

Invited Paper

Rosetta and 67P/Churyumov-Gerasimenko: a comet under observation

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ABSTRACT

After a ten year's expedition through the Solar system Europe's comet chaser Rosetta arrived at comet 67 P/Churyumov-Gerasimenko in August 2014. Less than 100 kilometers from the nucleus the eleven orbiter payload instruments started to map and characterize the comet in great detail. In November 2014 Philae was the first robotic subsystem ever that landed on a cometary surface performing *in situ* measurements with ten instruments. The mission's scientific program following the deployment of Philae is determined by the activity of the comet, which will increase as 67P approached perihelion in August 2015. This paper is a review article. It introduces the mission goals and profile. It gives an overview of some of the preliminary results of the mission. Selected results gained during the pre-landing phase of the subsystem Philae and the comet's escort phases are discussed.

Keywords: Planetary remote sensing, comets, Rosetta.

1. INTRODUCTION

Comets are the most primitive objects in the solar system. They can be considered as some of the remaining original elements in our 4.6 billion-years-old solar system. These minor bodies were formed in the outer and cold regions of the planetary system, and thus they are less altered containing information about the early solar nebula's state of matter^{1, 2}. The precursor cometary material may be a combination of unaltered interstellar grains and volatiles that would be subsequently condensed in the protoplanetary disk.¹ Therefore, comets represent material closest to the conditions of the early solar system. Previous spacecraft observations of comets with Giotto (1P/Halley)^{3, 4, 5}, Stardust (81P/Wild 2)⁶, Deep Impact (9P/Tempel 1)⁷, and EPOXI (103P/Hartley 2)⁸ provided insights into cometary structures and first close-up views of cometary nuclei. Nevertheless, all of these space missions have flown by their targets, and thus they took only time-limited snapshots of comets within their orbital evolutions.

ESA's cornerstone Rosetta to comet 67P/Churyumov-Gerasimenko is the first mission escorting a comet during its passage through the inner solar system. Additionally, a robotic device, "Philae", which landed on the cometary surface in November 2014, provided important *in situ* data. ESA's Rosetta mission was launched on March 2, 2004 on an Ariane 5 G+ rocket. It rendezvoused with comet 67P/Churyumov-Gerasimenko, henceforth shortly called 67P, in May 2014 starting its mapping campaign in August 2014⁹.

Rosetta consists of an orbiter and the lander system. The Rosetta orbiter's scientific payload includes eleven scientific instruments devoted to study the cometary nucleus and coma within the orbital evolution of 67P. The Philae lander houses ten scientific instruments for cometary *in situ* analyses⁹. During its first year of observation Rosetta performed unique investigations for periods of global mapping, lander deployment, and comet chase toward the Sun.

This paper aims to place Rosetta in context to previous space borne cometary missions. It summarizes the mission's key goals, the mission's profile, and some of the mission highlight results. The paper bases on recent results published by the different Rosetta instrument teams, whose specific scientific achievements were documented and carefully quoted.

2. ROSETTA MISSION

The Rosetta mission is a cooperative project between ESA, various European national space agencies, and NASA, and is comprised of eleven orbital and ten lander experiments, making it unprecedented in scale. Rosetta rendezvoused the comet 67P in May 2014 at 4 AU from the Sun. After a 10-years cruise, the Rosetta spacecraft began a close exploration of comet 67P in July 2014 and entered a 30-km bound orbit around the comet on September 9, 2014. It will accompany the comet's journey towards perihelion (August 13, 2015, 1.24 AU). ESA's cornerstone Rosetta is the first spacecraft to orbit a comet and was the first to land a robotic device on the surface of a comet. Therefore, Rosetta combines remote sensing and *in situ* investigations.

