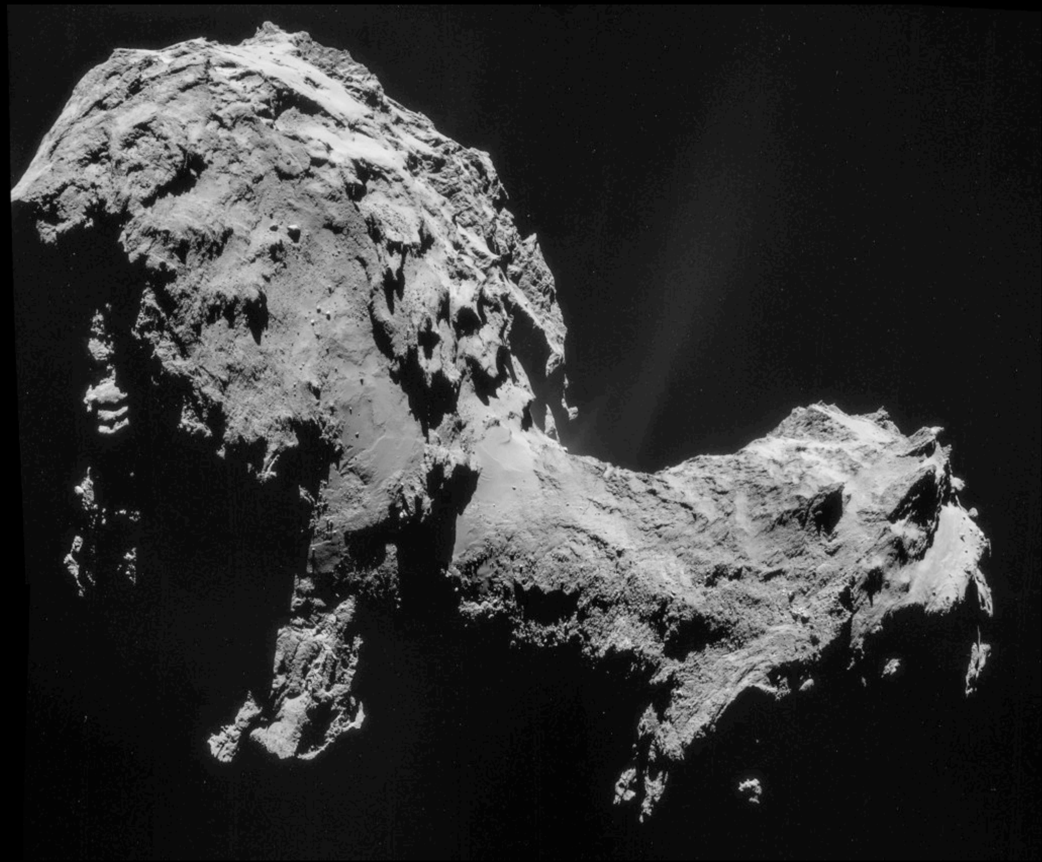
Voyage to the Planets
Lecture 5:
Rocks in Space
asteroids, comets and meteors

Presented by

Dr Helen Johnston
School of Physics

Spring 2017

THE UNIVERSITY OF SYDNEY



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.

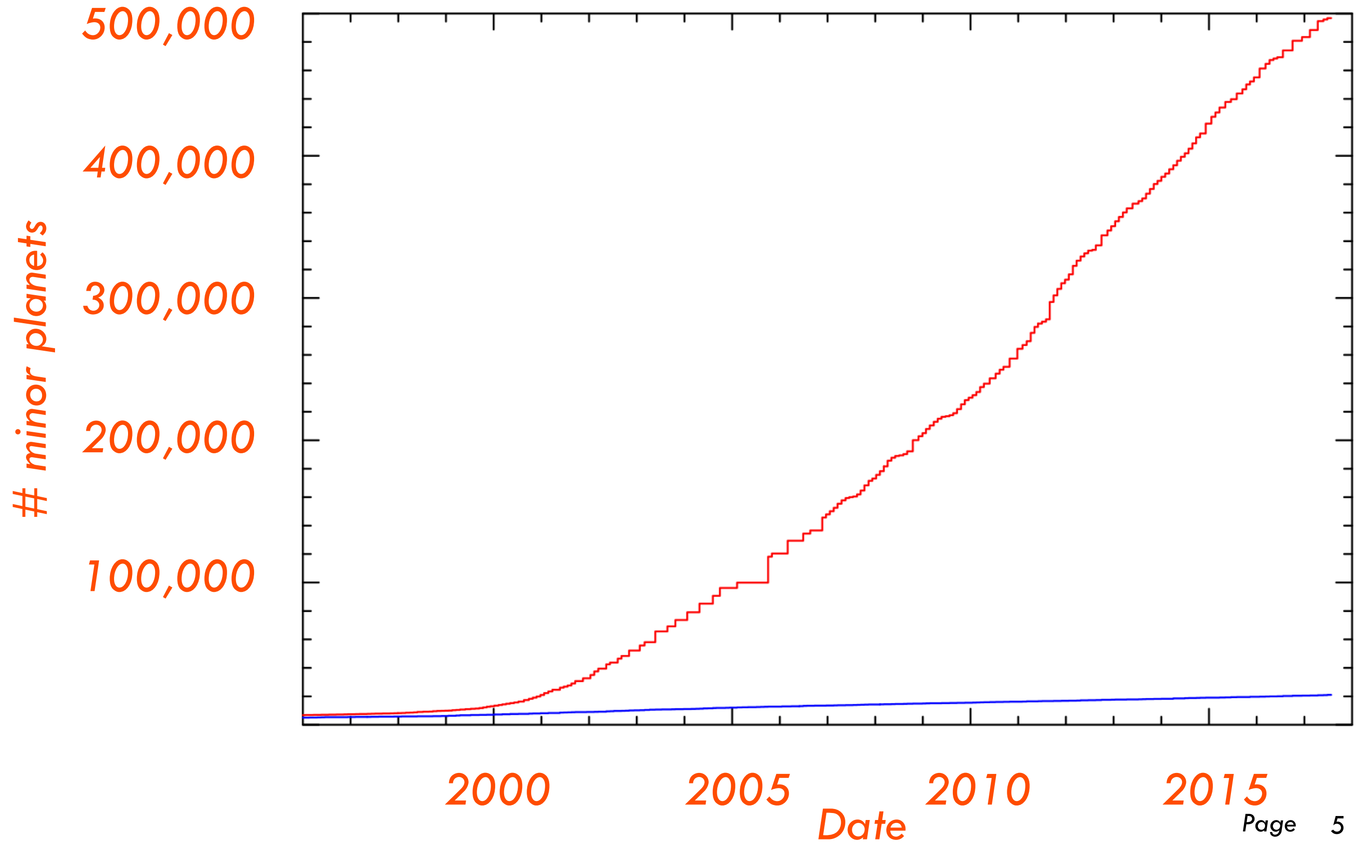
An asteroid (or strictly *minor planet**) is smaller than major planets, but larger than meteoroids, which are 10m or less in size.

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

As of September 2017, there are 496,815 asteroids which have been given numbers; 21,009 have been given names.

The rate of discovery of new bodies is about 3000 per month.

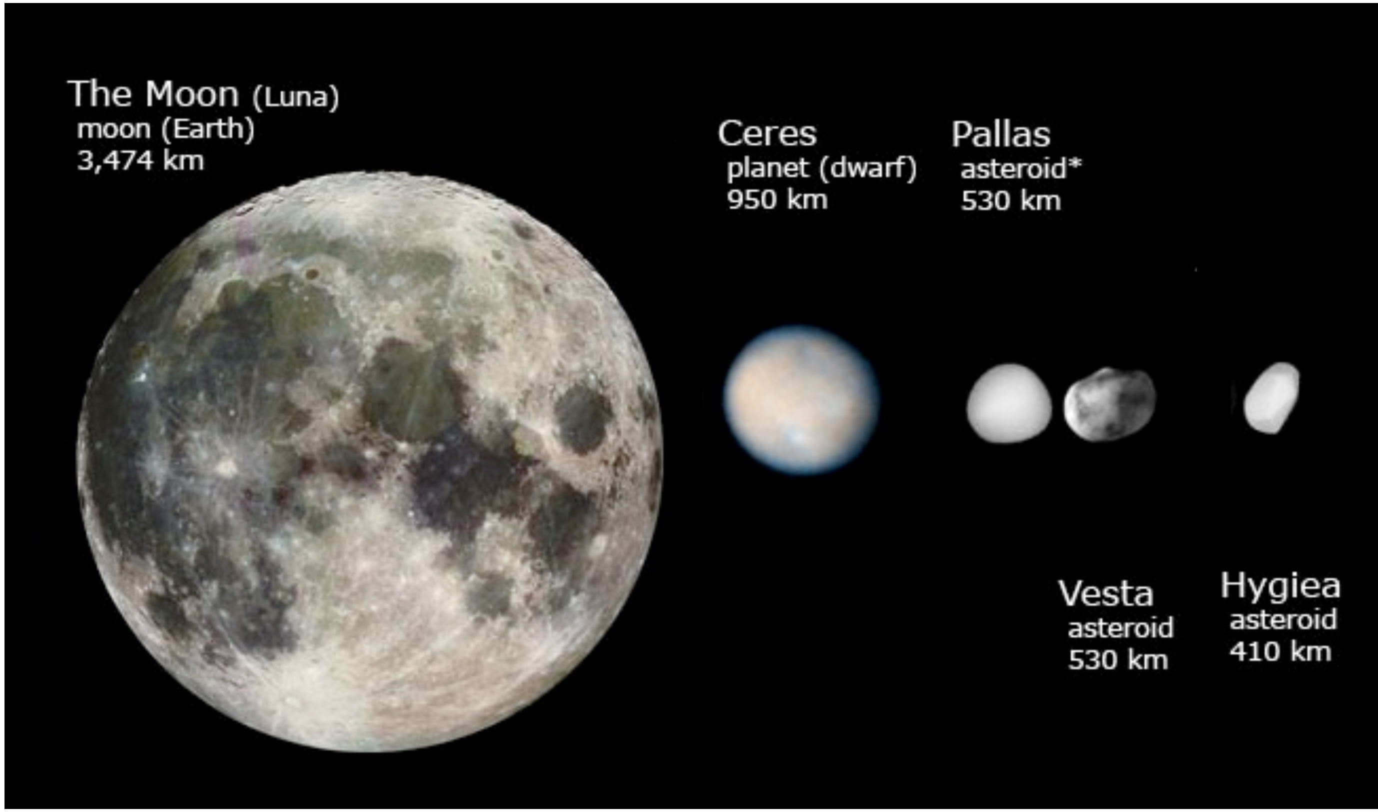
It is estimated there are between 1.1 and 1.9 million asteroids larger than 1 km in diameter.



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

The largest asteroids 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.

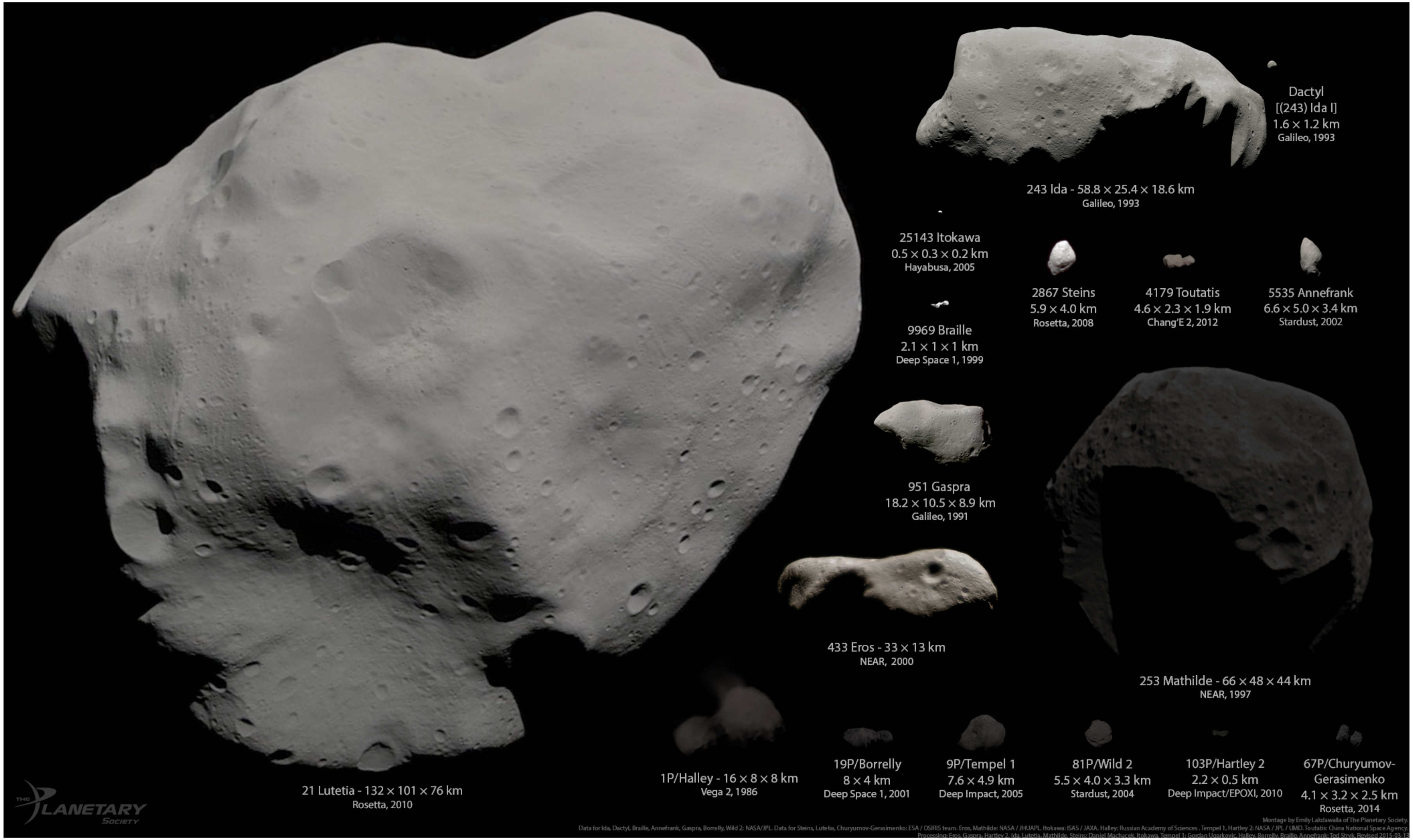
Altogether, the total mass of asteroids would make an object only about a twentieth the size of the Moon.



Six spacecraft have visited asteroids*:

- *Galileo* photographed the asteroids 951 Gaspra and 243 Ida in 1991 and 1993, on its way to Jupiter
- *NEAR Shoemaker* passed 253 Mathilde in 1997 before first orbiting then landing on 433 Eros in February 2001
- The Japanese mission *Hayabusa* landed on the asteroid 25143 Itokawa in 2005
- The *Rosetta* probe flew past asteroids 2867 Šteins and 21 Lutetia in 2008 and 2010, on its way to rendezvous with comet 67P/Churyumov–Gerasimenko.
- The Chinese spacecraft *Chang'e 2* flew past the asteroid 4179 Toutatis in 2012 at a distance of just 3.2 km.
- The *Dawn* spacecraft reached orbit around 4 Vesta in 2011, before leaving in September 2012 for 1 Ceres. It reached orbit around Ceres in March 2015, where it has spent the last few years mapping the dwarf planet.

** plus a couple of more distant fly-bys*



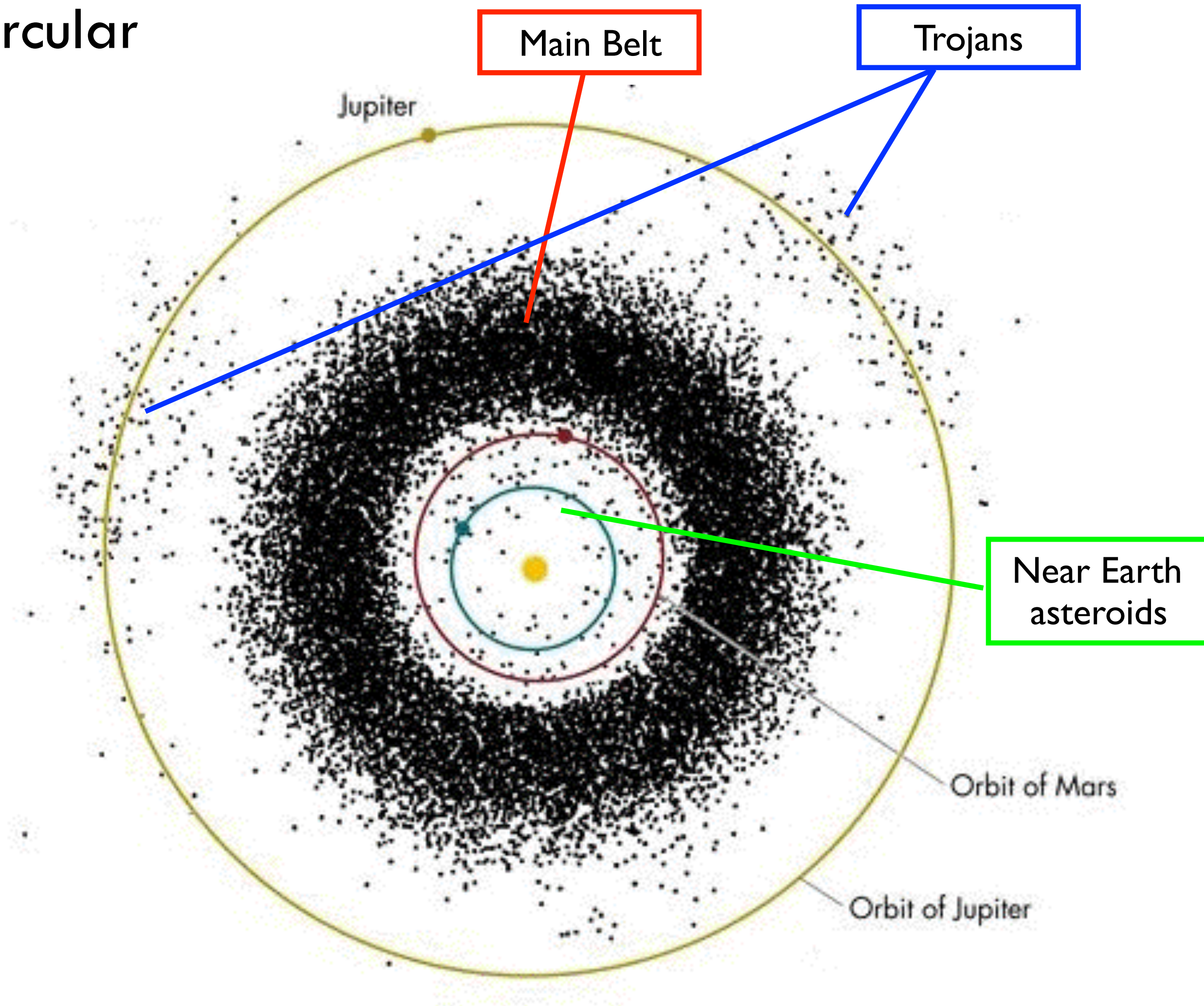
Montage of asteroids and comets that have been photographed up close; the bodies are shown with their correct relative (though not absolute) albedo or brightness. Vesta and Ceres are not included, as they are both many times larger than Lutetia

There are three main groups of asteroids:

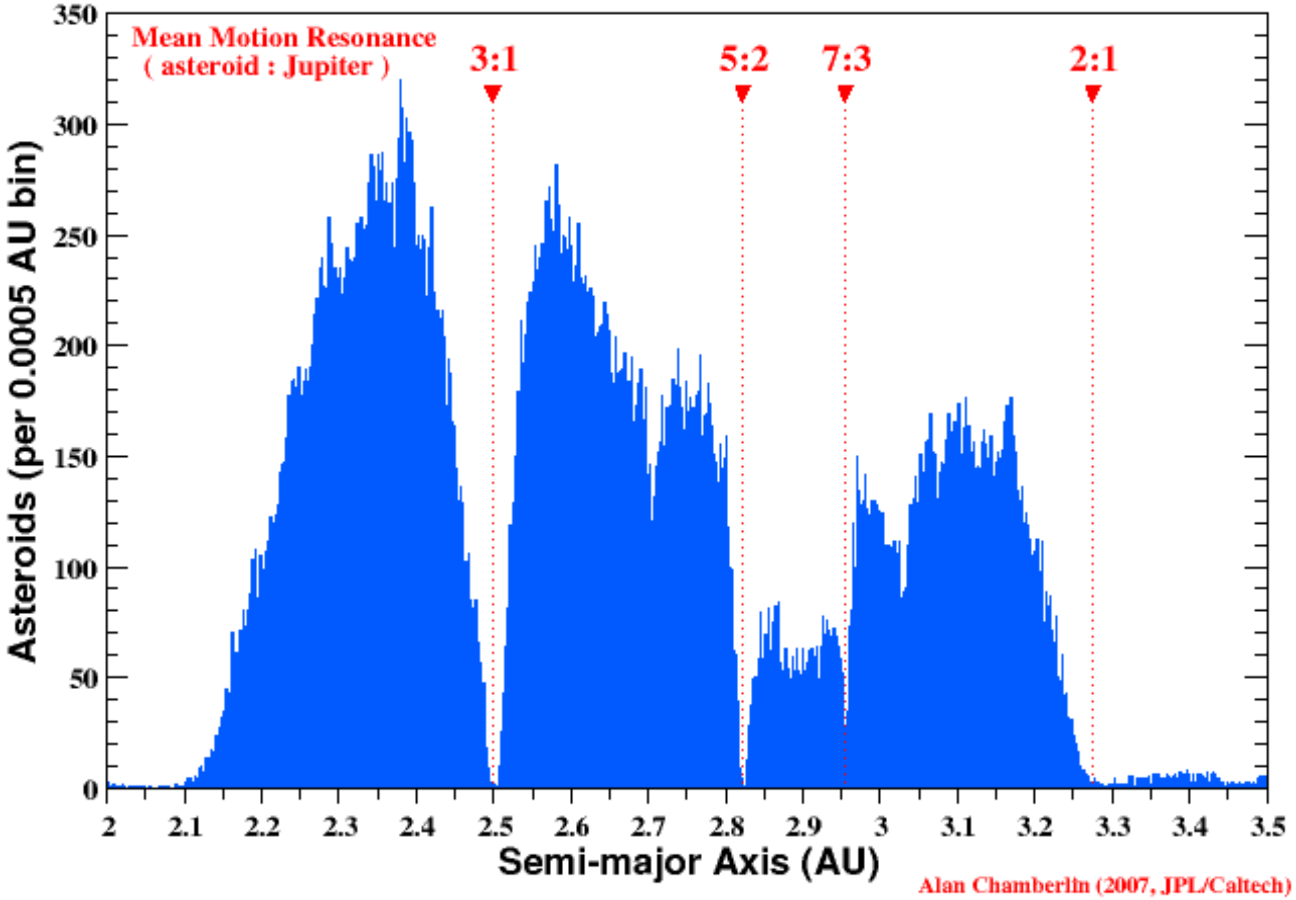
– the *Main Belt asteroids*, in stable circular orbits between Mars and Jupiter.

– the *Trojans*, which orbit in Jupiter's orbit, leading or trailing the planet by 60°. There are also Trojans associated with Mars, Neptune, and Earth.

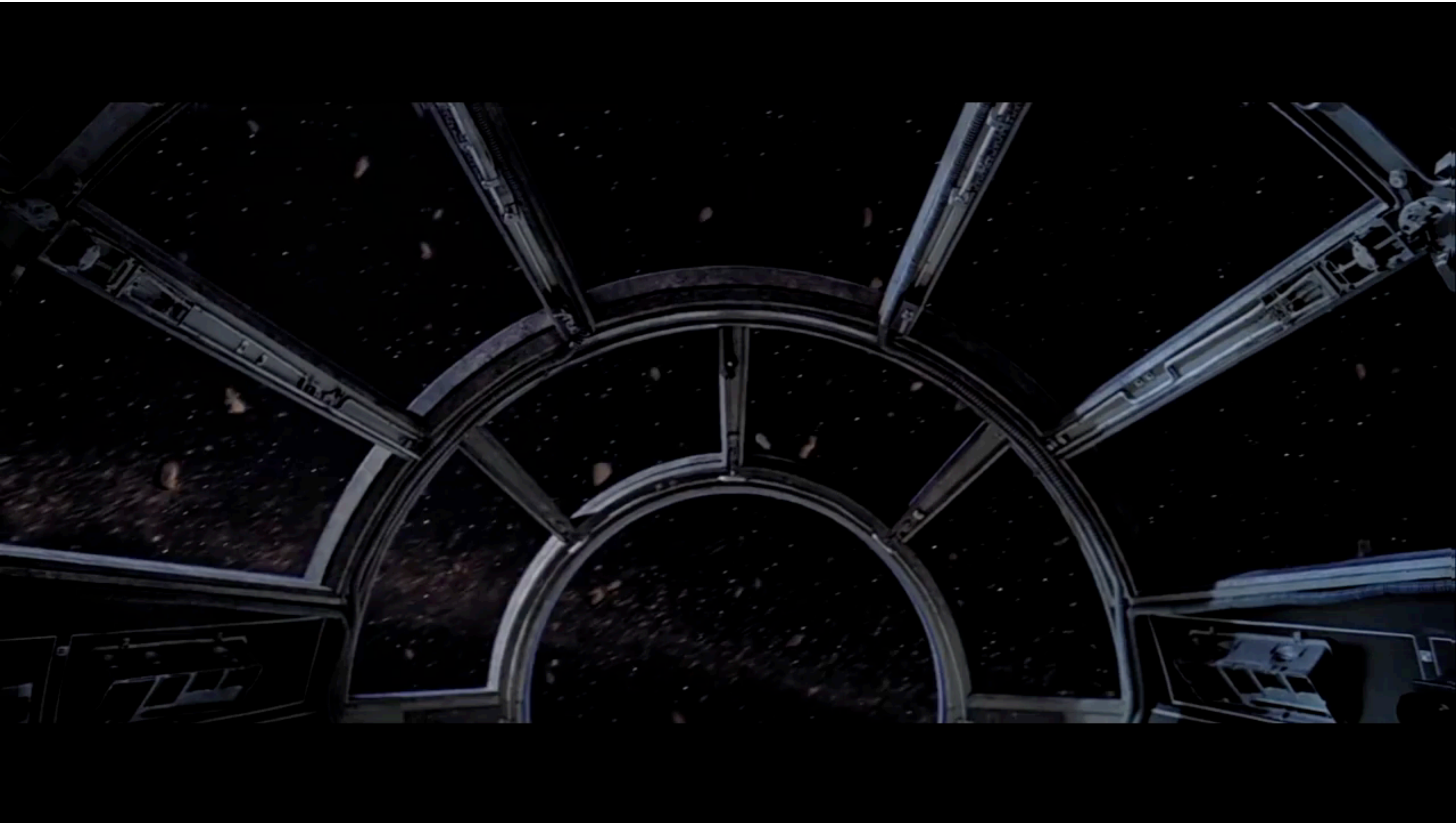
– the *near Earth asteroids*, which have elliptical orbits which approach the orbit of Earth.



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.

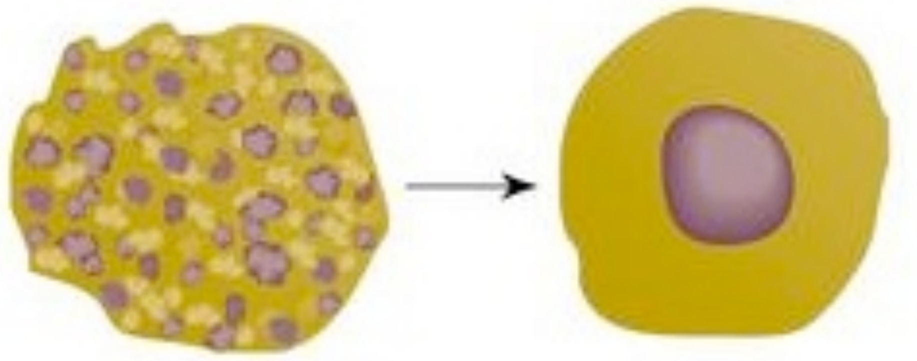
Asteroids are classified into several types, based on their composition.

