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Author for correspondence:
Geraint Jones
e-mail: g.h.jones@ucl.ac.uk

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Cometary Science After Rosetta

Geraint H. Jones[1,2], Matthew M. Knight[3], Alan Fitzsimmons[4], and Matt G. G. T. Taylor[5]

[1]UCL Mullard Space Science Laboratory, United Kingdom
[2]The Centre for Planetary Sciences at UCL/Birkbeck, United Kingdom
[3]University of Maryland, United States of America
[4]Queen's University Belfast, United Kingdom
[5]ESTEC, European Space Agency, Noordwijk, The Netherlands

The European Space Agency's *Rosetta* mission ended operations on 30 September 2016 having spent over two years in close proximity to its target comet, 67P/Churyumov-Gerasimenko. Shortly before this, in summer 2016, a discussion meeting was held to examine how the results of the mission could be framed in terms of cometary and solar system science in general. This paper provides a brief history of the *Rosetta* mission, and gives an overview of the meeting and the contents of this associated special issue.

1. Introduction

Comets are believed to provide us with a direct insight into the conditions that persisted when the Solar System was formed. To exploit this invaluable scientific resource, the European Space Agency (ESA)'s *Rosetta* mission was developed. It was the most ambitious and sophisticated cometary space project yet attempted.

In June 2016, a discussion meeting was held at The Royal Society on the topic of cometary science after *Rosetta*. The gathering brought together members of the cometary science field, the wider planetary community, and related astrophysical fields to discuss all aspects of comets' behaviour, and took place as the incredibly successful *Rosetta* mission neared its end. Here, we provide the context for the meeting: the motivation for the gathering, a brief history of the *Rosetta* mission, and an overview of this volume of papers resulting from it.

2. A Brief History of Rosetta

Following the great success of the ESA's *Giotto* mission to Comet 1P/Halley in 1986 [1] (a spacecraft that went on to encounter 26P/Grigg-Skjellerup in 1992), *Rosetta* was first proposed in the late 1980s as a comet sample return mission. The project underwent several changes until settling on a mission without a sample return element. Instead, the craft would travel to, and then accompany for many months, the Jupiter-family comet 46P/Wirtanen as it approached perihelion and then retreated from the Sun. The primary *Rosetta* spacecraft would monitor the comet's nucleus, coma, and plasma environment, and would deliver a lander – *Philae* – to descend to the comet nucleus's surface for *in situ* observations. A call for instrument proposals was issued by ESA in the mid-1990s, and a comprehensive suite of 21 instruments addressing a wide range of scientific questions were selected, for provision by institutions in the ESA member states and their collaborators.

A delay in *Rosetta*'s launch date occurred due to concerns with the launcher, which meant that a mission to 46P was no longer possible. A suitable alternative target – 67P/Churuymov-Gerasimenko – was identified, and some modifications made to the *Philae* lander's legs to accommodate the anticipated increased gravitational attraction of this target compared to Wirtanen.

On 2004 March 2, *Rosetta* was successfully launched on an Ariane 5 rocket. Following a journey that involved several planetary flybys plus two asteroid flybys, the spacecraft arrived safely at comet 67P/Churyumov-Gerasimenko in 2014 August. During its 2 years at the comet, *Rosetta* monitored the object continuously. On 2014 November 12, *Rosetta* enhanced its impressive science return by depositing *Philae* onto the surface of the comet. Despite a landing that differed from original plans, *Philae*'s instruments made direct, *in situ* measurements of the comet's surface and local environment for several days. Perihelion occurred on 2015 August 13, and the end of mission came when the orbiter was intentionally landed on the comet's surface on 30 September 2016. Further details of the mission are provided by Taylor et al. and Boehnhardt et al., (this issue).

3. Motivation

It can be argued that cometary science has undergone two key periods of advancement. The first of these involved the dedicated cometary encounter missions of the 1980s (*ISEE-3/ICE* [2], *Giotto* [1], *VeGA-1* and *VeGa-2*, *Suisei*, *Sakigake* [3]), which resulted in advancements that include the basic properties of nuclei, the fundamentals of their chemistry, localisation of surface activity, and the key aspects of their interactions with the solar wind.

