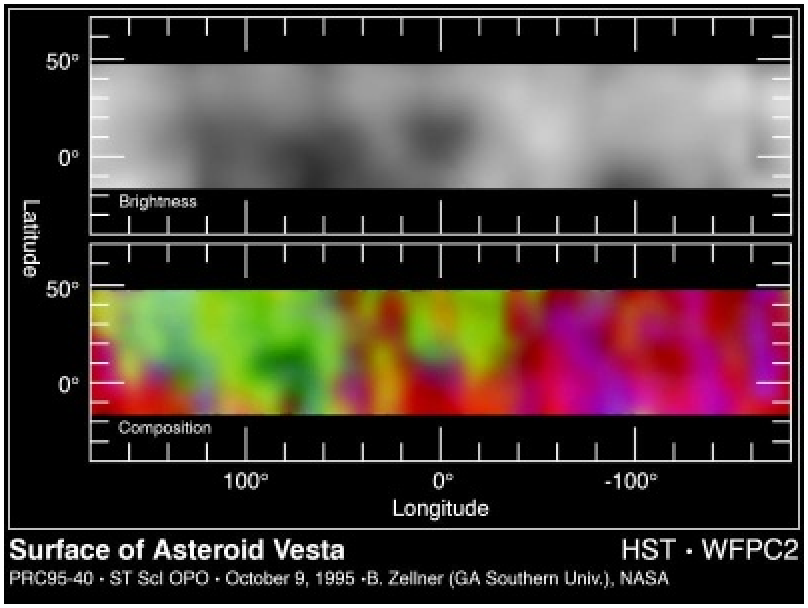
Surface features



Elevation map of 4 Vesta, as determined from Hubble Space Telescope images of May 1996

Some Vestian surface features have been resolved using the Hubble Space Telescope and ground based telescopes, e.g. the Keck Telescope.

The most prominent surface feature is an enormous crater 460 kilometres (290 mi) in diameter centered near the south pole. Its width is 80% of the entire diameter of Vesta. The floor of this crater is about 13 kilometres (8.1 mi) below, and its rim rises 4–12 km above the surrounding terrain, with total surface relief of about 25 km. A central peak rises 18 kilometres (11 mi) above the crater floor. It is estimated that the impact responsible excavated about 1% of the entire volume of Vesta, and it is likely that the Vesta family and V-type asteroids are the products of this collision. If this is the case, then the fact that 10 km fragments of the Vesta family and V-type asteroids have survived bombardment until the present indicates that the crater is only about 1 billion years old or younger. It would also be the original site of origin of the HED meteorites. In fact, all the known V-type asteroids taken together account for only about 6% of the ejected volume, with the rest presumably either in small fragments, ejected by approaching the 3:1 Kirkwood gap, or perturbed away by the Yarkovsky effect or radiation pressure. Spectroscopic analyses of the Hubble images have shown that this crater has penetrated deep through several distinct layers of the crust, and possibly into the mantle, as indicated by spectral signatures of olivine.



Spectral and albedo maps of 4 Vesta, as determined from Hubble Space Telescope images from November 1994

Several other large craters about 150 kilometres (93 mi) wide and 7 kilometres (4.3 mi) deep are also present. A dark albedo feature about 200 kilometres (120 mi) across has been named *Olbers* in honour of Vesta's discoverer, but it does not appear in elevation maps as a fresh crater would. Its nature is presently unknown; it may be an old basaltic surface. It serves as a reference point with the 0° longitude prime meridian defined to pass through its center.

The eastern and western hemispheres show markedly different terrains. From preliminary spectral analyses of the Hubble Space Telescope images, the eastern hemisphere appears to be some kind of high albedo, heavily cratered "highland" terrain with aged regolith, and craters probing into deeper plutonic layers of the crust. On the other hand, large regions of the western hemisphere are taken up by dark geologic units thought to be surface basalts, perhaps analogous to the lunar maria.

Fragments

4 Vesta, 1 Ceres and Earth's Moon shown to scale

Some small solar system objects are believed to be fragments of Vesta caused by collisions. The Vestoid asteroids and HED meteorites are examples. The V-type asteroid 1929 Kollaa has been determined to have a composition akin to cumulate eucrite meteorites, indicating its origin deep within Vesta's crust.

Because a number of meteorites are believed to be Vestian fragments, Vesta is currently one of only five identified Solar system bodies for which we have physical samples, the others being Mars, the Moon, comet Wild 2, and Earth itself.

Exploration

In 1981, a proposal for an asteroid mission was submitted to the ESA. Named the *Asteroidal Gravity Optical and Radar Analysis* (AGORA), this spacecraft was to launch some time in 1990–1994 and perform two flybys of large asteroids. The preferred target for this mission was Vesta. AGORA would reach the asteroid belt either by a gravitational slingshot trajectory past Mars or by means of a small ion engine. However, the proposal was refused by the ESA. A joint NASA-ESA asteroid missions was then drawn up for a *Multiple Asteroid Orbiter with Solar Electric Propulsion* (MAOSEP), with one of the mission profiles including an orbit of Vesta. NASA indicated they were not interested in an asteroid mission. Instead, the ESA set up a technological study of a spacecraft with an ion drive. Other missions to the asteroid belt were proposed in the 1980s by France, Germany, Italy, the Soviet Union and the United States, but none were approved.

In the early 1990s, NASA initiated the Discovery Program, which was intended to be a series of low cost scientific missions. In 1996, the program's study team recommended as a high priority a mission to explore the asteroid belt using a spacecraft with an ion engine. Funding for this program remained problematic for several years, but by 2004 the *Dawn* vehicle had passed its critical design review.

NASA's *Dawn* probe—launched on September 27, 2007—is the first space mission to Vesta. It will orbit the asteroid for nine months from August 2011 until May 2012. *Dawn* will then proceed to its other target, Ceres, and will possibly continue to explore the asteroid belt on an extended mission using any remaining fuel. The spacecraft is the first that can enter and leave orbit around more than one body as a result of its weight-efficient ion driven engines. Once *Dawn* arrives at Vesta, scientists will be able to calculate Vesta's precise mass based on gravitational interactions. This will allow scientists to refine the mass estimates of the asteroids that are in turn perturbed by Vesta.

Visibility

Vesta is seen from San Francisco on June 14, 2007

Its size and unusually bright surface make Vesta the brightest asteroid, and it is occasionally visible to the naked eye from dark (non-light polluted) skies. In May and June 2007, Vesta reached a peak magnitude of +5.4, the brightest since 1989. At that time, opposition and perihelion were only a few weeks apart. It was visible in the constellations Ophiuchus and Scorpius.

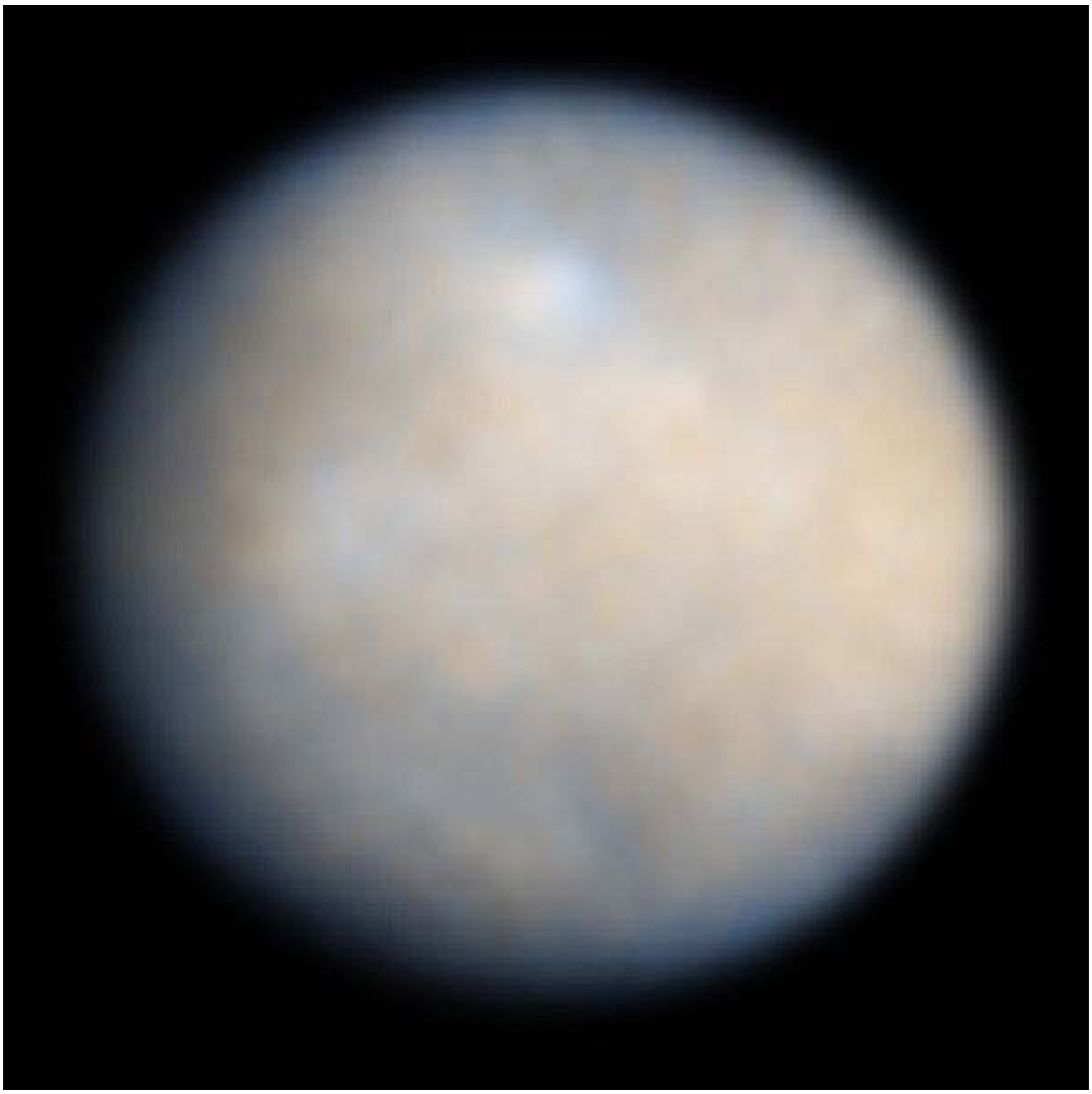
Less favorable oppositions during late autumn in the Northern Hemisphere still have Vesta at a magnitude of around +7.0. Even when in conjunction with the Sun, Vesta will have a magnitude around +8.5; thus from a pollution-free sky it can be observed with binoculars even at elongations much smaller than near opposition.

2010-2011

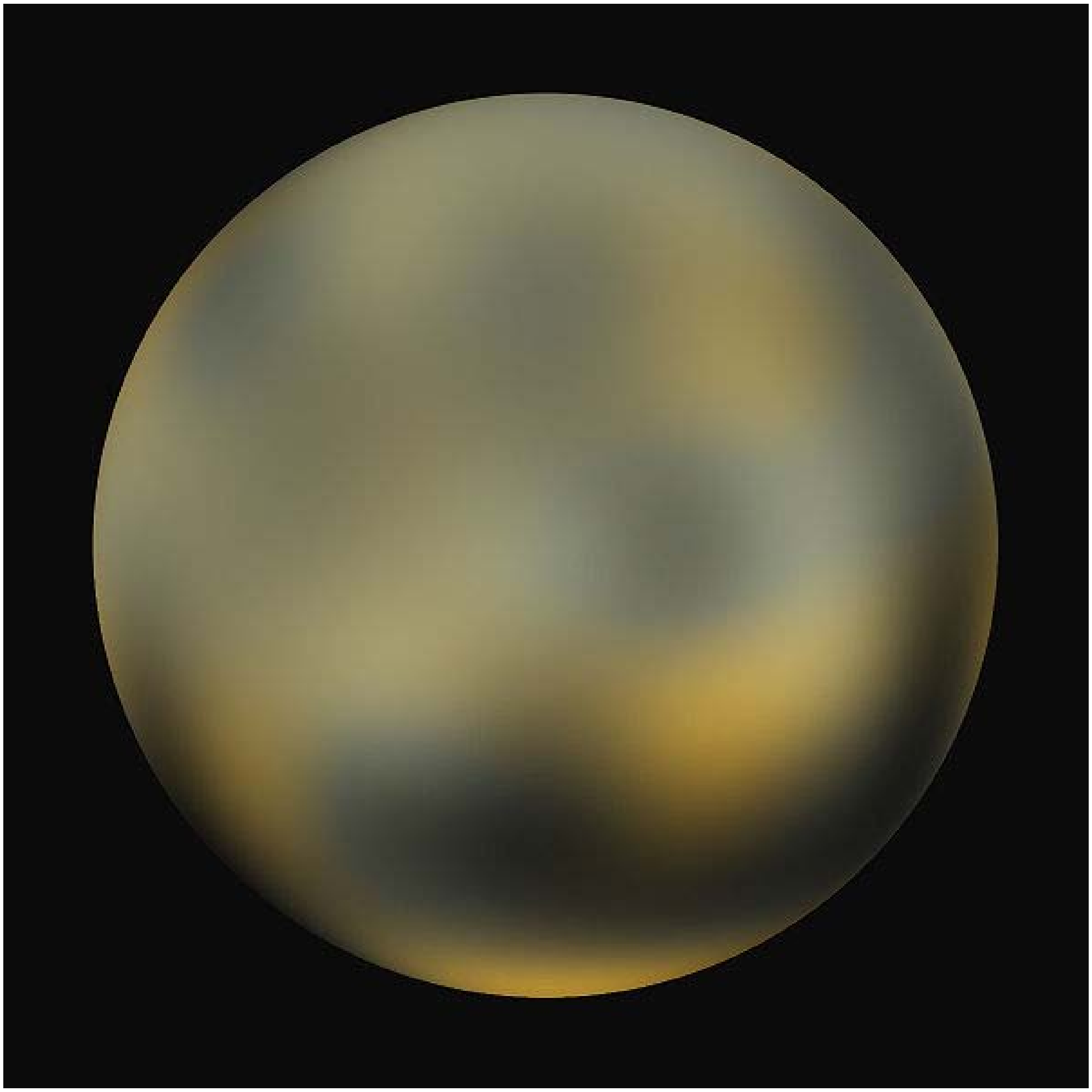
In 2010, Vesta reached opposition in the constellation of Leo on the night of February 17–18, when it was about magnitude 6.1, a brightness that makes it visible in binocular range but probably not for the naked eye. However, under perfect dark sky conditions where all light pollution is absent it might be visible to an experienced observer without the use of a telescope or binoculars. Vesta will next come to opposition on August 5, 2011, in the constellation of Capricornus at about magnitude 5.6.

Chapter 7

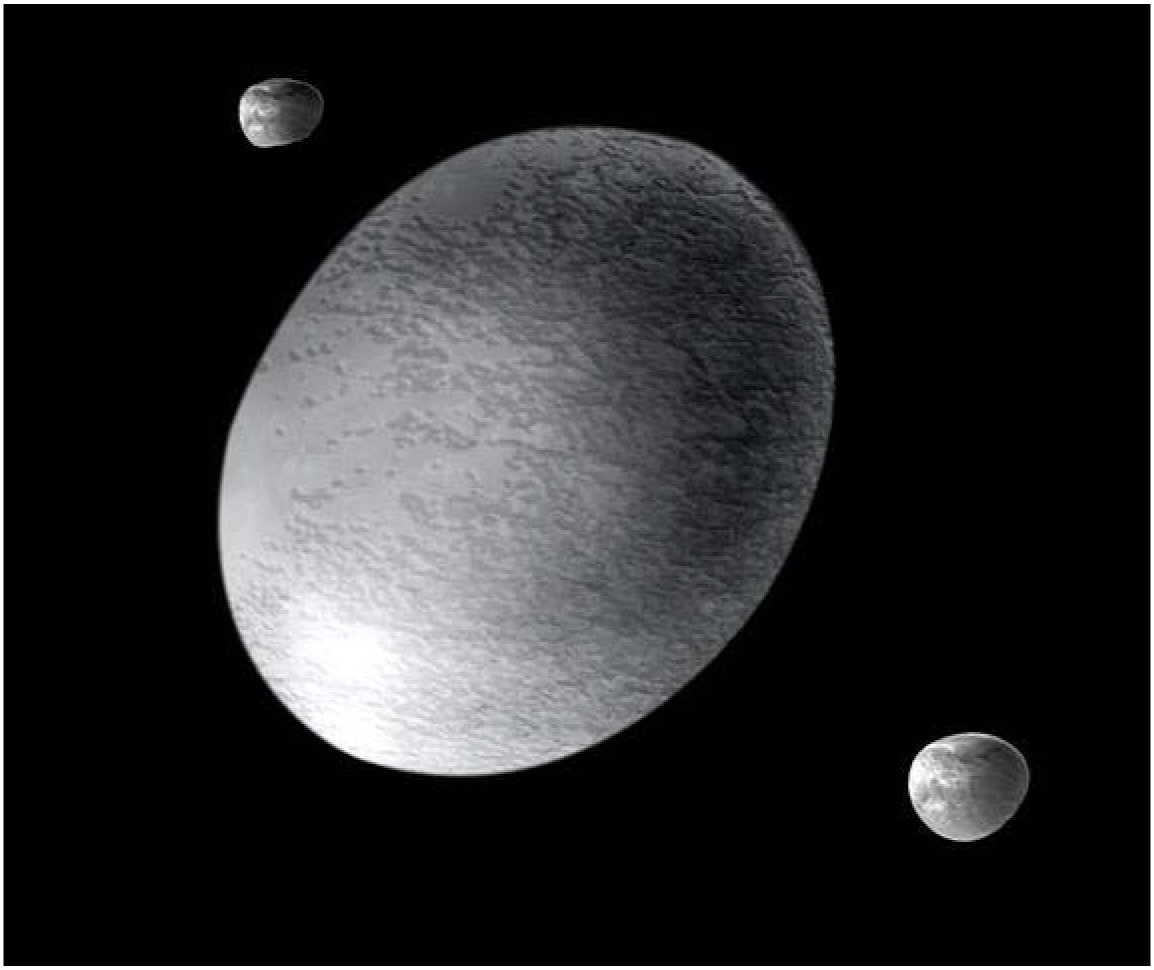
Dwarf Planet



Ceres as seen with the Hubble Space Telescope

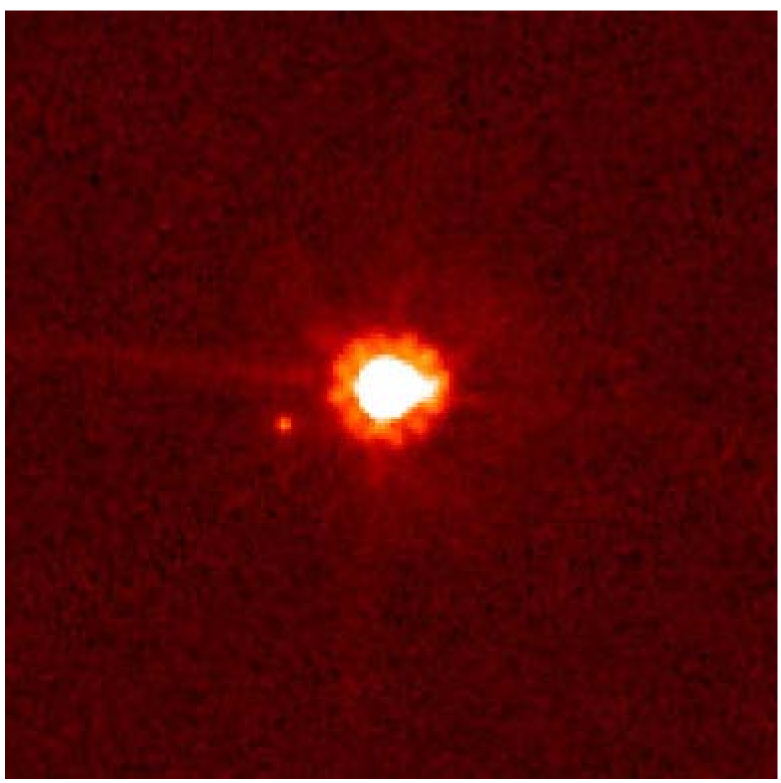


Pluto in approximate true colour based on Hubble Space Telescope albedo data



Haumea with its moons, Hiiaka and Namaka (artist's conception)

Makemake (artist's conception)



Eris as seen with the Hubble Space Telescope

A **dwarf planet**, as defined by the International Astronomical Union (IAU), is a celestial body orbiting the Sun that is massive enough to be spherical as a result of its own gravity but has not cleared its neighboring region of planetesimals and is not a satellite. More explicitly, it has to have sufficient mass to overcome its compressive strength and achieve hydrostatic equilibrium.

The term *dwarf planet* was adopted in 2006 as part of a three-way categorization of bodies orbiting the Sun, brought about by an increase in discoveries of trans-Neptunian objects that rivaled Pluto in size, and finally precipitated by the discovery of an even more massive object, Eris. This classification states that bodies large enough to have cleared the neighbourhood of their orbit are defined as *planets*, while those that are not massive enough to be rounded by their own gravity are defined as *small solar system bodies.* Dwarf planets come in between. The definition officially adopted by the IAU in 2006 has been both praised and criticized, and has been disputed by scientists such as Alan Stern.

The IAU currently recognizes five dwarf planets—Ceres, Pluto, Haumea, Makemake, and Eris. However, only two of these bodies, Ceres and Pluto, have been observed in enough detail to demonstrate that they fit the definition. Eris has been accepted as a dwarf planet because it is more massive than Pluto. The IAU subsequently decided that unnamed trans-Neptunian objects with an absolute magnitude brighter than +1 (and hence a mathematically delimited minimum diameter of 838 km) are to be named under the assumption that they are dwarf planets. The only two such objects known at the time, Makemake and Haumea, went through this naming procedure and were declared to be dwarf planets.

It is suspected that at least another 40 known objects in the Solar System are dwarf planets, and estimates are that up to 200 dwarf planets may be found when the entire region known as the Kuiper belt is explored, and that the number might be as high as 2,000 when objects scattered outside the Kuiper belt are considered.

The classification of bodies in other planetary systems with the characteristics of dwarf planets has not been addressed, although if they were detectable they would not be considered planets.

History of the concept

Before the discoveries of the early 21st century, astronomers had no strong need for a formal definition of a planet. With the discovery of Pluto in 1930, astronomers considered the Solar System to have nine planets, along with thousands of significantly smaller bodies such as asteroids and comets. For almost 50 years Pluto was thought to be larger than Mercury, but with the discovery in 1978 of Pluto's moon Charon, it became possible to measure Pluto's mass accurately and determine that it is much smaller than the initial estimates. It was roughly one-twentieth the mass of Mercury, which made Pluto by far the smallest planet. Although it was still more than ten times as massive as the largest object in the asteroid belt, Ceres, it was one-fifth that of Earth's Moon. Furthermore, having some unusual characteristics such as large orbital eccentricity and a high orbital inclination, it became evident it was a completely different kind of body from any of the other planets.

In the 1990s, astronomers began to find objects in the same region of space as Pluto (now known as the Kuiper belt), and some even farther away. Many of these shared some of the key orbital characteristics of Pluto, and Pluto started being seen as the largest member of a new class of objects, plutinos. This led some astronomers to stop referring to Pluto as a planet. Several terms including *minor planet, subplanet,* and *planetoid* started to be used for the bodies now known as *dwarf planets.* By 2005, three other bodies comparable to Pluto in terms of size and orbit (Quaoar, Sedna, and Eris) had been reported in the scientific literature. It became clear that either they would also have to be classified as planets, or Pluto would have to be reclassified. Astronomers were also confident that more objects as large as Pluto would be discovered, and the number of planets would start growing quickly if Pluto were to remain a planet.

In 2006, Eris (then known as 2003 UB_{313}) was believed to be slightly larger than Pluto, and some reports unofficially referred to it as the *tenth planet*. As a consequence, the issue became a matter of intense debate during the IAU General Assembly in August 2006. The IAU's initial draft proposal included Charon, Eris, and Ceres in the list of planets. After many astronomers objected to this proposal, an alternative was drawn up by Uruguayan astronomer Julio Ángel Fernández, in which he created a median classification for objects large enough to be round but that had not cleared their orbits of planetesimals. Dropping Charon from the list, the new proposal also removed Pluto, Ceres, and Eris, since they have not cleared their orbits.

The IAU's final resolution preserved this three-category system for the celestial bodies orbiting the Sun. Fernández suggested calling these median objects *planetoids,* but the IAU's division III plenary session voted unanimously to call them *dwarf planets.* The resolution read, in full:

The IAU ... resolves that planets and other bodies, except satellites, in our Solar System 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[2], (c) has not cleared the neighbourhood around its orbit, and (d) is not a satellite.
(3) All other objects[3], except satellites, orbiting the Sun shall be referred to collectively as "Small Solar System Bodies."

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

[2] An IAU process will be established to assign borderline objects either dwarf planet or other status.
[3] These currently include most of the Solar System asteroids, most Trans-Neptunian Objects (TNOs), comets, and other small bodies.

Although there were concerns about the classification of planets in other solar systems, this issue was not resolved; it was proposed instead to decide this only when such objects start being observed.

The 2006 IAU's Resolution 6a recognizes Pluto as "the prototype of a new category of trans-Neptunian objects". The name and precise nature of this category were not specified but left for the IAU to establish at a later date; in the debate leading up to the resolution, the members of the category were variously referred to as *plutons* and *plutonian objects* but neither name was carried forward. On June 11, 2008, the IAU Executive Committee announced a name, *plutoid*, and a definition: all trans-Neptunian dwarf planets are plutoids. On July 18, 2008, the Working Group for Planetary System Nomenclature reclassified the object then known as *(136472) 2005* FY_9 as a dwarf planet, and renamed it Makemake.

Characteristics

Body	Planetary discriminants **Mass (M_E*)**	Λ/Λ_E**	μ***
Mercury	0.055	0.012 6	9.1×10^4
Venus	0.815	1.08	1.35×10^6
Earth	1	1	1.7×10^6
Mars	0.107	0.006 1	1.8×10^5
Ceres	0.000 15	8.7×10^{-9}	0.33
Jupiter	317.7	8,510	6.25×10^5
Saturn	95.2	308	1.9×10^5
Uranus	14.5	2.51	2.9×10^4
Neptune	17.1	1.79	2.4×10^4
Pluto	0.002 2	1.95×10^{-8}	0.077
Haumea	0.000 67	1.72×10^{-9}	0.02
Makemake	0.000 67	1.45×10^{-9}	0.02
Eris	0.002 8	3.5×10^{-8}	0.10

*M_E in Earth masses.
**$\Lambda/\Lambda_E = M^2/P \times P_E/M^2_E$.
***$\mu = M/m$, where M is the mass of the body, and m is the aggregate mass of all the other bodies that share its orbital zone.

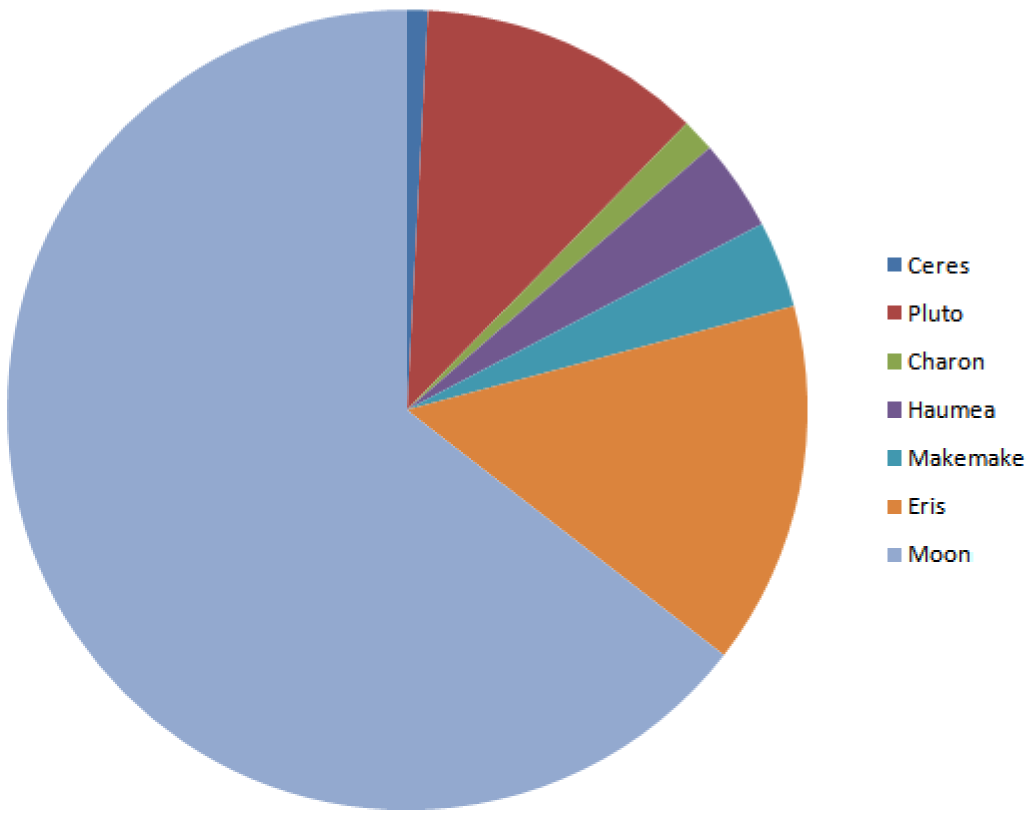
Orbital dominance

Alan Stern and Harold F. Levison introduced a parameter Λ (lambda), expressing the probability of an encounter resulting in a given deflection of orbit. The value of this parameter in Stern's model is proportional to the square of the mass and inversely proportional to the period. Following the authors, this value can be used to estimate the capacity of a body to clear the neighbourhood of its orbit. A gap of five orders of magnitude in Λ was found between the smallest terrestrial planets and the largest asteroids and Kuiper belt objects (third column of the planetary discriminants table to the right).

