

Cometary Science with ROSETTA and Deciphering the Message in a Bottle from the Formation Period of our Planetary System

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ROSETTA, the planetary cornerstone mission in the long-term space science program of the European Space Agency ESA, is the second European spacecraft that is sent to a comet. In 1986 ESA's GIOTTO mission to Comet 1P/Halley has provided the first images of a cometary nucleus and in many respects it has put the scientific picture and speculations about the nature of comets on firm grounds. During the past eighteen years, fly-bys of in total eight spacecraft at five different comets as well as tremendous progress in ground-based observations of these objects have filled in important contributions and tessera to the current paradigm of comets. However, it is ROSETTA that is meant to bring cometary science a quantum-leap forward and to aim, more than any other cometary mission so far, for deciphering the global picture of the formation of our own planetary system and of the role of comets therein.

The ROSETTA Mission

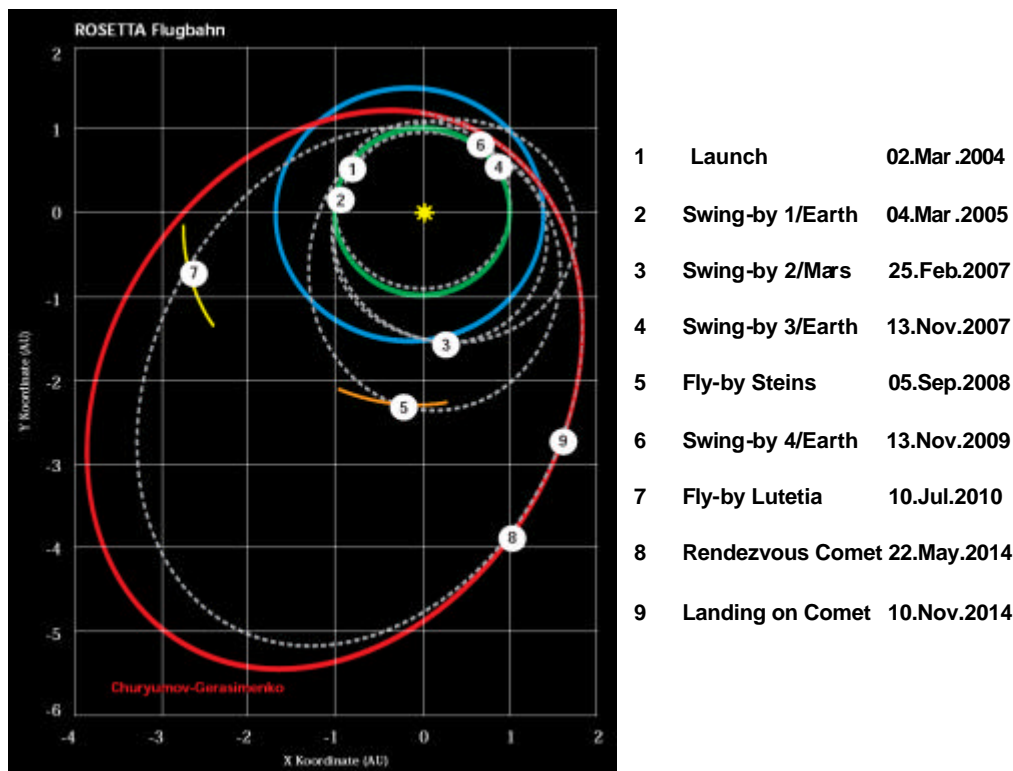


Figure 1: The ROSETTA Mission Plan in a Nutshell (copyright DLR).

ESA's ROSETTA project was started in 1993 with the aim to launch the mission in 2003 for an arrival at Comet 46P/Wirtanen in 2012. However, the launch of ROSETTA from Kourou had to be delayed by one full year due to problems with the launcher rocket, an ARIANE 5. As a consequence of the delay, a new suitable target comet had to be found among the small sample of objects accessible for space missions, and the ROSETTA mission required complete re-planning and re-scheduling. Finally, on 2nd March 2004 ROSETTA was launched successfully into interplanetary orbit and is now heading for the new target, Comet 67P/Churyumov-Gerasimenko. The spacecraft will travel for more than ten years, until it will rendezvous with the comet in August

2014. For the first time ever, ROSETTA will explore a comet in orbit (all other comet mission were fast fly-bys) on its way to perihelion from about 4 to 1.2 AU (1 AU = one astronomical unit = mean distance between Earth and Sun), i.e. ROSETTA will allow to investigate the comet from a very close distance (a few kilometers) and over a long period of time (about 1 ½ years). Another “first” and scientifically maybe even more important: In November 2014 ROSETTA will drop a lander spacecraft, called PHILAE, on the comet that will analyze the nucleus and its surface in-situ. On its way to the comet, ROSETTA will also visit two asteroids (2867 Steins in 2008 and 21 Lutetia in 2010) and will swing-by at the Earth (three times) and at planet Mars (see Fig. 1).

