All About Dwarf Planets

(Celestial Bodies)

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Table of Contents

Chapter 1 - Dwarf Planet

Chapter 2 - Ceres

Chapter 3 - Pluto

Chapter 4 - Haumea

Chapter 5 - Makemake

Chapter 6 - Eris

Chapter 7 - Plutoid

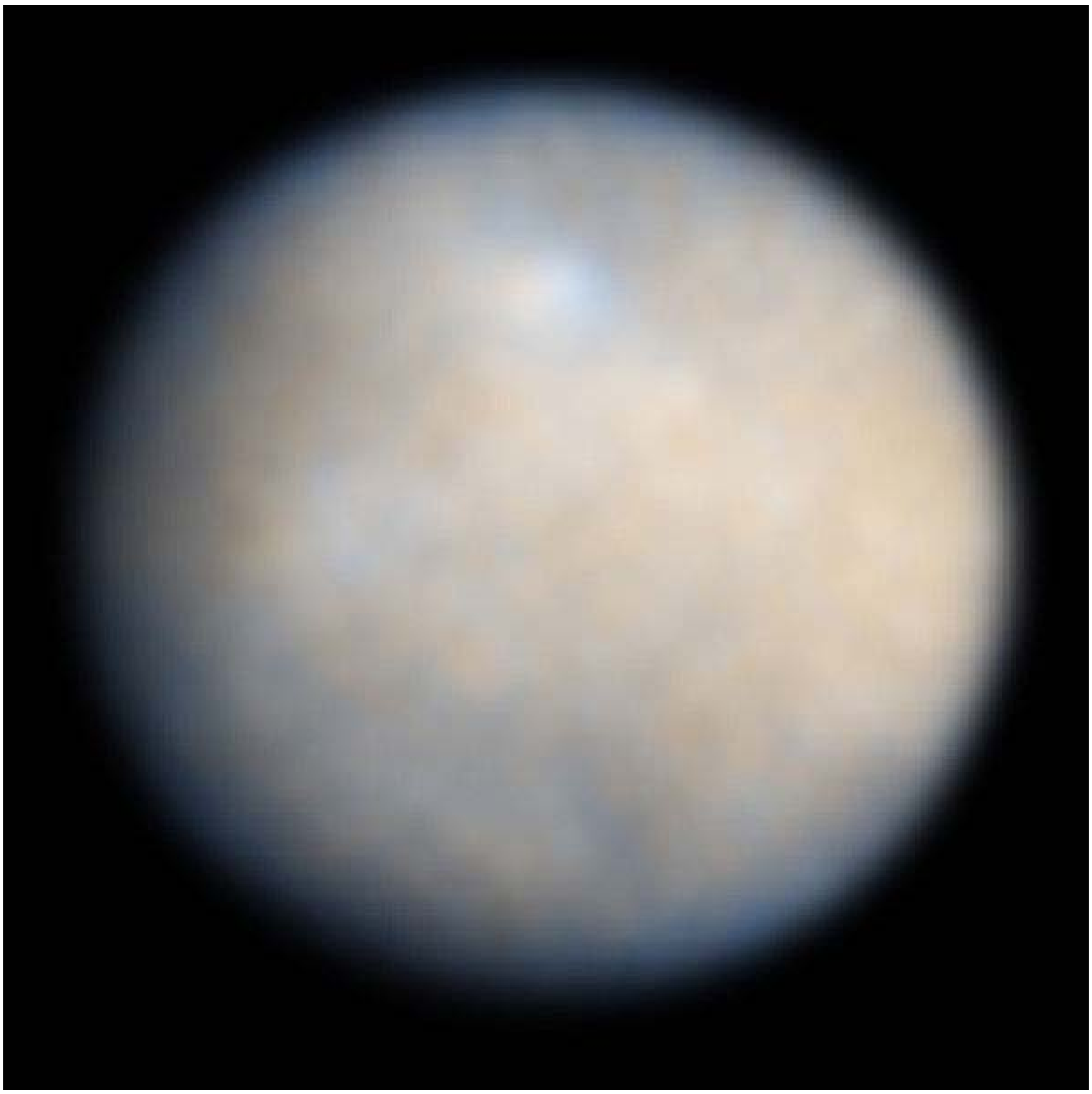
Chapter 8 - 90482 Orcus

Chapter 9 - 50000 Quaoar

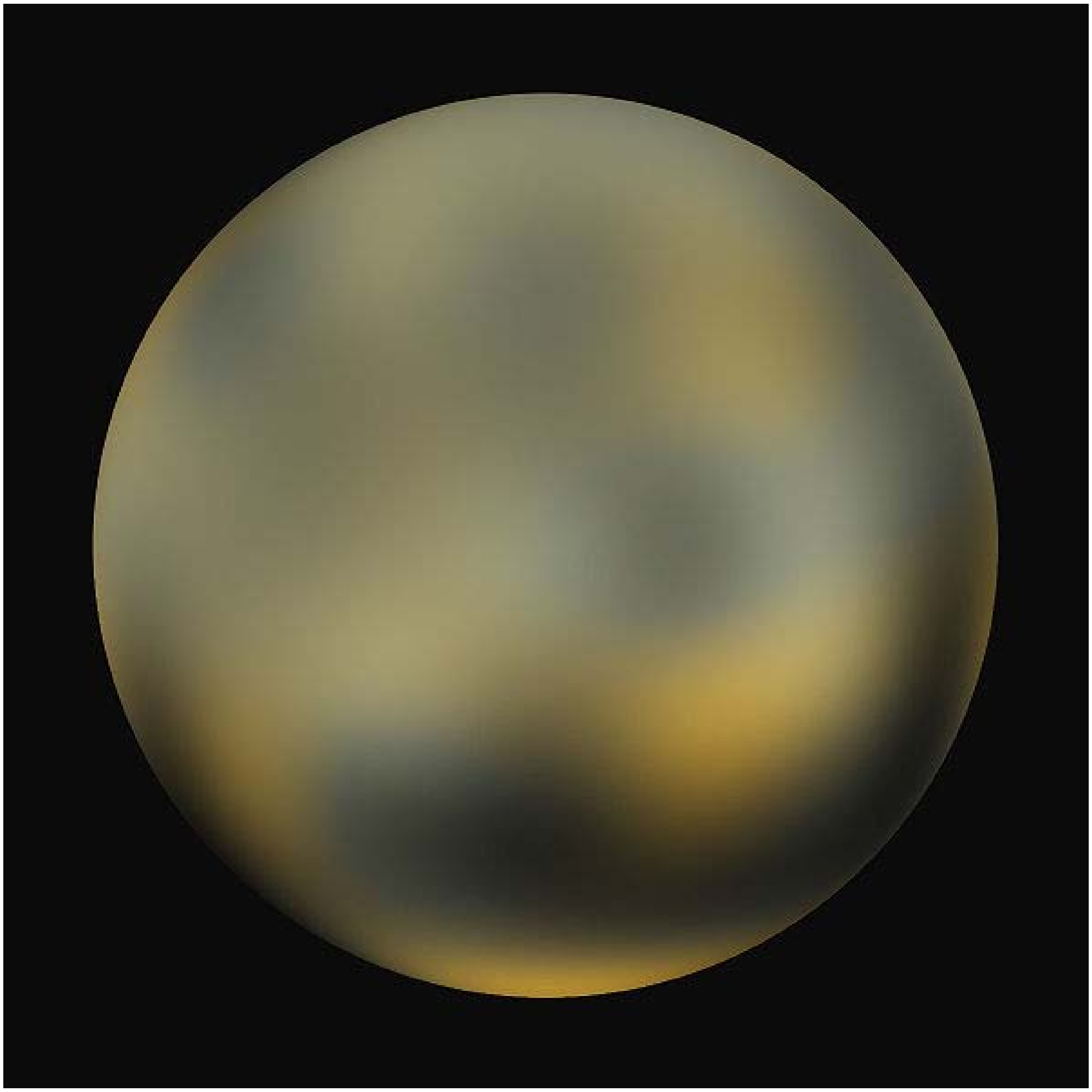
Chapter 10 - 90377 Sedna

Chapter- 1

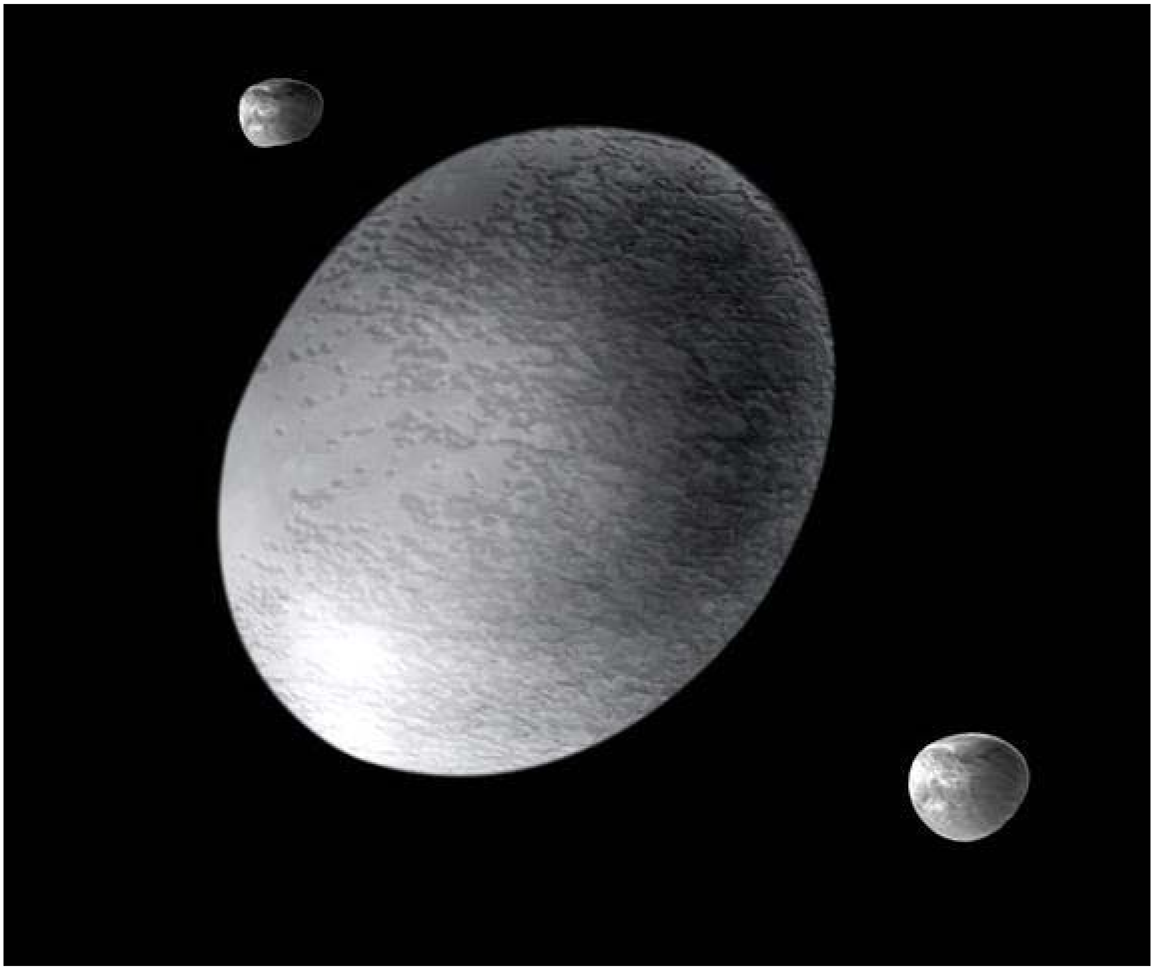
Dwarf Planet



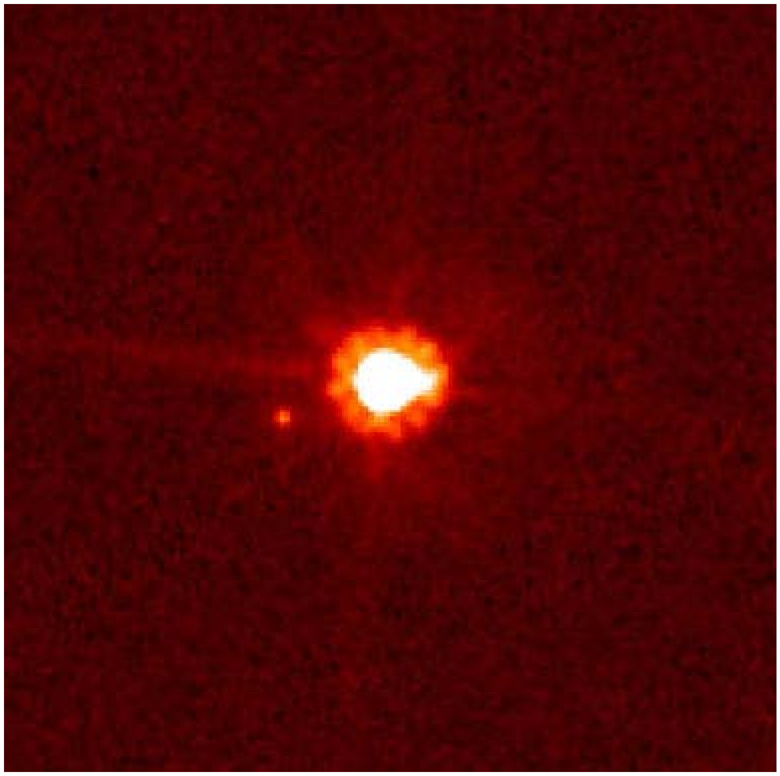
Ceres as seen with the Hubble Space Telescope



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


Haumea with its moons, Hiʻiaka 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

Planetary discriminants

Body	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.

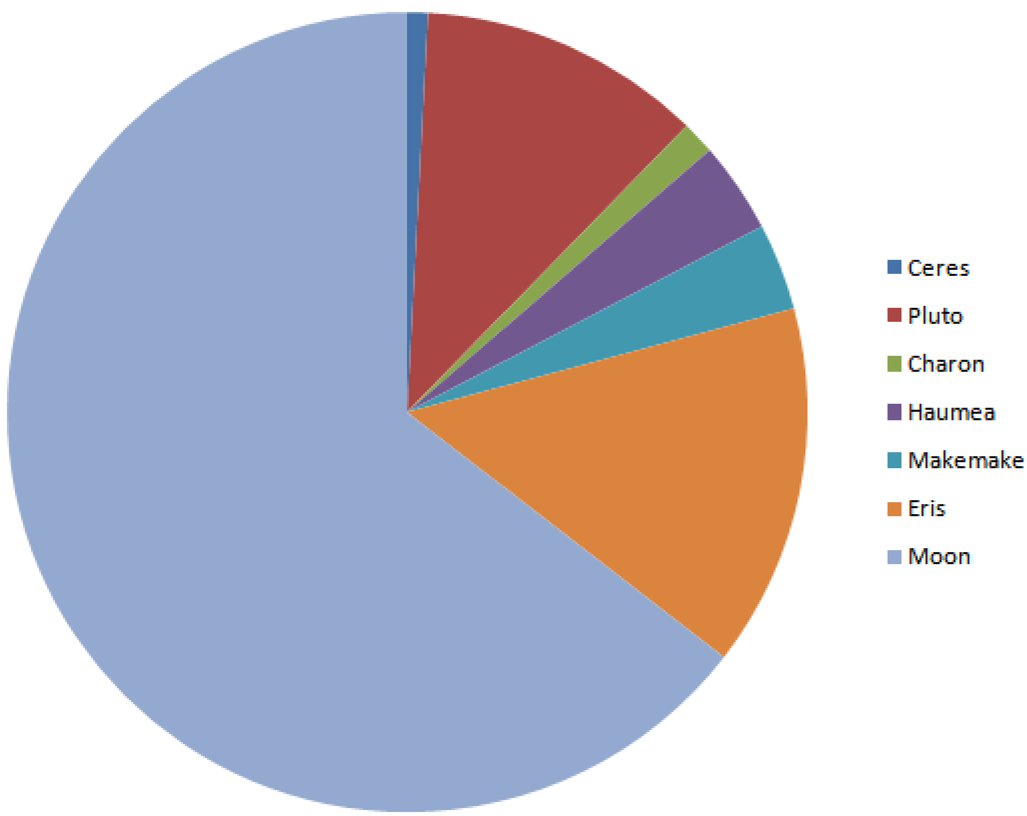
Orbital dominance

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	5.7%	4.2 ± 0.1	2.6–3.3	~0.44	~0.84			2	32 ± 3	?

		−100										
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

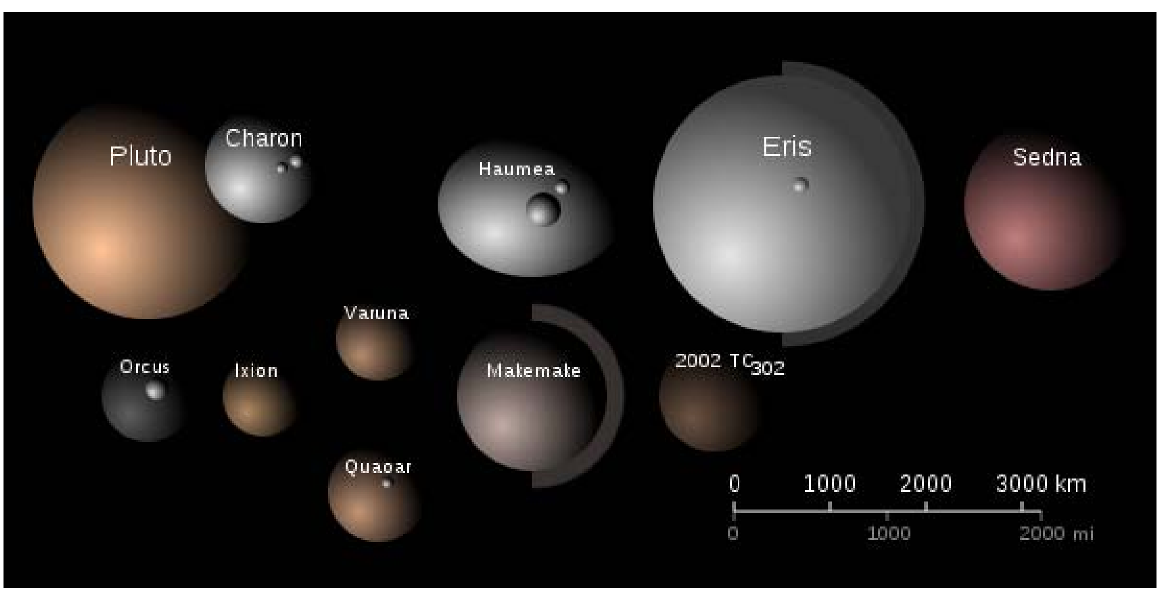


Illustration of the relative sizes, albedos, and colours of the largest Trans-Neptunian objects

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 (×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

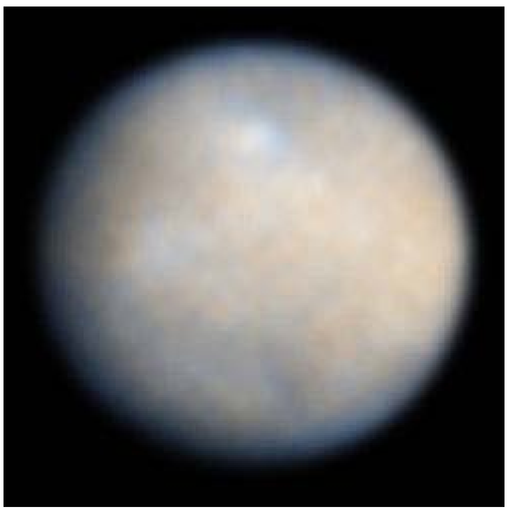
In the immediate aftermath of the IAU definition of dwarf planet, a number of scientists expressed their disagreement with the IAU resolution. Campaigns included car bumper stickers and T-shirts. Mike Brown (the discoverer of Eris) agrees with the reduction of the number of planets to eight.

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- 2

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"

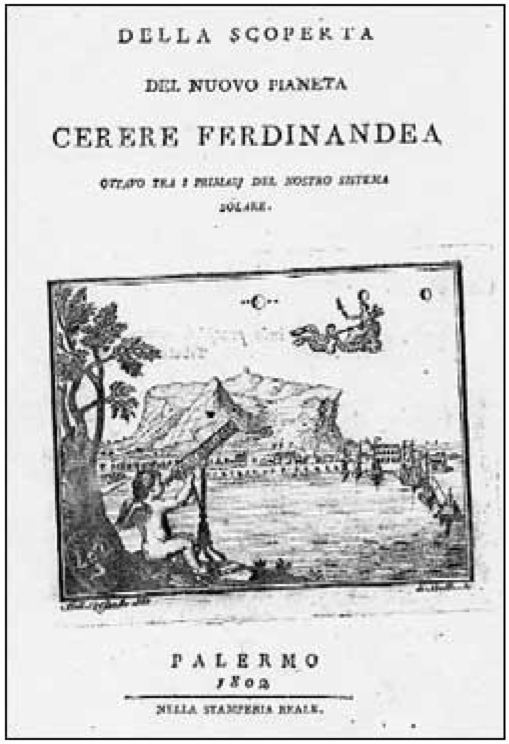
Ceres, formally designated **1 Ceres**, is the smallest identified dwarf planet in the Solar System and the only one in the asteroid belt. It was discovered on 1 January 1801 by Giuseppe Piazzi, and for half a century it was classified as the eighth planet. It is named after Ceres, the Roman goddess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


DELLA SCOPERTA
DEL NUOVO PIANETA
CERERE FERDINANDEA
OTTAVO TRA I PRIMARJ DEL NOSTRO SISTEMA SOLARE.
PALERMO
1802
NELLA STAMPERIA REALE.

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

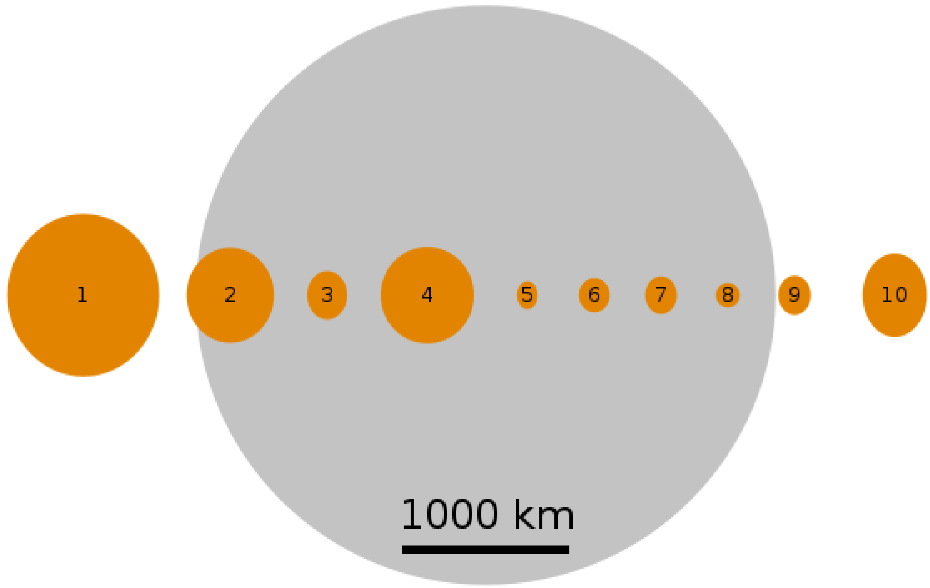
Ceres (bottom left), the Moon and the Earth, shown to scale.

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.

