

All About  
**Asteroids**  
(Minor planets)



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## Chapter- 1

# Asteroid



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

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

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

## Discovery



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

The first named minor planet, Ceres, was discovered in 1801 by Giuseppe Piazzi, and was originally considered a new planet. This was followed by the discovery of other similar bodies, which with the equipment of the time appeared to be points of light, like stars, showing little or no planetary disc (though readily distinguishable from stars due to their apparent motions). This prompted the astronomer Sir William Herschel to propose the term "asteroid", from Greek *αστεροειδής*, *asteroeidēs* = star-like, star-shaped, from ancient Greek *Αστήρ*, *astēr* = star. In the early second half of the nineteenth century, the terms "asteroid" and "planet" (not always qualified as "minor") were still used

interchangeably; for example, the *Annual of Scientific Discovery for 1871*, page 316, reads "Professor J. Watson has been awarded by the Paris Academy of Sciences, the astronomical prize, Lalande foundation, for the discovery of 8 new asteroids in one year. The planet Lydia (No. 110), discovered by M. Borelly at the Marseilles Observatory [...] M. Borelly had previously discovered 2 planets bearing the numbers 91 and 99 in the system of asteroids revolving between Mars and Jupiter" (emphasis added).

## Symbols

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

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

Johann Franz Encke made a major change in the *Berliner Astronomisches Jahrbuch* (BAJ, Berlin Astronomical Yearbook) for 1854. He introduced encircled numbers instead of symbols, although his numbering began with Astraea, the first four asteroids continuing to be denoted by their traditional symbols. This symbolic innovation was adopted very quickly by the astronomical community. The following year (1855), Astraea's number was bumped up to 5, but Ceres through Vesta would be listed by their

numbers only in the 1867 edition. A few more asteroids (28 Bellona, 35 Leukothea, and 37 Fides) would be given symbols and numbers. The circle would become a pair of parentheses, and the parentheses sometimes omitted altogether over the next few decades.

## **Naming**

A newly discovered asteroid is given a provisional designation (such as 2002 AT<sub>4</sub>) consisting of the year of discovery and an alphanumeric code indicating the half-month of discovery and the sequence within that half-month. Once an asteroid's orbit has been confirmed, it is given a number, and later may also be given a name (e.g. 433 Eros). The formal naming convention uses parentheses around the number (e.g. (433) Eros), but dropping the parentheses is quite common. Informally, it is common to drop the number altogether, or to drop it after the first mention when a name is repeated in running text.

## **Historical methods**

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

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

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

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

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

Norman Robert Pogson, E. W. Tempel, J. C. Watson, C. H. F. Peters, A. Borrelly, J. Palisa, the Henry brothers and Auguste Charlois.

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

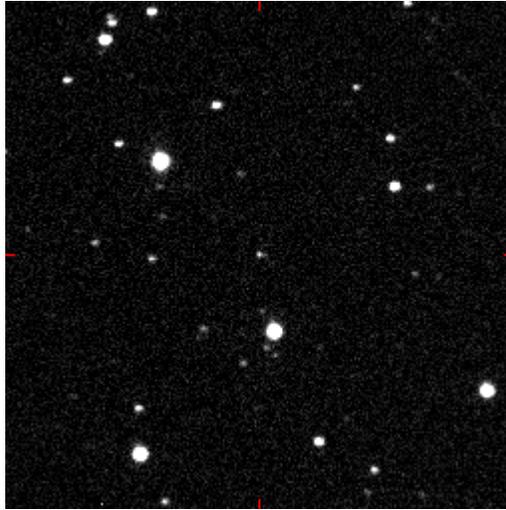
### **Manual methods of the 1900s and modern reporting**

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

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

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

### **Computerized methods**



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

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

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

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

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

- The Lincoln Near-Earth Asteroid Research (LINEAR) team
- The Near-Earth Asteroid Tracking (NEAT) team
- Spacewatch
- The Lowell Observatory Near-Earth-Object Search (LONEOS) team
- The Catalina Sky Survey (CSS)
- The Campo Imperatore Near-Earth Objects Survey (CINEOS) team
- The Japanese Spaceguard Association
- The Asiago-DLR Asteroid Survey (ADAS)

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

## Terminology

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

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

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

The innermost of these are the Kuiper belt objects, called "objects" partly to avoid the need to classify them as asteroids or comets. They are believed to be predominantly

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

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

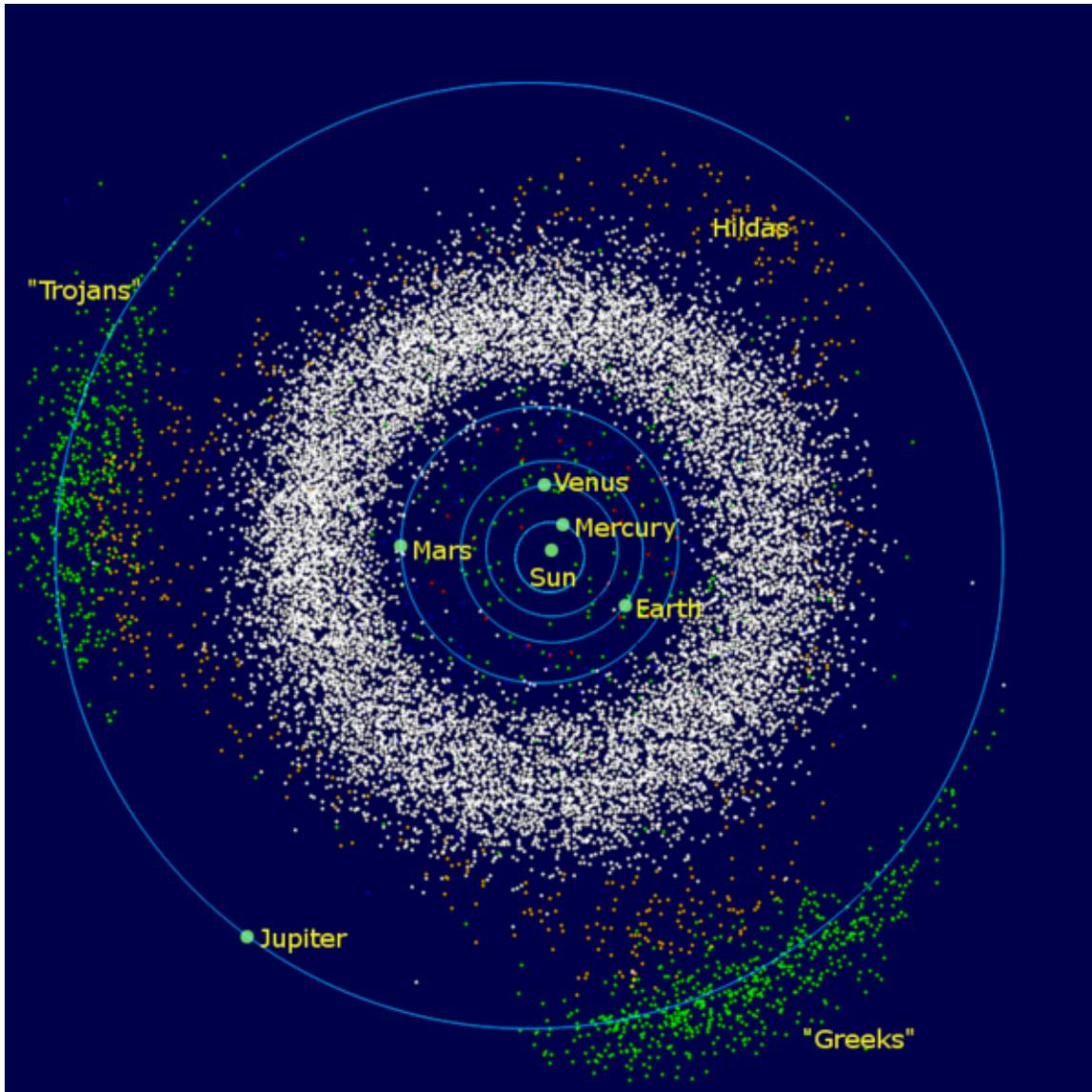
When the IAU introduced the class small solar system bodies in 2006 to include most objects previously classified as minor planets and comets, they created the class of dwarf planets for the largest minor planets—those that have enough mass to have become ellipsoidal under their own gravity. According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

## **Formation**

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

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

## **Distribution within the Solar System**



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

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

### **Main asteroid belt**

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

## Trojans

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

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

A couple trojans have also been found orbiting with Mars.

## Near-Earth asteroids

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

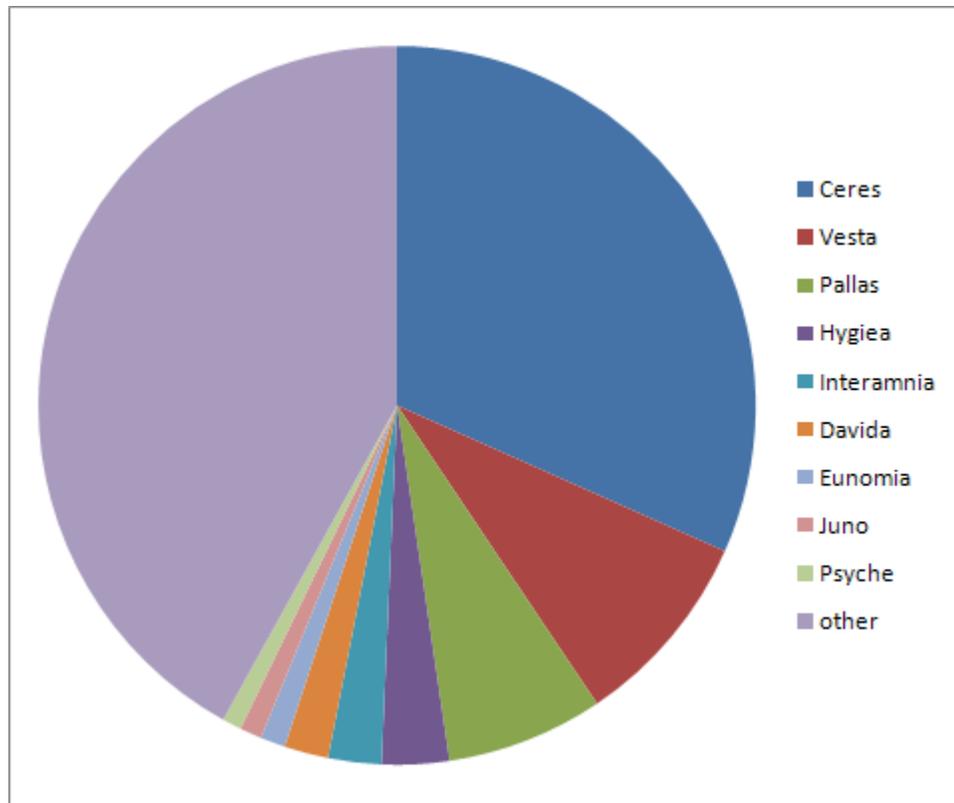
## Characteristics

### Size distribution

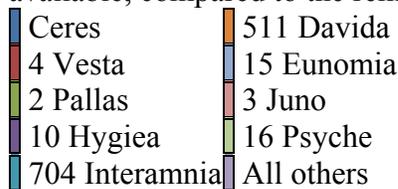


Asteroid Vesta (left) and dwarf planet Ceres (center), with Earth's Moon (right) shown to scale

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



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



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

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

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

Approximate number of asteroids N larger than diameter D														
D	100 m	300 m	500 m	1 km	3 km	5 km	10 km	30 km	50 km	100 km	200 km	300 km	500 km	900 km
N	~25,000,000	4,000,000	2,000,000	750,000	200,000	90,000	10,000	1100	600	200	30	5	3	1

## Composition

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

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

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

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

## Classification

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

### Orbital classification

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

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

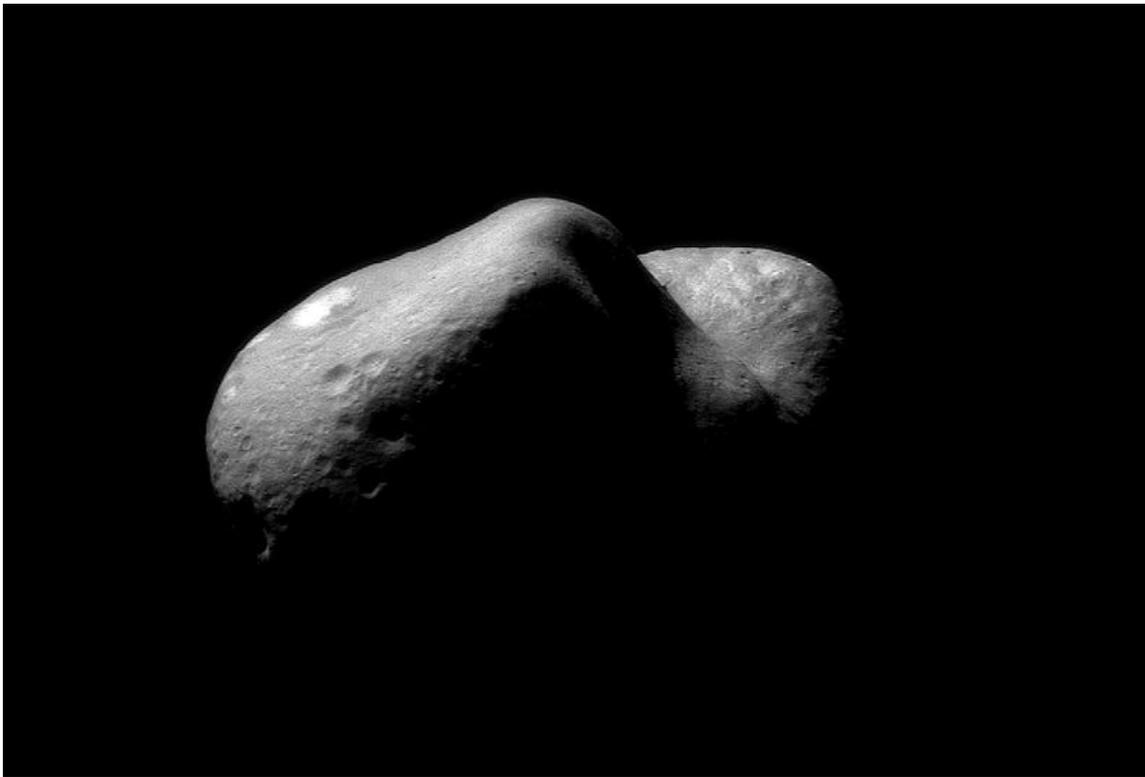
### **Quasi-satellites and horseshoe objects**

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

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

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

### **Spectral classification**



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

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

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

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

## **Problems**

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

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

## **Exploration**



Vesta, imaged by the Hubble Space Telescope



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

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

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

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

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

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

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

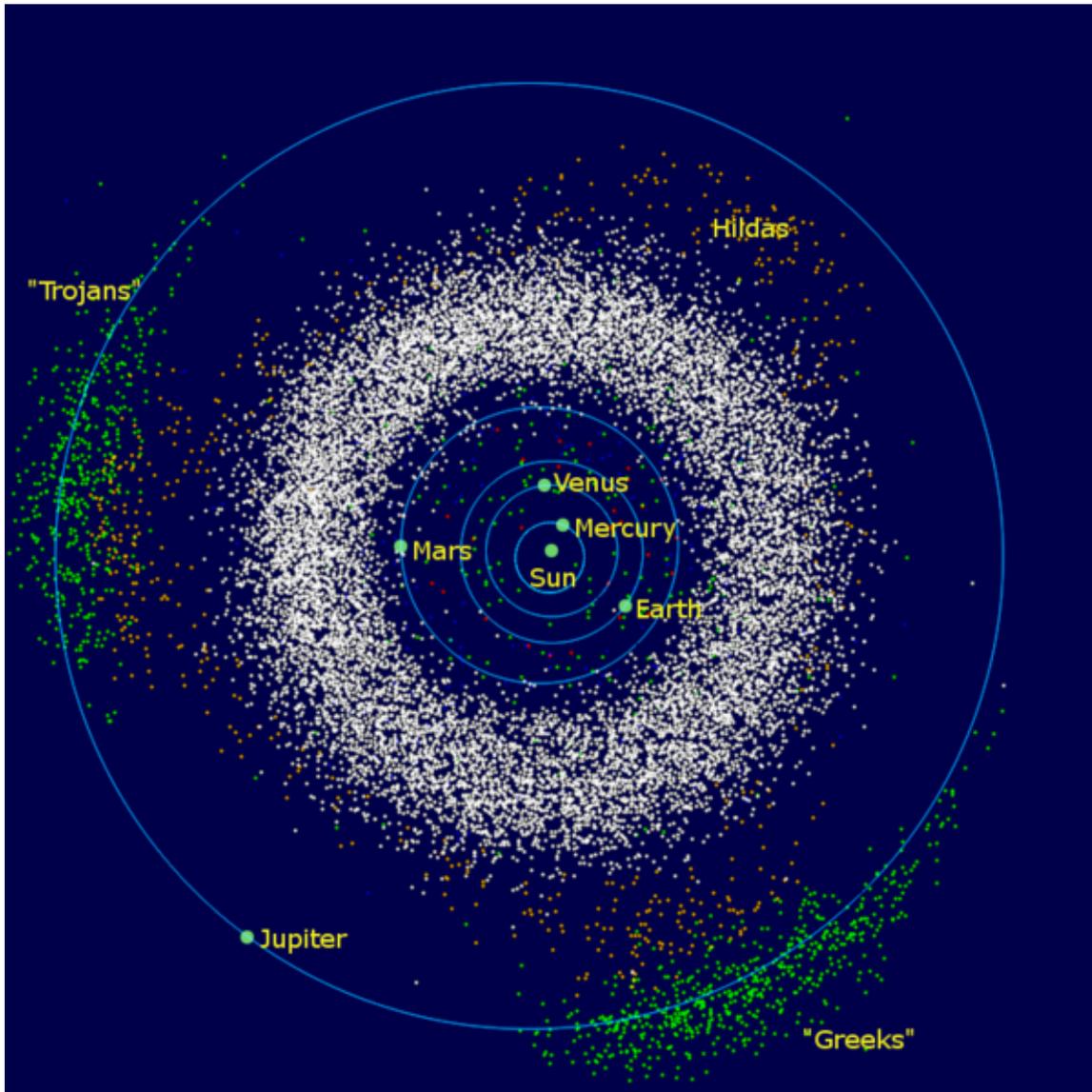
The European Rosetta probe (launched in 2004) flew by 2867 Šteins in 2008 and 21 Lutetia, the largest asteroid visited to date, in 2010.

