8 Comets and meteorites

8.1 Overview of minor bodies of the Solar system

Asteroids:
- Sizes: 500km (Ceres) down to the size of large boulders
- Made of rock & metals (density 2-3 g cm\(^{-3}\))

Meteoroids:
- Bits of rock and metal (iron)
- Sizes: grains of sand up to small boulders

Comets:
- Composite rock & ice "dirty snowballs"
- Develop long tails of gas & dust swept off them when they pass near the Sun.

The "Frost Line"

Rocks and metals can form anywhere it is cooler than about 1300 K
Carbon grains & ices can only form where the gas is cooler than 300 K

Inner Solar System:
- Too hot for ices & carbon grains
- Asteroid belt

Outer Solar System:
- Carbon grains & ices form beyond the "frost line"
- Ices condense very quickly onto rocky cores
- Stay small because of a lack of material
- Gravity of the proto-Neptune played an important role:
  - assisted the formation of Pluto-sized bodies in 3:2 resonance orbits (Pluto and Plutinos)
  - dispersed the rest into the Kuiper Belt to become Kuiper Belt Objects

The location of the "frost line" is a matter of some debate, but current understanding is that it is probably about 4 AU from the Sun. It depends on how much solar radiation can penetrate deep into the outer parts of the primordial Solar Nebula.

⇒ Comets and other Trans-Neptunian objects are the leftover icy planetosimals from the formation of the Solar System.

Time scales

- The whole planetary assembly process probably took about 100 Million years.
- Followed by a 1 Billion year period during which the planets were subjected to heavy bombardment by the remaining rocky & icy pieces leftover from planet formation.
8.2 Asteroids

Asteroids
- Small bodies in the inner solar system
- Asteroid Belt between Mars & Jupiter.
- Orbits are strongly influenced by Jupiter.
- Made of rock, metal, or a mix of the two.
- Monoliths and rubble piles


Asteroid belt

The gap between the orbits of Mars (1.5 AU) and Jupiter (5 AU) with no planets.

Searches started in the late 1700s to find a planet in this region
- 1801: Giuseppe Piazzi discovered Ceres at 2.8 AU
  - too small to be a planet (914 km)

By 2005, telescopic surveys have found:
- >20,000 asteroids with determined orbits and names
- another >60,000 with insufficient orbit data
- the name is given when the orbit is known

90% of asteroids are in the "main belt":
- between about 2.1 and 3.2 AU
- orbits can be tilted up to 15° (a few up to 30°)
- Some orbits are fairly eccentric (e=0.15)
- ~5 million km apart on average.
Kirkwood Gaps

Gaps in the asteroid population are found at orbital resonances with Jupiter:
- 2:1 resonance at 3.3 AU
- 3:1 resonance at 2.5 AU
- The Main Belt is between the 2:1 & 4:1 resonances

Confining resonances: Asteroids are confined to specific orbits (families):
- 3:2 (Hildas)
- 7:2 (Floras)
- 1:1 (Trojans, lead or trail Jupiter by 60°)

⇒ Asteroids are either cleared from resonant orbits or trapped in resonances

Sizes of Asteroids

Largest asteroid is Ceres:
- 914 km across
- mass of $2 \times 10^{-4}$ M⊕

The rest are much smaller:
- Only ~100 are >140 km across.
- About 100,000 >1 km across.
- Total mass in asteroids is only ~8 $\times 10^{-4}$ M⊕
- About enough for a mid-sized rocky moon (~0.1 of the Moon’s mass)
Shapes of Asteroids

Asteroids are irregular in shape:
- Too small for gravity to make them spherical
- Even the largest, Ceres, is only semi-round
- Have heavily cratered surfaces and a regolith of pulverized material.

Rotate as they orbit:
- Most have rotation periods of ~9 hours.
- Extreme range from <3 hours to many weeks, probably reflecting different collision histories.

Monoliths or Rubble Piles?

