Rendezvous **with a Primordial Rock**

Although the comparison with the manned moon landing may appear somewhat exaggerated, *Rosetta* is undoubtedly one of space travel's most daring enterprises: For the first time in history, a probe is accompanying a comet on its orbit around the Sun – and in mid-November, it set down the *Philae* lander on its surface. Scientists from the **Max Planck Institute for Solar System Research** in Göttingen have front row seats for the evaluation of the images and data from the comet named 67P/Churyumov-Gerasimenko.

TEXT **HELMUT HORNUNG**

This is the very heart of the comet! 67P/Churyumov-Gerasimenko as seen by the onboard camera of the *Rosetta* probe on August 3, 2014.

Photo: ESA/Rosetta/MPC for OSIRIS Team MPG/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA

MARCH 2, 2004, 8:17 A.M. CET

Darkness still shrouds the Kourou spaceport in French Guiana as an *Ariane 5G+* rocket shoots up into the cloudy sky, leaving a fiery trail in its wake. On board is a freight that is intended to shed more light on the origins of the solar system: *Rosetta*. The probe itself is slightly larger than a Smart car. Its two long wings with solar panels for the energy supply give it the appearance of a strange insect. Aboard *Rosetta*, in addition to the SREM detector for detecting high-energy particle radiation, are eleven instruments and a box as large as a refrigerator: *Philae*. It is to perform the trick of landing on the nucleus of a comet and conduct measurements there over several months with the aid of ten scientific devices.

Rosetta's history goes back to 1984. At that time, the European Space Agency ESA decided to undertake a mission to the nucleus of a comet, initially in partnership with NASA. After budget cuts forced the Americans to withdraw, the Europeans continued the plan alone. In Germany, the German Aerospace Center and the Max Planck Institute for Aeronomics (since 2004: Solar System Research) were initially the major players in the project, with the latter making a significant contribution to the development and construction of the lander, among other things.

On January 13, 2003, *Rosetta* and *Philae* were due to lift off to the Wirtanen comet. But a rocket from the *Ariane 5* series, like the one that was to transport the ambitious mission, had performed a spectacularly unsuccessful lift-off a few weeks prior. The European space program was halted temporarily, and the start of the comet scout postponed by more than a year. Moreover, a new destination had to be found. The choice was ultimately 67P/Churyumov-Gerasimenko. Two scientists, Churyumov and Gerasimenko, at the Institute for Astrophysics in Alma-Ata/Kazakhstan had discovered the celestial body as a tiny star on a photographic plate in the fall of 1969.

In the past, the gravitational field of the planet Jupiter had influenced the trajectory of "Chury." Before 1840, it orbited the Sun at a considerable distance, and the lack of heat meant it had not been able to develop any cometary activity up to this point. In other words, the nucleus should still be relatively fresh and pristine – which researchers see as a benefit. In its present orbit, the comet approaches the Sun to within a distance of around 193 million kilometers (Earth's distance to the Sun: 150 million kilometers) every 6 years and 203 days.

SEPTEMBER 7, 2008, 10:14 P.M. CEST

Signals from the depths of space appear on the screens at ESA's European Space Operations Center (ESOC) in Darmstadt. The flight engineers immediately forward them to the Max Planck Institute for Solar System Research. Although it is the middle of the night, 14 scientists here filter the first images from the raw data. These show a rock with an elongated shape that tapers to a point at one end; countless craters cover its surface, with a particularly large crater measuring two kilometers in diameter located at the North Pole. The subject is around 360 million kilometers from Earth – and shows the Šteins asteroid. *Rosetta* passed by it on September 5, 2008 at a distance of 800 kilometers.