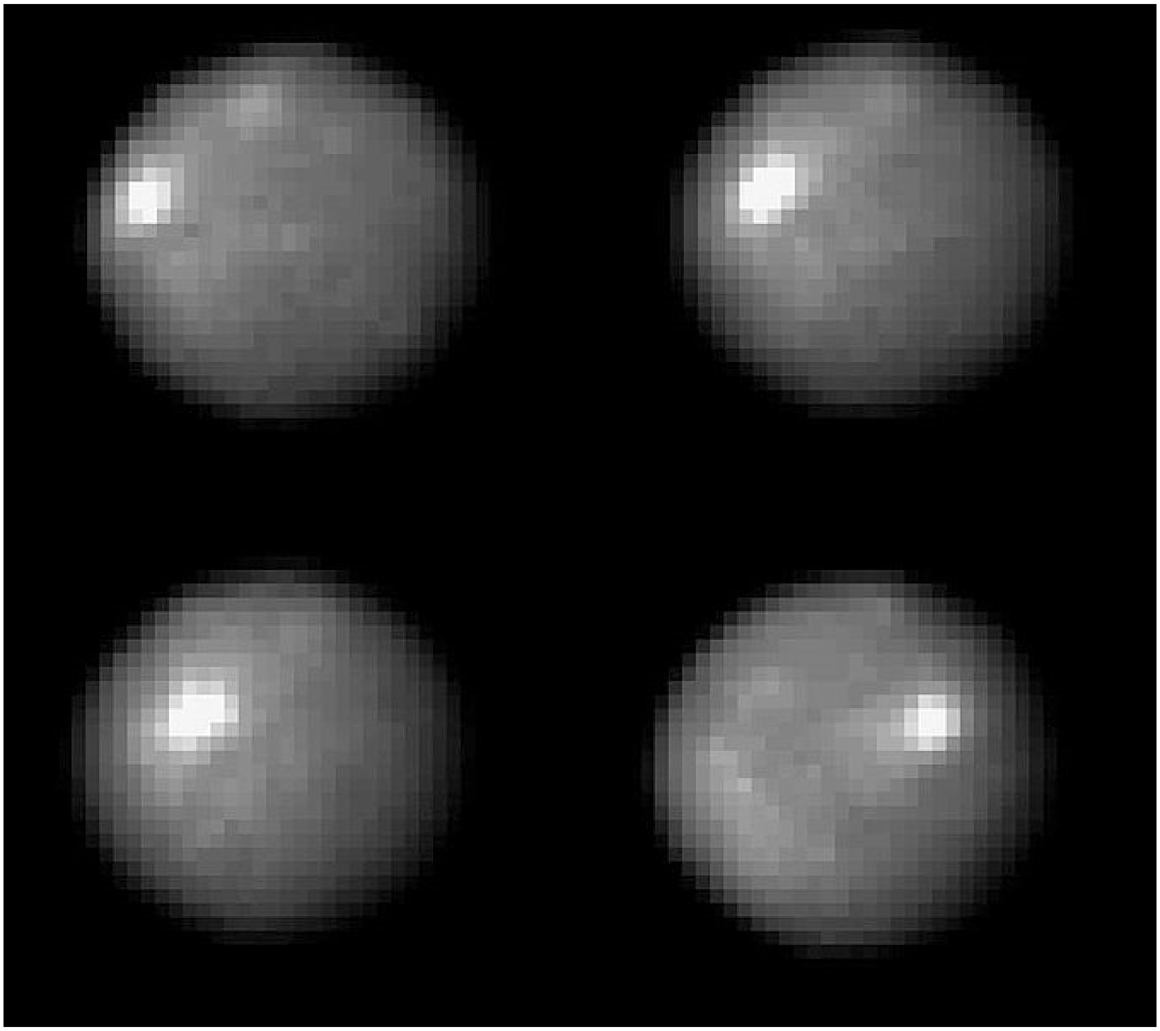
However, as other objects were discovered in the area it was realised that Ceres represented the first of a class of many similar bodies. In 1802 Sir William Herschel coined the term *asteroid* ("star-like") for such bodies, writing "they resemble small stars so much as hardly to be distinguished from 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



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



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.

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 $3.0 \pm 0.2\times10^{21}$ 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.

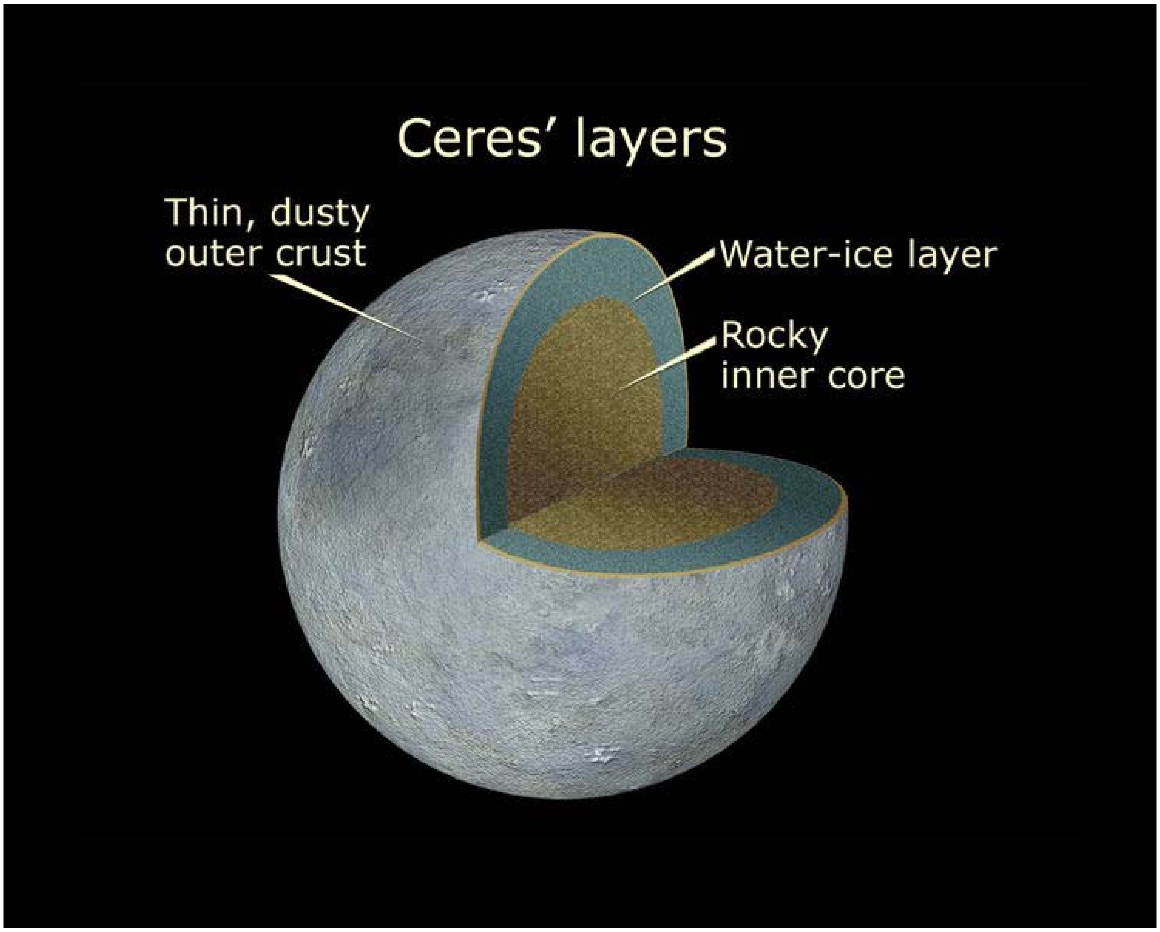


Diagram showing a possible internal structure of Ceres

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°.

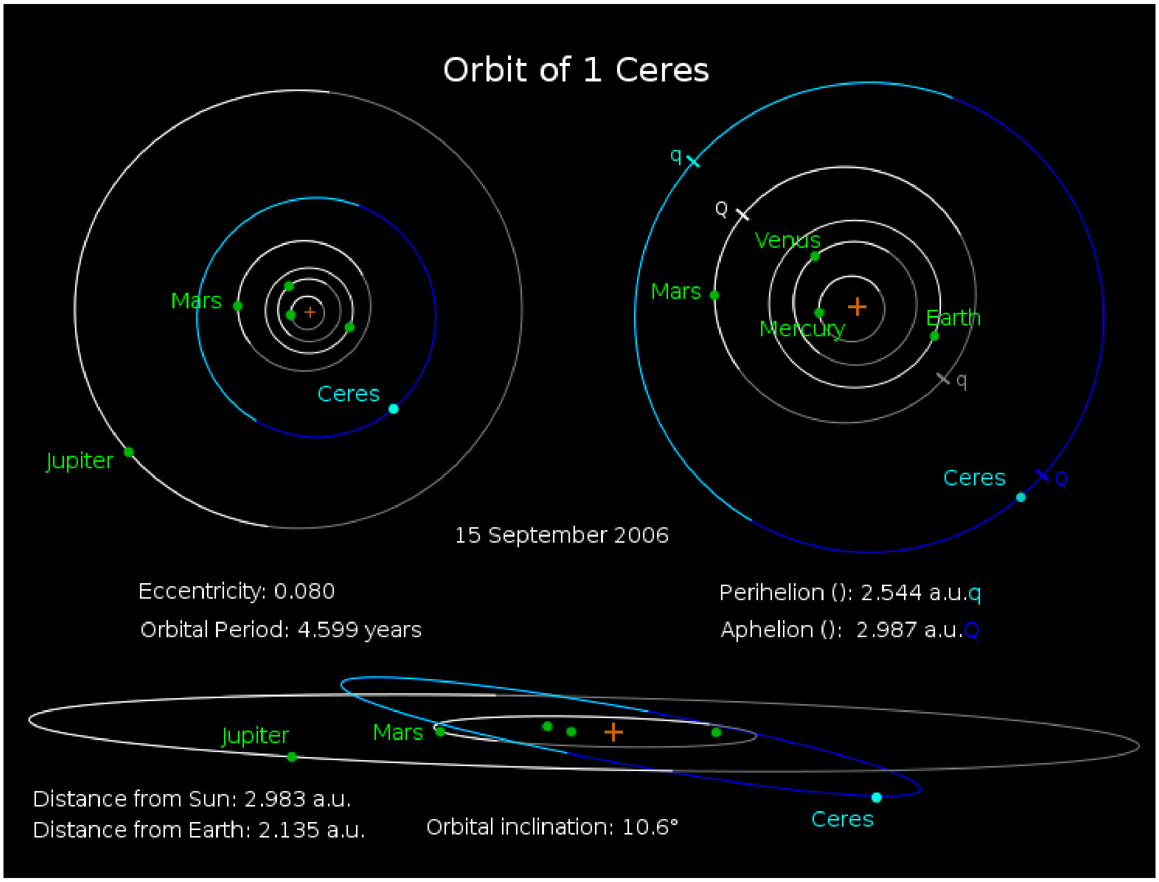
Atmosphere

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.

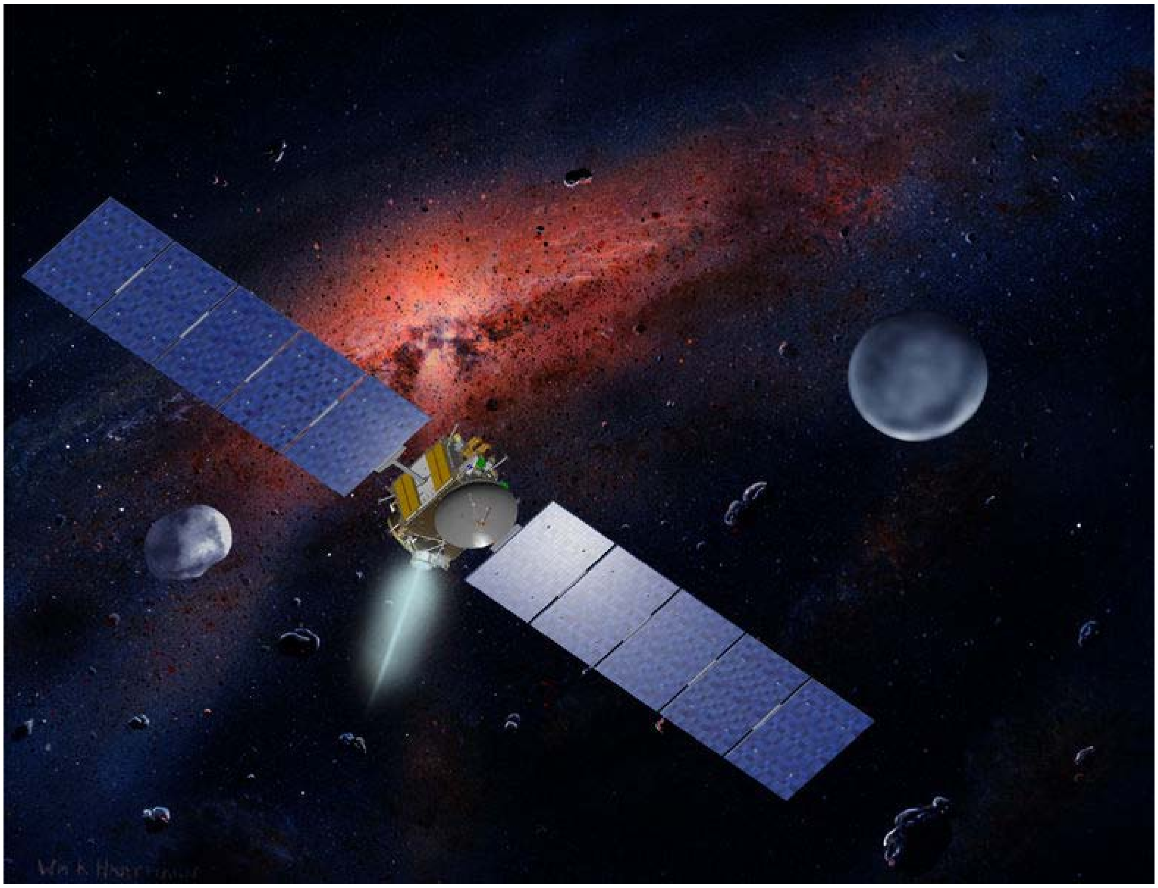
Observations

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

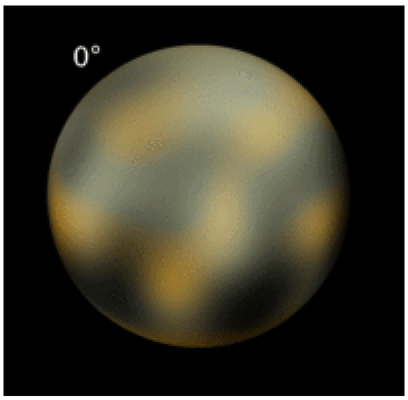
To date, no space probe has visited Ceres. Radio signals from spacecraft in orbit around and on the surface of Mars have been used to estimate the mass of Ceres from its perturbations on the motion of Mars.

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- 3

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.	**min** **mean** **max**
Kelvin	33 K 44 K 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

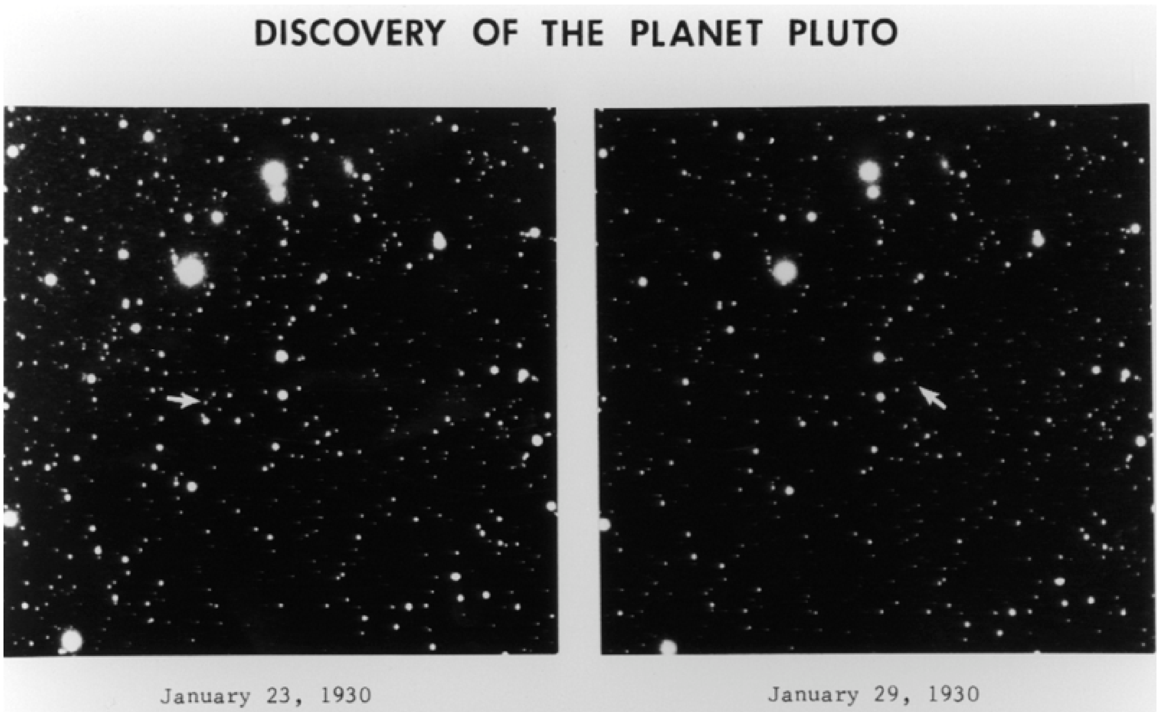
Pluto, formal designation **134340 Pluto**, is the second most massive known dwarf planet in the Solar System (after Eris) and the tenth most massive body observed directly orbiting the Sun. Originally classified as a planet, Pluto is now considered the largest member of a distinct population known as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

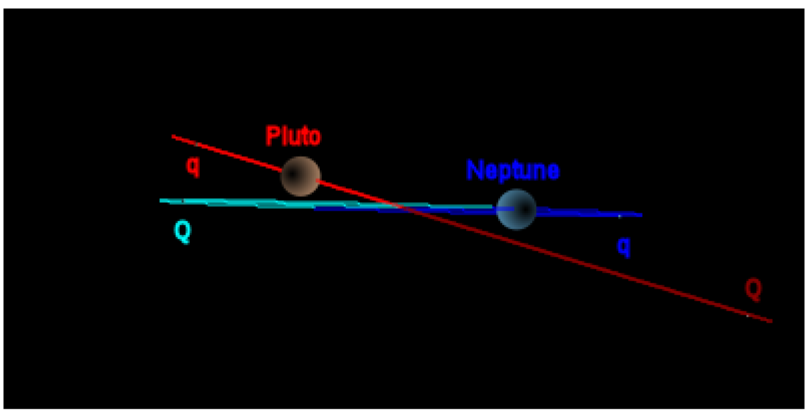
Clyde W. Tombaugh, the discoverer of Pluto

Mass estimates for Pluto:

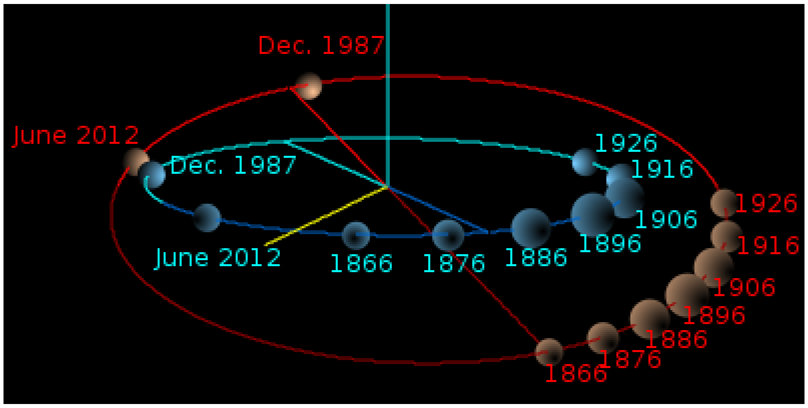
Year	Mass	Notes
1931	1 Earth	Nicholson & Mayall
1948	0.1 (1/10 Earth)	Kuiper
1976	0.01 (1/100 Earth)	Cruikshank, Pilcher, & Morrison
1978	0.002 (2/1,000 Earth)	Christy & Harrington

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

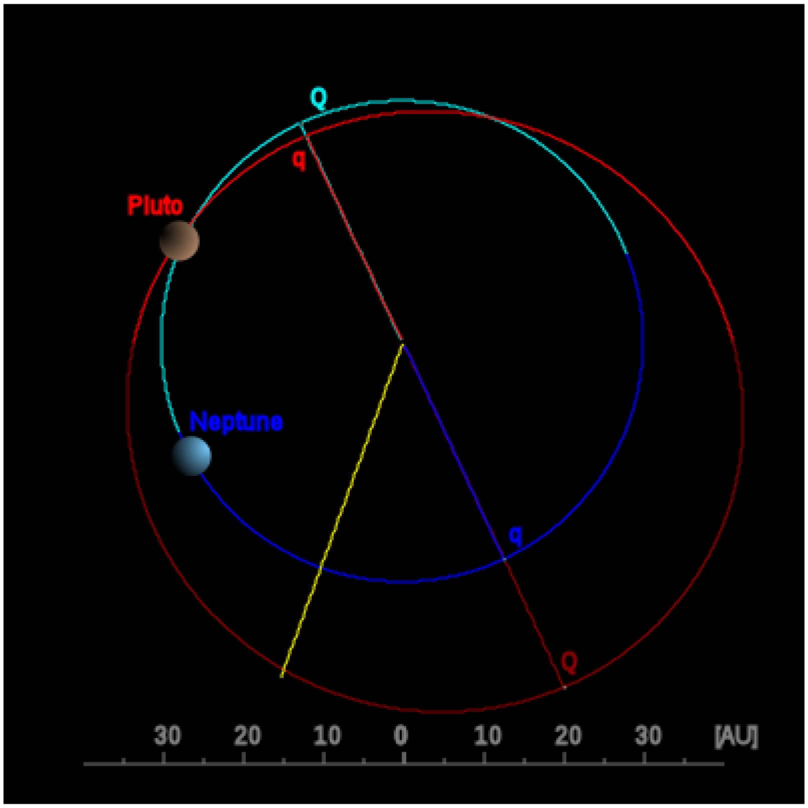


This diagram shows the relative positions of Pluto (red) and Neptune (blue) on selected dates. The size of Neptune and Pluto is depicted as inversely proportional to the distance between them to emphasise the closest approach in 1896.

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.

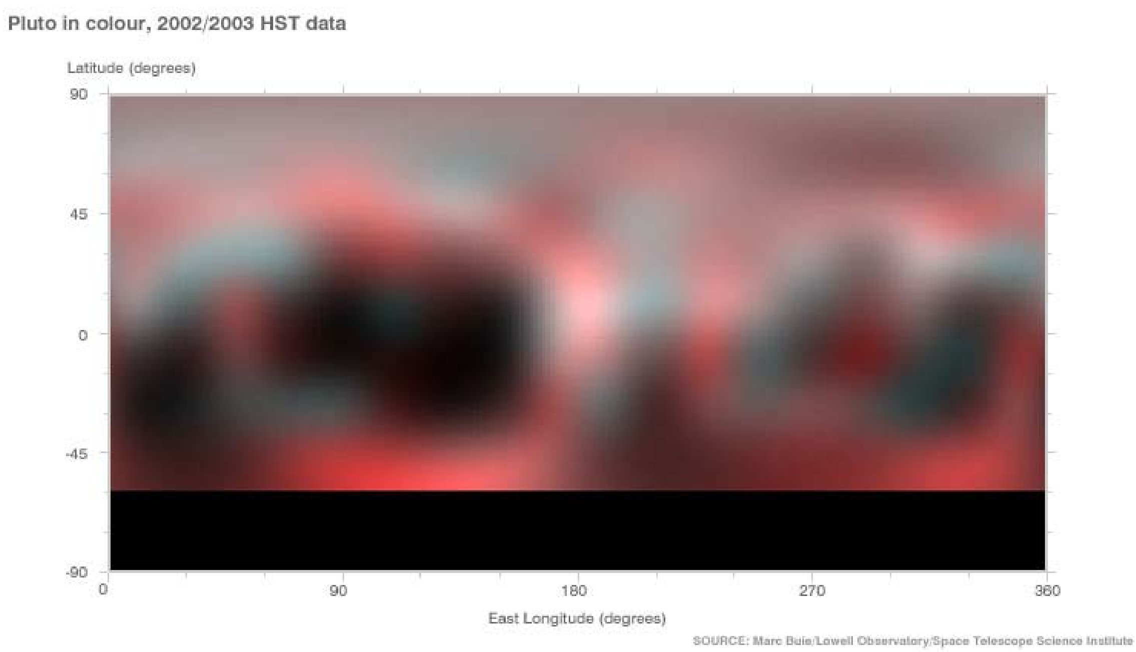
Second, the longitudes of ascending nodes of the two bodies—the points where they cross the ecliptic—are in near-resonance with the above libration. When the two longitudes are the same—that is, when one could draw a straight line through both nodes and the Sun—Pluto's perihelion lies exactly at 90°, 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.

