Rosetta:

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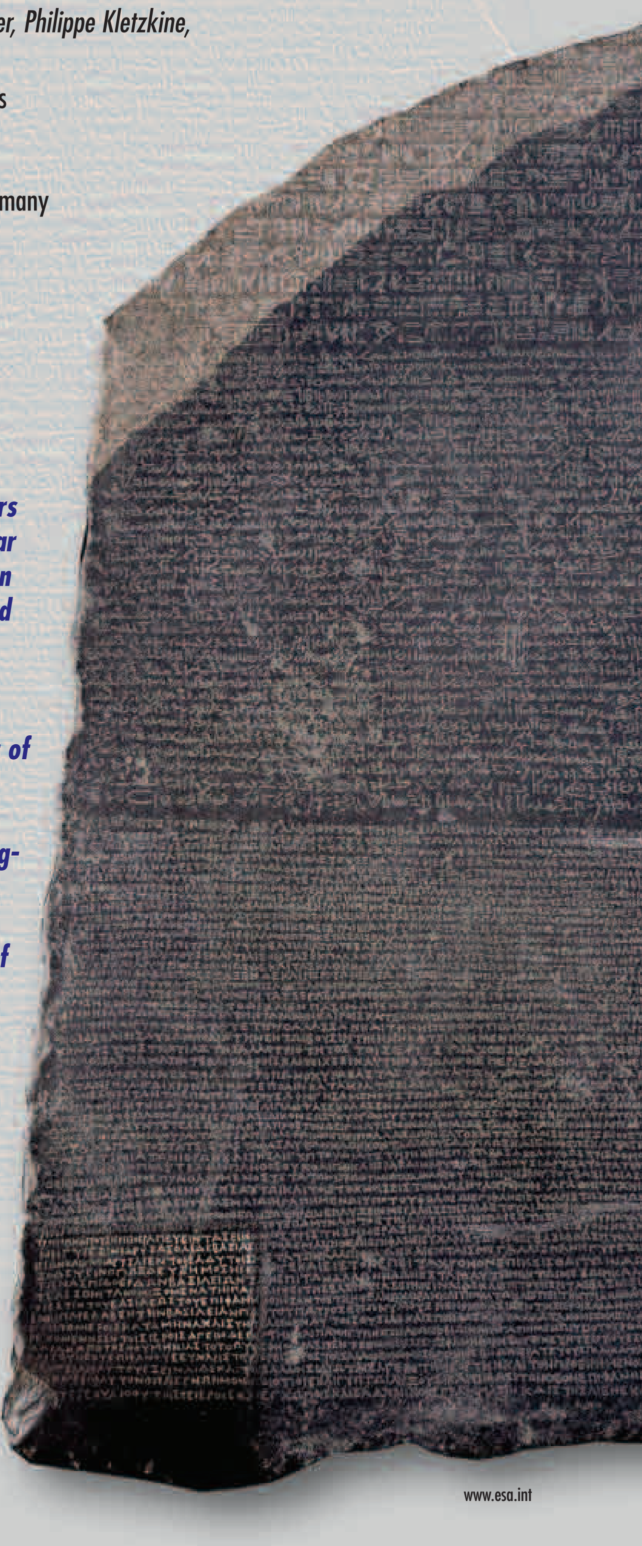
Why 'Rosetta'?

The Rosetta spacecraft is named after the famous Rosetta Stone, a slab of volcanic basalt now on display in the British Museum in London. French soldiers discovered the unique Stone in 1799, as they prepared to demolish a wall near the village of Rashid (Rosetta) in Egypt's Nile delta. The carved inscriptions on the Stone included hieroglyphics – the written language of ancient Egypt – and Greek, which was readily understood.

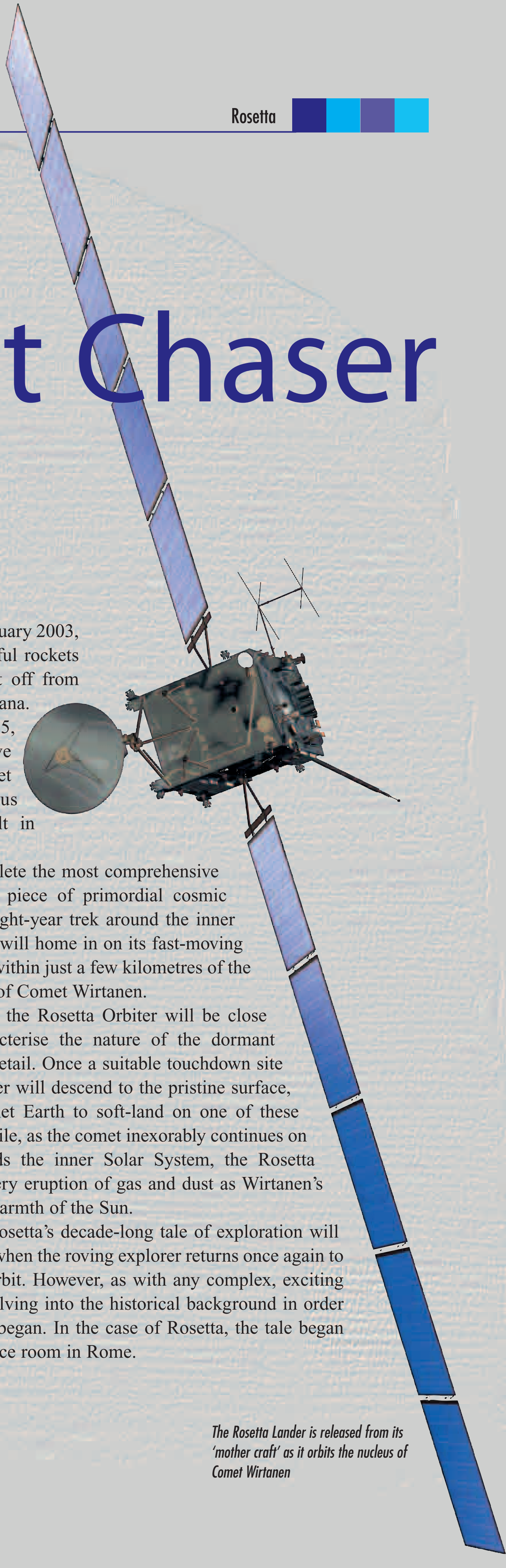
By comparing the inscriptions, it eventually became possible to decipher the mysterious figures that had been carved several thousand years earlier. Most of the pioneering work was carried out by the English physician and physicist, Thomas Young, and French scholar Jean François Champollion. As a result of their breakthroughs, scholars were able to piece together the history of a long-lost culture for the first time.

Just as the discovery of the Rosetta Stone eventually led to the unravelling of the mysterious hieroglyphics, so Rosetta will help scientists to unravel the mysteries of comets. Whereas hieroglyphics were the building blocks of the Egyptian language, comets are considered to be the most primitive objects in the Solar System, the building blocks from which the planets formed.

Billions of these giant chunks of ice still linger in the depths of space, the remnants of a vast swarm of objects that once surrounded our Sun and eventually came together to form planets. Virtually unchanged after 5 billion years in the deep freeze of the outer Solar System, they still contain ices and dust from the original solar nebula. They also contain complex organic compounds which some scientists believe may have provided the raw material from which life on Earth evolved.



ESA's Comet Chaser



On the night of 12-13 January 2003, one of the most powerful rockets in the world will blast off from Kourou spaceport in French Guiana. On top of the giant Ariane-5, cocooned inside a protective fairing, will be the Rosetta comet chaser, the most ambitious scientific spacecraft ever built in Europe.

Rosetta's mission is to complete the most comprehensive examination ever made of a piece of primordial cosmic debris – a comet. After an eight-year trek around the inner Solar System, the spacecraft will home in on its fast-moving target, eventually edging to within just a few kilometres of the solid nucleus, the icy heart of Comet Wirtanen.

By the summer of 2012, the Rosetta Orbiter will be close enough to map and characterise the nature of the dormant nucleus in unprecedented detail. Once a suitable touchdown site is identified, a small Lander will descend to the pristine surface, the first object from planet Earth to soft-land on one of these primitive worlds. Meanwhile, as the comet inexorably continues on its headlong rush towards the inner Solar System, the Rosetta Orbiter will catalogue every eruption of gas and dust as Wirtanen's volatiles vaporise in the warmth of the Sun.

The final chapter in Rosetta's decade-long tale of exploration will take place in July 2013, when the roving explorer returns once again to the vicinity of Earth's orbit. However, as with any complex, exciting adventure, it is worth delving into the historical background in order to understand how it all began. In the case of Rosetta, the tale began 17 years ago in a conference room in Rome.

The Rosetta Lander is released from its 'mother craft' as it orbits the nucleus of Comet Wirtanen

Comet Nucleus Sample Return

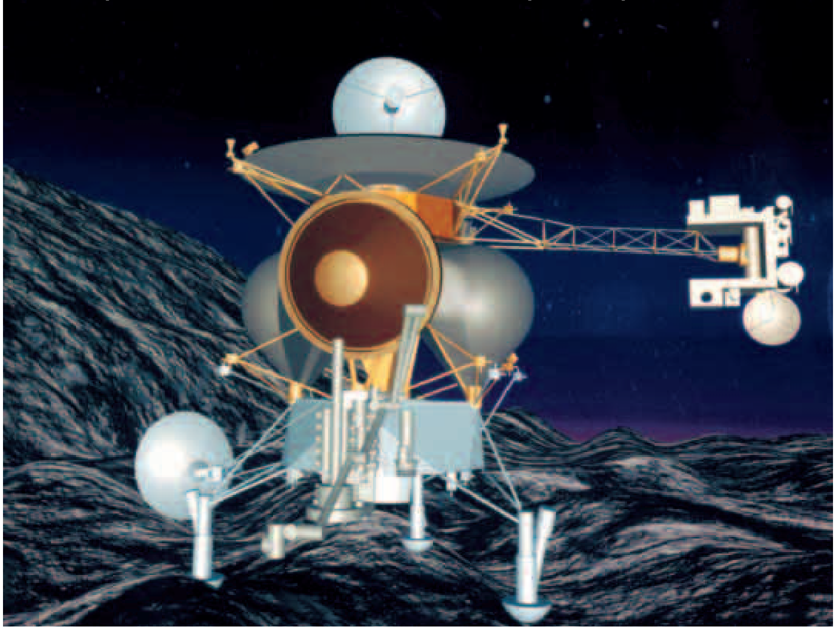
In January 1985, Ministers responsible for space matters in ESA's Member States came together to approve an ambitious and far-seeing programme of scientific and technological research. One of their most significant decisions involved approval of a long-term science plan, which was then named 'Horizon 2000'. A Resolution drafted by the Ministers stated, "The Council agrees to reinforce space-science activities in Europe during the next decade with a view to enabling the scientific community to remain in the vanguard of space research."

Based on inputs from the European space-science community, the revolutionary plan included ground-breaking missions that would be launched between the mid-1990s and the early years of the 21st century. The proposed programme was founded on four major Cornerstones, one of which was described as "a mission to primordial bodies including return of pristine materials". Even before its Giotto spacecraft reached Comet Halley, ESA was looking forward to establishing a leading role in the exploration of the smaller bodies of the Solar System by bringing back samples of material from either a comet or an asteroid.

After Giotto's remarkably successful Halley flyby in March 1986, the emphasis switched to comet sample return, but it soon became clear that the cost of such a mission would be too prohibitive for Europe to carry out alone. As a result, the ESA Science Executive began to investigate the possibility of conducting the Planetary Cornerstone as a collaborative venture with NASA, which was already pursuing its own Comet Rendezvous and Asteroid Flyby (CRAF) mission.

At this stage, scientists on both sides of the Atlantic were excitedly anticipating sending a mission to land on a relatively active, 'fresh' comet that did not approach too closely to the Sun. Apart from characterising the surface of the nucleus and obtaining high resolution imagery of the landing site, it was hoped to obtain three types of sample: a 'core' drilled to a depth of at least one metre; a sealed sample of volatile, icy material; and a sample of non-volatile surface material. Stored at the same frigid temperatures experienced on the comet, the samples would be returned for comprehensive analysis in laboratories on Earth.

Artist's impression of the ESA-NASA Rosetta Comet Nucleus Sample Return spacecraft



By 1991, a joint ESA-NASA Rosetta Comet Nucleus Sample Return mission had been defined, with launch anticipated in December 2002. The spacecraft was to comprise three modules. A large NASA Mariner Mark II Cruiser would provide attitude control, navigation, power, propulsion and communications. Attached to the main bus would be a Lander, which was to carry a drill and surface sampling tool, and an Earth-Return Capsule. Once the samples were safely transferred to a container in the Capsule, the spacecraft would lift off, leaving the Lander behind on the comet. Two and a half years later, the Capsule would parachute into the ocean with its precious cargo, ready for collection by helicopter and ship.

A Revised Rosetta

Within two years, NASA's financial difficulties and resultant cutbacks in its space-science programme (notably the cancellation of the CRAF mission) forced ESA to reconsider its options for Rosetta. The prime consideration was to define a core mission that could be performed by ESA alone, using European technology – although the door was left open for other agencies to participate. The revised baseline mission that emerged involved a rendezvous with a comet and at least one asteroid flyby. It was hoped that a small Lander would be added as an additional experiment provided by one or more scientific institutions.

To all intents and purposes, that is the mission that has survived to the present. The Rosetta that will be launched towards Comet Wirtanen in January 2003 comprises two spacecraft: a 3 ton Orbiter, including 165 kg of scientific instruments, and a 100 kg Lander provided by a consortium including ESA and institutes from Austria, Finland, France, Germany, Hungary, Ireland, Italy and the United Kingdom, under the leadership of the German Space Agency (DLR).

"That such a complex mission can be built in partnership and delivered on time is a great tribute to the management and cooperative spirit of industry, the scientists and the many agencies involved, as well as ESA's staff," says John Ellwood, Rosetta Project Manager.

Anatomy of a Spacecraft

Rosetta is truly an international enterprise, involving more than 50 industrial contractors from 14 European countries and the United States. The prime spacecraft contractor is Astrium Germany, while Astrium UK (spacecraft platform), Astrium France (spacecraft avionics) and Alenia Spazio (assembly, integration and verification) are major subcontractors.

The Rosetta Orbiter resembles a large aluminium box, 2.8 x 2.1 x 2.0 m. The 11 scientific instruments are mounted on the Payload Support Module (the 'top' of the spacecraft), while the subsystems are on the 'base' or Bus Support Module. Several kilometres of harness – electrical cable – are also built into the heart of each module.

