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Current sheets in comet 67P/Churyumov-Gerasimenko's coma

M. Volwerk (1), G. H. Jones (2;3), T. Broiles I(4), J. Burch (5), C. Carr (6), A. J. Coates (2;3), E. Cupido(6), M. Delva (1), N. J. T. Edberg (7), A. Eriksson (7), C. Goetz (8), R. Goldstein (5), P. Henri (9), H. Madanian (10), H. Nilsson (11), I. Richter (8), K. Schwingenschuh (1), G. StenbergWieser (11) and K.-H. Glassmeier (8)
(1) 1Space Research Institute, Austrian Academy of Sciences, Graz, Austria (martin.volwerk@oeaw.ac.at), (2) Mullard Space Science Laboratory, University College London, Holmbury St. Mary, UK, (3) Centre for Planetary Sciences, UCL/Birkbeck, London, UK, (4) Space Science Institute, Boulder, Colorado, USA, (5) Southwest Research Institute, San Antonio, Texas, USA, (6) Space and Atmospheric Physics Group, Imperial College London, London, UK, (7) Swedish Institute of Space Physics, Uppsala, Sweden, (8) Institute for Geophysics and Extraterrestrial Physics, TU Braunschweig, Braunschweig, Germany, (9) Laboratoire de Physique et Chimie de l'Environnement et de l'Espace, Orleans, France, (10) Department of Physics and Astronomy, University of Kansas, Lawrence, USA, (11) Swedish Institute of Space Physics, Kiruna, Sweden

Abstract

The Rosetta Plasma Consortium (RPC) data are used to investigate the presence of current sheets in the coma of comet 67P/Churyumov-Gerasimenko. The interaction of the interplanetary magnetic field (IMF) transported by the solar wind towards the outgassing comet consists amongst others of mass-loading and field line draping near the nucleus. The draped field lines lead to so-called nested draping because of the constantly changing direction of the IMF. It is shown that the draping pattern is strongly variable over the period of one month (Figure 1).

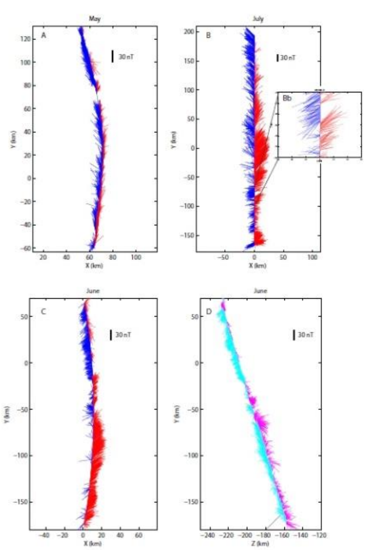

Figure 1: This is the example of an included figure.

Nested draping results in neighbouring regions with oppositely directed magnetic fields, which are separated by current sheets. Selected events on 5 and 6 June 2015 are studied, which show that there are strong rotations of the magnetic field with associated current sheets that have strengths from several 10s up to 100s of nA/m2.

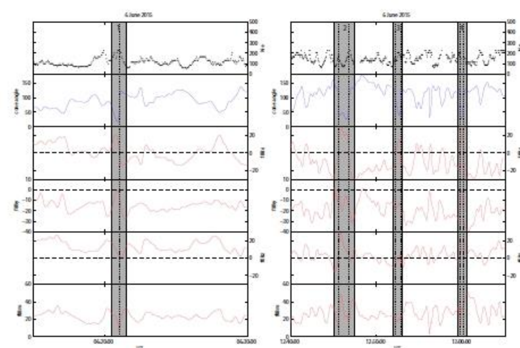

Figure 2: This is the example of an included figure.

Not all discussed current sheets show the characteristic peak in plasma density at the centre of the sheet, which might be related to the presence of a guide field (see Figure 2). There is no evidence for different kinds of plasmas on either side of a current sheet, and no strongly accelerated ions have been observed which could have been an indication of magnetic reconnection in the current sheets.

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Singing comet changes its song

Martin Volwerk (1), Charlotte Goetz (2), Magda Delva (1), Ingo Richter (2), Bruce T. Tsurutani (3), Anders Eriksson (4), Elias Odelstad (4), Patrick Meier (2), Hans Nilsson (5), and Karl-Heinz Glassmeier (2)
(1) Space Research Institute, Austrian Academy of Sciences, Schmiedlstr. 6, 8042 Graz, Austria (martin.volwerk@oeaw.ac.at), (2) Institute for Geophysics and Extraterrestrial Physics, TU Braunschweig, Mendelssohnstrasse 3, Braunschweig 38106, Germany, (3) California Institute of Technology, Pasadena, California, USA, (4) Swedish Institute of Space Physics, Uppsala, Sweden. (5) Swedish Institute of Space Physics, Kiruna, Sweden

Abstract

The singing comet [Richter et al., 2015] was discovered at the beginning of Rosetta's mission around comet 67P/Churyumov-Gerasimenko. It consists of large-amplitude compressional waves with a frequency in the range of 10 – 100 mHz. One possible description of these waves in a modified ion-Weibel instability [Meier et al., 2016]. Two-point measurements during the Philae landing allowed for determining the wave-number and dispersion of these waves [Richter et al., 2016]. Later in the mission, when the comet became more active, as it moved close to the Sun, the singing disappeared in the data, either because the instability criterion was no longer fulfilled or the signal may have been obscured by other effects.

In this presentation we will discuss observations of two days, 26 and 27 March 2016, during the Rosetta tail excursion, when the spacecraft moved down the tail and from the south to the centre, see Figure 1.

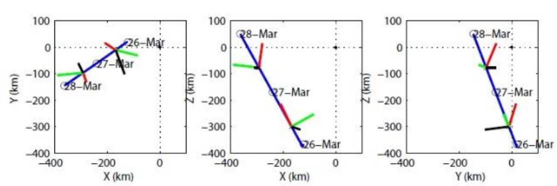

Figure 1: Orbit of Rosetta on 26-27 March 2016. The colored bars on the orbit display the magnetic field direction (black), the minimum variance (red) and maximum variance (green) direction during two intervals of interest.

Spectral analysis of the magnetic field data showed an interesting behaviour of the singing comet waves, as shown in Fig. 2, where the data are transformed to a mean-field aligned system and the transverse components are combined into left- and right-hand polarized components.

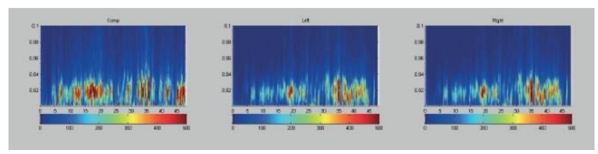

Figure 2: Dynamic spectra of the magnetic field data in a mean-field aligned coordinate system.

The dynamic spectra show strong wave power around 20 mHz, which on 26 March clearly shows a dominant compressional component, whereas on 27 March the left- and right-hand polarization dominates. This indicates that the singing comet changed its song.

Data from the magnetometer and plasma instruments are used to explain this change in wave mode, as well as a dispersion solver.

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Heterogeneity of Dust Particles of 67P/Churyumov–Gerasimenko

M.Hilchenbach and COSIMA Team
Max Planck Institute for Solar System Research, Justus-von-Liebig-Weg 3, 37077 Göttingen, Germany
(Hilchenbach@mps.mpg.de)

Abstract

Between August 2014 and September 2016, the dust analysis instrument COSIMA onboard Rosetta collected more than 1200 cometary particles in the size range of 14 um to more than 1 mm. The dust particles were imaged with an optical microscope and their compositions were analysed by a high resolution secondary ion time-of-flight mass spectrometer [1-7]. We will report on the heterogeneity of cometary dust particle morphologies and their composition in view of the present comet formation models.

Acknowledgements

COSIMA was built by a consortium led by the Max-Planck-Institut für Extraterrestrische Physik, Garching, Germany in collaboration with Laboratoire de Physique et Chimie de l'Environnement et de l'Espace, Orléans, France, Institut d'Astrophysique Spatiale, CNRS/ Université Paris Sud, Orsay, France, Finnish Meteorological Institute, Helsinki, Finland, Universität Wuppertal, Wuppertal, Germany, von Hoerner und Sulger GmbH, Schwetzingen, Germany, Universität der Bundeswehr, Neubiberg, Germany, Institut für Physik, Forschungszentrum Seibersdorf, Seibersdorf, Austria, Institut für Weltraumforschung, Österreichische Akademie der Wissenschaften, Graz, Austria and is led by the Max-Planck- Institut für Sonnensystemforschung, Göttingen, Germany with the support of the national funding agencies of Germany (DLR, grant 50 QP 1302), France (CNES), Austria and Finland. Rosetta is an ESA mission with contributions from its Member States and NASA.

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Thermal Fracturing on Comet 67P/Churyumov-Gerasimenko

Nicholas Attree (1), Olivier Groussin (1), Laurent Jorda (1), Anne-Thérèse Auger (1), David Nébouy (1), Nicolas Thomas (2), Yann Brouet (2), Olivier Poch (2), Ekkehard Kührt (3), Frank Preusker (3), Frank Scholten (3), Jörg Knollenberg (3), Stubbe Hviid (3), Paul Hartogh (4)

(1) Aix Marseille Univ, CNRS, LAM, Laboratoire d'Astrophysique de Marseille, Marseille, France (nicholas.attree@lam.fr), (2) Physikalisches Institut, Universität Bern, Sidlerstrasse 5, 3012 Berne, Switzerland, (3) Deutsches Zentrum für Luft-und Raumfahrt (DLR), Institut für Planetenforschung, Rutherfordstraße 2, 12489 Berlin, Germany, (4) Max-Planck-Institut für Sonnensystemforschung, Justus-von-Liebig-Weg 3, 37077 Göttingen, Germany

Abstract

We simulate the stresses induced by seasonal temperature changes in a putative hard layer near the surface of comet 67P/Churyumov-Gerasimenko with a thermo-viscoelastic model. We show that a hard, icy layer will experience large stresses, of up to tens of mega pascals, which far exceed its material strength down to depths of tens of centimetres to several metres (0.5 m in our nominal case of thermal inertia I = 50 J m^{-2} K^{-1} s$^{-1/2}$). This result is constant across all cometary latitudes and consistent with the detection of meter-scale thermal fracturing all over the comet. Thermal fracturing may be an important erosion process on cometary surfaces.

1. Motivation

Fracturing is prevalent at many scales on the consolidated terrains, boulders and cliffs of comet 67P/Churyumov-Gerasimenko, when observed by Rosetta's OSIRIS instrument [2]. Polygonal networks of intersecting fractures have been likened to thermal contraction crack polygons, also seen on Earth and Mars [2, 1]. Such features form when thermal stresses exceed material strengths over large, uniform areas, leading to fracture networks of a size related to the material and thermal environment in the subsurface. [1] suggest that the observed polygons, of a few metres in size, are consistent with a hard layer within a few centimetres of the surface. Such a layer would explain the high material strength encountered by the MUPUS instrument on the Philae lander, and could be formed by the recondensation or sintering of water-ice and dust grains, as suggested by laboratory experiments and computer simulations.

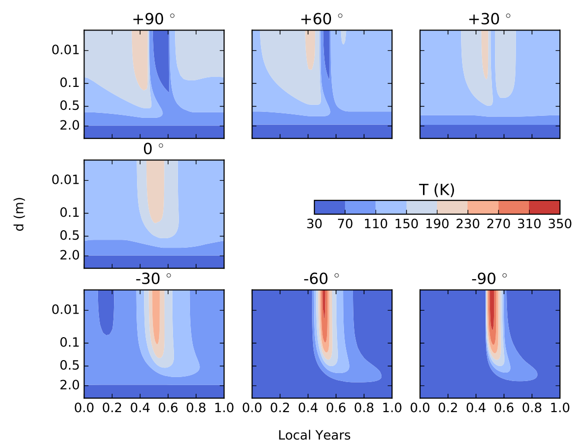

Figure 1: Temperature maps with depth and time for each of the labelled latitudes on comet 67P, produced by our 1-D thermal model with a thermal inertia of I = 50 J m^{-2} K^{-1} s$^{-1/2}$.

2. Modelling

2.1. Temperatures

We used a spherical shape model for the nucleus, orientated accordingly to its pole, to compute the temperature inside the nucleus as a function of time to derive the seasonal temperature trends. Our thermal model takes into account the solar insolation, the nucleus surface thermal emission and heat conductivity. The average diurnal temperature at each depth interval, i.e. the seasonal trend, is then computed.

The seasonal thermal wave can be seen (Fig.1) propagating downwards from the surface to some depth. The phasing of the seasonal change varies between the northern and southern hemispheres because of the comet's obliquity.

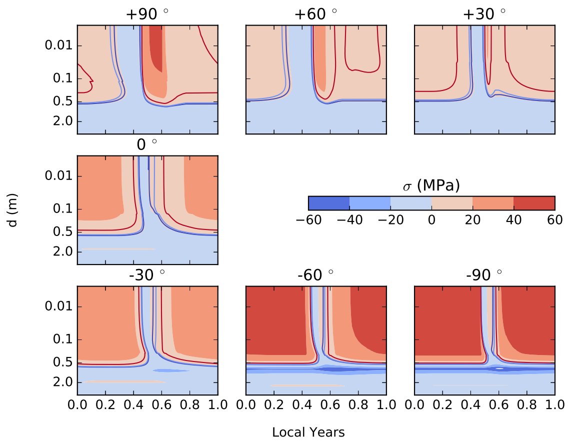

Figure 2: Thermal stresses with depth and time for each of the labelled latitudes on comet 67P, with I = 50 J m^{-2} K^{-1} $s^{-1/2}$. Highlighted contours are likely material strengths, from [3], of $1, 2.5$ and 10 MPa.

2.2. Thermal Stresses

Following the method of [4], we use a Maxwellian thermo-viscoelastic description of an ice-rock mixture. We solve the equations numerically for stress (σ) at each time- and depth-step of the temperature profiles from above. For our baseline mode, we use a thermal inertia of I = 50 J m^{-2} K^{-1} $s^{-1/2}$ and adopt the Martian permafrost material properties for a linear mixture of 45% ice and rock [4]. Ice, snow and ice-bonded soils all have similar rheologies so any hard layer, containing significant amounts of ice, should therefore exhibit the same type of viscoelastic behaviour.

As shown in Fig. 2, compressive (negative) stresses follow the thermal wave, followed by tensile (positive) stresses as the material cools. Tensile stresses remain large for much of the cycle, particularly in the cold southern hemisphere, and the maximum depth of the transition from tension to compression is roughly the same in all cases at ~ 0.5 m. The highlighted contours show various values for the tensile strength of a water-ice and rock-ice mixtures [3].

3. Summary and Conclusions

Thermal stresses are easily large enough to exceed the tensile strength of water-ice and ice-rock mixtures down to ~ 0.5 m, depending on thermal inertia. Fracturing can therefore be expected to at least this depth at all latitudes on the comet. These results are nearly independent of latitude but do vary with ice content, Young's modulus and thermal expansion coefficient. Stress decreases with decreasing ice-content and at zero ice-fraction the unconsolidated material probably cannot support fractures.

Polygons on Earth and Mars are typically a few times their fracture depth, entirely consistent with these results for polygons of mean size 3 m [1], measured on 67P. This agreement is suggestive of an ice-rich hard layer within about half a metre of the cometary surface. Because of the polygons' uniformity, little variation in the depth or mechanical properties of this hard layer is suggested

Thermal fracturing on the metre-scale may be an important erosion mechanism. Gradual weakening of material by thermal fatigue will break down boulders and weaken cliff walls, making collapse more likely. Debris fields at the bottom of many cliffs suggest this is a common process, while individual collapses have been linked with outburst activity. This kind of process could be occurring all over the comet, leading to the gradual retreat of cliffs and removal of material across the surface. Other Jupiter-family comets undergo comparable seasonal temperature changes and the presence of hard, ice layers and thermal fracturing is therefore also expected on them.

Acknowledgements

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Oxygen Isotopes in H_2O in the coma of 67P/Churyumov-Gerasimenko measured with ROSINA/DFMS

I. Schroeder (1), K. Altwegg (1,2), H. Balsiger (1), J. J. Berthelier (3), J. De Keyser (4), B. Fiethe (5), S. A. Fuselier (6), S. Gasc (1), T. I. Gombosi (7), M. Rubin (1), T. Sémon (1), C.-Y. Tzou (1), S. F. Wampfler (2), P. Wurz (1,2)

(1) Physikalisches Institut, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland
(2) Center for Space and Habitability, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland
(3) LATMOS, 4 Avenue de Neptune, F-94100 Saint-Maur, France
(4) Royal Belgian Institute for Space Aeronomy (BIRA-IASB), Ringlaan 3, B-1180, Brussels, Belgium
(5) Institute of Computer and Network Engineering (IDA), TU Braunschweig, Hans-Sommer-Strasse 66, D-38106 Braunschweig, Germany
(6) Space Science Division, Southwest Research Institute, 6220 Culebra Road, San Antonio, TX 78228, USA
(7) Department of Atmospheric, Oceanic and Space Sciences, University of Michigan, 2455 Hayward, Ann Arbor, MI 48109, USA

Abstract

Comets are widely considered to contain some of the most pristine material in the Solar System [1]. The degree of isotopic fractionation – the enrichment or depletion of an isotope in a molecule, relative to its initial abundance – observed in a comet is sensitive to the environmental conditions at the time of the comet's formation [2]. Therefore, measurements of isotopic abundances in cometary ices reveal important information regarding the early Solar System's composition, density and temperature and the amount of radiation present before the accretion of solid bodies, when the molecules were being formed during the chemical evolution of the presolar cloud to the protosolar nebula and protoplanetary disc. They are therefore vital to understanding and reconstructing the history and origins of material in the Solar System [3].

The $^{16}O/^{18}O$ ratio of CO_2 in the coma of the comet 67P/Churyumov-Gerasimenko was previously measured by Hässig et al. (2016) [2] with the ESA spacecraft Rosetta's ROSINA instrument package's Double Focusing Mass Spectrometer (DFMS) and found to be consistent, within 1σ uncertainty, with solar system abundances calculated by Lodders (2003) [4] but not with solar wind measurements by McKeegan et al. (2011) [5].

This study aims to examine the $^{16}O/^{18}O$ ratio of H_2O in the coma of the comet 67P, as measured by the Rosetta/ROSINA DFMS, and to compare it with solar values, as well as against the results from the aforementioned earlier investigation by Hässig et al. (2016) [2] into the $^{16}O/^{18}O$ ratio of CO_2. A long-term study of the $^{16}O/^{18}O$ ratio in H_2O will also be performed to investigate if changes in this ratio occurred over the course of the comet's passage through the inner heliosphere.

Acknowledgements

ROSINA would not have produced such outstanding results without the work of the many engineers, technicians, and scientists involved in the mission, in the Rosetta spacecraft, and in the ROSINA instrument team over the last 20 years, whose contributions are gratefully acknowledged. Rosetta is a European Space Agency (ESA) mission with contributions from its member states and NASA. We acknowledge herewith the work of the whole ESA Rosetta team.

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The Aswan cliff collapse on comet 67P/Churyumov-Gerasimenko

M. Pajola (1,2), S. Höfner (3), J.B. Vincent (3,4), N. Oklay (3,4), F. Scholten (4), F. Preusker (4), S. Mottola (4), G. Naletto (2,5,6), S. Fornasier (7), S. Lowry (8), C. Feller (7), P.H. Hasselmann (7), C. Güttler (3), C. Tubiana (3), H. Sierks (3), H. U. Keller (4,9) and the OSIRIS Team

(1) NASA Ames Research Center, Moffett Field, California 94035, USA (maurizio.pajola@gmail.com), (2) Center of Studies and Activities for Space, CISAS, 'G. Colombo', University of Padova, 35131 Padova, Italy, (3) Max-Planck-Institut für Sonnensystemforschung, 37077 Göttingen, Germany. (4) Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Planetenforschung, 12489 Berlin, Germany. (5) Department of Information Engineering, University of Padova, 35131 Padova, Italy. (6) CNR-IFN UOS Padova LUXOR, 35131 Padova, Italy. (7) LESIA Observatoire de Paris, PSL Research University, CNRS, Université Paris Diderot, Sorbonne Paris Cité, UPMC, Paris 06, Sorbonne Universités, Meudon Principal Cedex 92195, France. (8) The University of Kent, School of Physical Sciences, Canterbury, Kent CT2 7NZ, UK. (9) Institut für Geophysik und extraterrestrische Physik (IGEP), Technische Universität Braunschweig, 38106 Braunschweig, Germany.

Abstract

The ESA Rosetta mission was designed to witness the surface changes occurring on the cometary nucleus while approaching perihelion and how its activity evolves with time [1]. On 10 July 2015, after escorting comet 67P Churyumov-Gerasimenko for almost one year, the Rosetta Navigation Camera captured a large plume of dust that could be traced back to an area encompassing the Aswan escarpment [2] located on the Seth region of 67P [3], Fig. 1. Before such event, high-res images showed a 70 m long and 1 m wide fracture propagating almost perpendicularly from the Aswan scarp edge at its two ends and inward in a semi-circular fashion ~12 m away from the edge at its farthest point [4].

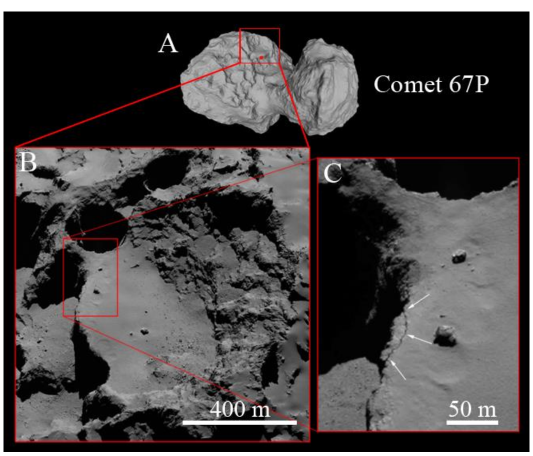

Fig. 1: The location of the Aswan site and fracture.

Five days later, the OSIRIS camera observed a fresh, sharp and bright edge on the Aswan cliff, at the location of the mentioned fracture (Fig. 2). The spectrophotometric study of the images focusing on the bright cometary interior revealed that it was highly saturated in the 600–900 nm range, resulting in a normal albedo with values >0.40 (lower limit) at 650 nm. This value is at least 6 times as bright as the overall surface of the nucleus itself [5] and it is explainable by the presence of fresh exposed water ice [6,7]. On December 26, 2015, the bright cliff was imaged again: the resulting normal albedo at its edge was already 50% less than ~5 months before, meaning that most of the exposed water ice had already sublimated. One year after the collapse (6 August 2016), the cliff has returned to the dark value (<0.12 at 650 nm), similar to the 67P terrains depleted in volatiles [5].

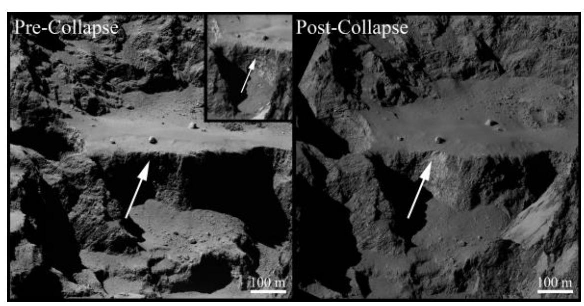

Fig. 2: Pre- and Post-Collapse images taken by the OSIRIS camera on 19 September 2015 and on 8 June 2016, respectively. The white arrows point at the cliff before and after the collapse.

Recent studies have speculated that thermal stresses may influence surface features on 67P [8], eventually predisposing cliff collapses [9]. We therefore investigated whether thermal effects, or thermal cracking could have weakened the already fractured Aswan cliff structure. We derived that in July 2015, at the cliff face, the surface is perpendicularly illuminated for a short time after a long cooling period in shadow (only 90 minutes during the cometary day (12.4 hours)) right after local sunrise. This means that a strong temperature gradient occurs here, with the cliff face's temperature rising from -140°C (130 K) to 50°C (320 K) in less than 20 min, with a maximum of 30 K °C/min shortly after sunrise (Fig. 3).

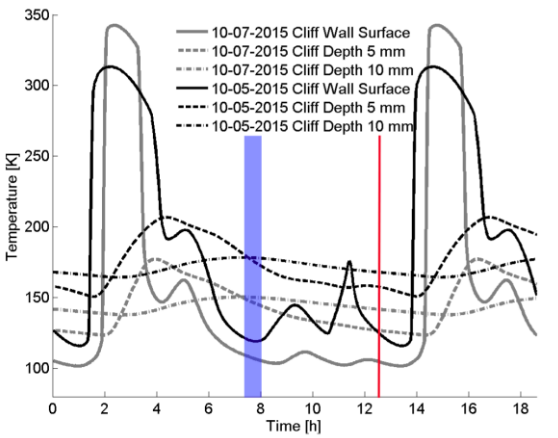

Fig. 3: Modelled temperatures for the cliff wall at three different depths on 10 May and 10 July 2015, respectively. The blue bar shows the observed NavCam outburst cliff collapse time, while the red line indicates the rotation period.

Despite such extreme factors, the collapse occurred during local midnight (blue bar of Fig. 3). Nevertheless, we underline that pervasive fracturing is present over the entire Aswan wall, hence the diurnal thermal gradients, as well as their seasonal and annual variations, may have driven cyclic and cumulative opening of such fractures, in a process similar to that observed on the Earth [10]. If thermal gradients have widened and deepened the fractures into the subsurface volatile-rich strata [11], heat may have been transferred to deeper layers causing the loss of in-depth ice. Moreover, the gas suddenly released by the subliming material could have infiltrated within the fractures [12], broadening them as well. For this reason, we suggest that the cumulative effect led by the thermal gradients could be a factor in weakening the cliff structure, predisposing it to subsequent collapse.

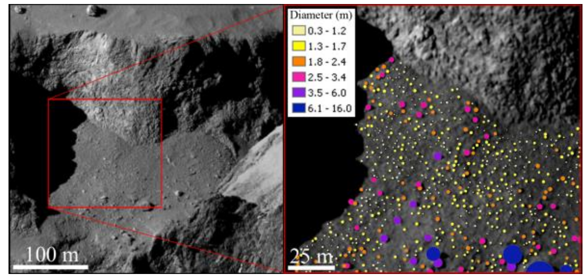

Fig. 4: The post-collapse talus boulder analysis.

Eventually, we studied the new deposit appeared at the cliff feet. We identified all boulders ≥1.5 m in size located on the Aswan talus, before and after the collapse and found that the resulting pre-collapse cumulative number of boulders ≥1.5 m was 11784 km^{-2}, whereas after the breakdown, this number changed to 18438 km^{-2}. Such an increase of density and surface roughness is due to the increase of the number of boulders in the 1.5–3.0-m size range, as a result of the collapse itself [13]. Indeed, the boulders' size-frequency distribution indicates that the crumbling wall has produced predominantly smaller chunks. This is similarly observed on the Earth, where the intrinsic weakening of cliff material owing to penetrative fracturing strongly affects the resulting size of the debris, and typically results in a crumble of finer material, instead of only a few large chunks [14]. In addition, by extrapolating the SFD to smaller sizes (0.50 m), we estimated that 99% of the volume of the collapsed wall is distributed in the talus, in blocks ranging from 0.5 to 10 m in diameter, while 1% of this volume has been lost to space during the collapse forming the outburst plume.

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Phase-ratio imagery of 67P/Churyumov-Gerasimenko at small phase angles using Rosetta-OSIRIS images

N. Masoumzadeh (1), H. Sierks (1), C. Tubiana (1), C. Güttler (1), S. Fornasier (2), M. A. Barucci (2), L. Jorda (3), and the OSIRIS team
(1) Max-Planck-Institut für Sonnensystemforschung, Justus-von-Liebig-Weg 3, 37077 Göttingen, Germany (masoumzadeh@mps.mpg.de), (2) LESIA, Observatoire de Paris, PSL Research University, CNRS, Univ. Paris Diderot, Sorbonne Paris Cité, UPMC Univ. Paris 06, Sorbonne Universités, 5 place Jules Janssen, 92195 Meudon, France. (3) Aix Marseille Université, CNRS, LAM (Laboratoire d'Astrophysique de Marseille), UMR 7326, 38 rue Frédéric Joliot-Curie, 13388 Marseille Cedex 13, France.

Abstract

The Rosetta spacecraft reached its target 67P/Churyumov-Gerasimenko (hereafter 67P) in July-August 2014 and orbited around the comet until 30th September 2016. During the 2.5 years of mission, Rosetta did two zero-phase-angle fly-bys: the spacecraft was flying between the Sun and the comet and therefore, the angle between the Sun and the observer (known as phase angle, α) approached zero. In this phase angles range, a phenomenon, known as, opposition effect, manifests itself as a rapid increase in the surface brightness.
The opposition effect is controlled by two mechanisms: coherent backscattering (CBOE) and shadow hiding (SHOE).
During the zero-phase-angle fly-bys, OSIRIS [1], the scientific imaging system onboard Rosetta, acquired high resolution images of the comet surface in different filters in the visible wavelength range. The first zero phase angle fly-by took place on 14th February 2015, with closest approach 6km from the nucleus. A study of this fly-by is presented in [2] and [3].
The second zero phase angle fly-by took place on 09-10th April 2016. Rosetta reached a minimum distance of 30 km from the comet and OSIRIS acquired 259 images with the Wide Angle Camera (WAC) and the Narrow Angle Camera (NAC).
For our study, we have used NAC images in the F84 (480.7 nm), F82 (649.2 nm), F88 (743.7 nm) filters, spanning the phase angle range from 0.65° to 6.1°. During the fly-by the Imhotep-Kherpy-Ash region was imaged (Figure 1).
We used the phase-ratio map technique in the different wavelengths in order to gain insight into the cause of the opposition effect.

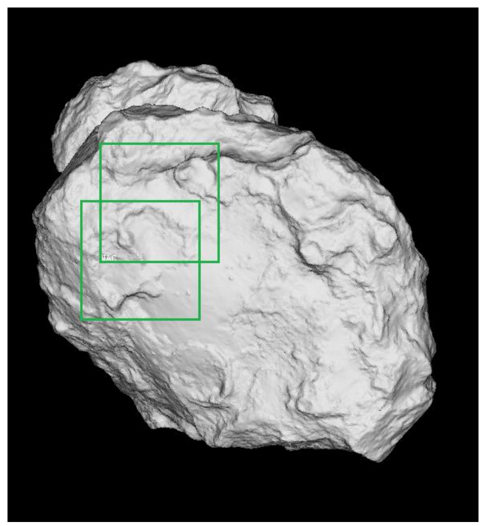

Figure 1: The location of NAC images covering the areas which are located in Imhotep-Kherpy-Ash region.

The phase-ratio (α1/α2, with α1 < α2) mapping is an effective tool to investigate surface structure in large phase angles [4, 5]. At small phase angles the phase-ratio approach is used to explore the phase function behavior when the contribution of CBOE is significant compared to SHOE [6, 7]. The phase-ratio maps are created from the map projected image pairs which are photometrically corrected. Hence, it is possible to calculate the ratio for the overlapped region. We study the phase-ratio map for the different regions of interest (ROIs) versus reflectance to analyze the phase function slope. Moreover, the wavelength dependency of the ratio allows to search for an evidence of CBOE [8].

Acknowledgements

OSIRIS was built by a consortium of the Max-Planck-Institut für Sonnensystemforschung, Göttingen, Germany, CISAS University of Padova, Italy, the Laboratoire d'Astrophysique de Marseille, France, the Instituto de Astrofísica de Andalucía, CSIC, Granada, Spain, the Research and Scientific Support Department of the European Space Agency, Noordwijk, The Netherlands, the Instituto Nacional de Tecnica Aeroespacial, Madrid, Spain, the Universidad Politechnica de Madrid, Spain, the Department of Physics and Astronomy of Uppsala University, Sweden, and the Institut für Datentechnik und Kommunikationsnetze der Technischen Universität Braunschweig, Germany. The support of the national funding agencies of Germany (DLR), France (CNES), Italy (ASI), Spain (MEC), Sweden (SNSB), and the ESA Technical Directorate is gratefully acknowledged. We thank the Rosetta Science Ground Segment at ESAC, the Rosetta Mission Operations Centre at ESOC and the Rosetta Project at ESTEC for their outstanding work enabling the science return of the Rosetta Mission. We also gratefully acknowledge the developers of SPICE and NAIF/PDS resources. This research has made use of the USGS Integrated Software for Imagers and Spectrometers (ISIS). This research made use of the *shapeViewer* software, available at www.comet-toolbox.com.

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The dust environment of 67P/Churyumov-Gerasimenko as seen through Rosetta/OSIRIS

C. Tubiana (1), C. Güttler (1), H. Sierks (1), I. Bertini (2) and the OSIRIS Team (3)

(1) Max-Planck-Institut für Sonnensystemforschung, Justus-von-Liebig-Weg 3, 37077 Göttingen, Germany (tubiana@mps.mpg.de), (2) Department of Physics and Astronomy "G. Galilei", University of Padova, Vicolo dell' Osservatorio 3, 35122 Padova, Italy, (3) MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA.

Abstract

The ESA's Rosetta spacecraft had the unique opportunity to be in the vicinity of comet 67P/Churyumov-Gerasimenko for 2.5 years, observing how the comet evolved while approaching the Sun, passing through perihelion and then moving back into the outer solar system. OSIRIS, the Optical, Spectroscopic, and Infrared Remote Imaging System [1], was the scientific camera system onboard Rosetta. Composed of two cameras (the Wide Angle Camera (WAC) and the Narrow Ange Camera (NAC)), it imaged the nucleus and the comet dust environment from March 2014 to September 2016, while 67P/Churuymov-Gerasimenko moved from 4.1 AU inbound to 3.8 AU outbound.

WAC images, thanks to the field of view of about 12°x12° are the most suited to study the unresolved dust coma, investigating its diurnal and seasonal variations and providing insights into the dust composition. Comparison with ground based observations will help us to understand whether the dust coma has similar behaviors at the small scales observed by OSIRIS and at the large scales observed from ground. Hundreds of individual particles have been identified in the thousands of images dedicated to dust studies. Those particles have been characterized in terms of color, size distribution, distance, light curves and orbits (see e.g. [2]; [3]; [4]; [5]; [6]; [7]; [8]).

Acknowledgements

OSIRIS was built by a consortium of the Max-Planck-Institut für Sonnensystemforschung, Göttingen, Germany, CISAS University of Padova, Italy, the Laboratoire d'Astrophysique de Marseille, France, the Instituto de Astrofísica de Andalucía, CSIC, Granada, Spain, the Research and Scientific Support Department of the European Space Agency, Noordwijk, The Netherlands, the Instituto Nacional de Tecnica Aeroespacial, Madrid, Spain, the Universidad Politechnica de Madrid, Spain, the Department of Physics and Astronomy of Uppsala University, Sweden, and the Institut für Datentechnik und Kommunikationsnetze der Technischen Universität Braunschweig, Germany. The support of the national funding agencies of Germany (DLR), France (CNES), Italy (ASI), Spain (MEC), Sweden (SNSB), and the ESA Technical Directorate is gratefully acknowledged. We thank the Rosetta Science Ground Segment at ESAC, the Rosetta Mission Operations Centre at ESOC and the Rosetta Project at ESTEC for their outstanding work enabling the science return of the Rosetta Mission.

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Characterization of dust aggregates in the vicinity of the Rosetta spacecraft

C. Güttler (1), P. H. Hasselmann (2), Y. Li (3), M. Fulle (4), C. Tubiana (1), G. Kovacs (1), J. Agarwal (1), H. Sierks (1), S. Fornasier (2), M. Hofmann (1), P. Gutiérrez Marqués (1), T. Ott (5), E. Drolshagen (5), I. Bertini (6) and the OSIRIS Team (7)

(1) Max-Planck-Institut für Sonnensystemforschung, Justus-von-Liebig-Weg 3, 37077 Göttingen, Germany (guettlerc@mps.mpg.de), (2) LESIA, Observatoire de Paris, CNRS, UPMC Univ Paris 06, Univ. Paris-Diderot, 5 place J. Janssen, 92195 Meudon Pricipal Cedex, France, (3) Space Science Institute, Macau University of Science and Technology, Macau, (4) INAF-Osservatorio Astronomico di Trieste, via Tiepolo 11, 34143 Trieste, Italy, (5) University of Oldenburg, Ammerländer Heerstraße 114, Oldenburg, Germany, (6) Department of Physics and Astronomy "G. Galilei", University of Padova, Vicolo dell' Osservatorio 3, 35122 Padova, Italy, (7) MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA.

Abstract

In a Rosetta/OSIRIS imaging activity in June 2015, we have observed the dynamic motion of particles close to the spacecraft. Due to the focal setting of the OSIRIS Wide Angle Camera (WAC), these particles were blurred, which can be used to measure their distances to the spacecraft. We detected 108 dust aggregates over a 130 minutes long sequence, and find that their sizes are around a millimetre and their distances cluster between 2 m and 40 m from the spacecraft. Their number densities are about a factor 10 higher than expected for the overall coma and highly fluctuating. Their velocities are small compared to the spacecraft orbital motion and directed away from the spacecraft, towards the comet. From this we conclude that they have interacted with the spacecraft and assess three possible scenarios. We prefer a scenario where centimeter-sized aggregates collide with the spacecraft and we would observe the fragments. Ablation of a dust layer on the spacecraft's z panel when rotated towards the sun is a reasonable alternative. We could also measure an acceleration for a subset of 18 aggregates, which is directed away from the sun and can be explain by a rocket effect, which requires a minimum ice fraction in the order of 0.1%.

Acknowledgements

OSIRIS was built by a consortium of the Max-Planck-Institut für Sonnensystemforschung, Göttingen, Germany, CISAS University of Padova, Italy, the Laboratoire d'Astrophysique de Marseille, France, the Instituto de Astrofísica de Andalucía, CSIC, Granada, Spain, the Research and Scientific Support Department of the European Space Agency, Noordwijk, The Netherlands, the Instituto Nacional de Tecnica Aeroespacial, Madrid, Spain, the Universidad Politechnica de Madrid, Spain, the Department of Physics and Astronomy of Uppsala University, Sweden, and the Institut für Datentechnik und Kommunikationsnetze der Technischen Universität Braunschweig, Germany. The support of the national funding agencies of Germany (DLR), France (CNES), Italy (ASI), Spain (MEC), Sweden (SNSB), and the ESA Technical Directorate is gratefully acknowledged. We thank the Rosetta Science Ground Segment at ESAC, the Rosetta Mission Operations Centre at ESOC and the Rosetta Project at ESTEC for their outstanding work enabling the science return of the Rosetta Mission.

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Recent Results on Cometary Dust by Rosetta/COSIMA

O. J. Stenzel(1), M. Hilchenbach(1), Jochen Kissel (1), Yves Langevin (2), Christelle Briois (3), Andreas Koch (4), Rita Schulz (5), Johan Silen (6), S. Merouane(1), J. Paquette(1), N. Fray(7), Jouni Rynö (6), and the COSIMA team

(1) Max-Planck-Institut für Sonnensystemforschung, Göttingen, Germany. (stenzel@mps.mpg.de), (2) Institut d'Astrophysique Spatiale, CNRS / Université Paris Sud, Bâtiment 121, 91405 Orsay,(3) Laboratoire de Physique et Chimie de l'Environnement et de l'Espace, CNRS / Université d'Orléans 3 Av. de la Recherche Scientifique, 45071 Orléans, France, (4) von Hoerner und Sulger GmbH, Schlossplatz 8, 68723 Schwetzingen, Germany, (5) ESA – ESTEC, Postbus 299, 2200AG Noordwijk, The Netherlands, (6) Finnish Meteorological Institute, Climate Research, Erik Palmenin aukio 1, P.O.Box 503, FI-00101 Helsinki, Finland, (7) Laboratoire Interuniversitaire des Systèmes Atmosphériques (LISA), UMR CNRS 7583, Université Paris Est Créteil et Université Paris Diderot, Institut Pierre Simon Laplace, 94000 Créteil, France

1. Introduction

The Cometary Secondary Ion Mass Analyzer (COSIMA) was a dust analysing instrument on board the Rosetta spacecraft which orbited the comet 67P/Churyumov-Gerasimenko (here after 67P) for more than two years before landing on the nucleus and thus ending the mission. COSIMA collected dust particles from the inner coma of 67P on metal target plates, imaged them, and used its ToF-SIMS to probe their composition.

2. Dust physical properties and flux

The registered particles have sizes between 14μm (image resolution) and about 1 mm. Most break apart on hitting either the funnel during entry or the target plate and can be classified according to their structure [4]. The internal strength of these particles was found to be on the order of 10^3 Pa, with sub-units of 30-40 μm being more stable [3]. The pre-perihelion flux has been analysed in [5].
More recently, [6] analysed the size distribution of collected dust for the whole mission (Fig. 1).

3. Composition

The cometary dust is composed of partly organic and partly silicatic phases. [8] and [2] found many rock forming elements in the dust, and the these elements (with the noteable execptions of C and Si) show in their abundances some similarities with carbonaceous chondrites [9] (Fig. 2). For the organic phase, the spectral signature of the cometary organic matter is mostly present in the low mass range (Fig. 3). This is related to the presence of a complex organic matter which could present some similarities with the IOM

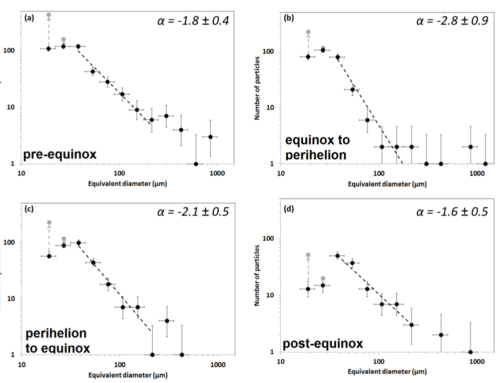

Figure 1: Distribution of collected particle size during different phases of the mission: Size distribution measured (a) between Aug. 2014 and the May 2015 equinox, (b) between the equinox and the perihelion, (c) between the perihelion and the Apr. 2016 equinox and (d) between Apr. 2016 and the end of Sept. 2016. The dashed lines are the best fits for the size distribution of the particles in the 30 μm to 150 μm size range. The corresponding cumulative power index is given in each panel. The grey dots indicate the number of particles adjusted for the estimated observational bias resulting from the detection method.

extracted from carbonaceous chondrites [1]. The isotopic ratio for oxygen shows VSMOW values within the uncertainties, see Fig. 4, [7].

Acknowledgements

COSIMA was built by a consortium led by the Max-Planck-Institut für Extraterrestrische Physik, Garching, Germany in collaboration with Laboratoire de Physique et Chimie de l'Environnement et de l'Espace, Orléans, France, Institut d'Astrophysique Spatiale, CNRS/ Université Paris Sud, Orsay, France, Finnish Meteorological Institute, Helsinki, Finland, Universität Wuppertal, Wuppertal, Germany, von Hoerner und Sulger GmbH, Schwetzingen, Germany, Universität der Bundeswehr, Neubiberg, Germany, Institut für Physik, Forschungszentrum Seibersdorf, Seibersdorf, Austria, Institut für Weltraumforschung, Österreichische Akademie der Wis-

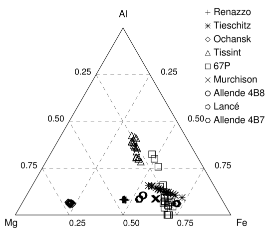

Figure 2: Ternary diagram of ion counts for the elements Mg, Fe and Al. Each data point marks the average abundance over a randomly chosen set of spectra from a specific sample.

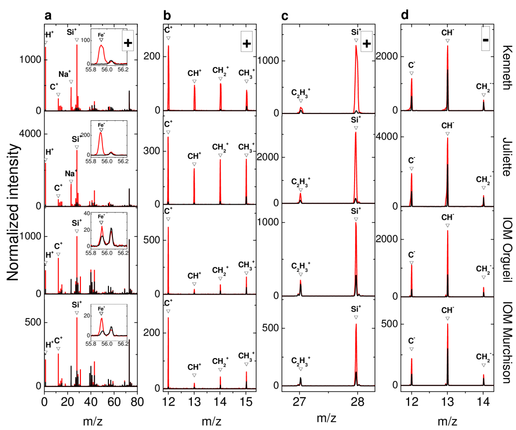

Figure 3: Mass spectra of cometary particles Keneth and Juliette (first and second row), and IOM from CI chondrites Orgueil and Murchison. Measurements on the target substrate and the sample are distinguished by the black and red color, respectively.

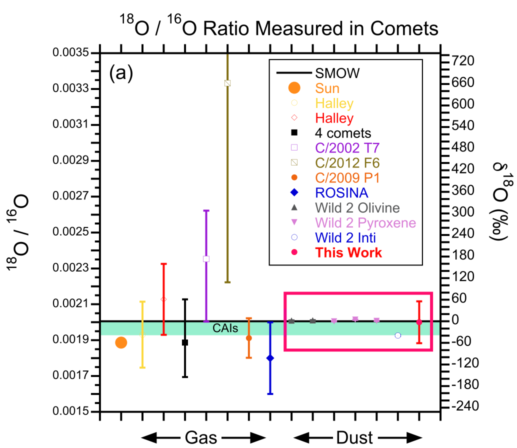

Figure 4: Oxygen isotop ratios for 67P dust compared with other measurements

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Aliphatic Compounds in the Coma of Comet 67P/Churyumov-Gerasimenko

M. Schuhmann[1], K. Altwegg[1], H. Balsiger[1], J.-J. Berthelier[2], J. De Keyser[3], B. Fiethe[4], S. A. Fuselier[5], S. Gasc[1], T. I. Gombosi[6], M. Rubin[1], I. Schroeder[1], C.-Y. Tzou[1]

(1) Physikalisches Institut, Universität Bern
(2) Institut Pierre Simon Laplace, CNRS, Université Pierre et Marie Curie
(3) Koninklijk Belgisch Instituut voor Ruimte-Aeronomie, Institut Royal Belge d'Aéronomie Spatiale
(4) Institut für Datentechnik und Kommunikationsnetze, TU Braunschweig
(5) Department of Space Science, Southwest Research Institute
(6) Department of Climate and Space Sciences and Engineering, University of Michigan

1. Abstract

European Space Agency's Rosetta mission was one of the cornerstones in cometary space science. For the first time a spacecraft has accompanied a comet for an extended time period instead of short-time flybys as done before at other comets. Furthermore, it was the first time a soft landing on a comet was successfully performed. This combination allowed an in-depth investigation of the physical and chemical properties of the nucleus and coma.

Comets consist of rock, dust, water ice, and frozen gases. Furthermore, they contain various organic compounds including hydrocarbons. [1] Comets belong to the most pristine objects in our Solar System, which makes them a highly valuable target to study the elementary and molecular composition. Depending on the distance to the Sun, outgassing of frozen volatiles can be observed. This leads to the formation and evolution of the coma, which contains gaseous molecules as well as solid dust particles.

The Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA) [2] has observed the coma of comet 67P/Churyumov-Gerasimenko for more than two years. By now its instruments, DFMS (Double Focusing Mass Spectrometer) and RTOF (Reflectron Time-of-Flight), have identified many components never previously detected in comets. This applies to many organic molecules as well.

DFMS space data indicates the presence of hydrocarbons in the coma of 67P. [3] Therefore a closer investigation of aliphatic compounds like n-Heptane, n-Pentane, and n-Octane is essential. The first step for the investigation of these compounds in the coma of 67P is a precise calibration of the DFMS instrument. The calibration is performed under laboratory conditions with the DFMS flight spare model.

DFMS ionization energy by 45eV electrons causes the aliphatic molecule chains to break up into smaller fragments.[1] This results in a characteristic fragmentation pattern allowing an determination of the aliphatic compounds and thus a study of the relative abundances of these hydrocarbons in the coma of 67P.

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Noble gases in the coma of comet 67P/Churyumov-Gerasimenko

M. Rubin (1), K. Altwegg (1,2), H. Balsiger (1), J.-J. Berthelier (3), C. Briois (4), M. Combi (5), J. De Keyser (6), B. Fiethe (7), S. A. Fuselier (8), S. Gasc (1), T. I. Gombosi (5), K. C. Hansen (5), A. Jäckel (1), E. Kopp (1), A. Korth (9), U. Mall (9), B. Marty (10), O. Mousis (11), H. Rème (12), M. Schuhmann (1), I. Schroeder (1), T. Sémon (1), C.-Y. Tzou (1), J. H. Waite (8), P. Wurz (1,2)

(1) Physikalisches Institut, University of Bern, Sidlerstr. 5, CH-3012 Bern, Switzerland. (2) Center for Space and Habitability, University of Bern, Sidlerstr. 5, CH-3012 Bern, Switzerland. (3) Laboratoire Atmosphères, Milieux, Observations Spatiales, Institut Pierre Simon Laplace, CNRS, Université Pierre et Marie Curie, 4 Avenue de Neptune, 94100, Saint-Maur, France. (4) Laboratoire de Physique et Chimie de l'Environnement et de l'Espace (LPC2E), UMR 6115 CNRS – Université d'Orléans, France. (5) Department of Climate and Space Sciences and Engineering, University of Michigan, 2455 Hayward, Ann Arbor, MI 48109, USA. (6) Koninklijk Belgisch Instituut voor Ruimte-Aeronomie - Institut Royal Belge d'Aéronomie Spatiale, Ringlaan 3, B-1180 Brussels, Belgium. (7) Institute of Computer and Network Engineering (IDA), TU Braunschweig, Hans-Sommer-Straße 66, D-38106 Braunschweig, Germany. (8) Space Science Directorate, Southwest Research Institute, 6220 Culebra Rd., San Antonio, TX 78228, USA. (9) Max-Planck-Institut für Sonnensystemforschung, Justus-von-Liebig-Weg 3, 37077 Göttingen, Germany. (10) Centre de Recherches Pétrographiques et Géochimiques, CNRS, Université de Lorraine, 15 rue Notre Dame des Pauvres, BP 20, 54501 Vandoeuvre lès Nancy, France. (11) Laboratoire d'Astrophysique de Marseille, CNRS, Aix Marseille Université, 13388, Marseille, France. (12) Institut de Recherche en Astrophysique et Planétologie, CNRS, Université Paul Sabatier, Observatoire Midi-Pyrénées, 9 Avenue du Colonel Roche, 31028 Toulouse Cedex 4, France.

Abstract

The European Space Agency's Rosetta mission accompanied comet 67P/Churyumov-Gerasimenko (67P) for over two years along its orbit around the Sun. Comets are among the most pristine objects in our solar system. Investigating their composition was one of the main goals of the Rosetta mission. Abundances and isotopic ratios of the different volatile species provide crucial insights into the physical and chemical conditions during and possibly even before the comet's formation in the early solar system.

The Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA) consisted of a pressure sensor and two mass spectrometers and was dedicated to the detection of volatiles in the coma of 67P [1]. Already early in mission, in October 2014, ROSINA detected the noble gas argon at the comet [2]. Then late in the mission in May 2016, after an intense phase of gas and dust activity around the perihelion, Rosetta spent several weeks within 7 to 10 km of 67P. These conditions allowed the detection of additional noble gases - krypton and xenon. In this presentation, we will report on our latest results from the investigation of the relative abundances and the isotopic ratios of these noble gases measured in the coma of 67P.

Acknowledgements

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Pre- and post-perihelion analysis of Seth's circular niches on comet 67P/Churyumov-Gerasimenko

A. Lucchetti (1), M. Pajola (2), S. Fornasier (3), S. Mottola (4), L. Penasa (5), L. Jorda (6), G. Cremonese (1), C. Feller (3), P.H. Hasselmann (3), M. Massironi (7), S. Ferrari (5), G. Naletto (8,9,5), N. Oklay (4) and the OSIRIS team

(1)INAF-Astronomical Observatory of Padova, Italy (alice.lucchetti@oapd.inaf.it); (2) NASA Ames Research Center, Moffett Field, CA 94035, USA; (3) LESIA, Observatoire de Paris, PSL Research University, CNRS, Univ. Paris Diderot, Sorbonne Paris Cité, UPMC Univ. Paris 06, Sorbonne Universités, Meudon, France; (4) Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Planetenforschung, Berlin, Germany; (5) Center of Studies and Activities for Space, CISAS, 'G. Colombo', University of Padova, Italy; (6) Laboratoire d'Astrophysique de Marseille, UMR 7326 CNRS & Aix-Marseille Université, 38 rue Frédéric Joliot-Curie, France; (7) Geosciences Department, University of Padova, Italy; (8) Department of Information Engineering, University of Padova, Italy; (9) CNR-IFN UOS Padova LUXOR, Italy.

Abstract

We provide a detailed geomorphological and spectrophotometric analysis of the circular niches located on the Seth region of 67P using OSIRIS images (Fig. 1) [1]. The features can be related to landslide events that occurred on 67P and shaped its surface. After performing a geomorphological map of the area that allows us to identify different terrain units, we computed the boulders cumulative size frequency distribution (SFD) of the niches, before and after the perihelion passage. Then, we perform the spectrophotometric analysis of this region comparing pre- and post-perihelion results. The overall analysis has been performed making use of the gravitational slope map and the erosion and insolation model of the area, which have been calculated on the high resolution digital terrain model.

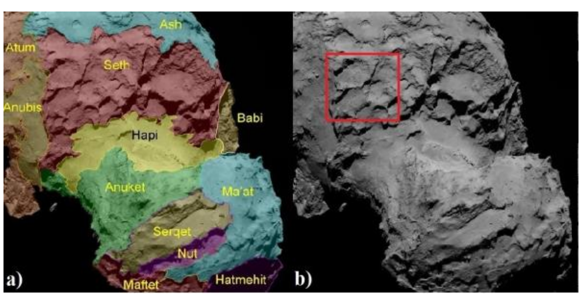

Figure 1: Geological context of the Seth region and the circular niches analysed in this work (NAC image acquired in 2014 August 6 with a scale of 2.2 m/px).

1. Geomorphological map

By means of the WAC image taken in 2016 August 24 with a scale of 0.31 m/px, we made a geomorphological map (Fig. 2) of the area identifying different terrain units. These niches are characterised by the presence of both gravitational accumulation deposits and talus deposits that can be separated on the basis of their texture. Such deposits cover the terrain outlined by the adjacent outcropping walls, which are defined as another geomorphological unit.

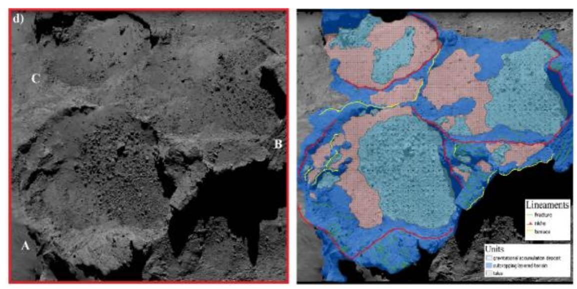

Figure 2: On the left the high resolution WAC image acquired in 2016 August 24 (scale of 0.31 m/px) which has been used to perform the analysis. On the right the performed geomorphological map.

2. Boulders counting

We identify boulders with different shapes with a diameter larger than 1 m through ArcGIS. We statistically analysed their distribution deriving a cumulative SFD [2] with similar power-law indices for niche A and B in post perihelion image (Fig. 3). The niche A is described by a power-law index equal to -2.3 for boulders diameter ranging from 1.8 m and 5 m and a power-law index of -5.0 for boulders larger than 5 m. The niche B is described by a similar behavior consisting in a power law index of -2.7 for boulders diameter ranging from 1.8 m and 5 m and a power-law index of -4.7 for boulders larger than 5 m. To detect if there have been any geomorphological changes, we used a NAC image taken before perihelion in March 2015 to compare the distribution of boulders within the niches finding similar pre/post results.

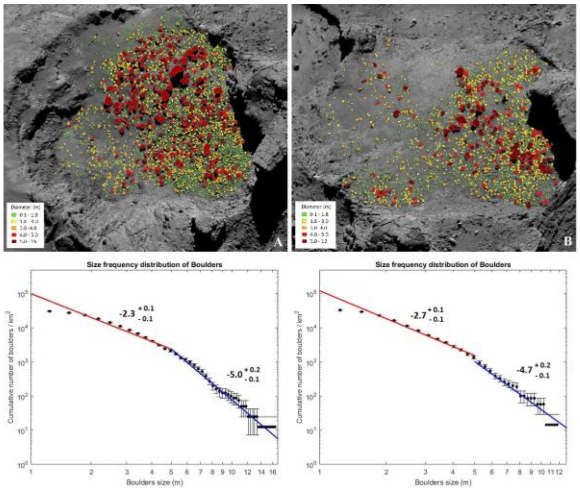

Figure 3: The spatial distribution of boulders on niches A and B counted on the WAC image acquired after perihelion. The lower panels show the cumulative size-frequency distribution of boulders larger than 5 px. The bin size is 0.31 m and vertical error bars indicate the root of the cumulative number of counting boulders (as from [3]).

3. Spectrophotometric analysis

We performed a spectrophotometric analysis on the NAC images acquired pre- and post-perihelion in order to study the colour changes after the Rosetta perihelion passage. The spectrophotometry performed on pre-perihelion images indicates a linear increasing of the reflectance with the wavelength, without any evidence of clear absorption bands, while the analysis computed on post-perihelion images reveals several bright and bluer regions close to or in the shadows, indicating a local enrichment in ice mixed to the refractory material (Fig. 4 for post-perihelion analysis).

Conclusions

The absence of boulders deposits changes suggest that the gravitational event that gave birth to these deposits is not related to the recent detected activity of 67P, thus the landslide that originated such deposits occurred in the past. This is also in agreement with [4], in which the analysis of detected surfaces changes imply a more active comet in the past. We found that the average spectral slope has not changed significantly after the *Rosetta* perihelion passage, but we observed bluer spots in images taken after perihelion indicating the presence of exposed water ice mixed to the refractory materials, in agreement with what previously observed in different nucleus regions [5, 6, 7].

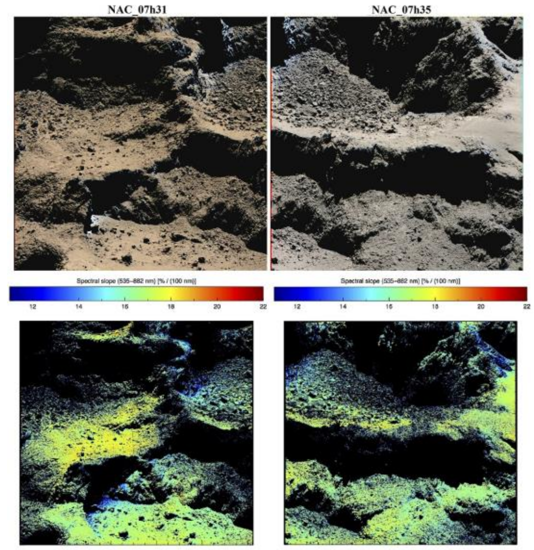

Figure 4: RGB images, in false colours, of the investigated region for images taken on 2016 July 23 with filters centred on 480, 649 and 882 nm (scale of 15 cm/px). Lower panel shows the spectral slope of the corresponding images at a phase angle of 89°. The slope is computed in the 535-882 nm range, after the normalisation at 535 nm and it is in %/100 nm

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COMPARISON OF SOME PROPERTIES OF COMETS 1P/HALLEY AND 67P/CHURYUMOV-GERASIMENKO

L.V. Ksanfomality
Space Research Institute of the Russian Academy of Sciences

The Halley comet (1P/Halley), one of the largest short-period comets was destined to play a major role twice in cometary research. First it was the work of Edmond Halley, who watched a comet first in 1682 in London and dedicated subsequently to comets whole his life. E. Halley first managed to establish the periodicity of the appearance of 1P/Halley and other comets, and created an analytical apparatus for their research. He succeeded in attracting I. Newton to this work. Around 1740, Halley's comet became one of the dominant catalysts in the development of astronomy and is still the subject of profound research. The second time Halley's comet came out on the front pages of scientific publications 300 years later, in 1986, as the first comet, to meet with the nucleus of which spacecraft cams. Historical studies of comet 1P/Halley (1986) by VEGA, Giotto and Suisei remain relevant for more than 30 years. Since then, spacecraft have explored 5 other comets. The most important is the direct investigation of the comet 67P/Churyumov-Gerasimenko (67P/CG) by the ROSETTA ESA mission that was carried out in 2014-2016. According to the performed studies of the comet 67P/CG, numerous of scientific papers have been published. One of the most significant conclusions is the ever-increasing physics of comets, indicating the extreme heterogeneity of the objects under investigation. Differences in the physical properties of comets indicate the extreme complexity of the physic-chemical properties of environment of their origin. Together with other goals the obvious task of the spacecraft is to study the relief, morphology and detailed composition of different parts of the cometary's nuclei. In this respect, the results of the ROSETTA mission of the 67P/CG comet exceeded all expectations. It was also planned to fulfill detailed direct studies on the surface of the nucleus, but the failed landing of the Philae lander in 2014 was a great loss of the mission. Further development of this type of research is inevitable in future.