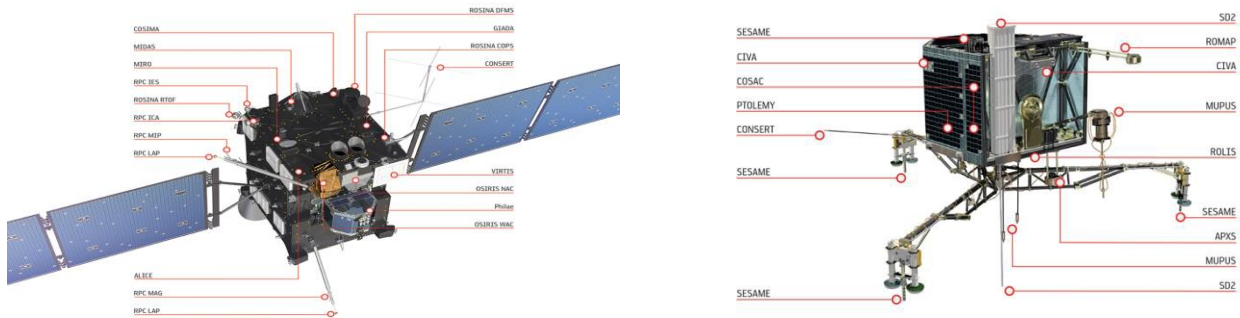


Figure 1. Rosetta Spacecraft: Left – Orbiter; credit: ESA, right – Philae lander; credits: ESA, DLR (Description of the instrument's acronyms is given in section 2.3).

2.1 Rosetta's goals

The mission aims at a global characterization of the cometary nucleus, the determination of dynamic properties, the surface morphology and composition, chemical /mineralogical /isotopic compositions of volatiles and refractories, physical properties, studies of cometary activity, and evolution of interaction with the solar wind⁹. The primary mission goals are:

- Perform an extended exploration of a comet at close quarters to observe how it is transformed by the warmth of the Sun along its elliptical orbit¹⁰,
- Land a probe on a comet's nucleus for in-situ analyses¹⁰,
- Observe the comet's nucleus (shape, dynamic properties, surface, and interior) and coma from close range,
- Analyse the chemical, mineralogical, and isotopic composition of the nucleus (volatiles and refractories),
- Study the physical properties of the cometary nucleus,
- Observe the comet's activity as it approaches the Sun and study its interaction with the environment,
- Investigate the dynamic coma structure and composition (structure, thermal, electrical, and magnetic properties),
- Study changes related to heliocentric distance, cometary, and seasons.

This will enable to investigate how the solar system evolved to its current state:

- How did comets originate and where have they been formed?
- What is the relationship of their materials to those found in other regions of the solar system and in interstellar space?
- How have comets contributed to the origin and evolution of planets, moons, and other minor bodies (relationship to asteroids) in the solar system?
- Which role do they play in feeding the inner solar system with volatiles?

To meet these goals the Rosetta mission was designed to rendezvous 67P in the cold outer region of the solar system when the comet was less active, orbit the cometary nucleus, examine it from close proximity, fly alongside the comet

towards the inner solar system, and land a robotic device on its surface. A sophisticated orbiter scientific payload consisting of optical, microwave, and radar systems, gas/dust analyzers, plasma/magnetic field and radio science instruments was selected to carry out the close-up remote observations¹¹. Philae's scientific instruments were aimed to perform multispectral and multicolor imaging at the comet's surface, study elemental composition, thermal, mechanical, electrical, and magnetic properties¹².

2.2 Rosetta's journey

Rosetta launched on 2 March 2004 by an Ariane-5 G+ from Kourou, French Guiana. During its ten year's journey until arrival at 67P the spacecraft received four gravity assist manoeuvres from Earth (March 2005, November 2007, and November 2009) and from Mars (February 2007)¹³. Passing the main asteroid belt Rosetta studied two asteroids flown by, 2867 Šteins on September 2008 and 21 Lutetia on July 2010. After the hibernation phase, which started in June 2011, Rosetta was waking up in January 2014 and rendezvoused 67P in May 2014. From August to November 2014 an extensive pre-landing observation phase followed to map the comet and select a landing site for Philae. Currently Rosetta is escorting 67P to collect comprehensive data, while the comet becomes progressively active. 67P passed the perihelion in August 13, 2015 and was tracked as the comet moves again away from the Sun.