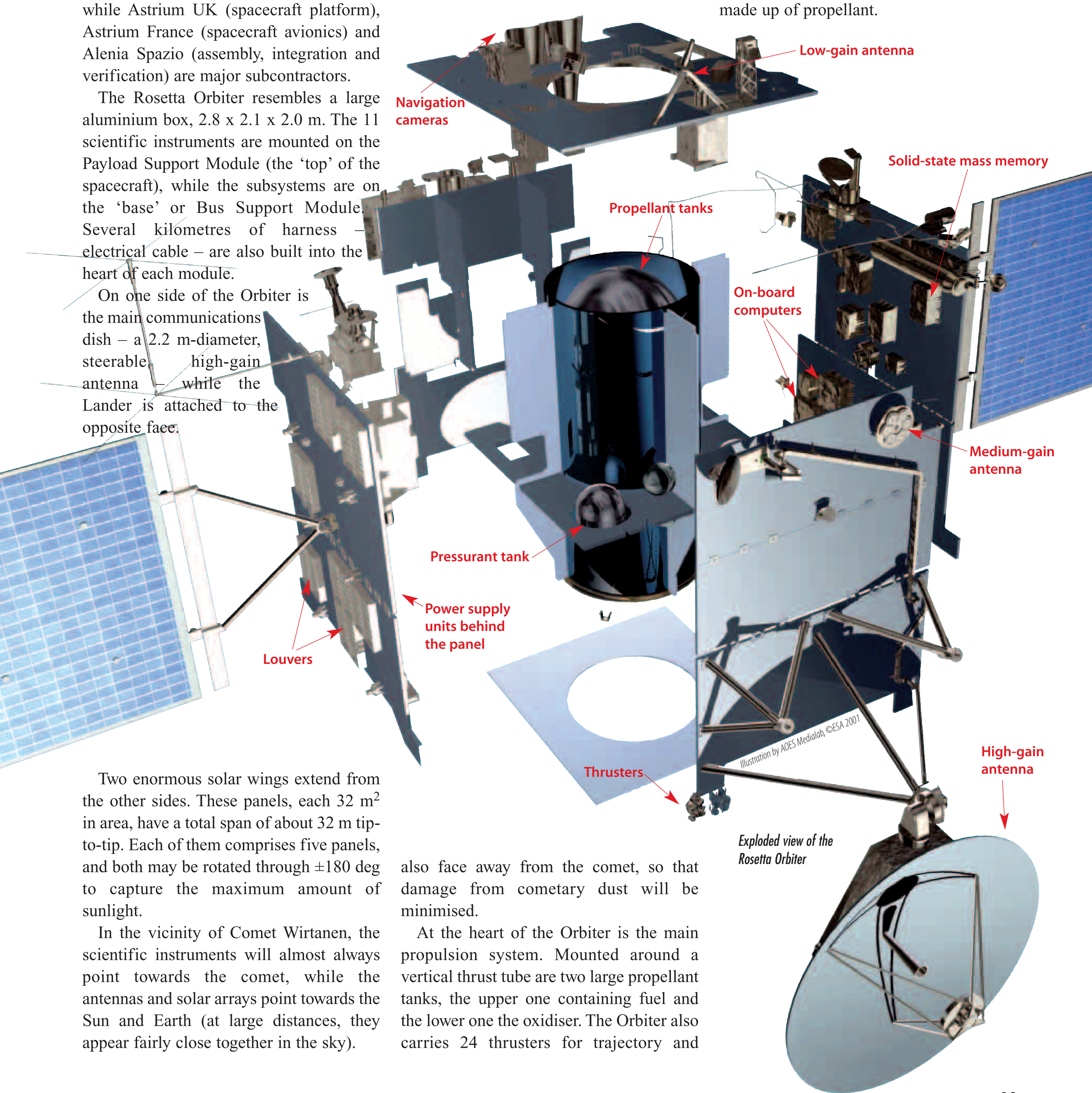
On one side of the Orbiter is the main communications dish – a 2.2 m-diameter, steerable, high-gain antenna – while the Lander is attached to the opposite face.

Two enormous solar wings extend from the other sides. These panels, each 32 m^2 in area, have a total span of about 32 m tip-to-tip. Each of them comprises five panels, and both may be rotated through ±180 deg to capture the maximum amount of sunlight.

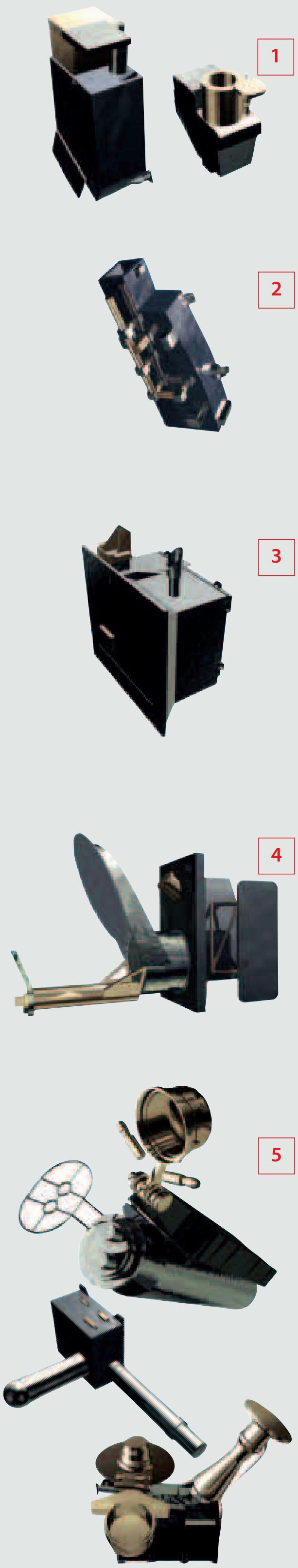
In the vicinity of Comet Wirtanen, the scientific instruments will almost always point towards the comet, while the antennas and solar arrays point towards the Sun and Earth (at large distances, they appear fairly close together in the sky).

By contrast, the Orbiter's side and back panels are in shade for most of the mission. Since these panels receive little sunlight, they are an ideal location for the spacecraft's radiators and louvers which regulate its internal temperature. They will also face away from the comet, so that damage from cometary dust will be minimised.

At the heart of the Orbiter is the main propulsion system. Mounted around a vertical thrust tube are two large propellant tanks, the upper one containing fuel and the lower one the oxidiser. The Orbiter also carries 24 thrusters for trajectory and attitude control. Each of these thrusters pushes the spacecraft with a force of 10 Newton, equivalent to that experienced by someone holding a bag of 10 apples. Over half the launch weight of the entire spacecraft – more than 1.7 tonnes – is made up of propellant.



Exploded view of the Rosetta Orbiter



OSIRIS (Optical, Spectroscopic, and Infrared Remote Imaging System): A Wide Angle Camera and a Narrow Angle Camera to obtain high-resolution images of the comet's nucleus and asteroids Siwa and Otawara.

ALICE (Ultraviolet Imaging Spectrometer): Analyses gases in the coma and tail and measures the comet's production rates of water and carbon monoxide/dioxide. Also provides information on the surface composition of the nucleus.

VIRTIS (Visible and Infrared Thermal Imaging Spectrometer): Maps and studies the nature of the solids and the temperature on the surface of the nucleus. Also identifies comet gases, characterises the physical conditions of the coma and helps to identify the best landing sites.

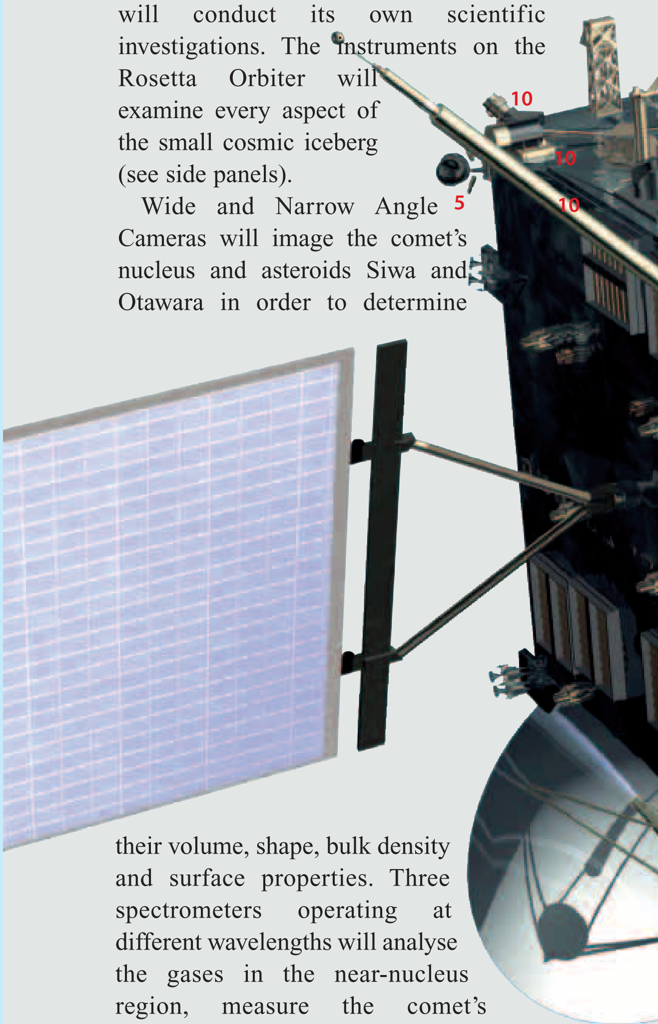
MIRO (Microwave Instrument for the Rosetta Orbiter): Used to determine the abundances of major gases, the surface outgassing rate and the nucleus subsurface temperature. It will also measure the sub-surface temperatures of Siwa and Otawara, and search for gas around them.

ROSINA (Rosetta Orbiter Spectrometer for Ion and Neutral Analysis): Two sensors will determine the composition of the comet's atmosphere and ionosphere, the velocities of electrified gas particles, and reactions in which they take part. It will also investigate possible asteroid outgassing.

The Rosetta Payload

The Orbiter's scientific payload includes 11 experiments and a small Lander, which will conduct its own scientific investigations. The instruments on the Rosetta Orbiter will examine every aspect of the small cosmic iceberg (see side panels).

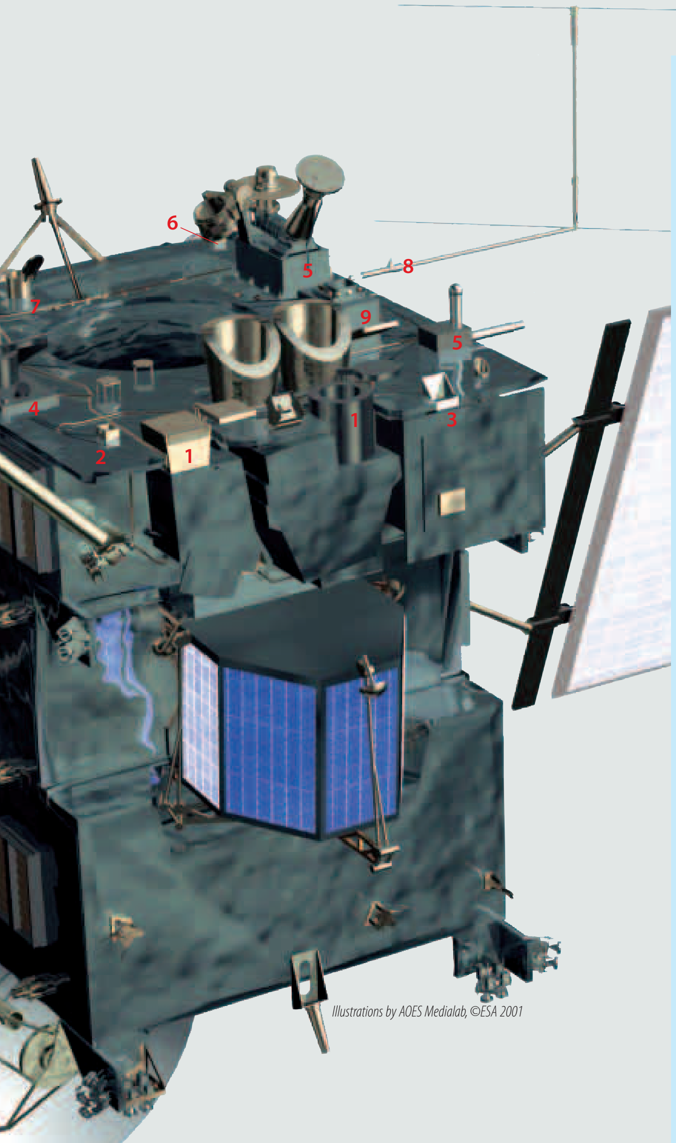
Wide and Narrow Angle Cameras will image the comet's nucleus and asteroids Siwa and Otawara in order to determine



their volume, shape, bulk density and surface properties. Three spectrometers operating at different wavelengths will analyse the gases in the near-nucleus region, measure the comet's production rates of water and carbon monoxide/dioxide, and map the temperature and composition of the nucleus.

Our knowledge of the nucleus should be revolutionised by the CONSERT experiment, which will probe the comet's interior by transmitting and receiving radio waves that are reflected and scattered as they pass through the nucleus.

Four more instruments will examine the comet's dust and gas environment, measuring the composition and physical



characteristics of the particles, e.g. population, size, mass, shape and velocity.

The comet's plasma environment and interaction with the electrically charged particles of the solar wind will be studied by the Rosetta Plasma Consortium and the Radio Science Investigation.

The 100 kg Rosetta Lander carries a further nine experiments, as well as a drilling system to take samples of sub-surface material. The Lander instruments are designed to study in situ for the first time the composition and structure of the surface and subsurface material on the nucleus.

COSIMA (Cometary Secondary Ion Mass Analyser): Will analyse the characteristics of dust grains emitted by the comet, including their composition and whether they are organic or inorganic.

MIDAS (Micro-Imaging Dust Analysis System): Studies the dust environment around the asteroids and comet. It provides information on particle population, size, volume and shape.

CONSERT (Comet Nucleus Sounding Experiment by Radiowave Transmission): Probes the comet's interior by studying radio waves that are reflected and scattered by the nucleus.

GIADA (Grain Impact Analyser and Dust Accumulator): Measures the number, mass, momentum and velocity distribution of dust grains coming from the nucleus and from other directions (reflected by solar radiation pressure).

RPC (Rosetta Plasma Consortium): Five sensors measure the physical properties of the nucleus; examine the structure of the inner coma; monitor cometary activity; and study the comet's interaction with the solar wind.

RSI (Radio Science Investigation): Shifts in the spacecraft's radio signals are used to measure the mass, density and gravity of the nucleu; define the comet's orbit; and study the inner coma. Also be used to measure the mass and density of Siwa, and to study the solar corona during the periods when the spacecraft, as seen from Earth, is passing behind the Sun.

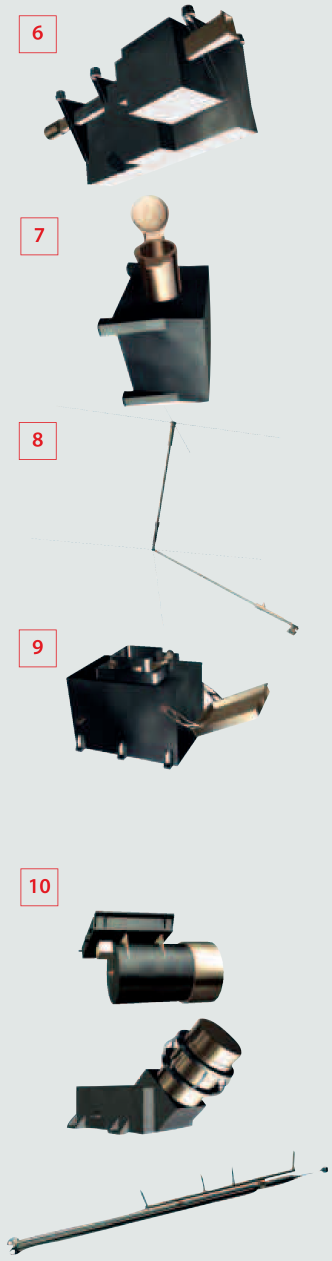


Illustration by AOES Medialab, ©ESA 2001

The Rosetta Lander

The box-shaped Lander piggybacks on the Orbiter until it arrives in close orbit around Comet Wirtanen. Once the 'mother craft' is aligned correctly, the ground commands the Lander to push off and unfold its three legs, ready for a gentle touch down at the end of the slow descent. On landing, the legs damp out most of the kinetic energy to reduce the chance of bouncing, and they can rotate, lift or tilt to return the Lander to an upright position.

Immediately after touchdown, a harpoon is fired to anchor the Lander to the ground and prevent it escaping from the comet's extremely weak gravity. The minimum mission target is 65 hours, but surface operations may continue for many months.

The Lander structure consists of a baseplate, an instrument platform, and a polygonal sandwich construction, all made of carbon fibre. Some of the instruments and subsystems are beneath a hood, which is covered with solar cells for power generation. An antenna transmits data from the surface to Earth via the Orbiter.

