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Comets are Nice to Touch *

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Abstract

Rosetta is the third cornerstone mission of the European Space Agency scientific program "Horizon 2000"and it is the first spacecraft to orbit around a comet nucleus and to send a lander on its surface with the aim of studying the real nature of these objects. It was launched in March 2004 and reached the comet 67P/Churymov-Gerasimenko in 2014. Its lander Philae was released on 12 November 2014 and landed on the comet surface to start the in-situ investigation. Philae then acted as an independent spacecraft, as it is provided with all subsystems needed to survive and work alone on the comet. This paper describes Rosetta mission and summarizes its first scientific results based on both observations from the orbiter and in-situ measurements from the lander.

1. Introduction

Much has been explained about comets to date, but much is still waiting for possible answers and confirmed truths. Current knowledge suggests that comets are the primitive leftovers of the solar system formation process. If so, they would be "bricks"of the solar system which have never been used to build planets or minor bodies. They carry records of the solar system in a very early phase and are thus a key to our understanding of its origin and development. Moreover, they contain information on the compositional mixture from which the planets formed about 4.6 billion years ago and are also known to harbour complex organic molecules, to the great interest of those who study the origins of life on Earth.

Unfortunately, the real nature of comets remains unknown. The discoveries of Fred Whipple and Jan Oort in the fifties highlighted the importance of telescopic observations from the ground. However, their limits and the recent achievements of space engineering pave the way to the only effective solution for unveiling this ancient secret: comets must be visited as close up as possible. Over the last three decades, several spacecraft have pursued this amazing task. The first probe to visit a comet was the ISEE-3/ICE probe [20]. More in detail, after completing its initial mission in 1982, the International Sun-Earth Explorer 3 (ISEE-3) was renamed the International Cometary Explorer (ICE) and sent to comet Giacobini-Zinner, coming within 7800 kilometers of its nucleus in 1985. The mission proved the "dirt-snowball"theory, that comets are composed of mixed rock and ice.

After ICE, a flotilla of spacecraft was sent to rendezvous with comet Halley in 1986: the so-called "Halley Armada". The Halley Armada consisted of two Russian spacecraft (Vega 1 and 2), two Japanese spacecraft (Sagigake and Suisei), and the European Space Agency's Giotto. The European Giotto would come closest of all (within 600km) to the comet, so close that the probe began to be hit by thousands of dust particles. The spacecraft survived, but its camera was destroyed just after sending more than 2000 images, showing Halley's rough and porous nucleus, and three outgassing jets on the sunlit side (Fig. 1). Of the volume of material ejected by Halley, 80% was water, with carbon monoxide, methane and ammonia found in the remaining fraction. This was not the end of Giotto's mission: the tireless probe continued its journey in the solar system, taking a close look at comet Grigg-Skjellerup in 1992 from about 200 km.

A more ambitious challenge was undertaken by space scientists in 1999 with the comet sample return mission known as Stardust [8]. In January 2004 the spacecraft had a close encounter with comet Wild 2, collecting samples of comet dust in a return capsule. The capsule returned to Earth in 2006, after a roundtrip of about 4.5 billion kilometers, together with its precious load of comet samples and interstellar dust, which is currently under analysis at NASA's Johnson Space Center.

However, no artificial objects had yet touched a comet before NASA's Deep Impact probe [6]. The purpose of this mission was to send a projectile to the comet Tempel 1, creating an impact crater so the

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Figure 1. Halley's comet as seen by the spacecraft Giotto in 1986 (Credits: ESA)

main craft could carry out spectroscopy of the internal structures. This result was actually achieved on 4 July 2005, producing a spectacular flash of light and a crater of undetermined depth (Fig. 2). The analysis performed on the ejection plume confirms the abundance of organic material, which bears out the theory that the Earth might have been infused with organics from similar comets.

Figure 2. The flash of light produced on comet Tempel 1 after collision with Deep Impact in 2005 (credits: NASA)

A more spectacular approach to comet exploration is under completion, thanks to the European Space Agency's probe Rosetta [4]. As one of ESA's cornerstone missions, Rosetta will enhance our understanding of the formation and evolution of the solar system as well as the origin of life by investigating the 4 km-wide comet 67P/Churyumov-Gerasimenko. Unlike past missions, Rosetta is the first probe to carry out a close study of the nucleus, orbiting a spacecraft around the target comet. Even more challenging was its further goal of attempting the first ever landing on a comet surface, enabling the first ever in-situ analysis of cometary soil.

