rosetta

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1

Rosetta at a glance

Rosetta at a glance

Rosetta is one of the most complex and ambitious missions ever undertaken.

It is performing unique science. No other mission has Rosetta's potential to look back to the infant Solar System when our planet was forming, and investigate the role comets may have played in seeding Earth with water, perhaps even the ingredients for life.

To do this, Rosetta became the first mission to orbit and land on a comet. To get there, scientists had to plan in advance, in the greatest possible detail, a ten-year trip through the Solar System.

Approaching, orbiting, and landing on a comet required delicate and spectacular manoeuvres. Rosetta's target, Comet 67P/Churyumov-Gerasimenko, is a relatively small object, about 4 kilometres along its longest side, moving at a speed as great as 120 000 kilometres per hour with respect to the Sun.

Prior to arriving at the comet, very little was known about its surface properties or the close environment. Only after arrival were we able to explore the comet in such detail that we could safely orbit it and deploy the lander, Philae.

During its short-lived operational life, Philae obtained the first images from a comet's surface and made the first in-situ analysis of a comet's nucleus.

Since its arrival, Rosetta has spent more than two years 'living' with this comet. Rosetta is the first mission to investigate a comet's nucleus and environment over an extended period of time. It has witnessed, at close proximity, how a comet changes as it approached the increasing intensity of the Sun's radiation and then returned to the outer Solar System.

Rosetta is an ESA mission with contributions from its member states and NASA.

2

Fast Facts

Fast Facts

Launch: 07:17 GMT on 2 March 2004, on an Ariane 5 G+ from Europe's spaceport at Kourou, French Guiana

Launch mass: 3000 kg (fully fuelled) of which the Orbiter accounted for 2900 kg (including 1670 kg propellant and 165 kg science payload), and the Lander 100kg (with 26.7 kg of science payload).

Orbiter dimensions: 2.8m x 2.1m x 2.0m with two 14m long solar wings

Orbiter payload: 11 experiments (Alice, CONSERT, COSIMA, GIADA, MIDAS, MIRO, OSIRIS, ROSINA, RPC [ICA, IES, LAP, MAG, MIP, PIU], RSI and VIRTIS) to study the comet's global and local environment, surface, and sub-surface.

Lander dimensions: 1 m x 1 m x 1 m (before deployment of landing gear)

Lander payload: 10 experiments (APXS, CIVA, CONSERT, COSAC, PTOLEMY, MUPUS, ROLIS, ROMAP, SD2, SESAME) to investigate the local comet environment, surface and sub-surface.

Distance travelled (by 30 September 2016*): more than 7,900 million km

One-way signal travel time (on 30 September 2016*): 2400 s (40 min)

Ground communications: NASA's 70 m Canberra station, DSS-43, will be on duty in the early hours of 30 September before handing over to NASA's 70 m antenna, DSS-63, at Madrid (Robledo de Chavela). ESA stations will act as backup.

Distance of Rosetta from Sun (on 30 September 2016*): 573 million km

Distance of Rosetta from Earth (on 30 September 2016*): 720 million km

Speed of spacecraft and comet with respect to Sun: 14 km/s (51,000 km/h)

***See Appendix B for equivalent numbers for other key periods of the mission. See also the 'Where is Rosetta?' online tool (sci.esa.int/where_is_rosetta/) for distances and speeds for the entire mission.

Cost: The total cost of the mission is 1.4 billion Euro. This includes the launch, the spacecraft, the science payload (instruments and lander), and mission and science operations.

Industrial contributions: The Rosetta spacecraft was built by an industrial team led by prime contractor Astrium GmbH (now Airbus Defence and Space), Friedrichshafen, Germany, and involving more than 50 contractors from 14 European countries and the USA. Major subcontractors were Astrium Ltd. who built the spacecraft platform, Astrium France who supplied the spacecraft avionics and Alenia Spazio, Turin, Italy, for assembly, integration and verification. Canada participated in the construction of ESA's first 35 m-diameter Deep Space Antenna in Australia, which was built for Rosetta. Scientific consortia from institutes across Europe and the United States provided the 11 experiments for the orbiter.

Rosetta's Philae lander is provided by a consortium led by DLR, MPS, CNES and ASI. Other members of the consortium are ESA and institutes from Austria, Finland, France, Hungary, Ireland, Italy and the UK.

What's in a name?

For the people charged with naming one of the most ambitious missions in planetary science this decade there was one name that seemed to have been destined for it: Rosetta.

The Rosetta Stone, an ancient Egyptian stone tablet from the second century BC was unearthed near Rashid (Rosetta) on the Nile delta in 1799. Famous for carrying the same text inscribed in three different languages – ancient Egyptian hieroglyphics, Demotic script (an everyday form of Egyptian) and ancient Greek – the stone allowed nineteenth-century archeologists to decipher hieroglyphics for the first time. This in turn provided the key to understanding an ancient civilisation. In a similar manner, ESA's Rosetta mission will allow scientists to unlock the mysteries of the oldest building blocks of our Solar System: comets.

Rosetta's lander Philae is named after an island in the Nile river, where archeologists found an inscription on an obelisk that confirmed their interpretation of the Rosetta Stone texts.

The place where Philae first touched down is called Agilkia after an island in the Nile River – this was the winning name in a competition open to the public. The place where Philae eventually came to rest, after it touched down, rebounded, tumbled and bounced across the comet, is called Abydos, after one of the oldest cities of ancient Egypt.

The Egyptian theme has continued with the naming of the twenty-six geological regions on the comet after ancient Egyptian deities. Regions on the small lobe, sometimes referred to as the ‘head’ of the comet, are named after Egyptian goddesses (Anuket, Bastet, Hathor, Hatmehit, Ma’at, Maftet, Neith, Nut, Serqet, Wosret), while regions on the large lobe, or ‘body’ of the comet, are named after gods (Anhur, Anubis, Aker, Apis, Ash, Aten, Atum, Babi, Bes, Geb, Imhotep, Khepry, Khonsu, Seth). The two regions on the neck of the comet are named after the Nile gods, Hapi and Sobek.

3

Landing Rosetta on the comet

Landing Rosetta on the comet

Rosetta has been a mission of 'firsts', from the first orbit around a comet to the first landing on a comet's surface. The end of the mission will also be another first because Rosetta was never designed to land on the comet.

Putting the spacecraft down onto the surface of Comet 67P/Churyumov-Gerasimenko is a prudent move enabling the mission to end, as it must, in a controlled and scientifically valuable way. Following the comet has taken Rosetta away from the Sun, and this means that the power generated by the spacecraft's solar panels will be insufficient to maintain the spacecraft activities.

Already, spacecraft operators are having to share the power between the instruments because not all of them can be switched on at the same time any more. In the absence of sufficient power, further out on its orbit around the Sun, the remaining fuel in the spacecraft would freeze.

Placing Rosetta on the comet before this happens is the best way to end the flight segment of the mission.

Starting in early August, Rosetta followed elliptical orbits that brought it closer and closer to the comet each time. Every three days, the spacecraft's elliptical orbit brought it into a flyby with the comet, enabling unprecedented close-up observations by its instruments. Its closest approach was to within 1.76 km of the rugged surface (as observed from a navigation camera image). On 24 September, after the final flyover, flight controllers began a series of manoeuvres to line it up for the final, fateful drop.

On the night of 29 September, at 20:50 UTC, one last manoeuvre will be executed in which the spacecraft will fire its thrusters, for about 3 minutes. It will then begin a leisurely 14-hour drop to the comet's surface. In those hours it will cover a distance of 20 km.

Initially its speed will be just 30 cm/s (about 1 km/h). This will gradually increase due to the gravity of the comet. At about 55 minutes before touchdown, at a distance of 2 km above the surface, Rosetta will be travelling at 60 cm/s.

Calculations show that the final impact speed will be about 90 cm/s. This is roughly walking pace and is about the same speed as Philae hit the surface back in November 2014.

Data and images will be transmitted for as long as possible in the run-up to the touchdown. Being that close to the comet, the spacecraft may be buffeted by dust and gas that continue to escape the weak gravitational field.

To prevent the spacecraft from entering a ‘safe mode' and losing contact before impact, spacecraft operators have reprogrammed some of its tolerance to errors. For example, some star tracker checks have been disabled for some weeks now. The star trackers are small telescopes that recognise the pattern of the stars and tell the spacecraft how it is oriented is space. Dust from the comet can blind these devices, and, in the past, this has led the spacecraft into ‘safe mode’ several times.

