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Progress in Physics (46)

Rosetta – a journey back to our origin

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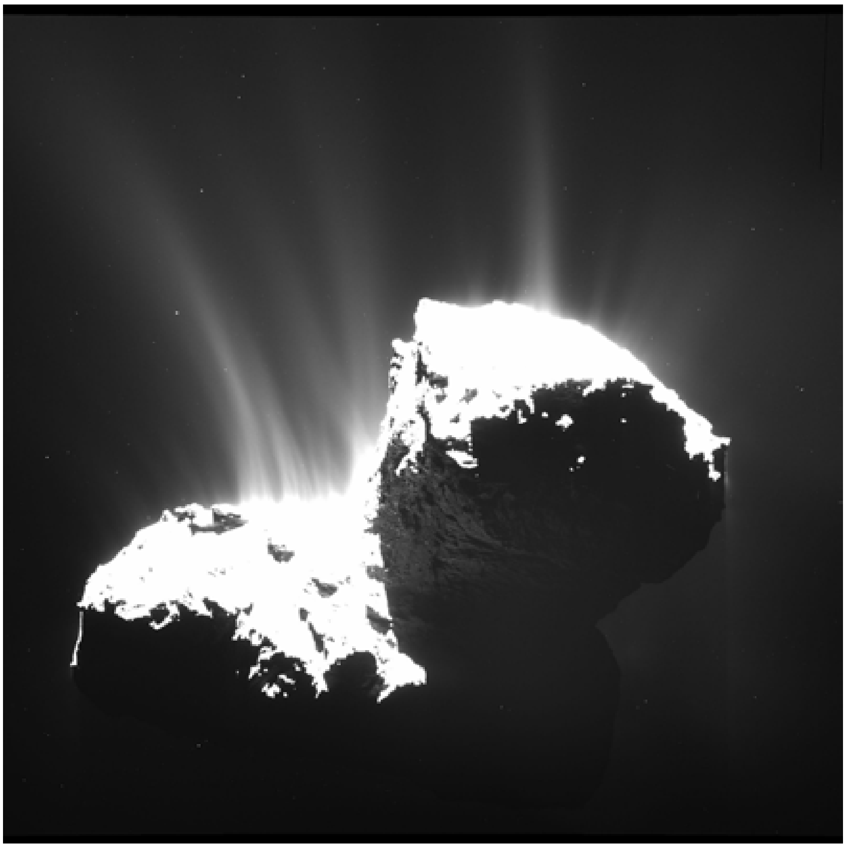

OSIRIS wide-angle camera image acquired on 22 November 2014 from a distance of 30 km from Comet 67P/Churyumov-Gerasimenko. The image resolution is 2.8 m/pixel. The nucleus is deliberately overexposed in order to reveal the faint jets of activity. See p. 11 for the article.

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

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Comets are the oldest, most primitive bodies in the Solar System, preserving the earliest record of material from the nebula out of which our Sun and planets were formed. Planets have gone through chemical transformations, but comets have remained almost unchanged. The comet's composition reflects the composition of the pre-solar nebula out of which the Sun and the planets of the Solar System formed, more than 4.6 billion years ago. Furthermore, comets may have brought volatile light elements to the planets and may have played an important role in forming oceans and atmospheres. Comets also carry complex organic molecules that may have been involved in the origin of life on Earth. The prime objective of the European cometary space probe Rosetta is therefore to help understand the origin and evolution of the Solar System.

Although there were several cometary missions in the past, all of them were flyby missions. Rosetta is the first mission which rendezvous with a comet and accompanies the comet from far out through its perihelion passage, therefore witnessing the evolution of cometary activity when it gets closer to the Sun and being able to monitor changes on the nucleus and in the coma during its perihelion passage.

On January 13, 2003 Rosetta should have been launched from Kourou, French Guyana on an Ariane 5 rocket. Shortly before an Ariane 5 rocket failed and the launch of Rosetta was postponed. The target comet, *46P Wirtanen* did not wait and scientists had to look for a new target, which they found in comet *67P/Churyumov-Gerasikmenko.* This comet is roughly 4 times the size of *46P* and needed three Earth flybys instead of only two and a Mars flyby to reach its orbit. It's a Kuiper belt comet, coming to the inner solar system since 1959 after an encounter with Jupiter with an orbital period of 6.5 years, a perihelion distance of 1.29 AU and an aphelion distance of 5.52 AU.