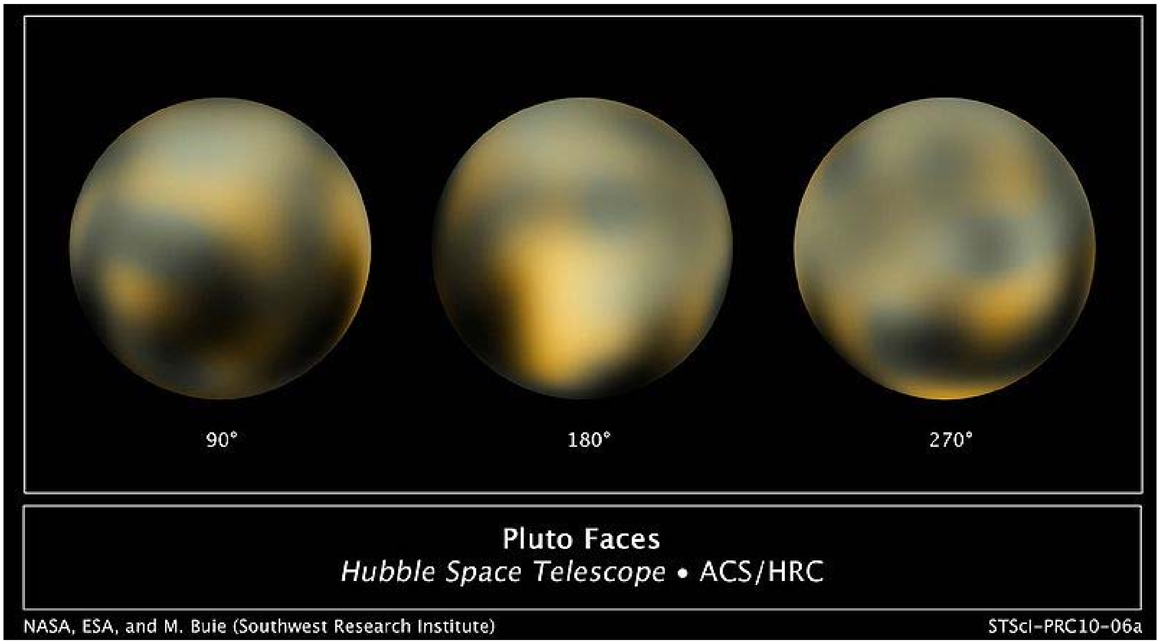
Rotation

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.

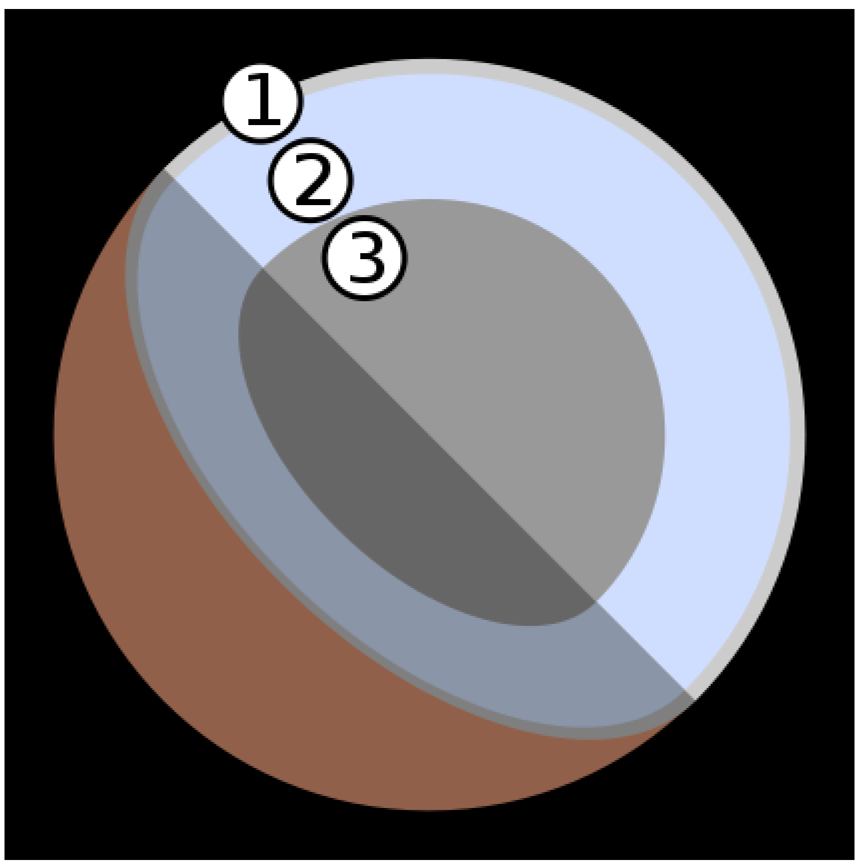
Current maps have been produced from images from the Hubble Space Telescope, which offers the highest resolution currently available, and show considerably more detail, resolving variations several hundred kilometres across, including polar regions and large bright spots. The maps are produced by complex 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.

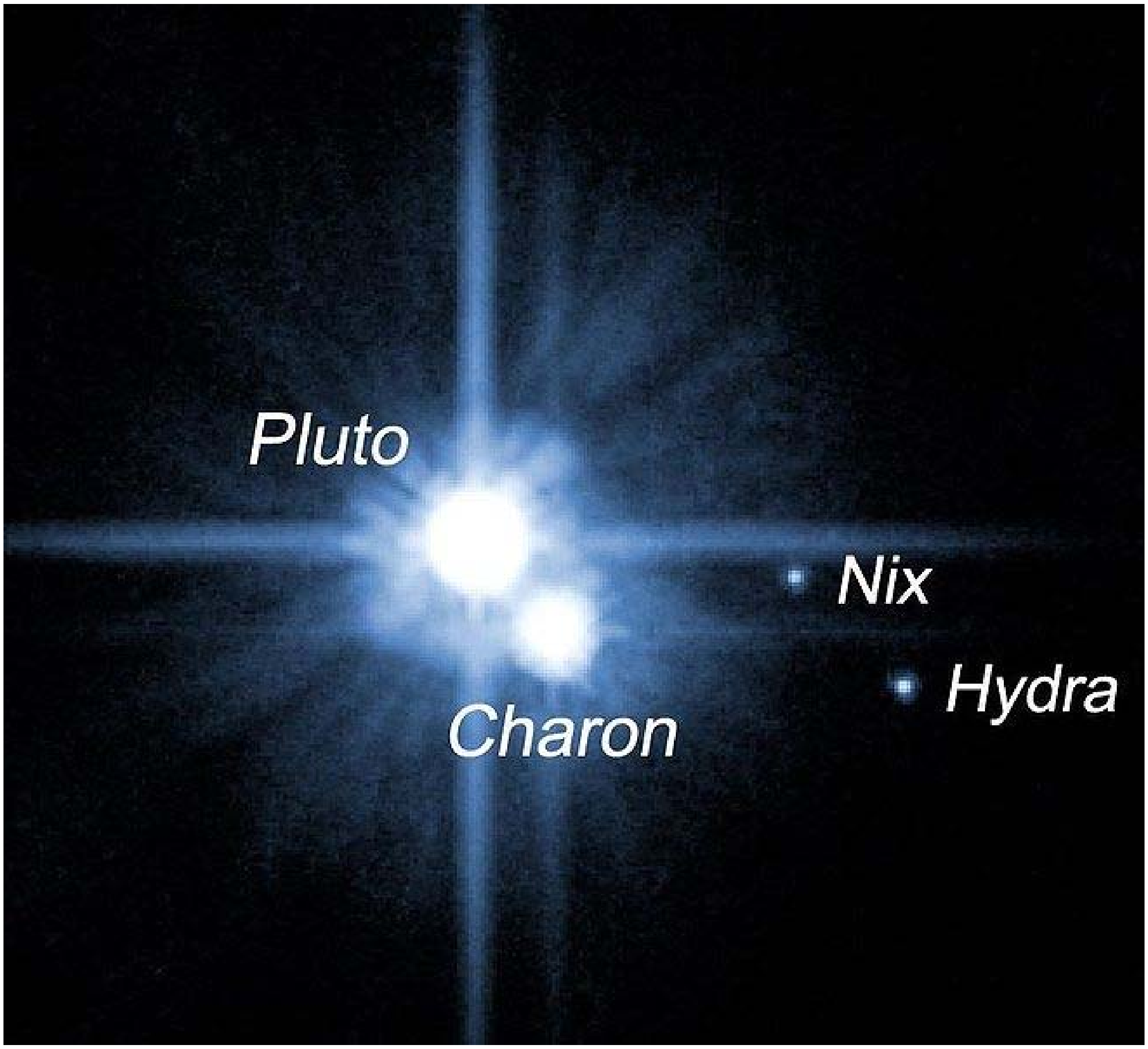
The presence of methane, a powerful greenhouse gas, in Pluto's atmosphere creates a temperature inversion, with average temperatures 36 K warmer 10 km above the surface. The lower atmosphere contains a higher concentration of methane than its upper atmosphere.

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

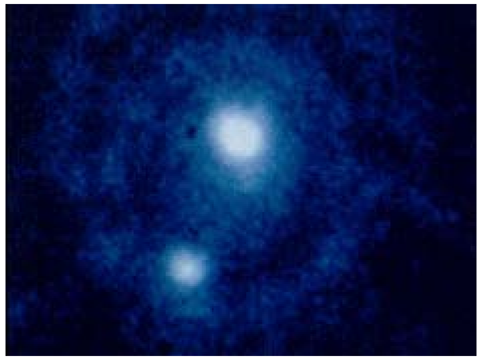


Pluto and its three known moons

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

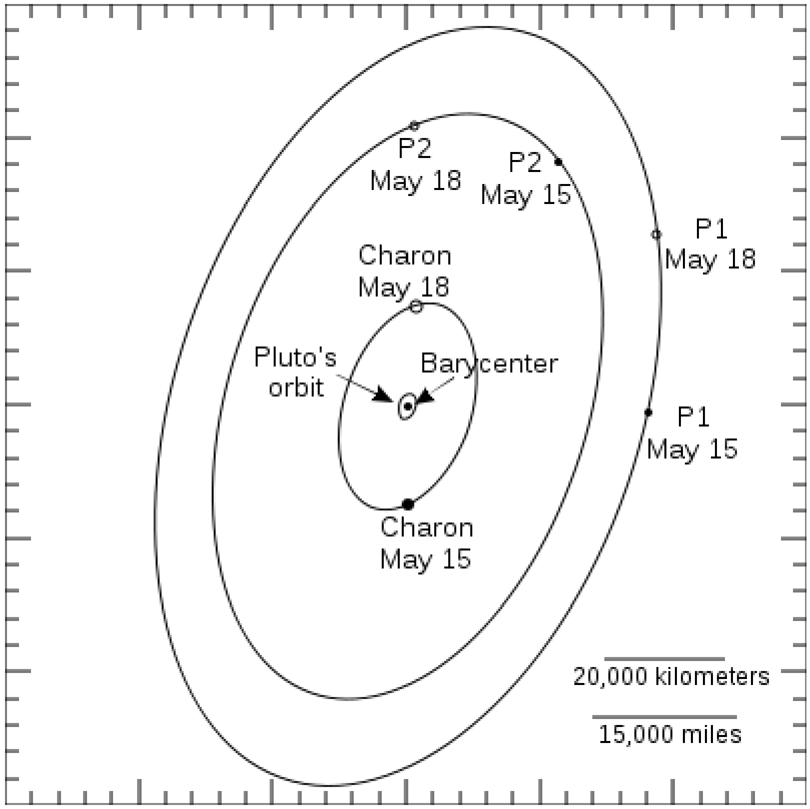


Diagram of the Plutonian system. P 1 is Hydra, and P 2 is Nix.

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.

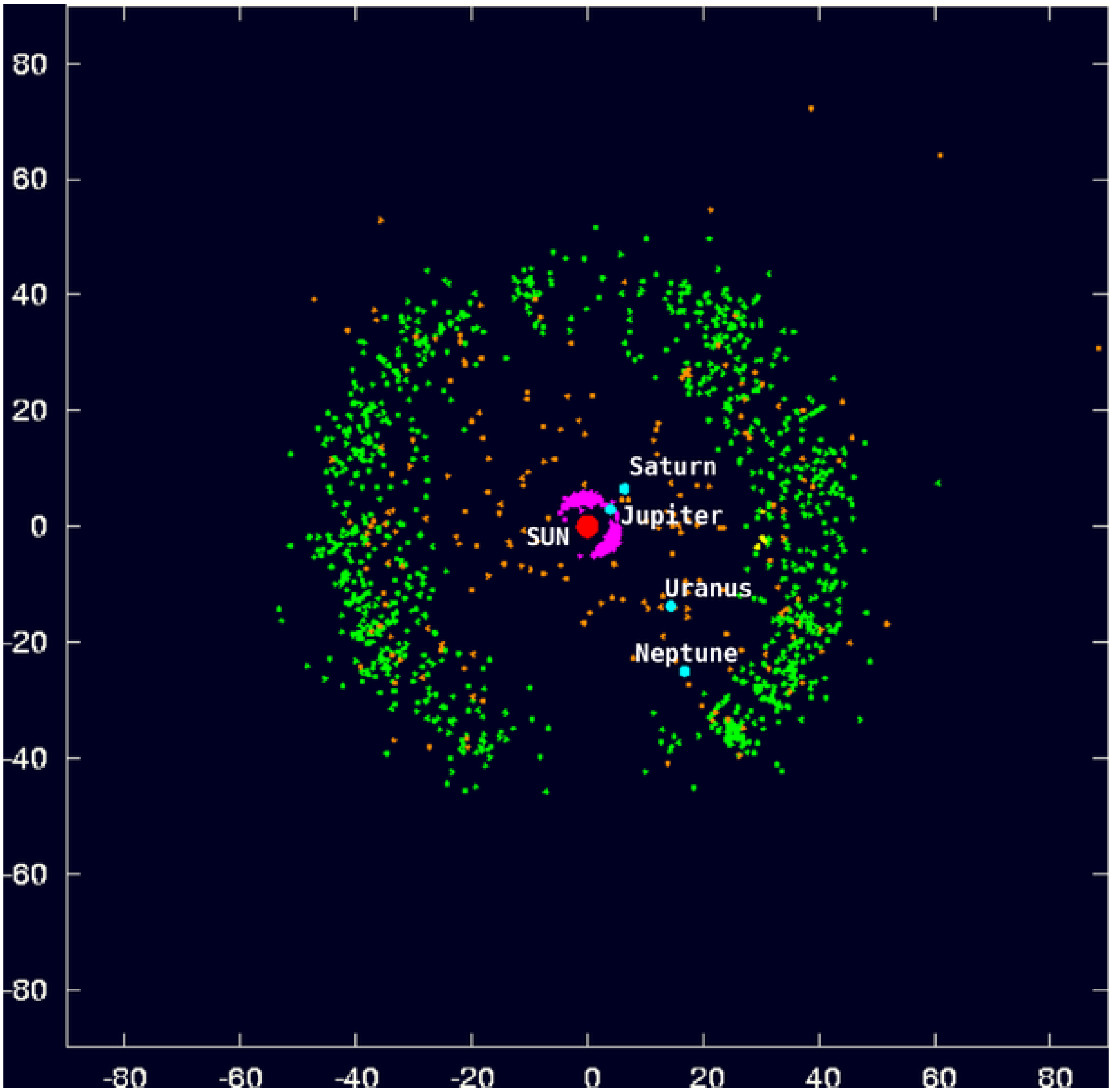
Similar conclusions have been made from occultation studies. In imaging the Plutonian system, observations from Hubble placed limits on any additional moons. With 90% confidence, no additional moons larger than 12 km (or a maximum of 37 km with an albedo of 0.041) exist beyond the glare of Pluto 5 arcseconds 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.

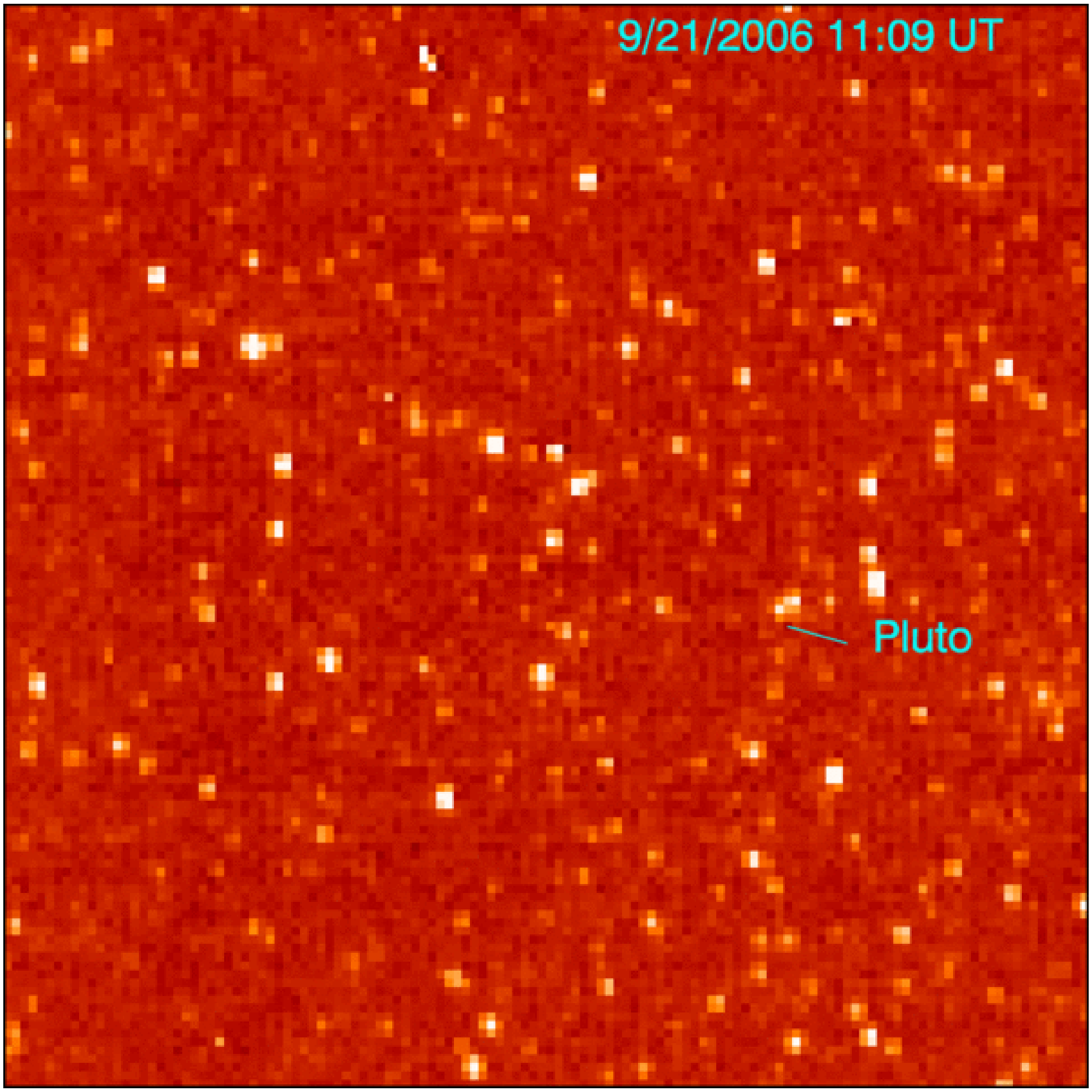
A large number of Kuiper belt objects, like Pluto, possess a 3:2 orbital resonance with Neptune. KBOs with this orbital resonance are called "plutinos", after Pluto.

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*

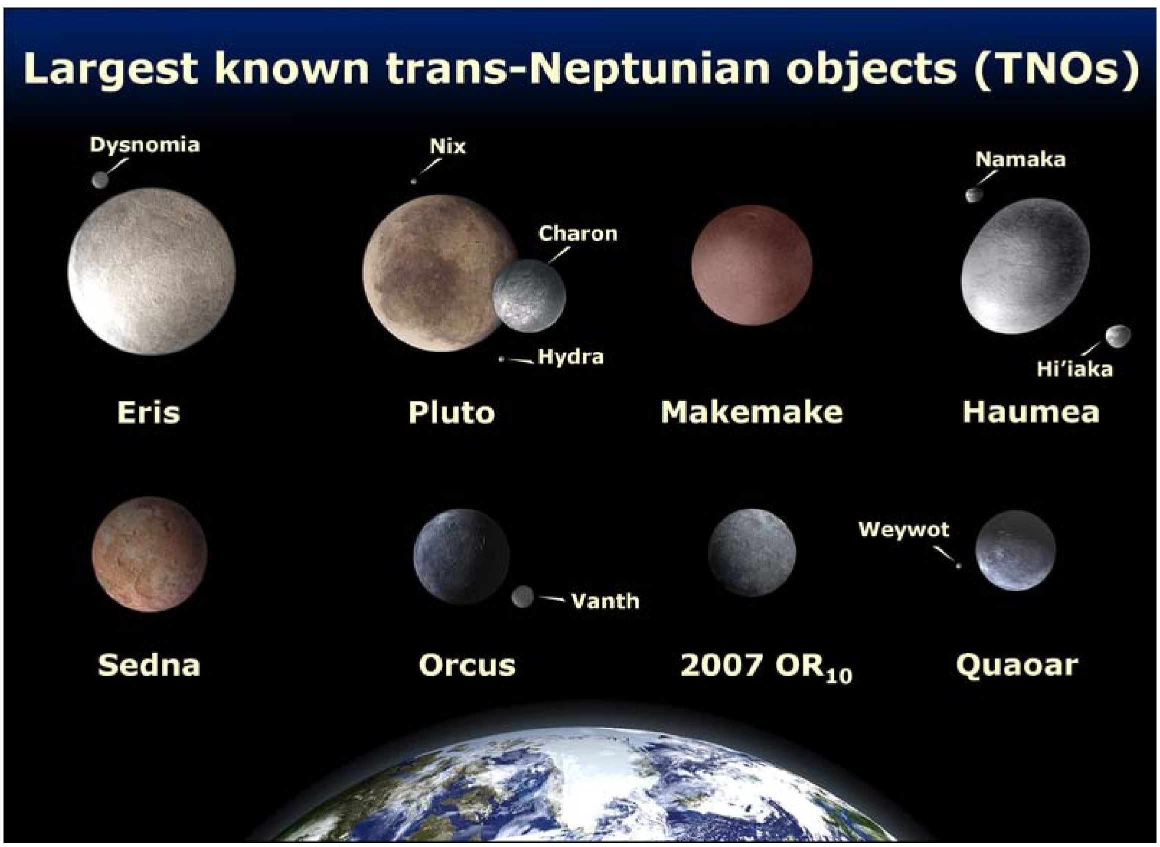
After an intense political battle, a revised mission to Pluto, dubbed *New Horizons*, was granted funding from the US government in 2003. *New Horizons* was launched successfully on January 19, 2006. The mission leader, S. Alan Stern, confirmed that some of the ashes of Clyde Tombaugh, who died in 1997,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

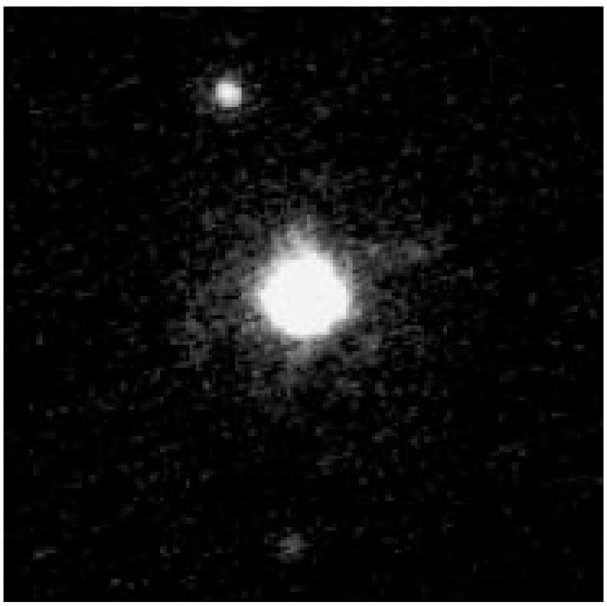
The verb "to pluto" (preterite and past participle: "**plutoed**") was a neologism coined in the aftermath of the 2006 IAU decision. In January 2007, the American Dialect Society chose "plutoed" as its 2006 Word of the Year, defining "*to pluto*" as "*to demote or devalue someone or something*", "as 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- 4

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)

