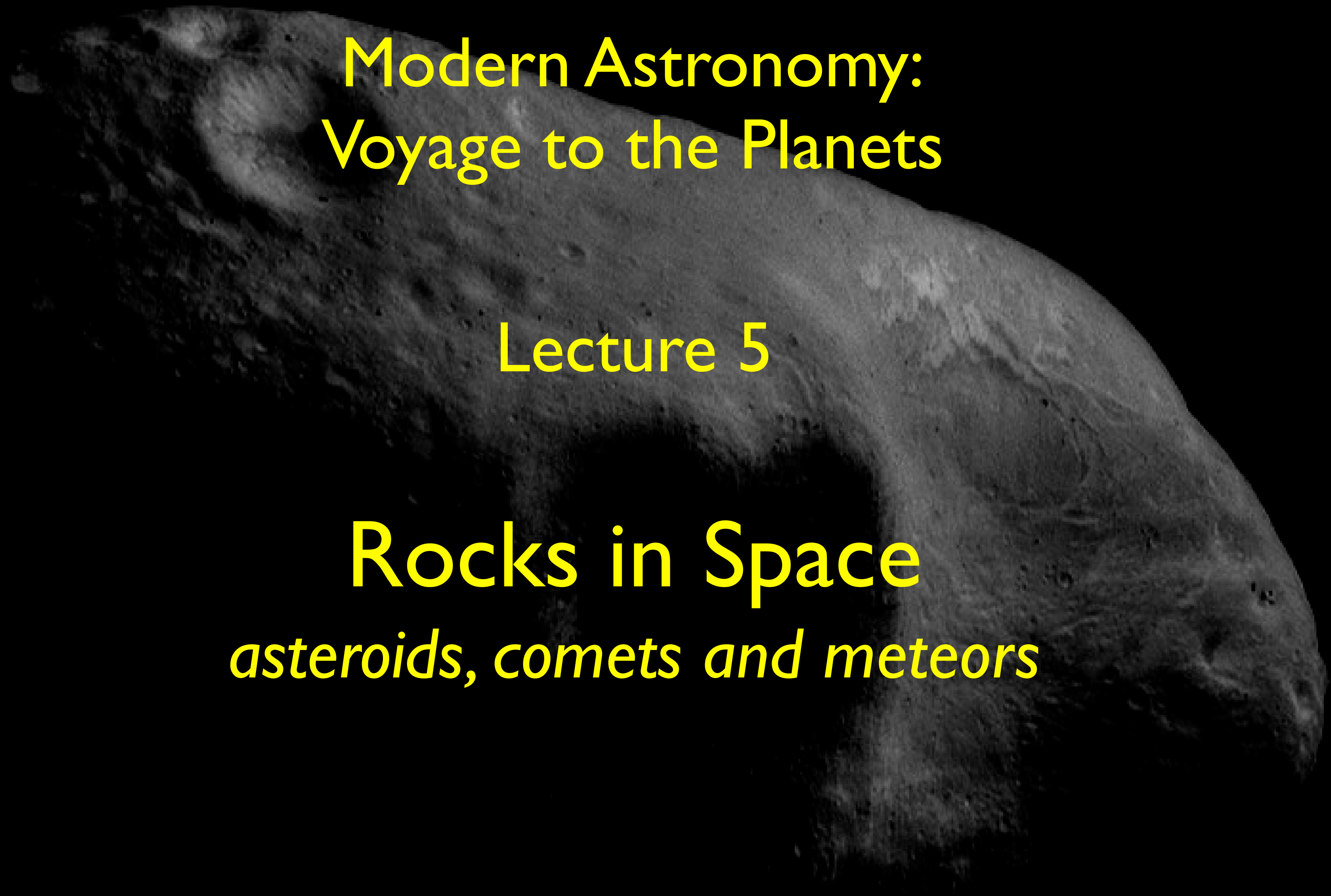


Modern Astronomy:
Voyage to the Planets

Lecture 5

Rocks in Space

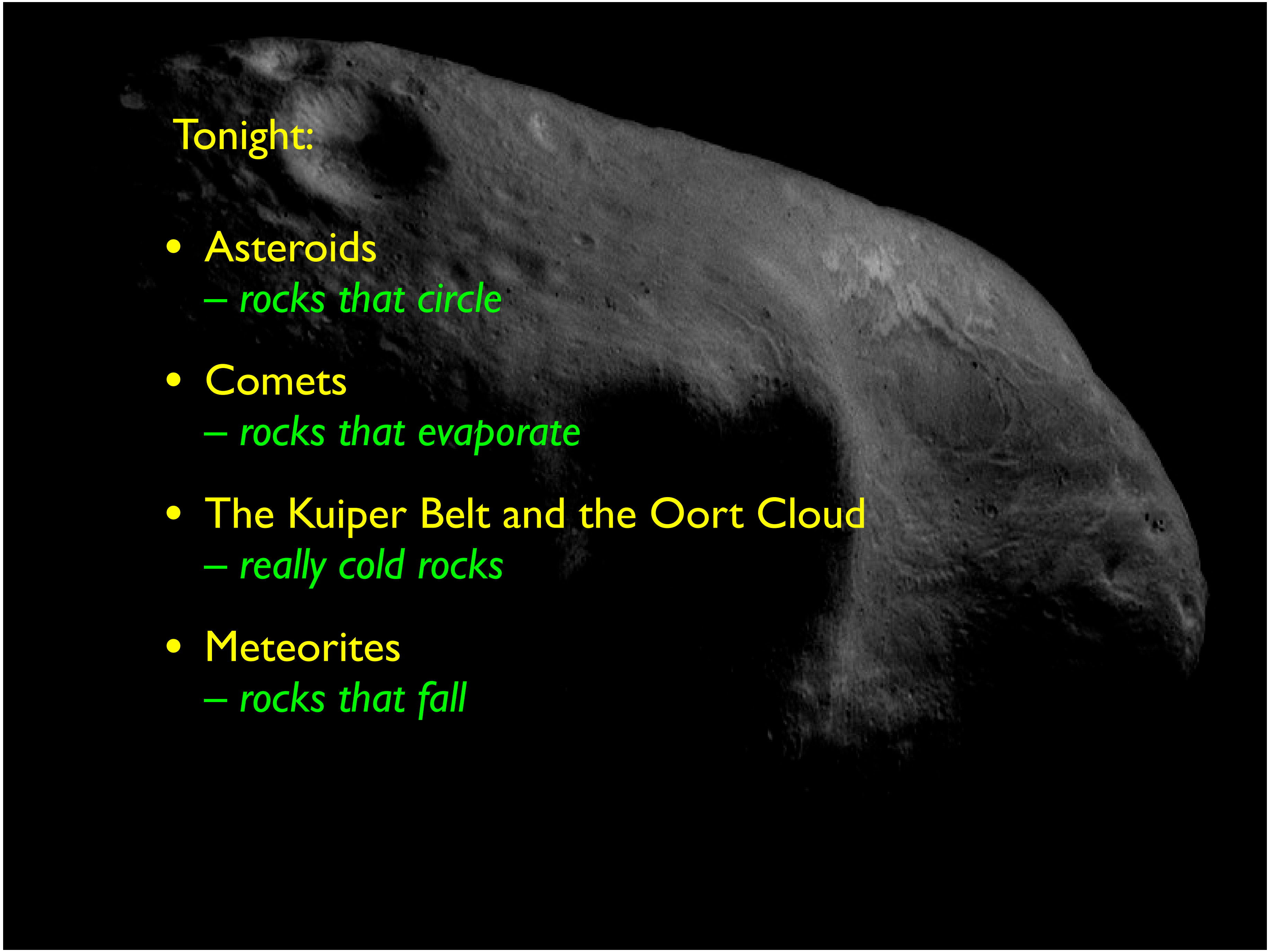
asteroids, comets and meteors

University of Sydney
Centre for Continuing Education
Autumn 2005


We’ll have a viewing evening on the roof of the Physics Building on
Wednesday May 11
(lecture 8). If that’s cloudy, there’s no backup date.

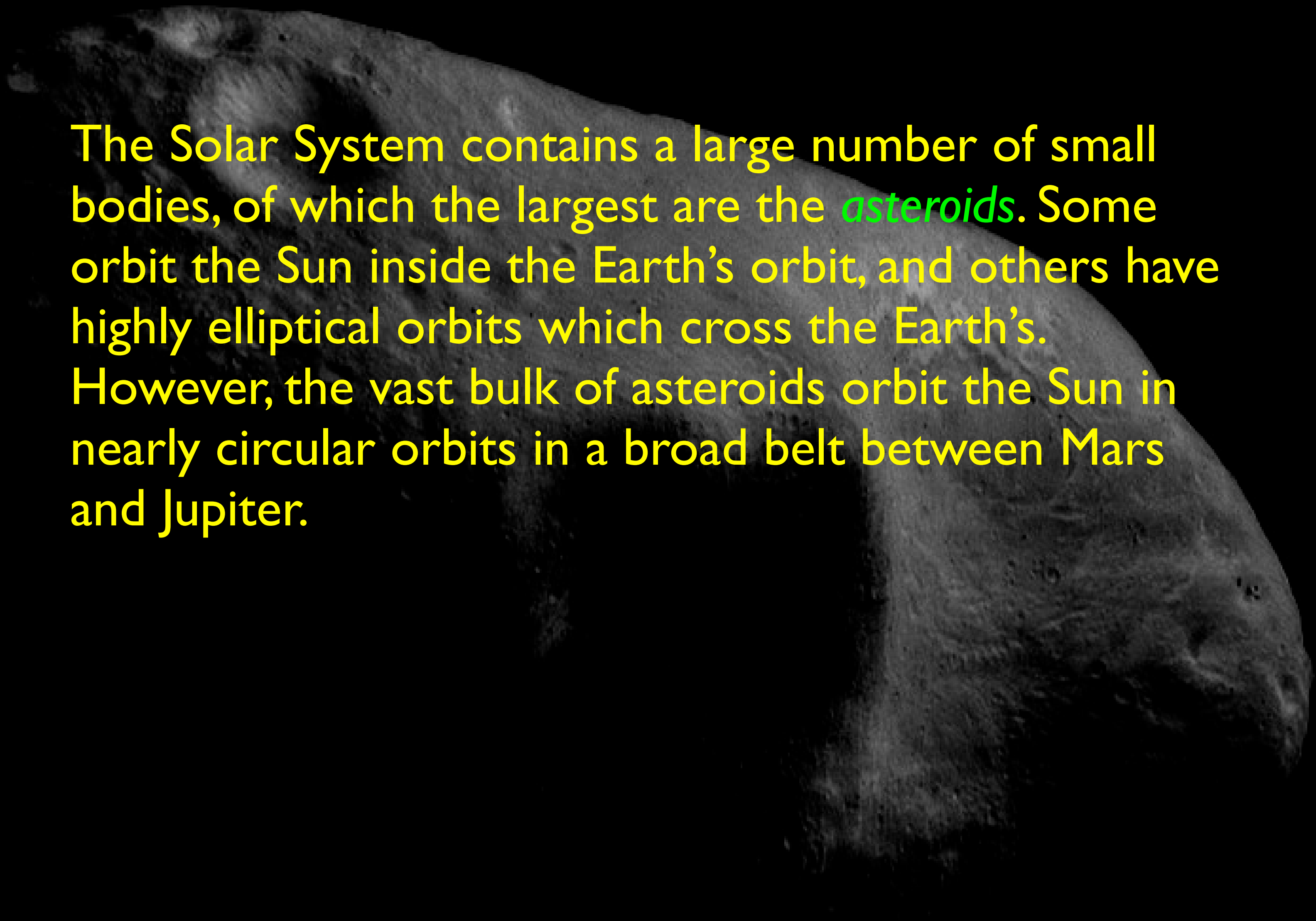
Tonight:

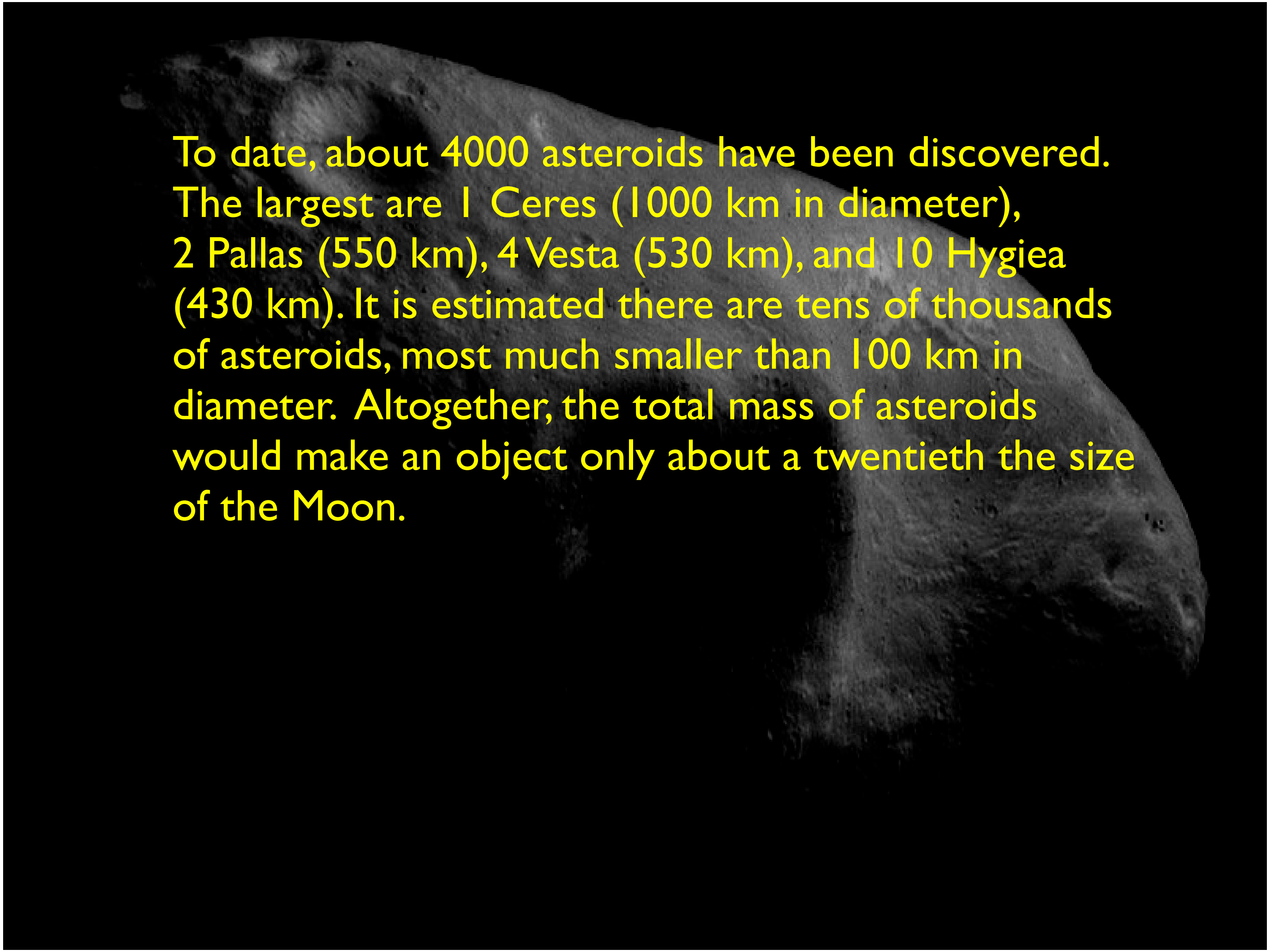
- Asteroids
  - *rocks that circle*
- Comets
  - *rocks that evaporate*
- The Kuiper Belt and the Oort Cloud
  - *really cold rocks*
- Meteorites
  - *rocks that fall*



Asteroids

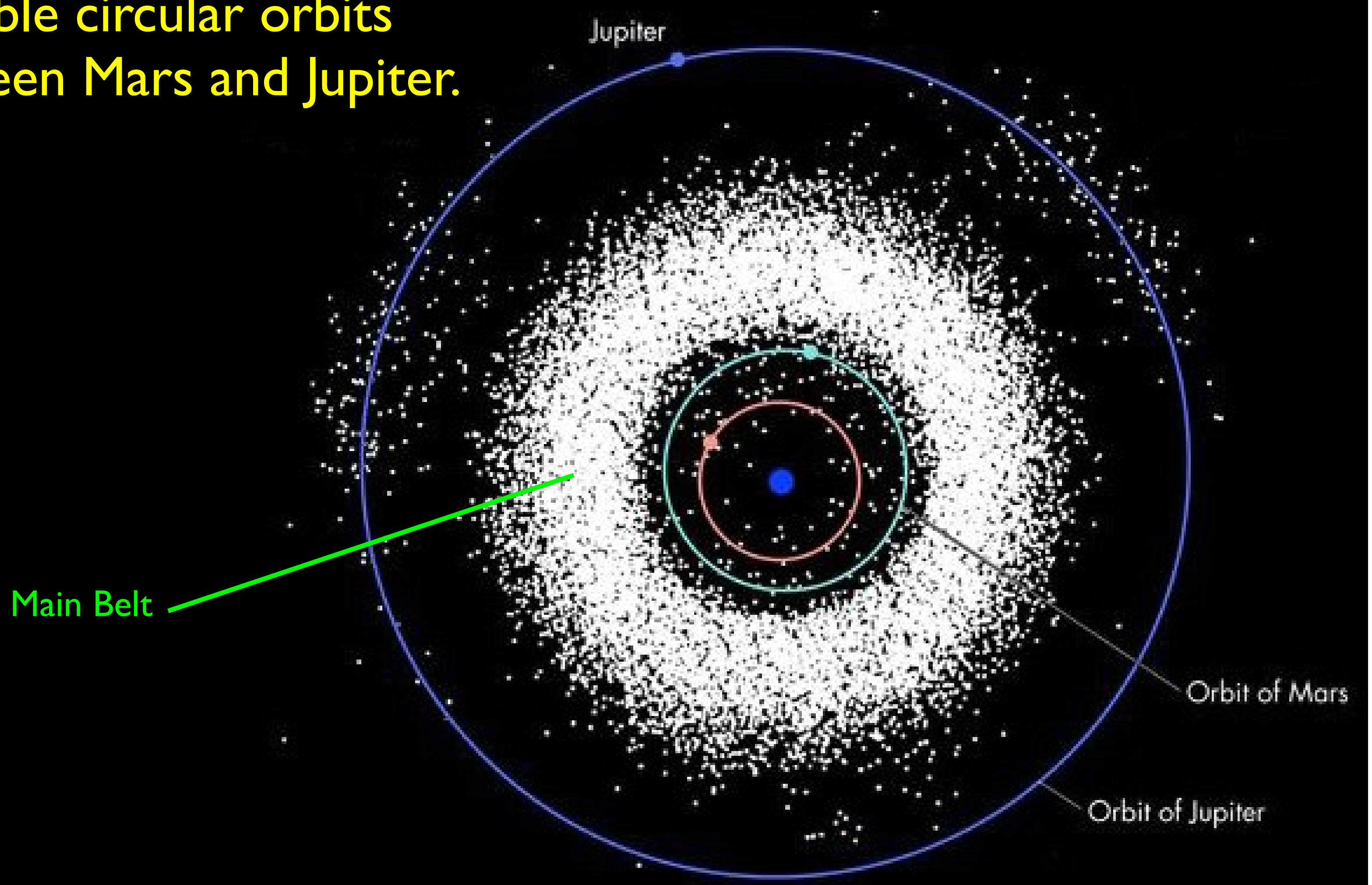
The Solar System contains a large number of small bodies, of which the largest are the *asteroids*. Some orbit the Sun inside the Earth's orbit, and others have highly elliptical orbits which cross the Earth's. However, the vast bulk of asteroids orbit the Sun in nearly circular orbits in a broad belt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




To date, about 4000 asteroids have been discovered. The largest are 1 Ceres (1000 km in diameter), 2 Pallas (550 km), 4 Vesta (530 km), and 10 Hygiea (430 km). It is estimated there are tens of thousands of asteroids, most much smaller than 100 km in diameter. Altogether, the total mass of asteroids would make an object only about a twentieth the size of the Moon.