On March 2, 2004 Rosetta was finally sent on its 10 year journey with a perfect launch. The idea for the mission, however, was much older. The first ideas came from the 1980s when a comet sample return mission was planned as joint mission between NASA and the European Space Agency ESA. It was the time when the return of the most famous comet, comet *Halley* was imminent and the first cometary missions ever were planned, among them the Giotto mission of ESA. Giotto, although only a very fast (68 km/s) flyby mission lasting a few hours was a huge success, for the first time detecting a cometary nucleus, for the first time determining the deuterium content in cometary water and for the first time detecting that a comet contains organic material like methanol and formaldehyde. When NASA abandoned the cooperation on Rosetta the Europeans decided to go for a comet rendezvous mission only, but containing two landers, a US – French led one and a German one. In 1995 the announcement of opportunity for the payload was launched and 10 scientific instruments were selected, among them the ROSINA instrument, a Swiss led instrument for the chemical analysis of the volatile material in the coma of the comet. After the one year confirmation phase unfortunately NASA drew back from the lander which left only one lander (French – German). Rosetta was a rare mission in so far that it was ready on time. Details on the Rosetta mission design can be found in Glassmeier et al., 2007.

As part of the core payload of the Rosetta mission, the Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA) was designed to answer outstanding que-

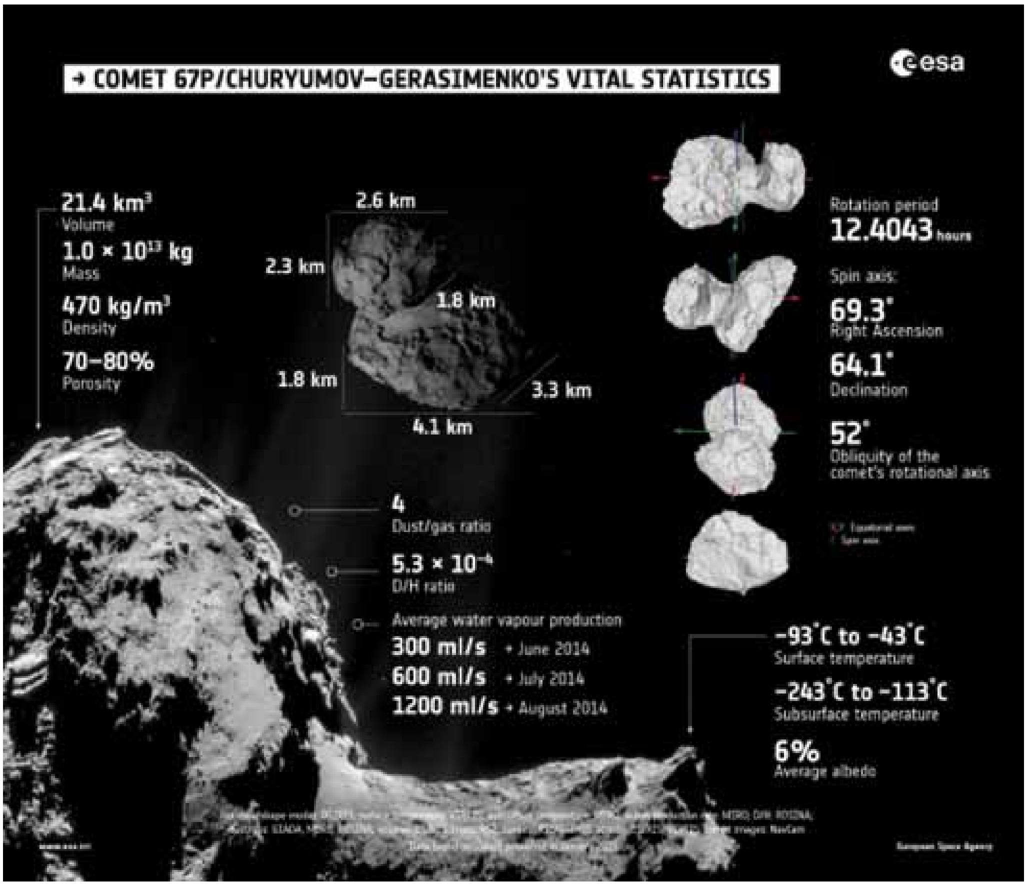

Figure 1: infographic comet 67P, Credits for individual results: Shape model, rotation properties, volume and porosity: OSIRIS, Mass: RSI, Density: RSI/OSIRIS, Dust/Gas ratio: GIADA, MIRO and ROSINA, D/H ratio: ROSINA, Surface temperature: VIRTIS, Subsurface temperature and water vapour production rate: MIRO, Albedo: OSIRIS and VIRTIS, Comet images: NavCam, Infographic credit: ESA