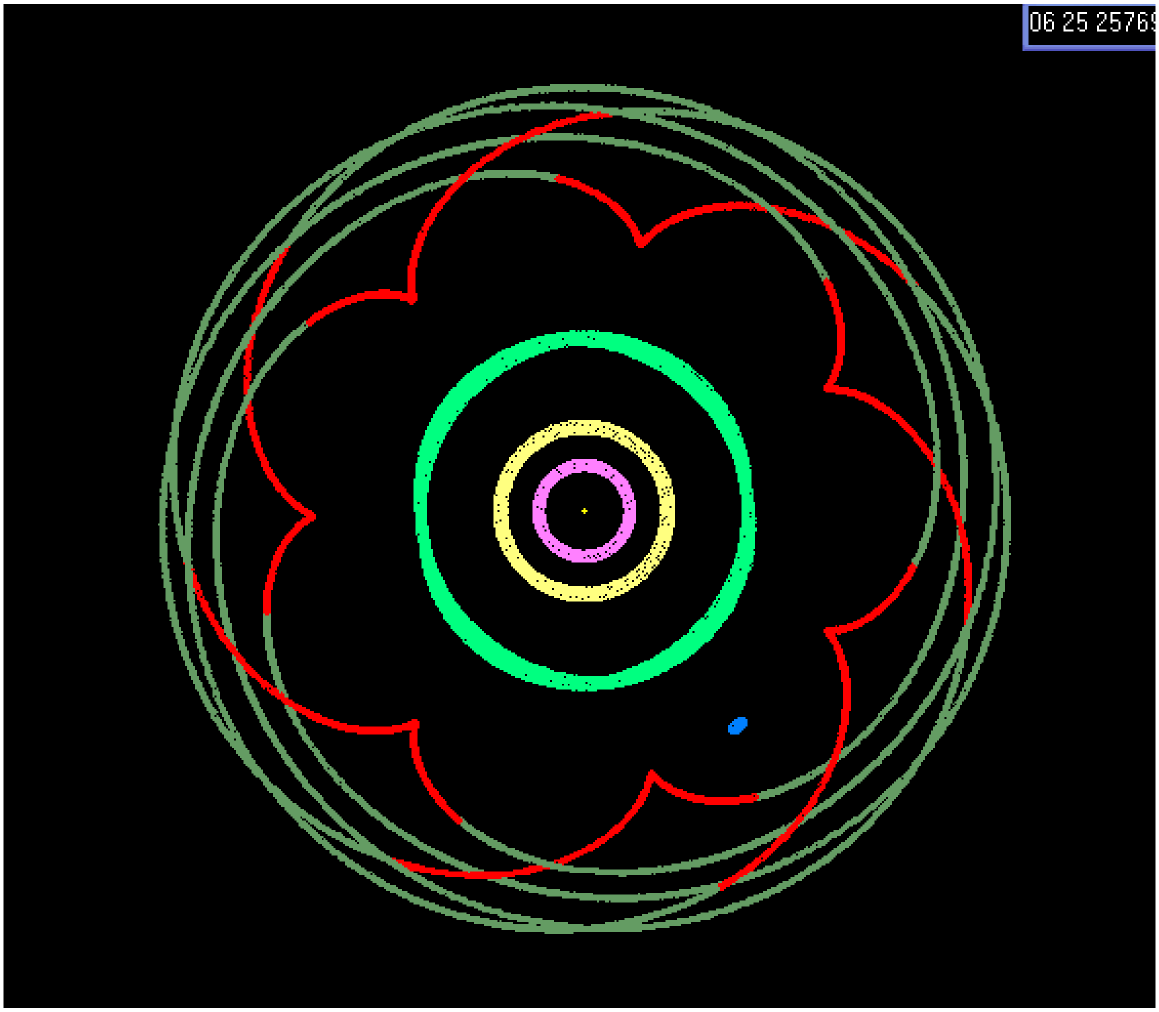
	fifth-order 12:7 resonance
Adjective	Haumean
Orbital characteristics	
Epoch 2008-11-30 (JD 2454800.5)	
Aphelion	51.544 AU 7.710 Tm
Perihelion	34.721 AU 5.194 Tm
Semi-major axis	43.132 AU 6.452 Tm
Eccentricity	0.195 01
Orbital period	103 468 d (283.28 yr)
Average orbital speed	4.484 km/s
Mean anomaly	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	$\approx 2\times10^{7}$ km^2
Mass	$(4.006 \pm 0.040)\times10^{21}$ 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.

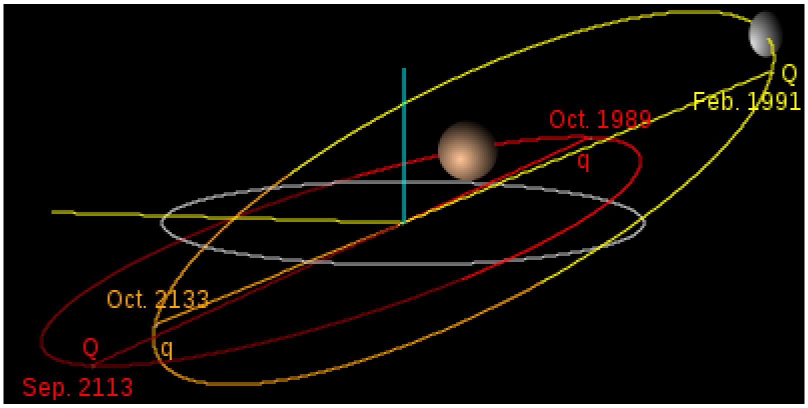
Discovery controversy

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

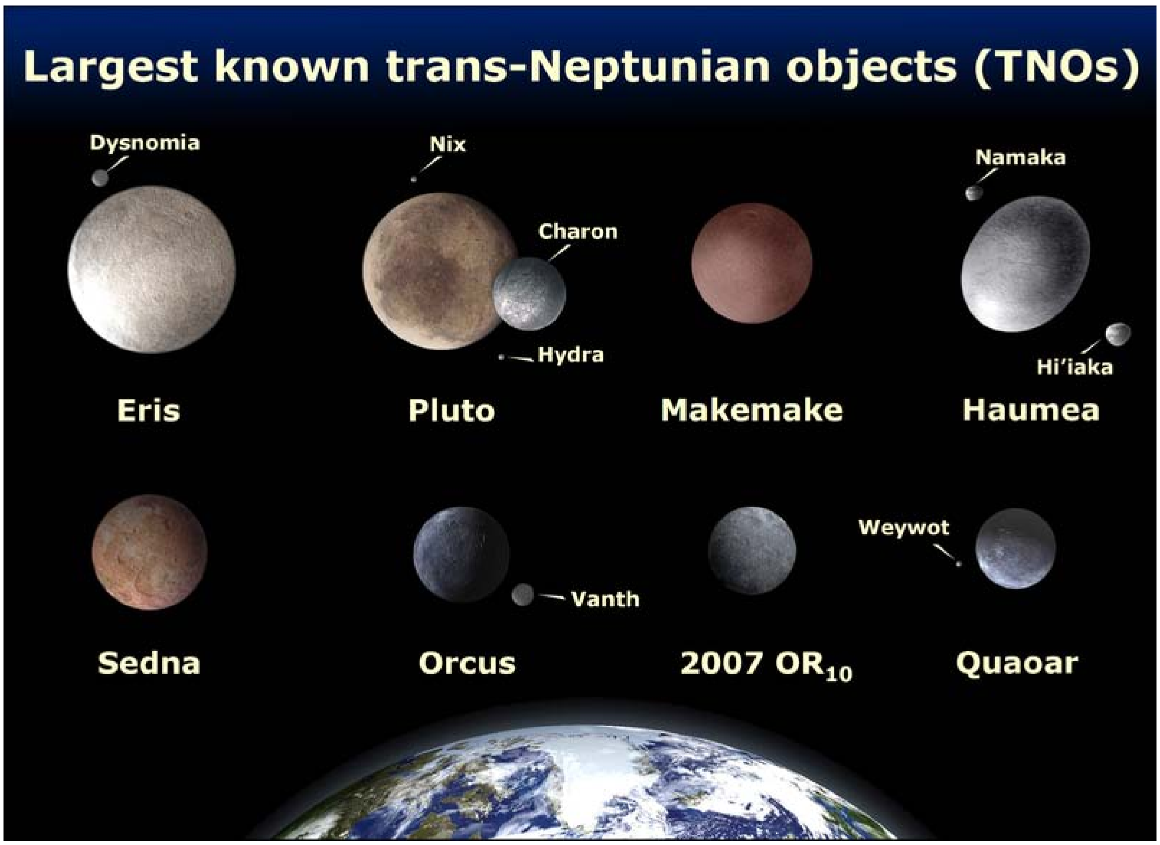
Haumea has a typical orbit for a classical Kuiper belt object, with an orbital period of 283 Earth years, a perihelion of 35 AU, and an orbital inclination of 28°. It passed aphelion in early 1992, and is currently more than 50 AU from the Sun.

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

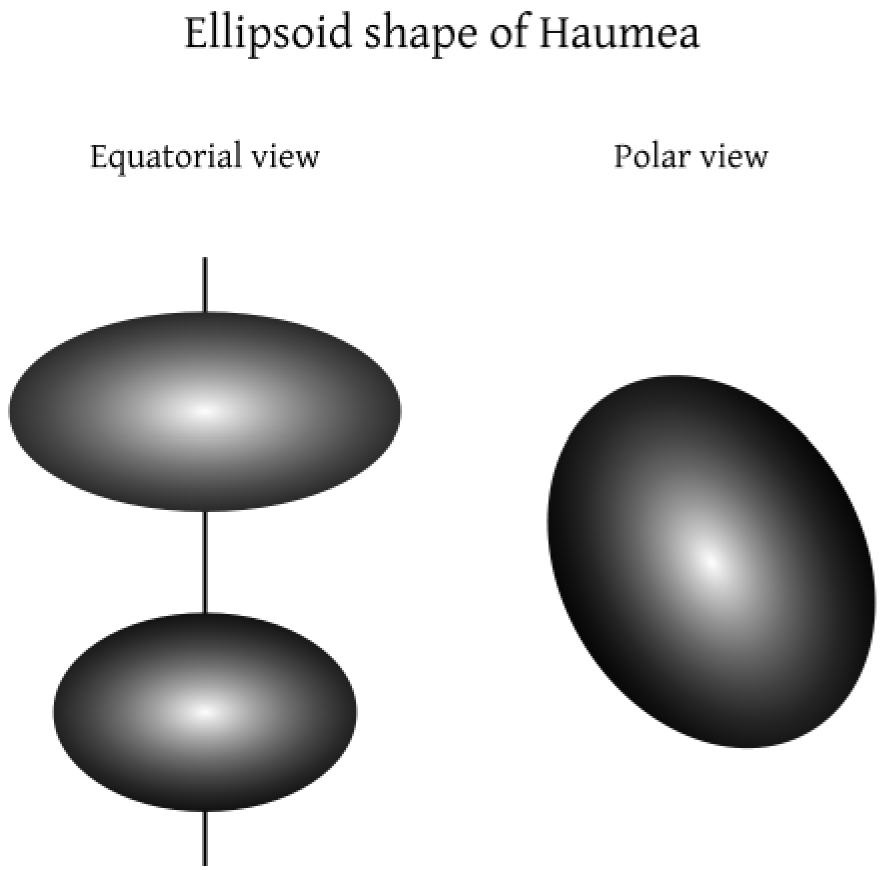


Comparison of Eris, Pluto, Makemake, **Haumea**, Sedna, Orcus, 2007 OR_{10}, Quaoar, and Earth (all to scale)

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.

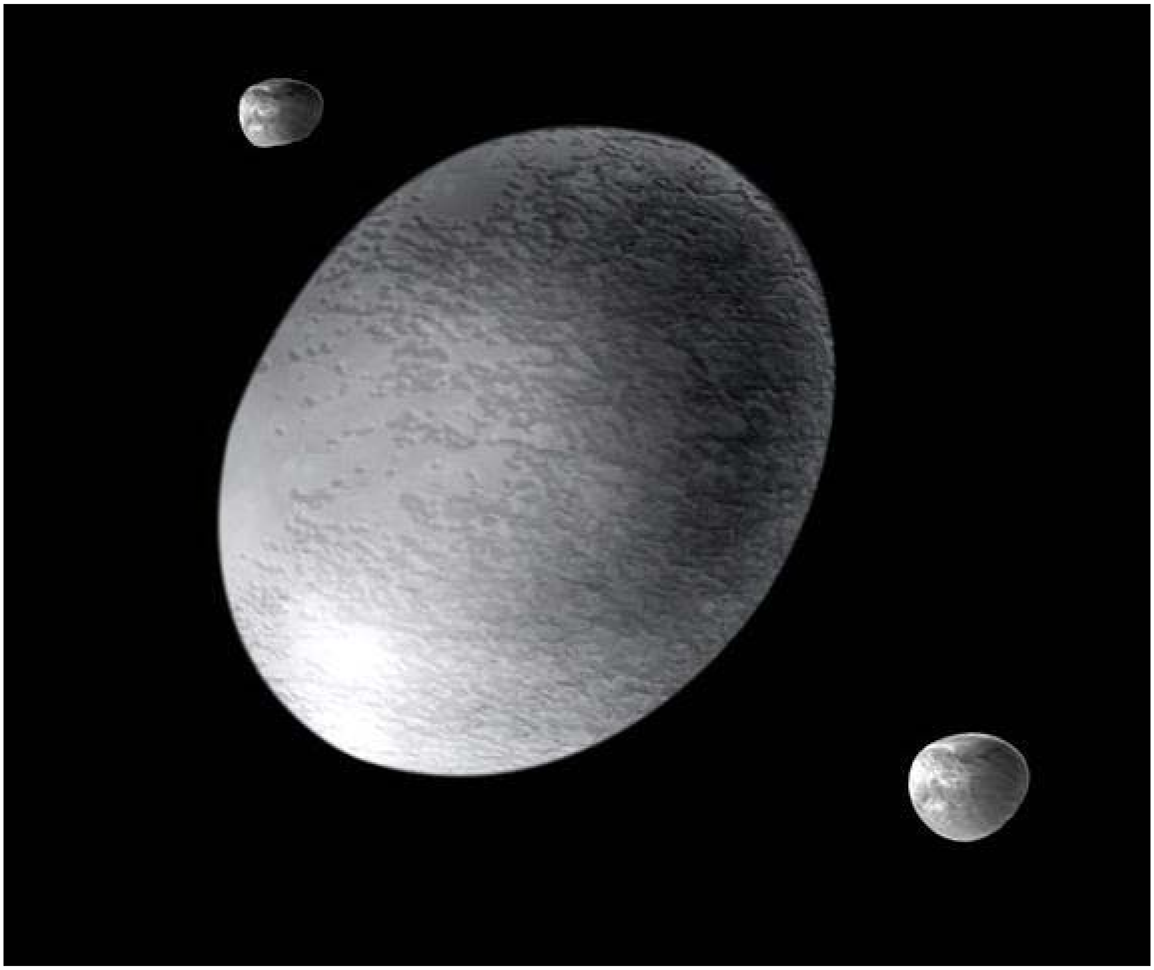
In 2005, the Gemini and Keck telescopes obtained spectra of Haumea which showed strong crystalline water ice features similar to the surface of Pluto's moon Charon. This is peculiar, because crystalline ice forms at temperatures above 110 K, while the surface temperature of Haumea is below 50 K, a temperature 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.

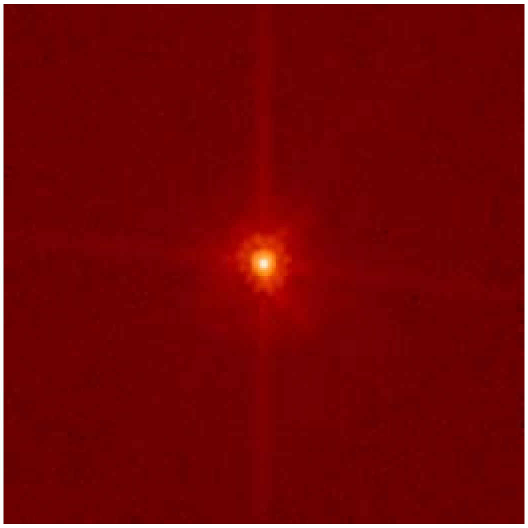
The presence of the collisional family could imply that Haumea and its "offspring" might have originated in the scattered disc. In today's sparsely populated Kuiper belt, the chance of such a collision occurring over the age of the Solar System is less than 0.1 percent. The family could not have formed 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- 5

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.

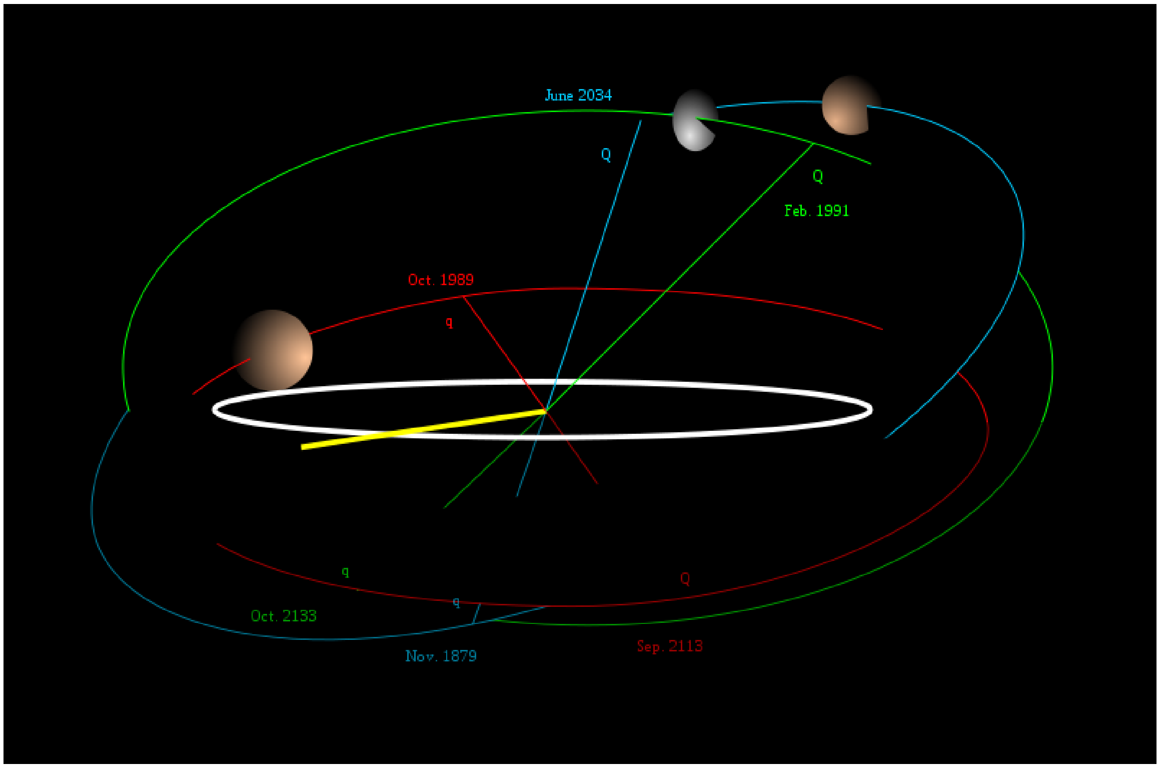
Besides Pluto, Makemake is the only other dwarf planet that was bright enough for Clyde Tombaugh to have possibly detected during his search for trans-Neptunian planets around 1930. At the time of Tombaugh's survey, Makemake was only a few degrees from the ecliptic, near the border of Taurus and Auriga, 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



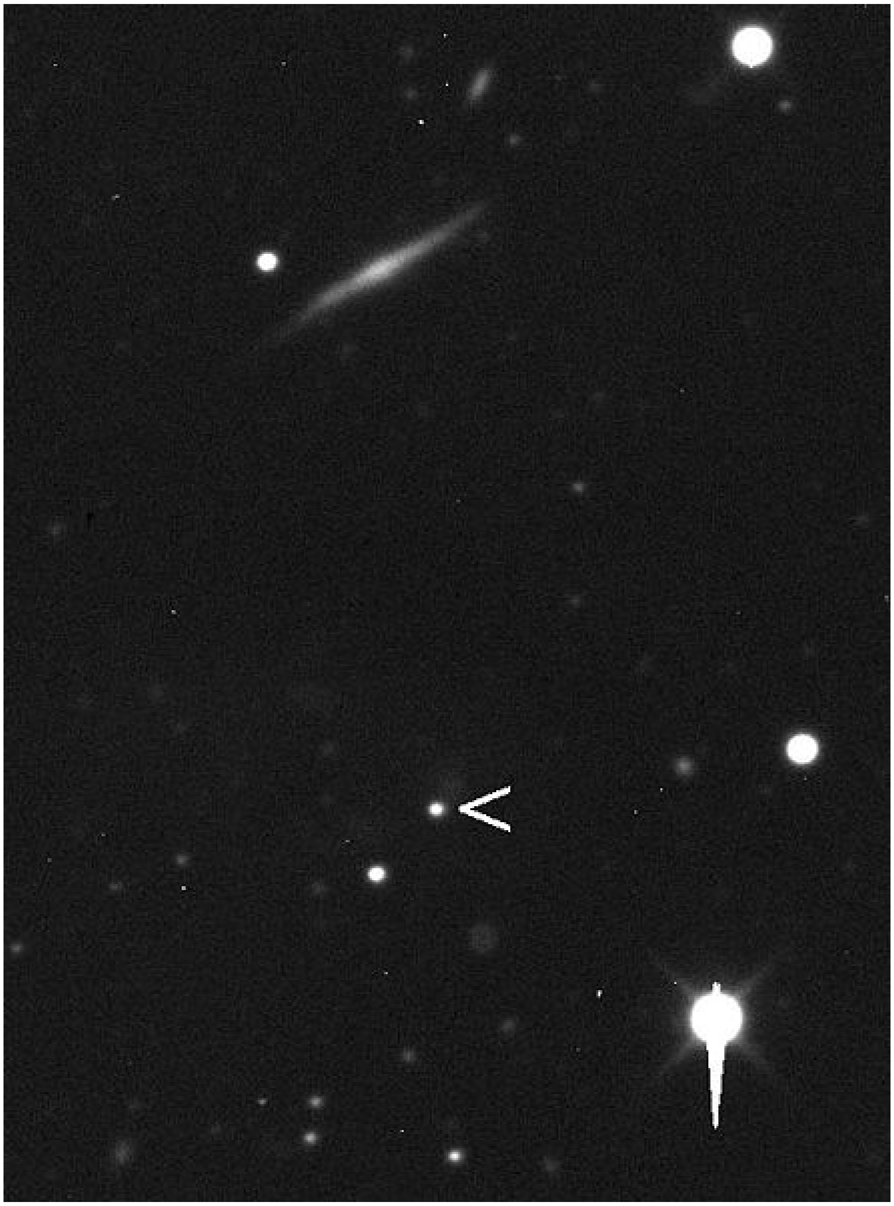
Orbits of Makemake (blue), Haumea (green), contrasted with the orbit of Pluto (red) and the ecliptic (grey). The perihelia (q) and the aphelia (Q) are marked with the dates of passage. The positions on April 2006 are marked with the spheres illustrating relative sizes and differences in albedo and colour.

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.