Some asteroids are clearly solid pieces of rock and metal:
- Densities of 3-5 g cm\(^{-3}\), like solid rock and metals
- Heavily cratered surfaces and dusty regoliths

Others appear to be "Rubble Piles"
- Lower in density (1-2 g cm\(^{-3}\)), but clearly composed of rock
- Loose aggregates of rock held together by mutual gravity
- Perhaps porous, up to 80% of voids

The rubble pile asteroids were probably formerly solid, but got shattered by impacts.
Examples of rubble pile asteroids with unusually low densities for their composition are 253 Mathilda (~1.3 g cm\(^{-3}\)) and 25143 Itokawa (~2.3 g cm\(^{-3}\)).

Near Earth Asteroids (NEAs)

Earth-crossing Asteroids:
- Apollo & Aten groups ~1AU
- Source of asteroids that could potentially hit the Earth.

NEAs
- ~2000 known objects
- ~400 Potentially Hazardous Asteroids (PHAs)
Composition of Asteroids

Since asteroids are relatively unchanged leftovers of the solar system formation process, it is very important to understand their chemical composition. This is normally done with spectroscopic observations.

In these two graphics are represented the normalized spectra of some asteroids (on the left) and the normalized spectra of some minerals (a: iron and nickel, b: olivine, c: orthopyroxene, d: feldspar, e: spinel).

Chemical classification of asteroids:

**C-type (where C stands for carbonaceous)**
- 75% of known asteroids
- extremely dark (albedo 0.03-0.07)
- similar to carbonaceous chondrite meteorites
- have approximately the same chemical composition as the Sun, except H and He
- spectra have relatively blue colors and are fairly flat and featureless
- contain significant amount of water and other volatiles
- porous
- located mainly at 3 AU, but can be found throughout the main belt (2-4 AU)

**S-type (the S stands for silicaceous)**
- 17% of all
- relatively bright objects (albedo 0.10-0.22)
- metallic composition (basically made of nickel, iron and magnesium-silicates)
- spectra are reddish and similar to those of stony-iron meteorites
- higher density than C-type
- reside in the inner part of the belt (2-3.5 AU)
M-type (M for metallic).
- This class includes most of the rest asteroids (<8%)
- bright asteroids (albedo 0.10-0.18)
- made of pure nickel-iron visible in absorption spectra
- can be high porosity
- preferentially located in the inner part of the belt, among S-types (2-3.5 AU)

E-Type (E for enstatite)
- Similar to S-type
- Contain magnesium silicates, mainly MgSiO₃
- tend to be closer to the Sun (2 AU)
- have higher albedos (0.25-0.6)

R-Type (R for red) (P- and D- types)
- redder appearance
- surfaces may contain ancient organic compounds
- low albedos (0.02-0.06)
- further from the Sun (4 AU)

Figure 7.12 Distribution of some of the major classes of asteroid within the asteroid belt as a function of distance from the Sun. B, G and F-types are sub-classes of C-types.
The differences in asteroid types with distance from the Sun are largely a result of condensation out of the solar nebula.

- Closer to the Sun, at higher temperatures, silicates could condense, while volatiles such as water and organic compounds could not
- Farther from the Sun, lower temperature allow more volatile compounds to condense and become parts of the asteroids
- In the middle of the belt, many C-type asteroids are hydrated
- more distant P- and D-types may contain water-ice

**Clues to Asteroid Origins**

**Differentiation** is the process by which a hot, possibly molten planetary body, segregates into compositionally distinct layers of different density.

- requires internal heat (accretion, impact, radioactive decay, etc.)
- surface basalt rocks indicate magma flows from interiors

Silicate- and iron-rich asteroids are probably fragments of larger, differentiated bodies:

- Parent bodies were hot enough to differentiate into silicate mantles & iron cores.
- Got shattered by collisions into smaller pieces

Carbonaceous asteroids may be the remnants of more primordial material that never got differentiated.

### 8.3 Meteorites

Peaces of rock and iron smaller than asteroids orbiting the Sun. Sizes range from grains to 100 meters across.

**Stony Meteorite:** (92%)
- Composed mostly of silicate rock.
- Probably fragments of S-type asteroids (differentiated)

**Iron Meteorite:** (6%)
- Composed almost entirely of iron-nickel.
- Probably fragments of M-type asteroids (differentiated)

**Carbonaceous Chondrites:** (rare)
- Carbon-rich, with complex carbon compounds (tar-like)
- Probably fragments of C-type asteroids (undifferentiated)
Origin of meteorites

Orbits of some meteors have been traced back after their entry into the atmosphere:
- Some originate in the main asteroid belt.
- Those making "meteor showers" are trails of debris left behind by passing comets.
- Rare meteors have been found that have been knocked off the Moon or Mars.