stions posed by the Rosetta mission's main objectives. The spectrometer's primary objective is to determine the elemental, isotopic and molecular composition of the comet's atmosphere and ionosphere, as well as the temperature and bulk velocity of the gas and the homogenous and inhomogeneous reactions of the gas and ions in the dusty cometary atmosphere and ionosphere.

To accomplish these very demanding objectives, ROSINA has unprecedented capabilities, including very wide mass range, from 1 Da (Hydrogen) to >300 Da (organic molecules); very high mass resolution (>3000 m/Δm) (ability to resolve CO from N_2 and ^{13}C from ^{12}CH); very wide dynamic range (10^{10}) and high sensitivity ($>10^{-5}$ A/mbar) to accommodate very large differences in ion and neutral gas concentrations and large changes in the ion and gas flux as the comet changes activity between aphelion and perihelion; and the ability to determine the outflowing cometary gas flow velocities.

A 3-sensor approach has been adopted: each sensor is optimized for part of the scientific objectives while complementing the other sensors. In view of the very long mission this approach also provides redundancy.

DFMS is a double focusing magnetic mass spectrometer with a mass range 1- 150 Da and a mass resolution of 3000 at 1 % peak height. It is optimized for very high mass resolution and large dynamic range;

RTOF is a reflectron type time-of-flight mass spectrometer with a mass range 1 to >300 Da and a high sensitivity. The mass resolution is better than 500 at 1 % peak height. It is optimized for high sensitivity over a very broad mass range;

COPS consists of two pressure gauges providing density and velocity measurements of the cometary gas.

Details on the instrument can be found in Balsiger et al., 2007.

After the long journey of more than 10 years, after two encounters with asteroids (Steins and Lutetia), after a long hibernation period with no contact between space probe and Earth, and after some big very precise manoeuvers Rosetta finally reached the orbit of the comet in August 2014. Pictures of the comet in summer 2014 revealed an astonishing sight (Figure 1): the comet is a very irregular object, resembling a rubber duck. It seems to be composed of two planetesimals although scientists are speculating if there are really two different planetesimals which collided or if the irregular shape is due to erosion. The comet has a spin period of 12.4 h and a somehow oblique spin axis which makes for seasonal effects on the comet. Early August the spacecraft S/C was at 100 km from the nucleus and the relative speeds were almost zero. At that time the ROSINA instrument started to sniff the sublimated cometary gases. Figure 2 shows measurements by the ROSINA COPS sensors of the total density of the coma. What can be clearly seen is that there is a diurnal (longitude) as well as a seasonal (latitude) variation. The diurnal variation can be explained by the irregular shape: the area facing the S/C and their illumination condition change during a cometary day giving a large peak every 12.4 h and a smaller one in between. The peaks happen when the S/C is facing the side of the "duck". The larger variations reflect seasonal effects. When the S/C is over the summer hemisphere (positive latitudes) the outgassing is much larger than over the winter hemisphere. Surprisingly there is also quite some compositional heterogeneity in the coma of the comet. Most of the times water is the dominant species, but especially over the winter hemisphere it's sometimes also CO or CO_2. This can probably be attributed to the different sublimation temperatures of these species (Hässig et al., 2015). What was also very surprising was the rich chemical composition of the coma. Besides the abundant species H_2O (100%), CO (~20%), CO_2 (~6%) especially sulphur bearing species are quite abundant. H_2S, OCS, CS_2, SO_2 and S_2 are clearly identified by the mass spectrometers. These species have all been detected in other comets, all from the Oort cloud, but never at distances from the Sun as far as 3.5 AU. Apart from sulphur bearing species there is also ammonia, cyanide and methanol together with a variety of heavier species which still have to be identified. It can be said that the comet actually "stinks" although the densities of course are very low.