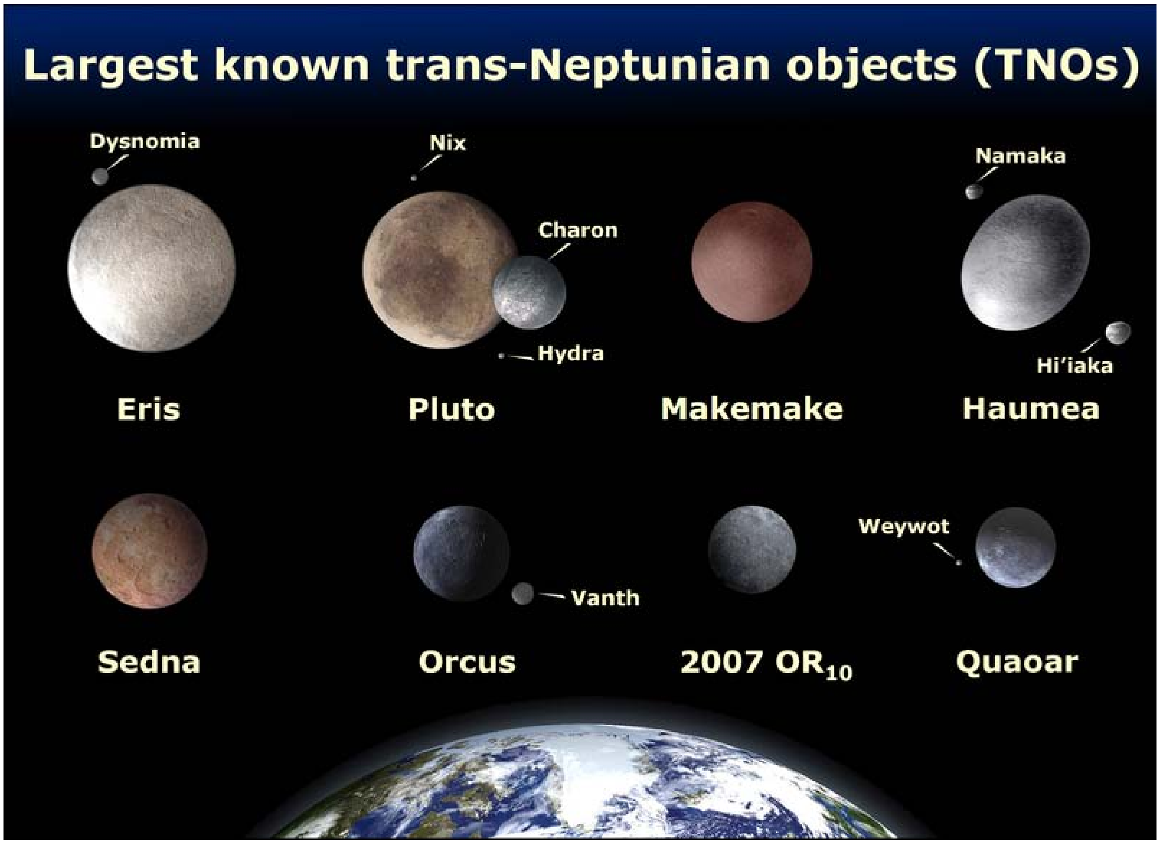
Physical characteristics

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- 6

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	$(1.67\pm0.02)\times10^{22}$ 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 *(H)*	−1.19 ± 0.3

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.

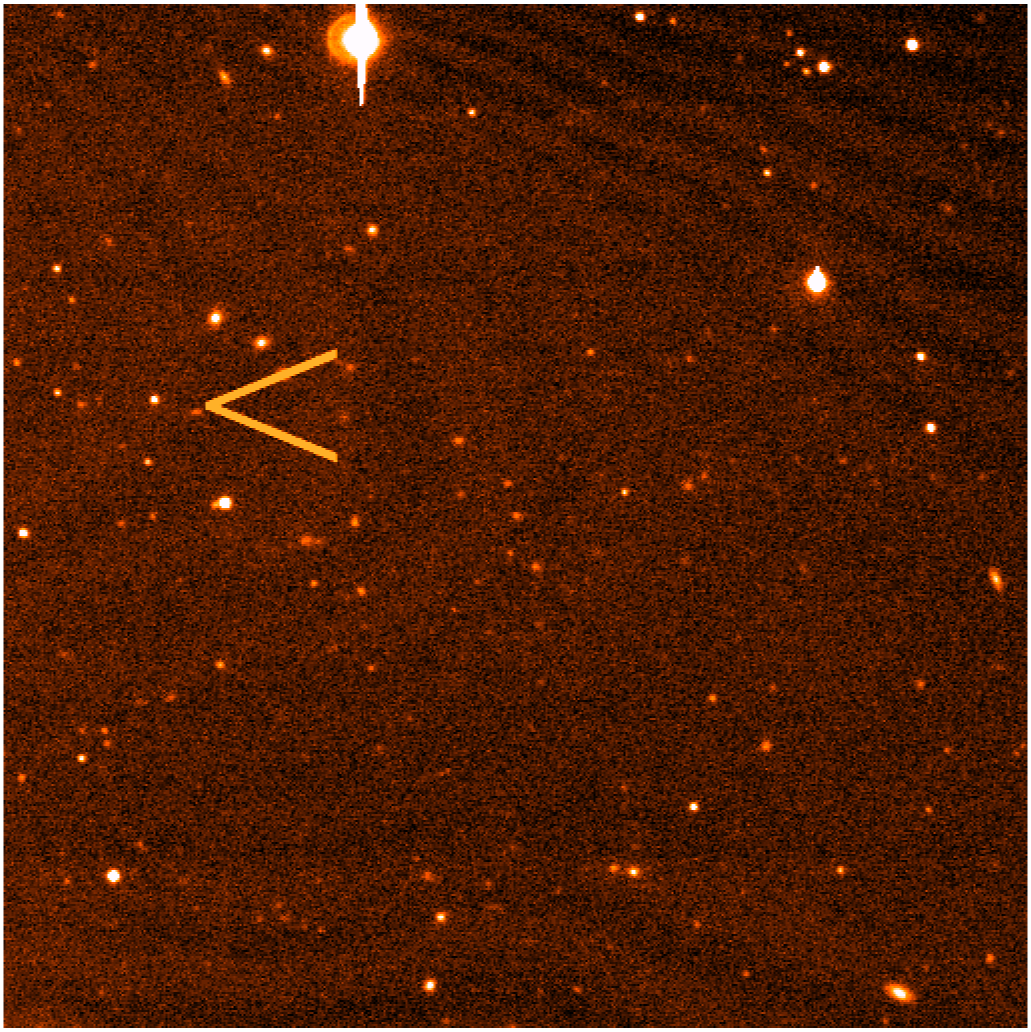
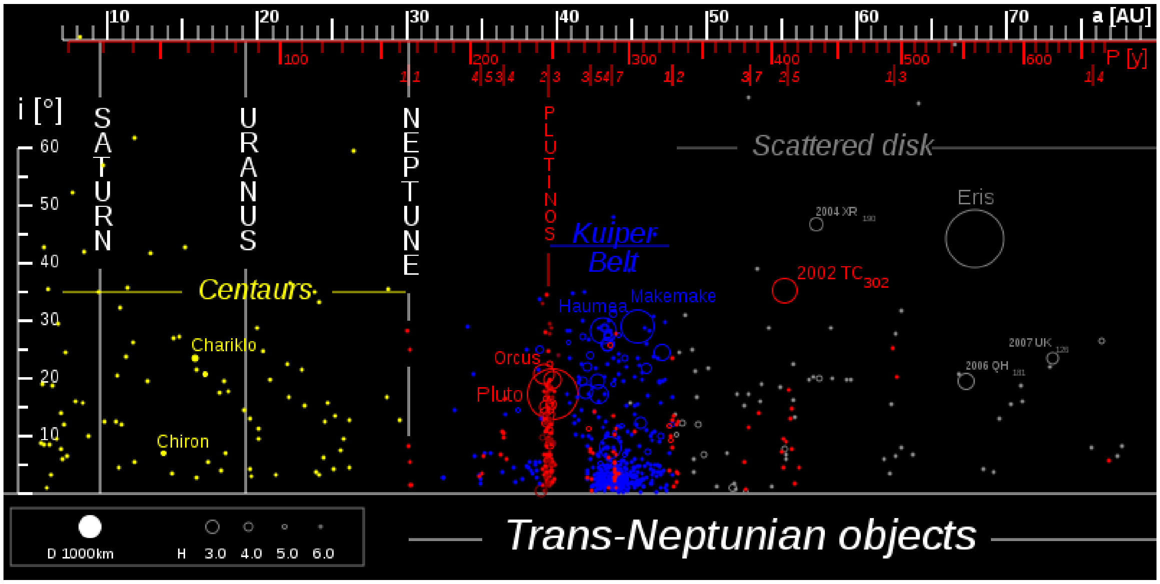


Image showing the movement of Eris on the images used to discover it. Eris is indicated by the arrow. The three frames were taken over a period of three hours.



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 $(1.66 \pm 0.02)\times10^{22}$ 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.

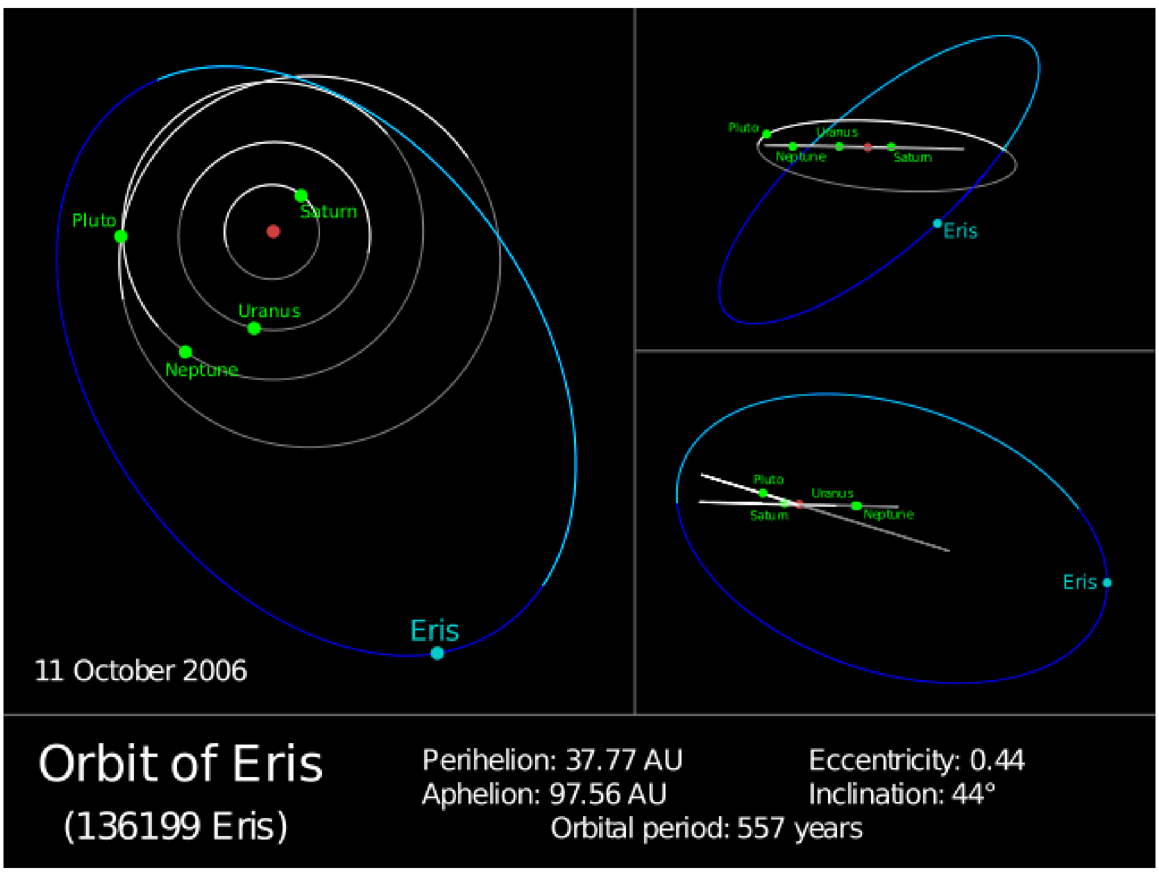
Choosing an official name

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.

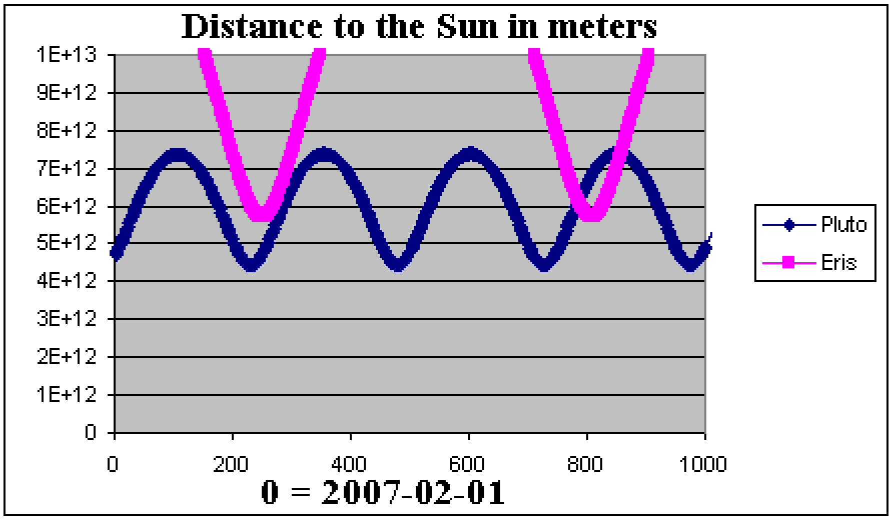
Brown had also speculated that *Persephone*, the wife of the god Pluto, would be a good name for the object. The name had been used several times in science fiction, and was popular with the public, having handily won a poll conducted by *New Scientist* magazine ("Xena", despite only being a nickname, 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

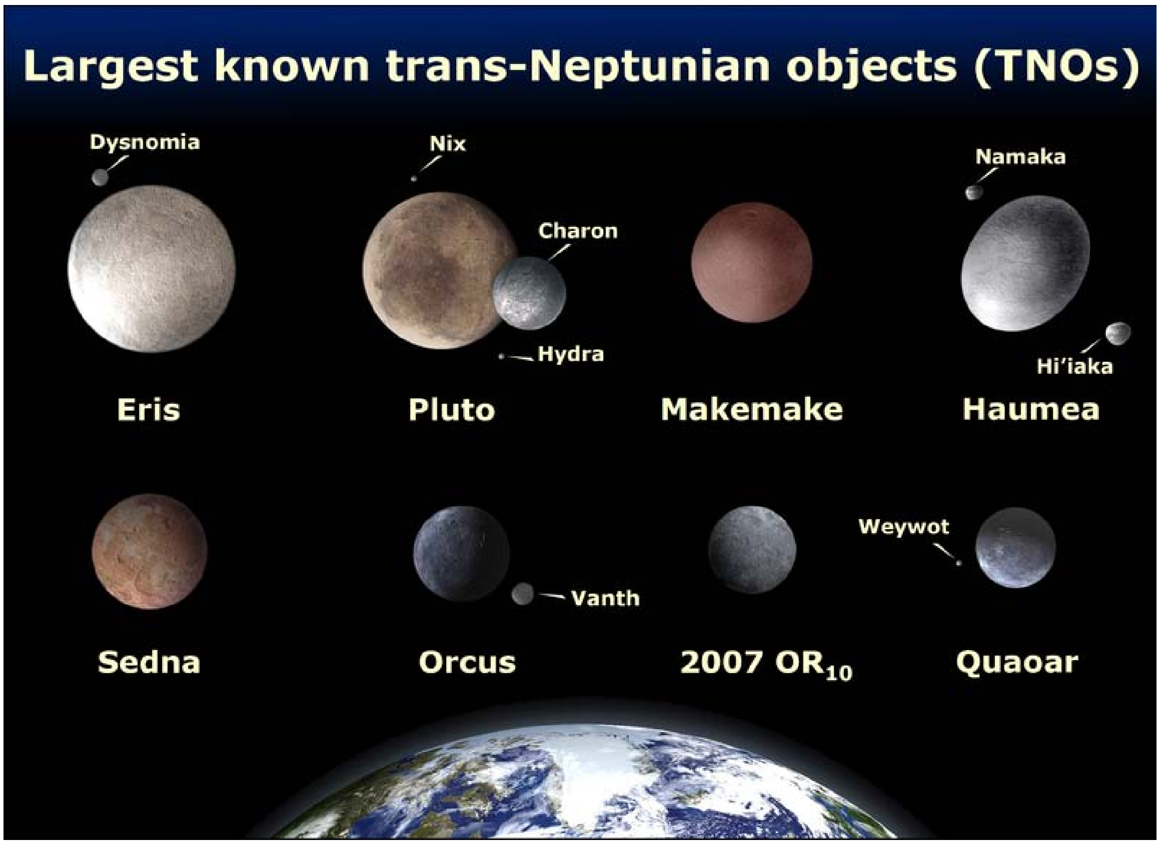
Eris has an orbital period of 557 years, and as of 2009 lies at 96.7 astronomical units from the Sun, almost its maximum possible distance (its aphelion is 97.5 AU). It came to perihelion between 1698 and 1699, to aphelion around 1977, and will return to perihelion around 2256 to 2258. Eris and its moon 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.

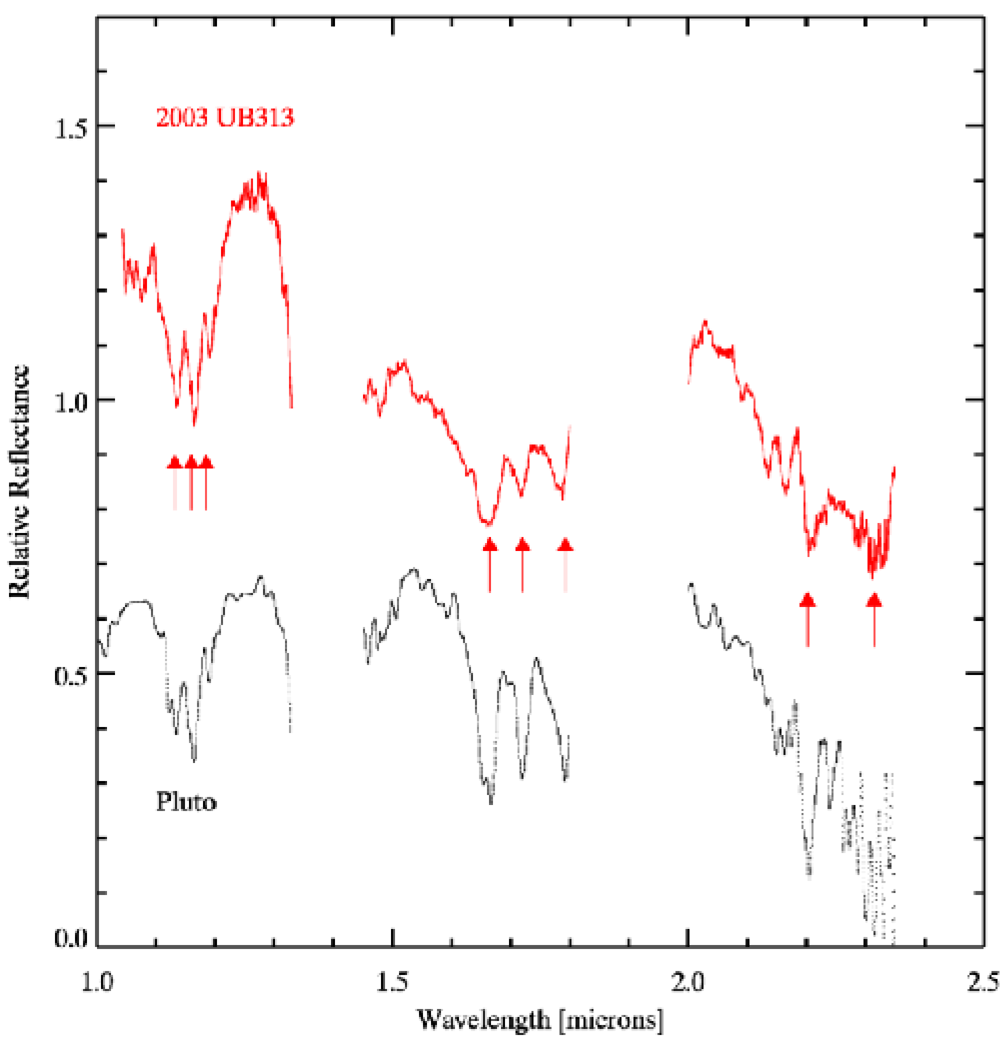
Thermal measurement

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.

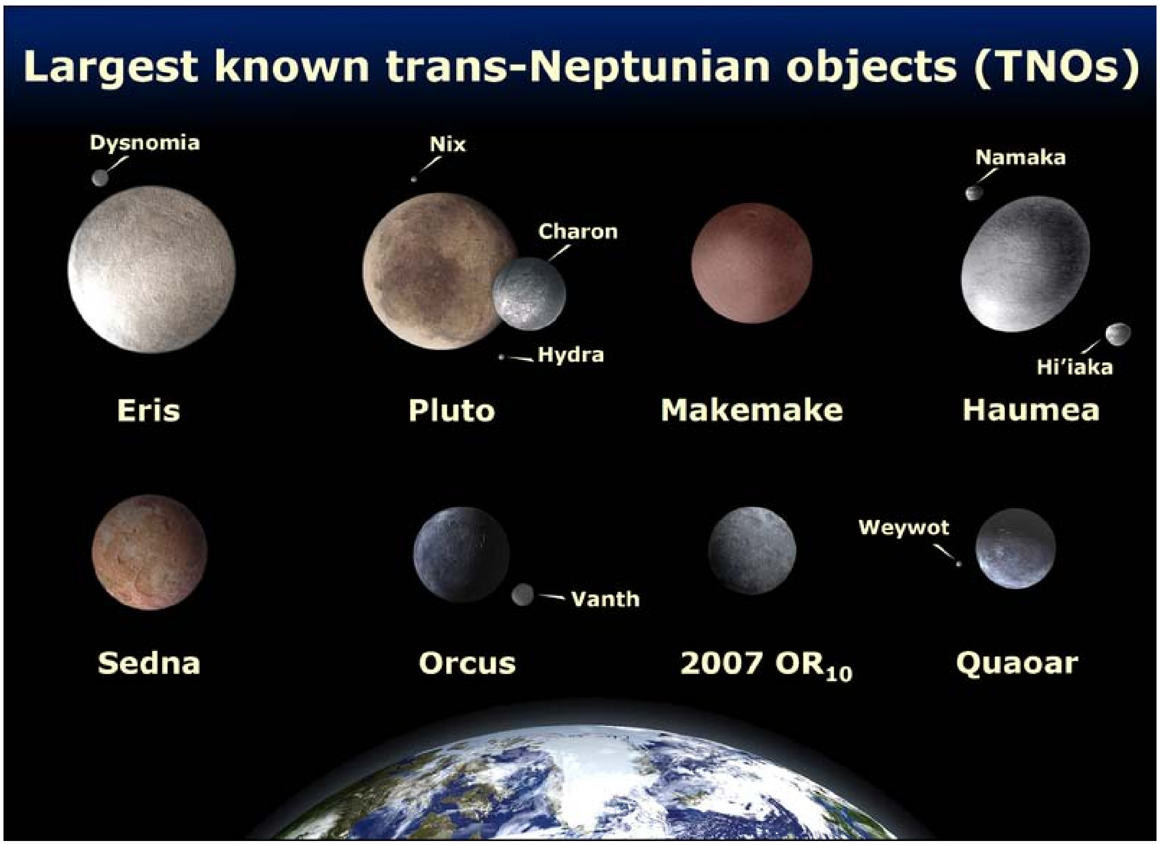
Even though Eris can be up to three times further from the Sun than Pluto, it approaches close enough that some of the ices on the surface might warm enough to sublimate. As methane is highly volatile, its presence shows either that Eris has always resided in the distant reaches of the Solar System where 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.

Chapter- 7

Plutoid



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

A **plutoid** is a trans-Neptunian dwarf planet. The International Astronomical Union (IAU) developed this category of astronomical objects as a consequence of its 2006 resolution defining the word "planet". The IAU's formal definition of 'plutoid,' announced 11 June 2008, is:

> Plutoids are celestial bodies in orbit around the Sun at a semimajor axis greater than that of Neptune that have sufficient mass for their self-gravity to overcome rigid body forces so that they assume a hydrostatic equilibrium (near-spherical)

shape, and that have not cleared the neighbourhood around their orbit. Satellites of plutoids are not plutoids themselves.

Accordingly, plutoids can be thought of as the intersection of the set of dwarf planets and the set of trans-Neptunian objects.

In light of the difficulty of remotely ascertaining hydrostasis, the IAU only formally confers "dwarf planet" (and by extension, "plutoid") status to those bodies whose minimum estimated size is substantially greater than what is generally thought necessary to guarantee hydrostatic equilibrium. As of 2009, Pluto, Eris, Haumea, and Makemake are the only objects officially recognized as plutoids, while upwards of seventy more bodies that currently lack formal recognition are thought likely to meet the definition, and can expect formal recognition at some time in the future.

Alan Stern of the Southwest Research Institute believes the outer planets show signs of collisions with plutoids 1,000 to 2,000 kilometers in diameter: Uranus could have been tipped off its axis by a plutoid, and Triton, the largest moon of Neptune, is probably a captured plutoid from the Kuiper Belt.

History of the term

On August 24, 2006, the IAU decided to re-classify Pluto as a dwarf planet, requiring that a planet must "clear the neighbourhood around its orbit."

The General Assembly of the IAU further resolved:

Pluto is [...] recognized as the prototype of a new category of Trans-Neptunian Objects.