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

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

## Chapter- 2

# Asteroid Belt



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

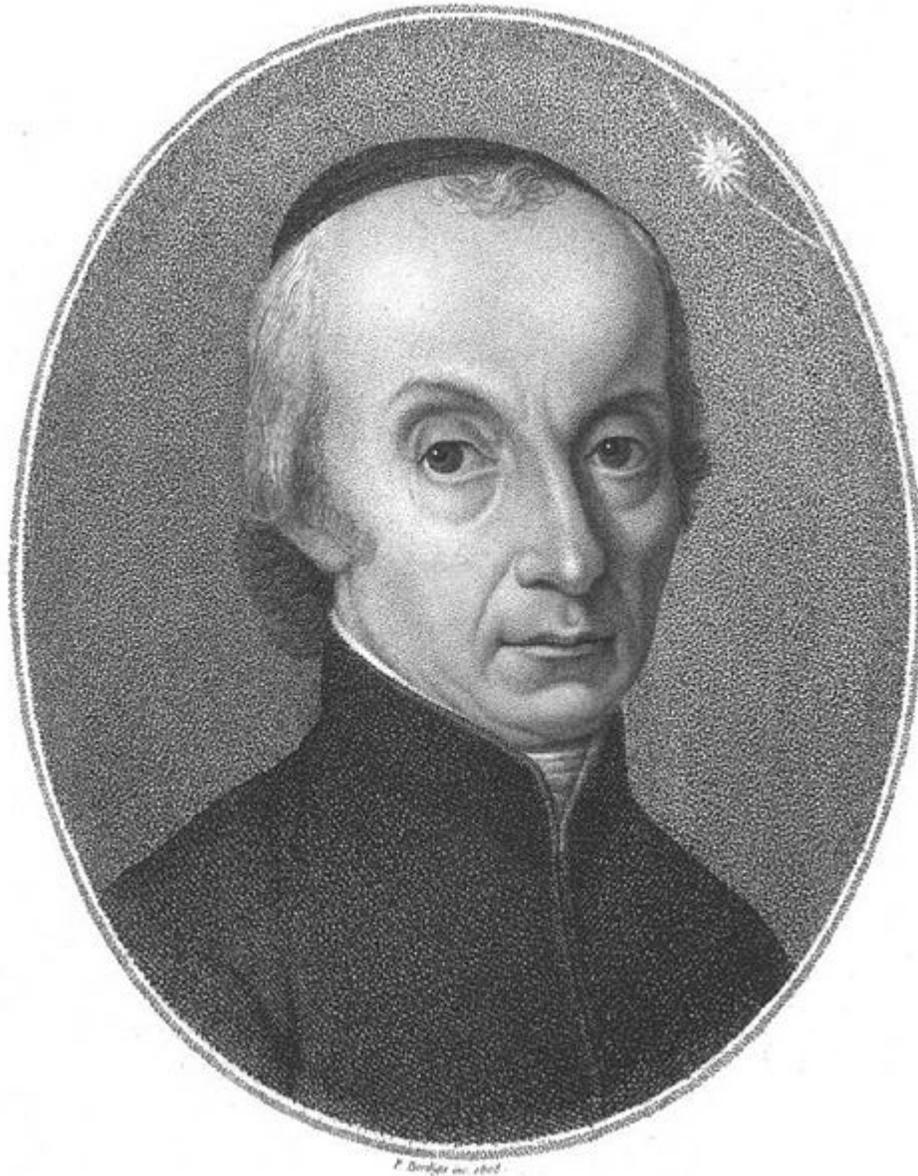
The **asteroid belt** is the region of the Solar System located roughly between the orbits of the planets Mars and Jupiter. It is occupied by numerous irregularly shaped bodies called asteroids or minor planets. The asteroid belt region is also termed the **main asteroid belt** or **main belt** because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

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

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

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

## **History of observation**



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

In an anonymous footnote to his 1766 translation of Charles Bonnet's *Contemplation de la Nature*, the astronomer Johann Daniel Titius von Wittenburg noted an apparent pattern in the layout of the planets. If one began a numerical sequence at 0, then included 3, 6, 12, 24, 48, etc., doubling each time, and added four to each number and divided by 10, this produced a remarkably close approximation to the orbits of the known planets as measured in astronomical units. This pattern, now known as the Titius-Bode Law, predicted the semi-major axes of the six planets of the time (Mercury, Venus, Earth, Mars, Jupiter and Saturn) provided one allowed for a "gap" between the orbits of Mars and Jupiter. In his footnote Titius declared, "But should the Lord Architect have left that space empty? Not at all". In 1768, the astronomer Johann Elert Bode made note of

Titius's relationship in his *Anleitung zur Kenntniss des gestirnten Himmels* but did not credit Titius, which led many to refer to it as "Bode's law". When William Herschel discovered Uranus in 1781, the planet's position matched the law almost perfectly, leading astronomers to conclude that there had to be a planet between the orbits of Mars and Jupiter.

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

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

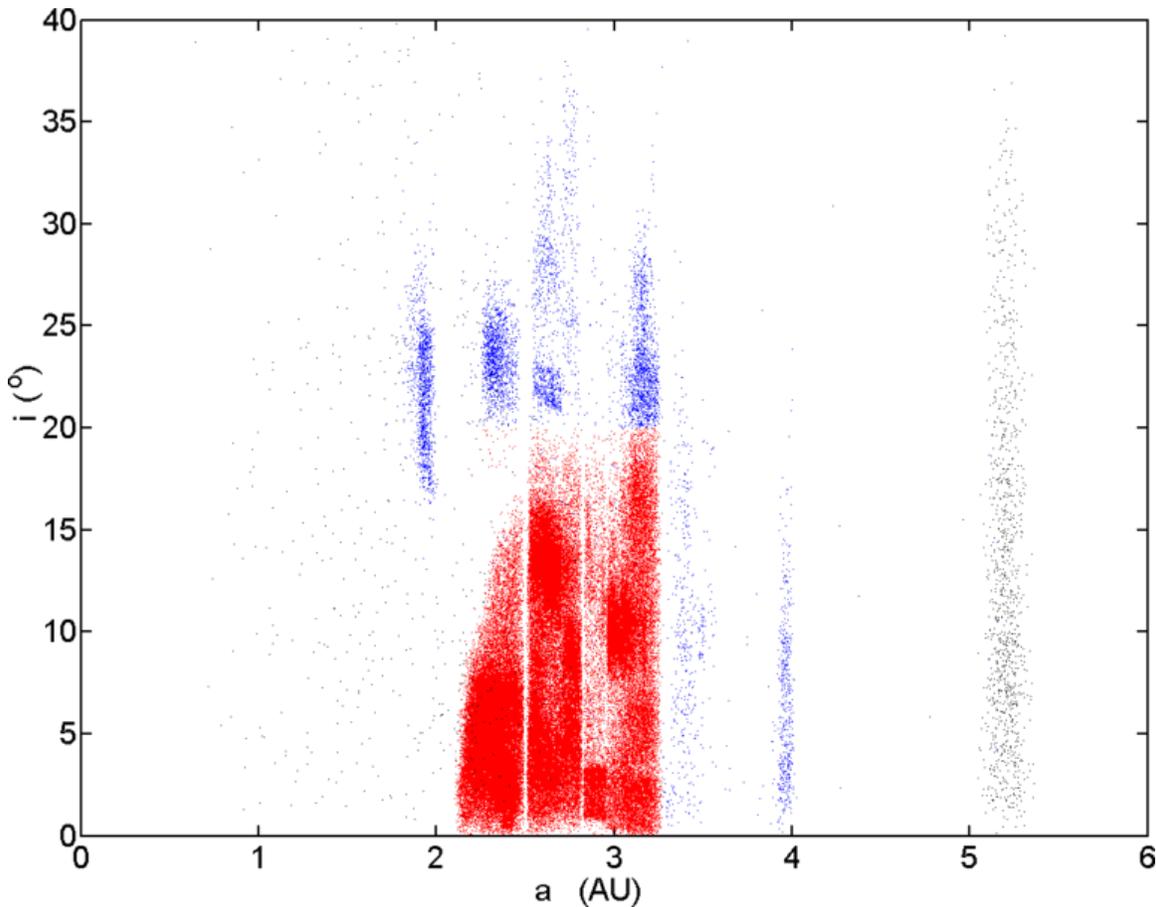
Neither the appellation of planets, nor that of comets, can with any propriety of language be given to these two stars ... They resemble small stars so much as hardly to be distinguished from them. From this, their asteroidal appearance, if I take my name, and call them Asteroids; reserving for myself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

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

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

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

## Origin



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

## **Formation**

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

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

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

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

## **Evolution**

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

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

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

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

## **Characteristics**



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



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

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

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

### **Composition**

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

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

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

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

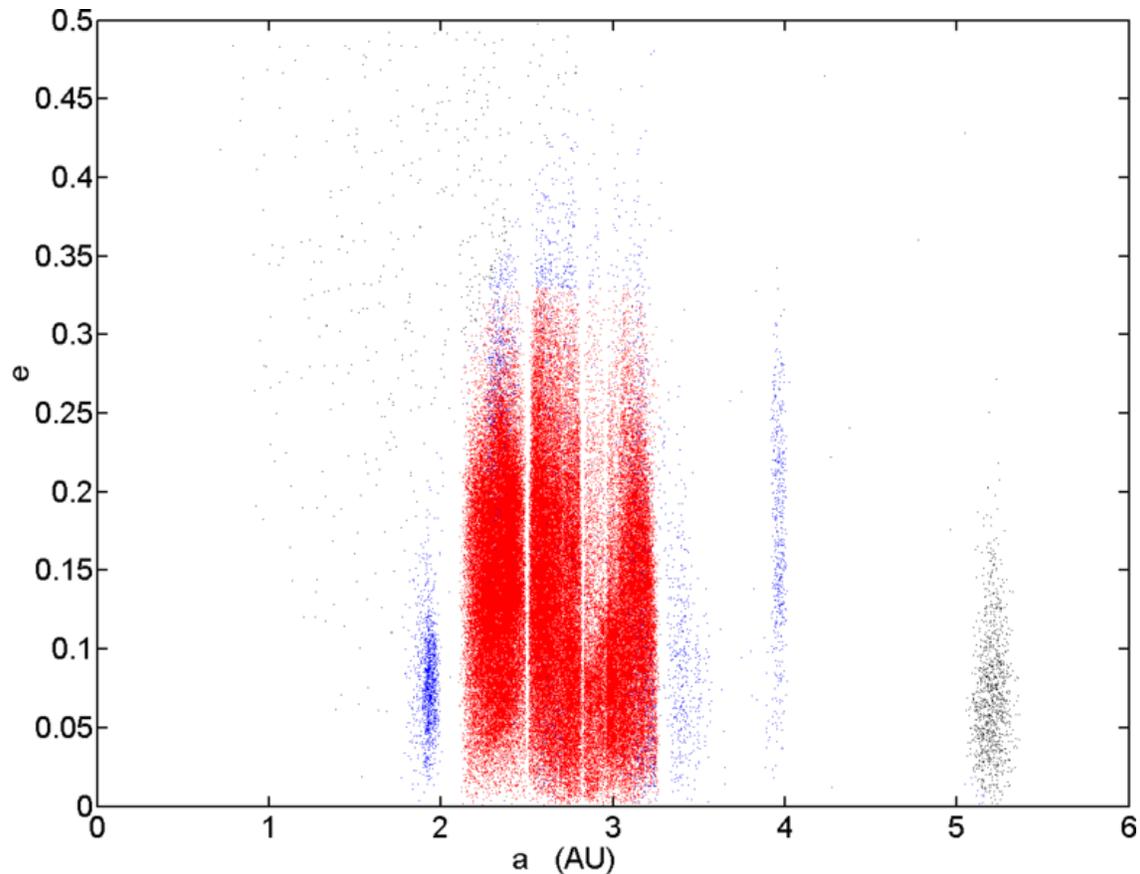
One mystery of the asteroid belt is the relative rarity of V-type, or basaltic asteroids. Theories of asteroid formation predict that objects the size of Vesta or larger should form crusts and mantles, which would be composed mainly of basaltic rock, resulting in more than half of all asteroids being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

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

## **Main-belt comets**

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

### Orbits and rotations



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

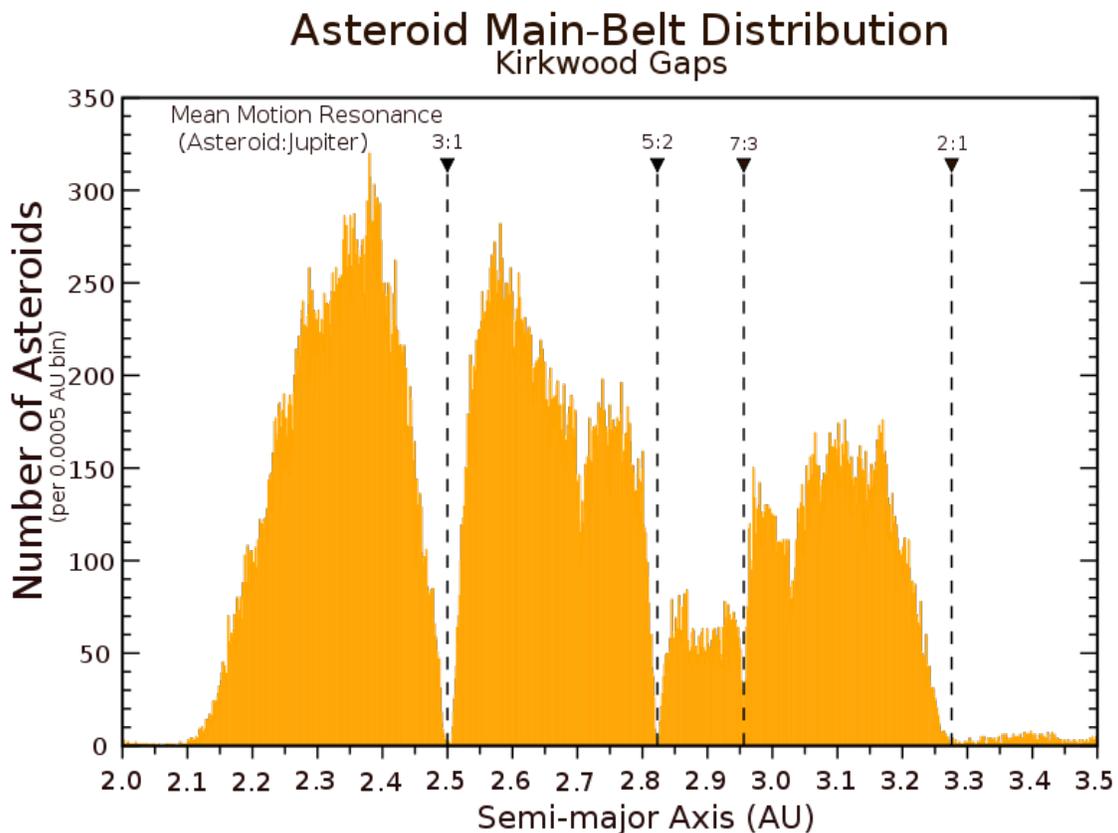
Most asteroids within the main belt have orbital eccentricities of less than 0.4, and an inclination of less than  $30^\circ$ . The orbital distribution of the asteroids reaches a maximum at an eccentricity of around 0.07 and an inclination below  $4^\circ$ . Thus while a typical asteroid has a relatively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

Sometimes, the term *main belt* is used to refer only to the more compact "core" region where the greatest concentration of bodies is found. This lies between the strong 4:1 and 2:1 Kirkwood gaps at 2.06 and 3.27 AU, and at orbital eccentricities less than roughly

0.33, along with orbital inclinations below about 20°. This "core" region contains approximately 93.4% of all numbered minor planets within the Solar System.