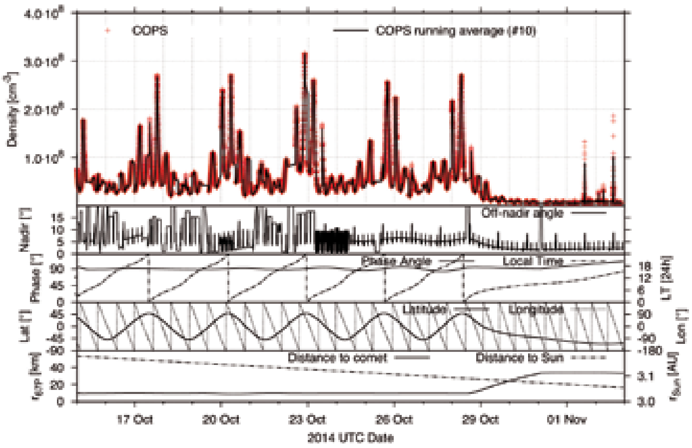

Figure 2: total density measured by ROSINA-COPS, when the spacecraft was 10 km from the cometary nucleus.

During the 10 years' cruise phase, whenever the instruments were tested, there were quite a lot of background gases from Rosetta. They also showed a rich chemistry: from water to fragments of solvents, adhesives, a lot of hydrocarbons, fragments of vacuum grease which is used to lubricate the antenna joints and to the products of the hydrazine burning (Schläppi et al., 2012) were detected on the order of 10^5 cm^3. Although this of course needs special attention when analysing the cometary signal it allowed te-

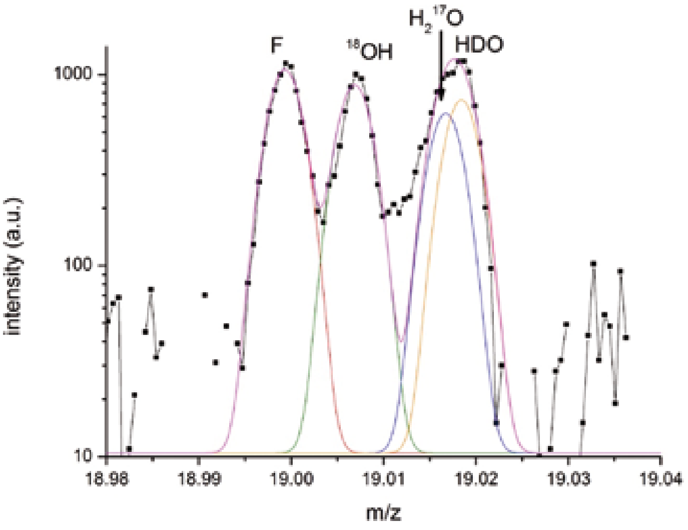

Figure 3: Mass spectrum of m/z 19 measured by ROSINA-DFMS in May 2014, >800'000 km from the comet.

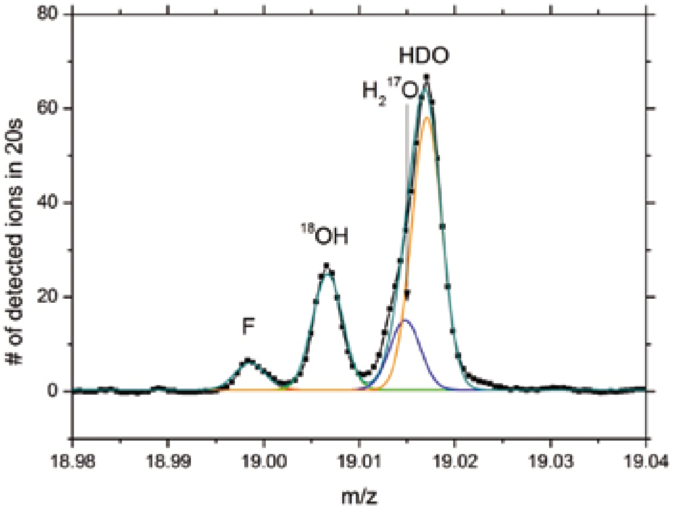

Figure 4: mass spectrum of m/z 19 ca. 50 km from the cometary nucleus, measured by ROSINA-DFMS.

