physics | P06

teach with space

→ COOKING A COMET

Ingredients for life?

teacher's guide and student activities

European Space Agency

→ INTRODUCTION

Comets are considered to be time capsules containing information about the conditions of the early Solar System. In order to understand what comets are, where they come from, and their influence on the evolution of Earth, it is necessary to find out what material they contain. This teacher demonstration and student practical activity, along with the resulting discussion, gives an insight into the chemical constituents of comets. An extension discussion and activity, looking at impact processes on Earth and calculations of the kinetic energy involved, is also included.

→ COOKING A COMET

Ingredients for life?

FAST FACTS

Age range: 14-18 years old

Type: teacher demonstration & student activity

Complexity: easy

Teacher preparation time: 20 minutes

Lesson time required: 20 minutes to 1 hour

Cost per kit: medium (5 - 25 euro)

Location: indoor (large, well ventilated classroom)

Includes use of: dry ice (solid carbon dioxide at a temperature below -78° C)

Students should already know

1. The kinetic energy equation.
2. The concepts of spectroscopy and infrared radiation.

Learning outcomes

1. Students should understand the basic differences between comets and asteroids.
2. Students should be familiar with the basic compositional parameters of comets.
3. Students should be able to make simple calculations of the energy conversions that take place when comets or asteroids impact planets.

You also need

↑ Cooking a comet video. See Links section.

Curriculum links

Physics
- Kinetic energy
- Conservation of energy
- Phase changes
- Impact processes
- Orbits (in the Solar System)

Astronomy
- Location and nature of asteroids and comets
- Identify features of a comet (nucleus, coma, dust and ion tails)
- Consequences of collisions in the Solar System
- Association of Kuiper Belt and Oort Cloud with comets
- Space probes studying Solar System bodies

Chemistry
- Phase changes

Outline

In this activity teachers and students simulate a comet nucleus in the classroom. The ingredients used accurately represent an analogue of the material found in a real comet nucleus, as discovered using spectroscopy combined with the results from spacecraft flybys of various comets.

→ BACKGROUND

What are comets?

Comets are small, icy worlds that originate primarily from two regions of the Solar System (Figure 1). Short period comets (those with an **orbital period*** of less than 200 years) originate from the Kuiper Belt, a disc-like collection of frozen remnants from the formation of the Solar System just beyond the orbit of Neptune. Long period comets (those with orbital periods of up to tens of thousands of years) are thought to originate from a spherical halo of icy material towards the edge of our Solar System known as the Oort Cloud. Reaching out to a distance of many thousands of **astronomical units (AU)***, the Oort Cloud is too far away to be imaged directly. Instead we must track a long period comet orbit back in time to determine its origin (Figure 2).

Figure 1

↑ Photo of comet Hale-Bopp taken in Croatia.

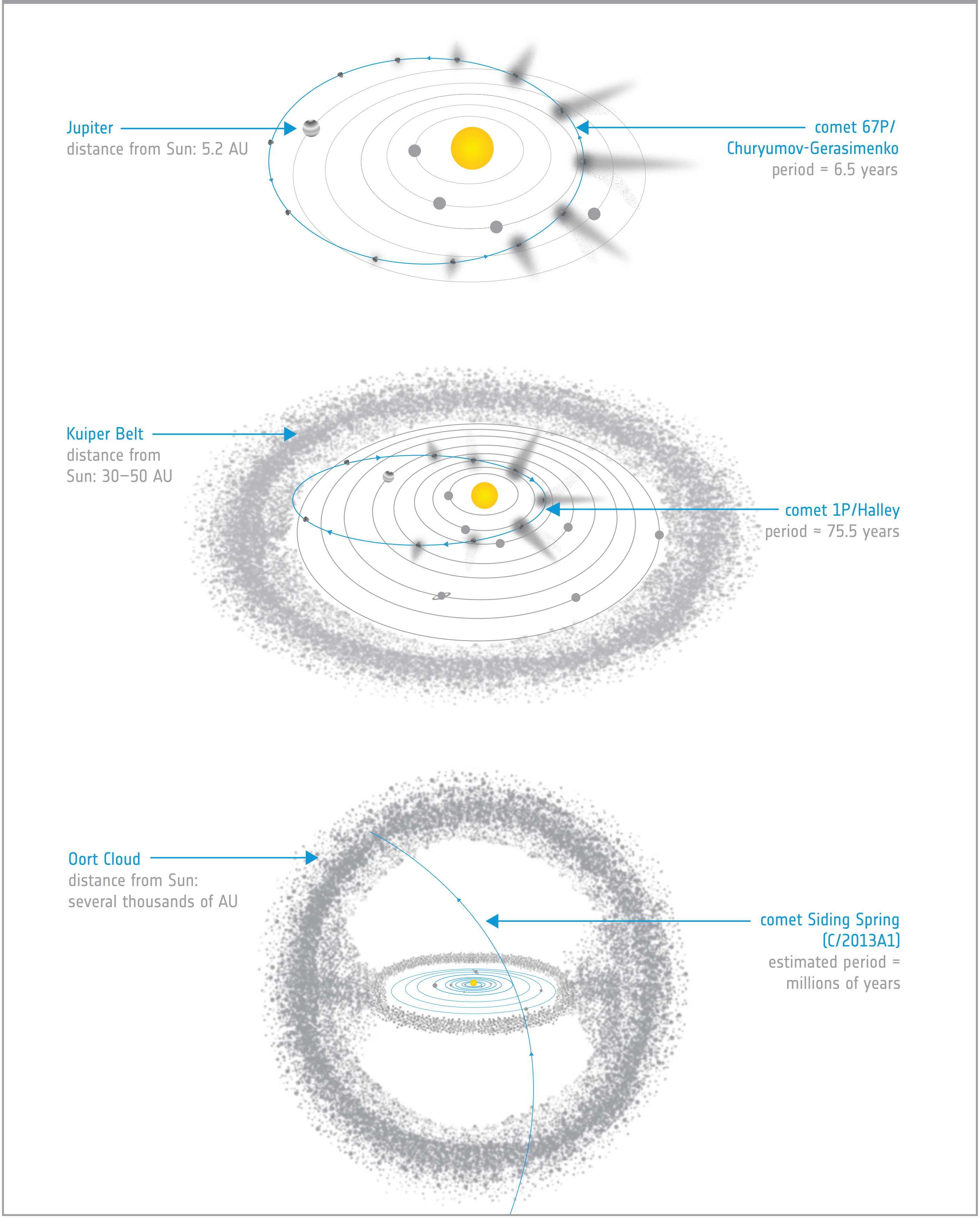
Comets will, for the most part, orbit the Sun in stable orbits. However, Kuiper Belt objects can be influenced by the gravitational fields of the giant planets (Jupiter, Saturn, Uranus and Neptune), and Oort Cloud objects by **gravitational perturbations*** caused by the motions of other stars. These perturbations can occasionally change the orbits of these small, cold worlds, sending them racing towards the inner Solar System.

As these objects approach the Sun they begin to heat up and the ice within them **sublimates***. The original structure is now referred to as a 'nucleus'. As the nucleus heats up, it gives off gas and dust forming a thin, but vast, 'atmosphere' known as the coma (Figure 3).

As the comet gets even closer to the Sun, the interaction of the coma with increasing levels of solar radiation and the **solar wind*** produce the spectacular 'tails' with which comets are most often associated. Very occasionally the tails are bright enough to be seen by an observer on Earth in daylight.

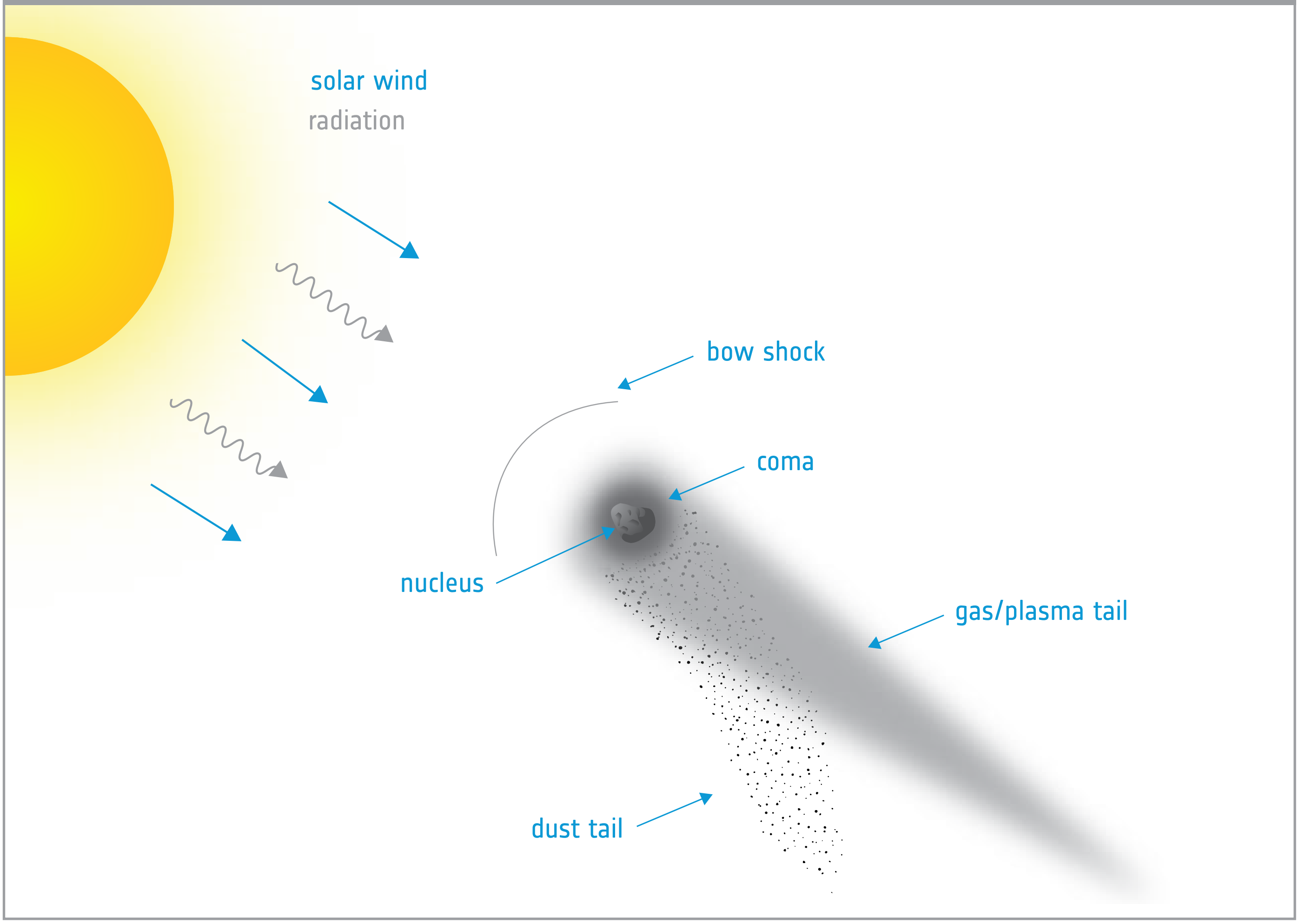
***Astronomical unit (AU)**: 1 AU is the average distance between the Earth and the Sun, or the Earth's orbital radius, which is approximately 150 million km.
***Gravitational perturbations**: changes to the orbit of a celestial body (e.g. planet, comet) due to interactions with the gravitational fields of other celestial bodies (e.g. giant planets, other stars).
***Orbital period**: time taken to complete one orbit.
***Solar wind**: a stream of high-energy particles (plasma) being emitted by the upper atmosphere of the Sun in all directions. It contains mostly electrons and protons.
***Sublimate (sublimation)**: when heating causes a substance to change directly from the solid phase to the gas phase, bypassing the liquid state. When the gas is re-cooled, it typically forms a solid deposit.