Using this parameter, Steven Soter and other astronomers argued for a distinction between dwarf planets and the other eight planets based on their inability to "clear the neighbourhood around their orbits": planets are able to remove smaller bodies near their orbits by collision, capture, or gravitational disturbance, (or establish orbital resonances that prevent collisions), while dwarf planets lack the mass to do so. Soter went on to propose a parameter he called the *planetary discriminant*, designated with the symbol μ (mu), that represents an experimental measure of the actual degree of cleanliness of the orbital zone (where μ is calculated by dividing the mass of the candidate body by the total mass of the other objects that share its orbital zone). There are several other schemes that try to differentiate between planets and dwarf planets, but the 2006 definition uses this concept.

Size and mass

When an object achieves hydrostatic equilibrium, also known as gravitational relaxation, there are no gravitational imbalances in its surface. A global layer of liquid placed on this surface (assuming for argument's sake it would remain a liquid) would form a liquid surface of the same shape, apart from small-scale surface features such as craters and fissures. This does not mean the body is a sphere; the faster a body rotates, the more oblate or even scalene it becomes, but such forces affect a liquid surface as well. The extreme example of a non-spherical body in hydrostatic equilibrium is Haumea, which is twice as long along its major axis as it is at the poles.



The masses of the five known dwarf planets, plus Charon, relative to the Earth's Moon. The mass of Makemake is a rough estimate.

The upper and lower size and mass limits of dwarf planets have not been specified by the

IAU. There is no defined upper limit, and an object larger or more massive than Mercury that has not "cleared the neighbourhood around its orbit" would be classified as a dwarf planet. The lower limit is determined by the requirements of achieving a hydrostatic equilibrium shape, but the size or mass at which an object attains this shape depends on its composition and thermal history. The original draft of the 2006 IAU resolution redefined hydrostatic equilibrium shape as applying "to objects with mass above 5×10^{20} kg and diameter greater than 800 km", but this was not retained in the final draft.

Empirical observations suggest that the lower limit may vary according to the composition of the object. For example, in the asteroid belt, Ceres, with a diameter of 975 km, is the only object presently known to be self-rounded, while 2 Pallas at approximately 600 km appears to be partially but incompletely differentiated. Therefore, it has been suggested that the limit where other rocky-ice bodies like Ceres become rounded might be somewhere around 900 km. The rocky body Vesta, at 530 km appears to have achieved equilibrium, only to have it disrupted by a massive impact after it solidified. More icy bodies like trans-Neptunian objects have less rigid interiors and therefore more easily relax under their self-gravity into a rounded shape. The smallest icy body known to have achieved hydrostatic equilibrium is Mimas, while the largest irregular one is Proteus; both average slightly more than 400 km (250 mi) in diameter. Mike Brown (a leading researcher in this field and discoverer of Eris) suggests that the lower limit for an icy dwarf planet is therefore likely to be somewhere under 400 km.

It is also not clear to what extent deviations from perfect equilibrium are to be tolerated, or whether *having* achieved equilibrium is sufficient for inclusion. All solid bodies in the solar system, such as Iapetus with its equatorial ridge and Mars with its shield volcanoes, deviate to some extent. This may be critical in the consideration of the asteroid 4 Vesta, which may deviate from equilibrium due to a large impact that removed part of one hemisphere.

Current members

As of 2008, the IAU has classified five celestial bodies as dwarf planets. Two of these, Ceres and Pluto, are known to qualify as dwarf planets through direct observation. The other three, Eris, Haumea, and Makemake, are thought to be dwarf planets from mathematical modeling—or in the case of Eris, because it is larger than Pluto—and qualify for the classification under IAU naming rules based on their magnitudes.

1. Ceres ⚳ – discovered on January 1, 1801 (45 years before Neptune), considered a planet for half a century before reclassification as an asteroid. Classified as a dwarf planet on September 13, 2006.
2. Pluto ♇ – discovered on February 18, 1930, classified as a planet for 76 years. Reclassified as a dwarf planet on August 24, 2006.
3. Eris – discovered on January 5, 2005. Called the "tenth planet" in media reports. Accepted as a dwarf planet on September 13, 2006.
4. Makemake – discovered on March 31, 2005. Accepted as a dwarf planet on July 11, 2008.
5. Haumea – discovered on December 28, 2004. Accepted as a dwarf planet on September 17, 2008.

No space probes have visited any of the dwarf planets. This will change if NASA's *Dawn* and *New Horizons* missions reach Ceres and Pluto, respectively, as planned in 2015. *Dawn* is also slated to orbit and observe another potential dwarf planet, Vesta, in 2011.

Orbital attributes of dwarf planets

Name	Region of Solar System	Orbital radius (AU)	Orbital period (years)	Mean orbital speed (km/s)	Inclination to ecliptic (°)	Orbital eccentricity	Planetary discriminant
Ceres	Asteroid belt	2.77	4.60	17.882	10.59	0.080	0.33
Pluto	Kuiper belt	39.48	248.09	4.666	17.14	0.249	0.077
Haumea	Kuiper belt	43.34	285.4	4.484	28.19	0.189	?
Makemake	Kuiper belt	45.79	309.9	4.419	28.96	0.159	?
Eris	Scattered disc	67.67	557	3.436	44.19	0.442	0.10

Physical attributes of dwarf planets

Name	Equatorial diameter relative to the Moon	Equatorial diameter (km)	Mass relative to the Moon	Mass ($\times 10^{21}$ kg)	Density (g/cm^3)	Surface gravity (m/s^2)	Escape velocity (km/s)	Axial inclination	Rotation period (days)	Moons	Surface temp. (K)	Atmosphere
Ceres	28%	974.6±3.2	1.3%	0.95	2.08	0.27	0.51	~3°	0.38	0	167	none
Pluto	69%	2306±10	17.8%	13.05	2.0	0.58	1.2	119.59°	-6.39	3	44	transient
Haumea	33%	1150^{+250}_{-100}	5.7%	4.2 ± 0.1	2.6–3.3	~0.44	~0.84			2	32 ± 3	?
Makemake	43%	1500^{+400}_{-200}	~5%?	~4?	~2?	~0.5	~0.8			0	~30	transient?
Eris	75%	<2340	22.7%	16.7	2.3	~0.8	1.3		~0.3	1	42	transient?

Candidates

After Ceres, the next most massive body in the asteroid belt, Vesta, might also be classified as a dwarf planet, as its shape appears to deviate from hydrostatic equilibrium only because of a large impact that occurred after it solidified; the definition of dwarf planet does not specifically address this issue. The *Dawn* probe scheduled to enter orbit around Vesta in 2011 may help clarify matters.

The status of Charon (currently regarded as a satellite of Pluto) remains uncertain, as there is currently no clear definition of what distinguishes a satellite system from a binary (double planet) system. The original draft resolution (5) presented to the IAU stated that Charon could be considered a planet because:

1. Charon independently would satisfy the size and shape criteria for a dwarf planet status (in the terms of the final resolution);
2. Charon revolves with Pluto around a common center of mass located between the two bodies (rather than within one of the bodies) because Charon's mass is not insignificant relative to that of Pluto.

This definition was not preserved in the IAU's final resolution and it is unknown if it will be included in future debates.

Plutoids

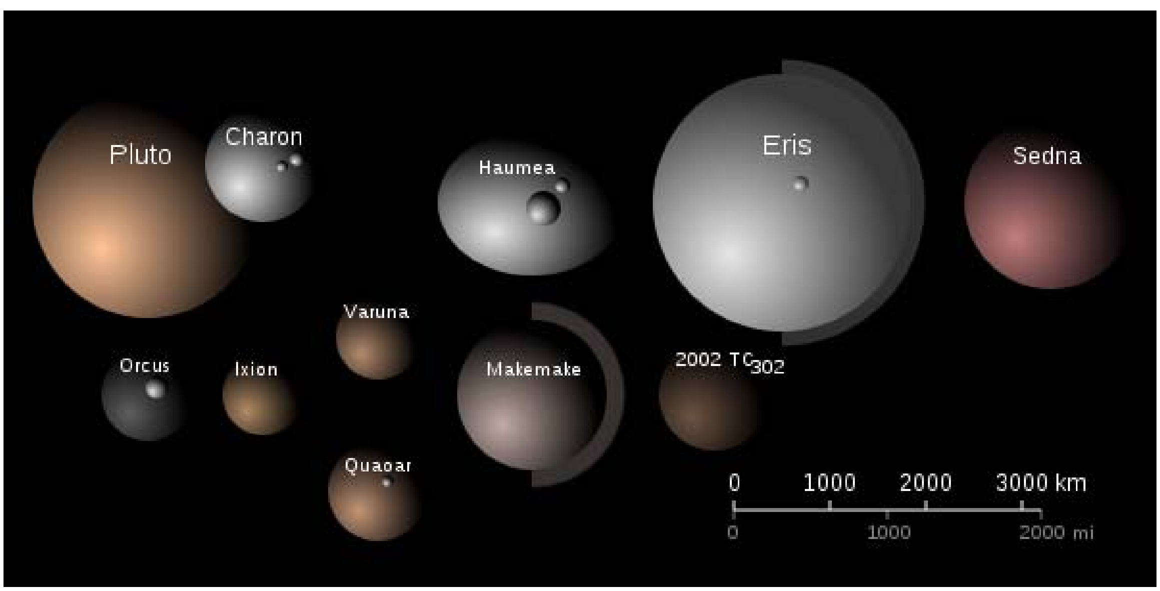


Illustration of the relative sizes, albedos, and colours of the largest Trans-Neptunian objects

Many Trans-Neptunian objects (TNOs) are thought to have icy cores and therefore would require a diameter of perhaps 400 km (250 mi)—only about 3% of that of Earth—to relax into gravitational equilibrium, making them dwarf planets of the plutoid class. Although only rough estimates of the diameters of these objects are available, as of August 2006, it was believed that another 42 bodies beyond Neptune (besides Pluto and Eris) were likely dwarf planets. A team is investigating another 30 such objects, and believe that the total number will eventually prove to be about 200 in the Kuiper belt, and many more beyond it.

Tancredi & Favre (2008) attempt to estimate which TNOs are likely to qualify, based on both direct measurements and lightcurve data. They propose that nine of the candidates be considered dwarf planets. Six of these have been estimated by one researcher or another to be at least 900 km in diameter, the size of the smallest known dwarf planet, Ceres, as has a tenth candidate, 2002 AW_{197}. These ten prime candidates are:

Prime plutoid candidates

Name	**Category**	**Estimated diameter (km)**				**Absolute Magnitude (H)**	**Mass ($\times 10^{20}$ kg)**	**Orbital radius (AU)**
		by	**by**	**by**	**by**			
Orcus	plutino (1 moon)	1,100	909	946	1,500	2.3	6.32 ± 0.05	39.2
Huya	plutino	480	480	—	—	4.7	0.6–1.8?	39.4
Pluto	*plutoid*	*2,306*				*–0.7*	*130*	39.4
Ixion	plutino	980	570	650	1,065	3.2	~3?	39.6
Varuna	cubewano	780	874	500	900	3.7	~3.7?	42.9
Haumea	*plutoid*	*1,436*				*0.17*	*40*	43.3
Quaoar	cubewano (1 moon)	1,290	1,260	844	1,200	2.7	21–29	43.5
Makemake	*plutoid*	*1,500*				*–0.45*	*30*	45.3
(55565) 2002 AW_{197}	cubewano	940	793	735	890	3.2	~4.1?	47.0
(84522) 2002 TC_{302}	5:2 SDO	710	1,200	1,150	—	3.8	15?	55.4
(225088) 2007 OR_{10}	10:3? SDO	1200?			—	1.9	?	67.3
Eris	*plutoid*	*2,600*				*–1.12*	*167*	68.0

(15874) 1996 TL_{66}	SDO	—	632	460–690	—	5.4	2?	83.9
Sedna	Detached object	1,800	1,500	< 1,600	< 1,500	1.5	8–70?	509

Additionally, the more recently discovered 2007 OR10 should probably be seen as a prime candidate, as Mike Brown estimates its size to be between that of Sedna and Quaoar.

Ellipsoidal moons

A total of 19 known moons are massive enough to have relaxed into a rounded shape under their own gravity. These bodies have no significant physical differences from the dwarf planets, but are not considered members of that class because they do not directly orbit the Sun. They are Earth's moon, the four Galilean moons of Jupiter (Io, Europa, Ganymede, and Callisto), seven moons of Saturn (Mimas, Enceladus, Tethys, Dione, Rhea, Titan, and Iapetus), five moons of Uranus (Miranda, Ariel, Umbriel, Titania, and Oberon), one moon of Neptune (Triton), and one moon of Pluto (Charon).

Contention

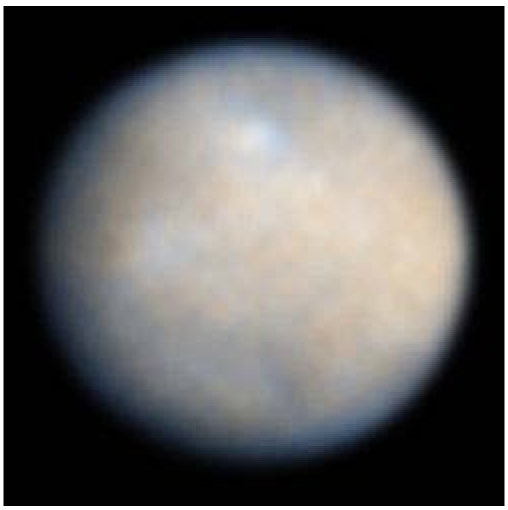
In the immediate aftermath of the IAU definition of dwarf planet, a number of scientists expressed their disagreement with the IAU resolution. Campaigns included car bumper stickers and T-shirts. Mike Brown (the discoverer of Eris) agrees with the reduction of the number of planets to eight.

NASA has announced that it will use the new guidelines established by the IAU. However, Alan Stern, the director of NASA's mission to Pluto, rejects the current IAU definition of planet, both in terms of defining dwarf planets as something other than a type of planet, and in using orbital characteristics (rather than intrinsic characteristics) of objects to define them as dwarf planets. Thus, as of January 2008, he and his team still referred to Pluto as the ninth planet, while accepting the characterization of dwarf planet for Ceres and Eris.

Chapter 8

Ceres

Ceres ⚳



Ceres as seen by Hubble Space Telescope (ACS). The contrast has been enhanced to reveal surface details.

Discovery	
Discovered by	Giuseppe Piazzi
Discovery date	1 January 1801
Designations	
MPC designation	**1 Ceres**
Named after	Ceres
Alternate name(s)	A899 OF; 1943 XB
Minor planet category	dwarf planet main belt
Adjective	Cererian
Orbital characteristics	
Epoch June 18, 2009	

	(JD 2455000.5)
Aphelion	446,669,320 km (2.9858 AU)
Perihelion	380,995,855 km (2.5468 AU)
Semi-major axis	413,832,587 km (2.7663 AU)
Eccentricity	0.07934
Orbital period	1680.5 days 4.60 years
Average orbital speed	17.882 km/s
Mean anomaly	27.448°
Inclination	10.585° to Ecliptic 9.20° to Invariable plane
Longitude of ascending node	80.399°
Argument of perihelion	72.825°
Physical characteristics	
Equatorial radius	487.3 ± 1.8 km
Polar radius	454.7 ± 1.6 km
Surface area	2,845,794.56 sq km (1,768,294.41 sq mi)
Mass	$9.43 \pm 0.07 \times 10^{20}$ kg 0.00015 Earths
Mean density	2.077 ± 0.036 g/cm^3
Equatorial surface gravity	0.27 m/s^2 0.028 *g*
Escape velocity	0.51 km/s
Sidereal rotation period	0.3781 d 9.074170 h
Axial tilt	about 3°
North pole right ascension	19 h 24 min 291°
North pole declination	59°
Albedo	0.090 ± 0.0033 (V-band geometric)
Surface temp. Kelvin	**min** ? / **mean** ~167 K / **max** 239 K
Spectral type	C
Apparent magnitude	6.7 to 9.32

Absolute magnitude *(H)*	3.36 ± 0.02
Angular diameter	0.84" to 0.33"

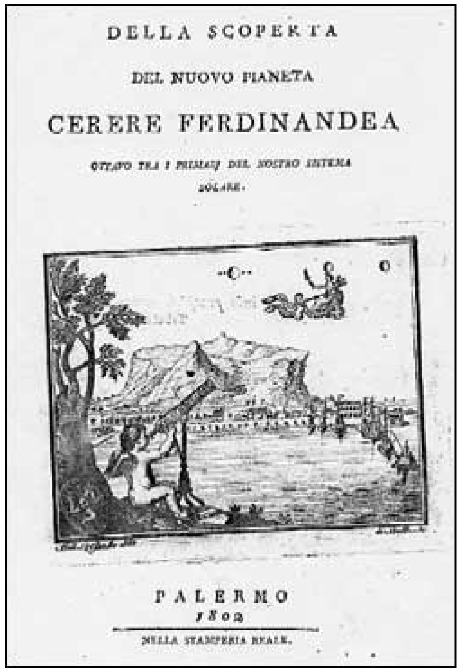
Ceres, formally designated **1 Ceres**, is the smallest identified dwarf planet in the Solar System and the only one in the asteroid belt. It was discovered on 1 January 1801 by Giuseppe Piazzi, and for half a century it was classified as the eighth planet. It is named after Ceres, the Roman goddess of growing plants, the harvest, and motherly love.

With a diameter of about 950 km (590 mi), Ceres is by far the largest and most massive body in the asteroid belt, and contains almost a third (32%) of the belt's total mass. Observations have revealed that it is spherical, unlike the irregular shapes of smaller bodies with lower gravity. The Cererian surface is probably a mixture of water ice and various hydrated minerals such as carbonates and clays. Ceres appears to be differentiated into a rocky core and ice mantle, and may harbour an ocean of liquid water underneath its surface.

From the Earth, Ceres' apparent magnitude ranges from 6.7 to 9.3, and hence at its brightest it is still too dim to be seen with the naked eye. On 27 September 2007, NASA launched the *Dawn* space probe to explore Vesta (2011–2012) and Ceres (2015).

Discovery

The idea that an undiscovered planet could exist between the orbits of Mars and Jupiter was first suggested by Johann Elert Bode in 1772. His considerations were based on the Titius–Bode law, a now-abandoned theory which had been first proposed by Johann Daniel Titius in 1766, observing that there was a regular pattern in the semi-major axes of the known planets marred only by the large gap between Mars and Jupiter. The pattern predicted that the missing planet ought to have a semi-major axis near 2.8 AU. William Herschel's discovery of Uranus in 1781 near the predicted distance for the next body beyond Saturn increased faith in the law of Titius and Bode, and in 1800, they sent requests to twenty-four experienced astronomers, asking that they combine their efforts and begin a methodical search for the expected planet. The group was headed by Franz Xaver von Zach, editor of the *Monatliche Correspondenz*. While they did not discover Ceres, they later found several large asteroids.



Piazzi's book *"Della scoperta del nuovo pianeta Cerere Ferdinandea"* outlining the discovery of Ceres

One of the astronomers selected for the search was Giuseppe Piazzi at the Academy of Palermo, Sicily. However, before receiving his invitation to join the group, Giuseppe Piazzi discovered Ceres on 1 January 1801. He was searching for "the 87th [star] of the Catalogue of the Zodiacal stars of Mr la Caille", but found that "it was preceded by another". Instead of a star, Piazzi had found a moving star-like object, which he first thought was a comet. Piazzi observed Ceres a total of 24 times, the final time on 11 February 1801, when illness interrupted his observations. He announced his discovery on 24 January 1801 in letters to only two fellow astronomers, his compatriot Barnaba Oriani of Milan and Bode of Berlin. He reported it as a comet but "since its movement is so slow and rather uniform, it has occurred to me several times that it might be something better than a comet". In April, Piazzi sent his complete observations to Oriani, Bode, and Jérôme Lalande in Paris. The information was published in the September 1801 issue of the *Monatliche Correspondenz*.

By this time, Ceres' apparent position had changed (mostly due to the Earth's orbital motion), and was too close to the Sun's glare for other astronomers to confirm Piazzi's observations. Toward the end of the year, Ceres should have been visible again, but after such a long time it was difficult to predict its exact position. To recover Ceres, Carl Friedrich Gauss, then 24 years old, developed an efficient method of orbit determination. He set himself the task of determining a Keplerian motion from three complete observations (time, right ascension, declination). In only a few weeks, he predicted the path of Ceres and sent his results to von Zach. On 31 December 1801, von Zach and Heinrich W. M. Olbers found Ceres near the predicted position and thus recovered it.

The early observers failed to determine the correct size of Ceres. Herschel underestimated its size, calculating its diameter to be 260 km in 1802, while in 1811 Johann Hieronymus Schröter inflated its diameter to 2,613 km.

Name

Piazzi originally suggested the name *Ceres Ferdinandea* (Italian, *Cerere Ferdinandea*) for his discovery, after both the mythological figure Ceres (Roman goddess of plants) and King Ferdinand III of Sicily. "Ferdinandea" was not acceptable to other nations of the world and was thus dropped. Ceres was also called Hera for a short time in Germany. In Greece, it is called Δήμητρα (Demeter), after the goddess Ceres' Greek equivalent; in English, that name is used for the asteroid 1108 Demeter. The adjectival form of the name is Cererian, or rarely *Cererean*, derived from the Latin genitive *Cereris*. Ceres' astronomical symbol is a sickle, (⚳ ; □ U+26B3), similar to Venus' symbol (♀ ; ♀ U+2640) but with a gap in the upper circle. The element cerium, discovered in 1803, was named after Ceres. In the same year, another element was also initially named after Ceres, but its discoverer changed its name to palladium (after another asteroid, 2 Pallas) when cerium was named.

Status

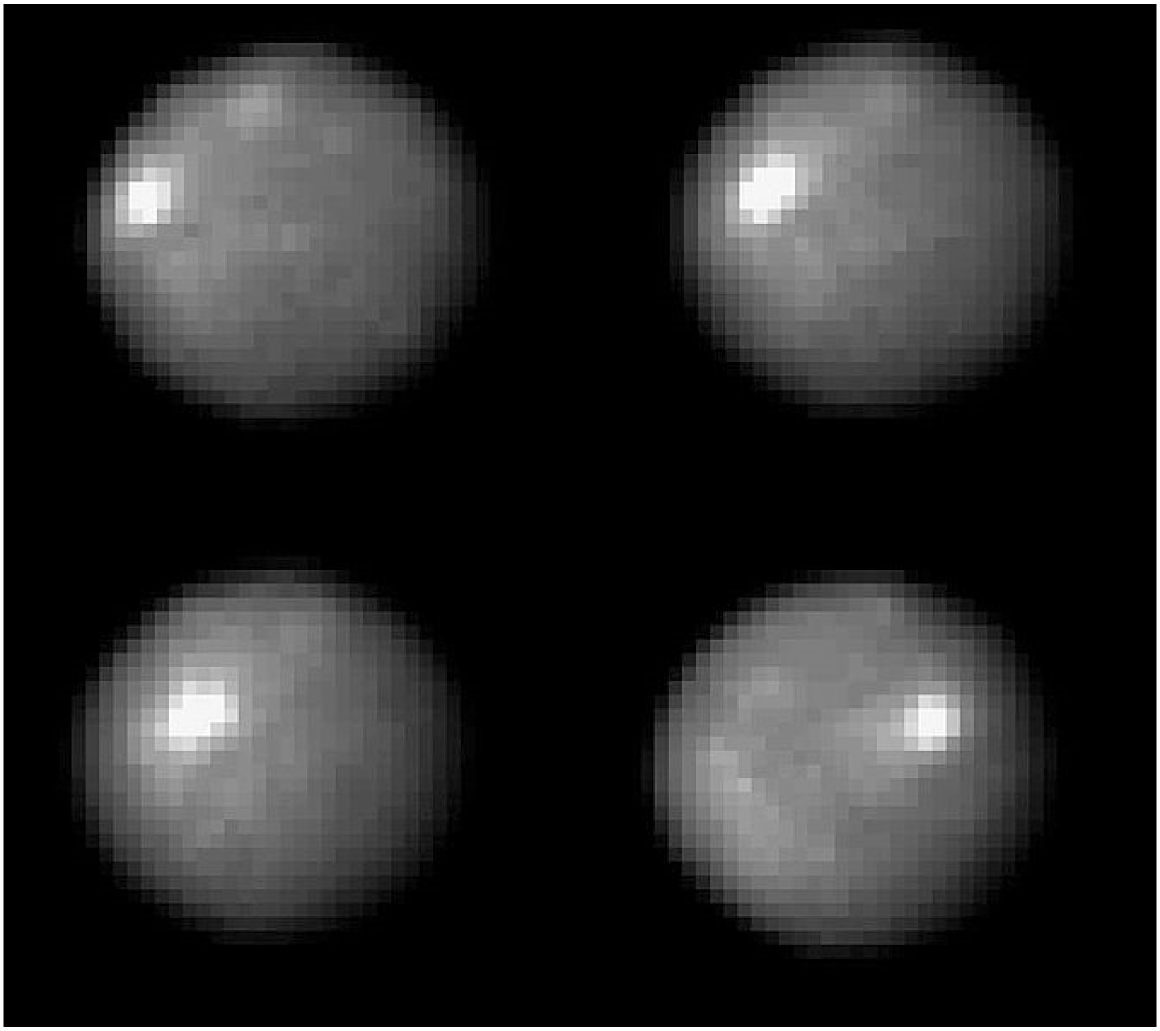
Ceres (bottom left), the Moon and the Earth, shown to scale

The classification of Ceres has changed more than once and has been the subject of some disagreement. Johann Elert Bode believed Ceres to be the "missing planet" he had proposed to exist between Mars and Jupiter, at a distance of 419 million km (2.8 AU) from the Sun. Ceres was assigned a planetary symbol, and remained listed as a planet in astronomy books and tables (along with 2 Pallas, 3 Juno and 4 Vesta) for about half a century.

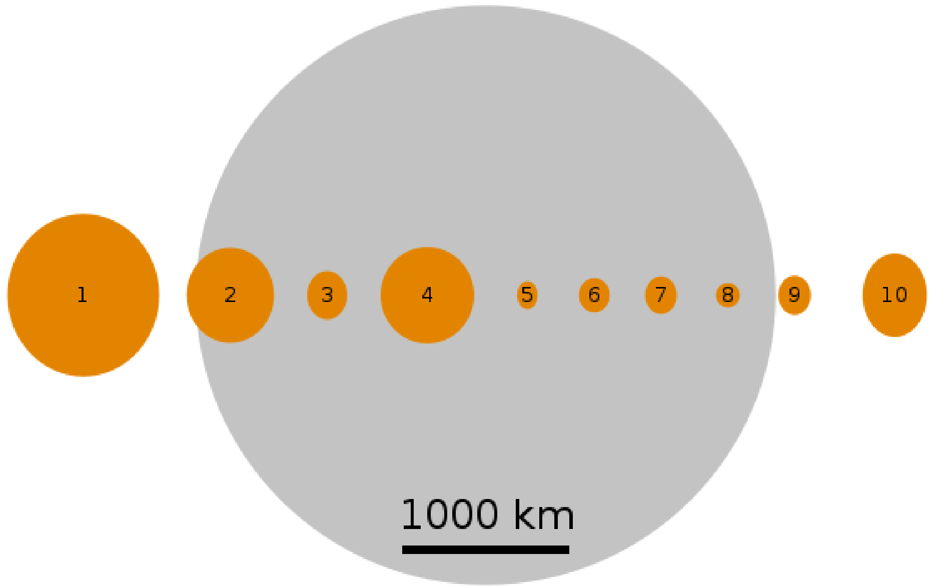
However, as other objects were discovered in the area it was realised that Ceres represented the first of a class of many similar bodies. In 1802 Sir William Herschel coined the term *asteroid* ("star-like") for such bodies, writing "they resemble small stars so much as hardly to be distinguished from them, even by very good telescopes". As the first such body to be discovered, it was given the designation 1 Ceres under the modern system of asteroid numbering.

The 2006 debate surrounding Pluto and what constitutes a 'planet' led to Ceres being considered for reclassification as a planet. A proposal before the International Astronomical Union for the definition of a planet would have defined a planet as "a celestial body that (a) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and (b) is in orbit around a star, and is neither a star nor a satellite of a planet". Had this resolution been adopted, it would have made Ceres the fifth planet in order from the Sun. However, it was not accepted, and in its place an alternate definition came into effect as of 24 August 2006, carrying the additional requirement that a "planet" must have "cleared the neighborhood around its orbit." By this definition, Ceres is not a planet because it shares its orbit with the thousands of other asteroids in the main belt. Instead it is classified as a "dwarf planet" within the asteroid belt rather than being considered the largest asteroid. However, dual classifications such as main-belt comets do exist, and being a dwarf planet does not preclude Ceres from having other designations. The issue of whether Ceres remains an asteroid was not fully addressed.

Physical characteristics



Hubble Space Telescope images of Ceres, taken in 2003/4 with a resolution of about 30 km. The nature of the bright spot is uncertain.



Sizes of the first ten main belt objects discovered profiled against Earth's Moon. Ceres is far left.

Ceres is the largest object in the asteroid belt, which lies between Mars and Jupiter. The Kuiper belt is known to contain larger objects, including Pluto, its moon Charon, and 136108 Haumea, while more distant Eris, in the scattered disc, is the most massive of all the trans-Neptunian objects.