2.3 Rosetta's scientific payload

Rosetta's orbital payload (see Fig. 1, right) consists of eleven scientific instruments. Among the optical systems it houses the OSIRIS Optical, Spectroscopic, and Infrared Remote Imaging System) camera¹⁴ the VIRTIS (Visible and Infrared Thermal Imaging Spectrometer)^{15, 16, 17} and the ALICE (miniaturized ultraviolet imaging spectrometer)¹⁸ spectrometers to observe 67P in the UV to IR spectral range. The microwave instrument MIRO (Microwave Instrument for the Rosetta Orbiter)¹⁹ aims to study minor gases and the nucleus' subsurface temperature. CONSERT (Comet Nucleus Sounding Experiment by Radiowave Transmission)^{20, 38} is the radar sounding device to investigate the comet's internal structure. Gas and dust analyzers like ROSINA (Rosetta Orbiter Spectrometer for Ion and Neutral Analysis)²¹, COSIMA (Cometary Secondary Ion Mass Analyser)²², GIADA (Grain Impact Analyser and Dust Accumulator)²³, and MIDAS (Micro-Imaging Dust Analysis System)²⁴ are dedicated to study the structure, composition, and dynamics of gaseous and dust material in the cometary coma. The Rosetta Plasma Consortium (RPC)²⁵ and the Rosetta Radio Science Investigations (RSI)²⁶ complete the orbiter payload aiming to measure the nucleus' physical properties, the comet's interaction with the solar wind, and to determine mass and gravity of the comet, respectively.

Philae's payload (see Fig. 1, right) combines a set of ten instruments to image, analyze, and study the comet by *in situ* measurements. The cameras CIVA (Comet Infrared and Visible Imager)²⁷ and ROLIS (Rosetta Lander Imaging System)²⁸ performed multispectral, color, and panchromatic imaging on the immediate cometary surface. COSAC (Cometary Sampling and Composition) is an instrument consisting of a gas chromatograph and a time-of-flight mass spectrometer (MS)²⁹. It enables to analyze samples delivered by a drilling device and can operate in a sniffing mode as well as using MS³⁰. The PTOLEMY³¹ instrument is designed to measure stable isotope ratios and elements such as H, C, N, and O of samples procured from the drilling device³². The instrument concept is termed MODULUS (Methods Of Determining and Understanding Light elements from Unequivocal Stable isotope compositions)³³. A further experiment to study chemical composition is APEX (Alpha Proton X-ray Spectrometer), which has not been active so far³⁴. MUPUS (Multipurpose Sensors for Surface and Sub-Surface Science)^{35, 36} and SESAME (Surface Electrical Sounding and Acoustic Monitoring Experiment)³⁷ are designed to investigate physical properties of the surface and sub-surface like temperature, thermal inertia, electrical conductivity, and mechanical characteristics. The Comet Nucleus Sounding Experiment by Radiowave Transmission (CONSERT) is a bi-static radar instrument, which propagates long-wavelength signals between the Rosetta orbiter and the lander Philae revealing information about the permittivity of the nucleus, which depends on porosity, composition, and temperature and thus providing insights into its internal structure^{20, 38}. The magnetometer and plasma monitor, ROMAP (Rosetta Magnetometer and Plasma Monitor)³⁹, is dedicated to study magnetic field and plasma properties, and the drilling device SD2 (Sample and Distribution Device) was aiming to collect and deliver samples to different ovens or microscope inspection⁴⁰.

Originally to by touched down the nucleus' region called Agilkia (see Fig. 2) Philae rebounded twice because the harpoon anchors to fire and gas repulsion mechanism failed, before finally landing at Abydos. Due to the unfavorable illumination conditions at the final landing site, the lander's solar arrays have not been illuminated sufficiently to reload its batteries for long duration measurements. Nevertheless, Philae was operating about sixty hours on the surface of the

comet in November 2014. Most of the experiments could collect *in situ* data. With the increase of solar insolation the contact to Philae could be reactivated in June 2015. Currently the future operation of Philae and its instruments is under investigation.