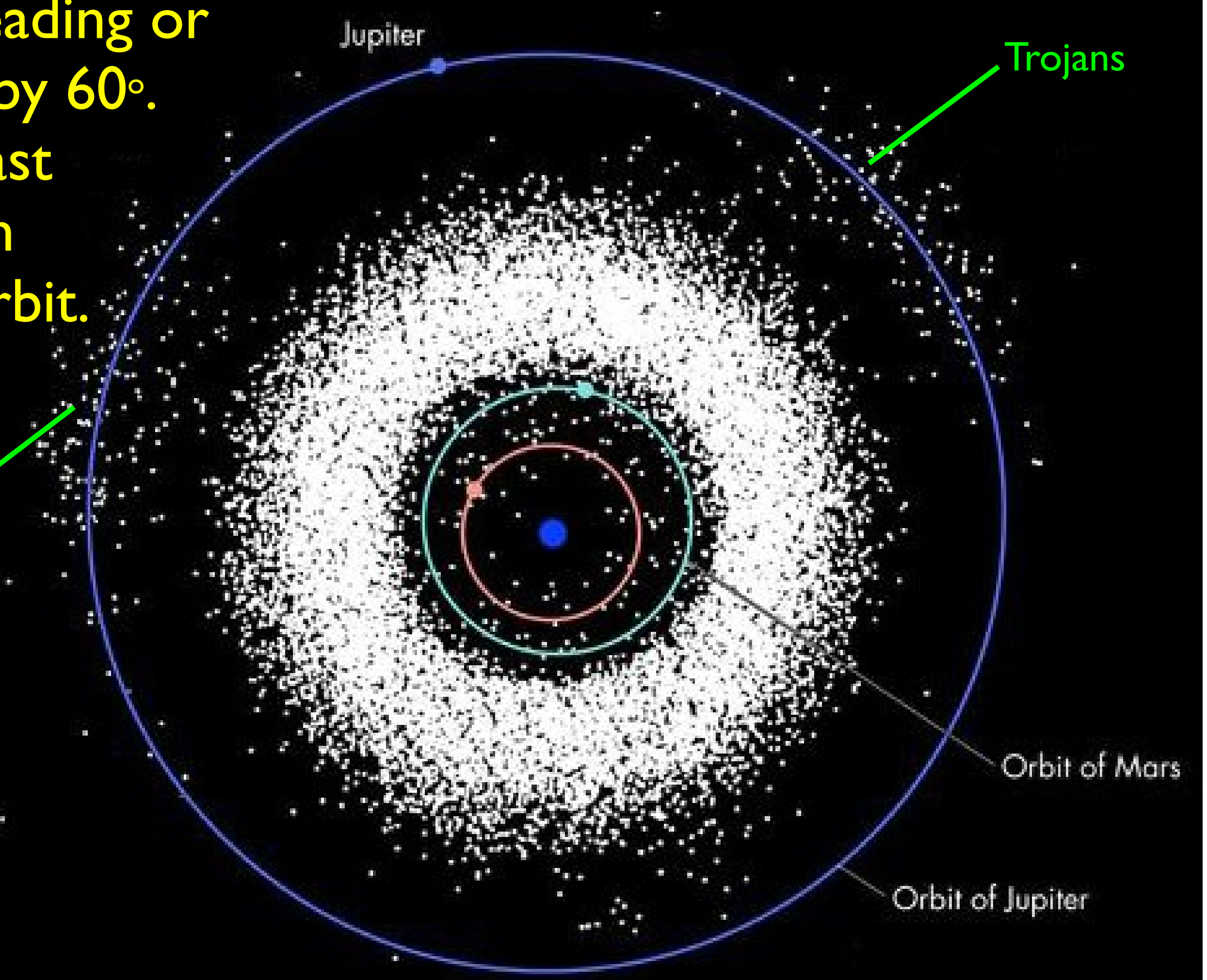
There are three main groups of asteroids:

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



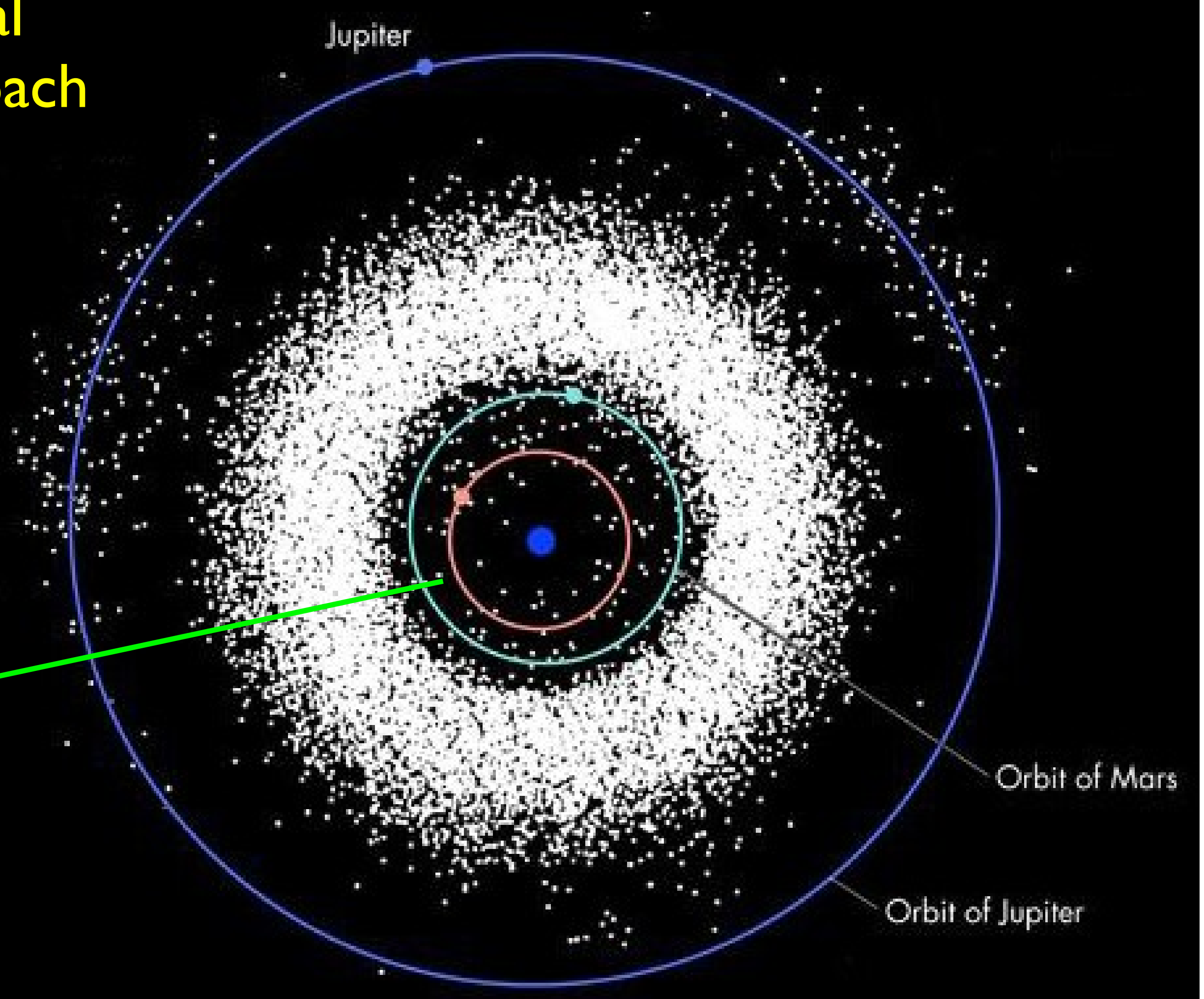
There are three main groups of asteroids:

– 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.



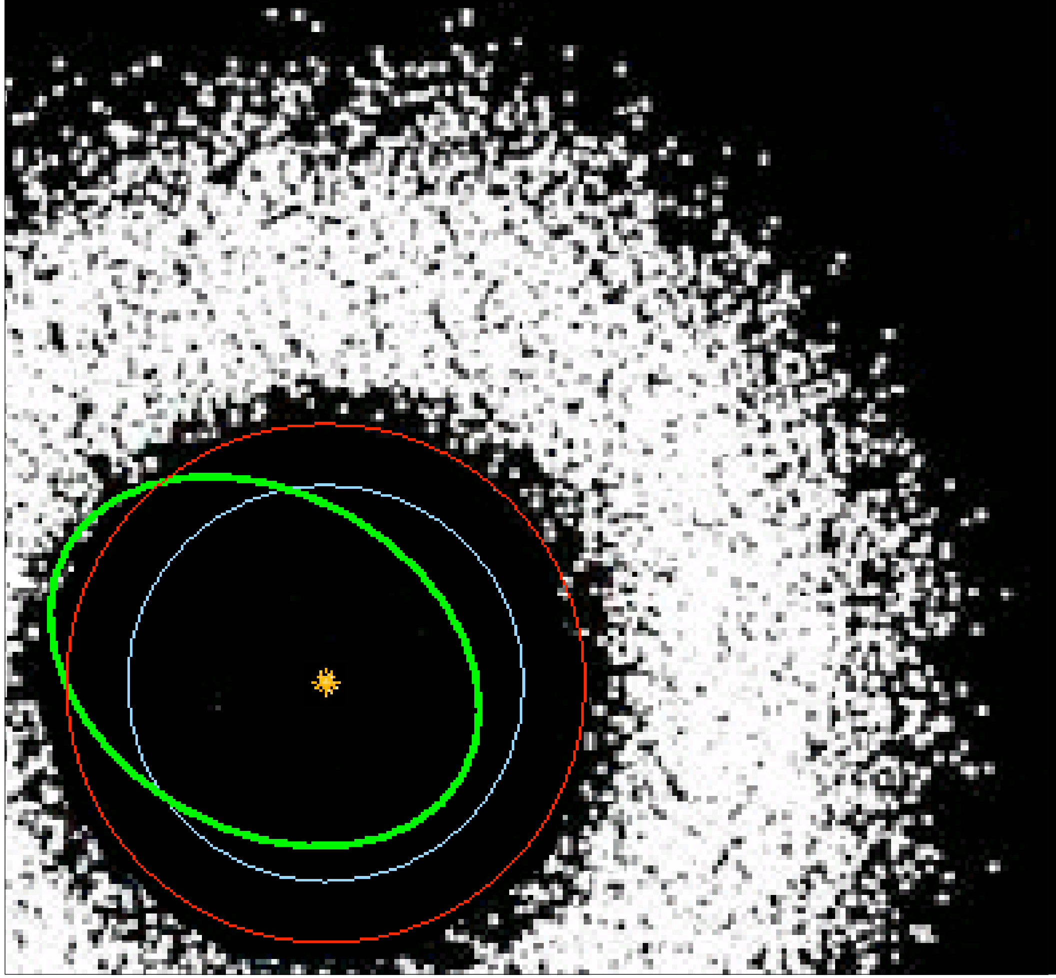
There are three main groups of asteroids:

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



Near Earth asteroids

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

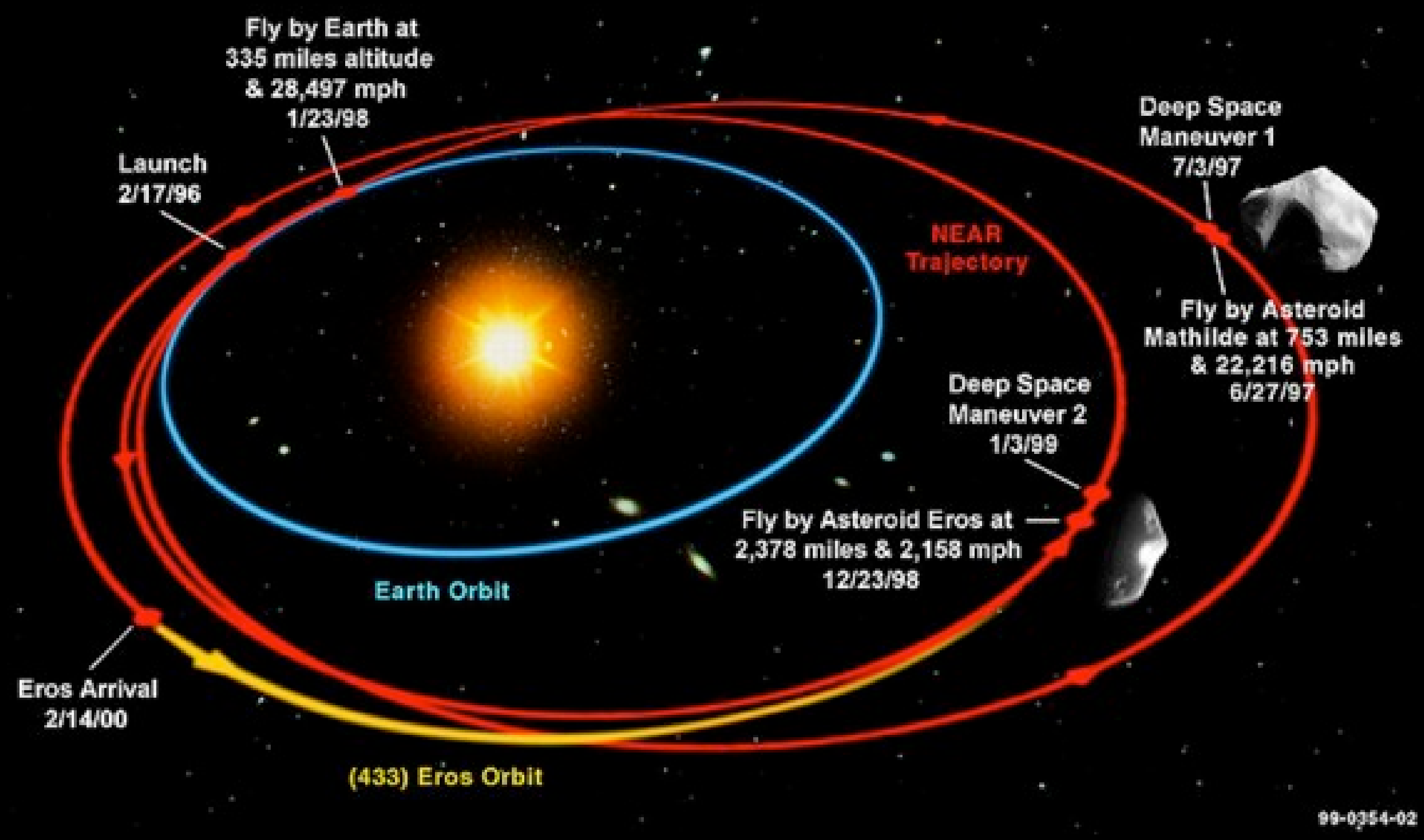


– The *Amor* asteroids cross Mars' orbit but do not reach Earth's orbit;

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

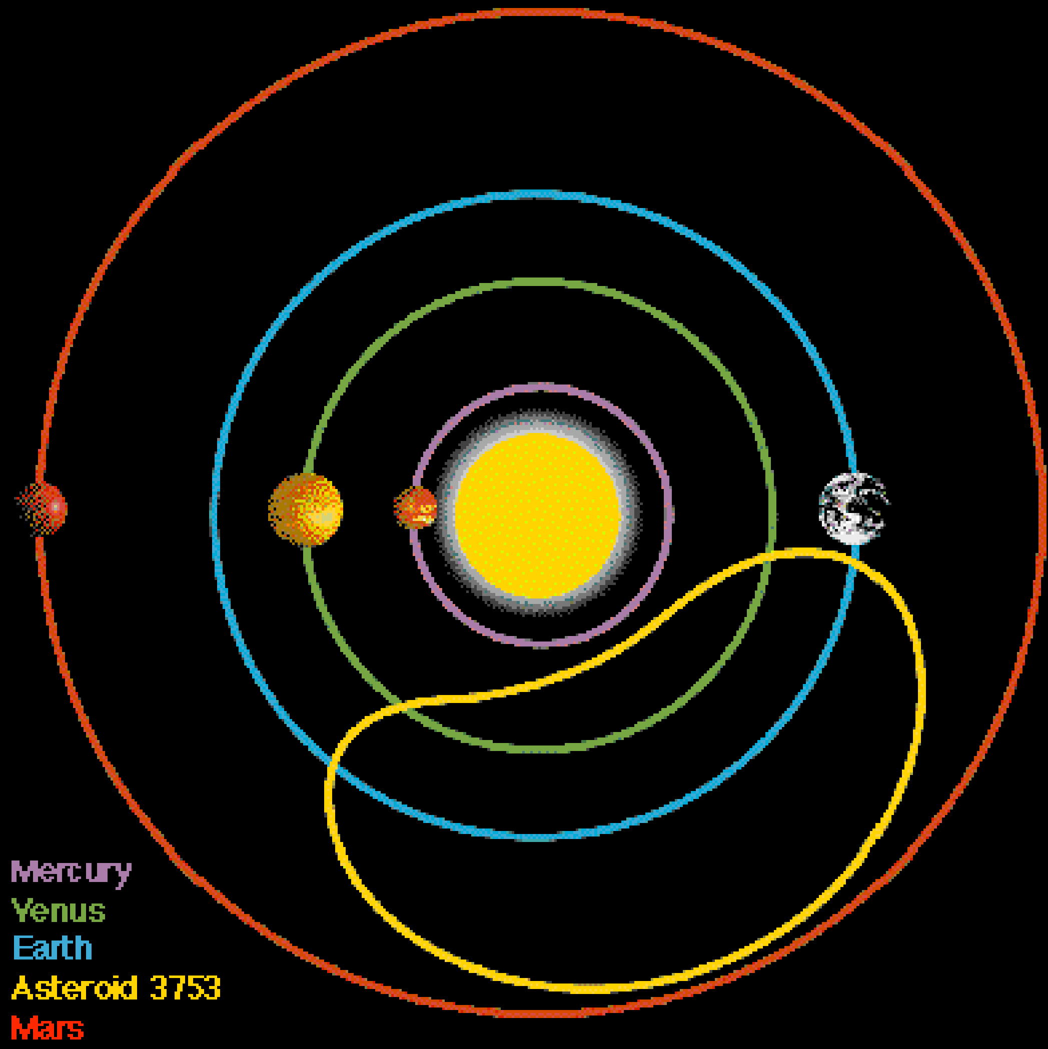
– the *Aten* asteroids have periods of less than 1 year.