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

### Kirkwood gaps



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

The semi-major axis of an asteroid is used to describe the dimensions of its orbit around the Sun, and its value determines the minor planet's orbital period. In 1866, Daniel Kirkwood announced the discovery of gaps in the distances of these bodies' orbits from the Sun. They were located at positions where their period of revolution about the Sun

was an integer fraction of Jupiter's orbital period. Kirkwood proposed that the gravitational perturbations of the planet led to the removal of asteroids from these orbits.

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

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

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

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

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

## **Collisions**



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

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

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

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

## **Meteorites**

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

Mexico, the remnant of the massive impact which is believed to have triggered the extinction of the dinosaurs 65 million years ago.

## **Largest asteroids**

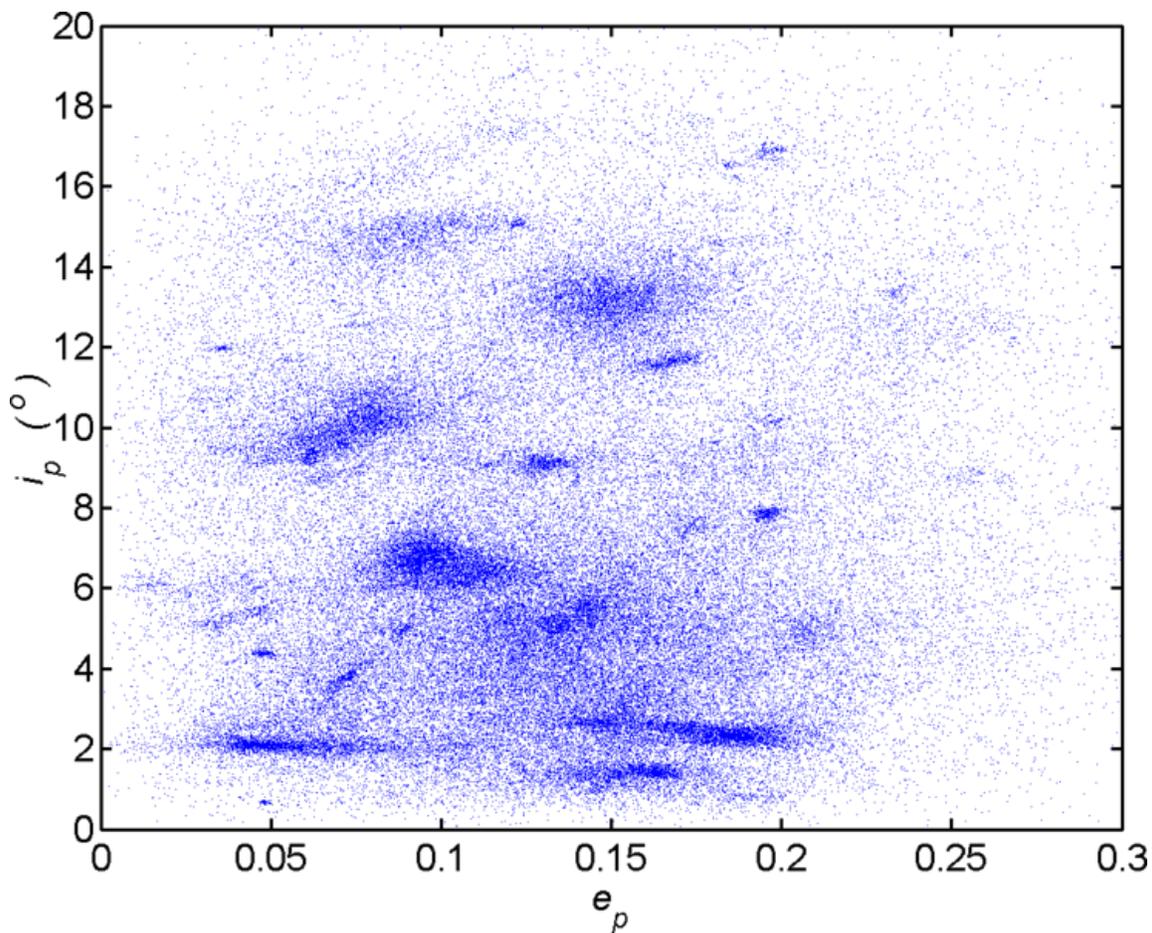


The dwarf planet Ceres

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

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

## Families and groups



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

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

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

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

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

## **Periphery**

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

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

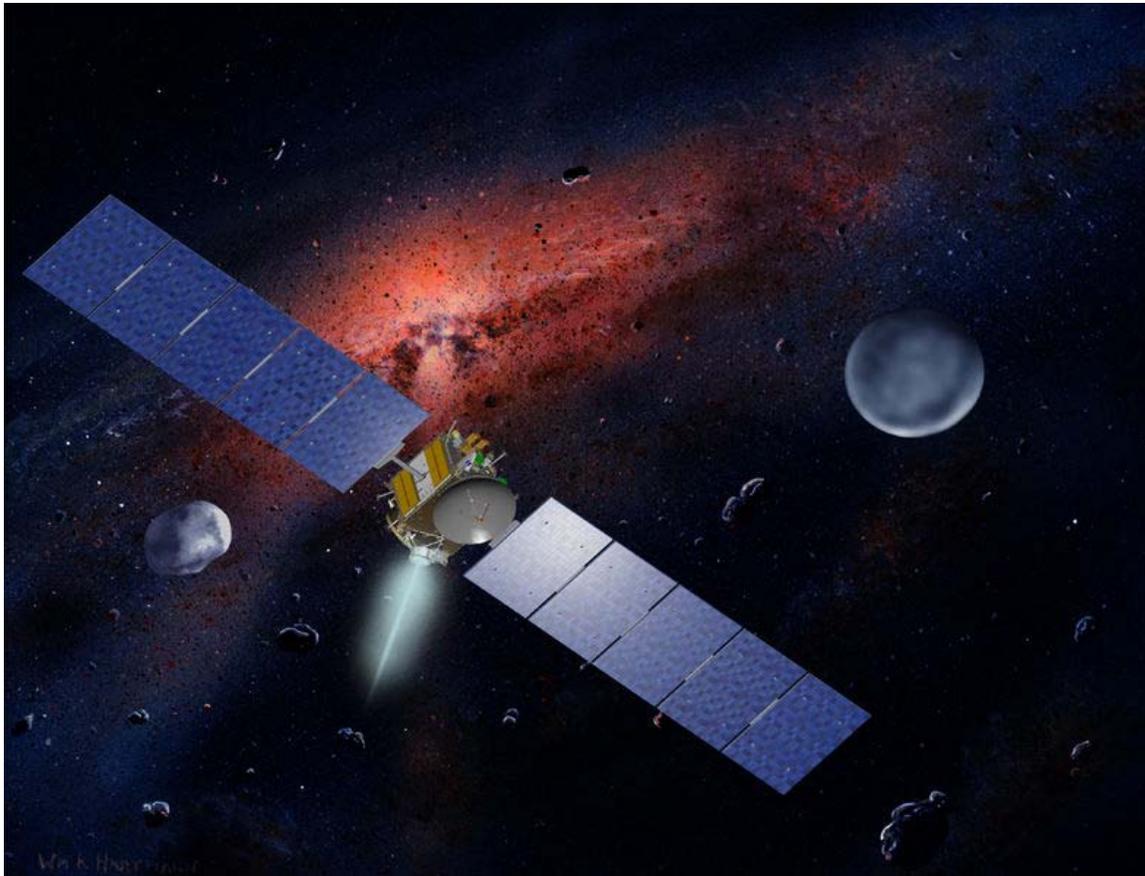
Skirting the outer edge of the main belt is the Cybele group, orbiting between 3.3 and 3.5 AU. These have a 7:4 orbital resonance with Jupiter. The Hilda family orbit between 3.5 and 4.2 AU, and have relatively circular orbits and a stable 3:2 orbital resonance with Jupiter. There are few asteroids beyond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

## **New families**

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

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

## Exploration



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

The first spacecraft to traverse the asteroid belt was Pioneer 10, which entered the region on July 16, 1972. At the time there was some concern that the debris in the belt would pose a hazard to the spacecraft, but it has since been safely traversed by 9 Earth-based craft without incident. Pioneer 11, Voyagers 1 and 2 and Ulysses passed through the belt without imaging any asteroids. Galileo imaged the asteroid 951 Gaspra in 1991 and 243

Ida in 1993, NEAR imaged 253 Mathilde in 1997, Cassini imaged 2685 Masursky in 2000, Stardust imaged 5535 Annefrank in 2002, New Horizons imaged 132524 APL in 2006, and Rosetta imaged 2867 Šteins in 2008. Due to the low density of materials within the belt, the odds of a probe running into an asteroid are now estimated at less than one in a billion.

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

## Chapter- 3

# Asteroid Groups and Asteroid Family

## Asteroid Groups

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

## Groups out to the orbit of Earth

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

- Vulcanoid asteroids are hypothetical asteroids with an aphelion less than 0.4 AU, i.e., they orbit entirely within the orbit of Mercury. A few searches for Vulcanoids have been conducted but there have been none discovered so far.
- Apoheles are asteroids whose aphelion is less than 0.983 AU, meaning they orbit entirely within Earth's orbit. Other proposed names for this group are Inner-Earth Objects or Interior Earth Objects (IEOs) and Anons (as in "Anonymous"). As of March 2008 there are only five known Apoheles with an arc of observations greater than 20 days: (163693) Atira, (164294) 2004 XZ<sub>130</sub>, 2004 JG<sub>6</sub>, 2005 TG<sub>45</sub> and 2006 WE<sub>4</sub>; while there are other four possible candidates, but with a too short arc of observations: 1998 DK<sub>36</sub>, 2006 KZ<sub>39</sub>, 2007 EB<sub>26</sub> and 2008 EA<sub>32</sub>.
- Mercury-crosser asteroids having a perihelion smaller than Mercury's 0.3075 AU.
- Venus-crosser asteroids having a perihelion smaller than Venus's 0.7184 AU. This group includes the above Mercury-crossers (if their aphelion is greater than Venus's perihelion. All known Mercury crossers satisfy this condition).
- Earth-crosser asteroids having a perihelion smaller than Earth's 0.9833 AU. This group includes the above Mercury- and Venus-crossers, apart from the Apoheles. They are also divided into the

- Aten asteroids having a semi-major axis less than 1 AU, named after 2062 Aten.
- Apollo asteroids having a semi-major axis greater than 1 AU, named after 1862 Apollo.
- Arjuna asteroids are somewhat vaguely defined as having orbits similar to Earth's; i.e., with an average orbital radius of around 1 AU and with low eccentricity and inclination. Due to the vagueness of this definition some asteroids belonging to the Apohele, Amor, Apollo or Aten groups can also be classified as Arjunas. The term was introduced by Spacewatch and does not refer to an existing asteroid; examples of Arjunas include 1991 VG.
- Earth Trojans are asteroids located in the Earth-Sun Lagrangian points  $L_4$  and  $L_5$ . Their location in the sky as observed from Earth's surface would be fixed at about 60 degrees east and west of the Sun, and as people tend to search for asteroids at much greater elongations few searches have been done in these locations. No Earth trojans are currently known.
- Near-Earth asteroids is a catch-all group for asteroids whose orbit closely approaches that of Earth. It includes almost all of the above groups, as well as the Amor asteroids.

## Groups out to the orbit of Mars

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

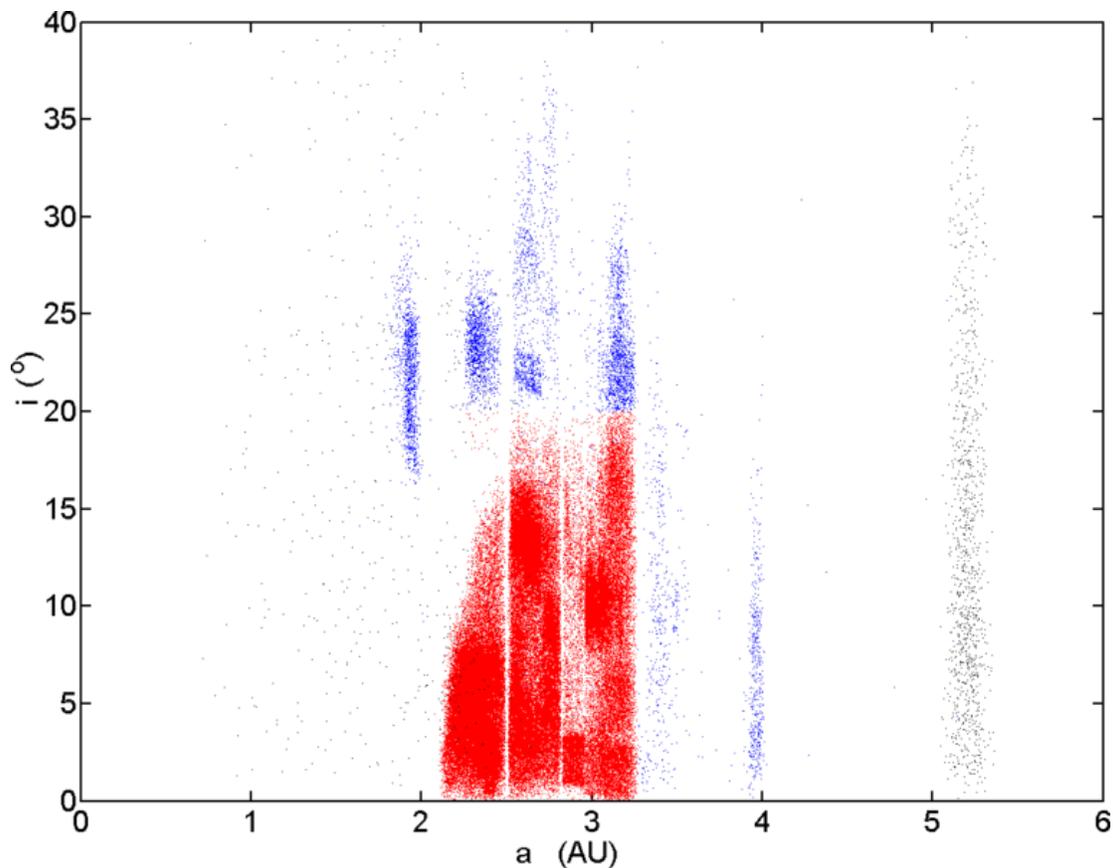
## The main asteroid belt

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

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

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

- It apparently also includes a group called the Main Belt I asteroids which have a semi-major axis between 2.3 AU and 2.5 AU and an inclination of less than  $18^\circ$ .
- **Middle** (or intermediate) **Main Belt**, between the 3:1 and 5:2 Jupiter orbital resonances, the latter at 2.82 AU. The largest member is Ceres. This group is apparently split into the:
  - Main Belt IIa asteroids which have a semi-major axis between 2.5 AU and 2.706 AU and an inclination less than  $33^\circ$ .
  - Main Belt IIb asteroids which have a semi-major axis between 2.706 AU and 2.82 AU and an inclination less than  $33^\circ$ .
- **Outer Main Belt** between the 5:2 and 2:1 Jupiter orbital resonances. The largest member is 10 Hygiea. This group is apparently split into the:
  - Main Belt IIIa asteroids which have a semi-major axis between 2.82 AU and 3.03 AU, an eccentricity less than .35, and an inclination less than  $30^\circ$ .
  - Main Belt IIIb asteroids which have a semi-major axis between 3.03 AU and 3.27 AU, an eccentricity less than .35, and an inclination less than  $30^\circ$ .



