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Philae Landing on Comet 67P/Churyumov-Gerasimenko – Planned Chirality Measurements and Ideas for the Future

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Abstract

Philae is a comet Lander, part of the ESA Rosetta Mission to comet 67P/Churyumov-Gerasimenko. After a ten year cruise through the solar system it successfully landed on the nucleus of the comet on November 12, 2014.

Philae's payload consists of ten scientific instruments, including COSAC, an evolved gas analyser with the capability to differentiate chiral molecules. After the touchdown of Philae, the anchoring harpoons, which were expected to fix the lander to ground, did not work, Philae bounced in the low gravity environment, and only came to rest after a 2 hours "hop" in an unforeseen area on the comet surface. Although, the scientific instruments, including cameras, mass spectrometers (including the one of COSAC), a magnetometer and a radar instrument could be operated, and fascinating, unprecedented scientific results were obtained, it was not possible to collect a sample of the surface material and no gas chromatography measurement could be performed. Thus, the measurement of the chirality of molecules on comets is still to be done in the future.

The paper gives an overview of the Philae mission and the attempts to measure chiral molecules with COSAC, and suggests future measurements with returned samples from the primitive asteroids (162173) Ryugu and (101955) Bennu with the spacecraft Hayabusa 2 (JAXA) and OSIRIS-REx (NASA), respectively. Both will reach their targets in 2018.

Keywords

Comets; Rosetta; Philae; COSAC; Chirality.

I INTRODUCTION

Rosetta was a Cornerstone Mission of the ESA Horizon 2000 programme (Glaßmeier *et al.*, 2007). The mission was launched from Kourou in March 2004 and did rendezvous with comet 67P/Churyumov-Gerasimenko (later referred to as 67P) in August 2014 after a ten year cruise, including three Earth gravity assist maneuvers, one at Mars and two asteroid fly-bys. After arrival at the comet, both its nucleus and coma were studied in great detail. The mission is still dramatically improving our understanding of the formation and evolution of the Solar System as well as the origin of life by investigating a comet both from orbit as well as in-situ with its Lander, Philae.

The Rosetta mission is in tradition with ESA's Giotto mission to comet 1P/Halley, and indeed, the idea for a more detailed investigation of a cometary nucleus was introduced already before Giotto's historic flyby in 1986. When Rosetta was defined by ESA as the third Cornerstone mission within the Science Program, two Surface Packages were proposed (Champollion and RoLand) which later were amalgamated to the Rosetta Lander design (Ulamec, 2009). An illustration of the Philae Lander is given in Fig. 1.

Rosetta is an ESA mission with contributions from its member states and NASA. Rosetta's Philae Lander was provided by a consortium led by DLR, MPS, CNES and ASI with additional contributions from Hungary, UK, Finland, Ireland and Austria.

II PHILAE LANDING

2.1 Philae Lander design

The Philae Lander, which has an overall mass of about 98 kg (including 26.7 kg of science payload) was based on a carbon fibre/aluminum honeycomb structure, a power system including a solar generator, primary- and secondary batteries, a central data management system and an S-band communications system, which had to rely on the Rosetta Orbiter as relay. The thermal control system of the Lander was designed to keep the so called "warm compartment" (thermally insulated experiment platform underneath the hood) within an acceptable temperature range (-55° to $+70^{\circ}\text{C}$) on the comet nucleus at distances between 3 and 2 AU from the Sun, assuming about 50% insolation per comet rotation (which was not the case at Philae's final landing site, later named "Abydos"). This was challenging as no radioactive heater units (RHU's) were used. Since at Abydos Philae was only illuminated for less than 1.5 h per comet rotation (about 12.4 h), the Lander went into an unforeseen hibernation and its interior is expected to have cooled down far below qualification limits, probably below -100°C .

During cruise the Lander was fixed to the Orbiter with the MSS (Mechanical Support System) which also included the push-off device, consisting of three lead screws; their rotation separated the Lander from the Orbiter.