2. Rosetta: the Orbiter

The main goals of Rosetta are measuring the global characteristics of the nucleus of the comet 67P/Churyumov-Gerasimenko, determining the composition of its volatiles, and studying the development of cometary activity and the processes in the surface layer of the nucleus and the inner coma. This set of information, with the aid of theoretical models, will be used to better understand the relationship between the comet's outer layers and the underlying material, and find out to what extent the analyzed material could resemble characteristics of the early solar nebula.

Rosetta was launched from the European spaceport of Kourou, French Guyana, in 2004, starting its ten-year journey to comet 67P/Churyumov-Gerasimenko (Fig. 3). Along its complex trek to the target comet, Rosetta bounced around the solar system, circling the Sun almost four times and passing very close to Earth and Mars to gain velocity from gravity assist maneuvers. During its journey, Rosetta reached a maximum distance from the Sun of about 785 million kilometers. This is a never achieved distance for a space probe powered by solar panels like Rosetta. The main consequences are the enormous solar panel "wings", with a total span of about 32 m tip to tip (Fig. 4). The solar panels allow Rosetta to survive over 800 million kilometers from the Sun, where solar radiation is only 4% of that on Earth. Thousands of specially developed non-reflective silicon cells generate up to 8700 W in the inner Solar System and around 400 W during the deep-space hibernation phase (395 W at 5.25 AU [14]).

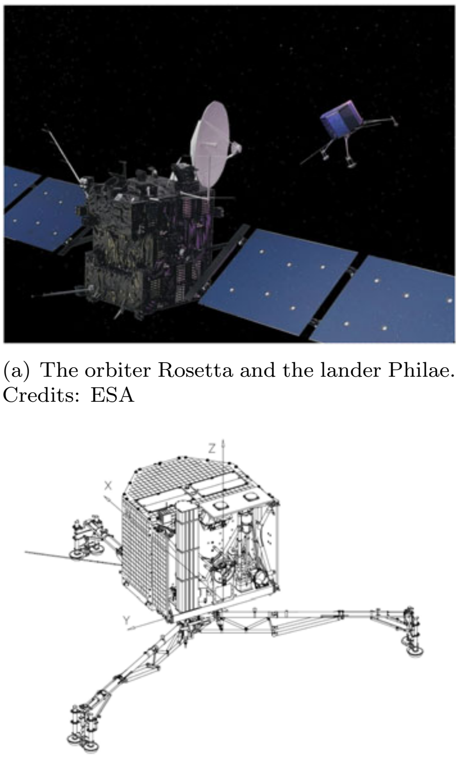
In addition to the four gravity assist maneuvers, two flybys of asteroid Šteins, September 2008, and Lutetia, July 2010, were performed to obtain additional scientific information on the composition of these minor bodies.

The Rosetta probe is composed of two spacecraft: an orbiter, Rosetta, with eleven observing instruments on-board, which keeps orbiting the comet after rendezvous, and a lander, Philae (Fig. 5). The orbiter is a 2.8 m x 2.1 m x 2.0 m aluminum box. A 2.2 m diameter, steerable, high-gain antenna enables communications between the orbiter and Earth. Two 14 m long solar panels, each about 30 m^2, may be rotated through ±180 degrees to catch the maximum amount of sunlight. The propulsion subsystem provides trajectory and attitude control using 24 bi-propellant 10 N thrusters (see Table 1 for additional technical data).

Figure 3. Rosetta's spacecraft lifting off from Kourou in 2004 (credits: ESA)

Figure 4. Rosetta solar panels during a deployment test (credits: ESA/CNES)

Right after arrival at the target comet in May 2014, Rosetta started investigating the comet nucleus and the gas and dust ejected from it, by combining remote sensing techniques, such as cameras and radio science measurements, with direct sensing systems such as dust and particle analyzers.



(a) The orbiter Rosetta and the lander Philae. Credits: ESA

(b) The Rosetta lander Philae

Figure 5. The Rosetta spacecraft

Table 1
Rosetta mission: technical data

Total launch mass (approx.):	3000 kg
Propellant mass (approx.):	1670 kg
Science payload mass:	165 kg
Philae mass:	100 kg
Area of Rosetta solar arrays:	61.5 m^2
Solar array generated output:	395–850 W
Operational mission duration:	12 years

3. Philae: the Lander

In November 2014, Philae was commanded to self-eject from Rosetta and unfold its three legs, ready for a soft touchdown at the end of a ballistic descent (Fig.

5). The lander Philae was attached to one side of the orbiter and has a mass of 97.9 kg including 26.7 kg for scientific payload. A truss assured the link with Rosetta during launch and cruise, while an RF-link is used after ejection from the orbiter. The structure of Philae is made of carbon fiber with aluminum honeycomb. It consists of a ground plate, an experiment platform and a polygonal sandwich construction. Once landed, Philae was designed to act as an independent spacecraft, as it is provided with all subsystems needed to survive and work alone on the comet. The orbiter is used only as a communication relay with the Earth.