This new category had been proposed under the name "*pluton*" or a "*plutonian object*" earlier in the General Assembly. The former was rejected, in part because "pluton" is actually a pre-existing geological term, and many geological experts wrote in complaints pointing this out. "Pluton" was dropped midway through the Assembly and was abandoned in the final draft resolution (6b); "Plutonian object" failed to win majority approval on a 183–186 vote in the IAU General Assembly on August 24, 2006.

The definition of the category also fluctuated during its early stages. When first proposed, the category (then named "pluton") defined members as planets whose rotation period around the Sun was more than 200 Julian years, and whose orbit was more highly inclined and more elliptical than a traditional planetary orbit. Once it had been counter-proposed to strip Pluto of planet status, this category of Pluto-like objects was then applied to dwarf planets that met the conditions of being trans-Neptunian and "like Pluto" in terms of period, inclination, and eccentricity. Ultimately, the final resolution left the formal definition, like the name, to be established at a later date.

Following the IAU General Assembly, the name "plutoid" was proposed by the members of the IAU Committee on Small Body Nomenclature (CSBN), accepted by the Board of

Division III, by the IAU Working Group for Planetary System Nomenclature (WGPSN) and approved by the IAU Executive Committee at its meeting in Oslo, Norway, on 11 June 2008. The term was announced after the Executive Committee meeting, along with a greatly-simplified definition: all trans-Neptunian dwarf planets are plutoids.

Analogous terminology

Prior to the emergence of the term "plutoid" as an IAU-sanctioned categorization, there had been some attempts at applying a title for this class of object.

The term *"ice dwarf"* saw some adoption as a near-synonym to the eventual term "plutoid". "Ice dwarf", however, also saw some use as an umbrella term for all so-called "distant minor planets" (trans-Neptunian objects plus centaurs) or other, broad applications; one attempted definition was that an ice dwarf "is larger than the nucleus of a normal comet and icier than a typical asteroid". There are large numbers of such objects in the Oort cloud and the Kuiper belt. However, it is not clear that all so-categorized ice dwarfs are actually icier than icy asteroids such as Ceres (now considered a dwarf planet). Nonetheless, Ceres is sometimes called a *terrestrial dwarf* to distinguish it from Pluto and Eris.

"Ice dwarf" as a term for an icy planetary body that generally orbits beyond Neptune was coined as part of a conception of a threefold division of the Solar System into inner *terrestrial planets*, central *gas giants*, and outer *ice dwarfs*, of which Pluto was the principal member. This conception foreshadowed the reclassification of Pluto to dwarf planet and plutoid after the discovery of Eris.

Naming process for plutoids

With the creation of the term "dwarf planet", some ambiguity was created as to which of two IAU bodies would be responsible for naming dwarf planets. Eris had been named through the IAU Committee on Small Body Nomenclature and the IAU Working Group for Planetary System Nomenclature working in cooperation with one another. Along with announcing the name "plutoid", the IAU decision of 11 June 2008 institutionalized this cooperative process involving the two bodies in the naming of new plutoids. In keeping with minor planet naming guidelines, priority will be given to names proposed by the discovery teams, and plutoids may not share a name with a small solar system body.

Complications related to "dwarf planet" definition

When the definition of "dwarf planet" was instated at the IAU General Assembly of 2006, Ceres, Pluto and Eris were identified by name as the initial members of the dwarf planet class. However, precise regulations as to how hydrostatic equilibrium would be measured were left undefined for the time being. Without an official procedure for calculating the lower bound of size to be a "dwarf planet", no further bodies could be formally recognized as either dwarf planets or plutoids.

It was noted that the naming process would remain stalled without such rules, and that even with them, few of these bodies can be imaged with sufficient resolution to determine their shapes. Therefore, the IAU announced that for naming purposes, a trans-Neptunian object will be *assumed to be a plutoid* if it has *an absolute magnitude brighter than H = +1 magnitude*.

Mathematically, the smallest possible object that could possess an absolute magnitude of +1 (a perfectly reflective one with an albedo of 1) would be 838 km in diameter. It is highly unlikely that any body of this size or larger, regardless of composition, would not also surpass whatever threshold is ultimately adopted as proof of hydrostatic equilibrium. That said, if it turns out upon further investigation that an object named as if it were a plutoid has *not* achieved hydrostatic equilibrium, the IAU has stated it will be reclassified, but keep its name.

This decision allowed for the naming of Makemake and Haumea, and their formal recognition as plutoids and dwarf planets, bringing the total number of official plutoids from 2 to 4.

Officially-recognized plutoids

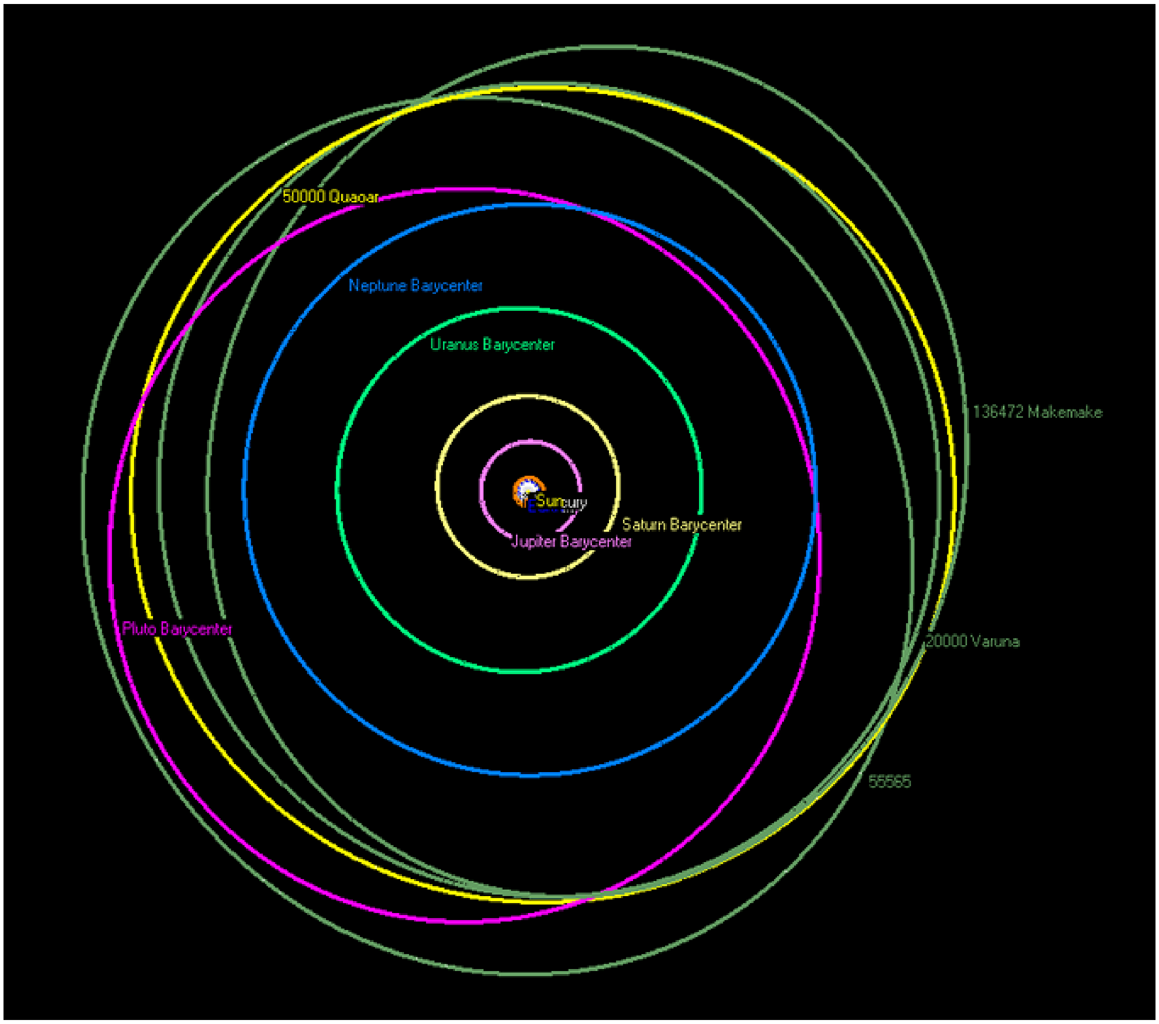
Four trans-Neptunian objects, Pluto, Eris, Haumea, and Makemake, are formally recognized as dwarf planets and therefore as plutoids.

Official Plutoids

Name	Pluto	Haumea	Makemake	Eris
Minor planet number	134340	136108	136472	136199
Absolute magnitude	−0.7	+0.00	-0.44	−1.19
Albedo	0.49–0.66	0.7 ± 0.1	0.8 ± 0.2	0.86 ± 0.07
Diameter	2306 km	~1960×1518×996 km	1300–1900 km	~2300 km
Mass in kg **compared to Earth**	1.305×10^{22} kg .0022	$(4.2 \pm 0.1)\times10^{21}$ kg .0007	$\sim4 \times 10^{21}$ kg .0007 *(est.)*	$(1.67 \pm 0.02) \times 10^{22}$ kg .0025
Density (in Mg/m^3)	2.03 ± 0.06	2.6–3.3	~2	2.3 ± 0.3
Equatorial gravity (in m/s^2)	0.58	~ 0.44 (varies)	~0.5	~0.8
Rotation period (d) (in sidereal	-6.387 18 (retrograde)	0.163 14	?	> 0.3 ?

days)				
Orbital radius* (AU) **semi-major axis in km**	29.66-49.30 39.481 686 77 5 906 376 200	35.2–51.5 43.3 6 484 000 000	38.5-53.1 45.8 6 850 000 000	37.77-97.56 67.668 1 10 210 000 000
Orbital period*(a) (in sidereal years)	248.09	285.4	309.88	557
Mean orbital speed (in km/s)	4.7490	4.484	4.419	3.436
Orbital eccentricity	0.248 807 66	0.188 74	0.159	0.441 77
Orbital inclination	17.141 75°	28.19°	28.96°	44.187°
Inclination of the equator from the orbit	119.61°			
Mean surface temperature (in K)	40	30	32±3	~30
Number of natural satellites	3	2	0	1
Date of discovery	February 18, 1930	December 28, 2004	March 31, 2005	October 21, 2003

Officially-unrecognized, but likely, plutoids



The orbit of Quaoar (yellow) and various other cubewanos compared to the orbit of Neptune (blue) and Pluto (pink).

Trans-Neptunian objects 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 April 2007 it was believed that another seventy Trans-Neptunian objects were likely to be plutoids.

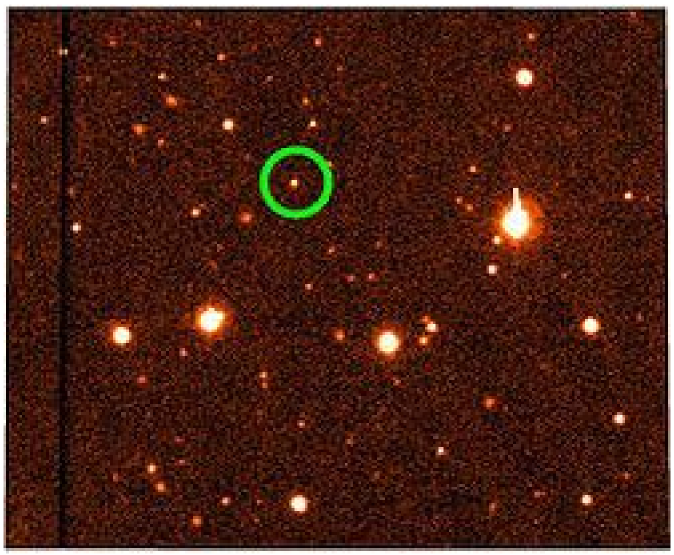
Prime plutoid candidates

Name	**Category**	**Estimated diameter** (km)				**Absolute Magnitude (H)**	**Mass (×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

Chapter- 8

90482 Orcus

90482 Orcus



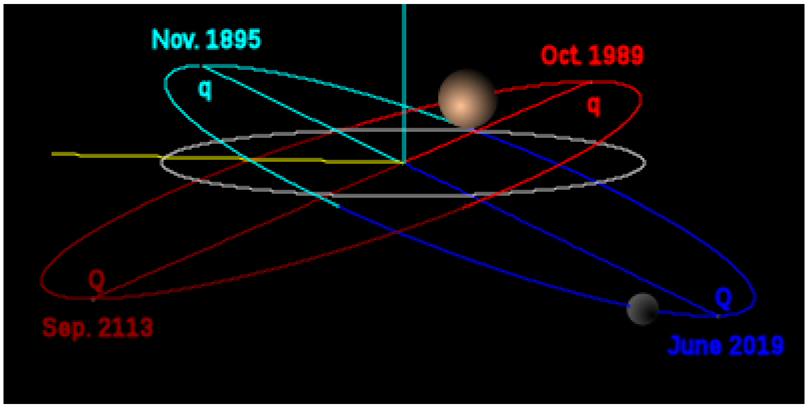
Discovery	
Discovered by	M. Brown, C. Trujillo, D. Rabinowitz
Discovery date	February 17, 2004
Designations	
MPC designation	90482 Orcus
Named after	Orcus
Alternate name(s)	2004 DW
Minor planet category	Plutino Plutoid candidate
Adjective	Orcean
Orbital characteristics	

Epoch July 23, 2010 (JD 2 455 400.5)	
Aphelion	7 191.17 Gm (48.07 AU)
Perihelion	4 528.33 Gm (30.27 AU)
Semi-major axis	5 860.18 Gm (39.173 AU)
Eccentricity	0.227 18
Orbital period	89 552 d (245.18 yr)
Mean anomaly	166.38°
Inclination	20.573°
Longitude of ascending node	268.606°
Argument of perihelion	73.031°
Satellites	Vanth
Physical characteristics	
Dimensions	946.3+74.1 −72.3 km 850 ± 90 km
Mass	$6.32 \pm 0.05 \times 10^{20}$ kg (system)
Mean density	1.5 ± 0.3 g/cm^3 (comparable to that of Charon)
Equatorial surface gravity	~0.23 m/s^2
Escape velocity	~0.44 km/s
Rotation period	10.08 ± 0.01 hr
Albedo	0.28 ± 0.04 19.75 +3.40 −2.76%
Temperature	<44 K
Spectral type	(neutral) B-V=0.68; V-R=0.37
Apparent magnitude	19.1 (opposition)
Absolute magnitude *(H)*	2.3 (2.27 ± 0.05) Moon: 4.88 ± 0.05

90482 Orcus is a large Kuiper belt object (KBO) with a large moon and is probably a dwarf planet. It was discovered on February 17, 2004 by Michael Brown of Caltech, Chad Trujillo of the Gemini Observatory, and David Rabinowitz of Yale University. Precovery images as early as November 8, 1951 were later identified. Orcus is a plutino, locked in a 3:2 resonance with Neptune, making two revolutions around the Sun, while Neptune makes three. This is much like Pluto, except that its orbit is constrained to always be in the opposite phase of its orbit from Pluto: Orcus is at aphelion when Pluto is at perihelion and vice versa. Because of this, along with its large moon Vanth that recalls Pluto's large moon Charon, Orcus has been seen as the **anti-Pluto**. This was a major consideration in selecting its name, as the deity Orcus was the Etruscan equivalent of the Roman Pluto, and later became an alternate name for Pluto.

The surface of Orcus is relatively bright with albedo reaching 30%, grey in color and water rich. The ice is predominantly in crystalline form, which may be related to past cryovolcanic activity. Other compounds like methane or ammonia may also be present. The existence of a satellite allowed astronomers to determine the mass of the system, which is approximately equal to that of the Saturnian moon Tethys. The ratio of masses of Orcus and Vanth is uncertain, possibly anywhere from 1:33 to 1:12. The diameter of Orcus is 800–900 km, while Vanth is thought to be 280 to 380 km, depending on what its albedo turns out to be.

Orbit and rotation



The orbits of Orcus (blue), Pluto (red) and Neptune (grey). Orcus and Pluto are shown in the April 2006 positions. The dates of their perihelia (q) and aphelia (Q) are also marked.

Orcus is a large plutino (an object in 2:3 orbital resonance with Neptune). Orcus's 247-year orbit is shaped similarly to Pluto's (both have perihelia above the ecliptic), but is differently oriented. Although at one point its orbit approaches that of Neptune, the resonance between the two bodies means that Orcus itself is always a great distance away from Neptune (there is always an angular separation of over 60 degrees between them). Over a 14,000 year period Orcus stays more than 18 AU from Neptune. Because their mutual resonance with Neptune constrains Orcus and Pluto to remain in opposite phases of their otherwise very similar motions, Orcus is sometimes described as the "anti-Pluto".

Orcus is currently 47.8 AU from the Sun and will come to aphelion (farthest distance from the Sun) in 2019. Simulations by the Deep Ecliptic Survey (DES) show that over the next 10 million years Orcus can acquire a perihelion distance (qmin) as small as 27.8 AU.

The rotation period is not known. Different photometric surveys have produced different results. Some show low amplitude variations with periods ranging from 7 to 21 hours, while others showed no variability. The value obtained by Ortiz *et al.*, about 10 hours, is often cited in the literature. The rotational poles of Orcus probably coincide with the orbital poles of its moon, Vanth. This means that Orcus is currently viewed pole-on, which could explain the near absence of any rotational modulation of its brightness. The true rotational period may coincide with the 9.5-day orbital period of Vanth.

Name

Under the guidelines of the International Astronomical Union's naming conventions, objects with a similar size and orbit to that of Pluto are named after underworld deities. Accordingly, the discoverers suggested naming the object after Orcus, a god of the dead in Etruscan and Roman mythology. The name was also a private reference to the homonymous Orcas Island, where Brown's wife Diane had lived as a child and which they visit frequently. *Orcus* was approved and published on November 22, 2004.

Physical characteristics

Size and magnitude

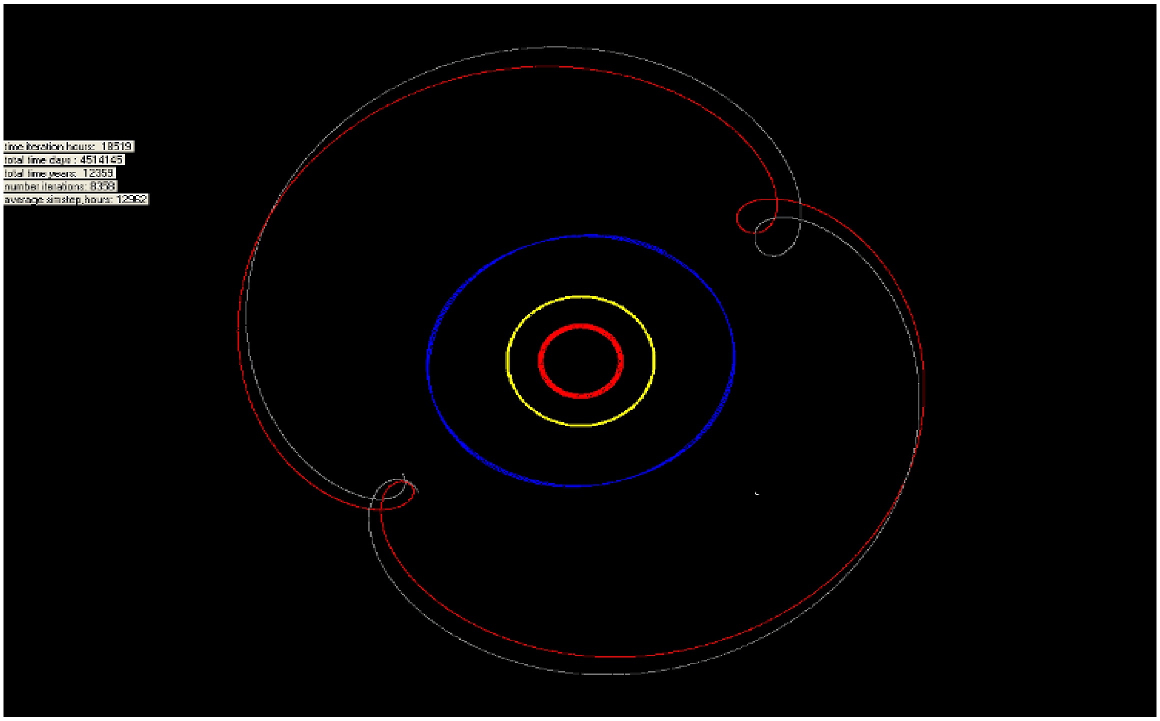
The absolute magnitude of Orcus is about 2.3 (comparable with the 2.6 of cubewano 50000 Quaoar). The detection of Orcus by the Spitzer space telescope in the far infrared and by Herschel Space Telescope in submillimeter constrains its diameter to 850^{+90}_{-90} km. Orcus appears to have an albedo of about 22% to 34%, which may be typical of trans-Neptunian objects approaching the 1000 km diameter range.

In the magnitude and size estimates reported above it was assumed that Orcus is a singular object. The presence of a relatively large satellite may change them considerably. The absolute magnitude of Vanth is estimated at 4.88, which means that it is about 11 times fainter than Orcus itself. If the albedos of both bodies are the same then the size of Orcus is about 900 km, while the size of Vanth is about 280 km. If, however, the albedo of Vanth is two times lower than that of Orcus then their sizes are 860 and 380 km, respectively.

Mass

Since Orcus is known to be a binary system, the mass of the system has been estimated to be $6.32 \pm 0.05 \times 10^{20}$ kg, or about 3.8% the mass of largest known dwarf planet Eris. How this mass is partitioned between Orcus and Vanth depends of their relative sizes. If the satellite's size is less than 1/3d of that of the primary, then its mass is only 3% of the total mass. On the other hand, if the size of Vanth is 380 km (see above), then its mass can be as high as 1/13 of the total system mass or about 8% of the mass of Orcus.

Spectra and surface

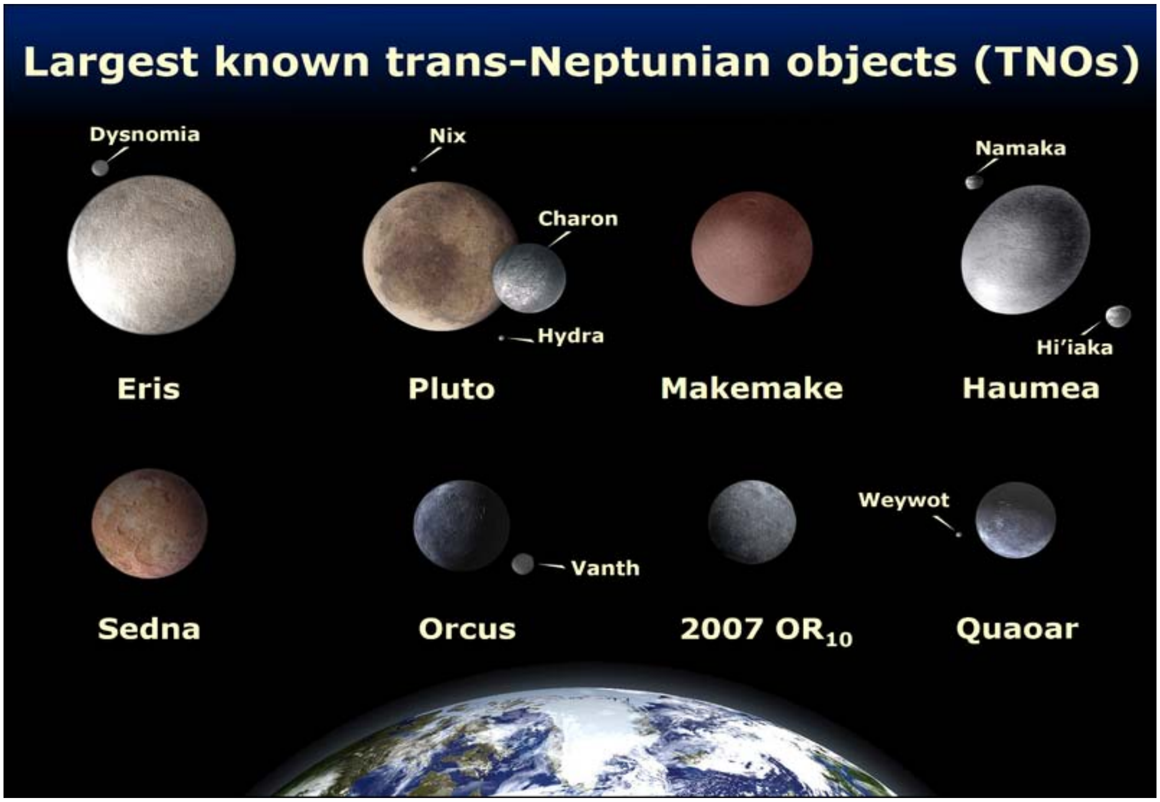


The orbital resonances of Orcus and Pluto in a rotating frame with a period equal to Neptune's orbital period. (Neptune is held stationary.)