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.

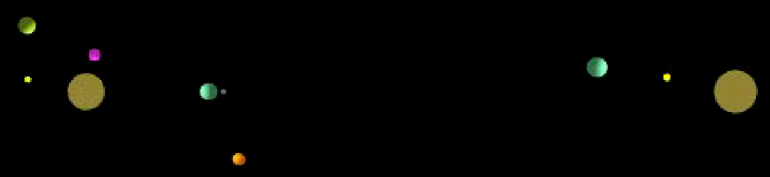


These animations show some of the many images returned by NEAR-Shoemaker, showing the detail it could see.

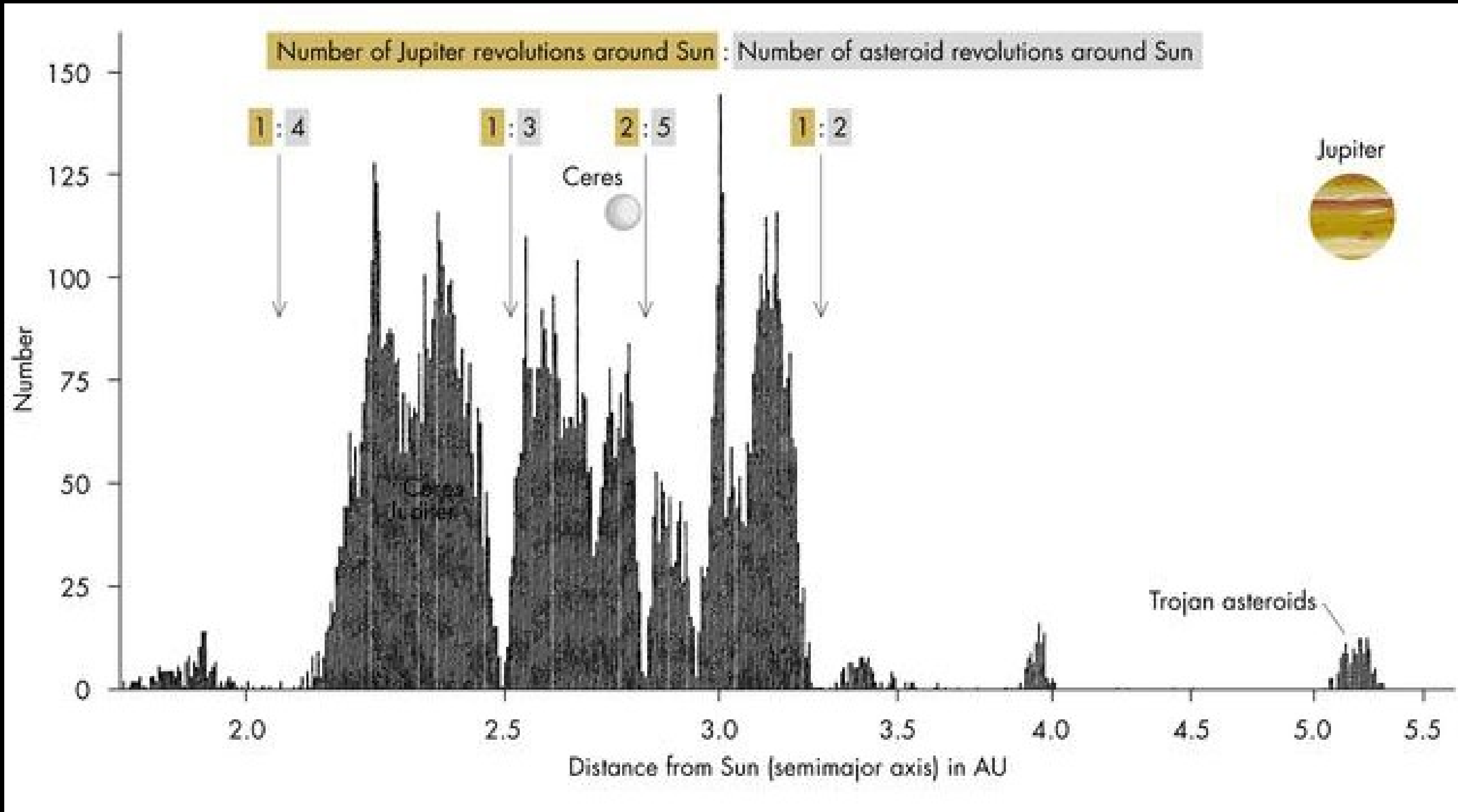
There are asteroids in all kinds of orbits. In 1996, Earth was found to have a companion asteroid: 3753 Cruithne, which executes a strange dance with Earth, following a kidney-bean shaped path near the Earth while orbiting with the same period.



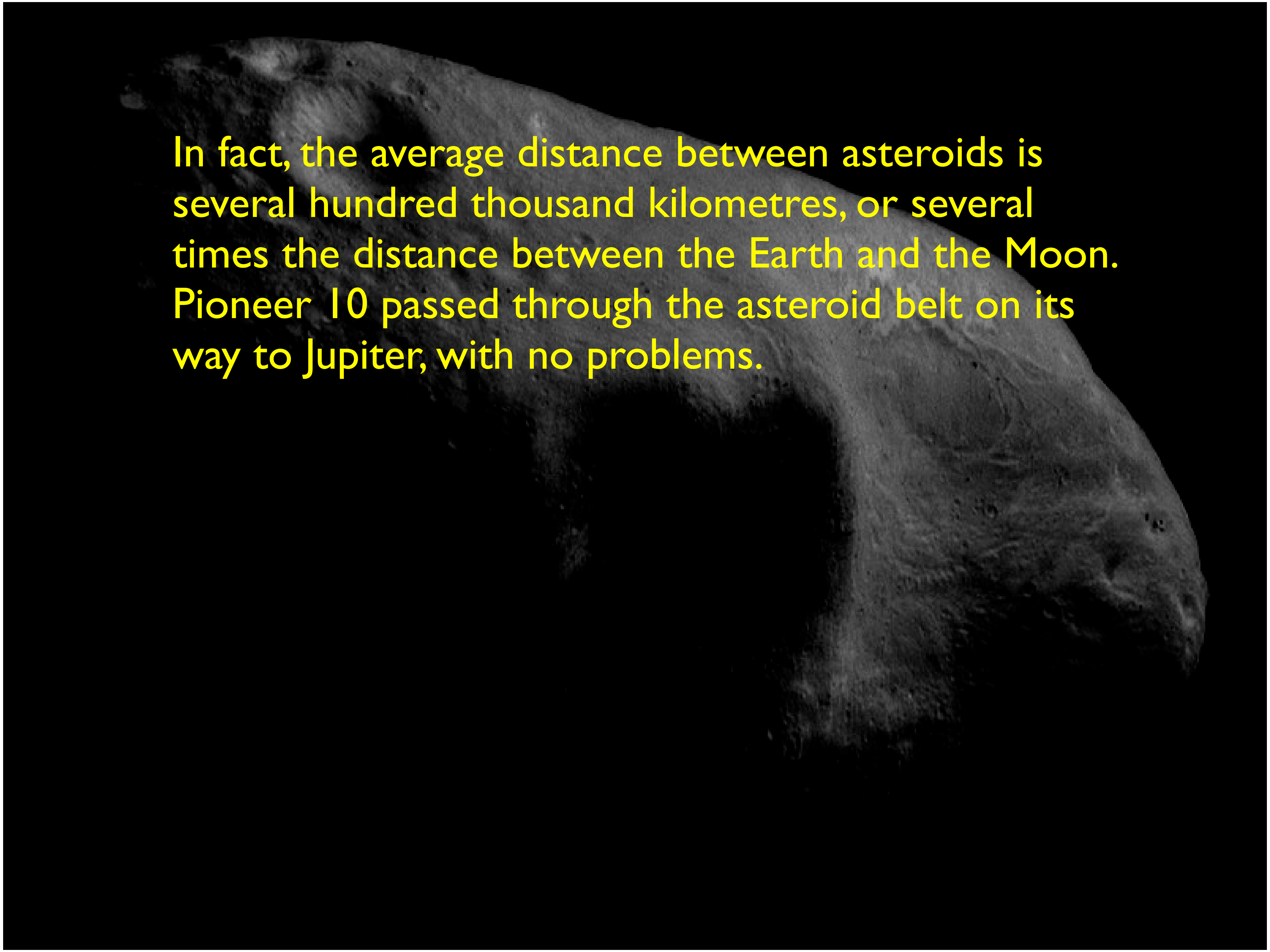
The motion of 3753 Cruithne is shown in this animation. From the Sun's perspective, the asteroid executes a standard elliptical orbit, but from our position on Earth, the relative motion is a peculiar kidney-bean shaped dance.

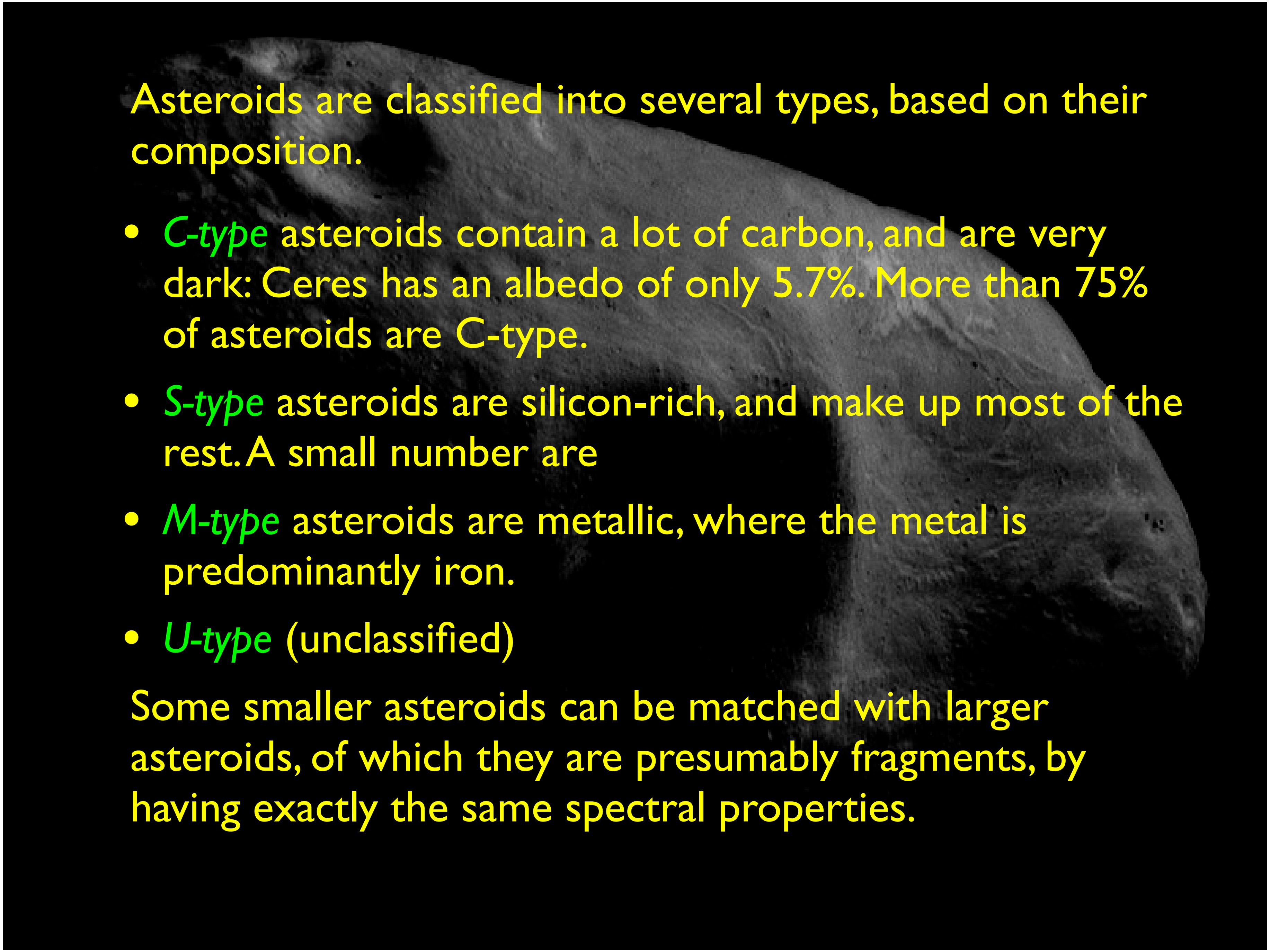


Asteroids are not distributed randomly in the Main Belt: there are gaps where they are scarce, called Kirkwood gaps. These occur where the orbital period has a simple integer relation to Jupiter's period.




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.

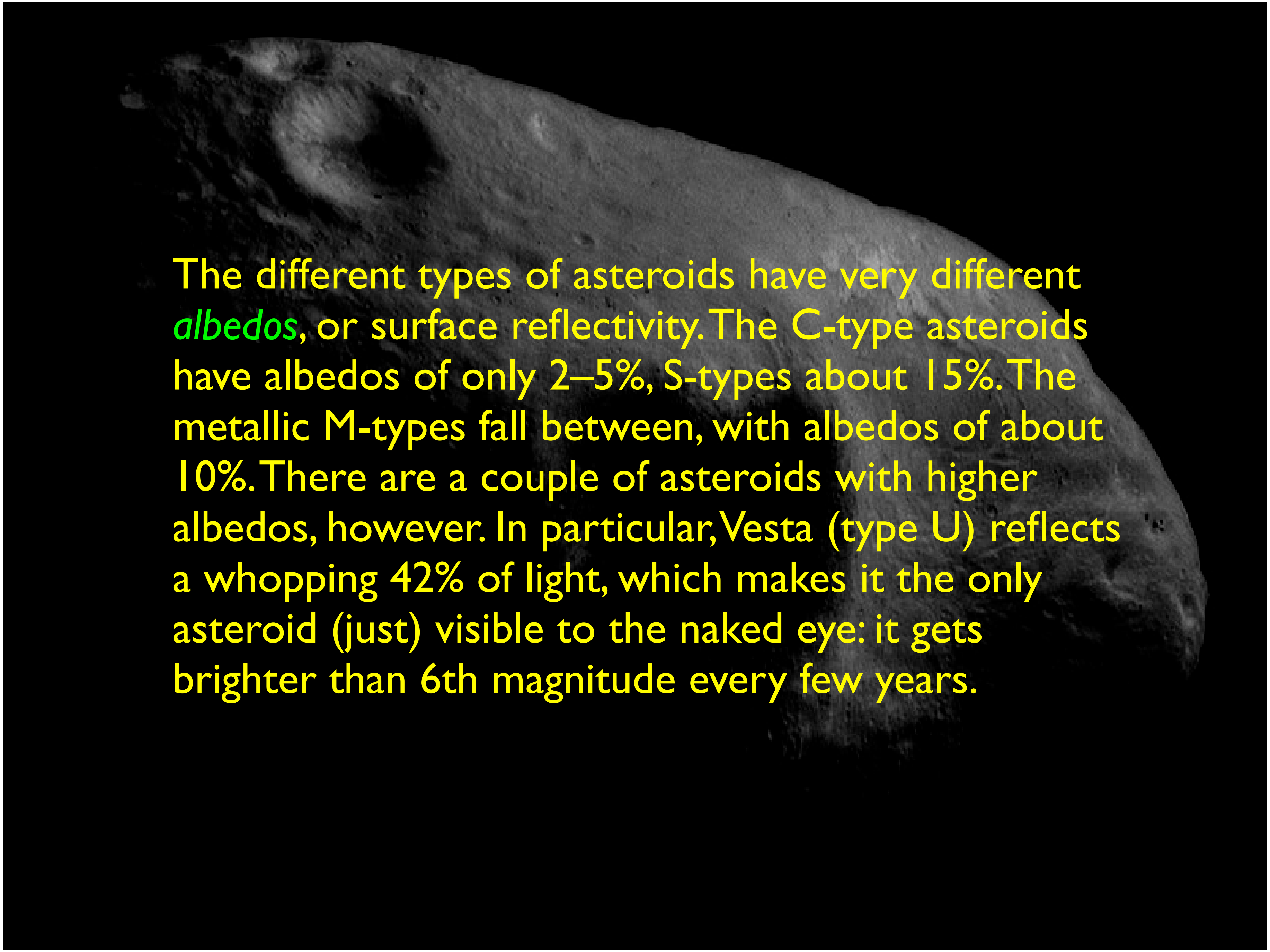

In fact, the average distance between asteroids is several hundred thousand kilometres, or several times the distance between the Earth and the Moon. Pioneer 10 passed through the asteroid belt on its way to Jupiter, with no problems.



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

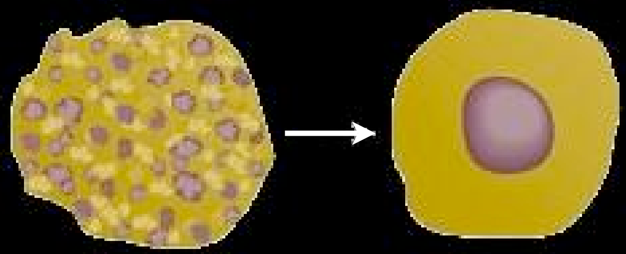
- *C-type* asteroids contain a lot of carbon, and are very dark: Ceres has an albedo of only 5.7%. More than 75% of asteroids are C-type.
- *S-type* asteroids are silicon-rich, and make up most of the rest. A small number are
- *M-type* asteroids are metallic, where the metal is predominantly iron.
-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

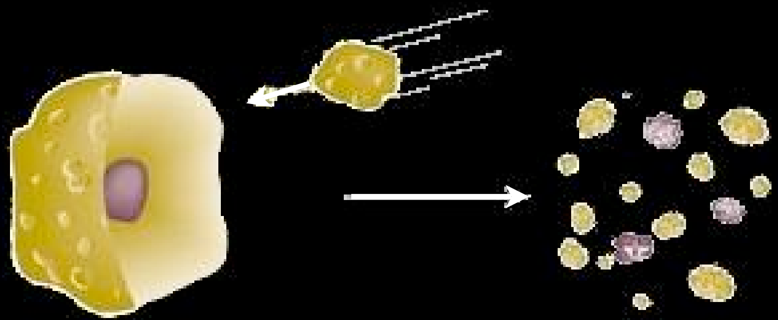
Some smaller asteroids can be matched with larger asteroids, of which they are presumably fragments, by having exactly the same spectral properties.


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.

