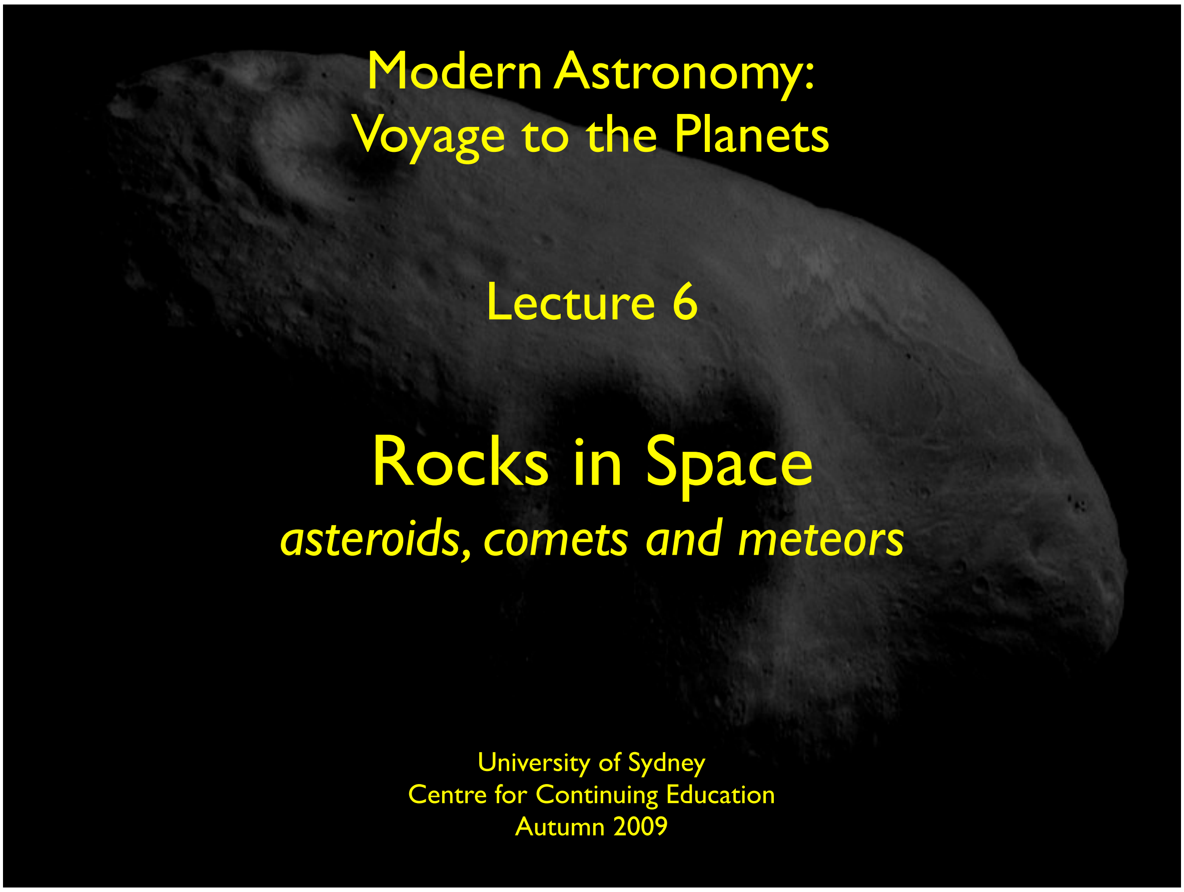
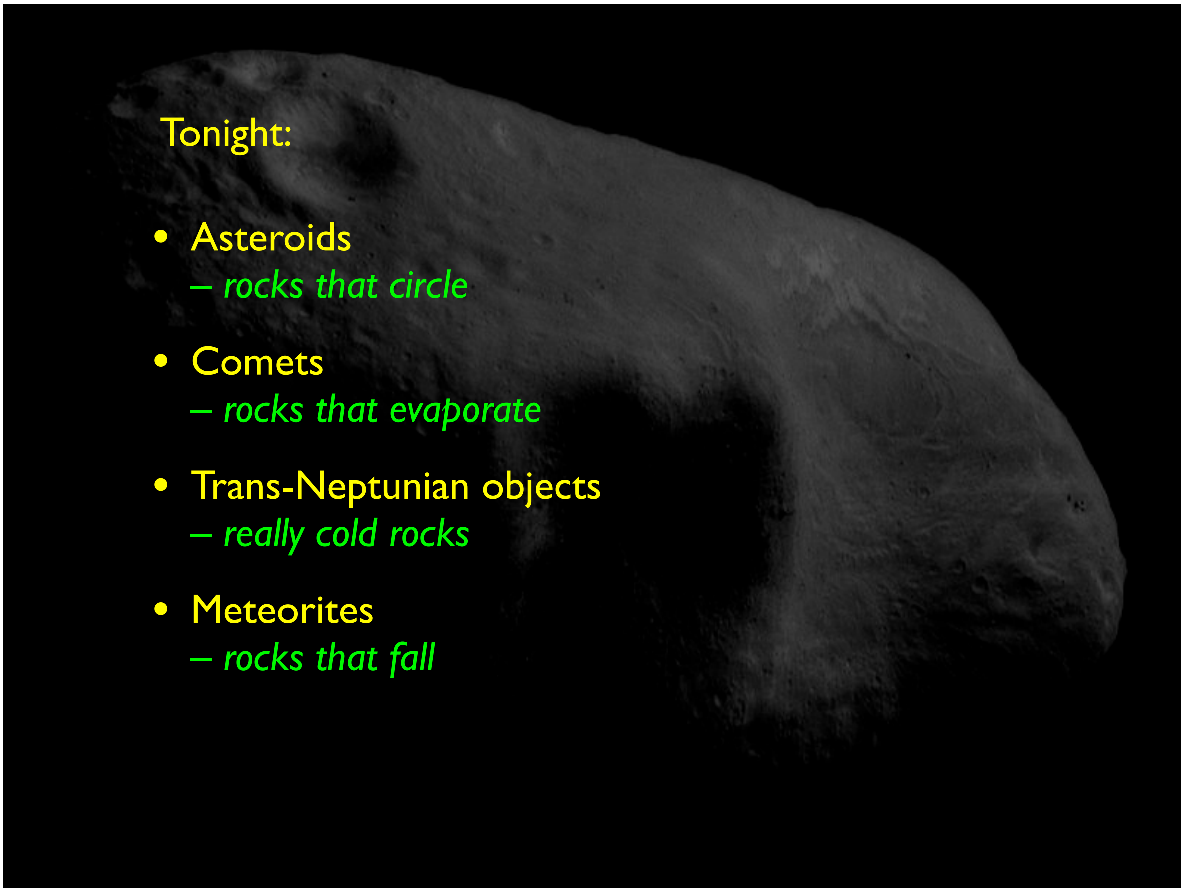

Modern Astronomy:
Voyage to the Planets
Lecture 6
Rocks in Space
asteroids, comets and meteors
University of Sydney
Centre for Continuing Education
Autumn 2009


Tonight:
• Asteroids
– *rocks that circle*
• Comets
– *rocks that evaporate*
• Trans-Neptunian objects
– *really cold rocks*
• Meteorites
– *rocks that fall*

Asteroids

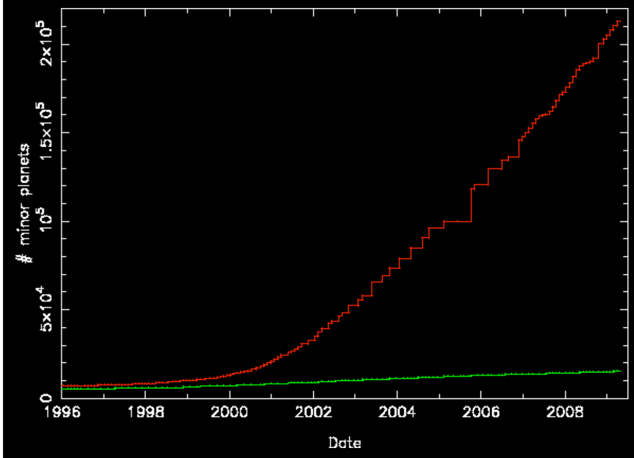
The Solar System contains a large number of small bodies, of which the largest are the *asteroids*. Some orbit the Sun inside the Earth's orbit, and others have highly elliptical orbits which cross the Earth's. However, the vast bulk of asteroids orbit the Sun in nearly circular orbits in a broad belt between Mars and Jupiter.

An asteroid (or strictly *minor planet**) is smaller than major planets, but larger than meteoroids, which are 10m or less in size.

* since 2006, these are now officially *small solar system bodies*, though the term "minor planet" may still be used

As of April 2009, there are 212,999 asteroids which have been given numbers; 15190 have been given names.

The rate of discovery of new bodies is about 5000 per month.



It is estimated there are between 1.1 and 1.9 million asteroids larger than 1 km in diameter.

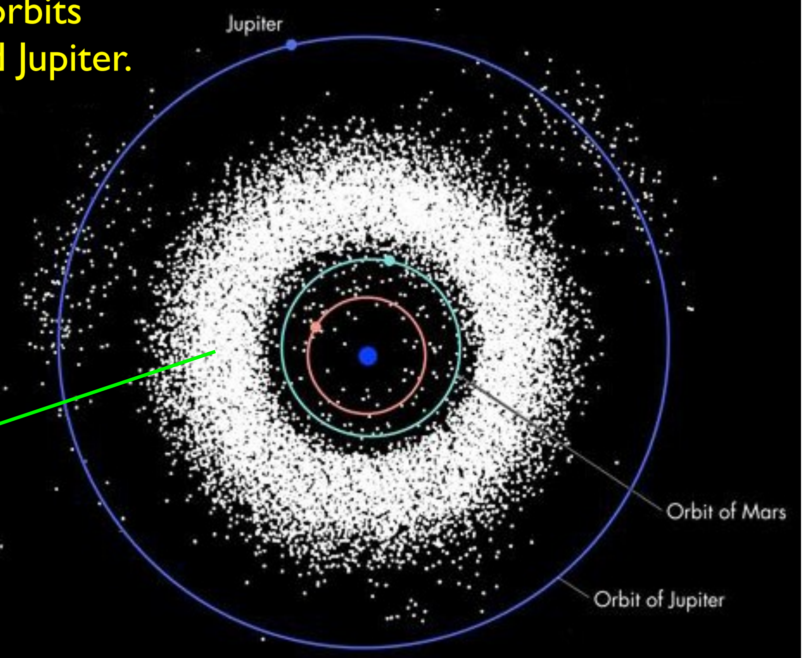
Number of minor planets with orbits (red) and names (green)

The largest are 1 Ceres (1000 km in diameter), 2 Pallas (550 km), 4 Vesta (530 km), and 10 Hygiea (410 km). Only 16 asteroids are larger than 240 km in size. Ceres is by far the largest and most massive body in the asteroid belt, and contains approximately a third of the belt's total mass.

Altogether, the total mass of asteroids would make an object only about a twentieth the size of the Moon.

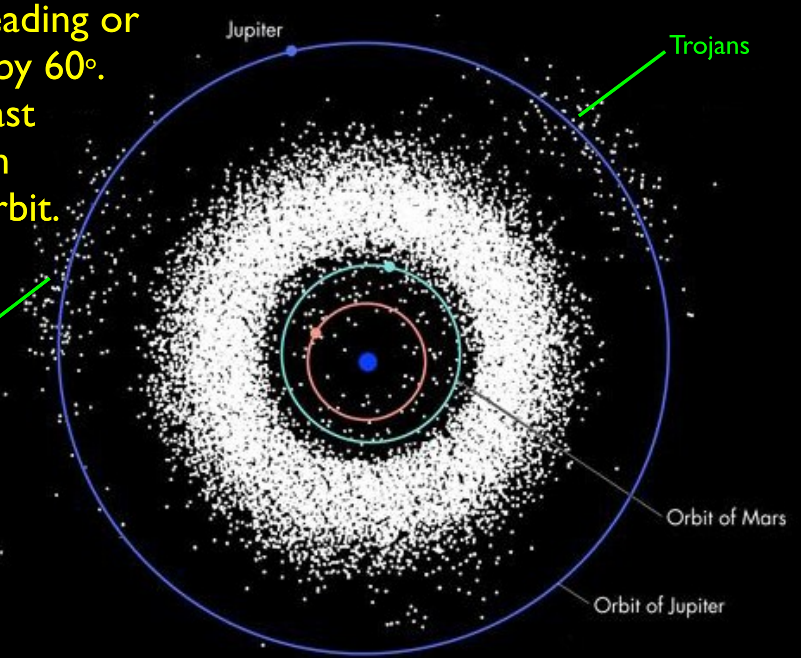
There are three main groups of asteroids:

– the *Main Belt asteroids*,
in stable circular orbits
between Mars and Jupiter.