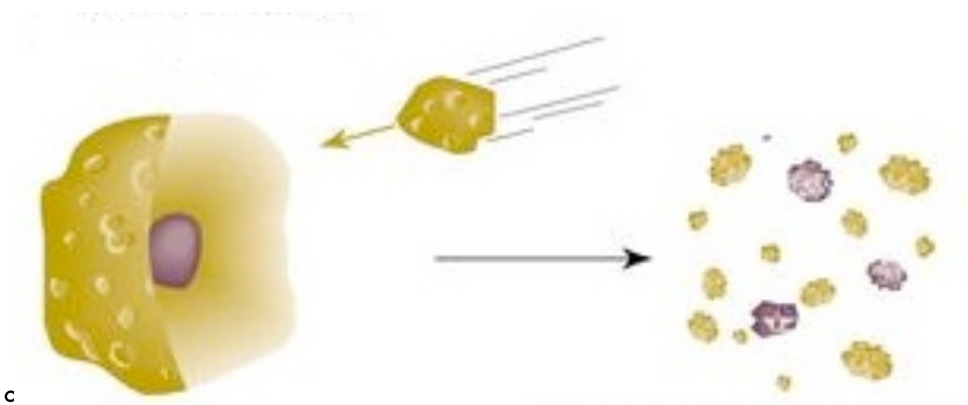
- *C-type* asteroids contain a lot of carbon, and are very dark: more than 75% of asteroids are C-type.
- *S-type* asteroids are silicon-rich, and make up most of the rest. A small number are
- *M-type* asteroids are metallic, where the metal is predominantly iron.
- *U-type* (unclassified)

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

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 while it is still hot, leaving silicates on the outside. We don't know how small an asteroid can be and still become differentiated, nor how large one can be and avoid it.

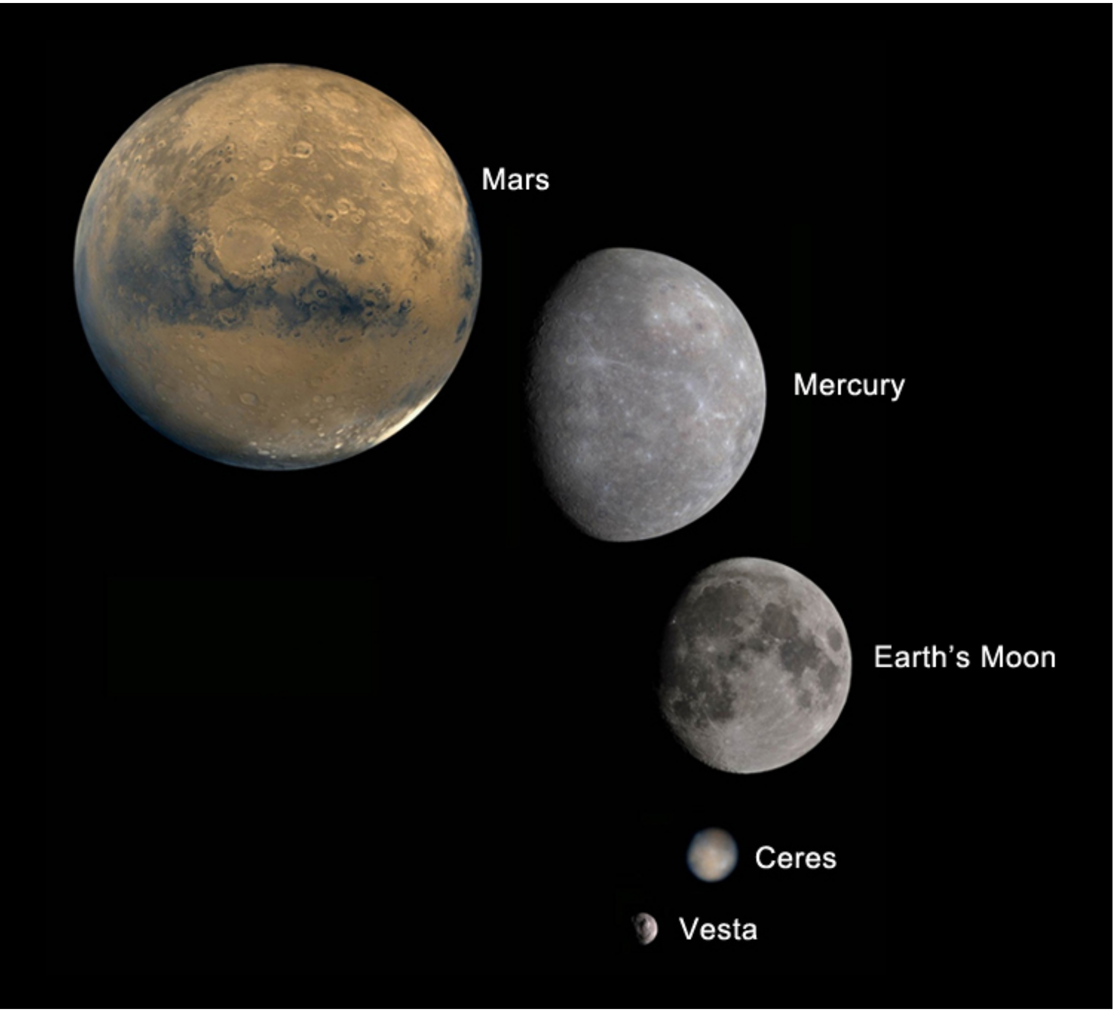
Differentiation: impact or radioactive heating leads to separation of metallic and rocky material.





Subsequent break-up leads to rocky and stony bodies.

Most asteroids show signs of heating and melting, and are probably left over from the mutual destruction of intermediate sized objects.



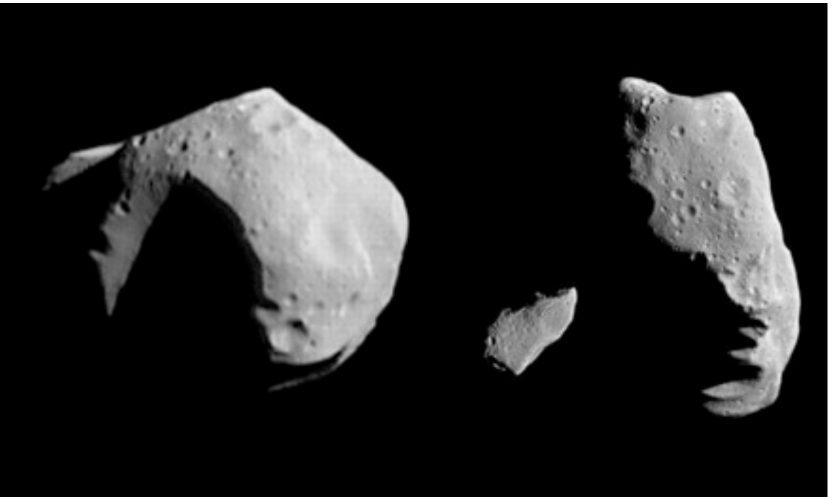
The largest asteroids, however – Ceres, Vesta, Pallas – seem to be intact. It has been argued that they should be considered *proto-planets* instead of asteroids.

We will see where they fit in when we discuss the formation of the Solar System in lecture 9.

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.



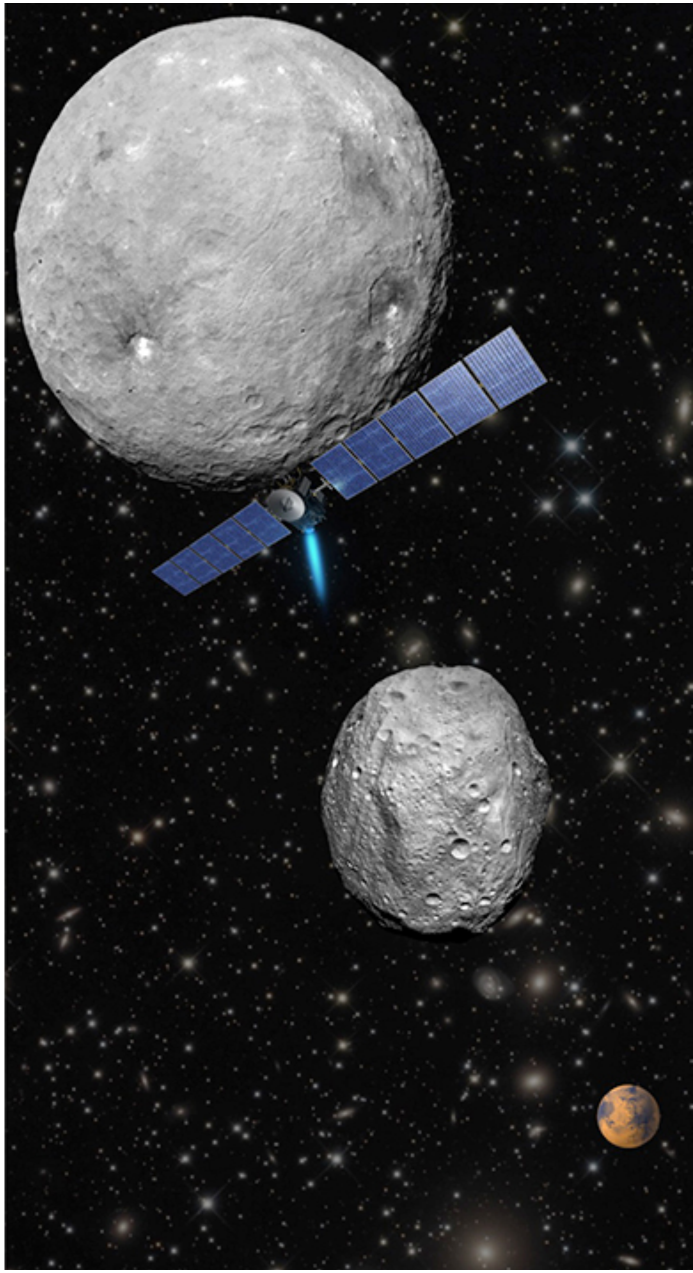
(left) Asteroids Mathilde, Gaspra, and Ida, shown to scale.
(right) Asteroid 433 Eros during approach by mission NEAR Shoemaker

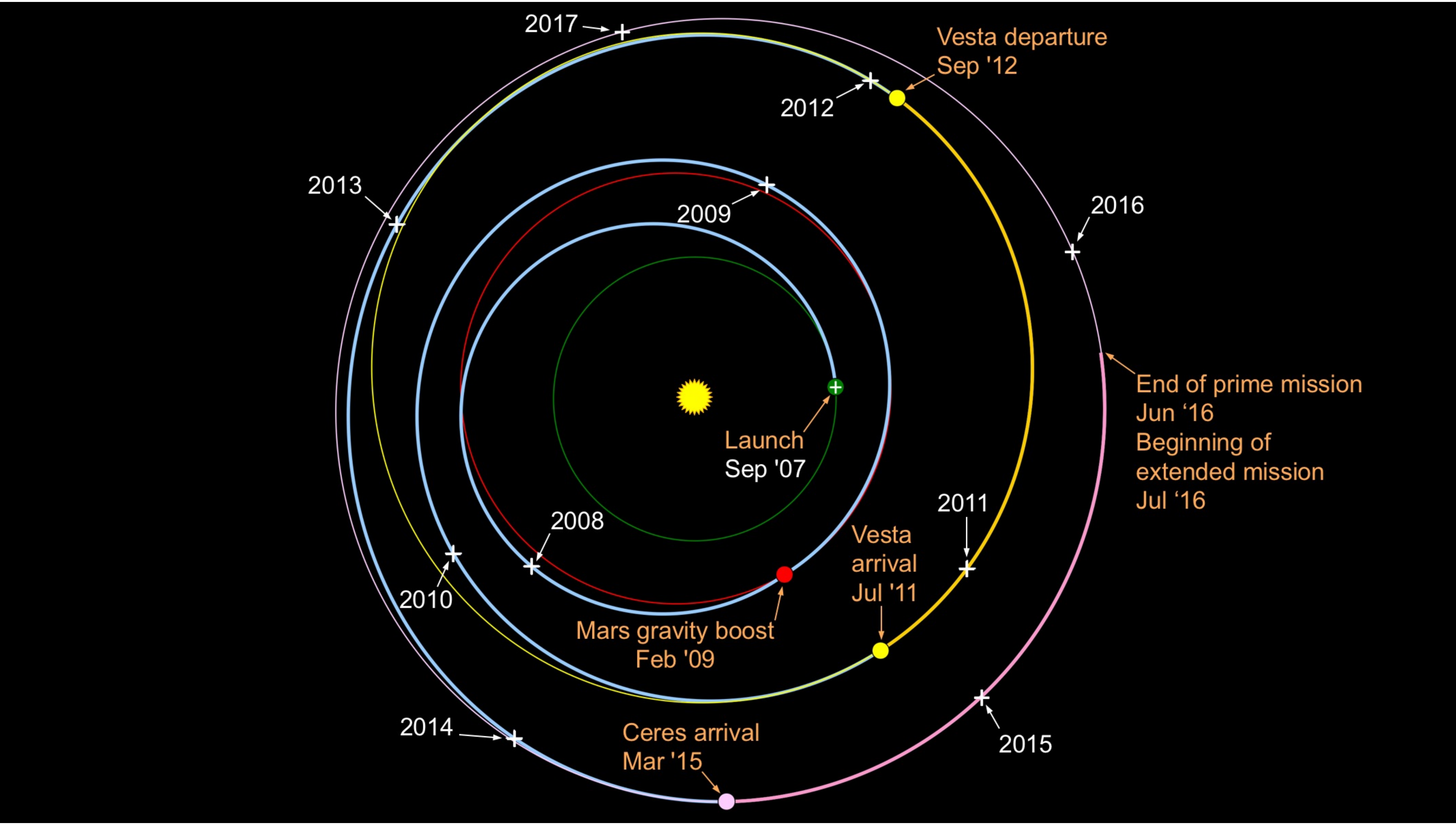
In fact, many asteroids are more like self-gravitating piles of rubble instead of monolithic slabs of rock. NEAR-Shoemaker found that Mathilde had a surprisingly low bulk density (1.3 g cm^{-3}) and a large number of giant craters. Simulations show that such large impacts would completely destroy a solid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

NEAR encounter with Mathilde

Vesta and Ceres

In 2007 NASA launched a mission called *Dawn* to Vesta and Ceres, the two largest asteroids. It reached Vesta in July 2011, and stayed in orbit around Vesta until September 2012, when it departed for Ceres. It reached orbit around Ceres in March 2015, becoming the first spacecraft to enter into orbit around a celestial body, study it, and then re-embark under powered flight to proceed to a second target. It is using ion thrusters for (very slow) continuous propulsion.

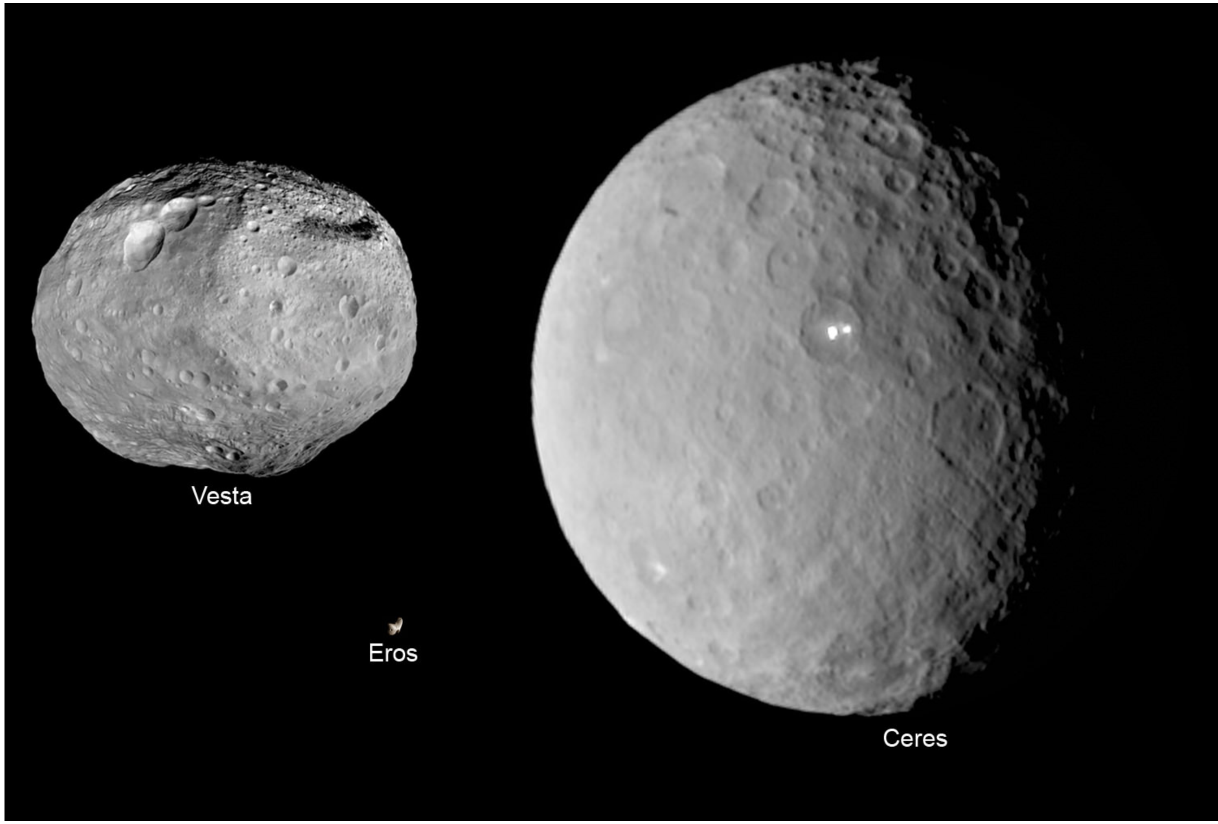




2017
Vesta departure
Sep '12
2012
2013
2009
2016
End of prime mission
Jun '16
Beginning of
extended mission
Jul '16
Launch
Sep '07
2011
2008
Vesta
arrival
Jul '11
2010
Mars gravity boost
Feb '09
2014
Ceres arrival
Mar '15
2015

Vesta and Ceres are the two largest asteroids; Ceres is large enough to be nearly spherical, which means it is classified as a *dwarf planet* – the only dwarf planet between the sun and Neptune.

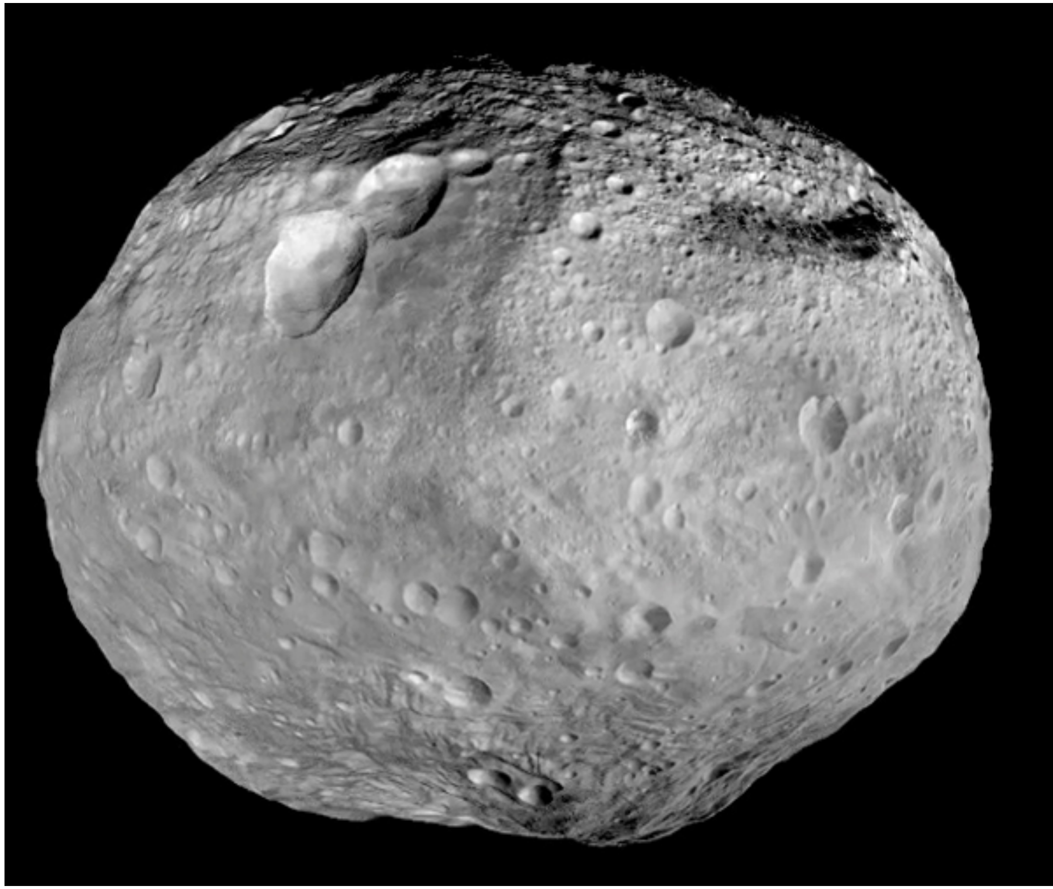
Ceres is much darker than Vesta (albedo 0.09), and significantly less dense.



Vesta was *Dawn's* first destination. Vesta is 565 km across at the equator, but its shape is dominated huge gouge out of the southern hemisphere.

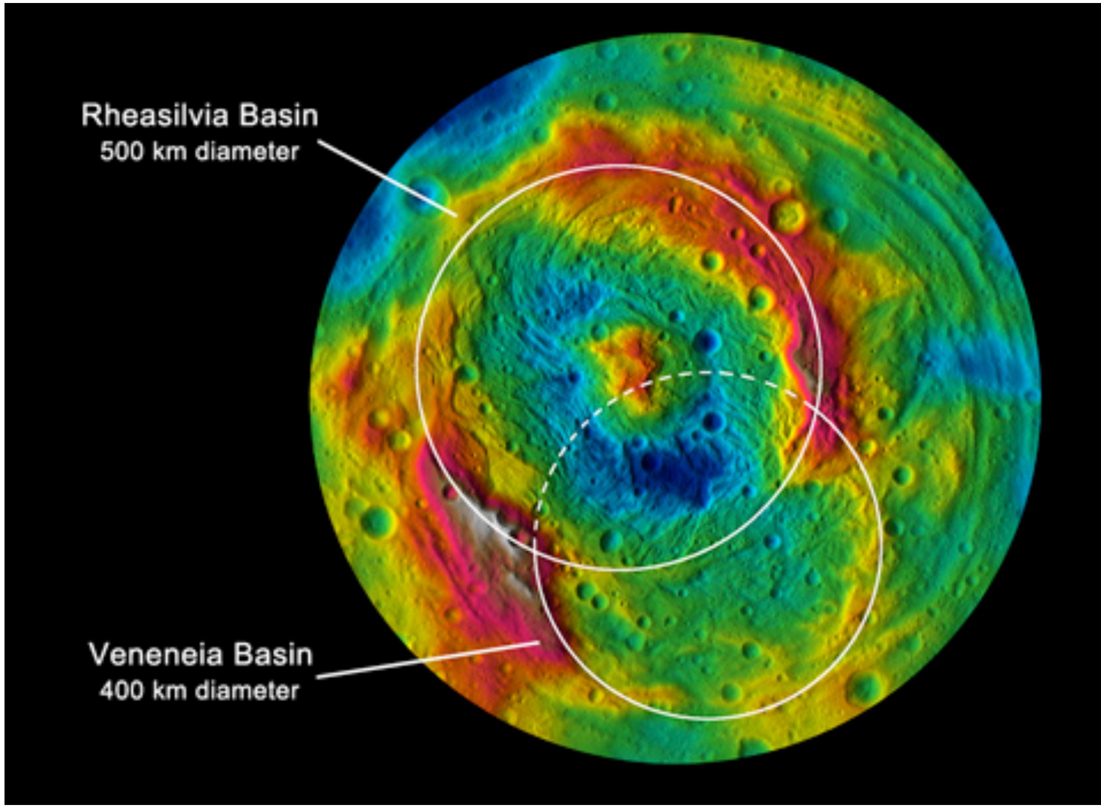
Dawn's measurements show that Vesta is differentiated, with an iron-nickel core surrounded by a mantle and a thin crust.

Vesta rotates once every 5.3 h.



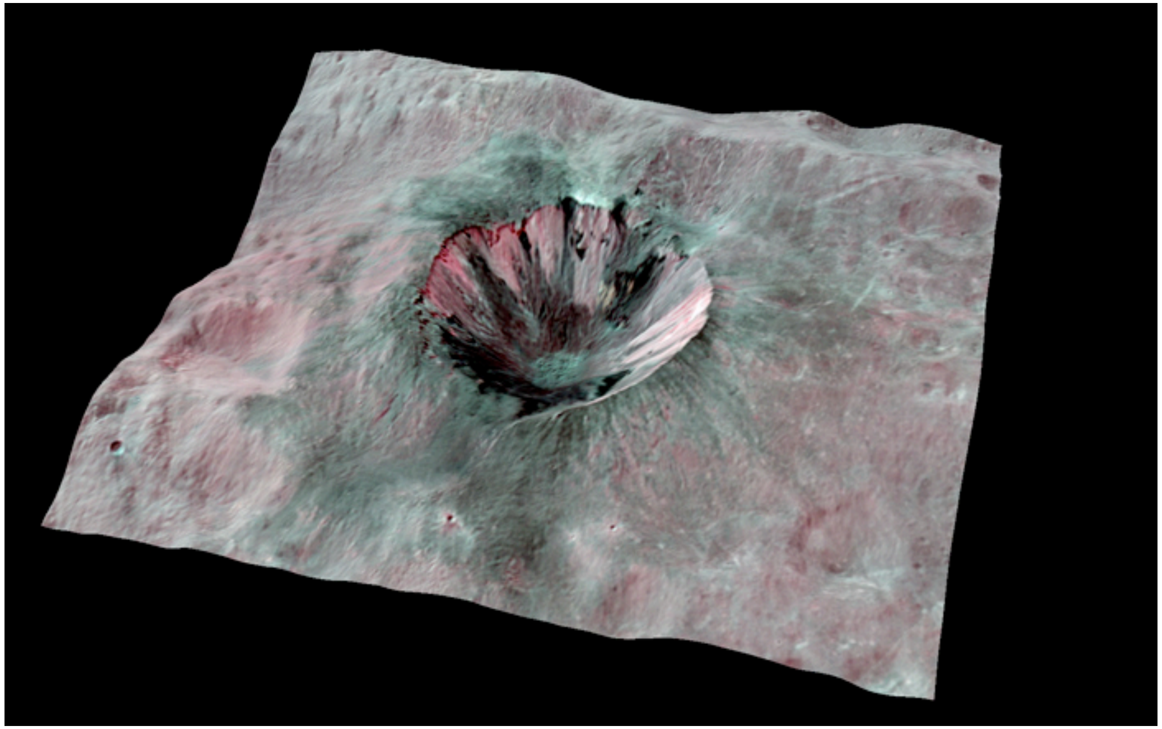
The giant impact basin at the south pole is called *Rheasilvia*. Its diameter is 505 km, 90% of the diameter of Vesta itself, making it one of the largest craters in the Solar System. It partially obscures an earlier crater that is almost as large.