The ROSETTA orbiter carries a suite of eleven scientific instruments for remote sensing of the nucleus, its surface and interior, and for in-situ exploration of the cometary atmosphere, its gas, plasma and dust content, and the magnetic field. PHILAE has another ten experiments onboard for in-situ imaging and scientific measurements of the nuclear surface and of the surface material. Table 1 provides a summary of the ROSETTA and PHILAE instruments. The sections below will try to briefly outline the key points of the current paradigm of comets and to highlight some ROSETTA experiments that are expected to provide answers to the related scientific issues. For further details and in particular for information on experiments not described in greater detail here, we refer the reader to ESA’s ROSETTA web page.

The Comet Paradigm

Comets that we observe from Earth, orbit the Sun in eccentric orbits. The nucleus, the source of the comet phenomenon, contains a mixture of frozen gases - so called volatile ices: mostly H₂O, CO and minor species, many of them still unknown - and of stony compounds - so called non-volatile solids: dust grains from sub-micron to centimeter size and possibly also larger boulders up to tens of meters in size. During most of its revolution around the Sun, the nucleus is deeply frozen at temperatures below 100 K, and it is only when it gets close to the Sun that surface and sub-surface material sublimates (for instance H₂O ice at solar distances smaller than ~3 AU), thus producing a diffusing non-permanent atmosphere of gas and dust around the nucleus (Fig. 2).

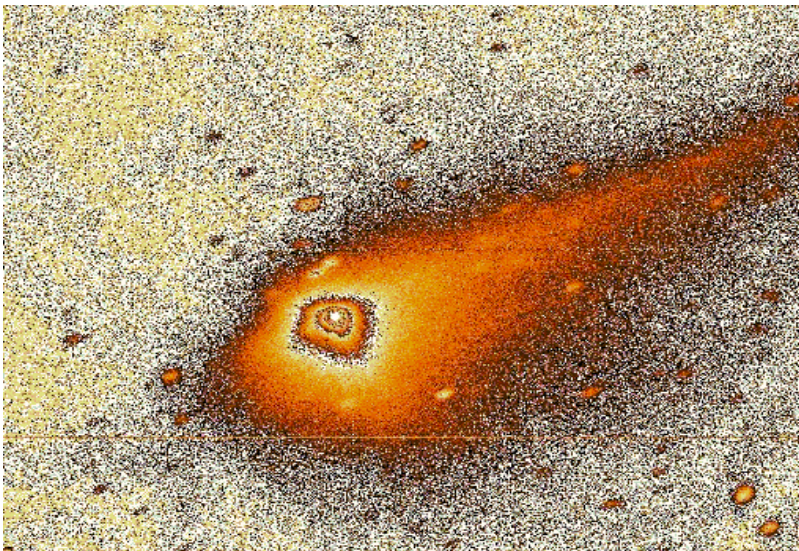


Figure 2: The ROSETTA Target Comet 67P/Churyumov-Gerasimenko. The nucleus of about 5 km size is hidden in the coma of gas and dust produced by sublimation of the volatile ices when the surface is heated by the Sun during the perihelion arc of its orbit. The coma extends over several 100 000 km distance and is diffusing into interplanetary space, i.e. for the gas by simple expansion and attenuation, for the dust by radiation pressure forming a narrow dust tail. Asymmetric isophotes in the coma indicate localized activity centers on the nucleus (copyright ESO/MPS Hermann Boehnhardt).

Comets are believed to originate from the formation disk of the planetary system around the Sun some 4.6 billion years ago, most likely before the run-away growth of the planets had started. The frozen character of comets argues for a formation distance beyond 4-5 AU from the Sun. Nowadays, comets are ‘stored in two reservoirs’, i.e. the Oort Cloud somewhere beyond 5000 AU and the Kuiper Belt at distances of 40-50 AU from the Sun (Fig. 3). Only the latter region, the Kuiper Belt, is also considered as birthplace of the comets that are still found there today, although it has lost with time the vast majority of its original mass (> 95 percent). The Oort Cloud instead did not exist at the time when the comets were formed and it was populated only after the formation of the outer planets which scattered comets, formed at solar distances of 5-30 AU, into the outskirts of the solar system. Comets from the Oort Cloud, also called long-period or new comets (revolution periods of hundreds to millions of years), are scattered towards the inner solar system by gravitational interaction with the Galactic neighborhood of the Sun, while comets from the Kuiper Belt, also called short-period comets (revolution periods of typically less than ten years), are cascading inward by repeated interaction with the major planets.