The first spectroscopic observations in 2004 showed that the visible spectrum of Orcus is flat (neutral in color) and featureless, while in the near-infrared there were moderately strong water absorption bands at 1.5 and 2.0 µm. Thus Orcus appeared to be different from other Trans-Neptunian objects like Ixion with red visible and often featureless infrared spectra. Further Infrared observations in 2004 by the European Southern Observatory and the Gemini telescope give results consistent with mixtures of water ice and carbonaceous compounds, such as tholins. The water and methane ices can cover no more than 50% and 30% of the surface, respectively. This means the proportion of ice on the surface is less than on Charon, but similar to that on Triton.

Later in 2008–2010 new infrared spectroscopic observations with a higher signal-to-noise ratio revealed additional spectral features. Among them are a deep water ice absorption band at 1.65 µm, which is an evidence of the crystalline water ice on the surface of Orcus, and a new absorption band at 2.22 µm. The origin of the latter feature is not completely clear. It can be caused either by ammonia/ammonium dissolved in the water ice or by methane/ethane ices. The radiative transfer modeling showed that a mixture of water ice, tholins (as a darkening agent), ethane ice and ammonium ion ($NH^{+4}{}_4$) provides the best match to the spectra, while a combination of water ice, tholins, methane ice and ammonia hydrate gives a slightly inferior result. On the other hand, a mixture of only ammonia hydrate, tholins and water ice failed to provide a satisfactory match. So, as of 2010, the only reliably identified compounds on the surface of Orcus are crystalline water ice and, possibly, dark tholins. A firm identification of ammonia, methane and other hydrocarbons requires better infrared spectra.

Comparison with moons and other TNOs



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

Orcus straddles the edge for trans-Neptunian objects massive enough to retain volatiles such as methane on the surface. The reflectance spectrum of Orcus shows the deepest water ice absorption of any Kuiper belt object (KBO) that is not associated with the Haumea collisional family. The large icy satellites of Uranus have infrared spectra quite similar to that of Orcus. Among other trans-Neptunian objects Pluto's moon Charon appears to be most similar to Orcus. It has a higher albedo but very similar visible and near-infrared spectra. Their densities are also similar and both have water ice rich surfaces. Quaoar—a trans-Neptunian object of similar size—has strong water ice absorption features in its spectra but also has a very red color in the visible implying the presence of the ultrared matter on its surface. Dwarf planet Haumea and objects from its collisional family have much higher albedos and much deeper water absorption bands than Orcus. Finally, (208996) 2003 AZ84—another large object in 3:2 resonance with Neptune—has spectral properties very similar to Orcus.

Cryovolcanism

The presence of crystalline water ice, and possibly ammonia ice may indicate that a renewal mechanism was active in the past on the surface of Orcus. Ammonia so far has not been detected on any TNO or icy satellite of the outer planets other than Miranda. The 1.65 μm band on Orcus is broad and deep (12%), as on Charon, Quaoar, Haumea, and icy satellites of giant planets. On other hand the crystalline water ice on the surfaces of TNOs should be completely amorphized by the galactic and Solar radiation in about 10 million years. Some calculations indicate that cryovolcanism, which is considered one of the possible renewal mechanisms, may indeed be possible for TNOs larger than about 1000 km. Orcus may have experienced at least one such episode in the past, which turned the amorphous water ice on its surface into crystalline. The preferred type of volcanism may have been explosive aqueous volcanism driven by an explosive dissolution of methane from water–ammonia melts.

Satellite

Vanth could easily be 1/4th to 1/3rd the diameter of Orcus.

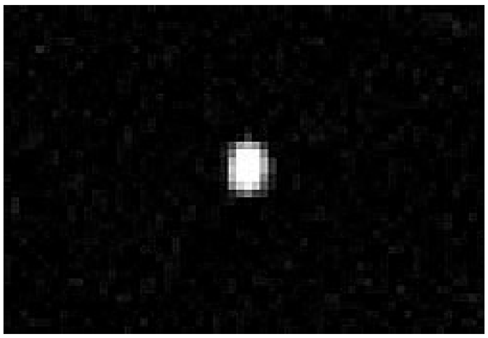
Using observations with the Hubble Space Telescope from November 13, 2005, Mike Brown and T.A. Suer detected a satellite. The discovery of a satellite of Orcus was reported in IAUC 8812 on 22 February 2007. The satellite was given the designation S/2005 (90482) 1 before later being named *Vanth*. It orbits Orcus in a nearly face-on circular orbit with an eccentricity less than 0.0036, and an orbital period of 9.53 days. Vanth orbits only 8980 ± 20 km from Orcus and is too close to Orcus for ground-based spectroscopy to determine the surface composition of the satellite. Mike Brown also suspects that like the Pluto-Charon system, Orcus and Vanth are likely tidally locked. Vanth does not resemble known collisional satellites because its spectrum is very different of that of primary, and may be a captured KBO.

On March 23, 2009, Brown asked readers of his weekly column to suggest possible names for the satellite, with the best one to be submitted to the International Astronomical Union (IAU) on April 5. The name Vanth, after the Etruscan goddess who guided the souls of the dead to the underworld, was eventually chosen from among a large pool of submissions. This submission will be assessed by the IAU's Committee for Small Body Nomenclature, which will vote on whether to approve it, in accordance with the normal object naming procedures.

Chapter- 9

50000 Quaoar

50000 Quaoar



Sum of 16 Hubble exposures registered on Quaoar

Discovery and designation	
Discovered by	Chad Trujillo, Michael Brown
Discovery date	2002 Jun 05 10:48:08 PDT on an image taken 2002 June 04 05:41:40 UT

Designations	
Named after	Quaoar
Alternate name(s)	2002 LM_{60}
Minor planet category	Cubewano

Orbital characteristics	
Epoch July 23, 2010 (JD 2 455 400.5)	
Aphelion	6.749 189 Tm (45.116 AU)
Perihelion	6.237 516 Tm (41.695 AU)
Semi-major axis	6.493 353 Tm (43.405 AU)
Eccentricity	0.039 4
Orbital period	104 451.3 d (285.97 a)

Average orbital speed	4.52 km/s
Mean anomaly	280.554°
Inclination	7.996°
Longitude of ascending node	189.033°
Argument of perihelion	155.624°
Satellites	Weywot (~74 km diameter)
Physical characteristics	
Dimensions	890 ± 70 km 844^{+207}_{-190} km (thermal)
Mass	1.6 ± 0.3 ×10^{21} kg 0.12 Eris masses
Mean density	4.2±1.3 g/cm^3 3.5 g/cm^3 2.8 g/cm^3 (assuming moon highly eccentric)
Equatorial surface gravity	0.276–0.376 m/s^2
Equatorial escape velocity	0.523–0.712 km/s
Geometric albedo	$0.199^{+0.13}_{-0.07}$
Temperature	~43 K
Spectral type	(moderately red) B-V=0.94, V-R=0.64
Apparent magnitude	19.3
Absolute magnitude *(H)*	2.7

50000 Quaoar is a binary trans-Neptunian object and dwarf planet candidate orbiting the Sun in the Kuiper belt. It was discovered on June 4, 2002 by astronomers Chad Trujillo and Michael Brown at the California Institute of Technology from images acquired at the Samuel Oschin Telescope at Palomar Observatory.

Discovery

The discovery of Quaoar, a magnitude 18.5 object located in the constellation Ophiuchus, was announced on October 7, 2002, at a meeting of the American Astronomical Society. The earliest prediscovery image proved to be a May 25, 1954 plate from Palomar Observatory. It may qualify as a dwarf planet, given its size inferred from direct observation by the Hubble Space Telescope.

Name

Size estimates:

Year	Diameter
2004	1260 km
2007	844 km
2010	890 km

Quaoar is named for the Tongva creator god, following International Astronomical Union naming conventions for non-resonant Kuiper belt objects. The Tongva are the native people of the area around Los Angeles, where the discovery of Quaoar was made. Prior to IAU approval of the name, Quaoar went by the provisional designation **2002 LM_{60}**. The minor planet number 50000 was not coincidence, but chosen to commemorate a particularly large object found in the search for a Pluto-sized object in the Kuiper belt, parallel to the similarly numbered 20000 Varuna. However, later even larger discoveries were simply numbered according to the order in which their orbits were confirmed.

Size

In 2004, Quaoar was estimated to have a diameter of 1260 ± 190 km, which at the time of discovery in 2002 made it the largest object found in the solar system since the discovery of Pluto. Quaoar was later supplanted by Eris, Sedna, Haumea, and Makemake. In addition, the subsequently discovered plutino Orcus is about the same size as Quaoar but Quaoar is notably more massive. It is roughly one tenth the diameter of Earth, one third the diameter of the Moon or half the size of Pluto.

Quaoar was the first trans-Neptunian object to be measured *directly* from Hubble Space Telescope (HST) images, using a new, sophisticated method. Given its distance Quaoar is on the limit of the HST resolution (40 Milliarcseconds) and its image is consequently "smeared" on a few adjacent pixels. By comparing carefully this image with the images of stars in the background and using a sophisticated model of HST optics (point spread function (PSF)), Brown and Trujillo were able to find the best fit disk size which would give a similar blurred image. This method was recently applied by the same authors to measure the size of Eris.

The uncorrected 2004 HST estimates only marginally agree with the 2007 infrared measurements by the Spitzer Space Telescope which suggest a brighter albedo (0.19) and consequently a smaller diameter ($844.4^{+206.7}_{-189.6}$ km). During the 2004 HST observations, little was known about the surface properties of Kuiper belt objects, but we now know that the surface of Quaoar is in many ways similar to those of the icy satellites of Uranus and Neptune. Adopting a Uranian-satellite limb darkening profile suggests that the 2004 HST size estimate for Quaoar was approximately 40% too large, and that a more proper estimate would be about 900 km. Using a weighted average of the Spitzer and corrected HST estimates, Quaoar, as of 2010, can be estimated at about 890 ± 70 km in diameter.

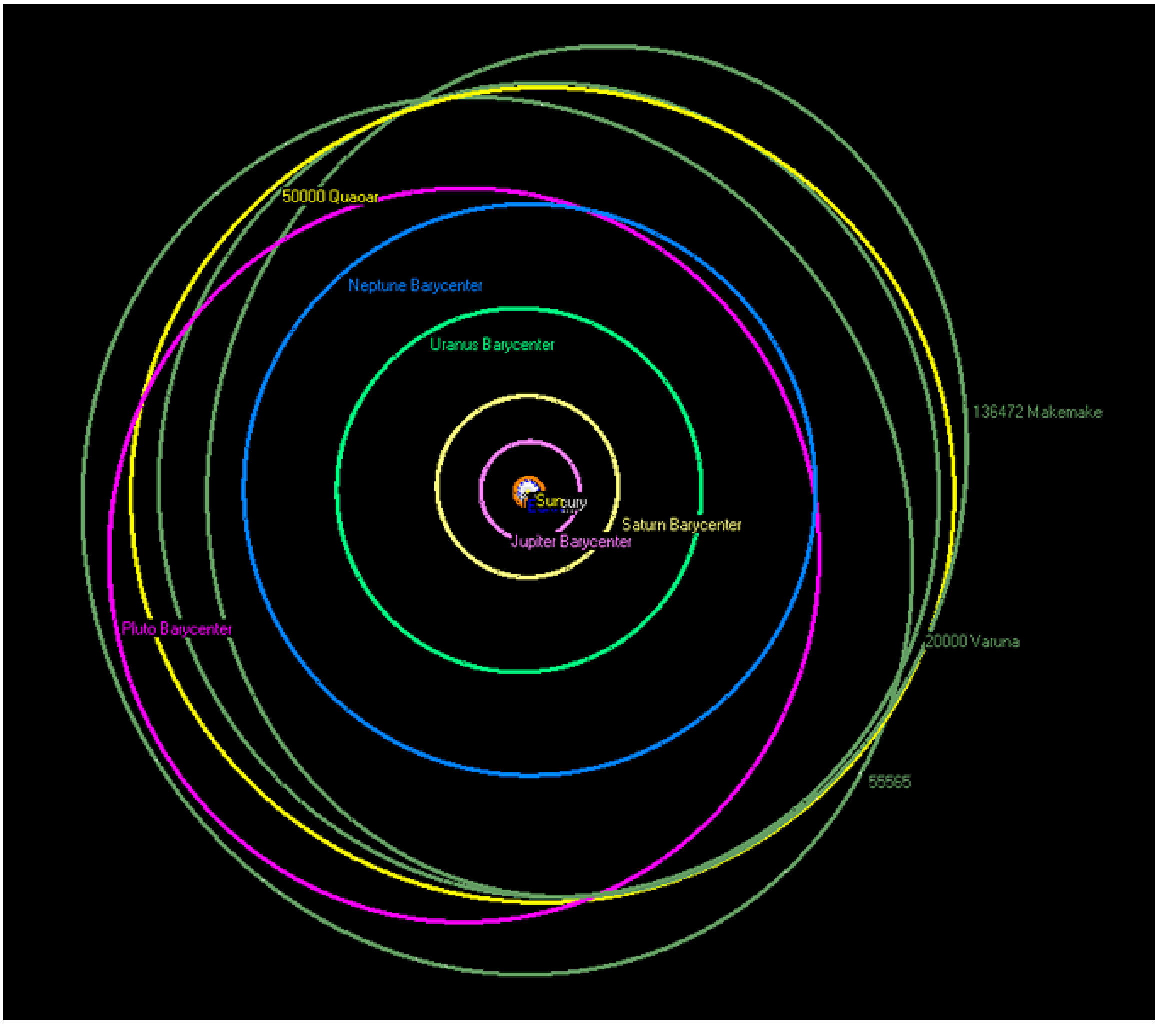
Dwarf planet?

Since Quaoar is a binary object, the mass of system can be calculated from the orbit of the secondary. Quaoar's estimated density of around 4.2 g/cm^3 and estimated size of 890 km suggests that it should qualify as a dwarf planet if the mass required for hydrostatic equilibrium is proven. Mike Brown estimates that rocky bodies around 900 km in diameter relax into hydrostatic equilibrium, and that icy bodies relax into hydrostatic equilibrium around 400 km. With an estimated mass greater than 1.3×10^{21} kg, Quaoar probably has the mass required (5×10^{20} kg) for being considered a dwarf planet under the 2006 IAU draft definition of a planet.

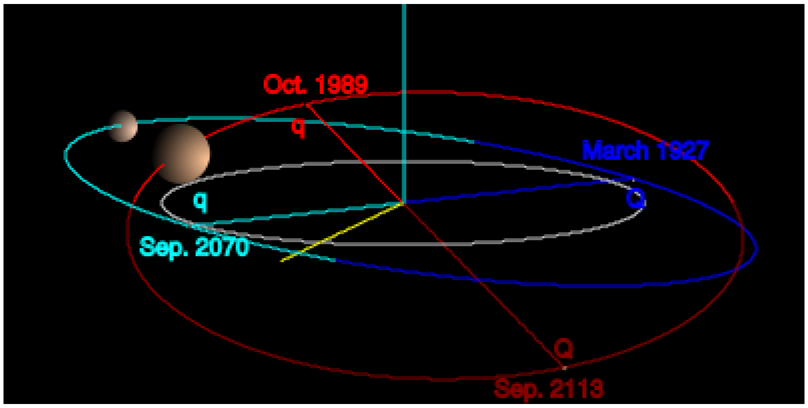
Hit-and-run collision

Planetary scientist Erik Asphaug has suggested that Quaoar may have collided with a dwarf planet up to the size of Mars, stripping the lower density mantle from Quaoar, and leaving behind the denser core. He envisions that Quaoar was originally covered by a mantle of ice that made it 300 to 500 kilometers bigger than it is today, and that it collided with another Kuiper-belt body about twice its size—an object roughly the diameter of Pluto, possibly Pluto itself.

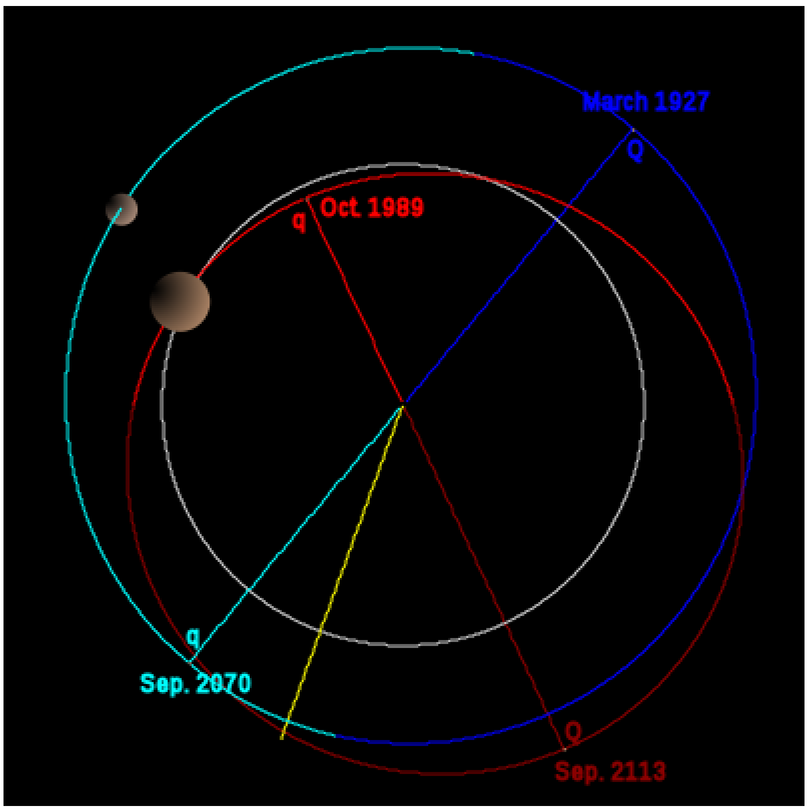
Orbit



The orbit of Quaoar (yellow) and various other cubewanos compared to the orbit of Neptune (blue) and Pluto (pink).



Orbits of Quaoar and Pluto - ecliptic view.



Orbits of Quaoar (blue) and Pluto (red) - polar view.

Quaoar orbits at about 43 astronomical units (6.4×10^9 km; 4.0×10^9 mi) from the Sun with an orbital period of 286 years.

The orbit is near-circular and moderately-inclined at approximately 8°, typical for the population of small classical Kuiper Belt object (KBO) but exceptional among the large KBO. Varuna, Haumea, and Makemake are all on highly inclined, more eccentric orbits.

Quaoar is the largest body that is classified as a cubewano by both the Minor Planet Center and the Deep Ecliptic Survey.

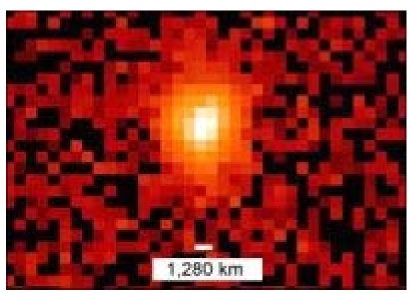
The polar view compares the near-circular Quaoar's orbit to highly eccentric (e=0.25) orbit of Pluto (Quaoar's orbit in blue, Pluto's in red, Neptune in grey). The spheres illustrate the current (April 2006) positions, relative sizes and colours. The perihelia (q), aphelia (Q) and the dates of passage are also marked.

At 43 AU and a near-circular orbit, Quaoar is not significantly perturbed by Neptune, unlike Pluto which is in 2:3 orbital resonance with Neptune. The ecliptic view illustrates the relative inclinations of the orbits of Quaoar and Pluto. Note that Pluto's aphelion is beyond (and below) Quaoar's orbit, so that Pluto is closer to the Sun than Quaoar at some times of its orbit, and farther at others.

As of 2008, Quaoar is currently only 14 AU from Pluto making it the closest large body to the Pluto-Charon system. By Kuiper Belt standards this is very close.

Physical characteristics

With a density estimated to be around 4.2±1.3 g/cm^3, Quaoar is believed to be a mixture of mostly rock with some ice and is possibly the densest known object in the Kuiper belt. Even dwarf planet Haumea is only estimated to have a density of 2.6 g/cm^3. The albedo could be as low as 0.1, which would still be much higher than the lower estimate of 0.04 for Varuna. This may indicate that fresh ice has disappeared from Quaoar's surface. The surface is moderately red, meaning that the object is relatively more reflective in the red and near-infrared than in the blue. 20000 Varuna and 28978 Ixion are also moderately red in the spectral class. Larger KBOs are often much brighter because they are covered in more ice and have a higher albedo, and thus they present a neutral colour.



Hubble photo used to measure size of Quaoar.

Cryovolcanism

In 2004, scientists were surprised to find signs of crystalline ice on Quaoar, indicating that the temperature rose to at least −160 °C (110 K or −260 °F) sometime in the last ten million years.

Speculation began as to what could have caused Quaoar to heat up from its natural temperature of −220 °C (55 K or −360 °F). Some have theorized that a barrage of mini-meteors may have raised the temperature, but the most discussed theory speculates that cryovolcanism may be occurring, spurred by the decay of radioactive elements within Quaoar's core.

Since then (2006), crystalline water ice was also found on Haumea, but present in larger quantities and thought to be responsible for the very high albedo of that object (0.7).

More precise (2007) observations of Quaoar's near infrared spectrum indicate the presence of small (5%) quantity of (solid) methane and ethane. Given its boiling point (112 K), methane is a volatile ice at average Quaoar surface temperatures, unlike water ice or ethane (boiling point 185 K). Both models and observations suggest that only a few larger bodies (Pluto, Eris, Makemake) can retain the volatile ices while the dominant population of small TNOs lost them. Quaoar, with only small amounts of methane, appears to be in an intermediary category.

If the *New Horizons* mission visits several Kuiper Belt Objects after visiting Pluto in 2015, our knowledge of the surfaces of small KBOs should improve but encounters with large objects seem unlikely.

Satellite

Artist's conception of the moderately red Quaoar and its moon Weywot.

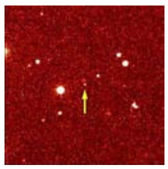
Quaoar has one known satellite, Weywot, formally (50000) Quaoar I Weywot. Its discovery was reported in IAUC 8812 on 22 February 2007. The satellite was found at 0.35 arcsec from Quaoar with an apparent magnitude difference of 5.6. It orbits at a distance of 14,500 km from the primary and has an orbital eccentricity of about 0.14. Assuming an equal albedo and density to the primary, the apparent magnitude suggests that the moon has a diameter of about 74 km (1:12 of Quaoar). Brown believes it is likely to be a collisional fragment of Quaoar, which he speculates lost much of its ice mantle in the process. Weywot is estimated to only have 1:2000 the mass of Quaoar.

Brown left the choice of a name up to the Tongva, who chose the sky god Weywot, son of Quaoar. The name was made official in MPC #67220 published on October 4, 2009.

Chapter- 10

90377 Sedna

90377 Sedna



Discovery image of Sedna (identified by the yellow arrow)

Discovery	
Discovered by	Michael E. Brown, C. Trujillo, D. Rabinowitz
Discovery date	November 14, 2003
Designations	
MPC designation	90377 Sedna
Named after	Sedna
Alternate name(s)	2003 VB_{12}
Minor planet category	Trans-Neptunian object detached object
Orbital characteristics	
Epoch 2010-Jul-23 (JD 2455400.5)	
Aphelion	960.78 AU (Q) 1.437×10^{14} m 143.7 Tm
Perihelion	76.361 AU (q) $1.142\ 3 \times 10^{13}$ m 11.423 Tm
Semi-major axis	518.57 AU (a) $7.757\ 6 \times 10^{13}$ m

	77.576 Tm
Eccentricity	0.8527
Orbital period	around 4,313,319 d (11,809 yr)
Average orbital speed	1.04 km/s
Mean anomaly	358.01°
Inclination	11.927°
Longitude of ascending node	144.26°
Argument of perihelion	311.02°
Physical characteristics	
Dimensions	1,200–1,600 km <1,600 km
Mass	1.8–4.3 x 10^{21} kg
Mean density	2.0? g/cm^3
Equatorial surface gravity	0.33–0.50 m/s^2
Escape velocity	0.62–0.95 km/s
Sidereal rotation period	0.42 d (10 h)
Albedo	0.16–0.30
Temperature	~12 K
Spectral type	(red) B-V=1.24; V-R=0.78
Apparent magnitude	21.1 20.5 (Perihelic)
Absolute magnitude *(H)*	1.58

90377 Sedna is a trans-Neptunian object discovered in 2003, which currently lies about three times as far from the Sun as Neptune. However, its farthest orbital distance from the Sun is estimated to be 960 astronomical units (32 times Neptune's distance) and thus it is, for most of its orbit, one of the most distant known objects in the Solar System after long-period comets.