The mass of Ceres has been determined by analysis of the influence it exerts on small asteroids. Results obtained by different authors are slightly different. The average of the three most precise values as of 2008 is approximately 9.4×10^{20} kg. With this mass Ceres comprises about a third of the estimated total $3.0 \pm 0.2 \times 10^{21}$ kg mass of the asteroids in the solar system, together totalling about four percent of the mass of the Moon. Ceres' size and mass are sufficient to give it a nearly spherical shape. That is, it is close to hydrostatic equilibrium. In contrast, other large asteroids such as 2 Pallas, 3 Juno, and in particular 10 Hygiea are known to be quite irregular.

Internal structure

Peter Thomas of Cornell University has proposed that Ceres has a differentiated interior; its oblateness appears too small for an undifferentiated body, which indicates that it consists of a rocky core overlain with an icy mantle. This 100 km-thick mantle (23–28 percent of Ceres by mass; 50 percent by volume) contains 200 million cubic kilometres of water, which is more than the amount of fresh water on the Earth. This result is supported by the observations made by the Keck telescope in 2002 and by evolutionary modelling. Also, some characteristics of its surface and history (such as its distance from the Sun, which weakened solar radiation enough to allow some fairly low-freezing-point components to be incorporated during its formation), point to the presence of volatile materials in the interior of Ceres.

Alternatively, the shape and dimensions of Ceres may be explained by an interior that is porous and either partially differentiated or completely undifferentiated. The presence of a layer of rock on top of ice would be gravitationally unstable. If any of the rock deposits sank into a layer of differentiated ice, salt deposits would be formed. Such deposits have not been detected. Thus it is possible that Ceres does not contain a large ice shell, but was instead formed from low density asteroids with an aqueous component. The decay of radioactive isotopes may not have been sufficient to cause differentiation.

Surface

The surface composition of Ceres is broadly similar to that of C-type asteroids. However, some differences do exist. The ubiquitous features of the Cererian IR spectra are those of hydrated materials, which indicate the presence of significant amounts of water in the interior. Other possible surface constituents include iron-rich clays (cronstedtite) and carbonate minerals (dolomite and siderite), which are common minerals in carbonaceous chondrite meteorites. The spectral features of carbonates and clay are usually absent in the spectra of other C-type asteroids. Sometimes Ceres is classified as G-type asteroid.

The Cererian surface is relatively warm. The maximum temperature with the Sun overhead was estimated from measurements to be 235 K (about −38 °C) on 5 May 1991.

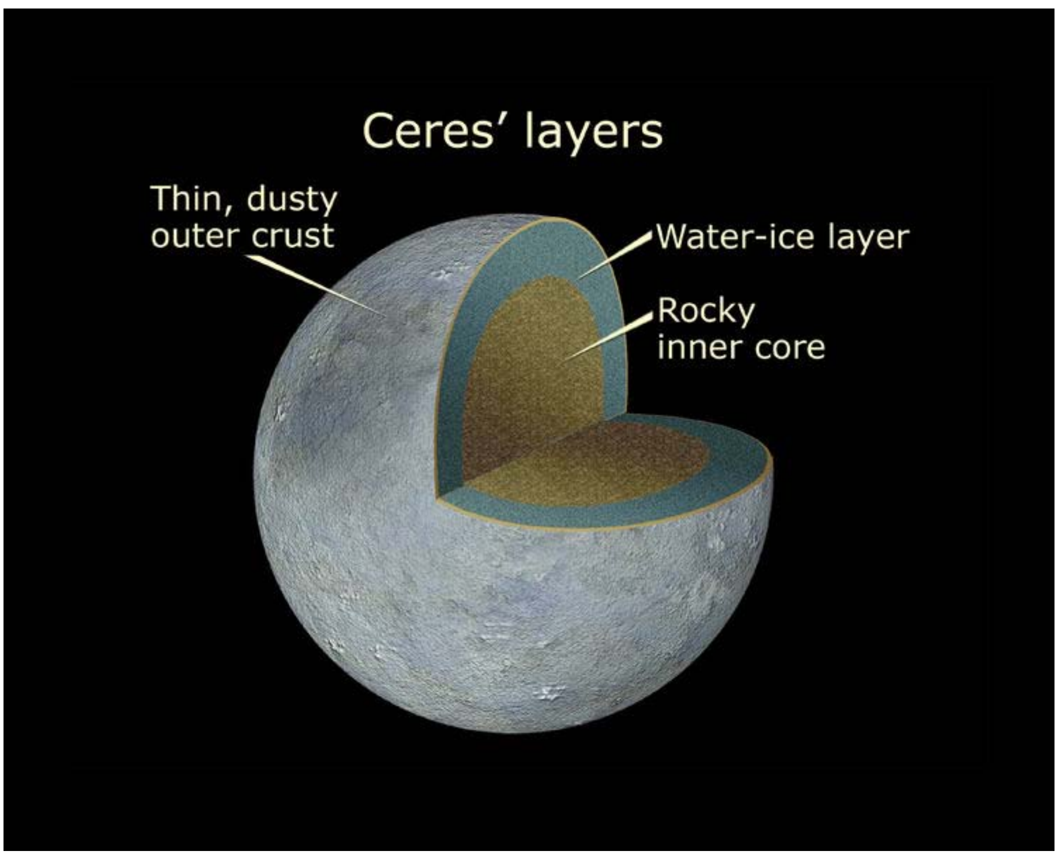


Diagram showing a possible internal structure of Ceres

Only a few Cererian surface features have been unambiguously detected. High resolution ultraviolet Hubble Space Telescope images taken in 1995 showed a dark spot on its surface which was nicknamed "Piazzi" in honour of the discoverer of Ceres. This was thought to be a crater. Later near-infrared images with a higher resolution taken over a whole rotation with the Keck telescope using adaptive optics showed several bright and dark features moving with the dwarf planet's rotation. Two dark features had circular shapes and are presumably craters; one of them was observed to have a bright central region, while another was identified as the "Piazzi" feature. More recent visible light Hubble Space Telescope images of a full rotation taken in 2003 and 2004 showed 11 recognizable surface features, the nature of which are currently unknown. One of these features corresponds to the "Piazzi" feature observed earlier.

These last observations also determined that Ceres' north pole points in the direction of right ascension 19 h 24 min (291°), declination +59°, in the constellation Draco. This means that Ceres' axial tilt is very small—about 3°.

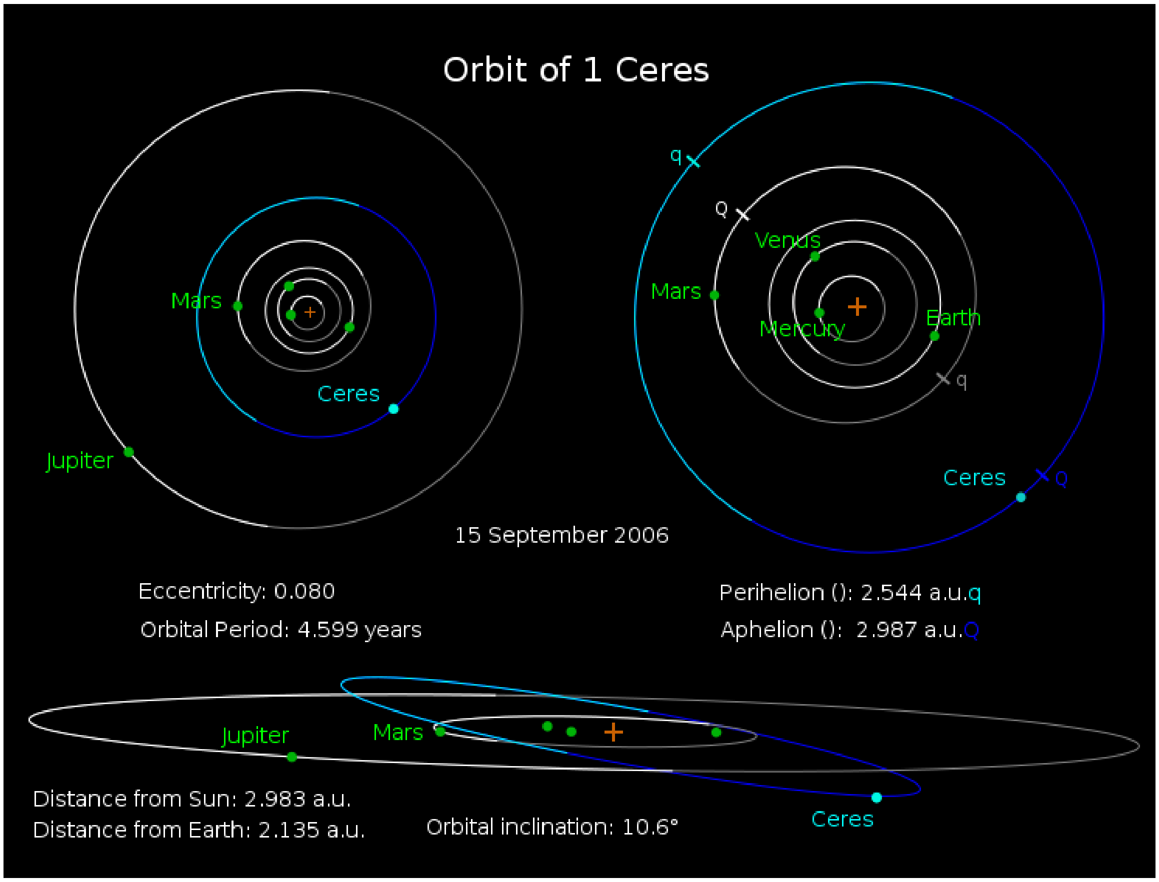
Atmosphere

There are indications that Ceres may have a weak atmosphere and water frost on the surface. Surface water ice is unstable at distances less than 5 AU from the Sun, so it is expected to sublime if it is exposed directly to solar radiation. Water ice can migrate from the deep layers of Ceres to the surface, but will escape in a very short time. As a result, it is difficult to detect water vaporization. Water escaping from Ceres's polar regions was possibly observed in the early 1990s but this has not been unambiguously proven. It may be possible to detect escaping water from the surroundings of a fresh impact crater or from cracks in the sub-surface layers of Ceres. Ultraviolet observations by IUE spacecraft detected statistically significant amounts of the hydroxide ion near the Cererean north pole, which is a product of water vapour dissociation by the solar ultraviolet radiation.

Potential for extraterrestrial life

While not as actively discussed as a potential home for extraterrestrial life as Mars or Europa, the potential presence of water ice has led some scientists to hypothesize that life may exist there, and that evidence for this could be found in hypothesized ejecta that could have come from Ceres to Earth. It has also been hypothesized that biologically active ejecta from Earth could have landed on Ceres and colonized it.

Orbit



Orbit of Ceres

Ceres follows an orbit between Mars and Jupiter, within the main asteroid belt, with a period of 4.6 Earth years. The orbit is moderately inclined (i = 10.6° compared to 7° for Mercury and 17° for Pluto) and moderately eccentric (e = 0.08 compared to 0.09 for Mars).

The diagram illustrates the orbits of Ceres (blue) and several planets (white and grey). The segments of orbits below the ecliptic are plotted in darker colours, and the orange plus sign is the Sun's location. The top left diagram is a polar view that shows the location of Ceres in the gap between Mars and Jupiter. The top right is a close-up demonstrating the locations of the perihelia (q) and aphelia (Q) of Ceres and Mars. The perihelion of Mars is on the opposite side of the Sun from those of Ceres and several of the large main belt asteroids, including 2 Pallas and 10 Hygiea. The bottom diagram is a side view showing the inclination of the orbit of Ceres compared to the orbits of Mars and Jupiter.

In the past, Ceres had been considered to be a member of an asteroid family. These groupings of asteroids share similar orbital elements, which may indicate a common origin through an asteroid collision some time in the past. Ceres, however, was found to have spectral properties different from other members of the family, and so this grouping is now called the Gefion family, named after the next-lowest-numbered family member, 1272 Gefion. Ceres appears to be merely an interloper in its own family, coincidentally having similar orbital elements but not a common origin.

The rotational period of Ceres (the Cererian day) is 9 hours and 4 minutes.

Transits of planets from Ceres

Mercury, Venus, Earth, and Mars can all appear to cross the Sun, or transit it, from a vantage on Ceres. The most common transits are those of Mercury, which usually happens every few years, most recently in 2006 and 2010. The corresponding dates are 1953 and 2051 for Venus, 1814 and 2081 for Earth, and 767 and 2684 for Mars.

Origin and evolution

Ceres is probably a surviving protoplanet (planetary embryo), which formed 4.57 billion years ago in the asteroid belt. While the majority of inner solar system protoplanets (including all lunar- to Mars-sized bodies) either merged with other protoplanets to form terrestrial planets or were ejected from the Solar System by Jupiter, Ceres is believed to have survived relatively intact. (Another possible protoplanet, Vesta, is smaller; it suffered a major impact after solidifying, losing ~1% of its mass.) An alternative theory proposes that Ceres formed in the Kuiper Belt and later migrated to the asteroid belt.

The geological evolution of Ceres was dependent on the heat sources available during and after its formation: friction from planetesimal accretion, and decay of various radionuclides (possibly including short-lived elements like ^{26}Al). These are thought to have been sufficient to allow Ceres to differentiate into a rocky core and icy mantle soon after its formation. This process may have caused resurfacing by water volcanism and tectonics, erasing older geological features. Due to its small size, Ceres would have cooled early in its existence, causing all geological resurfacing processes to cease. Any ice on the surface would have gradually sublimated, leaving behind various hydrated minerals like clays and carbonates.

Today, Ceres appears to be a geologically inactive body, with a surface sculpted only by impacts. The presence of significant amounts of water ice in its composition raises the possibility that Ceres has or had a layer of liquid water in its interior. This hypothetical layer is often called an ocean. If such a layer of liquid water exists, it is believed to be located between the rocky core and ice mantle like that of the theorized ocean on Europa. The existence of an ocean is more likely if dissolved solutes (i.e. salts), ammonia, sulfuric acid or other antifreeze compounds are dissolved in the water.

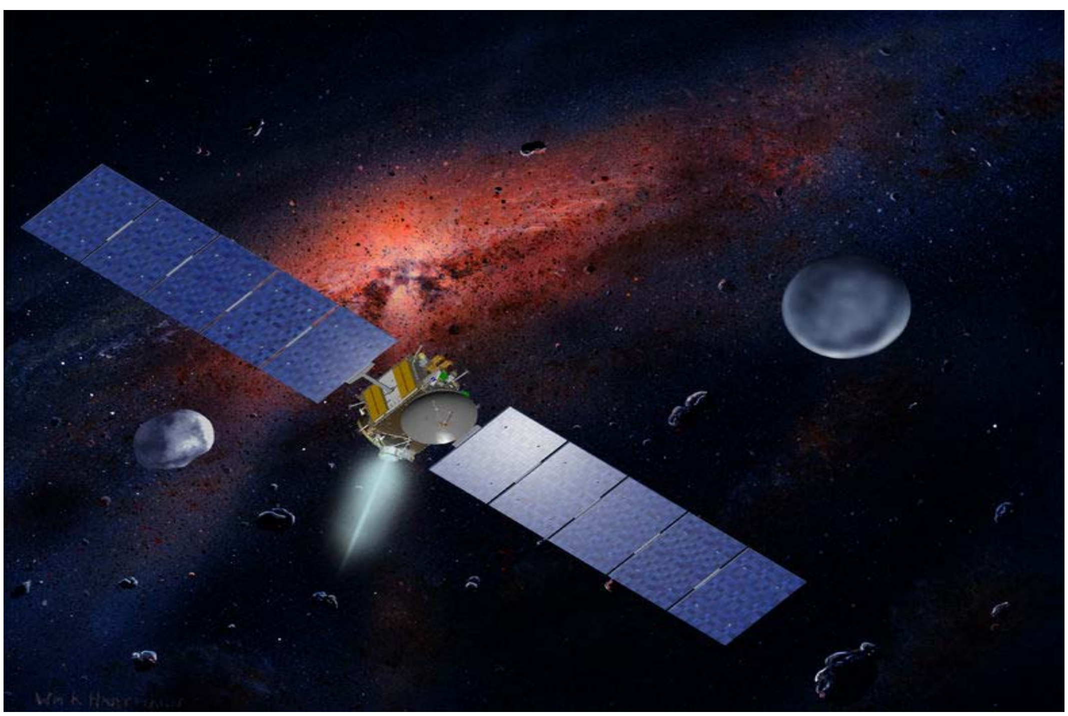
Observations

When Ceres has an opposition near the perihelion, it can reach a visual magnitude of +6.7. This is generally regarded as too dim to be seen with the naked eye, but under exceptional viewing conditions a very sharp-sighted person may be able to see this dwarf planet. Ceres will be at its brightest (6.73) on December 18, 2012. The only other asteroids that can reach a similarly bright magnitude are 4 Vesta, and, during rare oppositions near perihelion, 2 Pallas and 7 Iris. At a conjunction Ceres has a magnitude of around +9.3, which corresponds to the faintest objects visible with 10×50 binoculars. It can thus be seen with binoculars whenever it is above the horizon of a fully dark sky.

Some notable observational milestones for Ceres include:

- An occultation of a star by Ceres observed in Mexico, Florida and across the Caribbean on 13 November 1984.
- Ultraviolet Hubble Space Telescope images with 50 km resolution taken on 25 June 1995.
- Infrared images with 30 km resolution taken with the Keck telescope in 2002 using adaptive optics.
- Visible light images with 30 km resolution (the best to date) taken using Hubble in 2003 and 2004.

Exploration



Depiction of *Dawn* firing its ion thruster en route to Ceres

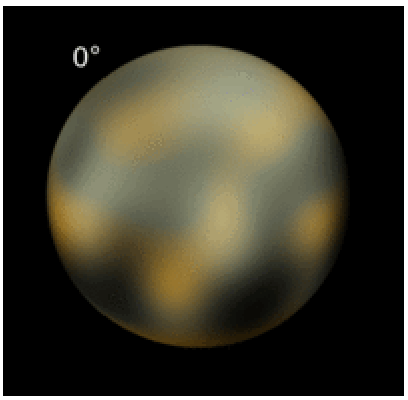
To date, no space probe has visited Ceres. Radio signals from spacecraft in orbit around and on the surface of Mars have been used to estimate the mass of Ceres from its perturbations on the motion of Mars.

The unmanned Dawn Mission, launched by NASA in 2007, is en route to Ceres. The mission is planned to explore the asteroid 4 Vesta in 2011 before arriving at Ceres in 2015. The mission profile calls for the *Dawn* spacecraft to enter orbit around Ceres at an altitude of 5,900 km. The spacecraft will reduce its orbital distance to 1,300 km after five months of study, and then down to 700 km after another five months. The spacecraft instrumentation includes a framing camera, a visual and infrared spectrometer, and a gamma-ray and neutron detector. These instruments will be used to examine the dwarf planet's shape and elemental composition.

Chapter 9

Pluto

Pluto ♇



Computer-generated map of Pluto from Hubble images, synthesised true colour and among the highest resolutions possible with current technology

Discovery	
Discovered by	Clyde W. Tombaugh
Discovery date	February 18, 1930
Designations	
MPC designation	**134340 Pluto**
Named after	Pluto
Minor planet category	dwarf planet, TNO, plutoid, KBO, plutino
Adjective	Plutonian
Orbital characteristics	
Epoch J2000	

Aphelion	7,375,927,931 km 49.305 032 87 AU
Perihelion	4,436,824,613 km 29.658 340 67 AU (1989-Sep-05)
Semi-major axis	5,906,376,272 km 39.481 686 77 AU
Eccentricity	0.248 807 66
Orbital period	90,613.305 days 248.09 years 14,164.4 Pluto solar days
Synodic period	366.73 days
Average orbital speed	4.666 km/s
Mean anomaly	14.86012204°
Inclination	17.141 75° 11.88° to Sun's equator
Longitude of ascending node	110.303 47°
Argument of perihelion	113.763 29°
Satellites	3
Physical characteristics	
Mean radius	1,153 ± 10 km (0.18 Earths) 1161 km (solid)
Surface area	1.665×10^{7} km^2 0.033 Earths
Volume	6.39×10^{9} km^3 0.0059 Earths
Mass	$(1.305 \pm 0.007)\times10^{22}$ kg 0.002 1 Earths 0.178 moon
Mean density	2.03 ± 0.06 g/cm^3
Equatorial surface gravity	0.658 m/s^2 0.067 g
Escape velocity	1.229 km/s
Sidereal rotation period	−6.387 230 day 6 d 9 h 17 m 36 s
Equatorial rotation velocity	47.18 km/h

Axial tilt	119.591 ± 0.014° (to orbit)
North pole right ascension	133.046 ± 0.014°
North pole declination	−6.145 ± 0.014°
Albedo	0.49–0.66 (geometric, varies by 35%)
Surface temp. Kelvin	**min** 33 K **mean** 44 K **max** 55 K
Apparent magnitude	13.65 to 16.3 (mean is 15.1)
Absolute magnitude *(H)*	−0.7
Angular diameter	0.065" to 0.115"
Atmosphere	
Surface pressure	0.30 Pa (summer maximum)
Composition	nitrogen, methane

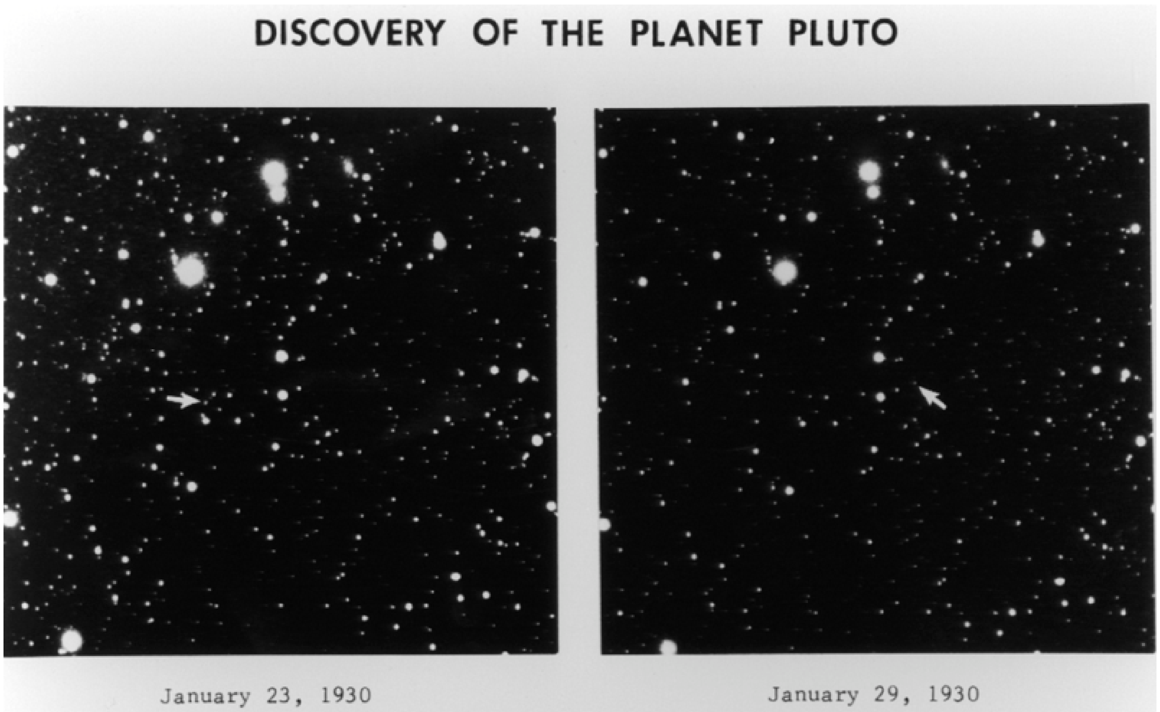
Pluto, formal designation **134340 Pluto**, is the second most massive known dwarf planet in the Solar System (after Eris) and the tenth most massive body observed directly orbiting the Sun. Originally classified as a planet, Pluto is now considered the largest member of a distinct population known as the Kuiper belt.

Like other members of the Kuiper belt, Pluto is composed primarily of rock and ice and is relatively small: approximately a fifth the mass of the Earth's Moon and a third its volume. It has an eccentric and highly inclined orbit that takes it from 30 to 49 AU (4.4–7.4 billion km) from the Sun. This causes Pluto to periodically come closer to the Sun than Neptune.

From its discovery in 1930 until 2006, Pluto was considered the Solar System's ninth planet. In the late 1970s, following the discovery of minor planet 2060 Chiron in the outer Solar System and the recognition of Pluto's relatively low mass, its status as a major planet began to be questioned. In the late 20th and early 21st century, many objects similar to Pluto were discovered in the outer Solar System, notably the scattered disc object Eris in 2005, which is 27% more massive than Pluto. On August 24, 2006, the International Astronomical Union (IAU) defined what it means to be a "planet" within the Solar System. This definition excluded Pluto as a planet and added it as a member of the new category "dwarf planet" along with Eris and Ceres. After the reclassification, Pluto was added to the list of minor planets and given the number 134340. A number of scientists continue to hold that Pluto should be classified as a planet.

Pluto and its largest moon, Charon, are sometimes treated as a binary system because the barycentre of their orbits does not lie within either body. The IAU has yet to formalise a definition for binary dwarf planets, and until it passes such a ruling, they classify Charon as a moon of Pluto. Pluto has two known smaller moons, Nix and Hydra, discovered in 2005.

Discovery



Discovery photographs of Pluto

In the 1840s, using Newtonian mechanics, Urbain Le Verrier predicted the position of the then-undiscovered planet Neptune after analysing perturbations in the orbit of Uranus. Subsequent observations of Neptune in the late 19th century caused astronomers to speculate that Uranus' orbit was being disturbed by another planet besides Neptune. In 1906, Percival Lowell, a wealthy Bostonian who had founded the Lowell Observatory in Flagstaff, Arizona in 1894, started an extensive project in search of a possible ninth planet, which he termed "Planet X". By 1909, Lowell and William H. Pickering had suggested several possible celestial coordinates for such a planet. Lowell and his observatory conducted his search until his death in 1916, but to no avail. Unknown to Lowell, on March 19, 1915, his observatory had captured two faint images of Pluto, but did not recognise them for what they were.

Due to a ten-year legal battle with Constance Lowell, Percival's widow, who attempted to wrest the observatory's million-dollar portion of his legacy for herself, the search for Planet X did not resume until 1929, when its director, Vesto Melvin Slipher, summarily handed the job of locating Planet X to Clyde Tombaugh, a 23-year-old Kansas man who had just arrived at the Lowell Observatory after Slipher had been impressed by a sample of his astronomical drawings.

Tombaugh's task was to systematically image the night sky in pairs of photographs taken two weeks apart, then examine each pair and determine whether any objects had shifted position. Using a machine called a blink comparator, he rapidly shifted back and forth between views of each of the plates, to create the illusion of movement of any objects that had changed position or appearance between photographs. On February 18, 1930, after nearly a year of searching, Tombaugh discovered a possible moving object on photographic plates taken on January 23 and January 29 of that year. A lesser-quality photograph taken on January 21 helped confirm the movement. After the observatory obtained further confirmatory photographs, news of the discovery was telegraphed to the Harvard College Observatory on March 13, 1930.

Name

Venetia Burney

The discovery made headlines across the globe. The Lowell Observatory, who had the right to name the new object, received over 1000 suggestions from all over the world, ranging from Atlas to Zymal. Tombaugh urged Slipher to suggest a name for the new object quickly before someone else did. Constance Lowell proposed *Zeus*, then *Percival* and finally *Constance* – her own first name. These suggestions were disregarded.

The name Pluto was proposed by Venetia Burney (1918–2009), an eleven-year-old schoolgirl in Oxford, England. Venetia was interested in classical mythology as well as astronomy, and considered the name, that of the Roman god of the underworld, appropriate for such a presumably dark and cold world. She suggested it in a conversation with her grandfather Falconer Madan, a former librarian at the University of Oxford's Bodleian Library. Madan passed the name to Professor Herbert Hall Turner, who then cabled it to colleagues in the United States.

The object was officially named on March 24, 1930. Each member of the Lowell Observatory was allowed to vote on a short-list of three: Minerva (which was already the name for an asteroid), Cronus (which had lost reputation through being proposed by the unpopular astronomer Thomas Jefferson Jackson See), and Pluto. Pluto received every vote. The name was announced on May 1, 1930. Upon the announcement, Madan gave Venetia five pounds as a reward.

It has been noted that the first two letters of *Pluto* are the initials of Percival Lowell, and Pluto's astronomical symbol (♇) is a monogram constructed from the letters 'PL'. Pluto's astrological symbol resembles that of Neptune (♆), but has a circle in place of the middle prong of the trident (⯓).

The name was soon embraced by wider culture. In 1930, Walt Disney introduced for Mickey Mouse a canine companion, named Pluto apparently in the object's honour, although Disney animator Ben Sharpsteen could not confirm why the name was given. In 1941, Glenn T. Seaborg named the newly created element plutonium after Pluto, in keeping with the tradition of naming elements after newly discovered planets, such as uranium, which was named after Uranus, and neptunium, which was named after Neptune.

In Chinese, Japanese and Korean the name was translated as *underworld king star* (冥王星), as suggested by Houei Nojiri in 1930. Many other non-European languages use a transliteration of "Pluto" as their name for the object; however, some Indian languages use a form of Yama, the Guardian of Hell in Hindu mythology, such as the Gujarati *Yamdev*.