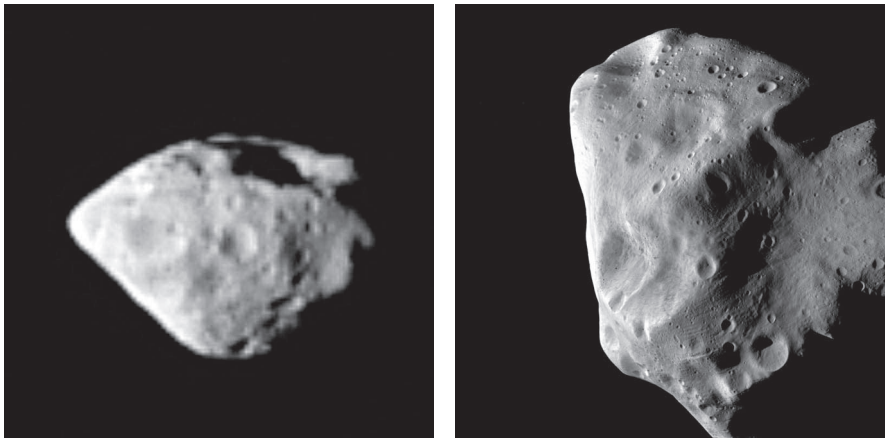
Although the OSIRIS telecamera switches into safety mode nine minutes before the rendezvous and only the wide-angle camera is working, the researchers are satisfied with their instruments. OSIRIS is the abbreviation for Optical, Spectroscopic and Infrared Remote Imaging System. Two cameras constructed as mirror systems take images in the ultraviolet, visible and infrared spectral ranges. The light-sensitive CCD detectors comprise 2048 by 2048 pixels, with each of these pixels measuring 13.5 micrometers (one-thousandth of a millimeter).

Before its rendezvous with Šteins, *Rosetta* had flown past Earth on March 4, 2005 at a distance of just 1,955 kilometers. At that time, it was even possible to see the probe with binoculars. On February 25, 2007, *Rosetta* passed Mars; on November 13 of the same year, it again gained momentum with the aid of our planet. After the rendezvous with Šteins, it executed another Earth fly-by on November 13, 2009.

Why is this extremely complicated trajectory necessary? A direct flight from Earth to Churyumov-Gerasimenko would have required enormous quantities of fuel. During the so-called swing-by maneuvers on tortuous paths, *Rosetta* gained the energy it needed from the gravitational fields of the planets free of charge, as it were. During each of the three Earth swing-bys, the speed of the vehicle increased by around 20,000 kilometers per hour.

JULY 10, 2010, 6:00 P.M. CEST

The pace is infernal: *Rosetta* is travelling at no less than 54,000 kilometers per hour as it points its camera eyes at the asteroid Lutetia. This cosmic potato – its longitudinal dimension of around 126 kilometers making it significantly larger than Šteins – has a varied landscape with mountains, large numbers of large and small craters, scattered boulders and parallel grooves. The surface of the celestial object seems to be covered by a thick layer of fine-grained, loose material (regolith). >



Ragged space potato: *Rosetta* photographed the two asteroids Šteins (left) and Lutetia during the fly-bys in September 2008 and July 2010. Despite the fleeting encounters, it succeeded in obtaining extremely detailed views, particularly of Lutetia. Craters, mountains and scattered rocks can be seen on its surface.

With 3.5 grams per cubic centimeter, Lutetia has an unusually high density. From the spectra, specialists conclude that it has a composition comparable to those of meteorites belonging to the carbonaceous chondrites, which have a high carbon content. However, there are also similarities with the so-called enstatite chondrites, which contain the mineral enstatite.

Rosetta can't solve the mystery of which family Lutetia belongs to, but the scientists are certain of one thing: "This is a completely new world that no one has ever seen before," says Holger Sierks from the Max Planck Institute for Solar System Research, head of the OSIRIS team. The instrument provides images with a resolution of 60 meters per pixel. Some images even provide indications of a landslide within a crater. All in all, it's a successful dress rehearsal for the meeting with Churyumov-Gerasimenko.

JUNE 8, 2011

After the engineers and technicians had installed upgraded software for the central computer in December 2010, they switched it off. Some months later, and slightly earlier than planned, on June 8, 2011, they then put the complete spacecraft into hibernation. *Rosetta* now slowly rotates about its own axis for stabilization.