The flight team have also solved a unique problem: how to turn the spacecraft off upon touchdown. Spacecraft are designed to be almost constantly in communication with their operators on Earth and to function autonomously when out of contact. And that means no one really builds them with an 'off switch'. If Rosetta survived the touchdown, the main transmitter could randomly transmit signals that might affect the ability of other spacecraft to communicate with Earth.

But how do you turn off a spacecraft that was never designed to be turned off? It proved a challenge for the flight control team to force the spacecraft to enter a special mode that was used during testing of the spacecraft on Earth more than a decade ago. But eventually they found a way, and have written and uploaded a software patch for this. When the spacecraft touches the surface, some of the checks that are still enabled will trigger, leading the spacecraft to that mode. This is called ‘passivation of the spacecraft’.

Like Philae before it, Rosetta may tumble on the surface before coming to rest. Unlike Philae, there will be no way to know exactly where it comes to rest because no communication will be possible and no telescope could possibly resolve anything on the comet's surface.

Although the flight phase of the mission is coming to an end, the scientific data will continue to be used for decades. Just recently, scientists gathered to consider what has been learned with the data from ESA’s first comet mission, Giotto, and from these early days with Rosetta. There is every reason to believe that the wealth of information recorded by Rosetta will be used long into the future.

4

Collecting science until the very end

Collecting science until the very end

Rosetta will continue to collect science data until the very end of its descent to the comet. The opportunity to study a comet at such close proximity makes the descent phase one of the most exciting of the entire mission.

Not all instruments will be working during the descent. Rosetta is so far from the Sun now that it cannot generate enough power from its solar panels to keep everything running.

As a result, careful consideration had to be given to which instruments would make measurements during the descent to the surface. Taking into account science operations constraints – some instruments require quite some time to obtain their measurements – and the potential science return, the timeline prepared by the science operations team with the Rosetta science working team, sees MIDAS, COSIMA and VIRTIS turned off. The other instruments will be working right up until the end of the mission.

Getting the data obtained close to the surface back from Rosetta is going to be a challenge because the main antenna will be switched off as soon as the spacecraft touches down. Even if it wasn't, Rosetta will almost certainly tilt or tumble in the comet's weak gravity and this will break the communication connection with Earth.

To know exactly when the impact is likely to take place, the NavCam navigation camera will take 5 images during the early part of the descent, shortly after the spacecraft has been set on a collision course for the comet. These images will be downloaded to Earth in the early hours of 30 September and will be used by the flight team to predict the impact time to within a four-minute window.

This is vital information because it is no use taking exquisitely detailed data but losing it because it takes too long to beam back.

During the descent, the OSIRIS cameras (narrow-angle and wide-angle) will image the regions of the large lobe that it passes over. As the spacecraft approaches the small lobe the cameras will image the walls of the Ma'at pits. The very high resolution data of these features will provide important information for our understanding of how activity is driven on the comet and maybe how the comet was formed in the first place. For the final hour of descent, OSIRIS will acquire images at a high cadence. The intention is to capture one last image about 15 m from the surface with a resolution of 3 mm per pixel.

Other instruments, such as GIADA, ROSINA, RPC and MIRO will be collecting and transmitting data and it is expected that the last observations to be transmitted will give data from between 20 m to five m above the surface.

ROSINA will collect unique data on the density of gas around the comet and its composition. It is expected to provide readings down to the Knudsen Layer, where the evaporation of the gases actually happens.

MIRO will complement OSIRIS and ROSINA measurements by measuring the surface temperature.

GIADA will measure the dust's density and the way the dust grains are accelerated away from the comet.

The RPC instrument suite will monitor the plasma environment, and also the smallest dust particles. This will give a unique close-up look at the interaction between the solar wind and the surface of the comet, and it will sample levitating charged grains.

Alice will get its highest resolution ultraviolet spectra of the surface of the whole mission and provide complementary measurements to some of the RPC data.

RSI will get the most accurate measurements of the gravity field during descent.

The unique measurements obtained during this final descent will be a fitting closing chapter to Rosetta's time spent living with this comet.

5

Rosetta's final resting place

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Rosetta will end its mission on 30 September 2016 with a controlled impact in the Ma'at region, on the small lobe of Comet 67P/Churyumov-Gerasimenko.

This region has been chosen for its scientific potential and taking into account key operational constraints involved in executing the descent.

Ma'at is scientifically very exciting: it is home to a number of active pits, measuring over 100 m across and 50-60 m deep, to which a number of dust jets emerging from the comet have been traced back.

The pit walls also exhibit metre-sized lumpy structures called 'goosebumps', which scientists think could be the signatures of early cometesimals that assembled to create the comet in the early phases of Solar System formation.

Rosetta will get its closest look yet at these fascinating structures on 30 September: the spacecraft will target a point adjacent to a 130 m-wide, well-defined pit that the mission team has informally named Deir el-Medina, after a structure with a similar appearance in an ancient Egyptian town of the same name.

Like the archaeological artefacts found inside the Egyptian pit that tell historians about life in that town, the comet's pit contains clues to the geological history of the region.

Rosetta will target a point very close to Deir el-Medina, within an ellipse of about 700 m x 500 m.

During the final approach, Rosetta will obtain close-up images, along with information on the dust, gas, and plasma environment very close to the pits, which will help scientists understand their connection to the comet's observed activity, as well as learn more about how they relate to the formation and evolution of the comet.

6

Highlights from the Rosetta Mission thus far

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There are many highlights from the Rosetta mission because there is nothing routine about the endeavour. It is a daring mission that demanded world-class ambition and technological development to match.

When Rosetta deployed the lander, Philae, to the surface of Comet 67P/Churyumov-Gerasimenko on 12 November 2014, the mission had already accumulated a significant number of successes.

The idea that became Rosetta was conceived in the late 1970's even before ESA's Giotto mission flew by comet 1P/Halley, returning the first detailed picture of a comet's nucleus ever seen. The success of Giotto meant that plans for a follow-on mission were enthusiastically considered.

Almost 20 years later, Rosetta was built, tested and ready to launch. But disaster struck just one month before the planned liftoff. In December 2002, an Ariane 5, similar to the one designated to launch Rosetta, failed while lifting a communications satellite into orbit. With one billion Euros of tax-payers money and the hopes of the world's comet scientists resting on the successful launch of Rosetta, the difficult decision was made to postpone the attempt until the launcher failure was understood.

This deprived the mission of its original target, comet 46P/Wirtanen. While the engineers worked to understand and prevent the loss of another Ariane 5, scientists and engineers searched for a replacement target. Eventually they settled on Comet 67P/Churyumov-Gerasimenko, a somewhat more massive comet than Wirtanen. This led to the strengthening of the legs on Rosetta's lander Philae, to cope with the slightly faster landing speed now expected.

With all this drama behind it, the first highlight of the mission was simply to leave the surface of the Earth behind and begin its interplanetary journey. The launch took place on 2 March 2004.

A complex journey

Rosetta could not head straight for the comet using only the energy from launch. Instead it began a series of looping orbits around the Sun that brought it back for three Earth fly-bys and one Mars fly-by. Each time, the spacecraft changed its velocity and trajectory as it extracted energy from the gravitational field of Earth or Mars. During these planetary fly-bys, the science teams checked out their instruments and, in some cases, took the opportunity to carry out science observations coordinated with other ESA spacecraft such as Mars Express, ENVISAT and Cluster.

Each of the fly-bys required months of intense preparation. In particular, the fly-by of Mars in February 2007 was a critical operation: the new mission trajectory to 67P/Churyumov-Gerasimenko required that Rosetta fly past Mars at just 250 km from the surface, and spend 24 minutes in its shadow.

The spacecraft had been designed for the mission to Wirtanen, which did not include a period in Mars's shadow. The flight team had to re-programme the spacecraft completely in the months preceding the Mars fly-by, teaching Rosetta "not to worry" and to avoid potentially catastrophic autonomous reactions to the absence of sunlight on the solar panels and Sun sensors.

When the Rosetta signal reappeared after the passage behind Mars, shortly after the end of the "shadow" period, there was a collective sigh of relief.

Getting to know Rosetta

More than a decade has passed since Rosetta was launched. This meant that by the time it arrived at the comet in 2014, it was an old-timer in terms of starting its main mission phase. Nevertheless, it had to work at peak efficiency to make the most use of the months it would have at the comet.

One advantage of the mission's 10-year cruise phase is that the flight team has had plenty of opportunities to become familiar with many aspects of the spacecraft's 'personality'. No matter how precisely designed and constructed, all complex machinery takes on a life of its own once it starts working. Spacecraft are no different.