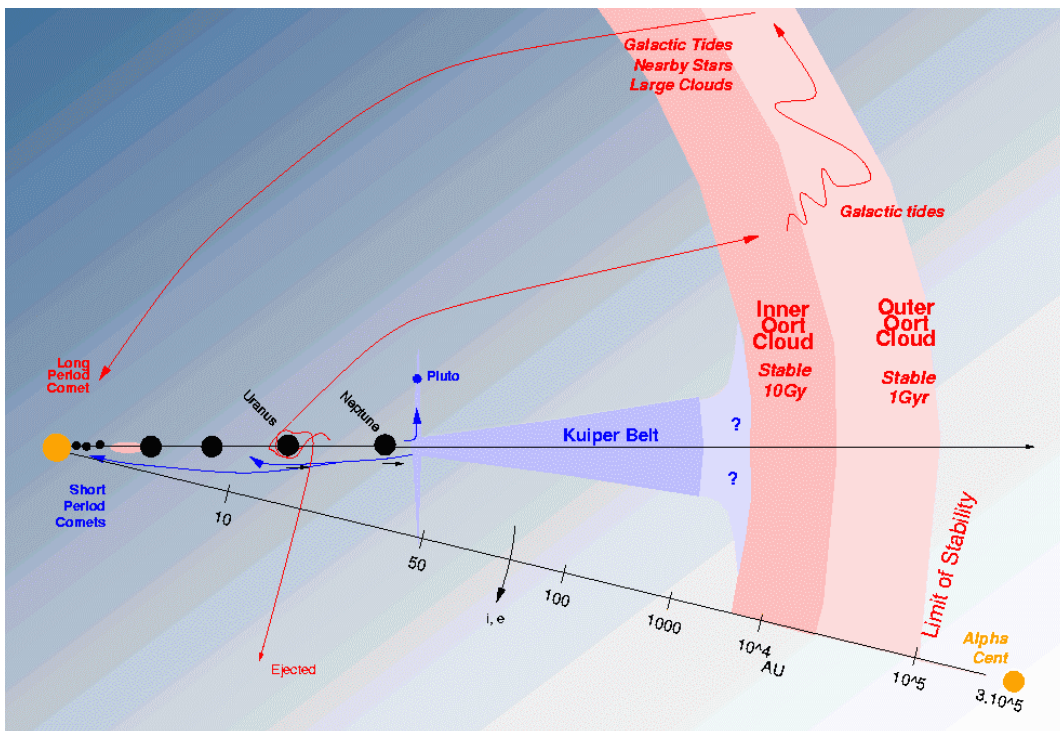


Figure 3: Schematic View of the Outer Solar System and of the Migration Processes Affecting Comets over the Lifetime in the Solar System (adapted from Olivier Hainaut).

The formation process in the planetary disk has apparently produced bodies of up to 1000 km in size (Pluto is to be considered one of the largest remnant of this kind). The majority of cometary nuclei is smaller in size (a few 100 meters up to 20 kilometers), and it may thus resemble a mixture of the size distributions produced by the original growth process in the formation disk and the destroying collisions during the subsequent disk clean-up. However, there is no doubt that comets have preserved the memory from their formation period and have evolved only very little and only in the upper surface layers (orders of few meters): They remained deeply frozen and unchanged due to the cold environment in the outer planetary system and beyond, where they come from and remain in for their whole lifetime except the few months per revolution when they get closer than ~5 AU to the Sun. The mass loss due to activity amounts to typically of the order of 1 m in radius per revolution. Thus, short-period comets have a relatively short lifetime of only a few 1000 to 100 000 years and must be continuously supplied from the Kuiper Belt.

Cometary and Solar System Science with ROSETTA

Comet 67P/Churyumov-Gerasimenko (Fig. 2), the ROSETTA target comet, is a short-period comet coming most likely from the Kuiper Belt. Its physical properties may thus reflect the conditions prevailing in this region at the time of formation and ever since. The ROSETTA mission with an orbiting and a landing spacecraft will provide a unique opportunity (1) to study, in a range of scales and in great detail, the physical processes and properties of a comet that are still not very well understood, and (2) to reveal some of the basic properties and conditions at the time of the comet formation in the outer planetary disk. To put it into a technical analogue of a steam engine: mission goal (1) is to understand how a steam engine works and which technical specifications it has; mission goal (2) is to find out information about the workshop and its environment that has built the engine.