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

## Other groups out to the orbit of Jupiter

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

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

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

## Groups beyond the orbit of Jupiter

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

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

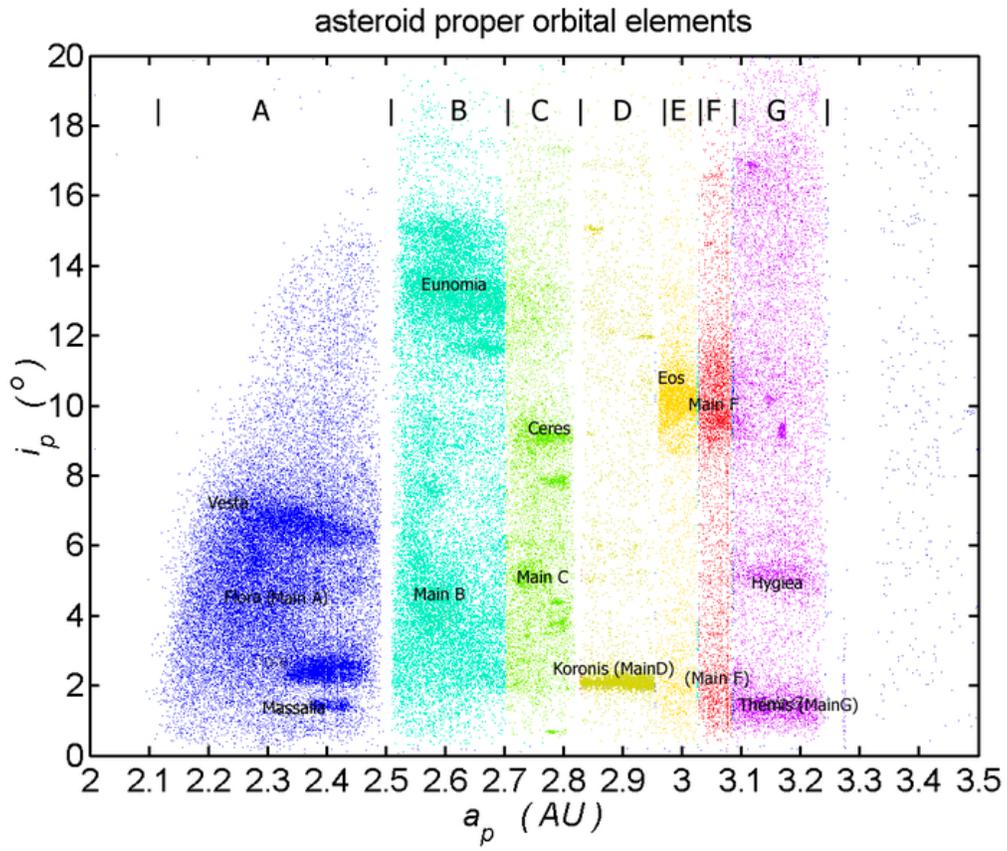
## Groups at or beyond the orbit of Neptune

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

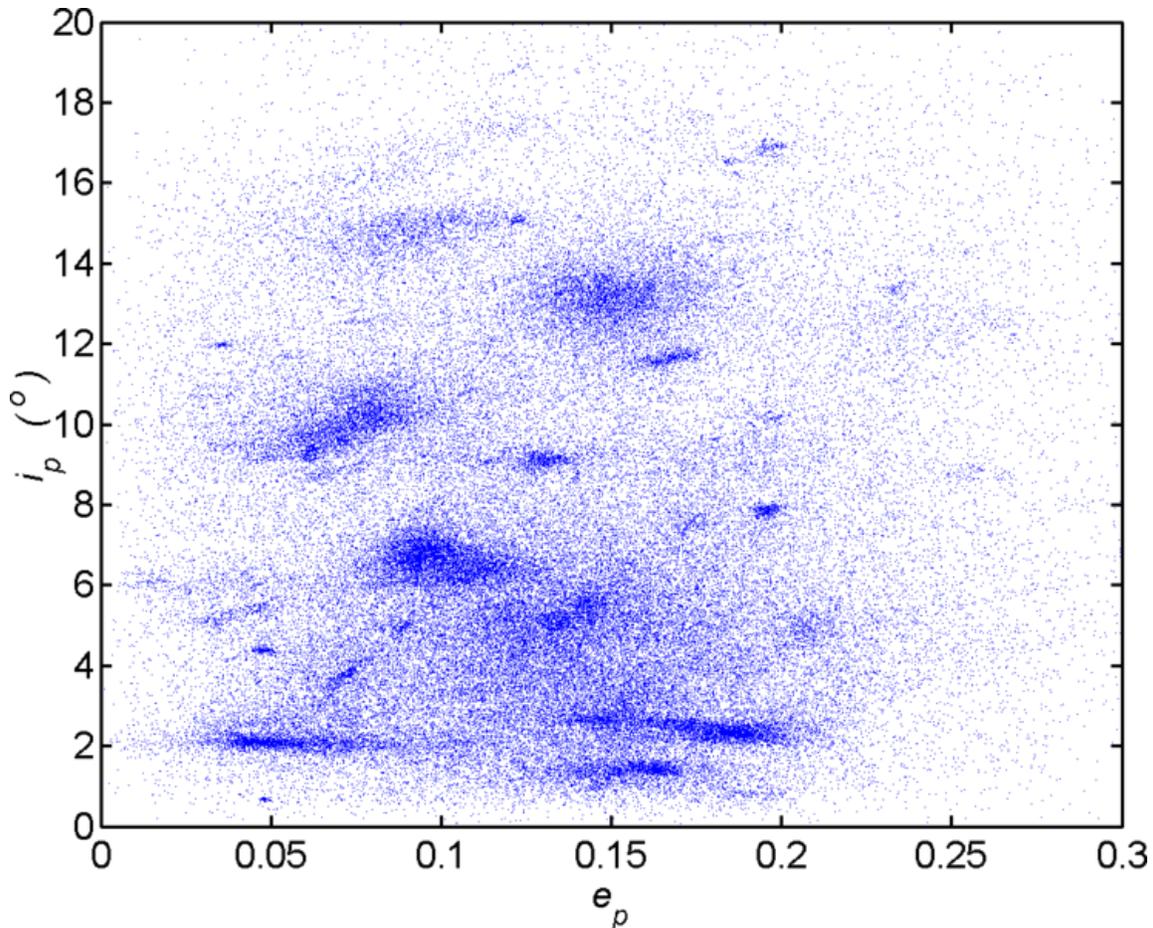
- are several objects in the 2:5 resonance (mean orbital radius of 55 AU), and objects in the 4:5, 4:7, 3:5, and 3:4 resonances.
- Scattered Disk Objects (SDOs), unlike cubewanos and resonant objects, typically have highly inclined, high-eccentricity orbits with perihelia that are still not too far from Neptune's orbit.. They are assumed to be objects that encountered Neptune and were "scattered" out of their initial more circular, close to the ecliptic orbits. The recently famous, Pluto-size Eris belongs to this category.
    - Extended Scattered Disk (detached) objects with generally highly elliptical, very large orbits of up to a few hundred AU. Their perihelion is too far away from Neptune for any significant interaction to occur. One typical member of the extended disk is 2000 CR<sub>105</sub>, while some researchers include Sedna in this class.
  - The Oort cloud is a hypothetical cloud of comets with a mean orbital radius between approximately 50,000 AU and 100,000 AU. No Oort cloud objects have been detected, the existence of this classification is only inferred from indirect evidence. Some astronomers have tentatively associated 90377 Sedna with the Oort cloud.

## Asteroid family

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



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



Plot of proper inclination vs. eccentricity for numbered asteroids.

## General properties

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

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

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

## Origin and evolution

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

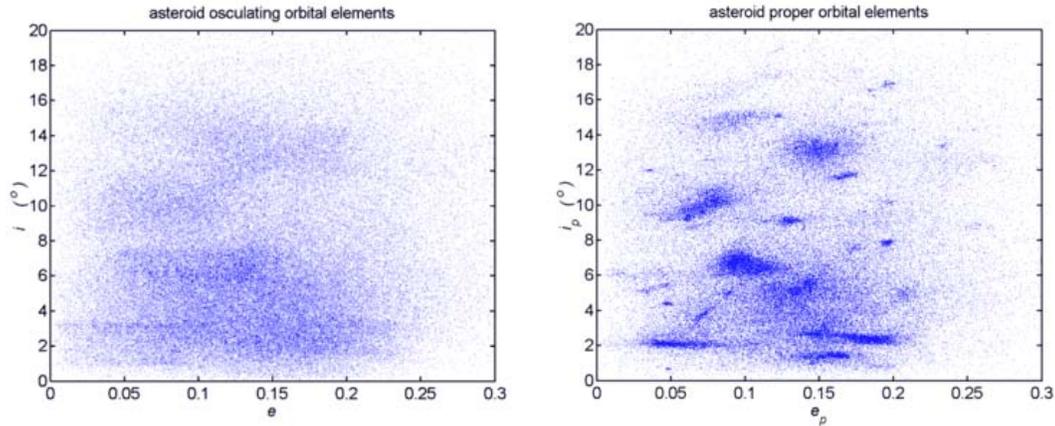
Due to the method of origin, all the members have closely matching compositions for most families. Notable exceptions are those families (such as the Vesta family) which formed from a large differentiated parent body.

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

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

## **Identification of members and interlopers**

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



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

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

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

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

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

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

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

## Family types

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

## List of families

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

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

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

Notes for table:

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

## Chapter- 4

# Near-Earth Object



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



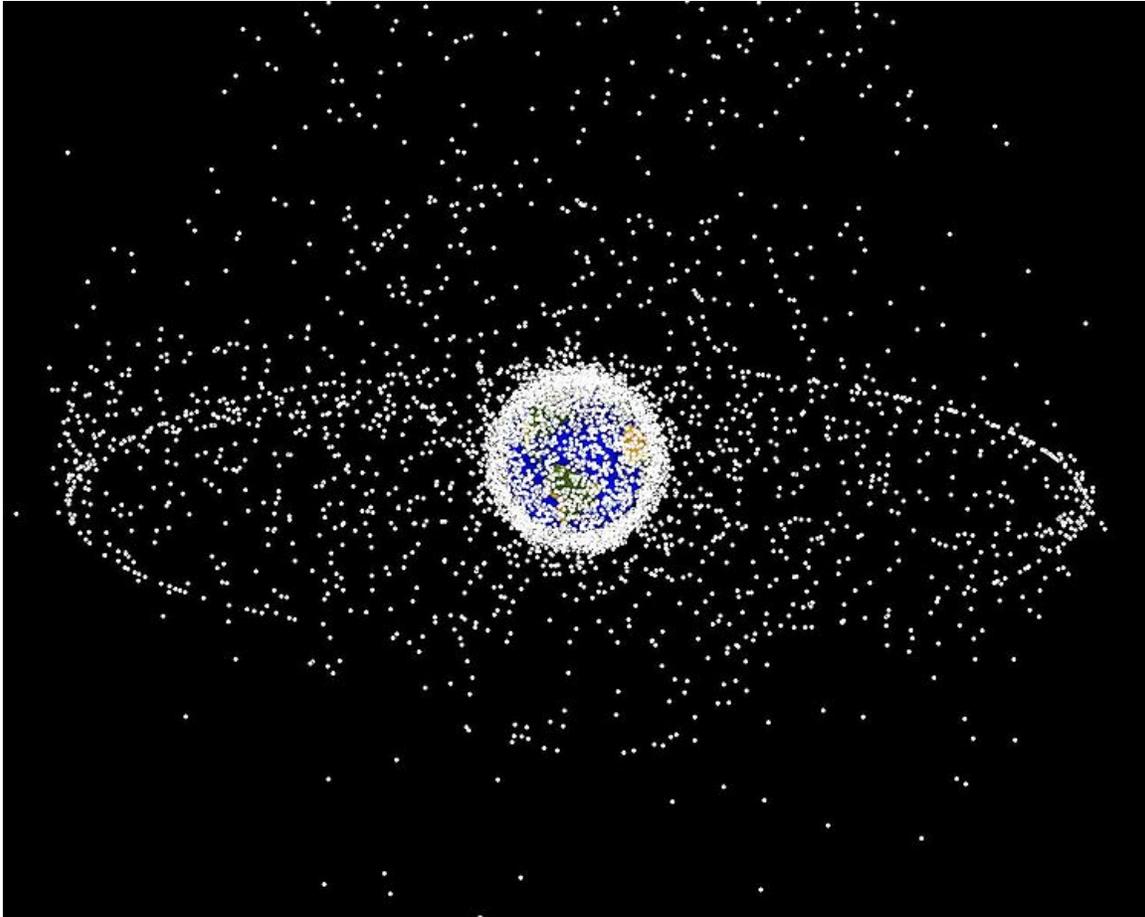
Asteroid (4179) Toutatis Passes the Earth  
(VLT KUEYEN + FORS 1)

ESO PR Photo 28c/04 (29 September 2004)

© European Southern Observatory



Asteroid Toutatis from Paranal.



Earth's artificial satellites form a halo of space debris.

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

Those NEOs that are asteroids (NEA) have orbits that lie partly between 0.983 and 1.3 astronomical units away from the Sun. When an NEA is detected it is submitted to the Harvard Minor Planet Center for cataloging. Some near-Earth asteroids' orbits intersect that of Earth's so they pose a collision danger. The United States, European Union and other nations are currently scanning for NEOs in an effort called Spaceguard. In the United States, NASA has a congressional mandate to catalogue all NEOs that are at least 1 kilometer wide, as the impact of such an object would be expected to produce severe to

catastrophic effects. As of October 2008, 982 of these mandated NEOs have been detected. It was estimated in 2006 that 20% of the mandated objects have not yet been found. Efforts are under way to use an existing telescope in Australia to cover the ~30% of the sky that has not yet been surveyed.

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

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

## Risk scales

There are two schemes for classification of impact hazards:

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

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

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

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

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

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

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

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

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

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

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

## Number and classification of near-Earth objects

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

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

As of May 2010, there are 290 NEAs on the impact risk page at the NASA website. A significant number of these NEAs – 215 as of May 2010 – are equal to or smaller than 50

meters in diameter and none of the listed objects are placed even in the "yellow zone" (Torino Scale 2), meaning that none warrant the attention of general public. As of May 2010, only one asteroid 2007 VK<sub>184</sub> is listed as having Torino Scale score 1.

### **Near-Earth meteoroids**

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

### **Near-Earth asteroids**



Computer model of the object 6489 Golevka, an Apollo asteroid

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

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

A small number of NEOs are extinct comets that have lost their volatile surface materials, although having a faint or intermittent comet-like tail does not necessarily result in a

classification as a near-Earth comet, making the boundaries somewhat fuzzy. The rest of the near-Earth asteroids are driven out of the asteroid belt by gravitational interactions with Jupiter.

There are three families of near-Earth asteroids:

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

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

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

## **Near-Earth comets**

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

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

## **Impact rate**

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

The rate of impacts of objects of at least 1 km in diameter is estimated as 2 per million years. Assuming that this rate will continue for the next billion years, there exist at least 2,000 objects of diameter greater than 1 km that will eventually hit Earth. However, most of these are not yet considered Potentially Hazardous Objects because they are currently

orbiting between Mars and Jupiter. Eventually they will change orbits and become NEOs. Objects spend on average a few million years as NEOs before hitting the Sun, being ejected from the Solar System, or (for a small proportion) hitting a planet.

## Historic impacts



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

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

### 1908 Tunguska Event

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

### 2002 Eastern Mediterranean event

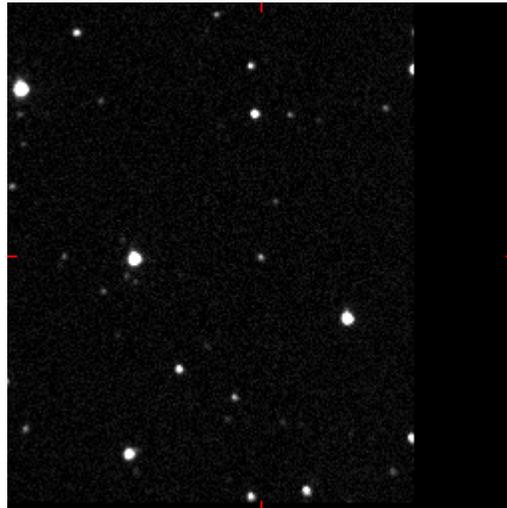
On June 6, 2002 an object with an estimated diameter of 10 meters collided with Earth. The collision occurred over the Mediterranean Sea, between Greece and Libya, at approximately 34°N 21°E and the object exploded in mid-air. The energy released was

estimated (from infrasound measurements) to be equivalent to 26 kilotons of TNT, comparable to a small nuclear weapon.