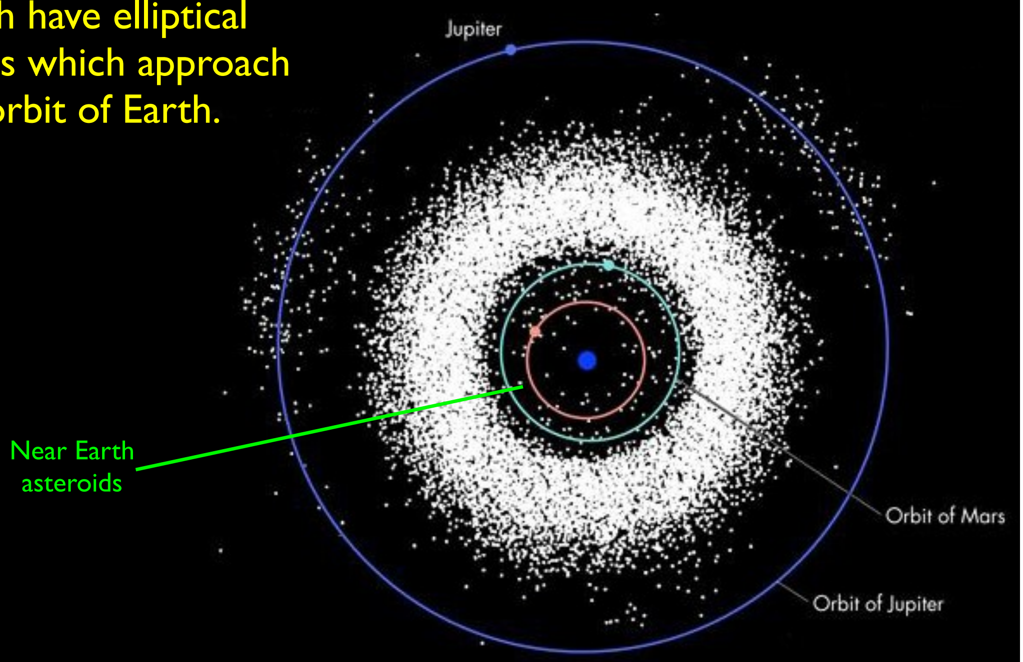
There are three main groups of asteroids:

– the *Trojans*, which orbit
in Jupiter's orbit, leading or
trailing the planet by 60°.
There is also at least
one asteroid which
trails Mars in its orbit.

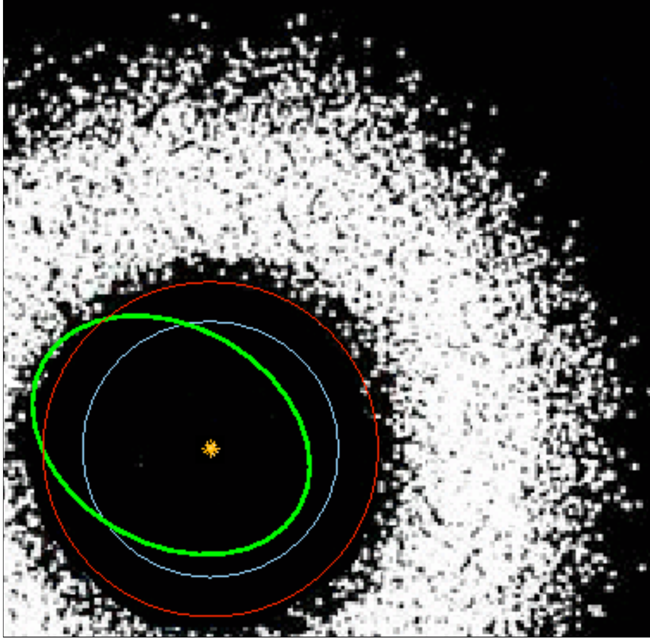


There are three main groups of asteroids:

– the *near Earth asteroids*, which have elliptical orbits which approach the orbit of Earth.



The near-Earth asteroids have different names, depending on the shape of their orbits:

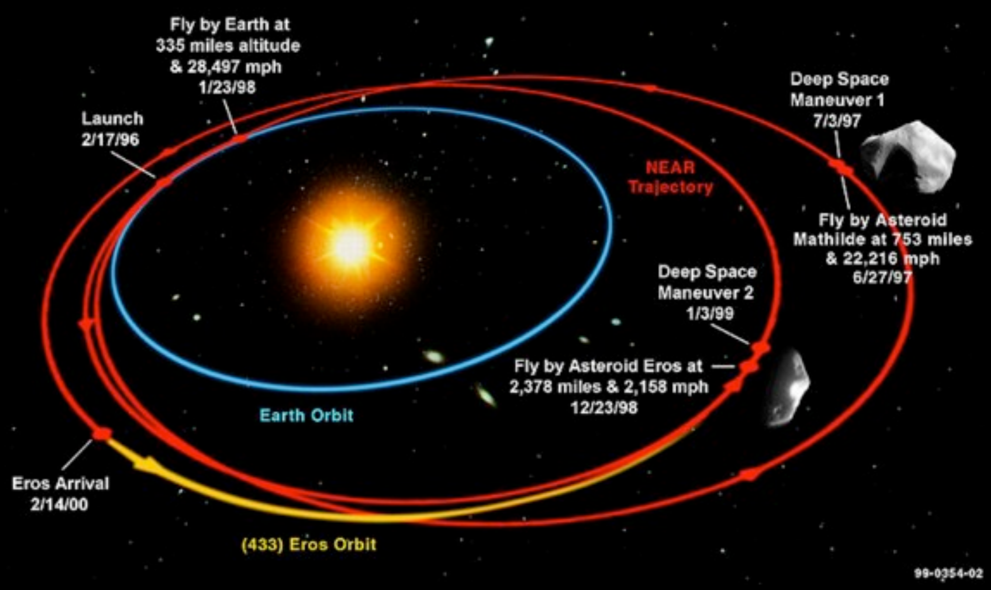


– The *Amor* asteroids cross Mars' orbit but do not reach Earth's orbit;

– the *Apollo* asteroids cross Earth's orbit and have a period greater than 1 year; and

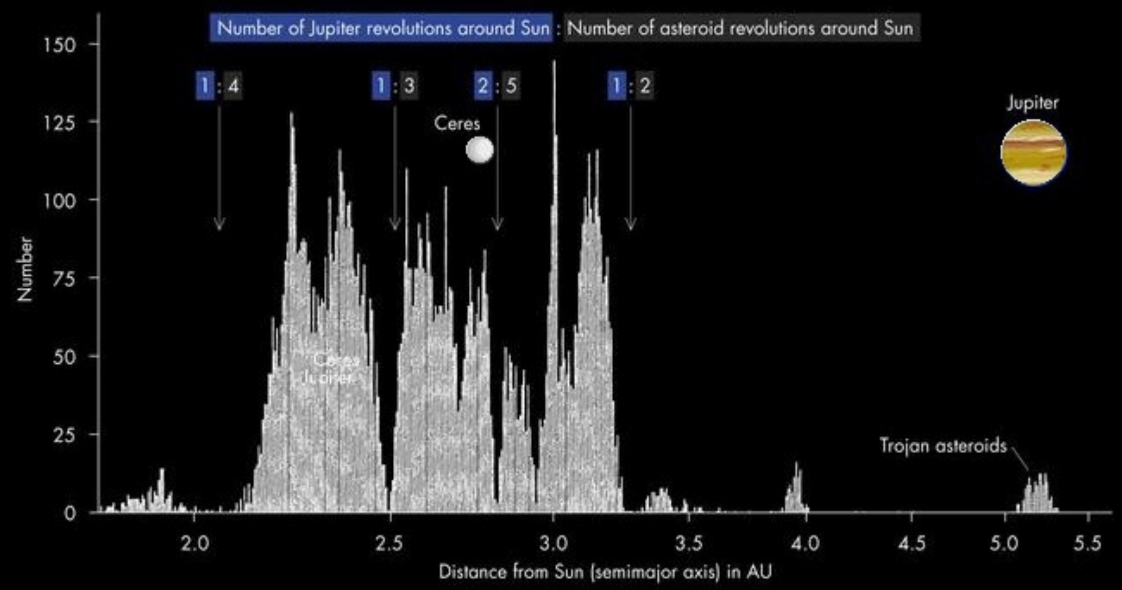
– the *Aten* asteroids have periods of less than 1 year.

A particularly well-studied Apollo asteroid is 433 Eros, which was studied in detail by NEAR-Shoemaker as it orbited then finally landed on the asteroid in February 2001.

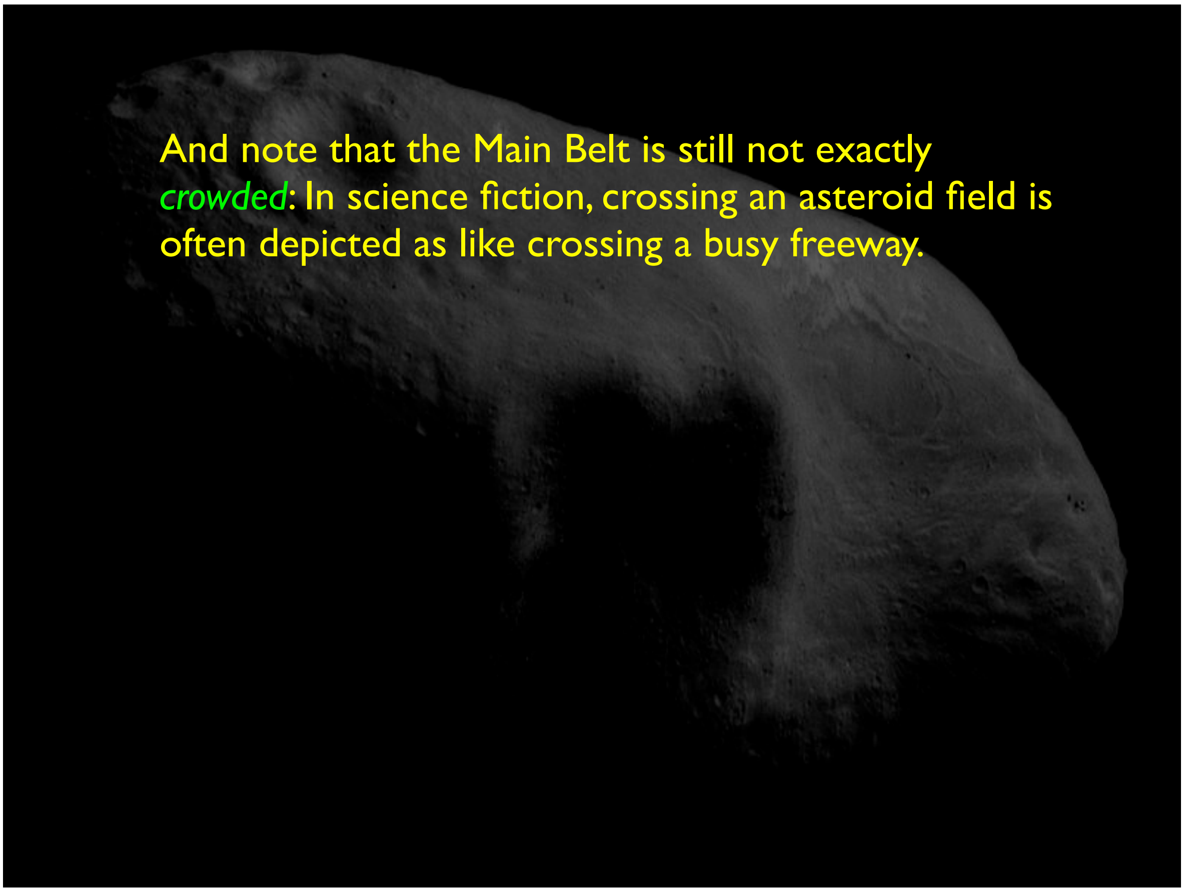


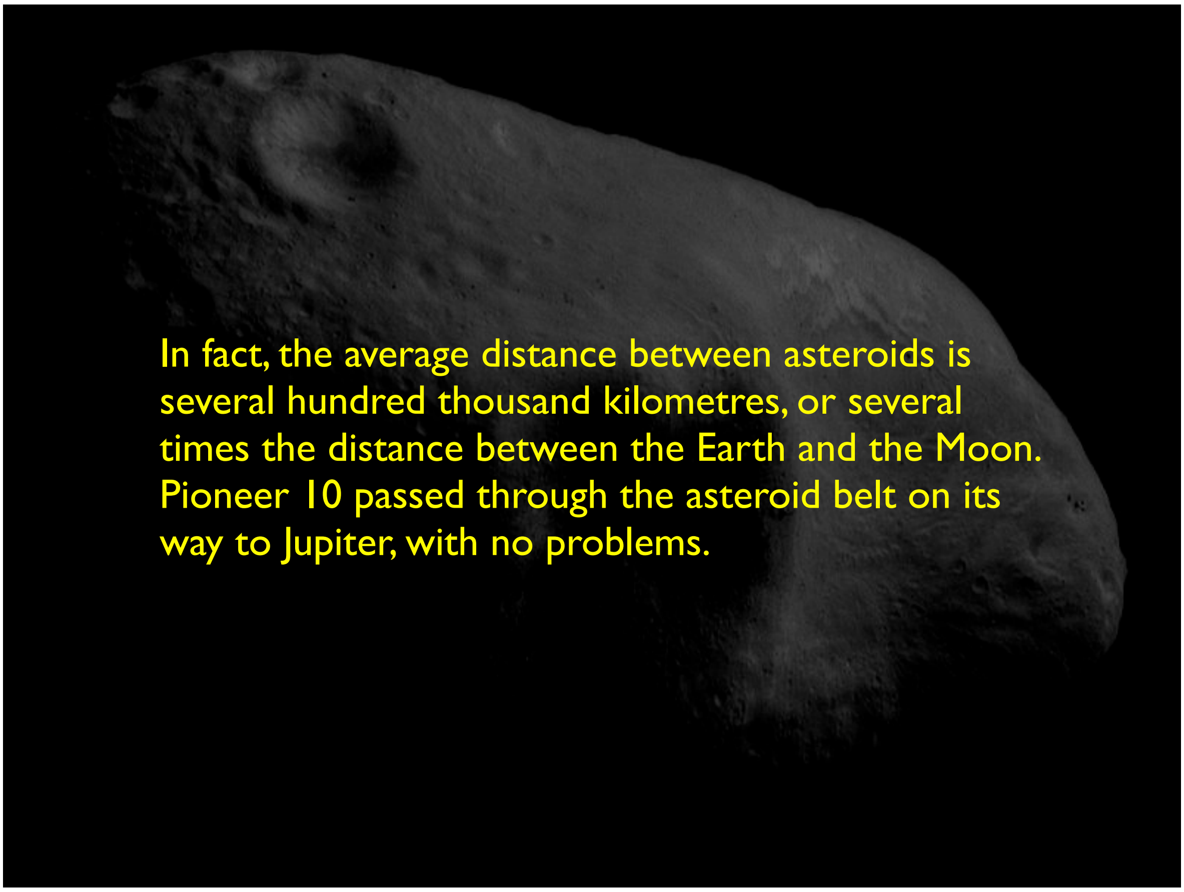
These animations show some of the many images returned by NEAR-Shoemaker, showing the detail it could see.