In the case of Rosetta, the flight team has learned to use the thrusters at slightly reduced efficiency to compensate for the fact that the fuel tanks cannot be re-pressurized. This is due to a leak in the Reaction Control System that manifested itself in 2006.

They have also learned to operate the reaction wheels at lower speeds than originally designed. The reaction wheels are critical to the mission. They are used to orient the spacecraft such that the instruments can point to the comet, the solar arrays to the Sun, and the main antenna to the Earth. Well into the mission, two out of the four reaction wheels started showing signs of vibrations when operated at their normal operating speed. An alternative software has been devised that uses only two wheels; this is ready to be uploaded and used in case the two reaction wheels completely fail.

The cruise phase has not been all quiet. Even in the periods of low activity, during the long arcs between fly-bys, the spacecraft had to be monitored once a week, and its flight plan continuously updated.

Science along the way

En-route to the comet, Rosetta encountered two asteroids. These allowed the scientists and flight team to practise with the instruments and to gain more valuable experience about how to navigate the spacecraft. A highlight from the first encounter was Rosetta executing a manoeuvre that had originally been termed too risky.

Asteroid Steins is tiny, just 5 kilometres across; about the size of a large village. On 5 September 2008, Rosetta was to fly past at a distance of 800 kilometres, roughly the distance between Paris and Munich, and keep everything in the sharpest focus possible. To do this throughout the fly-by would have meant exposing one face of the spacecraft to the Sun for longer than allowed.

The original strategy defined by the spacecraft manufacturer, taking into account Rosetta's thermal and mechanical constraints, involved stopping before the closest approach to turn the spacecraft back to its nominal attitude. This would have led to significant loss of data. Naturally, the data-hungry scientists wanted to take observations all the way through.

So the flight control team invented and tested a new strategy, such that Rosetta tracked the asteroid autonomously all the way through the encounter, boosting confidence in the spacecraft enormously.

However, not everything went according to plan. The OSIRIS science camera and the navigation cameras did not work exactly as expected during the fly-by, revealing another quirk of the spacecraft's personality. The team worked out how to ensure this did not happen again so that the next fly-by would be a success.

This paved the way for the mission's most celebrated science highlight prior to arriving at Comet 67P/Churyumov-Gerasimenko: the fly-by of asteroid Lutetia in July 2010.

Whereas Steins was a small jumble of rocky debris that resembled a solid object, Lutetia was a miniature world, with a diameter of 130 kilometres. At the time, it was the largest asteroid ever seen in close-up.

Rosetta was going to fly past at a greater distance, 3162 kilometres this time in order to allow the full asteroid to appear in the field of view of the scientific cameras. Nevertheless, the spacecraft would be out of communications with Earth for about 40 minutes as it turned its attention to Lutetia.

The vigil was worth it. Rosetta began streaming back its data, revealing a mini-world of the most complex geology. Its pulverised surface appeared to be poor in metals but showed the presence of hydrated minerals. There were rockslides and giant craters covering this battered relic from the formation of the Solar System.

In terms of aesthetics, the beauty-shot was an image that Rosetta had snapped on approach, showing the looming bulk of the asteroid in the foreground. In the distance, more than ten thousand times further away from the spacecraft, was the unmistakable shape of Saturn and its rings.

Rosetta sped on. It had charged past the asteroid at a relative speed of 54 000 kilometres per hour and was heading for the comet. Even at that great speed, there were still four more years to go. This meant that the moment many of the mission team dreaded was almost upon them: hibernation.

Hibernation and then …

Putting Rosetta to sleep for two years, seven months and twelve days was forced on the mission because it had to go so far out into the Solar System. Rosetta carries large solar panels based on completely new technology that makes them exceptionally efficient. But so far from the Sun, where no solar-powered spacecraft had gone before, there would not be enough power to keep all the spacecraft's systems operating. So everything was shut down, except for the on-board computer, some internal heaters and a few clocks to count down until 10:00 UTC on 20 January 2014. Then it was time for Rosetta to wake up, reactivate its communications system and phone home.

It did so, after a tense 18-minute delay, caused by the on-board computer rebooting. A memorable moment for the assembled scientists, flight team, officials and press, and a significant highlight ticked off the list. The mission was alive and ready for business. Next stop: the comet itself. Not that the flight team could relax. There was still a lot to do.

Destination in sight

Between wake-up and rendezvous, all twenty-one instruments had to be brought online and checked out. Software was updated and the spacecraft had to perform a series of 10 manoeuvres to reduce its speed sufficiently to rendezvous with the comet rather than fly by it.

The final arrival manoeuvre took place on 6 August 2014. During the preceding few weeks, as Rosetta approached the comet, it became increasingly obvious that the mission to orbit and land on the comet was going to be more difficult than anyone had imagined because of the comet's unexpected shape.

Instead of the expected 'potato' form, 67P/Churyumov-Gerasimenko was revealed to be a double-lobed structure with a 'head' and a 'body' separated by a narrow neck – some people have even likened the shape to that of a rubber duck.

The rendezvous with the comet took place with Rosetta at a distance of about 100 kilometres. This was too far away for the comet to hold the spacecraft with its weak gravitational field. The flight team executed a series of manoeuvres, known as pyramid trajectories, to steer Rosetta towards the comet. During this time, they studied how Rosetta responded to the weak but complex gravitational field generated by the comet's odd shape, while at the same time scientists gathered data to characterise the comet.

Gradually the distance between Rosetta and the comet was reduced until the spacecraft was captured by the comet's gravitational field on 10 September. At that point it was just 30 kilometres from the surface. In the following weeks, Rosetta edged even closer, at times getting as close as 9 kilometres from the centre of the comet.

Preparing for landing - Philae

In tandem, the Rosetta team was searching for a place to set down Philae. This too was complicated by the comet's shape. By 24 August 2014, using data collected when Rosetta was still about 100 km from the comet, five candidate regions had been identified for further analysis; three were on the head and two were on the body.

All were more difficult terrains than hoped. Cliffs, craters, and boulders populate each of the sites. A detailed analysis of Philae's capabilities and the opportunities offered by each site revealed that the best choice was a location originally referred to as Site J, and later named Agilkia.

On 12 November 2014, Rosetta deployed the Philae lander to the surface of Comet 67P/Churyumov-Gerasimenko. Philae was released at 08:35 UTC/09:35 CET, and touched down (for the first time) about seven hours later. Confirmation of the landing arrived at Earth at 16:03 UTC/17:03 CET.

Soon it became apparent that not everything had gone to plan. Instead of anchoring itself to the comet, Philae had bounced. The touchdown had triggered the science sequence to start and so the first readings were taken as the lander drifted across the comet's surface.

The instruments Ptolemy and COSAC detected gas and dust, showing that both contained carbon- and nitrogen-rich organic compounds, some of which had never been discovered on comets before. Among this collection were molecules that play a key-role in the synthesis of amino-acids, sugars and DNA's nucleobases. In other words, the building blocks of life.

The fact that these compounds are found on a primitive comet signals that they were present at the start of the Solar System, when the planets were forming. This could well be showing us the ingredients that became life on Earth.

Philae eventually came to rest angled up against a cliff face in a location on the comet later named Abydos. Here the MUPUS suite of instruments showed that the surface was harder than at the Agilkia site, where the lander had bounced.

For most of the remaining time of the mission, the exact location of Philae was unknown – radio ranging measurements had tied down its location to an area spanning a few tens of metres, but no definitive proof of its location had been uncovered. During 2015 and 2016 the search had continued when opportunities arose. Finally, on 2 September 2016, an image taken with the OSIRIS narrow-angle camera, within 2.7 km of the surface, showed the lander wedged into a dark corner of the comet. Knowing the location has provided the final pieces of information needed to put Philae's three days of science into their proper context.

The surprising comet

Meanwhile in orbit, data from the instruments on Rosetta show the comet to be one surprise after another.

During Rosetta's approach to the comet in 2014, the MIRO instrument registered that between June and August, the amount of water vapour being released by the comet increased by a factor of ten.

Early readings from the ROSINA instrument showed that the water on the comet was substantially different from the water on Earth. The difference with Earth's water is apparent in the ratio of deuterium to hydrogen atoms in the water. Deuterium is a heavier isotope of hydrogen. It contains a neutron particle as well as the normal proton. When deuterium combines with an oxygen molecule, it is known as semi-heavy water. On Earth there are roughly 160 molecules of heavy water for every million molecules of the normal stuff. ROSINA found that the amount of deuterium on 67P was greater by a factor of three.

Combining this result about the comet water with observations of molecular nitrogen and oxygen, and also the noble gas argon, indicates that the comet is ancient, being made from the cold components of an interstellar cloud rather than a warmer nebula surrounding the forming Sun. It could well be that some of the constituents of 67P are unaltered since before the formation of the Solar System.