## 2008 Sudan event

On 6 October 2008, scientists calculated that a small Near-Earth asteroid 2008 TC<sub>3</sub> just sighted that night should impact the Earth on 7 October over Sudan, at 0246 UTC, 5:46 local time. The asteroid arrived as predicted. This is the first time that an asteroid impact on Earth has been accurately predicted. However, no reports of the actual impact have so far been published since it occurred in a very sparsely populated area. A systematic search for fragments found a total of 600 fragments, with a mass of 10.5 kilograms. The object is confirmed to have entered Earth's atmosphere as a meteor above northern Sudan at a velocity of 12.8 kilometres per second (29,000 mph).

## Close approaches



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

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

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

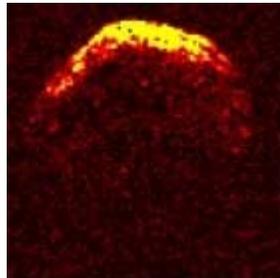
On March 18, 2004, LINEAR announced a 30 meter asteroid 2004 FH, which would pass the Earth that day at only 42,600 km (26,500 miles), about one-tenth the distance to the moon, and the closest miss ever noticed. They estimated that similar sized asteroids come as close about every two years.

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

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

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

## Future impacts



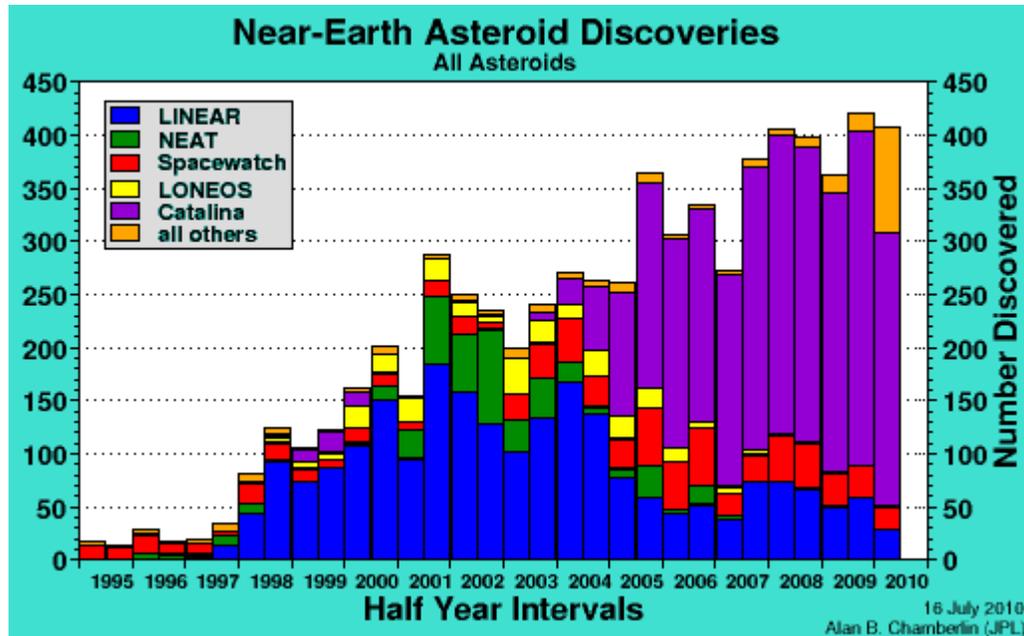
Radar image of Asteroid 1950 DA.

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

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

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

## Projects to minimize the threat



Number of NEOs detected by various projects.

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

## Chapter- 5

# 99942 Apophis

### 99942 Apophis

#### Discovery

<b>Discovered by</b>	Roy A. Tucker David J. Tholen Fabrizio Bernardi
<b>Discovery site</b>	Kitt Peak
<b>Discovery date</b>	June 19, 2004

#### Designations

<b>Named after</b>	Apep
<b>Alternate name(s)</b>	2004 MN <sub>4</sub>
<b>Minor planet category</b>	Aten

#### Orbital characteristics

Epoch January 4, 2010 (JD 2455200.5)

<b>Aphelion</b>	1.0987 AU
<b>Perihelion</b>	0.74604 AU
<b>Semi-major axis</b>	0.92241 AU
<b>Eccentricity</b>	0.19121
<b>Orbital period</b>	323.58 d (0.89 a)
<b>Average orbital speed</b>	30.728 km/s
<b>Mean anomaly</b>	339.94°
<b>Inclination</b>	3.3315°
<b>Longitude of ascending node</b>	204.43°
<b>Argument of perihelion</b>	126.42°

#### Physical characteristics

<b>Dimensions</b>	~270 m
<b>Mass</b>	$2.7 \times 10^{10}$ kg
<b>Mean density</b>	? g/cm <sup>3</sup>
<b>Equatorial surface gravity</b>	?
<b>Escape velocity</b>	~0.52 km/h
<b>Rotation period</b>	30.4 h
<b>Albedo</b>	0.33
<b>Temperature</b>	270 K
<b>Spectral type</b>	Sq
<b>Absolute magnitude (<i>H</i>)</b>	19.7

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

## Keyhole

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

## Space probe

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

## Basic data

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

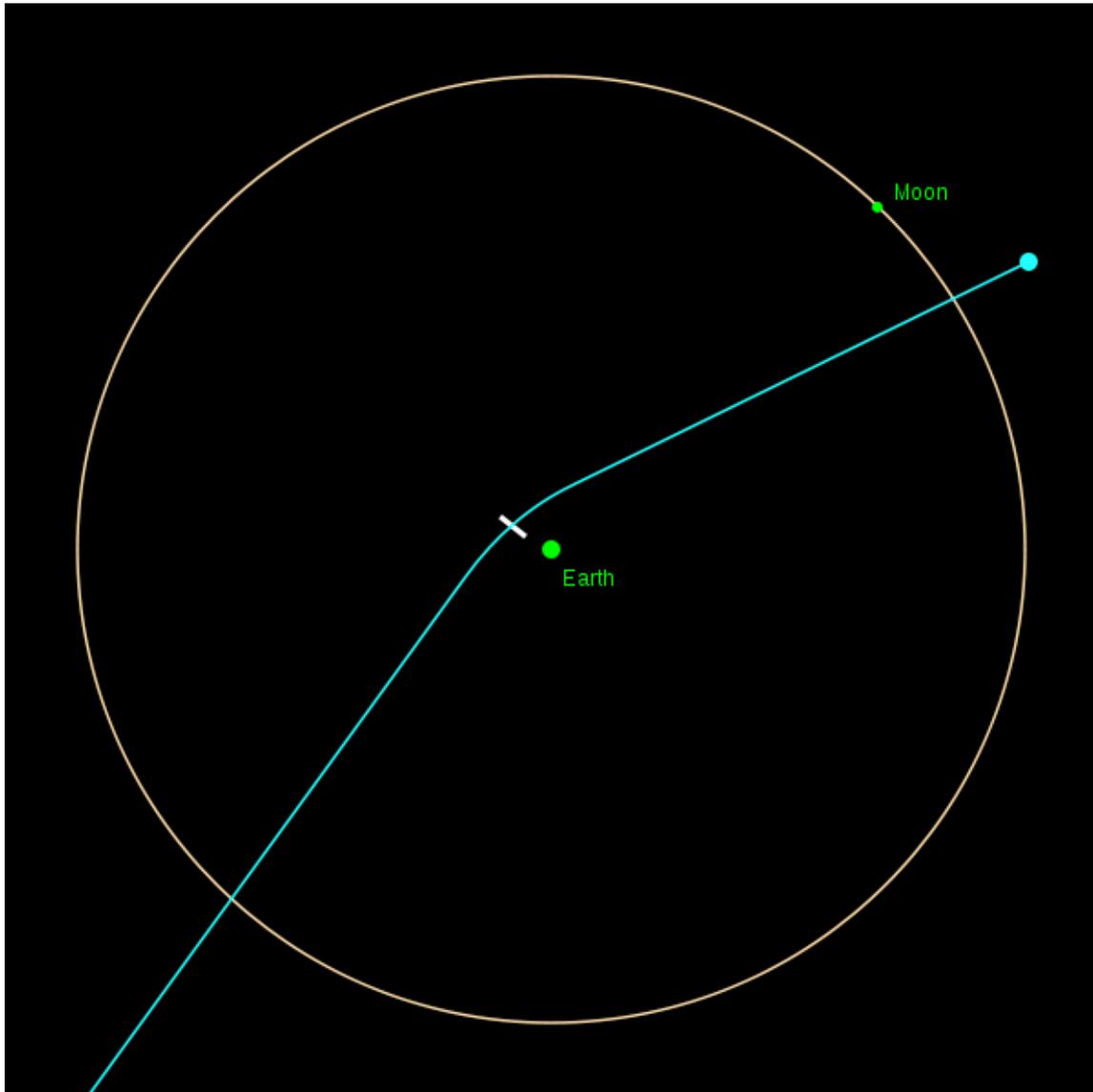
In October 2005 it was predicted that the asteroid will pass just below the altitude of geosynchronous satellites, which are at 35,786 kilometres (22,236 mi). Such a close approach by an asteroid of this size is expected to occur only every 1,300 years or so. Apophis' brightness will peak at magnitude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

## Naming

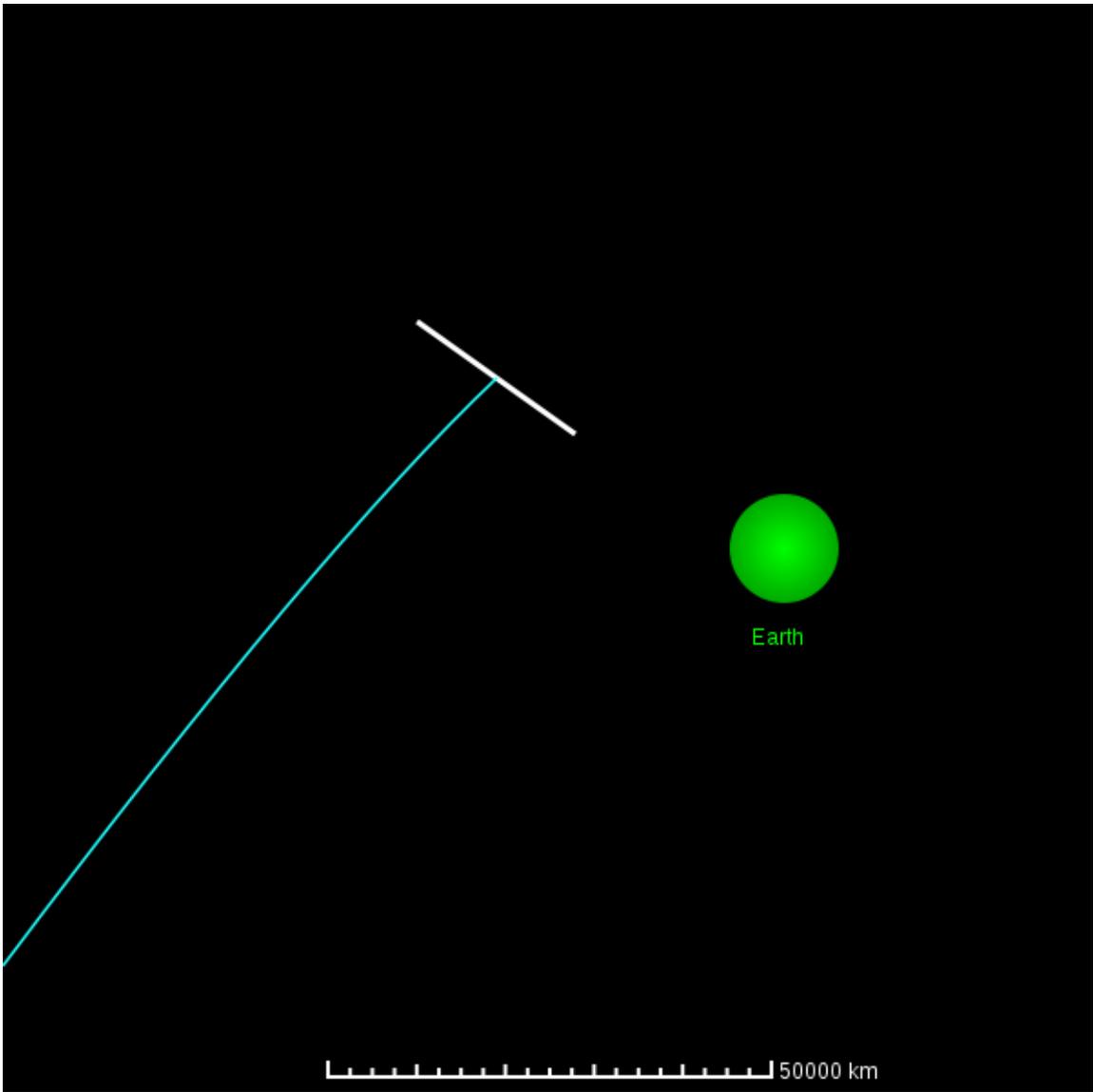
When first discovered, the object received the provisional designation 2004 MN<sub>4</sub> (sometimes written 2004 MN4), and news and scientific articles about it referred to it by that name. When its orbit was sufficiently well calculated, it received the permanent number 99942 (on June 24, 2005). Receiving a permanent number made it eligible for naming, and it received the name "Apophis" on July 19, 2005. Apophis is the Greek name of the Ancient Egyptian enemy of Ra: Apep, the Uncreator, a serpent that dwells in the eternal darkness of the Duat (earth's middle) and tries to swallow Ra during His nightly passage. Apep is held at bay by Set, the Ancient Egyptian god of Chaos.

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

## Close approaches



Close approach of Apophis on April 13, 2029



The white bar indicates uncertainty in the range of positions



### 99942 Apophis

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

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

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

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

## 2013 refinement

The close approach in 2029 will substantially alter the object's orbit, making predictions uncertain without more data. "If we get radar ranging in 2013 [the next good opportunity], we should be able to predict the location of 2004 MN<sub>4</sub> out to at least 2070." said Jon Giorgini of JPL. Apophis will pass within 0.09666 AU (14.4 million km) of the Earth in 2013 allowing astronomers to refine the trajectory for future close passes.

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

## History of impact estimates

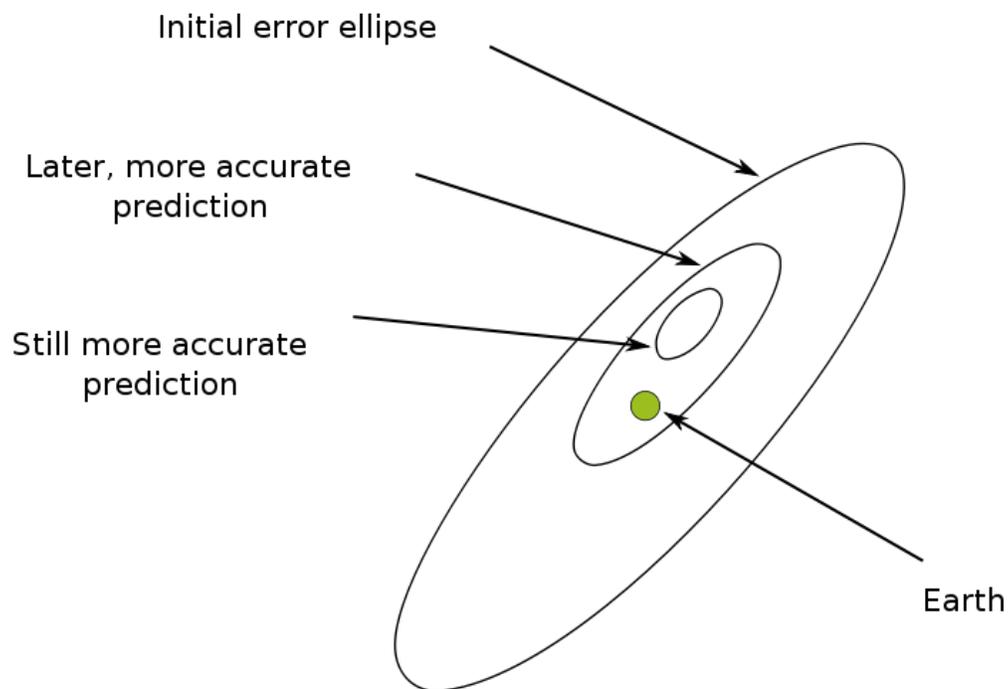


Illustration of a common trend where progressively reduced uncertainty regions result in an asteroid impact probability increasing followed by a sharp decrease.