3.1. Philae's Scientific Instruments and their Operation

The lander Philae is provided with ten scientific instruments to achieve its scientific goals, which include the determination of the elementary and mineralogical composition of the comet; the identification of traces elements and isotopic composition of cometary material from the surface and subsurface; the determination of comet's surface strength, density, texture, porosity, ice phases and thermal properties together with soil structure.

The ten scientific instruments include: an α-particle and X-ray spectrometer (APXS, [16]), a visible camera and near-infrared spectrometer (ÇIVA, [5]), a radio sounding experiment (CONSERT, [3]), a molecule mass spectrometer and gas chromatograph (COSAC, [19]), an accelerometer and thermal probe (MUPUS, [23]), a light elements and isotope mass spectrometer and gas chromatograph (PTOLEMY, [27]), a downlooking camera (ROLIS, [18]), a magnetometer and plasma package (ROMAP, [2]), a drilling system (SD2, [13]), and an acoustic and electric probe and dust impact sensor (SESAME, [21]).

The Lander Control Centre (LCC) at DLR, Cologne, and the Science Operations and Navigation Centre (SONC) at CNES, Toulouse, manage the operation of all Philae subsystems and instruments. These centers are equipped with all the necessary means to support data processing and distribution tasks, and are responsible for all lander operations, including:

- lander operations planning and verification;
- data monitoring and control of the subsystems and instruments;
- distribution and archiving of all received lander data.

An additional crucial responsibility of LCC and SONC is the coordination of the lander instruments during all operations. Nominal lander operations include also regular health checks of the system, subsystems and instruments during cruise, through the so-called "payload checkouts". Rosetta has performed a total of 13 payload checkouts (PCs) during its cruise period between commissioning and deep space hibernation. During each PC, the instruments had the opportunity to activate their units, exercise mechanisms, refresh EEPROM memories, and perform calibrations and software updates. Interactive operations were only possible during the active PCs, whereas passive PCs allowed for standard procedures for general monitoring of the instruments and lander status. Rosetta woke up from its 31-month Deep Space Hibernation period on January 2014. Both the orbiter and the lander were recommissioned. The data from the orbiter instruments were evaluated to plan the landing scenario, whereas Philae's scientific teams were involved in the detailed scheduling of the scientific operations.

The scientific operations of Philae were distributed over four different phases: the pre-landing phase (PDCS), which includes all the activities performed while the lander is still attached to the ROSETTA orbiter; the separation, descent and landing phase (SDL); the First Science Sequence (FSS) within about 3 days after landing; and the Long-Term Science phase (LTS), which follows the FSS after a possible hibernation period depending on the landing site and the related power situation of the lander [7].

Only a subset of the lander instruments were active with scientific measurements during the PDCS and SDL phases (ÇIVA, CONSERT, PTOLEMY, ROMAP, and SESAME during PDCS and CIVA, CONSERT, ROLIS, and ROMAP during SDL). The FSS and LTS phases utilize all ten Philae's instruments for science.

During FSS, the lander was powered to a large extent by its primary battery (capacity: 1 kWh) and several instruments and subsystems were operated simultaneously. Besides the scarce duration of the FSS, significant communication delays appeared during on-comet operations due to the relative visibility between the lander and the orbiter, and the visibility of the orbiter from ground. This prevented Philae's teams from operating the instruments interactively and limited the possibility of uploading telecommands during FSS activities. Consequently, operations had to be planned carefully and adapted for automatic execution, minimizing ground support. Energy consumption was a key parameter for planning, as the mission scientific outcome was maximized while satisfying the constraint of the energy stored in the primary battery. Moreover, the operation sequences were developed to be robust against uncertainties, in order to minimize the risk of failures and the need of uploading the associated recovery procedures.

The FSS will be followed by the long-term science (LTS). During LTS, the lander will rely on the power from the solar generator and a secondary battery. Instruments operations will mainly be performed in sequence and the data evaluation will be carried out primarily offline. The lander instruments operations are planned to last a few months on the comet surface after the possible short lander hibernation period.

4. Sampling, Drilling, and Distribution Subsystem

A crucial subsystem to ÇIVA, PTOLEMY, and COSAC activities is the sampling, drilling, and distribution (SD2) device. SD2 is devoted to support their activity by drilling into the cometary soil, collecting samples, and distributing them to the scientific instruments. SD2 is mounted on Philae's baseplate (see Fig. 6), and it is equipped with a drill able to collect several samples of 10-40 mm^3 at different depths (maximum depth of about 230 mm) from the same hole or different ones. It was designed to operate in critical thermo-vacuum environment and to meet the demanding mass/power resources limits of Rosetta mission. To this aim, innovative technological solutions were adopted during the design phase [13]: sampling tube for the drill/sampling operations, composite materials, dry lubrication, stepper motors, medium temperature ovens design.