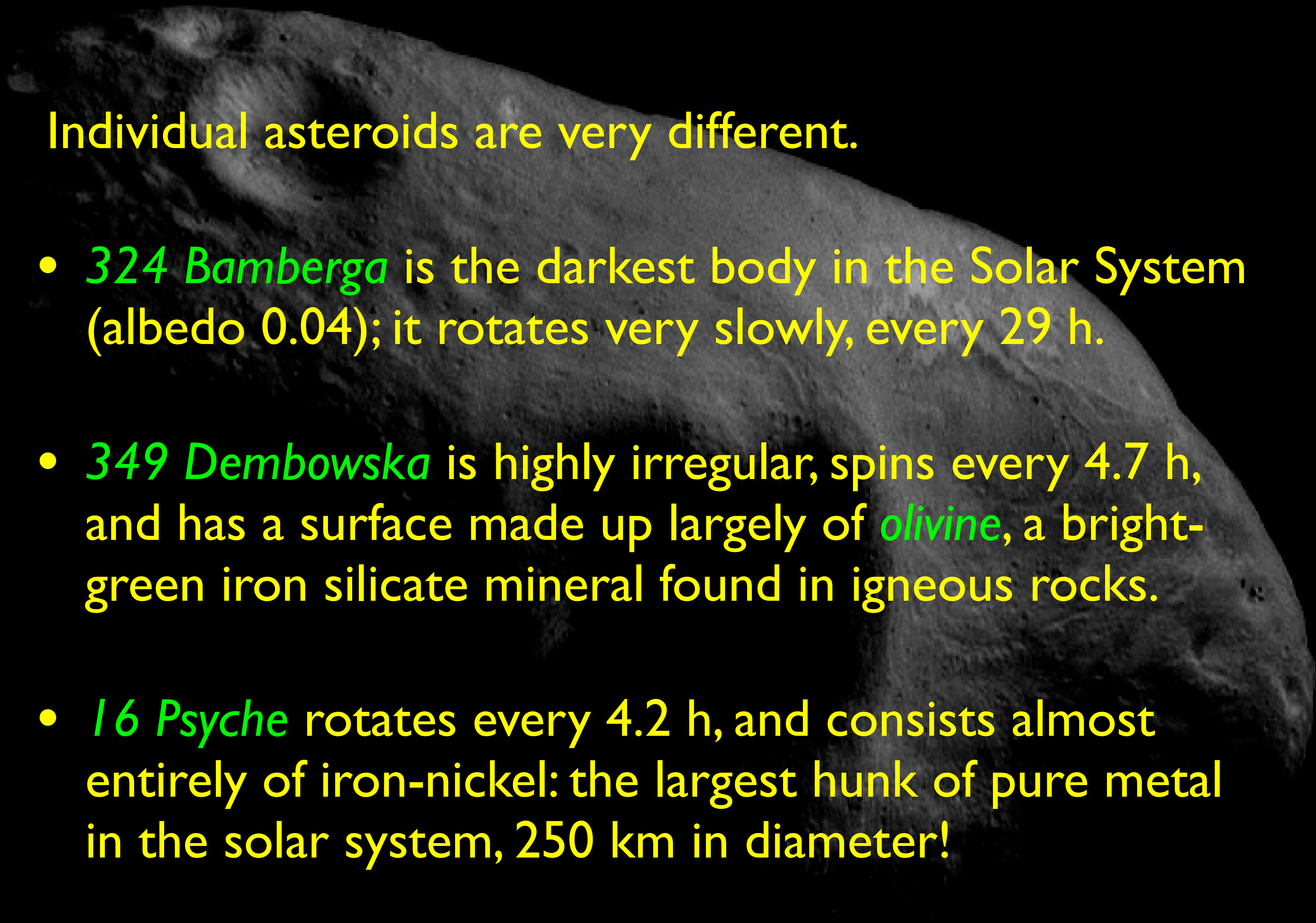
It is thought that the different types of asteroids arise through the break-up of larger bodies which became differentiated – the iron and nickel settle to the centre of the body, leaving silicates on the outside. This has clearly taken place in some asteroids (Vesta) and not in others, even larger (Ceres). 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.

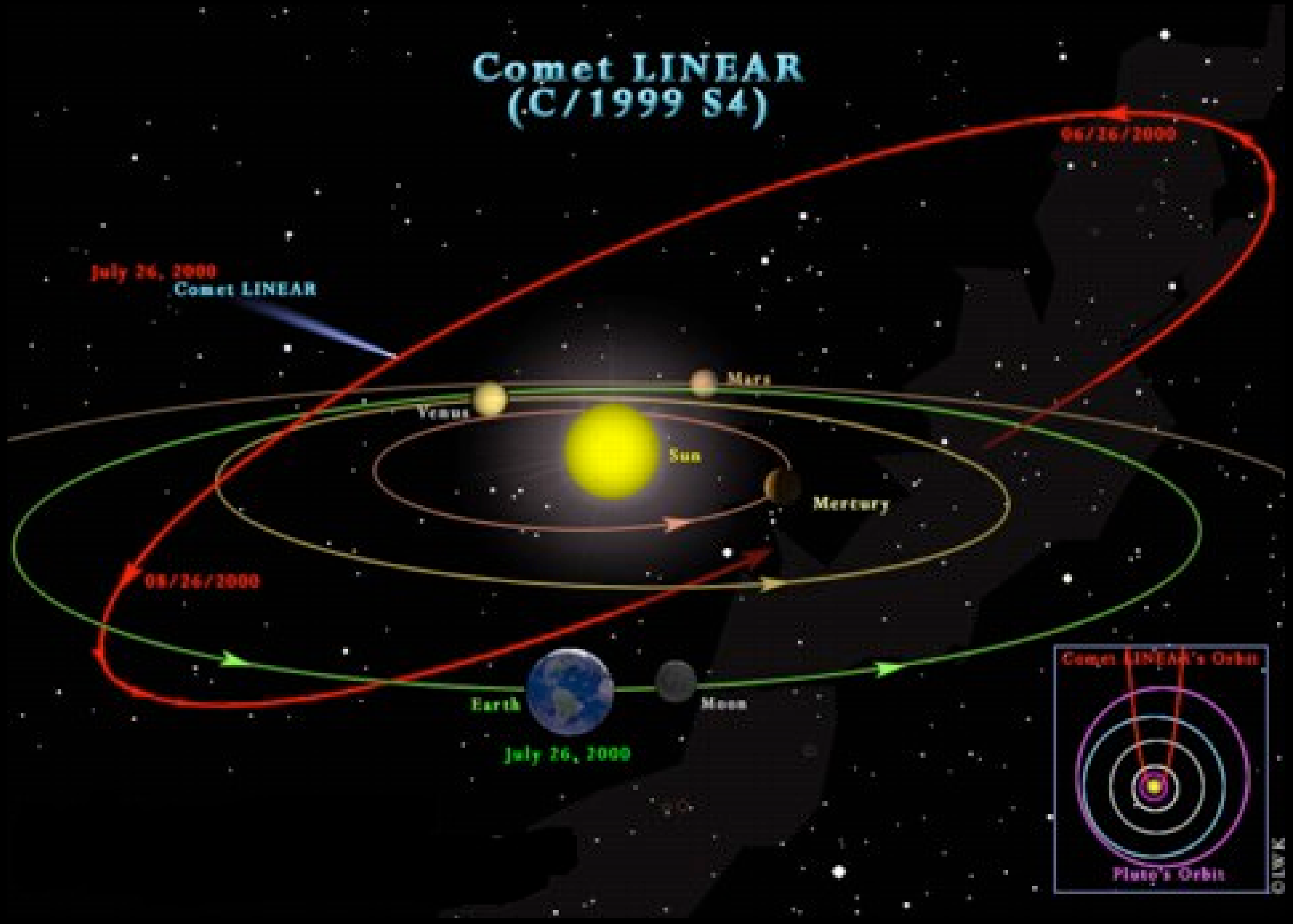
Asteroids Mathilde, Gaspra, and Ida, shown to scale.

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.

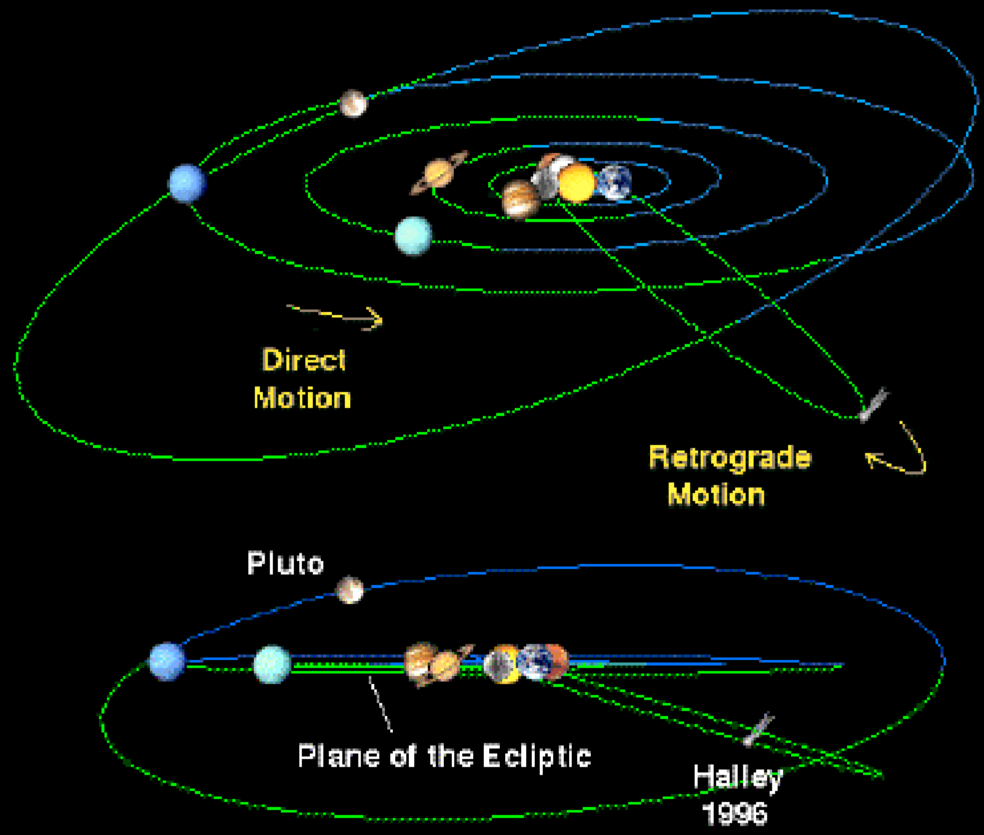
Vesta, shape model from HST images.

Comets

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



Cometary orbits are also not confined to the plane of the ecliptic like (most of) the other 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.



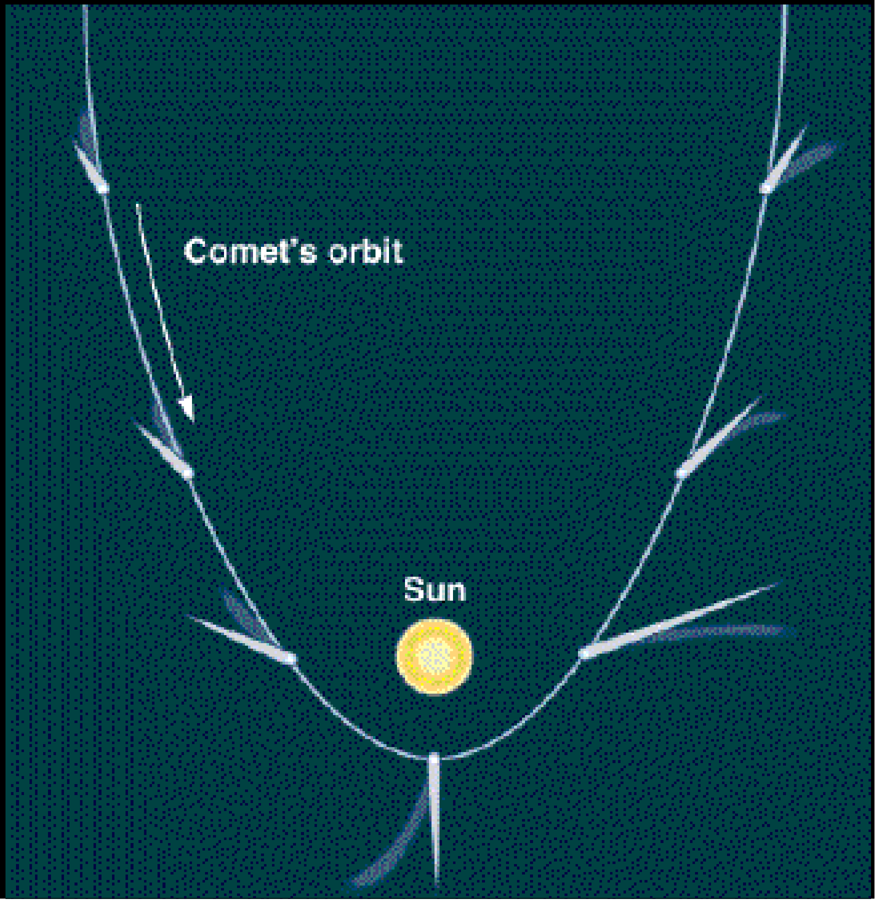
The orbit of Comet Halley

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.

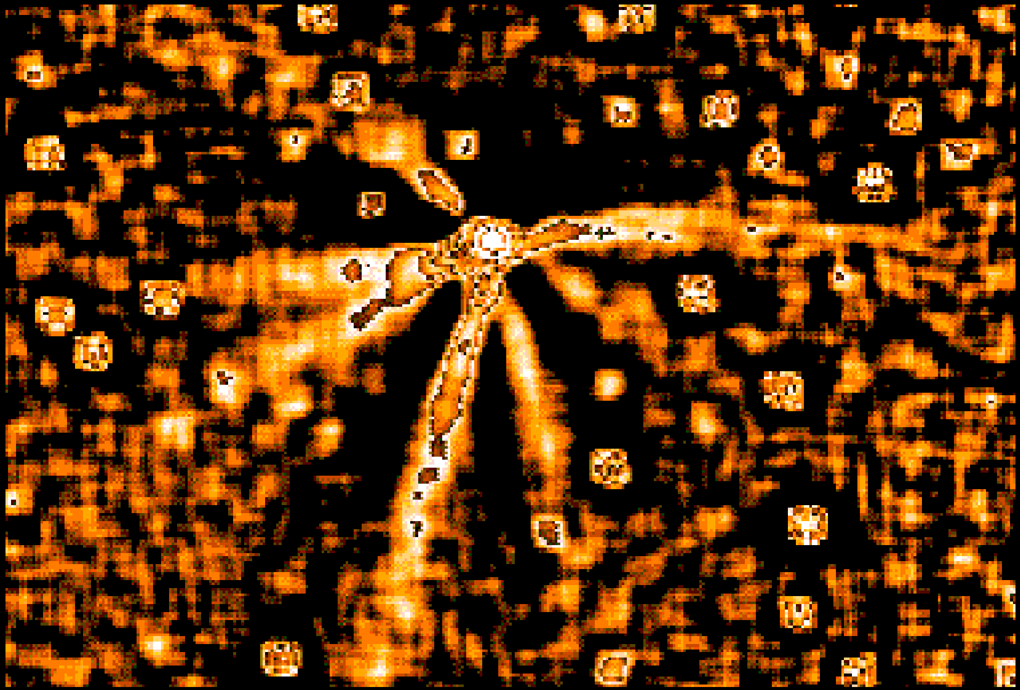
Comet Hale-Bopp in 1997, as it began its journey towards the Sun

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.

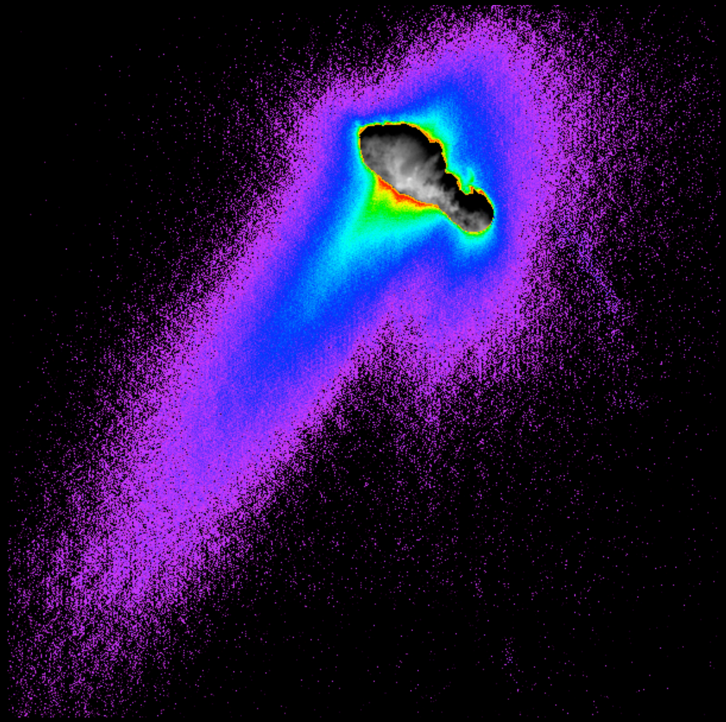


The comet’s motion is often affected by gases jetting out of the nucleus, so their orbits are somewhat disturbed from regular orbits.



