How to Simulate the Surface of a Cometary Nucleus for Public Science Demonstrations

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Research & Applications

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To celebrate and appropriately illustrate the rendezvous of the European *Rosetta* spacecraft with comet 67P/Churyumov–Gerasimenko and the landing of *Philae* on the surface of the comet's nucleus on 12 November 2014, the French science museum Palais de la Découverte developed and presented a new and original demonstration. The experiment simulates the behaviour of a cometary surface in a vacuum and shows the formation of jet-like features. We explain here how to prepare an analogue to cometary material from porous ices and carbon, how to approximately reproduce the cometary environment at low pressure, temperature and solar illumination, and how to present the experiment at a public science demonstration.

Introduction

On 12 November 2014, for the first time in the history of Solar System exploration, a module landed on the solid nucleus of a comet and sent back its observational data. The *Philae* lander was released from the *Rosetta* spacecraft, which had begun its rendezvous with comet 67P/ Churyumov–Gerasimenko (67P/C-G) in August 2014. The purpose of the *Rosetta* mission, a cornerstone of the European Space Agency (ESA) science programme, is to escort the comet until September 2016, and to study critical changes on the nucleus and in the cometary environment along its elongated orbit[1].

Local observations have already given evidence of unexpected properties of the interior of the nucleus, its surface and its surroundings. *Rosetta* continues the cometary exploration programme conducted by ESA, starting with flybys by the *Giotto* spacecraft of comets Halley and Grigg–Sjellerup (Reinhard, 1986; McBride et al., 1997), which produced the first images of a comet nucleus.

Figure 1. *The nucleus of comet 67P/C-G Churyumov–Gerasimenko, seen by the NavCam camera on board the Rosetta spacecraft on 19 August 2014. Credit: European Space Agency*

To celebrate the *Rosetta* rendezvous and prepare for the *Philae* landing, public initiatives were conducted by the media and science museums. The Palais de la Découverte in Paris worked with ESA and two French research laboratories — the Laboratoire de Physique et Chimie de l'Environnement et de l'Espace (LPC2E) in the National Centre for Science Research (CNRS), and the Laboratoire Atmosphères, Milieux, Observations Spatiales (LATMOS) at the Université Pierre et Marie Curie (UPMC) — to produce an original experiment for a public science demonstration that reproduces the composition and activity of a cometary nucleus. Although the experiment was designed before the *Philae* landing, the results obtained by *Rosetta* have confirmed that this experimental setup was appropriate.