Meteorites are among the oldest rocks in the solar system (radioactive ages of 4.6 Gyr), and are thus the leftovers from the formation of the solar system.

Meteor Impacts

About 100 tons of meteoroids hit the Earth each day:
- Most are no bigger than grains of sand or smaller.
- Stony meteorites <100 meters burn up before reaching the ground.
- Iron meteorites <40 meters burn up.

Rare large meteoroid or asteroid strikes:
- Carve a crater out of the ground.
- Large asteroid strikes could disrupt climates and trigger mass extinctions.

<table>
<thead>
<tr>
<th>Impactor size (m)</th>
<th>Mean impact interval (yr)</th>
<th>Energy released (megatons TNT)</th>
<th>Crater diameter (km)</th>
<th>Possible effects/comparable event</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>200</td>
<td>2</td>
<td>-</td>
<td>Fireball, shock-wave, minor damage.</td>
</tr>
<tr>
<td>50</td>
<td>2500</td>
<td>10</td>
<td>= 1</td>
<td>Tunguska explosion or small crater.</td>
</tr>
<tr>
<td>100</td>
<td>5000</td>
<td>80</td>
<td>2</td>
<td>Largest H-bomb detonation.</td>
</tr>
<tr>
<td>200</td>
<td>47,000</td>
<td>600</td>
<td>4</td>
<td>Destruction on national scale.</td>
</tr>
<tr>
<td>500</td>
<td>200,000</td>
<td>10,000</td>
<td>10</td>
<td>Destruction on European scale.</td>
</tr>
<tr>
<td>1000</td>
<td>600,000</td>
<td>80,000</td>
<td>20</td>
<td>Many millions dead, global effects.</td>
</tr>
<tr>
<td>5000</td>
<td>20 million</td>
<td>10 million</td>
<td>100</td>
<td>Billions dead, global climate change.</td>
</tr>
<tr>
<td>10,000</td>
<td>100 million</td>
<td>80 million</td>
<td>200</td>
<td>Destruction of human civilization.</td>
</tr>
</tbody>
</table>
Murchison Meteorite

The Murchison meteorite is named for the town in Australia close to its impact point, some 80 km north of Melbourne. It fell on September 28, 1969. About 82 kg of the meteorite was recovered. Eyewitnesses arriving at the scene reported smelling something like methanol or pyridine, an early indication that the object might contain organic material.

It is a carbonaceous meteorite containing a complex, tar-like substance. It has been a treasure of organic compounds, and has impacted our understanding about chemicals in the solar system.

Subsequent analysis by NASA scientists and a group led by Cyril Ponnamperuma revealed the presence 6 amino acids commonly found in proteins and 12 that did not occur in terrestrial life.

Amino Acids

Amino acids are organic compounds which contain both an amino group and a carboxyl group.

\[
\begin{align*}
\text{amine group} & \quad \text{carboxyl group} \\
\text{NH}_2 & \quad \text{COOH}
\end{align*}
\]

\[
\begin{align*}
\text{Glycine (gly)} & \quad \text{is the simplest amino acid.}
\end{align*}
\]

Amino acids are the structural elements from which proteins are built.

The human body can synthesize all of the amino acids necessary to build proteins except for the ten called the "essential amino acids". An adequate diet must contain these essential amino acids (meat, dairy products, cereal grains, beans, peanuts, etc.).

Amino acids can form isomers:
- molecules with identical chemical formulae
- but different structural arrangements
- separate into left-handed and right-handed form: chirality
A **chiral** molecule:
- the mirror image cannot be superimposed on the original
- all carbon atoms in a molecule have four different structures attached to them

An **achiral** molecule:
- the mirror image can be superimposed on the original
- all carbon atoms in a molecule have less than four different structures attached to them

The word chiral in Greek means “hand-like”. That is why we speak about left-handed (laevorotatory) and right-handed (dextro-rotatory) forms of amino acids. Some of them are chiral and some achiral.