3. ROSETTA'S OBSERVATION RESULTS

The Jupiter Family Comet 67P discovered in 1969 is characterized by an eccentricity of 0.64102, an inclination of 7.0405°, a perihelion distance of 1.2432 AU, and a semi-major axis of 3.4630 AU resulting in an orbital period of 6.44 years. In 1959 67P had a close encounter with Jupiter which changed its perihelion distance from 2.74 AU to its present value⁴¹. The current rotation period is about 12.4 h⁴². During the pre-landing (before November 12, 2014) and escort phase (after November 12, 2014), the orbiter instruments collected data to characterize the comet with remote sensing optical systems, with a microwave device, with radar sounding, gas and dust analyses, plasma and magnetic field studies, and radio sounding^{43, 44, 45, 46, 47, 48, 49}. First evaluation of Philae's *in situ* measurements revealed information about the chemical composition of the comet's gas and dust^{30, 32}. Complex organic molecules have been detected³², high resolution close-up images from the landing sites have been taken^{50, 51}, and physical-mechanical properties of cometary material have been determined^{36, 38, 39}.

3.1 Orbiter observations

Cometary nucleus mapping and physical properties: Rosetta's OSIRIS camera mapped the comet disclosing a structure of two lobes connected by a neck (see Fig. 2)⁴³. The cometary surface displays different morphologies including dust covered terrains (see Fig. 2, middle: see e.g. the region Ash), brittle material (see e.g. Seth), large scale depressions (see e.g. Aten), smooth terrains and exposed consolidated surfaces (see e.g. Aker; see also Fig. 1, reference 17, 9608-2, these proceedings)⁴⁴.

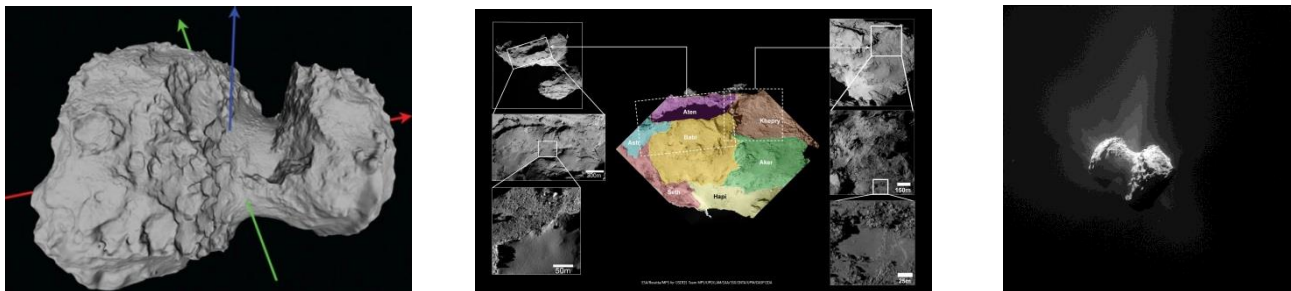


Figure 2. OSIRIS results. Left: shape model of 67P with rotation axis (blue) and equatorial x and y axis (red, green)⁴³.

Credit: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA.

Middle: Cometary surface details: Context image of 67P's surface features close to regional boundaries on comet's large lobe.

Credit: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA⁵².

Right: Observation of cometary activity (Rosetta NAVCAM), July 20, 2015.

Credits: ESA/Rosetta/NAVCAM – CC BY-SA IGO 3.0.

The larger lobe (body) has a size⁴³ of about 4.1 km × 3.3 km × 1.8 km, and the smaller one (head)⁴³ is 2.6 km × 2.3 km × 1.8 km. The preliminary calculated total volume is about 21.4 ± 2.0 km³. With a mass of 1.0 × 10¹³ kg determined by RSI⁵⁵ the resulting mean density is 470 ± 45 kg/m³ (see⁴³). This low density is comparable with cork and is an indication of high porosity of 70-80%.⁴³ The gravitational potential varies by less than a factor of two⁴³. The obliquity of the comet's rotation axis is 52° causing cometary seasons. Therefore, during the pre-landing, landing, and early escort phases only the northern hemisphere of 67P was illuminated. As the comet approaches its perihelion the southern hemisphere is progressively illuminated, enabling to disclose the southern part of 67P.