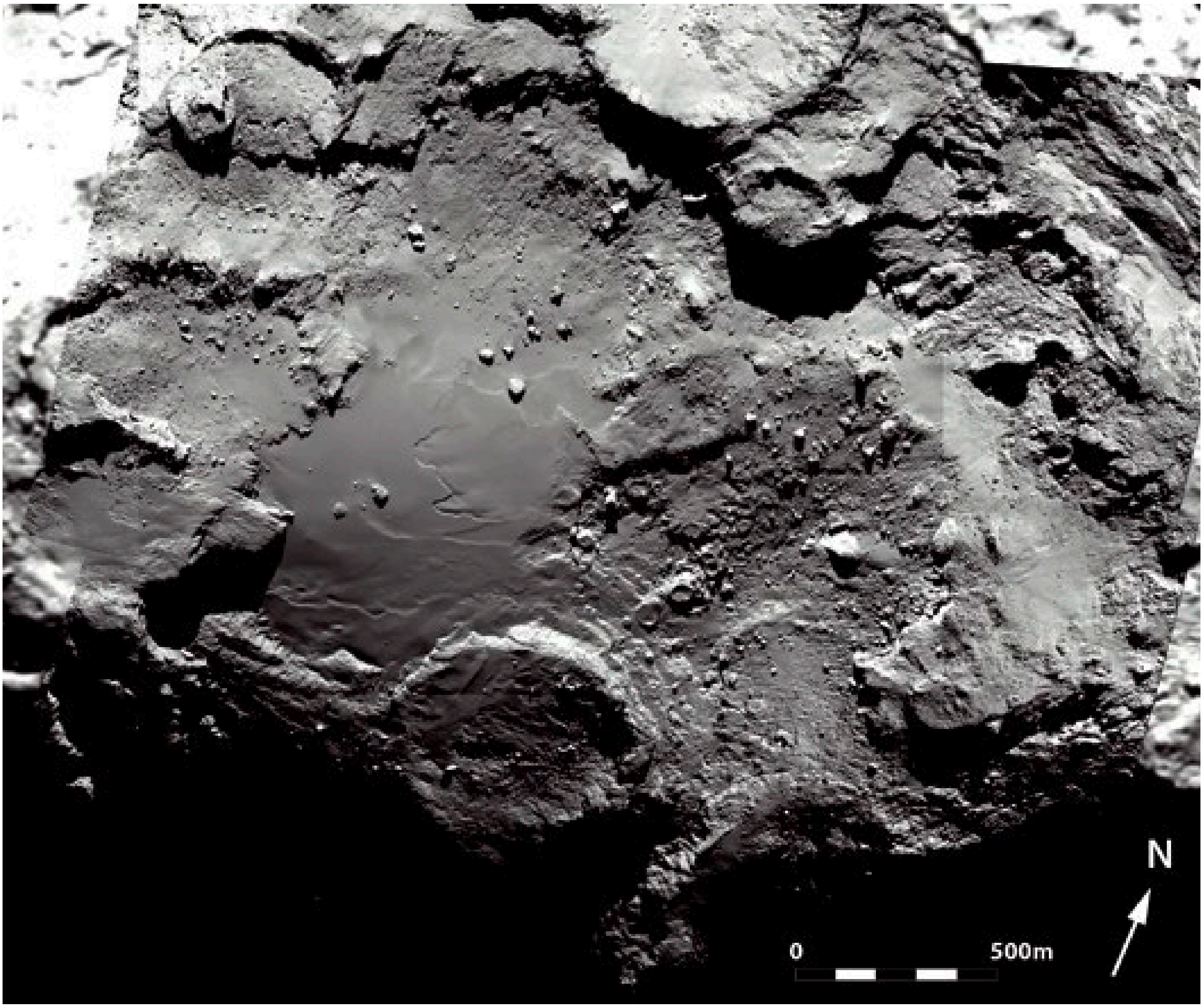

Figure 2. *Details of the surface of 67P/C-G (Imhotep region), obtained between 3 August and 5 September 2014 by the OSIRIS imaging system. Credit: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA*

The experiment, first presented to the public in October 2014 at the Palais de la Découverte, is now part of the permanent exhibition. It was also presented at the science museum La Cité des Sciences in Paris on 12 November 2014 during a special public event organised for the *Philae* landing. Public events are also planned to take place between the 29 and 30 September 2016. The mission will then be coming to an end as the distance between the spacecraft and the Earth increases.

We will first summarise the motivation behind studying comets, together with key preliminary results from the *Rosetta* mission. Then we will describe how to prepare material that is a reasonable approximation to the composition of a cometary nucleus, and how to present this experiment to the public.

Why study comets and why present them to the public?

Comets are unique remnants from the era when the Solar System was forming, composed of ices from water, carbon dioxide, silicates and complex organic compounds (Cochran et al., 2015). These dark, solid bodies of a few kilometres in size are usually located in the outer reaches of the Solar System, far from the Sun, and have barely changed since their creation four billion years ago, making them valuable time capsules.

Occasionally a comet will plunge into the inner Solar System, and when a cometary nucleus is unlucky enough to approach the Sun, the solar radiation supplies it with heat. The solar radiation turns the ices that comprise the nucleus into gases, which are ejected from the sunny side of the nucleus, carrying dust particles with them. Most of this dust and gas forms a coma, a non-permanent atmosphere that envelops

Figure 3. *The cometary analogue sample in a glass container.*

the comet nucleus and can extend for tens of thousands of kilometres.

The impressive appearance of comets and the fact that they can often be seen with the naked eye makes them popular among the public, but they are also associated with interesting historical stories that can be used to attract a public audience.

Because cometary material is kept in stasis in the outer Solar System, studying it as it enters the inner Solar System should lead to a better understanding of the material from which planets in the early Solar System formed, and provide clues that will help to decipher our origins.

The bombardment of planets by comets (together with some asteroids) may also be responsible for delivering a significant portion of Earth's water and enriching the surface of the Earth with the complex organic compounds needed for life. This combination of aesthetic interest and a window onto our history make comets a perfect subject for a public demonstration.

What does 67P/C-G look like?

Rosetta started its observations of 67P/C-G while the comet was still far from the Sun and not very active. However, at its closest point of orbit, which fell between the orbits of Mars and Earth on 13 August 2015, a surge of activity led to the onset of numerous jet-like features on the surface of the nucleus and to progressive changes on its surface.

Measurements from *Rosetta* and *Philae* showed the surface to be irregular (Figure 2), with dark, dusty smooth regions, local fracturing, and large depressions and wide pits most likely resulting from ice and dust ejection (Thomas et al., 2015). Before the time of closest orbit most of the surface will have been covered by dust (Schulz et al., 2015). Evidence for carbon-bearing molecules, including compounds not previously reported in comets, were also found (Capaccioni et al., 2015; Goesmann et al., 2015), as well as molecular nitrogen and oxygen ices (Rubin et al., 2015; Bieler et al., 2015). The interior of the nucleus, composed of ices and dust, appears to be fairly homogeneous on a spatial scale of tens of metres (Kofman et al., 2015).