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

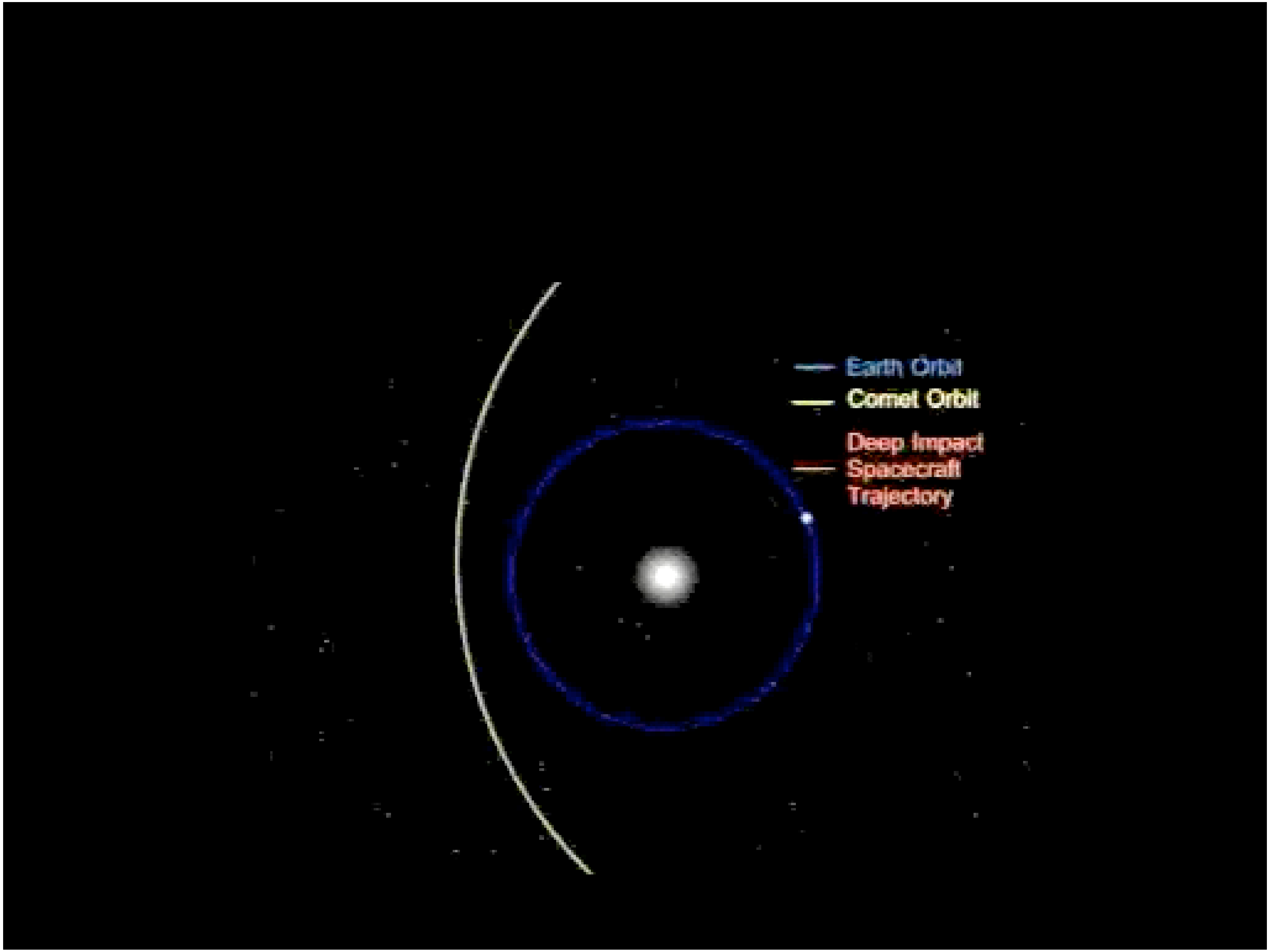
Several recent space missions have actually flown through a comet's coma to image the nucleus.



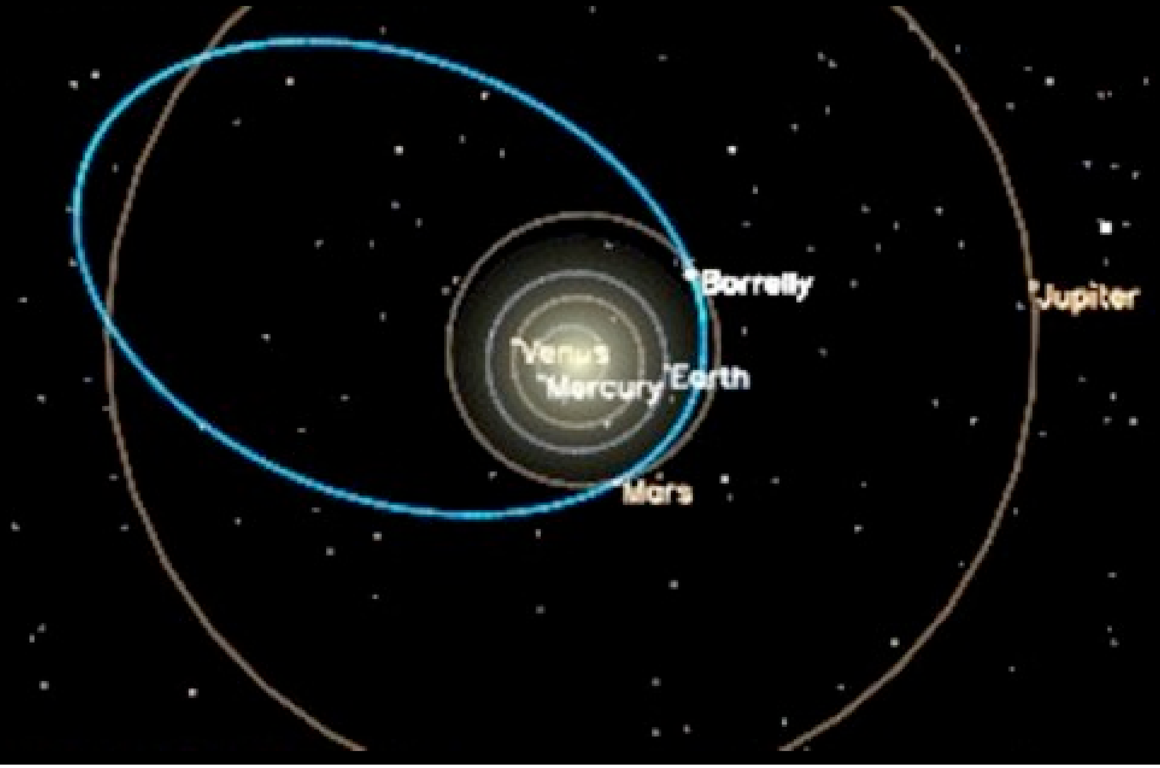
Deep Space 1 flew past Comet Borelly in September 2001.

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

In January 2005, NASA launched a *Deep Impact*, a mission to punch a hole in a comet, Tempel-1. Impact will occur on 4 July 2005.


Earth Orbit
Comet Orbit
Deep Impact
Spacecraft
Trajectory

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?



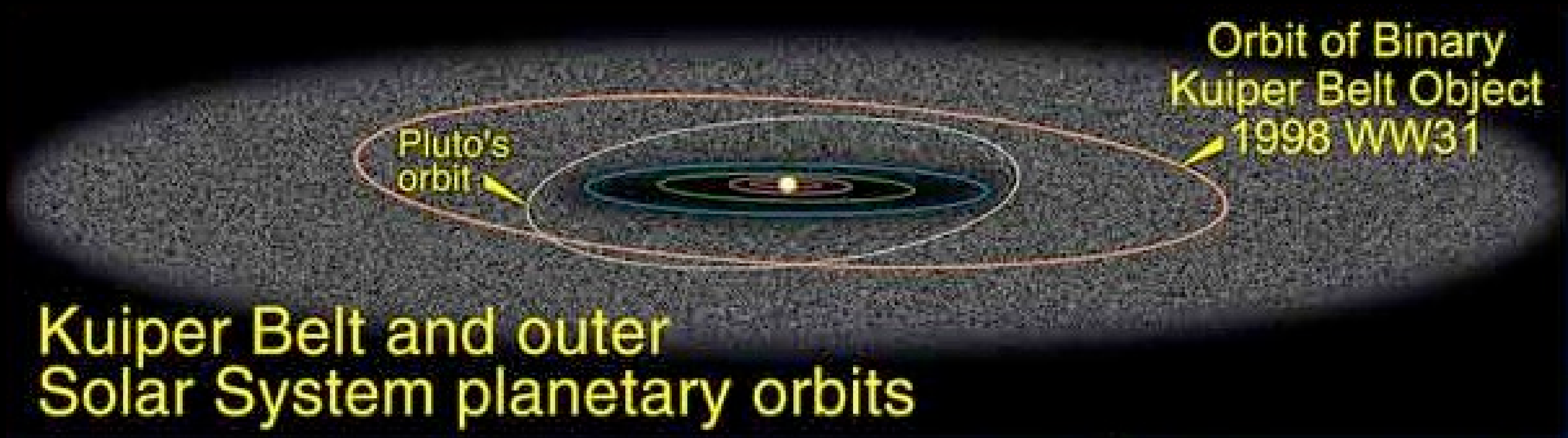
The Kuiper Belt and the Oort Cloud

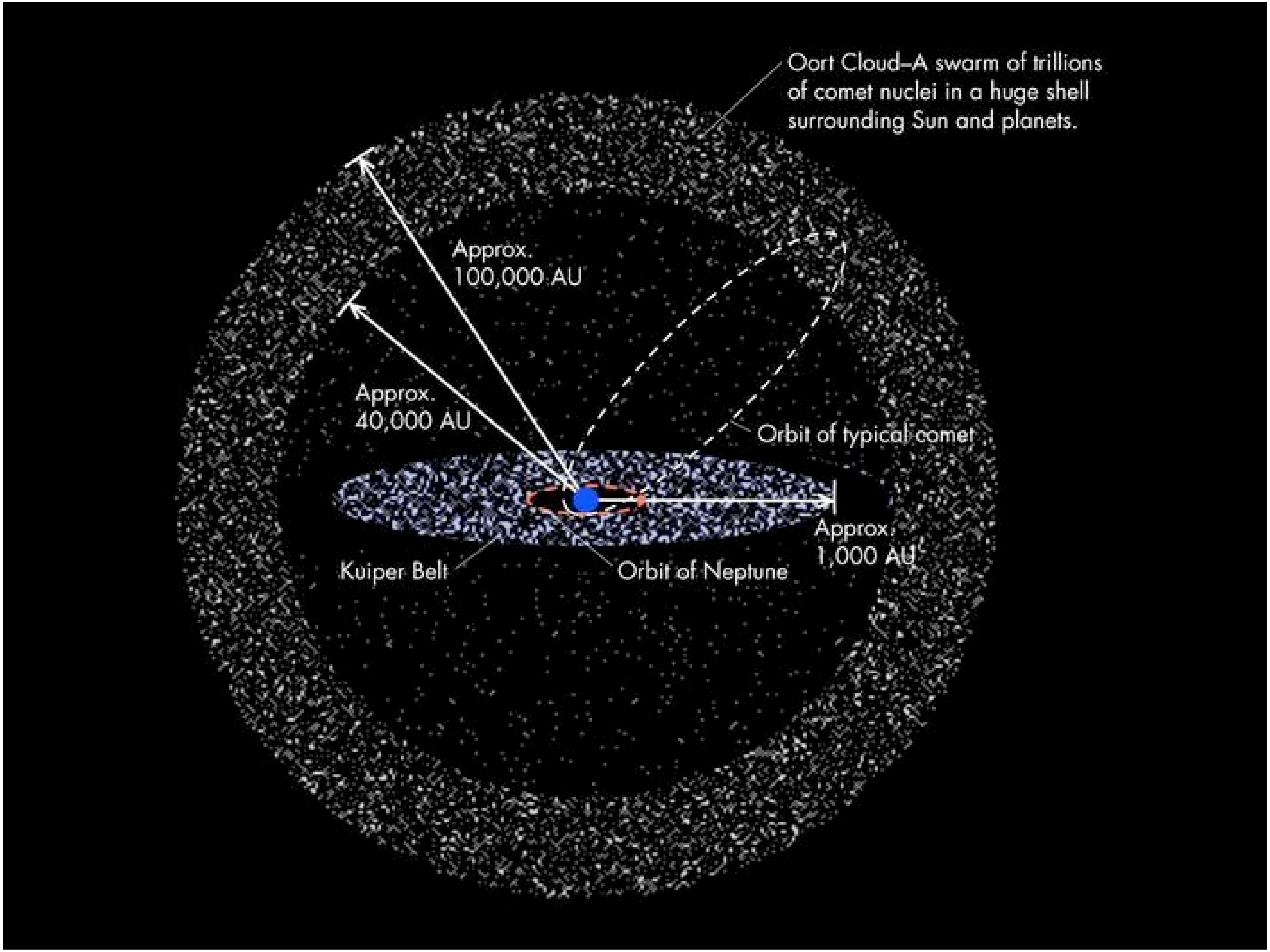
In 1950, Jan Oort noticed that

- 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.



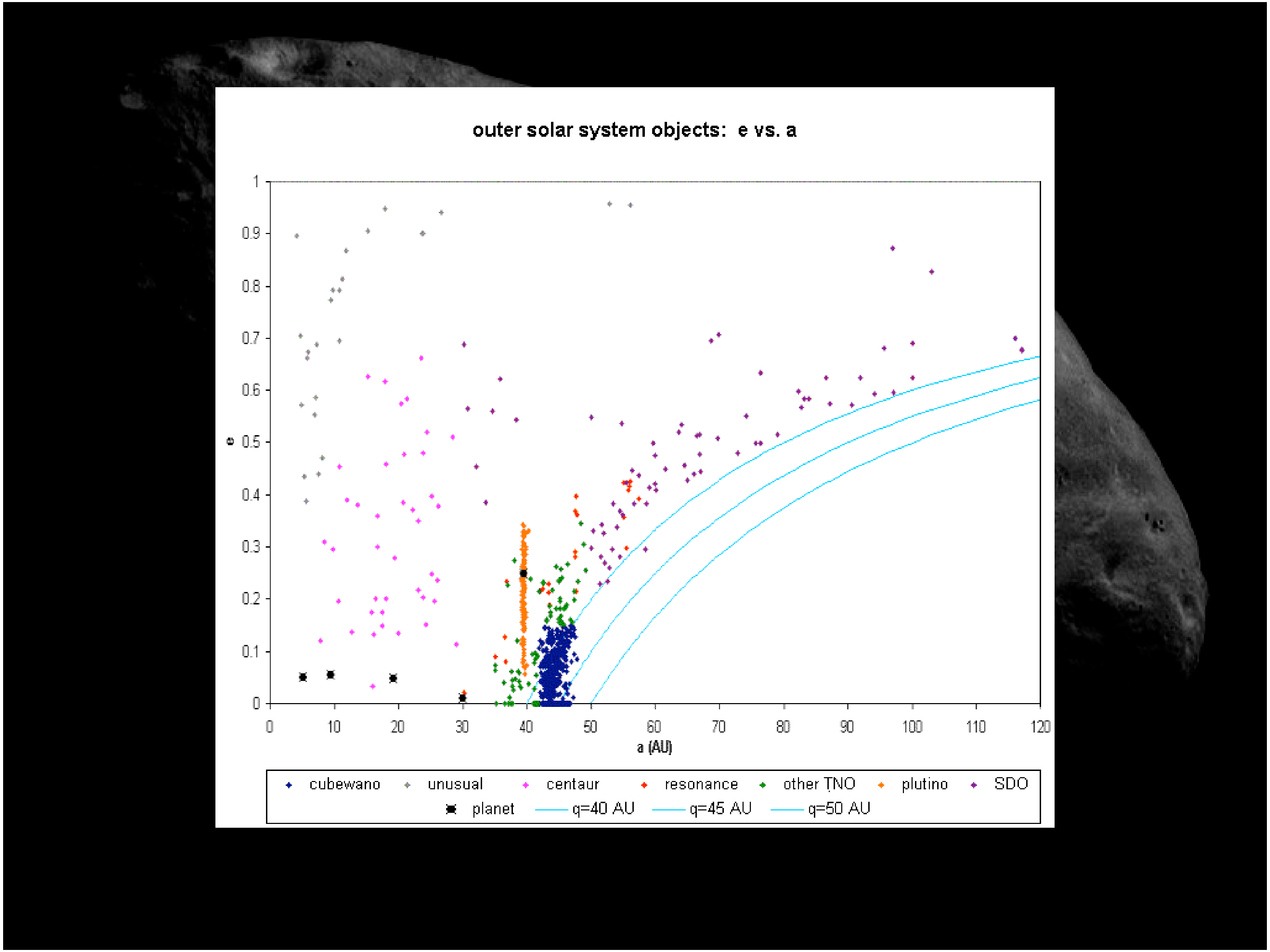

Oort Cloud–A swarm of trillions
of comet nuclei in a huge shell
surrounding Sun and planets.
Approx.
100,000 AU
Approx.
40,000 AU
Orbit of typical comet
Approx.
1,000 AU
Kuiper Belt
Orbit of Neptune

We discussed in the first lecture how Pluto should possibly not be called a planet at all. In fact, it fits very well into the category of Kuiper Belt objects, The Hubble Space Telescope has found over a hundred KBOs with sizes more than 20 km. Of these “trans-Neptunian” bodies, at least four have diameters of more than 1000 km: Varuna, Quaoar, Ixion and Sedna.

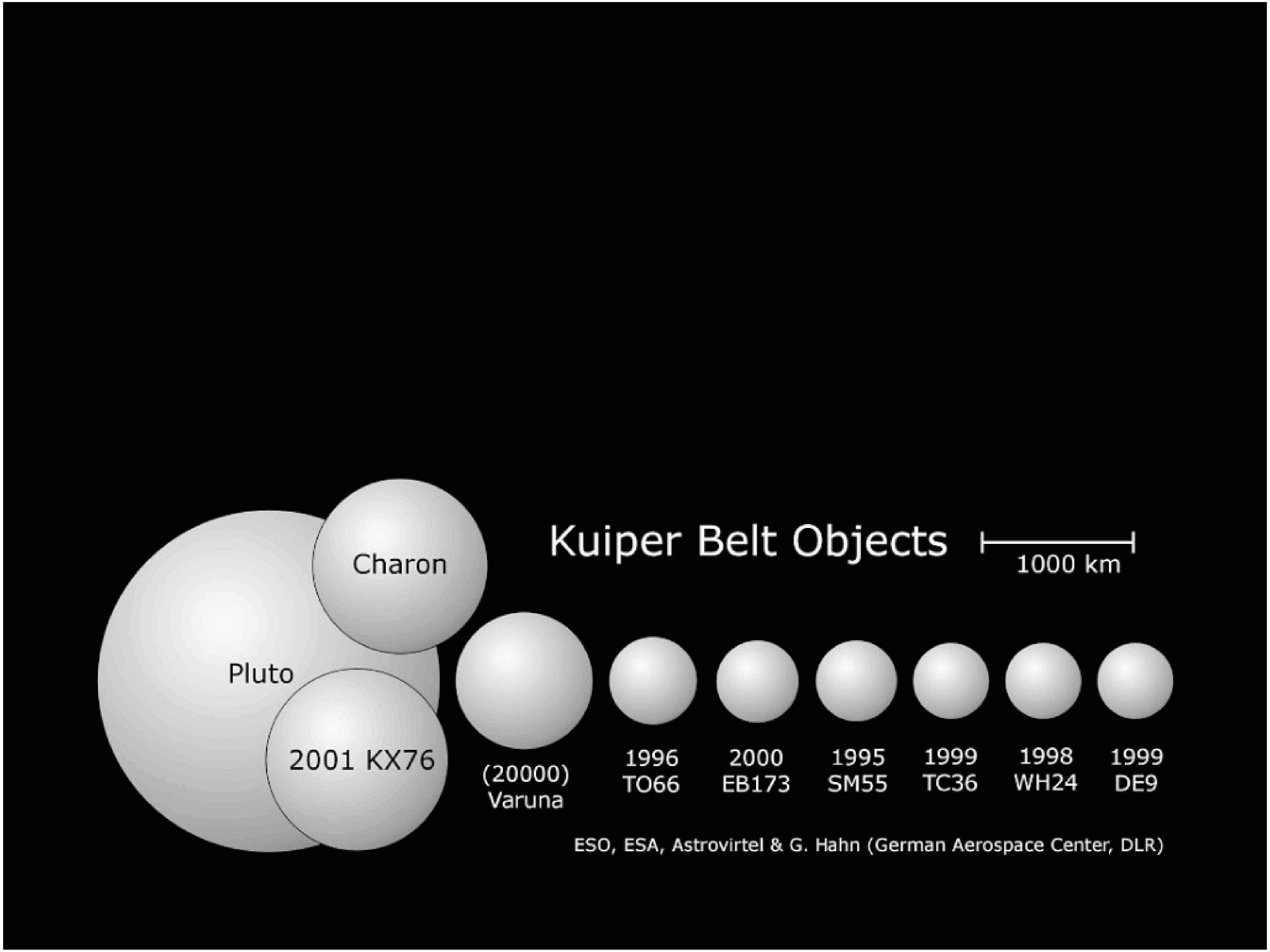
Artist’s impression of Quaoar.