- The original NASA report on December 23, 2004, mentioned impact chances of "around 1 in 300" in 2029, which was widely reported in the media. The actual

- NASA estimates at the time were 1 in 233; they resulted in the Torino scale rating of 2, the first time any asteroid had received a rating above 1.
- Later that day, based on a total of 64 observations, the estimates were changed to 1 in 62 (1.6%), resulting in an update to the initial report and an upgrade to a Torino scale rating of 4.
  - On December 25, 2004, the chances were first reported as 1 in 42 (2.4%) and later that day (based on 101 observations) as 1 in 45 (2.2%). At the same time, the asteroid's estimated diameter was lowered from 440 m to 390 m and its mass from  $1.2 \times 10^{11}$  kg to  $8.3 \times 10^{10}$  kg.
  - On December 26, 2004 (based on a total of 169 observations), the impact probability was still estimated as 1 in 45 (2.2%), the estimates for diameter and mass were lowered to 380 m and  $7.5 \times 10^{10}$  kg, respectively.
  - On December 27, 2004 (based on a total of 176 observations), the impact probability was raised to 1 in 37 (2.7%); diameter was increased to 390 m, and mass to  $7.9 \times 10^{10}$  kg.
  - On December 27, 2004, in the afternoon, a precovery increased the span of observations to 287 days and allowed more accurate calculations to re-rate the asteroid's 2029 approach as level zero on the Torino scale (no threat). The cumulative impact probability was estimated to be around 0.004%, a lower risk than asteroid 2004 VD<sub>17</sub>, which once again became the greatest risk object. A 2053 approach to Earth still poses a minor risk of impact, and Apophis was still rated at level one on the Torino scale for this orbit, and thus remains that way.
  - On December 28, 2004 at 12:23 GMT and (based on a total of 139 observations), produced a value of one on the Torino scale for 2044-04-13.29 and 2053-04-13.51.
  - By 01:10 GMT on December 29, 2004 the only pass rated 1 on the Torino scale was for 2053-04-13.51 based on 139 observations spanning 287.71 days (2004-Mar-15.1104 to 2004-Dec-27.8243). (As of 2010, the 2053 is now a 2056-04-13 risk of 1 in 10 million.)
  - By 19:18 GMT on December 29, 2004 this was still the case based upon 147 observations spanning 288.92 days (2004-Mar-15.1104 to 2004-Dec-29.02821), though the close encounters have changed and been reduced to 4 in total.
  - By 13:46 GMT on December 30, 2004 no passes were rated above 0, based upon 157 observations spanning 289.33 days (2004-Mar-15.1104 to 2004-Dec-29.44434). The most dangerous pass was rated at 1 in 7,143,000.
  - By 22:34 GMT on December 30, 2004, 157 observations spanning 289.33 days (2004-Mar-15.1104 to 2004-Dec-29.44434). One pass at 1 (Torino scale) 3 other passes.
  - By 03:57 GMT on January 2, 2005, 182 observations spanning 290.97 days (2004-Mar-15.1104 to 2004-Dec-31.07992) One pass at 1 (Torino scale) 19 other passes.
  - By 14:49 GMT on January 3, 2005, observations spanning 292.72 days (2004-Mar-15.1104 to 2005-Jan-01.82787) One pass at 1 (Torino scale) 15 other passes.
  - Extremely precise radar observations at Arecibo Observatory on January 27, 28, and 30 refine the orbit further and show that the April, 2029 close approach will

occur at only 5.6 Earth radii, approximately one-half the distance previously estimated.

- A radar observation on August 7, 2005, refines the orbit further and eliminates the possibility of an impact in 2035. Only the pass in 2036 remains at Torino Scale 1.
- A new radar observation at Arecibo Observatory on May 6, 2006, slightly lowered the Palermo scale rating, but the pass in 2036 remained at Torino Scale 1 despite the impact probability dropping by a factor of four.
- Additional observations through 2006 resulted in Apophis being lowered to Torino Scale 0 on August 6, 2006. Around this time, the impact probability was lowered to 1 in 45,000.
- As of October 7, 2009, refinements to the precovery images of Apophis by the University of Hawaii's Institute for Astronomy, the 90-inch Bok Telescope, and the Arecibo Observatory have generated a refined path that reduces the odds of a April 13, 2036 impact to about 1 in 250,000.

### **Possible impact effects**

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



Path of risk where 99942 Apophis may impact Earth in 2036.

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

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

## **Potential space missions**

### **Planetary Society competition**

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

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

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

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

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

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

Two teams tied for second place in the Student Category: Monash University, Clayton Campus, Australia, with Dilani Kahawala as Principal Investigator; and University of Michigan, with Jeremy Hollander as Principal Investigator. Each second place team won \$2,000. A team from Hong Kong Polytechnic University and Hong Kong University of Science and Technology, under the leadership of Peter Weiss, received an honorable mention and \$1,000 for the most innovative student proposal.

### **Proposed deflection strategies**

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

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

### **Don Quijote mission**

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

## Chapter- 6

# 4 Vesta

4 Vesta 



### Discovery

<b>Discovered by</b>	Heinrich Wilhelm Olbers
<b>Discovery date</b>	March 29, 1807

### Designations

<b>Named after</b>	Vesta
<b>Minor planet category</b>	Main belt (Vesta family)
<b>Adjective</b>	Vestian

### Orbital characteristics

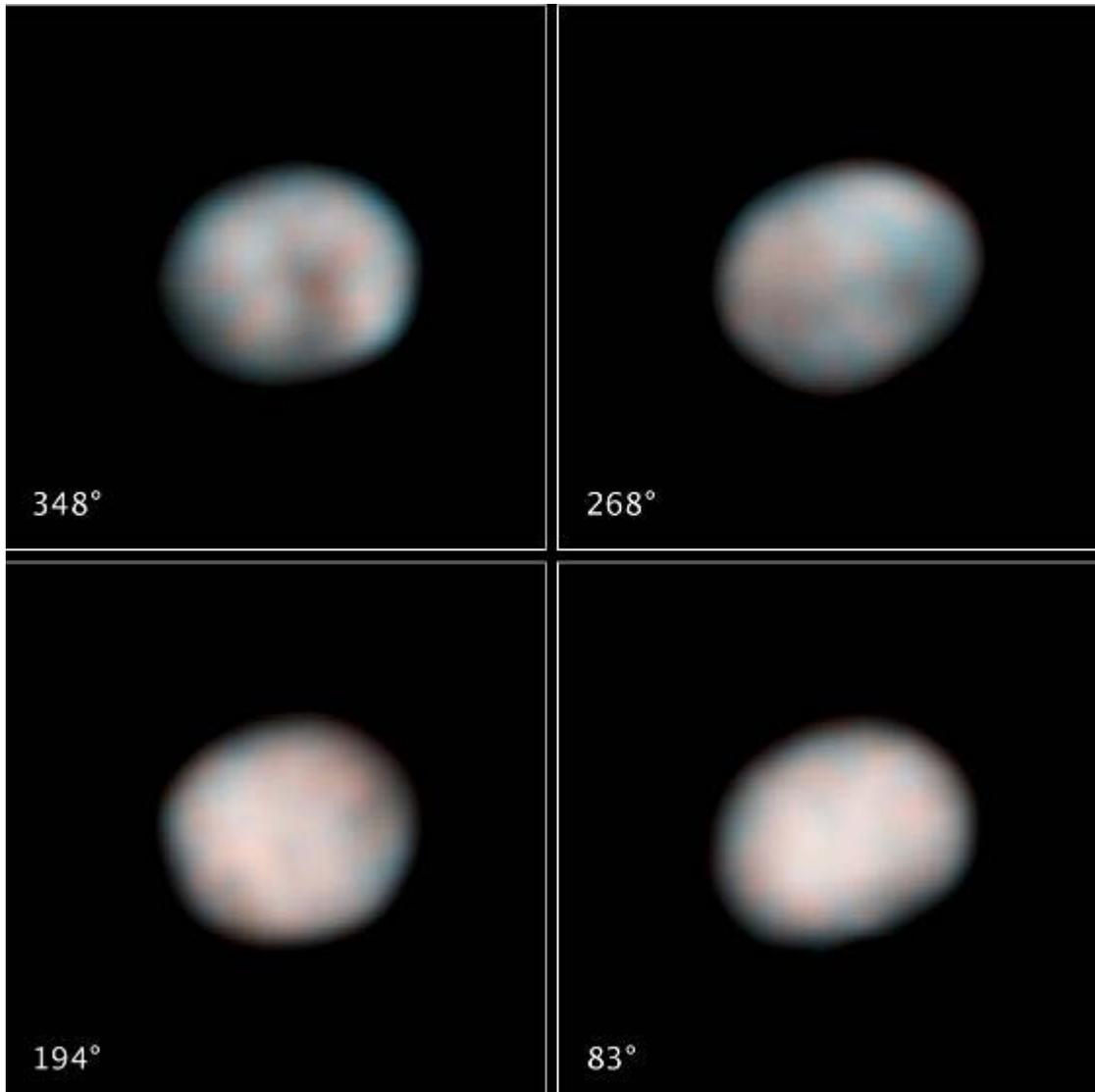
Epoch May 14, 2008 (JD 2454600.5)

<b>Aphelion</b>	384.72 Gm (2.572 AU)
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<b>Perihelion</b>	321.82 Gm (2.151 AU)
<b>Semi-major axis</b>	353.268 Gm (2.361 AU)
<b>Eccentricity</b>	0.089 17
<b>Orbital period</b>	1325.15 d (3.63 a)
<b>Average orbital speed</b>	19.34 km/s
<b>Mean anomaly</b>	90.53°
<b>Inclination</b>	7.135° to Ecliptic 5.56° to Invariable plane
<b>Longitude of ascending node</b>	103.91°
<b>Argument of perihelion</b>	149.83°

#### Physical characteristics

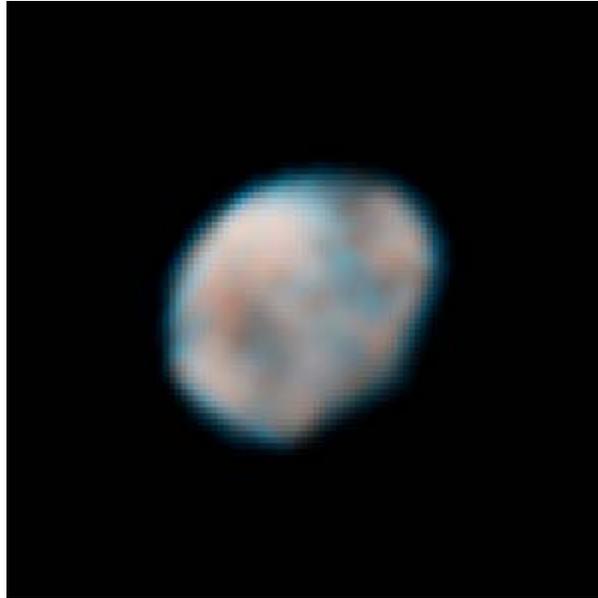
<b>Dimensions</b>	578×560×458 km 529 km (mean)
<b>Mass</b>	$(2.67 \pm 0.02) \times 10^{20}$ kg
<b>Mean density</b>	3.42 g/cm <sup>3</sup>
<b>Equatorial surface gravity</b>	0.22 m/s <sup>2</sup>
<b>Escape velocity</b>	0.35 km/s
<b>Rotation period</b>	0.222 6 d (5.342 h)
<b>Albedo</b>	0.423 (geometric)
<b>Temperature</b>	<i>min</i> : 85 K (−188 °C) <i>max</i> : 255 K (−18 °C)
<b>Spectral type</b>	V-type asteroid
<b>Apparent magnitude</b>	5.1 to 8.48
<b>Absolute magnitude (<i>H</i>)</b>	3.20
<b>Angular diameter</b>	0.64" to 0.20"



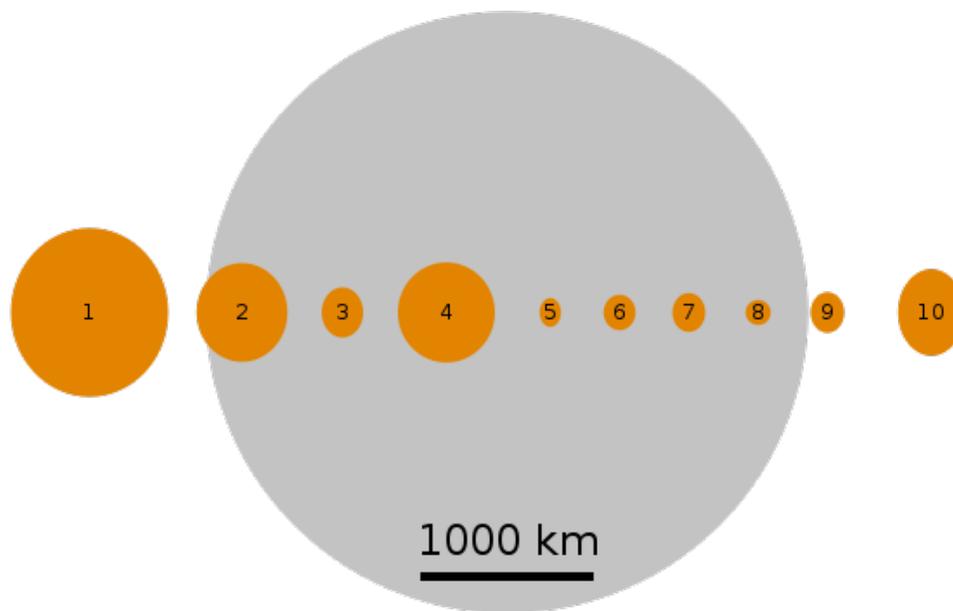
Four views of Vesta as it rotates. The dark patch in the center of the upper-left image is believed to be a lava flow. Orange areas are thought to be impacts.

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

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



## Discovery



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

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

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

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

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

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

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

## Physical characteristics



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

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

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

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

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

## Geology

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

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

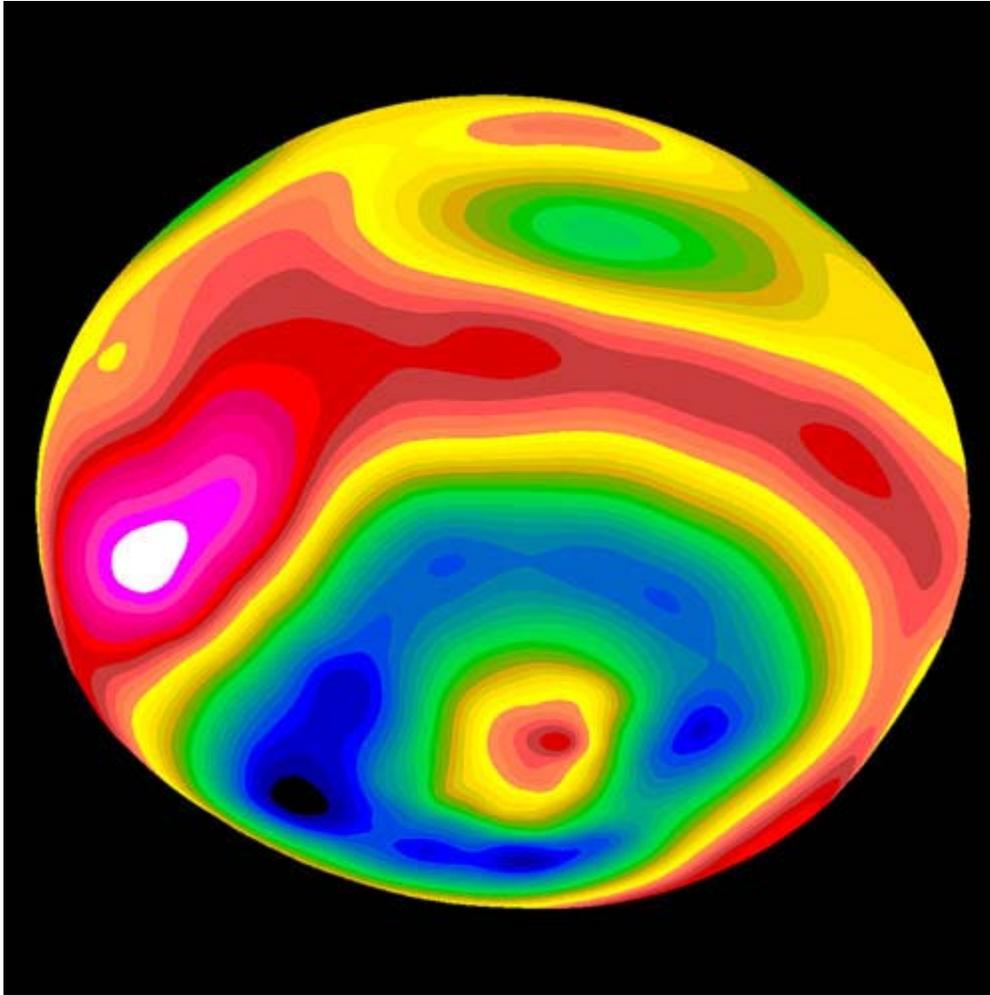
### Timeline of the evolution of Vesta

- 2–3 million years** Accretion completed
- 4–5 million years** Complete or almost complete melting due to radioactive decay of <sup>26</sup>Al, leading to separation of the metal core
- 6–7 million years** Progressive crystallization of a convecting molten mantle. Convection stopped when about 80% of the material had crystallized

Extrusion of the remaining molten material to form the crust, either as basaltic lavas in progressive eruptions, or possibly forming a short-lived magma ocean.