The object that formed Rheasilvia was probably 50 km across, and ejected rocks which still occasionally fall to Earth as meteorites, as we shall see later. The impact is estimated to have taken place about 1 Gyr ago.



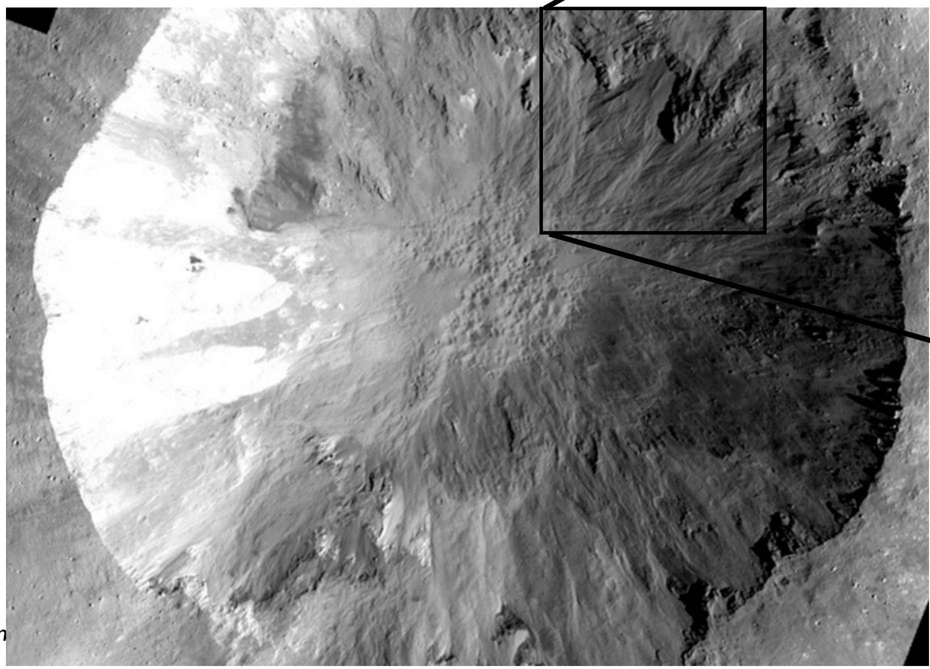
Troughs around Vesta's equator are concentric with these two basins, and are large-scale fractures resulting from the impact. The largest is 22 km wide and stretches most of the way around Vesta

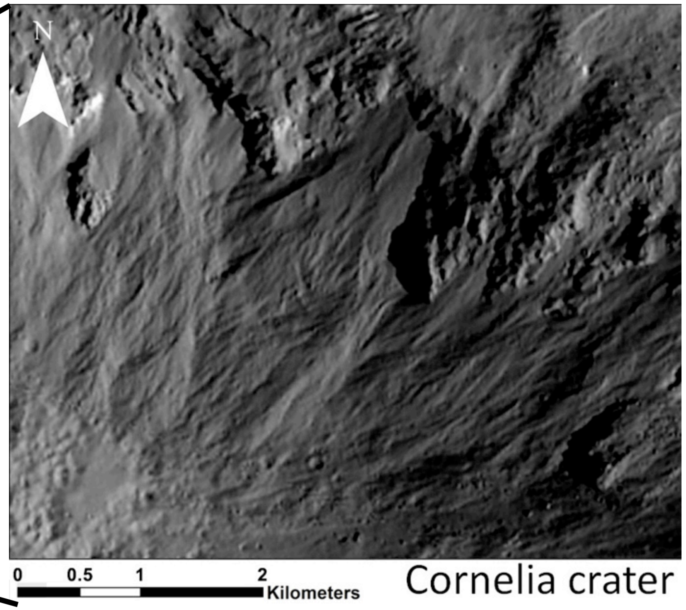
The same impacts may be responsible for dark streaks and speckles seen around many craters. Analysis shows the dark carbon-rich material was probably delivered to Vesta during the formation of the older Veneneia basin, when a slow impacting asteroid collided with Vesta. Much of this was later covered up by the impact that formed Rheasilvia.



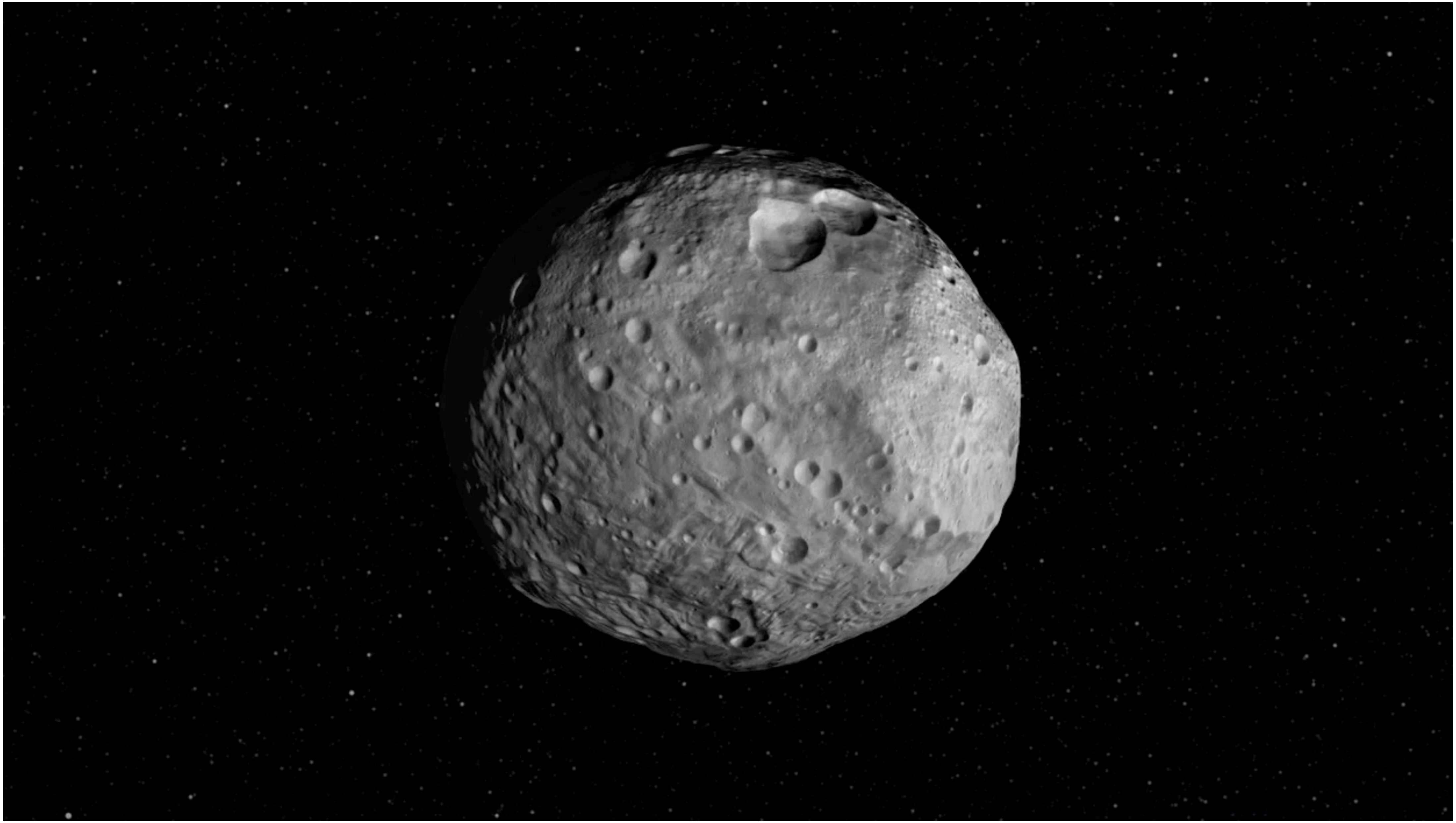
Dark streaks in Cornelia crater.

In an intriguing development, scientists have spotted intriguing gullies that sculpt the walls of geologically young craters. On Earth such features are carved by liquid water – but surely not on Vesta?!

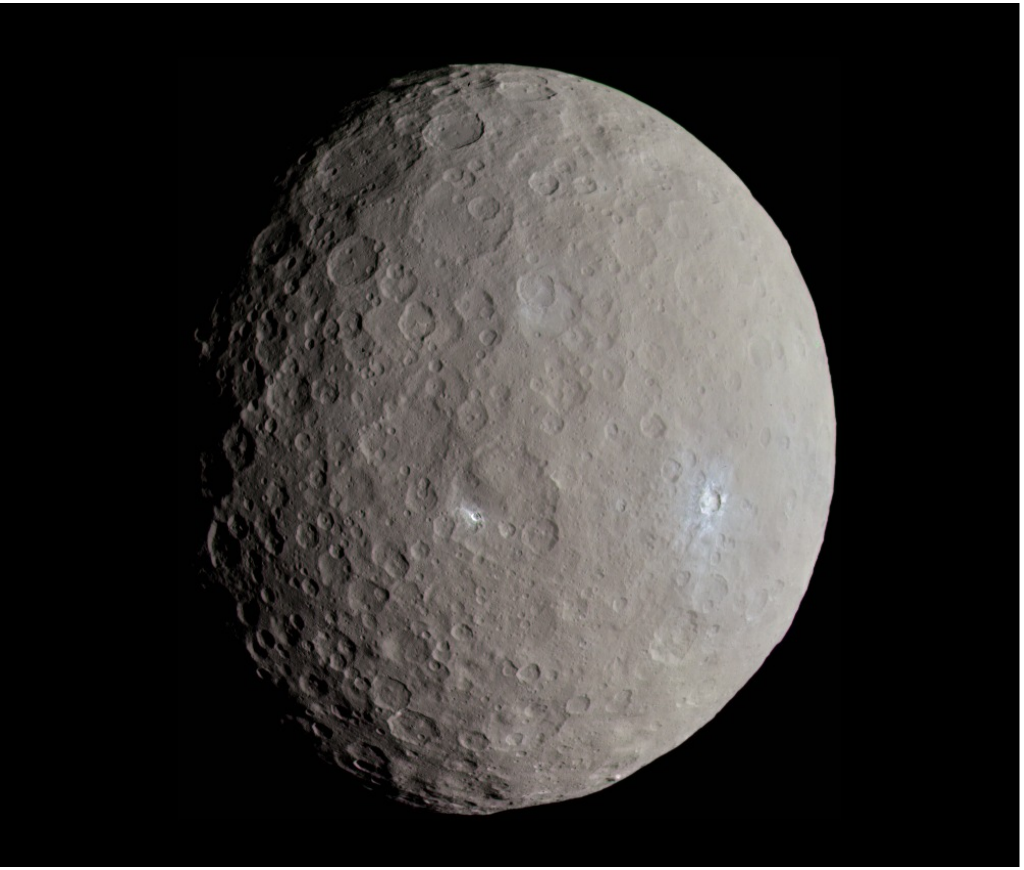




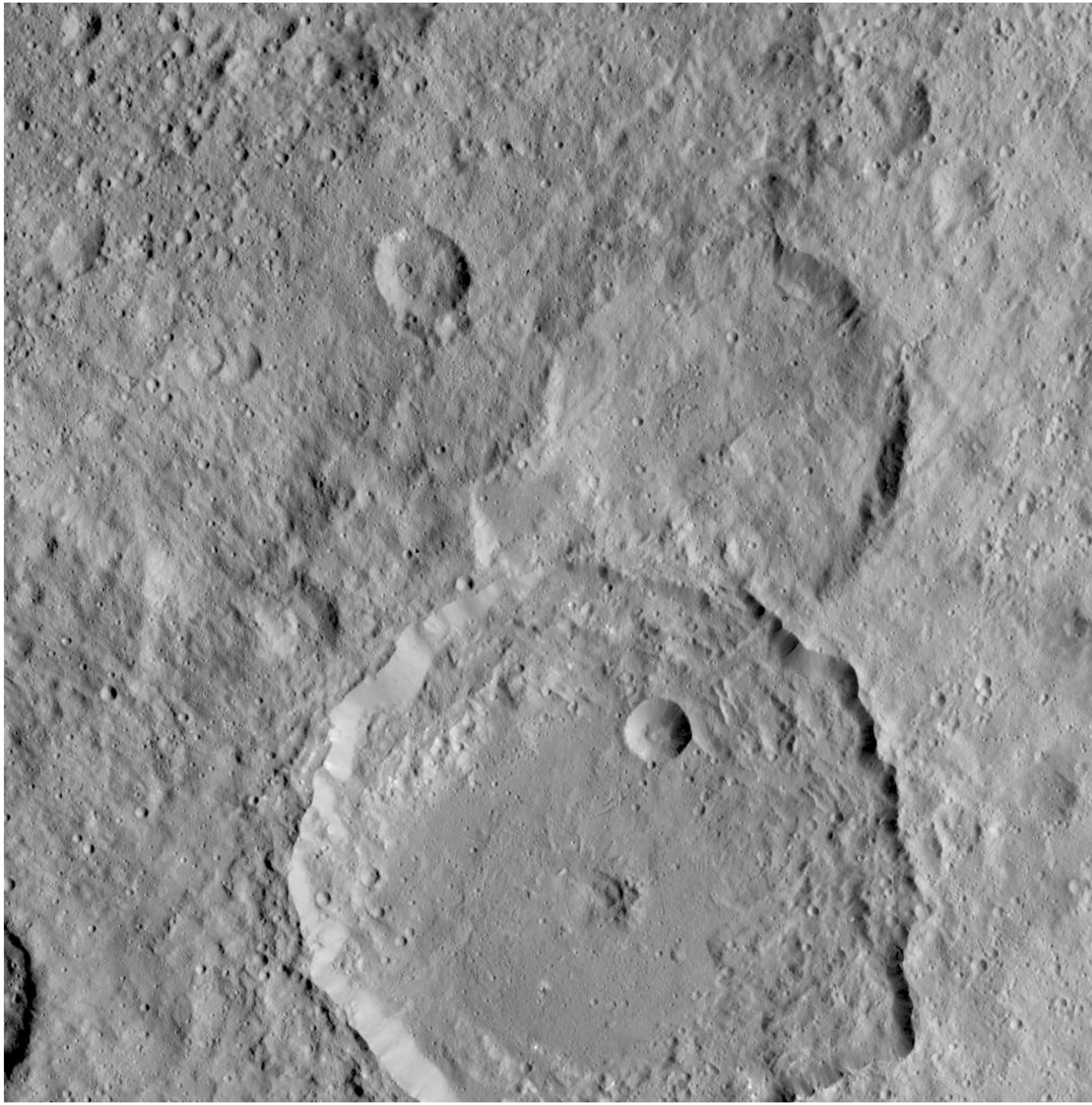
Examples of long, narrow, sinuous gullies around Cornelia crater.



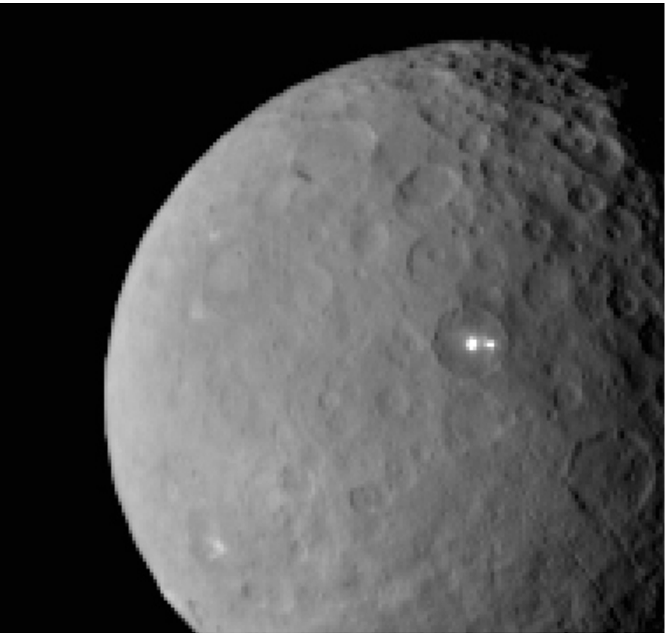
Ceres is heavily cratered, but has fewer large basins than expected, suggesting that there has been geological evolution, erasing the large craters.

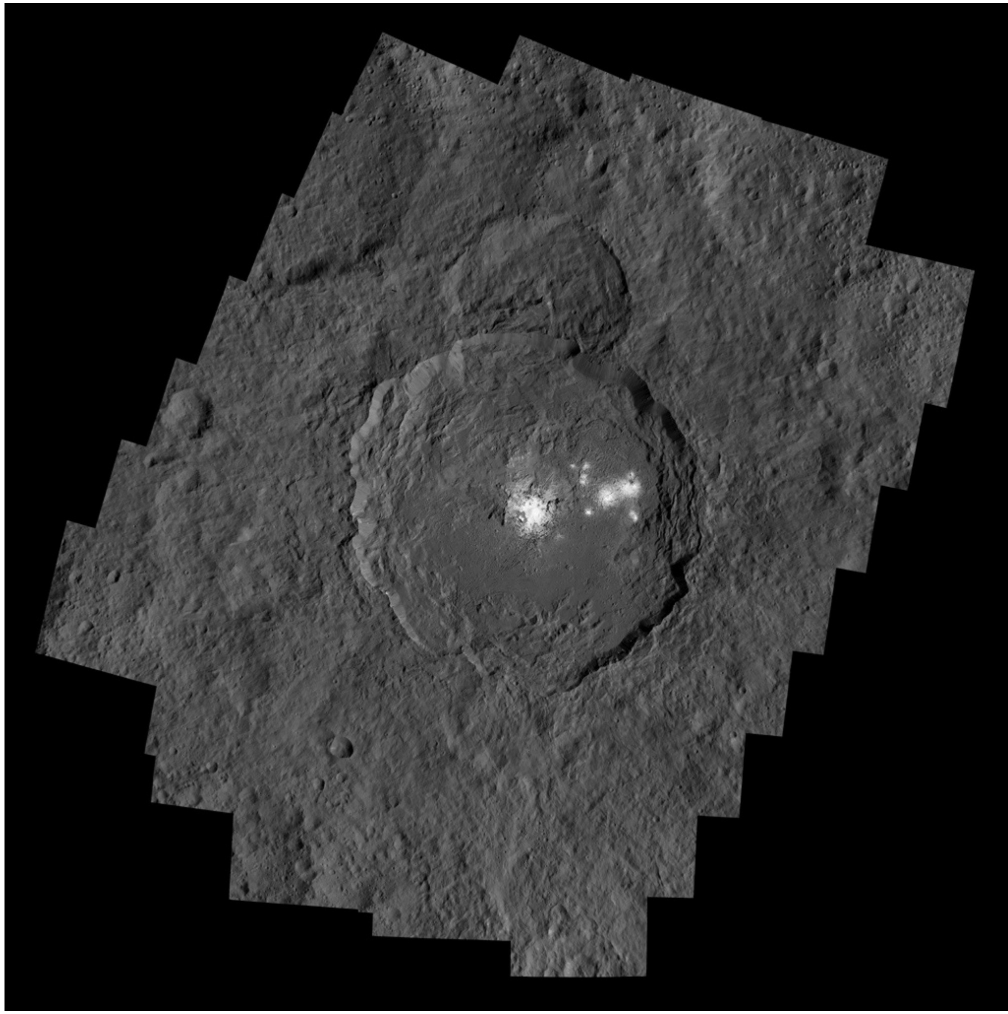


Many of Ceres' craters show sunken pits in their centres, suggesting that the crust is icy. Similar features are seen on some of Saturn's icy moons.



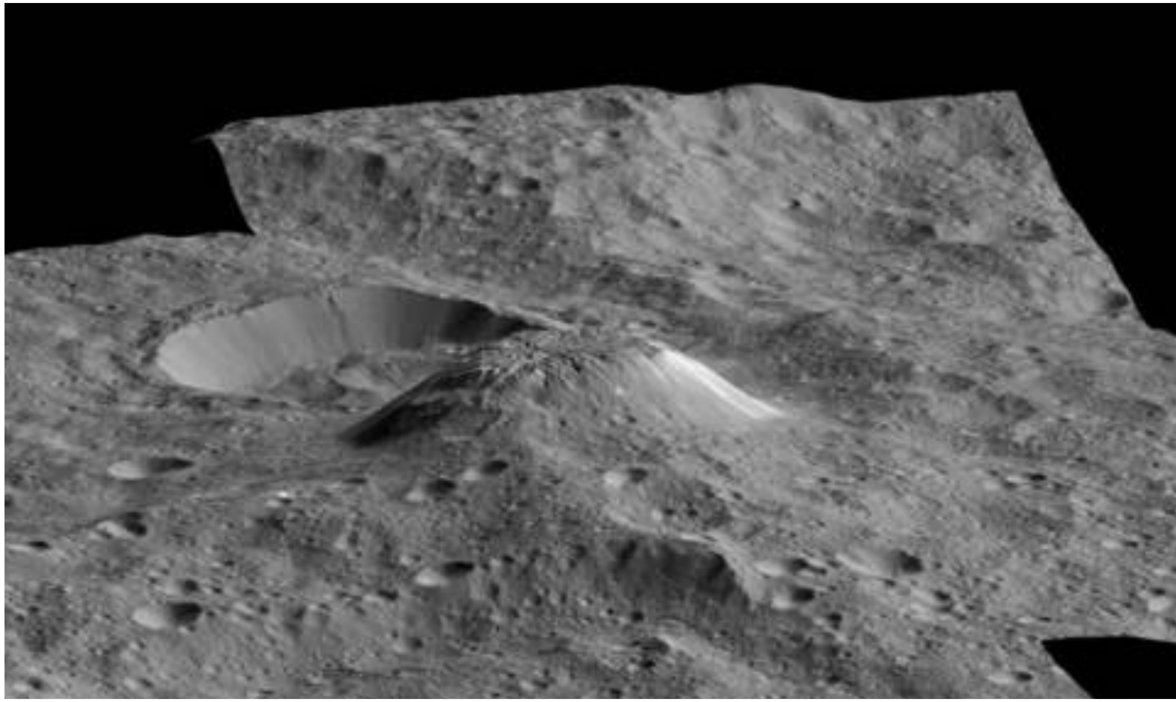
The most obvious feature on Ceres are the bright spots at the centre of Occator crater. The bright material seems to be some sort of salt, probably indicating the presence of a subsurface shell of ice-salt mix.





The 92 km wide Occator Crater, showing bright spots.

Ceres has a single enormous mountain: *Ahuna Mons*, which stands 5 km high and is 20 km across. The best guess is that it is a type of volcanic dome, made by a *cryovolcano*, involving involving salty water and mud. Its sharpness and brightness indicate it is young, possibly only a few hundred million years old.

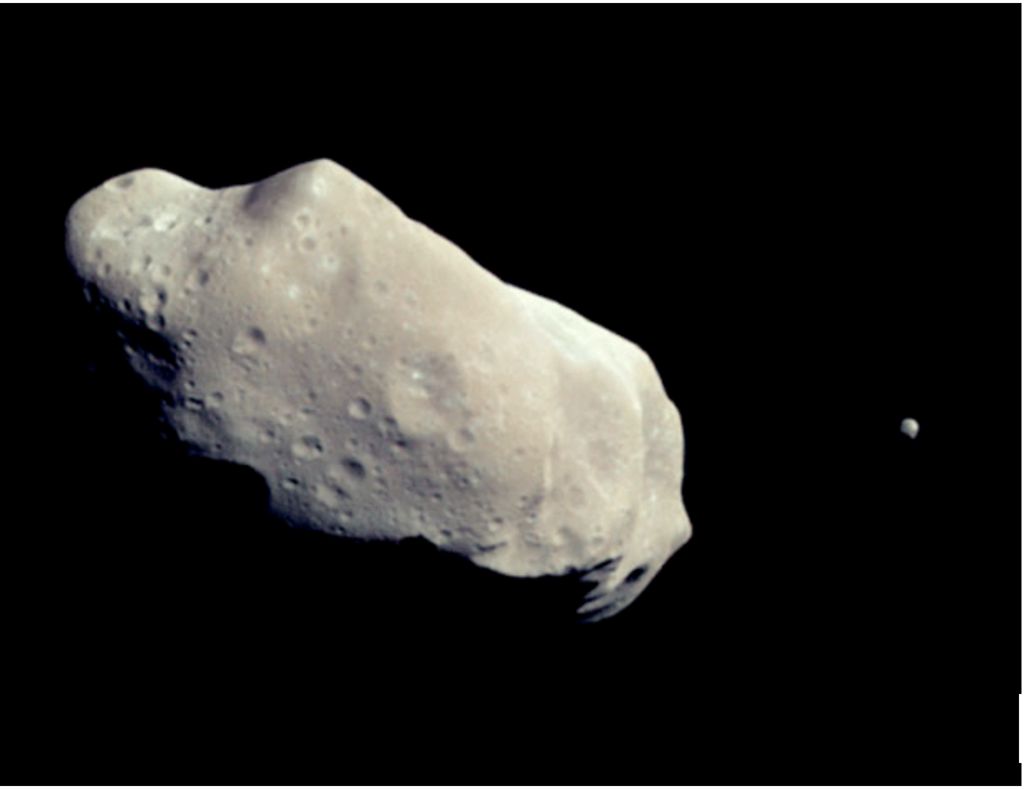



UNVEILING
Jet Propulsion Laboratory
California Institute of Technology

An increasing number of asteroids are found to be binary. As of 2017, there were 319 small bodies with companions.

These include

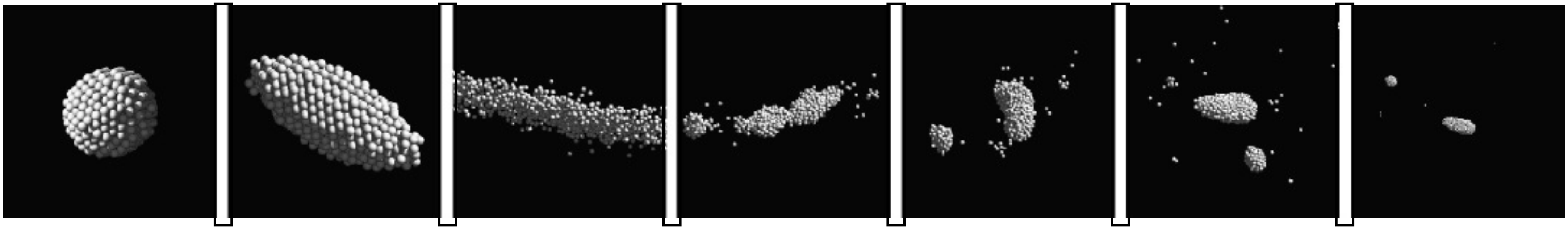
- 65 near-Earth asteroids,
- 24 Mars-crossing asteroids,
- 145 main-belt asteroids (eight with two satellites each),
- 4 Jupiter Trojan asteroids, and
- 81 trans-Neptunian objects (two with two satellites, one with five satellites).