**Figure 1.23** (a) An achiral molecule. Its mirror image can be superimposed on the original. (b) A chiral molecule. The mirror image cannot be superimposed on the original.

**Figure 1.24** (a) The achiral amino acid glycine. Its mirror image can be superimposed on the original. (b) The chiral amino acid alanine. The mirror image cannot be superimposed on the original.
Some of amino acids can be present in both left-handed and right-handed forms, e.g. alanine:

\[ \text{COOH} \quad \text{NH}_2 \quad \text{CH}_3 \]

\[ \text{COOH} \quad \text{NH}_2 \quad \text{CH}_3 \]

Figure 1.25  The chiral amino acid alanine can be present in both left-handed and right-handed forms.

Initially, the amino acids found in the Murchison meteorite were found to be equal mixtures of left and right-handed molecular symmetry. That fact alone points to the extra-terrestrial origin of the meteorite.

However, in 1997, John R. Cronin and Sandra Pizzarello of Arizona State University reported finding excesses of left-handed versions of four amino acids ranging from 7 to 9%, a result confirmed independently by another group.

The carbon isotope ratio \( ^{13}\text{C}/^{12}\text{C} \) in the Murchison meteorite was found to be about twice that usually found on the Earth, confirming the extraterrestrial origin of its organics.

More than 70 amino acids have been identified in Murchison altogether. To this organic mixture, in 2001, was added a range of polyols - organic substances closely related to sugars such as glucose.

**All life on the Earth contains only left-handed amino acids!**

- out of 20 amino acids used in proteins, 19 can exist as left-handed and right-handed
- mixture of different forms would prevent proteins to perform their biological functions
- once underway, biology was locked into one preference

Origin of the left-handed preference:

- initial guess: by chance
- second guess: inherited from life’s starting materials that may have come from space
- e.g. circularly polarized light (chiral phenomenon) would destroy one form of molecules more readily than the other form (UV photolysis)
- the preference was fixed in meteorites which brought prebiotic material to the Earth
**Meteorite ALH84001 (Allen Hills, 1984 #001)**

ALH84001 is a meteorite found in Allen Hills, Antarctica in December 1984 by a team of US meteorite hunters. ALH84001 is almost certainly from Mars. As established by a variety of radiometric dating techniques, it was shocked and broken by one or more meteorite impacts some 3.6 billion years ago, and blasted off of the surface of Mars in a separate impact about 15 million years ago.

In 1996 ALH became newsworthy when it was announced that it was believed that the meteorite contained traces of life from Mars, as published in an article in *Science* by David McKay.

Under the scanning electron microscope structures were revealed that for some time were considered to be the remains of bacteria-like life forms. The structures found on ALH84001 are 20-100 nm in diameters, similar in size to the hypothetical nanobacteria, but smaller than any non-hypothetical earthly life form. If the structures are really fossilized life forms, they would be the first proof of the existence of extraterrestrial life.

This caused a considerable stir at the time and opened up interest in Martian exploration. When the discovery was announced, many immediately conjectured that the fossils were the first true evidence of extraterrestrial life – making headlines around the world, and even prompting U.S. President Bill Clinton to make a formal televised announcement to mark the event.

As of 2005 however, most experts agree that the microfossils are not indicative of life, but of contamination by earthly biofilms. It has not yet conclusively been shown how they formed.

Recent studies on ALH84001 have shown that, although chances are low, eventually, martian rocks such as ALH84001 could actually transfer martian life to earth. 1 in 10 million meteorites from Mars arrives in less than a year, and around 10 rocks that weigh more than 100 grams make the journey in 2-3 years. Bacterial spores, and rock dwelling organisms can survive in space for 5 years, meaning transfer of martian life to our planet is entirely possible.
### 8.4 Trans-Neptunian Objects

Class of icy bodies that orbit the Sun in the space beyond Neptune's orbit:
- Range in distance from 30-50 AU from the Sun.
- May extend as far out as 100 AU

Roughly divided into various sub-classes:
- Classical Kuiper-Belt Objects (KBOs)
- Plutinos ("little Plutos")
- Scattered KBOs.

These classes are distinguished by the properties of their orbits.