In October 2012, the probe reaches the point of its trajectory furthest from the Sun; around 795 million kilometers separate it from the warming rays. At this enormous distance, even the 64 square meters of the solar sail generate only small amounts of power. Nevertheless, it is sufficient to keep the vehicle reasonably warm and a clock on board ticking.

JANUARY 20, 2014, 10:59 A.M. CET

An alarm clock rings in space. Its job is to bring *Rosetta* out of hibernation after 957 days. The probe is whizzing around in the depths of space, nearly 815 million kilometers from Earth. It's the beginning of anxious hours of waiting for the technicians, engineers and scientists in the European Space Operations Centre (ESOC) in Darmstadt.

Will *Rosetta* really wake up? If yes, the plan is as follows: The star sensors will slowly heat up to operating temperature, open their eyes and determine *Rosetta's* position from the sky. The steady rotation of the probe about its axis will gradually come to a halt, and the parabolic dish measuring 2.2 meters in diameter will align itself toward Earth and send the first sign of life.

JANUARY 20, 2014, 7:18 P.M. CET

Owing to the huge distance, it takes a bit more than 45 minutes until the signal from *Rosetta* reaches Earth, is received by a dish in Goldstone, Califor-

THE ROSETTA STONE AND THE ISLAND IN THE NILE

In 1822, Egyptologist Jean-François Champollion (1790 to 1832) succeeded in deciphering hieroglyphics. He did this by analyzing the *Rosetta* Stone, which bears the same text in three languages: hieroglyphics, demotic and Ancient Greek. Taking its inspiration from this stone, the *Rosetta* mission aims to help solve the mystery of comets and the early evolution of the solar system.

Before the start, ESA announced a competition to find a name for the lander. *Philae* came out on top – named after an island in the Nile on which a temple complex once stood. One of the remaining obelisks bears an inscription in Greek and Egyptian, and was used to help decipher hieroglyphics.

Photos: ESA/Rosetta/MPG for OSIRIS Team MPG/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA

Comet experts gather: Martin Hilchenbach, Holger Sierks, Paul Hartogh and Hermann Böhnhardt (from left) discuss the latest images of the *Rosetta* space probe in the Max Planck Institute for Solar System Research.

nia, and appears as a small line in an irregularly jagged green curve on the monitor in Darmstadt. Still, some scientists had expected that this would take place around 6:30 p.m. on January 20, 2014. It is now already after 7:00 p.m. and *Rosetta* has been overdue for three-quarters of an hour.

The nervousness is increasing at ESOC. Everyone present is looking up toward a monitor, as if spellbound. The clock in the control room shows 7:18 p.m. when a line finally appears on the screen – first short, then slowly becoming longer. Two technicians at the consoles are the first to throw up their arms. The cheering starts. People hug each other. A glass breaks somewhere. *Rosetta* is awake! It's now setting off on the final stage of a more than ten-year journey.

MARCH 21, 2014

The picture looks as if it was taken by a well-equipped amateur astronomer. The magnificent globular cluster known as Messier 107 in the Serpent Bearer constellation shimmers slightly left of center. Diagonally above M 107 there appears a weak spot of light, which a layperson could easily overlook. But for Holger Sierks, it's something very special: "To finally have our destination in sight after a ten-year trip through space is an indescribable feeling," says the Max Planck researcher. The unassuming little star is none other than 67P/Churyumov-Gerasimenko, as seen through OSIRIS' eyes.

The camera system on board *Rosetta* must operate to its performance limits. After all, more than five million kilometers separate the space probe and the comet from one another. This explains why the comet on the photos covers only a fraction of a pixel. What's more, the celestial body glimmers like a very dim light; a series of exposures from 60 to 300 seconds and additional image processing are required to make it visible at all.

While *Rosetta* and its instruments are slowly awakening, Churyumov-Gerasimenko is still in a kind of slumber. This is typical behavior for a comet. As with all members of the Jupiter family, it spends most of its life in the icy depths of the planetary system at a similar distance from the Sun as the gas giant Jupiter. This is where countless bodies measuring several kilometers in size whiz about as dead lumps of rock and frozen gases, such as carbon dioxide and ice.