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

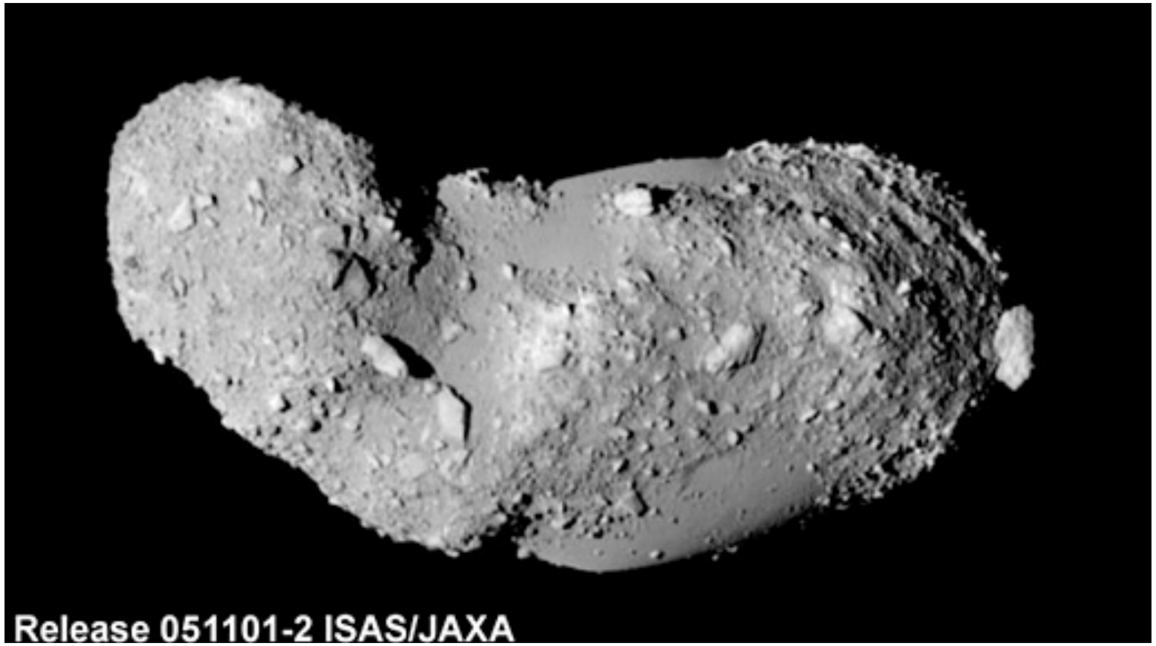
The fraction of binaries among near-Earth asteroids is much higher than among main-belt asteroids (1 in 6 NEAs is a binary). This suggests they form differently.

- 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* returned to Earth on 13 June 2010, with approximately 1500 grains of asteroid dust.



Some asteroids are even stranger:

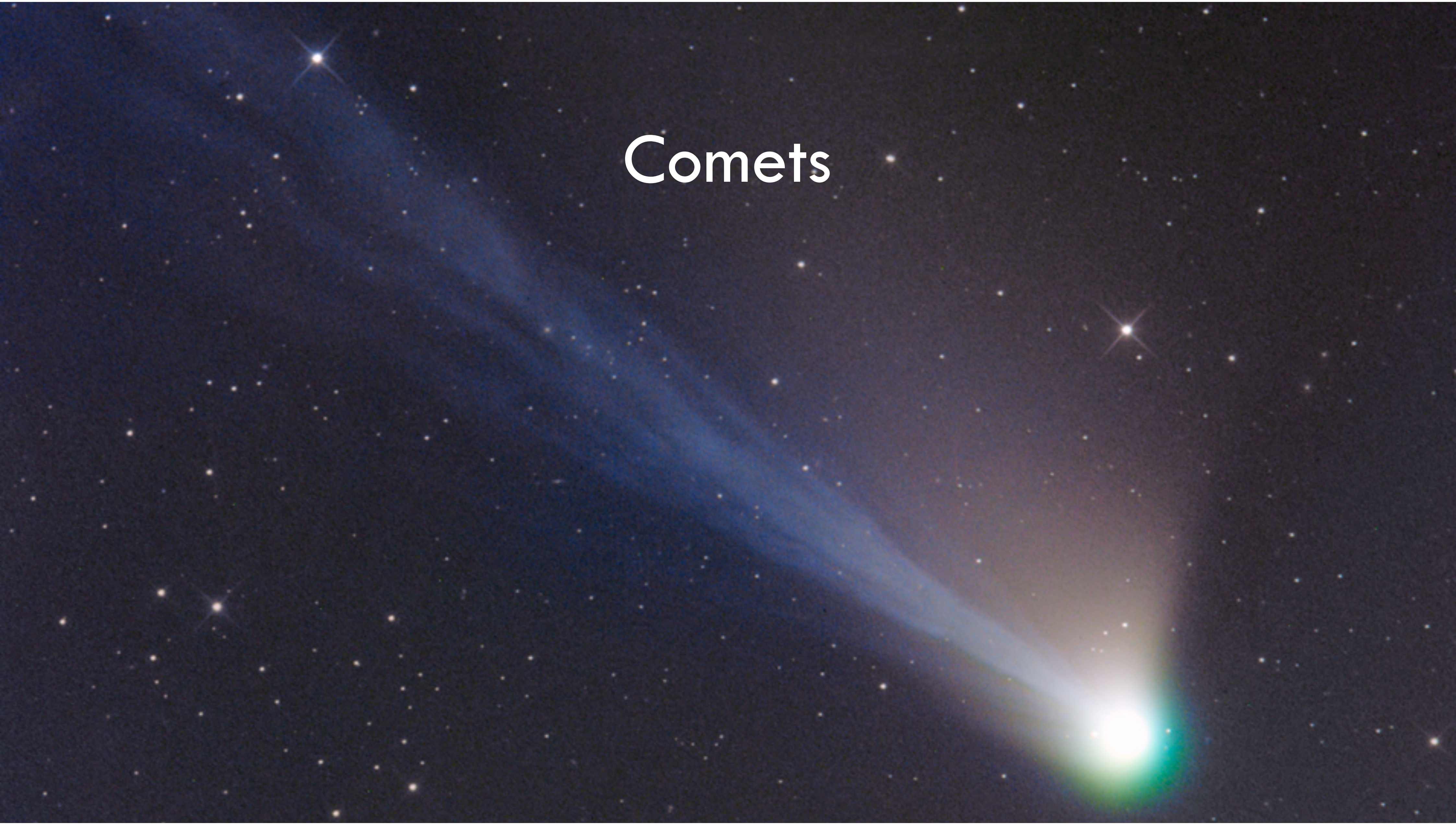
"[The near-earth asteroid] (29075) 1950 DA is covered with sandy regolith... and spins so fast – one revolution every 2.12 hours – that gravity alone cannot hold this material to its surface. This places the asteroid in a surreal state in which an astronaut could easily scoop up a sample from its surface, yet would have to hold on to the asteroid to avoid being flung off."

– Daniel Scheeres, "Sandcastles in space", Nature 512 (2014)

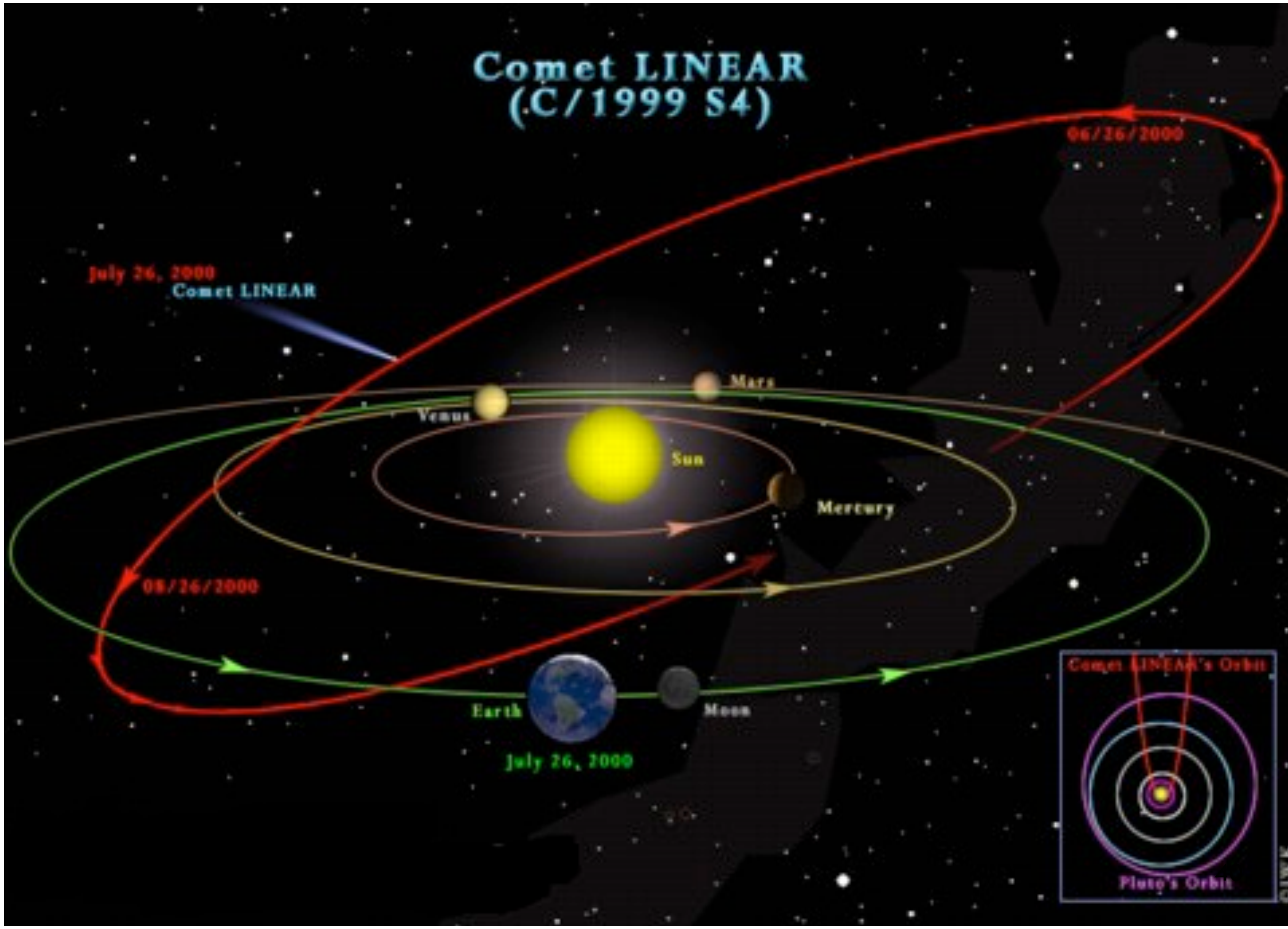
Between the orbits of Jupiter and Neptune are a class of planetoids called Centaurs. The first of these was discovered in 1977, and called 2060 Chiron. By 1988, it drew closer to the sun, it developed a coma, just like a comet.

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

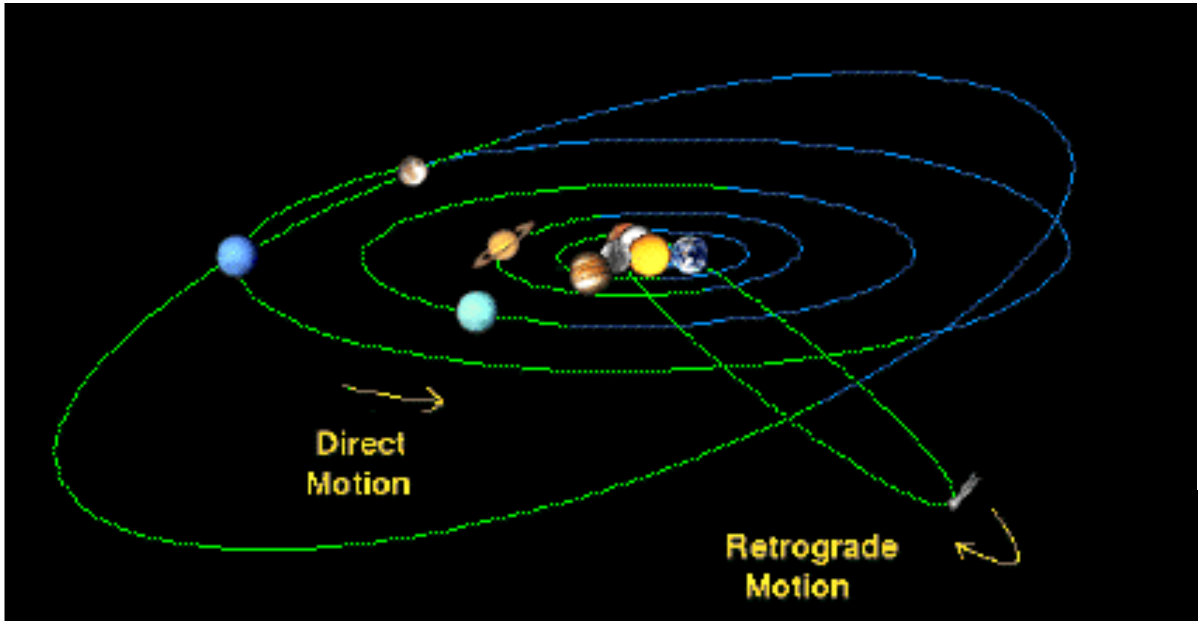
Artist's impression of the Centaur 8405 Asbolus. Light variations detected by Hubble could be caused by a fresh crater on one side.

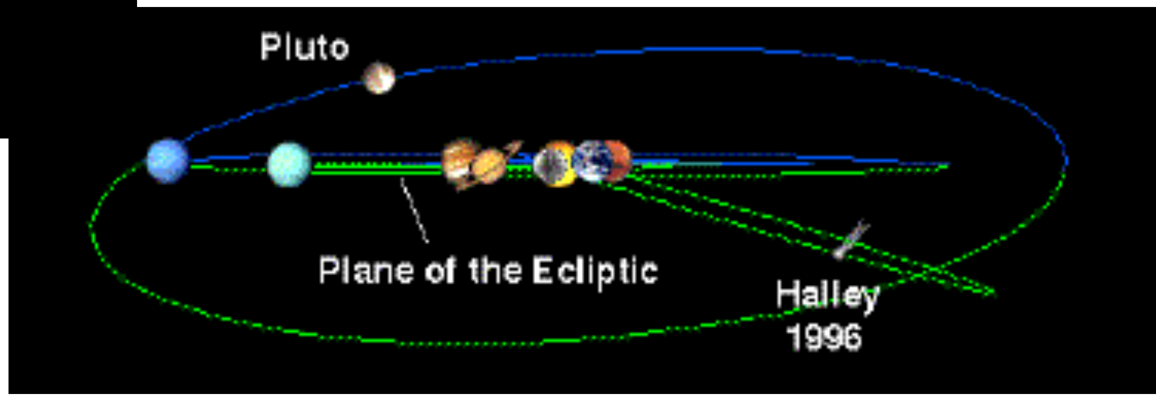

Comets

Comets are another class of small solar system bodies. Unlike asteroids, comets are predominantly icy bodies. And unlike most asteroids, comets tend to 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.



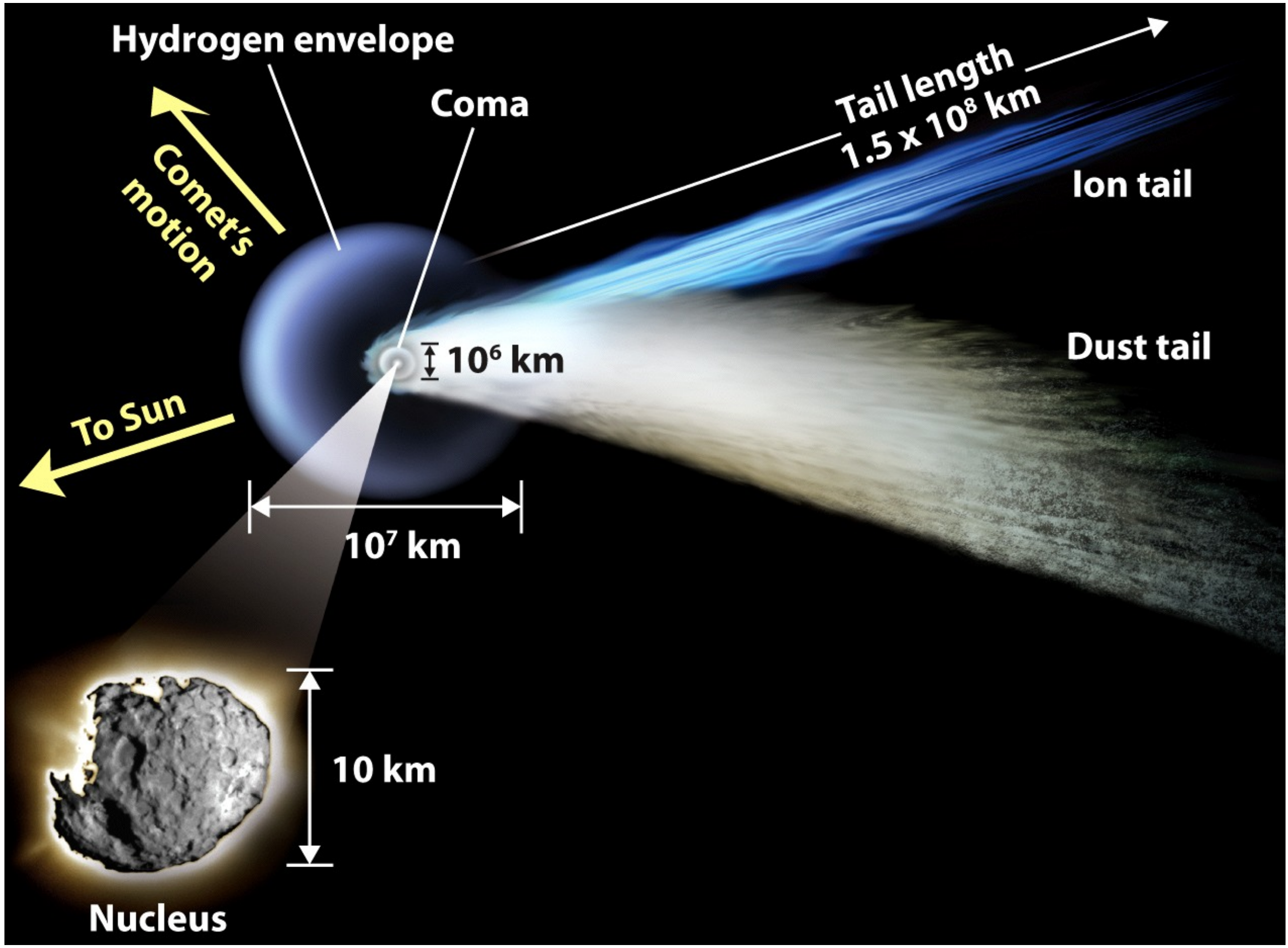


The orbit of Comet Halley

The *nucleus* of a comet is a ball of mostly ice, a few kilometres in radius.

As the comet 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 spherical *coma*, which may be a million kilometres in diameter.




Comet C/2013 X1 (PanSTARRS) in 2016
© Fritz Helmut Hemmerich

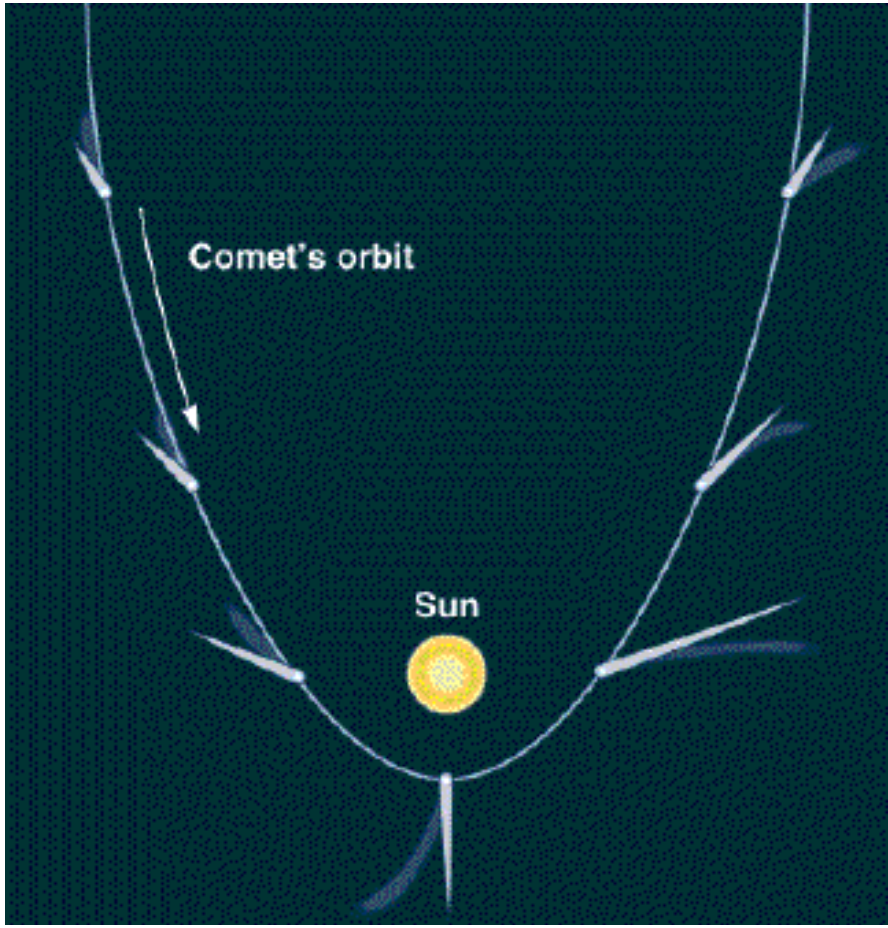
Some of the gas and dust emitted from the nucleus streams away in the *tail*. These tails can be up to 1 AU in length, but are extremely thin.

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.

Comet Hale-Bopp

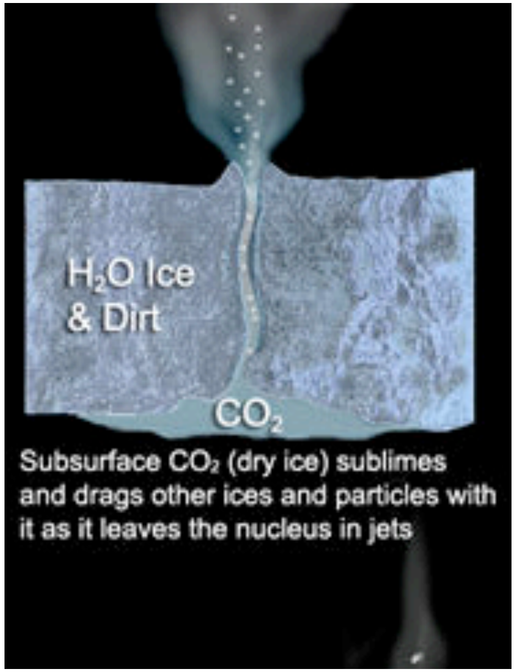

© 1997 Jerry Lodriguss

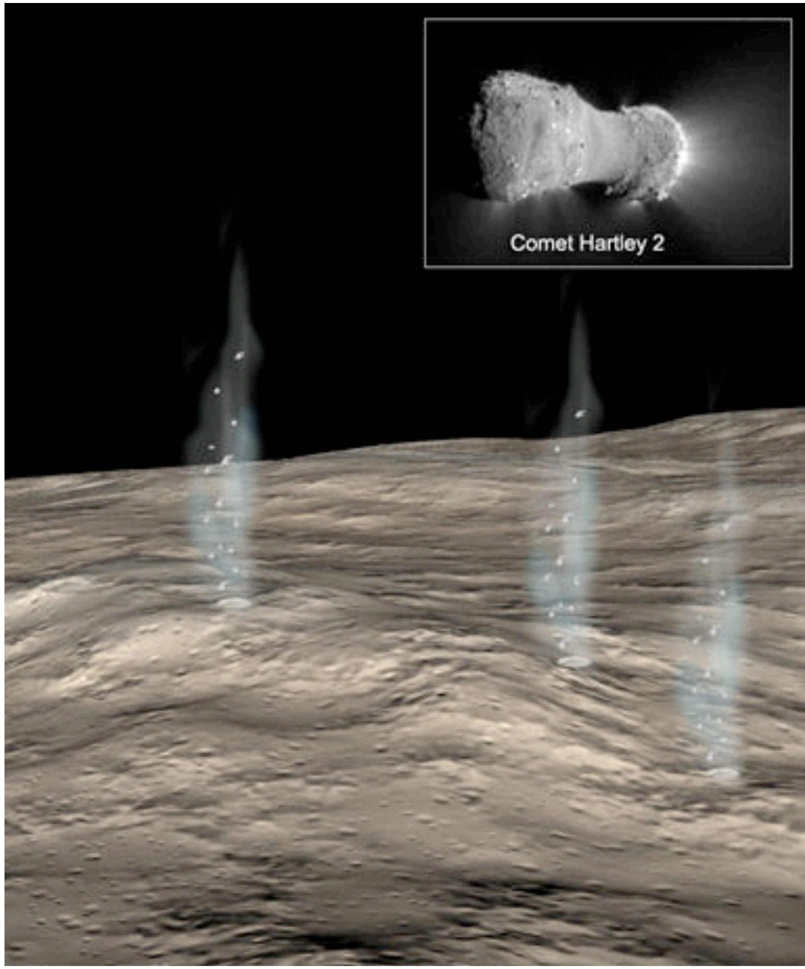
The ion tail always points away from the Sun, while the dust tail tends to curve behind the comet's motion. The ion tail is typically bluer in colour, narrow, and straight; the dust tail is more diffuse, often looks curved, and is more white in colour.



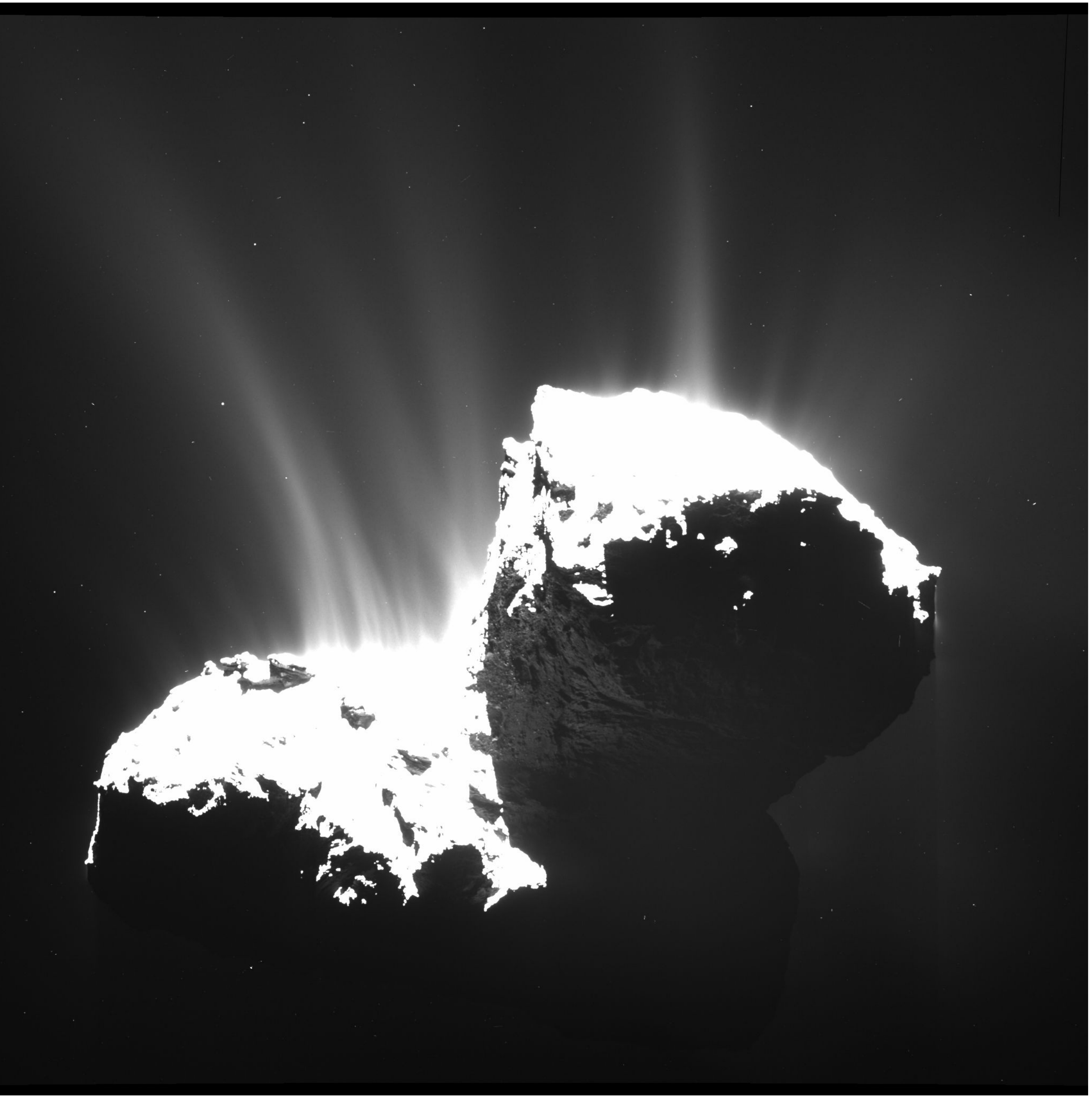
The comet's motion is often affected by gases jetting out of the nucleus, so their orbits are somewhat disturbed from regular orbits.