#### Classical Kuiper Belt Objects (KBOs)

Most Trans-Neptunian objects are in the **Kuiper Belt**:

- Flattened region extending from 30 AU (Neptune) to 50 AU from the Sun
- Scattered KBOs have long elliptical orbits, and are the likely source of short-period comets
- First KBO was discovered in 1992
- Many hundreds are now known.
- Expect ~70,000 objects >100 km across
- At least 9 are >1000 km

![Diagram of the Kuiper Belt](image-url)
**Plutinos ("little Plutos")**

KBOs in a 3:2 orbital resonance with Neptune:
- Complete 2 orbits for every 3 Neptune orbits.
- Comprise about 25% of known Trans-Neptunian objects.

Orbits are similar to Pluto's:
- About the same period and semimajor axis
- Different eccentricities, tilts, and orientations.

**Origin**

The icy Trans-Neptunian Objects are thought to be the leftover primordial material from the formation of the solar system. Understanding their properties is therefore of great interest to understanding the origin of the Solar System.

Slow outward migration of Neptune over the history of the Solar System has swept these objects into the 3:2 mean motion resonance, where they get trapped and clumped.

These objects will be the target of the **New Horizons** mission currently on-schedule to be launched in mid-January 2006 for a 2015 Pluto fly-by, followed by an exploration of various Kuiper Belt Objects from 2016-2020.

The total mass of the Kuiper Belt is about 0.1 \( M_\oplus \).
New class of objects: Dwarf planets

A candidate "tenth planet" was announced in August of 2005 by Mike Brown (Caltech), Chad Trujillo (Gemini Observatory), and David Rabinowitz (Yale).

The provisional name is 2003UB313, a formal designation indicating (in an arcane way) the order in which it was discovered in 2003.

Its properties as determined by observations appear to be as follows:
- Diameter: ~2600 km (estimate: makes it bigger than Pluto)
- Very Elliptical orbit: e=0.44
- Distant: Semi-major axis: a=68AU
- Period: 560 years
- Orbit Tilt: 45°
- Pluto-like Composition
- 1 small moon.

It was discovered near aphelion at ~98AU.

It is currently the largest Trans-Neptunian Object known, and bigger than Pluto.

Estimates suggest there should be at least a half-dozen more large objects of Pluto size or bigger further out.

Pluto and 2003UB313 are the largest members of a new class of distant icy worlds:
- Found only in the outer solar system
- Densities of 1-2 g cm$^{-3}$, so mostly icy
- Very cold and covered with N$_2$ and other ices

Examples:
- Triton
- Large (>1000 km) icy bodies like Sedna, Quaoar, 2003EL61, 2005FY9, Charon, etc.
- Smaller Trans-Neptunian Objects: Kuiper Belt Objects and Plutinos

What distinguishes all of thee objects is that they do not fit into either the terrestrial or Jovian categories, and instead are completely different type of object that predominates in the outer solar system beyond Neptune.

This view changes Pluto from being a peculiar planet into only the second largest of a new and important type of outer solar system object.

The discovery of 2003UB313, a former candidate 10th planet, reopened the debate on whether or not Pluto (and 2003UB313) are indeed "planets". In August 2006 the General Assembly of the International Astronomical Union voted these objects to be called “dwarf planets”.

8.5 Comets

Comets are small bodies consisting of aggregates of ices mixed with rock and dust. As they approach the Sun, they heat up and the ices sublimate (go from solid to gas):

- Gas and dust is swept back by solar radiation and the solar wind into a spectacular luminous tails.
- Many faint comets are seen every year.
- A bright naked-eye comet appears only once every 10 years or so.

Their sudden appearances have made them objects of wonder and fear throughout human history.

**Historical observations**

Aristotle thought comets were atmospheric phenomena:
- Unusual clouds in the Earth's atmosphere
- Could not be part of the perfect and unchanging heavenly realm.

Renaissance astronomers began more systematic studies:
- Observed that tails always point away from the Sun, suggesting cosmic phenomena.
- Tycho Brahe measured the parallax of the great comet of 1577 and showed it orbited the Sun.