On the comet surface, it was planned that Philae would rest on a landing gear forming a tripod. This tripod was connected to the structure by a mechanism that allowed rotation of the complete Lander above its legs. It was designed to dissipate most of the kinetic impact energy during landing by a damping mechanism, and indeed reduced the bounce significantly. Attached to the landing gear were two anchoring harpoons, supposed to fire immediately after touch-down to fix the lander to the comet surface. In addition a cold gas system was supposed

to give a hold down thrust and press Philae to the surface. Neither harpoons nor cold gas system did work, which led to the “hop” as described below.

For a more detailed description of the Philae Lander see e.g. Ulamec *et al.* 2006 or Biele and Ulamec 2008.

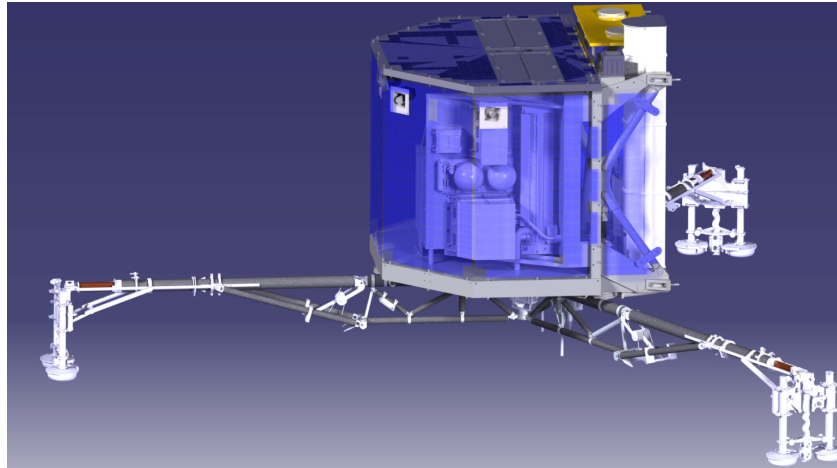


Figure 1: Philae Lander with its 3 legs, feet, ice-screws, harpoons, and the drill SD² on the right. The COSAC instrument with its sphere-shaped gas tanks is visible, here, below the solar panels. The distance from foot to foot is about 2 m.

2.2 Delivery and touch-down.

Philae was separated from the Rosetta main spacecraft on November 12th, 2014 and touched the comet surface after seven hours of descent. As both, a cold gas system as well as the two anchoring harpoons failed, the lander bounced off and only came to rest after a leap of about 2 hours, approximately one kilometre from the originally targeted site (Biele *et al.*, 2015). Despite the fact that Philae was not anchored at its final landing site, Abydos, which turned out to be poorly illuminated, the lander was operational for almost 64 hours after separation and provided unique information from the surface of the comet. All ten instruments aboard could be operated at least once. First scientific results including those from COSAC, were published e.g. in the Special Issue in *Science* 349, 2015, a review is given by Böhnhardt *et al.* 2017. The dynamics of the bounce could be reconstructed a-posteriori in detail, using data from the on board magnetometer, ROMAP (Heinisch *et al.* 2016).

When the first touch-down happened at “Agilkia”, the Philae system started a pre-programmed first science sequence (FSS), including measurements with the mass spectrometers of both evolved gas analysers, COSAC and Ptolemy, in “sniffing mode”. As it appears, some surface material was introduced into the venting systems of the evolved gas analysers, where they were exposed to the lander internal temperatures (~12°-15°C) and excellent mass spectra were obtained with both instruments, while the lander was leaping (Goesmann *et al.*, 2015; Wright, *et al.* 2015). No gas chromatography was performed in this phase.

2.3 Lander search and final position

During the FSS activities, besides of science operations, there have also been close interactions between ESA Flight Dynamics and the Philae team, in particular the CONSERT team to try to triangulate the location of the lander on the comet. And indeed, the final landing site could be

restricted to a region on the edge of the Hatmehit crater (for nomenclature of surface areas see Thomas *et al.*, 2015).