Short-period comets seem to display a wide variety of body shapes and surface structures as is indicated from the images of three fly-by mission and from Earth-based observations. Naturally, OSIRIS, the ultraviolet and visible imaging system onboard the ROSETTA orbiter and comprising a wide- and a narrow-angle camera with adapted cometary filter sets, will play a crucial role for the scientific goals to measure the shape and geology of the body. The unprecedented pixel resolution of 2 cm combined with the global, local and mineralogical mapping capabilities of the camera system will provide a rich framework of images to analyze the action of low-gravity icy geology, impacts, internal activity, and space weathering on a primordial body in the solar system. Certainly, a very challenging goal of the OSIRIS team is to disentangle which signatures from the formation period of the body still exist and what is to be attributed to its subsequent evolution and if so, which process is responsible for it. The camera will also be the 'eye of the mission' looking into the cometary coma and tail (for an early science example see Fig. 4) and will provide links with gas and dust features therein that are explored by other instruments, for instance by ALICE, VIRTIS, MIRO, ROSINA, COSIMA, GIADA. In turn, ALICE and VIRTIS, the ultraviolet and visible/near-infrared imaging spectrometers, respectively, will focus on the determination of the gas production by the nucleus (major constituents and less abundant ices) as well as on the global surface mineralogy. A particular interesting issue is the detection of parent species and their abundances of trace gases. Some of these gases (for instance noble gases) can provide clues on the temperature and pressure conditions in the region of the comet formation, others (for instance the still unknown parents of the C₂ and C₃ gas in the coma that is known since the very first spectra of comets were taken more than 100 years ago) will be instrumental to address the question of organic material in comets. MIRO, a microwave spectrometer, will measure the production of major coma gases (for instance H₂O, CO), the sub-surface temperature (down to a few centimeters), the gas velocity and the abundance of water isotopes in comets. The production rates and temperature measurements will have immediate impact on the physical understanding of the cometary surface activity. The gas velocity data will allow modeling the gas interaction and dynamics in the coma. The water isotopes measurement will address the mixing ratio in the formation disk and may provide ground truth for the long lasting debate on the contribution of comets to the ocean water on Earth. Finally, RPC, the plasma and magnetic field experiment package onboard ROSETTA, will address through a variety of instruments the electrical properties of the surface, the environment of charged particles and the magnetic field in the cometary coma and tail and its interaction with the solar wind.



Figure 4: Comet C/2002 T7 (LINEAR). Image taken with the OSIRIS camera onboard ROSETTA - an early science return from the spacecraft obtained during instrument commissioning shortly after launch (copyright ESA/MPG/ H.U. Keller).

CONSERT, the radio sounding experiment, and RSI, the radio science investigation, are two peculiar remote sensing instruments: CONSERT is a dual transmitter-receiver instrument with one part hosted onboard the ROSETTA orbiter, the other one on the lander PHILAE. The CONSERT radio link between orbiter and lander, on purpose, will pass through the nucleus body thus allowing to measure the radio wave scattering and from that the dielectric properties of the nucleus material and - most important and absolutely unique - to assess the internal structure of the body (existence voids, mass concentrations, sub-structures). Constraining the intrinsic global mass distribution and the existence of generic sub-units in the nucleus will have tremendous impact on the modeling scenarios of the planetary formation disk. RSI will use Doppler shift and ranging of the radio link between ROSETTA and the ground station on Earth to determine the mass and the gravitational field parameter of the nucleus. With the shape information from OSIRIS and the nucleus mass value from RSI it will be possible for the first time ever to determine the bulk density of a comet, a basic physical parameter of the nucleus with great impact on the understanding of its formation environment. Moreover, the gravity field parameters may tell about the internal mass distribution, thus providing complementary information to the efforts of CONSERT and OSIRIS for the characterization of the cometary interior.

Information on the chemical composition of the gas and dust in Comet 67P/Churyumov-Gerasimenko will be obtained by ROSINA and COSIMA, respectively. Both experiments will apply time-of-flight mass spectroscopy to measure the atomic, molecular and isotopic composition of coma material. The design and resolution of the instruments will allow the detection of trace species, namely of interest of organic compounds. Results of GIOTTO experiments at Comet 1P/Halley suggest the existence of CHON-rich dust and of heavy chain or ring carbonized molecules. GIADA and MIDAS, instead, focus exclusively on the dust component in the comet. GIADA is a particle counter system that measures the number, mass, and velocity of the dust grains encountered by the spacecraft. MIDAS has a closer microscopic look to individual grains collected on a test surface, thus providing information on their shape, structure, volume and mass. Although the dust emitted from the surface may display evolutionary effects, there is hope in particular for MIDAS that primordial grains that had entered into the planetary formation disk, might be distinguishable from others.