Asteroids are not distributed randomly in the Main Belt: there are gaps where they are scarce, called Kirkwood gaps. These occur where the orbital period has a simple integer relation to Jupiter's period.



And note that the Main Belt is still not exactly *crowded*: In science fiction, crossing an asteroid field is often depicted as like crossing a busy freeway.




In fact, the average distance between asteroids is several hundred thousand kilometres, or several times the distance between the Earth and the Moon. Pioneer 10 passed through the asteroid belt on its way to Jupiter, with no problems.

Asteroids are classified into several types, based on their composition.

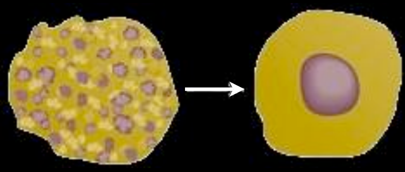
- *C-type* asteroids contain a lot of carbon, and are very dark: Ceres has an albedo of only 5.7%. More than 75% of asteroids are C-type.
- *S-type* asteroids are silicon-rich, and make up most of the rest. A small number are
- *M-type* asteroids are metallic, where the metal is predominantly iron.
- *U-type* (unclassified)

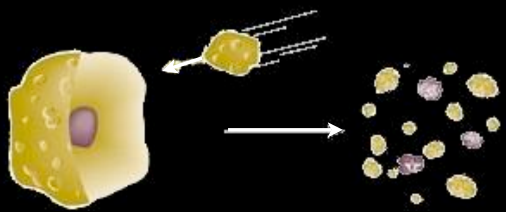
Some smaller asteroids can be matched with larger asteroids, of which they are presumably fragments, by having exactly the same spectral properties.

The different types of asteroids have very different *albedos*, or surface reflectivity. The C-type asteroids have albedos of only 2–5%, S-types about 15%. The metallic M-types fall between, with albedos of about 10%. There are a couple of asteroids with higher albedos, however. In particular, Vesta (type U) reflects a whopping 42% of light, which makes it the only asteroid (just) visible to the naked eye: it gets brighter than 6th magnitude every few years.

It is thought that the different types of asteroids arise through the break-up of larger bodies which became differentiated – the iron and nickel settle to the centre of the body, leaving silicates on the outside. This has clearly taken place in some asteroids (Vesta) and not in others, even larger (Ceres). We don't know how small an asteroid can be and still become differentiated, nor how large one can be and avoid it.

Differentiation: impact or radioactive heating leads to separation of metallic and rocky material.





Subsequent break-up leads to rocky and stony bodies.

Individual asteroids are very different.

- *324 Bamberga* is the darkest body in the Solar System (albedo 0.04); it rotates very slowly, every 29 h.
- *349 Dembowska* is highly irregular, spins every 4.7 h, and has a surface made up largely of *olivine*, a bright-green iron silicate mineral found in igneous rocks.
- *16 Psyche* rotates every 4.2 h, and consists almost entirely of iron-nickel: the largest hunk of pure metal in the solar system, 250 km in diameter!

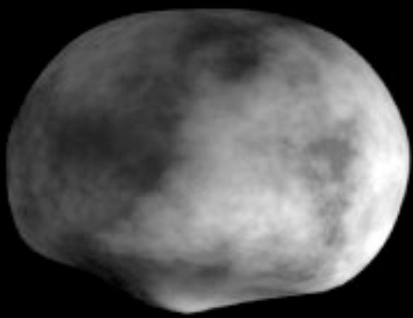
The largest asteroids are roughly spherical, while the smallest ones are very irregular. Objects above about 700 km in diameter have enough self-gravity to make their shape spherical, while smaller asteroids can accrete in a haphazard way, and may indeed be fragments broken off larger bodies.

Asteroids Mathilde, Gaspra, and Ida, shown to scale.

In fact, many asteroids are apparently self-gravitating piles of rubble instead of monolithic slabs of rock. NEAR-Shoemaker found that Mathilde had a surprisingly low bulk density (1.3 g cm^{-3}) and a large number of giant craters. Simulations show that such large impacts would completely destroy a solid body, while a porous body could absorb impacts more effectively.

NEAR encounter with Mathilde

One of the largest asteroids, Vesta, is not spherical, probably because it has suffered a large impact near the south pole. HST imaged Vesta as it rotated, enabling this model of the surface to be made.



Vesta, shape model from HST images.

An increasing number of asteroids are found to be binary. As of 25 April, there were 164 small bodies with companions. These include

- 35 near-Earth asteroids,
- 8 Mars crossing asteroids,
- 63 main-belt asteroids (four with two satellites each),
- 2 Jupiter Trojan asteroids, and
- 56 trans-Neptunian objects (one with two satellites, one with three satellites).

The asteroid Ida (58x23 km) with its moon Dactyl (1.6 km)

The fraction of binaries among near-Earth asteroids is much higher than among main-belt asteroids (1 in 6 NEAs is a binary). This suggests they form differently.

– NEA binaries are formed by break-up of porous parent body (spin-up, tidal disruption by close planet encounter)

– Main belt binaries may form by sub-catastrophic collisions.

Simulation of the formation of an asteroid moon by tidal disruption. From Walsh & Richardson (2006)

In 2005 the Japanese mission *Hayabusa* landed on the asteroid 25143 Itokawa. Instead of being monolithic rock, it turned out to be a shattered mass – the science team described it as a "pile of rubble". *Hayabusa* will return to Earth in 2010, hopefully with a sample from the asteroid.

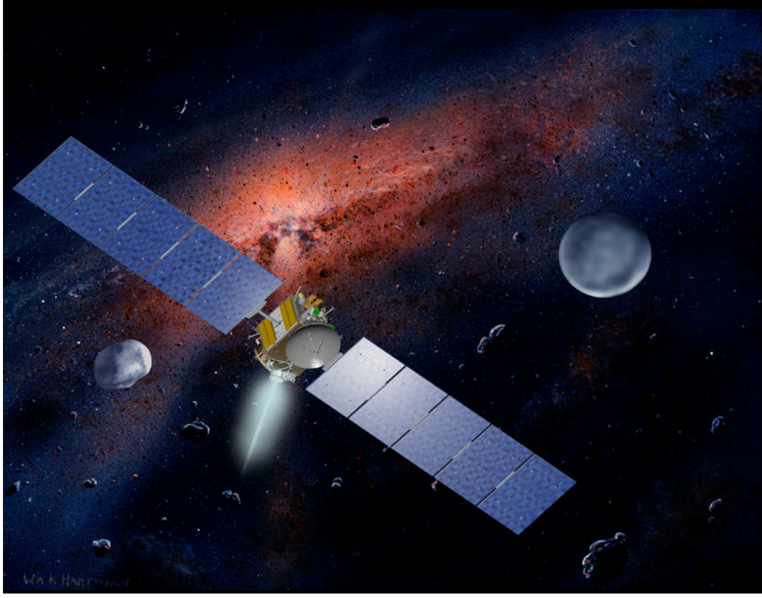
Release 051101-2 ISAS/JAXA

Between the orbits of Jupiter and Neptune are a class of planetoids called *Centaurs*. The first of these was discovered in 1977, and called 2060 Chiron. By 1988, it drew closer to the sun, it developed a coma, just like a comet.

Centaurs are thought to be related to other types of outer solar system bodies, to be discussed later.

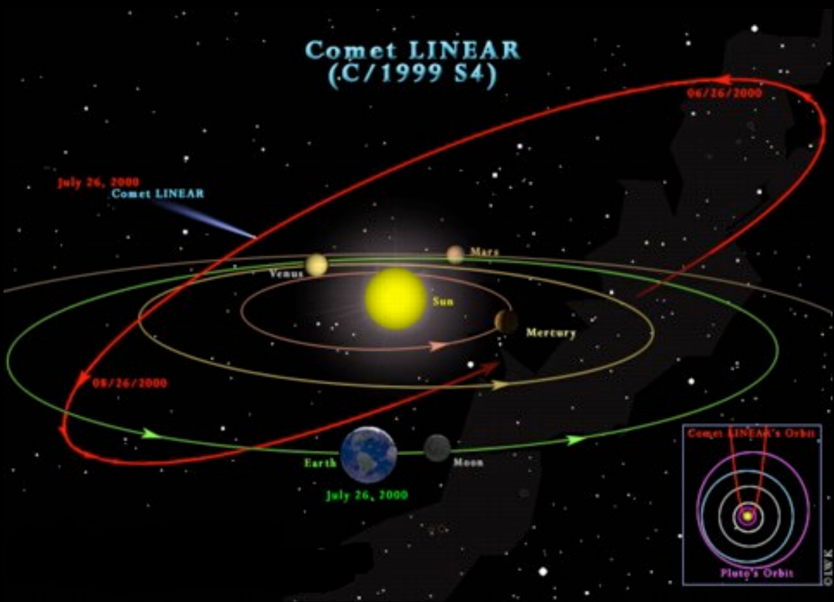
Artist's impression of the Centaur 8405 Asbolus. Light variations detected by Hubble could be caused by a fresh crater on one side.

In 2007 NASA launched a mission called *Dawn* to Vesta and Ceres, the two largest asteroids. It will reach Vesta in August 2011 and go into orbit, then depart Vesta in May 2012 and arrive at Ceres in February 2015.

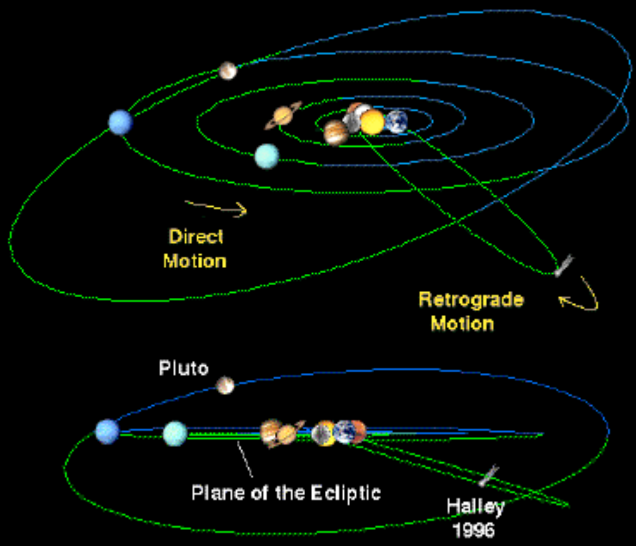


Comets

Comets are another class of small solar system bodies. Unlike asteroids, comets are predominantly icy bodies. And also unlike most asteroids, comets have extremely elliptical orbits.



Cometary orbits are also not confined to the plane of the ecliptic like the planets; and they can orbit in any direction. Comet Halley, for instance, orbits in a retrograde direction (opposite to the planets); it also spends nearly all its time below the plane of the ecliptic.