In all probability, "Chury" and its peers have their origins in the Kuiper Belt. This ring-like region at the very edge of our planetary system beyond Neptune's orbit is more than 30 times as far from the Sun as the Earth is, and is populated with thousands of cosmic rocks. Under the influence of Neptune, the orbits of individual bodies gradually shift toward the other gas giants in the planetary system – right down to Jupiter.

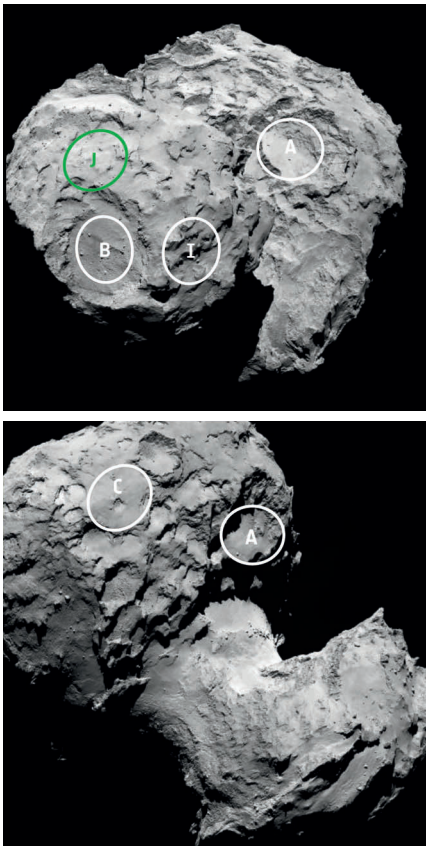
"Despite this migration – and the collisions that may have preceded it – comets in the Jupiter family are some of the purest material that has been preserved from the birth of the solar system more than 4.6 billion years ago," says Ulrich Christensen, Director at the Max Planck Institute for Solar System Research. While particularly the inner planets, such as Mercury and Venus, have undergone great changes as a result of the heat and the particle bombardment from the Sun and have lost volatile components, this material has been stored in an unaltered state in the ice of the comets for billions of years.

When the cosmic vagabond moves nearer to the Sun on its orbit, its surface begins to warm up, and water and frozen gases evaporate and entrain tiny dust particles. The comet becomes active: an atmosphere (coma) forms around its nucleus, and it finally develops the characteristic tail. >

Photo: Ronald Schmidt

This material is what *Rosetta* will investigate in greater detail than ever before. "The space probe is a kind of laboratory that is operated on-site at the comet," says Max Planck researcher Martin Hilchenbach, head of the COSIMA team. COSIMA is one of the instruments that are intended to specifically coax some of the secrets out of the cometary dust. In the microscopic, cauliflower-shaped pores of carriers measuring just a few millimeters in size, the dust catcher collects individual particles that are first localized under a microscope before being bombarded with indium ions. Ions are then released from the surface of the dust particles in this process and can be analyzed further. "We can identify not only individual elements, but also, above all, organic molecules," says Hilchenbach.

Five at one go: The circled regions were selected as landing sites and designated A, B, C, I and J. J – located on the "head" of the comet's nucleus – ultimately won.



APRIL 30, 2014

"Chury" really is a comet! At least the images taken by OSIRIS show a real coma. It stretches around 1,300 kilometers into space and envelops the nucleus with gas and dust. The researchers are astonished by this cloud, because the comet is still more than 600 million kilometers from the Sun. However, the splendor doesn't last very long: photos from the beginning of June show 67P as a tiny star again with no activity whatsoever. The comet apparently woke up too early and immediately nodded off again.

OSIRIS further reveals that the nucleus, which measures five by three kilometers, rotates about its axis once every 12.4 hours – 20 minutes shorter than determined previously from Earth. If this isn't due to a measurement error, something must have reduced the rotational time. This proves once again that comets are always good for a surprise.

JUNE 6, 2014

The comet is sweating. It's releasing a large glass of water every second, or more precisely, around 300 grams of water vapor. This was determined by an instrument called MIRO. The small radio telescope receives signals from a respectable 350,000 kilometers; this is now the separation between *Rosetta* and 67P.