The deeper layers of the crust crystallize to form plutonic rocks, while older basalts are metamorphosed due to the pressure of newer surface layers.

Slow cooling of the interior



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

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

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

A lithified regolith, the source of howardites and brecciated eucrites.

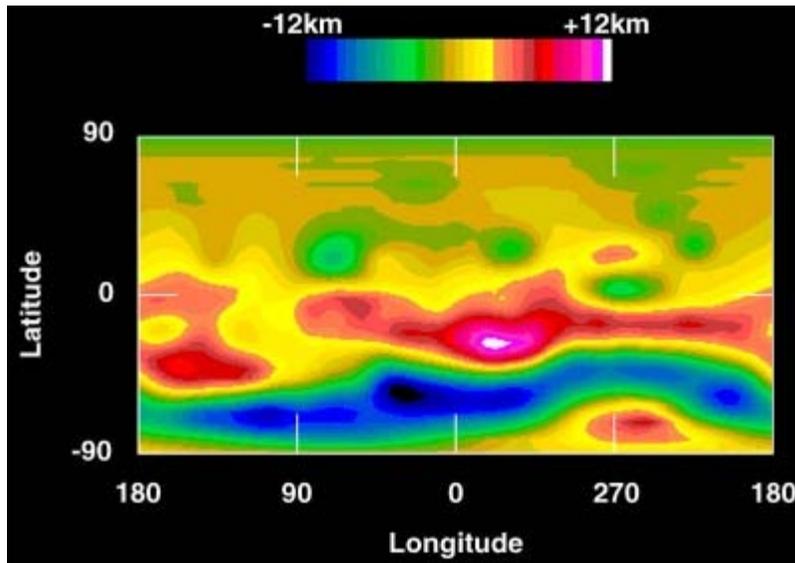
Basaltic lava flows, a source of non-cumulate eucrites.

Plutonic rocks consisting of pyroxene, pigeonite and plagioclase, the source of cumulate eucrites.

Plutonic rocks rich in orthopyroxene with large grain sizes, the source of diogenites.

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

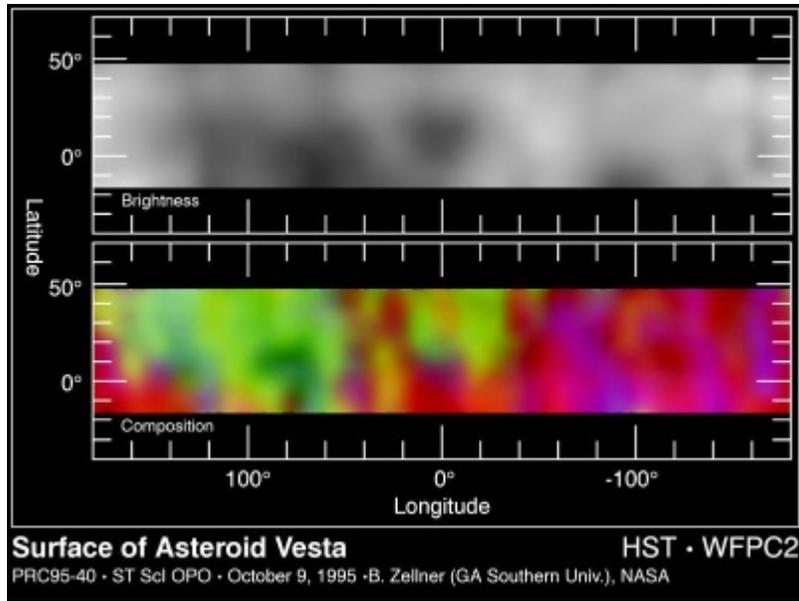
## Surface features



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

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

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



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

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

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

## Fragments



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

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

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

## Exploration

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

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

NASA's *Dawn* probe—launched on September 27, 2007—is the first space mission to Vesta. It will orbit the asteroid for nine months from August 2011 until May 2012. *Dawn* will then proceed to its other target, Ceres, and will possibly continue to explore the asteroid belt on an extended mission using any remaining fuel. The spacecraft is the first that can enter and leave orbit around more than one body as a result of its weight-efficient

ion driven engines. Once *Dawn* arrives at Vesta, scientists will be able to calculate Vesta's precise mass based on gravitational interactions. This will allow scientists to refine the mass estimates of the asteroids that are in turn perturbed by Vesta.

## Visibility



Vesta is seen from San Francisco on June 14, 2007

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

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

### 2010-2011

In 2010, Vesta reached opposition in the constellation of Leo on the night of February 17–18, when it was about magnitude 6.1, a brightness that makes it visible in binocular range but probably not for the naked eye. However, under perfect dark sky conditions

where all light pollution is absent it might be visible to an experienced observer without the use of a telescope or binoculars. Vesta will next come to opposition on August 5, 2011, in the constellation of Capricornus at about magnitude 5.6.

## Chapter- 7

# Asteroid Impact Avoidance



Artist's impression of a major impact event. The collision between Earth and an asteroid a few kilometres in diameter releases as much energy as the simultaneous detonation of several million nuclear bombs.

**Asteroid mitigation strategies** are "planetary defense" methods by which near-Earth objects could be diverted, preventing potentially catastrophic impact events. A sufficiently large impact would cause massive tsunamis and/or, by placing large quantities of dust into the stratosphere blocking sunlight, an impact winter. A collision between the earth and a ~10 km object 65 million years ago is believed to have produced the Chicxulub Crater and the Cretaceous–Tertiary extinction event.

While in theory the chances of such an event are no greater now than at any other time in history, recent astronomical events (such as Shoemaker-Levy 9) have drawn attention to such a threat, and advances in technology have opened up new options.

## **Detection efforts**

### **What do we need to know?**

Almost any deflection effort requires years of warning, allowing time to build a slow-pusher or explosive device to deflect the object.

An impact by a 10 km asteroid on the Earth is widely viewed as an extinction-level event, likely to cause catastrophic damage to the biosphere. Depending on speed, objects as small as 100 m in diameter are historically extremely destructive. There is also the threat from comets coming into the inner Solar System. The impact speed of a long-period comet would likely be several times greater than that of a near-Earth asteroid, making its impact much more destructive; in addition, the warning time is unlikely to be more than a few months.

Finding out the material composition of the object is also necessary before deciding which strategy is appropriate. Missions like the 2005 *Deep Impact* probe have provided valuable information on what to expect.

### **History of government mandates**

In a 1992 report to NASA, a coordinated Spaceguard Survey was recommended to discover, verify and provide follow-up observations for Earth-crossing asteroids. This survey was expected to discover 90% of these objects larger than one kilometer within 25 years. Three years later, another NASA report recommended search surveys that would discover 60-70% of short-period, near-Earth objects larger than one kilometer within ten years and obtain 90% completeness within five more years.

In 1998, NASA formally embraced the goal of finding and cataloging, by 2008, 90% of all near-Earth objects (NEOs) with diameters of 1 km or larger than could represent a collision risk to Earth. The 1 km diameter metric was chosen after considerable study indicated that an impact of an object smaller than 1 km could cause significant local or regional damage but is unlikely to cause a worldwide catastrophe. The impact of an object much larger than 1 km diameter could well result in worldwide damage up to, and potentially including, extinction of the human race. The NASA commitment has resulted in the funding of a number of NEO search efforts that are making considerable progress toward the 90% goal by 2008.

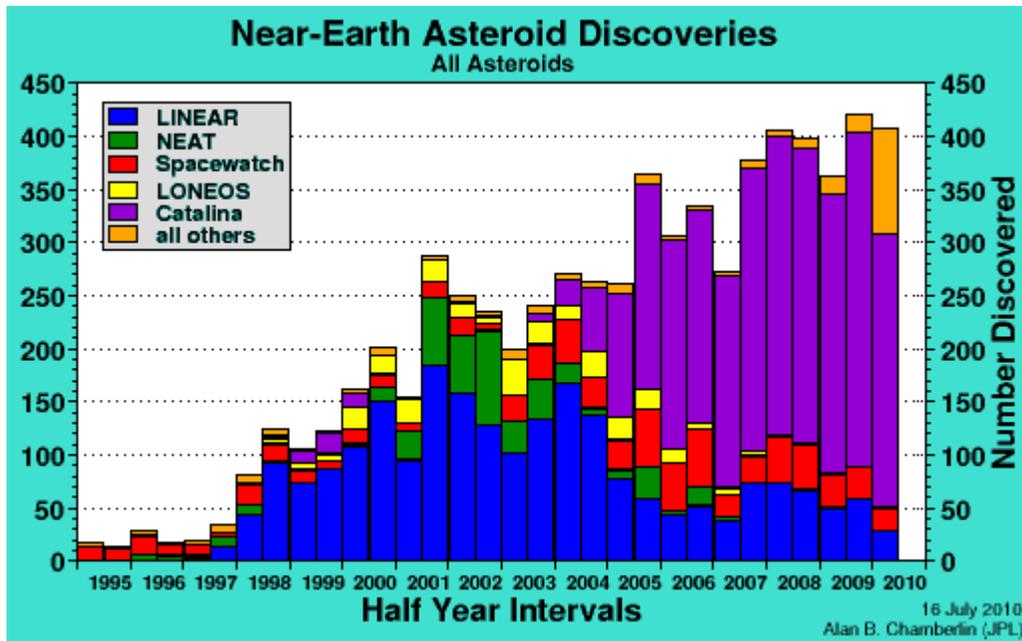
NASA is close to achieving this goal, and should achieve it within a few years. However, as the 2009 discovery of an NEO approximately 2 to 3 kilometers in diameter demonstrates, there are still large objects to be detected.

U.S. Representative George E. Brown, Jr. (D-CA) was quoted as voicing his support for planetary defense projects in *Air & Space Power Chronicles*, saying "If some day in the future we discover well in advance that an asteroid that is big enough to cause a mass extinction is going to hit the Earth, and then we alter the course of that asteroid so that it does not hit us, it will be one of the most important accomplishments in all of human history."

Because of Congressman Brown's long-standing commitment to planetary defense, a U.S. House of Representatives' bill, H.R. 1022, was named in his honor: The George E. Brown, Jr. Near-Earth Object Survey Act. This bill "to provide for a Near-Earth Object Survey program to detect, track, catalogue, and characterize certain near-earth asteroids and comets" was introduced in March 2005 by Rep. Dana Rohrabacher (R-CA). It was eventually rolled into S.1281, the NASA Authorization Act of 2005, passed by Congress on December 22, 2005, subsequently signed by the President, and stating in part:

The U.S. Congress has declared that the general welfare and security of the United States require that the unique competence of NASA be directed to detecting, tracking, cataloguing, and characterizing near-Earth asteroids and comets in order to provide warning and mitigation of the potential hazard of such near-Earth objects to the Earth. The NASA Administrator shall plan, develop, and implement a Near-Earth Object Survey program to detect, track, catalogue, and characterize the physical characteristics of near-Earth objects equal to or greater than 140 meters in diameter in order to assess the threat of such near-Earth objects to the Earth. It shall be the goal of the Survey program to achieve 90% completion of its near-Earth object catalogue (based on statistically predicted populations of near-Earth objects) within 15 years after the date of enactment of this Act. The NASA Administrator shall transmit to Congress not later than 1 year after the date of enactment of this Act an initial report that provides the following: (A) An analysis of possible alternatives that NASA may employ to carry out the Survey program, including ground-based and space-based alternatives with technical descriptions. (B) A recommended option and proposed budget to carry out the Survey program pursuant to the recommended option. (C) Analysis of possible alternatives that NASA could employ to divert an object on a likely collision course with Earth. The result of this directive was a report presented to Congress in early March 2007. This was an Analysis of Alternatives (AoA) study led by NASA's Program Analysis and Evaluation (PA&E) office with support from outside consultants, the Aerospace Corporation, NASA Langley Research Center (LaRC), and SAIC (amongst others).

## **Ongoing projects**



Number of NEOs detected by various projects.

Astronomers have been conducting surveys to locate the NEOs, many (as of early 2007) funded by NASA's Near Earth Object (NEO) program office as part of their Spaceguard program. One of the best-known is LINEAR that began in 1996. By 2004 LINEAR was discovering tens of thousands of objects each year and accounting for 65% of all new asteroid detections. LINEAR uses two one-meter telescopes and one half-meter telescope based in New Mexico.

Spacewatch, which uses a 90 centimeter telescope sited at the Kitt Peak Observatory in Arizona, updated with automatic pointing, imaging, and analysis equipment to search the skies for intruders, was set up in 1980 by Tom Gehrels and Dr. Robert S. McMillan of the Lunar and Planetary Laboratory of the University of Arizona in Tucson, and is now being operated by Dr. McMillan. The Spacewatch project has acquired a 1.8 meter telescope, also at Kitt Peak, to hunt for NEOs, and has provided the old 90 centimeter telescope with an improved electronic imaging system with much greater resolution, improving its search capability.

Other near-earth object tracking programs include Near-Earth Asteroid Tracking (NEAT), Lowell Observatory Near-Earth-Object Search (LONEOS), Catalina Sky Survey, Campo Imperatore Near-Earth Objects Survey (CINEOS), Japanese Spaceguard Association, and Asiago-DLR Asteroid Survey. Pan-STARRS is expected to complete telescope construction by 2012.

"Spaceguard" is the name for these loosely affiliated programs, some of which receive NASA funding to meet a U.S. Congressional requirement to detect 90% of near-earth asteroids over 1 km diameter by 2008. A 2003 NASA study of a follow-on program

suggests spending US\$250–450 million to detect 90% of all near-earth asteroids 140 meters and larger by 2028.

Orbit@home provides distributed computing resources to optimize search strategy, and NEODyS is an online database of known NEOs.

## **Detection from space**

On November 8, 2007, the House Committee on Science and Technology's Subcommittee on Space and Aeronautics held a hearing to examine the status of NASA's Near-Earth Object survey program. The prospect of using the Wide-field Infrared Survey Explorer was proposed by NASA officials.

WISE will survey the sky in the infrared band at a very high sensitivity. Asteroids that absorb solar radiation can be observed through the infrared band. NASA officials told Committee staff that NASA plans to use WISE to detect NEOs, in addition to performing its science goals. It is projected that WISE could detect 400 NEOs (roughly two percent of the estimated NEO population of interest) within the one-year mission.