**Halley's Comet**

In 1705, Edmund Halley computed the orbit of the great comet of 1682 using Newton's laws for describing planetary orbits. He found that the orbit of the 1682 comet was the same as that for comets seen in 1531 and 1607. On the basis of this, he predicted it would return again in 1758. It was seen again on Christmas day 1758, 12 years after Halley's death.

- Elliptical orbit, $e=0.967$
- Semimajor axis, $a=17.94$ AU, with aphelion at 35 AU, and perihelion at 0.6 AU.
- Period is 74-79 years.

Comet Halley is one of the most observed comets in history. The earliest recorded appearance is a Chinese observation of the apparition of 240 BC.
It has been seen every 76 years or so since 240 BC:
- Recorded in Nürnberg Chronicle of 684 AD
- Appeared in April 1066, and was put into the Bayeux Tapestry commemorating the Norman Conquest of England in October 1066.
- Appears as the "Star of Bethlehem" in Giotto's Adoration of the Magi (1301 apparition).
- Famous appearances in 1910 and 1986
- Next appearance is in 2062

Orbits

Comet orbits naturally divide into two types:

**Long-Period Comets: (P>200 years)**
- Long elliptical orbits, some almost parabolic, not confined to the ecliptic plane.
- About 700 known (e.g., Hale-Bopp)

**Short-Period Comets: (P<200 years)**
- Elliptical orbits close to the ecliptic plane.
- About 200 known (e.g., Halley)

Origin of Comets

The division of comets into long- and short-period comets reflects their origins.

Short-period comets are from the **Kuiper Belt:**
- Reservoir of comets between 30 and 100 AU
- Knocked into the inner solar system by passing stars
- Perturbed into smaller orbits by Jupiter's gravity
- Some are ejected or accreted by giant planets (lost comets)
Long-period comets are from the **Oort Cloud**:
- Ranges from 20,000 to 150,000 AU (about half-way to the nearest star)
- May be several trillions comets in the Oort cloud.
- Total mass of all Oort Cloud comets combined may approach ~1/3 the mass of Jupiter.
- Only a few are perturbed by passing stars into the inner solar system

### Structure of Comets

**Nucleus:**
- Few km across, a dirty snowball of ices & dust
- Contains >99% the mass of the comet.
- Source of the gas & dust in the coma & tails.

**Coma:**
- Bright "head" of the comet.
- Low-density cloud of gas and dust sublimed off the nucleus
- Extends out to 100,000 km or more.

**Dust Tail:**
- Composed of dusty particles swept back in a curved path by solar radiation.
- Can be 1-10 Million km long
- Pale white in color from reflected sunlight

**Ion Tail:**
- Composed of ionized atoms and molecules swept straight back by the solar wind.
- Can be up to 100 Million km long.
- Pale blue in color from emission lines of ions, especially the CO⁺ ion

**Hydrogen halo:**
- 10-100 Million km
- evaporating hydrogen due to water photolysis
- detected in UV hydrogen emission line Lyman alpha

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**Fig.** Structure of a comet (left) and a hydrogen halo of Hale-Bopp comet (right) detected in the UV as compared to the optical image (inlet). A tiny yellow circle on the right edge of the picture shows the relatively small size of sun's disk and its direction, but its distance is not to scale.
"Dirty Snowball" Model

The favored model for comet nuclei is the "icy conglomerate" model, usually called the "dirty snowball model". In this model a comet nucleus is an aggregate of:

- Mainly water ice, along with ices of CO₂ (dry ice), NH₃, CO, and others
- Ammonia
- Dust and large pieces of rock
- Carbon and complex carbon compounds

The interior may be porous, giving it a density lower than that of normal ices:

- This makes comets fragile and easily shattered by tidal forces or breaking into pieces
- Comets break apart as they pass around the Sun
- Shoemaker-Levy 9 comet split into fragments by Jupiter

Space missions to comets

Giotto

- 1985-86 encountered Comet Halley
- A close-up look at a cometary nucleus (~600 km from the surface)
- Found jets of vapor shooting out of the mineralized thin crust
- These jets can steer a comet slightly, varying its orbit
- The gas ends up in the coma of the comet, and eventually is lost in its tail.