Further work in the months after landing by CONSERT led to a result with the location of the lander defined within an ellipse measuring 16 x 160m² (Herique *et al.*, 2015).

It was only very shortly before the end of the Rosetta mission, on September 2nd, 2016 that an image by OSIRIS unambiguously showed the Lander at Abydos (Fig. 2), laying within a cavity, which explained the poor illumination as well as problems to re-establish a communications link during summer 2015 (Ulamec *et al.*, 2017, O'Rourke *et al.*, 2018). The exact location which was within the error ellipse as defined by CONSERT had already been proposed by Lamy *et al.* in 2015.

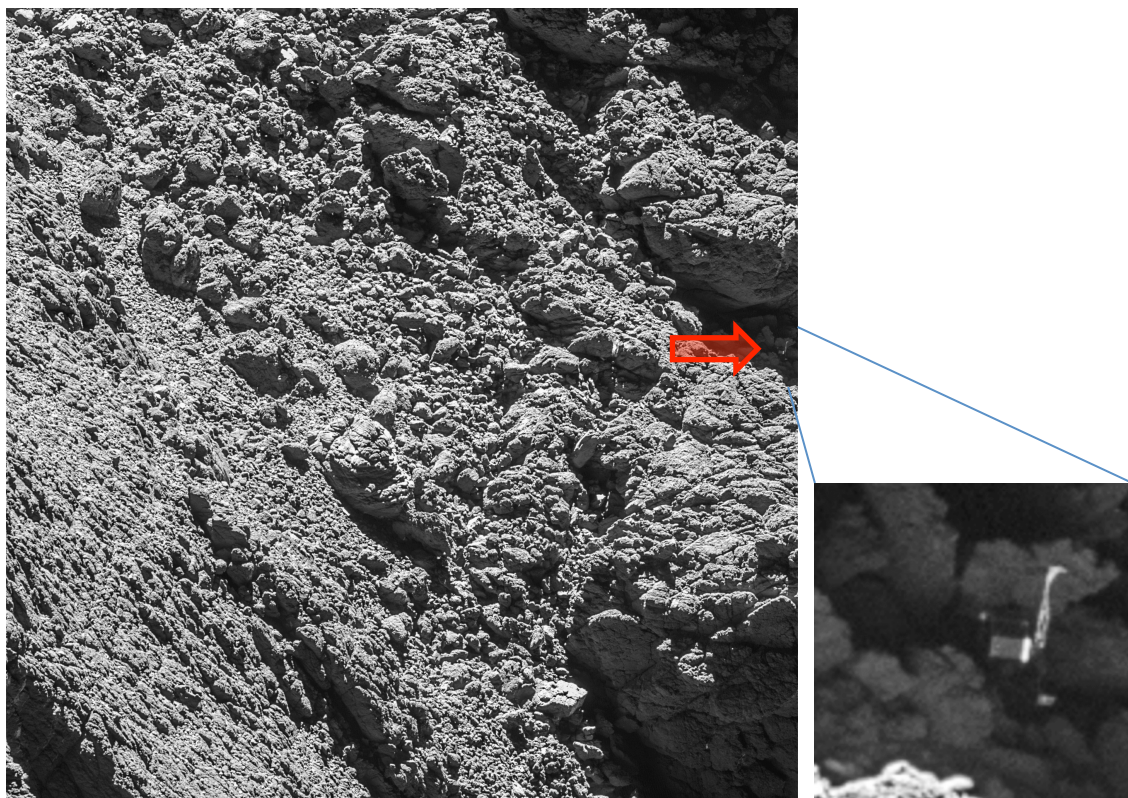


Figure 2: Philae Lander (see red arrow) with its 3 legs in vertical position spotted at Abydos after final landing on the surface of comet 67P/Churyumov-Gerasimenko. To the right there is a magnified view of the Lander. Credit: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA. Processed by ESA/Rosetta/SGS