MIRO analyzes the microwave radiation that originates from the gas molecules. Water and other substances leave characteristic fingerprints on the light in this wavelength range. "The signals that water molecules leave in our measurement data can be detected particularly well," says Paul Hartogh from the Max Planck Institute for Solar System Research, who supervised the development and construction of a subsystem of MIRO. The researcher is pleased with its sensitivity: it's as if one were to discover the evaporation of a cup of hot tea on the moon from Earth.

JULY 14, 2014

A rubber duck is orbiting in space! At least this is what the images that show Churyumov-Gerasimenko from a distance of less than 12,000 kilometers suggest; on Earth, this would correspond roughly to the distance between Germany and Hawaii. The images from the middle of July prove that the nucleus of the comet consists of two clearly separated parts: a larger "body" on which a smaller "head" sits.

JULY 21, 2014

The rubber duck has a collar. *Rosetta* is now just 5,500 kilometers away and providing images with a resolution of 100 meters per pixel. The images clearly show that the "neck region" located between the "head" and the "body" appears much brighter. This is where an abyss some 1,000 meters deep opens up, and where the camera discovers so-called jets – fountains of dust. The brightness of the band could be caused by differences in material, different grain sizes or topographic effects. It is still unclear how 67P got its duck-like shape. A few researchers speculate as to whether the "head" and "body" were originally two separate objects.

Photos: ESA/Rosetta/MPG for OSIRIS Team MPG/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA

Zoom into "Chury": Holger Sierks, head of the OSIRIS camera system, points to a section of the nucleus; researchers christened the rock to the right of Sierks' index finger Cheops.

Photo: Roland Keller/www.rkech.blogspot.com

JULY 25, 2014

The coma has appeared again. The images show an extensive cloud of dust around the nucleus. The diffuse cloud completely fills the camera's field of view, an area measuring 150 by 150 kilometers. It appears to be only the inner region of the coma, in which the particle density is highest. The total structure should be significantly larger, but it can't be imaged by *Rosetta* from a distance of a mere 2,500 kilometers. And so it seems that Churyumov-Gerasimenko – after a brief phase of activity in April – is finally fully awake.

AUGUST 6, 2014, 11:30 A.M. CEST

Arrived at last! *Rosetta* has travelled 6.4 billion kilometers. "After flying on the approach for nearly a decade, it seems almost unreal to have actually arrived," says Max Planck researcher Holger Sierks. Just before he made this statement, the European Control Centre in Darmstadt had received the redemptive signal. *Rosetta* had swiveled into pyramidal orbits around 67P, following a "triangular" orbit about the nucleus. The space probe initially approached the comet to within 100 kilometers; since the beginning of September, it has been 50 kilometers and less.

Even shortly before the thrust maneuver on August 6, the spatial resolution of the images was 5.5 meters per pixel, surpassing all previous images of cometary nuclei. In addition to stark differences in brightness on the surface, sharp-angled cliffs, mountains and deep escarpments now appear. Expanses of smooth surfaces and round hills can also be seen.

It is a landscape of strange beauty, partially formed by the comet's activity. During earlier approaches to the Sun, volatile substances from its surface vaporized and entrained jets of dust. If these dust particles are too heavy or too slow to leave the gravitational field of the comet, they fall back to the surface, where they accumulate in places and create different geological formations.

AUGUST 25, 2014

As level as possible, not too much shade, not too much sunlight – and scientifically interesting: these are the conditions that the region on the nucleus of 67P/Churyumov-Gerasimenko where *Philae* will land must fulfill. Today, researchers and engineers announce five possible candidates: three of the potential landing sites are on the "head," and the other two on the larger "body" of the comet. They are designated A, B, C, I and J.