67P has a low average normal albedo⁴⁹ of 0.060±0.003 and a geometric albedo⁵³ of $A_{geo} = 0.062 \pm 0.002$ at 550 nm. The analysis of the nucleus' surface composition by VIRTIS shows that the surface is depleted by volatiles. VIRTIS close-up observations revealed only very limited amounts of isolated ice patches. A broad absorption feature in the 2.9-to 3.6-μm

range across the entire illuminated surface was detected. This feature is assigned to nonvolatile organic macromolecular materials combining CH, C-OH, -COOH, and NH chemical groups^{49, 17}. Measurements of the surface⁴⁹ and sub-surface temperatures⁴⁵ enable to study the upper layered nucleus structure and its thermo-electrical properties.

OSIRIS, NAVCAM (see Fig. 2, right), VIRTIS, ROSINA, MIRO, and other orbital instruments detected the presence of a gaseous dusty coma increasingly intensifying as the comet approached its perihelion distance to the Sun. Early activity was first observed over the neck (Hapi) region.

Gas and dust observations: Very early water vapor was detected by MIRO in June 2014, when the comet was at 3.92 AU from the Sun. The mean total water production rate over one nucleus rotation was 1×10^{25} molecules/s (300 ml/s) in June 2015⁴⁵. VIRTIS-H measurements were performed to study the productions and distributions of water (2.67 μm signature) and carbon dioxide (4.27 μm) in the cometary coma, when the comet was between 2.47 and 2.91 AU from the Sun resulting in a water production rate of 6.1×10^{25} to 1.0×10^{26} molecules/s during the 12-h nucleus rotation⁵⁴. The water vapor production rate decreases for low solar illumination, whereas CO₂ is outgassing from both illuminated and non-illuminated areas⁵⁴. This distribution of the two species results in variable CO₂/H₂O column density ratios between 2% and 30%.⁵⁴ Rotational temperatures have been used to determine coma temperatures of typically 100 K above 1 km from the nucleus⁵⁴. ROSINA measured the gaseous coma composition in August and September 2014⁴⁶. Water, Carbon monoxide, and carbon dioxide have been identified. The measurements show large abundance fluctuations related to diurnal and seasonal variations and a coma composition being highly heterogeneous⁴⁶. The highest fluctuations occur for water vapor. Smaller abundance variations of CO₂ and CO may indicate that they sublimate from greater depths⁴⁶. Finally, GIADA and OSIRIS measurements⁴⁷ between 3.6 and 3.4 AU detected 35 outflowing dust grains of mass 10^{-10} to 10^{-7} kg and 48 grains of mass 10^{-5} to 10^{-2} kg.

3.2 First results of *in situ* measurements

In situ composition analysis, study of physical-mechanical surface and sub-surface properties: After the first touchdown COSAC and PTOLEMY analyzed the chemical composition of gas and dust close to the surface. COSAC revealed various organic components, including methyl isocyanide, acetone, propionaldehyde, and acetone³⁰. PTOLEMY detected the main components water vapor, CO, CO₂, and other minor species³². The MUPUS thermal probe inserted into the cometary surface by a hammer mechanism at Abydos landing site did not fully penetrate the near-surface layers, indicating the presence of a hard ground material located beneath a 3 cm thick thin dust layer (local resistance of the ground to penetration larger 4 MPa)³⁶. The MUPUS infrared radiometer revealed diurnal temperatures between 90 and 130 K, and a local thermal inertia³⁶ of $85 \pm 35 \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1/2}$. The CONSERT radiowave measurements lead to the conclusion that the upper part of 67P's head is homogeneous on a spatial scale of ten meters³⁸. Its permittivity results suggest a volumetric dust/ice ratio of 0.4 to 2.6 and a porosity of 75 to 85%³⁸, which is in good correlation with other Rosetta observations.