A Space Odyssey

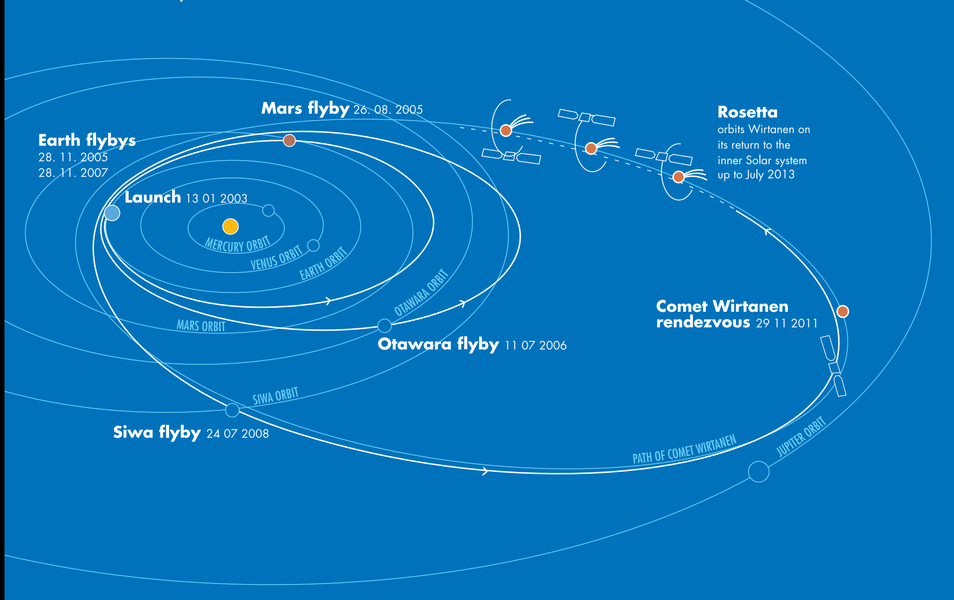
Although its cometary target has changed since Rosetta was first envisaged, the launch date has altered very little. Rosetta's 10-year odyssey will begin in January 2003, when an Ariane-5 launcher boosts the spacecraft into an elliptical (4000 km x 200 km) trajectory around the Earth. After about two hours, Ariane's upper stage re-ignites to send Rosetta on its way towards the asteroid belt.

The hardy spacecraft will then bounce around the inner Solar System like a cosmic billiard ball, circling the Sun almost four times during its eight-year trek to Comet Wirtanen. Along this roundabout route, Rosetta will enter the asteroid belt twice, enabling it to glimpse the ancient, battered surfaces of two contrasting rocky objects, Siwa and Otawara. It will also receive a boost in speed from gravitational 'kicks' provided by close flybys of Mars in 2005 and Earth in 2005 and 2007.

After a large deep-space manoeuvre, Rosetta will break the record for a solar cell-powered spacecraft as its elongated path carries it some 800 million km from the Sun. It will then be re-activated for the most difficult phase of the mission – the final rendezvous with the fast-moving comet.

Arriving in the comet's vicinity in November 2011, Rosetta's thrusters will brake the spacecraft so that it can match Comet Wirtanen's orbit. Over the next six months, it will edge closer to the black,

Rosetta's 'billiard ball' path to reach Comet Wirtanen



dormant nucleus until it is only a few dozen kilometres away. The first camera images will dramatically improve calculations of the comet's position and orbit, as well as its size, shape and rotation.

By the summer of 2012, Rosetta will enter orbit around the comet, sweeping to within a few kilometres of the coal-black surface. However, the almost imperceptible gravitational pull of the 'dirty snowball' will mean that Rosetta need only circle Wirtanen at a snail's pace – a few centimetres per second. With the alien landscape now looming large, the Orbiter's cameras will start to map the nucleus in great detail. Eventually, a number of potential landing sites will be selected for close observation.

Once a suitable site is chosen, the Lander will be released from a height of about 1 km. Touching down gently at walking speed – less than 1 metre per second – the ambassador from Earth will anchor itself to the nucleus before sending back high-resolution pictures and other information on the nature of the comet's ices and organic crust. Scientists back on the distant Earth will eagerly await the treasure trove of data from the pristine surface as it is relayed to ground stations via the Orbiter.

The way will then be clear for the exciting comet chase towards the Sun. Over a period of 12 months, the Orbiter will continue to orbit Wirtanen, observing the dramatic changes that take place as the icy nucleus begins to warm and vaporise during the headlong rush towards the Sun. The escort mission will end in July 2013, at the time of the comet's closest approach to the Sun (perihelion). More than 3800 days will have elapsed since Rosetta's dramatic space odyssey began.

"The Rosetta mission is something that we could only dream about 17 years ago, and now it is becoming an exciting reality", says Gerhard Schwehm, Rosetta Project Scientist.

Rosetta Lander Scientific Experiments

COSAC (Cometary Sampling and Composition experiment): One of two evolved gas analysers, it detects and identifies complex organic molecules from their elemental and molecular composition.

MODULUS PTOLEMY: Another evolved gas analyser, which obtains accurate measurements of isotopic ratios of light elements.

MUPUS (Multi-Purpose Sensors for Surface and Subsurface Science): Uses sensors on the Lander's anchor, probe and exterior to measure the thermal and mechanical properties of the surface.

ROMAP (Rosetta Lander Magnetometer and Plasma Monitor): A magnetometer and plasma monitor study the local magnetic field and the comet/solar-wind interaction.

SESAME (Surface Electrical, Seismic and Acoustic Monitoring Experiments): Three instruments measure properties of the comet's outer layers. The Cometary Acoustic Sounding Surface Experiment measures the way in which sound travels through the surface. The Permittivity Probe investigates its electrical characteristics, and the Dust Impact Monitor measures the dust environment to the surface.

APXS (Alpha X-ray Spectrometer): Lowered to within 4 cm of the ground, it detects back-scattered alpha particles and alpha-induced X-rays, which provide information on the elemental composition of the comet's surface.

CONSERT (Comet Nucleus Sounding Experiment by Radiowave Transmission): Probes the internal structure of the nucleus. Radio waves from the CONSERT experiment on the Orbiter travel through the nucleus and are returned by a transponder on the Lander.

ÇIVA: Seven micro-cameras - six mono and one stereo pair - take panoramic pictures of the surface. A visible-light microscope and coupled infrared spectrometer studies the composition, texture and albedo (reflectivity) of samples collected from the surface.

ROLIS (Rosetta Lander Imaging System): A CCD camera to obtain high-resolution images during descent and of the nucleus surface below the Lander and of the areas sampled by other instruments.

SD2 (Sample and Distribution Device): Drills more than 20 cm into the surface, collects samples and delivers them to different ovens or for microscope inspection.

Exploring A Cosmic Iceberg

"When beggars die, there are no comets seen:
The heavens themselves blaze forth the death of princes."

Shakespeare's Julius Caesar

For centuries, comets have inspired awe and wonder. Many ancient civilisations saw them as portents of death and disaster, omens of great social and political upheavals. Shrouded in thin, luminous veils with tails streaming behind them, these 'long-haired stars' were given the name 'comets' by the ancient Greeks (from the Greek word kome meaning 'hair').

Apart from their links to soothsaying and astrology, comets – particularly the very bright objects visible to the naked eye – have always been popular targets for all kinds of observations and speculation. Their sudden appearance and spectacular shape make them very appealing for amateur astronomers and photographers everywhere, and the 1997 apparition of Comet Hale-Bopp made headlines around

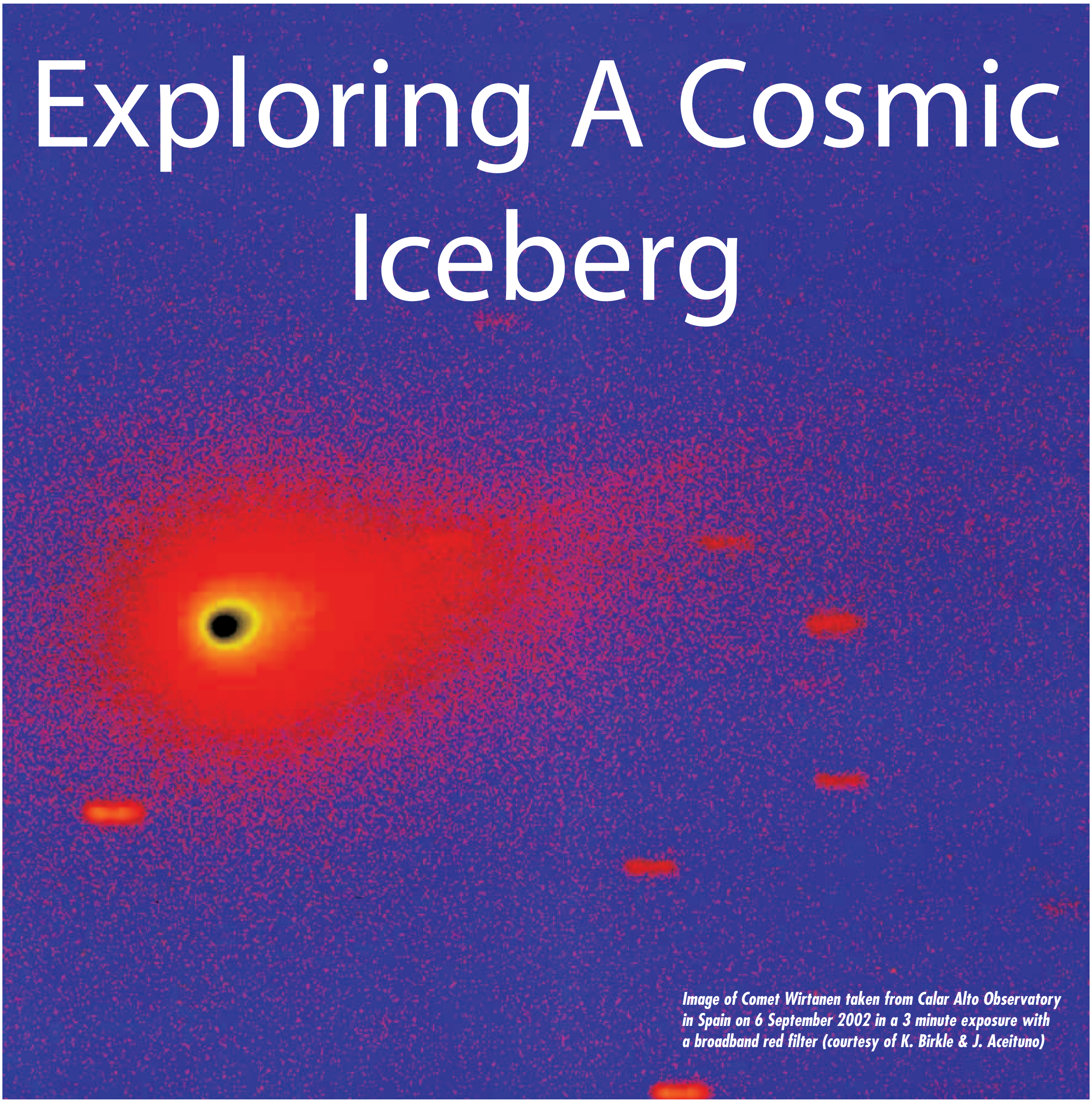


Image of Comet Wirtanen taken from Calar Alto Observatory in Spain on 6 September 2002 in a 3 minute exposure with a broadband red filter (courtesy of K. Birkle & J. Aceituno) the world. But why are scientists so keen to study these beautiful intruders into the inner Solar System?

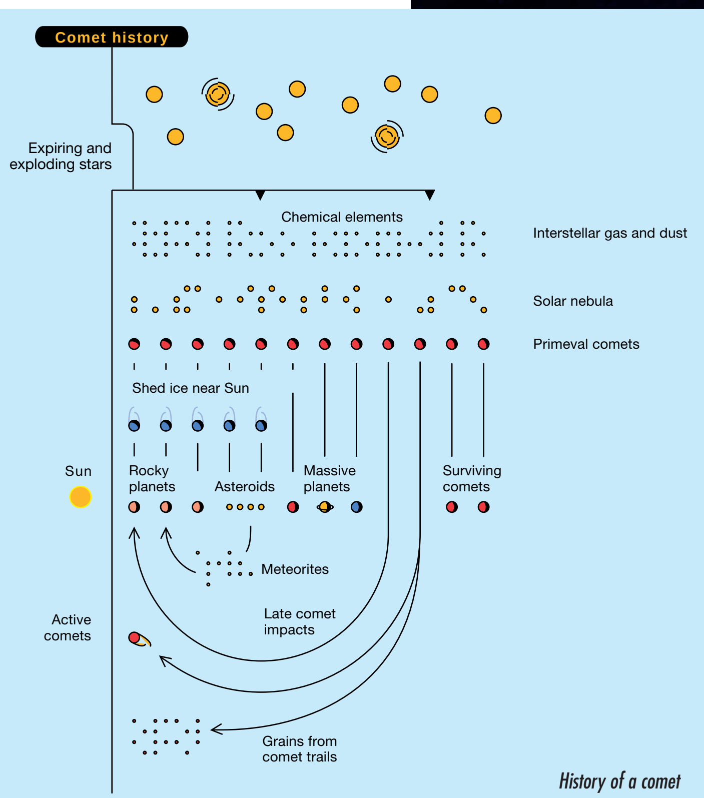
Planetary Building Blocks

Comets are small icy bodies, usually only a few kilometres across. Their basic ingredients are dust and frozen gases that were formed and preserved at very low temperatures in the vast, rotating cloud of material which surrounded the young Sun. Since they have not been altered by internal heating and spend most of their lives far from the Sun, these primitive bodies have changed little since their creation. Today we believe that comets represent the oldest building blocks of our Solar System, cosmic icebergs from which the planets were assembled some 4.6 billion (4 600 000 000) years ago.

In those violent times, many comets crashed into the infant planets. Craters caused by ancient comet and asteroid impacts can still be seen on the surfaces of the Moon, Mercury and many planetary satellites. Comets may also have provided much of the water that now forms Earth's oceans, and may even have delivered the complex organic chemicals that led to the first primitive life forms.

By learning more about individual comets, scientists also hope to get a broader understanding of the formation and evolution of our Solar System as a

Hubble Space Telescope time-lapse composite image of Comet Shoemaker-Levy approaching the planet Jupiter in 1994



History of a comet

whole. Like detectives trying to gather clues about a case, they need to obtain detailed information about the physical and chemical properties of comets in order to discover what the interplanetary environment was like when the planets were born. Unfortunately, this is far from easy since most of the comets have been hurled into the outer parts of the Solar System by gravitational interactions with the giant outer planets. As a result, only the modest number of comets deflected towards the Sun become accessible to our scrutiny.

Dirty Snowballs

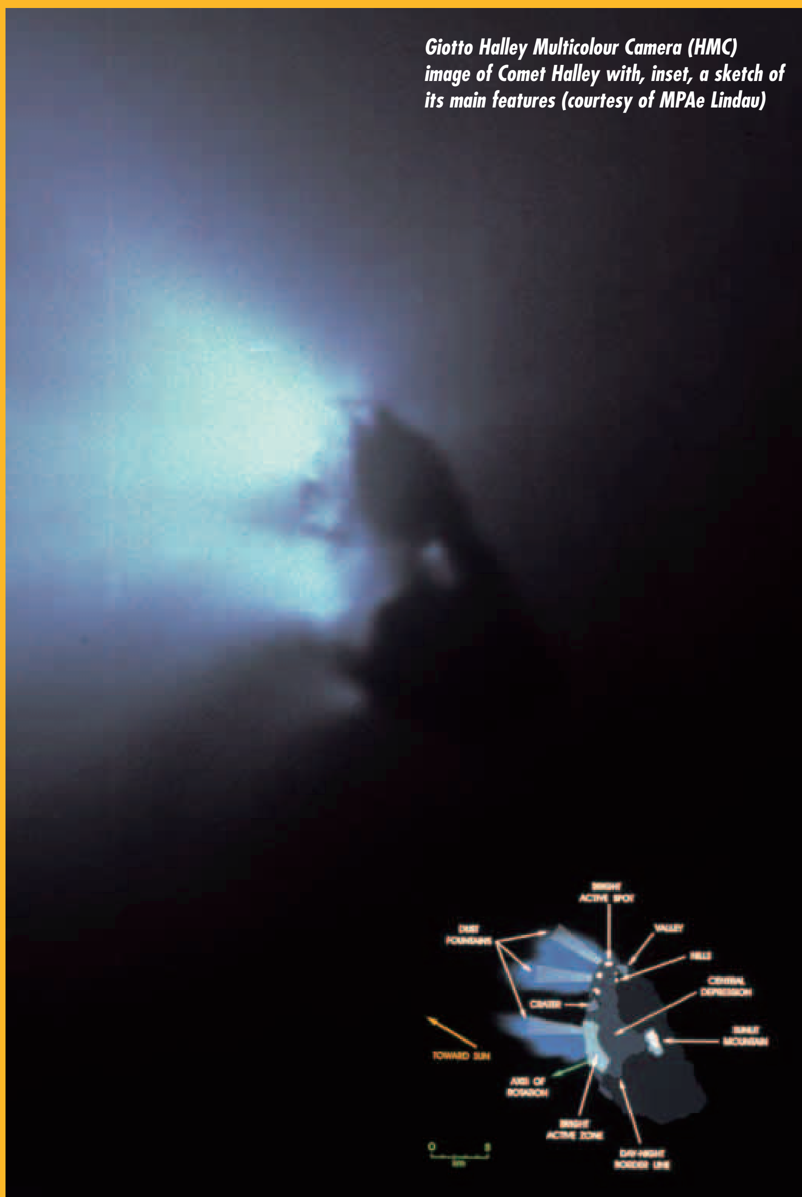
Until the 1986 flyby missions to Comet Halley, no one knew what a comet nucleus was really like. The icy heart of a comet is so small that it is almost impossible to see and analyse from Earth. As soon as the nucleus moves close enough to us for detailed observation, it is obscured from view by the coma, an all-enveloping shroud of gas and dust. When it is inactive, and not hidden by the coma, it is too far away to be resolved by even the best telescopes and too faint to allow detailed spectroscopic analysis of its surface material.