There are in fact many different types of minor outer solar system bodies, of which KBOs are only one. As of February 2005, there were 1,038 objects known. These include

- *Centaurs*: asteroid-like objects with orbits between Jupiter and Neptune
- *Trans-Neptunian objects (TNOs)* or *Kuiper Belt Objects (KBOs)*: non-cometary objects with semimajor axes beyond Neptune's orbit. 170 objects are in 2:3 resonance with Neptune, and are called are called *Plutinos*; 22 are in other resonances with Neptune (like 3:4, 2:5 etc.), called *resonance objects*
- *Classical Kuiper Belt objects* (or *Cubewanos*): objects in circular orbits that do not cross the orbit of Neptune.

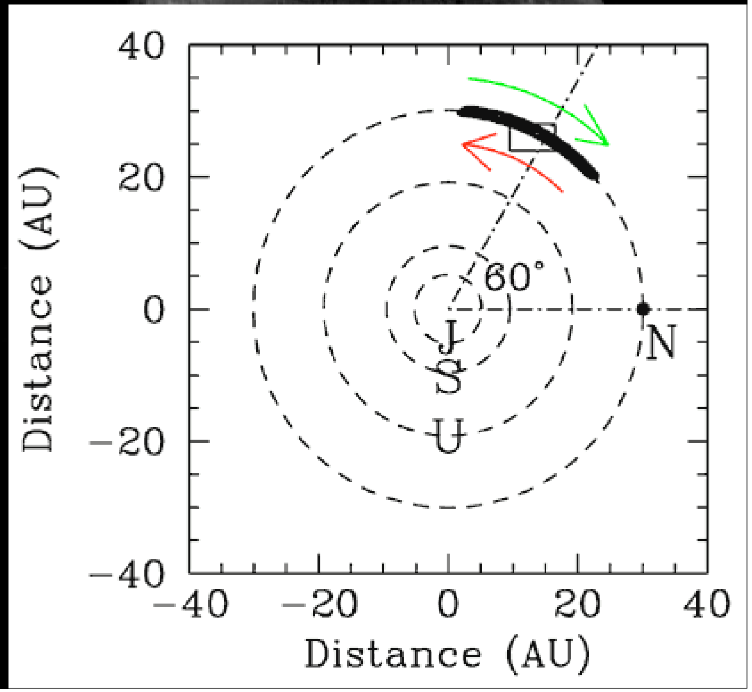


outer solar system objects: e vs. a
e
a (AU)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
10
20
30
40
50
60
70
80
90
100
110
120
cubewano
unusual
centaur
resonance
other TNO
plutino
SDO
planet
q=40 AU
q=45 AU
q=50 AU

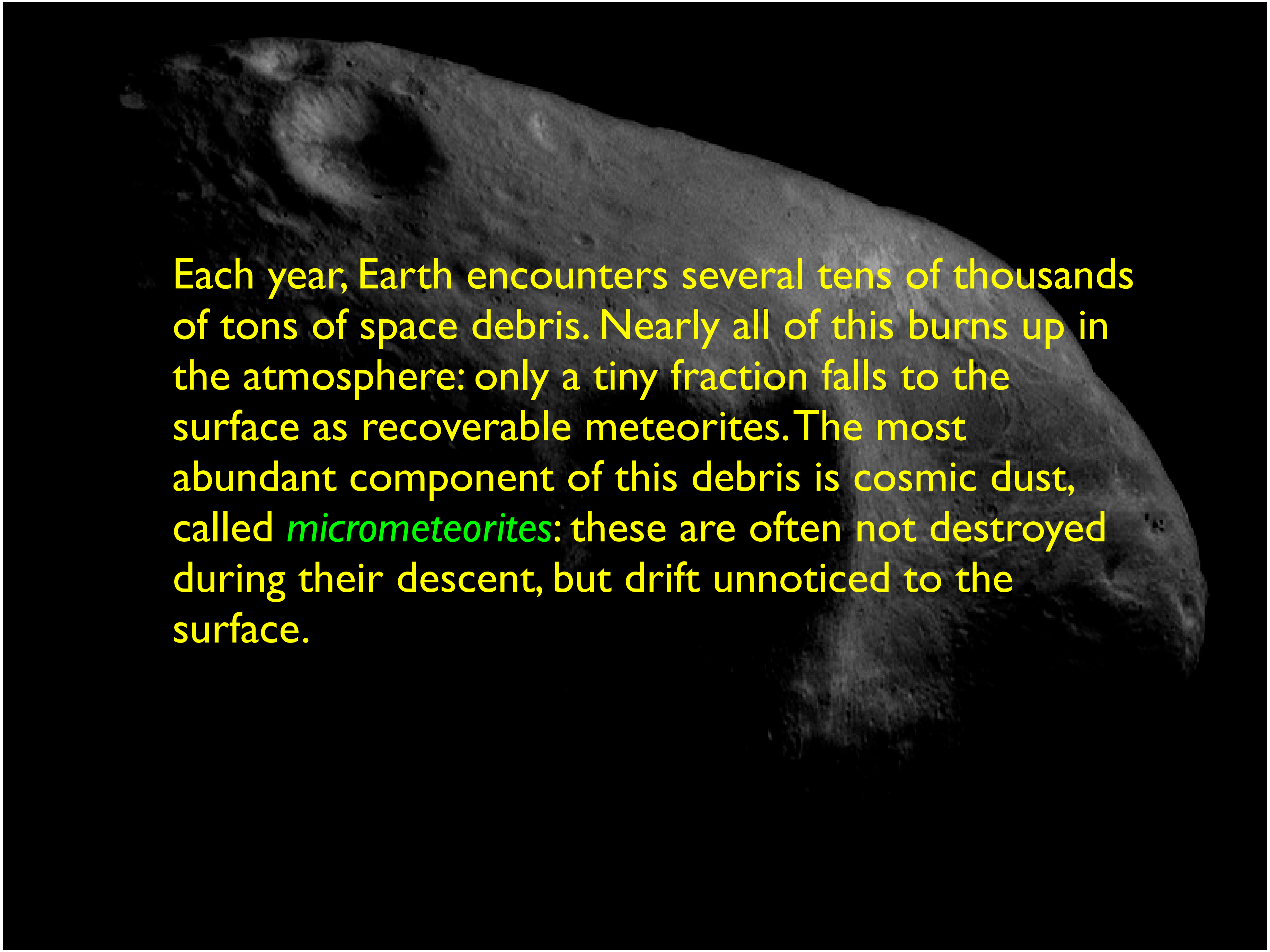

Kuiper Belt Objects
1000 km
Charon
Pluto
2001 KX76
(20000)
Varuna
1996
TO66
2000
EB173
1995
SM55
1999
TC36
1998
WH24
1999
DE9
ESO, ESA, Astrovirtel & G. Hahn (German Aerospace Center, DLR)

Just two years ago, the first Neptune Trojan was discovered. This small body, known as 2001 QR322, leads Neptune around its orbit in such a way as to maintain – on average – approximately equal distance from Neptune and the Sun. The object is estimated to be approximately 230 km in diameter and, like Neptune, requires about 166 years to complete each circuit of its orbit.

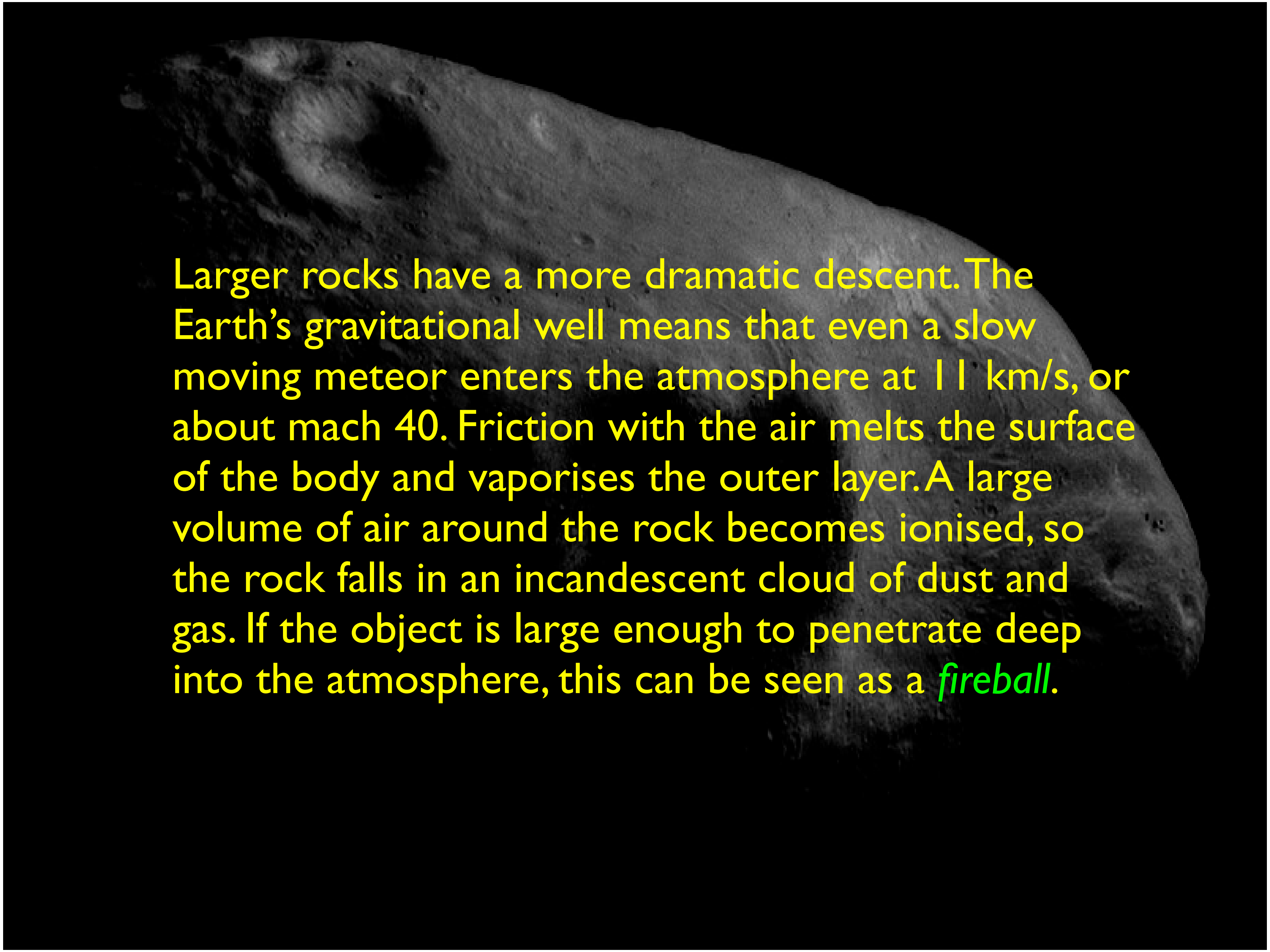
Models suggest there should be at least as many Neptune trojans as there are Jovian ones, possibly 10–30 times more.



Meteors

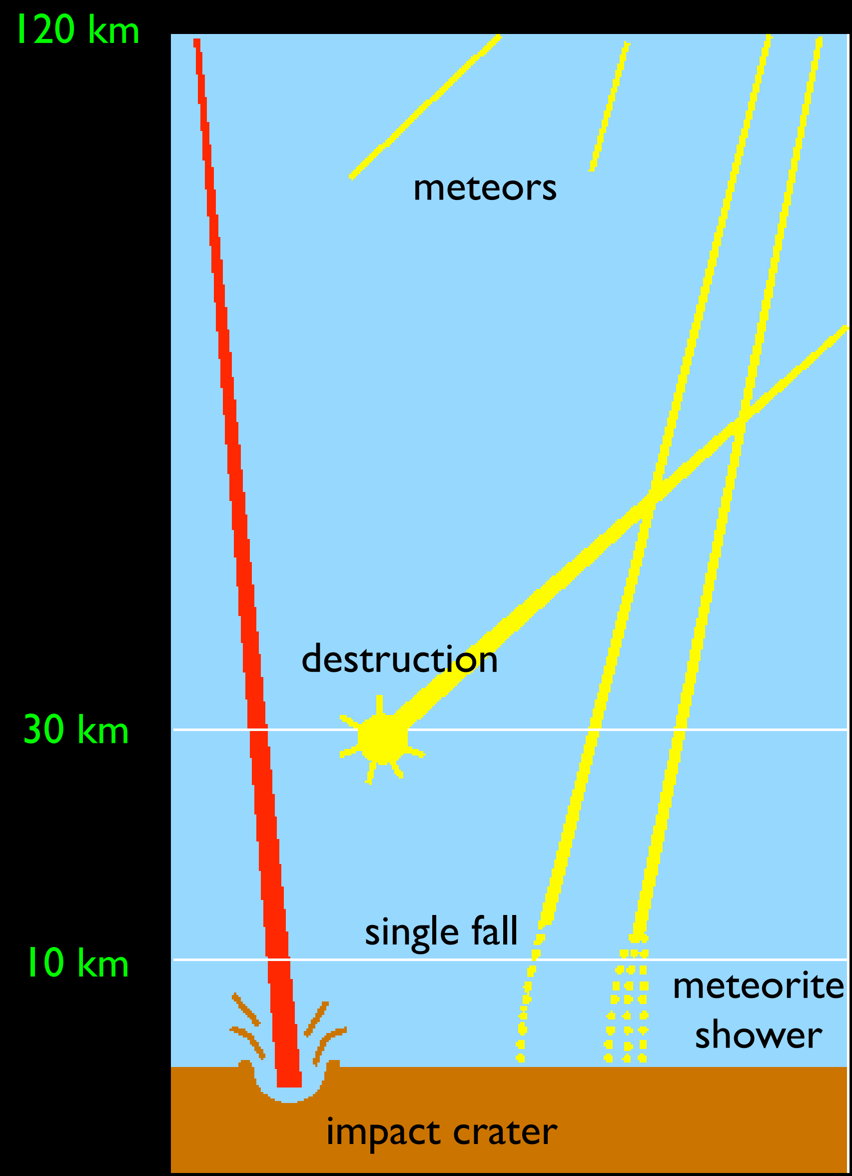


Each year, Earth encounters several tens of thousands of tons of space debris. Nearly all of this burns up in the atmosphere: only a tiny fraction falls to the surface as recoverable meteorites. The most abundant component of this debris is cosmic dust, called *micrometeorites*: these are often not destroyed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

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.

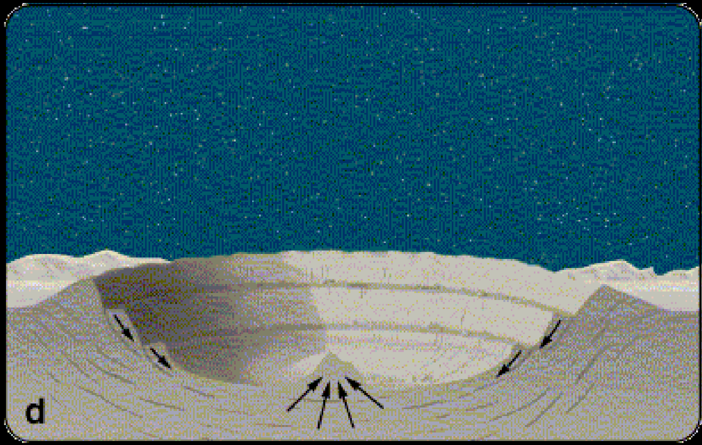


The meteorite approaches the surface at speeds of about 60 km/s.

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.

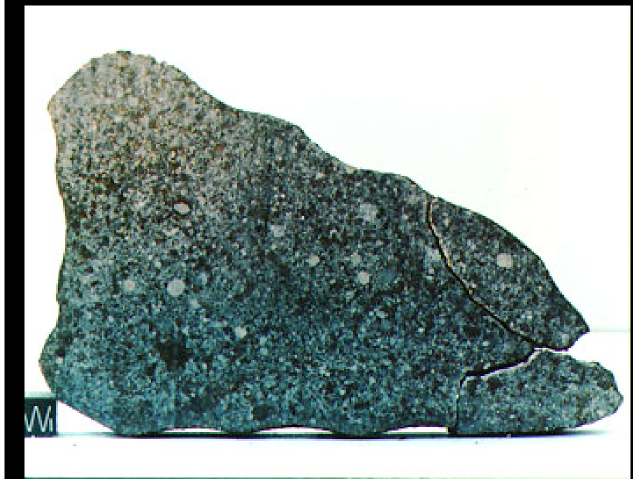
The walls of the crater are too steep and unstable, so they slump down, and a central peak forms.

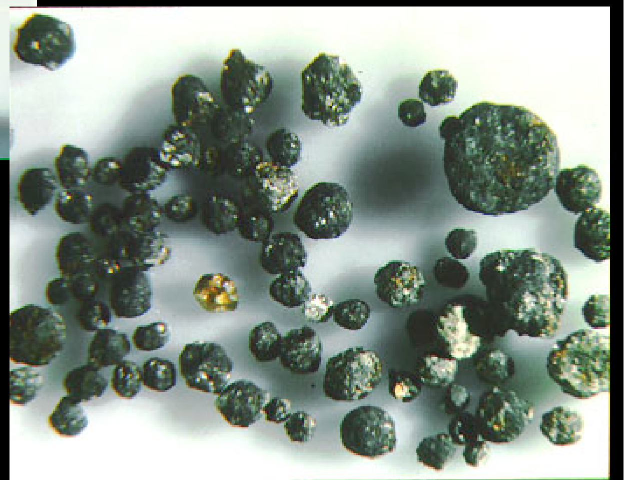


An impacting object a few km across generates a pressure hundreds of times the failure strength of rock. This means that *the rock effectively behaves as if it were water*. The stresses are so far beyond the strength of rocks that the impacted rocks behave as if they had no strength whatever. They flow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

There are three main types of meteorites:

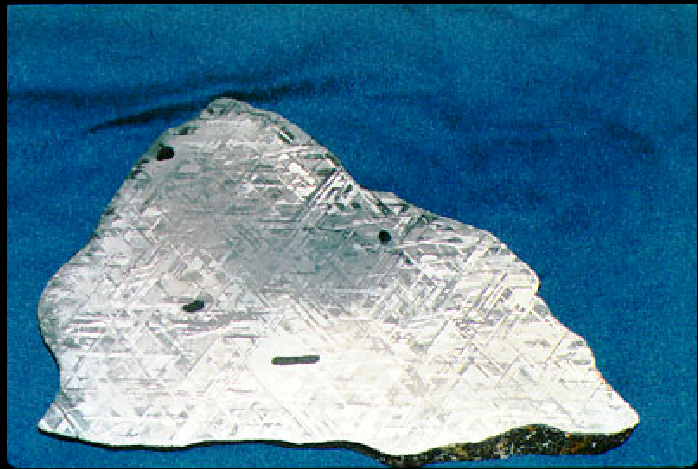
- *stony meteorites*, which are divided into *chondrites* and *achondrites*, depending on the presence or absence of chondrules, near-spherical beads which are believed to be very primitive building blocks from the early Solar System.