III COSAC INSTRUMENT

3.1 Instrument overview

The Cometary Sampling and Composition experiment, COSAC, is part of the payload of Philae and one of the ten Principal Investigator (PI) led instruments aboard the lander. It is an evolved gas analyser, consisting of ovens (to be fed with a sampling and drilling device, SD², see Ercoli-Finzi *et al.*, 2007) a tapping station, a mass spectrometer (MS) a gas-chromatograph (GC), Helium tanks and the respective instrument electronics. Fig. 3 shows the instrument as integrated onto an internal panel within the Philae structure. The instrument is

described in detail by Goesmann *et al.* 2007, the planned measurements on the surface of the comet are explained by Goesmann *et al.* 2014. COSAC was designed to detect and identify organic molecules in the surface material. The GC contains eight columns (see Fig. 4) including three which would have allowed chiral separation (see Table 1). The so-called enantioselective (“chiral”) capillary columns include stationary phases that contain chiral selector molecules such as L-valine (Table 1, N°7) or cyclodextrin (Table 1, N°6 and N°8) in a liquid polymer film inside of the capillary. These chiral selector molecules are capable of interacting with individual chiral analytes and thereby to resolve enantiomers. COSAC was designed to analyse gas with the MS, the GC (with selected columns) or a combination of both. The instrument could also be operated in “sniffing mode” analysing ambient gas, without requiring material in the ovens. MS “sniffings” were made on arrival at 67P/Churyumov Gerasimenko from 10 km above the surface, after initial touchdown, and at Abydos, the final landing site (Goesmann *et al.* 2015, Krüger *et al.*, 2017).

Table 1. Columns used in the COSAC gas chromatograph. Columns 6, 7 and 8 allowed chiral separation. (from Goesmann *et al.*, 2007)

Column	Inner diameter [mm]	Thickness of stationary phase [µm]	Length [m]
1	CarboBond	0.25	15
2	MXT U-PLOT	0.18	10
3	MXT 1701	0.18	15
4	MXT 20	0.18	15
5	MXT 1	0.18	10
6	Chirasil Dex CB	0.25	10
7	Chirasil L Val	0.25	12.5
8	Cyclodextrin G-TA	0.25	10

3.2 The planned chirality analyses

After detection of a remarkable diversity of organic compounds such as chiral amino acids (Munoz Caro *et al.*, 2002), chiral glyceraldehyde (De Marcellus *et al.*, 2015), and chiral sugar molecules including ribose (Meinert *et al.*, 2016) in simulated cometary ices, the analytical challenge was the identification of chiral analytes in cometary ices of 67P by the COSAC instrument. A key interest of the COSAC instrument was the separation, identification, and quantification of chiral organic molecules (Meierhenrich, 2015). The list of Rosetta-relevant chiral molecules including hydrocarbons (Meierhenrich *et al.*, 2003), amines, alcohols, diols, carboxylic acids (Meierhenrich *et al.*, 2001), and amino acids (Thiemann *et al.*, 2001) was investigated and established prior to the launch of the Rosetta comet probe. The investigators of the COSAC chiral module assume that there is a reasonable chance of finding partial enantiomeric excesses in chiral molecules resulting from the exposure of the cometary ices to extraterrestrial chiral fields (Meierhenrich, 2008). Despite of intense preparation and anticipation, as explained in section IV, the insufficient sample amount obtained for COSAC’s enantioselective GC-MS run after landing on the surface of comet 67P did not yet allow for the identification and resolution of chiral cometary species.