The most popular theory about the nature of comets was put forward by American astronomer Fred Whipple, often known as the ‘grandfather’ of modern cometary science. Whipple believed they were like dirty snowballs – large chunks of water ice and dust mixed with ammonia, methane and carbon dioxide. As the snowball approached the Sun, its outer ices began to vaporise, releasing large amounts of dust and gas, which spread through space to form the characteristic tails.

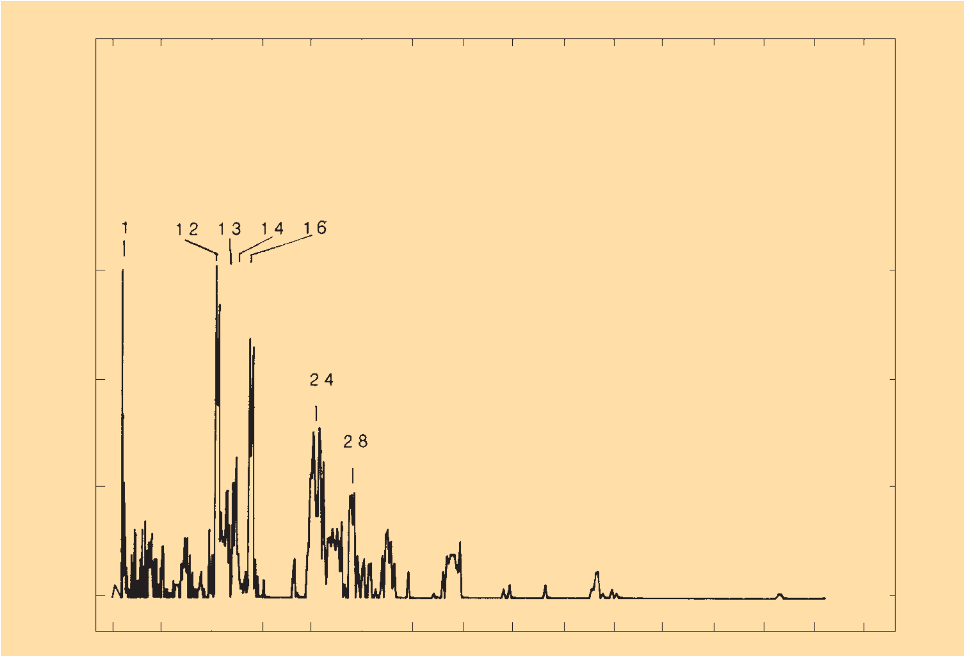
Today, largely thanks to data from ESA’s Giotto and two Russian Vega spacecraft, along with the recent encounter by NASA’s Deep Space 1, we now know that Whipple’s model was fairly accurate. Giotto’s pictures provided the final proof that Comet Halley resembles a lumpy, peanut-shaped body, about 15 km long and 7–10 km wide. The ‘dirty snowball’ was indeed very dark in appearance – blacker than coal. The images also showed at least seven jets of vaporised ice and dust spurting through vents in the surface material that coated the nucleus – convincing evidence to support the concept that cometary activity is confined to a small number of localised active areas on the rotating nucleus.

Analysis of the material released when Halley’s nucleus was exposed to the Sun led to major progress in the understanding of the comet’s composition. New insights were provided into the physical and chemical processes taking place in the inner coma, and the way in which the comet interacted with the electrified particles of the solar wind.

Simple organic (carbon-rich) molecules, such as formaldehyde and methanol, were also detected for the first time. A major surprise was the discovery of a new class of minuscule particles, each less than a millionth of a metre across – too small to be detectable by remote-sensing techniques. These were dubbed ‘CHON’ particles because they were rich in the light elements carbon, hydrogen, oxygen and nitrogen.



Giotto Halley Multicolour Camera (HMC) image of Comet Halley with, inset, a sketch of its main features (courtesy of MPAe Lindau)



Mass spectrum of a cometary 'CHON' particle recorded in 1986 by the Soviet Vega-1 spacecraft's dust-impact analyzer. The numbers are Atomic Mass Units (AMU)

Breakthroughs with Rosetta

The images and other data returned during these short-lived flybys have improved our knowledge of comets tremendously. However, despite such significant advances, scientists want to learn more about these fleeting visitors to the inner Solar System. Further studies are important in order to answer these key questions. What role, if any, did comets play in the evolution of life? How and why does a comet change during repeated approaches to the Sun? What lies at the heart of the nucleus, beneath its mysterious black blanket? Questions such as these can only be answered by Rosetta, the most sophisticated spacecraft ever to investigate a 'long-haired star'.

Rosetta will not just cast a cursory glance at its target, Comet Wirtanen, but it will provide the first intimate look at one of these intriguing objects. The investigation will begin while the intruder is still in deep space, 650 million km from the Sun. As it accompanies the comet on its headlong charge towards the Sun at speeds of up to 135 000 km/h, instruments on the Orbiter will determine the basic properties of the frozen, inactive nucleus, measuring its size, shape, mass and density.

After the Rosetta Orbiter has moved to within a few kilometres of the pristine surface, the entire nucleus will be surveyed at wavelengths covering almost the entire electromagnetic spectrum. Close-range images taken in visible light will be combined to map every bump and surface crack in the alien landscape down to a resolution of just a few centimetres. Parallel mapping from infrared to millimetre wavelengths will measure the corresponding surface temperatures, identify individual icy and mineralogical components and determine their distribution on the surface.

This will only be the beginning. As the nucleus is heated, the frozen volatiles (gases) start to vaporise and the dust is released, Rosetta will become the first spacecraft to witness how a dormant nucleus begins to stir into activity and evolve.

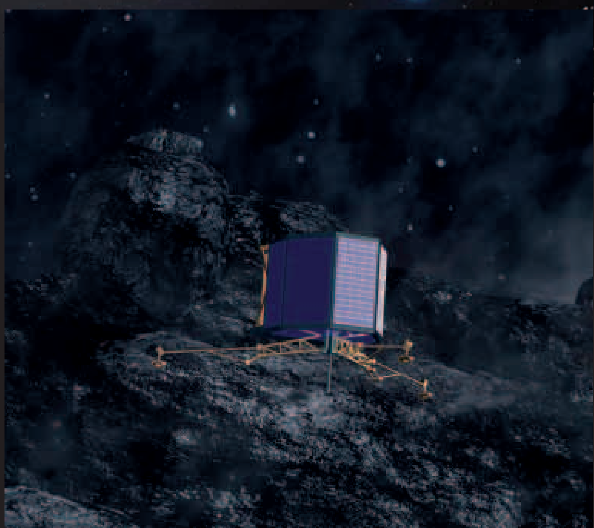
Over a full year, the Orbiter will observe from close range the extraordinary metamorphosis that takes place in the nucleus and its surrounding coma, providing the long-awaited information needed to understand the physical and chemical processes causing this phenomenon. Will the material be smoothly released from the entire heated area through micropores, or will the surface be cracked open at certain areas to release the material underneath? Nobody yet knows, but Rosetta will be on station to solve the mystery.

As soon as the nucleus becomes active, the Rosetta Orbiter will start to analyse the material that is released. The comet watch will continue as Wirtanen accelerates towards the inner Solar System and activity on the nucleus becomes ever more frenetic. Instruments will measure the elemental, molecular and isotopic composition of the gas and dust, along with the dust size distribution. Individual dust particles will also be collected and scanned by an atomic force microscope with an imaging resolution of a millionth of a millimetre.

From all of these studies, scientists will discover how the level of comet activity influences the properties of the material it spews into space. The interaction of the comet with the interplanetary magnetic field and the particles of the solar wind will complete the monitoring of the comet's evolution. Only when Wirtanen reaches perihelion, the closest point in its orbit to the Sun, will Rosetta's remarkable mission be terminated.

Rosetta Lander Science

By making the first soft landing on a comet, the Rosetta Lander will be able to conduct unique investigations into what the nucleus of Comet Wirtanen is made of. Equipped with 9 scientific experiments, the box-shaped spacecraft is dedicated to studies of the physical properties and the composition of the nucleus. All of the instruments will take at least one contingency measurement immediately after landing, and then continue to follow the evolution of the nucleus at it approaches the Sun. These in situ investigations will provide unprecedented knowledge of the comet's icy heart.



Samples of material will be obtained, not only from the surface but also to a depth of 20 cm, using a special sample drilling and handling device. The samples will then be imaged in visible and near-infrared light, and analysed in detail to discover their elemental, isotopic, molecular and mineralogical composition.

Panoramic and close-up images of the surface around and beneath the Lander will give Earthlings their first views of the alien, hostile landscape. The physical properties of the strange, black surface material, the local magnetic field and the comet/solar wind interaction will also be studied. Meanwhile, the CONSERT instrument (half of which is on the Lander and half on the Orbiter) will sound the interior of the 1.1 km-wide nucleus, rather like a physician using ultrasound to study an unborn child in its mother's womb.

Asteroid Science

Comet 140 Siwa

On the outward leg of its eight-year trek to Comet Wirtanen, Rosetta will make two excursions into the main asteroid belt between the orbits of Mars and Jupiter. This will enable the spacecraft to encounter two contrasting asteroids, 4979 Otawara in July 2006 and 140 Siwa in July 2008. These primordial, rocky worlds – leftovers from the formation of the planets – have been selected after careful evaluation of the scientific significance of the reachable targets combined with an assessment of the spacecraft's fuel budget.

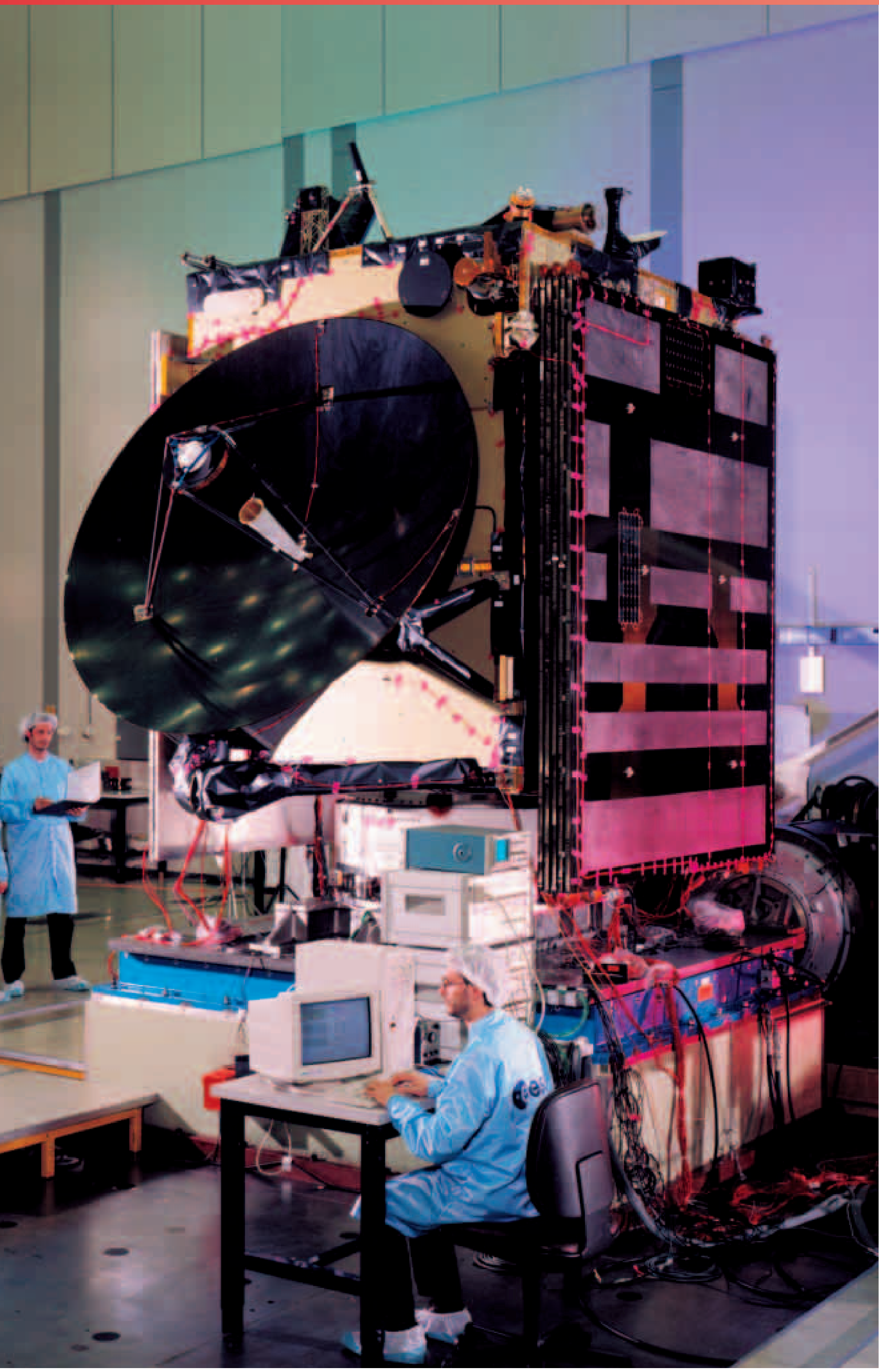
Siwa, a C-type (carbon-rich) asteroid, is particularly interesting. Unlike the more common S-type, the C-type asteroids are believed to have undergone little or no heating, so they are considered to be unaltered, volatile-rich bodies, darkened by opaque organic material. The meteorite analogues of these primitive asteroids are carbonaceous chondrites. Approximately 110 km in diameter, Siwa will be the largest asteroid ever studied during a spacecraft flyby.

Once Siwa was identified as the prime target, subsequent mission analysis showed that Rosetta's fuel budget would also allow a visit to Otawara, a 4-km-wide S-type asteroid. Otawara rotates faster (about once every three hours) than any asteroid so far visited by a spacecraft and so Rosetta should be able to image most of its surface during the fly past.

A multi-wavelength study will be performed of both asteroid targets. Apart from their basic characteristics such as size, shape and mass, the measurements will allow scientists to discover the mineralogical composition of their surfaces and to search for frozen volatiles, particularly water ice. Very sensitive sensors, designed to analyse the gas and dust in the coma of Comet Wirtanen, will also be switched on to search for evidence of any very sparse comas surrounding the asteroids, particularly the much larger Siwa.