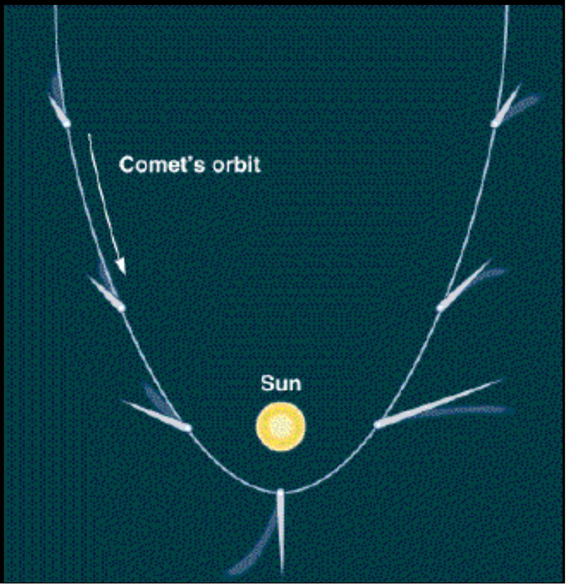
The orbit of Comet Halley

As a comet, a few kilometres in radius (the *nucleus*) approaches the Sun, heating causes material to boil off the comet's surface. This gas and dust, lit up by the Sun, is visible as the comet's *coma*, which may be a million kilometres in diameter.

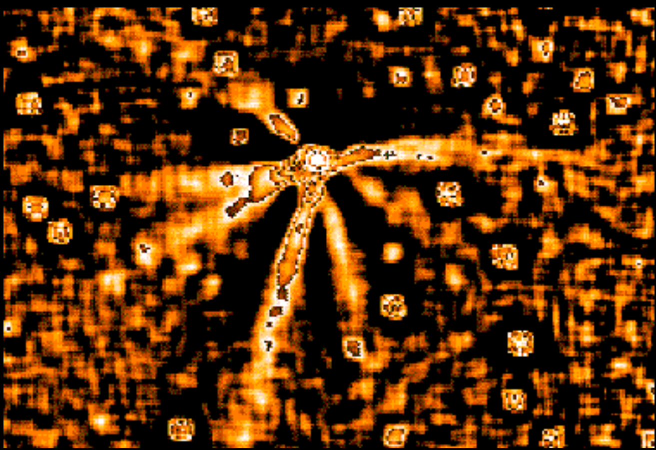
Comet Hale-Bopp in 1997, as it began its journey towards the Sun

Tails of comets, composed of gas and dust emitted from the nucleus, can be up to 1 AU in length, but are extremely thin. Comets often have two tails, an *ion tail*, composed of gas blown out of the comet by the solar wind, and a *dust tail*, made of dust liberated from the nucleus as the ice evaporates.

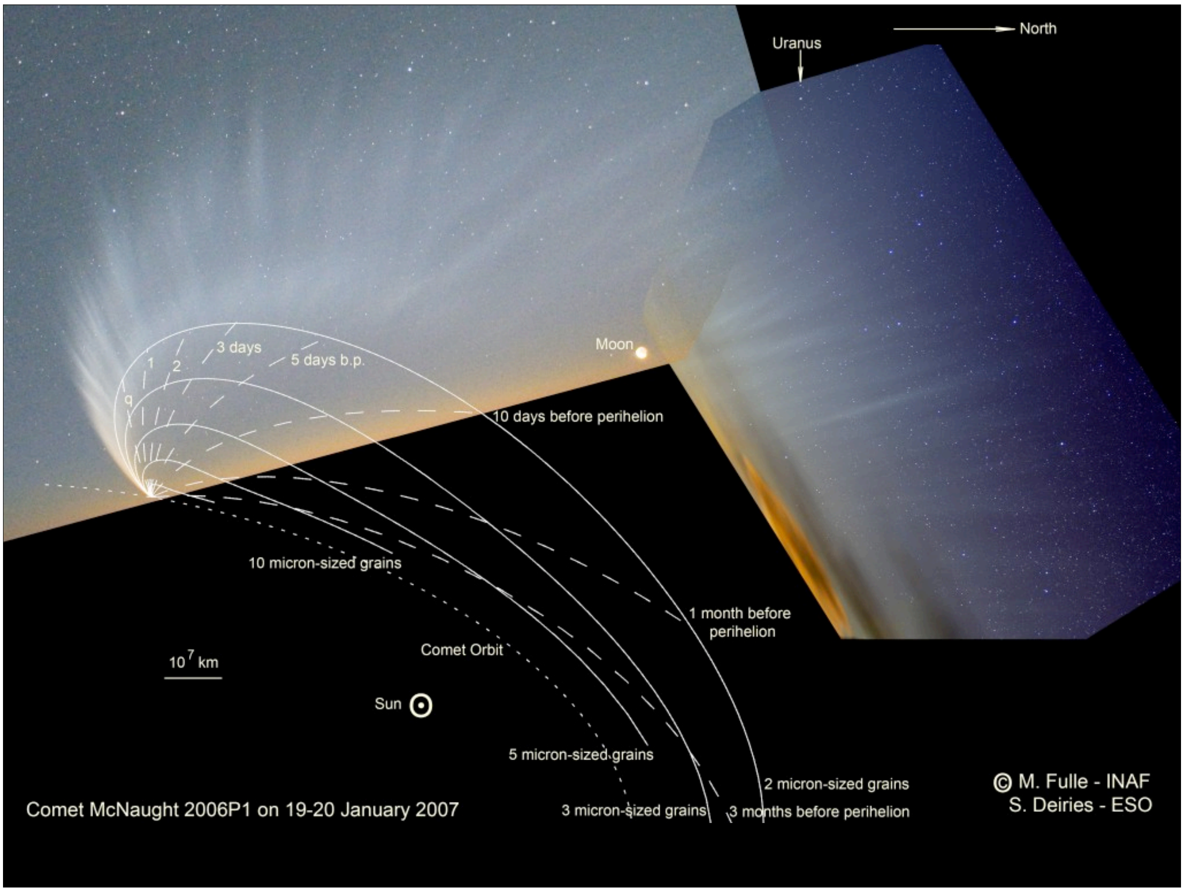
The ion tail always points away from the Sun, while the dust tail tends to curve behind the comet's motion. The ion tail is typically bluer in colour, narrow, and straight; the dust tail is more diffuse, often looks curved, and is more white in colour.



The comet's motion is often affected by gases jetting out of the nucleus, so their orbits are somewhat disturbed from regular orbits.



A false-colour image of the coma of Hale-Bopp, showing seven jets from the nucleus.


North
Uranus
Moon
3 days
5 days b.p.
1
2
q
10 days before perihelion
10 micron-sized grains
1 month before perihelion
Comet Orbit
10^7 km
Sun
5 micron-sized grains
2 micron-sized grains
3 micron-sized grains
3 months before perihelion
Comet McNaught 2006P1 on 19-20 January 2007
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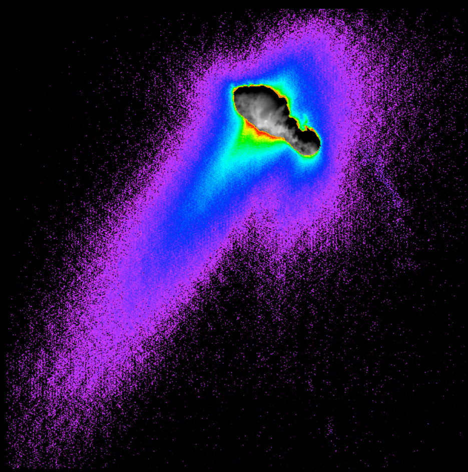
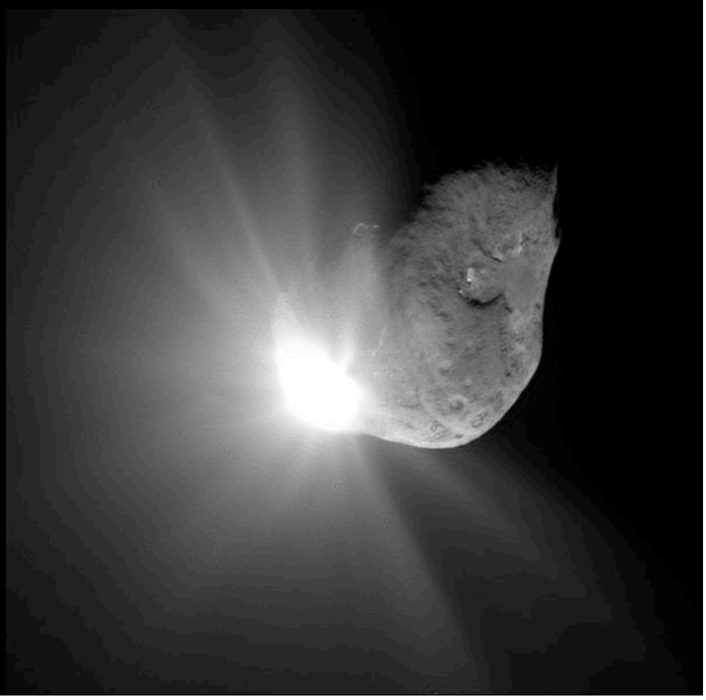
Several recent space missions have actually flown through a comet's coma to image the nucleus.



Deep Space 1 flew past Comet Borelly in September 2001.

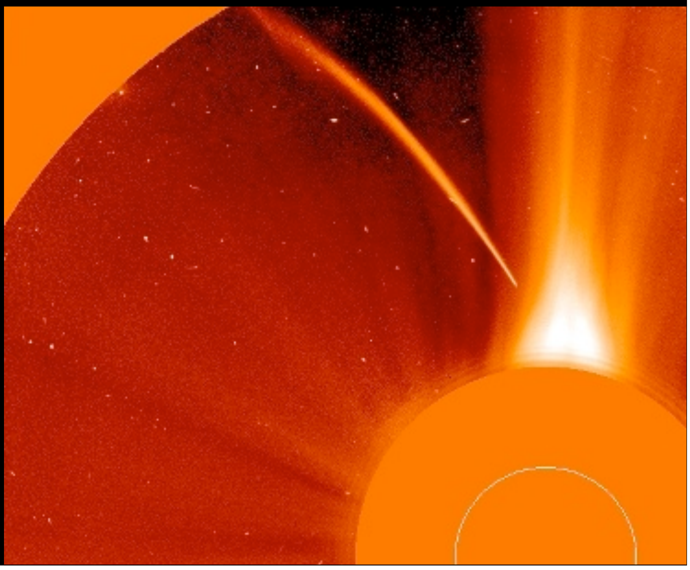
The Stardust mission flew past the nucleus of Comet Wild in January 2004.

In July 2005, *Deep Impact* punched a hole in the comet Tempel-1. The ejecta contained more dust and less ice than expected. In fact, so much dust was kicked up that it was never possible to get a good image of the crater to determine its size. Outgassing continued for at least 13 days after impact.



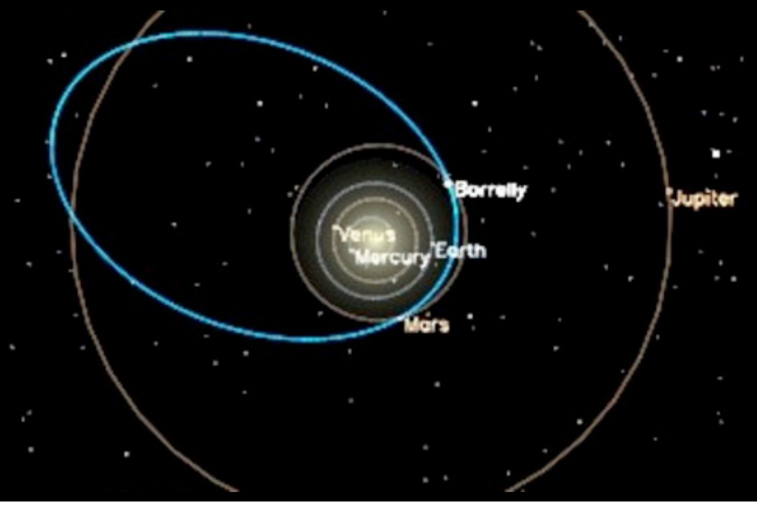
Comet Tempel 1 67 seconds after it collided with Deep Impact, taken by the high-resolution camera on the flyby spacecraft.

The solar observatory SOHO has found more than 1000 *sungrazer comets* – a family of comets with orbits which take them extremely close to the Sun at perihelion. They are believed to be fragments of one very large comet that broke up several centuries ago and are named for the astronomer Heinrich Kreutz, who first demonstrated that they were related. None of SOHO's small comets have survived perihelion passage.



SOHO image of comet SOHO-6 plunging toward the Sun on 23 December 1996

Most comets are in elliptical orbits which carry them out past Jupiter's orbit: the *short-period comets*. There are a dozen or so of these a year, but most of them can only be seen through a telescope. More rarely, a comet appears with a much longer orbital period: these comets are usually much brighter. Where do these *long-period comets* come from?