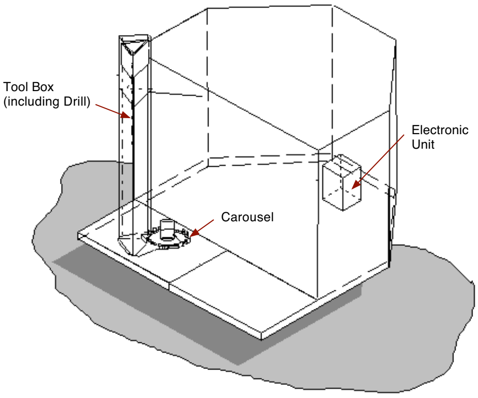


Figure 6. SD2 components distribution on Philae.

Table 2
Environmental parameters for SD2 design.

Parameters	Range
Comet strength	50 Pa–50 MPa
Temperature	-140 °C – +50 °C
Pressure	10^{-5} mbar – 1 bar

The driving environmental parameters for the subsystem design were comet soil strength, temperature and surface pressure (see Table 2). Parameters ranges, taken into account during the design phase, are wide in order to assure functioning in presence of high uncertainty.

SD2 has a total mass of 5100 g and is composed by a mechanical unit (3700 g), an electronic unit embedding SD2 software (1000 g), and the harness for electrical connection between the mechanical and electronic units (400 g).

The SD2 mechanical unit consists of the Tool Box, the Drill, and the Carousel:

- The Tool Box contains all the mechanisms for drilling and sample acquisition in a protective structural shell made of carbon fiber, which avoids drill damages due to vibrations and shocks during launch and landing phases.
- The Drill is made of aluminum alloy, and has a diameter of 12 mm and a maximum extension of 581.6 mm from the lander balcony; polycrystalline diamonds have been used to reinforce the drill bit for hard soil drilling; position, shape and geometry of the bits have been optimized by theoretical analysis, numerical simulations and experimental tests to maximize the cutting capability with a low vertical thrust (200 N) and a low power consumption. The power consumption during operations has a maximum average value of about 20 W. After the drill reaches the desired depth, a sampling tube is protracted from the drill bit to pick up the sample from the soil (Fig. 7). This solution was chosen for its simplicity and flexibility: the collection of the samples is performed by a pressure contact, as well as its release. The drill is then moved back to its home position, ready to deliver the sample to the assigned oven.
- The Carousel is a rotating platform on which 26 small ovens are mounted (Fig. 8). Once the drill is at its home position with the sample, the carousel is rotated to put the assigned oven under the drill. The drill translates downward to place the sampling tube on the oven opening and then pushes the sample into the oven. The carousel is then rotated to deliver the sample to the scientific ports of ÇIVA, PTOLEMY, or COSAC. The ovens provide the interface between the collected sample and the scientific instrument. According to the scientists requests, two kinds of ovens can be used (Fig. 9): 10 medium temperature ovens with an optical sapphire prism, suited for the analysis by visible I/R microscopes, before heating up for medium temperature experiment (+180°), and 16 high temperature ovens suited for high temperature ex-

periments (+800°).

(a) Drilling configuration

(b) Sampling configuration

Figure 7. SD2 drill bit.

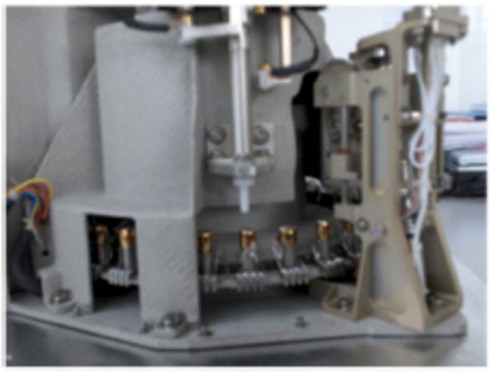


Figure 8. SD2 Carousel.

Figure 9. Medium-temperature (left) and high-temperature (right) ovens.

The electronic unit is installed into the warm compartment of the lander and incorporates all electronics to control the mechanical unit. The hardware and software installed provide the interface between the mechanical unit and the lander control system, the Command Data and Management System [11]. SD2 is supplied by Philae's power subsystem with a 28 V line from the lander primary bus, devoted to the mechanical unit, and some auxiliary power lines (±5 V, ±12 V) from the lander secondary converters.