Relative sizes of Otawara, Siwa and other known asteroids

A Race Against Time



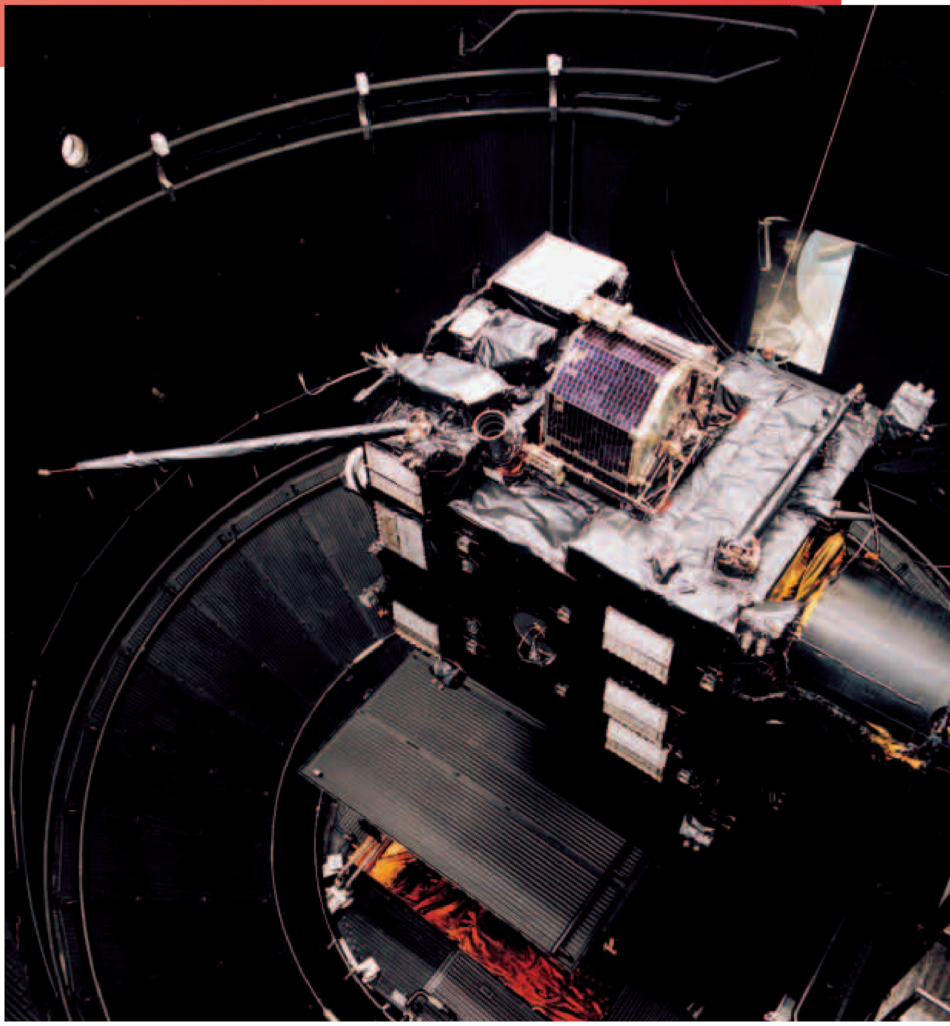
The International Rosetta Mission was approved as a Cornerstone mission within ESA's Horizon 2000 Science Programme in November 1993. Even at this early stage, it was envisaged that the ambitious mission would be scheduled for launch in the 2003 timeframe and a number of comet-rendezvous opportunities were identified. Although the original target, Comet Schwassman Wachmann 3, has since been superseded by another periodic intruder into the inner Solar System, Comet Wirtanen, there has been little shift in the original launch schedule. Rosetta is now set for lift-off from Kourou on the night of 12-13 January 2003.

Ever since the mission was accepted and given a slot in the long-term Horizons 2000 programme, the teams of ESA engineers and scientists have been engaged in a race against time. Once the design and specifications of the spacecraft and its payload were fixed in 1998, just four years remained for the Assembly, Integration and Verification phase.

Following the conventional spacecraft development philosophy, the Rosetta project team and its industrial partners were first required to build a Structural and Thermal Model in order to evaluate the design and thermal characteristics of the satellite. This was to be followed about seven months later by the delivery of an Engineering and Qualification Model that would be used to demonstrate that Rosetta's electrical and other subsystems would operate correctly in the extreme environment of deep space. Only then would the Flight Model be assembled and put through a final series of exhaustive tests that would check out overall performance and flight readiness.

Rosetta Structural and Thermal Model undergoing vibration testing at ESTEC in January 2001

Rosetta Flight Model in the Large Space Simulator (LSS) at ESTEC in March 2002



Meanwhile, teams from many countries were also required to deliver a Structural and Thermal Model, an Engineering and Qualification Model and a Flight Model of each of their instruments that would be used to survey the comet. With a three-month launch campaign scheduled to begin in early September, there was no time to pause for breath and 24-hour shifts became commonplace for the engineers and scientists who endeavoured to ensure that Rosetta would leave the pad on time.

"The heavens have their own timetable and the comet won't wait for us if we're late," said John Ellwood, Rosetta Project Manager.

The Flying Italian

Preparing a 3 tonne spacecraft for a series of endurance tests is far from easy. Before the thermal vacuum checks could take place, intrepid Alenia Spazio engineer Natalino Zampirolo was required to imitate an acrobat on a high wire. Suspended from an electric hoist, the engineer was required to 'fly' alongside the spacecraft at a height of 5 metres above the floor of the giant test chamber.

Dangling next to the Rosetta orbiter, Zampirolo gingerly removed the 'red tag' items – protective covers, arming plugs on the explosive connectors etc. – that were fitted as a safety precaution during normal work on the spacecraft. With his task successfully accomplished, the flying Italian was relieved to retreat to safety, leaving the spacecraft armed and ready to start its thermal trial.

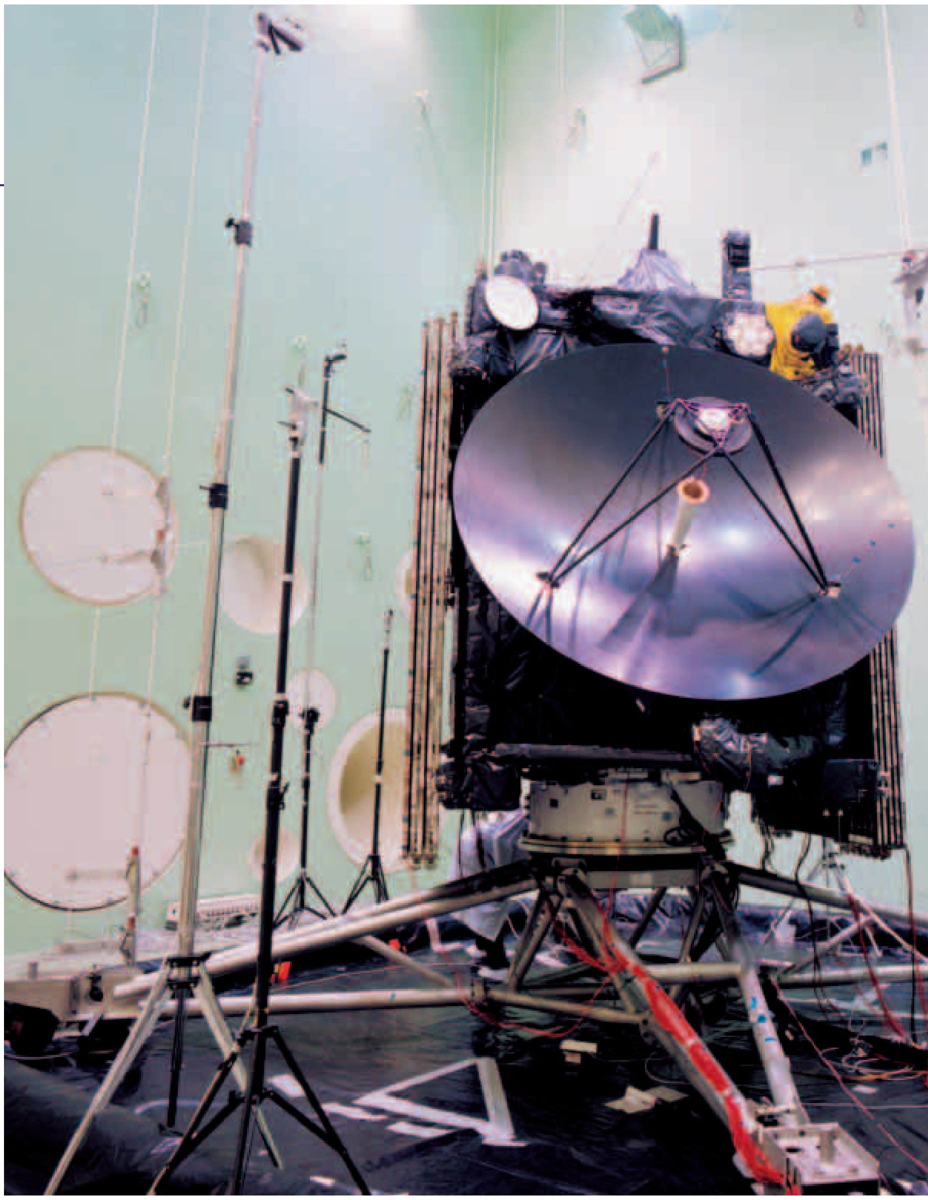
Rosetta Runs Hot and Cold

One of the key stages in the test programme was to establish whether Rosetta could maintain reasonable working temperatures throughout its circuitous trek to the orbit of Jupiter and back. In order to check the efficiency of Rosetta's thermal-control system, engineers at the European Space Research and Technology Centre (ESTEC) in the Netherlands placed the spacecraft in a thermal-vacuum chamber where the wildly fluctuating temperatures that Rosetta will experience could be replicated.

Imprisoned in the giant airless chamber, the Rosetta Orbiter, the Lander and their complement of 20 scientific instruments were alternately baked and frozen. In order to simulate the warmth of the inner Solar System, the exterior of the spacecraft was heated to a sizzling 150°C by a solar simulator comprised of 12 lamps each radiating 25 kW. During subsequent tests, liquid nitrogen was pumped through pipes in the chamber, causing the temperature inside to plummet to -180°C.

Sensors indicated that the spacecraft's insulation and heat control systems enabled Rosetta to survive these thermal tortures in fine shape, with internal temperatures restricted to between 40°C and -10°C. ESTEC engineers confidently predicted that, with the aid of its radiators and reflective louvers, Rosetta will be the 'coolest spacecraft' around.

"These tests show that Rosetta can survive the tremendous temperature contrasts it will endure as it flies from the vicinity of the Sun to the orbit of Jupiter," says Claude Berner, Payload and Operations Manager. "This gives us great confidence that the spacecraft will be able to survive its long exposure to the harsh environment of space."



Rosetta Breaks the Sound Barrier

Even before Rosetta has left the planet, the spacecraft has managed to break the sound barrier. In April 2002, the Flight Model was removed from the thermal vacuum chamber and prepared for the next stage of its pre-launch punishment. Once the high-gain antenna and huge solar arrays were mounted, the Orbiter was subjected to a series of deafening vibration tests in order to check whether it can survive the stresses it will experience during launch.

"The spacecraft was powered on, while the Lander, the high-gain antenna and the solar arrays were all in launch configuration," explained Claude Berner. "Even the propellant tanks were filled with 'dummy fuel'."

Placed in a giant acoustic/vibration chamber, a barrage of sound was directed at Rosetta from a huge amplifier in order to simulate the noise expected during lift-off. Soaring to a maximum of 135 decibels – ten times louder than Concorde at take-off – the sound levels were so severe that anyone straying into the chamber would have been killed within seconds.

Following these not-so-good vibrations, Rosetta returned to the clean room to complete a rock-and-roll ride on a giant shaker in order to simulate its ride into orbit aboard an Ariane-5 rocket. Attached to a table capable of moving the 3 tonne spacecraft from side to side like a metallic toy being mauled by a mastiff, Rosetta was severely shaken, first horizontally and then vertically, over a wide range of frequencies. Several hundred accelerometers on the structure were used to monitor the spacecraft's performance during each three-minute simulation. The results confirmed that the launch by the powerful Ariane-5 would leave Rosetta shaken but not stirred.

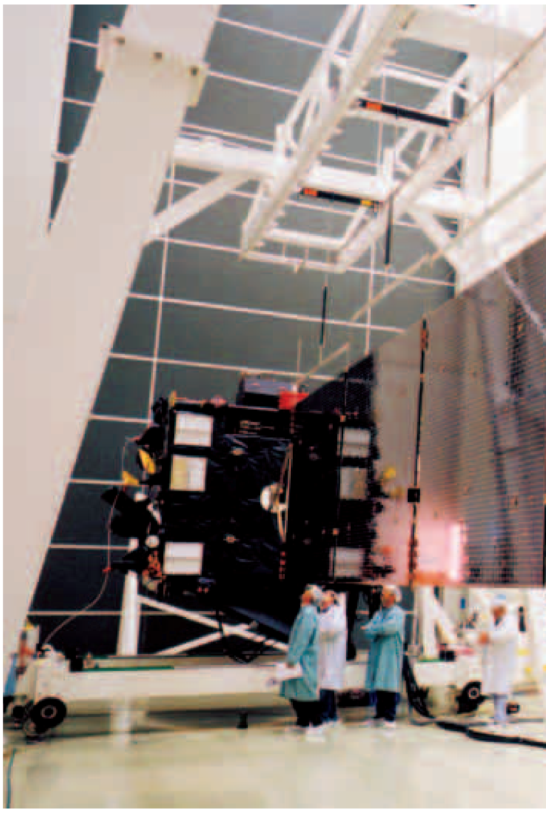
Solar Wings

Once the engineers at ESTEC had verified that all of the spacecraft's electronics had survived intact, it was time to check whether the pair of 14 m-long solar arrays and the delicate instrument booms had survived their potentially shattering ordeal.

Most critical of all were the deployment tests on the two giant 'wings' that will power Rosetta throughout its 10-year mission to deep space and back. These arrays, stretching one and a half times the length of a tennis court, must gently unfold to expose the special silicon cells that will generate electricity for the spacecraft to sunlight.

The 'minus-y' array, located to the left of the dish-shaped high-gain antenna, was the first to be unfolded. This was followed a day later by deployment of the 'plus-y' array on the opposite side of the spacecraft. Held in place by six Kevlar cables that will embrace the arrays during launch, each solar array was released after commands sent via the spacecraft activated the deployment sequence. 'Thermal knives' then severed each cable in turn by heating it to a temperature of several hundred degrees Celsius.

After the sixth cable was cut, the array began to unfold like a giant accordion. Attached to a huge, specially developed, deployment rig, the five panels in each array were gradually extended to their full



Rosetta Flight Model in the Acoustic Chamber at ESTEC

length across the clean room. To simulate the zero-gravity conditions of outer space, the weight of the arrays was counterbalanced by a mass-compensation device equipped with dozens of springs.

"Both tests went very well and there was a big round of applause when they were successfully completed," said Walter Pinter-Krainer, Principal AIV Systems Engineer for Rosetta.

Checking the Booms

Confident that their spacecraft's powerhouse would deploy properly after launch, the engineers went on to check out Rosetta's other movable parts. First came a partial deployment of the orbiter's 2.2 m-diameter high-gain antenna, when three pyros (explosive charges) were fired to release the dish from its stowed launch position.

The engineers also had to retreat to the safety of an observation area in the clean room for the firing of more pyros during the deployment of the upper and lower experiment booms on the Orbiter. Each 2 m-long boom carries probes and other equipment that will investigate the magnetic field and particle environment around Comet Wirtanen.

The fifth and final deployment test involved the release of a wire antenna to be used by the CONSERT experiment. After another explosive charge was fired, this unusual, H-shaped aerial was gently unfolded, suspended beneath five helium balloons to simulate the weightlessness of space.

The CONSERT experiment unfolded

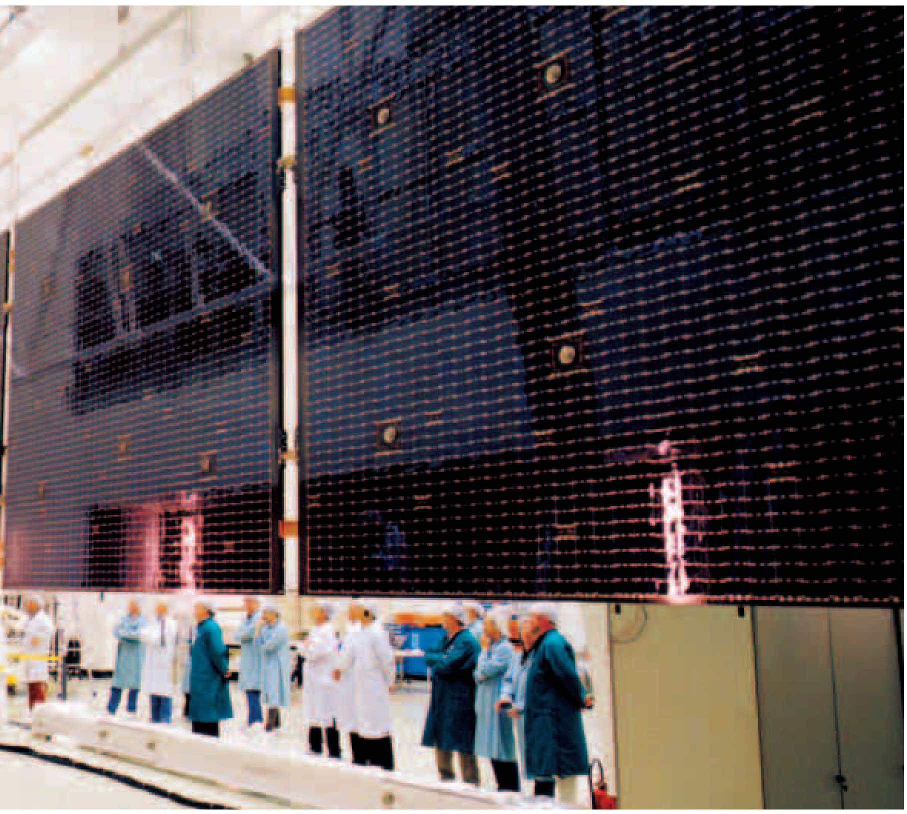
"Once again, the trial was completed without a hitch," announced a proud Marc Schwetterle, one of the payload engineers responsible for the tests.