Properties of Halley's nucleus:

Small and irregular in shape:

- Size is 16 x 8 km
- Thought to be large for a comet nucleus

Low density:

- Mean density ~0.2 g cm⁻³: porous ice and rock

Very dark and cratered surface:

- Surface reflects only ~4% of incident sunlight
- Appears encrusted with carbonaceous dust

Fig. The nucleus of Halley from the Giotto spacecraft. (NASA/ESA).
**Stardust** (US): Launched Feb 1999

- Flew past Comet Wild-2 in January 2004 (~230 km from the surface), returned a comet dust sample in mid-January 2006 (more than 10,000 particles in the 1-to 300-µm size range). The analysis of the sample is published on Dec 15, 2006.
- the first mission to return solid samples from a specific astronomical body other than the Moon

Flyby images showed at least 20 collimated jets of solid particles streaming into space from widely distributed small sources. The collected particles are expected to be a representative sampling of the nonvolatile component of the interior of the comet. Wild-2 is a Jupiter family comet (JFC) currently on an orbit that approaches the orbits of both Jupiter and Mars. Like other JFCs, this ~4.5-km-diameter body is believed to have formed in the Kuiper belt, exterior to the orbit of Neptune, and only recently entered the inner regions of the solar system where solar heat causes "cometary activity," processes mainly driven by the sublimation of water ice that lead to the loss of gas, rocks and dust at rates of tons per second. As a JFC, the most likely history of Wild-2 is that it formed beyond Neptune, where it spent nearly all of its life orbiting in the Kuiper belt. A close encounter with Jupiter on 10 September 1974 placed it in its current orbit, but its journey from the Kuiper belt to the inner solar system probably took millions of years and multiple encounters with outer planets. As a JFC, its orbit will change, and it has an expected dynamical lifetime of ~10⁴ years before it either hits a larger object or is ejected from the solar system. The active lifetime will be shorter because of mass loss or disintegration.

Most of the samples were collected in silica aerogel, a porous glass composed of nanometer-sized silica particles with bulk density that was made to vary from <0.01 g/cm³ at the impact surface to 0.05 g/cm³ at 3-cm depth. In addition to aerogel, about 15% of the total collection surface was aluminum, the frame used to hold aerogel. Impact on this metal produced bowl-shaped craters lined with melted, and in some cases unmelted, projectile residue. The craters provide important information that is complementary to the primary aerogel collection medium. The impacts into aerogel produced deep, tapered cavities (tracks) with shapes varying with the nature of the impacting particle (figure on the left). All but a few of the impact tracks contain deeply penetrating particles. Nonfragmenting particles produced carrot-shaped tracks with length/diameter ratios of >25, whereas fragmenting particles produced tracks with bulbous upper regions and sometimes multiple roots. In many cases it appears that the particles consisted of aggregates that separated into fragments on impact. The smaller fragments stopped in the upper (bulbous) region of the tracks, whereas the larger fragments traveled deeper into the aerogel.

Fig: Optical images of deceleration tracks of eight comet particles in aerogel that entered at the top and terminated at the base.
Results:

- the nonvolatile portion of the comet is an non-equilibrated assortment of materials that have both presolar and solar system origin
- the comet contains an abundance of silicate grains that are much larger than predictions of interstellar grain models
- many of these are high-temperature minerals that appear to have formed in the inner regions of the solar nebula
- their presence in a comet proves that the formation of the solar system included mixing on the grandest scales

Deep Impact (US): Launched 2005 January 12, Fly-by of Tempel 1 2005 July 4:

- Flew past Comet P/Tempel 1 on 2005 July 4th and launched a 370 kg impactor probe into the comet. Imagers on both spacecraft recorded the successful impact, and instruments in space and on the ground recorded image and spectra of the debris kicked out.

- 4.9 x 7.6 km dark nucleus with low density
- smooth and rough terrains, natural impact craters
- DI impact: fine dust ejected
- strong increase in silicate emission after the impact
- large increase in the amount of organics compared to water
**Rosetta** (ESA): Launched 2004 March 2
- Rendezvous with Comet P/Churyumov-Gerasimenko in 2014, go into orbit, and land a probe on its surface.
- the lander will drill the surface down to 20cm below the surface and will perform a chemical analysis of cometary volatiles by gas chromatography. More than 100 species might be detected.