A dedicated facility was designed and realized at Politecnico di Milano to test SD2 behavior and assess its performances in different realistic scenarios [12]. The operations that can be carried out at the SD2 facility include:

- mechanical verification of the drilling system; i.e., analysis of the drill structural behavior and assessment of the force and torque transmitted by the drill to the specimen;
- simulation of different comet-like soils and drilling scenarios;
- mechanical and functional verification of the sampling and collecting system;
- assessment of SD2 behavior during mission plan execution;
- definition of the optimal perforation strategies;
- design of the recovery procedures in case of SD2 non-nominal behavior;
- assessment of SD2 power consumption during drilling/sampling activities.

The design of the SD2 facility was accomplished to meet the requirements issuing from the previous tasks. The resulting facility is equipped with (see Fig. 10):

- the SD2 Flight Spare (FS) model;
- a support structure, designed for easy inspection and replicating the clamping system on the Flight Model (FM);
- an acquisition system used to acquire and process data during tests.

The support structure is made up by (see Fig. 11):

- four tubular beams (2 m high and with a radius of 30 mm);
- three aluminum plates used as baseplate, SD2 FS and sensor system support;
- four beams clamped at the top of the structure to reduce vibrations or distortions during drilling phase.

Figure 10. SD2 facility at Politecnico di Milano.

The plates are clamped to the tubular beams to avoid SD2 FS movements. A translation system allows the sensor system and the specimen to translate to a known position. This decreases the problem of misalignment between the drill and the drilled surface. The sensor system is composed by a biaxial strain gauge that measures the normal force and the torque applied to the specimen. The strain gauge has

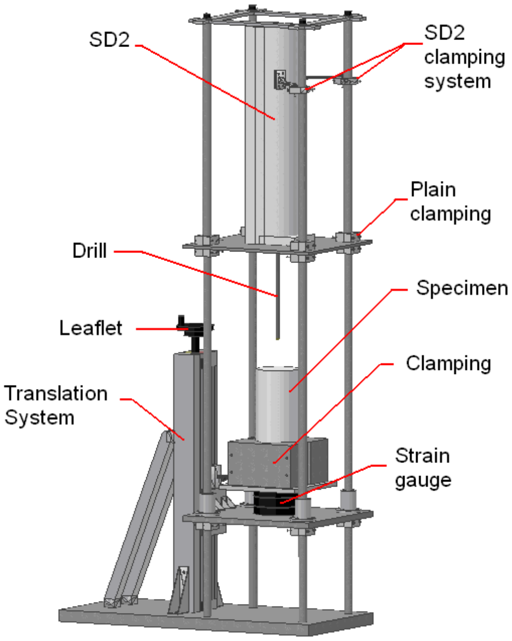


Figure 11. Support structure for the SD2 FS model.

- torque full scale of 25 Nm with a resolution of 0.01 Nm;
- vertical force full scale of 1000 N with a resolution of 1 N.

The strain gauge must measure load contributions given by the drill during perforation (maximum load of 200 N), the specimen, and the clamping system (220-500 N). The interface between the strain gauge and the structure is composed by eight screws, each of them tolerating a load range of 20-65 N. A current sensor is added to measure SD2 FS power consumption during operation.

5. First Scientific Results

5.1. Orbiter Results

Rosetta started its approach phase to the comet with a breaking maneuver in May 2014 and reached the comet nucleus on 6 August 2014, at 3.7 astronomical units (AU) from the Sun [24]. After rendezvous, the Rosetta spacecraft moved from 100 km above the comet to a bound orbit only ~10 km away. Meanwhile, the orbiter instruments started investigating the comet nucleus and the images taken by the onboard navigation camera, the OSIRIS scientific imaging system [25], and the Visible, Infrared and Thermal Imaging Spectrometer (VIRTIS [10]) were used to identify the most favorable landing sites for Philae. Previously unseen details of a comet nucleus were revealed.

Images from OSIRIS and the navigation camera showed that the nucleus of 67P/Churyumov-Gerasimenko consists of two lobes connected by a short neck (see Fig. 12). The comet mass was estimated to be on the order of 1013 kg, with a bulk density of ∼470 kg/m^3. The derived density suggests that the nucleus has a relatively fluffy nature, with a porosity of 70 to 80% [22]. The activity at the distance of rendezvous from the Sun (>3 AU) was predominantly from the neck (see Fig. 13). The surface morphology suggests that the major mass loss process may be related to explosive release of subsurface pressure or via creation of overhangs by sublimation. Investigation is ongoing to try to understand the origin of the comet; i.e., if the two lobes represent a contact binary or if they formed after mass loss from the neck. The surface of the comet shows evidence of many active processes and the data gave evidence of the importance of airfall, surface dust transport, mass wasting, and insolation weathering for cometary surface evolution [26].