The ratio of dust to gas has been studied by comparing the amount of both being released, and this shows the comet to be more of an icy dust ball. This "dryness" also constrains the likely location of the comet's formation in the embryo Solar System.

In August 2015, Rosetta followed 67P through its closest approach to the Sun. More surprising results followed. The largest chunks seen being thrown from the comet by OSIRIS were greater than 1 metre in size near perihelion. Before then, they were only around 1 centimetre.

Despite passing as close to the Sun as it ever gets, finding 67P's active regions has been an unexpected challenge. There is a lot of activity on the comet that gives birth to the surrounding cloud of dust and gas, known as the coma, but the mechanics of this activity is still being investigated and is proving a great challenge.

Computer models suggest that escaping water vapour must come from a nearly uniform distribution of dirty water ice spread across the comet's nucleus. However, the Hapi region has shown itself to be more active than other areas. More collimated activity has been tracked back from the coma to the location of pits and cliff edges, where ice deposits have been identified. During perihelion some very large, 'explosive' enhancements in the coma were seen. Combining these observations with modelling is a major activity, with scientists trying to reconcile the different mechanisms at play.

The outflowing coma interacts with the solar wind – a stream of charged particles continuously flowing from the Sun. As activity grows, these interactions become more intense and create a cavity, 'shielding' the nucleus from the solar wind. Such a cavity was expected to stand in front of the comet by only a few 10's of kilometres, but observations by the Rosetta Plasma Consortium have found that it is much more dynamic, its boundary reaching more than 170 kilometres from the comet. A new breed of plasma wave interaction has been discovered by Rosetta early on in the mission, when the activity was still low, and has been coined the 'comet sound'. How this interaction changes over time is still being investigated.

To study the comet's internal structure, the CONSERT experiment passed radio waves through the nucleus between the lander and the orbiter. It showed that the porosity of the 'head' of the comet is very high – about 75-85%. This is consistent with a very loosely compacted mixture of dust and ice, termed a 'rubble pile'. This observation was also supported by studies, conducted by the Radio Science Investigation team, of the way the Rosetta orbiter is pulled by the gravity of the comet, which allowed them to infer the porosity of 67P.

The high porosity suggests that the comet's formation was a relatively gentle affair with many small 'cometesimals' falling together at speeds of less than 1 metre per second. This would mean that they 'rested' against each other rather than melting into a single slab.

Tantalisingly, OSIRIS has seen pits 100 metres wide and deep. Visible in the walls are 'goosebumps' about 3 metres in diameter. Computer models suggest that the original cometesimals would be about this size. So, could these be the original building blocks that accumulated 4.6 billion years ago to become 67P/Churyumov-Gerasimenko? Time, close-up observations during Rosetta's final descent and further investigation will help answer this question.

The Grand Finale

Rosetta's mission is set to continue until 30 September 2016. At this time the comet will be around 3.6 times further from the Sun than the Earth is. This is the distance at which Rosetta finds it increasingly difficult to generate enough power from its solar panels to keep functioning.

Mission controllers will set the spacecraft down on the dusty, icy surface of the comet. They are targeting Ma'at, a region hosting some active pits on the small comet lobe, or 'head'. This region has been chosen for its scientific potential and taking into account the operational constraints involved in carrying out the descent. Although the data collecting will then be over, the analysis and investigation will continues for decades to come.

Clearly, it is not just the double-lobed structure of 67P that marks it out as an individual. Its composition, density and behaviour all suggest that we must substantially revise or even re-write our ideas about comets. Our understanding of comets, the formation of the Earth and other planets will never be the same again thanks to Rosetta and Philae.

7

No ordinary spacecraft: the challenges of flying Rosetta

No ordinary spacecraft: the challenges of flying Rosetta

The Rosetta mission has been a most remarkable challenge in controlling a spacecraft. The experience gained in doing this will set the stage for all future missions to comets and other small bodies in the Solar System.

Whereas missions to planets and large asteroids all rely on the gravity of the target body to pull the spacecraft into an orbit, at Comet 67P/Churyumov-Gerasimenko there is little gravity to speak of because the comet is so small; its gravity is several hundred thousand times weaker than Earth's.

This means that at first the flight team had to effectively *drive* the spacecraft around the comet, constantly altering Rosetta's orbit through repeated engine burns and learning how to fly in the challenging comet environment.

The extraordinary experience at the comet started when, after a journey of more than 10 years, that included three gravity-assist flybys of Earth and one of Mars, Rosetta caught up with 67P/C-G in August 2014. Simply lining up the spacecraft's trajectory with that of the comet was a major undertaking because the spacecraft had to dramatically slow down, relative to the comet, by about 2880 km/h, so that it could match the comet's speed.

Because it was impossible to pinpoint in advance exactly where the comet would be, a series of eight rendezvous manoeuvres, interleaved with optical navigation checks, was scheduled and carried out. Optical navigation was used to determine the orbit of the comet by checking how it was moving with respect to background stars and the changing field of view. This step-wise approach allowed the flight control team to slow down Rosetta, verify how far away it was from the comet and how fast it was approaching, and then brake again.

The most intensive manoeuvre was the second one. It took seven hours to complete and burnt 215 kilograms of fuel. In total, the eight manoeuvres used 500 kilograms of fuel, or about one third of all that Rosetta was carrying.

Once Rosetta had arrived, the major challenge was to estimate all the forces – gravity, aerodynamic drag from emitted gases, solar radiation pressure – that would constantly and unpredictably push the spacecraft off course. This problem became worse as the comet moved closer to the Sun and the outgassing activity increased due to the extra solar illumination.

Because the comet and spacecraft were so far from Earth, and so the round-trip communications time was often up to 50 minutes, it was impossible to command the spacecraft in real time – in fact, no deep space mission can be controlled in real time. All commands had to be programmed in advance and uploaded, for later execution on board. This meant that the instruments would be told to look where scientists and flight controllers thought that the comet would be.

Because of the unpredictable buffeting from the comet gas, however, Rosetta would be gradually pushed off course and the comet would drift out of view of the instruments. Occasionally, the outgassing was so much that the spacecraft was blinded by the emitted dust and it put itself in 'safe mode' waiting for operators to intervene.

As the mission went on, Rosetta's flight team became expert at navigating the spacecraft around the comet.

When Rosetta first approached the comet in August 2014, the operators flew distant, triangular 'pyramid' arcs around the comet. Gradually they edged Rosetta closer, sounding out its gravitational field to use it to pull the spacecraft into a 'bound' orbit, and developing a 'shape model' that they could use to determine the spacecraft's position around the comet.

Cautiously they approached to 20 km and then 10 km, taking up to 20 pictures a day to allow them to identify landmarks to aid in their calculations of where they were in their orbit. If at any moment, the comet disappeared from the camera's field of view, the operators would back Rosetta away.

One of the most precise manoeuvres during the early phase of the mission enabled the landing of the Philae probe on the comet's surface, in November 2014. The situation required that Philae was to be dropped, with no guidance or control. Once Rosetta released it, Philae would either hit or miss the comet. This was a major challenge.

Philae would drop through the comet's weak gravity for seven hours. To ensure hitting the target, the flight controllers had to know Rosetta's velocity to better than 1 cm/s, and its position in space to better than 100 m. And they managed to do this at a distance of 500 million km from Earth and while travelling at 50 000 km/s around the Sun.

Philae touched down nearly exactly on target: this is a testament to the extraordinary skill in flying Rosetta that the teams – the flight controllers and flight dynamics specialists – had developed in just a short period.

Since that time, the flight team has continued getting to know Rosetta and the comet environment in remarkable detail. It is a painstaking process but one that has given them great confidence in how to control the spacecraft. And this in turn, has enabled them to end the flight phase of the mission by performing a controlled landing on the comet.

During the last few weeks of the mission, operators have been as daring as possible, taking the spacecraft to less than two km above the surface of the comet. At distances below seven km, the strange shape of 67P/C-G has a marked effect on the trajectory of the spacecraft because of its complex local gravitational field.

The final proof of their ability to control the spacecraft will ironically be in the commands that end the mission. After a drop of 14 hours, if everything goes according to their calculations, Rosetta will touch the surface of the comet at the location planned and shut itself down. That will be the ultimate demonstration of precision parking made more than 700 million km away.

8

Meet Comet 67P/Churyumov-Gerasimenko

Meet Comet 67P/Churyumov-Gerasimenko

After a journey lasting 10 years and covering a distance of 6.5 billion km, Rosetta arrived at Comet 67P/Churyumov-Gerasimenko in August 2014. Since then, we have enjoyed a wealth of discoveries during Rosetta's time of 'living' with the comet.