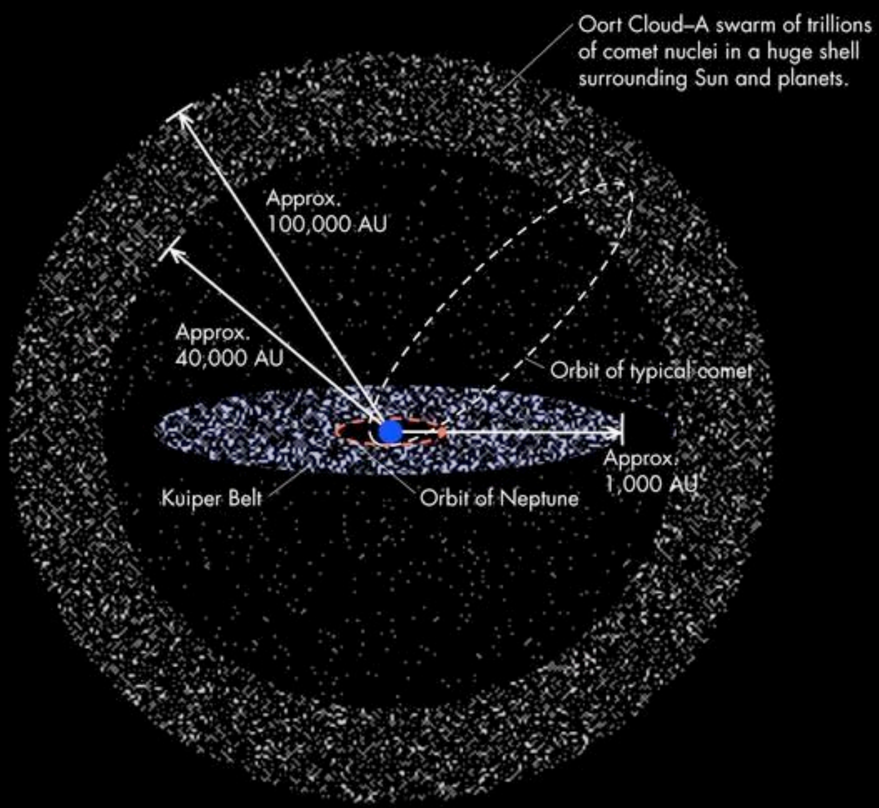
Trans-Neptunian objects

In 1950, Jan Oort noticed that

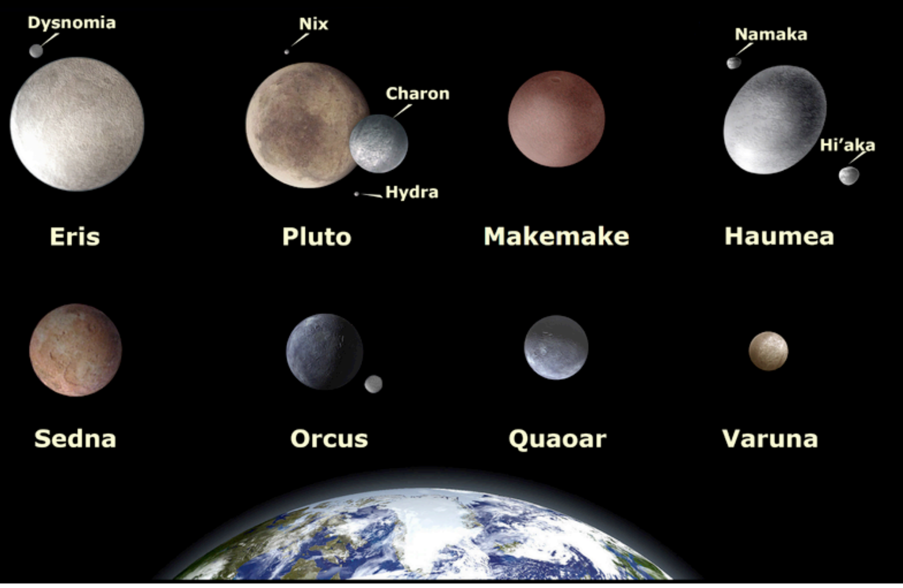
- no comet had an orbit indicating it came from interstellar space;
- the aphelion of most long-period comets lies at a distance of about 50,000 AU (1000 times the distance of Pluto); and
- comets come from all directions.

He proposed that there is a vast cloud of icy bodies at the outer edge of the Solar System: the *Oort Cloud*. Every so often, one of these is perturbed into an orbit which sends it into the inner reaches of the Solar System. The total mass of the Oort Cloud may be a significant fraction of the mass of the Solar System.

Gerard Kuiper suggested that short-period comets originate in another region: the Kuiper Belt, which is a disk-shaped region past the orbit of Neptune, between 30 and 100 AU from the Sun.



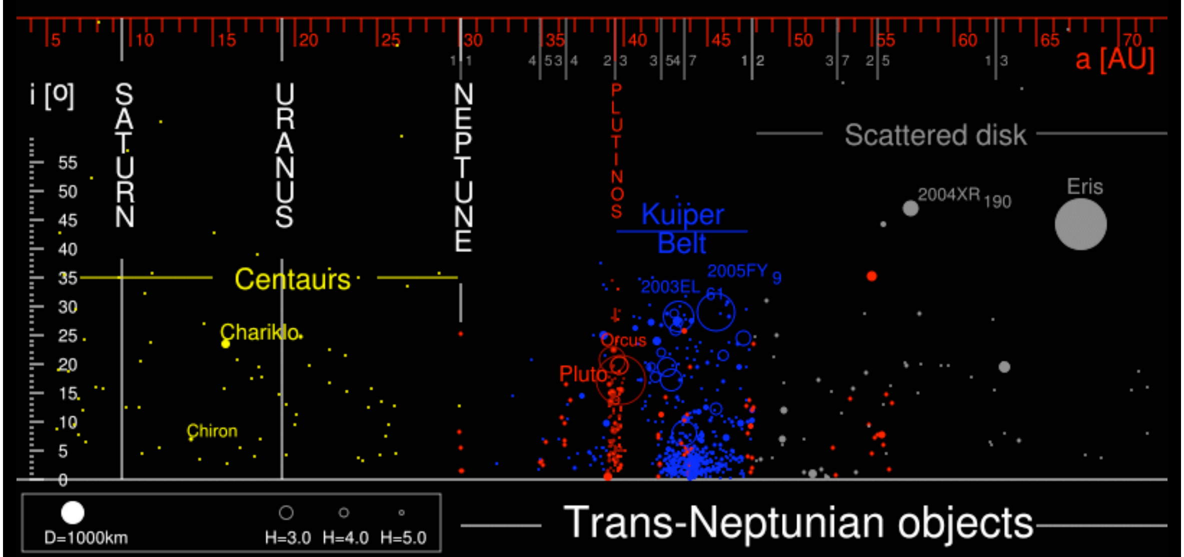
Objects in this region of space are collectively known as *trans-Neptunian objects* (TNOs). As of April 2009, there were 1092 objects known beyond the orbit of Neptune. At least eight TNOs (plus Charon) have diameters of more than 1000 km.



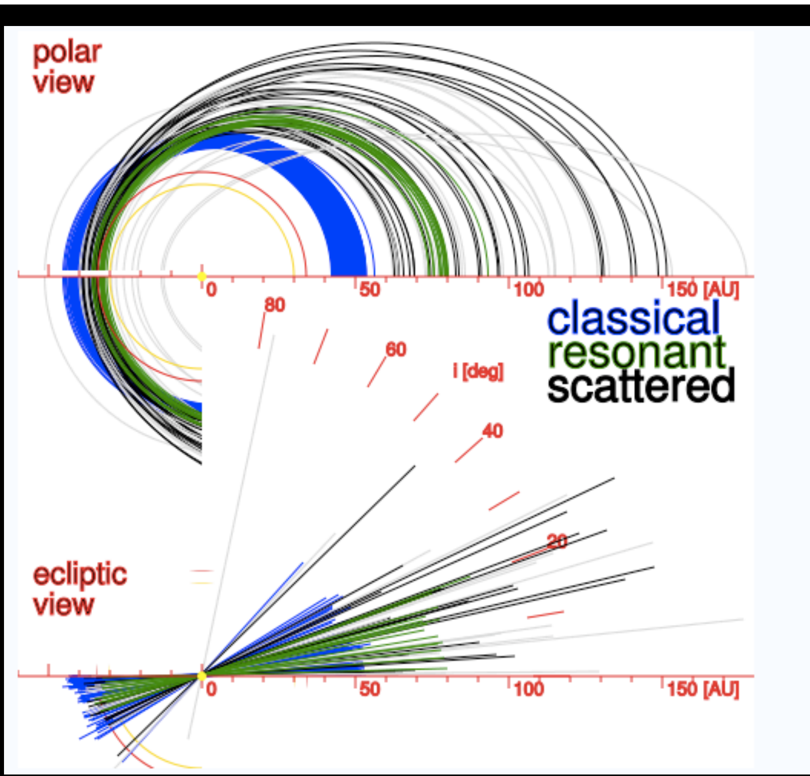
Name	Diameter	Class	Discovery
Eris	2400	SDO	2005
Pluto	2306	KBO	1930
(Charon)	*1205*	*KBO moon*	*1978*
Makemake	1800	KBO	2005
Haumea	~1500	KBO	2005
Sedna	1180–1800	SDO?	2003
Orcus	~1500	KBO	2004
Quaoar	1260	KBO	2002
Varuna	936	KBO	2000
Ixion	<822	KBO	2001

There are several sub-groups of TNOs:

- *Plutinos*, which are in 3:2 resonance with Neptune: these form the inner part of the Kuiper belt; e.g. Pluto
- *Classical Kuiper belt objects* (also called *cubewanos*), which are beyond Neptune but not in a resonance; e.g. 1992 QB1, Quaoar, Varuna
- *Scattered disc objects*, which are in larger and much more eccentric orbits; e.g. Eris, Sedna
- *Neptune Trojans*, which are in 1:1 resonance with Neptune and lead or trail it, maintaining – on average – approximately equal distance from Neptune and the Sun



Small solar-system bodies. Resonance objects are shown in red, Kuiper Belt objects in blue, and scattered disk objects in grey.



Orbits of the cubewanos (blue), resonant (green) and scattered disk objects, from above and side-on. Yellow represents Neptune's orbit.

The more we learn, the more we realise that the distinction between "asteroid" and "comet" is not as clear as we once thought. Asteroid 617 Patroclus is an asteroid that seems to belong to just about every club for small bodies in the solar system. It is a Trojan asteroid, with a binary companion Menoetius, and both bodies are less dense than water ice, 0.8 g cm^{-3}.

Artist's rendering of the binary asteroids Patroclus (centre) and Menoetius. Credit: W. M. Keck Observatory / Lynette Cook

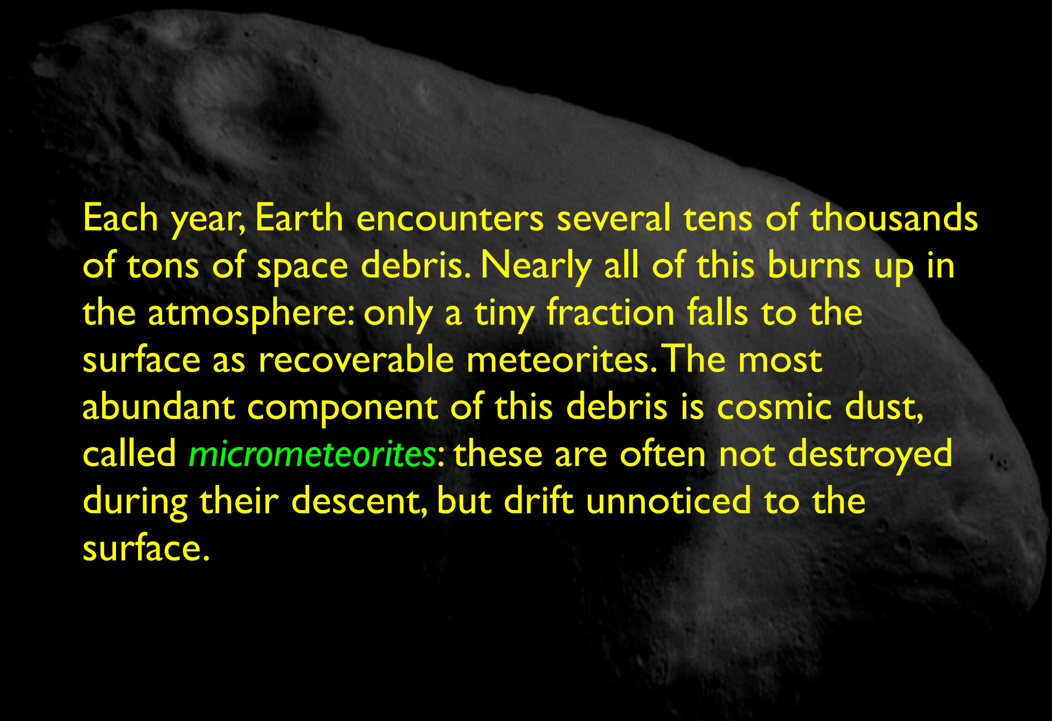
In 2006, the IAU introduced a new term to describe objects in the Solar System that are neither planets nor dwarf planets:

All other objects orbiting the Sun shall be referred to collectively as "Small Solar System Bodies" ... These currently include most of the Solar System asteroids, most Trans-Neptunian Objects (TNOs), comets, and other small bodies.

This encompasses:

- all minor planets apart from the dwarf planets, i.e.:
  - the classical asteroids, (except for 1 Ceres, the largest);
  - the centaurs and Neptune Trojans;
  - the Trans-Neptunian Objects (except for dwarf planets such as Pluto and Eris);
- all comets.