"All of the deployment tests were very successful," commented Walter Pinter-Krainer. "These were crucial moments in our test programme and we were very happy to see everything working so well."

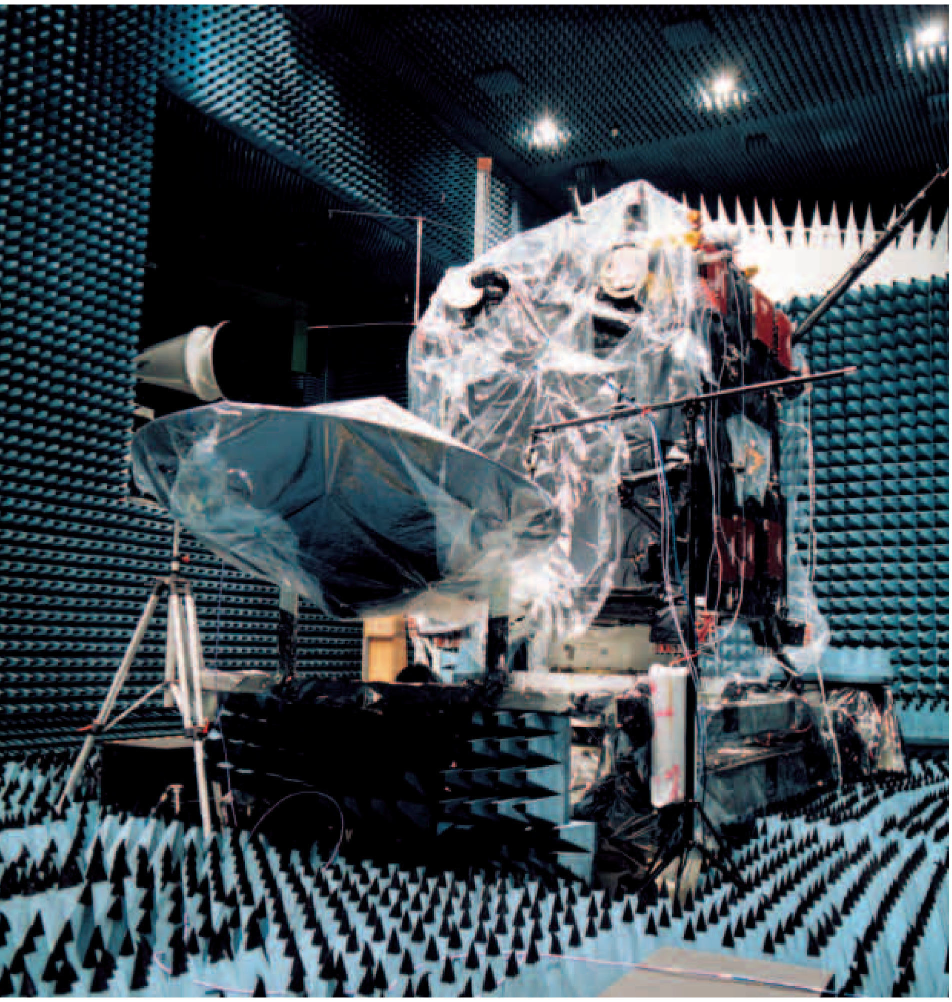
Rosetta Cleared of Interference

The hectic schedule continued in June when Rosetta was moved into another large test chamber at ESTEC, known as the Compact Test Range, where it was subjected to an extensive electromagnetic-compatibility (EMC) check.

In order to simulate the EMC environment during its long trek through deep space, Rosetta was placed inside a



Unfurling of the spacecraft's solar array



A 'cocooned' Rosetta Flight Model in the Compact Test Range facility at ESTEC

chamber lined with cones that absorb radio signals and prevent reflections. To avoid TV or radio interference, the chamber walls form a steel 'Faraday cage', impenetrable to electromagnetic signals from the outside world. In this radiation-free environment, the ESTEC team was able to study the radio signals and electrical noise coming from the various systems on the spacecraft and to check whether they caused any electromagnetic interference with each other.

"Before a satellite is launched it is essential to ensure that the electrical and electronic equipment within a spacecraft functions correctly," explains Flemming Pedersen, a senior AIV engineer for Rosetta. "For example, it could be fatal if, when switching on one unit, other instruments or systems such as the telecommunication link, were disturbed or even disrupted."

Like some alien creation, the spacecraft was cocooned in protective plastic foil while the engineers and scientists painstakingly prepared to switch on Rosetta's systems and payloads. At first, the see-through wrapping proved to be too tight, causing the spacecraft's temperature to rise. Once this was remedied and the staff vacated the chamber, all was set to simulate the various phases of Rosetta's 10-year mission.

"For some of the time we were measuring the energy emitted by the spacecraft's high-gain antenna, and this is hazardous, so the chamber was completely closed and everyone had to remain outside it whilst the measurements were made," said Flemming Pedersen. "It would be like exposing the engineers to the radiation from thousands of mobile phones simultaneously."

The first series of tests studied how the spacecraft behaved in 'launch mode'. At this time Rosetta was in its launch configuration, with a minimum of systems active while awaiting the lift-off of the Ariane-5 rocket. This was to ensure that signals from the spacecraft would not interfere with communications between the rocket and ground control during the launch phase.

Subsequent EMC tests took place when the spacecraft was at various levels of activity – from quiet periods when no science payloads were operating, to spells of hectic scientific investigation.

"We could switch on each instrument individually and measure the electromagnetic waves coming from it," explains Bodo Gramkow, Principal Payload engineer and EMC expert. "The rest of the instruments were put into listening mode to see if any of them detected any disturbance."

"On other occasions we switched on all of the instruments, including those on the Lander, in order to see whether we got any unexpected 'noise' or interference," he says. "From this we could determine whether we will need to switch a particular instrument off when we are making a very sensitive measurement with another one."

"All of the EMC tests proved to be very successful," says Bodo Gramkow. "This was the last of the three big system-validation tests and Rosetta passed with flying colours."

Ironing-out the 'Bugs' (from the Pilot's Seat)

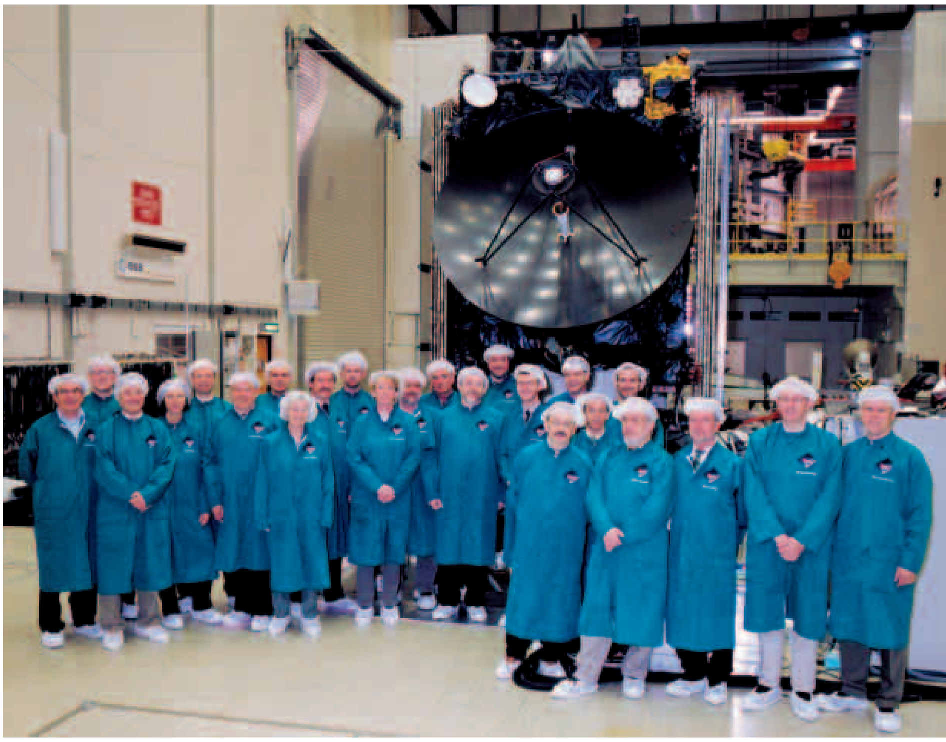
One key question that needs answering with confidence is: "Will Rosetta fly?" If the onboard computers are receiving all the right signals to convince them that the spacecraft is flying, will they react correctly? That question was asked and answered several times throughout 2002 in the form of an extensive set of Mission Simulation Tests.

It's 6 a.m. and a new shift starts. Into the control room come the software experts and they take up their positions in front of large, crowded, computer screens. Two sets of computers are synchronised: one set, on the ground, simulating a 'real-space' environment for their counterparts

onboard. The ground equipment feeds the Spacecraft Star Tracker with a simulated star-field image, and the onboard computers react and command a small attitude change for the spacecraft body.

Standing in the clean room and watching from the outside, nothing changes, but on the inside, from the perspective of the many onboard computers .... Yes! Rosetta is flying! So it goes on. For each mission phase the spacecraft computers are put through their paces.

"The functional testing of such a complex spacecraft as Rosetta should not be underestimated," says Mark Nesbit, the ESA engineer responsible for defining much of the functional test programme. "We test the spacecraft system in many closed-loop simulations, with the full scientific payload on-line, performing comet observations just as it will during the actual mission."



The Rosetta Team, with the Flight Model spacecraft in the background

The Rosetta Lander undergoing testing at ESTEC

"But for Rosetta," Mark continues, "we have to go a few steps further and we give the onboard computers a hard time. We feed them with unexpected situations, where the onboard autonomy has to take over and automatically recover the spacecraft into a safe mode. The variety in the mission profile and the long periods without ground contact mean that Rosetta has to be able to take care of itself, and on the ground we have to convince ourselves that it can."

The Trip to the Tropics

With the completion of the AIV programme, the final leg of Rosetta's race to the launch pad could get under way. It was time to transport ESA's comet chaser to the Kourou spaceport on the other side of the world. First to be packed was the ground-support equipment, which was loaded onto transporters for the short road journey to Rotterdam. There, the containers were transferred onto a regular Arianespace supply ship for the two-week voyage to French Guiana.

This was followed in early September by the Rosetta spacecraft itself, minus the large high-gain antenna and the twin solar arrays. Cocooned inside a protective container and purged with nitrogen to prevent contamination, the Orbiter and the attached Lander were loaded onto a Russian Antonov-124 air freighter at Amsterdam airport for the flight to Cayenne.

Over the next four months, the spacecraft would be prepared for launch in the specialist facilities at Kourou. After installation of the high-gain antenna, the folded solar wings, the explosive pyros and the spacecraft batteries, Rosetta is to be moved to another building for hazardous operations where its propellant tanks will be filled and pressurised. By early January 2003, it is scheduled for mating with the upper stage of the Ariane-5 launch vehicle. Five days after the fairing installation on 6 January, the huge rocket and its precious payload will inch along the causeway to the launch pad.

If all goes well, Rosetta's long, hard road from initial acceptance to successful launch will take place on the night of 12-13 January. Eight years later, the odyssey will be completed when Comet Wirtanen sails into view and the expedition to explore this small, primordial world begins in earnest.

Rosetta Rises to the Challenge

Few enterprises are more difficult or hazardous than space travel. Yet, even when compared with the achievements of its illustrious predecessors, ESA's Rosetta mission to orbit Comet Wirtanen and deploy a lander on its pristine surface must be regarded as one of the most challenging ventures ever undertaken in more than four decades of space exploration.

The first of the challenges faced by the Rosetta project team, the scientific collaborators and industrial partners was to design, build and test the complex comet chaser in time to meet the scheduled launch date in January 2003. With less than four years from the beginning of the development phase to launch, it was only possible to meet the series of tight deadlines through highly efficient and motivated team work, long shifts and remarkable dedication by all involved.

Having overcome the time constraints associated with the launch, the hundreds of engineers and scientists involved in Rosetta are now about to face the ultimate assessment of their endeavour – the ability of their creation to not only survive in deep space for more than a decade, but to successfully operate in the close vicinity of a comet and return a treasure trove of data that will revolutionise our knowledge of these mysterious worlds.

The Launch Window

As history has frequently shown, the first hours of a spacecraft's journey to the depths of the Solar System can be among the most critical. In the case of Rosetta, the odyssey will begin with launch from Kourou spaceport aboard an enhanced version (P1 Plus) of Ariane-5.

The first obstacle to be overcome is the limited launch window. In order to meet up with Comet Wirtanen, Rosetta must be launched within a period of 19 days, starting on 13 January 2003. On six of those days there will be a launch window of just 20-30 minutes. The remaining days account for a roll back of the rocket for replenishing of the cryogenic fuel. If this opportunity is missed, the mission will have to be postponed while another target is selected.

Fortunately, the Ariane-5 operator, Arianespace, has an excellent record in launching payloads within such a restricted time frame and has expressed its willingness to do everything possible to ensure that the launch will take place within the three-week window.

Meanwhile, the project team is also taking precautions to ensure that Rosetta launches on time:

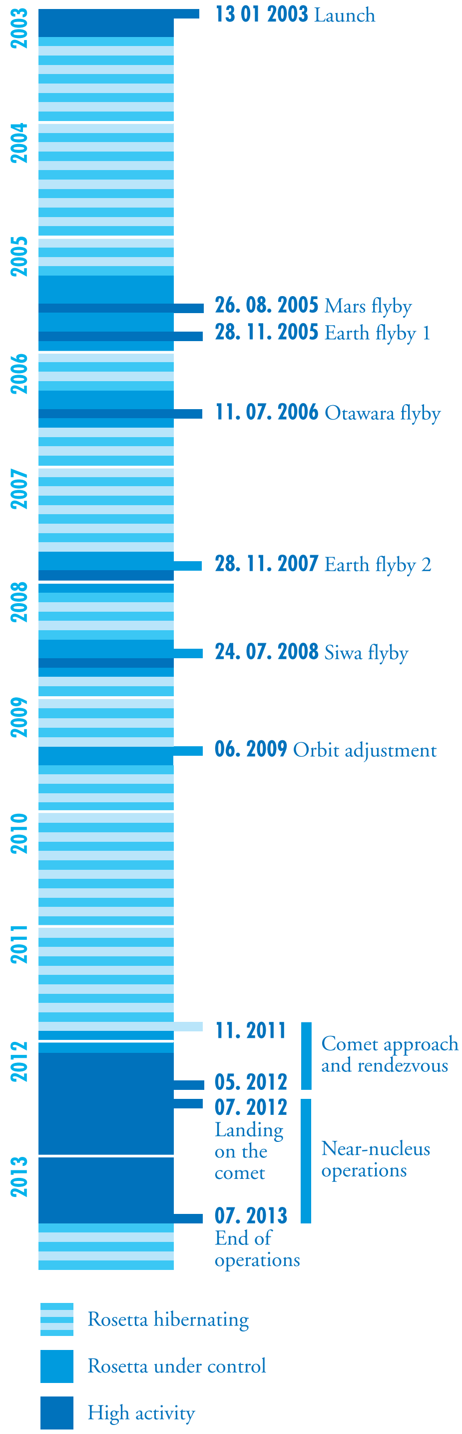
"We do not anticipate any drastic launch postponement," says John Ellwood, Rosetta project manager, "However, it is always prudent to have contingency plans. For example, we are able to work three shifts a day if the spacecraft testing or preparation fall behind schedule. There will be a spare upper stage at the Kourou launch centre if there are problems with Ariane-5 close to launch. A spare Ariane-5 main engine will also be on hand in France ready for shipment within 24 hours."