The comet was discovered in September 1969 by Ukranian astronomers Klim Churyumov and Svetlana Gerasimenko. It was the 67th discovered periodic comet – these are comets with a period of less than 200 years, whose passage by the Sun has been observed more than once.

With a period of 6.45 years, Comet 67P/C-G has been observed during eight approaches to the Sun: 1969 (discovery), 1976, 1982, 1989, 1996, 2002, 2009 and 2015. This Jupiter-family comet originated in the Kuiper Belt, a large reservoir of small bodies in the outer Solar System.

Analysis of the comet's orbital evolution shows that, up to 1840, its closest approach to the Sun – referred to as perihelion – was 4.0 AU (four Sun-Earth distances or about 600 million km). Then, a fairly close encounter with Jupiter caused the orbit to move inwards to a perihelion distance of 3.0 AU, which then decreased gradually to 2.77 AU. In 1959, another Jupiter encounter reduced the comet's perihelion to just 1.29 AU; the current value is 1.24 AU (about 186 million km).

After it was selected, in 2003, as the target for the Rosetta mission, the comet became the subject of many astronomical observations, both with ground-based and space-borne telescopes. Thought to be a lumpy, potato-shaped object some 5 km across, the nucleus of 67P/C-G started to reveal itself in June 2014 as Rosetta approached, finally disclosing its double-lobed shape in July, as Rosetta closed in.

The small and large lobes are often referred to as the 'head' and 'body', respectively, because of the nucleus shape's slight resemblance to that of a rubber duck. The small lobe measures 2.50 km × 2.14 km × 1.64 km and the large lobe 4.10 km × 3.52 km × 1.63 km.

The total volume of the nucleus is 18.7 km^3 and its mass is about 10 billion tonnes, yielding a density of 533 kg/m^3, less than half the density of water, meaning that this comet would float if placed in an ocean.

The comet has a very high porosity, of 70–80%, with no cavities larger than 100 m in its interior, and its internal structure likely consists of 'fluffy' aggregates of ice-dust clumps with small empty spaces between them.

Measurements made with the OSIRIS scientific camera as Rosetta approached 67P/C-G in 2014 showed that the comet was completing a full spin around its axis in 12.4 hours. The rotation period increased slightly up to the inbound equinox in May 2015, but then subsequently fell significantly before perihelion (in August 2015), settling into a rotation period of around 12.05 hours for the last few months – the comet currently completes one rotation in 12 hours and 3 minutes. The rotation axis passes through the 'neck' region that bridges the two lobes: for this reason, both the northern and southern hemisphere of 67P/C-G are part of both lobes.

The combination of its double-lobed shape, the inclination of its rotation axis, and its elliptical orbit means that the seasons on Comet 67P/C-G are distributed very unevenly between the two hemispheres. For most of the comet's orbit, the northern hemisphere experiences a very long summer, lasting over 5.5 years, and the southern hemisphere undergoes a long, dark and cold winter. However, a few months before the comet reaches perihelion, the situation changes, and the southern hemisphere transitions to a brief and very hot summer, with temperatures of around 54 °C on some parts of the comet.

Twenty-six geological regions have been identified on the surface of the nucleus, seven in the south and 19 in the north; the regions were named after divinities of Ancient Egypt. Five basic – but diverse – categories of terrain type have been identified: dust-covered; brittle materials with pits and circular structures; large-scale depressions; smooth terrains; and exposed more consolidated ('rock-like') surfaces.

Measurements performed by the Philae lander at its first and final touchdown points revealed a thin layer of dust overlying a much harder compacted mixture of dust and ice. Dark agglomerates, likely made of organic compounds, were mainly found on the surface.

With an albedo (a measure of how much light is reflected from the surface) of only 6%, about half as much as the Moon's, 67P/C-G is one of the darkest objects in the Solar System. Such a low reflecting power indicates that the surface of the comet contains minerals such as, for example, iron sulfides, but also carbon-based compounds.

Few examples of exposed water ice patches have been found on the surface, while the great majority of ice is believed to come from under the comet's crust. Water vapour is the main gas seen flowing from comet, followed by carbon monoxide (CO) and carbon dioxide (CO_2); many other gas species have been detected in the comet's atmosphere, including molecular oxygen (O_2), molecular nitrogen (N_2), the noble gases argon (Ar), krypton (Kr) and xenon (Xe), the amino acid glycine, which is commonly found in proteins, and phosphorus (P), a key component of DNA and cell membranes.

Dust grains covering the surface are lifted by the outgassing activity, especially close to perihelion; while some of them fall back to the surface and can be transferred to different regions on the nucleus, many of them are ejected into space, contributing to the gas-dust coma. Around the peak of its activity at the 2015 perihelion, the comet spewed out some 300 kg of water vapour and up to 1000 kg of dust per second.

The nucleus of 67P/C-G has no magnetic field of its own, but it is embedded in the interplanetary magnetic field carried by the solar wind – a stream of electrically charged particles streaming from the Sun. When the comet's activity was at its highest, close to perihelion, the interaction between the gas pouring from the comet and the solar wind slowed down the latter, diverting its flow around the comet and preventing it from directly impacting the nucleus. Along with the solar wind, its magnetic field was unable to penetrate the environment around the comet, creating a region devoid of magnetic field called a diamagnetic cavity.

These first results are only the tip of the iceberg of the scientific harvest that the Rosetta mission will provide. Although the operational phase of the mission is ending on 30 September 2016, the science exploitation phase will continue for decades.

Year of discovery	1969
Discoverers	Klim Churyumov & Svetlana Gerasimenko
Size: **Overall dimensions** **Small lobe** **Large lobe**	 4.34 km x 2.60 km x 2.12 km 2.50 km x 2.14 km x 1.64 km 4.10 km x 3.52 km x 1.63 km
Mass	1.0 x 10^{13} kg
Volume	18.7 km^3
Density	533 kg/m^3
Rotation period	12.40 hours (June 2014) 12.06 hours (September 2016)
Spin axis	Right ascension: 69 degrees; Declination: 64 degrees
Orbital period	6.45 years
Perihelion / Aphelion	186 million km (1.243 AU) / 849.7 million km (5.68 AU)
Orbital eccentricity	0.640
Orbital inclination	7.04 degrees
Water vapour production rate	300 g/s (June 2014); 300 kg/s (August 2015); 300 g/s (August 2016)
Surface temperature	-93 °C to 53 °C
Subsurface temperature	-243 °C to -113 °C (August 2014)
Gases detected	Water, carbon monoxide, carbon dioxide, ammonia, methane, ethane, propane, butane, pentane, hexane, heptane, formic acid, acetic acid, acetaldehyde, ethylenglycol, propylenglycol, butanamide, methanol, ethanol, propanol, butanol, pentanol, glycine, argon, krypton, xenon, cyanogen, acetylene, hydrogen cyanide, acetonitril, formaldehyde, sodium, potassium, silicon, magnesium, hydrogensulphide, carbonylsulphide, sulphur monoxide, sulphur dioxide, carbon disulphide, nitrogen, oxygen, hydrogenperoxy, benzene, toluene, xylene, benzoic acid, naphthalene, hydrogen fluoride, hydrogen chloride, hydrogen bromide, phosphorus, chloromethane, methylamine, ethylamine, sulphur, disulphur, trisulphur, tetrasulfur, methanethiole (CH_3SH), ethanethiol (C_2H_5SH), thioformaldehyde (CH_2S)
Dust grains	A few hundred nanometers to a few millimeters

9

Comets
an introduction

Comets – an introduction

What is so special about comets that ESA has spent ten years flying a spacecraft towards one?

These small icy bodies are the most primitive objects in our cosmic neighbourhood, preserving pristine material left over from the formation of the Solar System, 4.6 billion years ago. For this reason, studying the chemical composition of comets may help scientists to answer some of the open questions about the Solar System's formation, including the way Earth came together.

Comets may have played an important role in delivering water to the young Earth, as well as bringing carbon-based molecules that may have been key to the development of life. Locked up in their interiors are frozen water and other volatiles, including carbon monoxide, carbon dioxide, methane, and ammonia.

When comets approach the Sun these frozen worlds are gently heated, releasing their ices into space to produce a vast envelope of dust and gas around the nucleus. This 'coma' results from ices on (or under) the nucleus sublimating – changing directly from a solid to a gas – and carrying tiny dust particles into space. Sunlight reflecting off these particles makes the coma visible.