**Molecules in comets**

1864 first spectrum of a comet
1868 identification of carbon and Swan bands C₂
1881 identification of Na, other emissions of CH, CN, C₂, C₃
1911 identification of CO⁺
1941 identification of OH

Visible and UV windows:
- radicals and ions
- exceptions : CO and S₂

IR 2-5 mm window :
- fundamental bands of vibration
- hot bands of water

Radio window (cm to submm):
- cold atmospheres
A typical optical comet spectrum (Feldman et al. 2005)

![Optical Comet Spectrum](image1)

A typical UV spectrum (HST, Weaver et al. 1998; FUSE, Feldman et al. 2002)

![UV Spectrum](image2)
IR spectrum of comets (Keck, Mumma et al. 2001)

IR identified species:
- ro-vibrational lines of CH$_4$, C$_2$H$_2$, C$_2$H$_6$, CH$_3$OH, HCN

IR unidentified lines
- need for detailed ro-vibrational structure and strength of CH$_3$OH bands in 3 mm region
- other organic species

Radio spectroscopy:
- OH 18cm lines (1973, comet Kohoutek, Nançay)
- HCN 89 GHz (1985, comet Halley, IRAM 30-m)
- 19 molecules (not including isotopes, radicals, ions) now detected
- many first identifications in comets Hyakutake and Hale-Bopp
- Isotopes: HDO, DCN, H$^{13}$CN, HC$^{15}$N, C$^{34}$S, H$_2$$^{34}$S
- Radicals and ions: NS, CS, SO, CN, H$_3$O$^+$, CO$^+$
New organic molecules in Hale-Bopp comet (Crovisier et al. 2004):

- Chemical diversity among comets
- No systematic differences between comets in Oort cloud and Kuiper belt
Isotope ratios

<table>
<thead>
<tr>
<th>Isotope Ratio</th>
<th>Species</th>
<th>Value</th>
<th>Comet</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}$C/$^{13}$C</td>
<td>CH$_4$</td>
<td>93 ± 10</td>
<td>4 comets</td>
<td>Wyckoff et al. (2000)</td>
</tr>
<tr>
<td></td>
<td>CH$_3$N</td>
<td>95 ± 12</td>
<td>1P/Halley</td>
<td>Kleine et al. (1995)</td>
</tr>
<tr>
<td></td>
<td>CH$_3$N</td>
<td>111 ± 12</td>
<td>Hale-Bopp</td>
<td>Jewitt et al. (1997)</td>
</tr>
<tr>
<td>$^{14}$N/$^{15}$N</td>
<td>HCN</td>
<td>323 ± 46</td>
<td>Hale-Bopp</td>
<td>Jewitt et al. (1997)</td>
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<tr>
<td></td>
<td>CN</td>
<td>140 ± 35</td>
<td>Hale-Bopp</td>
<td>Arpigny et al. (2003)</td>
</tr>
<tr>
<td>$^{16}$O/$^{18}$O</td>
<td>H$_2$O</td>
<td>518 ± 45</td>
<td>1P/Halley</td>
<td>Balsiger et al. (1995)</td>
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<tr>
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<td>H$_2$O</td>
<td>470 ± 40</td>
<td>1P/Halley</td>
<td>Eberhardt et al. (1995)</td>
</tr>
<tr>
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<td>H$_2$O</td>
<td>450 ± 50</td>
<td>153P</td>
<td>Lepouch et al. (2003)</td>
</tr>
<tr>
<td>$^{32}$S/$^{34}$S</td>
<td>CS</td>
<td>27 ± 3</td>
<td>1P/Halley</td>
<td>Jewitt et al. (1997)</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>23 ± 6</td>
<td>1P/Halley</td>
<td>Altwegg (1996)</td>
</tr>
<tr>
<td></td>
<td>H$_2$S</td>
<td>16 ± 3</td>
<td>Hale-Bopp</td>
<td>Crovisier et al. (2004)</td>
</tr>
</tbody>
</table>

Origin of comet material

- molecular composition present analogies with composition of star forming regions and interstellar ices
- D/H ratios kept interstellar signatures
- low temperature formation
- highly processed material is present however (cristalline silicates)
  - mixing with nebular products

How to make a comet: