Closing the gap between ground based and in-situ observations of cometary dust activity: Investigating comet 67P to gain a deeper understanding of other comets.

Raphael Marschall & Oleksandra Ivanova et al.

Abstract

When cometary dust particles are ejected from the surface they are accelerated because of the surrounding gas flow from sublimating ices. As these particles travel millions of kilometres from their origin into the solar system they produce the magnificent tails commonly associated with comets. During their long journey the dust particles transition through different regimes of changing dominant forces such as gas drag, cometary gravity, solar radiation pressure, and solar gravity. The transition and link between the different regimes is to this day poorly understood. There are two main reasons for this. Firstly, the problem covers a vast range in spatial and temporal scales that need to be matched taking into account multiple transitions of the force regime. Furthermore, observational data covering these large spatial and temporal scales for at least one comet and thus characterising it in great detail has been lacking until recently.

For comet 67P/Churyumov-Gerasimenko (hereafter 67P) a small number of large scale structures in the outer dust coma and tail have been found from ground based observations. Conversely ESA's Rosetta mission has shown many small scale structures defining the innermost coma close to the nucleus surface. This disconnect between the observations on these different scales has yet to be understood and explained.

Solving this problem thus requires an interdisciplinary approach. This ISSI team shall bring together experts of the recent observational data from ground and in-situ of comet 67P as well as theorists that are able to model the dynamical processes over these different scales. By doing so we intend to answer some of the open questions that came out of the Rosetta mission and the accompanying ground based observations. The understanding gained about 67P will also be put in context by evaluating how it can be applied to furthering our knowledge of other comets.

1 Scientific rationale

After dust particles have been ejected from the cometary surface their dynamics is governed by a host of competing forces. The different forces act on various temporal and spatial scales which define different regimes. These can roughly be characterised as follows:

- **Inner coma:** The total force acting on the dust particles is dominated by gas drag and cometary gravity. This region extends from the surface to a few tens of km from it.

- **Outer coma:** The total force acting on the dust particles is dominated by solar radiation pressure and cometary gravity. This region extends from a few tens to thousands of kilometres from the surface.

- **Dust tail:** The total force acting on the dust particles is dominated by solar radiation pressure and solar gravity. This region extends from thousands to millions of kilometres from the surface.

For many centuries the observation and study of comets was restricted to ground based observations and thus only the outer coma and dust tail regimes were accessible. This changed with the fly-bys at comet 1P/Halley by six spacecraft. In the order of farthest to closest fly-by these were: from the USA (ICE), Japan (Sakigake & Suisei), Russia (Vega 1 & 2), and Europe (Giotto). The success of the Giotto mission prompted the European Space Agency (ESA) to pursue the Rosetta mission, launched in 2004 and escorting the comet for extensive observations from 2014-2016. The Rosetta target comet 67P was discovered on September 11, 1969 and is a short-period comet of the Jupiter family, with a current orbital period of 6.45 years.

Before the beginning of the Rosetta mission, comet 67P had been poorly studied despite the fact that it was on the list of nine comets selected as candidates for the spacecraft missions Stardust and Rosetta. There were very few observations of this comet in the 1982-83 and 1996-97 apparitions. Intensive observations were carried out in 2002-03 with a host of telescopes (HST, VLT, ...). The comet was found to be quite active around perihelion and the gas and dust production rates were determined at different heliocentric distances by many researchers (see Snodgrass et al., 2017, and references therein). Also multiple jet-like structures in the coma and an extended tail were detected (Lara et al., 2005). Supporting the Rosetta mission a large scale international campaign of ground-based observations of the comet was conducted covering the full mission time.

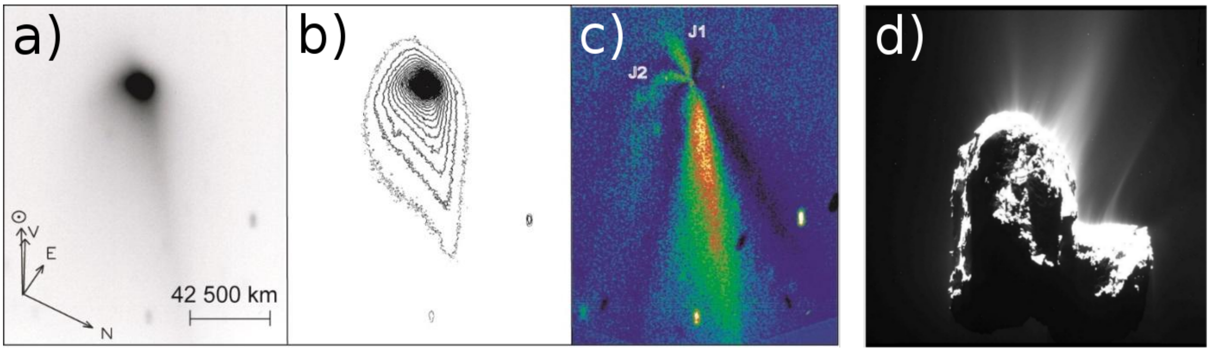

Figure 1: Panels a)-c) show intensity images of comet 67P on November 8, 2015: Panel a) shows the direct image of the comet from BTA/SCORPIO-2; panel b) shows the relative isophots of the cometary coma in logarithm intensity scale; and panel c) represents the processed intensity image emphasising structures of the coma. The coma jets are labelled as J1, and J2. The Arrows point in the direction to the Sun (☉), North (N), East (E), and the velocity vector of the comet in projection on the sky (V). Panel d) shows a stretched image of the near surface inner dust coma brightness of comet 67P as observed by OSIRIS on-board Rosetta on November 22, 2014 at 4:59:09 UTC. Adapted from Fig. A.3. of Vincent et al. (2016a).

Preliminary results of the analysis of the direct images of comet 67P show, that the comet displayed an extended coma (Fig. 1) with highly condensed material in the near-nucleus area and a tail in the anti-solar direction. Two well-defined morphological features are revealed which are seen in all of our images at approximately the same position angles during the whole observational period. Similar jet-like structures with almost the same position angles were observed during perihelion passage in 2002 (e.g. Weiler et al., 2004; Lara et al., 2005), in 2009 (e.g. Lara et al., 2015; Tozzi et al., 2011; Vincent et al., 2013), and during its last perihelion in 2015 (Boehnhardt et al., 2016; Hadamcik et al., 2016). At the same time there were other features, which changed from one apparition to the next.

The Rosetta mission has observed comet 67P in close proximity from August 2014 to September 2016. This period covered heliocentric distances of 3.5 AU inbound through to perihelion at 1.2 AU and then to 3.8 AU outbound. During this time multiple instruments monitored the dust and gas environment. In particular the scientific cameras OSIRIS (Keller et al., 2007) provided more than 70,000 images of the surface and inner dust coma. Notably the shape of this comet is very strongly non-spherical (Sierks et al., 2015; Preusker et al., 2017) and because of the large tilt in rotation axis (Preusker et al., 2015) strong seasonal changes in the activity were observed. A diverse morphology of the surface (Thomas et al., 2015; El-Maarry et al., 2015, 2016) and complex surface changes due to the activity (Fornasier et al., 2017; Hu et al., 2017) have been observed. Extensive studies using state of the art 3D gas dynamics models have been used to constrain the gas sources at the surface (e.g Bieler et al., 2015; Fougere et al., 2016; Marschall et al., 2016; Zakharov et al., 2018). This enabled the study of the dust dynamics (e.g. Marschall et al., 2017; Zakharov et al., 2018; Gerig et al., 2018) involved to reproduce the structures observed by OSIRIS as seen in panel d) of Fig. 1. The fine structures observed in the inner coma (Vincent et al., 2016a) stand in stark contrast to above discussed few large scale structures observed from ground. Bridging this gap in our understanding poses important questions.

We now know that the inner coma structures are highly influenced by the shape, topography and morphology of the surface (e.g. Marschall et al., 2016; Shi et al., 2018). How do these factors influence the structure of the outer coma and tail structure? Can we link the large scale tail structures directly to the observed inner coma activity? How are the seasonal effects observed in the inner coma reflected in the ground based observations? Are the frequent observed outbursts seen by Rosetta (Vincent et al., 2016b) detectable from ground? Furthermore, to this date there is no model (or set of models) that has been applied to all dust regimes to understand within one framework the data of one comet throughout these regimes in a self consistent way. The question as to how the result of the different regimes can be linked thus remains to be answered. By finding answers to these questions we seek to open the door for understanding other comets where we lack the high resolution in-situ data.

Therefore, the scientific objectives of the project are:

1. To make a parallel analysis of publicly available observational data from the Rosetta mission and ground-based observations in order to find interconnections and correlations.