Demise of Planet X

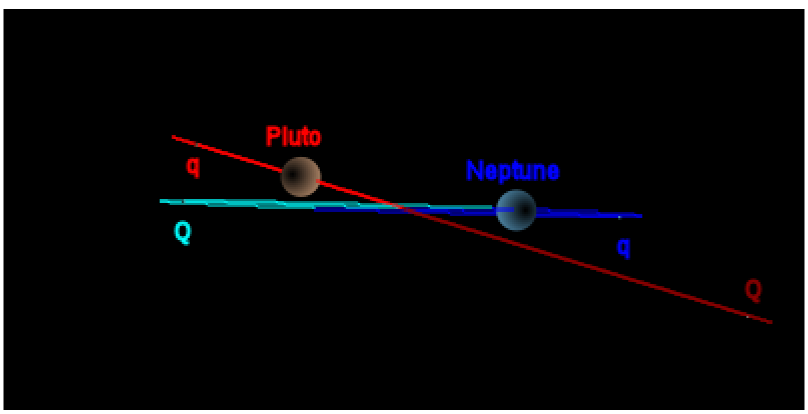
Clyde W. Tombaugh, the discoverer of Pluto

Mass estimates for Pluto:

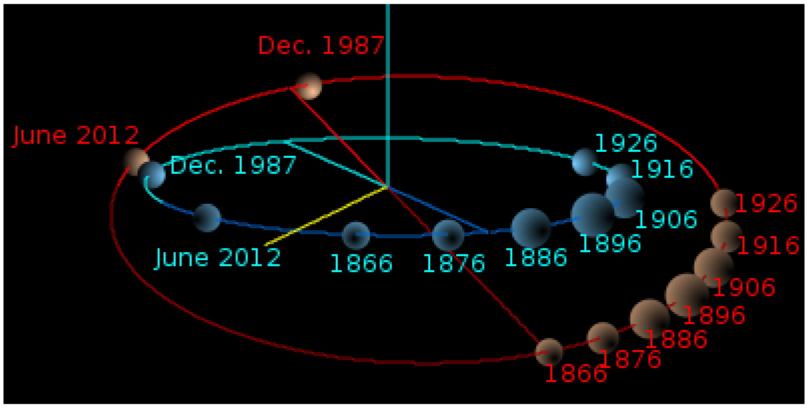
Year	Mass	Notes
1931	1 Earth	Nicholson & Mayall
1948	0.1 (1/10 Earth)	Kuiper
1976	0.01 (1/100 Earth)	Cruikshank, Pilcher, & Morrison
1978	0.002 (2/1,000 Earth)	Christy & Harrington

Once found, Pluto's faintness and lack of a resolvable disc cast doubt on the idea that it was Lowell's Planet X. Estimates of Pluto's mass were revised downward throughout the 20th century. In 1978, the discovery of Pluto's moon Charon allowed the measurement of Pluto's mass for the first time. Its mass, roughly 0.2% that of the Earth, was far too small to account for the discrepancies in the orbit of Uranus. Subsequent searches for an alternate Planet X, notably by Robert Sutton Harrington, failed. In 1992, Myles Standish used data from *Voyager 2*'s 1989 flyby of Neptune, which had revised the planet's total mass downward by 0.5%, to recalculate its gravitational effect on Uranus. With the new figures added in, the discrepancies, and with them the need for a Planet X, vanished. Today, the majority of scientists agree that Planet X, as Lowell defined it, does not exist. Lowell had made a prediction of Planet X's position in 1915 that was fairly close to Pluto's actual position at that time; however, Ernest W. Brown concluded almost immediately that this was a coincidence, a view still held today.

Orbit and rotation



Orbit of Pluto—ecliptic view. This 'side view' of Pluto's orbit (in red) shows its large inclination to Neptune's orbit (in blue). The ecliptic is horizontal

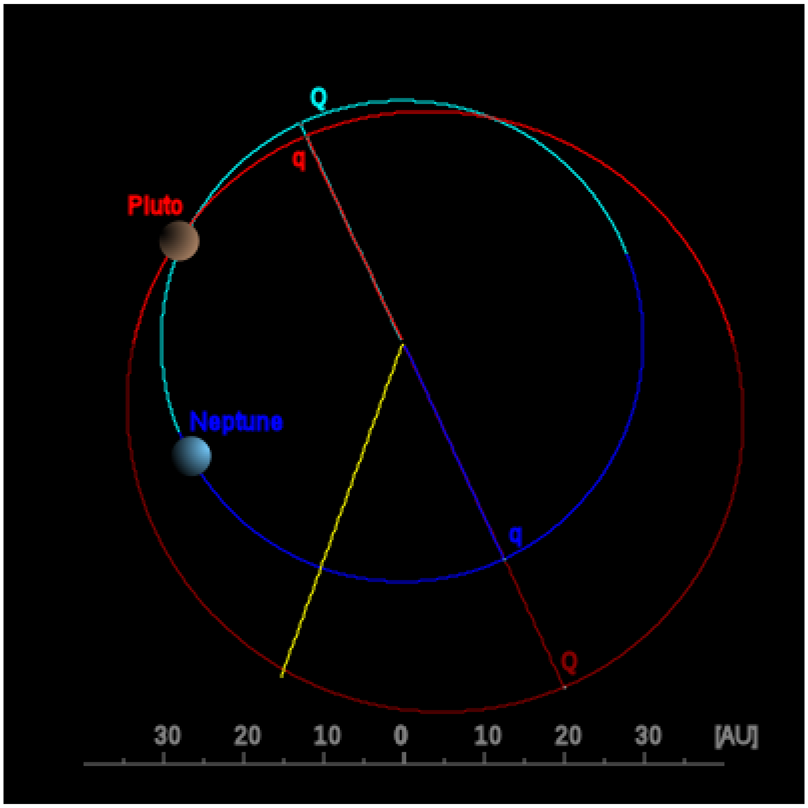


This diagram shows the relative positions of Pluto (red) and Neptune (blue) on selected dates. The size of Neptune and Pluto is depicted as inversely proportional to the distance between them to emphasise the closest approach in 1896.

Pluto's orbital period is 248 Earth years. Its orbital characteristics are substantially different from those of the planets, which follow nearly circular orbits around the Sun close to a flat reference plane called the ecliptic. In contrast, Pluto's orbit is highly inclined relative to the ecliptic (over 17°) and highly eccentric (elliptical). This high eccentricity means a small region of Pluto's orbit lies nearer the Sun than Neptune's. The Pluto–Charon barycentre came to perihelion on September 5, 1989, and was last interior to Neptune's orbit between February 7, 1979 and February 11, 1999. Detailed calculations indicate that the previous such occurrence lasted only fourteen years, from July 11, 1735 to September 15, 1749, whereas between April 30, 1483 and July 23, 1503, it had also lasted 20 years.

Although this repeating pattern may suggest a regular structure, in the long term Pluto's orbit is in fact chaotic. While computer simulations can be used to predict its position for several million years (both forward and backward in time), after intervals longer than the Lyapunov time of 10–20 million years, calculations become speculative: Pluto's tiny size makes it sensitive to unmeasurably small details of the solar system, hard-to-predict factors that will gradually disrupt its orbit. Millions of years from now, Pluto may well be at aphelion, at perihelion or anywhere in between, with no way for us to predict which. This does not mean Pluto's orbit itself is unstable, but its position *on* that orbit is impossible to determine so far ahead. Several resonances and other dynamical effects keep Pluto's orbit stable, safe from planetary collision or scattering.

Relationship with Neptune



Orbit of Pluto—polar view. This 'view from above' shows how Pluto's orbit (in red) is less circular than Neptune's (in blue), and how Pluto is sometimes closer to the Sun than Neptune. The darker halves of both orbits show where they pass below the plane of the ecliptic.

Despite Pluto's orbit appearing to cross that of Neptune when viewed from directly above, the two objects' orbits are aligned so that they can never collide or even approach closely. There are several reasons why.

At the simplest level, one can examine the two orbits and see that they do not intersect. When Pluto is closest to the Sun, and hence closest to Neptune's orbit as viewed from above, it is also the farthest above Neptune's path. Pluto's orbit passes about 8 AU above that of Neptune, preventing a collision. Pluto's ascending and descending nodes, the points at which its orbit crosses the ecliptic, are currently separated from Neptune's by over 21°.

However, this alone is not enough to protect Pluto; perturbations from the planets (especially Neptune) could alter aspects of Pluto's orbit (such as its orbital precession) over millions of years so that a collision could be possible. Some other mechanism or mechanisms must therefore be at work. The most significant of these is that Pluto lies in the 3:2 mean motion resonance with Neptune: for every three of Neptune's orbits around the Sun, Pluto makes two. The two objects then return to their initial positions and the cycle repeats, each cycle lasting about 500 years. This pattern is configured so that, in each 500-year cycle, the first time Pluto is near perihelion Neptune is over 50° *behind* Pluto. By Pluto's second perihelion, Neptune will have completed a further one and a half of its own orbits, and so will be a similar distance *ahead* of Pluto. Pluto and Neptune's minimum separation is over 17 AU. Pluto comes closer to Uranus (11 AU) than it does to Neptune.

The 3:2 resonance between the two bodies is highly stable, and is preserved over millions of years. This prevents their orbits from changing relative to one another; the cycle always repeats in the same way, and so the two bodies can never pass near to each other. Thus, even if Pluto's orbit were not highly inclined the two bodies could never collide.

Other factors

Numerical studies have shown that over periods of millions of years, the general nature of the alignment between Pluto and Neptune's orbits does not change. However, there are several other resonances and interactions that govern the details of their relative motion, and enhance Pluto's stability. These arise principally from two additional mechanisms (besides the 3:2 mean motion resonance).

First, Pluto's argument of perihelion, the angle between the point where it crosses the ecliptic and the point where it is closest to the Sun, librates around 90°. This means that when Pluto is nearest the Sun, it is at its farthest above the plane of the Solar System, preventing encounters with Neptune. This is a direct consequence of the Kozai mechanism, which relates the eccentricity of an orbit to its inclination to a larger perturbing body—in this case Neptune. Relative to Neptune, the amplitude of libration is 38°, and so the angular separation of Pluto's perihelion to the orbit of Neptune is always greater than 52° (= 90°–38°). The closest such angular separation occurs every 10,000 years.

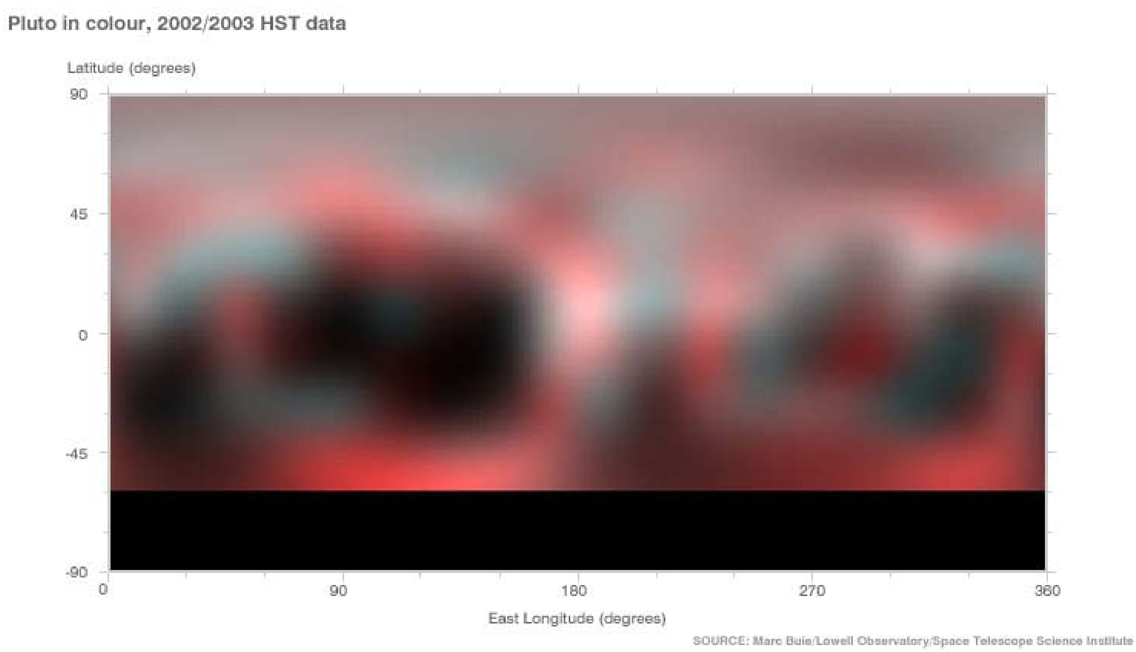
Second, the longitudes of ascending nodes of the two bodies—the points where they cross the ecliptic—are in near-resonance with the above libration. When the two longitudes are the same—that is, when one could draw a straight line through both nodes and the Sun—Pluto's perihelion lies exactly at 90°, and it comes closest to the Sun at its peak above Neptune's orbit. In other words, when Pluto most closely intersects the plane of Neptune's orbit, it must be at its farthest beyond it. This is known as the *1:1 superresonance*, and is controlled by all the Jovian planets.

To understand the nature of the libration, imagine a polar point of view, looking down on the ecliptic from a distant vantage point where the planets orbit counter-clockwise. After passing the ascending node, Pluto is interior to Neptune's orbit and moving faster, approaching Neptune from behind. The strong gravitational pull between the two causes angular momentum to be transferred to Pluto, at Neptune's expense. This moves Pluto into a slightly larger orbit, where it travels slightly slower, according to Kepler's third law. As its orbit changes, this has the gradual effect of changing the pericentre and longitudes of Pluto (and, to a lesser degree, of Neptune). After many such repetitions, Pluto is sufficiently slowed, and Neptune sufficiently speeded up, that Neptune begins to catch Pluto at the opposite side of its orbit (near the opposing node to where we began). The process is then reversed, and Pluto loses angular momentum to Neptune, until Pluto is sufficiently speeded up that it begins to catch Neptune again at the original node. The whole process takes about 20,000 years to complete.

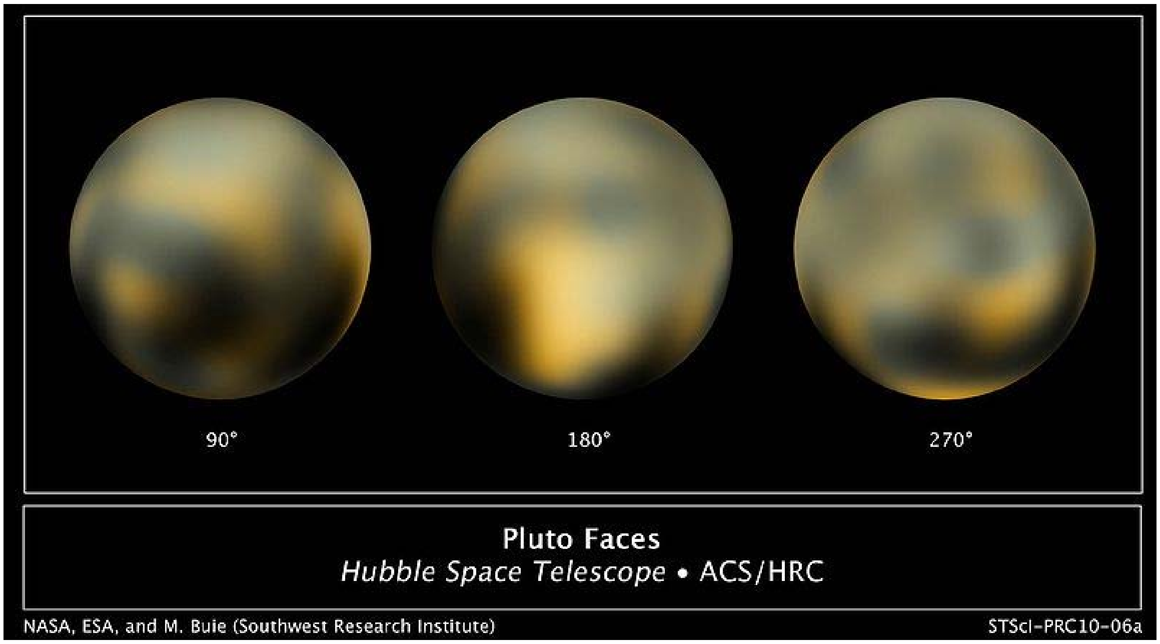
Rotation

Pluto's rotation period, its day, is equal to 6.39 Earth days. Like Uranus, Pluto rotates on its "side" on its orbital plane, with an axial tilt of 120°, and so its seasonal variation is extreme; at its solstices, one hemisphere is in permanent daylight, while the other is in permanent darkness.

Physical characteristics



Hubble map of Pluto's surface, showing great variations in color and albedo



Three views of Pluto from different orientations

Pluto's distance from Earth makes in-depth investigation difficult. Many details about Pluto will remain unknown until 2015, when the New Horizons spacecraft is expected to arrive there.

Appearance and surface

Pluto's visual apparent magnitude averages 15.1, brightening to 13.65 at perihelion. To see it, a telescope is required; around 30 cm (12 in) aperture being desirable. It looks star-like and without a visible disk even in large telescopes, because its angular diameter is only 0.11". Distance, and current limits on telescope technology, make it impossible to directly photograph surface details on Pluto.

The earliest maps of Pluto, made in the late 1980s, were brightness maps created from close observations of eclipses by its largest moon, Charon. Observations were made of the change in the total average brightness of the Pluto-Charon system during the eclipses. For example, eclipsing a bright spot on Pluto makes a bigger total brightness change than eclipsing a dark spot. Computer processing of many such observations can be used to create a brightness map. This method can also track changes in brightness over time.

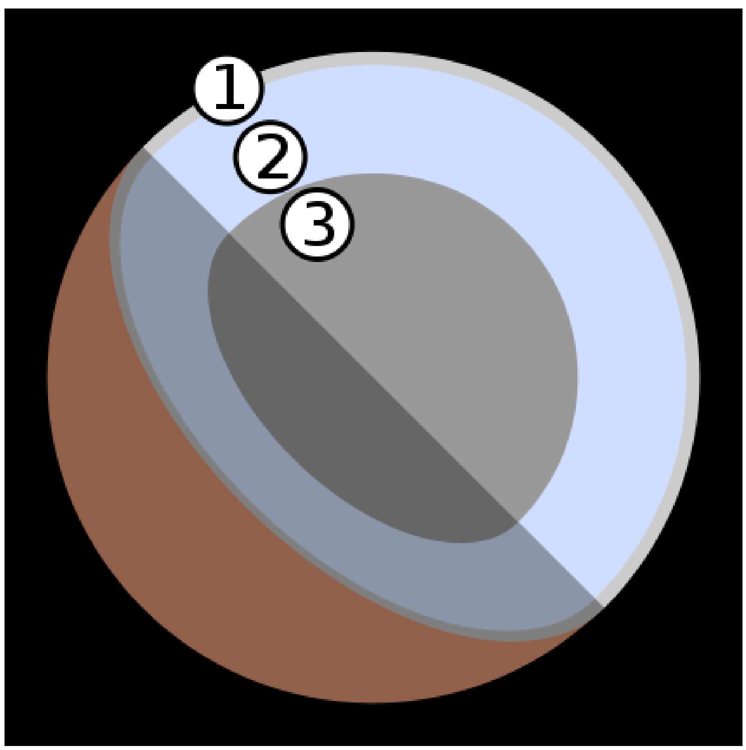
Current maps have been produced from images from the Hubble Space Telescope, which offers the highest resolution currently available, and show considerably more detail, resolving variations several hundred kilometres across, including polar regions and large bright spots. The maps are produced by complex computer processing, which find the best-fit projected maps for the few pixels of the Hubble images. As the two cameras on the HST used for these maps are no longer in service, these will remain the most detailed maps of Pluto until the 2015 flyby of New Horizons.

These maps, together with Pluto's lightcurve and the periodic variations in its infrared spectra, reveal that Pluto's surface is remarkably varied, with large changes in both brightness and colour. Pluto is one of the most contrastive bodies in the Solar System, with as much contrast as Saturn's moon Iapetus. The colour varies between charcoal black, dark orange and white: Buie et al. term it "significantly less red than Mars and much more similar to the hues seen on Io with a slightly more orange cast".

Pluto's surface has changed between 1994 and 2002-3: the northern polar region has brightened and the southern hemisphere darkened. Pluto's overall redness has also increased substantially between 2000 and 2002. These rapid changes are probably related to seasonal variation, which is expected to be complex due to Pluto's extreme axial tilt and high orbital eccentricity.

Spectroscopic analysis of Pluto's surface reveals it to be composed of more than 98 percent nitrogen ice, with traces of methane and carbon monoxide. The face of Pluto oriented toward Charon contains more methane ice, while the opposite face contains more nitrogen and carbon monoxide ice.

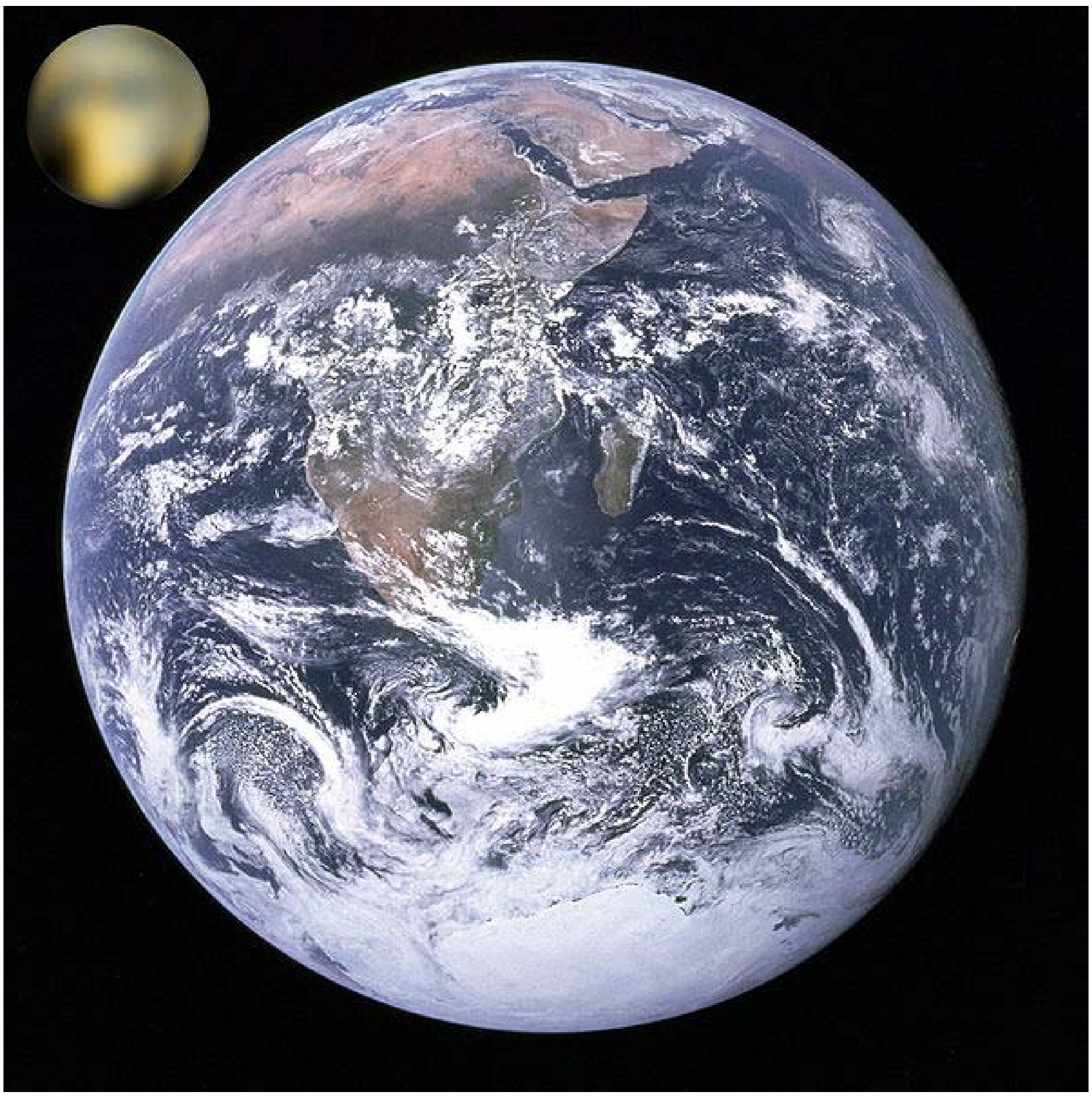
Structure



Theoretical structure of Pluto (2006)
1. Frozen nitrogen
2. Water ice
3. Rock

Observations by the Hubble Space Telescope place Pluto's density at between 1.8 and 2.1 g/cm^3, suggesting its internal composition consists of roughly 50–70 percent rock and 30–50 percent ice by mass. Because decay of radioactive minerals would eventually heat the ices enough for the rock to separate from them, scientists expect that Pluto's internal structure is differentiated, with the rocky material having settled into a dense core surrounded by a mantle of ice. The diameter of the core should be around 1,700 km, 70% of Pluto's diameter. It is possible that such heating continues today, creating a subsurface ocean layer of liquid water some 100 to 180 km thick at the core–mantle boundary. The DLR *Institute of Planetary Research* calculated that Pluto's density-to-radius ratio lies in a transition zone, along with Neptune's moon Triton, between icy satellites like the mid-sized moons of Uranus and Saturn, and rocky satellites such as Jupiter's Europa.

Mass and size



Pluto's volume is about 0.6% that of Earth

Pluto's mass is 1.31×10^{22} kg, less than 0.24 percent that of the Earth, while its diameter is 2,306 (+/- 20) km, or roughly 66% that of the Moon. Pluto's atmosphere complicates determining its true solid size within a certain margin.

Astronomers, assuming Pluto to be Lowell's Planet X, initially calculated its mass based on its presumed effect on Neptune and Uranus. In 1955 Pluto was calculated to be roughly the mass of the Earth, with further calculations in 1971 bringing the mass down to roughly that of Mars. However, in 1976, Dale Cruikshank, Carl Pilcher and David Morrison of the University of Hawaii calculated Pluto's albedo for the first time, finding that it matched that for methane ice; this meant Pluto had to be exceptionally luminous for its size and therefore could not be more than 1 percent the mass of the Earth. Pluto's albedo is 1.3–2.0 times greater than that of Earth.

Radius estimates for Pluto:

Year	Solid Radius	Notes
1993	1180 km	Millis, et al.
1994	1164 km	Young & Binzel
2006	1153 km	Buie, et al.
2007	1161 km	Young, Young, & Buie

The discovery of Pluto's satellite Charon in 1978 enabled a determination of the mass of the Pluto–Charon system by application of Newton's formulation of Kepler's third law. Once Charon's gravitational effect was measured, Pluto's true mass could be determined. Observations of Pluto in occultation with Charon allowed scientists to establish Pluto's diameter, while the invention of adaptive optics allowed them to determine its shape accurately.

Among the objects of the Solar System, Pluto is smaller and much less massive than the terrestrial planets, and at less than 0.2 lunar masses it is also less massive than seven moons: Ganymede, Titan, Callisto, Io, Earth's Moon, Europa and Triton. Pluto is more than twice the diameter and a dozen times the mass of the dwarf planet Ceres, the largest object in the asteroid belt. However, it is less massive than the dwarf planet Eris, a trans-Neptunian object discovered in 2005. Given the error bars in the different size estimates, it is currently unknown whether Eris or Pluto has the larger diameter. Both Pluto and Eris are estimated to have solid-body diameters of about 2330 km.

Atmosphere

CRIRES model-based computer-generated impression of the Plutonian surface by ESO—L. Calçada, with atmospheric haze, and Charon and the Sun in the sky.

Pluto's atmosphere consists of a thin envelope of nitrogen, methane, and carbon monoxide gases, which are derived from the ices of these substances on its surface. Its surface pressure ranges from 6.5 to 24 μbar. Pluto's elongated orbit is predicted to have a major effect on its atmosphere: as Pluto moves away from the Sun, its atmosphere should gradually freeze out, and fall to the ground. When Pluto is closer to the Sun, the temperature of Pluto's solid surface increases, causing the ices to sublimate into gas. This creates an anti-greenhouse effect; much as sweat cools the body as it evaporates from the surface of the skin, this sublimation cools the surface of Pluto. Scientists using the Submillimeter Array have recently discovered that Pluto's temperature is about 43 K (−230 °C), 10 K colder than would otherwise be expected.

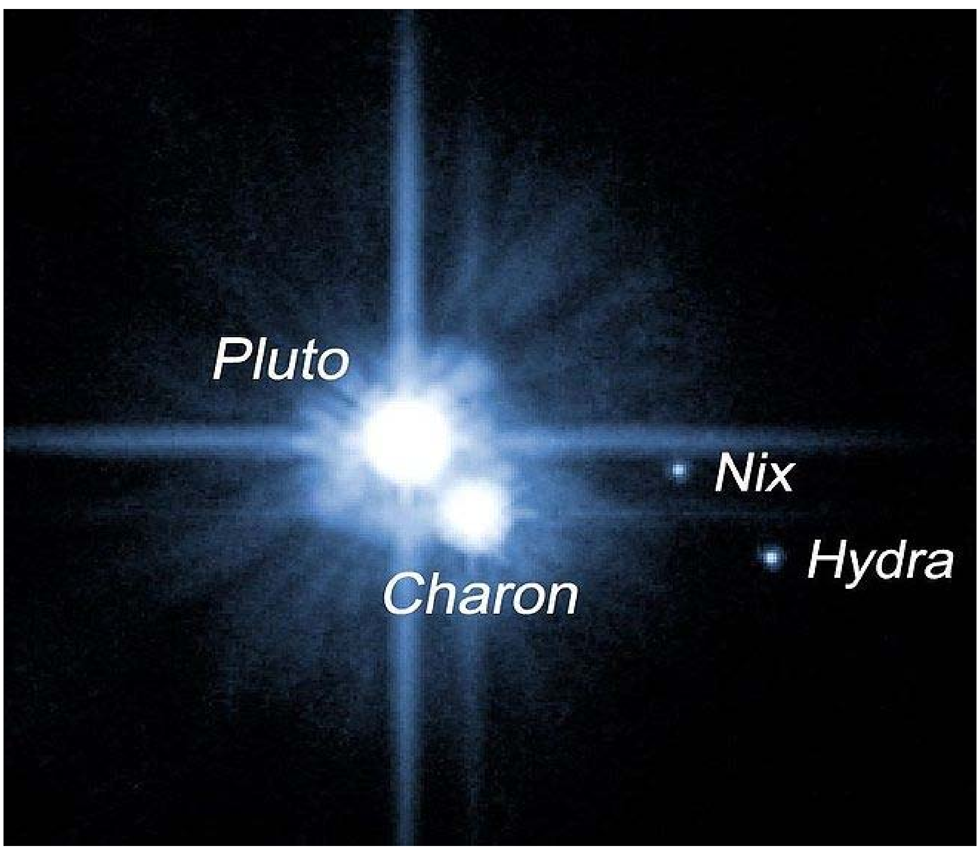
The presence of methane, a powerful greenhouse gas, in Pluto's atmosphere creates a temperature inversion, with average temperatures 36 K warmer 10 km above the surface. The lower atmosphere contains a higher concentration of methane than its upper atmosphere.