Meteors



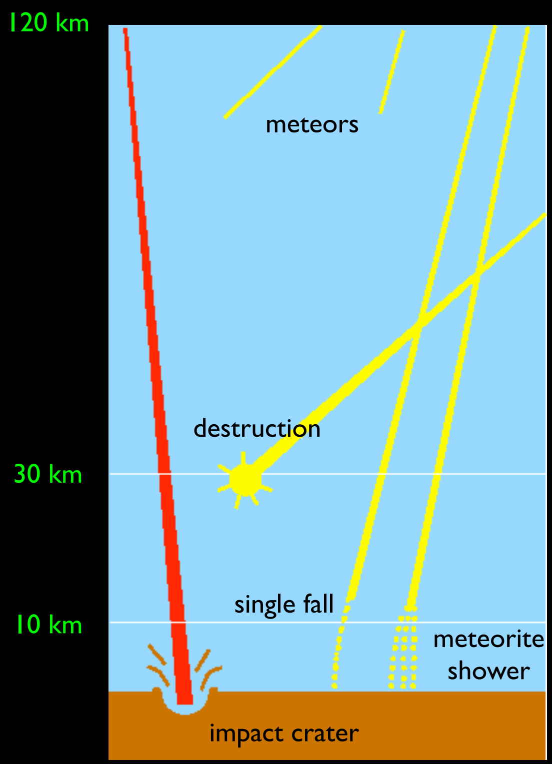
Each year, Earth encounters several tens of thousands of tons of space debris. Nearly all of this burns up in the atmosphere: only a tiny fraction falls to the surface as recoverable meteorites. The most abundant component of this debris is cosmic dust, called *micrometeorites*: these are often not destroyed during their descent, but drift unnoticed to the surface.

Larger rocks have a more dramatic descent. The Earth's gravitational well means that even a slow moving meteor enters the atmosphere at 11 km/s, or about mach 40. Friction with the air melts the surface of the body and vaporises the outer layer. A large volume of air around the rock becomes ionised, so the rock falls in an incandescent cloud of dust and gas. If the object is large enough to penetrate deep into the atmosphere, this can be seen as a *fireball*.

The melted material is stripped off the surface, leaving a trail of incandescent gas and solidified melted rock. This removes heat from the meteoroid so efficiently that the interior remains at the freezing temperature of outer space.

The great daylight fireball of 1972

If the object is large enough, it survives into the lower atmosphere, where the fireball is extinguished at an altitude of 10–30 km. Some objects break up to produce a meteor shower, some fall to the ground in one piece. Large objects are not slowed much and can form impact craters.

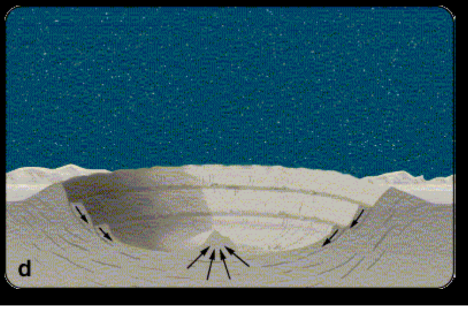


The meteorite approaches the surface at speeds of about 60 km/s.

The projectile hits the surface and forms shock waves which propagate into the crust.

Another shock wave travels back through the meteorite, and when it reaches the rear the projectile vaporises and explodes back outwards as a fireball. Material from the vaporised meteorite and target material is excavated and flung outwards.

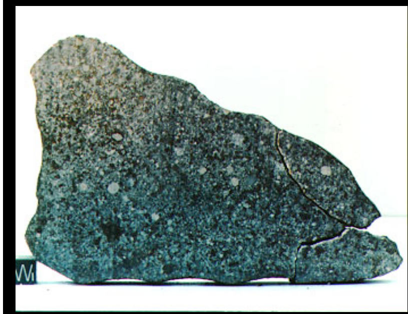
The walls of the crater are too steep and unstable, so they slump down, and a central peak forms.

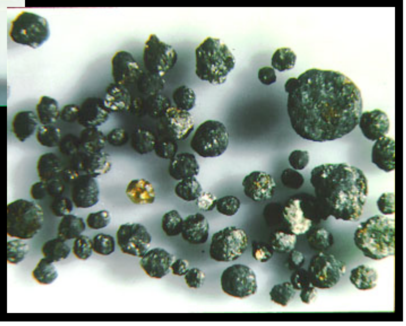


An impacting object a few km across generates a pressure hundreds of times the failure strength of rock. This means that *the rock effectively behaves as if it were water*. The stresses are so far beyond the strength of rocks that the impacted rocks behave as if they had no strength whatever. They flow plastically as if they were fluids.

There are three main types of meteorites:

- *stony meteorites*, which are divided into *chondrites* and *achondrites*, depending on the presence or absence of chondrules, near-spherical beads which are believed to be very primitive building blocks from the early Solar System.

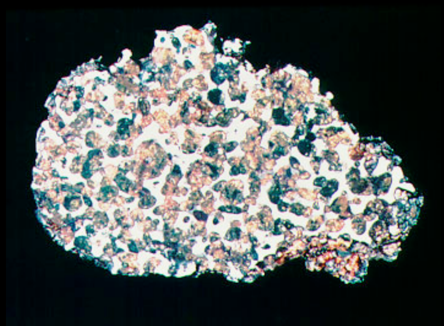




Chondrite (above left) and achondrite (above right) meteorites: the chondrite is made up of hundreds or thousands of small spherical chondrules (right).

- *iron meteorites*, primarily iron and nickel, similar to type M asteroids

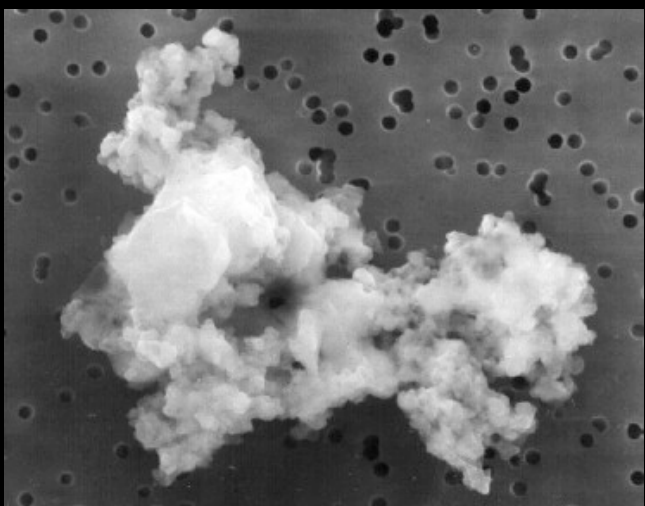
- *stony-iron meteorites*, mixtures of iron and stony material, like type S asteroids



There are a few other sorts. This meteorite was found in Western Australia in 1960. Its composition and unique spectral signature suggests it came from Vesta.

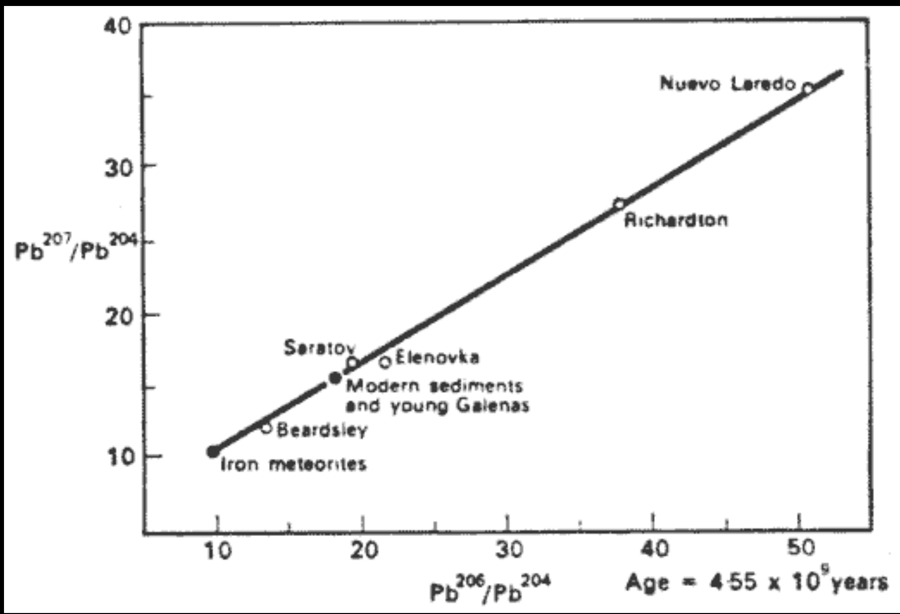
Stony meteorites makes up between 80 and 90% of all meteorites, with most of the rest being iron, and a few stony-iron.

Grains of interplanetary dust have been found, and these are composed of tiny mineral grains. The grains are a hundredth of a millimetre across.



Interplanetary dust grain collected in Earth's stratosphere.

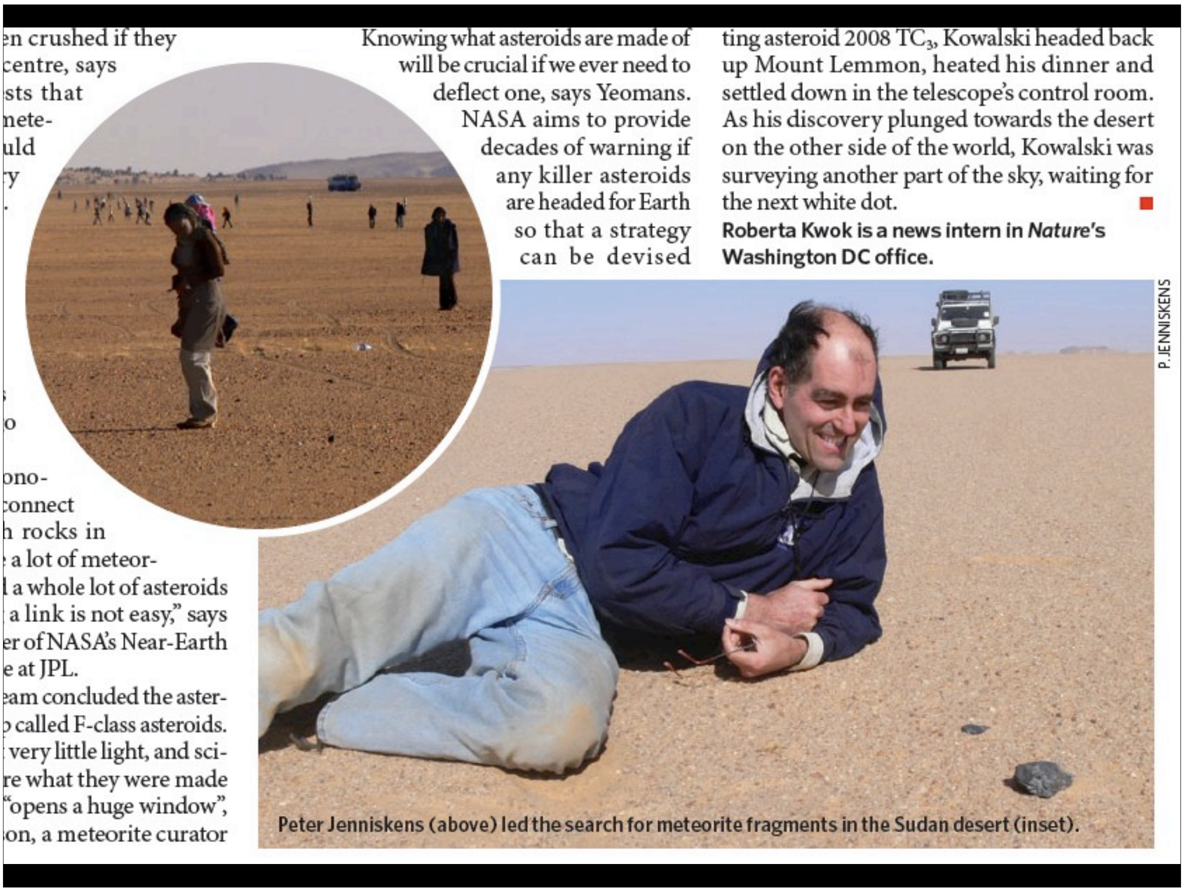
By measuring the amounts of different lead isotopes, we can construct an isochron diagram which enables us to measure the age of meteorites: 4.55 billion years.



What is needed is a meteorite from an object with a known orbit, to connect meteorites with asteroids.

In October 2008, a near-earth asteroid called 2008 TC_3 was tracked and its orbit determined, just 20 hours before it hit the Earth. The size of a small boulder, it was the first asteroid to be spotted before it hit the Earth.