Contrast-enhanced image obtained during Deep Impact's Nov. 4th flyby of Comet Hartley 2, showing a cloud of icy particles surrounding the comet's active nucleus





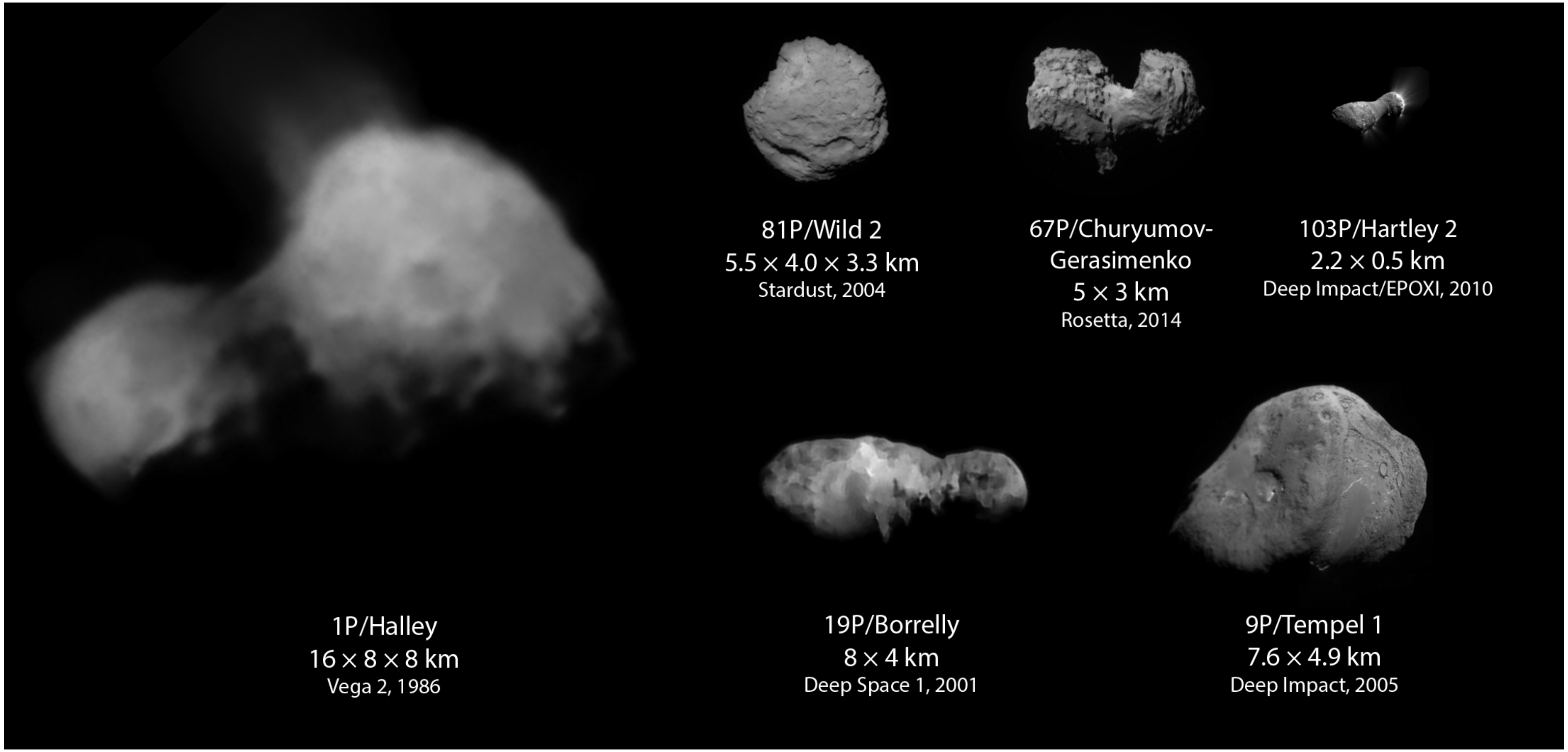
Artist's concept of Comet Hartley 2 shows how CO_2 jets drag water ice out of nucleus, producing a 'comet snowstorm' which falls upward.



Plumes of gas and dust escaping numerous places from Comet Churyumov-Gerasimenko's nucleus as it neared the Sun and heated up.

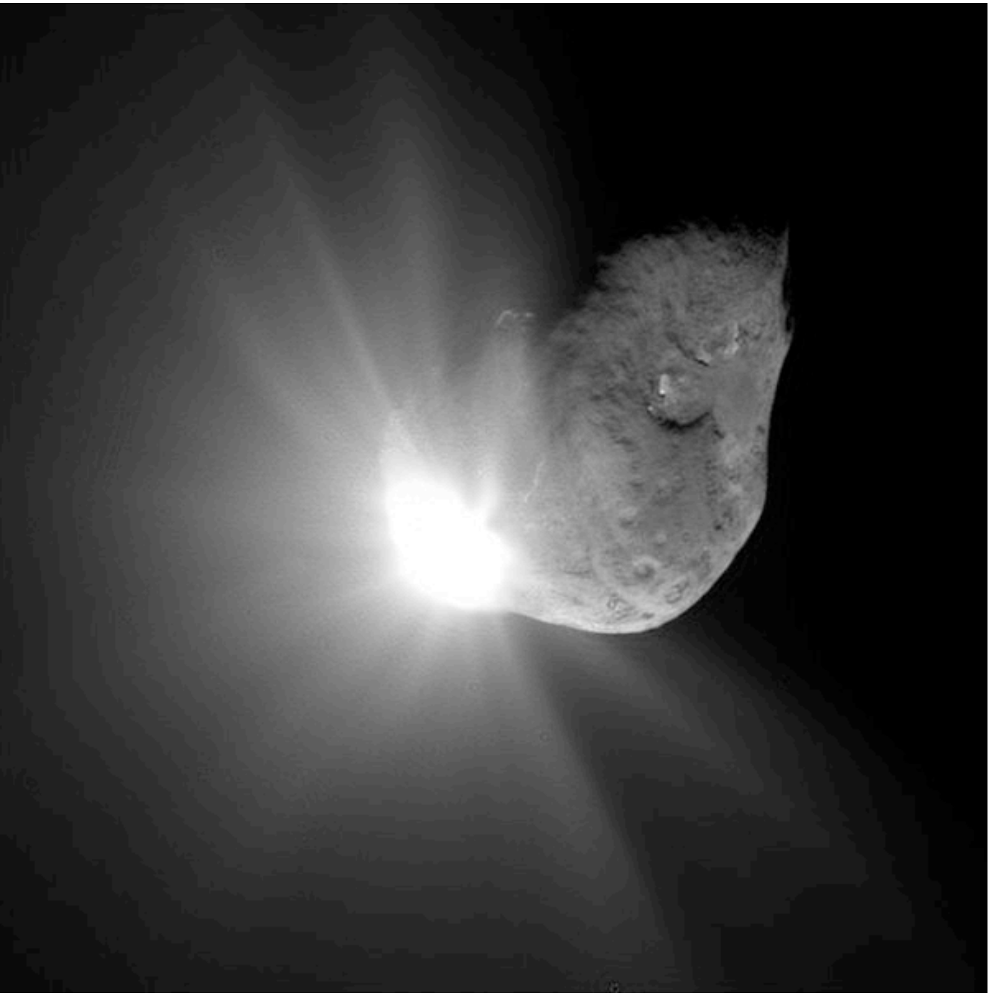
Comet McNaught, seen from Siding Spring Mountain (above) and Bendalong on the NSW south coast, in January 2007

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



Images at the same scale for all comet nuclei observed by spacecraft.

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 European Space Agency sent the *Rosetta* spacecraft to Comet 67P/Churyumov-Gerasimenko. It arrived in August 2014, where it went into orbit around the nucleus.

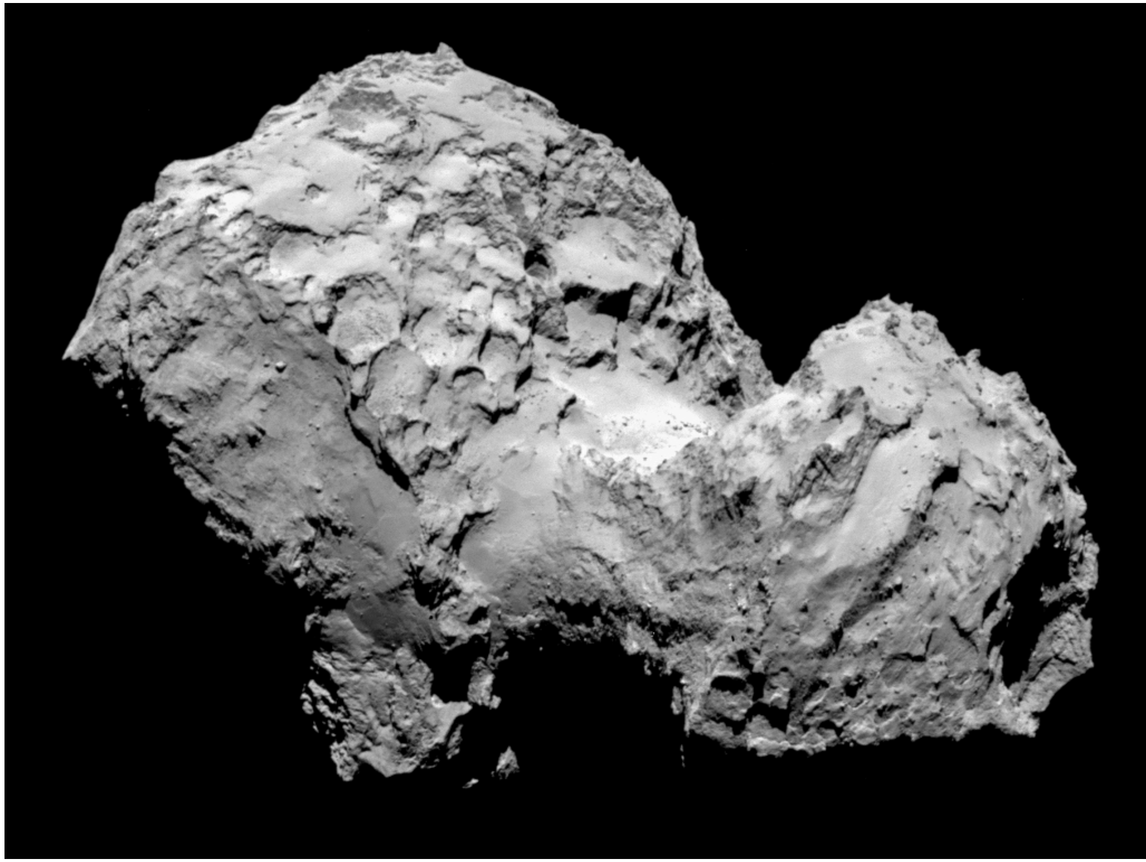


Image of the nucleus from a distance of 285 km. The nucleus is about 4 km across.

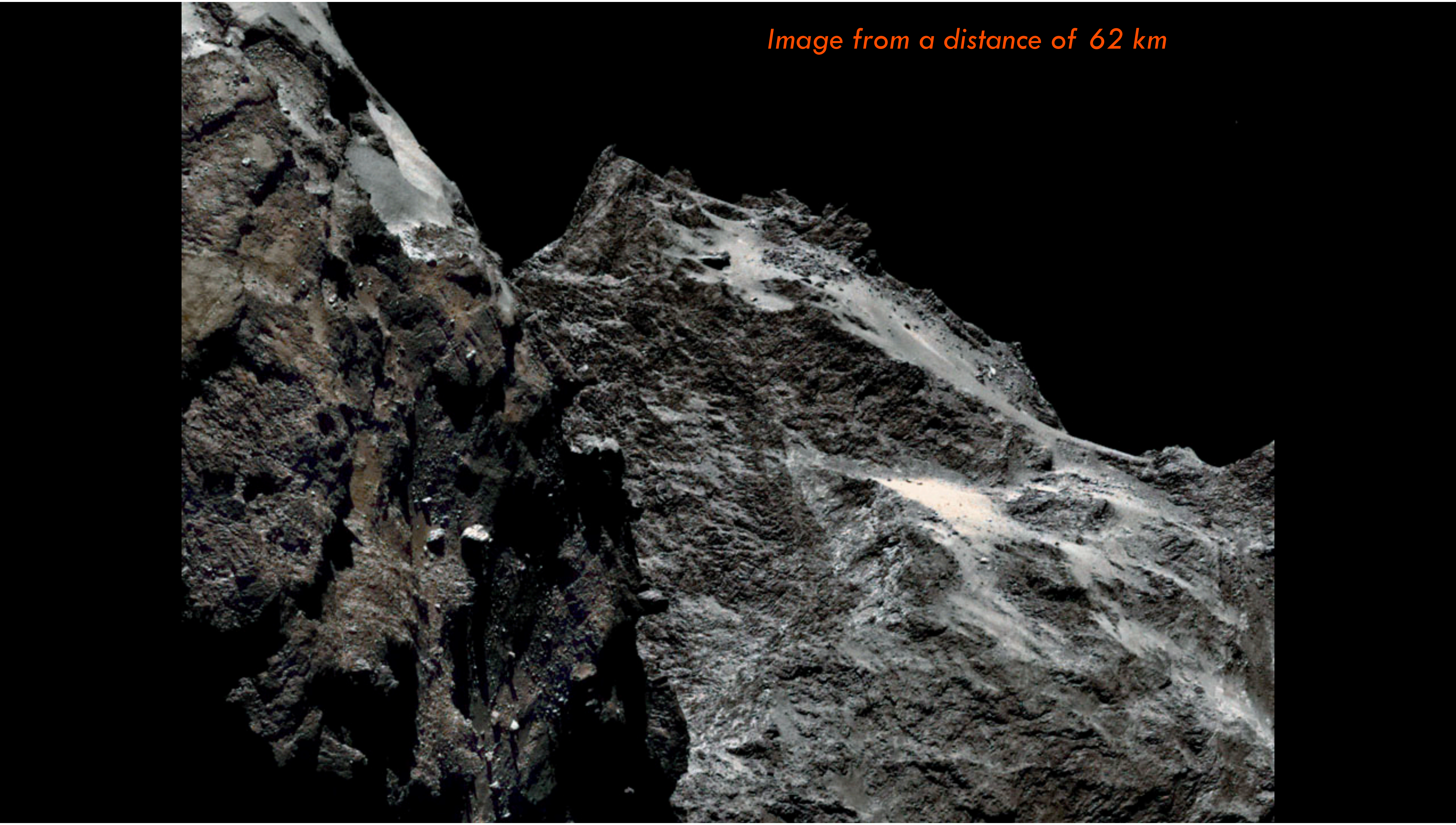
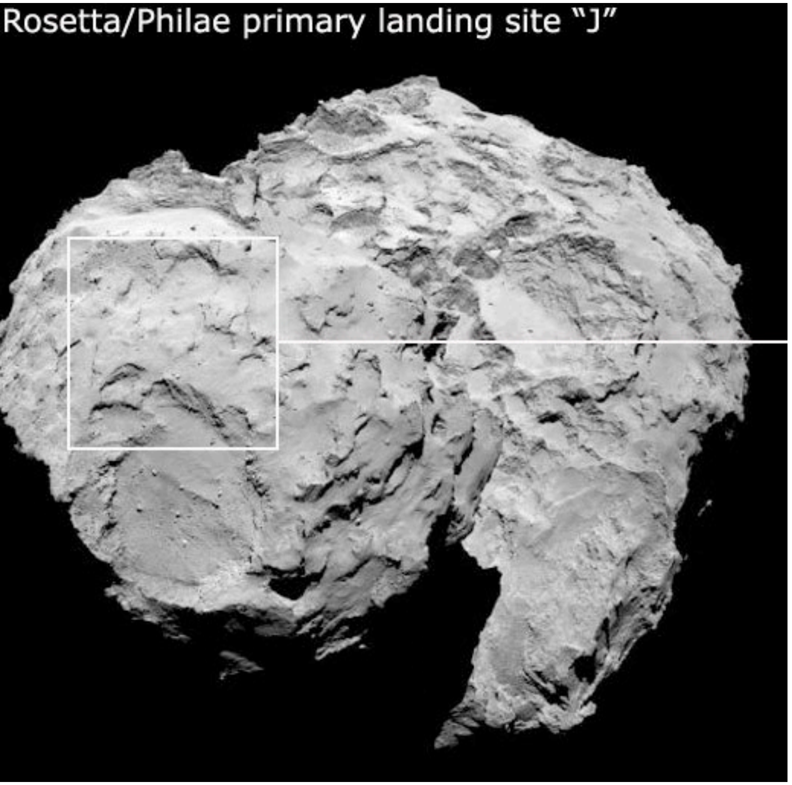
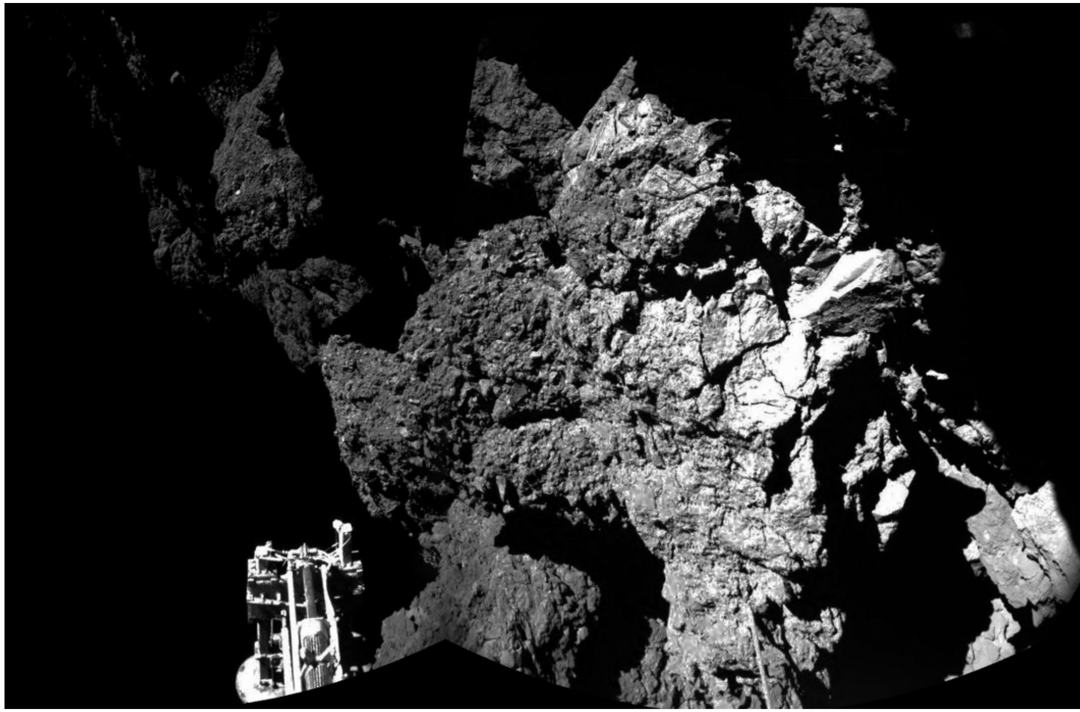
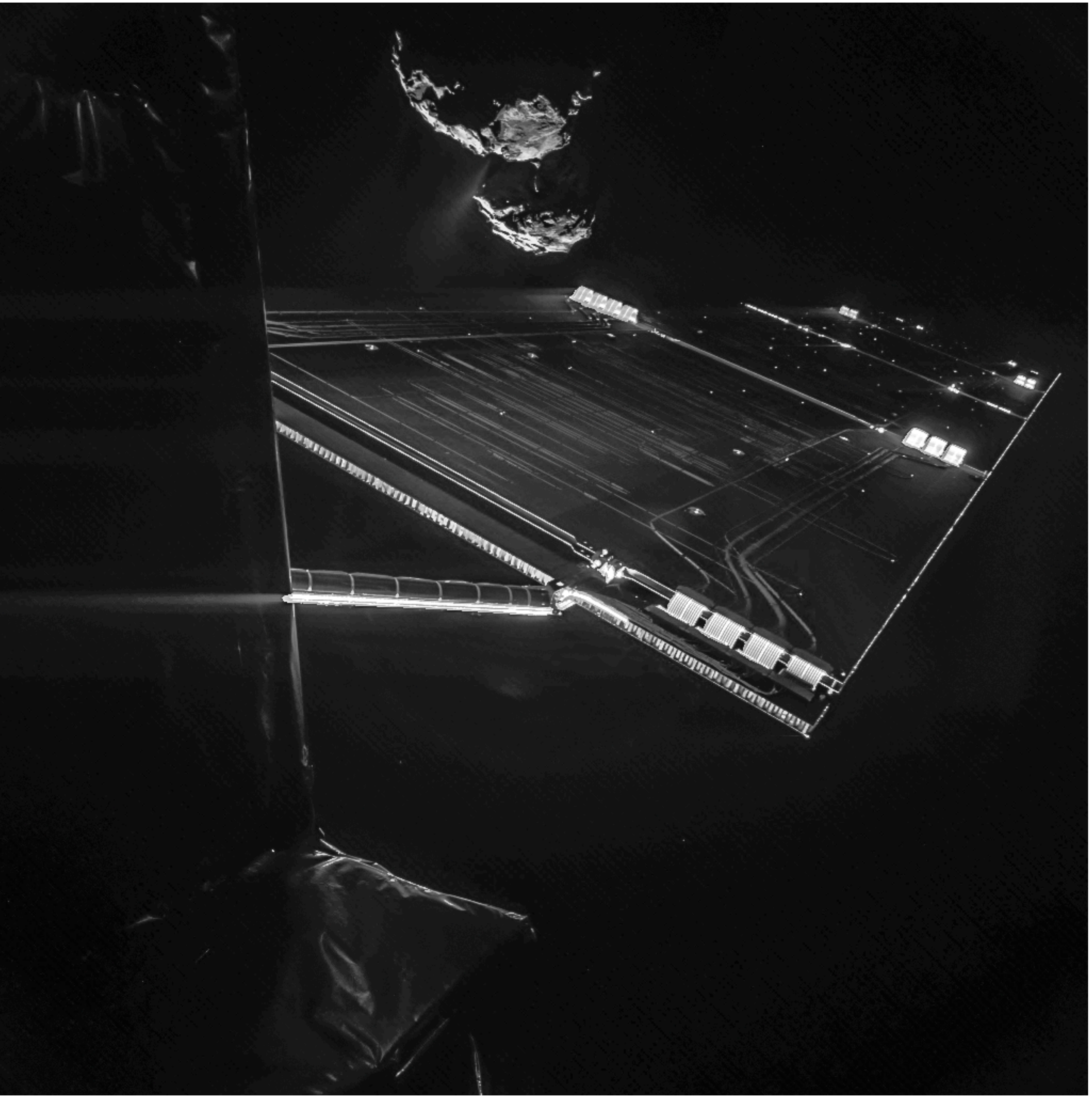


Image from a distance of 62 km

The *Philae* lander was released to land on the comet's surface in November 2014. Its harpoons failed to deploy, so the lander bounced off the surface twice, then came to rest in the first soft landing on a comet. Unfortunately, it settled in the shadow of a cliff, meaning its solar panels could not properly recharge its battery. Nonetheless, it sent back several pictures from the surface.



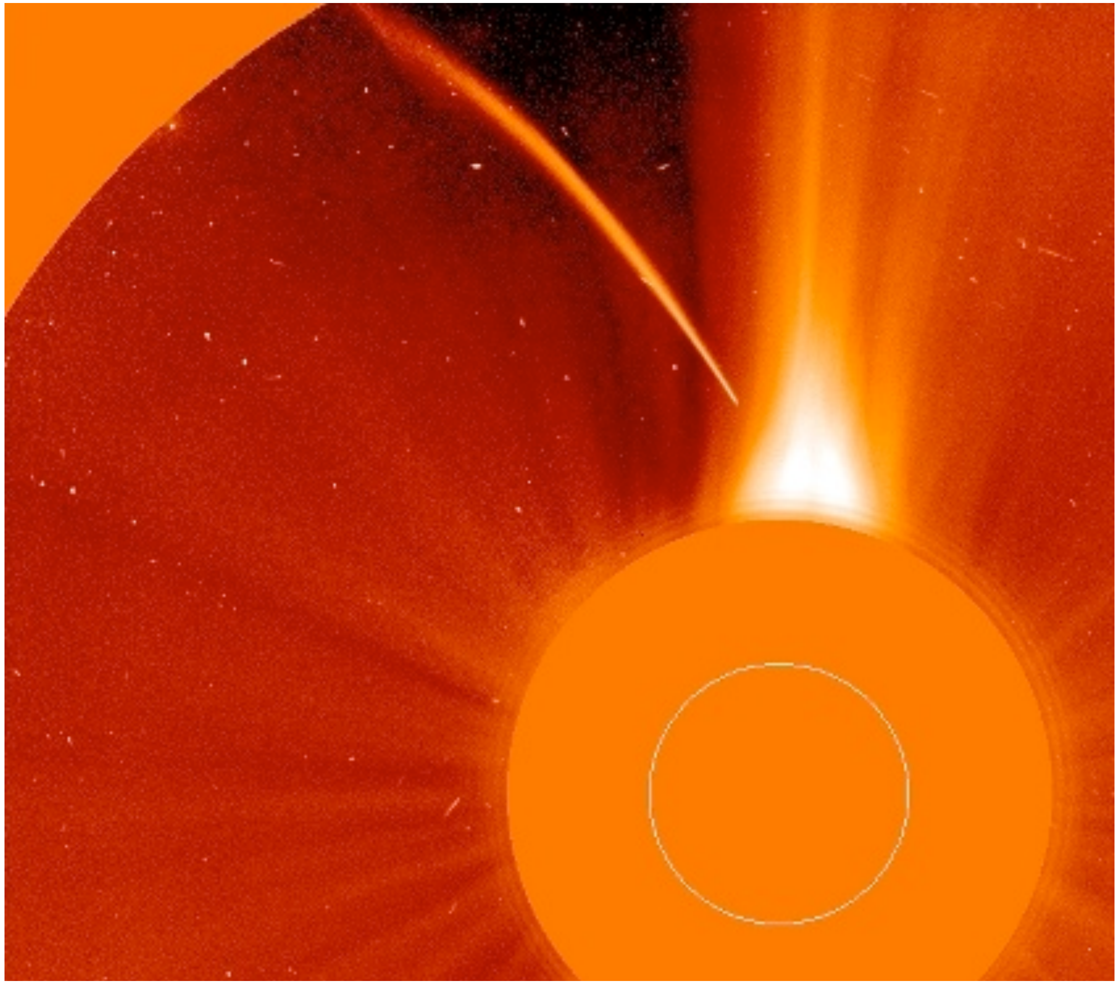




Selfie with comet, taken just before Philae separated from Rosetta.