The first evidence of Pluto's atmosphere was found by the Kuiper Airborne Observatory in 1985, from observations of the occultation of a star behind Pluto. When an object with no atmosphere moves in front of a star, the star abruptly disappears; in the case of Pluto, the star dimmed out gradually. From the rate of dimming, the atmospheric pressure was determined to be 0.15 pascal, roughly 1/700,000 that of Earth. The conclusion was confirmed and significantly strengthened by extensive observations of another similar occultation in 1988.

In 2002, another occultation of a star by Pluto was observed and analysed by teams led by Bruno Sicardy of the Paris Observatory, James L. Elliot of MIT, and Jay Pasachoff of Williams College. Surprisingly, the atmospheric pressure was estimated to be 0.3 pascal, even though Pluto was farther from the Sun than in 1988 and thus should have been colder and had a more rarefied atmosphere. One explanation for the discrepancy is that in 1987 the south pole of Pluto came out of shadow for the first time in 120 years, causing extra nitrogen to sublimate from the polar cap. It will take decades for the excess nitrogen to condense out of the atmosphere as it freezes onto the north pole's now permanently dark ice cap. Spikes in the data from the same study revealed what may be the first evidence of wind in Pluto's atmosphere. Another stellar occultation was observed by the MIT-Williams College team of James Elliot, Jay Pasachoff, and a Southwest Research Institute team led by Leslie Young on June 12, 2006 from sites in Australia.

In October 2006, Dale Cruikshank of NASA/Ames Research Center (a New Horizons co-investigator) and his colleagues announced the spectroscopic discovery of ethane on Pluto's surface. This ethane is produced from the photolysis or radiolysis (i.e., the chemical conversion driven by sunlight and charged particles) of frozen methane on Pluto's surface and suspended in its atmosphere.

Satellites

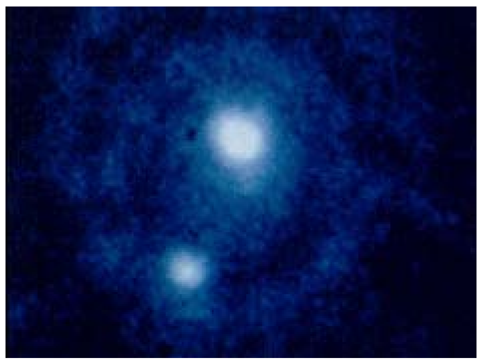


Pluto and its three known moons

Pluto has three known natural satellites: Charon, first identified in 1978 by astronomer James Christy; and two smaller moons, Nix and Hydra, both discovered in 2005.

The Plutonian moons are unusually close to Pluto, compared to other observed systems. Moons could potentially orbit Pluto up to 53% (or 69%, if retrograde) of the Hill sphere radius, the stable gravitational zone of Pluto's influence. For example, Psamathe orbits Neptune at 40% of the Hill radius. In the case of Pluto, only the inner 3% of the zone is known to be occupied by satellites. In the discoverers' terms, the Plutonian system appears to be "highly compact and largely empty", although others have pointed out the possibility of additional objects, including a small ring system.

Charon



A 1990 photograph of Pluto and Charon by the Hubble Telescope

The Pluto-Charon system is noteworthy for being the largest of the Solar System's few binary systems, defined as those whose barycentre lies above the primary's surface (617 Patroclus is a smaller example). This and the large size of Charon relative to Pluto has led some astronomers to call it a dwarf double planet. The system is also unusual among planetary systems in that each is tidally locked to the other: Charon always presents the same face to Pluto, and Pluto always presents the same face to Charon: from any position on either body, the other is always at the same position in the sky, or always obscured. Because of this, the rotation period of each is equal to the time it takes the entire system to rotate around its common centre of gravity. Just as Pluto revolves on its side relative to the orbital plane, so the Pluto-Charon system does also. In 2007, observations by the Gemini Observatory of patches of ammonia hydrates and water crystals on the surface of Charon suggested the presence of active cryo-geysers.

Nix and Hydra

Pluto and Charon as taken with the ESA/Dornier Faint Object Camera on Hubble Space Telescope in 1994

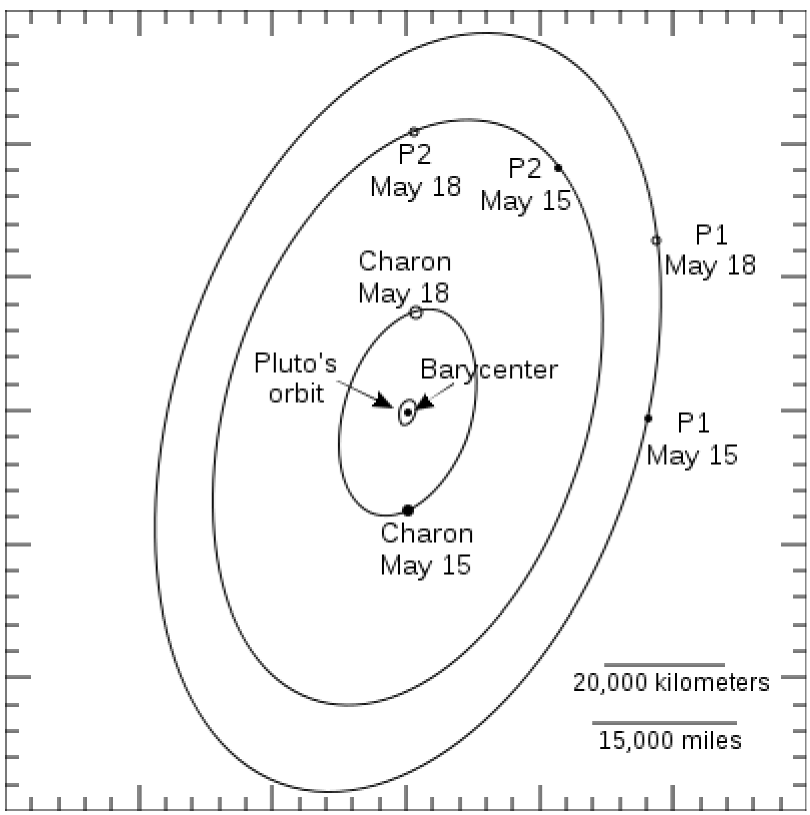


Diagram of the Plutonian system. P 1 is Hydra, and P 2 is Nix.

Two additional moons of Pluto were imaged by astronomers working with the Hubble Space Telescope on May 15, 2005, and received provisional designations of S/2005 P 1 and S/2005 P 2. The International Astronomical Union officially named Pluto's newest moons Nix (or Pluto II, the inner of the two moons, formerly P 2) and Hydra (Pluto III, the outer moon, formerly P 1), on June 21, 2006.

These small moons orbit Pluto at approximately two and three times the distance of Charon: Nix at 48,700 kilometres and Hydra at 64,800 kilometres from the barycenter of the system. They have nearly circular prograde orbits in the same orbital plane as Charon, and are very close to (but not in) 4:1 and 6:1 mean motion orbital resonances with Charon.

Observations of Nix and Hydra to determine individual characteristics are ongoing. Hydra is sometimes brighter than Nix, suggesting either that it is larger or that different parts of its surface may vary in brightness. Sizes are estimated from albedos. The moons' spectral similarity to Charon suggests a 35% albedo similar to Charon's; this value results in diameter estimates of 46 kilometres for Nix and 61 kilometres for the brighter Hydra. Upper limits on their diameters can be estimated by assuming the 4% albedo of the darkest Kuiper Belt objects; these bounds are 137 ± 11 km and 167 ± 10 km, respectively. At the larger end of this range, the inferred masses are less than 0.3% that of Charon, or 0.03% of Pluto's.

The discovery of the two small moons suggests that Pluto may possess a variable ring system. Small body impacts can create debris that can form into planetary rings. Data from a deep optical survey by the Advanced Camera for Surveys on the Hubble Space Telescope suggest that no ring system is present. If such a system exists, it is either tenuous like the rings of Jupiter or is tightly confined to less than 1,000 km in width.

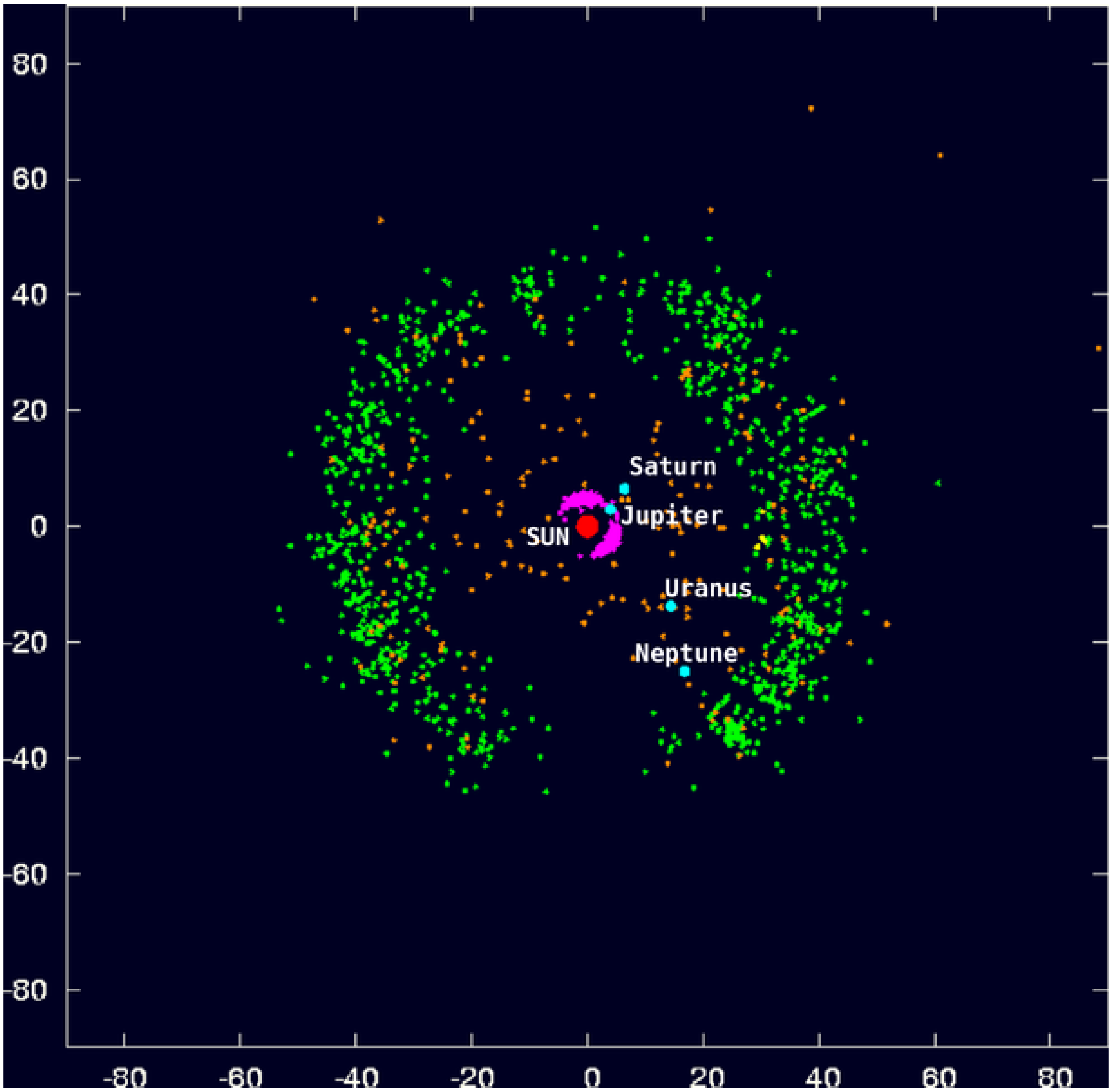
Similar conclusions have been made from occultation studies. In imaging the Plutonian system, observations from Hubble placed limits on any additional moons. With 90% confidence, no additional moons larger than 12 km (or a maximum of 37 km with an albedo of 0.041) exist beyond the glare of Pluto 5 arcseconds from the dwarf planet. This assumes a Charon-like albedo of 0.38; at a 50% confidence level the limit is 8 kilometres.

Pluto's satellites, with Earth's Moon comparison

Name	Discovery Year	Diameter (km)	Mass (kg)	Orbital radius (km) (barycentric)	Orbital period (d)
Pluto	1930	2,306 (66% Moon)	13,050 $\times 10^{18}$ (18% Moon)	2,040 (0.6% Moon)	
Charon	1978	1,205 (35% Moon)	1,520 $\times 10^{18}$ (2% Moon)	17,530 (5% Moon)	6.3872 (25% Moon)
Nix	2005	91	4 $\times 10^{17}$	48,708	24.856
Hydra	2005	114	8 $\times 10^{17}$	64,749	38.206

Mass of Nix and Hydra assumes icy/porous density of 1.0 g/cm^3

Origins



Plot of known Kuiper belt objects, set against the four gas giants

Pluto's origin and identity had long puzzled astronomers. One early hypothesis was that Pluto was an escaped moon of Neptune, knocked out of orbit by its largest current moon, Triton. This notion has been heavily criticised because Pluto never comes near Neptune in its orbit.

Pluto's true place in the Solar System began to reveal itself only in 1992, when astronomers found a population of small icy objects beyond Neptune that were similar to Pluto not only in orbit but also in size and composition. This trans-Neptunian population is believed to be the source of many short-period comets. Astronomers now believe Pluto to be the largest member of the Kuiper belt, a somewhat stable ring of objects located between 30 and 50 AU from the Sun. Like other Kuiper belt objects (KBOs), Pluto shares features with comets; for example, the solar wind is gradually blowing Pluto's surface into space, in the manner of a comet. If Pluto were placed as near to the Sun as Earth, it would develop a tail, as comets do.

Though Pluto is the largest of the Kuiper belt objects discovered so far, Neptune's moon Triton, which is slightly larger than Pluto, is similar to it both geologically and atmospherically, and is believed to be a captured Kuiper belt object. Eris (see below) is also larger than Pluto but is not strictly considered a member of the Kuiper belt population. Rather, it is considered a member of a linked population called the scattered disc.

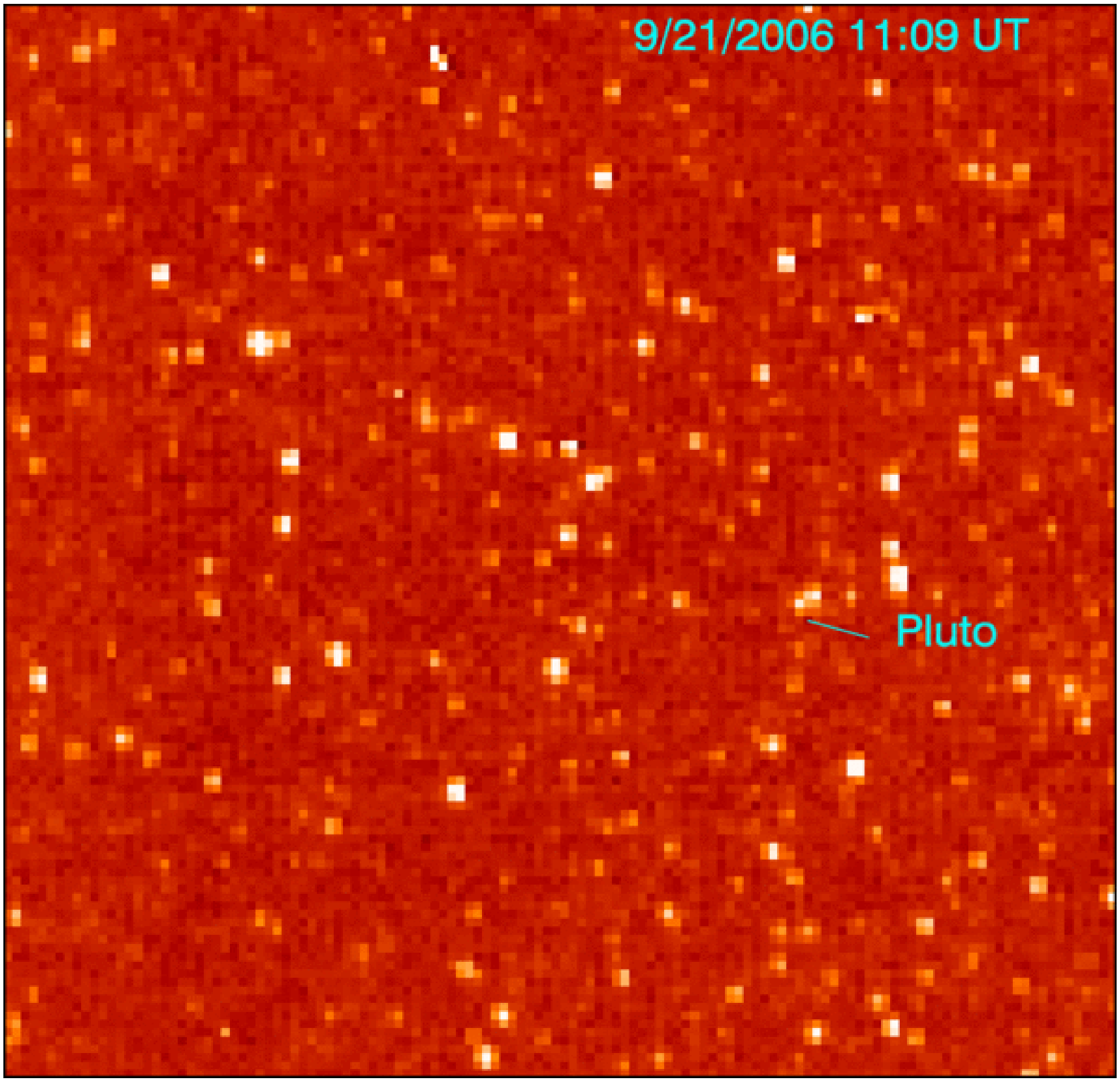
A large number of Kuiper belt objects, like Pluto, possess a 3:2 orbital resonance with Neptune. KBOs with this orbital resonance are called "plutinos", after Pluto.

Like other members of the Kuiper belt, Pluto is thought to be a residual planetesimal; a component of the original protoplanetary disc around the Sun that failed to fully coalesce into a full-fledged planet. Most astronomers agree that Pluto owes its current position to a sudden migration undergone by Neptune early in the Solar System's formation. As Neptune migrated outward, it approached the objects in the proto-Kuiper belt, setting one in orbit around itself, which became its moon Triton, locking others into resonances and knocking others into chaotic orbits. The objects in the scattered disc, a dynamically unstable region beyond the Kuiper belt, are believed to have been placed in their current positions by interactions with Neptune's migrating resonances. A 2004 computer model by Alessandro Morbidelli of the Observatoire de la Côte d'Azur in Nice suggested that the migration of Neptune into the Kuiper belt may have been triggered by the formation of a 1:2 resonance between Jupiter and Saturn, which created a gravitational push that propelled both Uranus and Neptune into higher orbits and caused them to switch places, ultimately doubling Neptune's distance from the Sun. The resultant expulsion of objects from the proto-Kuiper belt could also explain the Late Heavy Bombardment 600 million years after the Solar System's formation and the origin of Jupiter's trojan asteroids. It is possible that Pluto had a near-circular orbit about 33 AU from the Sun before Neptune's migration perturbed it into a resonant capture. The Nice model requires that there were about a thousand Pluto-sized bodies in the original planetesimal disk; these may have included the bodies which became Triton and Eris.

Exploration

New Horizons, launched on January 19, 2006

Pluto presents significant challenges for spacecraft because of its small mass and great distance from Earth. *Voyager 1* could have visited Pluto, but controllers opted instead for a close flyby of Saturn's moon Titan, resulting in a trajectory incompatible with a Pluto flyby. *Voyager 2* never had a plausible trajectory for reaching Pluto. No serious attempt to explore Pluto by spacecraft occurred until the last decade of the 20th century. In August 1992, JPL scientist Robert Staehle telephoned Pluto's discoverer, Clyde Tombaugh, requesting permission to visit his planet. "I told him he was welcome to it," Tombaugh later remembered, "though he's got to go one long, cold trip." Despite this early momentum, in 2000, NASA cancelled the *Pluto Kuiper Express* mission, citing increasing costs and launch vehicle delays.



First Pluto sighting from *New Horizons*

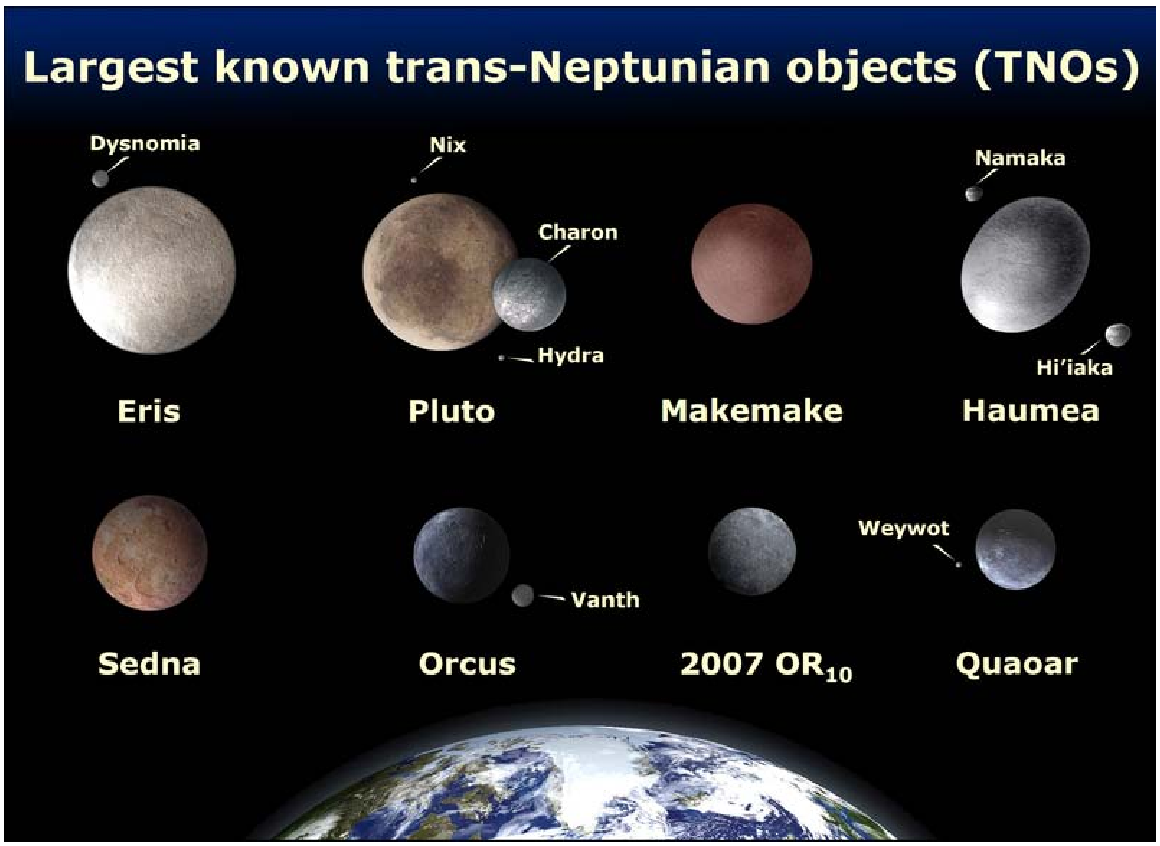
After an intense political battle, a revised mission to Pluto, dubbed *New Horizons*, was granted funding from the US government in 2003. *New Horizons* was launched successfully on January 19, 2006. The mission leader, S. Alan Stern, confirmed that some of the ashes of Clyde Tombaugh, who died in 1997, had been placed aboard the spacecraft.

In early 2007 the craft made use of a gravity assist from Jupiter. Its closest approach to Pluto will be on July 14, 2015; scientific observations of Pluto will begin 5 months before closest approach and will continue for at least a month after the encounter. *New Horizons* captured its first (distant) images of Pluto in late September 2006, during a test of the Long Range Reconnaissance Imager (LORRI). The images, taken from a distance of approximately 4.2 billion kilometres, confirm the spacecraft's ability to track distant targets, critical for maneuvering toward Pluto and other Kuiper Belt objects.

New Horizons will use a remote sensing package that includes imaging instruments and a radio science investigation tool, as well as spectroscopic and other experiments, to characterise the global geology and morphology of Pluto and its moon Charon, map their surface composition and analyse Pluto's neutral atmosphere and its escape rate. *New Horizons* will also photograph the surfaces of Pluto and Charon.

Discovery of moons Nix and Hydra may present unforeseen challenges for the probe. Debris from collisions between Kuiper belt objects and the smaller moons, with their relatively low escape velocities, may produce a tenuous dusty ring. Were New Horizons to fly through such a ring system, there would be an increased potential for micrometeoroid damage that could disable the probe.

Classification



Comparison of Eris, **Pluto**, Makemake, Haumea, Sedna, Orcus, 2007 OR_{10}, Quaoar, and Earth (all to scale)

After Pluto's place within the Kuiper belt was determined, its official status as a planet became controversial, with many questioning whether Pluto should be considered together with or separately from its surrounding population.

Museum and planetarium directors occasionally created controversy by omitting Pluto from planetary models of the Solar System. The Hayden Planetarium reopened after renovation in 2000 with a model of only eight planets. The controversy made headlines at the time.

In 2002, the KBO 50000 Quaoar was discovered, with a diameter then thought to be roughly 1280 kilometres, about half that of Pluto. In 2004, the discoverers of 90377 Sedna placed an upper limit of 1800 km on its diameter, nearer to Pluto's diameter of 2320 km, although Sedna's diameter was revised downward to less than 1600 km by 2007. Just as Ceres, Pallas, Juno and Vesta eventually lost their planet status after the discovery of many other asteroids, so, it was argued, Pluto should be reclassified as one of the Kuiper belt objects.

On July 29, 2005, the discovery of a new Trans-Neptunian object was announced. Named Eris, it is now known to be approximately the same size as Pluto. This was the largest object discovered in the Solar System since Triton in 1846. Its discoverers and the press initially called it the tenth planet, although there was no official consensus at the time on whether to call it a planet. Others in the astronomical community considered the discovery the strongest argument for reclassifying Pluto as a minor planet.

2006: IAU classification

The debate came to a head in 2006 with an IAU resolution that created an official definition for the term "planet". According to this resolution, there are three main conditions for an object to be considered a 'planet':

1. The object must be in orbit around the Sun.
2. The object must be massive enough to be a sphere by its own gravitational force. More specifically, its own gravity should pull it into a shape of hydrostatic equilibrium.
3. It must have cleared the neighbourhood around its orbit.

Pluto fails to meet the third condition, since its mass was only 0.07 times that of the mass of the other objects in its orbit (Earth's mass, by contrast, is 1.7 million times the remaining mass in its own orbit). The IAU further resolved that Pluto be classified in the simultaneously created dwarf planet category, and that it act as the prototype for the plutoid category of trans-Neptunian objects, in which it would be separately, but concurrently, classified.

On September 13, 2006, the IAU included Pluto, Eris, and the Eridian moon Dysnomia in their Minor Planet Catalogue, giving them the official minor planet designations "(134340) Pluto", "(136199) Eris", and "(136199) Eris I Dysnomia". If Pluto had been given a minor planet name upon its discovery, the number would have been a little over a thousand rather than over 100,000.

There has been some resistance within the astronomical community toward the reclassification. Alan Stern, principal investigator with NASA's *New Horizons* mission to Pluto, has publicly derided the IAU resolution, stating that "the definition stinks, for technical reasons." Stern's contention is that by the terms of the new definition Earth, Mars, Jupiter, and Neptune, all of which share their orbits with asteroids, would be excluded. His other claim is that because less than five percent of astronomers voted for it, the decision was not representative of the entire astronomical community. Marc W. Buie of the Lowell observatory has voiced his opinion on the new definition on his website and is one of the petitioners against the definition. Others have supported the IAU. Mike Brown, the astronomer who discovered Eris, said "through this whole crazy circus-like procedure, somehow the right answer was stumbled on. It’s been a long time coming. Science is self-correcting eventually, even when strong emotions are involved."

Researchers on both sides of the debate gathered on August 14–16, 2008, at The Johns Hopkins University Applied Physics Laboratory for a conference that included back-to-back talks on the current IAU definition of a planet. Entitled "The Great Planet Debate", the conference published a post-conference press release indicating that scientists could not come to a consensus about the definition of a planet. Just before the conference, on June 11, 2008, the IAU announced in a press release that the term "plutoid" would henceforth be used to describe Pluto and other objects similar to Pluto which have an orbital semimajor axis greater than that of Neptune and enough mass to be of near-spherical shape.