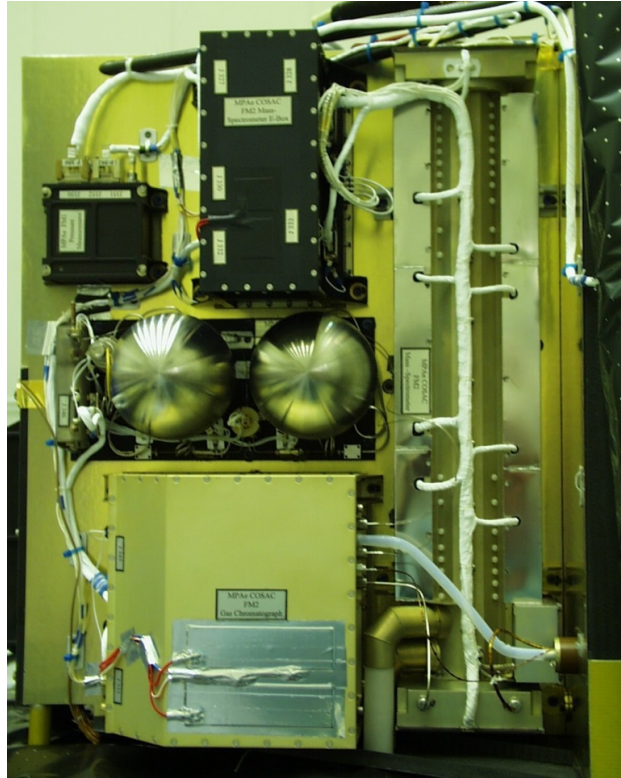


Figure 3: COSAC instrument as integrated into the Philae Lander (Goesmann *et al.*, 2007)

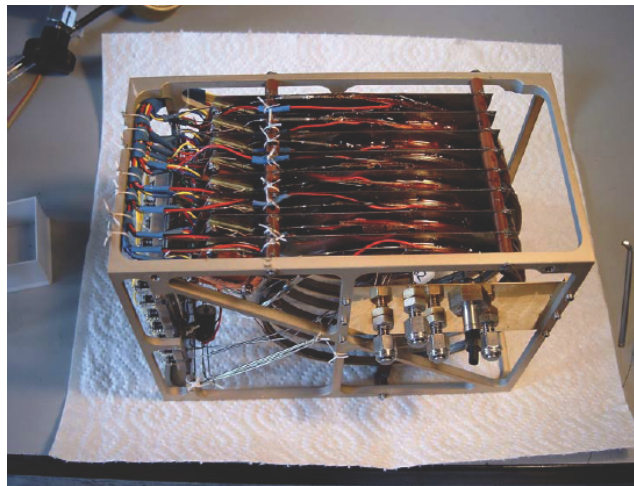


Figure 4: COSAC gas chromatograph including eight capillary columns operating in parallel before integration. (Goesmann *et al.*, 2007)

IV OPERATIONS ON THE COMET SURFACE

After Philae came to its final rest at 17:31 UTC at a distance of about 1 km from the originally anticipated site, a modified First Scientific Sequence (FSS) was quickly designed, uploaded, and executed on the comet surface. Operations are explained in detail by Ulamec *et al.* 2016, and science planning of Philae is discussed by Moussi *et al.* 2016.

While a first operational sequence (so called “Block 1”), including “sniffing” measurements with both, COSAC and Ptolemy, was executed autonomously following the reception of the touchdown signal, all further operations had to be initiated through explicit commanding from

ground. As described by Ulamec *et al.* 2016, after landing another four sequences with RF link to the orbiter could be used for science operations, before the Philae's batteries dropped below the minimum level necessary to operate, about 64 hours after separation.

During this time, COSAC was operated seven times in sniffing mode; the first mass spectrum obtained about 25 min after the initial touch-down being the "richest" and showing most counts. On November 14th, 2014 an attempt was made to sample surface material, deliver it into a COSAC oven, heat it and perform a measurement of the composition of the volatile fraction of nuclear matter close to the surface with the GC. Although the system worked fine, both SD² as well as COSAC performed as planned, no sample could be obtained and the oven stayed empty. As we know now, this was due to the actual 'vertical' orientation of Philae and its relative position to the comet surface, leading to the SD² drill progressing into a cavity and never touching ground (Di Lizia *et al.*, 2016).