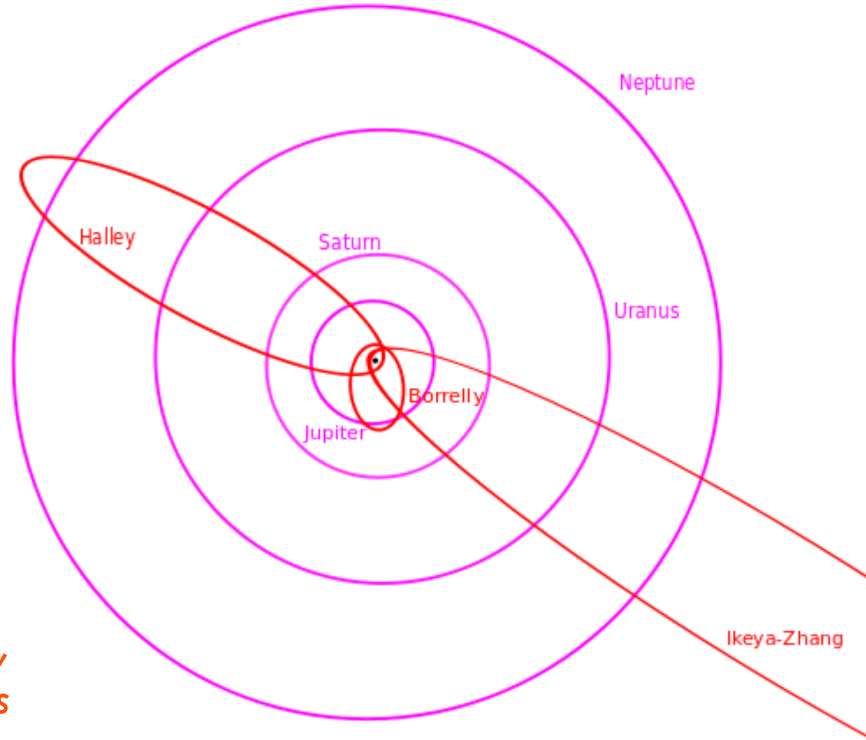
The solar observatory SOHO has found more than 1000 *sungrazer comets* – a family of comets with orbits which take them extremely close to the Sun at perihelion.

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.

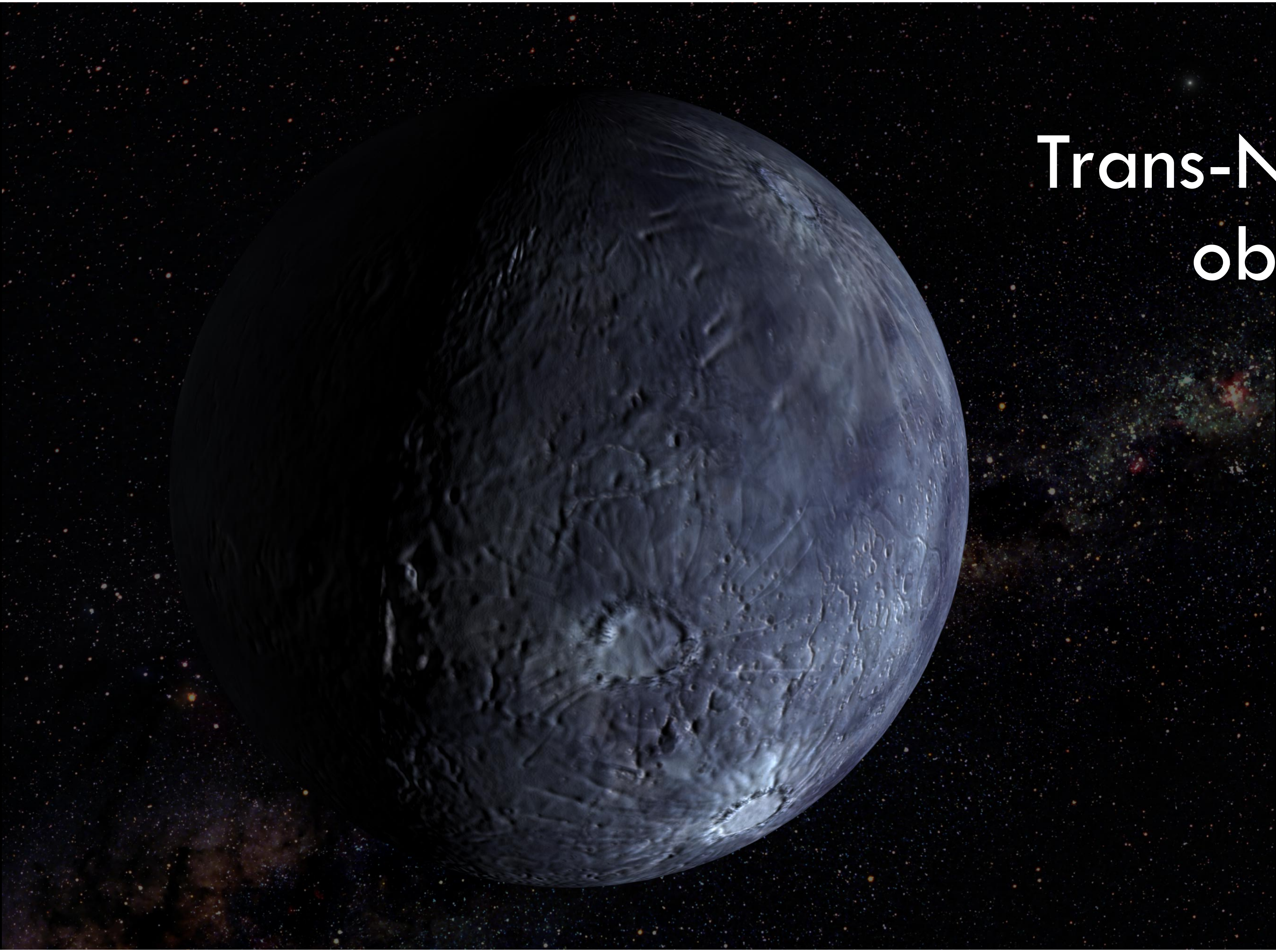


SOHO image of comet SOHO-6 plunging toward the Sun on 23 December 1996

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?



The orbits of three periodic comets, Halley, Borrelly and Ikeya–Zhang, set against the orbits of the outer planets

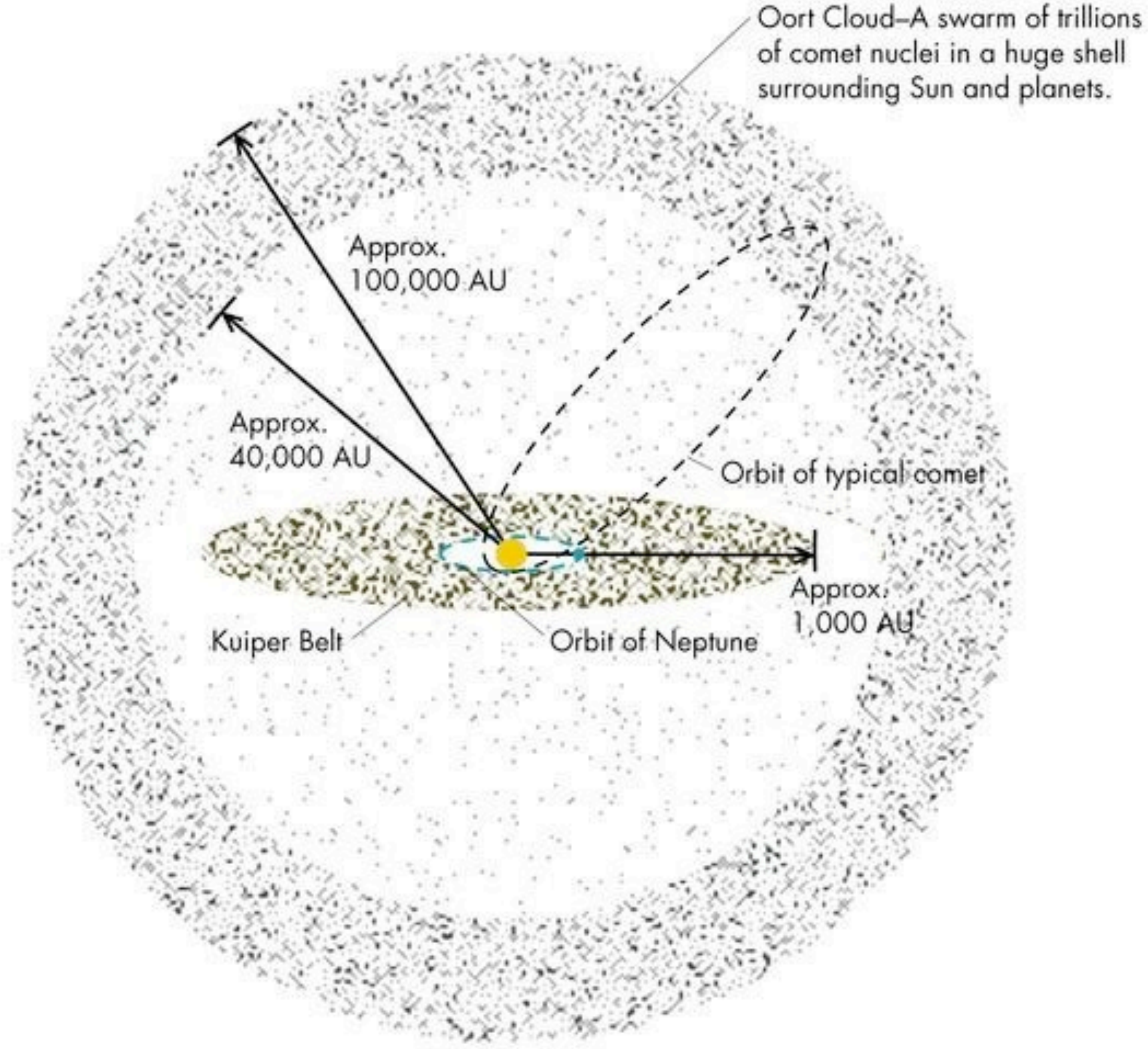


Trans-Neptunian objects

In 1950, Jan Oort noticed that

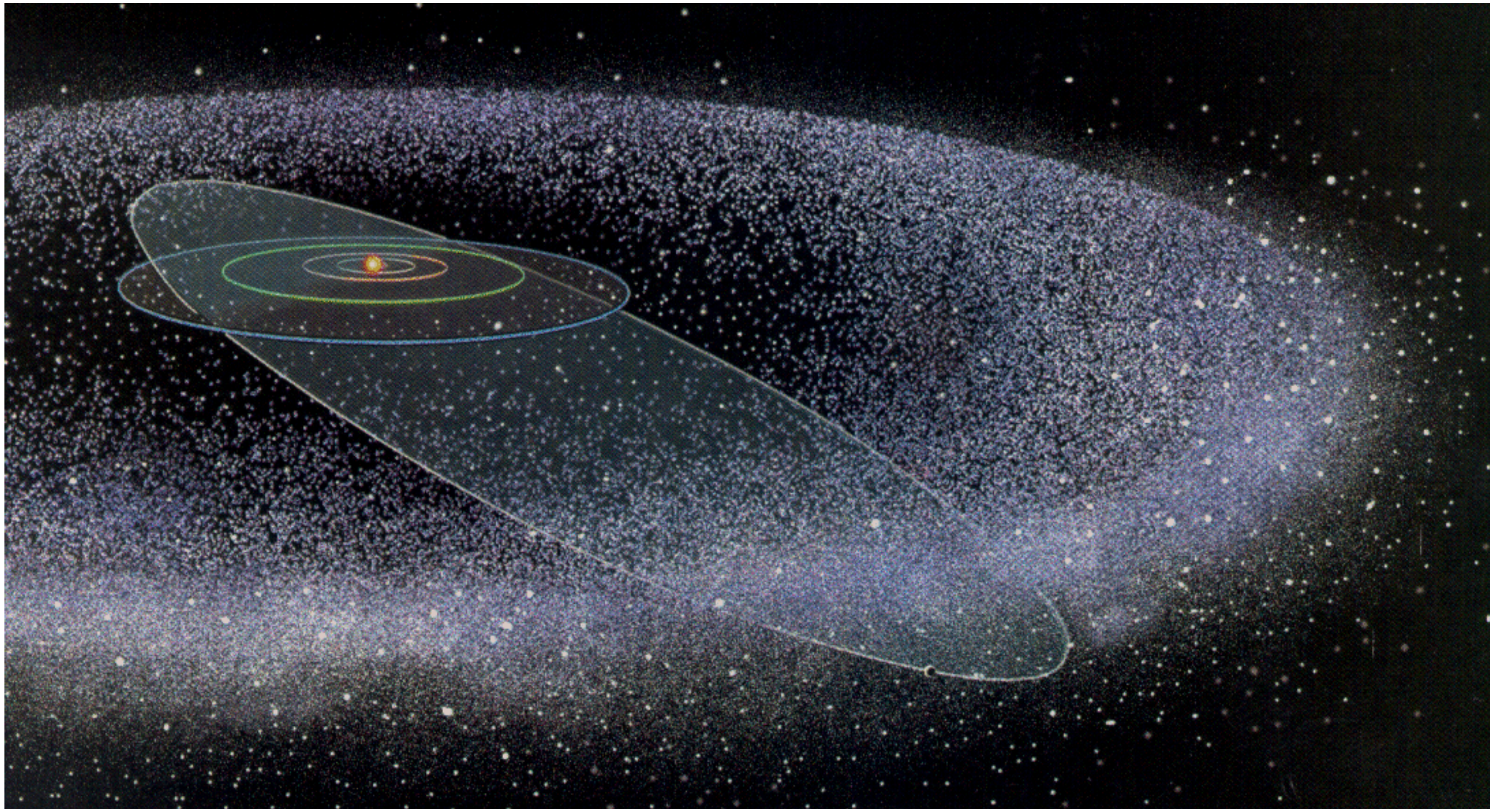
- no comet had an orbit indicating it came from interstellar space;
- the aphelion of most long-period comets lies at a distance of about 50,000 AU (1000 times the distance of Pluto); and
- comets come from all directions.

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.

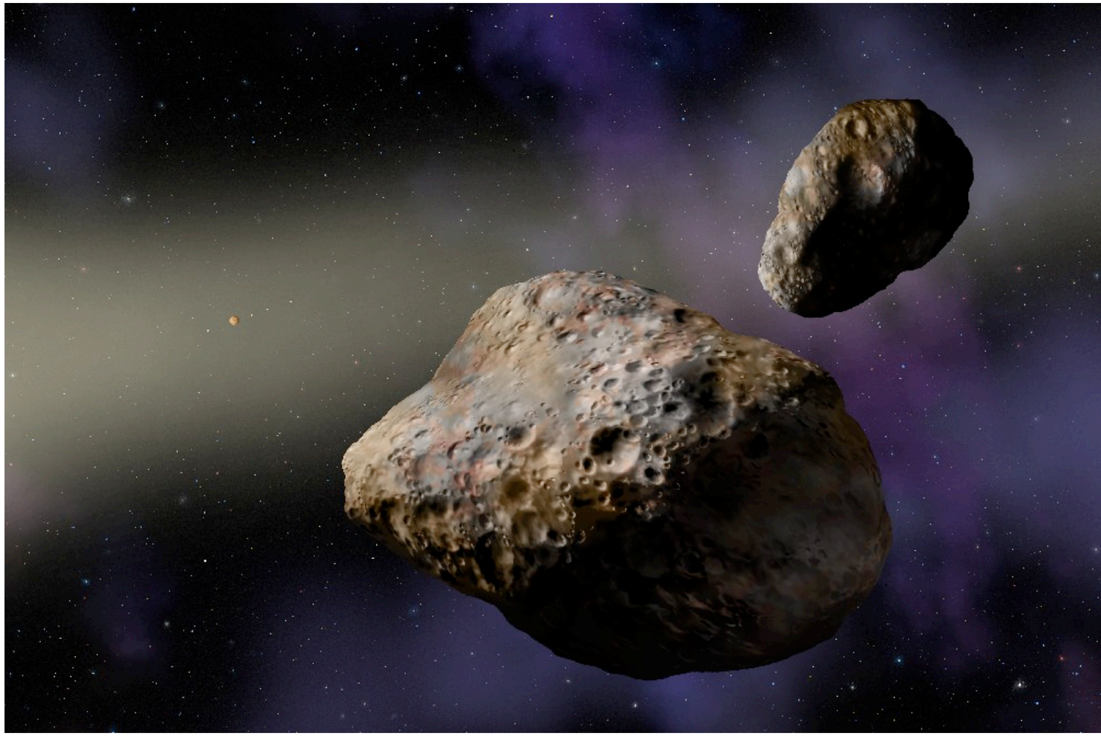

Oort Cloud–A swarm of trillions
of comet nuclei in a huge shell
surrounding Sun and planets.
Approx.
100,000 AU
Approx.
40,000 AU
Orbit of typical comet
Approx.
1,000 AU
Kuiper Belt
Orbit of Neptune

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.

We now know many objects in the Kuiper belt, but have not found any in the Oort Cloud. We will discuss the Kuiper Belt further in lecture 8.



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}.



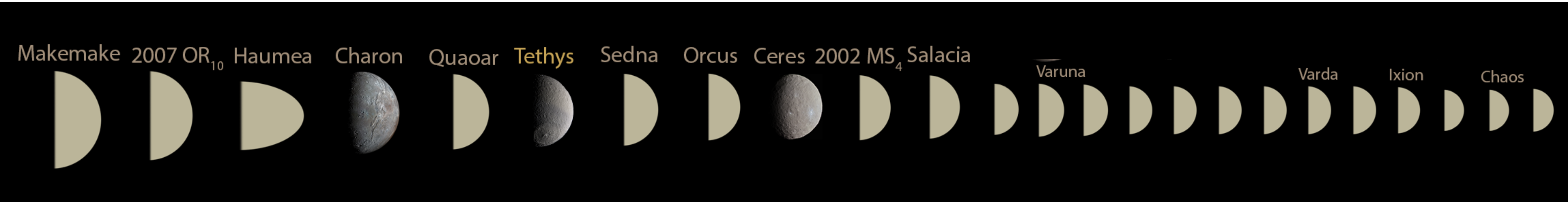
Artist's rendering of the binary asteroids Patroclus (centre) and Menoetius. Credit: W. M. Keck Observatory / Lynette Cook

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.

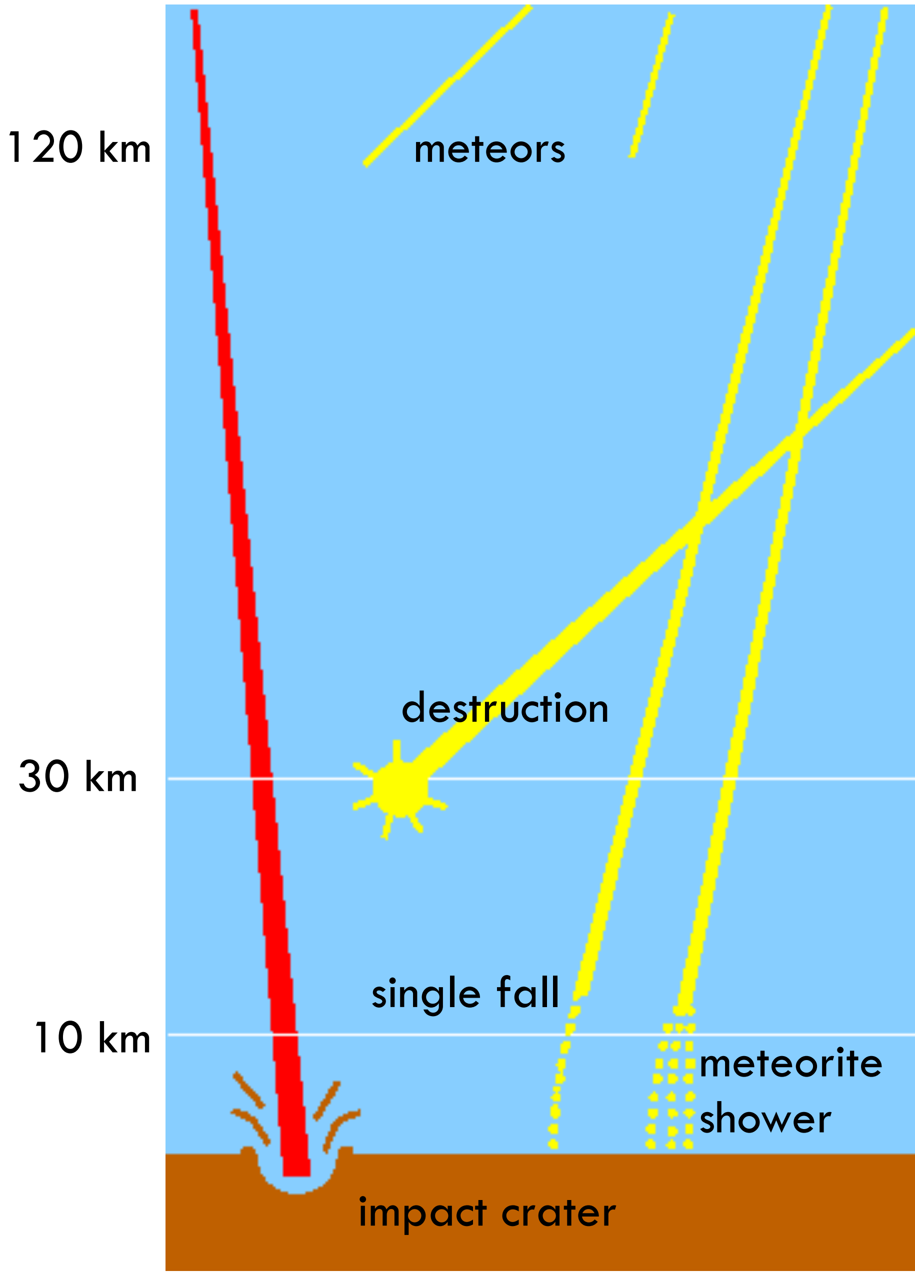
Larger rocks have a more dramatic descent. The Earth's gravitational well means that even a slow moving meteor enters the atmosphere at 11 km/s, or about mach 40. Friction with the air melts the surface of the body and vaporises the outer layer. A large volume of air around the rock becomes ionised, 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

Fireball meteor over Groningen in October 2009.

The vast majority of meteoroids are destroyed in the atmosphere. If the object is large enough and slow 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.

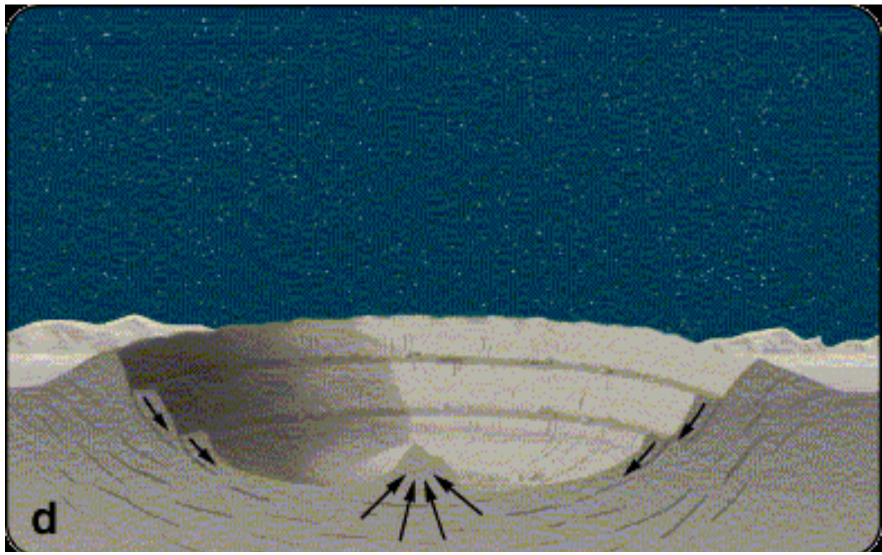


The meteorite approaches the surface at speeds of about 60 km/s.

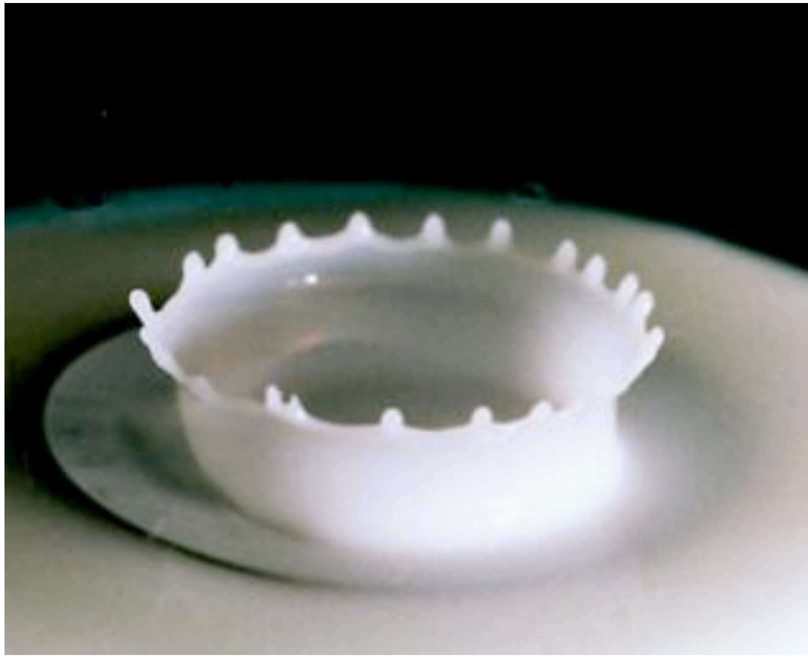
The projectile hits the surface and forms shock waves which propagate into the crust.

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.

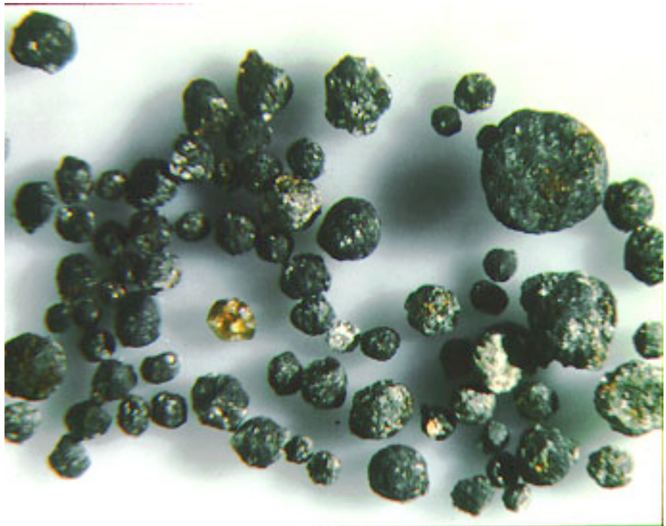


An impacting object a few km across generates a pressure hundreds of times the failure strength of rock. This means that *the rock effectively behaves as if it were water*. The stresses are so far beyond the strength of rocks that the impacted rocks behave as if they had no strength whatever. They flow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



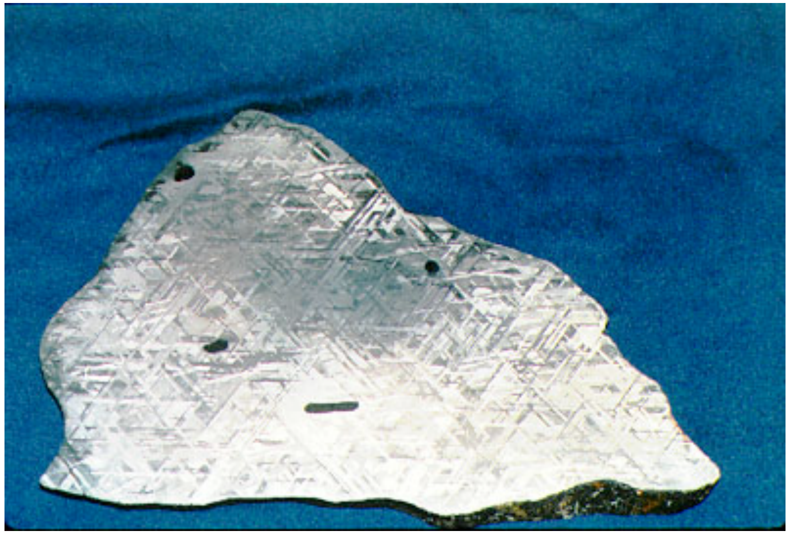
There are three main types of meteorites:

- 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.