To simulate the behaviour on the surface of this cometary nucleus we decided to simulate a low-density mixture of ices (not only water) and dark minerals and to supply heat to the surface in a vacuum to simulate proximity to the Sun and allow the formation of jet-like structures.

How to produce cometary material for a public demonstration

The original element of this science museum experiment is to reproduce most of the conditions encountered at the surface of a comet, including the local vacuum, low temperature, solar radiation and low gravity. While the latter cannot be reproduced, since the public is not likely to be watching the experiment on board the International Space Station, all the other conditions can be easily achieved during a public demonstration. The public are also invited to watch the setting up of the apparatus and the preparation of the material to learn more about how these conditions are replicated, which takes about ten minutes.

The ingredients that are used to simulate the cometary material are less complex than the real ones, but are acceptable as a first approximation: water, frozen carbon dioxide pellets and amorphous carbon powder. Gloves must be used to protect the hands from the low temperature of the carbon dioxide pellets.

The following procedure will produce a volume of about 200 cubic centimetres of cometary analogue:

1. Pour fifty cubic centimetres of liquid water into a soft container (a little plastic bottle cut to two thirds of its height).
2. Add a few grams of carbon powder and mix with water.
3. Using gloves, add around fifty grams of frozen carbon dioxide pellets (at -78 degrees centigrade).
4. Stir the mixture vigorously for one minute while kneading the bottom of the bottle.
5. Pour in another fifty grams of carbon dioxide pellets.
6. Continue to stir and knead the mixture for a further minute. This procedure will produce porous iced granules of the order of one centimetre in size rather than just an ice block.
7. Put the granules into a small glass container and lightly pack down the sample. The bulk density of the sample inside the glass container is about 0.5 grams per cubic centimetre, comparable to the density of 67P/C-G7.
8. The last step is to cover the surface with about one millimetre of carbon powder.

Figure 3 shows the cometary analogue in its glass container.

Experimental setup

1. The small glass container containing the cometary analogue should be put inside a transparent vacuum chamber.
2. The chamber should contain a tank into which liquid nitrogen (at –196 degrees centigrade) will be poured (Figure 4). This tank has two roles: first, to maintain a low temperature in the vacuum chamber, and secondly to condense and trap the water vapour and the carbon dioxide that will be released by the sample.
3. Liquid nitrogen is poured into the tank, then the vacuum pump is switched on. Tests have shown that a curious phenomenon occurs for a pressure below ten hectopascals, whereby all of the carbon dust is violently ejected from the surface of the analogue to the wall of the chamber. This phenomenon is also observed if the vacuum is prepared first and the liquid nitrogen is added later. Two possible explanations are proposed: there could be a delay before the sublimation (where ice turns to gas) takes place when the change-of-state conditions are sufficiently exceeded; or there could be a change in the ice's morphology for critical values of temperature

and pressure, as is invoked to explain sudden outbursts that are sometimes observed on comets that are far from the Sun (Prialnik & Bar-Nun, 1992). Thus we recommend maintaining the pressure just above ten hectopascals to avoid this phenomenon.

4. A halogen lamp of at least 250 watts should be mounted typically between ten and twenty centimetres above the sample, to simulate solar illumination. The amount of energy per unit surface area is obviously greater for our sample than at the comet's surface. This is motivated by the need to accelerate the process of ice sublimation for the public demonstration.

When the lamp is turned off (assuming the environmental lightening is not too strong), nothing will happen, mimicking the conditions far away from the Sun. When the lamp is switched on, small jets of dust are soon ejected from the surface of the sample (Figure 5). The black carbon on the surface absorbs the light and the surface heats up, just as the black surface of the comet does. The gas coming from the sublimating ice accumulates in the porous parts of the sample, and is suddenly ejected, carrying the dust. Jets appear at different locations over the surface and may last from several seconds to more than one minute.