Figure 2



↑ Comet orbits in the Solar System.

Figure 3



↑ The anatomy of a comet.

Not all comet tails are as spectacular as those shown in Figure 1, or even visible from Earth. It is the size of the nucleus, its constituents, how close to the Sun it approaches, and how many times the comet has previously approached the Sun that determine how spectacular its tail will look. Once past its closest approach to the Sun (**perihelion***), the comet will retreat to the colder regions of the Solar System again, having lost some of its mass permanently.

Comets have elliptical orbits with the Sun at one focus (Figure 2), and therefore are only visible for a short period of time, as they approach perihelion. For comets in highly elliptical orbits this is only a tiny proportion of the time it takes for them to complete one orbit around the Sun. The majority of their existence is spent slowly decelerating away from the Sun to **aphelion*** and accelerating towards the Sun to perihelion, due to the effects of the Sun's gravity.

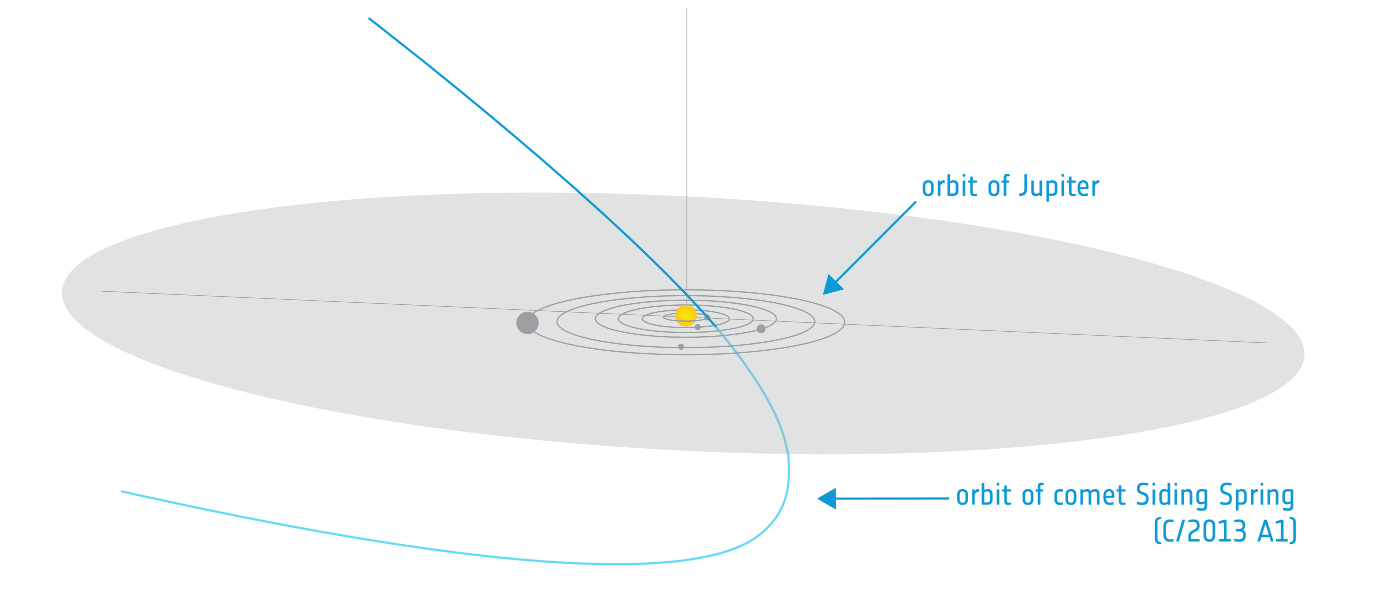
For more information about elliptical orbits and the orbits of comets please refer to ESA teach with space - marble-ous ellipses | P02 classroom resource (see the Links section).

*__Aphelion__: point in an orbit furthest from the Sun.
*__Bow shock (comet)__: surface of interaction between the ions in the comet coma and the solar wind. The bow shock forms because the relative orbital velocity of the comet and the solar wind are supersonic. The bow shock forms upstream of the comet in the flow direction of the solar wind. In the bow shock, large concentrations of cometary ions build up and load the solar magnetic field with plasma. The result is that the field lines bend around the comet, entraining the cometary ions, and forming the gas/plasma/ion tail.
*__Perihelion:__ point in an orbit closest to the Sun.

Impacts in the Solar System

Figure 2 shows the orbital paths of 3 different comets, which all appear to cross the orbits of the planets, suggesting that collisions between comets or asteroids and planets are inevitable. However, the orbits of comets travelling from the Oort Cloud can be highly inclined to the plane of the Solar System (the ecliptic). Therefore, due to perspective, many of the paths that appear to directly cross the planetary orbits are misleading. For example, the path of comet Siding Spring (C/2013 A1) during its approach to perihelion in 2014 has a high inclination relative to Earth's orbital plane (Figure 4).

Figure 4

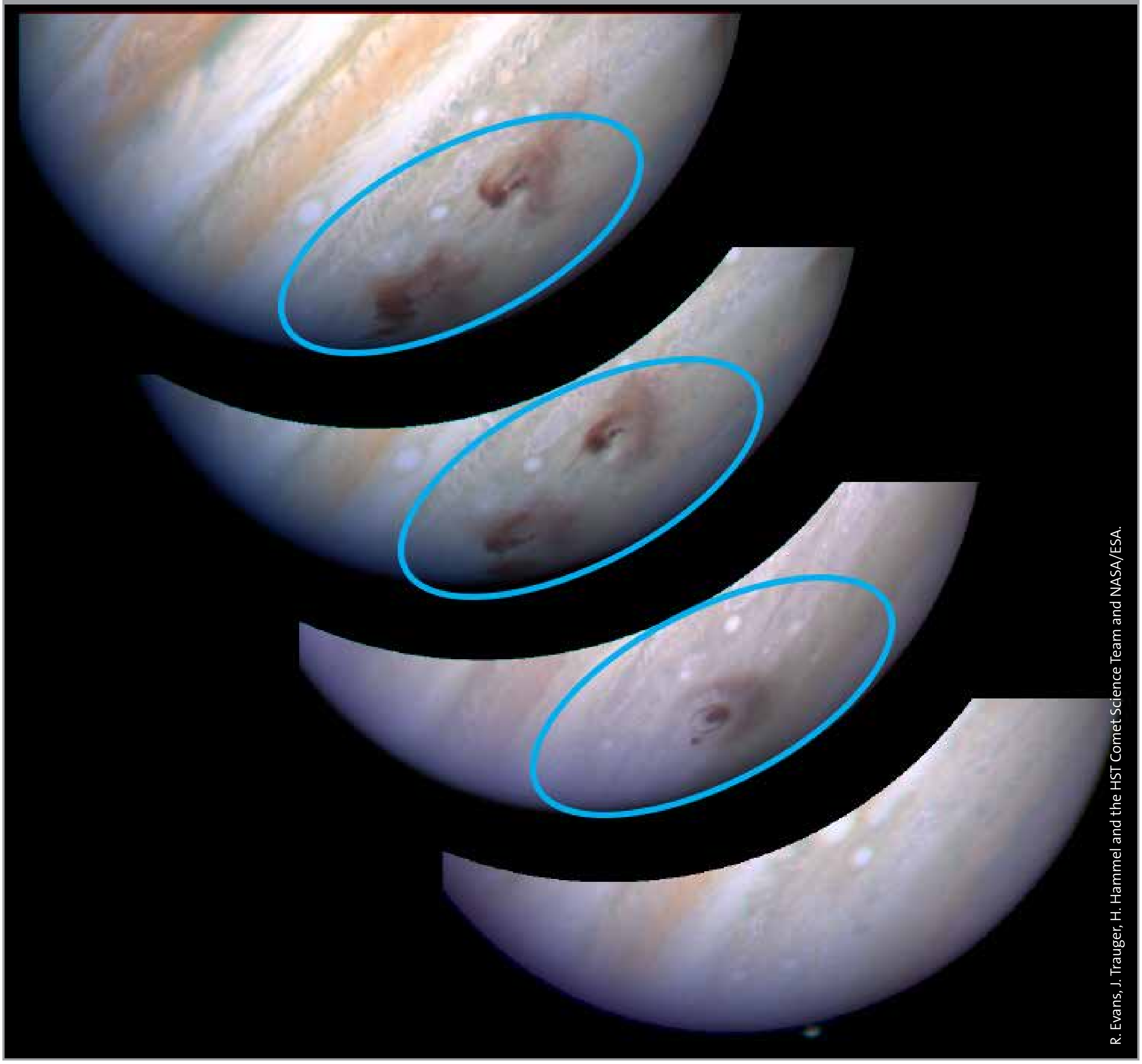


↑ Path of comet Siding Spring (C/2013 A1) through the Solar System.

Nevertheless, there is overwhelming evidence that planets are regularly (on geological timescales), hit by comets and asteroids. Impact processes formed most of the craters observed on the surfaces of moons and planets throughout the Solar System. The highest frequency of impacts occurred early in the history of the Solar System (Late Heavy Bombardment period), but impacts do still occur at the present time.

In 1994, numerous fragments of comet Shoemaker-Levy 9 (D/1993 F2) impacted the surface of Jupiter. The largest impact scar observed was thousands of kilometres in diameter. This was caused by the G fragment of the comet, which was only a few kilometres in size. The effects of this impact on Jupiter's atmosphere can be seen in Figure 5, a time-lapse montage of images taken by the Hubble Space Telescope.

Figure 5



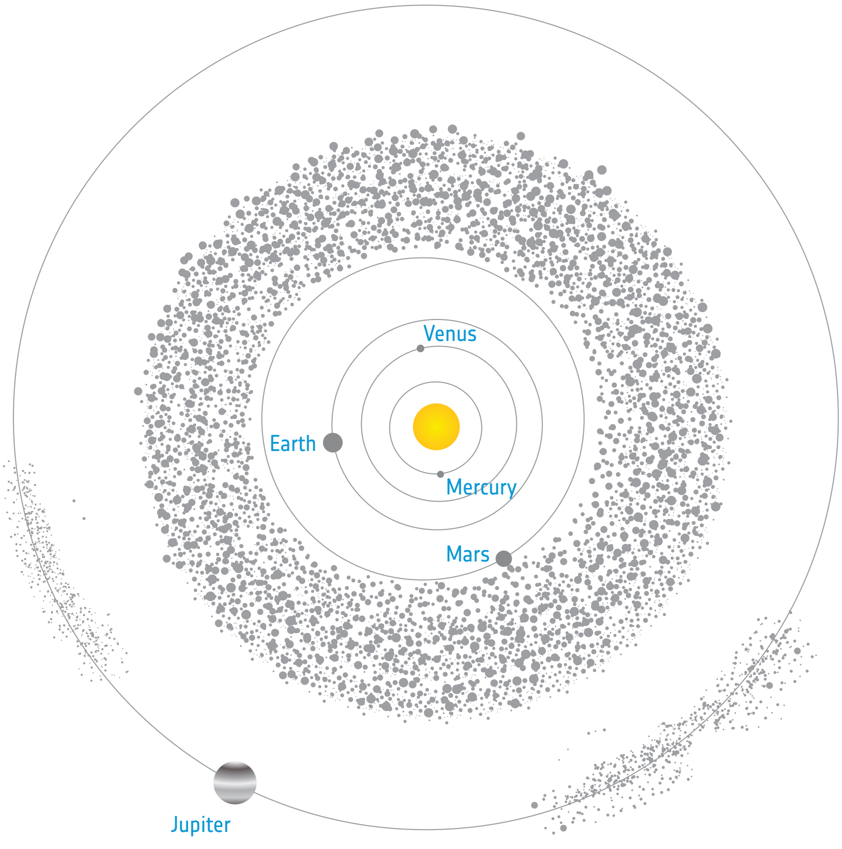
↑ This mosaic of images shows the evolution of the G impact site on Jupiter (highlighted by the blue ellipse).