Abydos was very poorly illuminated, temperatures fell, the batteries could not be re-charged and the Lander went into hibernation. It was not clear when and if it would be possible to receive signals from Philae again. However, June 13, 2015, about 7 months after the landing, signals from Philae were received again. By then, comet and Lander got much closer to the Sun (about 1.5 AU), so that the solar radiation was sufficient to warm up batteries and electronics and even re-charge the batteries. Unfortunately, despite several short communication phases with the Orbiter between mid-June and July 9th, it was not possible to re-command Philae or perform further scientific experiments (Ulamec *et al.*, 2016, 2017).

Philae was operated by the Lander Control Centre (LCC) at the German Aerospace Centre, DLR, in Cologne and the Science Operations and Navigation Centre (SONC) at the Centre national d'études spatiales, CNES, in Toulouse via the Rosetta Mission Operations Centre, RMOC at the European Spacecraft Operations Centre (ESOC) in Darmstadt.

V PROPOSED MEASUREMENTS FOR THE FUTURE

All the arguments for attempting to measure the chirality of organic molecules to be identified in-situ on a cometary surface, leading to the selection and design of the COSAC gas chromatograph and the inclusion of its particular GC columns, are still valid!

It is thus, highly recommended to include in the payload of future missions to not only comets but also primitive asteroids, instruments with similar capability. The fact that during the Philae measurements, this particular experiment could not be performed is sad, and forces the community to wait for future opportunities. There is no particular lesson learned during the Rosetta mission that would lead to a change of the principal design of the GC or the selection of the columns.

During 2018 two asteroid sample return mission will reach their respective target bodies: OSIRIS-REx, arriving at (101955) Bennu and Hayabusa2 at (162173) Ryugu (Lauretta *et al.*, 2017; Watanabe *et al.*, 2017). Both asteroids are believed to be primitive bodies (B- and C-type, respectively), containing a large fraction of organic compounds. An overview of the classification of asteroids is given e.g. by Barucci *et al.*, 1987. Obviously, measurements of the enantiomeric ratio shall be performed with the returned samples.

In the frame of NASA's New Frontiers program, a comet surface sample return mission (CAESAR) is considered to be selected for a launch in the 2024/25 timeframe (Squyres *et al.*, 2018). CAESAR would go back to 67P, returning samples to Earth where detailed analyses could be performed with the evolving capabilities of ground based instruments.

ESA's ExoMars Mission (Vago *et al.*, 2017) to be launched in 2020 for landing on the surface of planet Mars includes an enantioselective GC-MS instrument (Goesmann *et al.*, 2017) that inherited enantioselective equipment from COSAC. This ExoMars instrument is called the Mars Organic Molecule Analyser (MOMA) and will operate the Chirasil Dex CB phase as indicated in Table 1. We expect the MOMA instrument perform the separation, identification, and quantification of chiral molecules on the surface of Mars, in the frame of the ExoMars overall scientific objective to search for molecular traces of life on Mars.

VI CONCLUSION AND REFERENCES

6.1 Conclusions

Rosetta was the first comet rendezvous mission, allowing more detailed observations of the nucleus as compared to the fast fly-bys of earlier missions. Philae performed the historic first landing on a comet in November 2014. Despite bouncing, the Lander came to rest and performed outstanding science. However, due to the final attitude and position of Philae at Abydos, it was not possible to sample material and deploy it into an oven of the evolved gas analysers. Thus, unfortunately, no successful gas-chromatography could be performed and the measurements of the enantiomeric distribution of organic molecules in the cometary material were impossible. These important analyses are still to be done in the frame of future missions, in-situ or with returned samples.

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B Biography

Stephan Ulamec has been Project Manager of Philae and Co-Investigator of the COSAC instrument; Fred Goesmann is Principal Investigator of COSAC and Uwe Meierhenrich has been Co-I of COSAC, mainly involved in the preparation of chirality measurements.