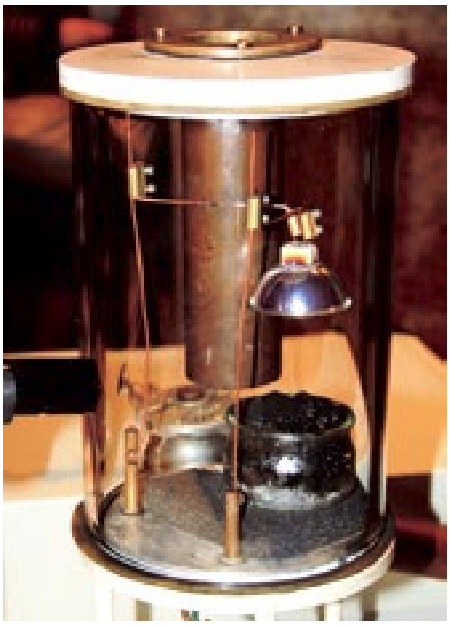

Figure 4. *Experimental setup. The glass container with the sample is in a vacuum chamber; the liquid nitrogen trap is the copper cylinder in the middle of the chamber which is open at its top; and the halogen lamp is above the sample.*

This behaviour is not observed if a single compact block of ice is used instead of granular ice. A careful examination of surface of the sample shows that some small solid particles move constantly on the surface, due to the sublimating ice and the flow of gas. After a few minutes, a crater of a few millimetres depth will form under the zone of illumination.

The jets seen in the experiment are quite similar to the large-scale jets observed by *Rosetta* (Figure 6). For our experiment, their velocity is about one metre per second. On comets, the velocity can be hundreds of times higher. This difference could be due to the near-absence of gravity on the comet, the larger pressure in the gas in the cometary material, and the acceleration of grains at larger distances by the expansion of water vapour into the interplanetary medium. The experiment can be continued until the nitrogen trap is empty, which takes about twenty minutes for the apparatus presented here.

Public demonstrations

This demonstration must be carried out by someone trained and familiar with the manipulation of liquid nitrogen and carbon ice. Some safety rules must be strictly applied: safety shoes, safety glasses and protective gloves must be worn when the carbon ice and the liquid nitrogen are being handled. Gloves and glasses can be removed after this point. Secondly, the audience must be at least one metre away from the vacuum chamber when the nitrogen trap is filled, to avoid any cold burns from any accidental spillage of liquid nitrogen.

Since the public will be standing fairly far from the vacuum chamber, a camera may be used to project the experiment in real time onto a screen; we recommend zooming in on the jets and the sample surface, to see the movement of the solid particles and the evolution of the surface better.

This demonstration has been given at the Palais de la Découverte without any age restriction, although it is not recommended for too young an audience. The audience, whatever its age, was impressed by the sudden appearance of jet-like structures when the light is switched on, and their disappearance when the light is switched off.

Figure 5. *Jets coming from the porous comet analogue sample once the halogen lamp is switched on. The nitrogen trap is visible on the upper left.*

When the nitrogen trap is empty, pressure can be slowly and steadily increased inside the chamber. Then, the glass container with the sample can be removed from the chamber and shown to the audience. It is even possible to touch the material, which is a dark mixture of water, ice and carbon, but do so quickly to avoid cold burns. Teenagers in particular seem to like to touch this cometary material and feel the chill from the surface.

Conclusion

This experiment is straightforward to prepare for a public demonstration and accurately illustrates the formation of jet-like structures near the surface of a comet when porous granules of ice and dust are locally illuminated in a vacuum. It also illustrates the change in the surface morphology of a comet under the local action of the jets. Obviously, the true composition of the cometary material is far more complex than the material used for this public demonstration. However, with regard to the sublimation, these laboratory conditions are not very different from the real ones. Thus, this easy-to-realise experiment can be a good complement, together with *Rosetta* and other spacecraft images or videos, to explanations of the nature and surface of comets and their evolution.

Figure 6. *Jet-like features rising from the nucleus of 67P/C-G on 16 August 2015, seen by the NavCam camera from a distance of 331 kilometres. Credit: ESA/Rosetta/NAVCAM*

Acknowledgements

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Notes

[1] More information on the *Rosetta* mission: http://www.esa.int/Our_Activities/Space_Science/Rosetta

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Biographies

Jean-Baptiste Renard is a senior scientist at le Laboratoire de Physique et Chimie de l'Environnement et de l'Espace (LPC2E-CNRS). He works on the detection of aerosols and dust in Earth's atmosphere and in comets. He has developed several experiments to determine the optical properties of the dust.

Sylvain Lefavrais was the creator of "*Un chercheur une manip*" at Palais de la Découverte in Paris and the director of their activity until 2015. For ten years, he has been inviting scientists to present their work for public exhibition, and helped them to design or adapt the necessary experiments.

Anny-Chantal Levasseur-Regourd is Professor Emeritus at Université Pierre et Marie Curie (UPMC), LATMOS. She works on the properties of dust particles in comets and on the structure of comets' nuclei. She is presently involved in the *Rosetta* mission and other space missions, and was the Principal Investigator for the Optical Probe experiment on board the *Giotto* spacecraft and for other space experiments. She is also active in public outreach activities related to astronomy, with emphasis on planetary sciences.