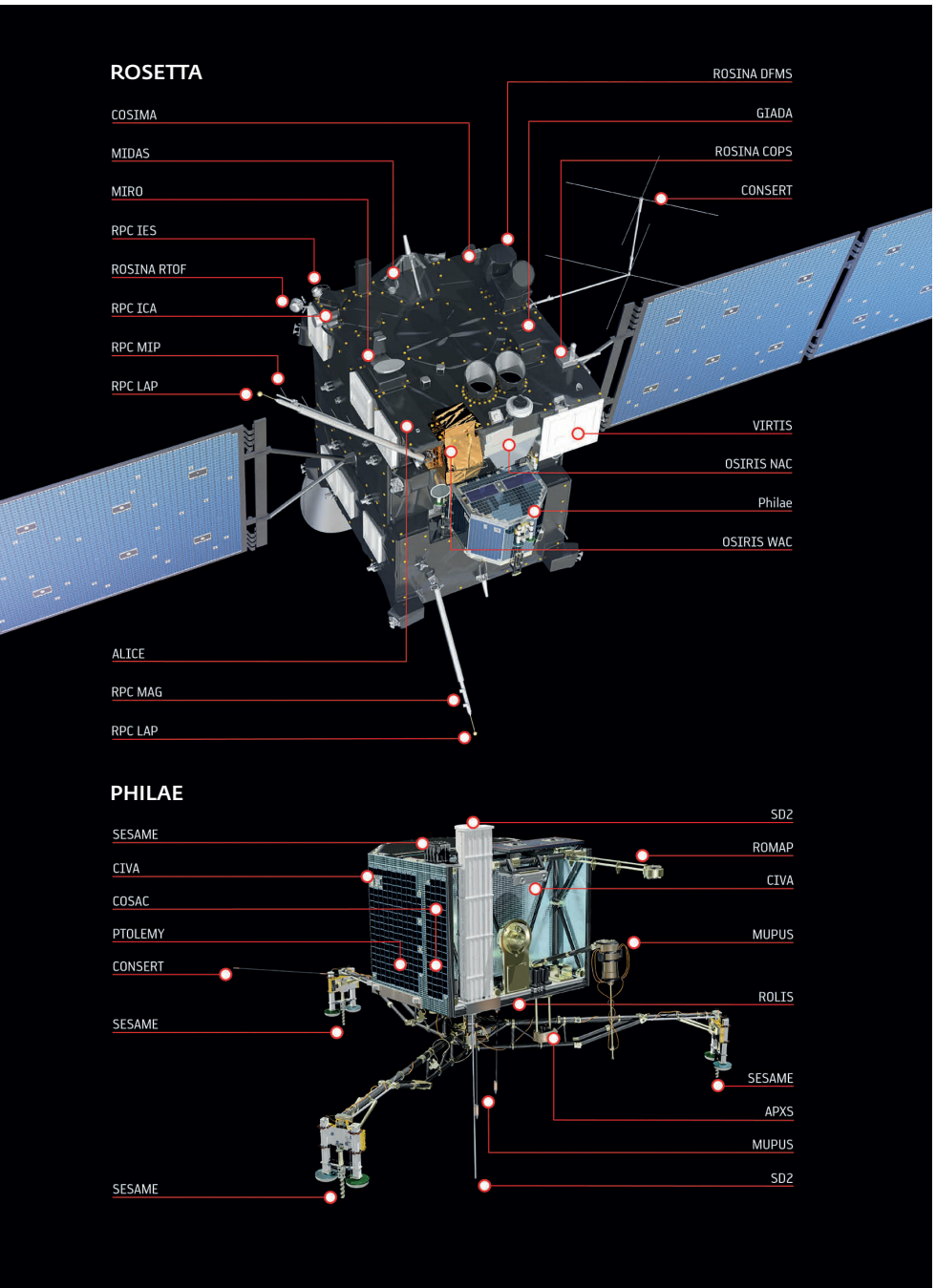
"The most important criterion, of course, was that *Philae* is able to reach the areas in the first place," says Hermann Böhnhardt from the Max Planck Institute for Solar System Research, Lead Scientist of the lander mission. This does not apply to all regions. Even if one takes into account all the conceivable velocities, trajectories and orientations of the space probe at the moment *Philae* undocks, as well as the different possible detaching speeds of the lander itself, the map of the comet still has no-go areas.