Roughly two-thirds the size of Pluto, Sedna is theoretically large enough to be rounded by its own gravity, and thus would qualify as a dwarf planet under current definitions. However, its distance from the Sun makes determining its shape difficult. Spectroscopy has revealed that Sedna's surface composition is similar to that of some other trans-Neptunian objects, being largely a mixture of water, methane and nitrogen ices with tholins. Its surface is one of the reddest in the Solar System.

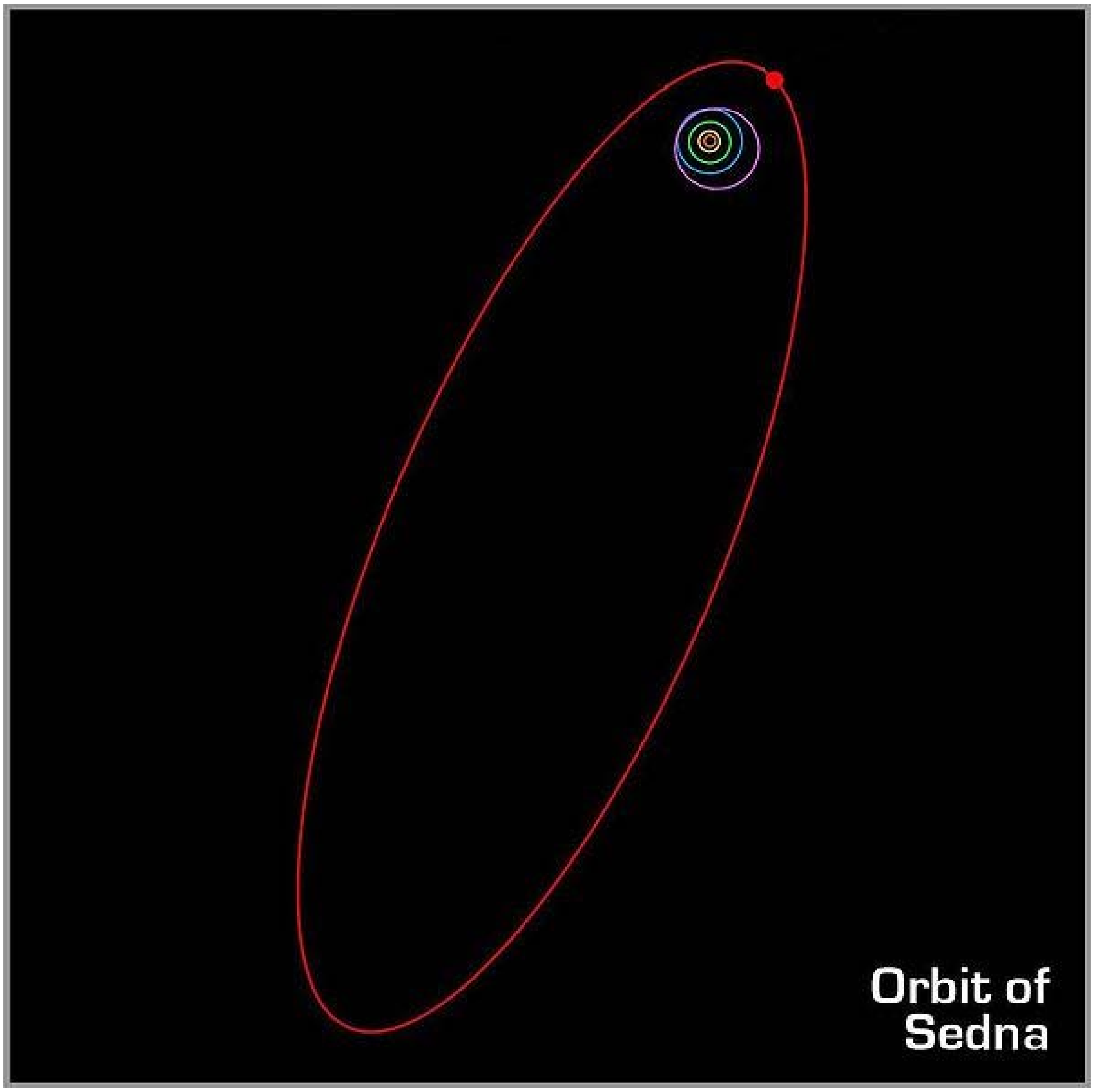
Sedna's exceptionally long and elongated orbit, taking approximately 12,000 years to complete, and distant point of closest approach to the Sun, at 76 AU, have led to much speculation as to its origin. The Minor Planet Center currently places Sedna in the scattered disc, a group of objects sent into highly elongated orbits by the gravitational influence of Neptune. However, this classification has been contested, as Sedna never comes close enough to Neptune to have been scattered by it, leading some astronomers to conclude that it is in fact the first known member of the inner Oort cloud. Others speculate that it might have been tugged into its current orbit by a passing star, perhaps one within the Sun's birth cluster, or even that it was captured from another star system. Another hypothesis suggests that its orbit may be evidence for a large planet beyond the orbit of Neptune. Astronomer Michael E. Brown, co-discoverer of Sedna and the dwarf planets Eris, Haumea, and Makemake, believes it to be the most scientifically important trans-Neptunian object found to date, as understanding its unusual orbit is likely to yield valuable information about the origin and early evolution of the Solar System.

Discovery and naming

Sedna (provisionally designated **2003 VB_{12}**) was discovered by Mike Brown (Caltech), Chad Trujillo (Gemini Observatory) and David Rabinowitz (Yale University) on November 14, 2003. The discovery formed part of a survey begun in 2001 with the Samuel Oschin telescope at Palomar Observatory near San Diego, California using Yale's 160 megapixel Palomar Quest camera. On that day, an object was observed to move by 4.6 arcseconds over 3.1 hours relative to stars, which indicated that its distance was about 100 AU. Follow-up observations in November–December 2003 with the SMARTS telescope at Cerro Tololo Inter-American Observatory in Chile as well as with the Tenagra IV telescope at the W. M. Keck Observatory in Hawaii revealed that the object was moving along a distant highly eccentric orbit. Later the object was identified on older precovery images made by the Samuel Oschin telescope as well as on images from the Near Earth Asteroid Tracking consortium. These previous positions expanded its known orbital arc and allowed a more precise calculation of its orbit.

"Our newly discovered object is the coldest most distant place known in the Solar System," said Mike Brown on his website, "so we feel it is appropriate to name it in honour of Sedna, the Inuit goddess of the sea, who is thought to live at the bottom of the frigid Arctic Ocean." Brown also suggested to the International Astronomical Union's (IAU) Minor Planet Center that any future objects discovered in Sedna's orbital region should also be named after entities in arctic mythologies. The team made the name "Sedna" public before the object had been officially numbered. Brian Marsden, the head of the Minor Planet Center, complained that such an action was a violation of protocol, and that some members of the IAU might vote against it. However, no objection was raised as to the name itself, and no competing names were suggested. The IAU's Committee on Small Body Nomenclature formally accepted the name in September 2004, and also considered that, in similar cases of extraordinary interest, it might in future allow names to be announced before they were officially numbered.

Orbit and rotation

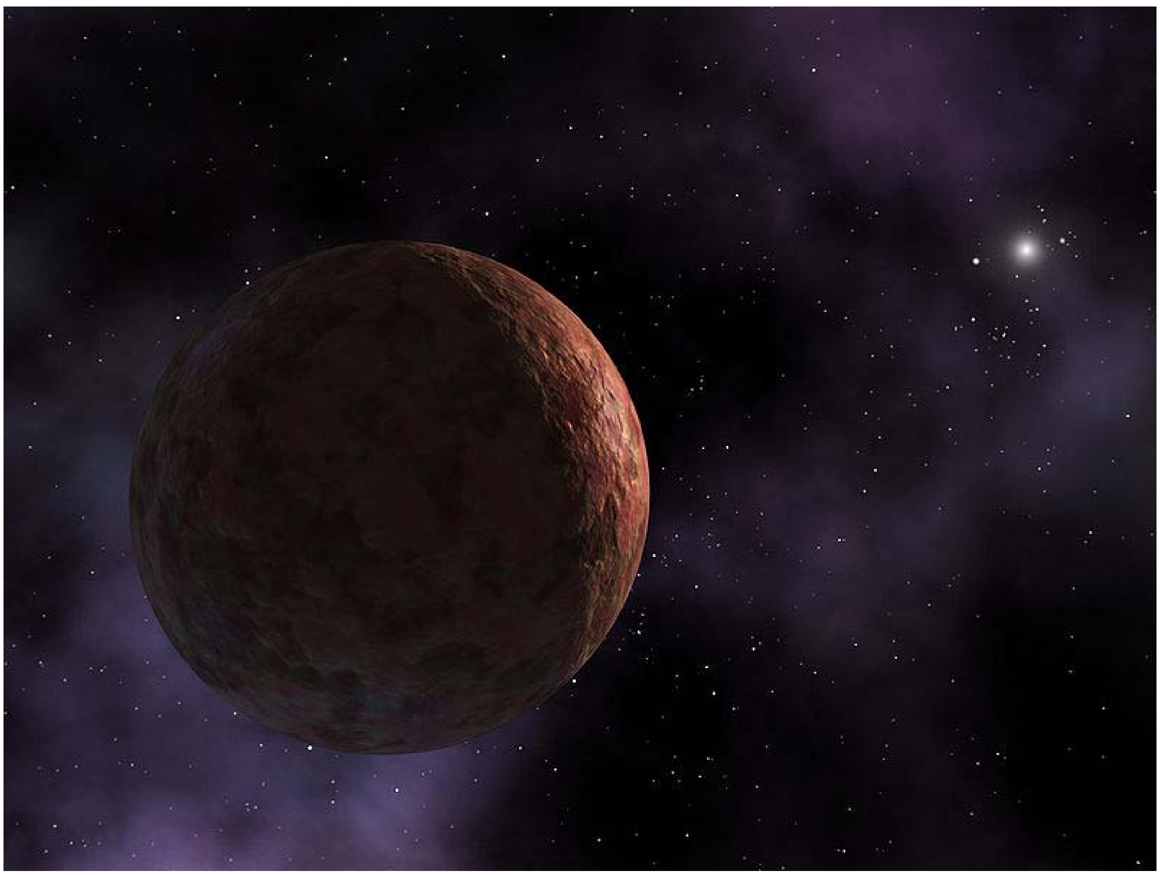


The orbit of Sedna (red) set against the orbits of Jupiter (orange), Saturn (yellow), Uranus (green), Neptune (blue), and Pluto (purple)

Barring comets and a handful of small solar system bodies, Sedna has the longest orbital period of any known object in the Solar System, calculated at between 11,800 and 12,100 years. This represents a best-fit solution, as Sedna has only been observed over a brief part of its orbital arc. Its orbit is extremely eccentric, with an aphelion estimated at 960 AU and a perihelion at about 76 AU. At its discovery it was approaching perihelion at 89.6 AU from the Sun, and was the most distant object in the Solar System yet observed. Eris was later detected by the same survey at 97 AU. Although the orbits of some long-period comets extend farther than that of Sedna, they are too dim to be discovered except when approaching perihelion in the inner Solar System. Even as Sedna nears its perihelion in late 2075 to mid 2076, the Sun would appear merely as a bright star in its sky: with an angular diameter too small to resolve as a disc, it would be only 100 times brighter than a full Moon on Earth.

When first discovered, Sedna was thought to have an unusually long rotational period (20 to 50 days). It was initially speculated that Sedna's rotation was slowed by the gravitational pull of a large binary companion, similar to Pluto's moon Charon. A search for such a satellite by the Hubble Space Telescope in March 2004 found nothing, and subsequent measurements from the MMT telescope suggest a much shorter rotation period, only about 10 hours, rather typical for bodies of its size.

Physical characteristics



Artist's impression of 90377 Sedna

Sedna has an absolute magnitude (H) of 1.6, and it is estimated to have an albedo of 0.16 to 0.30, thus giving it a diameter between 1,200 and 1,600 km. At the time of its discovery it was the largest object found in the Solar System since the discovery of Pluto in 1930. Mike Brown and colleagues now believe it to be the fifth largest known trans-Neptunian object after Eris, Pluto, Makemake, and Haumea. In 2004, the discoverers placed an upper limit of 1,800 km on its diameter, but by 2007 this was revised downward to less than 1,600 km after observation by the Spitzer Space Telescope. As Sedna has no known moons, determining its mass is very difficult. However, if the above estimates for its diameter are coupled with Pluto's density of 2.0 g/cm^3, the resultant estimated mass range is 1.8–4.3 x 10^{21} kg.

Observations from the SMARTS telescope show that in visible light Sedna is one of the reddest objects in the Solar System, nearly as red as Mars. Chad Trujillo and his colleagues suggest that Sedna's dark red colour is caused by a surface coating of hydrocarbon sludge, or tholin, formed from simpler organic compounds after long exposure to ultraviolet radiation. Its surface is homogeneous in colour and spectrum; this may be because Sedna, unlike objects nearer the Sun, is rarely impacted by other bodies, which would expose bright patches of fresh icy material like that on 8405 Asbolus. Sedna and two other very distant objects ((87269) 2000 OO_{67} and 2006 SQ_{372}) share their colour with outer classical Kuiper belt objects and the centaur 5145 Pholus, suggesting a similar region of origin.

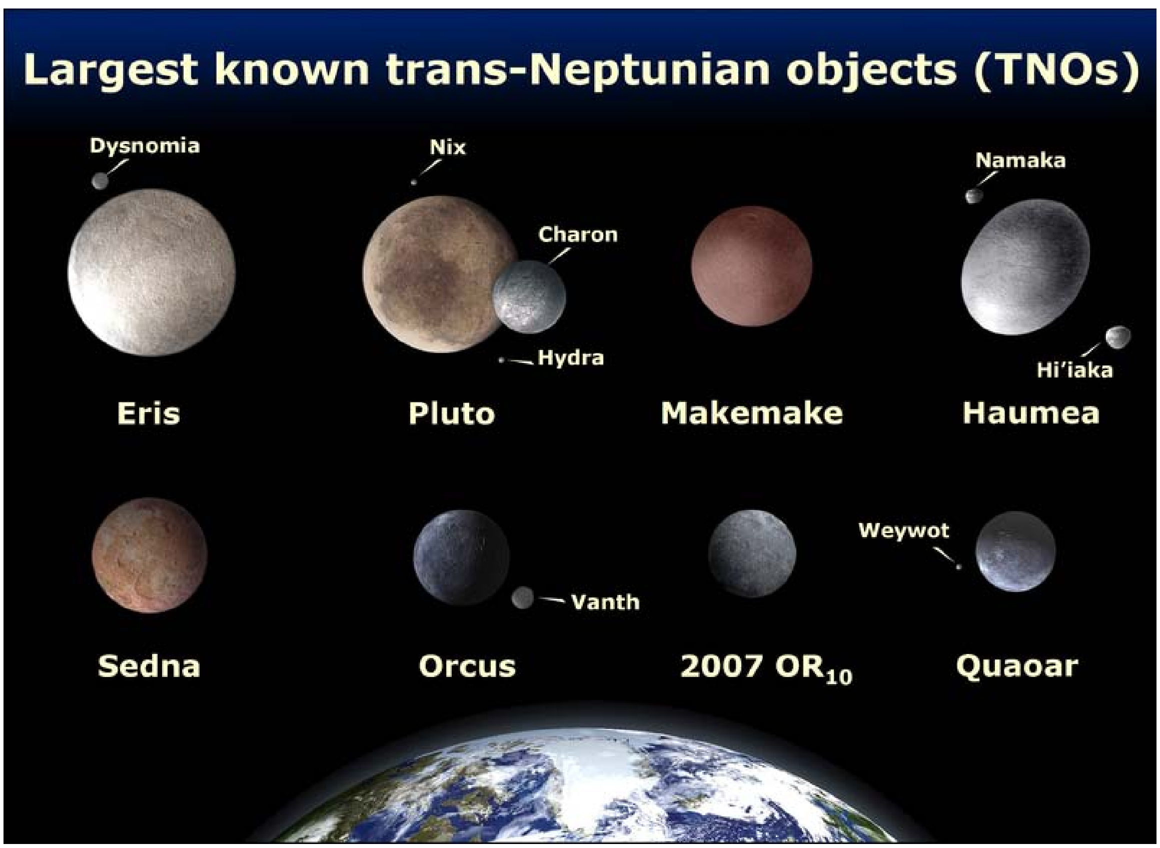
Trujillo and colleagues have placed upper limits in Sedna's surface composition of 60% for methane ice and 70% for water ice. The presence of methane further supports the existence of tholins on Sedna's surface, as they are produced by irradiation of methane. Barucci and colleagues compared Sedna's spectrum with that of Triton and detected weak absorption bands belonging to methane and nitrogen ices. From these observations, they suggested the following model of the surface: 24% Triton-type tholins, 7% amorphous carbon, 10% nitrogen, 26% methanol and 33% methane. The detection of methane and water ices was confirmed in 2006 by Spitzer Space Telescope mid-infrared photometry. The presence of nitrogen on the surface suggests the possibility that, at least for a short time, Sedna may possess an atmosphere. A 200-year period exists around its perihelion during which Sedna's surface temperature may rise above the 35.6 K (−237.6 °C) minimum required for nitrogen to sublimate from solid to gas. However, its deep red spectral slope is indicative of high concentrations of organic material on its surface, and its weak methane absorption bands indicate that methane on Sedna's surface is ancient, rather than freshly deposited. This means that Sedna is too cold for methane to evaporate from its surface and then fall back as snow, as happens on Triton and probably on Pluto.

Origin

In their paper announcing the discovery of Sedna, Mike Brown and his colleagues described it as the first observed body belonging to the Oort cloud, the hypothetical cloud of comets thought to exist nearly a light-year from the Sun. They observed that, unlike scattered disc objects such as Eris, Sedna's perihelion (76 AU) is too distant for it to have been scattered by the gravitational influence of Neptune. Because it is a great deal closer to the Sun than was expected for an Oort cloud object, and has an inclination roughly in line with the planets and the Kuiper belt, they described the planetoid as being an "inner Oort cloud object", situated in the disc reaching from the Kuiper belt to the spherical part of the cloud.

If Sedna formed in its current location, the Sun's original protoplanetary disc must have extended as far as 11 billion km into space. Also, Sedna's initial orbit must have been circular, otherwise its formation by the accretion of smaller bodies into a whole would not have been possible, as the large relative velocities between planetesimals would have been too disruptive. Therefore, it must have been tugged into its current eccentric orbit by a gravitational interaction with another body. In their initial paper, Brown, Rabinowitz and colleagues suggested three possible candidates for the perturbing body: an unseen planet beyond the Kuiper belt, a single passing star, or one of the young stars embedded with the Sun in the stellar cluster in which it formed.

Mike Brown and his team favored the hypothesis that Sedna was lifted into its current orbit by a star from the Sun's birth cluster, arguing that Sedna's aphelion of about 1,000 AU, which is relatively close compared to those of long period comets, is not distant enough to be affected by passing stars at their current distances from the Sun. They propose that Sedna's orbit is best explained by the Sun's having formed in an open cluster of several stars that gradually disassociated over time. That hypothesis has also been advanced by both Alessandro Morbidelli and Scott J. Kenyon. Computer simulations by Julio A. Fernandez and Adrian Brunini suggest that multiple close passes by young stars in such a cluster would pull many objects into Sedna-like orbits. A study by Morbidelli and Hal Levison suggested that the most likely explanation for Sedna's orbit was that it had been perturbed by a close (approximately 800 AU) pass by another star in the first 100 million years or so of the Solar System's existence.



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

The trans-Neptunian planet hypothesis has been advanced in several forms by a number of astronomers, including Gomes and Patryk Lykawka. One scenario involves perturbations of Sedna's orbit by a hypothetical planetary-sized body in the inner Oort cloud. Recent simulations show that Sedna's orbital traits could be explained by perturbations by a Neptune-mass object at 2,000 AU (or less), a Jupiter-mass at 5,000 AU, or even an Earth-mass object at 1,000 AU. Computer simulations by Patryk Lykawka have suggested that Sedna's orbit may have been caused by a body roughly the size of Earth, ejected outward by Neptune early in the Solar System's formation and currently in an elongated orbit between 80 and 170 AU from the Sun. Mike Brown's various sky surveys have not detected any Earth-sized objects out to a distance of about 100 AU. However, it is possible that such an object may have been scattered out of the Solar System after the formation of the inner Oort cloud.

It has been suggested that Sedna's orbit is the result of influence by a large binary companion to the Sun, thousands of AU distant. One such hypothetical companion is Nemesis, a dim companion to the Sun which has been proposed to be responsible for the supposed periodicity of mass extinctions on Earth from cometary impacts, the lunar impact record, and the common orbital elements of a number of long period comets. However, to date, no direct evidence of Nemesis has been found. John J. Matese and Daniel P. Whitmire, longtime proponents of the possibility of a wide binary companion to the Sun, have suggested that an object of five times the mass of Jupiter lying at roughly 7850 AU from the Sun could produce a body in Sedna's orbit.

Morbidelli and Kenyon have also suggested that Sedna did not originate in our Solar System, but was captured by the Sun from a passing extrasolar planetary system, specifically that of a brown dwarf about 20 times less massive than the Sun.

Population

Sedna's highly elliptical orbit means that the probability of its detection was roughly 1 in 80, suggesting that, unless its discovery was a fluke, another 40–120 Sedna-sized objects should exist within its region. Another object, 2000 CR_{105}, has a similar but less extreme orbit: it has a perihelion of 44.3 AU, an aphelion of 394 AU, and an orbital period of 3,240 years. It may have been affected by the same processes as Sedna.

Each of the proposed mechanisms for Sedna's extreme orbit would leave a distinct mark on the structure and dynamics of any wider population. If a trans-Neptunian planet was responsible, all such objects would share roughly the same perihelion (~80 AU). If Sedna were captured from another planetary system that rotated in the same direction as the Solar System, then Sedna's population would all possess relatively low inclinations and possess semi-major axes ranging from 100–500 AU. If it rotated in the opposite direction, then two populations would form, one with low inclinations and one with high. The gravity of perturbing stars would produce a wide variety of perihelia and inclinations, each dependent on the number and angle of such encounters.

Gaining a larger sample of such objects could therefore help in determining which scenario is most likely. "I call Sedna a fossil record of the earliest Solar System", said Brown in 2006. "Eventually, when other fossil records are found, Sedna will help tell us how the Sun formed and the number of stars that were close to the Sun when it formed." A 2007–2008 survey by Brown, Rabinowitz and Megan Schwamb attempted to locate another member of Sedna's hypothetical population. Although the survey was sensitive to movement out to 1,000 AU and discovered the dwarf planet candidate 2007 OR_{10}, it detected no new bodies in Sedna-like orbits. Subsequent simulations incorporating the new data suggested about 40 Sedna-sized objects probably exist in this region.

Classification

The Minor Planet Center, which officially catalogs the objects in the Solar System, classifies Sedna as a scattered object. However, this grouping is heavily questioned, and many astronomers have suggested that it, together with a few other objects (e.g. 2000 CR_{105}), be placed in a new category of distant objects named *extended scattered disc objects* (E-SDO), *detached objects*, *distant detached objects* (DDO) or *scattered-extended* in the formal classification by the Deep Ecliptic Survey.

The discovery of Sedna resurrected the question of which astronomical objects should be considered planets and which should not. On March 15, 2004, articles in the popular press reported that a tenth planet had been discovered. This question was answered under the International Astronomical Union definition of a planet, adopted on August 24, 2006, which mandated that a planet must have cleared the neighborhood around its orbit. Sedna has a Stern–Levison parameter estimated to be much less than 1, and therefore cannot be considered to have cleared the neighborhood, even though no other objects have yet been discovered in its vicinity. To qualify as a dwarf planet, Sedna must be shown to be in hydrostatic equilibrium. It is not bright enough to conclusively prove this by the absolute magnitude threshold of +1 specified by the IAU naming guidelines, so other evidence will have to be acquired. However, it remains bright enough that it is expected to be a dwarf planet.

Exploration

Sedna's perihelion will be reached around 2075–2076. This close approach to the Sun provides an opportunity of study which will not occur again for 12,000 years. Though Sedna is listed on NASA's solar system exploration website, NASA is not considering any type of mission at this time.