After the EPS upper stage and its Rosetta payload have been safely placed into a trajectory around the Earth, the next challenge will be to send the spacecraft on its way towards Comet Wirtanen, just two hours after lift-off from Kourou. Prior to reaching perigee (the closest point to the Earth), the upper stage will be re-ignited to inject Rosetta into the required Earth-escape trajectory towards Mars and the asteroid belt. This will be the first time that an Ariane-5 has boosted a spacecraft beyond Earth orbit.

Survival in Deep Space

Ensuring that the spacecraft survives the hazards of travelling through deep space for more than 10 years is one of the great challenges of the Rosetta mission. This prolonged journey will provide the ultimate test of the spacecraft's long-term reliability, robustness and ability to cope with unexpected problems.

Once the spacecraft is safely on its way,



its solar arrays and booms have been deployed and its systems checkout has been completed, Rosetta will have to survive lengthy periods of inactivity, punctuated by relatively short spells of intense action – the encounters with Mars, Earth and two asteroids.

Apart from the hazards posed by the hostile space environment – dust impacts, energetic solar particles, cosmic rays and extremes of temperature – the spacecraft will spend roughly two years in hibernation. To limit consumption of power and fuel, almost all of Rosetta's electrical systems will be switched off, with the exception of the radio receivers, command decoders and power supply. At such times, the spacecraft will spin once per minute while it faces the Sun, so that its solar panels can receive as much sunlight as possible.

Onboard Autonomy

Apart from the necessity to place Rosetta in hibernation for half of its interplanetary trek, the operational situation is further complicated by occasional communication blackouts (up to four weeks long) due to solar occultations, when the spacecraft passes behind the Sun. Even under optimum conditions, daily communication opportunities from the Australian ground station will last a maximum of about 12 hours.

So what happens if some unexpected malfunction or damage occurs during the prolonged interplanetary voyage? There were two options: (i) to provide Rosetta with enough 'artificial intelligence' to solve the problem without human intervention; or (ii) to analyse the problem on the ground and transmit remedial instructions to the spacecraft.

Unfortunately, although the second of these is usually preferable, the laws of physics and the vast distances involved mean that it is rarely feasible. For much of its trek to Comet Wirtanen, Rosetta will be beyond the orbit of Mars, eventually venturing all the way out to the orbit of Jupiter, 780 million kilometres from the Sun. Even travelling at the speed of light (300 000 km/s), radio signals will take up to 45 minutes to cross the vast gulf between the distant spacecraft and the Earth. By the time Rosetta receives a response, at least one and a half hours will have elapsed.

Since real time command and monitoring from the ground are out of the question, Rosetta has been designed with a considerable degree of autonomy. Although four onboard computers are programmed to deal with tasks such as data management and attitude and orbit control, only two are required to be operational at any one time. If the onboard monitoring system detects a problem that threatens the health of the spacecraft, the computers will take immediate corrective action, switching to a backup system if necessary.

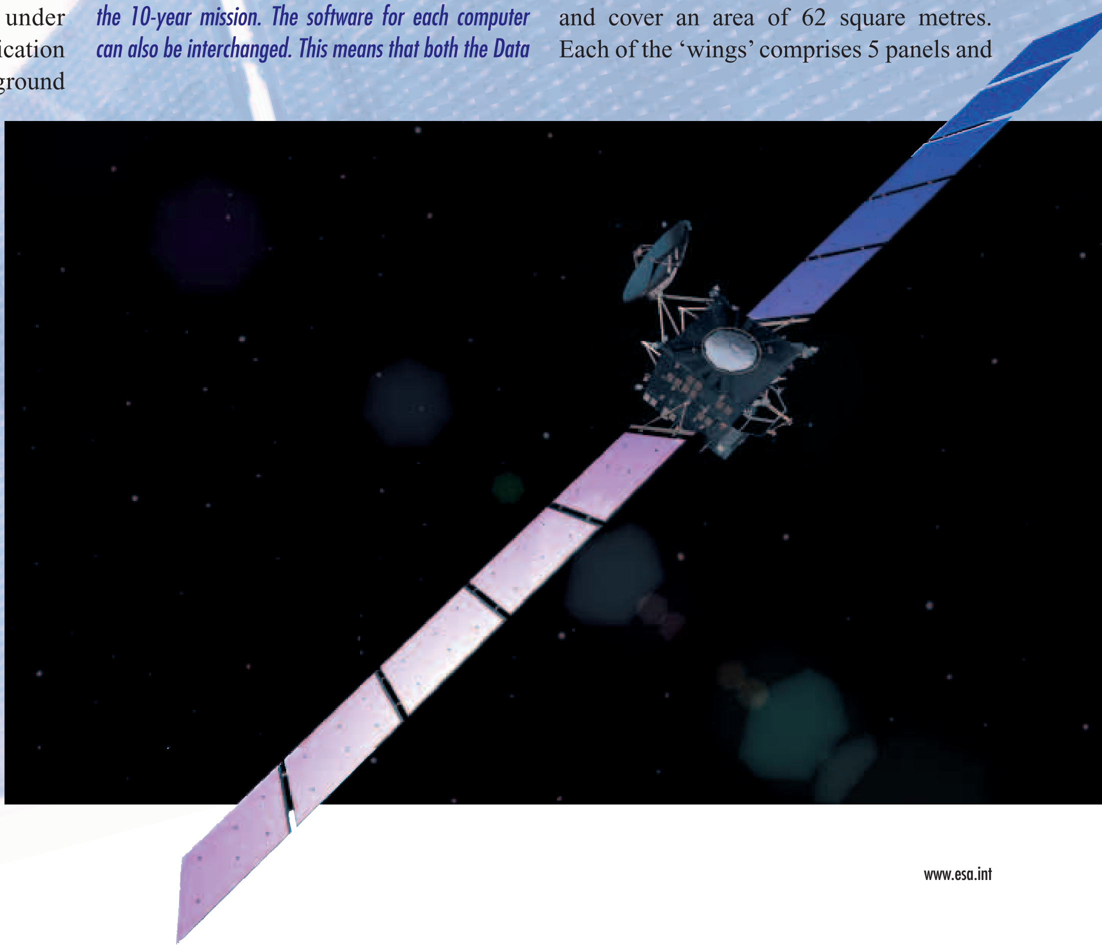
"Rosetta has been designed to carry multiple computers that provide it with a sophisticated failure recognition and recovery capability," explains Jan van Casteren, Spacecraft System Manager. "It's a highly autonomous system based on two computers, each with two separate parts that can be interchanged. We always have the option to upload new, enhanced software over the 10-year mission. The software for each computer can also be interchanged. This means that both the Data Management System and the Attitude and Orbit Control subsystem can be run on all processors. If the spacecraft is in serious trouble, it automatically goes into safe mode – in other words, it goes into hibernation with its solar arrays pointing at the Sun. These backup systems should ensure that the spacecraft will remain operational during critical mission phases, including the highly complex scientific observations when Rosetta is orbiting close to the comet's nucleus."

Solar Power

Venturing far from the Sun puts other serious constraints on Rosetta's design and performance, particularly its electricity supply and temperature.

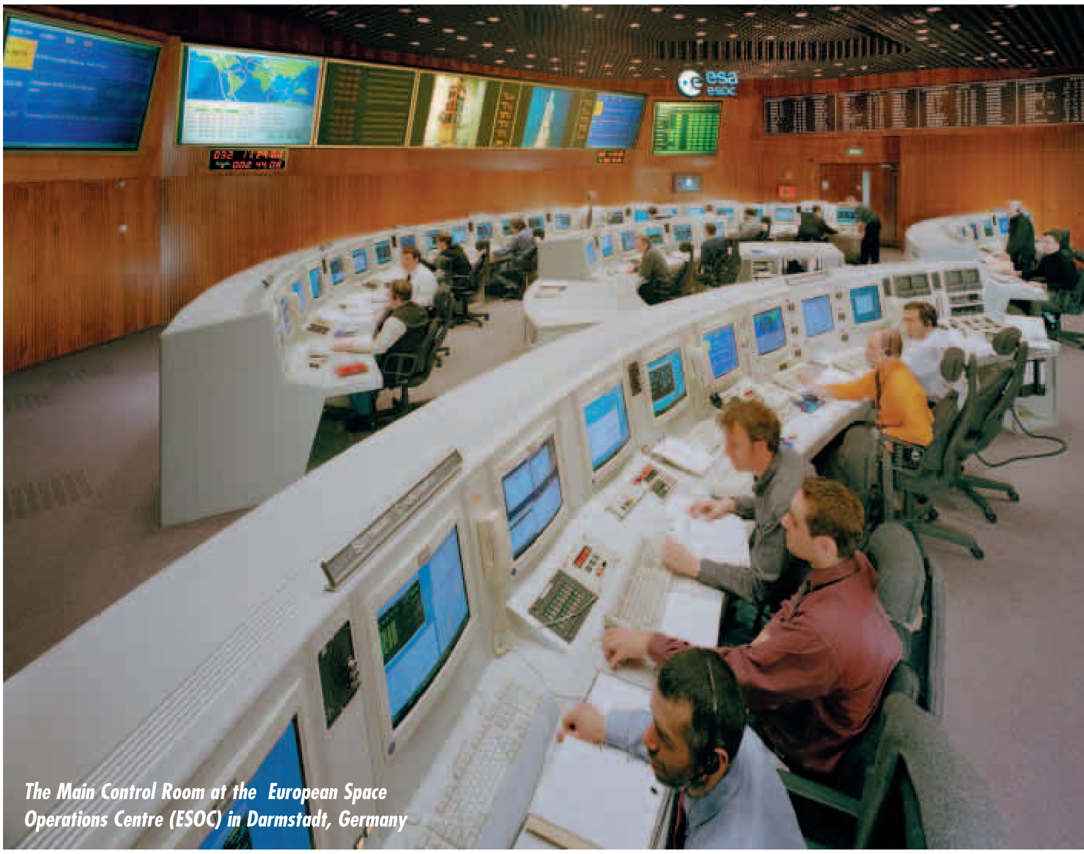
Rosetta will set a record as the first space mission to journey far beyond the main asteroid belt while relying solely on solar cells for power generation. Unfortunately, there is a price to pay. When Rosetta reaches the orbit of Jupiter, where levels of sunlight are only 4% those on Earth, the spacecraft will be generating only 1/25th of the electricity that it can produce when in the inner Solar System.

In order to compensate for this drop in power, Rosetta is equipped with two enormous, steerable solar arrays that span 32 m tip-to-tip (longer than a tennis court) and cover an area of 62 square metres. Each of the 'wings' comprises 5 panels and



is fitted to the spacecraft body with a yoke and drive mechanism, allowing 180° rotation in order to capture the maximum amount of sunlight. Both sides of the arrays are electrically conductive, to avoid a buildup of electrostatic charge.

More than 22 000 non-reflective silicon cells have been specially developed for the Rosetta mission. The main challenge was to achieve maximum efficiency by designing a pyramid-shaped, non-reflective upper cell surface. Optimised for low-sunlight (40 W/m^2), low-temperature (-130°C) operation, these cells should provide an end-of-life conversion efficiency of 15%. They will generate up to 8700 W in the vicinity of the Earth and around 400 W (equivalent to the power consumed by four normal light bulbs) during the deep-space comet encounter.



The Main Control Room at the European Space Operations Centre (ESOC) in Darmstadt, Germany

Hot and Cold

Imagine leaving home for 11 years, to embark on a trek that will take you from the frozen wastes of Antarctica to the scorching deserts of Arabia. Working out how to survive such extremes of hot and cold would be a major headache.

In the same way, dramatic temperature variations were a major cause of concern for Rosetta's designers. When the spacecraft is cruising around the inner Solar System, bathed in the warmth of the Sun, its surface temperature may soar to 130°C, and even internal equipment may reach 50°C. However, in order to rendezvous with Comet Wirtanen, Rosetta will have to probe the frigid regions beyond the asteroid belt, where temperatures plummet to -150°C.

Since it is not feasible to wrap a spacecraft in multiple layers of warm clothing for periods of deep freeze, then strip these away when sunbathing is the order of the day, Rosetta has been provided with alternative ways of regulating its temperature.

Near the Sun, overheating will be prevented by using radiators to dissipate surplus heat into space. 14 louvers – high-tech Venetian blinds that control heat loss from the spacecraft – are fitted over the radiators on two sides of the spacecraft. Lovingly polished by hand, these assemblies of thin metal blades must be handled like precious antiques, since any scratching, contamination or fingerprints will degrade their heat-reflecting qualities.

The principle behind the louvers is quite simple. In the balmy regions between Earth and Mars, they are left fully open, allowing as much heat as possible to escape into space from Rosetta's radiators. During the prolonged periods of hibernation and comet rendezvous, however, heat conservation is the order of the day. Since the spacecraft's limited internal power supply – equivalent to the output from a few light bulbs – then becomes the main source of warmth, it is essential to retain as much heat as possible. This means completely closing the louvers to prevent any heat from escaping. Heaters located at strategic points (e.g. fuel tanks, pipework and thrusters) will also be turned on and the multi-layered blankets of insulating material come into their own.

Communications

Communications play an even more important role in space missions than they do in our everyday lives. Whereas it is reasonable to believe that a good friend is safe and sound after several weeks without speaking to them, the same cannot be assumed for a spacecraft millions of kilometres from home.

The task of keeping in touch with the far-roaming Rosetta falls on the operations team in the Mission Control Centre at the European Space Operations Centre (ESOC) in Darmstadt, Germany. They are responsible for mission planning, monitoring and controlling the spacecraft throughout its circuitous voyage to Comet Wirtanen. The flight-dynamics team at ESOC will calculate and predict its attitude and orbit, prepare orbit manoeuvres, and evaluate spacecraft dynamics and navigation. Ground controllers will also evaluate Rosetta's performance, preparing and validating modifications to onboard software when necessary.

Planning of the scientific mission and generation of commands to experiments will be conducted either from the Science

Operations Centre at ESOC or from ESTEC. During the climax of the mission, ESOC will be responsible for pre-processing, archiving and distributing the unique cometary data to the scientific community. Lander operations will be undertaken from the DLR Lander Control Centre in Cologne, Germany, with support from the CNES Lander Science Centre in Toulouse, France.

In order to keep in touch with their itinerant explorer, ground control will be able to use radio communications at both S-band (2 GHz) and X-band (8 GHz) frequencies. Rosetta itself has the capability to 'speak' and 'listen' to Earth via several antennas. Two low-gain antennas with wide-angle coverage will support emergency operations in S-band. There are also two medium-gain antennas, one for S-band and one for X-band. However, the primary communications link will be the 2.2 m-diameter high-gain antenna, which will be able to send and receive large amounts of data at both frequencies. This lightweight steerable dish is largely made of carbon fibre and tips the scales at just 45 kg, including the electronics.

The rate at which information can be transmitted from the spacecraft will vary considerably with its distance from Earth (up to 930 million km) and its level of activity, ranging between 8 bit/s and 64 kbit/s. However, during the comet-exploration phase, the minimum telemetry data rate will be 5 kbit/s. New computer software will be used to compress the data, so compensating for the limited downlink bandwidth and ensuring that as much information as possible will be returned. The unique results from Rosetta's experiments can be stored temporarily in the spacecraft's 25 Gbit mass memory for relay to Earth at a convenient time.

To ensure that optimal contact is maintained with the wandering spacecraft, ESA's network of ground stations has been augmented with a specially-built ground station at New Norcia (Western Australia). Equipped with a newly constructed 35 m dish and cryogenically cooled, low-noise amplifiers to receive Rosetta's weak radio signal, the state-of-the-art antenna will be remotely controlled from ESOC. NASA's Deep Space Network will offer back up for telemetry, telecommand and tracking operations during critical mission phases, while the Kourou station in French Guiana will provide additional support during the launch, early-orbit and near-Earth phases of the mission.