Close-up in situ imaging: CIVA and ROLIS opened up the possibility to compare two different locations on the cometary surface by close-up *in situ* imaging^{50, 51}. The panoramic multispectral camera CIVA imaged the Abydos landing site. These data reveal a fractured surface less covered by dust and therefore perhaps exhibiting more pristine cometary material⁵⁰ (see Fig. 3, right). ROLIS acquired close-range images of the Agilkia⁵¹ site (see Fig. 3, left) during its descent onto 67P and at the final Abydos landing site (not published yet). The Agilkia and Abydos sites differ considerably. The ROLIS images of Agilkia were taken during Philae's descent. Fig. 3 (left) shows the last descent image a few seconds before touchdown⁵¹. The ground resolution is 0.95 cm/pixel disclosing the regolith's texture. Agilkia's surface texture is characterized by a photometrically uniform material composed of debris and blocks ranging in size from centimeters to 5 meters⁵¹. The surface appears granular (see inset of Fig. 3, left). The presence of aeolian-like features indicates that mobilization and erosion processes take place, which might be driven by airfall-induced deposits⁵¹.

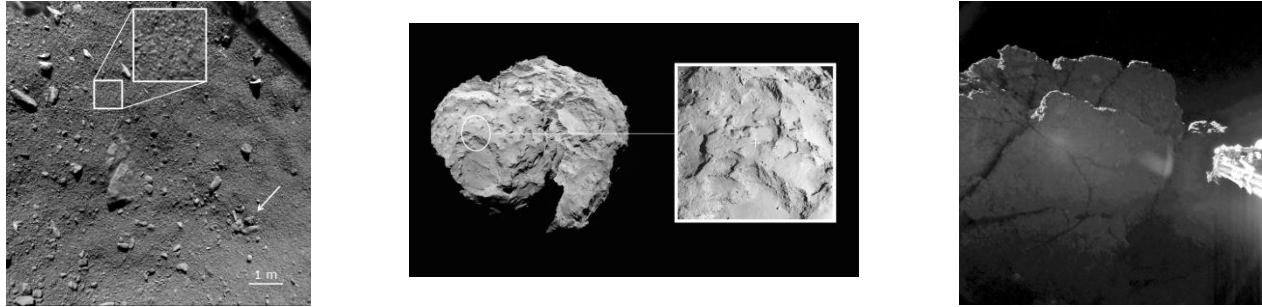


Figure 3. Left: Last image of ROLIS acquired a few seconds before first touchdown (Agilkia area) from an altitude of 9 m (ground resolution: 0.95 cm/pixel). The arrow indicates a cluster of blocks⁵¹.
 Middle: Image of the Agilkia site, OSIRIS, credit: ESA/Rosetta/MPS for OSIRIS Team
 MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA.
 Right: CIVA image (Abydos)⁵⁰.

4. CONCLUSION AND OUTLOOK

Rosetta was breaking new ground in many respects. Being the first to land a robotic device on a comet and being the first to orbit and escort a comet, Rosetta provides fundamental data for cometary science. Rosetta's orbiter and *in situ* measurements suggest that the major mass loss of 67P is driven by sublimation or via removal of material by explosive release from subsurface. Whether 67P's lobes are binary contacted since the early formation 4.6 billion years ago or a single body eroded to form the current shape is still under investigation. The surface morphology displays a high diversity between smooth terrains, large scale depressions, and brittle areas. This diversity is confirmed comparing the different surface textures of Philae's two landing sites. Airfall and surface dust transport form aeolian-like features at the cometary surface. The uppermost surface layer is dark, depleted in volatiles, and rich in complex organic refractories. The low thermal inertia of this material is confirmed by both the orbiter and *in situ* measurements. Studies of the developing coma enabled to investigate outgassing species and to draw conclusions about the interior composition. As 67P approached its perihelion position in August 2015 it became more and more active enabling to study details of the cometary gases and dust emissions. At the same time the southern hemisphere of 67P was illuminated progressively disclosing the southern part of the comet. Rosetta's studies of temporal and spatial dynamic processes regarding the nucleus and coma will contribute to understand the sources and effects of cometary activity, while monitoring the nucleus/coma composition will enable to trace the comet's evolutionary path.

5. ROSETTA TEAM

Scientific consortia from institutes across Europe and the United States have provided the state-of-the-art scientific instruments. Rosetta's industrial team involves more than 50 contractors from 14 European countries and the United States. The prime spacecraft contractor is Astrium Germany. Major subcontractors are Astrium UK (spacecraft platform), Astrium France (spacecraft avionics) and Alenia Spazio (assembly, integration and verification).

6. ACKNOWLEDGMENT

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