On 7 October it fell to Earth in northern Sudan. In December to March, search teams combed the desert multiple times, and recovered 280 meteorites.



en crushed if they centre, says sts that mete- uld y

o

ono- connect h rocks in a lot of meteor- l a whole lot of asteroids a link is not easy," says er of NASA's Near-Earth e at JPL.

eam concluded the aster- o called F-class asteroids. very little light, and sci- re what they were made "opens a huge window", on, a meteorite curator

Knowing what asteroids are made of will be crucial if we ever need to deflect one, says Yeomans. NASA aims to provide decades of warning if any killer asteroids are headed for Earth so that a strategy can be devised

ting asteroid 2008 TC_3, Kowalski headed back up Mount Lemmon, heated his dinner and settled down in the telescope's control room. As his discovery plunged towards the desert on the other side of the world, Kowalski was surveying another part of the sky, waiting for the next white dot. ■

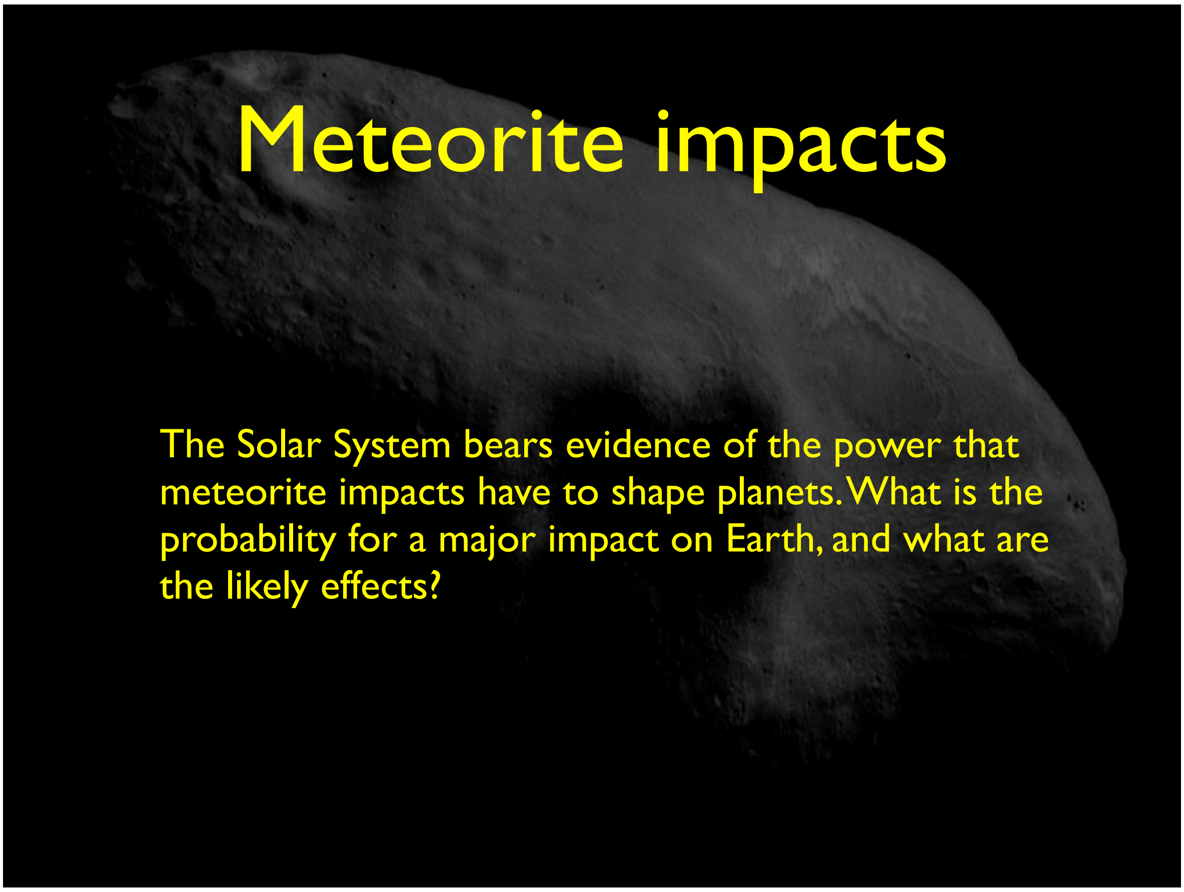
Roberta Kwok is a news intern in *Nature*'s Washington DC office.

P. JENNISKENS

Peter Jenniskens (above) led the search for meteorite fragments in the Sudan desert (inset).

The meteorites turned out to be achondrites, quite unusual and very porous. The asteroid appears to have been a F-class asteroid, which reflect very little light. The discovery offers a unique opportunity to study the asteroid's route and chemical make-up.

Path of the asteroid and location of the recovered meteorites. The white arrow shows the fireball, with the white star showing the location of the detonation at 37 km altitude.



Meteorite impacts

The Solar System bears evidence of the power that meteorite impacts have to shape planets. What is the probability for a major impact on Earth, and what are the likely effects?

Size	Example	Planetary effects	Effects on life
Tiny R > 100m	Tunguska event 1908	Major local effects Minor hemispheric dusty atmosphere	Romantic sunsets increase birthrate
Small R > 1 km	~ 500 NEAs	Global dusty atmosphere for months	Photosynthesis interrupted Individuals die but few species extinct Civilisation threatened
Medium R > 10 km	KT impactor 433 Eros (largest NEA)	Fires, dust, darkness; atmosphere/ocean chemical changes, large temperature swings	Half of species extinct
Large R > 30 km	Comet Hale-Bopp	Heats atmosphere and surface to ~ 1000 K	Continents cauterised
Extra large R > 70 km	Chiron (largest active comet)	Vaporises upper 100 m of oceans	Pressure-cooks photic zone May wipe out photosynthesis
Jumbo (R > 200 km)	4 Vesta (large asteroid)	Vaporises ocean	Life may survive below surface
Colossal R > 700 km	Pluto 1 Ceres (borderline)	Melts crust	Wipes out life on planet
Super colossal R > 2000 km	Moon-forming event	Melts planet	Drives off volatiles Wipes out life on planet

The K-T impact

Evidence has been growing that the mass extinction at the end of the Cretaceous – which marked the end of the dinosaurs – was caused by a giant meteor impact. An asteroid 10–12 km in diameter collided with the Earth, at a site on the Yucatan Peninsular of Mexico. The crater, now buried beneath a kilometre of limestone, is called Chicxulub (pronounced chick-shoe-lube).

Here's what we think the effects of the impact would have been.

During the late Cretaceous, the Yucatan Peninsular was a shallow sea, so the meteor probably landed in less than 100m of seawater.

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The impact triggered a submarine earthquake, which generated a tidal wave 100 m high, which flooded coastlines halfway across the world. The meteor punched through the Earth's crust, ejecting hundreds of cubic kilometres of dust high into the atmosphere.

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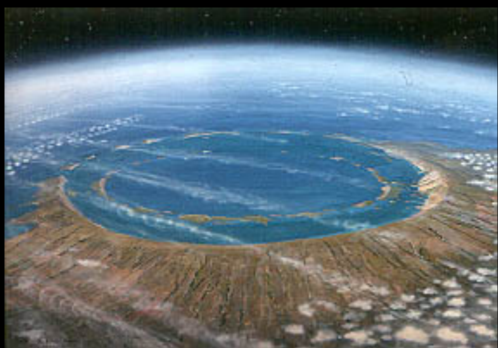
Everything within a radius of several hundred kilometres was incinerated by the fireball, and the dust covered the entire Earth for months.

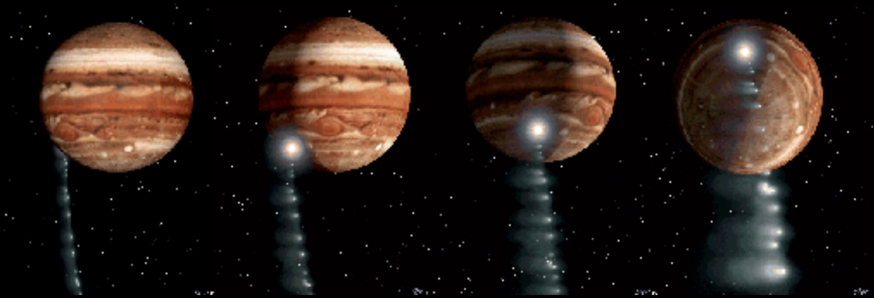
The excavated crater was 15–20 km deep and about 200 km in diameter. The impact caused an earthquake of magnitude 12 to 13.



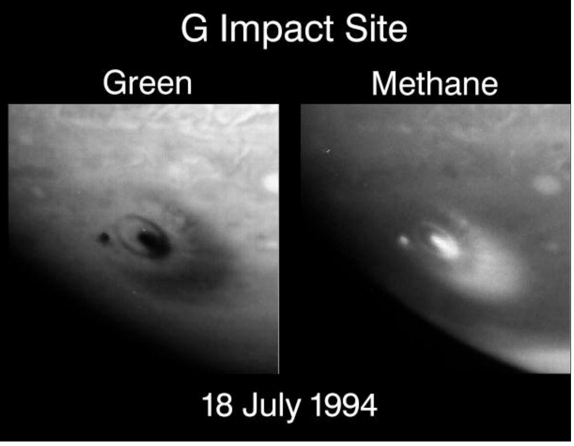
Over 70% of species were made extinct by the Yucatan impact. Some people estimate that 99% of individuals were killed, even in species which survived.

The likelihood of another Yucatan-size event is small: such potentially global catastrophic events probably only take place every 50–100 million years. However, an impact like the one which formed Wolfe Creek or Meteor Crater should happen once every 5000 years or so: there should have been one such impact in recorded history.

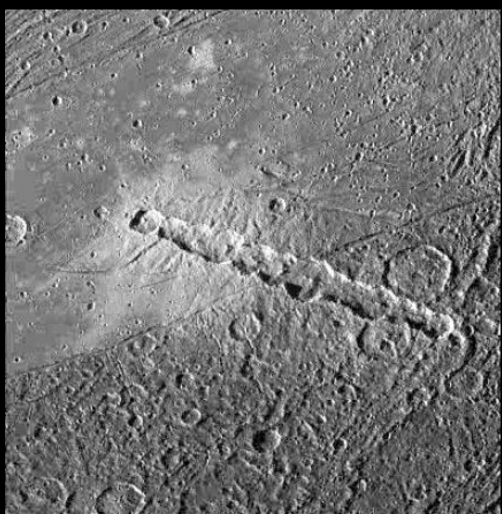
We recently got a chance to see a comet impact in detail, when Comet Shoemaker-Levy 9 impacted on Jupiter in July 1994. Several effects of the impact were just as predicted for the Chicxulub event.



(left) Composite photo, assembled from separate images of Jupiter and Comet P/Shoemaker-Levy 9, as imaged by the Hubble Space Telescope. (below) The G impact site 1h45m after impact, seen by HST.

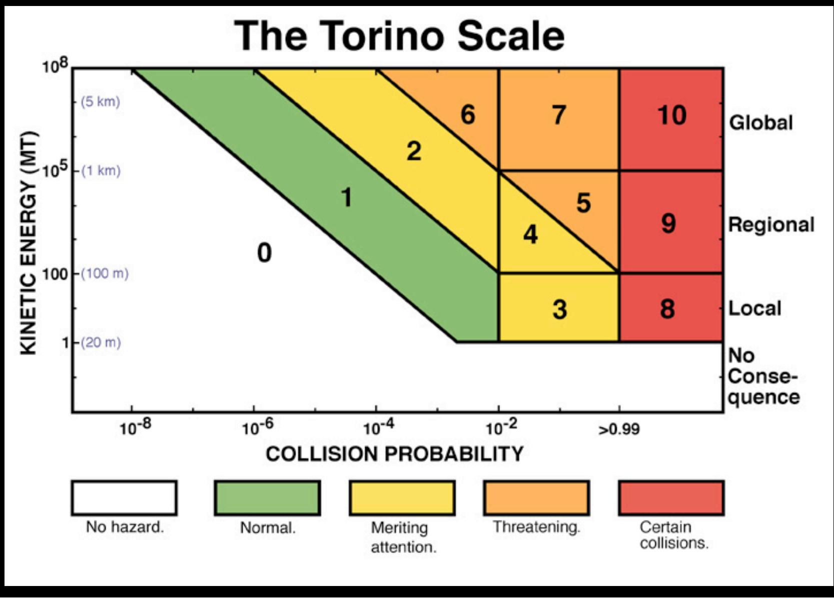


The Shoemaker-Levy collision offered a dramatic explanation for the mysterious *crater chains* that had been seen on several solar system bodies.



Crater chains on Ganymede (above) and the Moon (right).

In the past decade, there has been a push for systematic monitoring of Near-Earth Objects (NEOs). The *Torino Impact Scale* was devised for categorizing the Earth impact hazard of newly discovered asteroids and comets. In 2005 it was revised slightly.