The New Norcia ground station in Western Australia

Longevity

One of the most significant but least-tangible challenges to Rosetta's success is the insidious passage of time. Not only must the hardware survive for more than 10 years in the hostile environment of space, but the mission teams must continue to function efficiently throughout the entire voyage.

At the time of the critical near-comet operations, it is very likely that many of the engineers who designed and tested the spacecraft 10 or 15 years earlier will no longer be available to offer support if unforeseen circumstances arise. In fact, a fair number of them may well have retired. In preparation for this inevitable turnover of personnel, a number of younger people are being drafted into the instrument teams, including several principal scientific investigators. In order to ensure that the replacements can slot into the programme as easily as possible, the Rosetta project is creating a database that contains complete information about the spacecraft and its complex mission.

The unusual duration of the mission means that considerable attention must be paid to proficiency and cross training of staff to guarantee backup support, while refreshing skills and motivation. Facilities available at ESOC to support tests and simulations will include a spacecraft simulator, an onboard-software maintenance facility, and the spacecraft electrical model. If spacecraft anomalies arise, these items at ESOC will be indispensable for reproducing the problems, developing and testing solutions prior to implementing corrective actions on the spacecraft itself.

"The first eight months of the mission will involve intensive activity that will enable everyone to become familiar with the spacecraft's behaviour," explains Manfred Warhaut, Rosetta Ground Segment Manager.

"There will then be periodic training and communication activities – once every 6-12 months – to keep the team on the ball, as well as for the operations during the Earth and Mars flybys. We will take care to have adequate training before each manoeuvre."

Navigation

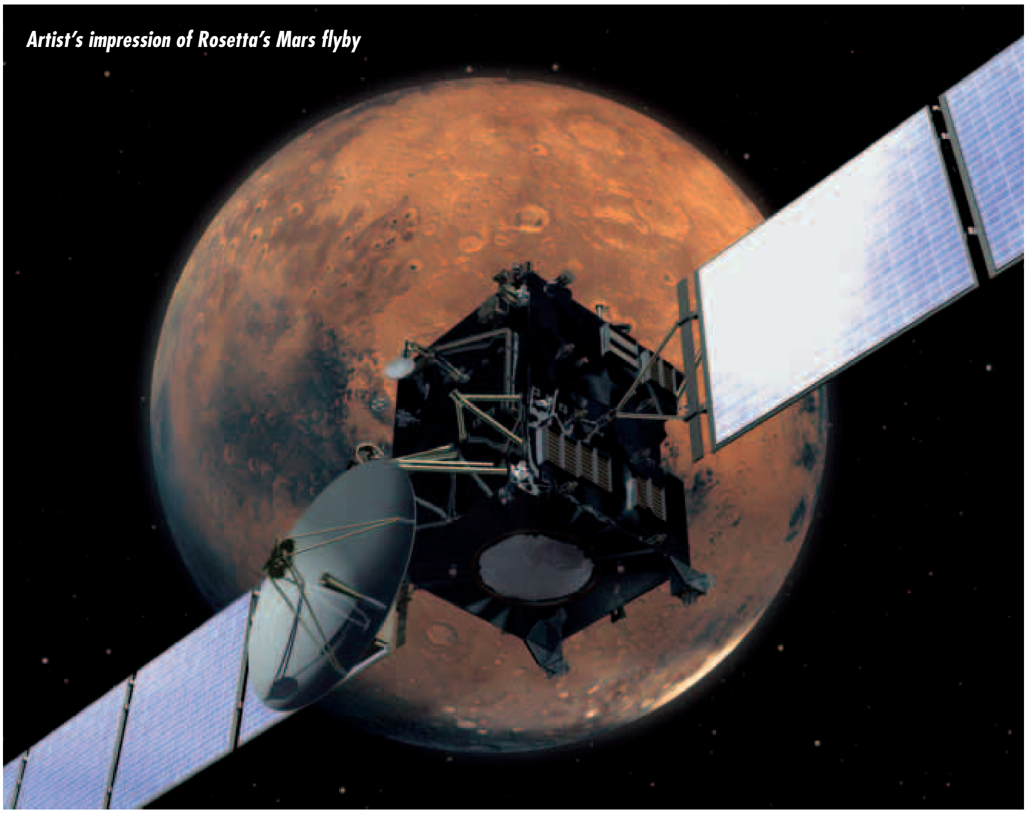
Rosetta's mission resembles a multi-million-kilometre, high-speed chase, hopefully culminating with the spacecraft and comet travelling alongside each other on parallel paths. Unfortunately, if Rosetta arrives too early or too late, the comet will not be there to meet it!

Achieving a long-distance rendezvous and matching orbits requires some highly complicated navigational calculations, particularly since not even the powerful Ariane-5 has the capability to send a three tonne spacecraft directly to Comet Wirtanen. To match the comet's velocity, Rosetta will have to be accelerated by 7.8 km/s after leaving Earth orbit. To achieve this, the spacecraft will bounce around the inner Solar System like a cosmic billiard ball, gaining speed from three planetary flybys. After an initial boost of 3.4 km/s from Ariane-5's upper stage, the spacecraft must take advantage of gravity assists from Mars (in 2005) and Earth (in 2005 and 2007).

In order to ensure that Rosetta stays on course throughout this circuitous passage, ground controllers will have to carefully monitor the spacecraft's velocity and position. This will be done by monitoring the telemetry and navigation images from the spacecraft, and by visual and radar tracking during the Earth encounters. Studies of the shift in frequency of the radio signals coming from Rosetta – the Doppler shift – will reveal how fast the robotic ambassador is travelling towards or away from us.

However, this is not sufficient to tie down Rosetta's motion. Like a Space Shuttle pilot trying to rendezvous with the fast-moving International Space Station, it is essential to know the quarry's position, speed and direction of movement. Unfortunately, comet orbits can be severely influenced by the gravitational pull of nearby planets. In the case of Comet Wirtanen, the orbit was significantly altered by close encounters with Jupiter in 1972 and 1984. As a result, the comet's orbital period was shortened from 6.7 years to 5.5 years. Outgassing from the nucleus may also modify a comet's trajectory, so a continuous observational programme using ground-based observatories has been put into place to accurately pin down Wirtanen's path.

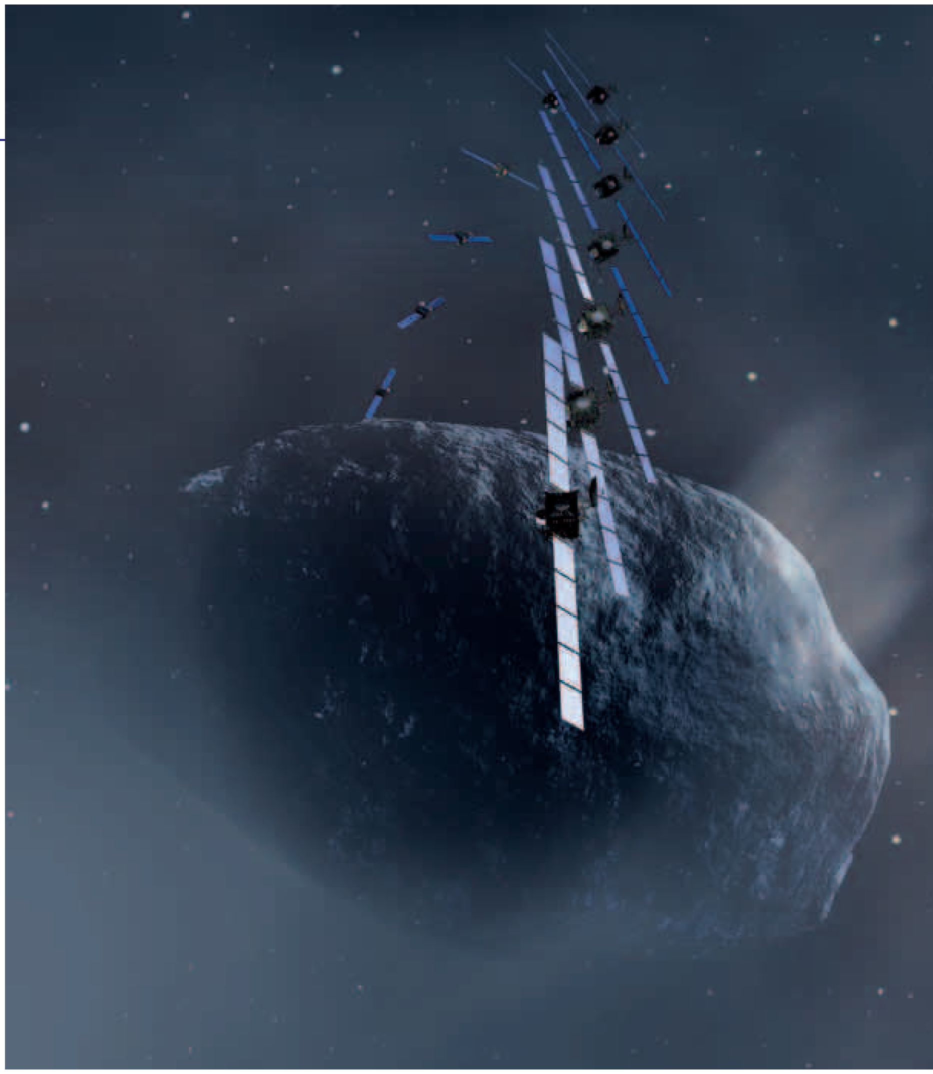
Even if Rosetta follows the optimum route to its target, the final rendezvous is complicated by the fact that the comet's and the spacecraft's orbital planes do not coincide. Thus, about 8.5 years into the mission, the spacecraft's bi-propellant reaction-control system will have to be fired to make the largest manoeuvres of the mission in order to phase Rosetta's orbital plane with that of the comet. Once the onboard navigation cameras have detected the dark, inactive comet from a distance of some 300 000 km, the task of closing on the nucleus will become more straightforward.



Artist's impression of Rosetta's Mars flyby

Remote Science

Rosetta exists for one purpose – to complete humankind's first extended exploration of a comet. Although it has been equipped with a suite of state-of-the-art instruments, this alone is insufficient to ensure a successful outcome. Different experiments need different conditions to work properly and optimally. A particular environment, spacecraft orientation or orbit that is perfect for one instrument might fatally compromise the performance of another. For instance, Rosetta's dust-collecting instruments must pass through a dust jet from time to time to gather the ejected pristine material, but care must be taken to ensure that too much dust does not collect on optical instruments and other sensitive surfaces.



Rosetta orbiting Comet Wirtanen (artist's impression)

Clearly, proper coordination of the science operations is very important and every effort has to be made to coordinate these operations in order to maximize the outcome of the mission. This has been done by defining different 'mission scenarios' to meet the needs of the different instruments. In the above example, one mission scenario will be dedicated to the collection of dust (and gas) in a very active part of the coma (a jet), during which the cameras will be protected by leaving their covers on.

Each investigation also presents its own challenges. One of the most revolutionary experiments is CONSERT, which will send short pulses of radio waves through the cometary nucleus. By transmitting and receiving the pulses on the Orbiter and the Lander, the attenuation and the time delay of the radio signal propagating through the comet are determined. From this sounding data, information on the interior of the nucleus can be retrieved.

Since the time taken for wave propagation through different nucleus materials varies by tiny amounts, it is crucial to ensure that the clocks on the Orbiter and Lander are offset by no more than 5 to 100 nanoseconds (a nanosecond is a billionth of a second).

Imaging with instruments such as OSIRIS presents a different type of challenge. During the fast flybys at two asteroids, scientists want to take as many images as possible of the illuminated areas, as well as numerous high-resolution images when Rosetta is at its closest to the surfaces.

A number of constraints have to be considered here. Due to the rotation required to follow the asteroid, the spacecraft has times where it is not stable enough to take images. Between images, it may be necessary to turn the filter wheel very rapidly. Furthermore, the precise flyby time is uncertain until a few hours beforehand and the number of images has to be restricted because of the limited memory onboard the spacecraft.

Simultaneous imaging of very luminous and very dim objects is a particular headache close to the comet. One of Rosetta's main objectives is to image the faint dust jets emanating from the nucleus whilst the brightly illuminated nucleus is also in the field of view. Such requirements were a major design driver for OSIRIS and could only be achieved by a combination of extremely flat mirror optics, complex high-resolution readout electronics and considerable work by the developers to remove any 'noise' from the system.

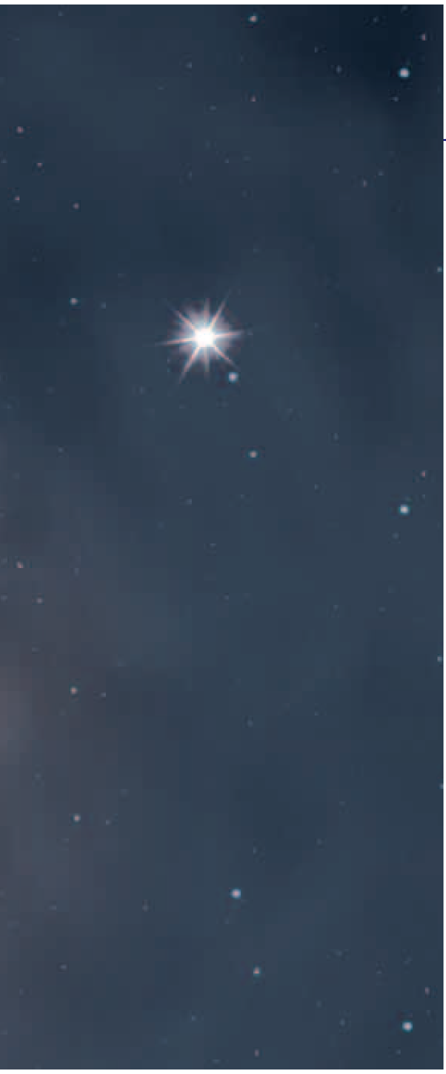
Landing on a Dirty Snowball

Landings on other worlds are remarkably difficult to achieve. During the last 40 years, the only objects in the Solar System on which robotic spacecraft have soft-landed have been the Moon, Venus, Mars and the near-Earth asteroid Eros. A decade from now, it will be the turn of Rosetta to make history with the first touch down on a comet.

By the summer of 2012, instruments on the Rosetta Orbiter will have mapped every square centimetre of the Comet Wirtanen's surface, enabling scientists to select a suitable landing site. The Orbiter's position and speed must by that stage have been precisely determined to within 10 cm and 1 mm/s, respectively, to ensure that Lander ejection takes place at the correct time for arrival at the selected site.

Following instructions uploaded from mission control, the 100 kg Lander will be released from the Rosetta Orbiter about one kilometre above the comet's nucleus. After a gentle push away from the 'mother ship', the box-shaped craft will deploy its landing gear and edge towards its target, prevented from tumbling by an internal flywheel that provides stability as its spins. A single cold-gas thruster will be able to provide a gradual upward push to improve the accuracy of the descent.

After a nail-biting 30 minute descent, sensors onboard the Lander will record the historic moment of touchdown for the helpless mission team back on Earth. Since the nucleus is so small, its gravitational pull will be extremely weak – 100 000 to 200 000 times lower than on the Earth's



surface – causing the Lander to touch down at no more than walking pace. Nevertheless, a damping system in the landing gear will be available to reduce the shock of impact and prevent a rebound.

The Lander also carries two harpoons. One of these will be fired at the moment of touchdown to anchor the spacecraft to the surface and prevent it from bouncing. Ice screws on each leg will also be rotated to bite into the nucleus and secure the Lander in place. The second harpoon will be held in reserve for use later in the mission if the first one becomes loose.

"Hopefully, gradient will not be a problem, since the spacecraft is designed to stay upright on a slope of up to about 30 degrees," says Philippe Kletzkine, Rosetta Lander Manager.

The operational lifetime of the Lander is highly uncertain. Its survival will depend on a number of factors such as power supply, temperature or surface activity on the comet. In order to ensure a significant science return, the most important images and measurements will be obtained within 60 hours of arrival. The remaining, more detailed investigations will be conducted as long as the Lander continues to function, relying on the remaining battery power and energy from the solar cells on the exterior of the Lander.

No one knows what this first soft landing on a cosmic iceberg will reveal. What we can be sure of is that the Orbiter and its little Lander will revolutionise our knowledge of comets, providing new insights into the nature and origins of these primordial objects.

The Rosetta Lander on Comet Wirtanen's surface (artist's impression)