Asteroids

Comets are not the only objects that hit the Earth and other Solar System bodies. Asteroids, which originate largely in the Asteroid Belt between Mars and Jupiter (Figure 6), are large rocky or metallic objects. On the whole asteroids formed much closer to the Sun and therefore contain fewer light elements than comets. Metals, metal oxides, minerals and silicates dominate the composition of asteroids. In comets, the larger quantities of light elements, such as, carbon, hydrogen, oxygen, nitrogen, phosphorus and sulphur, allow for the formation of certain compounds, for example, water, methane and carbon dioxide.

The largest known asteroids are Vesta and Pallas which are more than 500km in diametre. Figure 7 shows a size comparison of some asteroids and comets. The irregular asteroids shown in Figure 7 are much smaller than Vesta and Pallas, but many are considerably larger than the comet nuclei that have been imaged.

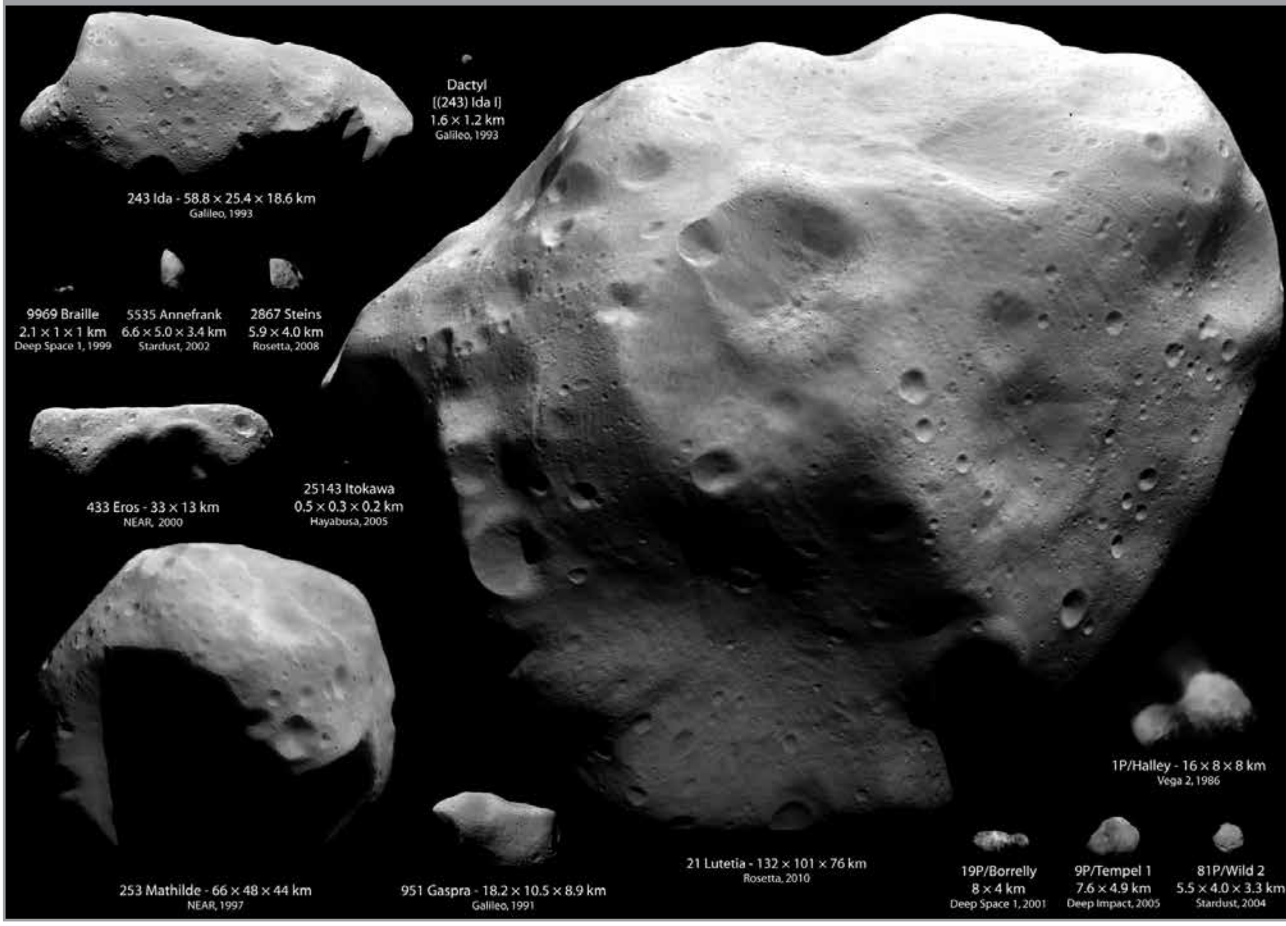
Figure 6



↑ A diagram of asteroid distribution in the Solar System. The majority of asteroids reside in the main belt between the orbits of Mars and Jupiter. Other large groups of asteroids are the Jupiter Trojans which occupy the stable **Lagrangian points***, L4 and L5, on the orbit of Jupiter.

***Lagrangian points**: in any orbital configuration there are five points at which an object only affected by gravity can orbit stably. For more information see the ESA teach with space - gravity wells video | VP04 (see Links section).

Figure 7



Montage by Emily Lakdawalla. Ida, Dactyl, Braille, Annefrank, Gaspra, Borrelly: NASA / JPL / Ted Stryk. Steins: ESA / OSIRIS team. Eros: NASA / JHUAPL. Itokawa: ISAS / JAXA / Emily Lakdawalla. Mathilde: NASA / JHUAPL / Ted Stryk. Lutetia: ESA / OSIRIS team / Emily Lakdawalla. Halley: Russian Academy of Sciences / Ted Stryk. Tempel 1: NASA / JPL / UMD. Wild 2: NASA / JPL.

↑ Size comparison of asteroids and comets.

Impacts on Earth

On Earth, active tectonic and weathering processes at the surface mean that craters generally last for a few million years before disappearing from visible sight. However, geological analysis of subsurface rocks, and other features, can be used to infer the past formation of a crater. In the early 1990s this led to the confirmation that around 65 million years ago a comet or asteroid, with a diameter of around 10 km, impacted the Earth in the area now known as Yucatán, Mexico. This impact formed a crater over 150 km in diameter. The subsequent global climatic change that occurred was a major contributor to one of the largest extinction events in Earth's geological history – the Cretaceous – Paleogene extinction – which ultimately led to the extinction of the dinosaurs.

On much more recent time scales, smaller craters have formed that are still visible, such as Meteor Crater (also known as the Barringer Crater) in Arizona, USA, shown in Figure 8.

Figure 8

↑ Left image: Meteor Crater, Arizona, USA. Right image: Meteor Crater photographed from the International Space Station.

Meteor Crater was formed approximately 50 000 years ago by a nickel-iron asteroid that smashed into the plains of Arizona, USA. This impact formed a crater nearly 200 m deep and 1.5 km in diameter. Fragments of the original impactor are scattered across the surrounding landscape.

In 1908 an asteroid or comet, thought to be over 50 m in diameter, exploded at an altitude of 5 - 10 km over a remote forest area near the Tunguska River in what is now Krasnoyarsk, Russia. Whilst the asteroid or comet is not thought to have impacted the Earth's surface, the force of the explosion flattened an area of forest more than 2000 km^2 (Figure 9).

Figure 9

↑ Trees knocked over in the Tunguska blast.

Cooking a comet

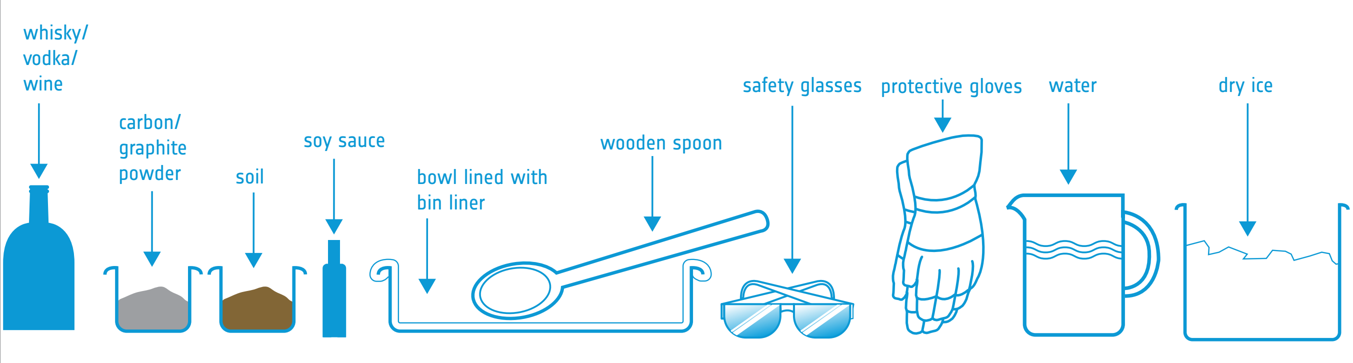
In this demonstration, teachers simulate a comet nucleus in the classroom. The ingredients used accurately represent an analogue of the material found in a real comet nucleus.

A student version of this activity uses smaller quantities in plastic cups. It is important that students are given clear instructions about the hazards and follow health and safety guidelines. Student instructions are provided in the Student worksheet after the Activity.

Equipment

- Dry ice (about 0.75 litres, the smallest pellets available)
- Water (about 0.75 litres)
- Large bin liners/garbage bags
- 10 tablespoons (4 very large wooden spoonfuls) of soil (make sure soil is not clumpy, but regular in consistency)
- 1 tablespoons of carbon dust/powder or graphite powder
- 2-3 tablespoons of whisky, vodka, or red wine (methanol/ethanol component)
- A few drops of soy sauce (organic component)
- A few drops of cleaning product (amonia component)
- Large plastic bowl
- Bucket for disposal
- Wooden spoon
- Clear safety screen
- Polystyrene container for dry ice
- Thermal protective gloves
- Safety glasses for all participants and demonstrators
- Protective laboratory coat for demonstrator (optional)
- Measuring jugs

Figure A1



↑ Experiment setup.

Health & Safety

- When handling dry ice always wear protective gloves and safety glasses. Do not touch, swallow or taste the dry ice. Give students clear instructions about the hazard, and the distance they should be seated away from the demonstration as the comet may 'spit'.
- Do not seal the dry ice into a container as explosive outgassing may result!
- Dispose of comet outside in a well-ventilated area that students cannot access.
- Never store dry ice in a domestic freezer.
- Do the experiment in a well ventilated area.

Instructions

Please refer to the accompanying video: Teach with space – cooking a comet | VC03.

1. Line the bowl with a bin liner. We suggest that you put the bowl inside the bin liner and line the bowl with the top layer. This will make it easier to dispose of the comet afterwards. Make sure that the bag is smooth along the inside of the bowl.

2. Add the following ingredients: water, soil, carbon dust, wine/alcohol, cleaning product and soy sauce. These represent some the compounds of a real comet. Volunteers from the audience could participate by adding some of the ingredients. Mix well with the wooden spoon.