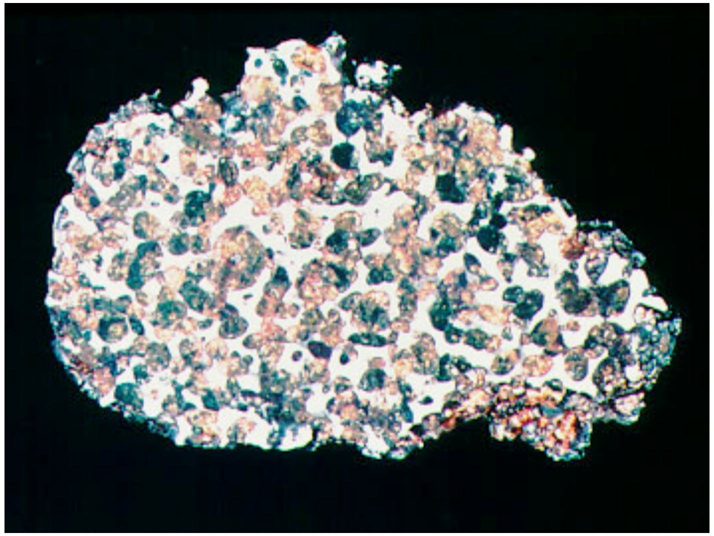


Chondrite (above left) and achondrite (above right) meteorites: the chondrite is made up of hundreds or thousands of small spherical chondrules (right).

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

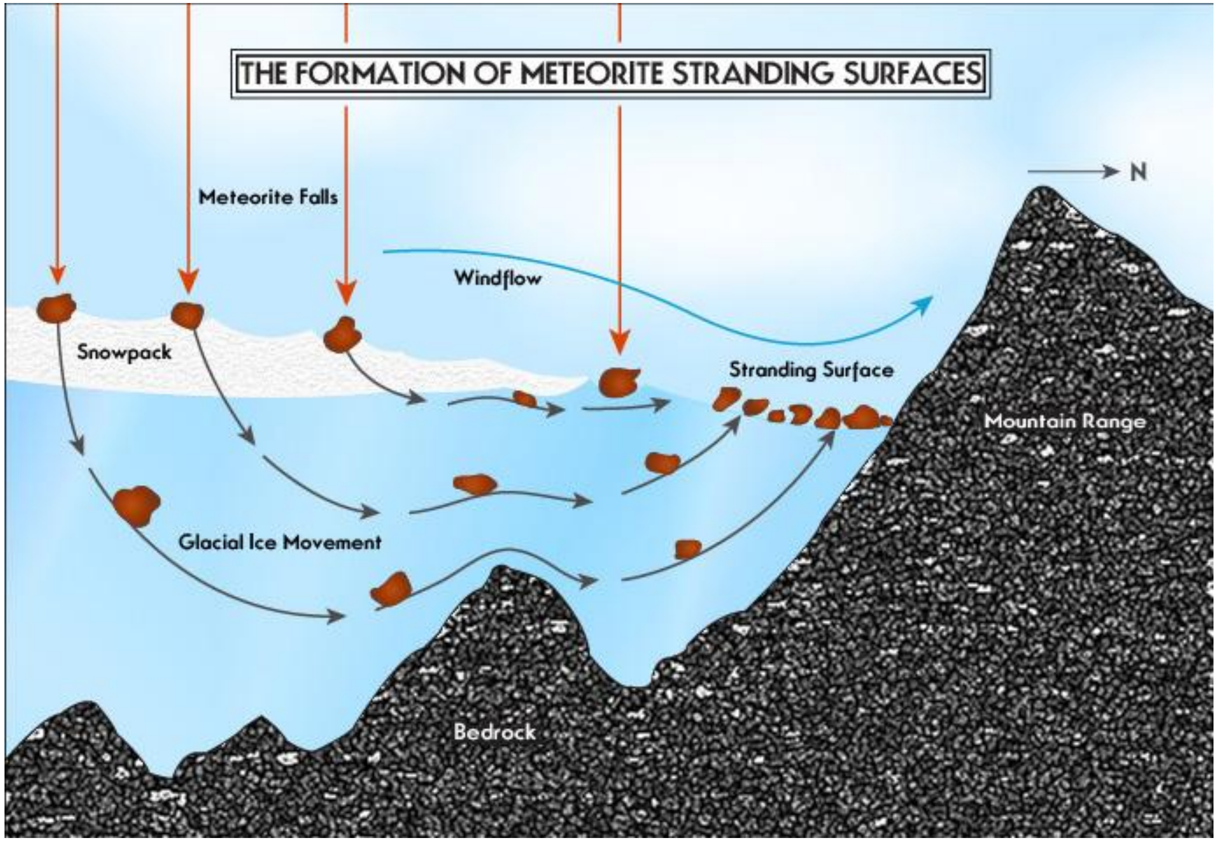


- stony-iron meteorites, mixtures of iron and stony material, like type S asteroids

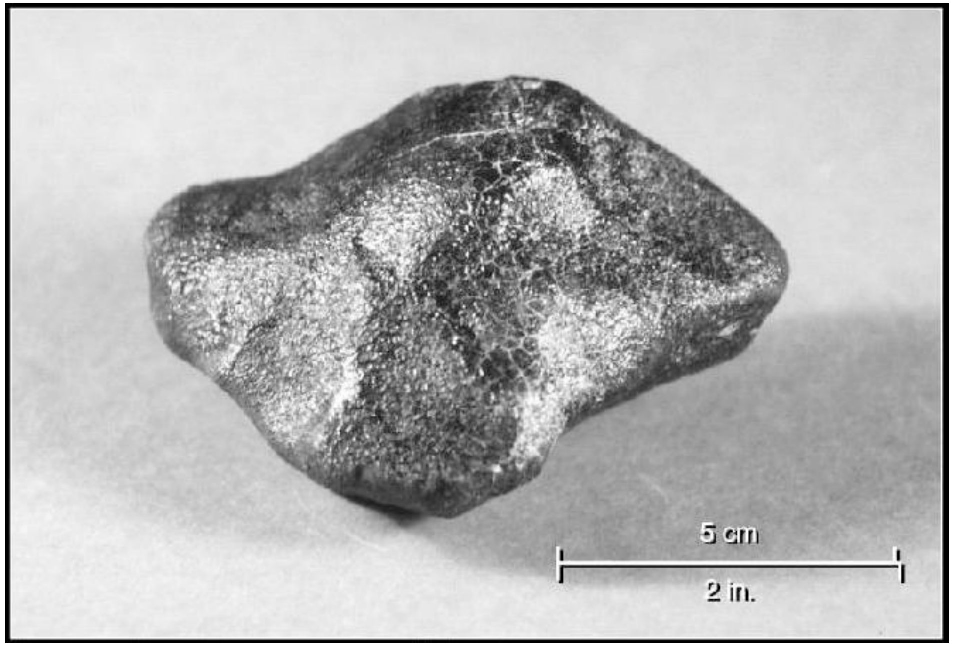


Iron meteorites are much easier to recognise than stony ones.

Antarctica turns out to be an excellent place to find meteorites.

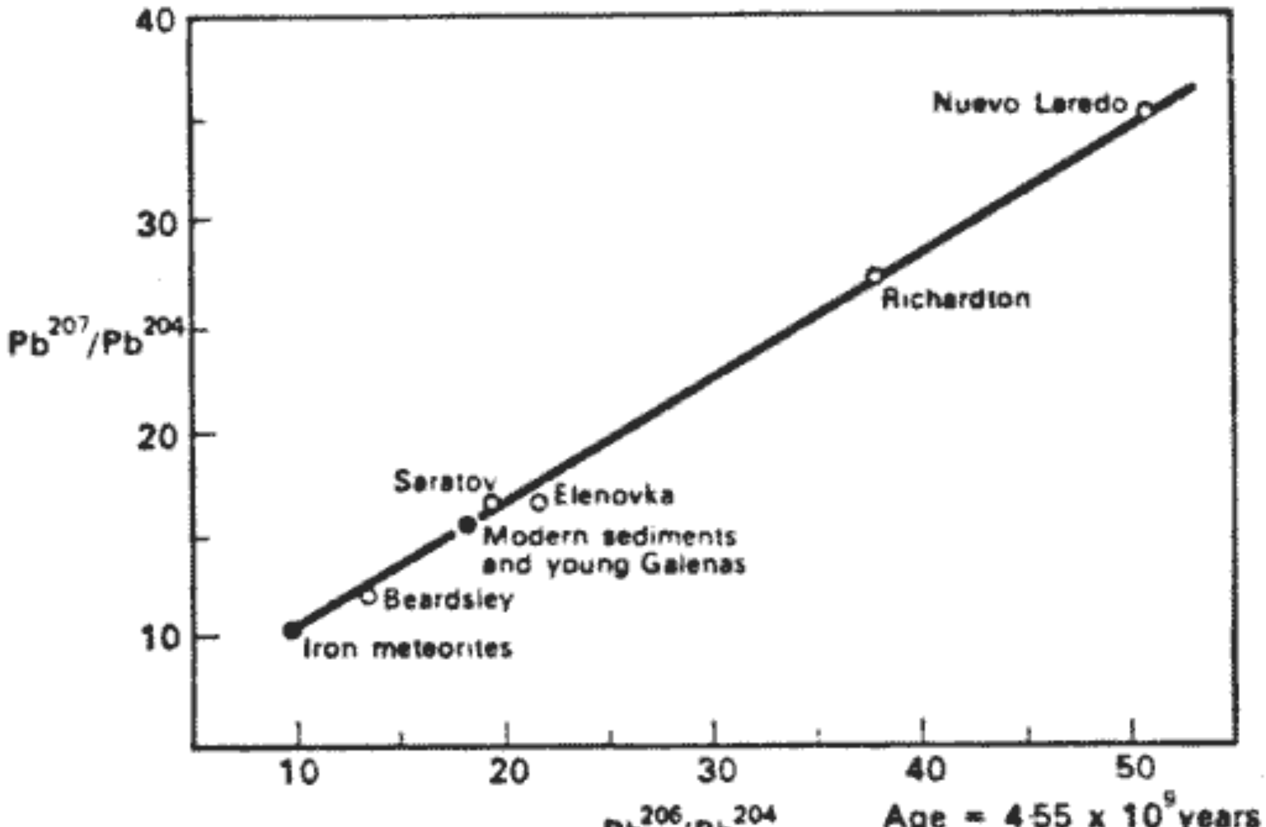


There are a few other types. This meteorite was found in Western Australia in 1960. Its composition and unique spectral signature suggests it came from Vesta.



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

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.



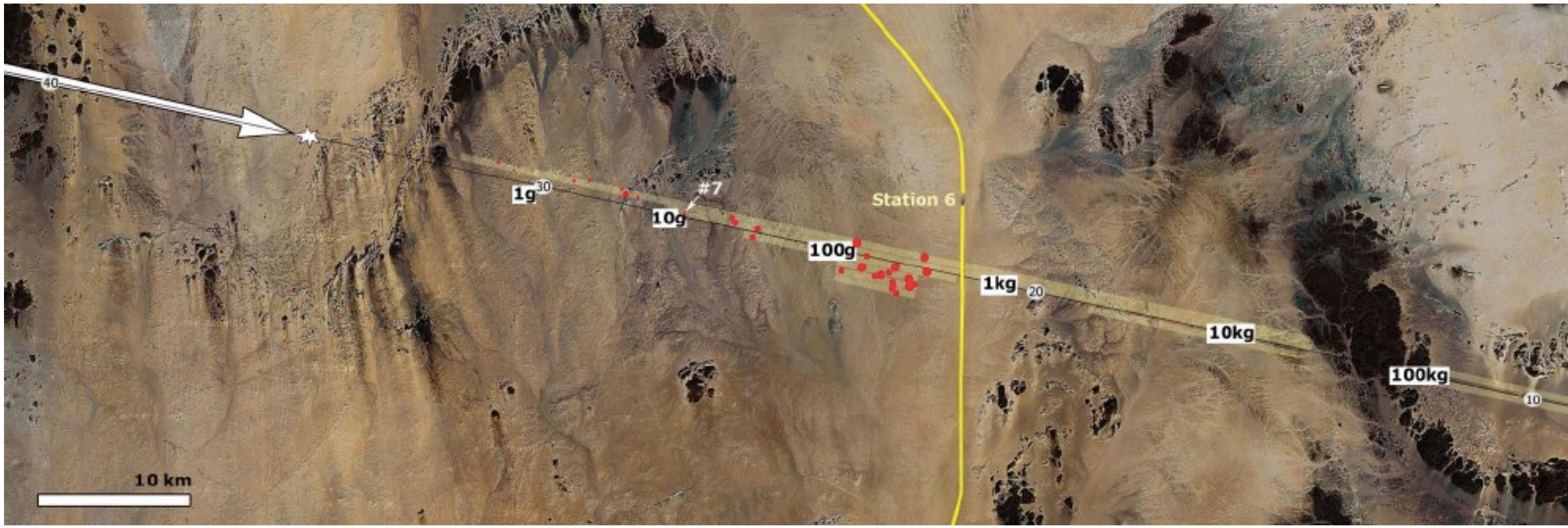
To fully understand meteorites, we need to know where they came from. Ideally, we would like to find meteorites where the entry fireball was captured by cameras from different angles, so that the orbit of the precursor meteor can be calculated. So far, there are just 26 such objects with reliable orbits.

These confirm that most meteorites are fragments of asteroids, though a small fraction may originate from comets.

There are also a handful of objects that must originate from the Moon or Mars, based on their composition, though none of these have documented orbits.

In October 2008, a near-earth asteroid called 2008 TC3 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, and hence the first meteorite fall to be predicted in advance.

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.



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.

en crushed if they
centre, says
sts that
nete-
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

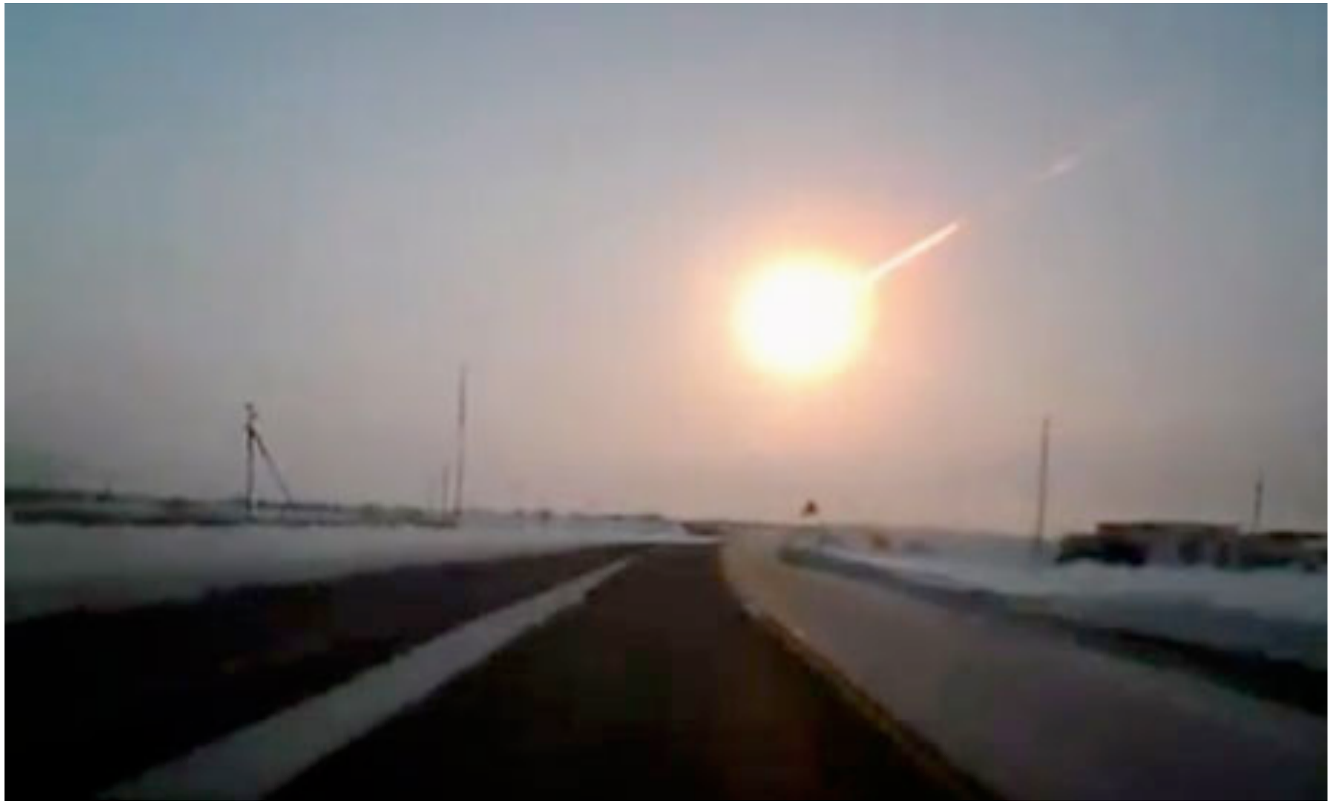
ting asteroid 2008 TC_3, Kowalski headed back up Mount Lemmon, heated his dinner and settled down in the telescope's control room. As his discovery plunged towards the desert on the other side of the world, Kowalski was surveying another part of the sky, waiting for the next white dot. ■

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).

On 15 February 2013 a large fireball – a *superbolide* – was seen over Chelyabinsk in Russia. The meteor had a diameter of about 20 m and weighed about 12,000 tons, making it the largest object to enter the atmosphere since the Tunguska event in 1908.



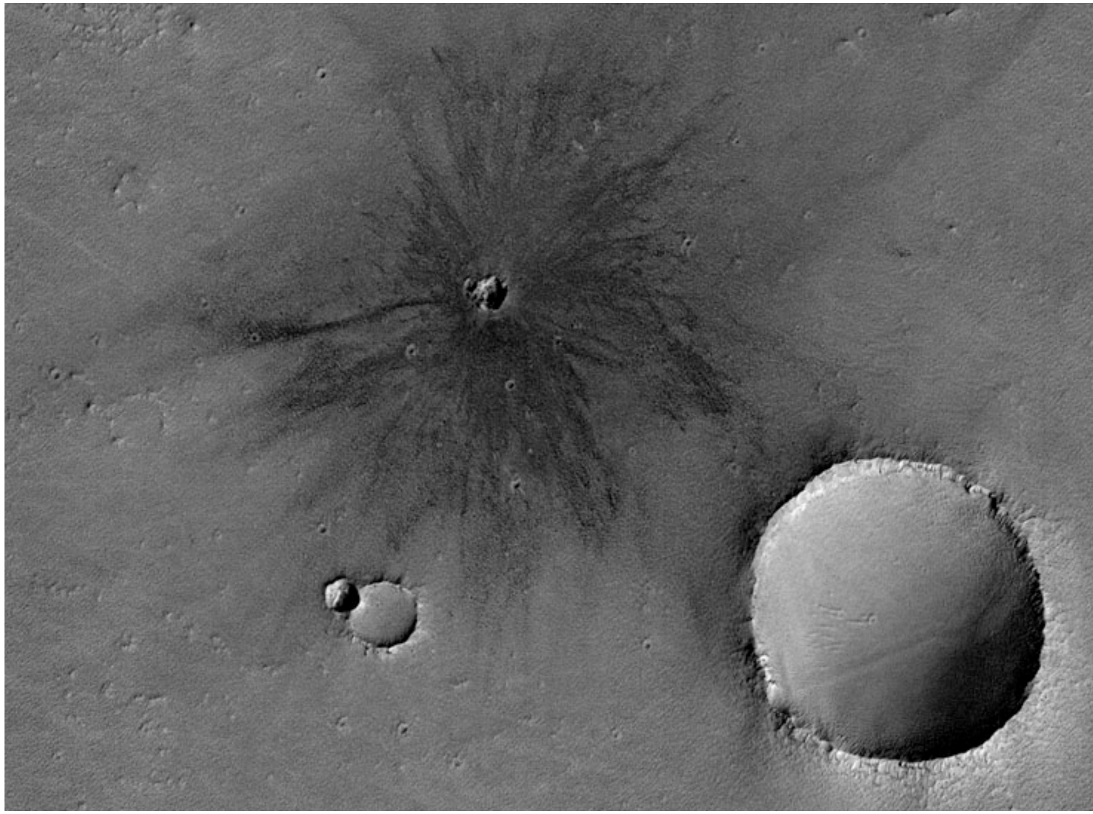
The event was recorded on a large number of dashboard cameras. 1500 people were injured, mainly by broken glass.

Fragments were recovered from the area, including a 654 kg fragment from the bottom of a lake. The recovered fragments were ordinary chondrite meteors, and the parent body is a member of the Apollo group of near-Earth asteroids.

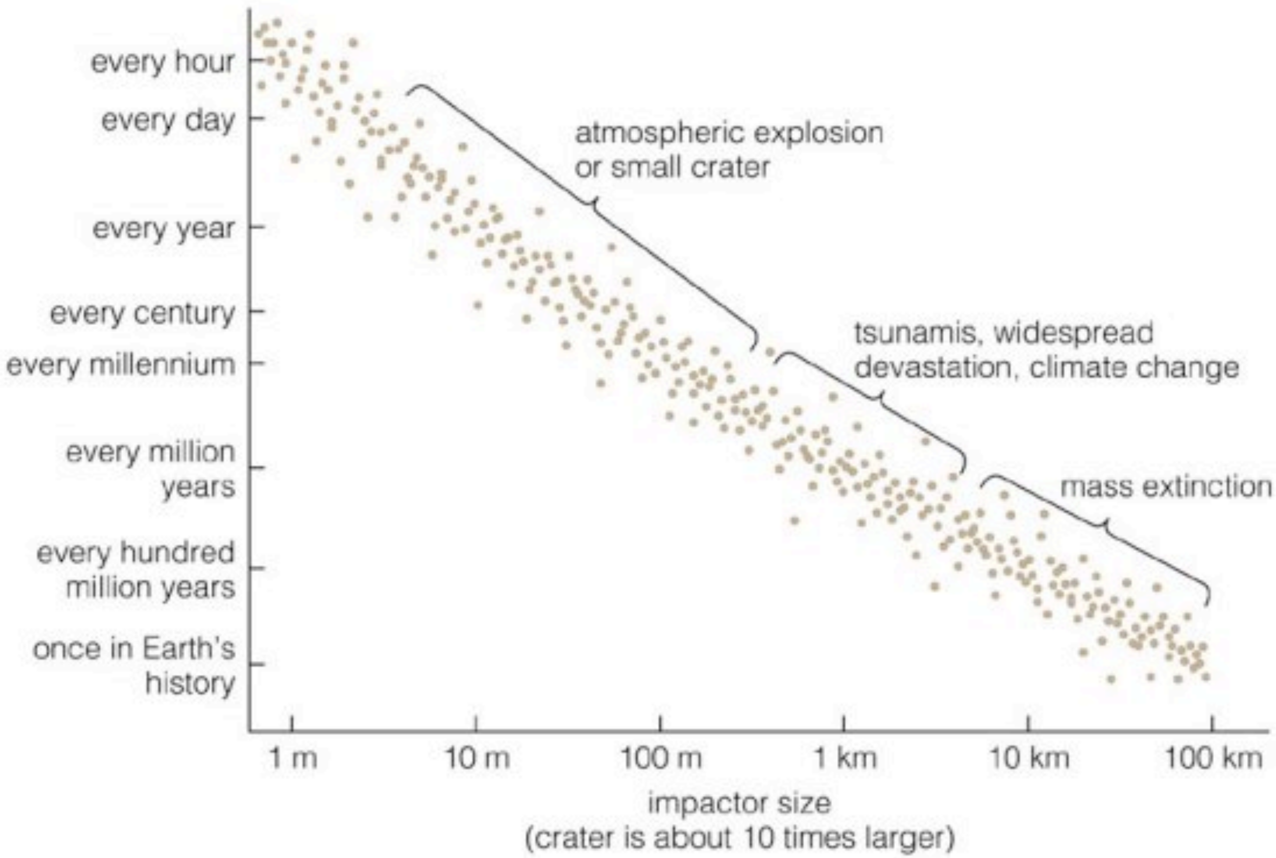
6-m wide hole in Chebarkul Lake made by meteorite debris.

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?



Fresh meteorite crater on Mars, about 8m in diameter, photographed in 2009. The crater was not present in images from Viking in the 1970s.


every hour
every day
every year
every century
every millennium
every million years
every hundred million years
once in Earth's history
atmospheric explosion or small crater
tsunamis, widespread devastation, climate change
mass extinction
1 m
10 m
100 m
1 km
10 km
100 km
impactor size
(crater is about 10 times larger)

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.

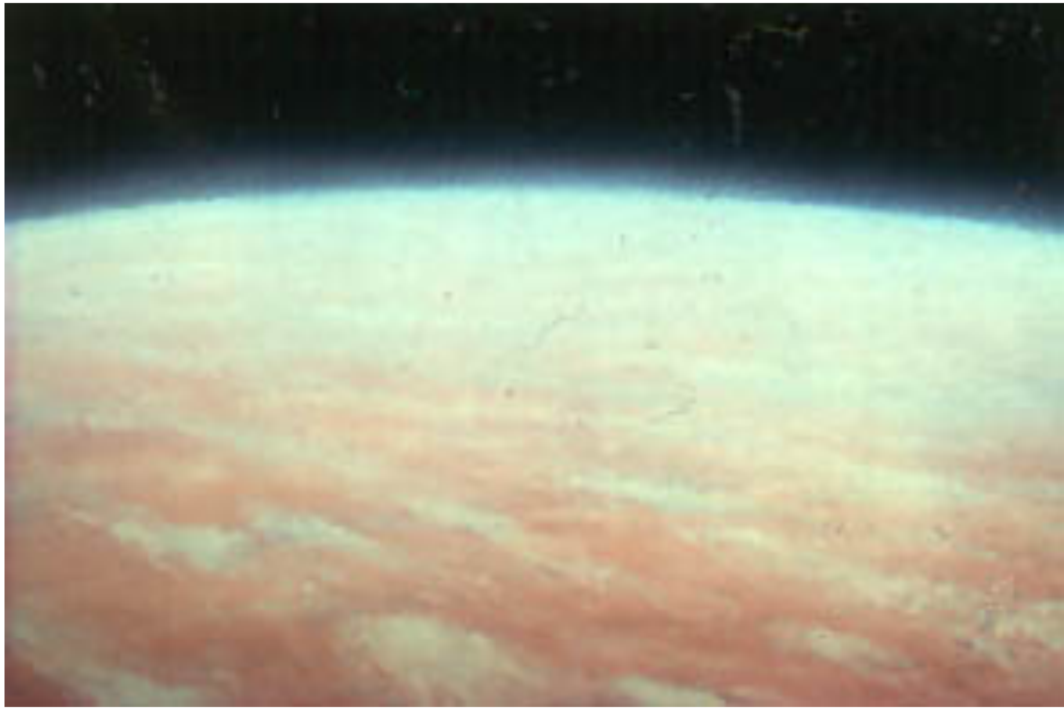
During the late Cretaceous, the Yucatan Peninsular was a shallow sea, so the meteor probably landed in less than 100m of seawater.

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.