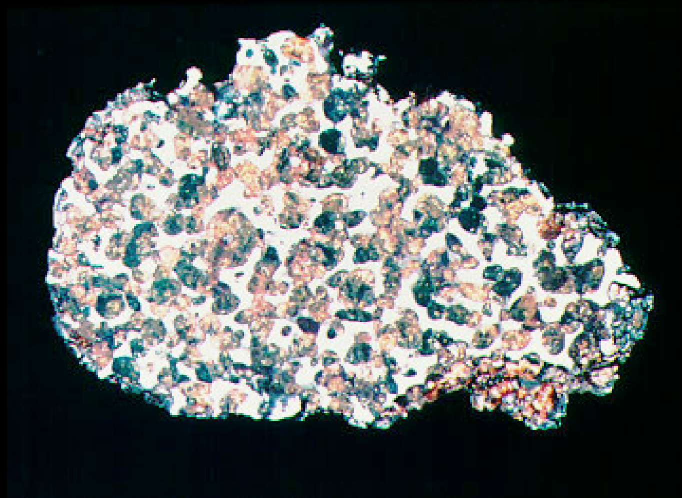


Chondrite (above left) and achondrite (above right) meteorites: the chondrite is made up of hundreds or thousands of small spherical chondrules (right).

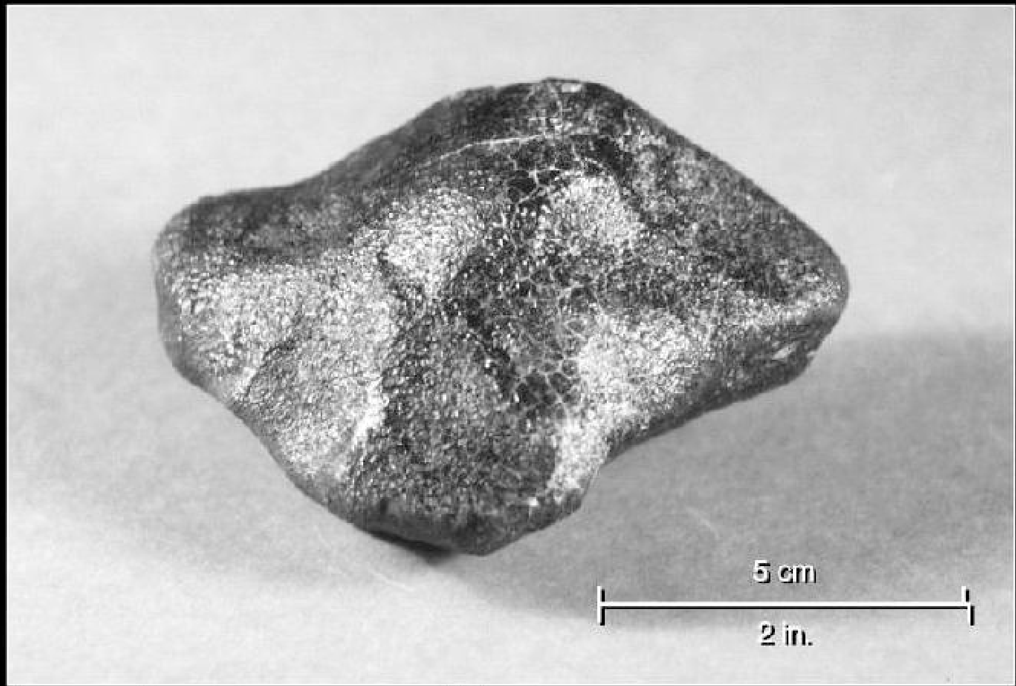
- *iron meteorites*, primarily iron and nickel, similar to type M asteroids



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

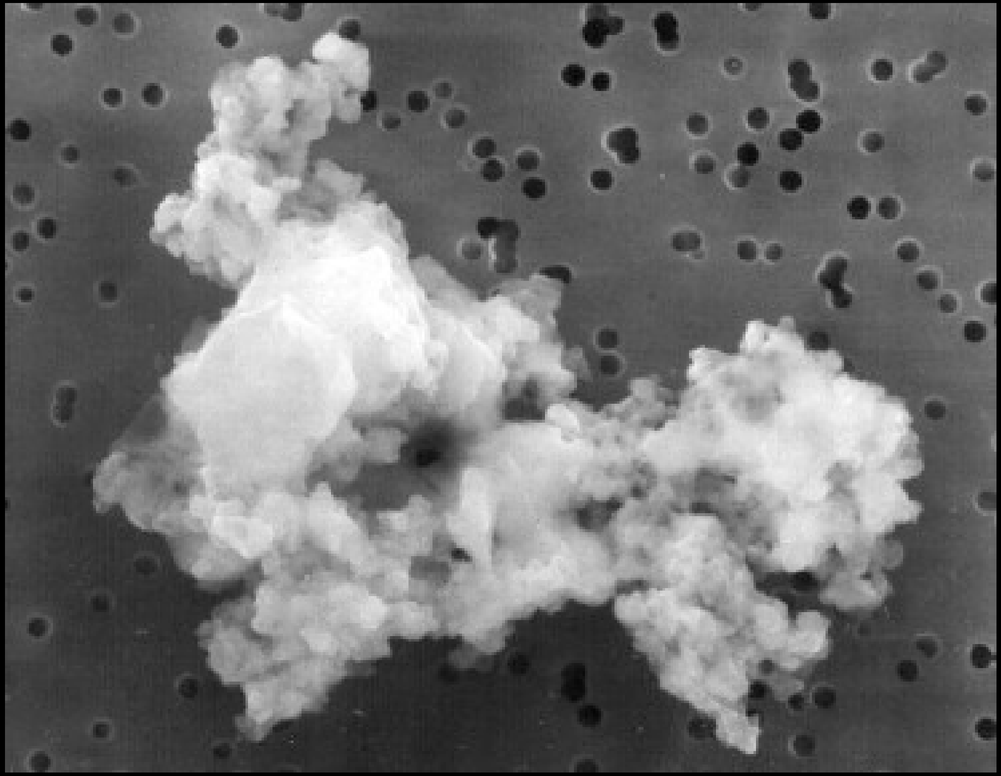


There are a few other sorts. This meteorite was found in Western Australia in 1960. Its composition and unique spectral signature suggests it came from Vesta.



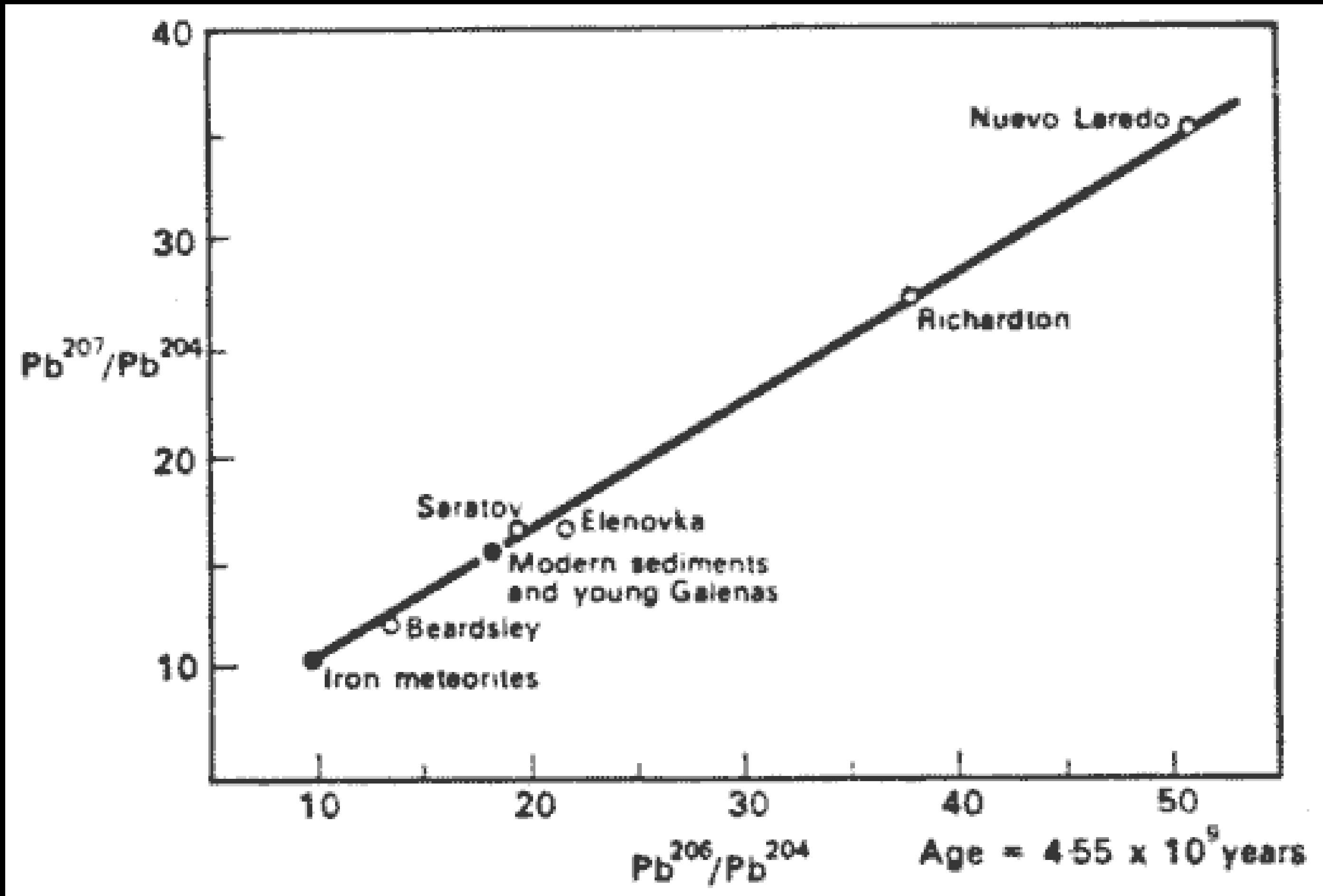
Stony meteorites makes up between 80 and 90% of all meteorites, with most of the rest being iron, and a few stony-iron.

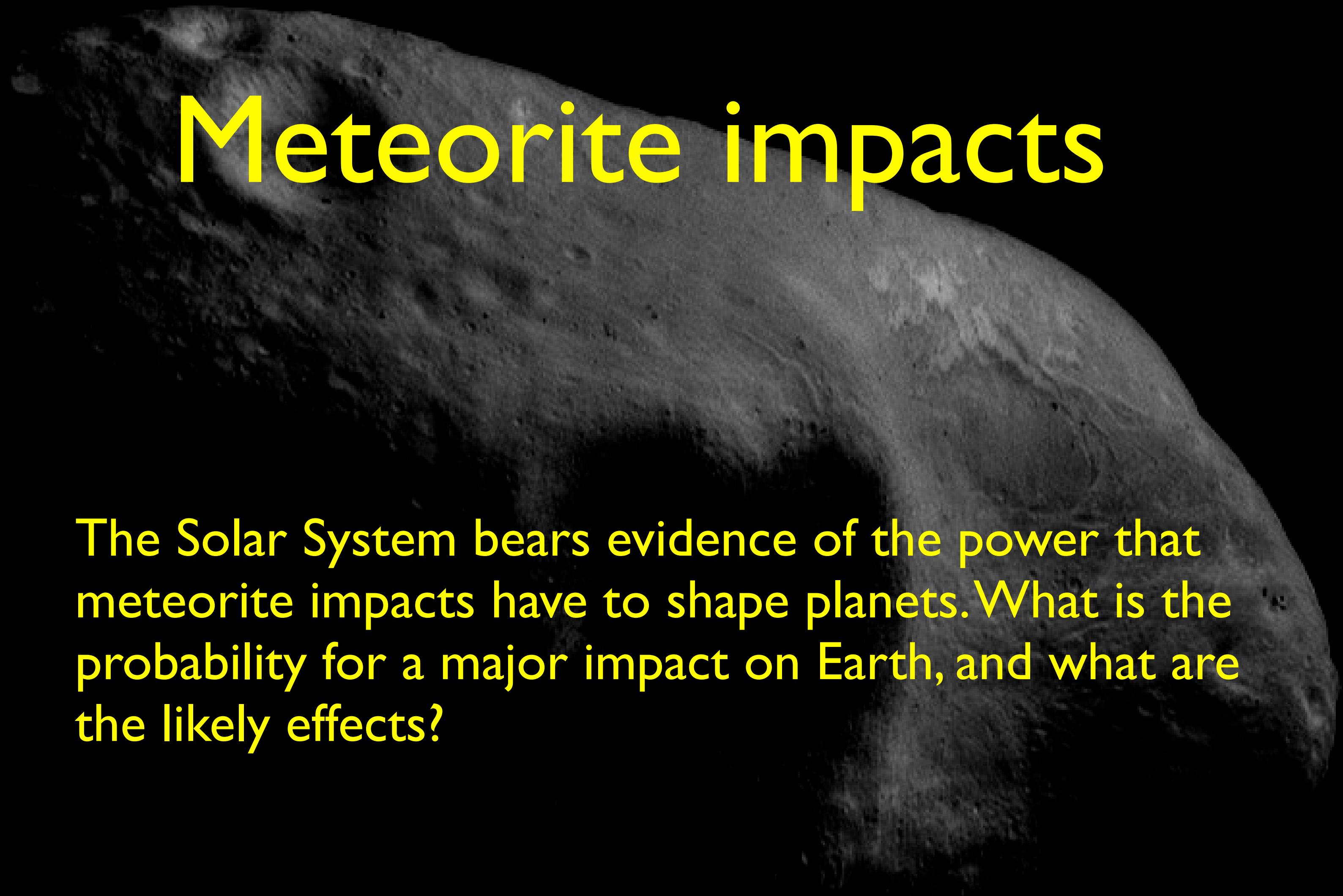
Grains of interplanetary dust have been found, and these are composed of tiny mineral grains. The grains are a hundredth of a millimetre across.



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.





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.

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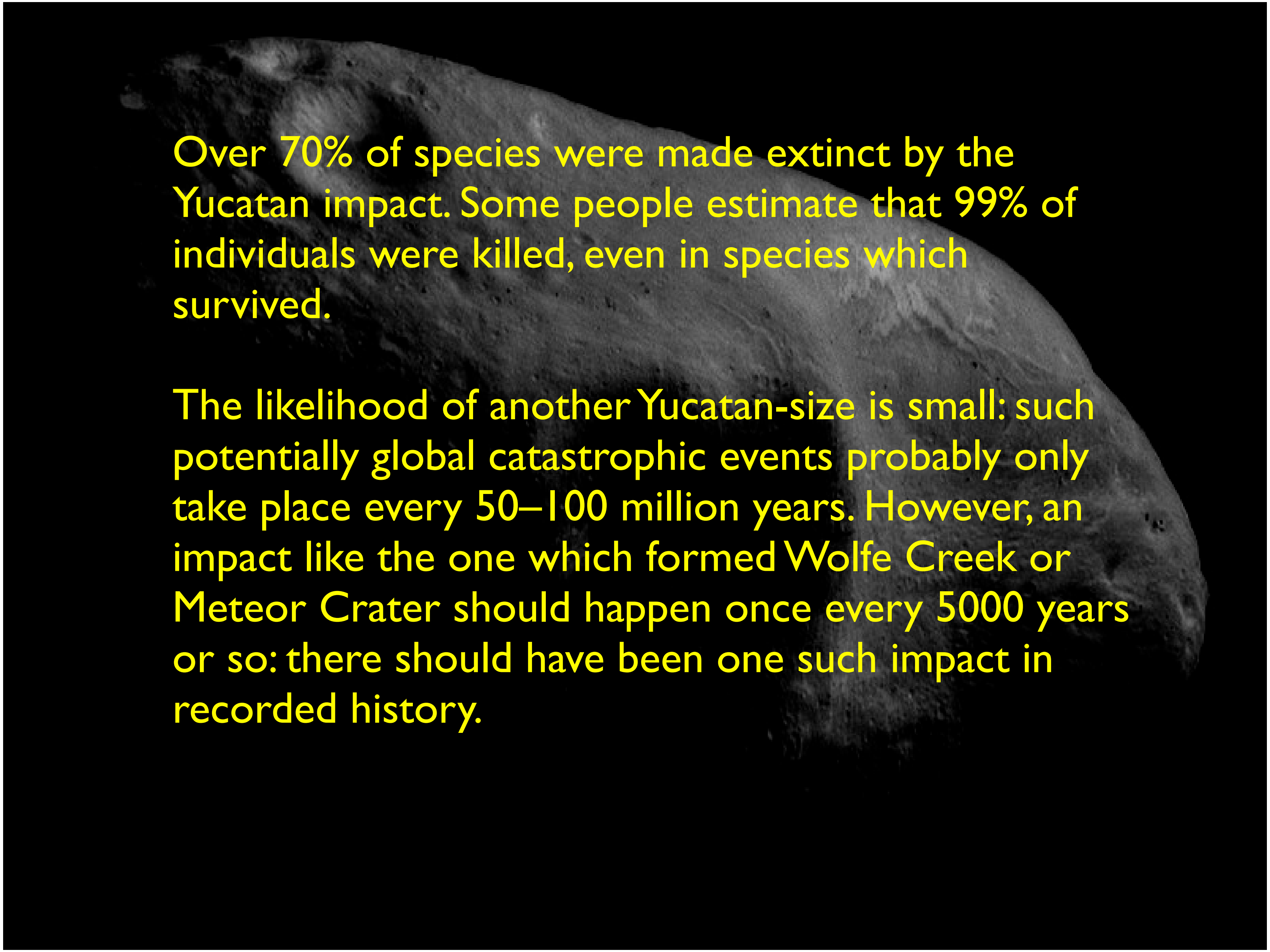
Everything within a radius of several hundred kilometres was incinerated by the fireball, and the dust covered the entire Earth for months.