For observers on Earth, the result of this process can be spectacular: the coma can grow to millions of kilometres in diameter and, eventually, pressure from solar radiation and the solar wind is enough to cause some of the material to stream out in the opposite direction to the Sun to form even longer tails. One tail is made of gas and plasma and points in a direction directly opposite to the Sun, and the other is made primarily of dust, following a slightly curved path that points back along the comet's orbit.

Humans have observed comets since ancient times, but only in the past few centuries have scientists started to grasp the nature of these fascinating bodies. And it wasn't until the second half of the twentieth century that a clear picture began to emerge.

The most famous of all comets is undoubtedly Halley, a so-called periodic comet that returns to our skies once every 76 years. In general, periodic (or short-period) comets have periods up to two hundred years; their orbits are elliptical and occupy a very similar region in the Solar System to the one where the giant planets are found.

But the majority of comets have longer periods, spend most of their time in the far reaches of the Solar System and have highly eccentric elliptical orbits that only bring them to our skies once every few hundreds of thousands of years or so. There are also non-periodic comets. As these fall towards the inner Solar System, the gravitational pull of the giant planets places them on ‘open orbits’. This means that they only pass by the Sun once.

Two reservoirs supply the Solar System with comets: Kuiper belt, a flattened, ring-like distribution that begins just outside Neptune’s orbit, and the Oort cloud, a huge spherical cloud that extends over a thousand times farther than the orbits of Neptune and Pluto. These two reservoirs are named after Dutch astronomers Gerard Kuiper and Jan Oort, respectively, who predicted their existence in the 1950s.

Comets in the Kuiper belt and Oort cloud are gravitationally bound to the Solar System. They originated from the same primordial nebula that gave birth to the Sun and the planets. It is likely that these comets formed closer to the Sun and were later expelled outwards as a consequence of repeated interactions with the giant planets.

As the Sun moves through the Galaxy, stars or gas clouds passing near the outer boundaries of the Oort cloud may perturb the motion of some of these ‘dormant’ comets just enough to modify their orbits. This can kick them into the inner Solar System, where they eventually develop the characteristic coma and tails. Then, as a comet leaves the inner Solar System, the rate of sublimation decreases significantly and the coma and tails disappear. But the comet’s activity does not completely die down, and occasional outbursts may occur also at larger distances from the Sun.

In some cases, the comet plunges back along its highly eccentric orbit into the far reaches of our planetary system (for long-period comets) or even beyond (for non-periodic comets). In other cases, it may be affected by the gravitational pull of one or more of the giant planets and remain trapped in a more regular, less eccentric orbit that keeps it closer to the Sun on a short-period orbit. For example, Rosetta’s Comet 67P/Churyumov-Gerasimenko is trapped on a 6.45 year commute around the Sun between the orbits of Jupiter and Earth.

Sometimes a comet meets a dramatic fate. If the comet comes too close to the Sun, the gravity of our parent star may tear it apart. This can happen either at a comet’s first passing by the Sun (as in the case of comet ISON, a ‘sungrazer’ that disintegrated in late 2013) or after many orbits (as for the short-period comet known as Biela’s Comet, which was seen to split in two pieces in 1852). Other Solar System bodies can also cause a comet’s demise, as witnessed by the collision of comet Shoemaker-Levy 9 with Jupiter in 1994. Or a comet can simply ‘fade away’, having exhausted its ices or developed a thick layer of dust.

Scientists have been observing comets remotely with the naked eye for millennia and using ground-based telescopes for the past four centuries, but the advent of the space age revolutionised the field. Now, spacecraft can fly past comets and study them up close. The first space mission to approach a comet, in 1985, was NASA's International Cometary Explorer (ICE), followed by Giotto and other spacecraft that flew past comet 1P/Halley in 1986. Five more comets have been visited by spacecraft after that, setting the stage for ESA's Rosetta mission, the first spacecraft to rendezvous with a comet, deploy a probe to its nucleus, accompany it as it moves closer to the Sun and, finally, end its mission by landing on the comet's surface.

10

Missions to comets Rosetta in context

Missions to comets – Rosetta in context

For much of history, humans have been fascinated by comets. Evidence for this can be found in Scottish rock carvings dating back to the second millennium BC, on clay tablets from ancient Babylon, and on an 11th century BC Chinese almanac transcribed on silk.

Comets were seen as omens of portent, and thought by many to be atmospheric phenomena rather than celestial. Gradually, astronomers realised that these apparitions were visitors from the distant reaches of outer space. In doing so, mere curiosity evolved over the centuries into scientific study.

Where did comets come from? How did they move through space? What were they made from? All of these became key drivers in the astronomers' pursuit of knowledge throughout the 18th century Age of Enlightenment, as comets were used as key test cases to develop Newton's law of universal gravitation.

Towards the end of the twentieth century, advances in space technology provided exciting new possibilities for comet scientists. Before they had relied solely on naked-eye observations or ground-based telescopes to study these ghostly messengers. Now it was possible to approach them with spacecraft, catching them as they journeyed towards the inner regions of the Solar System, relatively close to Earth.

In 1985, NASA's International Cometary Explorer (ICE) became the first space mission to pass through the tail of a comet. It flew past at a distance of 7800 kilometres from the nucleus of Comet 21P/Giacobini-Zinner.

Just one year later, when Halley's Comet returned to our skies, an armada of spacecraft was sent to study the famous comet up close: these included two probes from Russia (Vega-1 and Vega-2), two from Japan (Sakigake and Suisei), and ESA's Giotto spacecraft.

Giotto flew within 600 kilometres of comet 1P/Halley, closer than any other spacecraft, and sent back detailed images of the icy nucleus at the heart of the comet. This was a world-leading first. Giotto's unique data showed, among other things, that comets contain complex organic molecules. Studying these may help us understand if comets helped to 'seed' life on Earth.

After Halley, the spacecraft continued its journey. It was revived in 1992 to fly past Comet 26P/Grigg-Skjellerup. Giotto's camera had been blinded by dust particles during its encounter with Halley, but nonetheless its other instruments could sense

26P's nucleus as it flew within 200 km of it. It confirmed the picture from Halley that comets were solid objects rather than mere rubble piles or conglomerates of small fragments.

Other missions to comets followed. These include a trio of NASA probes: Deep Space 1, which flew by Comet 19P/Borelly in 2001; Stardust, which flew past Comet 81P/Wild in 2004 collecting samples from the comet's coma, the envelope of gases that surrounds the nucleus, that it returned to Earth two years later; and Deep Impact, which in 2005 shot a block of copper onto the nucleus of Comet 9P/Tempel to investigate the subsurface after the impact.

The Stardust mission was extended and as Stardust-NExT it flew by Comet 9P/Tempel in 2011 and imaged the crater created six years earlier by Deep Impact. The latter mission was also extended and as the EPOXI mission flew by comet 103P/Hartley in 2010 and remotely imaged Comet C/2009 P1 (Garradd) in April 2012 and Comet C/2012 S1 (ISON) in January 2013. Another NASA mission, the Comet Nucleus Tour (CONTOUR), launched in Summer 2002, failed when it was incorrectly inserted into its interplanetary trajectory.

Rosetta is much more ambitious and advanced than Giotto or any of the previous comet explorers. Its observation phase was planned to last much longer and not be limited to 'snapshots' from flybys.

Unlike all previous missions, Rosetta is capable of investigating the nucleus and the coma over an extended period of time. The mission includes an orbiter and a lander, so observations made from orbit can be correlated with in-situ measurements made on the surface.

Rosetta carries a much more advanced payload than any of its predecessors. The suite of eleven experiments on the orbiter have observed all aspects of the comet from close range for over two years as it moved along its orbit towards the inner Solar System, through perihelion, and back out towards the outer Solar System. The ten experiments on the lander, including spectrometers, high-resolution cameras and drill, were built to provide ground-truth measurements of the nucleus.

Rosetta is unique. It is the first mission to rendezvous with a comet, deploy a lander, accompany the comet through its closest approach to the Sun, and finally, land on the comet's surface.