2. To use state of the art theoretical models to describe and link the 3D structure of the

inner coma (< 100 km) to the outer coma and tail structures observed from the Earth.

3. To compare theoretical and observational results in order to elucidate some of the open questions recently revealed by Rosetta observations.

2 Program and Schedule

The work of this team shall be completed within the regular 18 months period of ISSI international teams. We will use the two one week meetings for in depth discussion and on-site analysis in addition to the work that will be completed at the respective institutes.
The two meetings are planned as follows:

- Meeting 1 (Q4/2019): Get all members from the different communities up to date on the available data, analysis and models. Define multi-scale numerical model test cases that can be analysed against the different data sets available

- Meeting 2 (Q3/2020): Analysis of the multi-scale model results and data analysis. Examination of the implications we have learned from comet 67P for other comets.

Between meetings we plan to have telecons to discuss the progress and if needed adjustments to the planned work. The website set up with the help of ISSI will be used for keeping track of the work. Further informal meetings can take place at major conferences where a substantial number of team members will attend.

3 Expected output

We expect **at least two papers** coming from the group as a whole to be submitted to peer-reviewed journals:

1. Paper on a comprehensive model from the surface to the tail where we examine how different initial conditions such as the nucleus shape, topography, active areas, outbursts, etc. are imprinted in the different regimes.

2. Paper on the understanding of the observed structures in the inner & outer coma and tail of comet 67P and how they link to each other.

In addition we foresee **two to three further papers** where two of the three sub-groups (see Sec. 5) collaborate. Moreover, we plan to propose a session for EPSC 2020 to promote, discuss, and seek engagement of the results with the wider cometary community.

4 ISSI added value

ISSI not only provides for a central location within Europe to hold such meetings but in addition offers close proximity to the University of Bern and it's strong Rosetta research groups (Rosetta/ROSINA team of Kathrin Altwegg and Martin Rubin; Planetary Imaging Group of Nicolas Thomas). This offers the opportunity to invite additional specialists to discuss specific

issues or to meet for informal talks at no additional cost to ISSI. Additionally, ISSI provides with its international team format a vehicle for members of different communities to meet in an interdisciplinary fashion. In our case this brings together experts from the Rosetta, ground based and theorist communities which often remain rather separate. ISSI can thus facilitate inter-community work in cometary science. Furthermore, ESA will suspend financial support for the Rosetta program by September 2019. ISSI's support for this team would thus create a platform for this kind of work and exchange that would otherwise not exist.
We request the standard ISSI facility and financial support. We would also like to take advantage of the 20% additional grant to invite two young scientists to join the team, one of whom will be Rosita Kokotanekova as listed below.

5 Team description

Our team is comprised of scientists from 7 countries and will be co-lead by Dr. Raphael Marschall and Dr. Oleksandra Ivanova. With 46% female scientist and one third within nine years of their Ph.D. the team has a good balance in gender and seniority. For six members this will be the first ISSI team, which will also benefit ISSI with additional exposure in the cometary community. The following team members (in alphabetical order) are confirmed:

Surname, Name	**Affiliation**	**Country**
Agarwal, Jessica	Max Planck Institute for Solar System Research	Germany
Fornasier, Sonia	LESIA, University Paris Diderot	France
Ivanova, Oleksandra*	Astronomical Institute of Slovak Academy of Sciences	Slovak Republic
Ivanovski, Stavro	INAF, Osservatorio Astronomico di Trieste	Italy
Kokotanekova, Rosita†	European Southern Observatory	Germany
Marschall, Raphael*	Southwest Research Institute	USA
Reshetnyk, Volodymyr	Taras Shevchenko National University of Kyiv	Ukraine
Shi, Xian	Max Planck Institute for Solar System Research	Germany
Skorov, Yuri	Technische Universität Braunschweig	Germany
Snodgrass, Colin	University of Edinburgh	Scotland
Tubiana, Cecilia	Max Planck Institute for Solar System Research	Germany
Vincent, Jean-Baptiste	German Aerospace Center (DLR)	Germany
Zakharov, Vladimir	IAPS-INAF & Sorbonne Universites, CNRS	Italy & France

*team leaders; †young scientist

The team consists of ground based observers (Ivanova, Kokotanekova, Snodgrass), Rosetta team members covering morphology, surface and inner coma activity (Agarwal, Fornasier, Ivanovski, Tubiana, Shi, Vincent) and theorists familiar with complex models (Ivanovski, Marschall, Reshetnyk, Skorov, Zakharov). Many members are strongly involved within two out of the three above mentioned sub-groups. The team thus covers all necessary areas of expertise and is thus ideally positioned to address the problems described above.