THE TORINO SCALE

Assessing Asteroid and Comet Impact Hazard Predictions in the 21st Century

No Hazard	0	The likelihood of collision is zero, or is so low as to be effectively zero. Also applies to small objects such as meteors and bolides that burn up in the atmosphere as well as infrequent meteorite falls that rarely cause damage.
Normal	1	A routine discovery in which a pass near the Earth is predicted that poses no unusual level of danger. Current calculations show the chance of collision is extremely unlikely with no cause for public attention or public concern. New telescopic observations very likely will lead to re-assignment to Level 0.
Meriting Attention by Astronomers	2	A discovery, which may become routine with expanded searches, of an object making a somewhat close but not highly unusual pass near the Earth. While meriting attention by astronomers, there is no cause for public attention or public concern as an actual collision is very unlikely. New telescopic observations very likely will lead to re-assignment to Level 0.
	3	A close encounter, meriting attention by astronomers. Current calculations give a 1% or greater chance of collision capable of localized destruction. Most likely, new telescopic observations will lead to re-assignment to Level 0. Attention by the public and by public officials is merited if the encounter is less than a decade away.
	4	A close encounter, meriting attention by astronomers. Current calculations give a 1% or greater chance of collision capable of regional devastation. Most likely, new telescopic observations will lead to re-assignment to Level 0. Attention by the public and by public officials is merited if the encounter is less than a decade away.
Threatening	5	A close encounter posing a serious, but still uncertain threat of regional devastation. Critical attention by astronomers is needed to determine conclusively whether or not a collision will occur. If the encounter is less than a decade away, governmental contingency planning may be warranted.
	6	A close encounter by a large object posing a serious, but still uncertain threat of a global catastrophe. Critical attention by astronomers is needed to determine conclusively whether or not a collision will occur. If the encounter is less than three decades away, governmental contingency planning may be warranted.
	7	A very close encounter by a large object, which if occurring this century, poses an unprecedented but still uncertain threat of a global catastrophe. For such a threat in this century, international contingency planning is warranted, especially to determine urgently and conclusively whether or not a collision will occur.
Certain Collisions	8	A collision is certain, capable of causing localized destruction for an impact over land or possibly a tsunami if close offshore. Such events occur on average between once per 50 years and once per several 1000 years.
	9	A collision is certain, capable of causing unprecedented regional devastation for a land impact or the threat of a major tsunami for an ocean impact. Such events occur on average between once per 10,000 years and once per 100,000 years.
	10	A collision is certain, capable of causing a global climatic catastrophe that may threaten the future of civilization as we know it, whether impacting land or ocean. Such events occur on average once per 100,000 years, or less often.

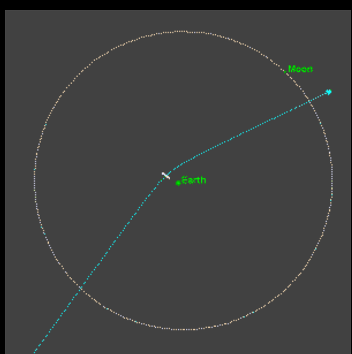
In June 2004, near-Earth asteroid 2004 MN4 (now called 99942 Apophis) was discovered. In December 2004 it was rediscovered at Siding Spring Observatory, and observations from around the world indicated that it would encounter the Earth in April 2029, and the possibility of impact could not be ruled out. It was assigned TS=2, the highest value yet found.

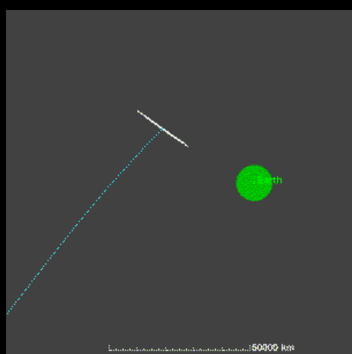
On December 24, the value was pushed to TS=4, with odds of impact 1 in 60, then 1 in 45, as the orbit was refined.

On December 27, the closest distance on 13 April 2029 was calculated to be 60,000 km with no chance of impact.

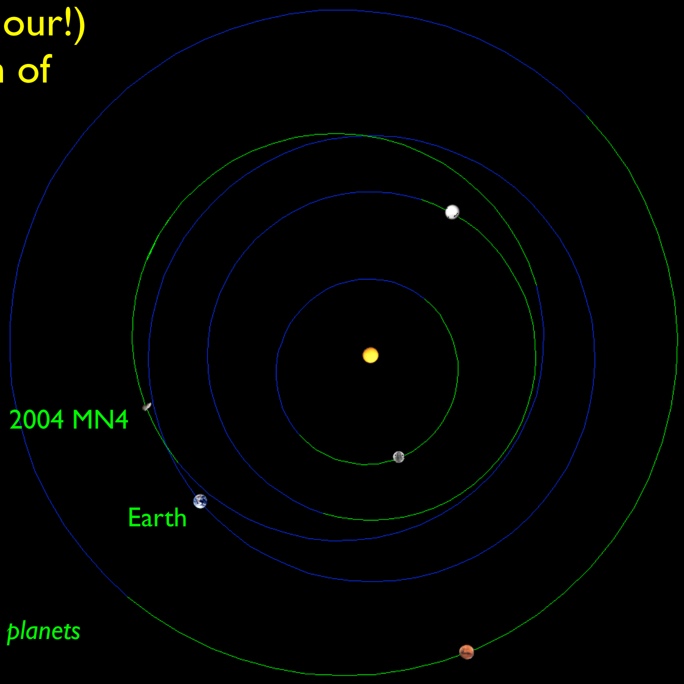
Radar observations were taken from Arecibo in late January 2005. The range was 294 km closer to the earth than the pre-radar orbit solution predicted.

The new estimate for closest approach on 13 April 2029 is 36700 +/- 9000 km or 5.7 +/- 1.4 earth radii. This is just below geosynchronous orbit and 28000 km closer than predicted by the pre-radar ephemeris.





Based on the albedo, the diameter of 2004 MN4 is about 320 meters. At the time of the closest approach, the asteroid will be a naked eye object (3.3 mag.) traveling rapidly (42 degrees per hour!) through the constellation of Cancer.



The position of 2004 MN4 and the inner planets on 1 May 2005.

Further reading

Several of the books I have already recommended have good sections about asteroids, comets and meteors. A few new ones are:

- **"Beyond Pluto: Exploring the outer limits of the solar system"** by John Davies (Cambridge, 2001) tells the story of the discovery of the Kuiper Belt and trans-Neptunian objects.
- **"Meteorites: A journey through space and time"** by Alex Bevan and John de Laeter (UNSW Press, 2002). This is a lovely book, by two Australian scientists, which covers all aspects of meteors and meteorites.
- Comet Shoemaker-Levy's spectacular demise is described in **"The Great Comet Crash: The impact of Comet Shoemaker-Levy 9 on Jupiter"** by John Spencer and Jacqueline Mitton (Cambridge, 1995)
- There are quite a few books particularly on the subject of the meteor impact which killed the dinosaurs. **"Night Comes to the Cretaceous: Dinosaur extinction and the transformation of modern geology"** by James Lawrence Powell (WH Freeman, 1998) and **"The End of the Dinosaurs: Chicxulub Crater and Mass Extinctions"** by Charles Frankel (Cambridge UP, 1999) were two I read and enjoyed. The book by Powell which I recommended in Lecture 1, **"Mysteries of Terra Firma"** (The Free Press, 2001) contains a more general discussion of impact geology on Earth.

- If you'd like to plot the orbits of solar system bodies, including comets and asteroids, try **"Solar System Live"** by John Walker, http://www.fourmilab.to/solar/solar.html
- You can use "Solar System Live" to plot comets and asteroids as well. Orbital elements of comets can be found at the IAU: Minor Planet Center "**Minor Planet & Comet Ephemeris Service"** page http://cfa-www.harvard.edu/iau/MPEph/MPEph.html. For instance, you can find the orbital elements for comet Halley by entering 1P/Halley. Select "MPC 8-line" as the "Format for elements output", and cut and paste the orbital elements directly into the Solar System Live site to see where the comet is now. Thus it's easy to see that, although it's only 23 years after its last perihelion, and there are 52 years until the next one, Halley is already at Neptune's orbit, nearly at aphelion: this is an excellent illustration of Kepler's second law. To get side on views, change the Heliocentric latitude to 0 degrees and the longitude to 90 degrees.
- Alan Taylor has put together a beautiful image of **"All (known) Bodies in the Solar System Larger than 200 Miles in Diameter"** (now including a new metric version with everything larger than 320 km in diameter) at http://www.kokogiak.com/gedankengang/2007/03/all-known-bodies-in-solar-system.html. Because this was made in 2007, some of the dwarf planets, like Haumea and Makemake, still have their provisional designations.
- There's a list of binary asteroids at **"Asteroids with Satellites"** by Wm. Robert Johnston, http://www.johnstonsarchive.net/astro/asteroidmoons.html
- The **Earth Impact Database** http://www.unb.ca/passc/ImpactDatabase/ lists every confirmed impact crater known

- If you need to report a meteor fireball, there's an on-line report form at the International Meteor Organisation's page, http://www.imo.net/fireball/index.html
- The **Impact Calculator** at http://simulator.down2earth.eu/index.html allows you to simulate smashing an asteroid into Earth and see how big a crater your asteroid made. You even get to choose which city you crash into (though unfortunately (!) Sydney is not on the list)
- NASA has an information site on Earth impact hazards at **"Asteroid and Comet Impact Hazards"**, http://impact.arc.nasa.gov/; see also the **"Near Earth Object Program: Current Risks"** http://neo.jpl.nasa.gov/risk/
- There is a list of all minor planets and asteroids predicted to approach within 0.2 AU of the Earth during the next 33 years at the IAU Minor Planet Center, **"Forthcoming Close Approaches To The Earth"**, http://cfa-www.harvard.edu/iau/lists/CloseApp.html
- The BBC has a news story about 2008 TC_3, the asteroid that hit Sudan, at http://news.bbc.co.uk/2/hi/science/nature/7964891.stm
- There's an article on **"The saga of Asteroid 2004 MN4"** at http://impact.arc.nasa.gov/news_detail.cfm?ID=154.
- The Association of Space Explorers (ASE), the international organization of astronauts and cosmonauts, is leading the effort to develop a UN treaty and other international mechanisms about asteroid deflection. Their report is available on-line at http://www.space-explorers.org/ATACGR.pdf; it contains a good discussion of the issues involved.

Sources for images used:

- Background image: Eros, taken by NEAR-Shoemaker, from Astronomy Picture of the Day 2001 February 11 http://antwrp.gsfc.nasa.gov/apod/ap010211.html
- Asteroid cover picture: Galileo image of asteroid 951 Gaspra, from APOD 2002 October 27 http://antwrp.gsfc.nasa.gov/apod/ap021027.html
- Asteroid orbits: from "Explorations: An Introduction to Astronomy!" by Thomas T. Arny, Fig. 10.4 http://www.mhhe.com/physsci/astronomy/arny/instructor/graphics/ch10/1004.html
- NEAR trajectory: from NEAR Mission Profile at the NASA Planetary Missions site http://nssdc.gsfc.nasa.gov/planetary/mission/near/near_traj.html
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- Comet cover image: Comet West from Astronomy Picture of the Day 26 August 1995 http://antwrp.gsfc.nasa.gov/apod/ap950826.html
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- Orbit of Comet Halley: from "Comet Halley" http://csep10.phys.utk.edu/astr161/lect/comets/halley.html
- Coma: Hale-Bopp, from Astronomy Picture of the Day February 12, 1997 http://antwrp.gsfc.nasa.gov/apod/ap970212.html
- Comet's tail: Hale-Bopp, from Astronomy Picture of the Day 27 December 2000 http://antwrp.gsfc.nasa.gov/apod/ap001227.html
- Two tails: from http://www.physics.fsu.edu/courses/spring99/ast1002h/solarsystem/fig16-14/fig16-142.htm. Hale-Bopp in 1997: Jerry Lodriguss, from Astronomy Picture of the Day 2007 March 31 http://antwrp.gsfc.nasa.gov/apod/ap070331.html
- Comet McNaught: picture by Robert McNaught, from Astronomy Picture of the Day 2007 January 22 http://antwrp.gsfc.nasa.gov/apod/ap070122.html; comet over Bendalong, photo by Alain Picard
- McNaught's tail: Astronomy Picture of the Day 2007 February 1 http://antwrp.gsfc.nasa.gov/apod/ap070201.html
- Deep Impact image: from Deep Impact gallery http://deepimpact.jpl.nasa.gov/gallery/index.cfm
- SOHO comet: from SOHO gallery http://sohowww.nascom.nasa.gov/gallery/images/xmascomet.html
- Oort cloud/Kuiper Belt title image: artist's conception of the Kuiper Belt object Quaoar, from Hubble Site News Center Archive, http://hubblesite.org/newscenter/archive/2002/17/
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- Trans-Neptunian objects: Wikipedia http://en.wikipedia.org/wiki/Trans-Neptunian_Objects
- Orbits of TNOs: Wikipedia http://en.wikipedia.org/wiki/Scattered_disk
- A list of known trans-Neptunian objects can be found at http://www.johnstonsarchive.net/astro/tnos.html
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- Crater formation: from The Terrestrial Planets by Gareth Wynn-Williams http://www.ifa.hawaii.edu/~wynnwill/110/images/crater_formation.gif
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- Dust grain: from "Stardust: Catching particles in Space", http://stardust.jpl.nasa.gov/science/sd-particle.html
- Isochron: from "The Talk.Origins Archive: The Age of the Earth" by Chris Stassen http://www.talkorigins.org/faqs/faq-age-of-earth.html
- Images of 2008 TC_3, from Nature vol 458, pp 401 and 485
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- Illustrations of K-T impact: from "The Impact that Wiped Out the Dinosaur" by William Hartmann http://www.psi.edu/projects/ktimpact/ktimpact.html
- Comet Shoemaker-Levy: Hubble images, from HubbleSite News Archive, http://hubblesite.org/newscenter/newsdesk/archive/releases/1994/26/ and http://hubblesite.org/newscenter/newsdesk/archive/releases/1994/32/
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