Equally important is that, from the landing site, there must be regular radio contact with the space probe in order to exchange operational commands and data. A surface that is as level as possible should ensure a safe landing. Moreover, six hours of sunlight are necessary every day for at least six months to charge *Philae*'s solar batteries. However, the Sun must

THE ONBOARD INSTRUMENTS...

...of *Rosetta*		...of *Philae*	
OSIRIS*	camera system with telecamera and wide-angle camera	SD2	drills and sampler
ALICE	UV spectrometer	COSAC*	gas chromatograph, mass spectrometer
VIRTIS	spectrometer for the visible and infrared range	Ptolemy	gas chromatograph, mass spectrometer
MIRO*	microwave spectrometer	APXS**	alpha X-ray spectrometer
RSI	radiowave experiment	ROLIS	camera system
CONSERT*	radar tomograph	CIVA	camera system, infrared spectrometer, microscope
ROSINA*	neutral gas and ion mass spectrometer	MUPUS	penetrator, thermal probe, radiometer
COSIMA*	dust mass spectrometer	SESAME*	acoustic seismometer, dust monitor
MIDAS	dust microscope	CONSERT*	radio wave experiment
GIADA	dust analyzer	ROMAP***	magnetometer, plasma monitor
RPC	plasma analyzer		

* Participation of the Max Planck Institute for Solar System Research
** Participation of the Max Planck Institute for Chemistry
*** Participation of the Max Planck Institutes for Solar System Research and for Extraterrestrial Physics



not shine for too long, either, otherwise the lander could overheat.

SEPTEMBER 10, 2014

Mapping a comet. The images transmitted by OSIRIS achieve a resolution of 75 centimeters per pixel. With areas characterized by steep cliffs, depressions, craters, scattered boulders and parallel grooves, 67P exhibits many different landscapes. Some of these regions appear quiet; others were apparently formed by the activity of the comet.

The scientists combine the various expansive landscapes into a map – and puzzle over it: "So far, nobody really understands how the morphological differences that we see have formed," says Max Planck researcher Holger Sierks.

SEPTEMBER 16, 2014

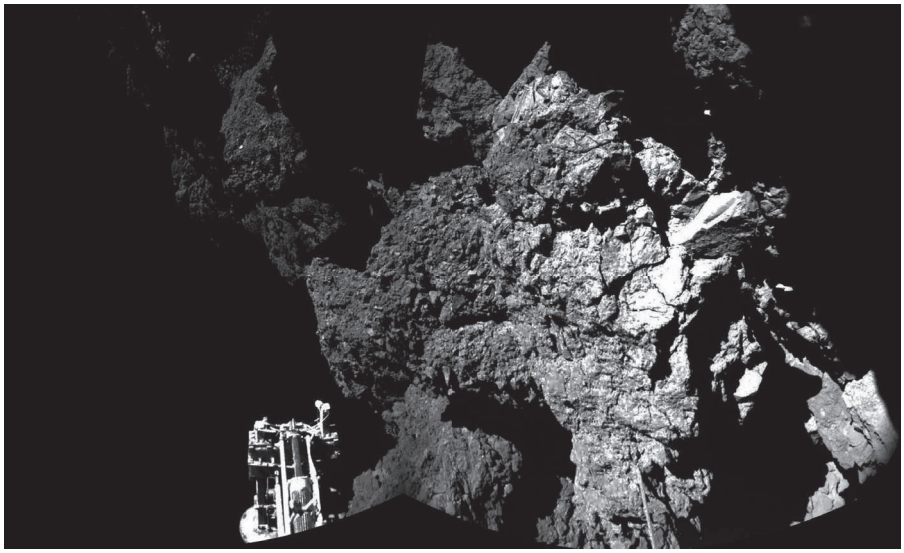
J wins. Although the images show a very rugged terrain there, almost in the center of the "head" of the comet, computations show that the chances for a landing are good. The researchers and technicians take into account the topography of the area and the mechanical characteristics of *Philae*'s landing gear. The spot on which *Philae* touches down can be determined to within only 500 meters or so.