Comparing the morphology of the 67P/CG and 1P/Halley surfaces is most difficult. If for 67P/CG there is a rich album of detailed images with a resolution of up to tens of centimeters, the resolution on the images of the surface of the Halley's comet nucleus is close to 1 km. The nucleus was observed through a rather dense medium of gas and dust, which were ejected intensively by the nucleus. Using new processing methods, it was possible to get a more detailed image of it given in this presentation. By this way, to some extent, the nuclei of Halley's comet and 67P / CG can already be compared. In general, the similarity of the surface of both comets is traced in large detail. As a result of these observations, the known assumptions that the dumbbell form of cometary nuclei are the result of a long-lasting merger of independent bodies, rather than a signal about the impending destruction of them, began attracting more and more interest. The nuclei of comets 1P/Halley and 67P/CG represent such evidence. The shapes of the nuclei and other properties of them raise the question, whether the body formed in contact between two large planetesimals 4.5 billion years ago, or it is a single body whose evolution follows the path of slow destruction. The idea of the formation of a nucleus from colliding bodies is not new, but it meets with the difficulty that the energy released in collisions rather destabilizes the impactors than unites them. Of course, in most cases it was such destructive collisions that occurred. But there were a lot of colliding bodies, among them there were also those which had small collision velocities, 1-1.5 m/s. These impactors could unite without significant damage, and the “neck” material could be compressed. Precisely such conditions could lead to the formation of dumbbell-shaped comet nuclei (67P/CG, 103P/Hartley-2, 1P/Halley), which, of course, does not contradict their gradual destruction in a narrow section. The probability of collision damage is much higher than the pooling, but during the formation of the Solar system low-speed collisions occurred among the countless primary bodies. The report is illustrated by calculations that allow estimating approximately the collision speed on the basis of the geometric characteristics of cometary’s nuclei.

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Geomorphology and spectrophotometric properties of the highly active Anhur-Bes regions on the 67P/Churyumov-Gerasimenko comet

S. Fornasier (1), C. Feller (1), J.-C. Lee (2), S. Ferrari (3), M. Massironi (3,4), P. H. Hasselmann (1), J.D.P. Deshapriya (1), S. Mottola (5), M.A. Barucci (1) and the OSIRIS-Team
(1) LESIA, Observatoire de Paris, PSL Research University, CNRS, Univ. Paris Diderot, Sorbonne Paris Cité, UPMC Univ. Paris 06, Sorbonne Universités, 5 Place J. Janssen, 92195 Meudon Principal Cedex, France; (2) Department of Earth Sciences, National Central University, Chung-Li 32054, Taiwan; (3) Dipartimento di Geoscienze, University of Padova, via G. Gradenigo 6, 35131 Padova, Italy; (4) Center of Studies and Activities for Space (CISAS) *G. Colombo*, University of Padova, Via Venezia 15, 35131 Padova, Italy; (5) Deutsches Zentrum für Luft und Raumfahrt (DLR), Institut für Planetenforschung, Asteroiden und Kometen, Rutherfordstrasse 2, 12489 Berlin, Germany

Abstract

In this work we present the spectrophotometric and geomorphological analysis of the Anhur and Bes regions located in the Southern hemisphere of the 67P/Churyumov-Gerasimenko nucleus (see Fig. 1). These regions are more fragmented than other areas on the nucleus and show local compositional heterogeneities with fresh exposure of several ice-rich patches. They are also highly active regions and sources of several jets, including the strongest outburst observed by Rosetta, which took place at the comet's perihelion passage.

1. Introduction

Comet 67P/Churyumov-Gerasimenko has been observed with the OSIRIS cameras on board Rosetta with unprecedented spatial and temporal resolutions. The OSIRIS images revealed a comet having a peculiar bilobated shape with a surface characterised by a variety of astounding morphological regions including both fragile and consolidated terrains, dusty areas, depressions, pits, boulders, taluses, fractures and extensive layering (1, 2, 3, 4). The Southern hemisphere became visible from Rosetta only since March 2015, two months before the Southern vernal equinox. This side of the comet was illuminated during its perihelion passage and therefore it contains the regions that experienced the strongest heating and erosion, thus exposing the subsurface most pristine material. The Southern hemisphere shows a clear morphological dichotomy compared to the Northern one, with much less variety associated with the absence of wide-scale smooth terrains.

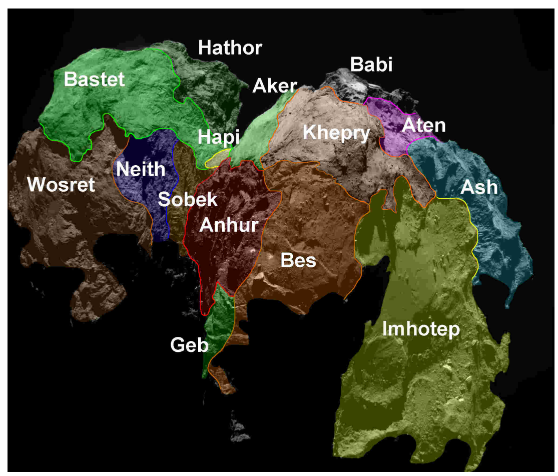

Figure 1: Image from 2 May 2015 UT 07:53 showing the morphological regions visible at that time and in particular the location of the Anhur and Bes regions.

2. Results and discussion

Bes region is dominated by outcropping consolidated terrain covered with fine particle deposits, while Anhur appears strongly eroded with elongated canyon-like structures, scarp retreats, different kinds of deposits, and degraded sequences of strata indicating a pervasive layering. The Anhur/Bes regions are sculpted by staircase terraces that support the nucleus stratification hypothesis formulated by (4). Anhur shows the presence of several scarps dissecting the different strata. Interestingly, at the feet of scarps and cliffs, we observed both taluses and gravitational accumulation deposits. These deposits often have a relatively bluer spectral behaviour than the surround-

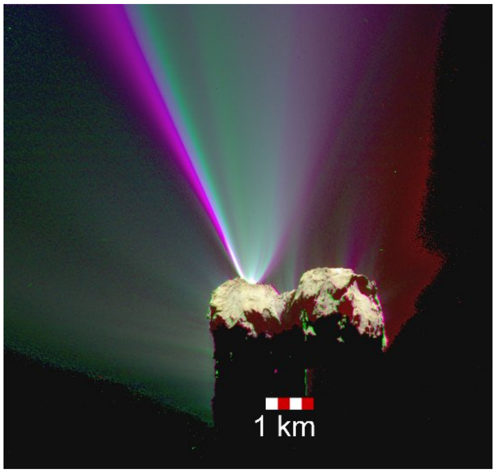

Figure 2: RGB map showing the 12 August 2015 outburst originating from the Anhur region.

ings, pointing to an enrichment in the surface water ice content, and in some cases a higher reflectance and a flat spectrophotometric behaviour, consistent with the presence of exposed water ice. These deposits are sometimes also sources of activity. These observations thus reinforce the hypothesis that the fresh material falling from cliffs/scarps is volatile rich and may become active (5).

In the boundary between Anhur and Bes, two water-ice-rich patches were visible for about 10 days, and they were observed one month after the unique detection of exposed CO_2 ice on the 67P's nucleus (6). These ice-rich patches formed in a smooth terrace covered by a layer of fine deposits on the consolidated material. The fact that first the CO_2 ice and then the H_2O ice was exposed, indicates a progressive stratification of different volatiles resulting from recondensation and sintering of the subsurface material during previous perihelion passages, and clearly points to local compositional heterogeneities on scales of several tens of meters.

In this peculiar Anhur/Bes boundary, we also noticed a new scarp formed sometime between the perihelion passage and December 2015. The scarp is about 140 m long and 10 m high, bounding a depressed area of about 4000-5000 m^2, and generated a collapse of the material with the formation of new boulders. The strong activity throughout the perihelion passage, together with the observed local surface and subsurface enhancement in volatiles in these areas presumably triggered the formation of this new scarp. The freshly exposed material collapsed from the scarp shows a relatively bluer colour and a lower spectral slope indicating the presence of some water ice, reaching abundance of about 17% in the shadows of some boulders located in the new depression.

Several jets have been observed originating from these regions, including the strong perihelion outburst (Fig. 2), as well as an active pit. We detected fainter jets up to 2.2 AU outbound, including an optically thick plume with an estimated optical depth of 0.43.

The spectral slope evolution from April 2015 to June 2016 indicates that the Anhur/Bes regions, as observed for other regions of the comet, became spectrally redder post-perihelion at heliocentric distances $>$ 2.0 AU compared to the pre-perihelion data. This indicates continuous changes of the physical properties of the uppermost layers. Close to perihelion the strong cometary activity thinned out the nucleus dust, partially exposing the underlying ice-rich layer, resulting in lower spectral slope values seen all over the nucleus as shown by (7). This implies that water ice is abundant just beneath the surface on the whole nucleus.

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Investigating the physical properties of outbursts on comet 67P/Churyumov-Gerasimenko

Zhong-Yi Lin (1), J. Knollenberg (2) J.-B. Vincent (2) M. F. A'Hearn (3) W.-H. Ip (1,4,5) H. Sierks (6) and OSIRIS team
(1) Institute of Astronomy, National Central University, Zhongli 32054, Taiwan (zylin@astro.ncu.edu.tw)(2) Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Planetenforschung, Rutherfordstrasse 2, 12489 Berlin, Germany (3) Department for Astronomy, University of Maryland, College Park, MD 20742-2421, USA (4) Space Science Institute, Macau University of Science and Technology, Macau (5) Institute of Space Sciences, National Central University, Chung-Li 32054, Taiwan (6) Max-Planck Institut für Sonnensystemforschung, Justus-von-Liebig-Weg, 3, 37077 Göttingen, Germany

Abstract

Cometary outbursts have been observed on several comets by ground-based telescopes and in situ instruments of spacecraft. However, the mechanism and physical properties for these phenomena are still unclear. The OSIRIS camera onboard the Rosetta spacecraft provided first-hand information on the transient events (outbursts) of comet 67P/Churyumov-Gerasimenko during its perihelion passage in 2015. The physical properties of the outbursts can be therefore investigated via time-series images with high-resolution images.

1. Introduction

Unlike the "snap shots" from the previous flyby observations, the OSIRIS measurements can provide precise information on the timing and location of the outbursts via time-series images with high-resolution images. After the first detection in March, 2015, the OSIRIS wide-angle camera (WAC) and narrow-angle camera (NAC) captured another outburst in mid-July, 2015. Since then, many more outbursts from the nightside and sunslit regions have been detected ([1, 2]), with most of their source regions were located at the southern hemisphere of comet 67P ([3]). The detected outburst events show a variety of morphological features that have been classified into three different types: broad fans, narrow jets and complex plumes. In this work, we investigate the morphology of these events and characterize their physical properties in detail, including the surface brightness profiles, ejected mass and speed if there are two or more sequential images acquired by the same filter in short duration during the outburst timeframe.

2 Observations

The data sets used in the present investigation consist of pairs of consecutive images obtained in short time interval of ∼6 s to ∼20 s from July 29 to September 30, 2015, with the NAC orange filter (center wavelength =6486 Å, FWHM =852.4 Å). All images listed in Table 1 were acquired in 1x1 binning mode which results in a pixel scale of ∼3 m to ∼26 m depending on the changing distances between the Rosetta spacecraft and the nucleus. Fig. 1 shows an example of an outburst event can be easily detected without any image enhancement technique or high lighting the image with a particular display scale (i.e. log-log scale).

Fig. 2 shows the case when additional image processing must be applied to find the outburst events directly from the consecutive images. These low contrast mini-outbursts can be extracted through the difference images as the activity might become stronger or weaker with time. In this work, we used the positive detection method in the difference image to obtain the physical properties of outbursts.

Several data sets from both NAC and WAC were especially designed for monitoring the activity of the nucleus. The observed sequences ranged from 1 hour to one full rotation (∼12.4 hours). Starting in late-August 2015, the high cadence observations (every 5 minutes) in some sequences were designed to search for outburst events. Before then, normal cadences like 20 or 30 minutes in NAC and 1 hour in WAC had been scheduled.

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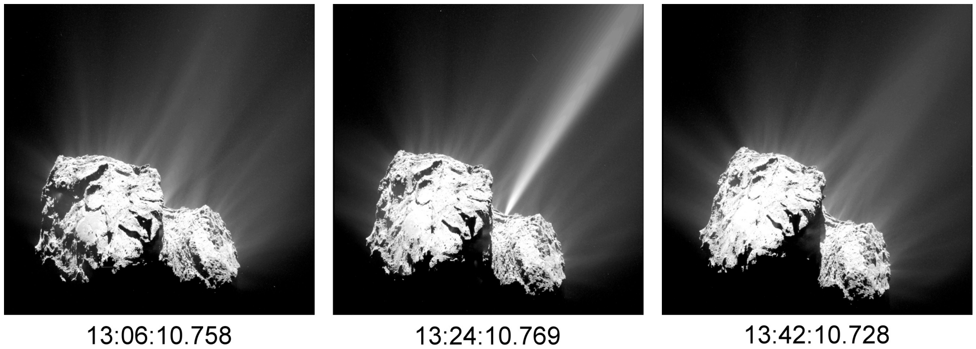

Figure 1: The time sequence of the coma structure on 29 July 2015 showing the sudden appearance of a dramatic outburst at 13:24 UT. The FOV is 7 km $\times$ 7 km. The Sun is coming from the top of the image.

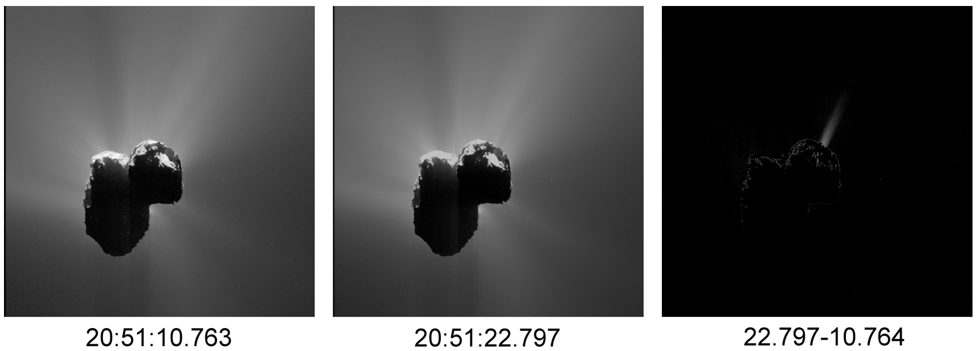

Figure 2: An example of how the difference image (right-panel, September 10, 2015) obtained by subtracting the brightness of two images with a time interval of 12 seconds can extract an outburst feature when there is no clear detection from the consecutive images. The frame is 12.02 km by 12.02 km. Sun is toward the top.

sity of Padova, Italy, the Laboratoire d'Astrophysique de Marseille, France, the Instituto de Astrofísica de Andalucía, CSIC, Granada, Spain, the Scientific Support Office of the European Space Agency, Noordwijk, Netherlands, the Instituto Nacional de Técnica Aeroespacial, Madrid, Spain, the Universidad Politéchnica de Madrid, Spain, the Department of Physics and Astronomy of Uppsala University, Sweden, and the Institut für Datentechnik und Kommunikationsnetze der Technischen Universität Braunschweig, Germany.

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Are large organic molecules in comets similar to the Diffuse Interstellar Bands carriers?

Jean-Loup Bertaux (1) and **Rosine Lallement** (2)
(1) LATMOS/CNRS Université de Versailles Saint Quentin, France, jean-loup.bertaux@latmos.ipsl.fr
(2) GEPI/ Observatoire de Paris,France, rosine.lallement@obspm.fr.

Abstract

We suggest that the refractory organic material found by COSIMA in 67P/CG comet dust (Fray et al., 2016) is made of aggregates of the same organic molecules which are present in the interstellar medium (ISM) and are producing in observed stellar spectra the absorptions called Diffuse Interstellar Bands (DIBs). Such a link would increase the scientific interest of a comet sample return mission, addressing both comets and interstellar material. The refractory character of comet organic matter does not necessitate a cooled return capsule, an important sample return mission cost-driver.

1. Introduction

One major outcome of the Rosetta space investigation of the nucleus of comet 67P Churyumov-Gerasimenko is the idea that this comet is the result of a gentle, hierarchical process, growing slowly from interstellar material up to the size of the nucleus (Davidsson et al., 2016). Therefore, the interstellar material which formed the proto-solar nebula is likely to have been preserved pristine at the distance of formation of comets, and still be present in the nucleus.

2. Diffuse interstellar Bands (DIBs)

The diffuse interstellar bands (DIBs) are more than 500 irregular weak absorptions in optical and IR stellar or galaxy spectra (figure 1). According to observed DIB properties and correlations, DIB carrier candidates should primarily be sought among carbon-based organic molecules in the gaseous phase and not in dust grains. They probably constitute "… the largest reservoir of organic matter in the Universe" (Snow, 2014).

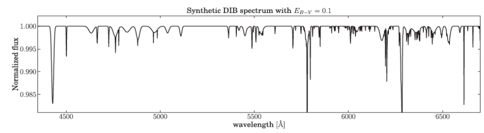

Figure 1: A synthetic spectrum of DIB absorption representative of a line of sight with E(B − V) ~0.1 mag. Note the expected absorption is at the 1 per cent level. From Lan et al., 2015 and references therein.

We are reproducing on Fig. 2 some of the equivalent widths (EW) curves of Lan et al. (2015), normalized at 1 for a color excess E(B-V)= 0.4. It is clear that equivalent widths of these mono-cloud observations acquired outside of the galactic plane all start to increase proportionally with extinction (measured by the color excess). Then they **all** stop to increase linearly (in a log plot) with the color excess E(B-V) and instead seem to level-off (saturate) above E(B-V) ≈ 1, i.e. again when sightlines cross very dense cloud cores, or even begin to **decrease** above E(B-V)= 0.4 for some of them.

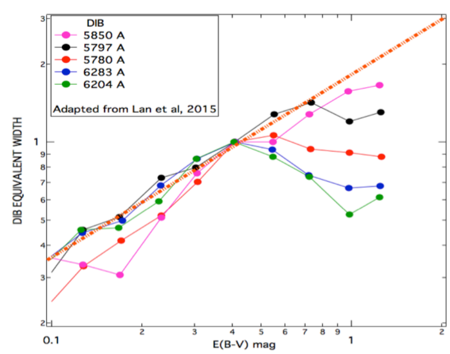

Figure 2: Average DIB equivalent width as a function of the color excess along the line-of-sight, for five strong DIBs. The data are taken from Fig. 8 panels of Lan et al. (2015). All curves have been

scaled to EW= 1 at E(B-V)= 0.40. The dashed-dotted line serves as a guide to visualize departures from linearity above this color excess value.

Some DIBs start to deviate from proportionality to the dust column at a lower color excess compared to the other 5797 Å and 5850 Å DIBs. However, **all** DIBs tend to saturate or even decrease. Having in mind that the LOS crosses a single cloud, we may assign large extinctions to LOS crossing the center of a cloud, while more modest extinctions suggest LOS crossing more external parts of a cloud. We suggest that these recent observations of global DIB leveling-off in cloud dense and UV-shielded cores are simply due to the fact that in the dense cores the DIB carriers do not exist but instead are part of a solid phase of organic material, their "parent" material. If this happens in existing molecular clouds, it may have happened also in the molecular cloud from which was formed our solar system, suggesting the relevance to organic matter in comets.

3. Carbon inventory of DIB carriers in the ISM and in comets.

With some reasonable assumptions, we could derive from the Equivalent Widths of all visible (Hobbs et al., 2009) and Infra red DIBs (up to 1.5 µm) that at least 30 % of interstellar carbon is locked up in a DIB carrier, yielding a ratio R_{ISM} of organic to minerals of about 0.32 (Bertaux and Lallement, 2017). This is comparable and similar to a value $R_C \approx 0.5$ organic to minerals as reported by COSIMA team (Baklouti et al., 2017) which reported the presence of refractory large organic molecules in the dust particles collected at Rosetta spacecraft (Fray et al., 2016). The simplest explanation for this similarity of R_C and R_{ISM} is that the ISM organic material has been directly incorporated in comets without major chemical processing (except perhaps for some re-hydrogenation). Following the Occam's razor principle claiming that the simplest explanation is the most likely, we adopt this explanation.

4. Conclusion

The connection between DIB carriers and comet nuclei increases substantially the scientific interest of a comet sample return mission for the study of both comet and ISM materials. Since this cometary organic material is refractory, the sample return capsule does not need to be maintained at cool temperatures to preserve ices, a technical requirement that increases considerably the cost of a comet sample return mission.

Acknowledgements

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Evolution of the magnetic field at comet 67P/Churyumov-Gerasimenko

C. Goetz (1), M. Volwerk (2), I. Richter (1) and K.-H. Glaßmeier (1,3)
(1) Institut für Geophysik und extraterrestrische Physik, Technische Universität Braunschweig, Mendelssohnstr. 3, 38106 Braunschweig, Germany
(2) Space Research Institute, Austrian Academy of Sciences, Schmiedlstr. 6, Graz 8042, Austria
(3) Max-Planck-Institut für Sonnensystemforschung, Justus-von-Liebig-Weg 3, 37077 Göttingen, Germany

Abstract

The magnetic field at a comet is significantly influenced by the solar wind on one side and the outgassing rate on the other. There are no simple radial models for the magnetic field, neither at a comet with low outgassing rates ($\sim 10^{25}\,\mathrm{s}^{-1}$) where ion gyroradius effects are non-negligable, nor at high outgassing rates ($\sim 10^{27}\,\mathrm{s}^{-1}$) where plasma boundaries form. However, the long duration of the ESA Rosetta mission has made it possible to track the evolution of the magnetic field while comet 67P/Churyumov-Gerasimenko approaches the Sun. Herein we present a simple model that seems to fit the data quite well, depending on input parameters. The study also includes the influence of the comet's gas production rate and the solar wind conditions, which both have complex effects on the magnetic field, but are clearly recognizable. The evolution of the magnetic field direction related to draping is more complex than previously suggested. Classical draping only exists at the comet for high outgassing rates, for lower rates, the magnetic field roughly follows the Parker angle. It is shown that the interaction of the solar wind with the comet can be roughly devided into three main classes.

1. Introduction

The Rosetta spacecraft was the first to explore the plasma environment at a comet for an entire perihelion passage, thus observing the growth and diminishment of the environment. As the comet approaches the Sun, the insolation leads to outgassing of mostly water of the nucleus and ionization of a significant part of these neutrals. Theser ions need to be incorporated in the incoming solar wind which leads to the formation of different plasma regions depending on the ion number density. These regions include (but are not limited to) the diamagnetic cavity, the bow shock the solar wind cavity and possibly an ion collisionopause [3, 4, 2, 5]. All of these regions have different magnetic field signatures that change with the outgassing rate. The long term development of the magnetic field is studied using different techniques.

2. The magnetic field at comets

The pile-up of the magnetic field in the vicinity of the comet was predicted and then observed by multiple spacecraft [1, 6]. This behaviour was also observed at comet 67P and it is shown that the magnetic field pile-up may be calculated using an MHD model. However to correctly account for the high variability of the magnetic field measured by Rosetta, the solar wind input parameters need to be based on real solar wind observations. Investigations of the global structure of the plasma environment are complicated by the fact that the spacecraft is constantly changing position and therefore the model is also used to disentangle the effect of this from the solar wind influence.

It is also found that the variance of the magnetic field significantly increases with the outgassing rate, meaning that the magnetic field strength and variance are largest shortly after the perihelion passage.

As the comet nucleus rotates, the outgassing profile changes due to the different active regions on the surface. This should then also be reflected in the different magnetic field strength corresponding to the ion density variations. However, the magnetic field is not as sensitive to the neutral density changes as the ion density and therefore, on short time scales, there is no observable correlation between the comet's rotation and the magnetic field. However for very long periods of time the statistics are significantly improved and the cometary rotation may be linked to enhancements in different frequency bands of the magnetic field.

As the pile-up is significantly dependent on the incoming solar wind dynamic pressure, the magnetic

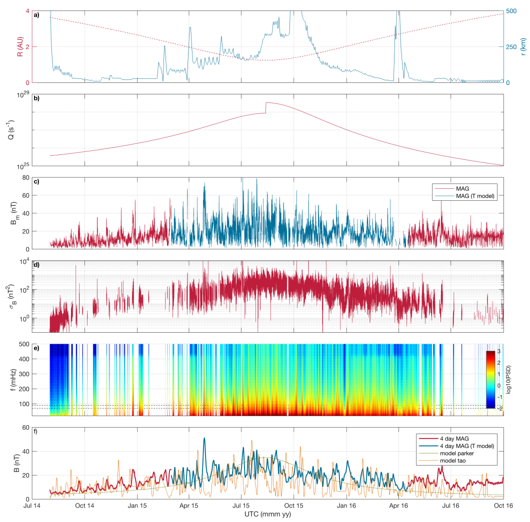

Figure 1: An overview of the data examined in the publication. The panels show a) Rosetta's distance to the comet (blue) and the comet's distance to the Sun (red), b) the outgassing rate, c) the magnetic field magnitude using two different offset models, d) the magnetic field variance, e) magnetic field spectral density and f) the magnetic field compared to a model.

field strength may also be related to the rotation period of the Sun, as this in turn correlates with the appearance of high speed solar wind time intervals.

On short-scales, the expected draping of the magnetic field is only observable close to the nucleus, further away transient effects dominate the plasma environment. But when examining longer intervals it becomes apparent that the draping structure is observable for high ($> 10^{27}\,\mathrm{s}^{-1}$) gas production rates. In general the structure of the plasma environment significantly changes when the gas production rate increases, leading to the categorization of the interaction regimes into three groups: the weak, the intermediate and high activity case.

3. Summary and Conclusions

Here we show that the long duration of the Rosetta mission not only may be used to observe the evolution of the plasma environment, but it also affords the opportunity to use increased statistics to find tenuous connections between magnetic field and other parameters.

We find that the pile-up at the comet can (on timescales of more than a month) be described by a simple MHD model, although short-time variations are not covered well by this model. Classical draping is found only for high gas production rates, for lower rates, the magnetic field on average follows the solar wind parker angle. We also show that the cometary rotation period as well as the Sun rotation period influence the magnetic field strength in the comet's plasma environment.

Acknowledgements

The RPC-MAG data will be made available through the PSA archive of ESA and the PDS archive of NASA. Rosetta is a European Space Agency (ESA) mission with contributions from its member states and the National Aeronautics and Space Administration (NASA). The work on RPC-MAG was financially supported by the German Ministerium für Wirtschaft und Energie and the Deutsches Zentrum für Luft- und Raumfahrt under contract 50QP 1401. We are indebted to the whole of the Rosetta Mission Team, SGS, and RMOC for their outstanding efforts in making this mission possible. We acknowledge the staff of CDDP and IC for the use of AMDA and the RPC Quicklook database (provided by a collaboration between the Centre de Données de la Physique des Plasmas, supported by CNRS, CNES, Observatoire de Paris and Université Paul Sabatier, Toulouse and Imperial College London, supported by the UK Science and Technology Facilities Council).

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A global study of the bright features observed on comet 67P/Churyumov-Gerasimenko during the Rosetta mission

J.D.P. Deshapriya (1), M.A. Barucci (1), S. Fornasier (1), C. Feller (1), P.H. Hasselmann (1), H. Sierks (2) and OSIRIS team
(1) LESIA, Observatoire de Paris, PSL Research University, CNRS, Univ. Paris Diderot, Sorbonne Paris Cité, UPMC Univ. Paris 06, Sorbonne Universités, 5 place Jules Janssen, 92195 Meudon, France, (2) Max-Planck-Institut für Sonnensystemforschung, Justus-von-Liebig-Weg, 3, 37077, Göttingen, Germany
(prasanna.deshapriya@obspm.fr / Fax: +33-145077144)

Abstract

During the course of the Rosetta mission, its OSIRIS (Optical, Spectroscopic and Infrared Remote Imaging System) [1] scientific cameras revealed exposed bright features on the nucleus of the Jupiter-family comet 67P/Churyumov-Gerasimenko (hereafter 67P). These have been attributed to the presence of H_2O ice based on their spectrophotometric properties [2],[3], [4], [5]. In this context, we report a comprehensive study of exposed bright features observed by OSIRIS instrument during Rosetta's time spent at 67P. We catalogue such features from early August 2014 up to the end of September 2016, taking into account their morphology and temporal evolution as the heliocentric distance of the comet varied. The objective of this study is to better constrain the morphologies of these bright features, introduce potential triggers for their appearance and monitor their temporal evolution in the event of the availability of multi-filter observations.

Depending on the morphologies and potential formation scenarios of the studied features, we divide them into 5 categories as follows.

1. Isolated patches on smooth terrain
2. Isolated patches close to irregular structures
3. Patches resting on boulders
4. Cluster of features
5. Frost

Results & Discussion

Generally, these bright features are preferably located in equatorial regions of the cometary nucleus. The majority of them are concentrated in the range of -30° to +30° of latitudes as evidenced in the map in Fig.1, where red dots correspond to the locations of features attributed to H_2O ice and the blue dot corresponds to the CO_2 ice. The locations of 10 of the H_2O ice features and the CO_2 ice feature hitherto studied are also included therein for the sake of completeness of the map [3],[6],[7].

We find that the isolated patches located on smooth terrain are not directly influenced by shadows whereas on the contrary, isolated patches close to irregular structures often find themselves under shadows. In our analysis of temporal evolution of bright features, we find lifetimes in the order of few weeks and several months for the former and the latter respectively. This indicates that the patches on smooth terrain sublimate away faster than their counterparts. We suggest that both these feature types are created due to surface erosion dominated by the cometary activity towards the perihelion passage of the comet. Then, there have been a number of bright features observed resting on the surface of boulders throughout the course of the Rosetta's observations of 67P. We are able to correlate 2 of them with cometary activity sources. These include an outburst during the perihelion passage that would have modified the local terrain resulting in exposed subsurface icy material in the Khonsu region, and a displacement of a boulder in the Bes region. For the latter we observe that after the displacement, some bright material has appeared on its surface, which was absent beforehand when it was at its original location. Although we are not able to trace any kind of activity for other patches resting on boulders probably due to the absence of observations during the transient activity time, supported by the above 2 cases, it is rational to mention that they are correlated to sources of cometary activity. Furthermore, there have been several observations of clusters of bright features, individually smaller in size compared to the aforementioned features. These clusters have mostly been observed in the pre-perihelion period and they are located near to cliff structures.

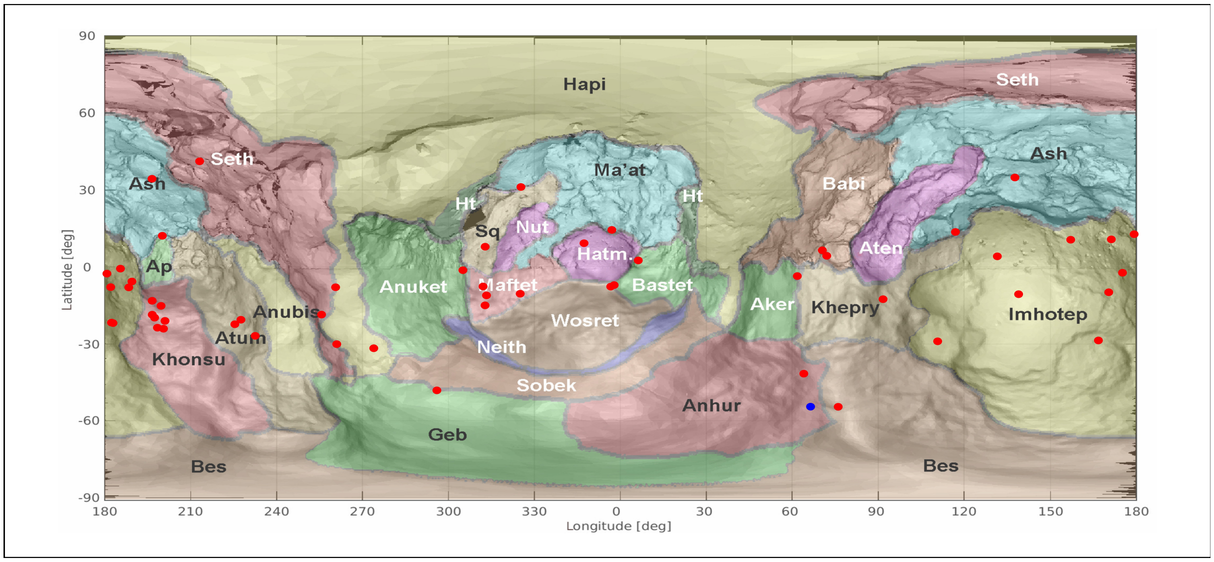

Figure 1: Map of bright features observed on 67P.

structures. Therefore they could be related to cliff collapse events, where the resulting debris expose water ice contained and preserved inside since their formation. Despite the fact that such a cluster could include numerous smaller bright features, it is noteworthy that we consider the cluster in its entirety as a single unit feature in our catalogue.

Frost has been observed since September 2014 (~3.36 AU inbound) [8] to the perihelion passage (1.24 AU) and has been continuously observed towards the end of the mission (~3.8 AU outbound). This frost could be observed at the morning of the comet, where the sun light returns after about 12 hours. Gradually the shadows cast by different morphological structures get shorter as the sun moves towards the local zenith, revealing the frost formed over the cometary night due to condensation of water ice already sublimated previously [9]. Frost is observable for few minutes as it rapidly sublimates away. This process keeps continuing as long as the solar irradiation is strong enough to sublimate the frost and once the comet is beyond the snowline of the solar system, the frost becomes ice as there would not be further sublimation. This diurnal cycle of water got more pronounced as 67P got closer to its perihelion, leading to greater water production rates, as the incident solar radiation increased following the inverse square law. During 67P's perihelion passage, frost was ephemerally visible on a given location cast by shadows.

Acknowledgements

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EPSC Abstracts
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The interior of 67P/C-G comet as seen by CONSERT bistatic radar on ROSETTA, key results and implications.

W. Kofman (1,2), A. Herique (1). V. Ciarletti (3), J. Lasue (4), AC. Levasseur-Regourd (5), S. Zine (1), D. Plettemeier (6) and the CONSERT team.
(1) Univ. Grenoble Alpes, IPAG, F-38000 Grenoble, France, CNRS, IPAG, F-38000 Grenoble, France
(2) Space Research Centre, PAN, Warsaw, Poland
(3) LATMOS/IPSL, UVSQ (Université Paris-Saclay), UPMC (Sorbonne Univ.); CNRS, Guyancourt, FR
(4) Université de Toulouse; UPS-OMP; IRAP-CNRS; Toulouse, France
(5) UPMC (Sorbonne Univ.); UVSQ (UPSay); CNRS/INSU; LATMOS-IPSL, Paris, France
(6) Technische Universitat Dresden, Dresden, Sachsen, Germany

Abstract

The structure of the nucleus is one of the major unknowns in cometary science. The scientific objectives of the Comet Nucleus Sounding Experiment by Radiowave Transmission (CONSERT) [3] aboard ESA's spacecraft Rosetta are to perform an interior characterization of comet 67P/Churyumov-Gerasimenko nucleus. This is done by means of a bistatic sounding between the lander Philae laying on the comet's surface and the orbiter Rosetta. We will describe shortly measurements that explored the interior of the comet, discuss results, their interpretation in terms of the internal structure and composition.

1. Introduction

During the first night after Philae landing in Nov. 2014, CONSERT operated during 9 hours and has made measurements through the small lobe (head) of comet 67P/ C-G. The analyses and interpretation have been done using the shape of the received signals and then 3D modeling of the signal propagation through the comet. The first analyses concerned the propagation time from which the average permittivity of the cometary interior was derived. This was done using the 3D model of wave propagation through the comet. Dielectric data for ices and dusts particles, compared with CONSERT measurements, constrains the possible constituents of comet 67P/C-G [2], [4]. The shape of the signal, which is very close to the shape of the calibration, shows that scattering by inhomogeneities in the medium is not detected. This indicates that the interior is homogenous at the scale of few wavelengths (1 wavelength is about 3.3m in vacuum) [4]. This conclusion lead to 3D simulation of the signal propagation in the non-homogeneous medium, to define the sensitivity of CONSERT to detect the inhomogeneities and to constrain the internal structures in terms of size and composition at a scale commensurate with the wavelength [1]. Properties of meter-scale inhomogeneities inside the comet are essential to understand cometary formation. These major results are discussed during the presentation.

2. Interpretation of results

2.1 Bulk dielectric properties and interior composition.

The measured propagation time permitted to derive the dielectric properties of the interior [4]. The inferred real part of permittivity is 1.27, which is very low (permittivity of vacuum is 1, water ice is about 3.1 and dust constituents even higher). Thus, the interior of the comet is very porous. This value of the permittivity excludes, as expected for primitive small bodies, a major component similar to ordinary chondrites in the refractory component. CONSERT measurements are consistent with dust/ice volume ratio of 0.4 to 2.6, and the porosity range of 75 to 85%. In [2], compositional analyses were developed using a large database of organic materials from the literature and from laboratory measurements. Since many materials have similar permittivity values in CONSERT frequency range, using permittivity does not discriminate materials directly, but allows to exclude some. To this end, one tests different composition models of the nucleus corresponding to cosmochemical end members of 67P/C-G dust. They include pure silicate dust and its mixture with increasing content of a carbonaceous material (comprising both insoluble and soluble species). It was concluded that an important fraction of carbonaceous material is required in the dust in order to match CONSERT permittivity observations. The minimum required content of the carbonaceous material is 75 vol. per cent. This suggests that comets represent a massive carbon reservoir (Figure 1)

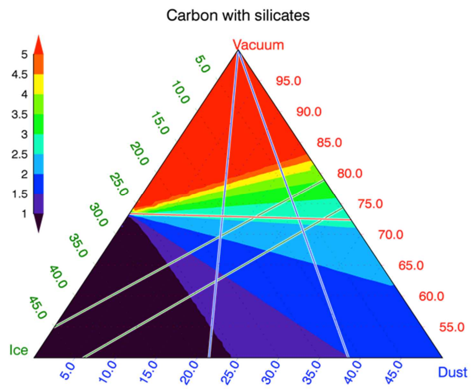

Figure 1: Diagram of the permittivity of the refractory material as a function of the volume proportion of ice (green axis), of dust (blue axis) and of the porosity (red axis): the color scale represents the maximum permittivity value of the refractory material in a given dust-ice-vacuum mixture of permittivity 1.27 (from [2]).

The diagram in Figure 1 shows that a mixture consisting of 75% carbonaceous material and 25% minerals (red line limit on the graph) is compatible with the dielectric constant determined by CONSERT, as well as with other results related to density (green line limits) and dust / ice ratio (blue line limits). The nucleus of the comet must then be very porous (72-87%), with 6-12% ice and 16-21% refractory (dust) by volume [2].

2.2 Interior structure

The measurements of the width of the signal at 3 and 6 dB levels were compared with the 3D simulation in the non-homogenous medium; fractal and spheres based structures. Comparison (figure 2) with the experimental pulse width values have been used to find constraints of the structures inside the nucleus that would be compatible with the CONSERT's data. It was shown that CONSERT's observations cannot exclude or give constraints on any scale of 1 meter or below and the 3-m size scale structures are compatible with CONSERT's measurements provided that the permittivity contrast of the structure is less than 0.25.

Given the high bulk porosity of 75% inside the sounded part of the nucleus, a likely interior model would be obtained by a mixture, at this 3-m size scale, of voids (vacuum) and blobs with material made of ices and dust with a porosity larger than 60% [1]. The absence of any pulse spreading due to scattering allows us to exclude heterogeneity with higher contrast (0.25) and larger size (3m) (but smaller than few wavelengths scale, since larger scales would be responsible for multipath propagation).

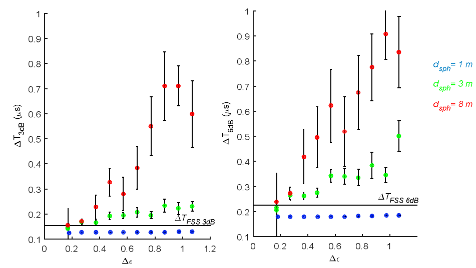

Figure 2: Pulse width at 3 dB (left) and 6 dB (right) versus the permittivity contrast $\Delta\varepsilon$ for 3 sizes of spheres. The travelled distance is L=200 m. the experimental threshold values $\Delta T_{FSS\,3dB}$ and $\Delta T_{FSS\,6dB}$ are represented by the solid horizontal line (figure from [1]).

3. Conclusions

CONSERT is the first successful radar probe to study the sub-surface of a small body. Current interpretation of the signals is consistent with a highly porous carbon rich primitive body. Internal inhomogeneities are not detected at the wavelength scale and are either smaller, or present a low dielectric contrast. The analyses and interpretation of the signals amplitude are still on going and their progress will be presented during the conference.

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The Evolution of Aeolian-Like Morphologies on Comet 67P Churyumov-Gerasimenko

K. A. Otto (1), D. Tirsch (1), S. Mottola (1), K.-D. Matz (1), S. Hviid (1), R. Jaumann (1,2), H. U. Keller (3), E. Kührt (1), S. E. Schröder (1), H. Sierks (4) and the OSIRIS Team
(1) German Aerospace Center, Insitute of Planetary Reasearch, Germany (katharina.otto@dlr.de), (2) Freie Universität Berlin, Germany, (3) Technical University of Braunschweig, Germany, (4) Max Planck Institute for Solar System Research, Germany

Abstract

We investigate aeolian-like wind-tails on comet 67P Churyumov-Gerasimenko. These features are associated with particle transport induced by cometary activity. Our aim is to understand their formation processes for which we use OSIRIS and ROLIS images to characterize changes in wind-tail morphologies and orientation that occur over the timespan of the Rosetta visit at the comet.

Introduction

High resolution image data of the ROLIS and OSIRIS instruments on-board the Rosetta spacecraft and its lander Philae revealed the presence of aeolian-like morphologies on 67P's surface [e.g. 1, 2, 3], such as elongated wind-tail like deposits and moat-like depressions around some larger boulders (> 5 m, Figure 1). Such features are commonly associated with wind accumulation and wind erosion on Earth and other planets [e.g. 4, 5]. However, the formation mechanism of wind-tail-like features on Churyumov-Gerasimenko appears to be of different origin. It is probable that they form as a result of abrasion of a sand-bed of air-fall particles [3]. This process may be dependent on the activity level of the comet. Fortunately, the Rosetta Mission accompanied 67P during a range of different activity levels from the relatively calm pre-perihelion phase to the active perihelion passage. The image data of the OSIRIS camera on-board Rosetta of these different activity stages give us the opportunity to relate the aeolian-like wind-tail morphology, distribution and formation process with cometary activity levels.

Previously, we have reported on the distribution and orientation of such wind-tails found in pre-perihelion images and reported an accumulation of wind-tails in the Ma'at region and a tendency of the wind-tails to point north [6]. In this work, we investigate the evolution with time of aeolian-like wind-tails on 67P aiming at a better understanding of how they form and what they tell us about the particle distribution processes on comet 67P.

Method and Data

We investigate boulders with wind-tail like morphologies in OSIRIS images and ROLIS descent images. We concentrate on a set of exemplary boulders with associated wind-tail like morphology in a series of subsequent images and analyze their morphologic evolution with time. This includes the characterization of the orientation, size, slope and volume of the wind-tails. The specific boulders are located near the first touchdown area of the Philae lander in the Ma'at region (small lobe) and the Ash region (big lobe). We also investigate the evolution of the wind-tail like morphology of the boulder observed with the ROLIS camera during the Philae descent (Figure 1).

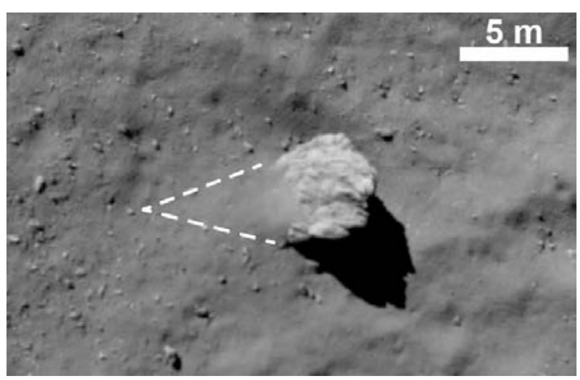

Figure 1: Boulder with wind-tail like feature imaged by the ROLIS camera onboard the Philae lander. The boulder is approximately 5 m across and possesses a moat opposing a wind-tail like feature (dashed line). Image extracted from Mottola et al. (2015) [3].

Results

Due to Rosetta's changing distances from the comet surface, the resolution of the image data varies with time. Additionally, different illumination and observation angels posed difficulties in tracking changes. Having these limitations in mind, the wind-tail like morphologies did not significantly change their shape or orientation over the timespan observed. This may hint at the wind-tail like morphologies being less fragile compared to other features observed in smooth areas on 67P (e.g. [7]) or at the wind-tail formation as a sustainable process.

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How MIDAS improved our understanding of micrometre-sized cometary dust

T. Mannel (1)(2), M.S. Bentley (1), P. Boakes (1), H. Jeszenszky (1), A.C. Levasseur-Regourd (3), R. Schmied (1)(4), K. Torkar (1) and the MIDAS team.
(1) Space Research Institute of the Austrian Academy of Sciences, Graz, Austria, (2) Physics Institute, University of Graz, Graz, Austria, (3) LATMOS-IPSL, UPMC (Sorbonne Universités), Paris, France (4) ams AG, Premstaetten, Austria (thurid.mannel@oeaw.ac.at)

Abstract

The MIDAS atomic force microscope on the Rosetta orbiter was an instrument developed to investigate, for the first time, the morphology of nearly unaltered cometary dust. It acquired the 3D topography of about 1 - 50 µm sized dust particles with resolutions down to a few nanometres. These images showed the agglomerate character of the dust and confirmed that the smallest subunit sizes were less than 100 nm. MIDAS acquired the first direct proof of a fractal dust particle, opening a new approach to investigate the history of our early Solar System and of comets.

1. Introduction

As comets are considered the least altered bodies in our Solar System, the properties of their building blocks are key parameters in understanding our early Solar System and its evolution. Remote observations, fly-by missions and sample return have provided a foundation for our knowledge about cometary dust particles, which has been tested and greatly extended by the dust instruments onboard Rosetta, namely COSIMA, GIADA and MIDAS. The latter was a novel instrument selected to investigate the morphology of micro- to nanometer sized particles collected around the comet. Being able to collect the least altered cometary dust particles from a known body, MIDAS gave a first view of the morphology at the smallest scales. This paper summarises advances in the understanding of the smallest cometary dust with focus on the findings of MIDAS and suggests possible directions for future research.

2. The MIDAS atomic force microscope

MIDAS was designed to make the first *in situ* atomic force microscope (AFM) measurements of cometary dust to address key questions about the size, shape, texture and morphology of the smallest particles [1]. It collected dust by exposing specially coated silicon targets to the dust flux coming from comet 67P/Churyumov-Gerasimenko and imaged the particles with an AFM [1,2]. The key data were 3D topographic images with nano- to micrometre resolution which gave the first view on the smallest, nearly pristine, cometary particles.

3. Post-Rosetta knowledge

Pre-Rosetta models of cometary dust predicted that cometary dust at the (sub-)micrometre scale would fall in two groups: compact particles and porous agglomerates [3,4]. Contrary to these expectations MIDAS only found an agglomerate character at all size scales and for all collection periods. The particle surfaces show clusters of small, bulbous subunits. These characteristic features can also be found for the order of magnitude larger dust particles collected with the COSIMA instrument at comet 67P [5] and for the most primitive interplanetary dust particles (IDPs) collected in Earth's atmosphere [2]. However, in contrast to IDPs, MIDAS observed no evidence of euhedral crystalline structures. The larger dust particles show an extreme fragility, which often leads to fragmentation during AFM scans. None of the particles broken apart in this way showed an interior structure different from that observed on the surface, suggesting that most of the tens of micron-sized cometary particles are indeed agglomerates throughout. Despite this commonality, dust at 67P falls in two groups. The majority shows an arrangement of the subunits with a medium packing density. However, due to the gentle dust collection at Rosetta, one extremely porous particle was detected. Its structure was found to be fractal with a dimension of 1.7 ± 0.1 [6]. As the existence of a majority of denser dust particles and a minority of fractal dust was confirmed by the GIADA instrument [7], comet

67P is suggested to consist mainly of the denser dust particles, where the voids between them can be filled by fractals [8]. The latter structure is characteristic of early dust agglomeration in the protoplanetary disc but is thought to be compacted to denser, non-fractal dust before inclusion in comets. The existence of fractals nevertheless strongly constrains the dust environment in the early Solar System and the evolution of the comet [9]. This theory is supported by the surprisingly similar subunit sizes of the fractal and more compact particles. The smallest subunits comprising the agglomerates are less than 100 nm in size [10]. However, these measurements appear to be still limited by instrument resolution and the presence of smaller dust grains cannot be excluded.

A further surprise was the size of the collected dust. The number of collected particles was estimated by optical observations and data from the Halley fly-by, which had large uncertainties for the flux of the small, micro- to nanometre sized particles [1]. However, it was always expected that in a given period more small than large dust particles would be collected. Surprisingly, this was not the case; MIDAS detected several particles larger than about tens of micrometres, but only few with micrometre size and none at smaller sizes [2]. To date it is not clear if the dust size distribution of comet 67P is depleted in particles smaller than some micrometres, or if there was a bias preventing their detection (e.g. spacecraft charging).

4. Conclusions and possible directions for future research

MIDAS acquired a unique dataset revealing the morphology of dust particles with sizes between about 1 and 50 µm at resolutions of 8 to 1500 nm per pixel. The expectation of porous agglomerate dust particles with subunits having sizes down to less than 100 nm was confirmed. A new approach to decipher the processes in our early Solar System and its evolution might be found in the shape of the fractal dust population. The lack of individual compact particles, the absence of clear euhedral structures, and the low flux of particles smaller than a few micrometres were surprising and are not yet fully understood. As MIDAS data has not yet been exhaustively analysed, it still holds the potential to reveal a wealth of cometary dust properties as, e.g., its material strength or the detection of magnetic inclusions. Further open questions concern the true end of the smallest subunit sizes, and the internal structure of the particles. Answering these would further define processes in the early Solar System, and help to understand cometary physics like, e.g., the comet's internal structure, heat transport, and the to date unclear mechanism leading to dust ejection.

Acknowledgements

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Surface changes on comet 67P/Churyumov-Gerasimenko: How do comets evolve with time?

M. R. El-Maarry (1) , O. Groussin (2) , N. Thomas (3) , M. Pajola (4) , A.-T. Auger (2) , B. Davidsson (5) , X. Hu (6) , S. F. Hviid (7) , J. Knollenberg (7) , C. Güttler (6) , C. Tubiana (6) , D. Bodewits (8) , S. Fornasier (9) , H. Sierks (6) , and the OSIRIS team.

(1) Laboratory for Atmospheric and Space Physics, University of Colorado, 3665 Discovery Drive, CO 80303, USA (Mohamed.el-maarry@lasp.colordao.edu), (2) Aix Marseille Université, CNRS, France, (3) Physikalisches Institut, Universität Bern, Switzerland, (4) NASA Ames Research Center, USA, (5) Jet Propulsion Laboratory, USA., (6) Max-Planck-Institut für Sonnensystemforschung, Germany, (7) Deutsches Zentrum für Luft- und Raumfahrt (DLR), Germany, (8) Department of Astronomy, University of Maryland, USA, (9) LESIA, Observatoire de Paris, CNRS, France.

Abstract

The Rosetta mission spent nearly two years orbiting comet 67P/Churyumov-Gerasimenko allowing it to observe how the comet's surface changed with time. During the Dec 2014–Jun 2016 period, numerous remarkable, yet localized, changes were observed [1–4]. These changes included collapsing cliffs, moving boulders, growing fractures, and peculiar transient surface changes on smooth deposits. The localized changes suggest compositional or physical heterogeneity. However, their scale has not resulted in significant alterations to the comet's landscape. This suggests that most of the major landforms were created early in the comet's current orbital configuration, or earlier if the comet had a larger volatile inventory, particularly of CO/CO_2 ices, or contained amorphous ice, which could trigger activity at larger distances from the Sun.

1. Introduction

During the Dec 2014–Jun 2016 period, numerous remarkable, yet localized, changes were observed using OSIRIS [5] images. Here, we present the most significant events that have occurred.

2. Erosion

Erosion on the surface of the comet appears to begin as in-situ weathering of consolidated surfaces, which acts to weaken these materials causing their fragmentation. This effect is evident in a number of locations as collapsing cliffs. So far, we have observed at least three such events. Two of them on the large lobe [1,2], one of which was also found to be associated with a large outburst [2], and another in

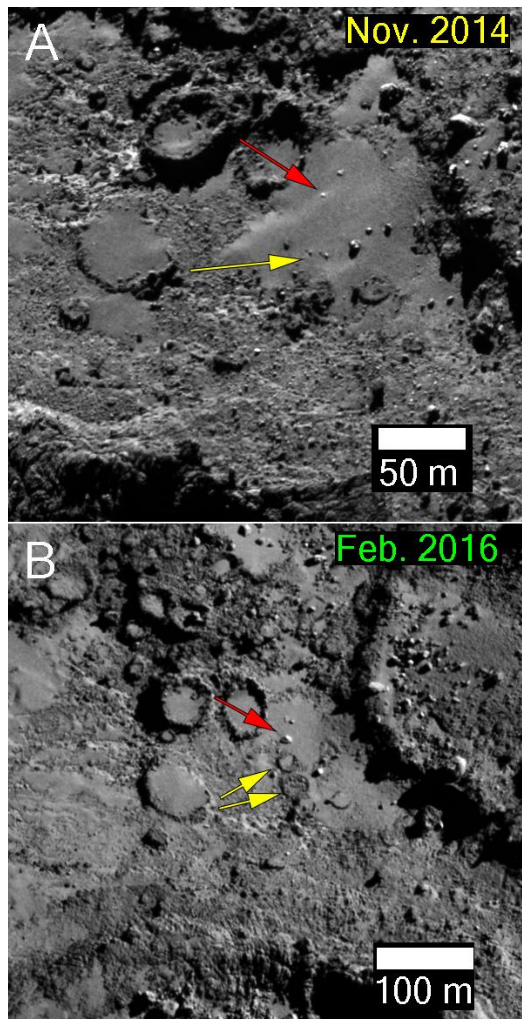

Figure 1: Evidence for erosion on 67P. Smooth materials were removed (> 3 m-thick) exposing underlying features.

the southern neck region. We have also observed extension of a large pre-existing >500 m-long fracture running through the northern neck, whose timing appears to be consistent with changes in the orbital period of the comet and possible evolution of orbital-induced stress in the neck region [e.g., 6]. We also observe movements of large boulder, particularly the displacement of a ~30 m-wide boulder for a distance of ~140 m in the equatorial regions. We have also observed indicators of erosional transport of unconsolidated materials on the surface resulting in the exhumation of previously covered surfaces (Fig. 1).

3. Transient changes

We have observed unique morphological transient changes in the smooth unconsolidated materials that appear to gradually fade away with time or simply stop evolving. These changes are marked by the appearance and/or receding of shallow scarps that tend to exhibit brightening in the rims preceding, and usually persistent during, the changes. Spectrophotometric analysis of these brightened rims is consistent with exposure of ground ice (not frost). Finally, starting in Mar. 2015, numerous patches on the surface of dust-covered terrains underwent textural changes marked by increase in surface roughness to form "honeycomb"-like features [4]. Similar to other seasonal changes, these features have faded substantially in post-perihelion images.

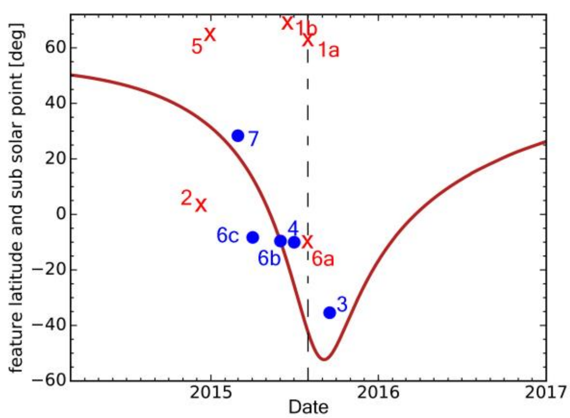

Figure 2: Changes vs. sub solar point. Most events appear to be driven by insolation (blue) with few exceptions (in red). (1) Cliff collapses, (2) Neck fracture evolution, (3) Boulder movement in equatorial region, (4) Erosion (Fig. 1), (5–7) transient changes in smooth materials. Dashed line marks perihelion.

4. Summary and Conclusions

The significant, yet localized, changes in the comet's landscape especially during perihelion suggest that changes to the surface of comets occur on a seasonal scale. Surface changes have mostly occurred around perihelion when the comet was around 2–3 AU. Most changes occur at or close to the sub-solar point, suggesting they are insolation-driven. However, no major changes to the comet's landscape have occurred that have significantly altered its shape or major landforms, even in the southern hemisphere where lower resolution, yet adequate data is available from May 2015. Given that the comet has only spent <10 orbits in its current close configuration since 1959 [7], it is possible that earlier perihelion passages were substantially more active. Alternatively, the comet's landscape may have been shaped up at an earlier period of the comet's lifetime if it had a larger volatile inventory, particularly of CO/CO2 ices or underwent large-scale crystallization of amorphous ice, possibly during its centaur phase [8].

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Sublimation of water ice with organic volatiles, comet 67P/Churyumov-Gerasimenko.

K.J. Kossacki, J. Leliwa-Kopystynski, A. Jasiak, and A. Dubiel
University of Warsaw, Faculty of Physics (kjkossac@igf.fuw.edu.pl)

Abstract

Evolution of the surfaces of cometary nuclei is determined by the sublimation of ice. The rate of sublimation is commonly calculated using the simple Hertz-Knudsen formula. It is inaccurate because it assumes equilibrium distribution of the velocities of molecules. The Hertz-Knudsen formula can be corrected by a temperature dependent sublimation coefficient α_s (e.g. [1, 2, 3]). It was found, that the sublimation coefficient of a frozen spring water is different than that of pure H_2O ice [3]. The cometary nuclei contain H_2O ice with admixtures [4, 5]. The temperature dependence of the sublimation coefficient may significantly affect evolution of cometary nuclei, including the sublimation driven erosion of the surface.

The temperature dependence of the sublimation coefficient of H_2O ice with admixtures, and its influence on the evolution of comet 67P/Churyumov-Gerasimenko will be presented.

1. Introduction

Investigations of comets indicate, that they contain many organics, also volatile, were detected [4, 5]. Laboratory investigations dealing with selected admixtures C_3H_6O (acetone), and CH_3OH (methanol) show that the sublimation coefficient is sensitive to very small concentrations of admixtures [6].

For investigation of comets it is important to know to what extent the temperature dependent sublimation coefficient affects the calculated sublimation rate of ice, ether exposed, or covered by a dust mantle. Performed were example simulations dealing with the recession of the surface in the region Hatmehit on the nucleus of comet 67P/Churyumov-Gerasimenko. The model is and extended version of these described in [7, 8].

Below are described the basic features of the model.

The model nucleus is layered. At the top is a layer composed of agglomerates of dust particles. The dust has thermal conductivity λ_{dm}, and the specific heat depending on the temperature. Beneath the dust mantle is a layer composed of agglomerates of crystalline H_2O ice and dust. In the interior of the nucleus H_2O ice is in amorphous form. The particles of H_2O ice are mantled by CO ice.

Boundary conditions are at the surface and at the largest considered depth i.e. at the bottom of the numerical grid. At the surface the temperature is determined by the energy balance taking into account among other variable illumination, which is calculated in 3D.

The thermal conductivity of the dust mantle is temperature dependent.

The ice-dust material strengthens due to the vapor diffusion from the surface source (Kelvin effect), and the volume diffusion form the boundary source.

Porosity of the ice-dust material evolves due to sublimation/condensation of vapor, as well as due to sintering of ice grains.

2. Results

Calculation of the sublimation rate using uncorrected Hertz-Knudsen equation is equivalent to the assumption $\alpha_s = 1$ at any temperature. Experiments indicate, that $\alpha_s(T > 235\ K) \sim 0.15$. This result is valid both for pure H_2O ice [1, 2, 3, 6], and for ice with acetone, or methanol [6]. At small temperatures the sublimation coefficient significantly depends on the presence of admixtures. When the admixture is acetone and the mass fraction $f = 0.005$ $\alpha_s(215K) \sim 0.46$ instead of ~ 0.18 for pure water ice; when $f = 0.01$ $\alpha_s(215K) \sim 0.74$; when $f = 0.02$ $\alpha_s(215K) \sim 0.78$ [6]. If we assume, that the classical approach $\alpha_s(T) = 1$ is acceptable when $\alpha_s(T) > 0.9$ the uncorrected Hertz-Knudsen equation can be used at: $T < 200$ K in the case of pure water ice, and $T < 210$ K, when ice contains acetone and its mass fraction is 0.01 [6].

The temperature dependent sublimation coefficient of H_2O ice with admixtures affects the energy balance at the interface between the dust mantle and the underlying ice-dust material. Decrease of the sublimation coefficient leads to an increase of the local temperature. This results in an enhancement of the heat flux conducted to the rich in CO interior of the nucleus, and in some enhancement of the emission of CO molecules.

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Compressive strength and elastic modulus of Comet 67P interpreted from a material science point of view

W. Arnold (1), C. Faber (2), M. Knapmeyer (2), and H. Krüger (3), and the SESAME Team
(1) Saarland University, Department of Materials Science and Technology, Saarbrücken, Germany, and I. Physik. Institut, Georg-August University, Göttingen, Germany (w.arnold@mx.uni-saarland.de), (2) DLR Institute of Planetary Research, Berlin, Germany, (3) Max Planck Institute for Solar System Research, Göttingen, Germany

Abstract

The analysis of Cometary Acoustic Surface Sounding Experiment (CASSE) data yielded values of surface compression strength and elastic modulus at the landing site Agilkia. These data are interpreted with fracture mechanical concepts from material science taking into account the high porosity of Comet 67P.

1. Introduction

The lander Philae of the Rosetta Mission carried the Surface Electric Sounding and Acoustic Monitoring Experiment (SESAME) instruments on board [1]. One of them, CASSE, consisted of transmitters and accelerometers as receivers built in the foot soles of the landing gear. They were intended to generate and receive elastic waves and to monitor seismic activity. The accelerometers were operational during the landing on comet 67P in order to record the acceleration signals caused by the landing shock.

2. Results

We reported recently an analysis of these acceleration data obtained at Philae's first touch-down site Agilkia on comet 67P [2]. First the amplitudes of the signals were analyzed. Based on calibration tests at the LAMA test facility of the DLR, and a theoretical analysis of the transfer function of the legs of the landing gear for external forcing via the foot-soles, the impact forces acting on the soles at the first touch-down site Agilkia were determined [3]. They ranged from 7 N to 23 N. Depending on the contact area between the soles and the comet surface, the compression strength calculated extended from 0.5 kPa as a lower limit to 12 kPa as an upper limit.

Furthermore, the signals contained distinct frequency bands which were analyzed regarding the soles as mechanical contact oscillators which were excited due to the landig shock. Their frequencies depend on the contact stiffness of the lander foot soles to the comet surface regolith determined by the contact area, elasticity and compression strength. In a spherical contact, the stiffness k^* is given by $k^* = 2aE_r^*$ where a is the contact radius and E_r^* is the reduced Young's modulus of the sole material and of the comet surface material. Calibrating again the response of the sole contact-oscillator to an external force, a calibration curve for the sole's contact oscillations was obtained. This translates into an elastic surface modulus of about 3 – 25 MPa.

3. Discussion

In view of the various results obtained for strength values of comet 67 P which cover some 10 Pa to 4 MPa, we would like to discuss and explain these rather different values by using relations known from material science and from rock mechanics.

Large porosity is a dominant factor which reduces all strength parameters and elastic moduli of a given material. Besides, large pores can be viewed as stress concentrators which limit the strength upon external loading, here the forces exerted by the Lander Philae. There are strength-elastic modulus relations for foam-like structure with open cells [4]:

$$\sigma_c/E_c = 0.03\left(\rho_p/\rho_s\right)^2\left(1+\sqrt{\rho_p/\rho_s}\right)^2 \qquad (1)$$

Here, σ_c is the elastic stress for compression failure, and for our case ρ_p and ρ_s are the mass densities of the comet material with porosity and for the pore free material, respectively. E_c is its Young's modulus. Inserting for the porosity $(1-\rho_p/\rho_s) = 0.7$ to 0.8 for 67P at Agilkia, one obtains $2.5\times10^{-3} < \sigma_c/E_c < 6.5\times10^{-3}$ For $\sigma_c = 8$ kPa [2], this yields 1.2 MPa $< E_c <$ 3.2 MPa.

Similar expressions like Eq. 1 have been derived for other cellular materials. Considering the high porosity, the comet surface material may be viewed as a cellular material with the ice being the walls between the regolith particles [5,6]. There are experimentally determined master curves for cellular materials for the ratio of the elastic collapse strength/elastic modulus of the cells by cell-wall buckling. i.e. crushing [7]. Again for a porosity of 0.7

to 0.8, this ratio is $1.7\times10^{-3} < \sigma_c/E_c < 7.9\times10^{-3}$ i.e. for E_s = 8 GPa (ice) [8] we get 13 MPa < σ_c < 63 MPa.

Independent of the question whether ice serves as glue between the regolith particles, brittle cellular porous materials fail in compression by crushing after elastic deformation. There is a plateau regime of stress versus strain during which energy is absorbed upon further straining the material and eventually densification sets in at larger strains ε. Such a scenario has taken place according to the analysis of the energy balance of the landing events [9,10].

The fracture of a material is sensitive to defects such as pre-existing cracks, inclusions or large cells or voids in cellular materials because, as said, defects act as stress concentrators. This is the basic concept of fracture mechanics [11]. For a porosity of 80% [7]:

$$\sigma \approx 10^{-2}\, \sigma_{wall} \Big/ \sqrt{d/L_c} \qquad (2)$$

Here, σ is the fracture stress, L_c is the length of the cells and d is the linear defect size, for example a local crack Eq. 2 holds for $d > L_c$. The smallest cell size for the comet regolith is L_c = 0.4 mm [12]. Let us assume we have d = 10 cm. This yields a fracture stress of 6.5 kPa if we assume again that the cell walls are ice, i.e. $\sigma_{wall} \approx$ 10 MPa. It should be mentioned that Greenberg et al. [5] stated, that a fracture mechanics would be the correct way of describing the fracture strength of comet materials.

Similar considerations and relations exist for the elastic moduli and fracture strength of ceramics before sintering which are either slurries or dry-pressed powders, so-called green bodies [13,14]. Green bodies have an appreciable amount of porosity and also, as assumed for the comet material, the individual particles in the unfired material contact each other at certain points, where interatomic forces hold the particle agglomerate together [15]. They deform the particles at the contact points elastically. The energy needed to separate two particles is $a_{cp}^2\times\Gamma$ where a_{cp} is the radius of the contact points and Γ is the surface energy. When the two particles are separated, the elastic energy is released which *reduces* the total energy needed for separation. The number of contacts in the ensemble with a surface area πa_{cp}^2 depends on the overall porosity. In various theoretical descriptions, this dependence was determined to be proportional to $(\rho_p/\rho_s)^z$ with z being 2, 3, and 4 [16] instead of the almost squared power dependence of Eq. 1 and the master curves cited above. Independent which equation describes the experimental situation best, the relation is very sensitive to the porosity at small values of ρ_p/ρ_s.

Summarizing, it is the porosity which determines the elasticity and the strength of a porous material for small ρ_p/ρ_s. On the one hand the porosity reduces the number of contacts or the coordination number between the individual constituents of the agglomerate and on the other hand large pores act as stress concentrator initiating failure upon loading. This holds also for rocks [17]. The large variations of strength values reported on comet 67P (from a few tens of Pa [18, 19] to several MPa [20] can be explained by local variations in porosity.

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EPSC Abstracts
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Radiogenic heating of comet 67P/Churyumov-Gerasimenko and implications for its formation time

O. Mousis (1), A. Drouard (1), P. Vernazza (1), J. I. Lunine (2), M., Monnereau (3), R. Maggiolo (4), K. Altwegg (5,6), H. Balsiger (5), J.-J. Berthelier (7), G. Cessateur (4), J. De Keyser (4), S. A. Fuselier (8), S. Gasc (5), A. Korth (9), T. Le Deun (1), U. Mall (9), B. Marty (10), H. Rème (3), M. Rubin (5), C.-Y. Tzou (5), J. H. Waite (8), and P. Wurz (5)
(1) Aix Marseille Université, CNRS, LAM (Laboratoire d'Astrophysique de Marseille) UMR 7326, 13388, Marseille, France (olivier.mousis@lam.fr), (2) Department of Astronomy and Carl Sagan Institute, Space Sciences Building Cornell University, Ithaca, NY 14853, USA, (3) Université de Toulouse; UPS-OMP-CNRS; IRAP, Toulouse, France, (4) Royal Belgian Institute for Space Aeronomy, BIRA-IASB, Ringlaan 3, B-1180 Brussels, Belgium, (5) Physikalisches Institut, University of Bern, Sidlerstr. 5, CH-3012 Bern, Switzerland, (6) Center for Space and Habitability, University of Bern, Sidlerstr. 5, CH-3012 Bern, Switzerland, (7) LATMOS/IPSL-CNRS-UPMC-UVSQ, 4 Avenue de Neptune F-94100, Saint-Maur, France, (8) Department of Space Science, Southwest Research Institute, 6220 Culebra Rd., San Antonio, TX 78228, USA, (9) Max-Planck-Institut für Sonnensystemforschung, Justus-von-Liebig-Weg 3, 37077 Göttingen, Germany, (10) Centre de Recherches Pétrographiques et Géochimiques, CRPG-CNRS, Université de Lorraine, 15 rue Notre Dame des Pauvres, BP 20, 54501 Vandoeuvre lès Nancy, France

Abstract

We investigate how heat generated by the radioactive decay of ^{26}Al and ^{60}Fe influences the formation of comet 67P/Churyumov-Gerasimenko, as a function of its accretion time and size of parent body. To fully preserve its volatile content, we find that either 67P/Churyumov-Gerasimenko's formation was delayed between ∼2.2 and 7.7 Myr after that of Ca-Al-rich Inclusions (CAIs) in the protosolar nebula, depending on the primordial size of its parent body and the composition of the icy material considered.

1. Introduction

To depict the thermal evolution of 67P/Churyumov-Gerasimenko (67P/C-G) as a function of time due to radiogenic decay, we used a one-dimensional thermal evolution model [1], which has been recently utilized to depict the formation of pits on the surface of 67P/C-G [2] and to characterize the subsurface of the ESA/*Rosetta* descent module *Philae* landing site [3]. Our thermal evolution model does not account for the growth of the body during its accretion phase. Consequently, the nucleus accretion time is assumed to be small compared to the delay t_D. The computation of the thermal evolution starts at time zero after t_D, from an initial temperature of 30 K, which corresponds to the surface temperature of a planetesimal orbiting the Sun at a distance of ∼85 AU. No additional accretional heating is accounted for. Our computations have been conducted under the assumption that 67P/C-G results from the merging of two lobes originally formed separately. Therefore, two extreme body sizes have been considered. In the first case, we assumed that these lobes are primordial and reached their current sizes at the end of their accretion. We then used an average value inferred from the measured sizes of 67P/C-G's lobes. In the second case, we postulated that these lobes originated from the disruption of larger bodies. Consequently, we adopted a generic Hale-Bopp-like size for the body under consideration, a value close to the average sizes of P– and D–types asteroids as well as of Jovian Trojans, which are good candidates for comets' parent bodies [4]. Two distinct ice structures have been investigated for each size:

- *Mixed model.* The icy phase is made of pure solid water distributed half as pure crystalline ice and half in clathrate form. Clathrate destabilization is simulated without any volatile inclusion in the cages.

- *Amorphous model.* The icy phase of the nucleus is exclusively made of pure amorphous water ice.

Water is the only volatile species considered in our model, allowing the computational time of each simulation to be significantly reduced. Finally, two values of dust-to-ice ratios, namely 4 and 1, have been investigated in our simulations.

2. Results

Figure 1 represents the extent of the devolatilized region as a function of the formation delay within bodies with radii of 1.3 and 35 km, respectively. It shows that the accretion of a typical lobe of 67P/C-G must start at least between ∼2.2 and 2.5 Myr after CAI formation for dust-to-ice ratios of 1 and 4, respectively, to fully preserve its volatile content in the case of the amorphous model. With values of ∼3.4 and 4.4 Myr for dust-to-ice ratios of 1 and 4, respectively, formation delays become longer in the case of the mixed model, as a result of its higher thermal inertia. The figure also shows that the formation delay of a Hale-Bopp sized body requires more time to fully preserve its volatile content. Here, to match this criterion, the body must start its accretion at least ∼5.6 and 5.9 Myr after CAI formation for dust-to-ice ratios of 1 and 4, respectively, in the case of the amorphous model. Meanwhile, the accretion must start at least ∼7.3 and 7.7 Myr after CAI formation for dust-to-ice ratios of ∼1 and 4, respectively, in the case of the mixed model.

3. Discussion

Our computations support the conclusion that 67P/C-G's volatile content can either be explained via its agglomeration from building blocks originating from the protosolar nebula or from debris resulting from the disruption of a larger body having a Hale-Bopp size. Each composition case considered can be matched by these two scenarios via a particular set of plausible values for the formation delay t_D. Our calculations show that, to fully retain their initial volatile budget, the two lobes of 67P/C-G must have accreted in the 2.2–4.4 Myr range after CAI formation, depending on the adopted type of ice and dust-to-ice ratio, and assuming they assembled from building blocks originating from the PSN. If 67/C-G's lobes assembled from chunks issued from the disruption of a parent body having a size similar to that of Hale-Bopp, their accretion time is delayed to 5.6–7.7 Myr after CAI formation, based on similar assumptions. Because accretion occurring during a given time span induces a similar extent of devolatilization within the body as instantaneous accretion happening at the end of the time span, the aforementioned numbers also correspond to the accretion time taken by the comet/parent body to reach its current/original size (see [5] for further details).

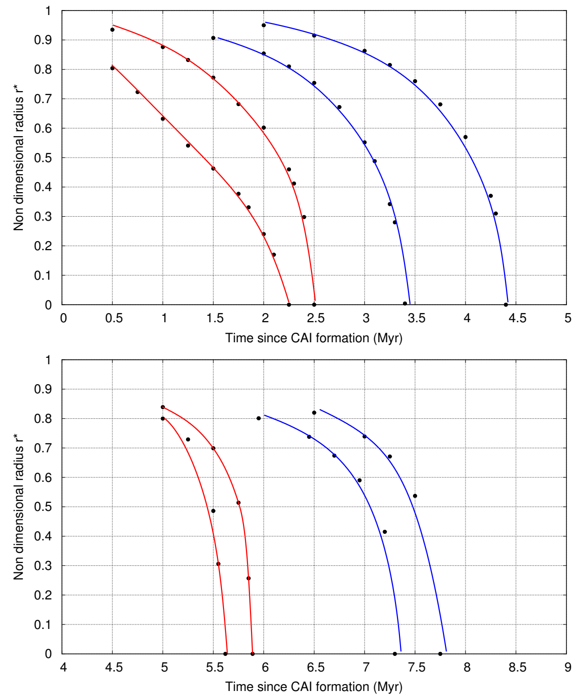

Figure 1: Extent of the devolatilized region (between 0 and the normalized radius r^*) within a body with a radius of 1.3 km (top panel) and within a Hale-Bopp sized body (bottom panel) as a function of its formation delay. The red and blue curves correspond to the amorphous and mixed models, respectively. In each model, the left and right curves correspond to dust–to–ice ratios of 1 and 4, respectively.

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Seasonal Changes of the Icy Dust Cover on Comet 67P/Churyumov-Gerasimenko

X. Hu (1,2), X. Shi (1), H. Sierks (1), M. Fulle (3), J. Blum (2), H.U. Keller (2,4), E. Kührt (4), B. Davidsson (5), C. Güttler (1), B. Gundlach (2), and the OSIRIS Team
(1) Max-Planck-Institut für Sonnensystemforschung, Justus-von-Liebig-Weg 3, 37077 Göttingen, Germany (hu@mps.mpg.de). (2) Institut für Geophysik und extraterrestrische Physik (IGEP), Technische Universität Braunschweig, Mendelssohnstraße 3, 38106 Braunschweig, Germany. (3) INAF Osservatorio Astronomico di Trieste, Via Tiepolo 11, 34014 Trieste, Italy. (4) Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Planetenforschung, Rutherfordstraße 2, 12489 Berlin, Germany. (5) Jet Propulsion Laboratory, M/S 183-301, 4800 Oak Grove Drive, Pasadena, CA 91109, USA.

Abstract

The morphology of comet 67P/Churyumov-Gerasimenko (67P) is distinctly dichotomous. Notably, the northern hemi-nucleus of the comet is covered by expansive dust deposits [1]. Over the two-(and-plus-)year rendezvous of Rosetta with 67P, the OSIRIS cameras onboard the spacecraft observed in detail the evolution of the dust cover around the 2015 perihelion passage of the comet. We catalog the observed surface changes before and after perihelion. We will elaborate on the global distribution as well as timeline of the changes and illustrate how the dust cover is cyclically eroded and renewed around each perihelion. We will discuss how the expansive changes were likely driven by sublimation of small amount of water ice preserved in the dust cover.

1. Introduction

The prevalent dust cover over the northern hemi-nucleus of 67P had formed by the deposition of ejecta from the south that was briefly but intensely illuminated during the previous perihelion passage of the comet (before 2015) [2]. The dust cover had undergone wide and continuous transformations from early 2015 when 67P reached the heliocentric distance of about 2.5 au inbound [3, 4, 5]. Many changes were manifested in an increase of surface roughness, for example, the formation of "honeycombed" textures over formerly smooth surfaces, that had probably resulted from uneven erosions of dust deposits [3]. Other forms of changes, such as emergence of consolidated substrates, retreating of scarps, and etc., had also been noted, that were likewise invigorated by the intensifying solar illumination as 67P approached perihelion (Figure 1). The aftermath of the pre-perihelion surface changes was buried with the renewal of the dust deposits during the northern polar night by dust ejected from southern hemi-nucleus around perihelion (Figure 1).

2. Results

Potential surface changes are detected via comparison of images of common locations and indicated by visual differences between observed surface morphologies. The shape-from-shading technique is applied to reconstruct the topography of surface roughness from observations. The comparison of the resulting topographic models enables a quantification of the (minimum) thickness of surface erosion and restoration. At most locations of detected changes, the surface had been excavated by at least several decimeters before perihelion and replenished by at least a comparable amount during perihelion.

The distribution of the surface changes exhibits a clear latitudinal dependence and a concentration between about 20°N and 40°N. In particular, the changes occurred in open surface areas amply illuminated and, thus, susceptible to strong surface erosion before perihelion. They occurred in phase with the movement of the sub-solar point toward the south across the latitudes of their distribution. The surface erosion was ostensibly driven by water sublimation. The roles of other, more volatile species are unclear, but were most likely secondary.

We apply thermal models to estimate the accumulated erosion of water ice in response to the increasing insolation over the visibly eroded surface areas. The comparison of model estimates with the minimum amount of surface changes quantified from OSIRIS observations provides a constraint on the abundance of water ice in the dust cover.

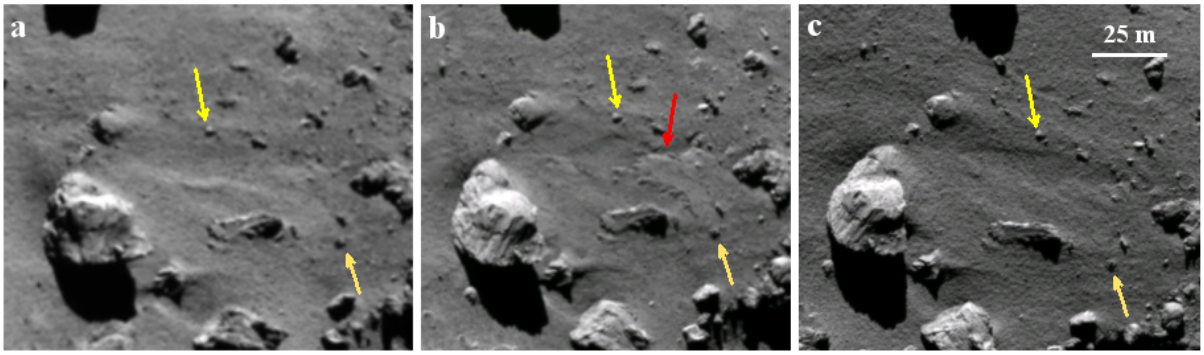

Figure 1: Erosion and restoration of dust deposits in the Ma'at region on comet 67P observed by OSIRIS. The dust deposits had been visibly eroded between December 2, 2014 (**a**) and March 28, 2015 (**b**), forming a V-shaped scarp and exposing the sharp edges of several consolidated boulders or outcrops. Observation on June 6, 2016 shows the disappearance of the scarp after perihelion, probably veiled by the renewed deposits (**c**). Red arrow in **b** indicates the newly formed scarp. Yellow arrows point to a common boulder in three panels as a landmark. This figure is adapted from [5].

3. Conclusions

The erosion and restoration of dust deposits over the northern hemi-nucleus of 67P are seasonal and cyclic phenomena as a result of cometary activity. The dust deposits were icy: it is found that they contained a few percent of water ice in mass, which corresponds to an average dust-to-ice ratio in excess of ten and, thus, greater than the dust-to-gas ratio of six as measured in the coma of 67P [6, 7]. This is a necessary consequence of the observed redistribution of an appreciable amount of non-escaping dust ejecta over the nucleus surface, which most notably shaped the surface morphology of the northern hemi-nucleus.

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Long-term survival of water-ice observed on comet 67P

N. Oklay (1), S. Mottola (1), J.-B. Vincent (1), M. Pajola(2), S. Fornasier (3) and the OSIRIS Team
(1) German Aerospace Center (DLR), Institute of Planetary Research, Rutherfordstraße 2, 12489 Berlin, Germany (Nilda.OklayVincent@dlr.de), (2) NASA Ames Research Center, Moffett Field, CA 94035, USA, (3) LESIA, Observatoire de Paris, PSL Research University, CNRS, Univ. Paris Diderot, Sorbonne Paris Cité, UPMC Univ. Paris 06, Sorbonne Universités, 5 place Jules Janssen, 92195 Meudon, France

Abstract

Numerous water-ice-rich features sizes from centimetres to tens of meters, mostly located in rough terrains, surviving more than several months on comet 67P/Churyumov-Gerasimenko were observed during the Rosetta mission (Oklay et al. 2016a; Barucci et al. 2016; Deshapriya et al. 2016). We present the first-time detection of areas enriched in water ice surviving up to two years since their first observation via narrow angle camera (NAC) of Optical, Spectroscopic and Infrared Remote Imaging System (OSIRIS Keller et al. 2007). Their existence on the nucleus of comet 67P at the arrival of the Rosetta spacecraft suggests that they were exposed to the surface during the comet's previous orbit. We investigated the temporal variation of large patches to understand the long-term sustainability of water ice on cometary nuclei on time scales between half a year, and two years i.e. until the end of the mission.

Large clusters are stable over typical periods of half a year and reduce their size significantly around the comet's perihelion passage, while smaller exposures disappear in shorter time scales (Oklay et al. 2017). By studying multispectral images taken by OSIRIS NAC, we characterized the multispectral signatures of features enriched in water ice. Individual features have low spectral slopes and flat spectra, while clusters show similar spectra to the average surface but with lower spectral slopes. Within the first ten months of observations, spectral slopes increase by about 3%/100 nm within large clusters, indicating the ongoing sublimation process. However, several small boulders enriched in water ice within the talus field still display typical low spectral slopes of ∼8%/100 nm. At the first detection, the large isolated features had spectral slopes typically ∼5%/100 nm but increased by 3-5%/100 nm in the next ten months.

We investigated the association of water ice features and activity. Most of the regions enriched in water ice are the sources of activity (Oklay et al. 2016b; Vincent et al. 2016). In large clusters, dust jets were detected, whereas in large isolated ones no associated activity was detected.

Our thermal analysis shows that the long-term sustainability of water-ice-rich features can be explained by the scarce energy input available at their locations over the first half year. However, the situation reverses for the period lasting several months around perihelion passage. Within one of the isolated patch, our two end-member mixing analysis estimates a pure water-ice equivalent thickness up to 15 cm and 0.9 cm in the cases of intimate and areal mixtures respectively. For the isolated one still observable through the end of the mission, the water-ice equivalent thickness could be up to 2 m and 0.5 m in the case of intimate and areal mixtures respectively .

Our spectral modelling of areal mixture of water-ice with the cometary material estimates up to 48% water-ice content for one of the large isolated feature, and up to 25% water ice on the large boulders located within clusters.

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Constraints on cometary surface evolution from a statistical analysis of 67P's topography

J.-B. Vincent (1), S.F. Hviid (1), S. Mottola (1), E. Kührt (1), F. Preusker (1), F. Scholten (1), H. U. Keller (2), N. Oklay (1), D. de Niem (1) & the OSIRIS team
(1) DLR Institute for Planetary Research, *jean-baptiste.vincent@dlr.de*
(2) Institute for Geophysics and Extraterrestrial Physics, TU Braunschweig, 38106 Braunschweig, Germany

Abstract

We present a statistical analysis of the distribution of large scale topographic features on comet 67P/Churyumov-Gerasimenko. We observe that the cumulative cliff height distribution across the surface follows a power law with a slope equal to -1.69 $\pm$ 0.02. When this distribution is studied independently for each region, we find a good correlation between the slope of the power law and the orbital erosion rate of the surface.

Our study suggest that the current size of a cliff or other topographic feature on the comet is not controlled only by material cohesion but by the dominant erosional process in each region. Therefore, a measure of the topography can provide a quantitative assessment of a comet erosional history. We argue that our observations of 67P lead to a general model which can be applied to all other comets. We propose that primordial nuclei are characterized by the presence of large cliffs with a cumulative height power index equal or above -1.5, while eroded cometary surfaces are broken in smaller blocks with a power index equal or beyond -2.3 [1].

The primordial topographic power law distribution is particularly important as it may bring some insights on the stratification of the nucleus [2] but also on early erosional processes such has low speed impacts in the early Kuiper Belt, a poorly constrained epoch particularly fundamental to understand comet formation [3].

Ultimately, our work allows to define an age for the surface of a comet or at least characterize its degree of erosion since it entered the Inner Solar System [1]. We propose that this technique can be applied in a similar way as crater statistics coupled with dynamical models are used to date rocky surfaces on asteroids and planets. This brings a whole new sets of constraints to refine dynamical models of cometary orbits, often limited to the last few orbits. Indeed, any backward integration beyond the last encounter with Jupiter will often lead to a wide range of solutions, due to the chaotic nature of such orbits [4]. Our results, for instance, lead to the exclusion of orbital solution which would have brought 67P as close the Sun as in the current orbit (since 1959), and favor ancient orbits more similar to that of comet 81P/Wild 2, another dynamically young comet.

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OSIRIS was built by a consortium led by the Max Planck Institut für Sonnensystemforschung, Göttingen, Germany, in collaboration with CISAS, University of Padova, Italy, the Laboratoire d'Astrophysique de Marseille, France, the Instituto de Astrofisica de Andalucia, CSIC, Granada, Spain, the Scientific Support Office of the European Space Agency, Noordwijk, The Netherlands, the Instituto Nacional de Tecnica Aeroespacial, Madrid, Spain, the Universidad Politecnica de Madrid, Spain, the Department of Physics and Astronomy of Uppsala University, Sweden, and the Institut für Datentechnik und Kommunikationsnetze der Technischen Universität Braunschweig, Germany.

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An atlas of comet 67P/Churyumov-Gerasimenko

J.-B. Vincent, N. Oklay, & the OSIRIS team
DLR Institute for Planetary Research, *jean-baptiste.vincent@dlr.de*

Abstract

The cartography of celestial bodies is a fundamental tool in comparative planetology as maps display various types of information in a common reference frame. This allows a direct comparison of many data sets at different epochs and for different objects. In the case of comet 67P, however, a full high resolution mapping of the surface remains unpublished so far, due to the complexity of the nucleus' shape, especially its very large concavities.

This work present a new software package developed for the purpose of mapping such non trivial body. We are now able to texture the 3D shape model of the comet with an arbitrary number of images and unwrap this data set onto several types of maps, with the highest accuracy. Although we have mainly used OSIRIS data (the highest resolution available), our approach is not limited to images. We can indeed map different types of products such as spectral units, elevation, gravity, slopes...

We are now processing all the data to produce a global atlas of the comet which will be presented at this conference. We will display full 3D views and global maps of the comet obtained at different epochs (before and after perihelion) with a spatial resolution of about 1 m per pixel or better. Spectral maps and other products will be used to show how different data sets can be combined together.

Mapping the comet also provides a quick way to track changes over time. With high resolution images we can investigate signatures of surface evolution far beyond what can be achieved from shape models alone. To illustrate this, we will present a change detection algorithm developed to automate the cataloging of small scale features. We will showcase some examples such has meter-sized objects traveling across the surface, boulder fracturing, moving dune fields, and collapses of the topography, all detected automatically. This catalog of changes will be used to provide new constraints on the various processes governing cometary evolution.

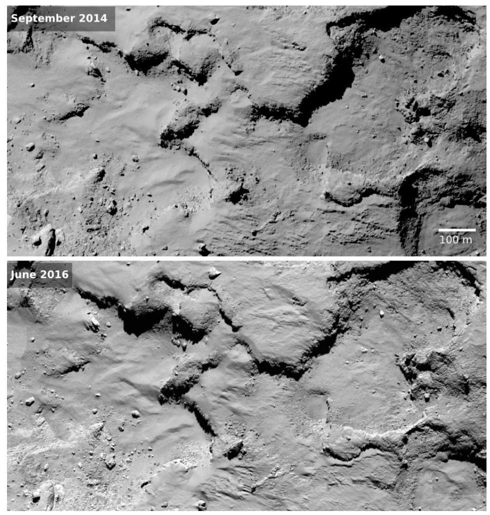

Figure 1: Two mosaics (top panel: 8 images, bottom panel: 10 images) of a small area of 67P's small lobe, automatically generated by our mapping tool. Such mosaic contains several hundred minor changes of topography.

Acknowledgements

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Thermally-driven Formation Mechanisms for Fractures on Comet 67P/Churymov-Gerasimenko

J.L. Molaro (1), P. Becerra (2), C. Herny (2), R. Marschall (2), M.R. El-Maarry (3), N. Thomas (2), A. Pommerol (2), and P. Theologou (2)
(1) Jet Propulsion Laboratory, Pasadena, California, USA (2) Physikalisches Institut, Universität Bern, Switzerland (3) LASP, University of Colorado in Boulder, Boulder CO-80303, USA.

Abstract

We investigate the role of thermally induced stresses in fracture propagation at the surface of comet 67P/Churymov-Gerasimenko by comparing images from the Rosetta spacecraft of fractures before and after perihelion passage. We then simulate the stress fields induced within the associated topography and relate the results to the observed fractures, providing insight into the efficacy and nature of this process.

1. Introduction

The Optical, Spectroscopic, and Infrared Remote Imaging System (OSIRIS) [1] on board ESA's Rosetta spacecraft observed many fractures on the surface of comet 67P/Churymov-Gerasimenko [2]. These appear over many morphological regions at scales from sub-meter (fig 1a,b) to hundreds of meters (fig. 1c), and were initially assessed and classified by [3] based on their morphology and possible formation mechanisms. Evidence suggests that fracturing of consolidated material on the comet contributes to the development of unconsolidated regolith [4], thus investigating these formation mechanisms will provide insight into the recent history of the cometary surface. Here, we focus on testing the most likely mechanism for smaller scale fractures: thermally induced crack propagation, which is thought to operate on a variety of airless bodies [e.g., 5-8]. Recent work [5] has shown that spatially and temporally varying stress fields are induced in boulders undergoing diurnal thermal cycling on the Moon, which drive crack propagation in different directions and at different locations within their volume. While propagation rates and stress thresholds are not well constrained, OSIRIS images of fractures on comet 67P provide an unparalleled opportunity to study this process. Relating simulated stress fields to observed fractures will allow us to constrain these properties and provide insight into how these features develop over time. For this purpose, we will characterize and compare OSIRIS images of fractures before and after perihelion passage, and model the macroscopic stresses induced in the associated topographic features along the comet's orbital path.

2. Observations

The initial assessment of OSIRIS images from 2014 to 2016 showed evidence for fracturing during the mission timeline on the scale of <1-10s of meters [4, fig. 1]. This type of fracturing is not observed everywhere on the comet. Therefore, we suspect that their location is associated to specific conditions favouring this process. If thermal breakdown is a driving mechanism for these fractures and cliff failures, this suggests that the locations in which the cracks appear experience enhanced stresses (relative to other areas of the comet) due to differences in incident radiation and shadowing effects.

3. Modeling

Following the work of [5], we use COMSOL Multiphysics to perform 3D finite element simulations of the thermomechanical response of boulders on the surface of the comet to diurnal thermal cycling, allowing us to investigate the magnitude and distribution of resulting stresses. We model a spherical boulder embedded in a volume of regolith, impose incident solar radiation on the surface and solve the heat and displacement equations over one solar day. The model accounts for the radiative and conductive interaction between the boulder and surrounding regolith, as well as the size of the solar disk. We approximate the regolith as lunar regolith, with temperature and depth dependent material properties following [9], producing a temperature range and thermal inertia that are consistent with measurements taken by the MIRO instrument aboard Rosetta [10]. The boulder is composed of a mixture of water ice and basalt, which also have temperature dependent properties [5, 8]. Preliminary results suggest that stresses up to 6 MPa may be induced in consolidated objects at the comet's surface. Figure 2 shows an example of the stress induced along a 2D cross-section of a 1 m boulder (25% water ice by volume) at mid-morning. The boulder's temperature ranges from 251-277 K, suggesting that sublimation effects within pores may produce additional stresses that interact with the thermally induced stress field.

4. Future Work

The unique shape of comet 67P/Churymov-Gerasimenko suggests that certain locations will experience larger diurnal temperature ranges, and thus may be more susceptible to thermally induced fracturing. We will simulate the comet's global surface temperatures to identify these locations, and compare OSIRIS images of fractures before and after perihelion passage. We will then quantify the spatially and temporally varying macroscopic stress fields within the associated boulders and surface features to assess whether the observed fractures are thermally driven. We will constrain crack propagation rates, stress thresholds, and ice volume in the comet's consolidated material, providing valuable insight into the role of diurnal thermal cycling on the landscape evolution of comets.

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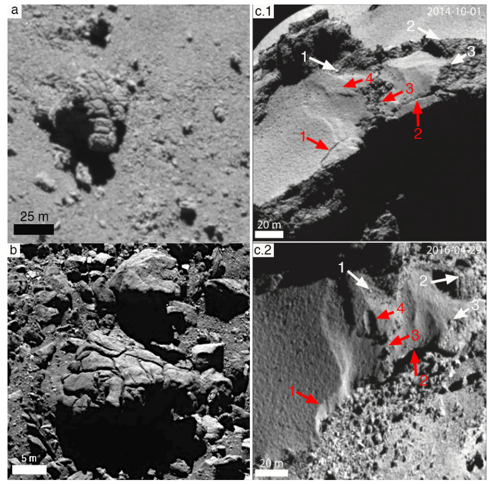

Figure 1: OSIRIS images of fractured boulders taken (a) before and (b) after perihelion. (c) Evolution of a cliff in the Ash region (c.1) before perihelion and (c.2) after perihelion [4]. Red arrows indicate morphological changes between images, and white arrows indicate reference points where no changes occur. Red arrows 1 and 2 point to meter-scale fractures in (c.1) that led to cliff collapse in (c.2). Red arrow 3 reveals rocky material in (c.1) that is covered by dust debris and/or eroded in (c.2). Red arrow 4 shows dry mass wasting feature associated to the destabilization of the terrain due to cliff collapse.

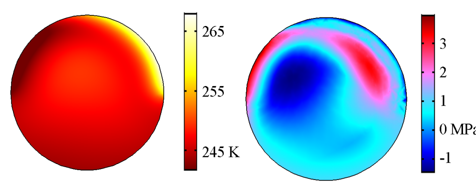

Figure 2. Snapshot of the temperature (left) and stress (right) in a 2D cross section through a 1m-diameter boulder (25% water ice) during mid-morning. We present the maximum principal stress (tensile stress is positive), which represents the idealized energy available for crack propagation at a given location.

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Automated determination of dust particles trajectories in the coma of comet 67P

J. Marín-Yaseli de la Parra, M.Küppers, F. Perez, S.Besse, R.Moissl and the OSIRIS team.
Operations Department, Directorate of Science, European Space Astronomy Center (ESAC), European Space Agency, Camino bajo del Castillo s/n, Urb. Villafranca del Castillo P.O. Box 78 - 28691 Villanueva de la Cañada, Madrid, Spain
(jmarin@sciops.esa.int / T: +34-91-8131577)

Abstract

During more than two years Rosetta spent at comet 67P, it took thousands of images that contain individual dust particles. To arrive at a statistics of the dust properties, automatic image analysis is required. We present a new methodology for fast-dust identification using a star mask reference system for matching a set of images automatically. The main goal is to derive particle size distributions and to determine if traces of the size distribution of primordial pebbles are still present in today's cometary dust [1].

1. Introduction

During more than 2 years that Rosetta stayed at comet 67P, the OSIRIS camera system monitored the evolution of the dust coma from 4.1 AU inbound to 3.8 AU outbound. One of the intriguing results was the large number of big (cm to dm sized) particles that could be identified visually. We plan to analyze the dust populations to compare measured size distributions to those predicted by formation models.

Many thousand images were obtained by the OSIRIS cameras for different purposes; in many of those observing sequences, 100s of dust particles are identifiable in single images. The dust detected by OSIRIS can be divided into near-spacecraft dust with its apparent motion being dominated by spacecraft motion and near-nucleus dust, moving radially away from the nucleus. In the latter case, the distance is known approximately and the size (with an assumed albedo and phase function) and velocity of the particles can be determined. In addition, the rotational lightcurve of some particles is detectable in the images, providing additional information about spin period and shape [2].

2. The method

We demonstrate the method with a specific series of images as an example: we take a set of 90 images obtained on 11th May of 2015 with the OSIRIS wide angle camera (WAC) at a heliocentric distance of 1.67 AU and a spacecraft-comet distance of 140 km. The phase angle of the nucleus was approximately 70 deg. The spacecraft pointed 9.7 degrees off the nucleus in sunward direction, so that the phase angle of the observed dust grains is about 80 deg.

After processing the set of images, 22 images were chosen in a period of time between 08:37:07 and 09:08:14 hours. We co-register the images on selected stars to derive the inertial motion of the dust particles relative to the spacecraft (Figure 1), defined as reference frame, when 20 stars were used in a subset of 12 images. Tracks of dust particles are identified in Figure 2. This mask is enough for matching the images at first approximation with errors in the pixel match near to R^2=1, as shown in the graph in figure 3.

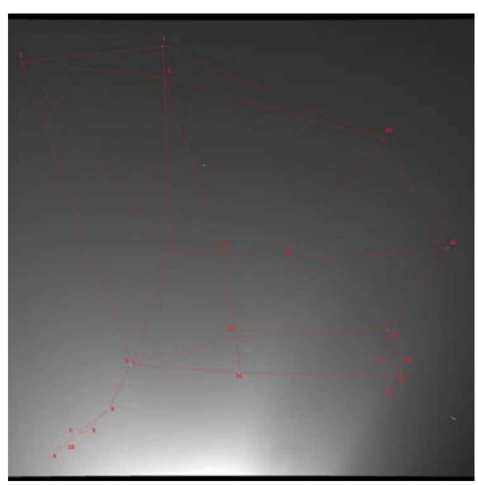

Figure 1: Mask of stars used for this analysis.

Figure 2 shows the processed images to correlate the stars and to distinguish them from dust particles with very low velocity relative to the spacecraft. The motion of the stars can be easily detected.

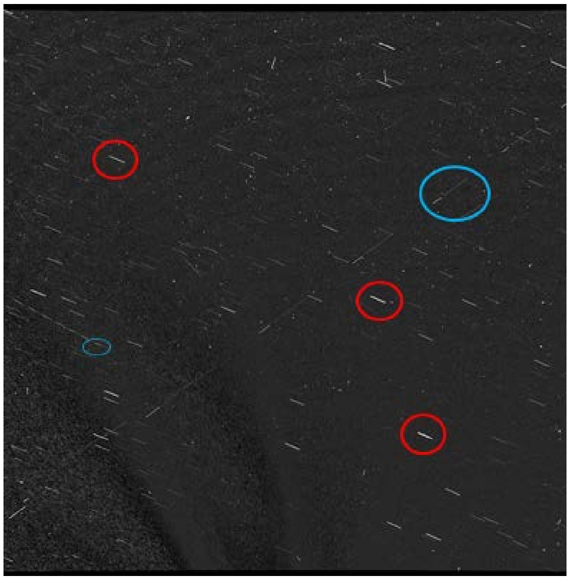

Figure 2: 22 images taken on 11 May 2015 which each image pixel summed up and divided by the median. Red circles show examples of stars , blue circles show examples of dust particles.

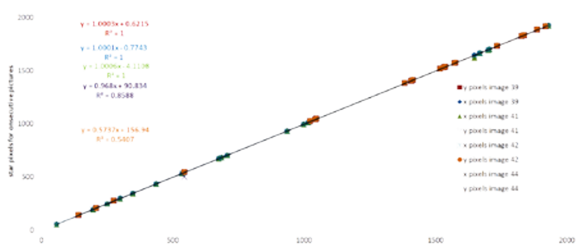

Figure 3: Pixel coord x and pixel coord y set over the field of view. It was found the mask of stars moves with a max velocity of 6 pixels per hour relative to the first image, but the pixel matching along the different images can be settled with relatively low errors.

3. Summary and Conclusions

We present an ongoing study with the goal of describing the evolution of the cometary dust population over the mission, and to search for changes on various timescales. The outcome will be used to evaluate if there is a preferred size range of dust particles and if their measured size distribution is primordial. In terms of methodology, it seems feasible to use stars as reference points.

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The size distribution of dust from comet 67P/Churyumov-Gerasimenko

J. Agarwal and H. Böhnhardt
Max-Planck-Institut für Sonnensystemforschung, Göttingen, Germany (agarwal@mps.mpg.de)

Abstract

The size distribution in a given ensemble of cometary dust grains reveals, e.g., which particles dominate the optical scattering cross-section when observed from a distance, and which particles carry the bulk of mass ejected into the interplanetary environment by the comet. The size distribution reflects the conditions under which the refractory material was stored in the comet and the processes releasing the dust from the surface. Potentially, it also preserves information on the material of which the comet has formed.

All instruments on board Rosetta have been sensitive to dust, and many have contributed to determining the size distribution, in situ or remotely [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12]. Different instruments were sensitive to different size ranges and measured different physical quantities from which the particle sizes were derived.

We will give a synopsis of published Rosetta measurements of the dust size distribution in comet 67P, identify comparable measurements, and check their compatibility. We will address systematic variations of the size distribution with season (comet true anomaly), region of origin of the dust, and spacecraft position. We will briefly discuss possible reasons if variations are found.

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On causes of deviations from free-radial outflow in the inner dust coma of comet 67P/Churyumov-Gerasimenko using OSIRIS data

R. Marschall (1,2), S.-B. Gerig (1), N. Thomas (1), C.C. Su (3), Y. Liao (1), J.S. Wu (3), L. Jorda (4), F. Preusker (5), F. Scholten (5), and the OSIRIS team
(1) Physikalisches Institut, Sidlerstr. 5, University of Bern, CH-3012 Bern, Switzerland (E-mail: raphael.marschall@space.unibe.ch), (2) International Space Science Institute (ISSI), Hallerstrasse 6, CH-3012 Bern, Switzerland, (3) Department of Mechanical Engineering, National Chiao Tung University, 1001 Ta-Hsueh Road, Hsinchu 30010, Taiwan, (4) Laboratoire d'Astrophysique de Marseille, 38 Rue de Frederic Joliot-Curie, 13388 Marseille Cedex 13, France, (5) Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Planetenforschung, Asteroiden und Kometen, Rutherfordstrasse 2, 12489 Berlin, Germany

1 Introduction

In this work, we study the light scattered by dust particles, which provides a means of studying processes in the inner coma of comet 67P/Churyumov-Gerasimenko (hereafter 67P). The scattered light was observed by the Optical, Spectroscopic, and Infrared Remote Imaging System (OSIRIS) [1] on board of ESA's Rosetta. Dust emitted from the surface is accelerated by gas drag [2] and follows, albeit in a complex way, the flow of gas from the nucleus. There has been an increasing effort to model the flow of gas and dust in 3D and these kinds of models are now becoming increasingly common ([3]; [4]).

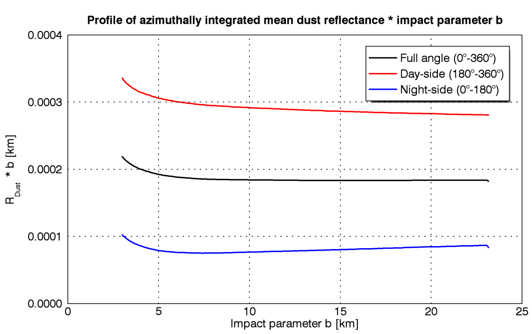

Figure 1: $R_{Dust} \cdot b$ for the full, day-, and night-side integration as a function of the impact parameter, b

In the point source, force-free radial outflow approximation, the product of the radiance from the dust I_{Dust} and the impact parameter, b, is a constant (often referred to as a "1/r law"). However, deviations from this behaviour can arise from a) non-point source geometry [5], b) particle acceleration effects, c) optical depth effects, d) particle fragmentation (into either optically active or inactive daughters), e) sublimation of particles (reducing the effective scattering area), f) condensation effects (increasing the scattering area), and g) gravitationally-bound particles. Distinguishing between these phenomena is extremely challenging. The most comprehensive way to study the outflow properties of the dust is to integrate azimuthally the dust brightness, $R_{Dust} = \int_0^{2\pi} I_{Dust} d\phi$, at different impact parameters. [6] used this approach in which conservation of radiance (as a proxy for dust column density) on concentric surfaces is used to assess whether specific processes from the list above are dominant. They found $R_{Dust} \cdot b$ increasing with b out to 50 km from the nucleus of Halley's coma.

2 Analysis of OSIRIS data

As we are interested in the behaviour of $R_{Dust} \cdot b$ we have filtered the full OSIRIS database to study only images which (1) make use of the full detector and thus are comprised of 2048x2048 pixels for the highest possible resolution, and (2) cover a field of view between 7 km and 50 km from the centre of the comet to each edge of the image. Of the $\sim 70'000$ images $\sim 5'500$ satisfied these criteria and have thus been studied. For images with phase angles of close to 90°, we have also performed partial integrations for the projected day and night side of the comet. Fig. 1 shows as an example the result of this analysis for one image. At about an impact parameter of 6 km the curve becomes flat indicating the point at which the dust flow becomes radial, force-free and with no further process influencing the dust scattering cross-section. The day side shows a slightly decreasing slope matched by a rising slope on the night side which we interpret as the effects of non-radial dust transport. The decrease with b to a constant value close to the nucleus is opposite to that seen at Halley and suggests that different processes are dominant at 67P.

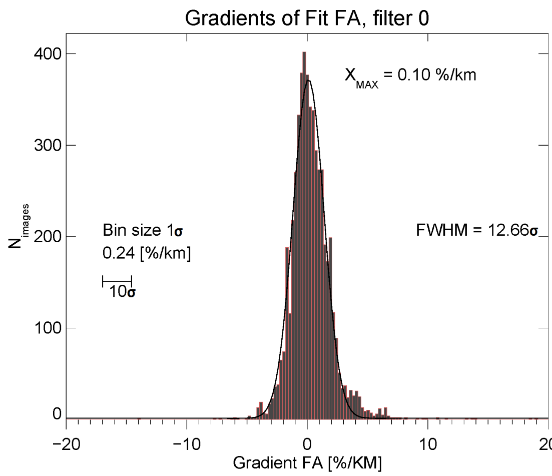

Figure 2: Histogram of the slopes for the full azimuthal integrated $R_{Dust} \cdot b$ and Gaussian fit.

For all considered images we have calculated the slope of $R_{Dust} \cdot b$ at maximum b as well as the point at which the curve becomes flat. We have found that $R_{Dust} \cdot b$ converges to a constant value - representing the beginning of the free radial outflow regime - between 6 and 20 km. This is illustrated in Fig. 2 which shows the distribution function of the slope of $R_{Dust} \cdot b$ once a constant slope is reached. It is normally distributed about zero indicating that $R_{Dust} \cdot b$ is a constant beyond a measurable, definable, distance. The statistical result gives a gradient of 0.10% change in $R_{Dust} \cdot b$ per kilometre with the error in the gradient determined being $0.24\%/\mathrm{km}$ (1σ). Deviations of $> 3\sigma$ from the mean are being investigated.

3 Dust dynamics simulations

To fully understand the deviations from free radial outflow we have performed first simulations (Fig. 3) using the model of [4] for a spherical nuclei and the shape of comet 67P varying the gas production, emission distribution, and dust size. Deviations from $R_{Dust} \cdot b$ = constant are clearly apparent for non-point source geometries in the absence of any fragmentation, condensation, or optical depth effects. The trends in the model are similar to those seen in the data. We have also assessed analytically and through numerical simulation, the effects of gravitational-bound particles on $R_{Dust} \cdot b$ which will allow us to place constraints on the total scattered light from bound particles. Further analyses will help interpret the results gained in the analysis of the OSIRIS data and constrain dust properties.

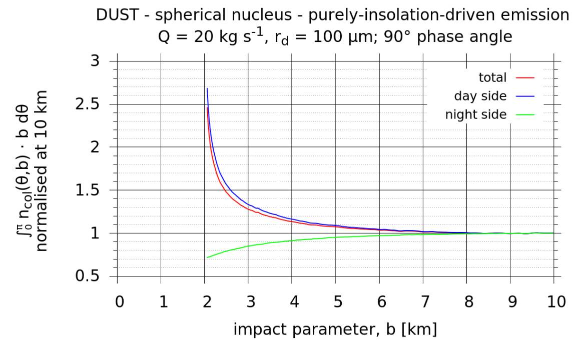

Figure 3: Modelled $n_{col} \cdot b$ ($\sim R_{Dust} \cdot b$) as a function b for dust particles with a radius of 100 μm

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Motion of landslides on 67P/Churyumov-Gerasimenko

Leszek Czechowski (1)

(1) University of Warsaw, Institute of Geophysics, Faculty of Physics, ul. Pasteura 7, 02-093 Warsaw, Poland (E-mail: lczech@op.pl)

Abstract

We investigate motion of landslides on 67P/ Churyumov-Gerasimenko. Even a small meteorite could trigger the landslide – see [3]. Presently, we concentrate on the dynamics of the moving mass. The motion of the landslide could last several hours depending on many factors. We include realistic shape of the comet's surface and realistic shape of the gravity field to find the trajectory and the final position of the moving mass.

1. Introduction

Landslides were observed on a few comet's nuclei, e.g. [1], [2] and Fig. 1. We considered beginning of the motion in [3] – see some summary in the present and the next sections.

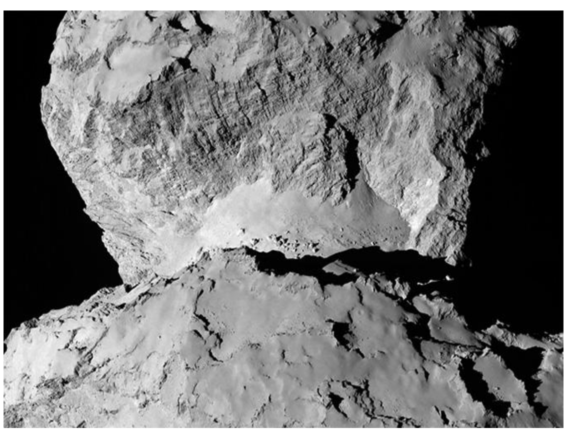

Fig. 1 An example of landslide on the 67P/ Churyumov-Gerasimenko comet.

The motion could be triggered by many factors, e.g. by increasing the surface activity of the comet resulting from intensive heating near perihelion, by meteoroids impacts, by the tidal forces, etc. Some of these factors depend on properties of the nucleus. Comets nuclei are believed to be built of soft materials like snow and dust. However, the lander Philae indicates a different situation. According to [5]: "thermal probe did not fully penetrate the near-surface layers, suggesting a local resistance of the ground […] equivalent to >2 MPa of uniaxial compressive strength". We assume here that elastic properties of the comet's nuclei could be similar to elastic properties of dry snow, namely Young modulus is assumed to be 1 – 100 MPa, see [4] and [2].

2. Impact as triggering

The nature of triggering the motion is not critical for later motion of the landslide therefore simplified model of the comet is satisfying. In [3] we found that impact of 1 kg meteoroid could lead to comet's vibrations with acceleration of the ground higher than local gravity resulting in triggering the mass motion. The three modes of vibrations are considered – see [3] and Fig. 2.

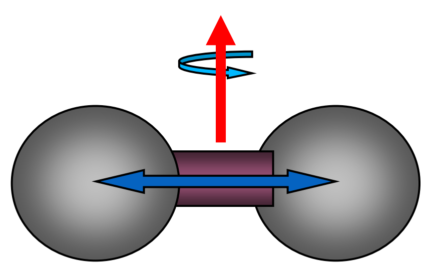

Fig. 2 One of the possible modes of vibration of simple model of irregular comet. The red arrow is the angular velocity, while the blue arrow indicates the mode of oscillation. Other modes are: bending and twisting.

The impact or tidal forces result in changing of rotation of the comet. In general, the vector of angular velocity will be a subject to nutation and consequently could be an additional factor triggering the landslides.

3. Coefficient of friction

After triggering, the later motion depends on other parameters. For near spherical comets the problem of coefficient of friction is critical because of low angle of the normal to the surface in respect to the gravity field. The mechanism of low friction is not unique. According to [2] fluidization and multiphase transport of cometary material could be an explanation.

4. Gravity and the surface of comet

We investigate motion of landslides on a comet of irregular shape. The mechanism of low friction is not critical here. In fact, mass motion often occurs without contact with the surface. However, for such motion the shape of the comet and its gravity must be realistic. We consider nucleus of the 67P/Churyumov- Gerasimenko comet with density 470 kg/m^3.

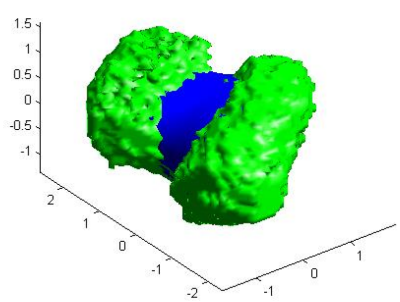

Fig. 3 The surface of the comet (green) and the surface of constant value of the gravitational potential of low value (blue).

Note that nucleus' shape does not resemble the shape of surface of constant value of gravitational potential (i.e. 'geoid'). The differences between the 'geoid' and physical shape of the nuclei could be dramatic. It is an important difference comparing to terrestrial geoid where the physical surface and geoid are close one to another.

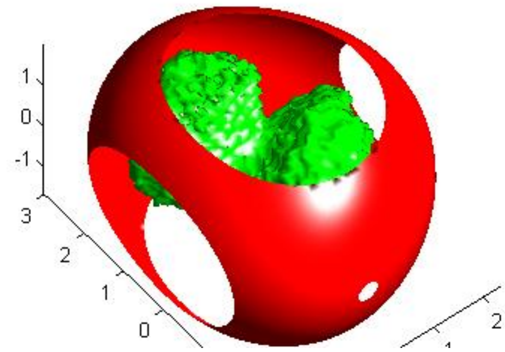

Fig. 4 The surface of the comet (green) and the surface of the constant value of the gravitational potential of high value (red). For visualization some parts of the red surface are cut and removed.

5. Summary and Conclusions

Our numerical models indicate the parts of the nucleus where landslides start, the trajectory of motion and the parts where landslides stop. The motion of the mass is often complicated because of complicated distribution of the gravity and complicated shape of the nucleus. We performed several simulations to find the most probable source of the matter of landslides seen in Fig. 1.

Acknowledgements

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Diurnal and seasonal variations of gas emissions in the inner coma of comet 67P/Churyumov-Gerasimenko observed with OSIRIS/Rosetta

F. La Forgia (1), M. Lazzarin (1), D. Bodewits (2), M. F. A'Hearn (2), I. Bertini (1), L. Penasa (3), G. Naletto (4,3,7), G. Cremonese (5), M. Massironi (3,6), F. Ferri (3), E. Frattin (5,1), A. Lucchetti (5), S. Ferrari (3), C. Barbieri (1) and the OSIRIS team

(1) Department of Physics and Astronomy "G. Galilei", University of Padova, Italy (fiorangela.laforgia@unipd.it) (2) Astronomy Department, University of Maryland, USA (3) Center of Studies and Activities for Space, CISAS, "G. Colombo", University of Padova, Italy (4) Department of Information Engineering, University of Padova, Italy (5) INAF - OAPD Astronomical Observatory of Padova, Padova, Italy (6) Geosciences Department, University of Padova, Padova, Italy (7) CNR-IFN UOS Padova LUXOR, Padova, Italy

Abstract

The European Rosetta mission spent more than two years orbiting the Jupiter family comet 67P/Churyumov-Gerasimenko. Such long duration allowed a very comprehensive analysis of the changes in the comet's activity along its orbit around the Sun.

The OSIRIS/Wide Angle Camera (WAC) [1] on board the spacecraft, was designed to study the gas coma around the comet nucleus. It was equipped with several narrow-band filters centered on the typical cometary emission bands of various gas species, in particular: OH (309.8 nm), NH (335.9 nm), CN (388.4 nm), NH_2 (572.1 nm) and OI (631.6 nm). For most of the mission timeline these filters were used to monitor the evolution of the production and spatial distribution of these gas species in the coma of comet 67P.

Several gas monitoring sequences were acquired with a well defined comet-spacecraft configuration (e.g. nadir pointing, phase angle below 100° to avoid straylight) employing the largest possible set of gas filters and spanning a period of time of about 14 hours, longer than one rotation period of the comet (12 h) allowing us to study diurnal variations. Our dataset incudes 32 gas sequences, going from January to September 2015, i.e. from 2.47 AU pre-perihelion, to 1.37 AU post-perihelion. After September 2015 the camera shutter had to be operated in a fast frame mode; since the data acquired aftwerwards needed a different reduction approach, they have been excluded from this analysis.

The filter bandpass includes both gas emission lines and the continuum reflected by the comet's dust. To create "pure" gas images, the continuum needs to be removed. Five multiband sequences have been used to study the continuum, almost evenly spanning the gas observation window. These sequences have been acquired typically with the NAC camera of OSIRIS intrument [1], equipped with medium and large band filters for nucleus and continuum analysis. For each epoch we used from 8 to 30 multiband data (cubes) to investigate the continuum spectral behavior depending on the rotation status of the comet. A typical dust spectral slope has been derived for each epoch, revealing a blue enhancement at smaller heliocentric distances. The dust spectral slope has been then interpolated for each gas observation epoch, and continuum removal factors have been derived, changing with heliocentric distance.

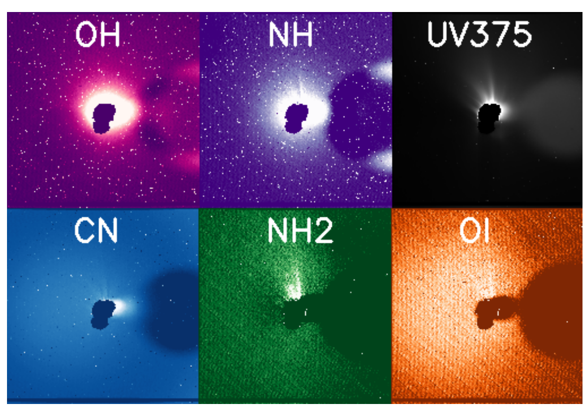

Figure 1: "Pure" gas images acquired by OSIRIS on 12/04/2015 showing the spatial distribution of gaseous species and UV375 continuum image for comparison.

The "pure" gas images (Fig. 1) reveal the spatial distribution of the fragment species being quite stable for a long period of time and confirm that the spatial distribution found by Bodewits et al. 2016 [2] for five of the considered epochs remained substantially steady with time. OH and NH fragments show an isotropic distribution, typical of fragment species coming from dissociation of other parent molecules. CN and OI show instead a two-component distribution throughout the dataset possibly connected to additional prompt emissions. NH_2 has a very small signal to noise ratio and its interpretaion is not straightforward.

The gas surface brightness is then converted into column density for each gas species using specific fluorescence efficiency factors [4, 3] interpolated for the heliocentric distance and velocity of the comet at each epoch.

An "extraction zone" was defined between 1 and 3 km from the nucleus limb in the sunward direction between 10 and 2 o'clock in order to exclude straylight, ghosts and other instrumental effects [5] from the analysis. For each epoch we therefore obtained gas light curves for each species and consequently a long-term variation behavior.

Results will be presented on the gas diurnal light curves and on the long-term variations such as the dependence and correlation with time, heliocentric distance, range, phase angle and sub-solar point. Gas ratios are studied searching for evidence of any compositional change with time and orbital evolution. We will search for connections between particular "active zones" on the nucleus surface using the projection of the comet shape model (SHAP5-v1.5) and the relevant NAIF Spice Kernels and IDL toolkit. Correlations with dust outbursts and jets are also investigated. This study will be helpful in connecting ground based observations of 67P with Rosetta in situ observations.

Acknowledgements

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The footprint of cometary dust analogs in the lab: comparison with Rosetta data

L.E. Ellerbroek (1), B. Gundlach (2), S. Merouane (3), J. Blum (2), C. Dominik (1), M. Hilchenbach (3), M.S. Bentley (4)
(1) Astronomical Institute "Anton Pannekoek", University of Amsterdam, The Netherlands, (2) Institut für Geophysik und extraterrestrische Physik, Technische Universität Braunschweig, Germany, (3) Max-Planck-Institut für Sonnensystemforschung, Göttingen, Germany, (4) Space Research Institute, Austrian Academy of Sciences, Graz, Austria
(ellerbroek@uva.nl)

Abstract

The structure of cometary dust provides a window on growth mechanisms in the early solar nebula. Measurements made by the Rosetta spacecraft of the coma dust population of comet 67P/Churyumov-Gerasimenko show particles up to a few hundred μm in size to have a granular structure. However, these dust particles are likely to have been modified during their collection by the spacecraft instruments. In this contribution, we will present the results of a series of experiments to simulate the impact of dust aggregates onto the detector surfaces of the Rosetta COSIMA and MIDAS instruments. These experiments provide a tool to retrieve the structure of cometary dust before it entered the spacecraft. We find that in most cases only part of the particle sticks, and velocity is the main driver for the appearance of deposits. Extending this conclusion to the Rosetta data implies that COSIMA and MIDAS measure only part of the initial particle, and that the same species of particle may produce a variety of morphologies. In a second series of experiments, we varied the size distribution of the silica dust particles. We find that in order to reproduce the rubble pile-like structure observed by the Rosetta instruments, the presence of small monomers is needed.

1. Introduction

Comets are considered to be the most pristine bodies in the solar system that survive to this day. They were formed in a range of environments within the protoplanetary disk, and their structure contains traces of dust growth mechanisms [1].