Public reaction to the change

A promotional event with a staged Pluto "protest". Members playing protesters of the reclassification of Pluto on the left, with those playing counter-protesters on the right

Reception to the IAU decision was mixed. While some accepted the reclassification, others seek to overturn the decision with online petitions urging the IAU to consider reinstatement. A resolution introduced by some members of the California state assembly light-heartedly denounces the IAU for "scientific heresy," among other crimes. The U.S. state of New Mexico's House of Representatives passed a resolution in honor of Tombaugh, a longtime resident of that state, which declared that Pluto will always be considered a planet while in New Mexican skies and that March 13, 2007 was Pluto Planet Day. The Illinois State Senate passed a similar resolution in 2009, on the basis that Clyde Tombaugh, the discoverer of Pluto, was born in Illinois. The resolution asserted that Pluto was "unfairly downgraded to a 'dwarf' planet" by the IAU.

Some members of the public have also rejected the change, citing the disagreement within the scientific community on the issue, or for sentimental reasons, maintaining that they have always known Pluto as a planet and will continue to do so regardless of the IAU decision.

Plutoed

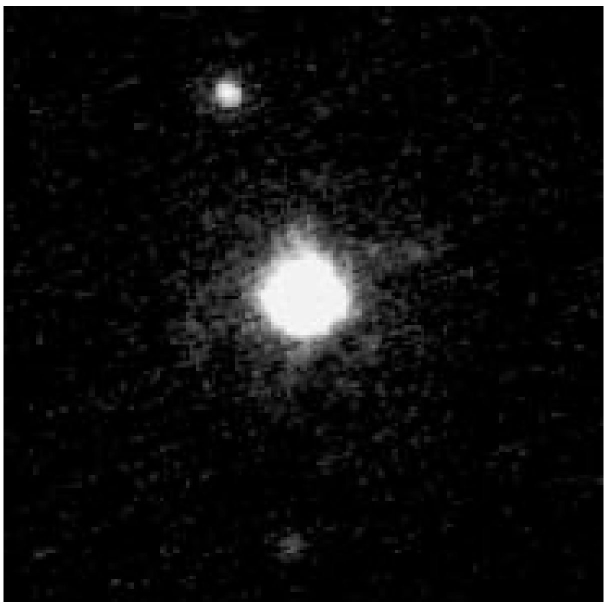
The verb "to pluto" (preterite and past participle: "**plutoed**") was a neologism coined in the aftermath of the 2006 IAU decision. In January 2007, the American Dialect Society chose "plutoed" as its 2006 Word of the Year, defining "*to pluto*" as "*to demote or devalue someone or something*", "as happened to the former planet Pluto when the General Assembly of the International Astronomical Union decided Pluto no longer met its definition of a planet."

Society president Cleveland Evans stated the reason for the organization's selection of "plutoed": "Our members believe the great emotional reaction of the public to the demotion of Pluto shows the importance of Pluto as a name. We may no longer believe in the Roman god Pluto, but we still have a sense of connection with the former planet."

Chapter 10

Haumea

Haumea



Keck image of Haumea and its two moons. Hiʻiaka is above Haumea (centre), and Namaka is directly below.

Discovery	
Discovered by	Brown *et al.*; Ortiz *et al.* (neither official)
Discovery date	2004 December 28 (Brown *et al.*); 2005 July (Ortiz *et al.*)
Designations	
MPC designation	(136108) Haumea
Named after	Haumea
Alternate name(s)	2003 EL_{61}
Minor planet category	dwarf planet, plutoid, TNO (delisted cubewano)

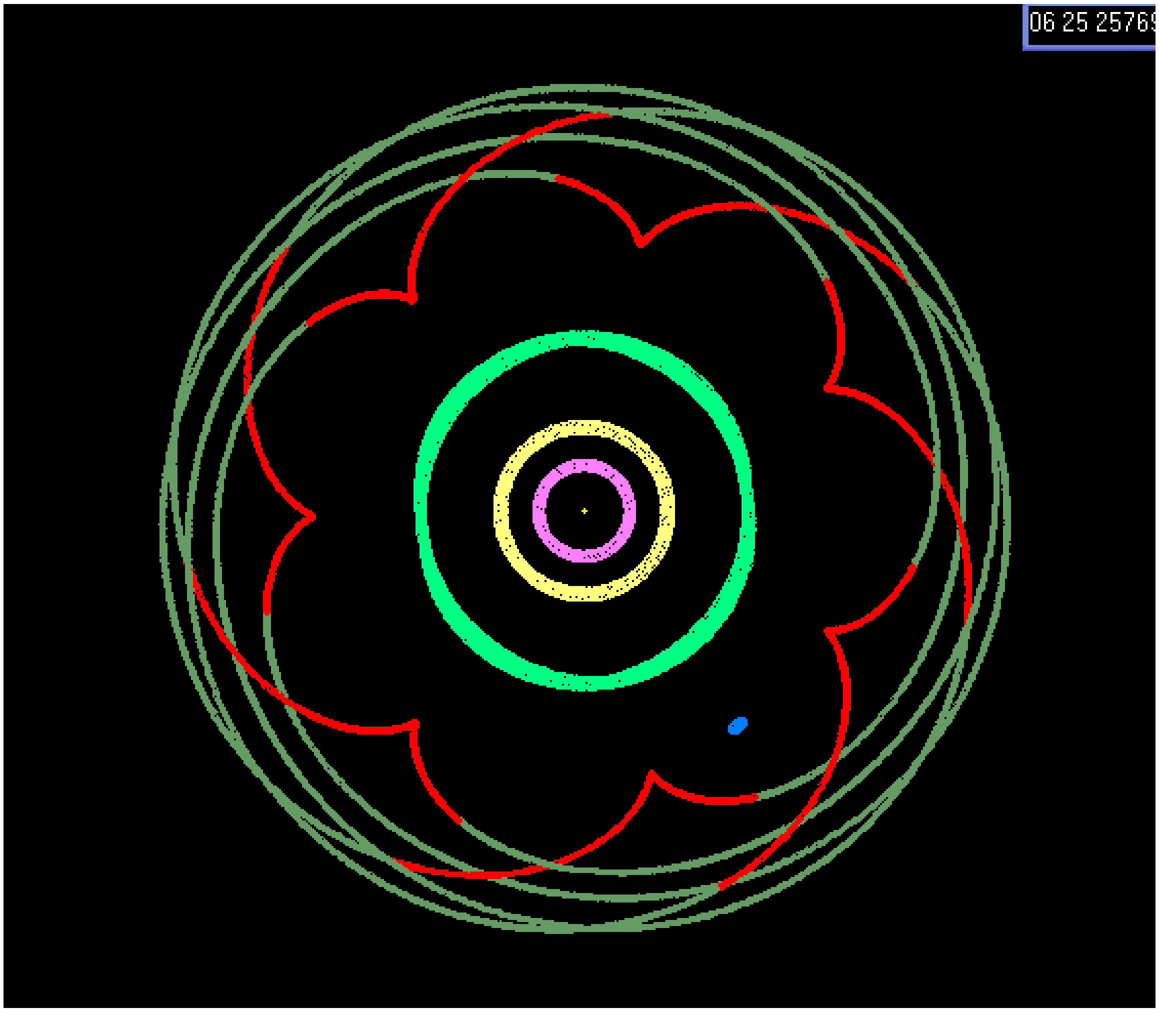
	fifth-order 12:7 resonance
Adjective	Haumean
Orbital characteristics	
Epoch 2008-11-30 (JD 2454800.5)	
Aphelion	51.544 AU 7.710 Tm
Perihelion	34.721 AU 5.194 Tm
Semi-major axis	43.132 AU 6.452 Tm
Eccentricity	0.195 01
Orbital period	103 468 d (283.28 yr)
Average orbital speed	4.484 km/s
Mean anomaly	202.67°
Inclination	28.22°
Longitude of ascending node	121.10°
Argument of perihelion	239.18°
Satellites	2
Physical characteristics	
Dimensions	≈1,960 × 1,518 × 996 km (Keck)
Mean radius	≈718 km 575+125 −50 km (Spitzer) 762 ± 83 km(Hershel)
Surface area	≈$2×10^7$ km^2
Mass	$(4.006 ± 0.040)×10^{21}$ kg 0.00066 Earths
Mean density	2.6–3.3 g/cm^3
Equatorial surface gravity	0.44 m/s^2
Escape velocity	0.84 km/s
Sidereal rotation period	0.163 146 ± 0.000 004 d (3.915 5 ± 0.000 1 h)
Albedo	0.7 ± 0.1 0.84 +0.1

	−0.2 0.70–75
Temperature	<50 K
Spectral type	(Neutral) B-V=0.64, V-R=0.33 B_0-V_0=0.646
Apparent magnitude	17.3 (opposition)
Absolute magnitude *(H)*	0.002 ± 0.4

Haumea, formal designation **136108 Haumea**, is a dwarf planet in the Kuiper belt. Its mass is one-third the mass of Pluto. It was discovered in 2004 by a team headed by Mike Brown of Caltech at the Palomar Observatory in the United States and, in 2005, by a team headed by J. L. Ortiz at the Sierra Nevada Observatory in Spain, though the latter claim has been contested. On September 17, 2008, it was designated a dwarf planet by the International Astronomical Union (IAU) and named after Haumea, the Hawaiian goddess of childbirth.

Haumea's extreme elongation makes it unique among known dwarf planets. Although its shape has not been directly observed, calculations from its light curve suggest it is an ellipsoid, with its greatest axis twice as long as its shortest. Nonetheless, its gravity is believed sufficient for it to have relaxed into hydrostatic equilibrium, thereby meeting the definition of a dwarf planet. This elongation, along with its unusually rapid rotation, high density, and high albedo (from a surface of crystalline water ice), are thought to be the results of a giant collision, which left Haumea the largest member of a collisional family that includes several large TNOs and its two known moons.

Classification



The nominal libration of Haumea in a rotating frame, with Neptune stationary

Haumea is a plutoid, a technical term used to describe dwarf planets beyond Neptune's orbit. Its status as a dwarf planet means it is presumed to be massive enough to have been rounded by its own gravity but not to have cleared its neighbourhood of similar objects. Although Haumea appears to be far from spherical, its ellipsoidal shape is thought to result from its rapid rotation, in much the same way that a water balloon stretches out when tossed with a spin, and not from a lack of sufficient gravity to overcome the compressive strength of its material. Haumea was initially listed as a classical Kuiper belt object (classical KBO) in 2006 by the Minor Planet Center, but no longer. The nominal trajectory suggests that it is in a fifth-order 7:12 resonance with Neptune since the perihelion distance of 35 AU is near the limit of stability with Neptune. There are precovery images of Haumea dating back to March 22, 1955 from the Palomar Mountain Digitized Sky Survey (observatory code #261). Further observations of the orbit will be required to verify its dynamic status.

Name

Until it was given a permanent name, the Caltech discovery team used the nickname "Santa" among themselves, as they had discovered Haumea on December 28, 2004, just after Christmas. The Spanish team proposed a separate discovery to the Minor Planet Center (MPC) in July 2005. On July 29, 2005, Haumea was given its first official label, the temporary designation 2003 EL_{61}, with the "2003" based on the date of the Spanish discovery image. On September 7, 2006, it was numbered and admitted into the official minor planet catalogue as (136108) 2003 EL_{61}.

Following guidelines established by the IAU that classical KBOs be given names of mythological beings associated with creation, in September 2006 the Caltech team submitted formal names from Hawaiian mythology to the IAU for both (136108) 2003 EL_{61} and its moons, in order "to pay homage to the place where the satellites were discovered". The names were proposed by David Rabinowitz of the Caltech team.

Haumea is the matron goddess of the island of Hawaiʻi, where the Mauna Kea Observatory is located. In addition, she is identified with Pāpā, the goddess of the earth and wife of Wākea (space), which is appropriate because 2003 EL_{61} is thought to be composed almost entirely of solid rock, without the thick ice mantle over a small rocky core typical of other known Kuiper belt objects. Lastly, Haumea is the goddess of fertility and childbirth, with many children who sprang from different parts of her body; this corresponds to the swarm of icy bodies thought to have broken off the dwarf planet during an ancient collision. The two known moons, also believed to have been born in this manner, are thus named after two of Haumea's daughters, Hiʻiaka and Nāmaka.

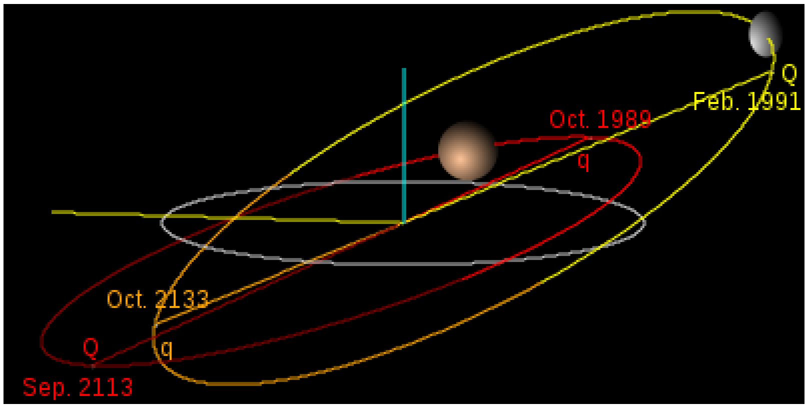
Discovery controversy

Two teams claim credit for the discovery of Haumea. Mike Brown and his team at Caltech discovered Haumea in December 2004 on images they had taken on May 6, 2004. On July 20, 2005, they published an online abstract of a report intended to announce the discovery at a conference in September 2005. At around this time, José Luis Ortiz Moreno and his team at the Instituto de Astrofísica de Andalucía at Sierra Nevada Observatory in Spain found Haumea on images taken on March 7–10, 2003. Ortiz emailed the Minor Planet Center with their discovery on the night of July 27, 2005.

Brown came to suspect the Spanish team of fraud upon learning that his observation logs were accessed from the Spanish observatory the day before the discovery announcement. These logs included enough information to allow the Ortiz team to precover Haumea in their 2003 images, and they were accessed again just before Ortiz scheduled telescope time to obtain confirmation images for a second announcement to the MPC on July 29. Ortiz later admitted he had accessed the Caltech observation logs but denied any wrongdoing, stating he was merely verifying whether they had discovered a new object.

IAU protocol is that discovery credit for a minor planet goes to whoever first submits a report to the MPC with enough positional data for a decent determination of its orbit, and that the credited discoverer has priority in choosing a name. However, the IAU announcement on September 17, 2008, that Haumea had been accepted as a dwarf planet, did not mention a discoverer. The location of discovery was listed as the Sierra Nevada Observatory of the Spanish team, but the chosen name, Haumea, was the Caltech proposal; Ortiz's team had proposed "Ataecina," named for the ancient Iberian goddess of Spring.

Orbit and rotation



Orbits of Haumea (yellow) and Pluto (red), relative to that of Neptune (grey), as of May 2009

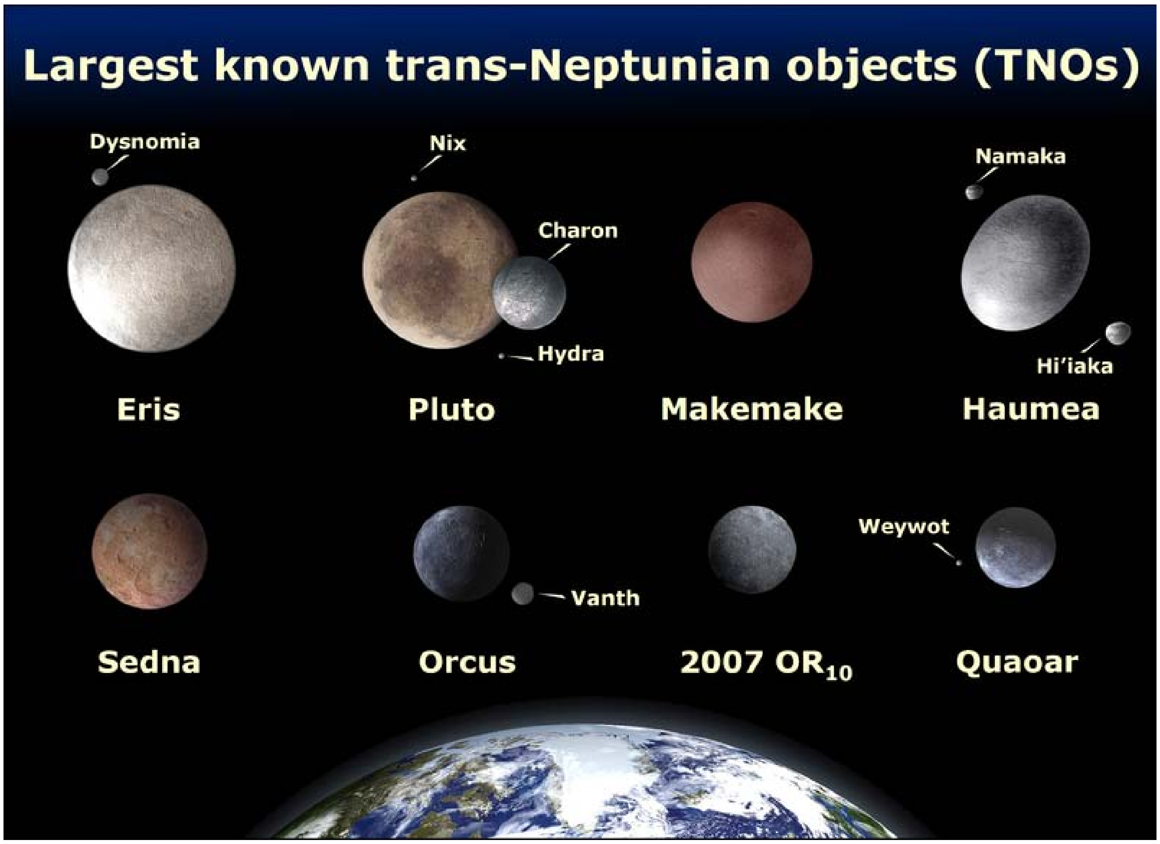
Haumea has a typical orbit for a classical Kuiper belt object, with an orbital period of 283 Earth years, a perihelion of 35 AU, and an orbital inclination of 28°. It passed aphelion in early 1992, and is currently more than 50 AU from the Sun.

Haumea's orbit has a slightly greater eccentricity than the other members of its collisional family. This is thought to be due to Haumea's weak fifth-order 12:7 orbital resonance with Neptune gradually modifying its initial orbit, over the course of a billion years, through the Kozai effect, which allows the exchange of an orbit's inclination for increased eccentricity.

With a visual magnitude of 17.3, Haumea is the third brightest object in the Kuiper belt after Pluto and Makemake, and easily observable with a large amateur telescope. However, since the planets and most small Solar System bodies share a common orbital alignment from their formation in the primordial disk of the Solar System, most early surveys for distant objects focused on the projection on the sky of this common plane, called the ecliptic. As the region of sky close to the ecliptic became well explored, later sky surveys began looking for objects that had been dynamically excited into orbits with higher inclinations, as well as more distant objects, with slower mean motions across the sky. These surveys eventually covered the location of Haumea, with its high orbital inclination and current position far from the ecliptic.

Haumea displays large fluctuations in brightness over a period of 3.9 hours, which can only be explained by a rotational period of this length. This is faster than any other known equilibrium body in the Solar System, and indeed faster than any other known body larger than 100 km in diameter. This rapid rotation is thought to have been caused by the impact that created its satellites and collisional family.

Physical characteristics

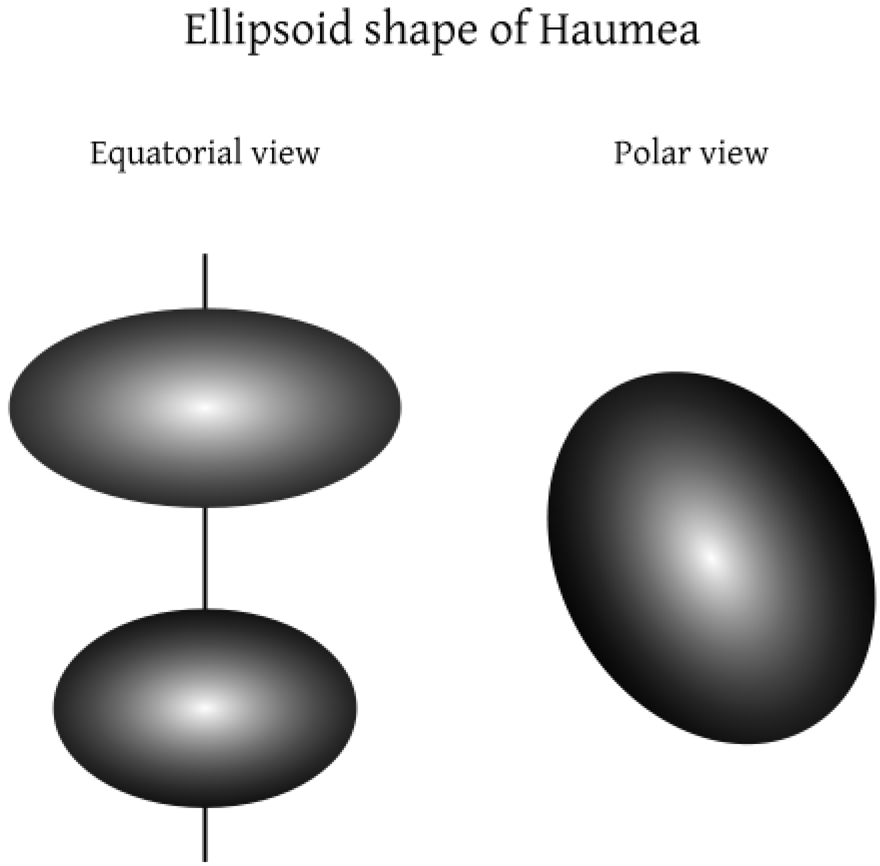


Comparison of Eris, Pluto, Makemake, **Haumea**, Sedna, Orcus, 2007 OR_{10}, Quaoar, and Earth (all to scale)

Since Haumea has moons, the mass of the system can be calculated from their orbits using Kepler's third law. The result is 4.2×10^{21} kg, 28% the mass of the Plutonian system and 6% the mass of the Earth's Moon. Nearly all of this mass is in Haumea.

Size, shape, and composition

The size of a Solar System object can be deduced from its optical magnitude, its distance, and its albedo. Objects appear bright to Earth observers either because they are large or because they are highly reflective. If their reflectivity (albedo) can be ascertained, then a rough estimate can be made of their size. For most distant objects, the albedo is unknown, but Haumea is large and bright enough for its thermal emission to be measured, which has given an approximate value for its albedo and thus its size. However, the calculation of its dimensions is complicated by its rapid rotation. The rotational physics of deformable bodies predicts that over as little as a hundred days, a body rotating as rapidly as Haumea will have been distorted into the equilibrium form of a scalene ellipsoid. It is thought that most of the fluctuation in Haumea's brightness is caused not by local differences in albedo but by the alternation of the side view and end view as seen from Earth.



The calculated ellipsoid shape of Haumea, 1,960×1,518×996 km (assuming an albedo of 0.73). At left are the minimum and maximum equatorial silhouettes (1,960×996 and 1,518×996 km); at right is the view from the pole (1,960×1,518 km).

The rotation and amplitude of Haumea's light curve place strong constraints on its composition. If Haumea had a low density like Pluto, with a thick mantle of ice over a small rocky core, its rapid rotation would have elongated it to a greater extent than the fluctuations in its brightness allow. Such considerations constrain its density to a range of 2.6–3.3 g/cm^3. This range covers the values for silicate minerals such as olivine and pyroxene, which make up many of the rocky objects in the Solar System. This suggests that the bulk of Haumea is rock covered with a relatively thin layer of ice. A thick ice mantle more typical of Kuiper belt objects may have been blasted off during the impact that formed the Haumean collisional family.

The denser the object in hydrostatic equilibrium, the more spherical it must be for a given rotational period, placing constraints on Haumea's possible dimensions. Fitting its accurately known mass, its rotation, and its inferred density to an equilibrium ellipsoid predicts that Haumea is approximately the diameter of Pluto along its longest axis and about half that at its poles. Since no observations of occultations of stars by Haumea or occultations of the dwarf planet with its moons have yet been made, direct, precise measurements of its dimensions, like those that have been made for Pluto, do not yet exist.

Several ellipsoid-model calculations of Haumea's dimensions have been made. The first model produced after Haumea's discovery was calculated from ground-based observations of Haumea's light curve at optical wavelengths: it provided a total length of 1,960 to 2,500 km and a visual albedo (p_v) greater than 0.6. The most likely shape is a triaxial ellipsoid with approximate dimensions of 2,000 x 1,500 x 1,000 km, with an albedo of 0.71. The Spitzer Space Telescope has estimated Haumea to have a diameter of 1,150+250
−100 km and an albedo of 0.84+0.1
−0.2, from photometry at infrared wavelengths of 70 µm. Subsequent light curve analyses have suggested an equivalent circular diameter of 1,450 km. In 2010 an analysis of measurements taken by Herschel Space Telescope together with the older Spitzer Telescope measurements yielded a new estimate of the equivalent diameter of Haumea—about 1300 km. These independent size estimates overlap at an average geometric mean diameter of roughly 1,400 km. This makes Haumea one of the largest trans-Neptunian objects discovered, third or fourth after Eris, Pluto, and perhaps Makemake, and larger than Sedna, Orcus, or Quaoar.

Surface

In addition to the large fluctuations in Haumea's light curve due to the body's shape, which affect all colours equally, smaller independent colour variations seen in both visible and near-infrared wavelengths show a region on the surface that differs both in colour and in albedo. More specifically, a dark red area on Haumea's bright white surface has been seen, which indicates an area rich in minerals and organic (carbon-rich) compounds, or possibly a higher proportion of crystalline ice. Thus Haumea may have a mottled surface reminiscent of Pluto, if not as extreme.

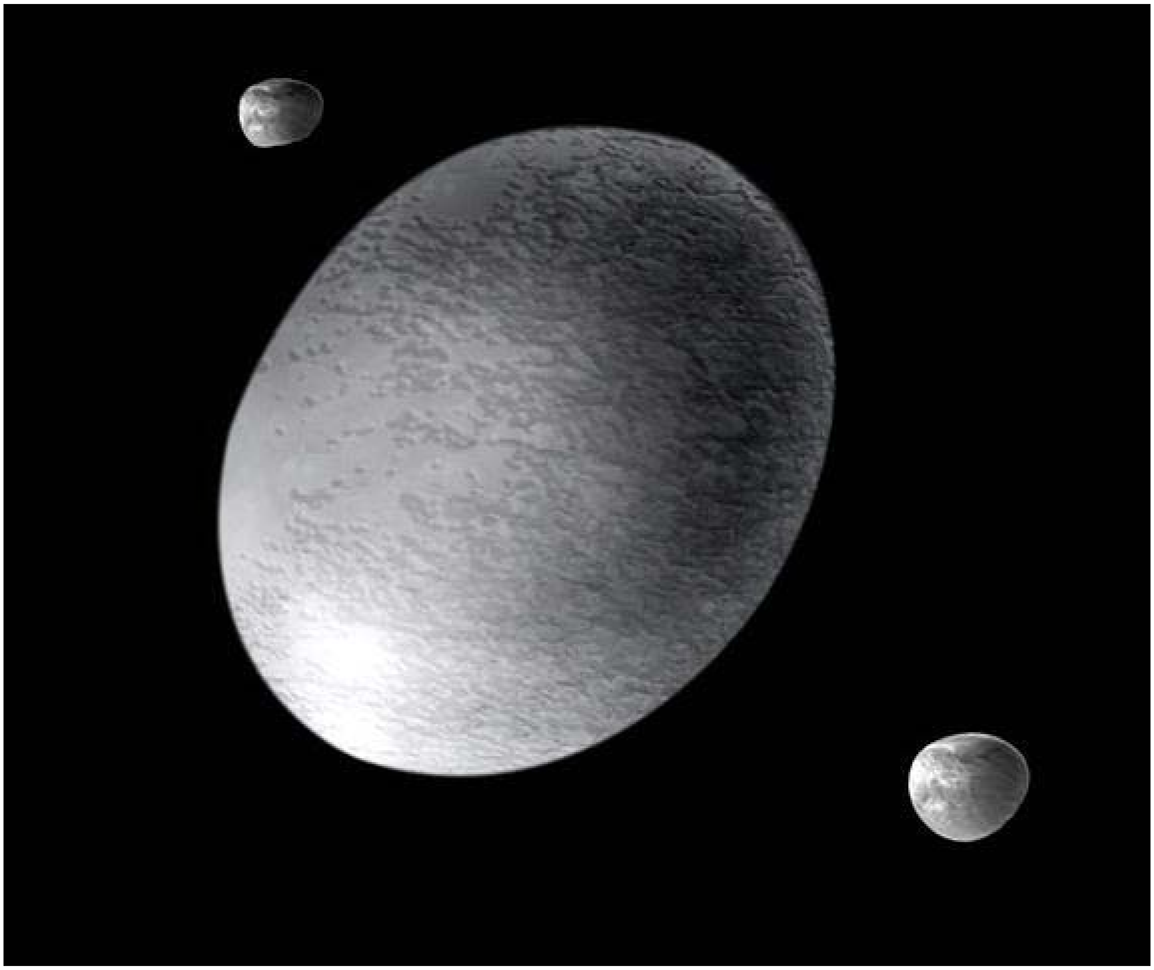
In 2005, the Gemini and Keck telescopes obtained spectra of Haumea which showed strong crystalline water ice features similar to the surface of Pluto's moon Charon. This is peculiar, because crystalline ice forms at temperatures above 110 K, while the surface temperature of Haumea is below 50 K, a temperature at which amorphous ice is formed. In addition, the structure of crystalline ice is unstable under the constant rain of cosmic rays and energetic particles from the Sun that strike trans-Neptunian objects. The timescale for the crystalline ice to revert to amorphous ice under this bombardment is on the order of ten million years, while trans-Neptunian objects have been in their present cold-temperature locations for timescales of thousands of millions of years. Radiation damage should also redden and darken the surface of trans-Neptunian objects where the common surface materials of organic ices and tholin-like compounds are present, as is the case with Pluto. Therefore, the spectra and colour suggest Haumea and its family members have undergone recent resurfacing that produced fresh ice. However, no plausible resurfacing mechanism has been suggested.