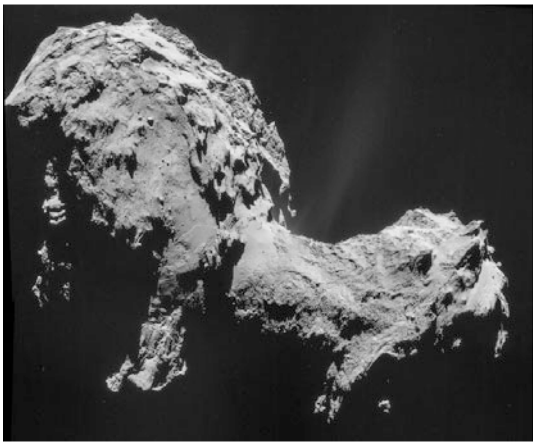


Figure 12. Four-image NAVCAM mosaic of Comet 67P/Churyumov-Gerasimenko (19 September 2014). Credits: ESA/Rosetta/NAVCAM.

The analysis of VIRTIS' data showed that the nucleus has a low reflectance (normal albedo of 0.060 ± 0.003 at 0.55 micrometers) and a broad absorption feature in the 2.9-to-3.6 micrometer range [9]. This seems to suggest that the surface may be rich of opaque minerals associated with nonvolatile organic macromolecular materials belonging to carbon-hydrogen and/or oxygen-hydrogen chemical groups, with little contribution of nitrogen-hydrogen groups. However, no ice-rich patches were observed on the surface of the comet, even if the presence of water ice is not excluded in the subsurface. This indicates a generally dehydrated nature for the surface.

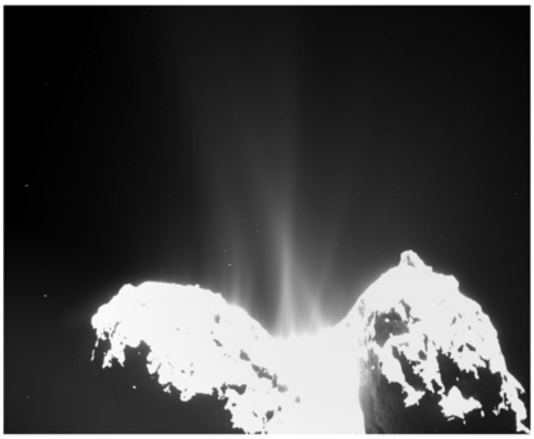


Figure 13. Rosetta OSIRIS wide-angle camera image of Comet 67P/Churyumov-Gerasimenko (10 September 2014): jets of cometary activity. Credits: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/ INTA/UPM/DASP/IDA.

The coma produced by ices sublimating from the nucleus is highly variable. The Microwave Instrument on the Rosetta Orbiter (MIRO) acquired maps of the subsurface temperature of comet 67P/Churyumov-Gerasimenko at different wavelengths, and spectra of water vapor. The total H2O production rate varied from 0.3 $\mathrm{kg\,s^{-1}}$ in early June 2014 to 1.2 $\mathrm{kg\,s^{-1}}$ in late August and showed periodic variations related to nucleus rotation and shape. As expected from OSIRIS images, water outgassing was localized to the "neck" region of the comet [15].

The D/H ratio in water production was measured by the ROSINA mass spectrometer to be (5.3 ± 0.7) x 10^{-4}, which is approximately three times the terrestrial value [1]. This precludes the idea that Jupiter family comets like 67P/Churyumov-Gerasimenko contain solely Earth ocean-like water.

5.2. Lander Results

During the approach phase to comet 67P/Churyumov-Gerasimenko, the Landing Site Selection Group (LSSG) started its investigation of the comet surface in order to identify the best locations for Philae's landing. The LSSG included the ESA Rosetta team, Philae's scientific team, SONC, and LCC.

The selection was based on a trade-off between opposing needs. The lander had to be deployed before the phase of intense comet activity started, as this could have affected Philae's landing. On the other hand, the need of producing enough power from Philae's solar cells to operate during LTS prevented Philae from being released too early. In addition, the scientific and navigation cameras onboard the orbiter began to provide useful information on surface features. This allowed the LSSG to start discarding areas based on technical feasibility. Considerations on landing trajectory, lander speed, slope of the surface, lander orientation at touchdown, and presence of large boulders on the surface were gathered to this purpose. Additional aspects were taken into account to meet scientific needs, such as the balance between comet day and comet night.

At the end of this first phase of the selection process, five landing sites were preliminary selected on 24 August 2014 (sites A, B, C, I and J in Fig. 14). A comprehensive analysis of the five candidates followed this first selection. Both technical and scientific aspects were considered to finally select J as the primary landing site for Philae on 14 September 2014, whereas site C was chosen as backup site. The primary site J was then renamed Agilkia.