"This means we need, not one perfect spot, but a complete region where as many landing scenarios as possible have a happy end," says Hermann Böhnhardt. This area is dotted with relatively few large rocks that could present a danger to *Philae*, for example. In

Graphics: ESA/ATG medialab

addition, measurements indicate that organic material is present here. Finally, CONSERT should find very acceptable conditions for its radio observations at the landing site selected.

CONSERT is the only experiment of the *Rosetta* mission that is part of both the orbiter and the lander. It is to use radio waves to investigate the inner structure of the comet's nucleus. A radio signal will be transmitted from the space probe through the nucleus to the lander and back. The shape of the nucleus and the flight path of the orbiter mean that not every spot on the surface of 67P is equally suited to penetrate the whole of the comet's nucleus. Landing site J is one of the best sites for this task. On October 14, 2014, J is confirmed. It is named "Agilkia." One of the greatest adventures of space travel can begin.



On firm ground: This image of the surface of comet 67P/Churyumov-Gerasimenko was snapped by the CIVA camera on board the *Philae* lander. At the front left, one of the three landing legs can be seen.

NOVEMBER 12, 2014, 9:35 A.M. CET

Already on November 8, the ground crew had sent *Philae* the computer sequence that controls the landing via its orbiter. On the morning of November 12, the *Rosetta* mother ship is still hovering more than 22 kilometers above the surface of the comet. After the control center gives the final "Go!" three preloaded springs maneuver *Philae* away and push it off into space at 9:35 a.m. The refrigerator-sized box drifts away from *Rosetta*. Around two hours after separation, data transmission starts. The lander sends signals to the orbiter, which transmits them to Earth at the speed of light. Since the comet is flying through space at a distance of more than 500 million kilometers from our planet, these signals take 28 minutes and 20 seconds to arrive.

Around two hours after separation, the OSIRIS camera aboard *Rosetta* turns its gaze toward the landing probe as it retreats. "*Philae* is making good progress," says Hermann Böhnhardt. The current image proves that the landing gear has unfolded as it was intended to.

NOVEMBER 12, 2014, 4:34 P.M. CET

Touchdown, *Philae* has landed! The probe touches down at a speed of approximately one kilometer per hour. A cold gas thruster should now push the lander gently onto the comet's surface, harpoons should be launched, and the screw-like tips of the three landing legs should also bore into the surface. But the cold gas thruster and the harpoons fail to work! *Philae* bounces off and floats for approximately 110 minutes around one kilometer further away. The probe then touches down again, lifts off slightly and, after a second little "hop," finally lands for a third time.

NOVEMBER 15, 1:36 A.M. CET

The exact landing site is initially unknown. It's possible that *Philae* touches the ground with only two of its three legs. The first images show rocky material and a cliff. Sunlight reaches the landing site for only one and a half hours a day, so the solar-powered batteries aren't taking in enough energy. Thanks to the primary battery, however, the board instruments start to record data and conduct measurements as planned.

This "critical phase" of the scientific work ends after just under 60 hours. On November 15, 1:36 a.m., *Philae* falls into an automatic sleep mode; contact with it is interrupted. Whether the lander will make contact again remains uncertain. One thing, however, is certain: the mission has been successful. *Rosetta* will revolutionize our knowledge of comets! ◀

TO THE POINT

- ***Rosetta*** **has been travelling through space for more than a decade already. In August 2014, the probe reached its destination, the comet 67P/Churyumov-Gerasimenko.**
- ***Rosetta*** **is the first mission in the history of space travel planned to accompany a comet on its orbit around the Sun for several months, and put down the *Philae* lander on its nucleus in mid-November 2014.**
- **Churyumov-Gerasimenko has an elongated, two-part shape. It reminds some researchers of a rubber duck, with the "body" and "head" connected by a bright "collar." The nucleus measures approximately five by three kilometers.**
- **With steep cliffs, depressions, craters, scattered boulders and parallel grooves, 67P exhibits many different relief features.**

Photo: ESA/Rosetta/Philae/CIVA