Measurements by the Rosetta spacecraft have returned images of the dust in the coma of comet 67P/Churyumov-Gerasimenko. These particles, up to a few hundred μm in size, are seen to have a granular structure up to sub-μm scale [2, 3]. Also, different morphologies of particles are detected. COSIMA detects two different families of deposits; 'single' deposits of intact agglomerates, and rubble-pile-like deposits consisting of a loose array of smaller elements [4]. A key question is whether these two groups are dust types with an intrinsically different substructure, or that their different appearance only depends on the velocity and subsequent breakup of their parent particles. To find the answer to this question, and to derive the makeup of their parent particles, experiments are needed.

2. Methods

Dust aggregates are mechanically launched within a vacuum chamber onto replicas of the COSIMA and/or MIDAS target plate, using a parameter space in size and velocity that overlaps the results found by Rosetta instruments. We use synthetic SiO_2 aggregates whose size, velocity and bulk density are comparable to cometary dust aggregates. The impact of particles is monitored by a high-speed camera, and the resulting deposits on the targets are studied with the COSIMA and MIDAS flight spares so as to allow a direct comparison to the spacecraft data. Additional imaging at higher resolution with optical and laser confocal microscopes provides a further tool to interpret structures seen on Rosetta data not accessible to the resolution limit of the spacecraft instrument.

We will present the results of two series of experiments, using aggregates of sizes in the range $30-400$ μm consisting of different test material:

1. SiO_2 aggregates consisting of amorphous monomers with a polydisperse (0.5-10 μm) size distribution (Ellerbroek et al., submitted to MNRAS)

2. SiO_2 aggregates consisting of spherical monomers with a monodisperse size distri-

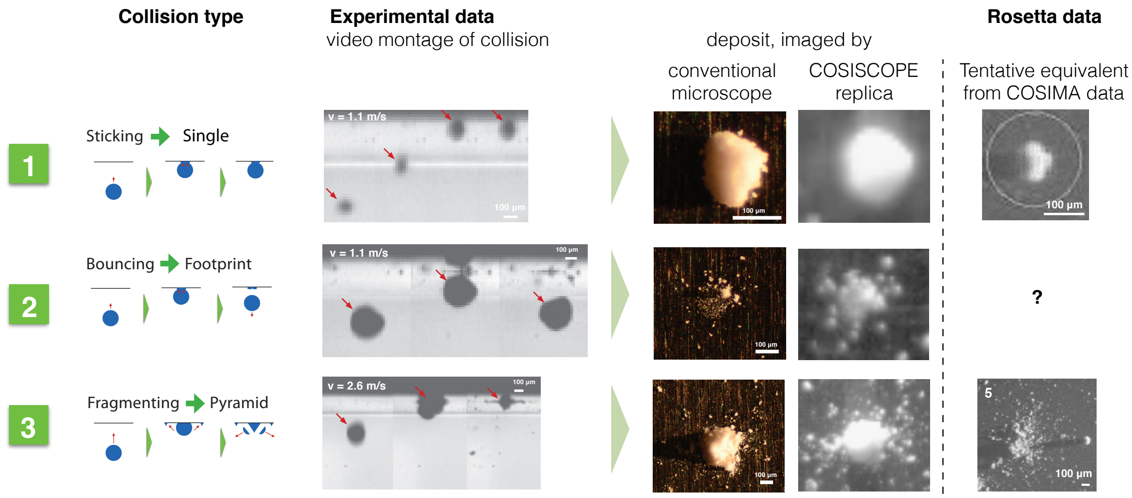

Figure 1: Summary of three cases of collisions of aggregates of polydisperse SiO_2 on COSIMA targets, and their comparison with COSIMA data.

bution (three samples: 0.3, 1.0 and 1.5 μm) (Ellerbroek et al., in prep.)

3. Results

Figure 1 displays a summary of the different cases of collisions on COSIMA targets observed at different velocities, and the deposits left on the target surface. The results are consistent earlier experiments of collisions of silica aggregates [5], although this is the first study to describe and quantify the deposits on the target plate.

Three collision types are seen to occur:

- Sticking - small ($< 80\mu$m) particles at velocities < 2 m s^{-1}: the entire particle sticks to the target surface;
- Bouncing - large ($> 80\mu$m) particles at velocities < 2 m s^{-1}: the bulk of the particle stays intact and bounces off the target surface, leaving a shallow footprint of small fragments;
- Fragmenting - particles at velocities > 2 m s^{-1}: the particle fragments, leaving a deposit with a pyramid-shaped core surrounded by smaller fragments on the target surface.

Qualitatively, different morphologies observed by COSIMA [2] can be produced in our experiments. The 'shallow footprint' left on the targets after a bouncing collision has no apparent equivalent in the COSIMA data.

The result of the second series of experiments with a varying range of monomer sizes confirms the theoretical prediction that particles with smaller monomers have a higher internal strength. As a result, the amount of mass transferred onto the target scales negatively with the aggregate size. This result implies that in order to produce the morphologies detected by COSIMA, a mixture of large and small size elements is needed.

4. Summary and work in progress

We have conducted experiments where silica aggregates of different porosity were impacted onto detector surfaces of the COSIMA and MIDAS instruments. Different morphologies detected by the Rosetta instruments were qualitatively reproduced by varying only impact velocity. In subsequent experiments, material properties will be varied further, so as to refine the interpretation of cometary dust measurements.

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Multi-instrument observations of the 67P outburst of 3 July 2016

J. Agarwal[1], V. Della Corte[2,3], P. D. Feldman[4], B. Geiger[5], S. Merouane[1], I. Bertini[6], D. Bodewits[7], S. Fornasier[8], E. Grün[9,10], P. Hasselmann[8], M. Hilchenbach[1], S. Höfner[1], S. Ivanovski[3], L. Kolokolova[7], M. Pajola[11], A. Rotundi[2,3], H. Sierks[1], A. J. Steffl[12], N. Thomas[13] and the Teams of Alice, COSIMA, GIADA, and OSIRIS;
(1) Max-Planck-Institut für Sonnensystemforschung, Göttingen, Germany (agarwal@mps.mpg.de), (2) Università degli Studi di Napoli "Parthenope", Naples, Italy, (3) INAF Institute for Space Astrophysics and Planetology, Roma, Italy, (4) The Johns Hopkins University, Baltimore, USA, (5) European Space Astronomy Centre, Villanueva de la Cañada, Spain, (6) University of Padova, Italy, (7) University of Maryland, USA, (8) LESIA, Observatoire de Paris, PSL Research University, CNRS, Univ. Paris Diderot, Sorbonne Paris Cité, UPMC Univ. Paris 06, Sorbonne Universités, 5 place Jules Janssen, 92195 Meudon, France, (9) Max Planck Institute for Nuclear Physics, Heidelberg, Germany, (10) Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, USA, (11) NASA Ames Research Center, Moffett Field, CA 94035, USA, (12) Southwest Research Institute, Boulder, USA, (13) University of Bern, Switzerland.

Abstract

On 3 July 2016, the signature of a small outburst on comet 67P was detected by several instruments on board ESA's Rosetta spacecraft, at a heliocentric distance of 3.32 AU, outbound from perihelion. The event affected a 10 m-sized patch on the surface in the circular Basin F structure in the Imhotep region. We report on the nature of the surface change and on the properties of the ejected dust, found to consist of refractory grains of several hundred microns, and submicron-sized water ice particles. The activity was triggered at the local sunrise and continued over a time interval of 14 – 70 minutes. The high dust mass production rate is incompatible with the free sublimation of crystalline water ice as the only acceleration process. Additional energy stored near the surface must have increased the gas density. We suggest a pressurised sub-surface gas reservoir, or the crystallisation of amorphous water ice as possible alternatives.

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The Rosetta Science Archive: Status and Plans for Completing and Enhancing the Archive Content

D. J. Heather (1), M. Barthelemy (1), D. Fraga (1), E. Grotheer (1), L. O'Rourke (1), M. Taylor (2)
(1) ESA/ESAC Camino Bajo del Castillo s/n, Ur. Villafranca del Castillo, 28692 Villanueva de la Canada, Madrid, Spain (dheather@cosmos.esa.int);
(2) ESA/ESTEC, 2200 AG Noordwijk, Netherlands

Abstract

This presentation will outline the current status of the Rosetta archive, as well as highlighting some of the 'enhanced archiving' activities planned and underway with the various instrument teams on Rosetta to ensure the scientific legacy of the mission.

1. Introduction

On 30 September 2016, Rosetta's signal flat-lined, confirming that the spacecraft had completed its incredible mission by landing on the surface of Comet 67P/Churyumov-Gerasimenko. Although this marked an end to the spacecraft's active operations, intensive work is still on-going with instrument teams preparing their final science data increments for delivery and ingestion into ESA's Planetary Science Archive (PSA) [2]. In addition to this, ESA is establishing contracts with a number of instrument teams to enhance and improve their data and documentation in an effort to provide the best long-term archive possible for the Rosetta mission.

2. Status of the Rosetta Data in the Planetary Science Archive

All science data from the Rosetta mission are hosted jointly by the Planetary Science Archive (PSA) at ESA (http://psa.esa.int) [2], and by NASA's PDS Small Bodies Node (SBN).

The long duration of the Rosetta mission, along with its diverse suite of instrumentation and the range of targets observed throughout its lifetime combine to make this an extremely challenging mission to archive [1]. A number of independent data reviews have taken place over course of the mission in an attempt to track the evolution of the data pipelines from each instrument and ensure that the science data are documented and formatted in the best possible way to allow end-users to exploit them. The last of these reviews was completed in spring 2016, based on the first science data received from the comet phase. Many issues were raised by the reviewers, and the instrument teams have been working very hard to implement the fixes requested. In many cases this work is ongoing, and for all instruments, the review process has understandably resulted in a slow down of the standard delivery schedule.

Currently, the majority of teams have delivered all of their data from the nominal mission (up to the end of 2015), and are working on their remaining increments from the 1-year mission extension. The aim is to complete the nominal archiving with data from the complete mission by the end of this year, when a full mission archive review will be held. This review will assess the complete data holdings from Rosetta and ensure that the archive is ready for the long-term.

It should be noted that, with the updates being made to the data pipelines as a result of the last review, teams have been asked to re-run all of their older data through the new pipelines to ensure we have consistently the best and most up to date data available in the final archive. This whole exercise is ongoing for all teams, and is expected to be completed this year before the mission archive review takes place.

3. Rosetta Enhanced Archiving Activities

The nominal archive deliveries from the Rosetta mission are of excellent quality, and will be of immense interest and use for many decades to come thanks to the efforts of all involved in their production, assessment, storage and dissemination. However, there is, as always, much more to do!

With the resources from the operational mission now coming to an end, ESA has decided to establish a number of contracts for work with the Rosetta instrument teams that will enhance their archive content. Updates are focused on key aspects of an instrument's calibration or the production of higher level data / information, and are therefore very specific to each instrument's needs. These contracts are in the process of being kicked off, and they will run for various lengths depending upon the activities to be undertaken. The full 'archive enhancement' process will run until September 2019, when the post operations activities for Rosetta will come to a close. This presentation will highlight just a few of the activities within the archive enhancement to give a flavour of the updates that can be expected.

Most instrument teams will work on providing a *Science User Guide* for their data, as well as updating calibrations for their data. Several teams will also be generating and delivering higher level processed data and derived products. For example, the VIRTIS team will be working to update both their spectral and geometrical calibrations, and will aim to deliver mapping products to the final archive. Similarly, the OSIRIS team will be improving their calibrations and delivering data additionally in FITS format.

The Rosetta Plasma Consortium (RPC) instrument suite will be working on cross-calibrations that will greatly improve the final data to be delivered from each experiment, as well as a number of activities individual to each instrument (e.g. removal of spacecraft noise from the MAG instrument).

The MIDAS team will similarly be working on instrument cross-calibrations and the production of a dust particle catalog from the comet coma.

The GIADA team will be producing higher-level products in the form of dust environment maps, with products being developed in 3D plus time.

A contract has also been established to produce and deliver data set(s) containing supporting ground-based observations from amateur astronomers. These data were taken simultaneously with Rosetta operations and could provide some important contextual information.

In addition to these contracts, the Rosetta ESA archiving team will be producing calibrated data sets for the NAVCAM instrument, and will be working to include the latest shape models from the comet into the final Rosetta archive. The Rosetta ESA archiving team are also working on providing a centralized solution to the problem of geometry on the comet for implementation within the final Rosetta data holdings.

4. Final Reviews

Following the final incremental deliveries from the nominal archiving, a final 'mission archive review' will be held with independent reviewers to assess the complete Rosetta data holdings. This will be completed at the end of 2017.

A further review is expected in 2019 to assess the deliverables from the archive enhancement phase and ensure that the final Rosetta archive within the PSA is as good as it can be and will allow for scientists to fully exploit the data holdings for decades to come.

Summary and Conclusions

This presentation will outline the current status of the Rosetta science archive in ESA's PSA and in NASA's PDS. In addition, an overview of the activities planned and underway for enhancement of the archive content will be provided.

With the support of the instrument teams and the completion of the archive enhancement, the Rosetta archive can become an immensely valuable resource for scientists in years to come, and the full scientific potential of the mission can be realized.

Acknowledgements

The PSA Teams would like to acknowledge the continuing hard work of the Rosetta instrument teams in preparing and supporting the archive deliverables.

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Comparison between layers stacks of 67P/CG comet and spectrophotometric variability obtained from OSIRIS data

S. Ferrari (1), L. Penasa (1), La Forgia F. (2), Massironi M. (1,3), Naletto G. (1,4,5), Lazzarin M. (2), Fornasier S. (6), Barucci M.A. (6), Lucchetti A. (7), Pajola M. (8), Frattin E. (2,7), Bertini I. (2), Ferri F. (1), Cremonese, G. (7) and the OSIRIS Team. (1) Center of Studies and Activities for Space (CISAS) G. Colombo, University of Padova, Via Venezia 15, 35131 Padova, Italy (sab.ferrari@gmail.com); (2) Department of Physics and Astronomy "G. Galilei", University of Padova, Vic. Osservatorio 3, 35122 Padova, Italy; (3) Geosciences Department, University of Padova, via G. Gradenigo 6, 35131 Padova, Italy; (4) Department of Information Engineering, University of Padova, Via Gradenigo 6/B, 35131 Padova, Italy; (5) CNR-IFN UOS Padova LUXOR, Padova, Italy; (6) LESIA, Observatoire de Paris, PSL Research University, CNRS, Univ. Paris Diderot, Sorbonne Paris Cité, UPMC Univ. Paris 06, Sorbonne Universités, 5 Place J. Janssen, 92195 Meudon Principal Cedex, France; (7) INAF-OAPD Astronomical Observatory of Padova, Vic. Osservatorio 5, 35122 Padova, Italy; (8) NASA Ames Research Center, Moffett Field, CA 94035, USA.

Abstract

The Rosetta/OSIRIS cameras unveiled the layered nature of comet 67P/Churyumov-Gerasimenko, suggesting that the comet bilobate shape results from the low-velocity merging of two independent onion-like objects [1]. Several physiographical regions of the southern-hemisphere *big lobe* show stacks of layers forming high scarps, terraces and mesas [2]. A spectrophotometric analysis of OSIRIS images based on multispectral data classifications was conducted in order to identify possible morphological, textural and/or compositional characters that allow to distinguish regional stacks of layers.

Method

Multiple NAC image sequences were selected in order to cover the largest landscape of the selected regions as long as the broadest range of available filters (9 to 11). Such sequences meet comparable spatial resolutions and phase angles and include filters frequently used in previous 67P/CG studies [3,4,5]. Since potential diurnal and seasonal changes are expected to homogeneously occur along the same stack of layers, no constrain on a specific survey period was done, picking both pre- and post-perihelion sequences. Geomorphological domains were identified and mapped on each image set. Fine material and deposits were firstly discerned by outcropping consolidated material, which is expected to be meaningful for textural and spectral characters of layers' stacks. The outcrop domain was then distinguished in relatively unaltered consolidated material and degraded outcrops (e.g., *in-situ degraded material* rather than *polygonal consolidated material*).

NAC sets were used to generate several multispectral images, which represent different views of the selected regions. The illumination and topographic effects were corrected using Akimov photometric model [6], which was used and tested in previous analysis of the same body [4]. The 7th stereo-photoclinometry shape model (SPC) [7] was used, combined with the most recent NAIF-SPICE kernels and relative IDL code toolkit to produce high-resolution synthetic images and derive the illumination angles.

Multispectral data were then processed applying combinations of supervised and unsupervised classifications using ENVI software. The *fine material* class was extracted through specific training sites identified by geomorphological mapping, then obliterated on each multispectral image.

A linear interpolation of the multispectral data allowed to produce spectral slope maps between green (535 nm) and near-IR (882.1 nm) filters, which are comparable with global and local spectral slope overviews of the large lobe [3,4,5].

Reworked multispectral images were finally processed proposing two or more classes clustering similar spectra behaviour (Fig. 1). Image class distributions were compared to the geomorphological domains distributions, and class spectral properties were discussed to identify possible trends of the regional stacks of layers. Class distributions were also analysed as a function of incidence and emergence angles, verifying the photometric correction improvement.

Subsequently the classes were compared to the overall geometrical arrangement of the layers, as predicted by the Ellipsoidal Model (EM, Fig. 1) [8]. Furthermore, class distributions were evaluated as the elevation of the big-lobe onion-like structure changes, using values provided by the EM (Fig. 2).

Conclusions

Several classifications suggest a relationship between the spectral properties of the outcrop and the elevation of the EM. An overall comparison of all multispectral-image classification results could shed a light on the spectophotometrical variability of CG's big-lobe layers.

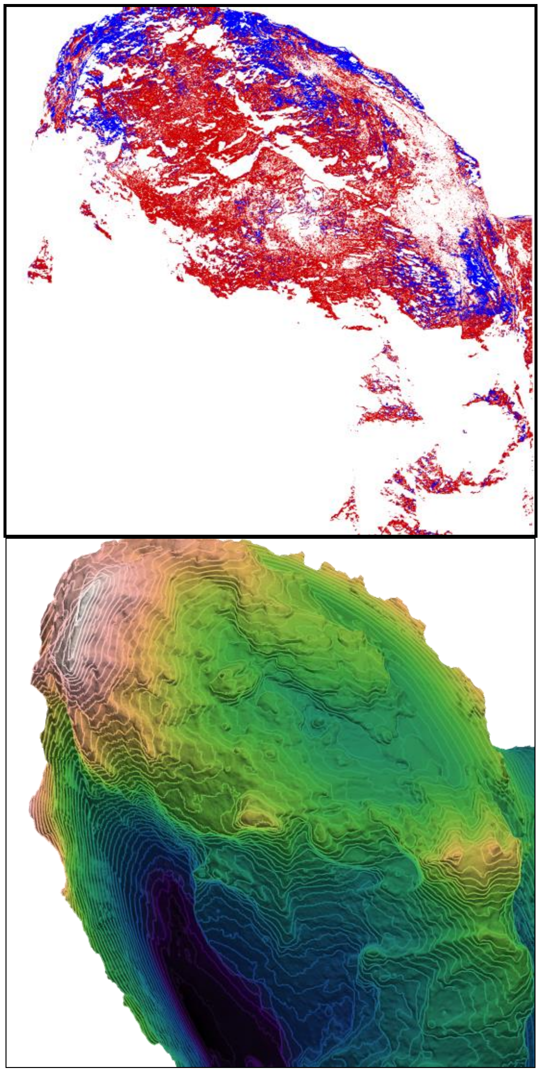

Figure 1. Khonsu region: above an example of supervised classification of the corresponding multispectral image (Maximum Likelihood classification, 2 classes, good separability of the training sites), and relative average spectra; below, the corresponding shape model, where contour lines represent the intersections of a set of spaced ellipsoidal shells defined by the Ellipsoidal Model.

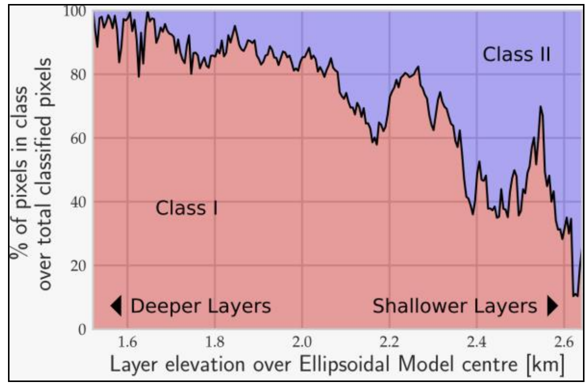

Figure 2. Classes of Fig. 1 are shown in relative percentage in function of their elevation with respect to the EM centre.

Acknowledgements

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The layered structure of the nucleus of the comet 67P: implications on missing volumes and lobes orientations

L. Penasa (1), M. Massironi(1,2), S. Ferrari (1), M. Pajola(3), F. Marzari (4), G. Naletto (5,1,7), I. Bertini (4), G. Cremonese (6), F. Ferri (1), F. La Forgia (4), E. Frattin (6,4), M. Lazzarin (4), A. Lucchetti (6), E. Simioni (6,7), and the OSIRIS team.
(1) Center of Studies and Activities for Space, CISAS, 'G. Colombo', University of Padova, Italy (luca.penasa@gmail.com) (2) Geosciences Department, University of Padova, Padova, Italy (3) NASA Ames Research Center, Moffett Field, California, USA (4) Department of Physics and Astronomy "G. Galilei", University of Padova, Italy (5) Department of Information Engineering, University of Padova, Italy (6) INAF - OAPD Astronomical Observatory of Padova, Padova, Italy (7) CNR-IFN UOS Padova LUXOR, Padova, Italy

Abstract

The OSIRIS cameras onboard Rosetta revealed that each lobe of comet 67P/Churyumov-Gerasimenko (67P) is characterized by a deep layering that can be modelled as sets of concentric ellipsoidal shells. We present several implications of this geological model that can be useful to shed light on the evolution of the planetesimal. The model allows to estimate that more than the 50% of the original material forming the comet is now missing. Furthermore the geological models of the two lobes appear to have their axes consistently aligned, possibly helping to better understand the dynamics of the low velocity impact that merged two independent planetesimals into a single bilobate body.

Introduction

The OSIRIS cameras onboard the Rosetta orbiter allowed to observe the bilobate comet 67P/Churyumov-Gerasimenko with unprecedented resolution, revealing the presence of geomorphological features that are unequivocally related to layered materials.

From these observations the first geological cross sections of the northern hemisphere were produced [1], while by fitting the observed terraces using concentric shells shaped like ellipsoids the first three dimensional model of the inner layering was provided [2]. These investigations well demonstrated that the comet bilobate shape results from the merging of two independent onion-like objects, but it can also provide additional constraints on the evolution of the body. The 3D model allows to quantify a lower bound for the volumes that have been lost since its formation, and possibly providing some indication about its evolution.

We will thus review some of the major results that have been obtained from the three dimensional modelling of the layered structure of 67P in terms of the lost volumes.

Geometry of the layers

Figure 1 helps visualizing the models of the layering based on ellipsoids, their centres and orientations. Each lobe is characterized by a different model (here only one of the skins of the onion-like model is shown) which is not aligned with the average topography of the lobes.

The two red arrows extending from the ellipsoids centres represents the orientation of the semi-major axes of the ellipsoids. Both the major axes resulted to be roughly aligned, and lay in a plane orthogonal to the actual axis of rotation of the body (z-axis). Furthermore the junction of the two lobes is aligned with the direction of the minor axis of the Big Lobe ellipsoidal model.

Missing Volumes

The presence of terraced terrains on 67P has been considered as the main evidence of a layered structure of global extension. Terraces are morphological features that have been observed on the whole cometary body and are usually related to layered terrains. Indeed each terrace is a flat patch of terrain bounded on one or multiple sides by cliffs. Sets of terraces are organized in a staircase pattern representing superimposed layers of cometary material.

Each terrace is the morphological expression of an inner surface. The geometrical concept is illustrated in Figure 2 which shows a geological section of the comet cutting the latest shape model [3] through Imhotep, Bes and Anhur regions. Each terrace has been highlighted with a blue segment, while the cliffs are shown as red segments. The geometry of terraces can be explained as the results of discontinuity surfaces running within the nucleus, here represented by the dotted lines.

Each layer is bounded by two 3D surfaces. Some of

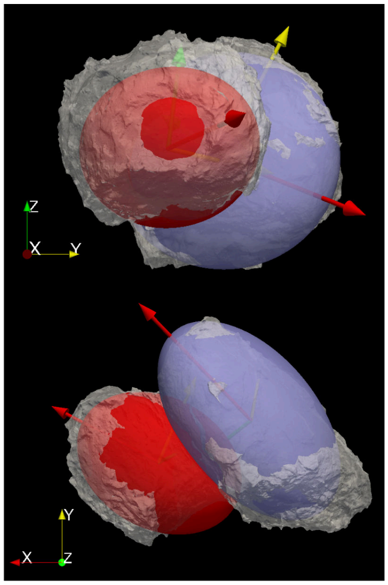

Figure 1: Overview of two *skins* of the onion-like model as resolved from terraces orientations. The two major axes are practically aligned and coplanar, and roughly perpendicular to the rotation axis of 67P.

these surfaces (e.g. on beneath the Imhotep surface) are completely enclosed within the nucleus, while others (e.g. at the top of Bes) are preserved only in restricted portions on the surface. The geological model permits to reconstruct a surface passing through that locations, allowing to compute the amount of lost material. Applying this technique to both the lobes we obtained a total volume loss of $\sim 60\%$ of the initial volume for the Big Lobe and $\sim 70\%$ for the Small Lobe. These losses correspond to an evolution from an initial volume of the Big Lobe of $33km^3$ to the observed 12km^3 and from 20km^3 to 6km^3 for the Small Lobe. Therefore, the overall missing volume is about $35\ \text{km}^3$. Notice that these values provide an order of magnitude and only a lower limit for the estimated volumes: indeed the "primordial" external layer might not be preserved at all on the cometary surface.

Conclusions

The peculiar alignment of the two lobes ellipsoidal model axes suggests that the two lobes are joined along their minor axis. These observations could help in developing better models to describe the impact that

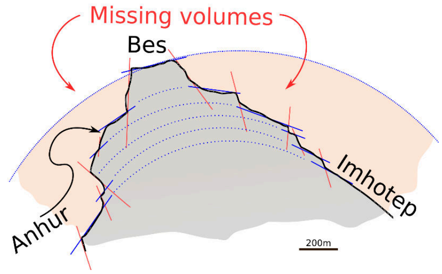

Figure 2: The ellipsoidal models can be used to reconstruct the latest preserved layer on the surface and derive the missing volumes.

created the peculiar bilobate shape of 67P, and possibly to resolve the primordial rotational axes of the two cometesimals.

Results show that a volume of at least $35km^3$ is missing, and that it is highly localized on the cometary body, with locations that have experienced enhanced material removal and others that still preserve some of the shallower layers that were once present on the body. Furthermore the missing volumes cannot be easily justified as mass loss by sublimation, as measured by the RSI (Radio Science Investigation) onboard Rosetta [4], meaning that some other processes of material removal must be considered. The mass loss from the lobes may have occurred either during the gentle collision that lead to the merging of the two cometesimal or during the subsequent cycles of split and merging of the cometary body [5].

Acknowledgements

OSIRIS was built by a consortium of the Max-Planck-Institut für Sonnensystemforschung, in Göttingen, Germany, CISAS-University of Padova, Italy, the Laboratoire d'Astrophysique de Marseille, France, the Instituto de Astrofisica de Andalucia, CSIC, Granada, Spain, the Research and Scientific Support Department of the European Space Agency, Noordwijk, The Netherlands, the Instituto Nacional de Tecnica Aeroespacial, Madrid, Spain, the Universidad Politechnica de Madrid, Spain, the Department of Physics and Astronomy of Uppsala University, Sweden, and the Institut für Datentechnik und Kommunikationsnetze der Technischen Universität Braunschweig, Germany. The support of the national funding agencies of Germany (DLR), Italy (ASI), France (CNES), Spain (MEC), Sweden (SNSB), and the ESA Technical Directorate is gratefully acknowledged. We thank the ESA teams at ESAC, ESOC and ESTEC for their work in support of the Rosetta mission.

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Observing and modeling the near-nucleus coma structure around terminators on 67P/Churyumov-Gerasimenko

X. Shi (1), X. Hu (1,2), S. Mottola (3), M. Rose (4), H. Sierks (1), C. Güttler (1), H. U. Keller (2,3) and the OSIRIS-Team
(1) Max Planck Institute for Solar System Research, Göttingen, Germany (shi@mps.mpg.de), (2) Institute for Geophysics and Extraterrestrial Physics (IGEP), TU Braunschweig, Braunschweig, Germany, (3) Institute of Planetary Research, German Aerospace Center (DLR), Berlin, Germany, (4) PI-DSMC, Sindelfingen, Germany

Abstract

We present analysis on the structure of near-nucleus coma of comet 67P/Churyumov-Gerasimenko using imaging data from OSIRIS camera on-board Rosetta spacecraft. The emergence and cease of dust jets on diurnal time scale show that dust emission starts instantly upon sunrise, while diminishes gradually after sunset. Local gas field around terminators are modeled using 3-D Direct Simulation Monte Carlo with boundary condition provided by thermal models. Simulation results reveal that fine structures in the water gas coma form immediately upon local sunrise, that correlates well with jet-like features in the dust field. Modeling the trajectories of dust particles provide further insight into the ejection scenario, initial velocity and collimation of dust ejecta.

1. Introduction

Observing and studying the inner gas- and dust-comae of comets is the key to understanding cometary activity. The inner comae are the link between the sources of cometary activity on the nucleus and the outer-coma or tail structures that are extensively observed via ground-based and space-borne telescopes from afar. Analyzing the dynamics of gas and dust in the near-nucleus regime sheds light on the nucleus properties, the mechanisms of volatile sublimation as well as dust release. However, the cometary nuclei and their ambient dust coma structures could not be resolved until 1986, when spacecraft Giotto, Vega 1 and 2, observed comet 1P/Halley during the close flybys. Since then, spacecraft data of increasing spatial resolution and time coverage have been gathered of several comets, with the most recent and most comprehensive dataset acquired by Rosetta, the European Space Agency's rendezvous and landing mission to the Jupiter Family Comet 67P/Churyumov-Gerasimenko (hereafter 67P).

As observed by various Rosetta instruments, the near-nucleus comae of 67P exhibit complex visual structures that may reflect local variations of number densities of gas molecules and dust ejecta [1, 2, 3]. However, given the odd shape of the nucleus and uncertainty in physical properties, it is often difficult to connect coma structure directly with distribution of activity on the nucleus. Significant effort has been put into modeling the global gas and dust comae via state-of-the-art 3-D Direct Simulation Monte Carlo (DSMC), for interpreting in situ and remote sensing observations [4, 5].