11

Appendices

APPENDIX A
Mission Milestones

Date	Event	Comment
2 March 2004	Launch	Launched from Kourou, French Guiana, on an Ariane 5 G+
4 March 2005	1st Earth flyby	Distance from Earth: 1950 km. Purpose: Gravity assist from Earth
25 February 2007	Mars flyby	Distance from Mars: 250 km. Purpose: Gravity assist from Mars
13 November 2007	2nd Earth flyby	Distance from Earth: 5300 km. Purpose: Gravity assist from Earth
5 September 2008	Asteroid Šteins flyby	Distance from Šteins: 803 km. Purpose: Scientific investigation of asteroid (2867) Šteins
13 November 2009	3rd Earth flyby	Distance from Earth: 2480 km. Purpose: Gravity assist from Earth
10 July 2010	Asteroid Lutetia flyby	Distance from Lutetia: 3162 km. Purpose: Scientific investigation of asteroid (21) Lutetia
8 June 2011	Enter deep space hibernation	Distance from Sun: 667 million km. Purpose: To conserve energy while far from the Sun
20 January 2014	Exit deep space hibernation	Distance from Sun: 672 million km. Purpose: To prepare for comet rendezvous
May to August 2014	Comet rendezvous manoeuvres	Distance from comet: 230,000 km to 100 km. Purpose: To approach the comet for scientific investigations
6 August 2014	Arrival at comet	Distance from comet: 100 km. Purpose: To enter close orbit around comet
10 September 2014	Global mapping	Distance from comet: 30 km. Purpose: To obtain high-resolution science data to help characterise the potential landing sites for Philae, and to monitor how the spacecraft responds to the environment of an active comet.
September - October 2014	Close observations	Distance from comet: from 20 km to 10 km. Purpose: close observations of the comet
31 October 2014	Move to lander delivery orbit	Distance from comet: 34 km. Purpose: to prepare for lander delivery.
12 November 2014	Delivery of Philae lander to comet and start of Philae's First Scientific Sequence	Distance from comet: 22.5 km at time of deployment from orbiter Distance from Earth: 510 million km Distance from Sun: 448 million km Purpose: To deliver the lander on the comet surface
15 November 2014	Completion of Philae's First Science Sequence	

14 February 2015	Close flyby	Distance from surface: approximately 6 km. Purpose: to study the comet from close by
28 March 2015	Close flyby	Distance from surface: within 14 km. Safe mode triggered
1 April 2015	Distant excursion	Distance from surface: 400 km. Purpose: to study the plasma environment
13 June 2015	Contact with Philae	First contact following Philae's completion of FSS
9 July 2015	Last contact with Philae	Further attempts to contact the lander were not successful
13 August 2015	Perihelion	Distance from comet: 300 km Distance from Sun: 186 million km. Purpose: To study the comet during the closest point to the Sun on the comet's orbit
2 October 2015	Far excursion	Distance from comet: 1500 km: Purpose: to study the coma and plasma environment of 67P/C-G on a broader scale.
30 March 2016	Nightside excursion	Distance: up to 1000 km from comet. Purpose: to study the plasma environment
10 April 2016	Close flyby	Distance: 30 km from comet. Purpose: to fly over surface with Sun directly behind the spacecraft (at zero phase)
May - July 2016	Close 5 km orbit	Distance from comet: between 27 and 5 km. Purpose: science investigations
8 August 2016	Start of final flyovers	Distance from comet: ranging from 4-17 km from the comet centre. Purpose: to study the comet close up
2 September 2016	Philae imaged on comet surface	Distance from comet: within 2.7 km
24 September 2016	End of flyover phase	Prepare for end of mission
26 September 2016	Change orbit inclination	Inject Rosetta into transfer orbit
29 September 2016	Set collision course	Cancel orbital velocity and inject spacecraft into collision course
30 September 2016	Descent to comet surface	Distance from Sun: 573,153,251 km Distance from Earth: 719,742,176 km Purpose: Conclude mission by descending to the comet surface, taking unique science measurements on the way

APPENDIX B

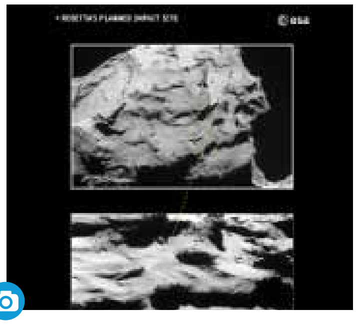
Distances, dates and times for mission milestones

Date	Event	Distance Rosetta - Earth	Distance Rosetta - Sun	Distance Rosetta - comet	Distance travelled y Rosetta	One-way signal travel time
2 March 2004	Launch	–	148 million km	585 million km	–	1 s
4 March 2005	Earth swingby	1950 km (at closest approach)	148 million km	777 million km	941 million km	1 s
25 February 2007	Mars swingby	316 million km (250 km from Mars)	216 million km	553 million km	2.5 billion km	1053 s
13 November 2007	Earth swingby	5300 km (at closest approach)	148 million km	721 million km	3 billion km	1 s
5 September 2008	Steins flyby	359 million km	319 million km	393 million km	3.7 billion km	1197 s
13 November 2009	Earth swingby	2480 km (at closest approach)	148 million km	537 million km	4.5 billion km	1 s
10 July 2010	Lutetia flyby	454 million km	406 million km	276 million km	5 billion km	1514 s
8 June 2011	Enter deep space hibernation	549 million km	667 million km	141 million km	5.5 billion km	1831 s
20 January 2014	Exit deep space hibernation	807 million km	672 million km	9.2 million km	6.2 billion km	2693 s
7 May 2014	Start of manoeuvres towards comet	538 million km	609 million km	1.9 million km	6.3 billion km	1796 s
6 August 2014	Arrival at comet	404 million km	539 million km	100 km	6.5 billion km	1349 s
12 November 2014	Deploy lander	510 million km	448 million km	22.5 km	6.6 billion km	1700 s
13 August 2015	Closest approach to the Sun (Perihelion)	265 million km	186 million km	300 km	7.2 billion km	884 s
30 September 2016	End of mission	720 million km	573 million km	–	7.9 billion km	2400 s

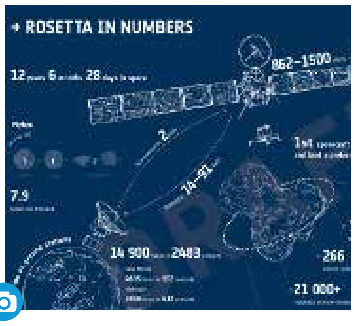
APPENDIX C
Selected Images and Videos

Descent to the surface
sci.esa.int/rosetta/58335

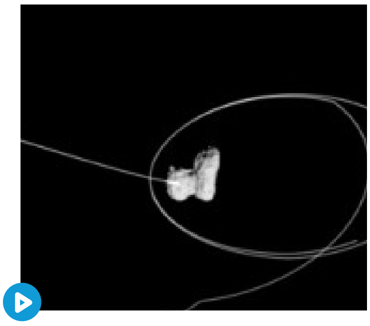
Rosetta's final destination
sci.esa.int/rosetta/58254



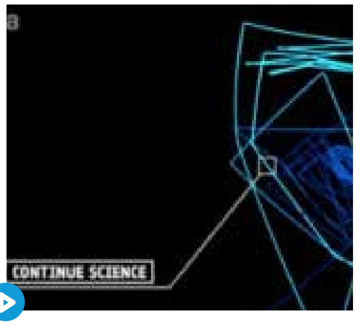
Rosetta's planned impact point
sci.esa.int/rosetta/58251



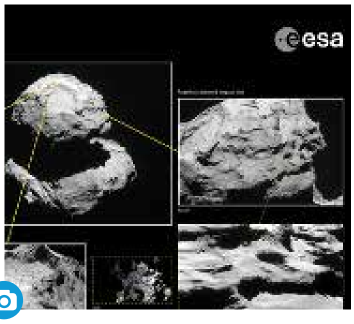
Rosetta by numbers
sci.esa.int/rosetta/58336



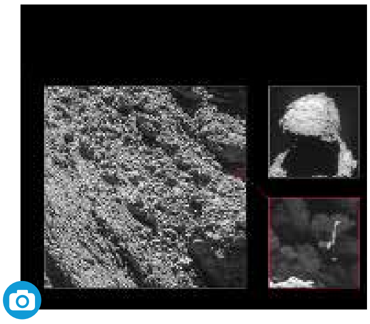
Rosetta's last orbits
sci.esa.int/rosetta/58305



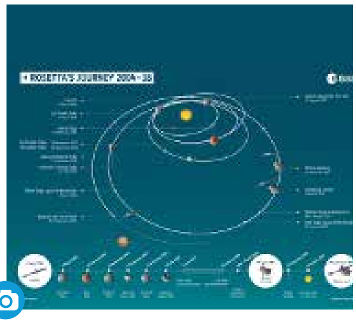
Journey around the comet
sci.esa.int/rosetta/58141



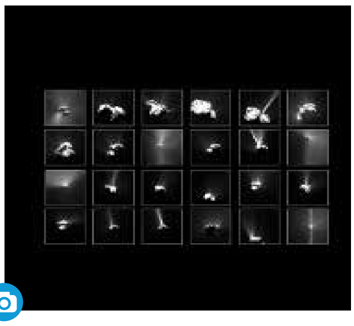
Comet landing sites
sci.esa.int/rosetta/58325