The PHILAE lander (Fig. 5) will put, for the first time ever, scientific experiments on a comet. The PHILAE mission is technically very challenging and operationally not without risk, since it means to land on a comet body about which not much is known to the detailed level one would like to have for the design and manufacturing of the spacecraft and its instruments. Moreover, due to the unforeseen change of target, the landing scenario got further complicated, since landing is now to be done on a larger and more active comet. After all, PHILAE is not a suicidal enterprise and has a high chance for success and, if successful, it will provide the long-expected, scientifically essential, possibly unpredictable and surprising ground-truth on the cometary material. PHILAE brings the experiments in touch with the comet and it brings surface material in touch with man-made lab equipment.



Figure 5: Artist Impression of the PHILAE Lander at the Comet (copyright ESA).

The ten PHILAE experiments (this includes the lander part of the CONSERT orbiter instrument, see above) are devoted to the analysis of the composition, of the physical properties and to the characterization of the local and global environment of the nucleus and its surface (Tab. 1). An important pre-requisite of several PHILAE experiments is the drill SD2 which has the main task to supply the lab equipment onboard the lander with samples of cometary material from the surface and underneath. The drill itself is also to be seen as a scientific instrument allowing active measurements of mechanical properties like the tensile strength of the material. Further special sensors (MUPUS and SESAME) complement the characterization of the cometary material and of the surface as a whole in terms of basic physical properties like density, heat and electrical conductivity. ROLIS and CIVA, two imaging systems, will take images of the landing site (panoramic view by CIVA, local surface view by ROLIS) and will also allow the study of the porosity and grain structure as well as mineralogical composition of the surface or sub-surface material. ROMAP and SESAME are to be seen as the PHILAE counterparts to the RPC instrument onboard the ROSETTA orbiter, i.e. to measure the plasma and magnetic environment at the surface of a comet.

Table 1: The Complement of Scientific Experiments onboard the ROSETTA Orbiter and onboard the PHILAE Lander.

ROSETTA Orbiter Instrument Name	ROSETTA Orbiter Instrument Type
ALICE	Ultraviolet Imaging Spectrometer
CONSERT	Comet Nucleus Sounding Orbiter Part
COSIMA	Cometary Secondary Ion Mass Analyser

GIADA	Grain Impact Analyser and Dust Accumulator
MIDAS	Micro-Imaging Analysis System
MIRO	Microwave Instrument for the Rosetta Orbiter
OSIRIS	Rosetta Orbiter Imaging System
ROSINA	Rosetta Orbiter Spectrometer for Ion and Neutral Analysis
RPC	Rosetta Plasma Consortium
RSI	Radio Science Investigation
VIRTIS	Visible and Infrared Mapping Spectrometer
PHILAE Lander	PHILAE Lander
Instrument Name	Instrument Type
APXS	Alpha Proton X-ray Spectrometer
ÇIVA	Rosetta Lander Imaging System I
CONSERT	Comet Nucleus Sounding Lander Part
COSAC	Cometary Sampling and Composition Experiment
PTOLEMY	Evolved Gas Analyser
MUPUS	Multi-Purpose Sensor for Surface and Subsurface Science
ROLIS	Rosetta Lander Imaging System II
ROMAP	Roland Magnetometer and Plasma Monitor
SD2	Sample and Distribution Device
SESAME	Surface Electrical and Accoustic Monitoring Experiment, Dust Impact Monitor

A set of three experiments onboard PHILAE will focus through X-ray (APXS) and time-of-flight mass spectroscopy as well as gas chromatography (PTOLEMY, COSAC) on the elemental, isotopic, and molecular composition of cometary material using surface and sub-surface samples from the SD2 drill. Evidently, the ultimate scientific motivation for all three experiments is to find the imprints in cometary matter from the formation period of the solar system, on the first place what the primordial composition was. Beyond that, COSAC carries a very interesting experimental add-on: It will allow to measure through special gas-chromatographic columns the chirality of cometary molecules and it is capable of detecting aminoacid-type compounds. Behind this life science question stands of course the scenario, whether or not comets may have played a role in the formation of life on Earth through supplying biologically important molecular ingredients by impacts of cometary nuclei on Earth during the period of the heavy bombardment (about the first billion years after formation of the planets) and/or through a continuous and destruction-free deposition of small dust grains that originate from comets and are collected by the Earth from interplanetary space on its revolutions around the Sun.