sting the performance of the instruments already during the cruise phase. It was even possible to determine the deuterium to hydrogen (D/H) ratio in the background water of Rosetta (Figure 3). Once inside of 100 km from the comet where cometary water clearly dominated the background water it became immediately clear from the signals on mass 19 Da that the D/H from the comet differs significantly from terrestrial water (Figure 4). On mass 19 Da there are four peaks: Fluorine, a fragment of vacuum grease, ^{18}OH, a fragment of $H_2{}^{18}O$, $H_2{}^{17}O$ and HDO. The mass spectrometer produces well defined peaks where the width of the Gaussian does not change with position on the detector. Therefore all peaks have the same width, the masses are known which then leaves only the amplitude as a variable. With this $H_2{}^{17}O$ and HDO can clearly be separated. Prior to arrival at the comet all four peaks had roughly the same amplitude which of course is a coincidence. Once at the comet the HDO peak got significantly higher than the others, while Fluorine stayed constant, reflecting its origin from the S/C. Detailed analysis showed a D/H ratio in cometary water of $5.3 \pm 0.7 \times 10^{-4}$, or more than three times terrestrial. This means that comets like *67P/C-G* cannot be the only providers of terrestrial water. It also means that Jupiter family comets probably have a very diverse origin as the only Jupiter family comet, *Hartley 2*, where D/H was measured so far, has a terrestrial ratio (Hartogh et al., 2011). The new measurements make it more likely that terrestrial water was supplied by asteroids to the Earth and/or that the Earth kept some of its primordial water.

During August to end of October 2014 Rosetta went closer and closer to the cometary nucleus, finally reaching a bound 10 km orbit which allowed high resolution images of its surface revealing quite an astonishing morphology (Thomas et al., 2015). This was also necessary to find a spot on the nucleus where Philae, the lander, could land. For such an irregular object this was not an easy task. It was clear that landing would be risky. On November 12, Philae was released from the orbiter at an altitude of 22 km. Philae itself is completely passive and could not alter its trajectory down to the comet, which was governed by the very low gravity of the comet alone. It took the lander all of seven hours to reach the cometary surface with a speed of roughly 1 m/s. However it hit the comet at exactly the right position. Unfortunately the harpoons to anchor the lander to the comet did not fire and the thruster which should have kept the lander down did also not operate. This led to a bouncing of the lander from the surface (Figure 5), reaching again roughly an altitude of 1 km and finally landing, after two more bounces 1 kilometre from its first landing site. However, despite its unplanned hopping over the cometary surface the lander measured successfully for more than 60 h, being able to communicate as foreseen with the orbiter. After this time the primary batteries were empty. Because the lander sits in the shadow of a cliff somewhere in a dip the solar illumination is currently not strong and long enough to recharge the batteries. Although the results are not yet analysed in detail it can be said today that landing was a full success. Due to the seasonal variations on the cometary surface it might even be possible that the lander becomes active again after May 2015 and could then stay active through perihelion in August.

Meanwhile Rosetta continues its journey around the comet as the comet gets slowly more active. There certainly are more surprises coming from this spectacular mission around a very ancient object of our solar system.

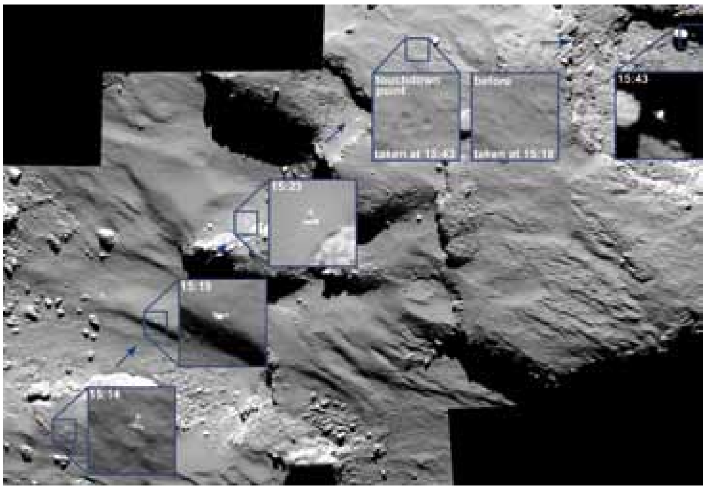

Figure 5: first landing of Philae. A series of OSIRIS pictures shows Philae shortly before landing approaching the landing site (landing at 15:34h) and shortly after flying away. At the landing site three depression show the impact by Philae. Credit: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA

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