3. Add the dry ice to the mixture. Stir the mixture with the wooden spoon. It is helpful to have an assistent tilt the bowl during mixing. Then, wearing the protective gloves, mould the comet into one lump for around 30 seconds. If the comet does not easily stick together, add a little more water. Do not compress it too much as the comet may break.

4. When the demonstration has been completed, place the comet inside the bowl and carefully remove the bowl from the bin liner, enclosing the comet in the bin liner. Put the bin liner into the bucket. Make sure the bin liner is still open so that gases can escape. Dispose of the nucleus in an outdoor area where access is limited. The dry ice in the nucleus should sublimate within 24 hours.

Tip: if the experiment is done in the morning, students could return in the afternoon to see how the comet has evolved.

Practice makes better comets! To obtain the best results it is a good idea to practice a few times before doing the experiment with the students.

Discussion

How do the ingredients represent what we find in actual comet nuclei? What are the implications for life on our planet?

The first spectroscopic observations of comets took place in the late 19th and early 20th centuries. Spectroscopy enabled astronomers to begin to uncover the chemical composition of comet comas. These early observations identified diatomic carbon, sodium ions and a variety of carbon-, oxygen- and nitrogen-based molecules.

In 1950, US astronomer Fred Whipple proposed a new model to describe a comet nucleus. Whipple's 'dirty snowball' model suggested that comets have an icy nucleus made up of traces of dust, rock and mostly frozen volatiles, such as **water, carbon dioxide, methane and ammonia**. Ground- and space-based observations later confirmed Whipple's model, although some small changes were necessary as the observations showed comet nuclei to be larger and darker than described in the model.

A recent study of comet 103P/Hartley showed that its **water** content has the same isotopic ratio of deuterium to hydrogen (heavy water) as the Earth's oceans. This was a very significant discovery. Water is a key molecule for life as we know it. It is a universal solvent allowing for the dissolving of various chemical components within it. Scientists believe that water is key for the development of life. Comet impacts early in Earth's history may have been a major source of Earth's original water inventory.

The **carbon** content of comets is significant because all life as we know it is carbon based. This key ingredient for life on the Earth could have been delivered by comet impacts.

The **soy sauce** represents the amino acids and amino acid precursors present in comets. In 2004 NASA's Stardust mission took samples of the dust in the coma of comet 81P/Wild that were returned to Earth. Analysis of this dust confirmed the presence of glycine, the simplest amino acid. This was monumentally important. Amino acids are the building blocks for proteins. As such, they are a major building block of life itself. To find these biological molecules (chemical formula $C_2H_5NO_2$) on a body that is not the Earth could be a teasing hint for scientists that perhaps some of the ingredients for life on our planet were brought by comet impacts billions of years ago.

In addition to the **carbon dioxide** (dry ice) used in the demonstration, other gases have been discovered in the comas of comets using spectroscopy. These include (but are not limited to) those listed in Table 1.

→ ACTIVITY

Table A1	
C_2H_4	ethylene
NH_3	ammonia
CH_4	methane
C_2H_6	ethane
$C_2H_5NH_2$	ethylamine
O_2	oxygen
CH_3OH	methanol
NH_2CH_2OH	aminomethanol
H_2O_2	hydrogen peroxide
H_2	hydrogen
CH_3COOH	acetic acid
CH_3NH_2	methylamine
C_2H_2	acetylene
HCN	hydrogen cyanide

↑ Gases found in the nuclei of comets.

What is dry ice?

Dry ice is frozen carbon dioxide - CO_2, which is a gas under standard temperature and pressure conditions.

The process of sublimation, during which carbon dioxide changes directly from a solid to a gas, is responsible for the formation of a comets' coma. The reverse process is called desublimation, or deposition. At normal atmospheric pressure, carbon dioxide will change directly from a gas to a solid, forming dry ice, at -78°C.

What are the white clouds/fumes seen during the demonstration?

As the dry ice used in the demonstration rises above -78° C, it sublimates to form a cold gas. This has the effect of cooling the water vapour present in the surrounding air, which condenses to form the white billowing clouds observed.

What causes the explosive outgassing seen during the demonstration?

In this activity, as the analogue comet nucleus forms, there are two competing factors at work. Liquid water comes into thermal contact with dry ice, which has a temperature below -78° C - the liquid water freezes forming an 'ice cage' around the dry ice. As the dry ice is in thermal contact with material above -78°C it begins to sublimate. The change in the dry ice from solid to gas phase results in a volume change of more than 600 times. This means that subliming pockets of dry ice occasionally explosively outgas through the water ice crust of the nucleus. For this reason wearing a protective lab coat is strongly advised, as well as the protective gloves and safety glasses.

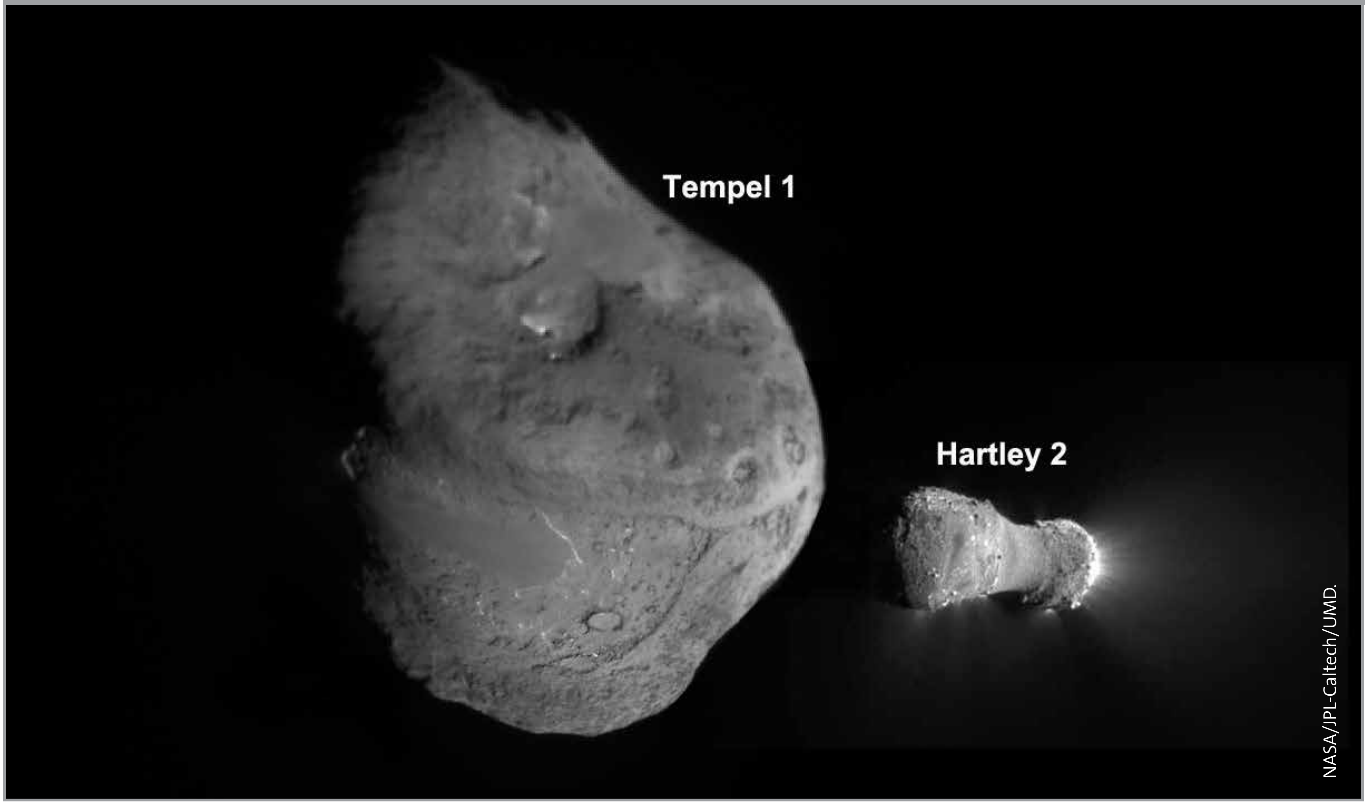
What shape, and how big, are the nuclei of comets?

A number of spacecraft **flybys*** have confirmed a variety of shapes and sizes of comet nuclei. These missions include Giotto (ESA – comet 1P/Halley and comet 26P/Grigg-Skjellerup), Stardust (NASA – comet 81/PWild and comet 9P/Tempel), Deep Impact (NASA – comet 9P/Tempel and comet 103P/Hartley), and Rosetta (ESA – comet 67P/ Churyumov-Gerasimeko). In the scale image shown in Figure A2, the long axis of comet 103P/Hartley's nucleus is about 2.2 km long, and the nucleus of comet 9P/Tempel is about 7.6 km at its longest dimension. Preliminary measurements made by ESA's Rosetta mission on arrival at comet 67P/Churyumov–Gerasimenko confirmed its longest dimension to be 4.1 km.

* **Flyby:** close passage of a spacecraft around a planet or other celestial body. If the spacecraft uses the gravitational field of the planet to boost the spacecraft's velocity and change its trajectory, this is called a swing by or gravity assist manoeevre.

The montage shown in Figure 7 displays several imaged comet nuclei in comparison to images taken from various spacecraft flybys (up to the year 2010) of asteroids and several Solar System moons. Comet nuclei are shown in the lower right corner of Figure 7.

Figure A2

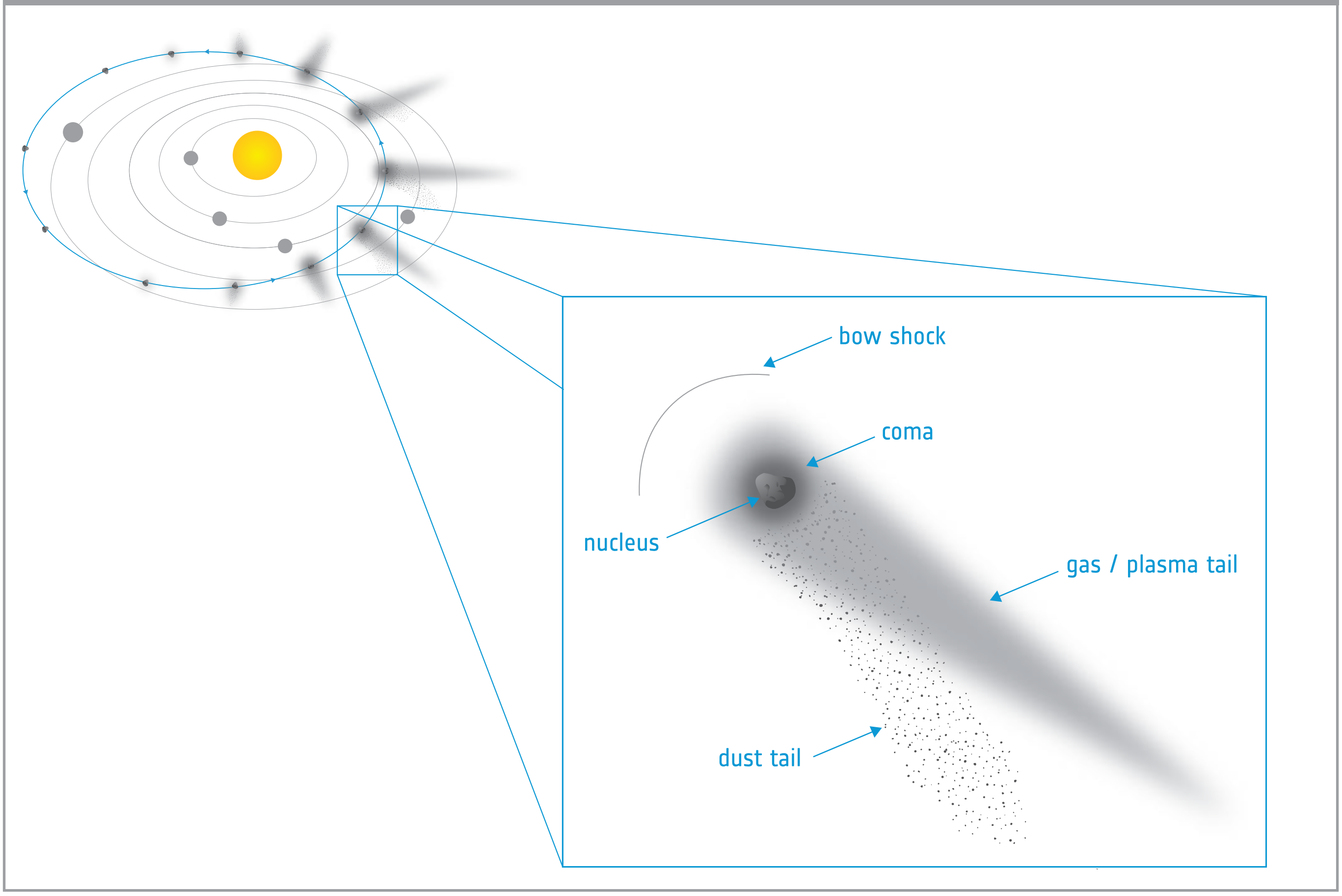


↑ Size comparison of the nuclei of comet 9P/Tempel and comet 103P/Hartley.