References

Snodgrass, C., A'Hearn, M.F., Aceituno, F., Afanasiev, V., Bagnulo, S., Bauer, J., et al. The 67P/Churyumov-Gerasimenko observation campaign in support of the Rosetta mission. Philosophical Transactions of the Royal Society of London Series A 2017;375:20160249. doi:10.1098/rsta.2016.0249. arXiv:1705.10539.

Lara, L.M., de León, J., Licandro, J., Gutiérrez, P.J.. Dust Activity in Comet 67P/Churyumov Gerasimenko from February 20 to April 20, 2003. Earth Moon and Planets 2005;97:165–175. doi:10.1007/s11038-006-9067-9.

Vincent, J.B., Oklay, N., Pajola, M., Höfner, S., Sierks, H., Hu, X., et al. Are fractured cliffs the source of cometary dust jets? Insights from OSIRIS/Rosetta at 67P/Churyumov-Gerasimenko. A&A 2016a;587:A14. doi:10.1051/0004-6361/201527159. arXiv:1512.03193.

Weiler, M., Rauer, H., Helbert, J.. Optical observations of Comet 67P/Churyumov-Gerasimenko. A&A 2004;414:749–755. doi:10.1051/0004-6361:20031610.

Lara, L.M., Lowry, S., Vincent, J.B., Gutiérrez, P.J., Rożek, A., La Forgia, F., et al. Large-scale dust jets in the coma of 67P/Churyumov-Gerasimenko as seen by the OSIRIS instrument onboard Rosetta. A&A 2015;583:A9. doi:10.1051/0004-6361/201526103.

Tozzi, G.P., Patriarchi, P., Boehnhardt, H., Vincent, J.B., Licandro, J., Kolokolova, L., et al. Evolution of the dust coma in comet 67P/Churyumov-Gerasimenko before the 2009 perihelion. A&A 2011;531:A54. doi:10.1051/0004-6361/201116577. arXiv:1105.0329.

Vincent, J.B., Lara, L.M., Tozzi, G.P., Lin, Z.Y., Sierks, H.. Spin and activity of comet 67P/Churyumov-Gerasimenko. A&A 2013;549:A121. doi:10.1051/0004-6361/201219350.

Boehnhardt, H., Riffeser, A., Kluge, M., Ries, C., Schmidt, M., Hopp, U.. Mt. Wendelstein imaging of the post-perihelion dust coma of 67P/Churyumov-Gerasimenko in 2015/2016. MNRAS 2016;462:S376–S393. doi:10.1093/mnras/stw2859. arXiv:1611.03085.

Hadamcik, E., Levasseur-Regourd, A.C., Hines, D.C., Sen, A.K., Lasue, J., Renard, J.B.. Properties of dust particles in comets from photometric and polarimetric observations of 67P. MNRAS 2016;462:S507–S515. doi:10.1093/mnras/stx030.

Keller, H.U., Barbieri, C., Lamy, P., Rickman, H., Rodrigo, R., Wenzel, K.P., et al. OSIRIS The Scientific Camera System Onboard Rosetta. Space Sci. Rev. 2007;128:433–506. doi:10.1007/s11214-006-9128-4.

Sierks, H., Barbieri, C., Lamy, P.L., Rodrigo, R., Koschny, D., Rickman, H., et al. On the nucleus structure and activity of comet 67P/Churyumov-Gerasimenko. Science 2015;347:aaa1044. doi:10.1126/science.aaa1044.

Preusker, F., Scholten, F., Matz, K.D., Roatsch, T., Hviid, S.F., Mottola, S., et al. The global meter-level shape model of comet 67P/Churyumov-Gerasimenko. A&A 2017;607:L1. doi:10.1051/0004-6361/201731798.

Preusker, F., Scholten, F., Matz, K.D., Roatsch, T., Willner, K., Hviid, S.F., et al. Shape model, reference system definition, and cartographic mapping standards for comet 67P/Churyumov-Gerasimenko - Stereo-photogrammetric analysis of Rosetta/OSIRIS image data. A&A 2015;583:A33. doi:10.1051/0004-6361/201526349.