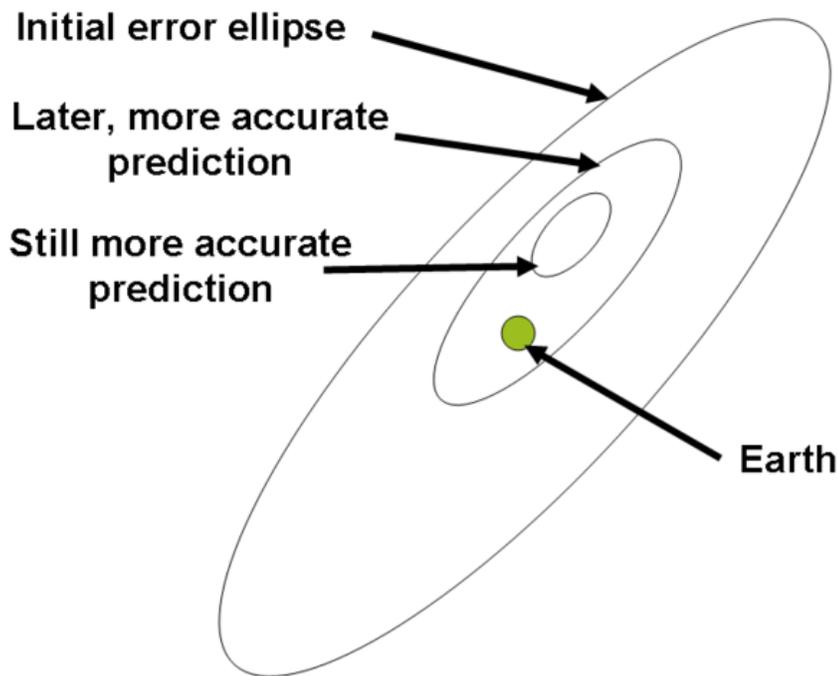
NEOSSat is a micro satellite by Canada's CSA that will hunt for NEOs from space.

## **Results**

Research published in the March 26, 2009 issue of the journal Nature, describes how scientists were able to identify an asteroid in space before it entered Earth's atmosphere, enabling computers to determine its area of origin in the solar system as well as predict the arrival time and location on Earth of its shattered surviving parts. The four-meter-diameter asteroid, called 2008 TC3, was initially sighted by the automated Catalina Sky Survey telescope, on October 6, 2008. Computations correctly predicted impact would occur 19 hours after discovery in the Nubian Desert of northern Sudan.

A number of potential threats have been identified, such as 99942 Apophis (previously known by its provisional designation 2004 MN<sub>4</sub>), which had been given an impact probability of ~3% for the year 2029. This probability has been revised to zero on the basis of new observations.

## **Impact probability calculation pattern**



Why asteroid impact probability goes up, then down.

The ellipses in the diagram at right show the likely asteroid position at closest earth approach. At first, with only a few asteroid observations, the error ellipse is very large and includes the Earth. Further observations shrink the error ellipse, but it still includes the Earth. This raises the impact probability, since the Earth now covers a larger fraction of the error region. Finally, yet more observations (often radar observations, or discovery of a previous sighting of the same asteroid on archival images) shrink the ellipse until the Earth is outside the error region, and the impact probability returns to near zero.

## Collision avoidance strategies

Various collision avoidance techniques have different trade-offs with respect to metrics such as overall performance, cost, operations, and technology readiness. There are various methods for changing the course of an asteroid/comet. These can be differentiated by various types of attributes such as the type of mitigation (deflection or fragmentation), energy source (kinetic, electromagnetic, gravitational, solar/thermal, or nuclear), and approach strategy (interception, rendezvous, or remote station). Strategies fall into two basic sets: destruction and delay.

Destruction concentrates on rendering the impactor harmless by fragmenting it and scattering the fragments so that they miss the Earth or burn up in the atmosphere. This does not always solve the problem, as sufficient amounts of material hitting the Earth at high speed can be devastating even if they are not collected together in a single body. The amount of energy released by a single large collision or many small collisions is essentially the same, given the physics of kinetic and potential energy. If a large amount of energy is transmitted, it could heat the surface of the planet to an uninhabitable temperature.

Collision avoidance strategies can also be seen as either direct, or indirect. The direct methods, such as nuclear bombs or kinetic impactors, violently intercept the bolide's path. Direct methods are preferred because they are generally less costly in time and money. Their effects may be immediate, thus saving precious time. These methods might work for short-notice, or even long-notice threats, from solid objects that can be directly pushed, but probably not effective against loosely aggregated rubble piles. The indirect methods, such as gravity tractors, attaching rockets or mass drivers, laser canons, etc., will travel to the object then take more time to change course up to 180 degrees to fly along side, and then will also take much more time to change the asteroids path just enough so it will miss Earth.

Many NEOs are "flying rubble piles" only loosely held together by gravity, and a deflection attempt might just break up the object without sufficiently adjusting its course. If an asteroid breaks into fragments, any fragment larger than 35 m across would not burn up in the atmosphere and itself could impact Earth. Tracking the thousands of fragments that could result from such an explosion would be a very daunting task. Many small impacts could cause greater devastation than one large impact.

Against some rubble piles, a nuclear bomb may be delivered to it and dock with it, then it could penetrate to its center, and explode sending fragments in all directions, thus reducing the amount of material reaching the Earth. The explosion can also increase the surface area of the threat enough so that more pieces will burn up harmlessly high in the atmosphere.

Delay exploits the fact that both the Earth and the impactor are in orbit. An impact occurs when both reach the same point in space at the same time, or more correctly when some point on Earth's surface intersects the impactor's orbit when the impactor arrives. Since the Earth is approximately 12,750 km in diameter and moves at approx. 30 km per second in its orbit, it travels a distance of one planetary diameter in about 425 seconds, or slightly over seven minutes. Delaying, or advancing the impactor's arrival by times of this magnitude can, depending on the exact geometry of the impact, cause it to miss the Earth. By the same token, the arrival time of the impactor must be known to this accuracy in order to forecast the impact at all, and to determine how to affect its velocity.

## **Nuclear weapons**

Detonating a nuclear explosion above the surface (or on the surface or beneath it) of an NEO would be one option, with the blast vaporizing part of the surface of the object and nudging it off course with the reaction. This is a form of nuclear pulse propulsion. Even if not completely vaporized, the resulting reduction of mass from the blast combined with the radiation blast and rocket exhaust effect from ejecta could produce positive results.

Another proposed solution is to detonate a series of smaller nuclear bombs alongside the asteroid, far enough away as not to fracture the object. Providing this was done far enough in advance, the relatively small forces from any number of nuclear blasts could be enough to alter the object's trajectory enough to avoid an impact. The 1964 book *Islands in Space*, calculates that a nuclear megatonnage necessary for several deflection scenarios exists. In 1967, graduate students under Professor Paul Sandorff at the Massachusetts Institute of Technology designed a system using rockets and nuclear explosions to prevent a hypothetical impact on Earth by the asteroid 1566 Icarus. This design study was later published as Project Icarus which served as the inspiration for the 1979 film *Meteor*.

### **Kinetic impact**

The hurling of a massive object at the NEO, such as a spacecraft or another near-earth object, is another violent possibility. A small asteroid or large mass in a stable high-Earth orbit would have tremendous kinetic energy stored up. With the addition of some thrust from mounted rockets (plasma or otherwise), it could be used like a stone from a slingshot to deflect the incoming threat.

An alternative means of deflecting an asteroid is to attempt to directly alter its momentum by sending a spacecraft to collide with the asteroid.

The European Space Agency is already studying the preliminary design of a space mission able to demonstrate this futuristic technology. The mission, named Don Quijote, is the first real asteroid deflection mission ever designed.

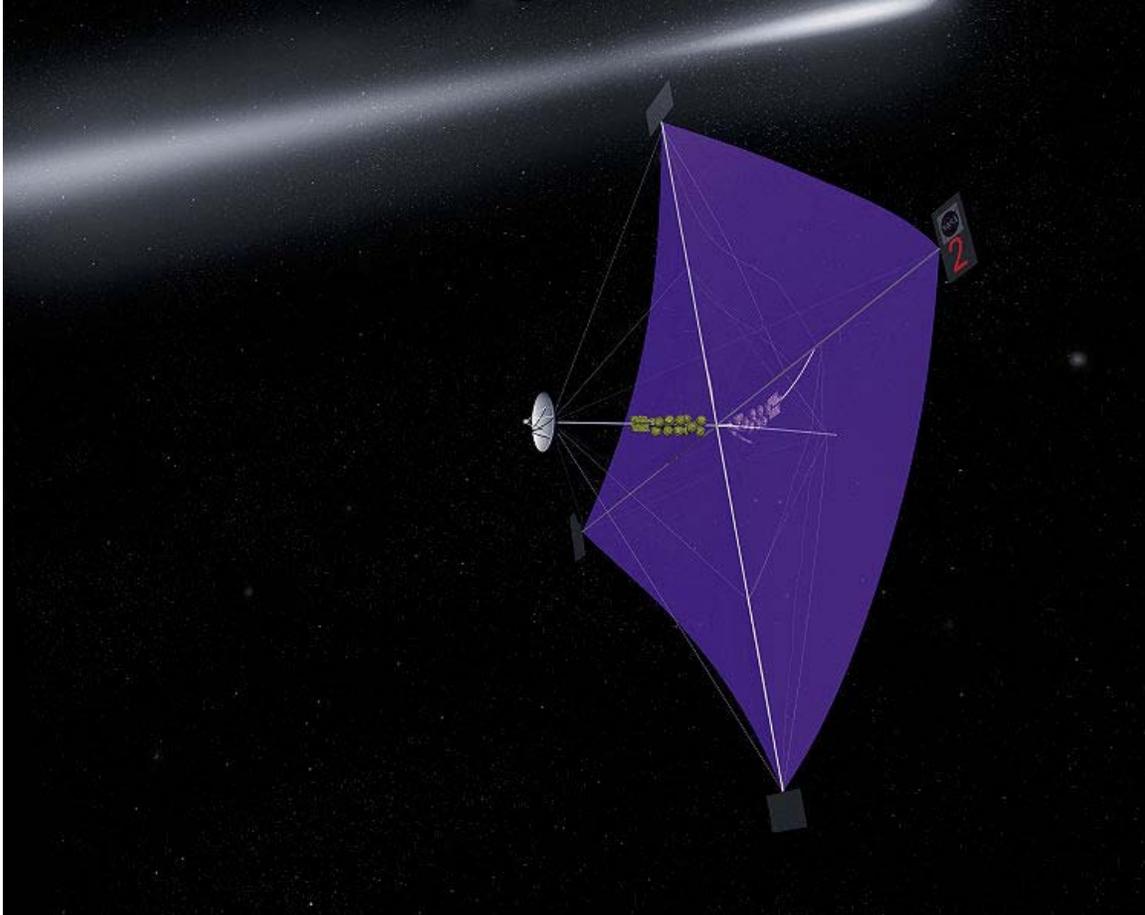
In the case of 99942 Apophis it has been demonstrated by ESA's Advanced Concepts Team that deflection could be achieved by sending a simple spacecraft weighing less than one ton to impact against the asteroid. During a trade-off study one of the leading researchers argued that a strategy called 'kinetic impactor deflection' was more efficient than others.

### **Asteroid gravitational tractor**

One more alternative to explosive deflection is to move the asteroid slowly over a time. Tiny constant thrust accumulates to deviate an object sufficiently from its predicted course. Edward T. Lu and Stanley G. Love have proposed using a large heavy unmanned spacecraft hovering over an asteroid to gravitationally pull the latter into a non-threatening orbit. The spacecraft and the asteroid mutually attract one another. If the spacecraft counters the force towards the asteroid by, e.g., an ion thruster, the net effect is

that the asteroid is accelerated towards the spacecraft and thus slightly deflected from its orbit. While slow, this method has the advantage of working irrespective of the asteroid composition or spin rate — rubble pile asteroids would be difficult or impossible to deflect by means of nuclear detonations while a pushing device would be hard or inefficient to mount on a fast rotating asteroid. A gravity tractor would likely have to spend several years beside the asteroid to be effective.

### **Use of focused solar energy**



NASA study of a solar sail. The sail would be 0.5 km wide.

H. Jay Melosh proposed to deflect an asteroid or comet by focusing solar energy onto its surface to create thrust from the resulting vaporization of material, or to amplify the Yarkovsky effect. Over a span of months or years enough solar radiation can be directed onto the object to deflect it.

This method would first require the construction of a space station with a system of gigantic lens and magnifying glasses near earth. Then the station would be transported toward the Sun.

## **Mass driver**

A mass driver is an (automated) system on the asteroid to eject material into space thus giving the object a slow steady push and decreasing its mass. A mass driver is designed to work as a very low Specific Impulse system, which in general uses a lot of propellant, but very little power.

The idea is that when using local material as propellant, the amount of propellant is not as important as the amount of power, which is likely to be limited.

Another possibility is to use a mass driver on the moon aimed at the NEO to take advantage of the moon's orbital velocity and inexhaustible supply of "rock bullets".

## **Conventional rocket motor**

Attaching any spacecraft propulsion device would have a similar effect of giving a steady push, possibly forcing the asteroid onto a trajectory that takes it away from Earth. An in-space rocket engine that is capable of imparting an impulse of  $10^6$  N·s (E.g. adding 1 km/s to a 1000 kg vehicle), will have a relatively small effect on a relatively small asteroid that has a mass of roughly a million times more. Chapman, Durda, and Gold's white paper calculates deflections using existing chemical rockets delivered to the asteroid.

## **Other proposals**

- Non-conventional engines, such as VASIMR
- Wrapping the asteroid in a sheet of reflective plastic such as aluminized PET film as a solar sail
- "Painting" or dusting the object with titanium dioxide (white) or soot (black) to alter its trajectory via the Yarkovsky effect.
- Planetary scientist Eugene Shoemaker in 1996 proposed deflecting a potential impactor by releasing a cloud of steam in the path of the object, hopefully gently slowing it. Nick Szabo in 1990 sketched a similar idea, "cometary aerobraking", the targeting of a comet or ice construct at an asteroid, then vaporizing the ice with nuclear explosives to form a temporary atmosphere in the path of the asteroid.
- Attaching a tether and ballast mass to the asteroid to alter its trajectory by changing its center of mass.
- Laser ablation
- Magnetic Flux Compression
- NEONet

## **Deflection technology concerns**

Carl Sagan, in his book *Pale Blue Dot*, expressed concerns about deflection technology: that any method capable of deflecting impactors *away* from Earth could also be abused to divert non-threatening bodies *toward* the planet. Considering the history of genocidal political leaders and the possibility of the bureaucratic obscuring of any such project's true goals to most of its scientific participants, he judged the Earth at greater risk from a man-made impact than a natural one. Sagan instead suggested that deflection technology should only be developed in an actual emergency situation.

Analysis of the uncertainty involved in nuclear deflection shows that the ability to protect the planet does not imply the ability to target the planet. A nuclear bomb which changed an asteroid's velocity by 10 meters/second (plus or minus 20%) would be adequate to push it out of an earth-impacting orbit. However, if the uncertainty of the velocity change was more than a few percent, there would be no chance of directing the asteroid to a particular target.

According to Rusty Schweickart, the gravitational tractor method is also controversial because during the process of changing an asteroid's trajectory the point on Earth where it could most likely hit would be slowly shifted across different countries. It means that the threat for the entire planet would be minimized at the cost of some specific states' security. In Schweickart's opinion, choosing the way the asteroid should be "dragged" would be a tough diplomatic decision.

## Planetary defense timeline

- In their 1964 book, *Islands in Space*, Dandridge M. Cole and Donald W. Cox noted the dangers of planetoid impacts, both those occurring naturally and those that might be brought about with hostile intent. They argued for cataloging the minor planets and developing the technologies to land on, deflect, or even capture planetoids.
- In the 1980s NASA studied evidence of past strikes on planet Earth, and the risk of this happening at our current level of civilization. This led to a program that maps which objects in our solar system both cross Earth's orbit and are large enough to cause serious damage if they ever hit.
- In the 1990s, US Congress held hearings to consider the risks and what needed to be done about them. This led to a US\$3 million annual budget for programs like Spaceguard and the near-earth object program, as managed by NASA and USAF.
- In 2005 the world's astronauts published an open letter through the Association of Space Explorers calling for a united push to develop strategies to protect Earth from the risk of a cosmic collision.
- It is currently (as of late 2007) believed that there are approximately 20,000 objects capable of crossing Earth's orbit and large enough (140 meters or larger) to warrant concern. On the average, one of these will collide with Earth each 5,000 years, unless preventative measures are undertaken. It is now anticipated that by year 2008, 90% of such objects that are 1 km or more in diameter will have been identified and will be monitored. The further task of identifying and

monitoring all such objects of 140m or greater is expected to be complete around 2020.

- The Catalina Sky Survey (CSS) is one of NASA's four funded surveys to carry out a 1998 U.S. Congress mandate to find and catalog by the end of 2008, at least 90 percent of all near-Earth objects (NEOs) larger than 1 kilometer across. CSS discovered 310 NEOs in 2005, 400 in 2006 and the record will be broken with 450 NEOs found in 2007. In doing this survey they discovered on November 20, 2007, an asteroid, designated 2007 WD<sub>5</sub>, which initially was estimated to have a chance of hitting Mars on January 30, 2008, but further observations during the following weeks allowed NASA to rule out an impact. NASA estimated a near miss by 26,000 km.