Why are some comet tails such different shapes?

The shape and appearance of comet tails are due to the interaction between the solar wind and solar radiation with material ejected from the nucleus. Two tails are often seen that point in different directions. One always points directly away from the Sun. This is the plasma or ion tail. Ultraviolet light from the Sun ionises gases in the coma. These ionised particles are then dragged away from the comet by the solar wind. The other tail is the dust tail, which is formed by solar radiation pressure pushing the small solid particles in the coma away from the Sun. The dust tail slightly curves back, or arcs, in the direction from which the comet has travelled (Figure A3). Since rates of solar activity, nucleus rotation and outgassing velocities vary tremendously from comet to comet a plethora of different tail shapes can be observed.

Figure A3

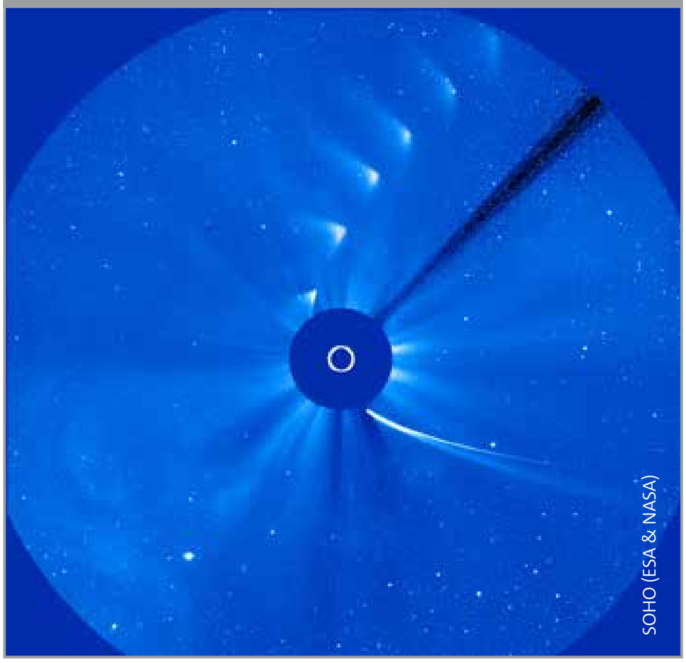


↑ A diagram showing the two tails of a comet and how they vary in a comet's orbit around the Sun.

How long will a comet nucleus last?

Comets lose volatiles (for example, carbon dioxide and water) and dust during each perihelion passage, leaving behind trails of debris. This means that a given nucleus may have a finite number of perihelion passes before all of its volatiles are depleted. An example of this was comet 2012/S1 ISON, a Sungrazing comet that made its first close perihelion approach in 2013 (Figure A4). Comet 2012/S1 ISON appeared to stop producing gas and dust shortly before it raced passed the Sun.

Figure A4



↑ Comet ISON's brush with the Sun as seen by the ESA/NASA SOHO satellite 28-30 November 2013.

What effects might change a comet's orbit during its closest approach to the Sun?

When the volatiles in a comet nucleus (such as carbon dioxide and water) start heating up as it approaches the Sun, the outgassing can create a recoil effect. As gas is ejected it exerts an equal and opposite force (Newton's third law) on the comet, therefore giving the comet a very slight push. The effect of this can be to slightly alter the orbital path of the comet, and also its period around the Sun as the nucleus is deflected away from its predicted path. Given that most nuclei are also in a state of spinning (perhaps around multiple axes, tumbling both forwards and sideways) the deviations can vary tremendously from comet to comet.

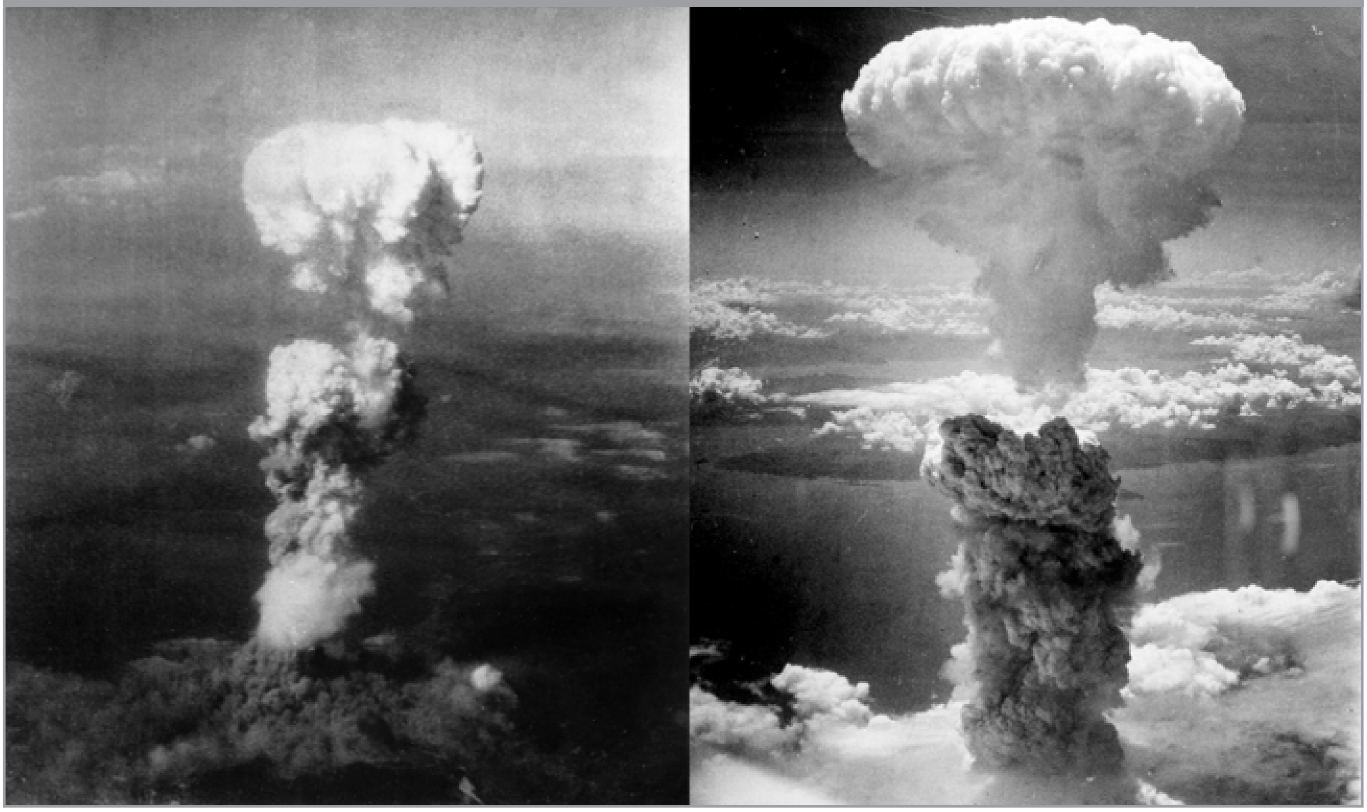
Discussion extension - can comets or asteroids ever hit Earth?

Using what has been learned during nuclear explosions conducted by various nations since 1945, and the kinetic energy equation, it is possible to make a good approximation of the size of the impactor that created Meteor Crater.

Nuclear weapon energies are measured in kilotons (kt) – with 1 kt equal to the energy yield of 1000 tons of TNT. 1 kt = 4.2×10^{12} J.

The Hiroshima and Nagasaki atomic bombs (Figure A5) each had an energy yield of around 20 kt.

Figure A5



↑ Left image: smoke billowing above Hiroshima from first atomic bomb. Right image: atomic bombing of Nagasaki.

To create a crater the size of Meteor Crater, in the type of rock found in the area, it would take around 2.5 Mt (2500 kt), or about 125 Hiroshima bombs. One mathematical/computer simulation model suggests that the impactor hit the Earth at around 12.8 km s^{-1}. This gives enough information to calculate an approximate size of the impactor.

There are many fragments of the impactor which formed Meteor Crater scattered about the surrounding landscape. Analysis of these fragments shows that the impactor was composed of 92% iron and 7% nickel (the remaining 1% contained silicate inclusions and other trace elements). The impactor had a mean density of around 7000 kg m^{-3}.

With this information it is possible to make the following calculations, assuming that all of the kinetic energy of the impactor was converted into blast energy to form the crater:

1. Summary of the parameters
   Kinetic energy, E_K = 2500 kt
   Entry velocity = 12.8 km s^{-1}
   1 kt = 4.2×10^{12} J
   Density of iron meteorite, ρ = 7000 kg m^{-3}

2. Convert the energy needed to blast out the crater into joules.
   $E_K = 2500 \text{ kt} = 2500 \times 4.2 \times 10^{12}\text{J} = 1.05 \times 10^{16}$ J

3. Use the kinetic energy equation to work out the mass of the impactor.
   $E_K = 1/2\ mv^2$

   Rearranging for m:
   $m = (2E_K)/v^2 = (2 \times 1.05 \times 10^{16}\text{ J})/(12\,800 \text{ m s}^{-1})^2 = 128 \times 10^6 \text{ kg} = 128\,000$ t

4. Use the density equation to work out the volume of the impactor.
   Since mass = density x volume
   Volume = mass/density = $(128 \times 10^6 \text{ kg})/(7000 \text{ kg m}^{-3}) = 1.83 \times 10^4 \text{ m}^3$

5. Assuming the impactor is spherical, use the sphere equation to work out the radius of the impactor. An alternatively is to model the impactor as a cube.
   And since the volume of a sphere = $(4/3)\pi r^3$

   By rearranging,
   $r^3 = (3 \times 1.83 \times 10^4 \text{ m}^3)/(4 \times \pi) = 4371$ m

   and so $\underline{r = 16.4 \text{ m}}$

Students can then investigate the limitations/uncertainties in the assumptions made in the modelling, these include:

- assuming 100% conversion of kinetic energy. Energy would have also been lost in other forms such as sound and thermal heating of the atmosphere.
- the uncertainty in impact velocity. This value is a deduced value from observations of an old impact crater and so could be inaccurate leading to an incorrect size calculation.
- effect of the angle of impact. The amount of rock that would be vapourisedvaporised/ejected will vary depending on the angle of entry. Since many of the original factors are deduced from this evidence, the angle of entry makes a lot of difference to the results. Experimenting with different angles of entry for the same impactor using the Down2Earth impact simulator (see below and Links section) could help to expand on this point.