The second period of advancement has been concentrated in the past 15 years, with results from more recent missions (*Deep Space 1* [4], *Stardust* [5], *Deep Impact* [6], *EPOXI* [7], *Stardust NExT* [8]). In addition to dedicated comet missions, cometary science in general has advanced tremendously in that time, largely due to the advent of substantial new facilities and instruments (e.g., *Herschel* [9], *Spitzer* [10], *SOHO* [11], *STEREO* [12], *ALMA* [13], and *Pan-STARRS* [14]) that have become operational in recent years and have allowed novel scientific investigations. This second period has of course culminated in *Rosetta*. Its mission was fundamentally different to earlier dedicated comet missions through its long-term monitoring of a comet over changing solar distances using a comprehensive suite of instruments, and has yielded unprecedented insights into the surface properties and the nucleus's interior.

Rosetta has proven to be truly groundbreaking, by providing detailed information on its target comet in exquisite detail for an extended period, as its activity levels rose then waned. The mission's observations provide our first *in-situ* record of the changing nature of a comet's nucleus and coma over an extended period, complementing the "snapshots" of comets provided by other targetted cometary missions. This wealth of information should lead to great steps forward in our understanding of comets, and hence the conditions prevalent in the early Solar System. The results therefore promise to make significant impacts on planetary science as a whole, including in our understanding of the origin of Earth and the other planets, the origins of the volatile species that exist on our planet and elsewhere in our Solar System, and the potential organic chemistry occurring in other planetary systems.

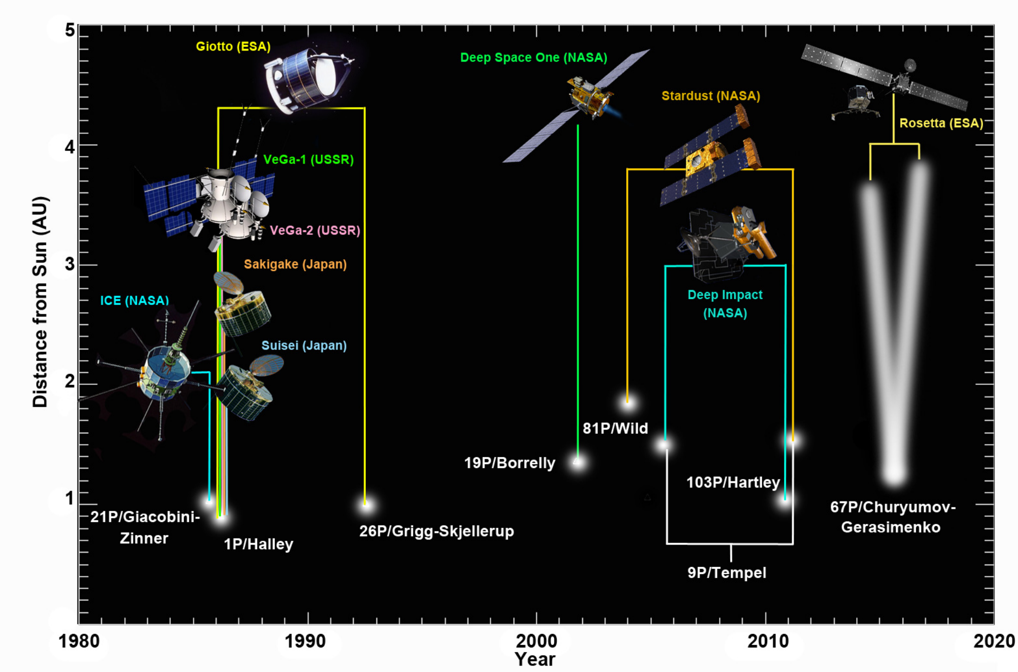

Figure 1. All targetted cometary missions to date, from the *International Cometary Explorer* (*ICE*) in 1985, to *Rosetta*. *Giotto*, *Stardust*, and *Deep Impact* all encountered two comets. 1P/Halley was encountered by five spacecraft, whilst comet 9P/Tempel has been encountered twice, on consecutive perihelion passages. The continuous line representing comet 67P denotes the two year period during which it was studied by *Rosetta*, over a wide range of heliocentric distances.

The discussion meeting was convened, and this volume of papers produced, to bring together a comprehensive summary of the ground-breaking discoveries from *Rosetta*, placing them in the context of cometary science as a whole. As well as reporting on the primary results from *Rosetta*, this volume is also timely, as the last comprehensive review of comets was the book "Comets II", published in 2004. Many of the key new advances in this field have been made since the publication of that volume, and have altered our understanding of where comets formed, how they evolved, and where they can be found today. These include the proposal of the Nice model of solar system evolution [15–17], the detection of an Earth-like D/H ratio in a comet [18], and the discovery of the existence of populations of comets in the asteroid belt [19], and on short-period "sunskirting" orbits [20]. For the discussion meeting and this resultant collection of works, we assembled speakers/authors who have been involved in most of these advances.