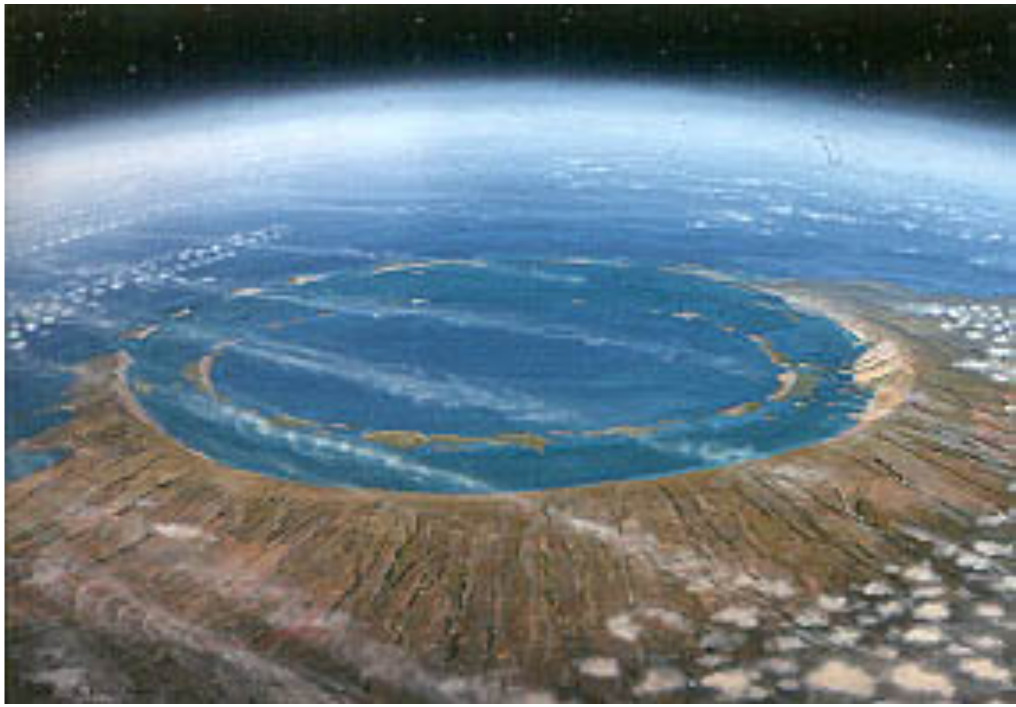
During the late Cretaceous, the Yucatan Peninsular was a shallow sea, so the meteor probably landed in less than 100m of seawater.

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.

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



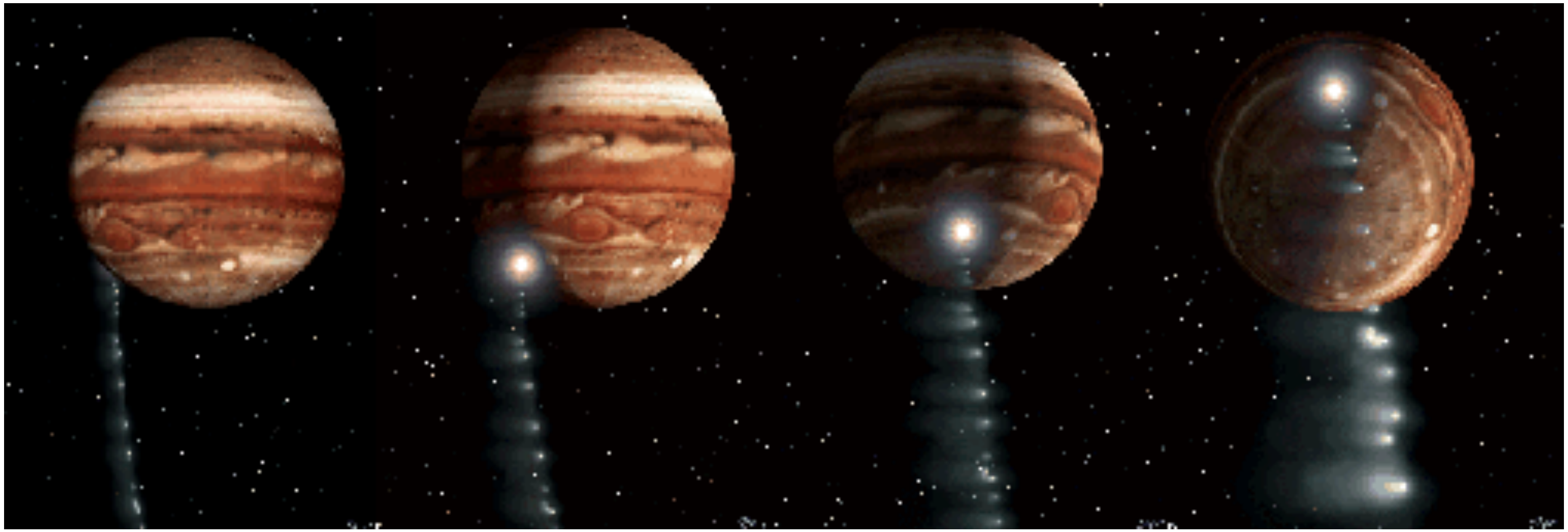
The excavated crater was 15–20 km deep and about 200 km in diameter. The impact caused an earthquake of magnitude 12 to 13.



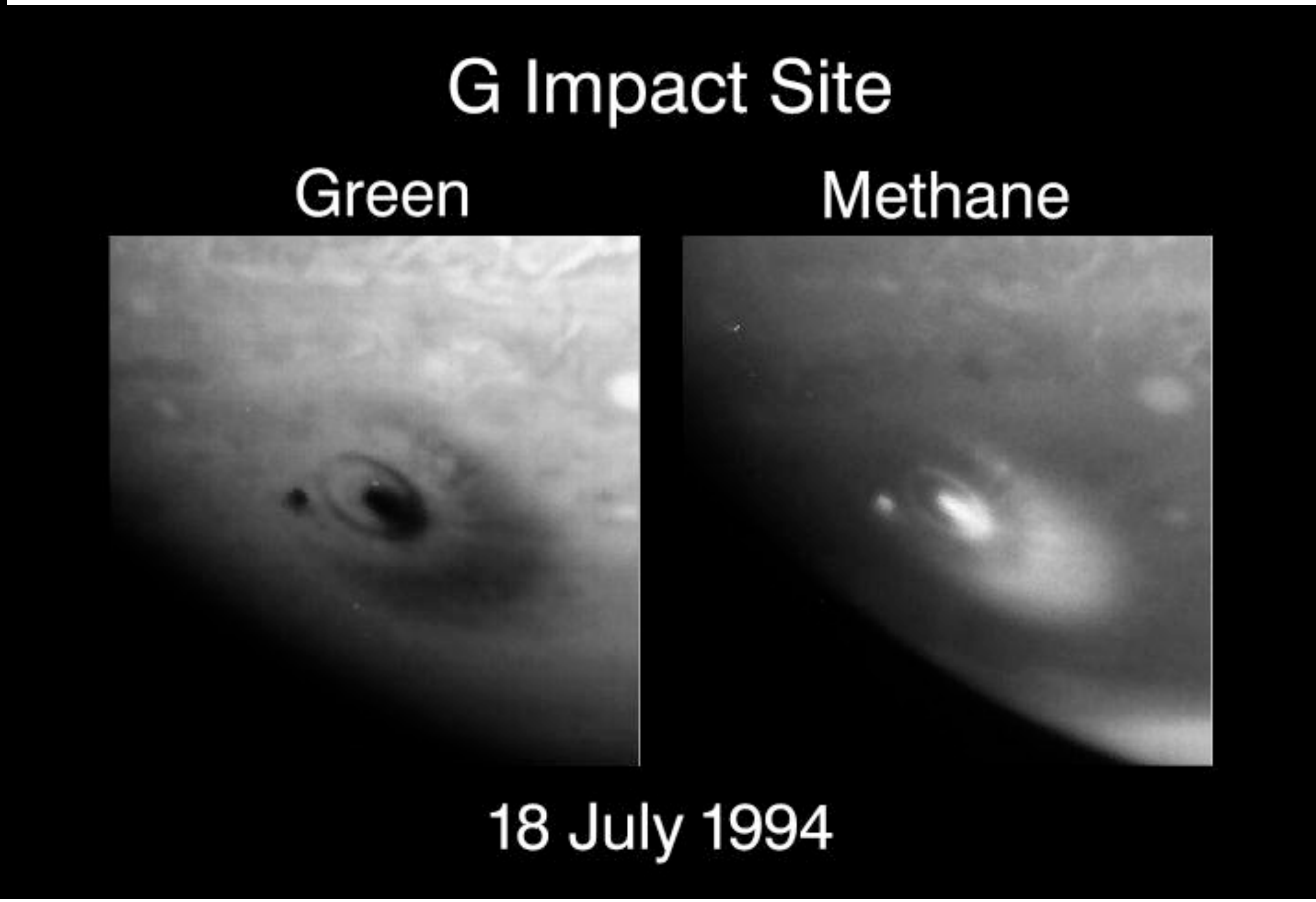
Over 70% of species were made extinct by the Yucatan impact. Some people estimate that 99% of individuals were killed, even in species which survived.

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.

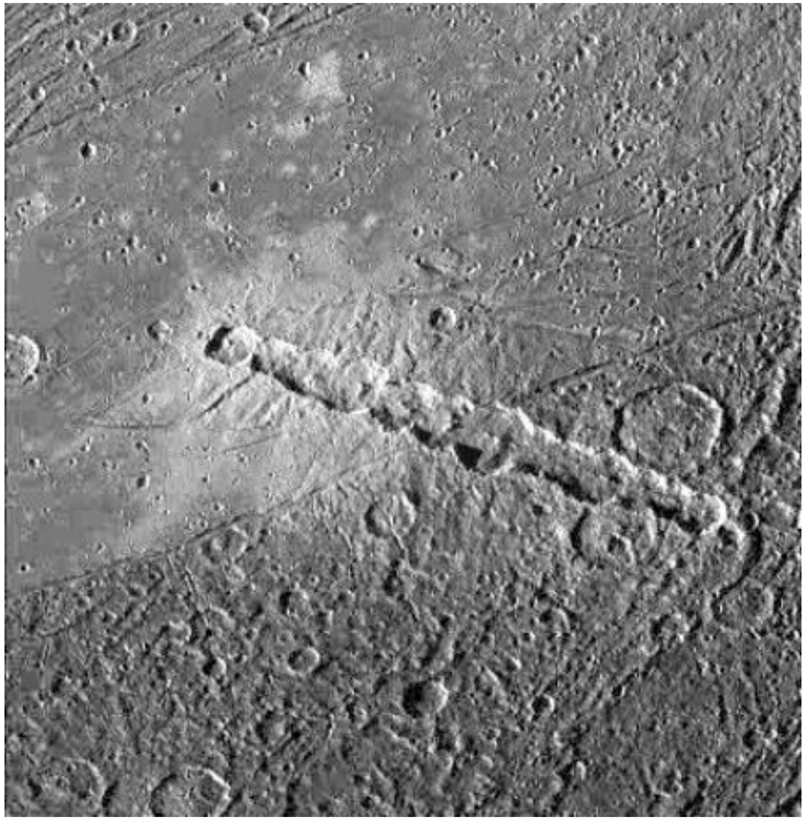
In July 1994, we got a chance to see a comet impact in detail, when Comet Shoemaker-Levy 9 impacted on Jupiter. Several effects of the impact were just as predicted for the Chicxulub event.



(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.

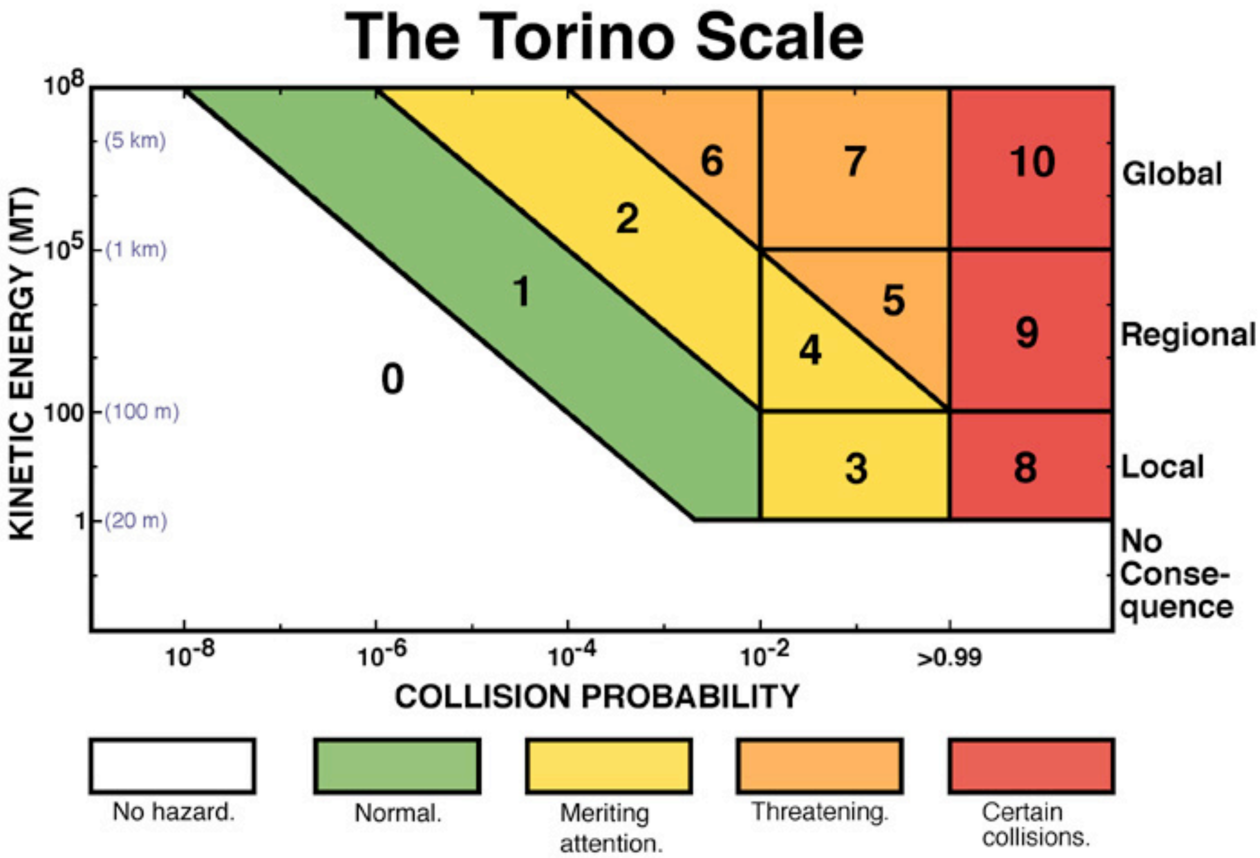


The Shoemaker-Levy collision offered a dramatic explanation for the mysterious *crater chains* that had been seen on several solar system bodies.



Crater chains on Ganymede (left) 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

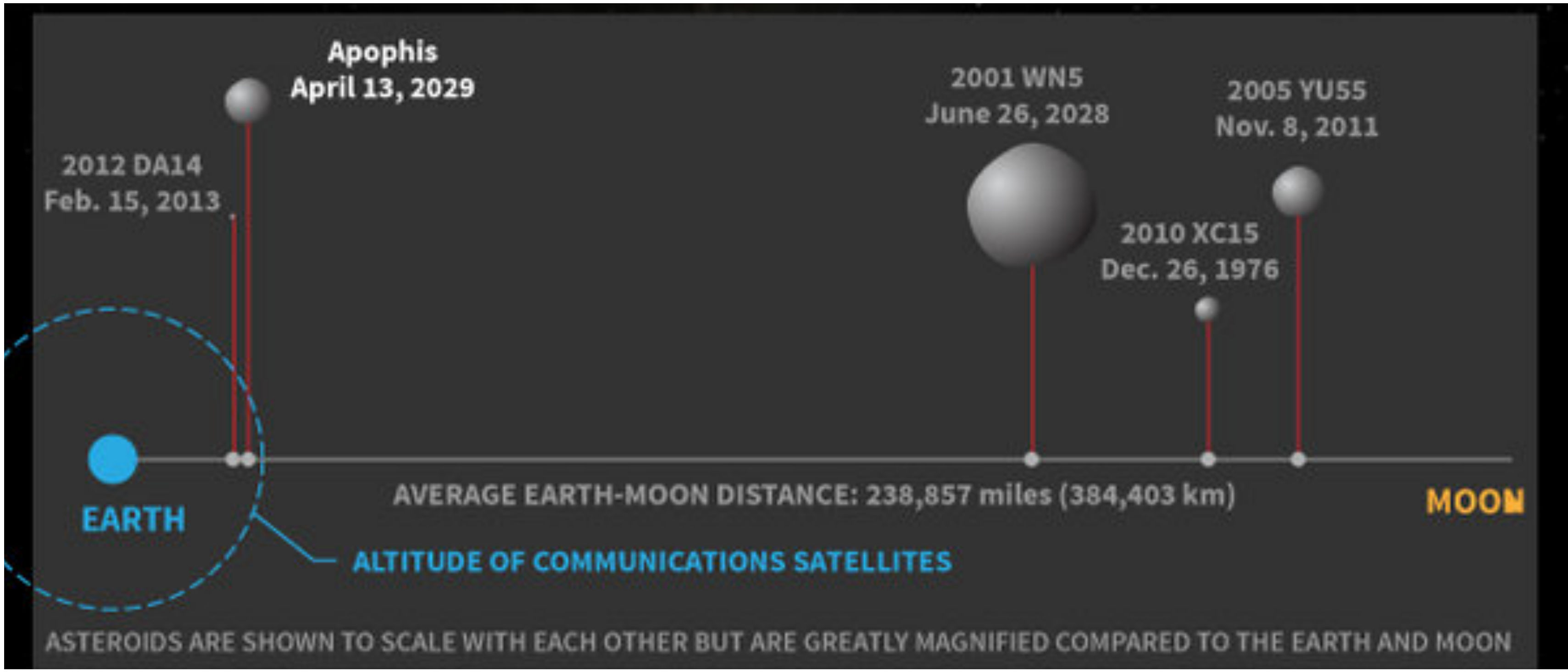
No Hazard	0	The likelihood of collision is zero, or is so low as to be effectively zero. Also applies to small objects such as meteors and bolides that burn up in the atmosphere as well as infrequent meteorite falls that rarely cause damage.
Normal	1	A routine discovery in which a pass near the Earth 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 24 December 2004, the value was pushed to TS=4, with odds of impact 1 in 60, then 1 in 45, as the orbit was refined.

Subsequent observations, as well as “precovery” observations, have reduced the odds of impact to 1 in 250,000.

Based on the albedo, the diameter of 99942 Apophis is about 320 meters. At the time of the closest approach, the asteroid will be a naked eye object (3.3 mag.) travelling rapidly (42 degrees per hour!) through the constellation of Cancer.



The close approach of 99942 Apophis in 2029

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:

- "**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.
- 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.greater-san-antonio.com/kokogiakcom/solarsystembodieslargerthan200miles. Because this was made in 2007, some of the dwarf planets, like Haumea and Makemake, still have their provisional designations.
- Mike Brown's list of dwarf planets http://www.gps.caltech.edu/~mbrown/dps.html

- 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.ch/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, then press "Update" to see where the comet is now. Thus it's easy to see that, although it's only 31 years after its last perihelion, and there are 44 years until the next one, Halley is past 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.
- 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.
- The home page of the Dawn mission to Vesta and Ceres is at http://dawn.jpl.nasa.gov/
- The home page for the Rosetta mission is at http://sci.esa.int/rosetta/
- 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
- 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/

- 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).
- 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://www.minorplanetcenter.net/iau/lists/CloseApp.html
- The BBC has a news story about 2008 TC3, the asteroid that hit Sudan, at http://news.bbc.co.uk/2/hi/science/nature/7964891.stm
- A list of currently known meteorites with orbits is at http://www.meteoriteorbits.info/
- 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:

- Asteroid cover picture: Galileo image of asteroid 951 Gaspra, from APOD 2002 October 27 https://apod.nasa.gov/apod/ap021027.html
- Moon and asteroids: from Alan Taylor's "All (known) Bodies in the Solar System Larger than 200 Miles in Diameter", http://www.greater-san-antonio.com/kokogiakcom/solarsystembodieslargerthan200miles
- Asteroids visited by spacecraft: montage by Emily Lakdawalla, from http://www.planetary.org/multimedia/space-images/small-bodies/asteroids-and-comets-color-2012.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
- 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
- Moon-Ceres-Vesta comparison: from "Vesta in perspective", https://dawn.jpl.nasa.gov/multimedia/vesta_in_perspective.asp
- Asteroid shapes: Mathilde, Gaspra, and Ida, from Astronomy Picture of the Day March 13, 1998 https://apod.nasa.gov/apod/ap980313.html
- Mathilde flyby: NEAR images: animation and video http://near.jhuapl.edu/Images/.Anim.html
- Dawn mission image: from https://www.jpl.nasa.gov/events/lectures_archive.php?year=2016&month=7; orbit, from https://dawn.jpl.nasa.gov/mission/journal_09_27_17.html
- Ceres/Vesta size comparison: image credit NASA/JPL, from https://www.universetoday.com/121807/the-dwarf-planet-ceres/
- Animation and model of Vesta: from the Hubble News Center Archive http://hubblesite.org/newscenter/archive/1997/27/
- Vesta compared: from http://www.sciencemag.org/content/336/6082/684.figures-only
- Rheasilvia basin: from http://dawn.jpl.nasa.gov/multimedia/images/PIA15665_700.jpg
- Troughs on Vesta: from http://dawn.jpl.nasa.gov/multimedia/asteroid_vesta_surface.asp
- Gullies: from http://dawn.jpl.nasa.gov/feature_stories/what_is_creating_gullies_on_vesta.asp
- Dawn's Greatest Hits at Vesta video, from https://www.jpl.nasa.gov/video/details.php?id=1136
- Dwarf planet Ceres: from APOD 2016 February 4 https://apod.nasa.gov/apod/ap160204.html
- Gaue crater showing sunken pit: from https://www.nasa.gov/jpl/pia19633/gaue-crater-ceres
- Occator crater: from https://dawn.jpl.nasa.gov/science/ceres.html and https://www.jpl.nasa.gov/spaceimages/details.php?id=PIA20350
- Ahuna Mons: from https://dawn.jpl.nasa.gov/multimedia/images/image-detail.html?id=PIA20348
- Binary asteroid: Astronomy Picture of the Day 2004 June 19 https://apod.nasa.gov/apod/ap040619.html
- Tidal disruption simulation: from Walsh & Richardson 2006, "Binary near-Earth asteroid formation: Rubble pile model of tidal disruptions", Icarus 180, 201
- Itokawa: from Wikipedia http://en.wikipedia.org/wiki/25143_Itokawa
- Patroclus and Menoetius: Frank Marchis "Study of Patroclus and Menoetius: A Double Trojan System" http://astro.berkeley.edu/~fmarchis/Science/Asteroids/Patroclus/
- Asbolus: Hubble Site release STScI-2000-31 http://hubblesite.org/newscenter/archive/releases/solar-system/kuiper-belt-object/2000/31/
- Comet cover image: Comet Lemmon, image by Gerald Rhemann, from APOD 2013 May 6 https://apod.nasa.gov/apod/ap130506.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
- Structure of a comet: from *Universe*, Fig. 15_26 http://www.public.asu.edu/~atpcs/atpcs/Univ10e/Images/figure_15_26.jpg
- Coma: Comet C/2013 X1 (PanSTARRS), from Astronomy Picture of the Day 2016 June 5 https://apod.nasa.gov/apod/ap160605.html
- Comet’s tail: Hale-Bopp, from Astronomy Picture of the Day 27 December 2000 https://apod.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 https://apod.nasa.gov/apod/ap070331.html
- Hartley 2: from http://science.nasa.gov/science-news/science-at-nasa/2010/18nov_cometsnowstorm/ Jets from Comet Churyumov-Gerasimenko: from APOD 2015 Feb 3 https://apod.nasa.gov/apod/ap150203.html
- Comet McNaught: picture by Robert McNaught, from Astronomy Picture of the Day 2007 January 22 https://apod.nasa.gov/apod/ap070122.html; comet over Bendalong, photo by Alain Picard
- Comets visited by spacecraft: from The Planetary Society, http://www.planetary.org/multimedia/space-images/small-bodies/comets-visited-by-spacecraft-2014.html
- Deep Impact image: from Deep Impact gallery 1
- Rosetta image of nucleus: from APOD 7 August 2014 http://apod.nasa.gov/apod/ap140807.html
- 67P from 62 km above the surface: APOD 15 September 2014 http://apod.nasa.gov/apod/ap140915.html
- Landing site and probe on surface: from http://www.bbc.com/news/science-environment-29203284
- Rosetta image from 19 September: http://blogs.esa.int/rosetta/2014/09/19/cometwatch-19-september/
- SOHO comet: from SOHO gallery http://sohowww.nascom.nasa.gov/gallery/images/xmascomet.html
- Comet orbits: from Wikipedia https://en.wikipedia.org/wiki/153P/Ikeya%E2%80%93Zhang
- Artist's view of Kuiper belt object “Quaoar”: image by NASA and G. Bacon, http://hubblesite.org/image/1220/news/60-kuiper-belt-objects
- 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
- Kuiper belt: from http://www.dailygalaxy.com/my_weblog/2016/04/odd-oort-cloud-object-reveals-ancient-clues-to-origin-of-our-solar-system.html
- Binary asteroid: from http://www.berkeley.edu/news/media/releases/2006/02/01_patroclus.shtml
- Small solar system bodies: from http://www.planetary.org/multimedia/space-images/charts/every-round-object-under-10k-2015.html
- Meteor title image: Comet dust over Enchanted Rock, by Jared Tennant, from APOD 2015 August 14 https://apod.nasa.gov/apod/ap150814.html
- Fireball: Leonid fireball, from Astronomy Picture of the Day 2 December 1999 https://apod.nasa.gov/apod/ap991202.html
- Fireball over Groningen: from APOD 2009 October 15, http://apod.nasa.gov/apod/ap091015.html
- Chelyabinsk fireball: from http://www.theguardian.com/science/2013/dec/30/chelyabinsk-meteorite-earth-warning-shot-space
- Chelyabinsk video compilation: from https://www.youtube.com/watch?v=SMnZr5DDRIA
- 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
- Finding meteorites in Antarctica: from http://expeditions.fieldmuseum.org/antarctic-meteorites/media/collecting-meteorites
- 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 TC3, from Nature vol 458, pp 401 and 485

- Meteorite crater on Mars: from Discovery News, “Mars scarred by meteorite impact” http://news.discovery.com/space/mars-hirise-impact-crater.html
- Impact frequency: from “Collisions with near Earth objects” http://www.aerospaceweb.org/question/astronomy/q0296.shtml
- Impacts and life: Table 1 from “How common are habitable planets” by Jack Lissauer, 1999, Nature 402, C11, available at http://www.kepler.arc.nasa.gov/papers.html
- K-T impact with dinosaurs: from CNN, “Scientists to drill at site of dinosaur-killing asteroid crater”, http://edition.cnn.com/2016/03/04/world/scientists-drill-impact-crater-irpt/index.html
- Animation of K-T impact: from The Wright Center for Science Education, Tufts University, "It's Judgement Day" http://www.tufts.edu/as/wright_center/impact/impacta.html
- 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/
- Crater chains: Ganymede: from Astronomy Picture of the Day, 2001 December 15, https://apod.nasa.gov/apod/ap011215.html. Moon: from Lunar Photo of the Day, January 27 2004, http://www.lpod.org/archive/2004/01/LPOD-2004-01-27.htm
- Torino Impact Scale: from “Asteroid and Comet Impact Hazards”, http://impact.arc.nasa.gov/torino.cfm
- 99942 Apophis orbit predictions: from “Collisions with near Earth objects” http://www.aerospaceweb.org/question/astronomy/q0296.shtml
- B612 Impact video: from http://www.wired.co.uk/news/archive/2014-04/22/asteroid-impacts