Online impact simulator – 'Down2Earth'

Down2Earth (see Links section) is a web based impact simulator for educational purposes that allows students to set parameters for an impact, such as composition of the impactor (asteroid or comet), entry angle, size, type of rock at the impact site and the location of impact. Students can predict the effect of these factors on the crater size and link these to energy transfers during impact. Students can then test their predictions in a virtual environment.

→ CONCLUSION

Comets provide an interesting context for teaching many different classroom topics from gravitational fields and orbits, kinetic energy and energy transfer, to comet spectroscopy and the ingredients for life. Our fascination with these frozen worlds provides a wealth of exciting learning opportunities.

Cooking a mini comet

In this activity, you will make an analogue of a comet nucleus using common ingredients to represent the main groups of materials found in comet nuclei. Some of the materials, like dry ice, are hazardous – your teacher will give you instructions on how to use them.

Equipment

- Dry ice (about 100 ml)
- Water (about 100 ml)
- Small bin liners
- 3 teaspoon of soil
- 1 teaspoon of carbon dust/powder or graphite powder
- 1 teaspoon of whisky, vodka, or red wine (methanol/ethanol component)
- A few drop of soy sauce (organic component)
- A drop of cleaning product (amonia product)
- Disposible plastic cup
- Bucket for disposal
- Teaspoon
- Polysterene container for dry ice
- Thermal protective gloves
- Safety glasses for all participants
- Protective laboratory coat

Instructions

1. Place the following ingredients into a lined disposable plastic cup: water, soil, carbon dust, wine/alcohol, cleaning product and soy sauce. These represent some the compounds of a real comet. Mix well with the teaspoon.

2. Add the dry ice. Stir the water and dry ice mixture. Then, wearing the protective gloves, mould the comet into one lump for around 30 seconds. Do not compress it too much as the comet may break.

3. When the activity has been completed, place the comet inside a bin liner and put it into the bucket provided by your teather.

STUDENT WORKSHEET

Calculating comet mass, velocity and energy

Through this series of questions you will investigate the mass, velocities and energies of comets using the data given in the table below.

Mass of the Sun	$m_{Sun} = 2 \times 10^{30}$ kg
Density of ice	$r = 1000$ kg m^{-3}
Gravitational constant	$G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}

Questions

1. A comet has a kinetic energy of 4.5×10^{13} J. It is travelling with a velocity of 34 km s^{-1}. Calculate the mass of the comet.

2. A large comet of mass 5.2×10^8 kg has a near miss with the Earth and skims the atmosphere. At the time of measurement its velocity was 49.0 km s^{-1}.

   a) Calculate the kinetic energy of the comet (in J).

   b) If the energy released by 1 kiloton (1000 tons) of TNT exploding is 4.2×10^{12} J, how many kilotons of energy would this comet have had if it had impacted the Earth?

   c) After the near miss, the mass and trajectory of the comet were altered. Suggest a reason for this.

3. A comet is in an elliptical orbit around the Sun. Its closest approach to the Sun is at a distance of 4.9×10^{10} m. At this point its speed is 8.9×10^4 m s^{-1}. It originated in the Oort cloud, far beyond the orbit of Neptune. What is its speed when it is 1.5×10^{11} m from the Sun (this is the orbital distance of the Earth from the Sun)?

4. How do you think comet and asteroid impacts have affected the Earth and life on the Earth over the course of its history?

→ SPACE CONTEXT @ ESA

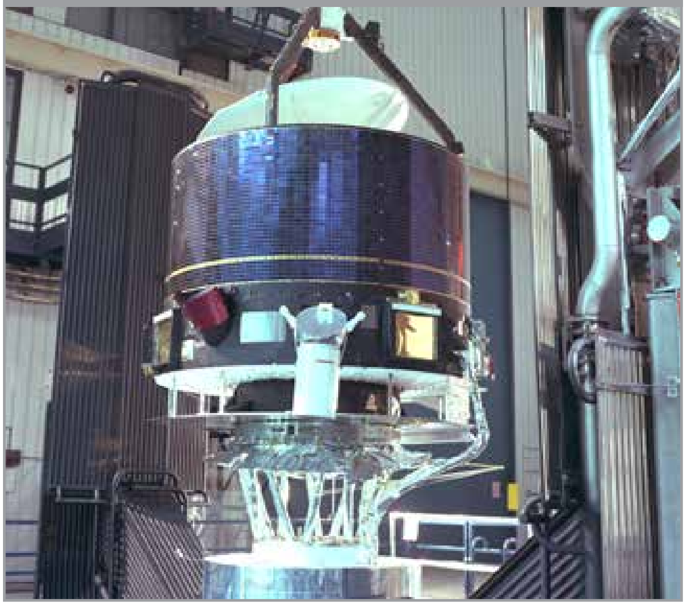
Giotto

Comet 1P/Halley has an orbital period of around 75.5 years (the figure varies slightly from orbit to orbit due to outgassing from its nucleus and gravitational perturbations). This comet has been observed from Earth (with the naked eye) on a regular basis and sightings have been recorded since around 240 BC. Records of these observations have enabled astronomers to confine the orbit of comet 1P/Halley to a few months around perihelion. One famous record of comet 1P/Halley's visibility from Earth was made on the Bayeux Tapestry that depicts the Battle of Hastings in 1066 (Figure 10).

Figure 10

↑ Comet 1P/Halley depicted on the Bayeux tapestry.

Figure 11



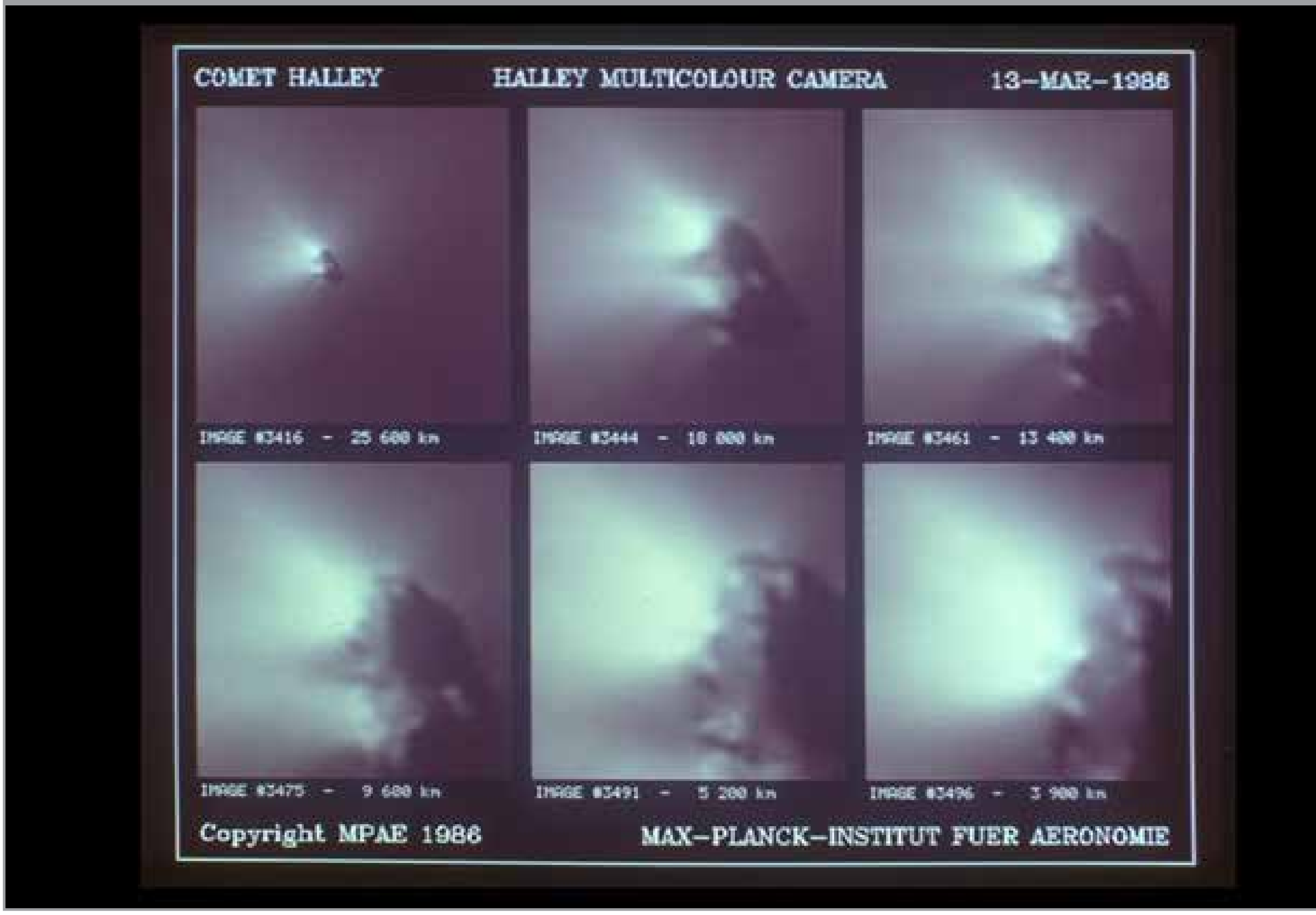
↑ Giotto ready for the solar simulation test. Copyright: ESA

More recently, in 1986, comet 1P/Halley made its first approach to the Sun since the beginning of the space age. ESA's Giotto spacecraft (Figure 11) flew past its nucleus at a distance of less than 600 km, obtaining the first ever close-up images of a comet nucleus (Figures 12 & 13). These observations transformed scientists' understanding of these icy objects.

Giotto observed that the surface of the nucleus was very dark, blacker than coal: this suggested that it was covered in a layer of dust. The data showed that the abundance or ratio of light elements (hydrogen, carbon and oxygen) in comet 1P/Halley was similar to the Sun's meaning that it is made up of the original material from which the Solar System formed.

The montage of images in Figure 12 shows more features becoming visible as the craft closed in on the nucleus.

Figure 12



MPAE, courtesy of Dr. H.U. Keller.