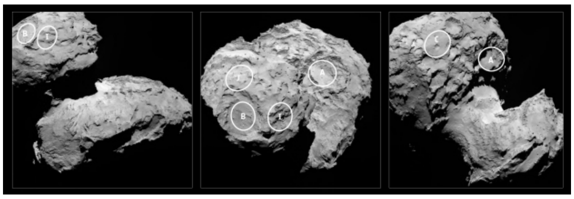


Figure 14. The five candidate landing sites identified on Comet 67P/Churyumov-Gerasimenko on 24 August 2014. Credits: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA.

Philae's landing happened on 12 November 2014, headed to Agilkia as planned. The release and descent happened as planned: ROLIS monitored SDL by taking regular images (see Fig. 15); CONSERT focused on ranging activities, while ROMAP measured the evolution of the comet magnetic properties. The lander touched down in Agilkia within an error of 100 meters. Immediately after touchdown, harpoons were commanded to fire in order to anchor the lander to the ground and prevent it escaping from the comet's extremely weak gravity.

Not all went as planned: some elements of Philae landing system (the cold gas thruster, the anchors and the helices) were unable fix onto the surface at touch down. Consequently, two re-bounces occurred in a totally unexpected pattern and finally Philae got to rest on the comet, at a landing site later named Abydos.

(a) From a distance of about 30 km.

(b) From a distance of about 40 m.

Figure 15. ROLIS descent images of Comet 67P/C-G. Credits: ESA/Rosetta/Philae/ROLIS/DLR.

Despite the non-nominal landing conditions, Philae's primary, non-rechargeable battery allowed the instruments to operate for 63 hours during FSS. However, the sequence of operations had to be reshuffled and adapted to the unexpected scenario.

Right after landing in Abydos, ÇIVA obtained and sent to Earth panoramic images of the surrounding cometary material, from mm- to m- scale. ROLIS was able to image the soil under the lander at the first and last touchdown. Images from the first touchdown showed granular material on the cm to dm scale, with a lack of dust deposits.

CONSERT bistatic radar investigated the internal structure of a comet nucleus. In addition, it served the purpose of obtaining an accurate identification of the final landing site on the comet surface, by reducing the size of possible locations down to approximately 21x34 m^2. COSAC and PTOLEMY measurements focused on the volatile constituents of the grains at both Agilkia and Abydos. They confirmed that the grains are primarily constituted of carbon-rich species.

The instruments requiring mechanical movements (MUPUS, APXS, and SD2) were finally operated in the latest FSS activity blocks. MUPUS measured the thermal and mechanical properties of the nucleus at Abydos. The thermal inertia was found to be 85±35 $J\ m^{-2}\ K^{-1}\ s^{-1/2}$, whereas the temperature was measured to vary between 90 and 130 K. MUPUS PEN was then activated to measure the penetration resistance of the soil, which was constrained to be more than 4 MPa. Based on MUPUS PEN results, the upper layers of the comet's surface are believed to consist of a thin dust layer overlaying mechanically strong ice or ice and dust mixtures.

As far as SD2 operations are concerned, the unexpected events during landing caused major consequences [17]:

- the lander was not anchored onto the surface (no reaction available for the thrust SD2 would have generated);
- the Philae possible movements during drilling operations might have favoured jamming conditions.

Nevertheless, SD2 operated on the comet on 14 November 2014. SD2 was commanded to reach the position 560 mm (corresponding to a distance of 468.5 mm from the lander baseplate), perform the sampling sequence, discharge the sample into a high-temperature oven, and serve the sample to COSAC for later analysis. More specifically, the operation sequence included the following activities:

1. Drill bit rearming (the sampling tube had indeed been travelling in extracted configuration during the entire cruise phase);
2. Drill roto-translation to position 560 mm;
3. Sample acquisition: the sampling tube was extracted and the drill rotated for 20 seconds to perform a coring of the soil;
4. Drill translation back to position 0 mm to uplift the drill rod (and sampling chamber);
5. Rotation of the carousel to put HTO#17 under the sampling tube;
6. Sample release inside HTO#17;
7. Rotation of the carousel to put HTO#17 under COSAC main port.

In addition, the Carousel was eventually rotated back to its home position to allow PTOLEMY perform a sniffing activity. The telemetry produced shows that SD2 performed nominally. All mechanical operations and kinematical trajectories were executed correctly: the commanded drill and Carousel positions were reached within the admissible tolerances and the movements were performed with the commanded speeds. In addition, SD2 power and energy consumption matched the expectations.