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

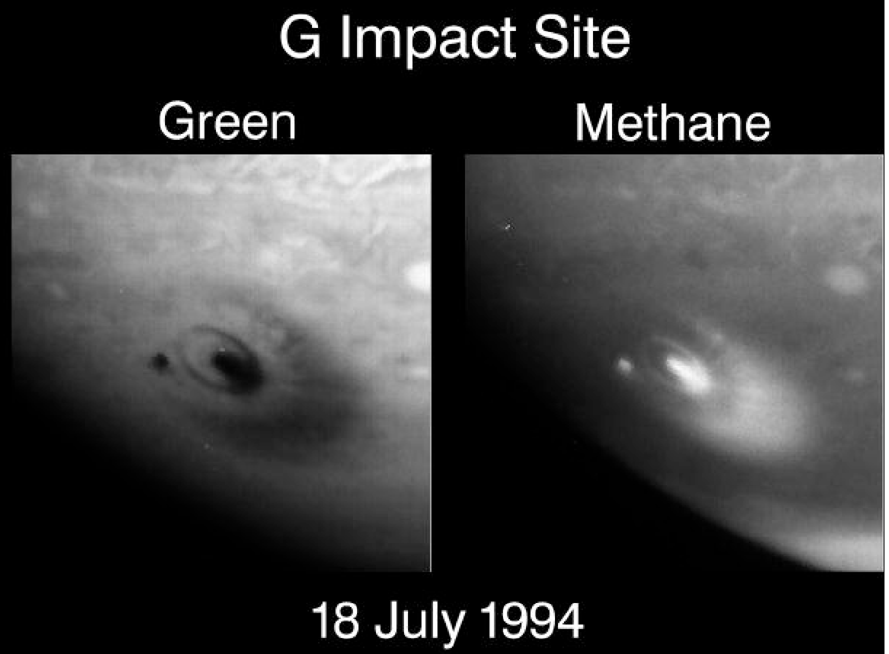


Over 70% of species were made extinct by the Yucatan impact. Some people estimate that 99% of individuals were killed, even in species which survived.

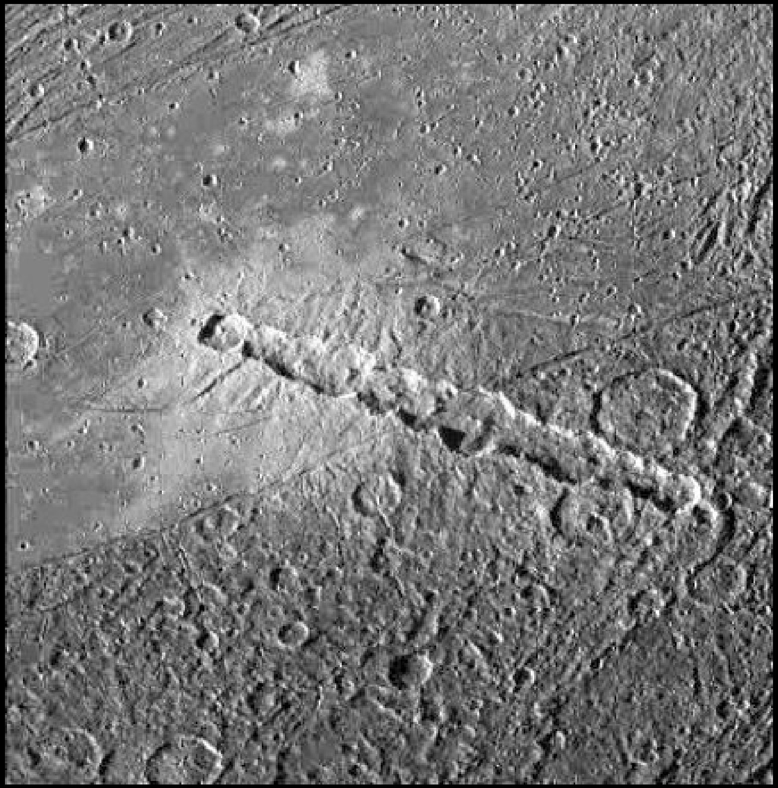
The likelihood of another Yucatan-size is small: such potentially global catastrophic events probably only take place every 50–100 million years. However, an impact like the one which formed Wolfe Creek or Meteor Crater should happen once every 5000 years or so: there should have been one such impact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

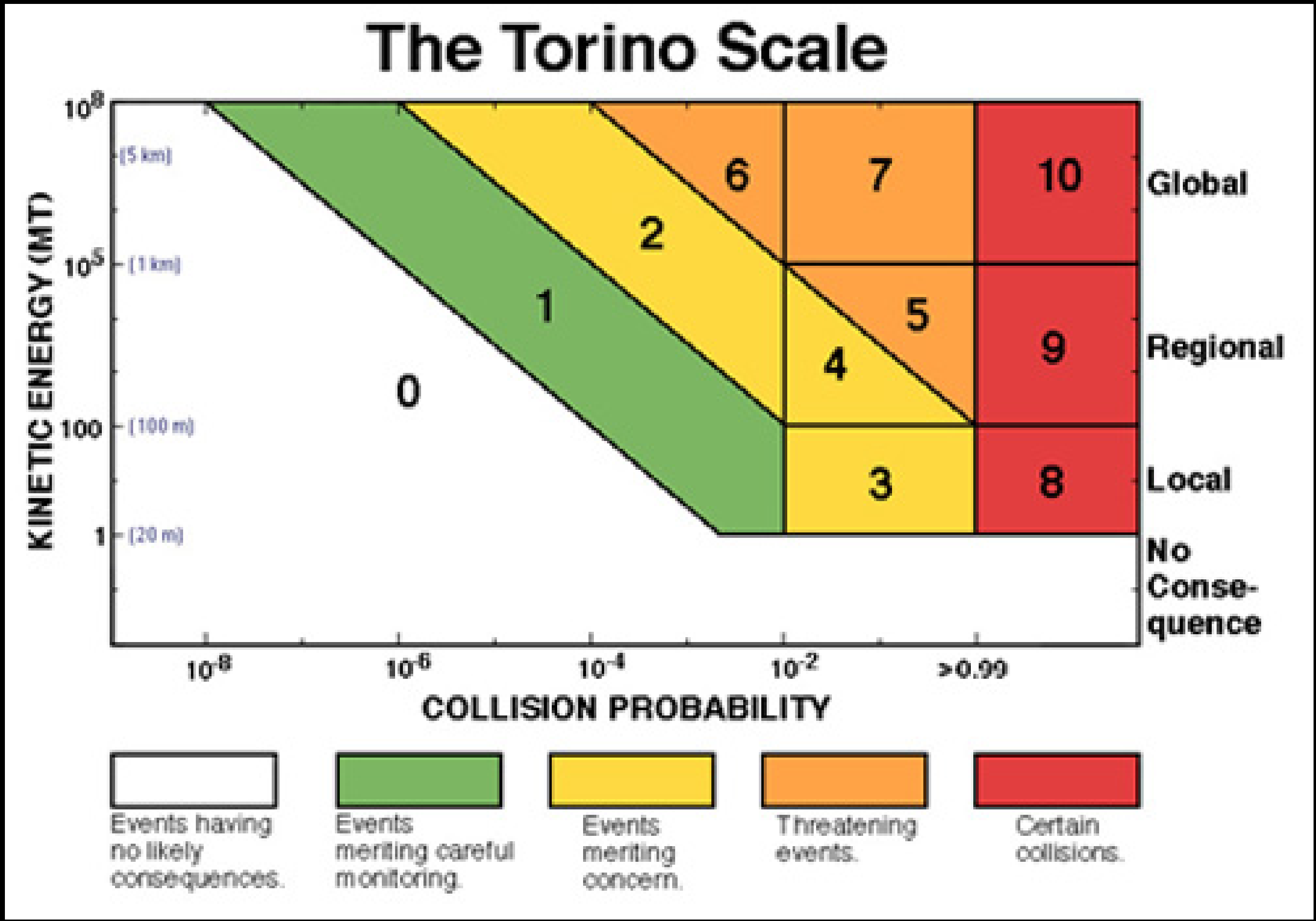


The Shoemaker-Levy collision offered a dramatic explanation for the mysterious *crater chains* that had been seen on several solar system bodies.



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.



THE TORINO SCALE

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

Events Having No Likely Consequences	0	The likelihood of a collision is zero, or well below the chance that a random object of the same size will strike the Earth within the next few decades. This designation also applies to any small object that, in the event of a collision, is unlikely to reach the Earth's surface intact.
Events Meriting Careful Monitoring	1	The chance of collision is extremely unlikely, about the same as a random object of the same size striking the Earth within the next few decades.
Events Meriting Concern	2	A somewhat close, but not unusual encounter. Collision is very unlikely.
	3	A close encounter, with 1% or greater chance of a collision capable of causing localized destruction.
	4	A close encounter, with 1% or greater chance of a collision capable of causing regional devastation.
Threatening Events	5	A close encounter, with a significant threat of a collision capable of causing regional devastation.
	6	A close encounter, with a significant threat of a collision capable of causing a global catastrophe.
	7	A close encounter, with an extremely significant threat of a collision capable of causing a global catastrophe.
Certain Collisions	8	A collision capable of causing localized destruction. Such events occur somewhere on Earth between once per 50 years and once per 1000 years.
	9	A collision capable of causing regional devastation. Such events occur between once per 1000 years and once per 100,000 years.
	10	A collision capable of causing a global climatic catastrophe. Such events occur once per 100,000 years, or less often.

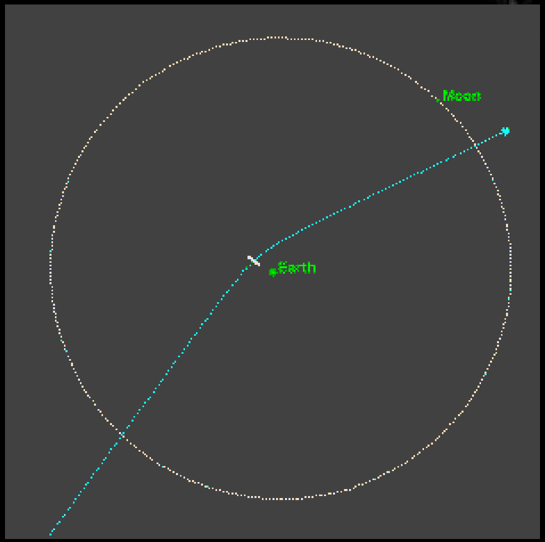
In June 2004, near-Earth asteroid 2004 MN4 was discovered. In December 2004 it was rediscovered at Siding Spring Observatory, and observations from around the world indicated that it would encounter the Earth in April 2029, and the possibility of impact could not be ruled out. It was assigned TS=2, the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

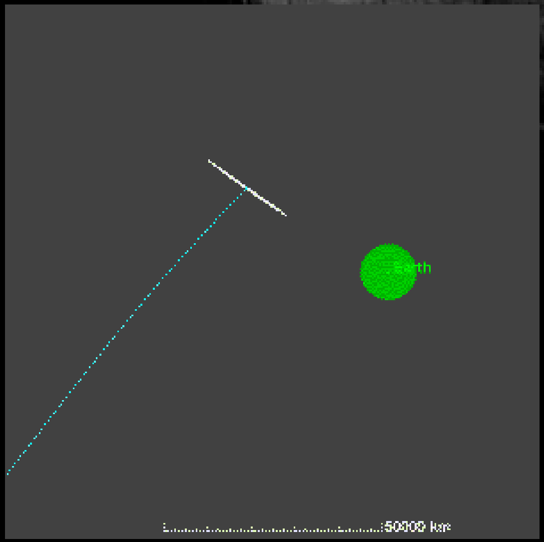
On December 24, the value was pushed to TS=4, with odds of impact 1 in 60, then 1 in 45, as the orbit was refined.

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

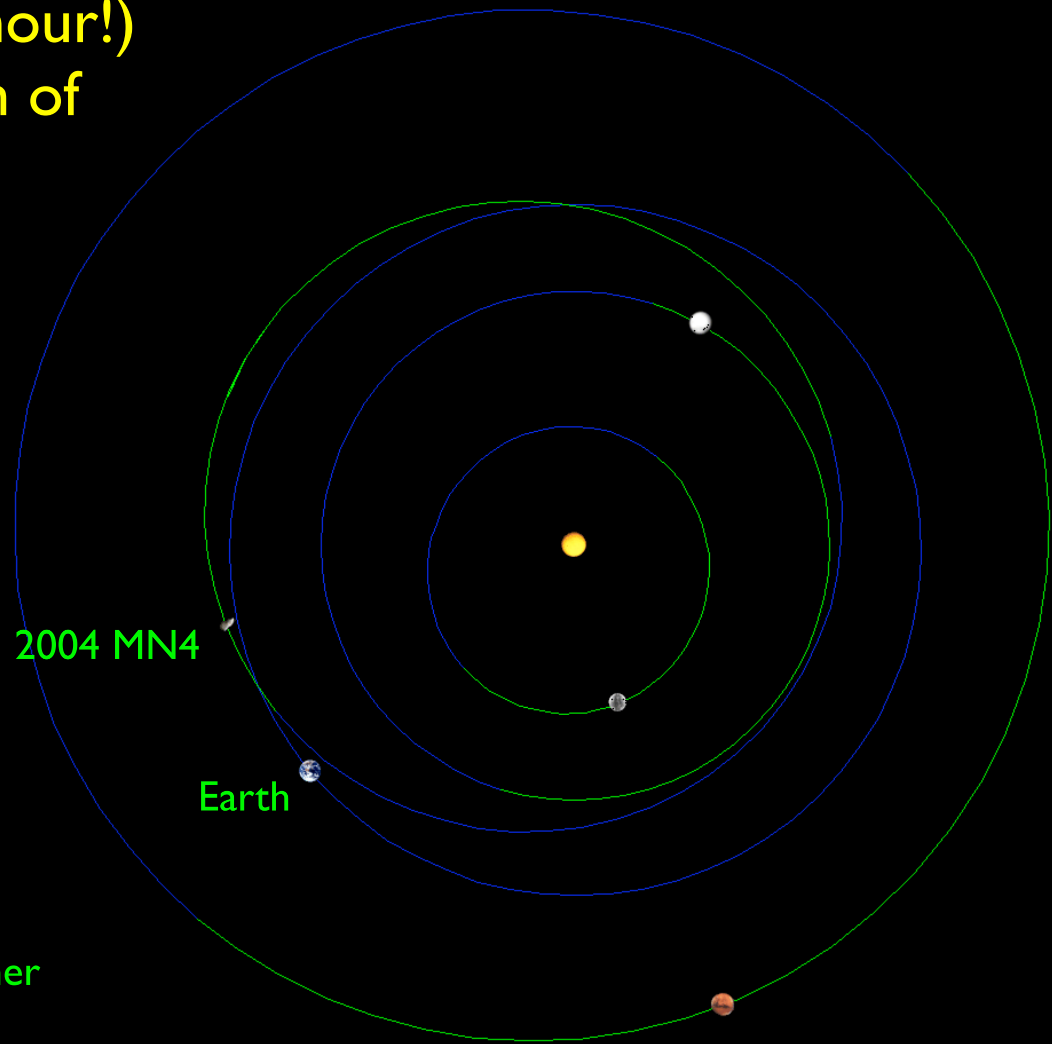
Radar observations were taken from Arecibo in late January 2005. The range was 294 km closer to the earth than the pre-radar orbit solution predicted.

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.

Next week...

... we'll look at Jupiter and its amazing family of moons.

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
- Orbital elements of comets can be found at the IAU: Minor Planet Center **"Observable Comets"** page http://cfa-www.harvard.edu/iau/Ephemerides/Comets/index.html. The orbital elements for comet 1P/Halley are at http://cfa-www.harvard.edu/iau/Ephemerides/Comets/0001P.html. You can cut and paste the orbital elements from these pages directly into the Solar System Live site to see where any given comet is now. Thus it's easy to see that, although it's only 19 years after its last perihelion, and there are 57 years until the next one, Halley is already most of the way out to Neptune's orbit: 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.
- 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
- There's an article on **"The saga of Asteroid 2004 MN4"** at http://128.102.32.13/impact/news_detail.cfm?ID=154.
- 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

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
- Eros animations: from NEAR Eros Animations http://nssdc.gsfc.nasa.gov/planetary/mission/near/near_eros_anim.html
- Earth's companion, Cruithne 3753: from Astronomy Picture of the Day June 18, 1997
  http://antwrp.gsfc.nasa.gov/apod/a970618.html
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- Kirkwood gaps: from "Explorations: An Introduction to Astronomy!" by Thomas T. Arny, Fig. 10.7
  http://www.mhhe.com/physsci/astronomy/arny/instructor/graphics/ch10/1007.html
- Differentiation: from "Explorations: An Introduction to Astronomy!" by Thomas T. Arny, Fig. 10.6
  http://www.mhhe.com/physsci/astronomy/arny/instructor/graphics/ch10/1006.html
- Asteroid shapes: Mathilde, Gaspra, and Ida, from Astronomy Picture of the Day March 13, 1998
  http://antwrp.gsfc.nasa.gov/apod/ap980313.html
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  http://hubblesite.org/newscenter/archive/1997/27/

- Comet cover image: Comet West from Astronomy Picture of the Day 26 August 1995 http://antwrp.gsfc.nasa.gov/apod/ap950826.html
- Orbit of comet LINEAR: from Chandra X-ray Observatory Photo Album http://chandra.harvard.edu/photo/cycle1/c1999s4/more.html
- 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
- Deep Impact image and animation: from Deep Impact: Gallery, http://deepimpact.jpl.nasa.gov/gallery/index.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/
- Kuiper belt: from Views of the Solar System by Calvin Hamilton http://www.solarviews.com/cap/index/oortcloud1.html
- Oort cloud/Kuiper belt: from "Explorations: An Introduction to Astronomy!" by Thomas T. Arny, Fig. 7.4 http://www.mhhe.com/physsci/astronomy/arny/instructor/graphics/ch07/0704.html
- A list of known trans-Neptunian objects can be found at http://www.johnstonsarchive.net/astro/tnos.html
- Meteor title image: Leonids over Uluru, from Astronomy Picture of the Day 30 October 2002 http://antwrp.gsfc.nasa.gov/apod/ap021030.html
- Fireball: Leonid fireball, from Astronomy Picture of the Day 2 December 1999 http://antwrp.gsfc.nasa.gov/apod/ap991202.html
- Meteoroid endpoints: re-drawn from “Meteorites: A journey through space and time” by Bevan and de Laeter, p. 31
- Crater formation: from The Terrestrial Planets by Gareth Wynn-Williams http://www.ifa.hawaii.edu/~wynnwill/110/images/crater_formation.gif

- Meteorite images: from "Exploring Meteorite Mysteries"
  http://www-curator.jsc.nasa.gov/outreach1/expmetmys/slideset/Slides35-42.htm
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- Isochron: from "The Talk.Origins Archive: The Age of the Earth" by Chris Stassen
  http://www.talkorigins.org/faqs/faq-age-of-earth.html
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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
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- Crater chains: Ganymede: from Astronomy Picture of the Day, 2001 December 15,
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  http://www.lpod.org/archive/2004/01/LPOD-2004-01-27.htm
- Torino Impact Scale: from "Asteroid and Comet Impact Hazards", http://128.102.32.13/impact/torino.cfm
- 2004 MN4 orbit predictions: from "Radar observations refine the future motion of Asteroid 2004 MN4",
  http://neo.jpl.nasa.gov/news/news149.html
- Positions of 2004 MN4 and the planets: from Solar System Live http://www.fourmilab.to/cgi-bin/uncgi/Solar