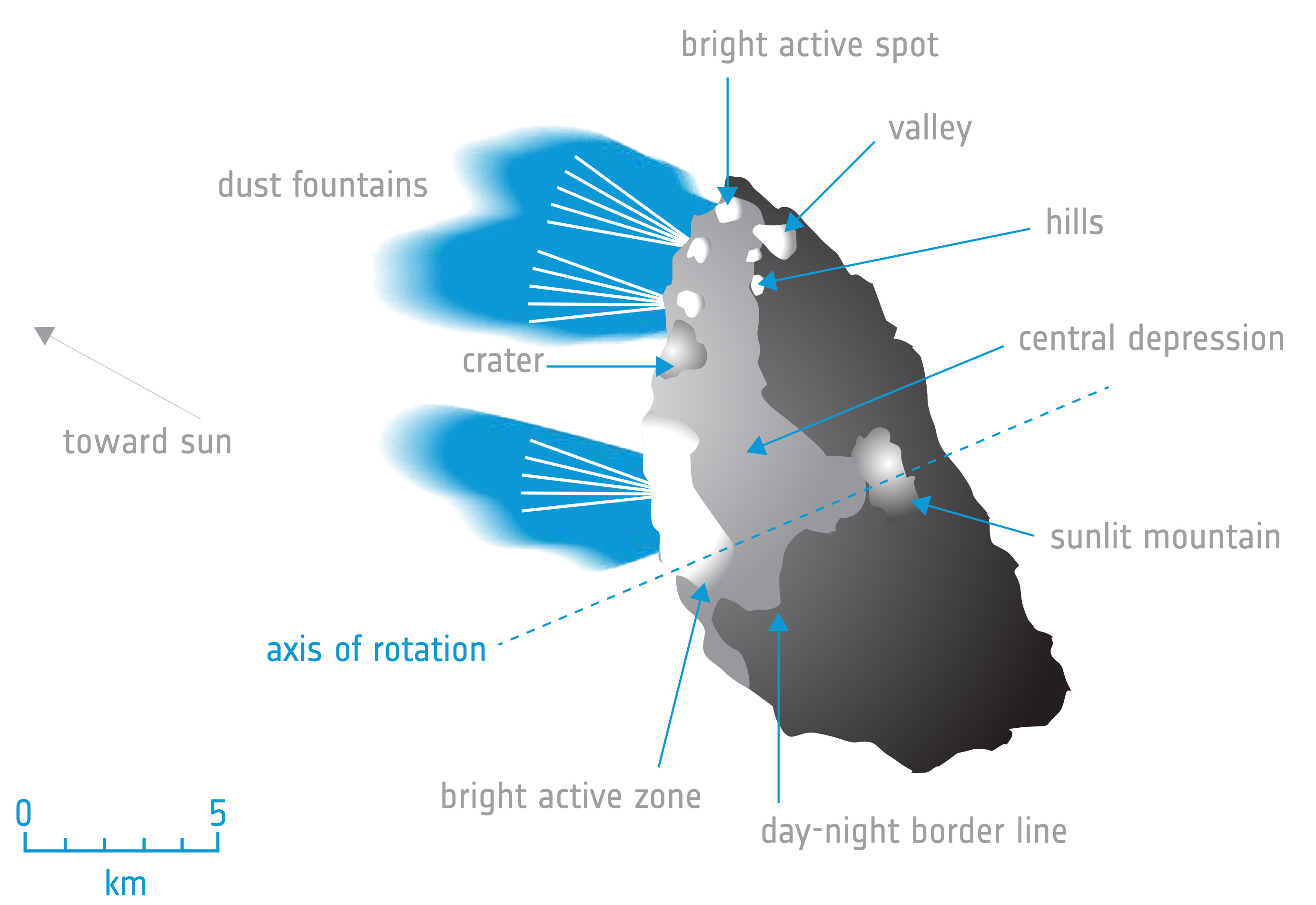
↑ The nucleus of comet 1P/Halley, as seen by Giotto during its closest approach.

Figure 13

ESA. Courtesy of MPAe, Lindau.

↑ Image of the nucleus of comet 1P/Halley as viewed by Giotto.

Figure 14



↑ Principal features identified on the images of comet 1P/Halley returned by ESA's Giotto probe.

Figure 14 shows features interpreted from an image of comet 1P/Halley's nucleus (Figure 13). Jets of material, or dust fountains, can be seen emerging from the surface of the nucleus. This is caused by the rapid sublimation of the volatiles on and near the surface of the nucleus. As the pressure of these expanding volatiles increases, they are eventually released in a process known as outgassing.

SOHO - Solar and Heliospheric Observatory

The ESA/NASA Solar and Heliospheric Observatory, or SOHO, monitors the Sun from a distance of 1.5 million kilometres away from the Earth (Figure 15). Here the combined gravity of the Earth and the Sun keeps the spacecraft in an orbit locked to the Earth-Sun line. From this position SOHO has an uninterrupted view of the Sun and can therefore make observations 24 hours a day.

SOHO was designed to study the internal structure of the Sun, its extended outer atmosphere (the corona) and the origin of the solar wind. Launched in 1995, SOHO has watched the Sun over a complete solar cycle, supplying scientists with valuable data to help understand the highs and lows of the Sun's long-term behaviour.

From its unique viewing point SOHO has also had the opportunity to observe thousands of sungrazing comets, including comet 2012/S1 ISON, a sungrazing comet that made a close perihelion approach in 2013 . SOHO is one of the greatest comet discoverers of all time and has found more than 2700 comets since it was launched.

Figure 15

↑ Artist's impression of SOHO.

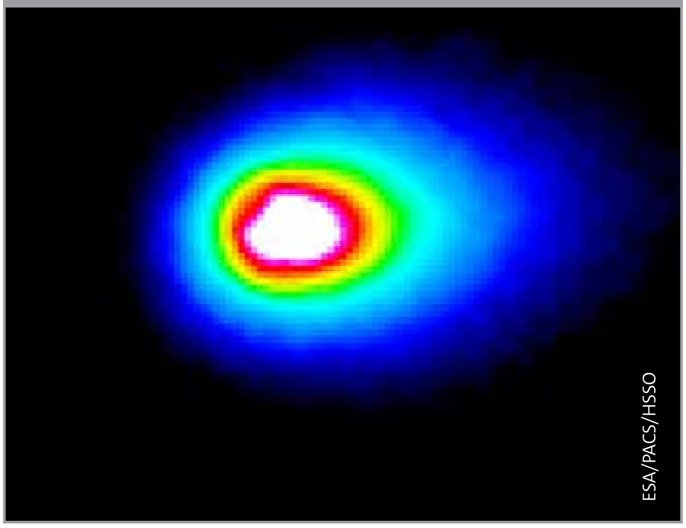
Comet 103P/Hartley and Herschel

ESA's Herschel infrared space observatory (Figure 16) was launched in 2009 and carried the largest, most powerful infrared telescope ever flown in space. It was the first observatory to cover the entire range from far infrared to submillimetre wavelengths. Herschel's observations explored further into the far infrared than any previous mission by studying otherwise invisible dusty and cold regions of the cosmos, both near and far.

Figure 16

↑ Artist impression of the Herschel infrared space observatory.

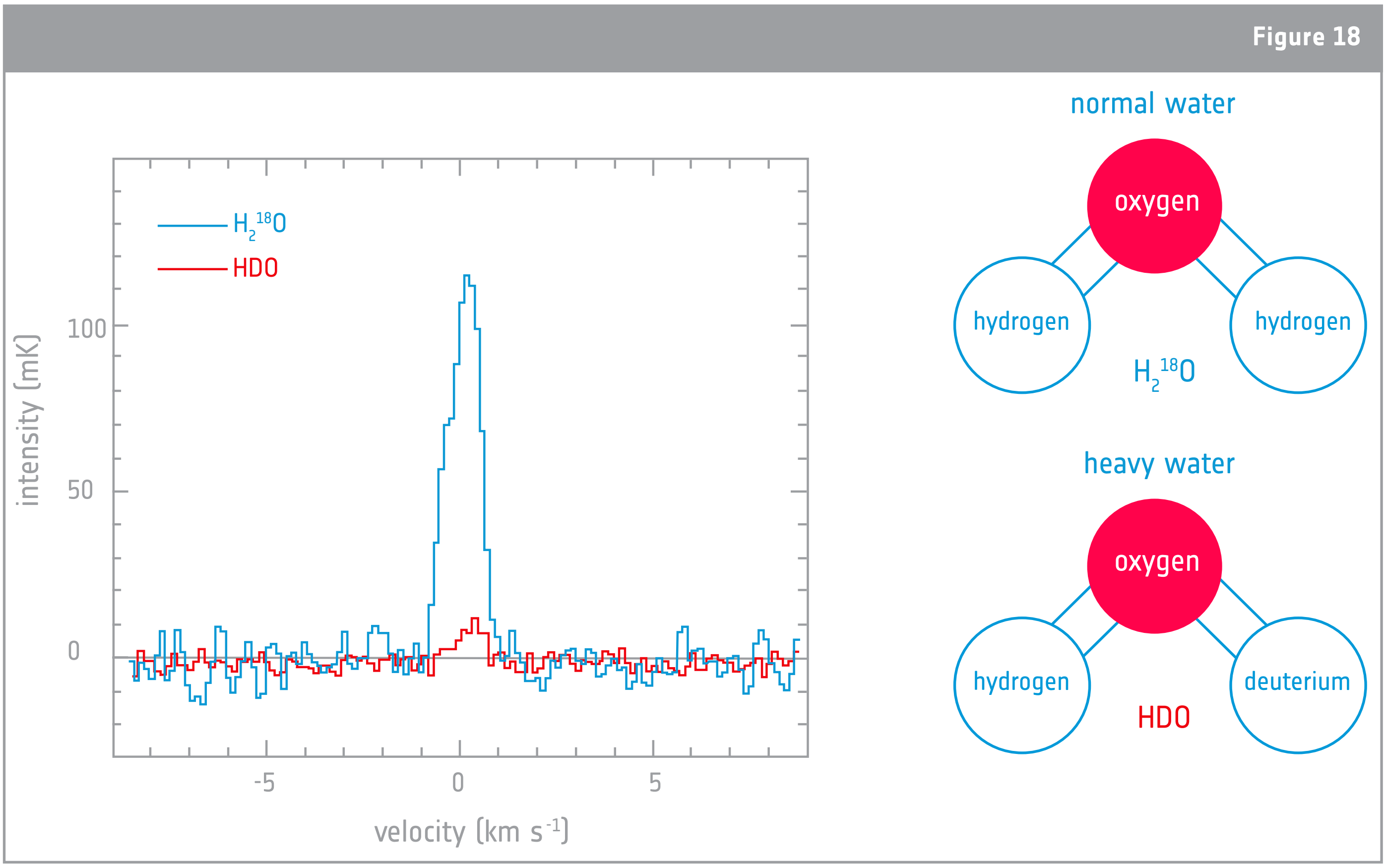
Figure 17



↑ Comet 103P/Hartley as seen by the PACS instrument on the Herschel infrared space observatory.

In 2010, Herschel conducted far-infrared spectroscopic observations of comet 103P/Hartley and observed the emission of vast quantities of water from its nucleus as shown in red and white in Figure 17. These observations were conducted near the comet's perihelion (closest approach to Sun).

The infrared spectroscopy measurements, made by the HIFI instrument on board Herschel, enabled estimates to be made of the ratio of deuterium ('heavy hydrogen' – hydrogen atoms with a neutron in their nuclei as well as a proton) to hydrogen within the water emitted by the comet's nucleus (i.e. the ratio of normal water to 'deuterated' water; Figure 18). It was found that the water content of this particular comet has, unlike others observed, an identical ratio to the water content of Earth's oceans. This provided the first direct evidence to support the theory that Earth's original water content came from the same source as some comets.



↑ With an extra neutron in one of the hydrogen components of the molecule, heavy water produces a smaller spectral peak.