Thomas, N., Sierks, H., Barbieri, C., Lamy, P.L., Rodrigo, R., Rickman, H., et al. The morphological diversity of comet 67P/Churyumov-Gerasimenko. Science 2015;347:aaa0440. doi:10.1126/science.aaa0440.

El-Maarry, M.R., Thomas, N., , Giacomini, L., , Massironi, M., , Pajola, M., , Marschall, R., , et al. Regional surface morphology of comet 67p/churyumov-gerasimenko from rosetta/osiris images. A&A 2015;583:A26. URL: http://dx.doi.org/10.1051/0004-6361/201525723. doi:10.1051/0004-6361/201525723.

El-Maarry, M.R., Thomas, N., Gracia-Berná, A., Pajola, M., Lee, J.C., Massironi, M., et al. Regional surface morphology of comet 67P/Churyumov-Gerasimenko from Rosetta/OSIRIS images: The southern hemisphere. A&A 2016;593:A110. doi:10.1051/0004-6361/201628634.

Fornasier, S., Feller, C., Lee, J.C., Ferrari, S., Massironi, M., Hasselmann, P.H., et al. The highly active Anhur-Bes regions in the 67P/Churyumov-Gerasimenko comet: results from OSIRIS/ROSETTA observations. MNRAS 2017;469:S93–S107. doi:10.1093/mnras/stx1275. arXiv:1707.02945.

Hu, X., Shi, X., Sierks, H., Fulle, M., Blum, J., Keller, H.U., et al. Seasonal erosion and restoration of the dust cover on comet 67P/Churyumov-Gerasimenko as observed by OSIRIS onboard Rosetta. A&A 2017;604:A114. doi:10.1051/0004-6361/201629910.

Bieler, A., Altwegg, K., Balsiger, H., Berthelier, J.J., De Keyser, J., Fuselier, S., et al. The role of numerical models in data analysis for the Rosetta mission. In: European Planetary Science Congress; vol. 10. 2015, p. EPSC2015.

Fougere, N., Altwegg, K., Berthelier, J.J., Bieler, A., Bockelée-Morvan, D., Calmonte, U., et al. Three-dimensional direct simulation Monte-Carlo modeling of the coma of comet 67P/Churyumov-Gerasimenko observed by the VIRTIS and ROSINA instruments on board Rosetta. A&A 2016;588:A134. doi:10.1051/0004-6361/201527889.

Marschall, R., Su, C.C., Liao, Y., Thomas, N., Altwegg, K., Sierks, H., et al. Modelling observations of the inner gas and dust coma of comet 67P/Churyumov-Gerasimenko using ROSINA/COPS and OSIRIS data: First results. A&A 2016;589:A90. doi:10.1051/0004-6361/201628085.

Zakharov, V., Crifo, J.F., Rodionov, A., Rubin, M., Altwegg, K.. The near-nucleus gas coma of comet 67P/Churyumov-Gerasimenko prior to the descent of the surface lander PHILAE . A&A 2018;in press.:A90. doi:10.1051/0004-6361/201628085.

Marschall, R., Mottola, S., Su, C.C., Liao, Y., Rubin, M., Wu, J.S., et al. Cliffs versus plains: Can ROSINA/COPS and OSIRIS data of comet 67P /Churyumov-Gerasimenko in autumn

2014 constrain inhomogeneous outgassing? A&A 2017;605:A112. doi:10.1051/0004-6361/201730849.

Gerig, S.B., Marschall, R., Thomas, N., Bertini, I., Bodewits, D., Davidsson, B., et al. On deviations from free-radial outflow in the inner coma of comet 67P /Churyumov-Gerasimenko. Icarus 2018;311:1–22. doi:10.1016/j.icarus.2018.03.010.

Shi, X., Hu, X., Mottola, S., Sierks, H., Keller, H.U., Rose, M., et al. Coma morphology of comet 67P controlled by insolation over irregular nucleus. Nature Astronomy 2018;2:562–567. doi:10.1038/s41550-018-0481-5.

Vincent, J.B., A'Hearn, M.F., Lin, Z.Y., El-Maarry, M.R., Pajola, M., Sierks, H., et al. Summer fireworks on comet 67P. MNRAS 2016b;462:S184–S194. doi:10.1093/mnras/stw2409. arXiv:1609.07743.