Philae found
sci.esa.int/rosetta/58221

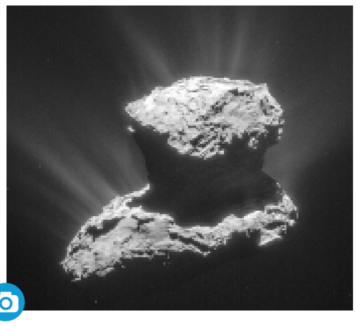


Rosetta's journey & timeline
sci.esa.int/rosetta/54787

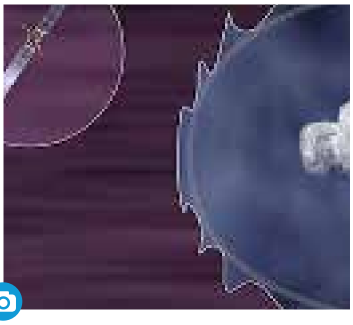


Comet outbursts
sci.esa.int/rosetta/58319

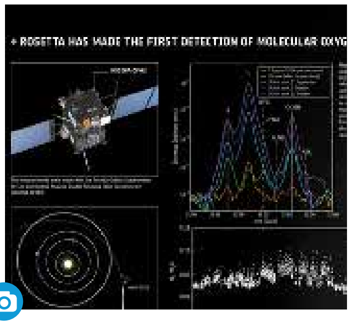
Rosetta's shadow
sci.esa.int/rosetta/58013



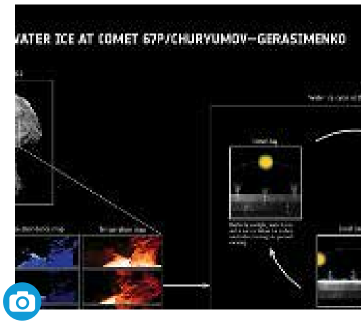
Rosetta's comet
sci.esa.int/rosetta/57859



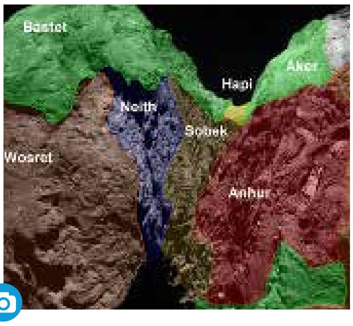
Magnetic field-free cavity
at comet
sci.esa.int/rosetta/57578



First detection of molecular
oxygen at a comet
sci.esa.int/rosetta/56728

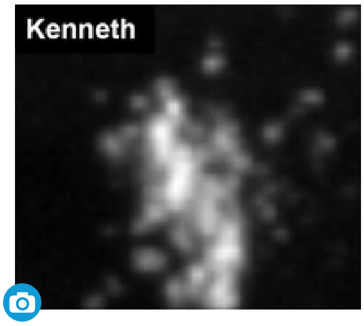


The water-ice cycle of
Rosetta's comet
sci.esa.int/rosetta/56514

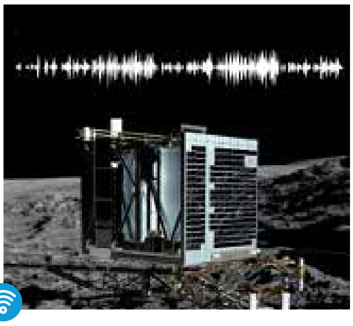


Comet regions
sci.esa.int/rosetta/58337

Comet in 3D – August 2015
sci.esa.int/rosetta/56626

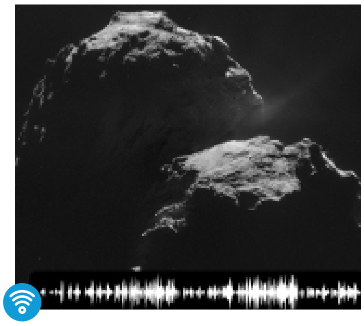


COSIMA images of dust particles
sci.esa.int/rosetta/58234

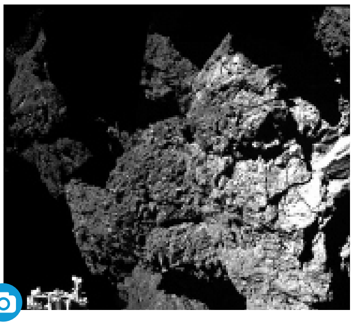


Sound of Philae hammering
sci.esa.int/rosetta/56828

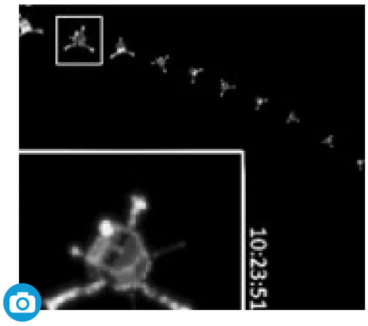
Sound of Philae landing
sci.esa.int/rosetta/55036



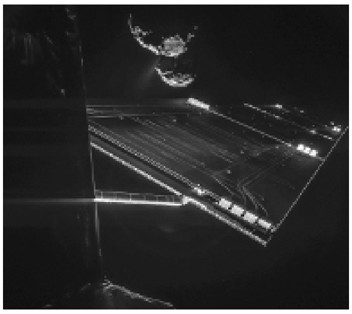
The singing comet
sci.esa.int/rosetta/55034



Philae selfie on the surface
sci.esa.int/rosetta/54938



Philae descending to the surface
sci.esa.int/rosetta/55364



Rosetta selfie at 16km
sci.esa.int/rosetta/54770

67P from ground-based telescope (2014)
sci.esa.int/rosetta/54629

Lutetia with Saturn
sci.esa.int/rosetta/47423

OSIRIS images of asteroid Steins
sci.esa.int/rosetta/43363

Self-portrait at Mars
sci.esa.int/rosetta/54869

Philae lander with instruments
sci.esa.int/rosetta/53556

Philae lander
sci.esa.int/rosetta/53297

Rosetta orbiter with Instruments
sci.esa.int/rosetta/53555

Rosetta spacecraft
sci.esa.int/rosetta/53296

Rosetta lift-off
sci.esa.int/rosetta/53348

Rosetta spacecraft
sci.esa.int/rosetta/54421

K. Churyumov & S. Gerasimenko (1975)
sci.esa.int/rosetta/54673

Images of 67P from 1969
sci.esa.int/rosetta/54804

APPENDIX D

Rosetta online

Rosetta is present on social media platforms:
Twitter: @ESA_Rosetta
FaceBook: www.facebook.com/RosettaMission
YouTube: bit.ly/rosettaYT
Flickr: bit.ly/rosettaFlickr
Instagram: instagram.com/rosettamission

Information about the mission and the role of the partners can be found on the following websites:

European Space Agency

www.esa.int/rosetta - the entry point for all ESA web pages covering the Rosetta mission.
sci.esa.int/rosetta - detailed information about the Rosetta mission.
blogs.esa.int/rosetta - regular updates, behind-the-scenes reports, contributions from guest writers.
www.cosmos.esa.int/web/psa/rosetta - access to all public Rosetta data

The Rosetta pages on the websites of our partners are at:
NASA rosetta.jpl.nasa.gov/
DLR www.dlr.de/rosetta and www.dlr.de/en/rosetta
CNES www.cnes.fr/rosetta and www.cnes.fr/rosetta-blog
ASI www.asi.it/it/attivita/sistema_solare/rosetta

Rosetta science papers

Special issues of scientific journals dedicated to results from Rosetta

Science journal special issue: Catching a comet
First results from the Rosetta orbiter.
Papers available open access here:
sci.esa.int/rosetta/56403-science-special-issue-catching-a-comet/

Science journal special issue: Philae's first look
Early results from Philae's first observations at the comet.
Papers available open access here:
sci.esa.int/rosetta/56291-science-special-issue-philaes-first-look/

Astronomy & Astrophysics special issue: Rosetta mission results pre-perihelion
Papers available open access here:
sci.esa.int/rosetta/56496-rosetta-papers-in-astronomy-and-astrophysics/

Monthly Notices of the Royal Astronomical Society (MNRAS) special issue: The ESLAB 50 Symposium - spacecraft at comets from 1P/Halley to 67P/Churyumov-Gerasimenko
Papers available open access here:
mnras.oxfordjournals.org/content/462/Suppl_1.toc

APPENDIX E

Media contacts

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sci.esa.int/rosetta/media-contacts

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