Rosetta

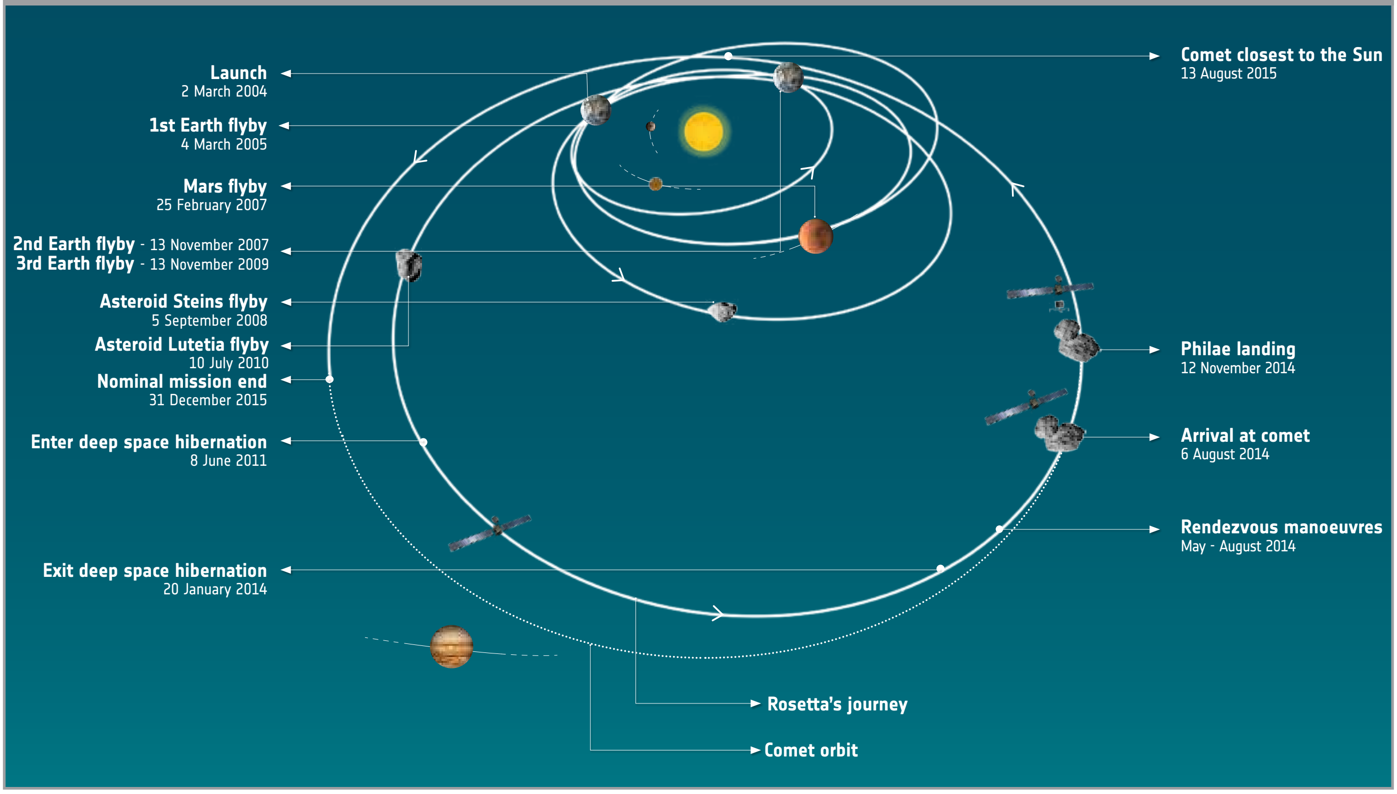
The ESA Rosetta mission to comet 67P/Churyumov-Gerasimeko was launched in 2004 on a 10 year journey to rendezvous with, and land on the nucleus of, a comet.

Rosetta's prime objective is to help understand the origin and evolution of the Solar System. A comet's composition reflects that of the pre-solar nebula out of which the Sun and the planets of the Solar System formed, more than 4.6 billion years ago. An in-depth analysis of comet 67P/Churyumov-Gerasimenko by Rosetta and its lander will provide essential information to understand how the Solar System formed.

There is convincing evidence that comets played a key role in the evolution of the planets, because cometary impacts are known to have been much more common in the early Solar System than today. Comets, for example, might have brought water to Earth. The chemistry of the water in comet 67P/Churyumov-Gerasimenko will be analysed to see if it is the same as that of Earth's oceans. In addition to ice and dust, comets contain many complex molecules, including organic materials that may have played a crucial role in the evolution of life on Earth.

In order to get to the comet, Rosetta had to perform a series of gravitational 'slingshots', where the gravity of a celestial body is used to help accelerate the spacecraft (Figure 19). To fly deeper into space, Rosetta needed to make four slingshot manoeuvres including three close flybys of the Earth and one with Mars. Each slingshot altered the kinetic energy of Rosetta, and therefore changed the velocity of the spacecraft, altering the dimensions of the elliptical orbit.

Figure 19



↑ ESA's Rosetta spacecraft performed a series of planetary 'slingshots' in order to reach its destination.

With such a long journey to make, Rosetta was placed into hibernation mode in June 2011 to limit its consumption of power and fuel, and to minimise operating costs. Almost all of Rosetta's electrical systems were switched off, with the exception of the computer and several heaters.

In January 2014, Rosetta's pre-programmed internal 'alarm clock' carefully woke up the spacecraft in preparation for its rendezvous with comet 67P/Churyumov-Gerasimeko. Following wake-up, the orbiter's 11 science instruments and the 10 lander instruments were reactivated and readied for science observations. Then a series of ten critical orbital correction manoeuvres were carried out to reduce the spacecraft's velocity relative to the comet, and therefore match its elliptical orbit.

After Rosetta arrived at comet 67P/Churyumov-Gerasimeko, on 6 August 2014, it began further manoeuvres to place it into an 'orbit' around the comet nucleus. From this vantage point, Rosetta's suite of instruments can provide a detailed scientific study of the comet scrutinising and mapping the surface in unprecedented detail (Figure 20).

Figure 20

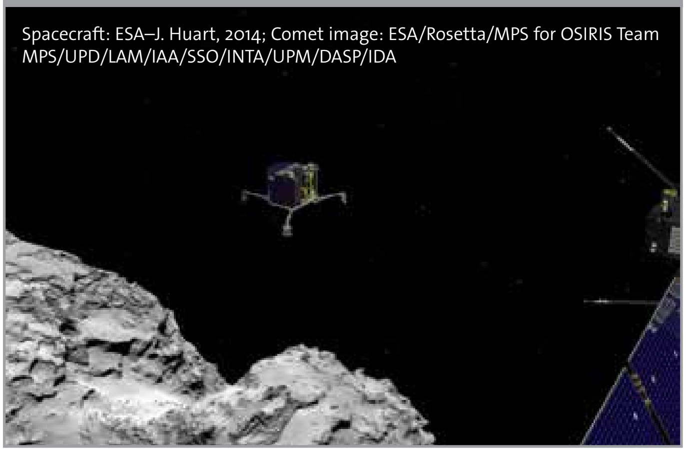
↑Four-image NAVCAM mosaic of comet 67P/Churyumov Gerasimenko, using images taken on 19 September 2014 when Rosetta was 28.6 km from the comet.

After the landing Rosetta will continue to accompany the comet on its elliptical journey. Rosetta will accelerate back towards the inner Solar System with the comet and will continue to study and watch from close quarters as the icy comet nucleus heats up as it approaches the Sun.

In November 2014, after mapping and analysing the comet nucleus for several months, Rosetta will deploy its lander Philae to attempt the first ever landing on a comet nucleus. As the comet has such low gravity, Philae will use harpoons and ice screws to attach itself to the surface. Figure 14 shows an artist's impression of Philae deploying onto the surface.

The Philae lander will use 10 instruments, including a drill to collect samples of the surface and **spectrometers***, to directly analyse the structure and composition of the comet.

Figure 21



↑ The Philae lander will deliver unprecedented information about the surface and internal structure of a comet.

* **Spectrometer:** instrument to split light into its constituent wavelengths so that the properties of the light source can be measured.

→ APPENDIX

Glossary

Aphelion: point in an orbit furthest from the Sun.

Astronomical Unit (AU): 1 AU is the average distance between the Earth and the Sun, or the Earth's orbital radius, which is approximately 150 million kilometres.

Bow shock (comet): surface of interaction between the ions in the comet coma and the solar wind. The bow shock forms because the relative orbital velocity of the comet and the solar wind are supersonic. The bow shock forms upstream of the comet in the flow direction of the solar wind. In the bow shock, large concentrations of cometary ions build up and load the solar magnetic field with plasma. The result is that the field lines bend around the comet, entrailing the cometary ions, and forming the gas/plasma/ion tail.

Flyby: close passage of a spacecraft around a planet or other celestial body. If the spacecraft uses the gravitational field of the planet to boost the spacecraft's velocity and change its trajectory, this is called a swing by or gravity assist manoevre.

Gravitational perturbations: changes to the orbit of a celestial body (e.g. planet, comet) due to interactions with the gravitational fields of other celestial bodies (e.g. giant planets, other stars).

Lagrangian points: in any orbital configuration there are five points at which an object only affected by gravity can orbit stably. For more information see the ESA teach with space - gravity wells video | VP04 (see Links section).

Orbital period: time taken to complete one orbit.

Perihelion: point in an orbit closest to the Sun.

Retrograde motion of a planet: Apparent motion of a planet in the night sky in the direction opposite to what is normally observed (prograde motion).

Solar wind: a stream of high energy particles (plasma) being emitted by the upper atmosphere of the Sun in all directions. It contains mostly electrons and protons.

Sublimate (sublimation): when heating causes a substance to change directly from the solid phase to the gas phase, bypassing the liquid state. When the gas is re-cooled, it typically forms a solid deposit.

Links

Rosetta

ESA Rosetta website: www.esa.int/rosetta
ESA Rosetta blog: blogs.esa.int/rosetta/
Rosetta videos and animations: www.esa.int/spaceinvideos/Missions/Rosetta
Rosetta images: www.esa.int/spaceinimages/Missions/Rosetta/(class)/image
Rosetta factsheet, including mission timeline: www.esa.int/Our_Activities/Space_Science/Rosetta/Rosetta_factsheet
The story so far: www.esa.int/spaceinvideos/Videos/2014/01/Rosetta_the_story_so_far
Chasing a comet:www.esa.int/spaceinvideos/Videos/2014/01/Chasing_a_comet
A 12 year journey through space: www.esa.int/spaceinvideos/Videos/2013/10/Rosetta_s_twelve-year_journey_in_space
Rosetta's orbit around a the comet: www.esa.int/spaceinvideos/Videos/2014/01/Rosetta_s_orbit_around_the_comet
How to orbit a comet: www.esa.int/spaceinvideos/Videos/2014/08/How_to_orbit_a_comet

Comets

ESA Kids article on comets: www.esa.int/esaKIDSen/SEMWK7THKHF_OurUniverse_0.html
ESA Rosetta website (technical): www.esa.int/Our_Activities/Space_Science/Rosetta
ESA Giotto website: sci.esa.int/giotto/
ESA Rosetta website: www.esa.int/rosetta
ESA Kids article on our Universe: www.esa.int/esaKIDSen/SEMYC9WJD1E_OurUniverse_0.html

Giotto

Giotto overview: www.esa.int/Our_Activities/Space_Science/Giotto_overview

Herschel

ESA Herschel space observatory website: www.esa.int/herschel
Did Earth's oceans come from comets?: www.esa.int/Our_Activities/Space_Science/Herschel/Did_Earth_s_oceans_come_from_comets

SOHO

ESA SOHO website: soho.esac.esa.int
Video of comet ISON's brush with the Sun as seen by the ESA/NASA SOHO satellite: sci.esa.int/soho/54346-soholasco-view-of-comet-ison-27-30-november-2013/

Earth impact

Down2Earth impact simulator: education.down2earth.eu/

Teach with space collection

ESA teach with space - gravity wells video | VP04: www.esa.int/spaceinvideos/Videos/2014/07/Gravity_wells_-_classroom_demonstration_video_VP04
ESA teach with space - marble-ous ellipses teacher's guide and student activities | P02: esamultimedia.esa.int/docs/edu/P02_Marble-ous_ellipses_teacher_guide.pdf
ESA teach with space - marble-ous ellipses video | VP02: www.esa.int/spaceinvideos/Videos/2014/07/Marble-ous_ellipses_-_classroom_demonstration_video_VP02
ESA teach with space - cooking a comet video | VP06: www.esa.int/spaceinvideos/Videos/2014/10/Cooking_a_comet_ingredients_for_life_-_classroom_demonstration_video_VP06

teach with space – cooking a comet | P06
www.esa.int/education

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