The drill position profile during the roto-translation to 560 mm and the subsequent translation back to 0 mm is illustrated in Fig. 16. As can be seen, the drill bit reaches the required position of 560 mm. The different slopes and durations of the two movements are due to the different commanded speeds: a speed of about 7 mm/min was commanded for the roto-translation to 560 mm, whereas a speed of about 13 mm/min was used for the translation back to 0 mm.

The Carousel position profile during the last Carousel movement is shown in Fig. 17. The rotation started from position 15120 arcmin, which corresponds to having HTO#17 under COSAC main port. After about 80 s, the Carousel reached the commanded home position (i.e. 0 arcmin, or equivalently, 21600 arcmin) with an error of 1 arcmin.

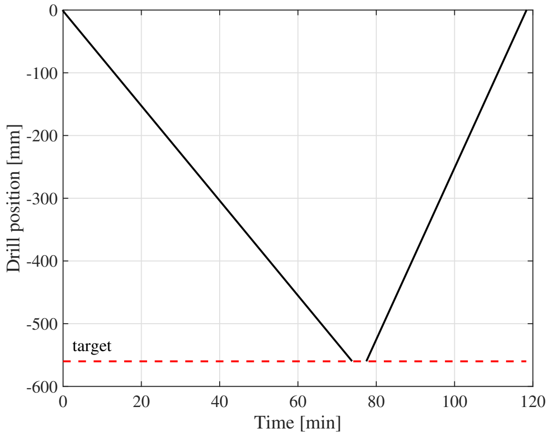


Figure 16. Drill position profiles during the roto-translation to 560 mm and the translation back to 0 mm.

The nominal behavior of SD2 during on-comet operations is a remarkable success: after more than ten years in space and a dramatic landing, the system has proven to satisfy the design requirements and to withstand the stringent operating conditions. Nevertheless, the telemetry of SD2 is not sufficient to rigorously

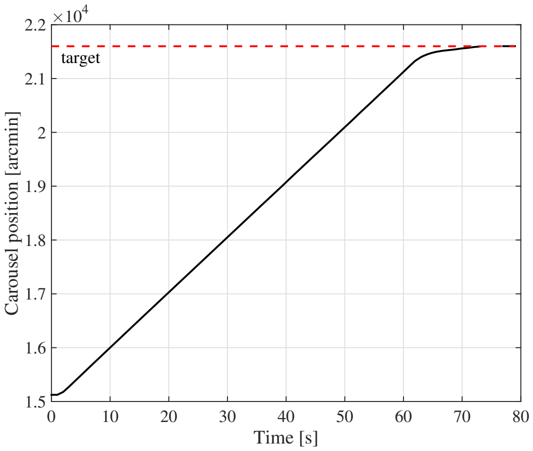


Figure 17. Carousel position profile during the Carousel rotation back to home position.

confirm that the drill bit has reached the soil, and that the sample has actually been collected in the sampling tube and discharged into the oven. In fact, due to the non-nominal landing and the unknown Philae conditions on the comet, the soil itself could also be too far away to be reached by the drill.

Other instruments on board Philae may help to clarify this point. The camera system ROLIS could be used to reconstruct a three-dimensional model of the comet surface under the lander. The SD2 team is currently interacting with ROLIS team to determine the distance of the soil from the lander baseplate in the drilling area, so as to check that it is compatible with the commanded roto-translation of 560 mm.

6. Conclusions

This note described Rosetta mission, the instruments onboard the orbiter and the lander, and the first scientific results derived from both remote observations from the orbiter and in-situ measurements from the lander. In addition, the analysis of SD2 telemetry was presented, giving evidence of the first attempt of comet drilling. At the time of this writing, after about 6 months from landing, Philae has just woke up from its hibernation period after FSS. An intense activity is ongoing to decipher the status of Philae and prepare both the orbiter and the lander to the subsequent LTS phase. Future measurements will investigate the evolution of the comet across its perihelion passage in August 2015 and during its journey back to deep space, away from the Sun. Philae is provided by a European consortium under the leadership of the German Aerospace Research Institute (DLR). Other members of the consortium are the European and French Space Agencies, and institutes from Austria, Finland, France, Hungary, Ireland, Italy and the UK. Ten different principal investigators from all over Europe manage the ten instruments onboard the lander Philae. Each principal investigator leads a group of scientists working on a specific instrument. A comparable number of engineers manage all additional subsystems needed to operate on the comet. This means dozens of people from all over Europe interacting to achieve one ambitious goal: landing a spacecraft on a comet for the closest investigation ever to unveil the secrets of the solar system. A great example of international cooperation in a multidisciplinary environment, involving engineers and scientists from different areas of space science and technology.

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