One aspect of dedicated cometary missions is that all comets are different; hence the results from one cannot necessarily be applied to others. The handful of nuclei that have been investigated at relatively close range have shown a remarkable diversity in appearance, composition, and activity levels. It is therefore important to place the *Rosetta* results in the context of our wider understanding of comets: in reviewing the results from the mission, it is important to consider observations made by other missions.

Below we provide an overview of the topics covered in the discussion meeting and this issue. We note that some special journal issues dedicated to initial results from *Rosetta* itself have already been published. These include a collection of papers in *Science* in 2015 [21], *Astronomy* *and Astrophysics* in 2015 [22], and a dedicated issue of *Monthly Notices of the Royal Astronomical Society* reporting results from an ESLAB symposium held in March 2016 [23]

4. Topics and Themes Covered

A wealth of information was presented at the meeting, beginning with Karen Meech (University of Hawai'i, USA), who provided an overview of where the field of cometary research stood before the results of *Rosetta*. Numerous presentations naturally concentrated on results from *Rosetta* itself. Matt Taylor (European Space Agency) described the mission in some detail, and provided an overview of the science results obtained by the orbiter. The *Philae* lander and its observations and results were presented by Hermann Boehnhardt (Max-Planck-Institut für Sonnensystemforschung, Germany).

Dominique Bockelée-Morvan (Observatoire de Paris, France) and Kathrin Altwegg (Universität Bern, Switzerland) reported on advances made in our knowledge and understanding of cometary composition, using remote observations instruments operating at various wavelengths, and *in situ* mass spectrometry such as with *Rosetta*'s ROSINA instrument. Altwegg summarized the "zoo" of molecular species identified at 67P.

Rosetta carried three dedicated dust instruments; Martin Hilchenbach (Max-Planck-Institut für Sonnensystemforschung, Germany) reported on the phenomenology and composition of cometary dust particles collected near 67P by one of these – COSIMA. Most gaseous atomic and molecular species are eventually ionized; once that happens, the newly-born cometary ions join the flow of the solar wind streaming past a comet. Karl-Heinz Glassmeier (Technische Universität Braunschweig, Germany) summarized our understanding of the complex interactions between 67P and the wind, in light of the extensive measurements made of the plasma environment by the *Rosetta* Plasma Consortium suite of sensors.

In the years leading up to *Rosetta*'s arrival at 67P, and during the mission itself, an intensive international observing campaign was conducted to ascertain the typical activity levels of the comet pre-arrival, and to provide remote observations to complement the ground truth measurements made by *Rosetta* in the vicinity of the nucleus. These observations were reported on by Colin Snodgrass (The Open University, UK).

Ingrid Mann (Universitetet i Tromsø, Norway) provided an overview of cometary dust throughout the Solar System, addressing both models and physics. Diane Wooden (NASA Ames Research Center) presented her overview on the diversity of primitive cometary dust particles and their implications for understanding conditions in the early Solar System. Karl Battams (Naval Research Laboratory, USA) addressed the topic of objects that experience extreme conditions: sungrazers and sunskirters that venture much closer to the Sun than most comets that are observed from Earth. Main belt comets – active bodies that reside in the asteroid belt – were covered by Henry Hsieh (Planetary Science Institute, USA). These objects may be the "missing link" between active comets such as 67P, and volatile–poor asteroids. Understanding the nature of this gradation in activity informs us about the cometary population in general, and how typical or unique many of these individual objects are in the context of planetary bodies.

Three talks were given at the meeting that are unfortunately not represented in this volume. Stephen Lowry (University of Kent, UK) discussed the bulk properties of 67P's nucleus as gleaned from *Rosetta* observations, especially through the OSIRIS instrument, and placed them into context with the community's knowledge of cometary nuclei. An overview of the chemical composition of the surface of 67P was presented by Ian Wright (The Open University, UK), the Principal Investigator of the Ptolemy instrument on *Philae*. Alessandro Morbidelli (Observatoire de la Côte d'Azur, France) presented an overview of current theories of the formation and evolution of the Solar System, focussing on recent insights into the collisional evolution of cometary nuclei.

To conclude the meeting, Michael A'Hearn (University of Maryland, USA) provided a valuable summary of the presentations and discussions that had taken place. As well as placing the *Rosetta* results in context, A'Hearn addressed the next steps in cometary science.

5. Conclusion

As organizers of the discussion meeting, the authors hope that the meeting, and in particular the contents of this volume, are seen as valuable resources that summarize the status of cometary science at the culmination of the *Rosetta* mission.

Competing Interests. The authors declare that they have no competing interests.

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