Haumea is as bright as snow, with an albedo in the range of 0.6–0.8, consistent with crystalline ice. Other large TNOs such as Eris appear to have albedos as high or higher. Best-fit modeling of the surface spectra suggested that 66% to 80% of the Haumean surface appears to be pure crystalline water ice, with one contributor to the high albedo possibly hydrogen cyanide or phyllosilicate clays. Inorganic cyanide salts such as copper potassium cyanide may also be present.

However, further studies of the visible and near infrared spectra suggest a homomorphous surface covered by an intimate 1:1 mixture of amorphous and crystalline ice, together with no more than 8% organics. The absence of ammonia hydrate excludes cryovolcanism and the observations confirm that the collisional event must have happened more than 100 million years ago, in agreement with the dynamic studies. The absence of measurable methane in the spectra of Haumea is consistent with a warm collisional history that would have removed such volatiles, in contrast to Makemake.

In September 2009, Haumea was discovered to have a large dark reddish spot, possibly an impact feature, and not to be uniformly bright as previously believed. While the reason for the color is unknown, possibilities include crystalline ice or higher concentrations of minerals and organic compounds than the rest of the surface.

Moons



Artist's conception of Haumea with its moons Hiʻiaka and Namaka. The moons are much more distant than depicted here.

Two small satellites have been discovered orbiting Haumea, (136108) Haumea I Hiʻiaka and (136108) Haumea II Namaka. Brown's team discovered both in 2005, through observations of Haumea using the W.M. Keck Observatory.

Hiʻiaka, at first nicknamed "Rudolph" by the Caltech team, was discovered January 26, 2005. It is the outer and, at roughly 310 km in diameter, the larger and brighter of the two, and orbits Haumea in a nearly circular path every 49 days. Strong absorption features at 1.5 and 2 micrometres in the infrared spectrum are consistent with nearly pure crystalline water ice covering much of the surface. The unusual spectrum, along with similar absorption lines on Haumea, led Brown and colleagues to conclude that capture was an unlikely model for the system's formation, and that the Haumean moons must be fragments of Haumea itself.

Namaka, the smaller, inner satellite of Haumea, was discovered on June 30, 2005, and nicknamed "Blitzen". It is a tenth the mass of Hiʻiaka, orbits Haumea in 18 days in a highly elliptical, non-Keplerian orbit, and as of 2008 is inclined 13° from the larger moon, which perturbs its orbit. The relatively large eccentricities together with the mutual inclination of the orbits of the satellites are unexpected as they should have been damped by the tidal effects. A relatively recent passage by a (3:1) resonance might explain the current excited orbits of the Haumean moons.

At present, the orbits of the Haumean moons appear almost exactly edge-on from Earth, with Namaka periodically occulting Haumea. Observation of such transits would provide precise information on the size and shape of Haumea and its moons, as happened in the late 1980s with Pluto and Charon. The tiny change in brightness of the system during these occultations will require at least a medium-aperture professional telescope for detection. Hiʻiaka last occulted Haumea in 1999, a few years before discovery, and will not do so again for some 130 years. However, in a situation unique among regular satellites, Namaka's orbit is being greatly torqued by Hiʻiaka, preserving the viewing angle of Namaka–Haumea transits for several more years.

Collisional family

Haumea is the largest member of its collisional family, a group of astronomical objects with similar physical and orbital characteristics thought to have formed when a larger progenitor was shattered by an impact. This family is the first to be identified among TNOs and includes—beside Haumea and its moons—(55636) 2002 TX_{300} (≈364 km), (24835) 1995 SM_{55} (≈174 km), (19308) 1996 TO_{66} (≈200 km), (120178) 2003 OP_{32} (≈230 km), and (145453) 2005 RR_{43} (≈252 km). Brown et al. proposed that the family were a direct product of the impact that removed Haumea's ice mantle, but a second proposal suggests a more complicated origin: that the material ejected in the initial collision instead coalesced into a large moon of Haumea, which was later shattered in a second collision, dispersing its shards outwards. This second scenario appears to produce a dispersion of velocities for the fragments that is more closely matched to the measured velocity dispersion of the family members.

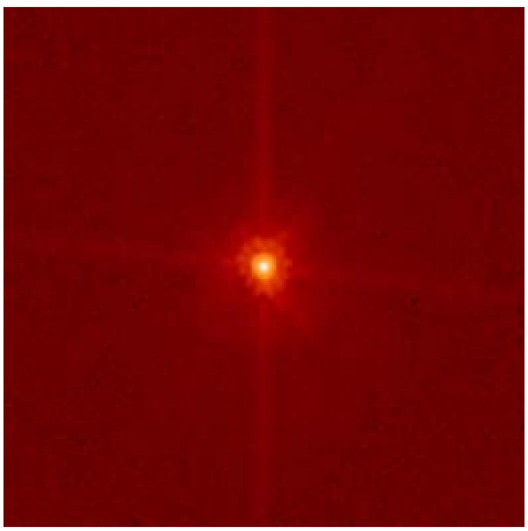
The presence of the collisional family could imply that Haumea and its "offspring" might have originated in the scattered disc. In today's sparsely populated Kuiper belt, the chance of such a collision occurring over the age of the Solar System is less than 0.1 percent. The family could not have formed in the denser primordial Kuiper belt because such a close-knit group would have been disrupted by Neptune's migration into the belt—the believed cause of the belt's current low density. Therefore it appears likely that the dynamic scattered disc region, in which the possibility of such a collision is far higher, is the place of origin for the object that generated Haumea and its kin.

Because it would have taken at least a billion years for the group to have diffused as far as it has, the collision which created the Haumea family is believed to have occurred very early in the Solar System's history.

Chapter 11

Makemake

Makemake



Makemake as seen by the Hubble Space Telescope

Discovery	
Discovered by	Michael E. Brown, Chad Trujillo, David Rabinowitz
Discovery date	March 31, 2005
Designations	
MPC designation	(136472) Makemake
Named after	Makemake
Alternate name(s)	2005 FY_9
Minor planet category	dwarf planet, plutoid, TNO (cubewano)
Adjective	Makemakean
Orbital characteristics	

Epoch January 28, 1955 (JD 2 435 135.5)

Aphelion	53.074 AU 7.939 billion kilometres
Perihelion	38.509 AU 5.760 billion kilometres
Semi-major axis	45.791 AU 6.850 billion kilometres
Eccentricity	0.159
Orbital period	113,183 d (309.88 yr)
Average orbital speed	4.419 km/s
Mean anomaly	85.13°
Inclination	28.96°
Longitude of ascending node	79.382°
Argument of perihelion	298.41°
Physical characteristics	
Mean radius	750+200 −100 km 710 ± 30 km
Surface area	~6,300,000 km^2
Volume	~1.5×10^9 km^3
Mass	~3×10^{21} kg (assumed) 0.0005 Earths
Mean density	~2 g/cm^3 (assumed)
Equatorial surface gravity	~0.4 m/s^2
Escape velocity	~0.75 km/s
Sidereal rotation period	7.771±0.003 hours
Axial tilt	*unknown*
Albedo	78.2+10.3 −8.6 (geometric)
Temperature	30–35 K (assuming the same albedo)
Spectral type	B-V=0.83, V-R=0.5
Apparent magnitude	16.7 (opposition)
Absolute magnitude *(H)*	-0.44

Makemake, formally designated **(136472) Makemake**, is the third-largest known dwarf planet in the Solar System and one of the two largest Kuiper belt objects (KBO) in the classical KBO population. Its diameter is roughly three-quarters that of Pluto. Makemake has no known satellites, which makes it unique among the largest KBOs. Its extremely low average temperature, about 30 K (−243.2 °C), means its surface is covered with methane, ethane, and possibly nitrogen ices.

Initially known as **2005 FY_9** and later given the minor planet number 136472, it was discovered on March 31, 2005, by a team led by Michael Brown, and announced on July 29, 2005. Its name derives from the Rapanui god Makemake. On June 11, 2008, the International Astronomical Union (IAU) included Makemake in its list of potential candidates to be given "plutoid" status, a term for dwarf planets beyond the orbit of Neptune that would place the object alongside Pluto, Haumea and Eris. Makemake was formally classified as a plutoid in July 2008.

Discovery

Makemake was discovered on March 31, 2005, by a team at the Palomar Observatory, led by Michael Brown, and was announced to the public on July 29, 2005. The discovery of Eris was made public the same day, following the announcement of Haumea two days earlier.

Despite its relative brightness (it is about a fifth as bright as Pluto), Makemake was not discovered until well after many much fainter Kuiper belt objects. Most searches for minor planets are conducted relatively close to the ecliptic (the region of the sky that the Sun, Moon and planets appear to lie in, as seen from Earth), due to the greater likelihood of finding objects there. It probably escaped detection during the earlier surveys due to its relatively high orbital inclination, and the fact that it was at its farthest distance from the ecliptic at the time of its discovery, in the northern constellation of Coma Berenices.

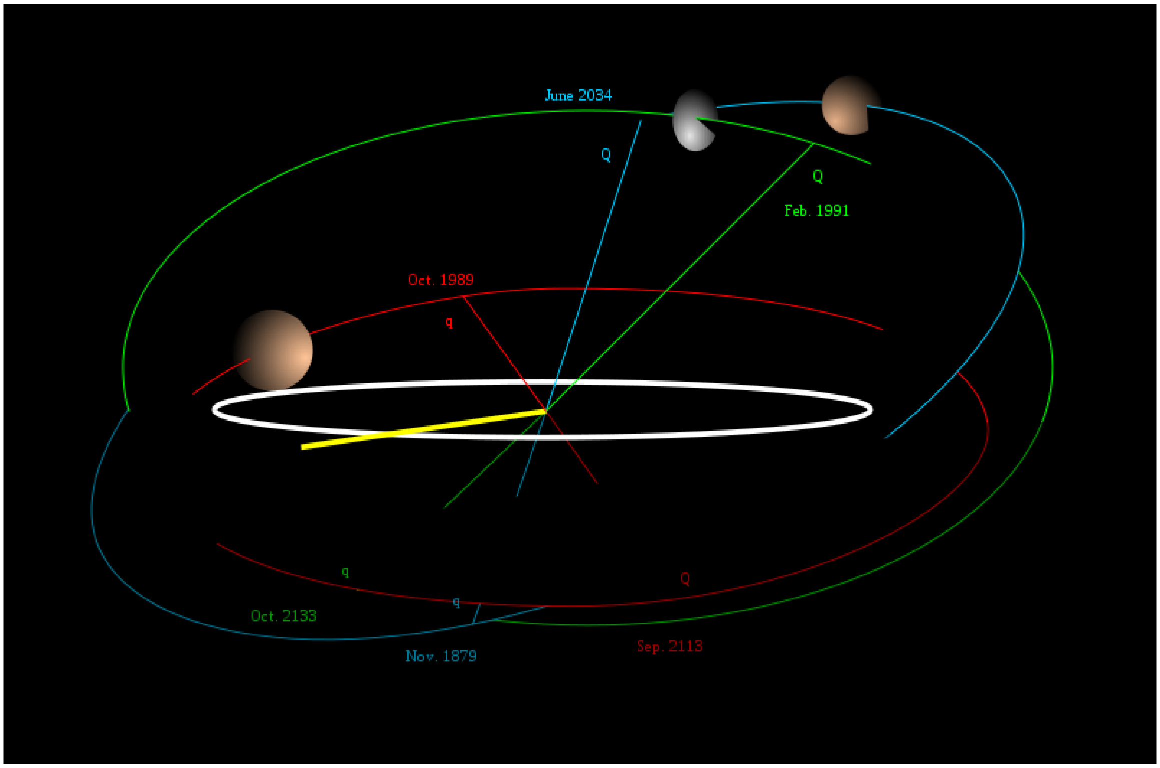
Besides Pluto, Makemake is the only other dwarf planet that was bright enough for Clyde Tombaugh to have possibly detected during his search for trans-Neptunian planets around 1930. At the time of Tombaugh's survey, Makemake was only a few degrees from the ecliptic, near the border of Taurus and Auriga, at an apparent magnitude of 16.0. This position, however, was also very near the Milky Way, and Makemake would have been almost impossible to find against the dense background of stars. Tombaugh continued searching for some years after the discovery of Pluto, but he failed to find Makemake or any other trans-Neptunian objects.

Name

The provisional designation 2005 FY_9 was given to Makemake when the discovery was made public. Before that, the discovery team used the codename "Easterbunny" for the object, because of its discovery shortly after Easter.

In July 2008, in accordance with IAU rules for classical Kuiper belt objects, 2005 FY_9 was given the name of a creator deity. The name of Makemake, the creator of humanity and god of fertility in the mythos of the Rapanui, the native people of Easter Island, was chosen in part to preserve the object's connection with Easter.

Orbit and classification



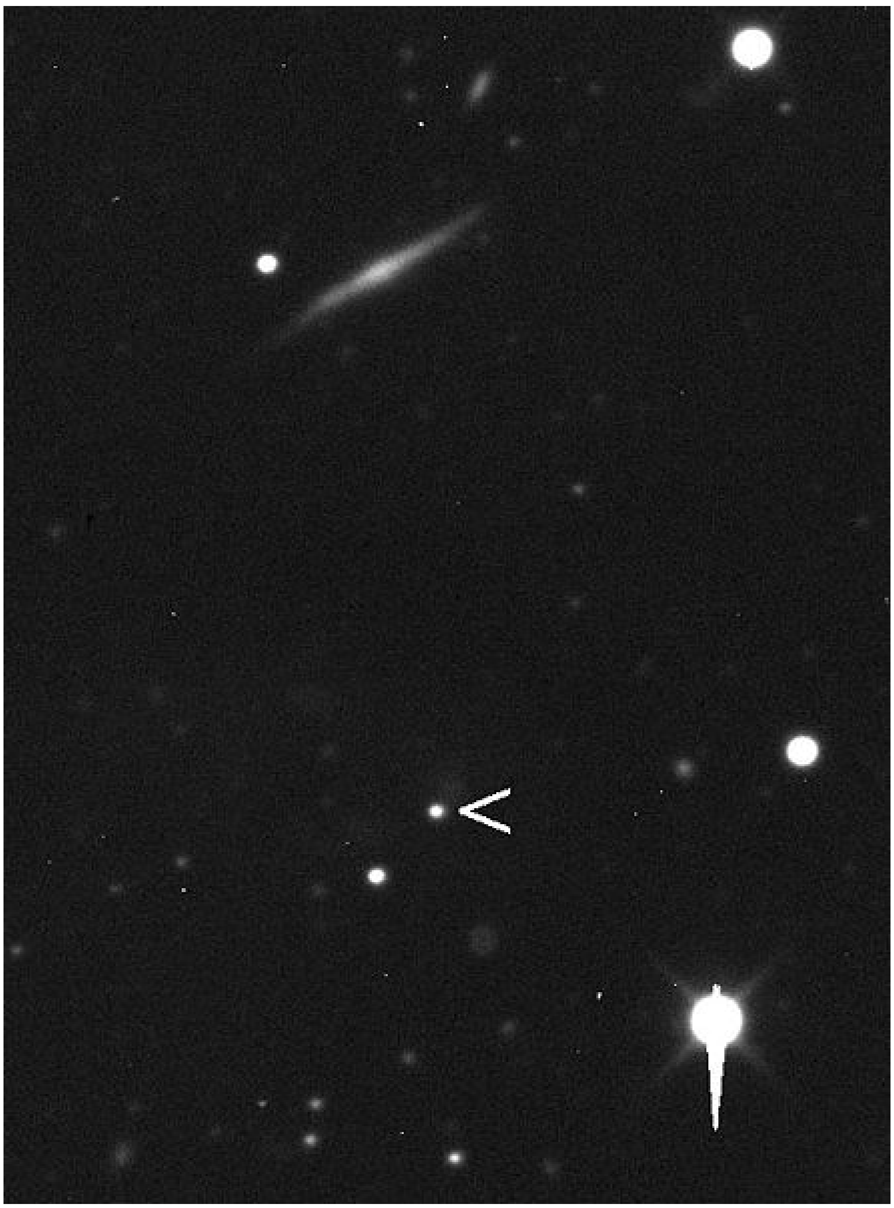
Orbits of Makemake (blue), Haumea (green), contrasted with the orbit of Pluto (red) and the ecliptic (grey). The perihelia (q) and the aphelia (Q) are marked with the dates of passage. The positions on April 2006 are marked with the spheres illustrating relative sizes and differences in albedo and colour.

As of 2009, Makemake is at a distance of 52 astronomical units (7.8×10^9 km) from the Sun, almost as far from the Sun as it ever reaches on its orbit. Makemake follows an orbit very similar to that of Haumea: highly inclined at 29° and a moderate eccentricity of about 0.16. Nevertheless, Makemake's orbit is slightly farther from the Sun in terms of both the semi-major axis and perihelion. Its orbital period is nearly 310 years, more than Pluto's 248 years and Haumea's 283 years. Both Makemake and Haumea are currently far from the ecliptic—the angular distance is almost 29°. Makemake is approaching its 2033 aphelion, while Haumea passed its aphelion in early 1992.

Makemake is classified a classical Kuiper belt object, which means its orbit lies far enough from Neptune to remain stable over the age of the Solar System. Unlike plutinos, which can cross Neptune's orbit due to their 2:3 resonance with the planet, the classical objects have perihelia further from the Sun, free from Neptune's perturbation. Such objects have relatively low eccentricities (*e* below 0.2) and orbit the Sun in much the same way the planets do. Makemake, however, is a member of the "dynamically hot" class of classical KBOs, meaning that it has a high inclination compared to others in its population. Makemake is, probably coincidentally, near the 11:6 resonance with Neptune.

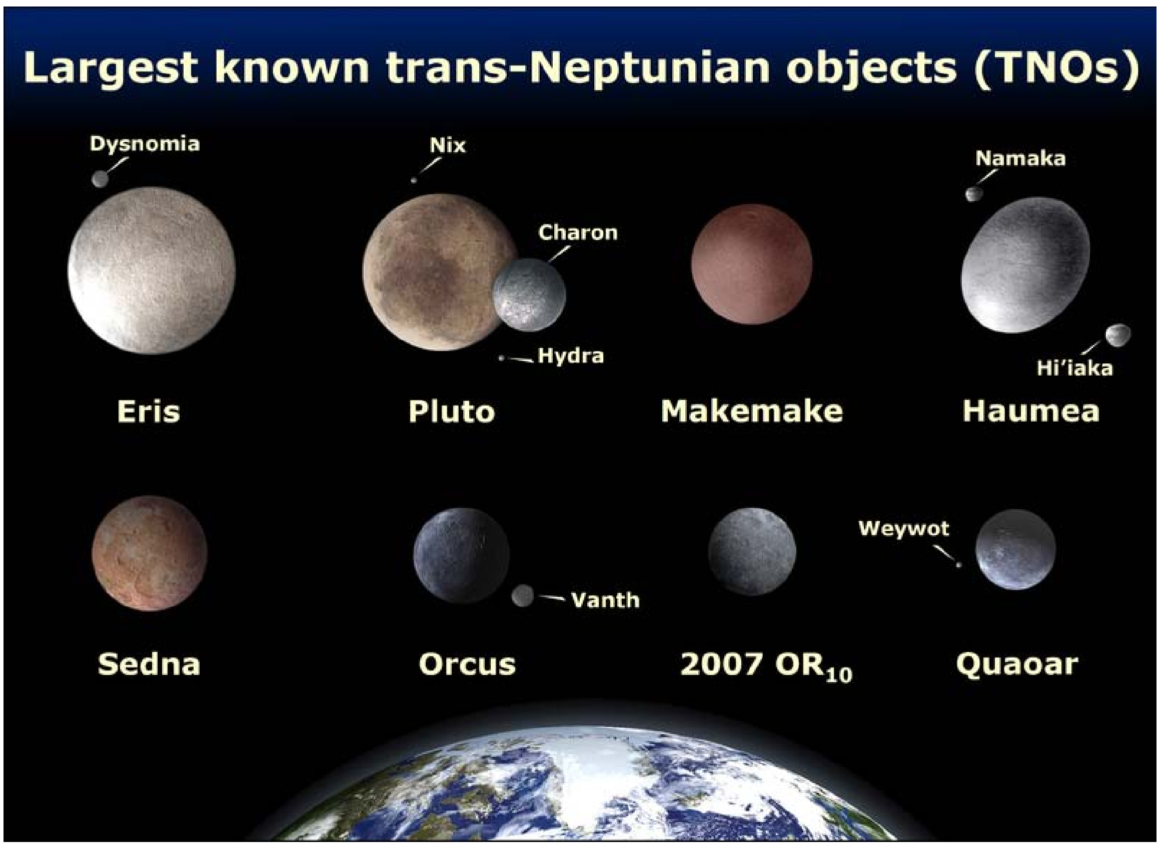
Physical characteristics

Brightness, size, and rotation



Makemake (apmag 16.9)

Makemake is currently visually the second-brightest Kuiper belt object after Pluto, having a March opposition apparent magnitude of 16.7 in the constellation Coma Berenices. This is bright enough to be visible using a high-end amateur telescope. Makemake's high albedo of roughly 80 percent suggests an average surface temperature of about 30 K. The size of Makemake is not precisely known, but the detection in infrared by the Spitzer space telescope and Herschel Space Telescope, combined with the similarities of spectrum with Pluto yielded an estimate of the diameter from 1,360 to 1480 km. This is slightly larger than the size of Haumea, making Makemake possibly the third largest known Trans-Neptunian object after Eris and Pluto. Makemake is now designated the fourth dwarf planet in the Solar System because it has a bright V-band absolute magnitude of −0.44. This practically guarantees that it is large enough to achieve hydrostatic equilibrium and become an oblate spheroid.



Comparison of Eris, Pluto, **Makemake**, Haumea, Sedna, Orcus, 2007 OR_{10}, Quaoar, and Earth (all to scale)

Spectra and surface

In a letter written to the journal *Astronomy and Astrophysics* in 2006, Licandro *et al.* reported the measurements of the visible and near infrared spectrum of Makemake. They used the William Herschel Telescope and Telescopio Nazionale Galileo and showed that the surface of Makemake resembles that of Pluto. Like Pluto, Makemake appears red in the visible spectrum, but significantly less red than the surface of Eris. The near-infrared spectrum is marked by the presence of the broad methane (CH_4) absorption bands. The methane is observed also on Pluto and Eris, but its spectral signature is much weaker.

Spectral analysis of Makemake's surface revealed that methane must be present in the form of large grains at least one centimetre in size. In addition large amounts of ethane and tholins may be present as well, most likely created by photolysis of methane by solar radiation. The tholins are probably responsible for the red color of the visible spectrum. Although evidence exists for the presence of nitrogen ice on its surface, at least mixed with other ices, there is nowhere near the same level of nitrogen as on Pluto and Triton, where it composes more than 98 percent of the crust. The relative lack of nitrogen ice suggests that its supply of nitrogen has somehow been depleted over the age of the Solar System.

The far-infrared (24–70 μm) and submillimeter (70–500 μm) photometry performed by Spitzer and Herschel telescopes revealed that the surface of Makemake is not homogeneous. While the majority of it is covered by nitrogen and methane ices, where the albedo ranges from 78 to 90%, there are small patches of dark terrain whose albedo is only 2 to 12%, and which make up 3–7% of the surface.

Atmosphere

The presence of methane and possibly nitrogen suggests that Makemake could have a transient atmosphere similar to that of Pluto near its perihelion. Nitrogen, if present, will be the dominant component of it. The existence of an atmosphere also provides a natural explanation for the nitrogen depletion: since the gravity of Makemake is weaker than that of Pluto, Eris and Triton, a large amount of nitrogen was probably lost via atmospheric escape; methane is lighter than nitrogen, but has significantly lower vapor pressure at temperatures prevalent at the surface of Makemake (30–35 K), which hinders its escape; the result of this process is a higher relative abundance of methane.

Lack of satellites

No satellites have been detected around Makemake so far. A satellite having a brightness 1% of that of the primary would have been detected if it had been at the distance 0.4 arcseconds or further from Makemake. This contrasts with the other largest trans-Neptunian objects, which all possess at least one satellite: Eris has one, Haumea has two and Pluto has three. From 10% to 20% of all trans-Neptunian objects are expected to have one or more satellites. Since satellites offer a simple method to measure an object's mass, lack of a satellite makes obtaining an accurate figure for Makemake's mass more difficult.

Chapter 12

Eris

Eris

Eris (centre) and Dysnomia (left of centre).
Hubble Space Telescope

Discovery	
Discovered by	M. E. Brown, C. A. Trujillo, D. L. Rabinowitz
Discovery date	January 5, 2005

Designations	
MPC designation	**136199 Eris**
Named after	Eris
Alternate name(s)	2003 UB_{313}
Minor planet category	dwarf planet, TNO, plutoid, and SDO

Adjective	Eridian
Orbital characteristics	
Epoch March 6, 2006 (JD 2453800.5)	
Aphelion	97.56 AU 14.60×10^9 km
Perihelion	37.77 AU 5.65×10^9 km
Semi-major axis	67.67 AU 10.12×10^9 km
Eccentricity	0.441 77
Orbital period	203,600 days 557 years
Average orbital speed	3.436 km/s
Mean anomaly	197.634 27°
Inclination	44.187°
Longitude of ascending node	35.869 6°
Argument of perihelion	151.430 5°
Satellites	Dysnomia
Physical characteristics	
Mean radius	1300+200 −100 km (2007) Preliminary: ≤1170 (2010)
Surface area	78,500,000 sq km (48,777,638.6 sq mi)
Mass	$(1.67 \pm 0.02) \times 10^{22}$ kg 0.002 Earths
Mean density	2.25–2.5 g/cm^3
Equatorial surface gravity	~0.8 m/s^2
Sidereal rotation period	25.9 ± 8 hr
Albedo	0.86 ± 0.07
Surface temp. (approx)	**min** 30 K; **mean** 42.5 K; **max** 55 K
Spectral type	B-V=0.78, V-R=0.45
Apparent magnitude	18.7
Absolute magnitude	−1.19 ± 0.3

(H)	
Angular diameter	40 milli-arcsec

Eris, formal designation **136199 Eris**, is the most massive known dwarf planet in the Solar System and the ninth most massive body known to orbit the Sun directly. It is estimated to be approximately 2300–2400 km in diameter, and 27% more massive than Pluto or about 0.27% of the Earth's mass.

Eris was first identified in January 2005 by a Palomar Observatory-based team led by Mike Brown, and its identity verified later that year. It is a trans-Neptunian object (TNO) native to a region of space beyond the Kuiper belt known as the scattered disc and has one known moon, Dysnomia. As of 2011, its distance from the Sun is 96.6 AU, roughly three times that of Pluto. With the exception of some comets, Eris and Dysnomia are currently the most distant known natural objects in the Solar System.

Because Eris appeared possibly to be larger than Pluto, its discoverers and NASA initially described it as the Solar System's tenth planet. This, along with the prospect of other similarly sized objects being discovered in the future, motivated the International Astronomical Union (IAU) to define the term *planet* for the first time. Under the IAU definition approved on August 24, 2006, Eris is a "dwarf planet" along with Pluto, Ceres, Haumea and Makemake.

In 2010, preliminary results from observations of a stellar occultation by Eris on November 6 suggested that its diameter may be only 2320 km, which would make it almost the same size as Pluto. Given the error bars in the different size estimates, it is currently unknown whether Eris or Pluto has the larger diameter. Both Pluto and Eris are estimated to have solid-body diameters of about 2330 km.

Discovery

Eris was discovered by the team of Mike Brown, Chad Trujillo, and David Rabinowitz on January 5, 2005, from images taken on October 21, 2003. The discovery was announced on July 29, 2005, the same day as Makemake and two days after Haumea. The search team had been systematically scanning for large outer solar system bodies for several years, and had been involved in the discovery of several other large TNOs, including 50000 Quaoar, 90482 Orcus, and 90377 Sedna.

Routine observations were taken by the team on October 21, 2003, using the 1200 mm Samuel Oschin reflecting telescope at Mount Palomar Observatory, California, but the image of Eris was not discovered at that point due to its very slow motion across the sky: The team's automatic image-searching software excluded all objects moving at less than 1.5 arcseconds per hour to reduce the number of false positives returned. When Sedna was discovered, it was moving at 1.75 arcsec/h, and in light of that the team reanalyzed their old data with a lower limit on the angular motion, sorting through the previously excluded images by eye. In January 2005, the re-analysis revealed Eris' slow motion against the background stars.

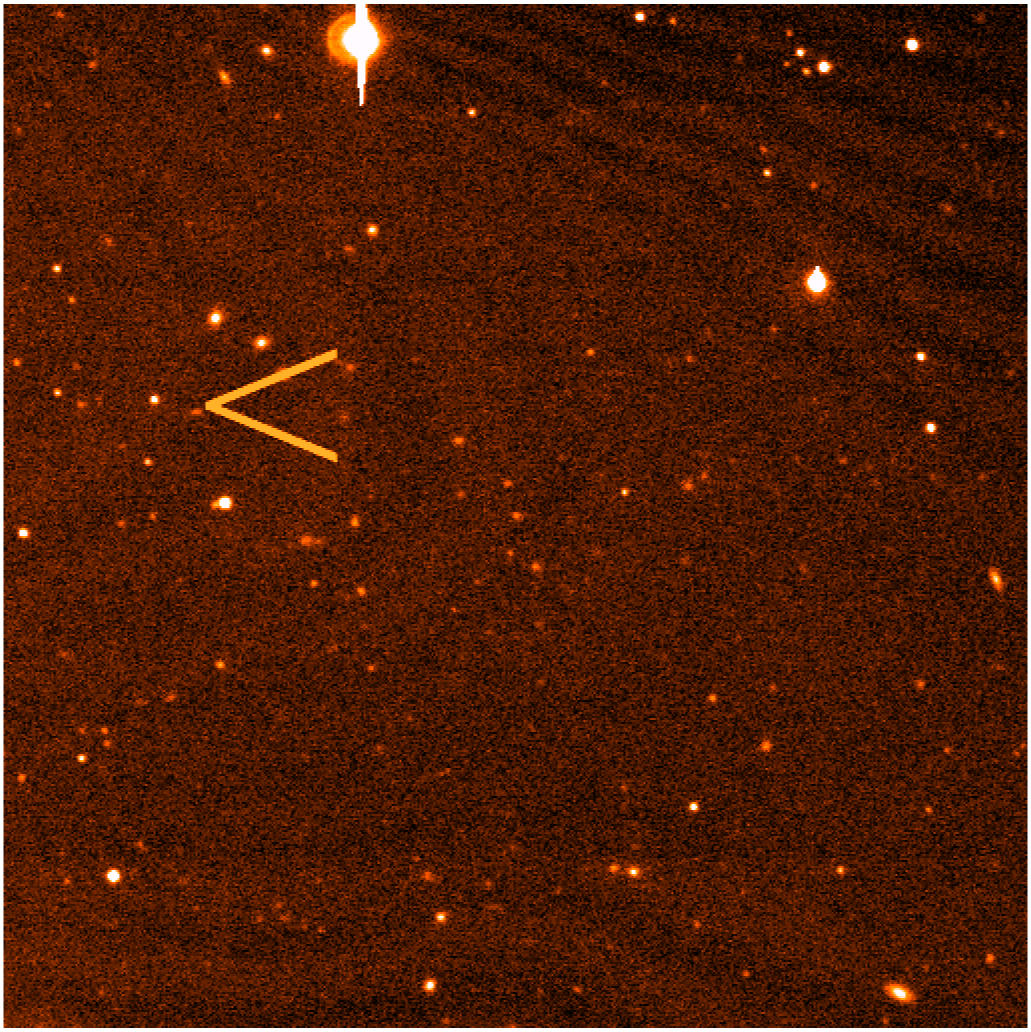
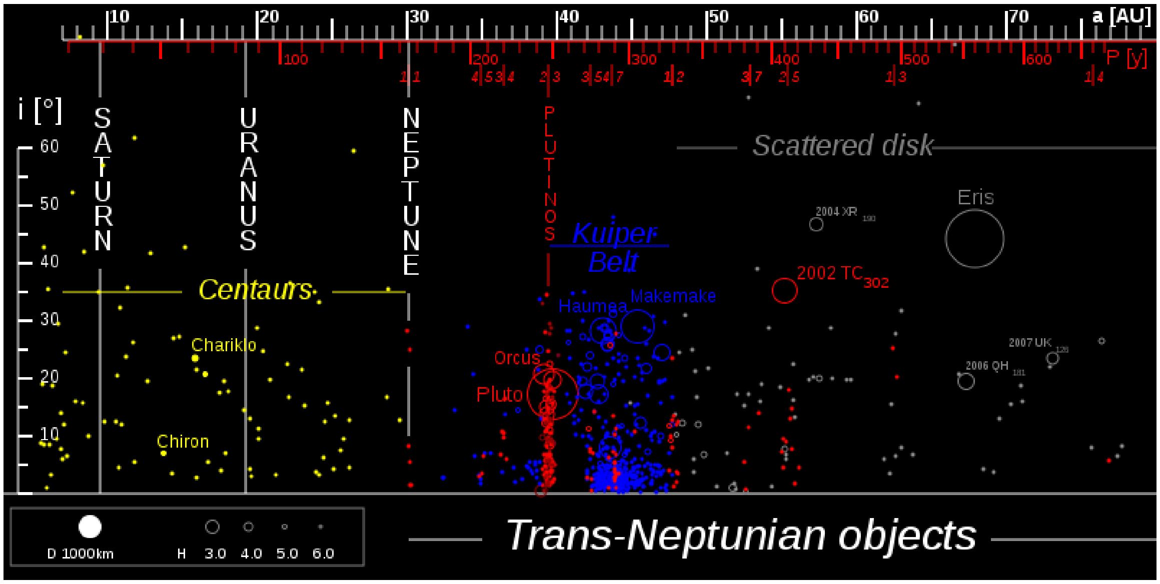


Image showing the movement of Eris on the images used to discover it. Eris is indicated by the arrow. The three frames were taken over a period of three hours.



Distribution of trans-Neptunian Objects

Follow-up observations were then carried out to make a preliminary determination of Eris' orbit, which allowed the object's distance to be estimated. The team had planned to delay announcing their discovery until further observations allowed more accurate calculations of Eris' orbit, but brought their announcement forward when the discovery of another large TNO they had been tracking, Haumea, was announced by a different team in Spain.

More observations released in October 2005 revealed that Eris had a moon, later named Dysnomia. Observations of Dysnomia's orbit permitted scientists to determine the mass of Eris, which in June 2007 they calculated to be $(1.66 \pm 0.02) \times 10^{22}$ kg, 27% greater than Pluto's.

Classification

Eris is classified as a plutoid; a trans-Neptunian object that is also a dwarf planet. Its orbital characteristics more specifically categorize it a scattered disk object (SDO), or a TNO that is believed to have been "scattered" from the Kuiper belt into more distant and unusual orbits following gravitational interactions with Neptune as the Solar System was forming. Although its high orbital inclination is unusual among the known SDOs, theoretical models suggest that objects that were originally near the inner edge of the Kuiper belt were scattered into orbits with higher inclinations than objects from the outer belt. Inner-belt objects are expected to be generally more massive than outer-belt objects, and so astronomers expect to discover more large objects like Eris in high-inclination orbits, which have traditionally been neglected.

Because Eris may be larger than Pluto, it was initially described as the "tenth planet" by NASA and in media reports of its discovery. In response to the uncertainty over its status, and because of ongoing debate over whether Pluto should be classified as a planet, the IAU delegated a group of astronomers to develop a sufficiently precise definition of the term *planet* to decide the issue. This was announced as the IAU's *Definition of a Planet in the Solar System,* adopted on August 24, 2006. At this time, both Eris and Pluto were classified as *dwarf planets,* a category distinct from the new definition of *planet.* Brown has since stated his approval of the "dwarf planet" label. The IAU subsequently added Eris to its Minor Planet Catalogue, designating it *(136199) Eris.*

Name

Athenian painting of Eris, circa 550 BC

Eris is named after the Greek goddess Eris (Greek *Ἔρις),* a personification of strife and discord. The name was assigned on September 13, 2006 following an unusually long period in which the object was known by the provisional designation **2003 UB_{313}**, which was granted automatically by the IAU under their naming protocols for minor planets. The regular adjectival form of *Eris* is *Eridian.*

Xena

Due to uncertainty over whether the object would be classified as a planet or a minor planet, as different nomenclature procedures apply to these different classes of objects, the decision on what to name the object had to wait until after the August 24, 2006 IAU ruling. As a result, for a time the object became known to the wider public as *Xena*.

"Xena" was an informal name used internally by the discovery team. It was inspired by the eponymous heroine of the television series *Xena: Warrior Princess*. The discovery team had reportedly saved the nickname "Xena" for the first body they discovered that was larger than Pluto. According to Brown,

We chose it since it started with an X (planet "X"), it sounds mythological (OK, so it's TV mythology, but Pluto is named after a cartoon, right?), and (this part is actually true) we've been working to get more female deities out there (*i.e.* Sedna). Also, at the time, the TV show was still on TV, which shows you how long we've been searching!

"We assumed [that] a real name would come out fairly quickly, [but] the process got stalled," Mike Brown said in interview,

One reporter called me up from the *New York Times* who happened to have been a friend of mine from college, [and] I was a little less guarded with him than I am with the normal press. He asked me, "What's the name you guys proposed?" and I said, "Well, I'm not going to tell." And he said, "Well, what do you guys call it when you're just talking amongst yourselves?"... As far as I remember this was the only time I told anybody this in the press, and then it got everywhere, which I only sorta felt bad about—I kinda like the name.

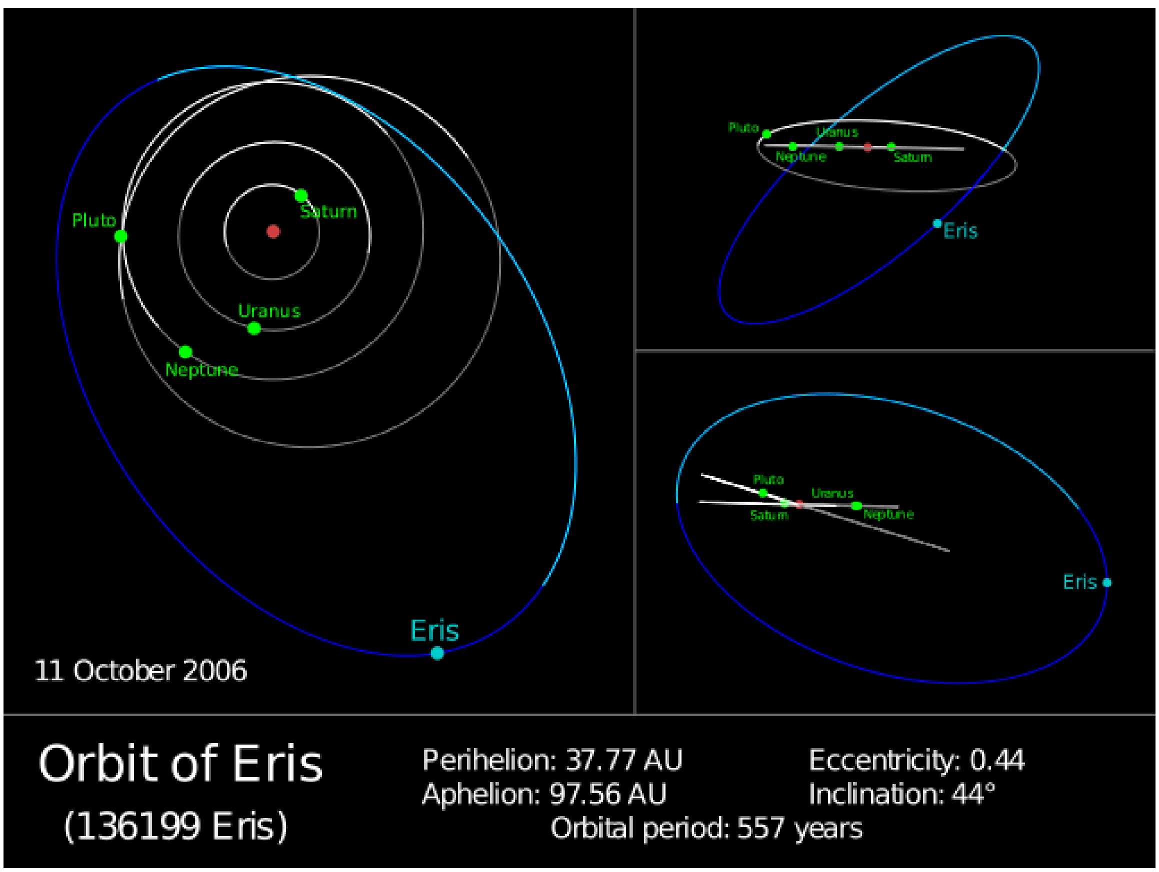
Choosing an official name

According to science writer Govert Schilling, Brown initially wanted to call the object "Lila", after a concept in Hindu mythology that described the cosmos as the outcome of a game played by Brahma. The name was very similar to "Lilah", the name of Brown's newborn daughter. Brown was mindful of not making his name public before it had been officially accepted. He had done so with Sedna a year previously, and had been heavily criticised. However, he listed the address of his personal web page announcing the discovery as */~mbrown/planetlila* and in the chaos following the controversy over the discovery of Haumea, forgot to change it. Rather than needlessly anger more of his fellow astronomers, he simply said that the webpage had been named for his daughter and dropped "Lila" from consideration.

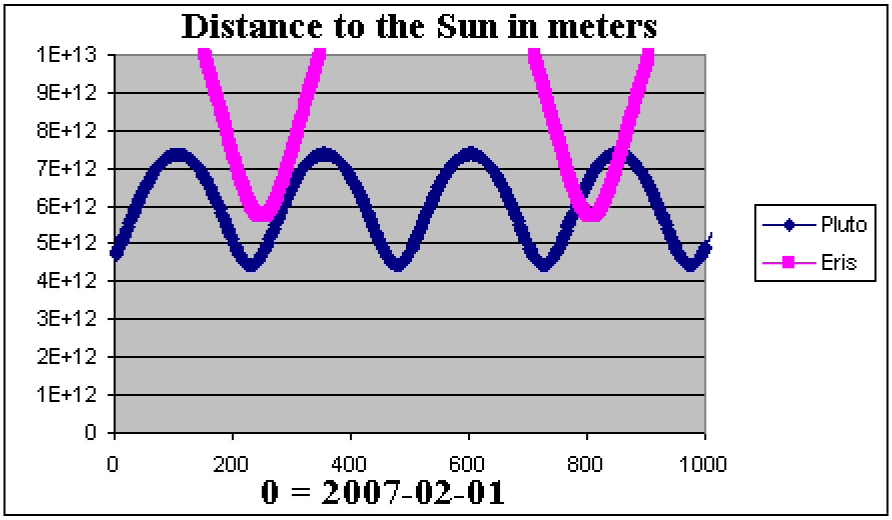
Brown had also speculated that *Persephone*, the wife of the god Pluto, would be a good name for the object. The name had been used several times in science fiction, and was popular with the public, having handily won a poll conducted by *New Scientist* magazine ("Xena", despite only being a nickname, came fourth). However, this was not possible once the object was classified as a dwarf planet, because there is already an asteroid with that name, 399 Persephone. Because IAU regulations require a name from creation mythology for objects with orbital stability beyond Neptune’s orbit, the team had also been considering such possibilities.

With the dispute resolved, the discovery team proposed *Eris* on September 6, 2006. On September 13, 2006 this name was accepted as the official name by the IAU. Brown decided that, as the object had been considered a planet for so long, it deserved a name from Greek and Roman mythology, like the other planets. However, the asteroids had taken the vast majority of Graeco-Roman names. *Eris*, whom Brown described as his favourite goddess, had fortunately escaped inclusion. The name in part reflects the discord in the astronomical community caused by the debate over the object’s (and Pluto’s) nature.

Orbit



The orbit of Eris (blue) compared to those of Saturn, Uranus, Neptune, and Pluto (white/grey). The arcs below the ecliptic are plotted in darker colours, and the red dot is the Sun. The diagram on the left is a polar view while the diagrams on the right are different views from the ecliptic.



The distances of Eris and Pluto from the Sun in the next 1,000 years

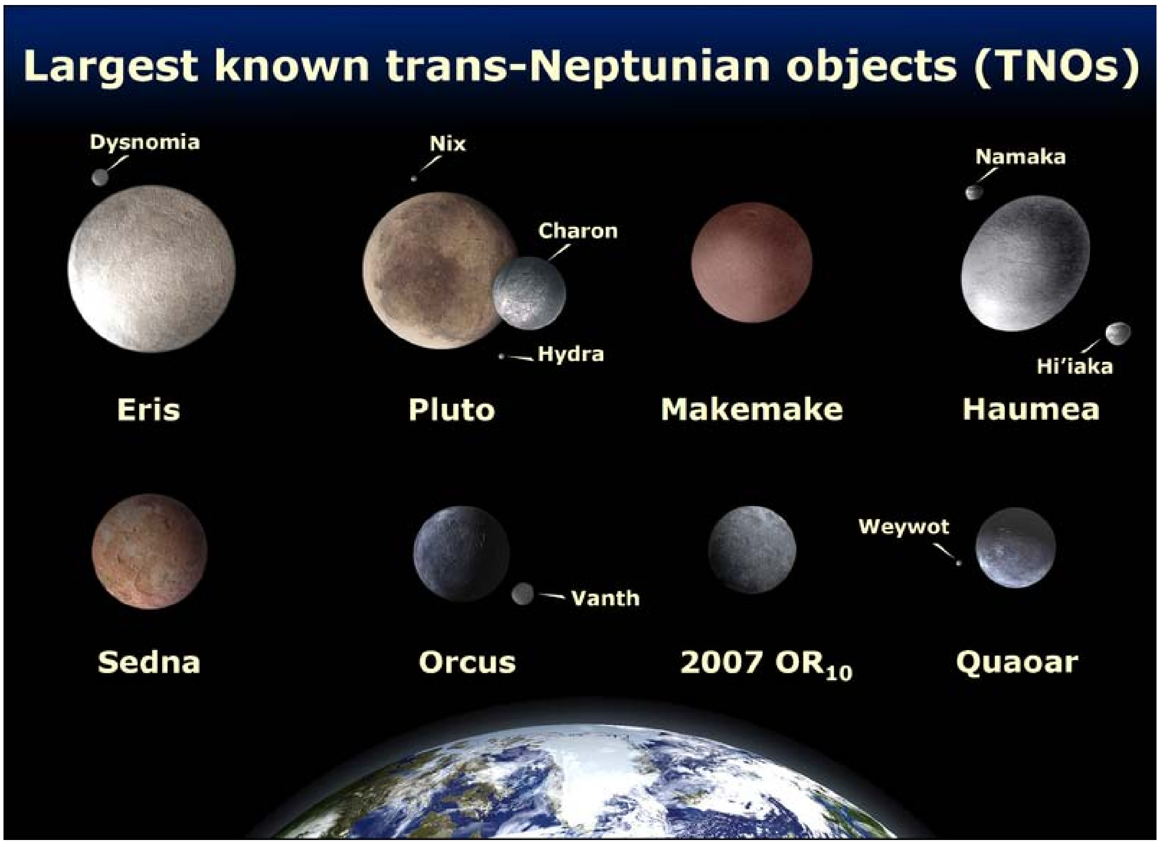
Eris has an orbital period of 557 years, and as of 2009 lies at 96.7 astronomical units from the Sun, almost its maximum possible distance (its aphelion is 97.5 AU). It came to perihelion between 1698 and 1699, to aphelion around 1977, and will return to perihelion around 2256 to 2258. Eris and its moon are currently the most distant known objects in the Solar System apart from long-period comets and space probes. However, approximately forty known TNOs, most notably 2006 SQ_{372}, 2000 OO_{67} and Sedna, while currently closer to the Sun than Eris, have greater average orbital distances than Eris' semimajor axis of 67.7 AU.

The Eridian orbit is highly eccentric, and brings Eris to within 37.9 AU of the Sun, a typical perihelion for scattered objects. This is within the orbit of Pluto, but still safe from direct interaction with Neptune (29.8–30.4 AU). Pluto, on the other hand, like other plutinos, follows a less inclined and less eccentric orbit and, protected by orbital resonance, can cross Neptune's orbit. It is possible that Eris is in a 17:5 resonance with Neptune, though further observations will be required to check that hypothesis. Unlike the eight planets, whose orbits all lie roughly in the same plane as the Earth's, Eris' orbit is highly inclined: It is tilted at an angle of about 44 degrees to the ecliptic. In about 800 years, Eris will be closer to the Sun than Pluto for some time.

Eris currently has an apparent magnitude of 18.7, making it bright enough to be detectable to some amateur telescopes. A 200 mm telescope with a CCD can detect Eris under favourable conditions. The reason it had not been noticed until now is its steep orbital inclination; most searches for large outer Solar System objects concentrate on the ecliptic plane, where most bodies are found.

Eris is now in the constellation Cetus. It was in Sculptor from 1876 until 1929 and Phoenix from roughly 1840 until 1875. In 2036 it will enter Pisces and stay there until 2065, when it will enter Aries. It will then move into the northern sky, entering Perseus in 2128 and Camelopardalis (where it will reach its northernmost declination) in 2173. Because of the high inclination of its orbit, Eris only passes through a few constellations of the traditional Zodiac.

Size, mass, and density



Comparison of **Eris**, Pluto, Makemake, Haumea, Sedna, Orcus, 2007 OR_{10}, Quaoar, and Earth (all to scale)

Size estimates:

Year	Radius (Diameter)	Source
2005	1199 (2397) km	Hubble
2007	1300 (2600) km	Spitzer
2010	1170 (2340) km	Occultation

In 2005, the diameter of Eris was measured to be 2,397 km, give or take 100 km, using images from the Hubble Space Telescope (HST). The size of an object is determined from its absolute magnitude (H) and the albedo (the amount of light it reflects). At a distance of 97 AU, an object with a diameter of 3,000 km would have an angular size of 40 milliarcseconds, which is directly measurable with the Hubble Space Telescope.

Although resolving such small objects is at the very limit of the telescope's capabilities, sophisticated image processing techniques such as deconvolution can be used to measure such angular sizes fairly accurately.

This makes Eris only 0–8% larger than Pluto, which is about 2,306 km across. It also indicates an albedo of 0.86, higher than that of any other large body in the Solar System except Enceladus. It is speculated that the high albedo is due to the surface ices being replenished because of temperature fluctuations as Eris's eccentric orbit takes it closer and farther from the Sun.

In 2007, a series of observations of the largest trans-Neptunian objects with the Spitzer Space Telescope gave an estimate of Eris's diameter of 2,600 (+400; -200) km. The Spitzer and Hubble estimates overlap in the range of 2,400–2,500 km, 4–8% larger than Pluto. However, astronomers now suspect that Eris's spin axis is pointing toward the sun, at the moment—a possibility that would keep the sunlit hemisphere warmer than average and skew any infrared measurements toward higher values. So the outcome from the 2010 Chile occultation is actually more in line with the Hubble result from 2005.

In November 2010, Eris was the subject of one of the most distant stellar occulations yet achieved from Earth. Preliminary data from this event, which has not yet been published in peer-reviewed scientific journals, cast doubt on previous size estimates. The three teams that observed the Eris occulation are still analyzing their data. Furthermore, when using preliminary data from this event for comparison to Pluto, there is a range of figures available for Pluto's radius/diameter that can be selected. This is due in part to Pluto's atmosphere which interferes with making measurements of its solid surface (as opposed to gaseous haze).

The mass of Eris can be calculated with much greater precision. Based on the currently accepted value for Dysnomia's period—15.774 days— Eris is 27 percent more massive than Pluto. Within the margin of error for Eris's diameter, this figure suggests Eris and Pluto are broadly similar in composition, as Eris's diameter need only be 7% larger than Pluto's to achieve the same density. However, if the 2010 occultation results are used, then Eris is substantially denser than Pluto, and thus must be composed largely of rocky materials.

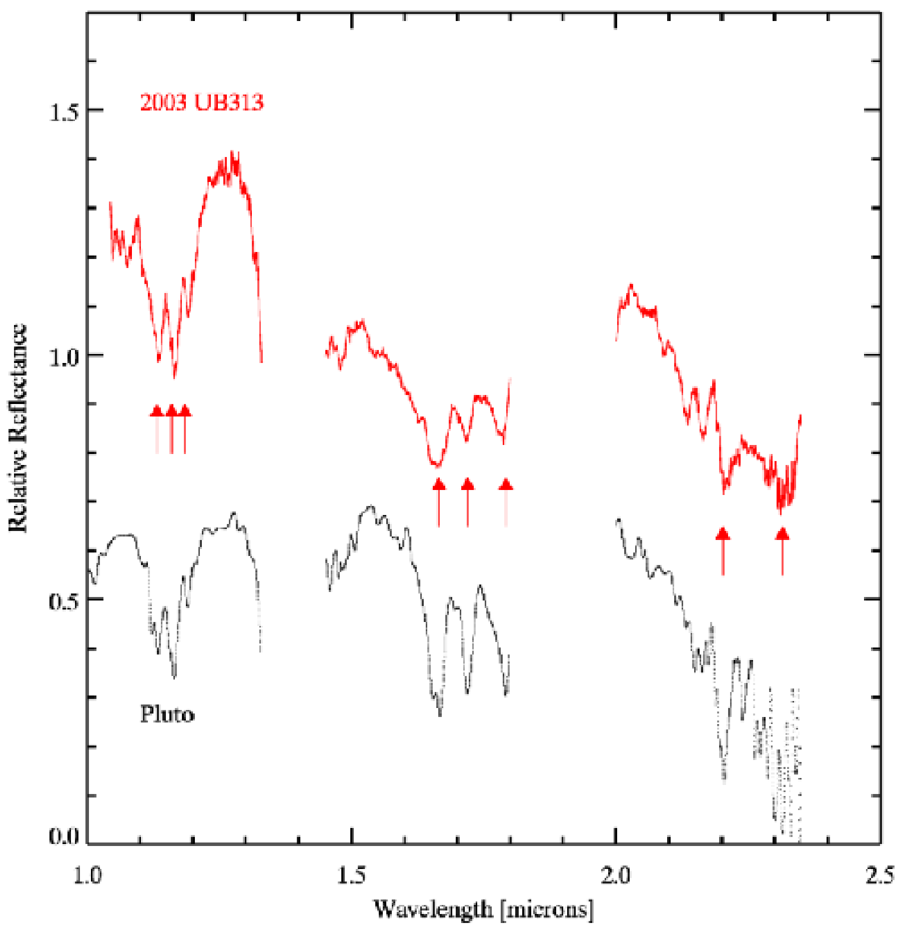
Thermal measurement

Previous observations of the thermal emission of Eris at a wavelength of 1.2 mm, where the object's brightness depends only on temperature and surface area, indicated a diameter of 3,000 ± 400 km, about a third larger than Pluto. If Eris rotates quickly, resulting in a more even heat distribution and a temperature of 23 to 24 kelvins (−250 to −249 degrees Celsius), a likely diameter would be in the higher portion of the range (best fit 3,090 km); if it rotates slowly, the visible surface would be warmer (about 27 K, or −246 degrees Celsius) and a likely diameter would be in the smaller end of the range (best fit 2,860 km). The 2,860 km figure implies a Pluto-like albedo of 60%, consistent with Eris's Pluto-like spectral signature.

The apparent inconsistency of the HST PSF results (2,400 ± 100 km) with the above IRAM results (3,000 ± 370 km) will certainly be studied at greater length. Brown explains it by a slightly lower absolute magnitude than the one assumed by Bertoldi (−1.12 ± 0.01 versus −1.18 ± 0.1, resulting by itself in almost 100 km difference in diameter). Assuming further the highest diameter (2,500 km) and pole-on position of the object, the difference between the results would appear consistent with 1.1-σ error margin.

Another possible explanation for the IRAM results is offered by the Max-Planck-Institut für Radioastronomie. The ratio between the bolometric albedo (representing the total reflected energy and used in the thermal method) and the geometric albedo (representing the reflection in some visual wavelength and used to calculate the diameter from HST pictures) is not known with high precision and depends on many factors. By itself, this uncertainty could bridge the gap between the two measures.

Surface and atmosphere



The infrared spectrum of Eris, compared to that of Pluto, shows the marked similarities between the two bodies. Arrows denote methane absorption lines.

Artist's impression of Eris and Dysnomia. Eris is the main object, Dysnomia the small grey disk just above it. The flaring object top-left is the Sun.

The discovery team followed up their initial identification of Eris with spectroscopic observations made at the 8 m Gemini North Telescope in Hawaii on January 25, 2005. Infrared light from the object revealed the presence of methane ice, indicating that the surface may be similar to that of Pluto, which at the time was the only TNO known to have surface methane, and of Neptune's moon Triton, which also has methane on its surface.

Due to Eris's distant eccentric orbit, Eridian surface temperatures are estimated to vary between about 30 and 56 kelvins (−243 and −217 degrees Celsius).

Unlike the somewhat reddish Pluto and Triton, however, Eris appears almost grey. Pluto's reddish colour is believed to be due to deposits of tholins on its surface, and where these deposits darken the surface, the lower albedo leads to higher temperatures and the evaporation of methane deposits. In contrast, Eris is far enough away from the Sun that methane can condense onto its surface even where the albedo is low. The condensation of methane uniformly over the surface reduces any albedo contrasts and would cover up any deposits of red tholins.

Even though Eris can be up to three times further from the Sun than Pluto, it approaches close enough that some of the ices on the surface might warm enough to sublimate. As methane is highly volatile, its presence shows either that Eris has always resided in the distant reaches of the Solar System where it is cold enough for methane ice to persist, or that the celestial body has an internal source of methane to replenish gas that escapes from its atmosphere. This contrasts with observations of another recently discovered TNO, Haumea, which reveal the presence of water ice but not methane.

Moon

In 2005, the adaptive optics team at the Keck telescopes in Hawaii carried out observations of the four brightest TNOs (Pluto, Makemake, Haumea, and Eris), using the newly commissioned laser guide star adaptive optics system. Images taken on September 10 revealed a moon in orbit around Eris. In keeping with the "Xena" nickname already in use for Eris, Brown's team nicknamed the moon "Gabrielle", after the television warrior princess's sidekick. When Eris received its official name from the IAU, the moon received the name *Dysnomia,* after the Greek goddess of lawlessness who was Eris's daughter. The name also retains an oblique reference to Eris's old informal name *Xena*, portrayed on TV by Lucy Lawless.