In this work, we concentrate on localized near-nucleus coma by modeling gas and dust emission around terminators. It has been discovered that a diurnal water cycle is at work on the nucleus that brings subsurface water upwards at night to form a layer of frost on the surface, which sublimates at local sunrise [6]. While at sunset, dust activity tends to lag into night side as jets beyond dusk terminator were observed [7]. Taking advantage of the high spatial and temporal resolution of OSIRIS images, we try to link this diurnal water cycle with the onset and end of local dust activity on 67P, and investigate the formation and evolution of complex structures in the observed inner coma.

2. Analysis and results

We present and analyze a selection of OSIRIS images where prominent dust jets are observed close to terminators. Local shape model of the nucleus with resolution of approximately 30 m is used to simulate the condition of insolation at the epoch of observation. Thermal models are applied to generate temperature and mass flux of water outgassing from the nucleus, which provide the boundary conditions for 3-D DSMC simulations of the gas field.

Fig.1 shows an OSIRIS observation of fine structures of the inner dust coma along the terminator, in contrast with the shadowed nucleus background. We modeled gas emission from the terminator by simulating temperature and outgasing rate considering sublimation of dusty ice. The modeled gas field exhibits fine structures comparable to those in OSIRIS observations. Although the exact mechanisms of dust ejection are thus far little understood, the correlation indicates that the motions of the dust ejecta are likely coupled with the gas field of water molecules. In addition, our results suggest that water outgassing and the induced dust activity along terminators may play a distinct role in shaping the visual pattern of the inner coma of comets. The contributions of terminator activity are probably most pronounced on such irregular-shaped nuclei as 67P, where abrupt topography gives rise to complex and prevalent shadowing effect.

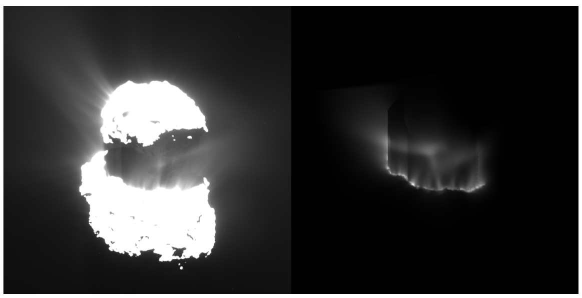

Figure 1: Left: Contrast-stretched OSIRIS image of comet 67P taken in February 2015. The sun is towards top of the image. The "neck" of the nucleus is in the shadow cast by the small lobe. Filaments of dust, or so called "jets", are seen against the shadowed neck region. Right: DSMC modeled local water gas field around the neck region. Brightness refelects column density calculated by taking into consideration shadowing effects.

Acknowledgements

OSIRIS was built by a consortium led by the Max-Planck- Institut für Sonnensystemforschung, Göttingen, Germany, in collaboration with CISAS, University of Padova, Italy, the Laboratoire d'Astrophysique de Marseille, France, the Instituto de Astrofísica de Andalucia, CSIC, Granada, Spain, the Scientific Support Office of the European Space Agency, Noordwijk, The Netherlands, the Instituto Nacional de Técnica Aeroespacial, Madrid, Spain, the Universidad Politéchnica de Madrid, Spain, the Department of Physics and Astronomy of Uppsala University, Sweden, and the Institut für Datentechnik und Kommunikationsnetze der Technischen Universität Braunschweig, Germany. The support of the national funding agencies of Germany (DLR), France (CNES), Italy (ASI), Spain (MEC), Sweden (SNSB), and the ESA Technical Directorate is gratefully acknowledged.

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Forming a Churyumov-Gerasimenko–like comet by sublimation

D. E. Vavilov (1), Yu. D. Medvedev (1) and P. B. Zatitskiy (2,3,4)
(1) Institute of Applied Astronomy of the Russian Academy of Science, St. Petersburg, Russia (2) Département de mathématiques et applications, École normale supérieure, CNRS, PSL Research University, Paris, France (3) Chebyshev Laboratory, St. Petersburg State University, St. Petersburg, Russia (4) St. Petersburg Department of V.A.Steklov Institute of Mathematics of the Russian Academy of Sciences, St. Petersburg, Russia
(vavilov@iaaras.ru)

Abstract

The Rosetta spacecraft, which was sent to the comet 67P/Churyumov-Gerasimenko, collected data of the nucleus revealing its peculiar bi-lobed shape. A discussion about whether the shape is primordial or a result of some processes occurred with the comet such as collisions and sublimation still goes on. One hypothesis suggests that two separately formed components of 67P were brought together at low speed making such a dumbbell-like nucleus [1]. Another idea based on the fact that collisions with other bodies change the comet shape and can lead to transforming it into a bi-lobed one [2]. However, over than a half of comets, which have been imaged with high resolution, have bi-lobed shapes [3] and the precise mechanism of making such objects is still unknown. Here we illustrate that sublimation of matter from the nucleus surface makes a comet more elongated and, in some cases, transforms an originally convex cometary nucleus into a bi-lobed one.

1. Introduction

Sublimation is a physical phenomenon that transits a solid matter directly to the gas phase without passing through the intermediate liquid phase. This process occurs on the surface of a cometary nucleus due to the Sun radiation and, hence, modifies the shape of the nucleus.

2. Differential equation

To investigate how the nucleus shape transforms with time by sublimation we considered the following model.

- The initial shape of a comet is axially symmetrical.
- The comet spins rapidly, so we can average the shape changes over one spin period.
- The spin axis of the comet is perpendicular to the orbital plane.

Since the spin rate is high and the spin axis perpendicular to the orbital plane, the comet shape remains axially symmetrical. That is why we consider a slice of the comet's nucleus in a plane, which contains the spin axis, as a function $y(x)$, where the y-axis counter-directed with the direction of sun rays and the x-axis coincides with the spin axis. $y(x)$ gives us the curve that determines the comet shape and the change of the curve determines the change of the comet shape.

The differential equation, which describes the shape transformations, is the following:

$$\frac{\partial y}{\partial t}(x,t) = -\frac{Z}{\cos\Theta}, \tag{1}$$

where Z is the sublimation rate at point x and Θ is the angle between the normal to the curve and the direction of sun rays, measured from the normal counterclockwise. The function Z depends on the intensity of Sun rays, therefore it can be considered as a function of heliocentric distance, r, and $\cos\Theta$.

2.1. Sublimation function and initial structure

A sublimation rate from a unit area perpendicular to the sun rays over unit time is a sublimation function. In this work we considered two well-known sublimation functions.

1. r^{-2}
2. $g(r) = \alpha\left(\frac{2.808}{r}\right)^m\left(1+\left[\frac{r}{2.808}\right]^n\right)^k$

The first function implies that sublimation rate is proportional to the sun radiation intensity. The second one is a standard sublimation function of ice derived by Marsden et al. [4], where $\alpha = 0.111262$, $m = 2.15$, $n = 5.093$, $k = -4.6142$.

Also in the work we considered two cases of initial nucleus structure.

1. Homogeneous spherical nucleus with a uniform density and composition

2. Inhomogeneous spherically symmetric nucleus, the gradient of sublimation rate of which is positive towards the center of the nucleus.

The positive gradient can be explained by the decrease of matter density towards the center as well as the increase of porosity and lighter elements (for example CO or CO_2). In the case of inhomogeneous nucleus we multiply the right hand part of equation (1) by some function $\Gamma(R)$, which is a function of the distance to the center of the comet.

3. Results

The differential equation for a homogeneous initial structure was solved analytically with **any** sublimation functions. For the second initial structure with sublimation function r^{-2} we also found the analytically solution, however, with the sublimation function $g(r)$ we found only a numerical solution.

A homogeneous nucleus remains being convex with both sublimation functions. In the inhomogeneous case after some time the comet shape can become bi-lobed. Here we present pictures of a nucleus after some time for the sublimation function $g(r)$ and as a function of $\Gamma(R)$ we considered e^{-R}. The orbit of the comet was a circle with the radius equals to 4 au.

4. Summary and Conclusions

To sum up we considered how a spherical comet shape changes by sublimation. We got able to solve this problem analytically for **any** sublimation function for a homogeneous nucleus as well as for inhomogeneous spherically symmetric nucleus for sublimation function r^{-2}. For inhomogeneous spherically symmetric nucleus with sublimation function $g(r)$ we found only a numerical solution. It was found that a homogeneous nucleus remains being convex, but an inhomogeneous nucleus could become bi-lobed.

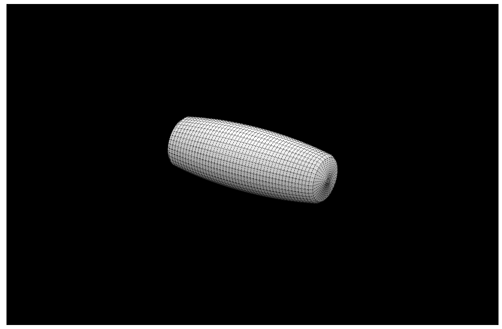

Figure 1: A homogeneous nucleus after some time for sublimation function $g(r)$.

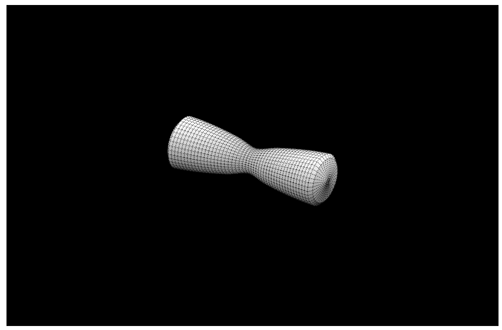

Figure 2: An inhomogeneous nucleus after some time for sublimation function $g(r)$.

Acknowledgements

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Evolution of the cometary ionospheric sourcing of 67P throughout Rosetta escort phase

K.L. Heritier (1), M. Galand (1), P. Henri (2), E. Odelstad (3), K. Altwegg (4), A. Beth (1), J. Burch (5), C. Carr (1), E. Cupido (1), A. Eriksson (3), H. Nilsson (6), M. Rubin (4), X. Vallières (2), E. Vigren (3)
(1) Department of Physics, Imperial College London, London, UK, (2) LPC2E, CNRS, Université d'Orléans, Orléans, France, (3) Swedish Institute of Space Physics, Ångström Laboratory, Lägerhyddsvägen 1, Uppsala, Sweden, (4) Physikalisches Institut, Universität Bern, Bern, Switzerland, (5) SouthWest Research Institute (SwRI), San Antonio, TX, USA, (6) Swedish Institute of Space Physics, Kiruna, Sweden
(k.heritier15@imperial.ac.uk)

Abstract

A data-based robust ionospheric model, which computes the ion number density, has been developed in order to quantify the sources of ionization in the coma of 67P/Churyumov- Gerasimenko. The model is driven by Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA)/Cometary Pressure Sensor (COPS) neutral density. There are three ionization sources: photo-ionization by solar extreme ultraviolet (EUV) radiation, electron- impact ionization from energetic electrons (> 12 eV) and charge-exchange between solar wind protons and cometary neutrals. The EUV radiation is estimated from fluxes measured by the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED)/ Solar EUV Experiment (SEE) from Earth's orbit, taking into account the phase shift and the heliocentric distance ratio, between Earth and comet 67P. The electron-impact ionization frequencies are derived from Rosetta Plasma Consortium (RPC)-Ion and Electron Sensor (IES) integrated electron fluxes and corrected for the S/C potential from RPC/LAngmuir Probe (LAP) measurements. Charge-exchange is computed from solar wind estimated local conditions in terms of density and bulk velocity. The effect of the neutral composition of the coma on the ionization rates is assessed. Our results are compared with in-situ measurements of the plasma density from RPC-Mutual Impedance Probe (MIP) and RPC-LAP.

The ionospheric model has been used to derive the plasma densities at the location of the spacecraft at different periods during the escort phase. These densities are in agreement with in-situ plasma measurements. In addition, the relative importance of the different sources of ionization has been evaluated. Heliocentric distance, solar activity, seasonal variations, solar absorption, electron cooling and heating processes are key parameters to take into account in order to evaluate the contribution of the different ionization sources. At high heliocentric distances, the two main sources contributing to local plasma densities are photo-ionization and electron-impact ionization. As the mission progressed, the relative importance of photo-ionization declined due to the decrease in solar activity and electron-impact happened to become the main source of ionization. However, at low heliocentric distances, when the outgassing rate is the highest, photo-ionization is the dominant process. Charge-exchange is never observed to be the main ionization source in the periods that we studied but its contribution is highly variable and depends on the solar wind local conditions.

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Characterization of the Abydos landing site of Philae on comet 67P/Churyumov-Gerasimenko

P. Lamy (1), G. Faury (2), L.Jorda (1), D. Romeuf (3), C. Capanna (1), M. R. El-Maarry (4), R. Gaskell (5), O. Groussin (1), D. Nebouy (1), and the OSIRIS Team
(1) Laboratoire d'Astrophysique de Marseille, Marseille, France, (2) AKKA Technologies, Toulouse, France, (3) Université Lyon I, Lyon, France, (4) Laboratory for Atmospheric and Space Physics, University of Colorado (CO), USA, (5) Planetary Science Institute, Tucson (AZ), USA

Abstract

On 12 November 2014, the Philae surface module of the Rosetta mission did not land at the planned Algika "J" site on the surface of the nucleus of comet 67P/Churyumov-Gerasimenko but rebounded several times before final touchdown at an unknown place later labeled "K" and named Abydos. Unambiguous detection of Philae was achieved in March 2015 and was later confirmed by twelve campaigns carried out in 2016. They resulted in a detailed mapping of the Abydos region in several filters thus allowing a detailed characterization on the basis of anaglyphs, a digital terrain model at a spatial scale of ~40 cm and color maps, all constructed from OSIRIS-NAC images. We present the regional setting of Abydos and define geological units. Abydos is essentially an alcove at the foot of a scarp composed of heavily fractured consolidated materials.

1. Introduction

After a first touchdown at the selected Agilkia "J" landing site on the head of the nucleus of comet 67P/Churyumov-Gerasimenko on 12 November 2014, the Philae surface module of the ESA Rosetta mission bounced for a two-hour flight and finally landed at a site later named Abydos. Unambiguous detection of Philae was achieved in March 2015 by comparing images taken with the OSIRIS Narrow Angle Camera in October (pre-landing) and December (post-landing) 2014 [1]. Starting in early March 2016, twelve campaigns were carried out to image Philae thus resulting in a detailed mapping of the Abydos region at a pixel scale down to 5 cm/pixel and in various filters ranging from 362 to 986 nm (Fig. 1). This region has therefore benefited from the best coverage of the nucleus except for the Rosetta landing site.

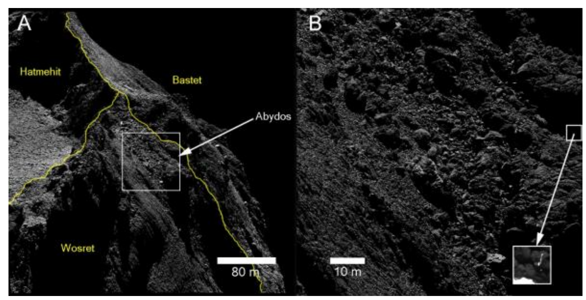

Figure 1: Regional setting of Abydos. [A] WAC image showing the regional context of Abydos with the regional boundaries outlined. The area lies in the southern hemisphere, ~150 m away from the Hatmehit depression. [B] NAC image showing a high resolution view of Abydos. Boxes mark the location of Philae and a close-up of the actual lander.

2. Analysis and Results

We have analyzed the whole set of images of the Abydos region obtained over the period 2014-2016. Different geological/geomorphological units have been identified and delimited by regional boundaries as displayed in Fig. 2. Two complementary approach

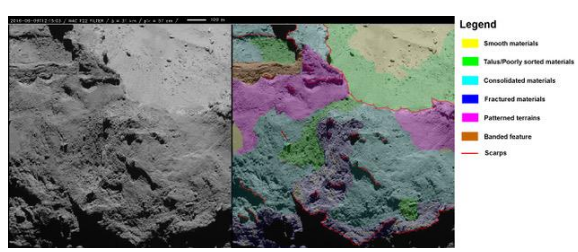

Figure 2: Geological units of Abydos

were implemented to characterize the 3-dimensional topography of the Abydos region. Twenty stereo anaglyphs (an example is presented in Fig.3) offer spectacular views at different scales down to 5 cm/pixel. A digital terrain model (DTM) has been successfully constructed at a sampling of 40 cm although the conditions in terms of incidence and emission angles were unfavorable (Fig. 4). The photometric proper-ties of the surface as related to its composition have been characterized by the reddening slope of the spectral reflectance. An example of the map of this slope is given in Fig. 5.

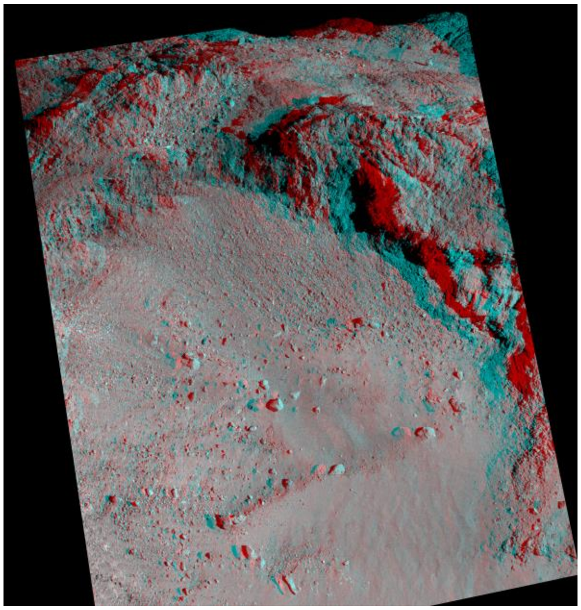

Figure 3: Stereo anaglyph allowing a 3D perspective view of the Abydos region above the rim of the Hatmehit depression.

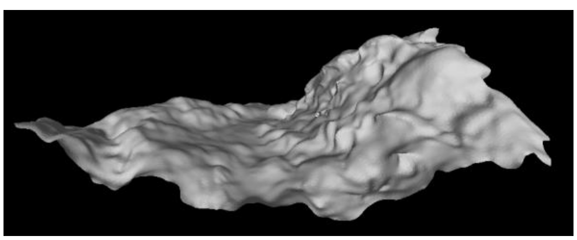

Figure 4: Digital terrain model of the Abydos region. The longitudinal extent (left to right) is 40 m.

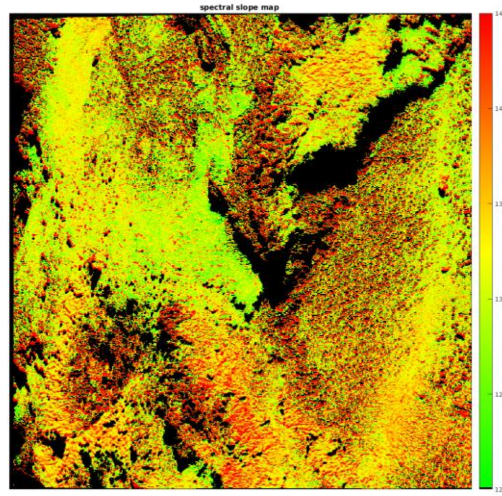

Figure 5: Map of the reddening slope of the spectral reflectance (in %/100 nm) of the Abydos region in the spectral range 362-986 nm. The square has dimensions of 630 x 630 m. Part of the Hatmehit depression is seen at right.

Acknowledgements

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Analysis of the Cometary Plasma Environment of 67P/Churyumov-Gerasimenko Near Perihelion

K. Ostaszewski (1), C. Goetz (1), U. Motschmann (2,3) and K.H. Glassmeier (1,4)
(1) Institut für Geophysik und extraterrestrische Physik, Technische Universität Braunschweig, Braunschweig, Germany
(2) Institut für theoretische Physik, Technische Universität Braunschweig, Braunschweig, Germany
(3) DLR-Institut für Planetenforschung, Berlin, Germany
(4) Max-Planck Institut für Sonnensystemforschung, Göttingen, Germany

Abstract

Over the course of its two year escort phase the Rosetta spacecraft has provided various observations that furthered our understanding of the cometary plasma environment. The use of numerical simulations is essential for this understanding because they allow to place the in situ measurements in a global context, in turn, through observations the numerical models can be extended and improved.
We use the simulation code A.I.K.E.F (Müller [7]) to simulate the cometary plasma environment of 67P/Churyumov-Gerasimenko (67P/CG). Based on observations made by the Rosetta spacecraft we extend the numerical model by electron impact ionization and the anisotropic outgassing model by Hansen et al. [4]. Both extensions result in an increase in the cometary ion production rate on the dayside. Therefore, the size of the interaction region and the contained structures increases. This causes the position of the different boundaries, e.g. bow shock, to shift further away from the comet. Considering this we can explain why no bow shock crossings could be observed during the dayside excursion of Rosetta in September 2015.

Motivation for the Extensions

The ionization of cometary neutrals is the dominating process in the interaction between the comet and the solar wind. Therefore, the modeling of the different ionization sources is an integral part in simulating the cometary environment. Although photo-ionization by solar UV radiation is the dominant process, various authors, e.g. Cravens et al. [1], investigated the importance of electron impact ionization as an ionization source. Recently, Galand et al. [3] showed that in the case of a weakly active comet at heliocentric distances higher than 3.0 AU electron impact ionization needs to be taken into account in order to explain the measured electron densities. The authors showed that in certain regions the electron impact ionization frequency is of the order of the photo-ionization frequency. Previously only photo-ionization and charge exchange have been implemented in A.I.K.E.F. Therefore, it is important to include the additional ionization source in our simulations.
Another integral part in the modeling of the cometary environment is the neutral background. The most common model used for the neutral coma is the spherically symmetric model by Haser [5]. However, this is only a crude approximation as the difference between the day- and nightside and the shape of the nucleus are not taken into account. Moreover, recent observations have shown that the shape of the nucleus of 67P/CG is irregular. Therefore, different regions on the surface of the comet show different levels of activity. .

Results

We find that by including electron impact ionization the bow shock stand-off distance increases. Figure 1 shows the evolution of the bow shock position over time normalized to the ion gyroperiod t_{gyr} for two simulations: one with electron impact ionization (blue) and one without (red). Both simulations were performed for parameters representing the solar wind conditions at a heliocentric distance of 1.3 AU. Over the course of the simulation increasingly more cometary ions are picked up as the bow shock evolves. Consequently, the bow shock stand-off distance increases over time until it reaches a steady state at 7200 km for the simulation with electron impact ionization and 4800 km for the simulation without. Similar, an increase in the bow shock position can be observed for the Hansen model. Compared to the

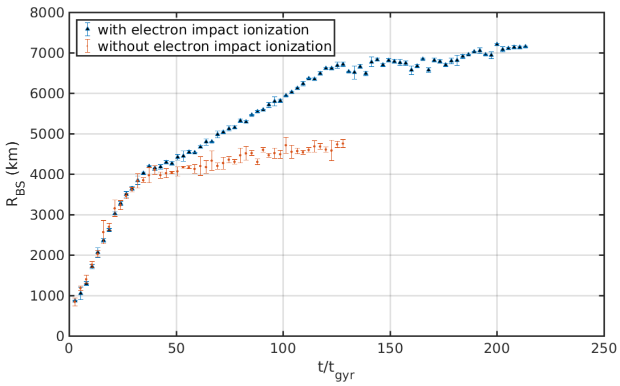

Figure 1: Evolution of the bow shock stand-off distance with time at the subsolar point for a simulation with electron impact ionization (blue) in comparison with a simulation without electron impact ionization (red). The ion gyroperiod amounts to $t_{gyr} = 2.06s$.

Haser model the neutral density computed through the Hansen model, and therefore also the ion production rate, is significantly higher on the dayside. Moreover, the anisotropy increases the asymmetry of the interaction region which affects the shape of the structures in the cometary plasma.

In September 2015 Rosetta embarked on an excursion from the vicinity of the comet up to a distance of 1500 km on the dayside. At this time simulations indicated a bow shock position of about 2000 km (Koenders et al. [6]). However, Edberg et al. [2] showed that during the excursion the magnetic field is nearly constant and no indications of a bow shock crossing could be observed. As was noted by Koenders et al. [6] the bow shock position varies strongly with the outgassing rate, neutral velocity and solar wind conditions. The fact that no variation of the magnetic field over the excursion could be observed implies that the bow shock is positioned significantly further outwards than expected.

Through the inclusion of electron impact ionization and the anisotropic outgassing model the bow shock in our simulations moved further outwards to about 8000 km. This explains why no indication of a bow shock could be observed during the dayside excursion. Furthermore, the nearly constant magnetic field up to a distance of 1500 km can be reproduced in the simulations.

Acknowledgements

The RPC-MAG data will be made available through the PSA archive of ESA and the PDS archive of NASA. Rosetta is a European Space Agency (ESA) mission with contributions from its member states and the National Aeronautics and Space Administration (NASA). The work on RPC-MAG was financially supported by the German Ministerium für Wirtschaft und Energie and the Deutsches Zentrum für Luft- und Raumfahrt under contract 50QP 1401. We are indebted to the whole of the Rosetta Mission Team, SGS, and RMOC for their outstanding efforts in making this mission possible. The hybrid simulations were performed on the system of the Norddeutsche Verbund für Hoch- und Höchstleistungsrechnen (HLRN) cluster.

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Ion variability at 67P during perihelion: cross-comparison between ROSINA/DFMS and RPC dataset

A. Beth (1), K. Altwegg (2), E. Behar (3), J. L. Burch (4), C. Carr (1), A. Eriksson (5), M. Galand (1), C. Goetz (6), P. Henri (7), K. Heritier (1), H. Nilsson (3), E. Odelstad (5), I. Richter (6), M. Rubin (2), X. Vallières (7), the ROSINA and RPC teams
(1) Department of Physics, Imperial College London, London, UK (2) Physikalisches Institut, Universität Bern, Bern, Switzerland (3) Swedish Institute of Space Physics, Kiruna, Sweden (4) SouthWest Research Institute, San Antonio, Texas, USA (5) Swedish Institute of Space Physics, Ångström Laboratory, Lägerhyddsvägen 1, Uppsala, Sweden (6) Institut für Geophysik und extraterrestrische Physik, TU Braunschweig, Braunschweig, Germany (7) LPC2E, CNRS, Université d'Orléans, Orléans, France (arnaud.beth@gmail.com)

Abstract

During the escort phase, the Double Focusing Mass Spectrometer (DFMS), one of the three Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA) sensors onboard Rosetta, probed the neutral and plasma composition of the coma of comet 67P/Churyumov-Gerasimenko (67P). Major ion species detected include water ions (e.g., H_2O^+, H_3O^+, HO^+). The analysis of DFMS data revealed a large zoo of ion species near perihelion (summer 2015). During this period, the Rosetta Plasma Consortium (RPC), made up of five sensors (Ion Composition Analyzer (ICA), Ion and Electron Spectrometer (IES), Langmuir Probe (LAP), Magnetometer (MAG), and Mutual Impedance Probe (MIP)), probed the plasma properties, such as ion/ electron number density, electron temperature, ion and energetic electron distribution, magnetic field magnitude and component.

We will show a cross comparison between ROSINA/DFMS and RPC data to interpret the ion composition variability. Our primary goal is to highlight any correlation between observations from these different sensors and to find relevant signatures of physical processes which can affect the chemistry and dynamics (e.g., acceleration and deflection) of the involved neutral and ion species.

Introduction

For two years, ROSINA/DFMS gave us the opportunity thanks to its high mass resolution to probe the neutral and ion species within 67P's coma. Analyses of the dataset have revealed strong day-to-day variations of the plasma composition through the entire mission.

Complementary to the ROSINA/DFMS ion dataset, the five sensors from RPC probed the properties of the plasma surrounding 67P.

In this study, we highlight and emphasise the strong correlation between the data from these different sensors and the necessity to perform further analyses all together.

Preliminary results

The first results already revealed a strong correlation between ROSINA ion data, the spacecraft potential from RPC/LAP and diamagnetic crossings identified by RPC/MAG.

Spacecraft potential: On the one hand, for a positive spacecraft potential, the spacecraft repelled ions such that they cannot enter into ROSINA/DFMS instrument to be detected. On the other hand, for a too negative spacecraft potential, incoming ions may earn too much kinetic energy close to the spacecraft so that they have a too high energy within the instrument to be detected.

Diamagnetic crossings: The cross-comparison between ROSINA/DFMS and RPC/MAG data showed that the ion count rate strongly increased when the Rosetta entered into the diamagnetic cavity, supporting which has been previously observed at 1P/Halley.

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Illumination maps of 67P: availability for the community

A. Beth (1), M. Galand (1), C. Carr (1), B. Geiger (2), V. Génot (3,4), N. Jourdane (3,4), M. Gangloff (3,4), S. Erard (5), B. Cecconi (5)
(1) Department of Physics, Imperial College London, London, UK (2) European Space Astronomy Center, European Space Agency, Villanueva de la Cañada, Spain (3) Université de Toulouse, UPS-OMP, IRAP, Toulouse, France (4) CNRS, IRAP, 9 Av. Colonel Roche, BP 44346, F-31028 Toulouse Cedex 4, France (5) LESIA, Observatoire de Paris, Meudon, France
(arnaud.beth@gmail.com)

Abstract

The initial analysis of the comet 67P-CG and its coma by the ESA/Rosetta probe has shown a strong correlation between the illumination on the comet and the outgassing activity. Thus, it has proved essential to determine the illumination of 67P for a given epoch in order to help interpreting the variability of the outgassing rate with local time and season.

In this sense, the ESA/Navigation Camera (NAVCAM) images offered the opportunity to reconstruct accurately the 3D shape model of comet 67P. Based on the last publicly available version generated by ESA of the shape model CSHP_DV_130_01_______00200.obj (52098 nodes, 104192 faces) (http://npsadev.esac.esa.int/3D/67/Shapes/), we have developed an efficient and fast algorithm to assess the illumination. For a given direction of the Sun, the algorithm which we have developed calculates the cosine between the normal of each face and the Sun direction in less than 1 s.

We have produced 37800 illumination maps, and files containing the information for users to retrieve - and to rebuild from the 3D model - the illumination of the comet. The number of maps and files corresponds to 1° step for both the subsolar longitude, varying from 0° to 359°, and the subsolar latitude, varying from −52° to 52°, in the comet frame. These maps and files are available through the Virtual European Solar and Planetary Access (VESPA) (http://vespa.obspm.fr/) with the support of CDPP (http://www.cdpp.eu). The distribution system includes search functions on all parameters.

Examples

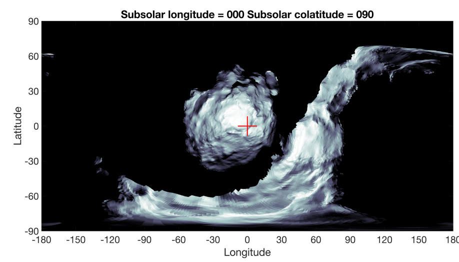

Figure 1: Illumination map in 2D of the surface of 67P for a given subsolar point location (here 0° in longitude and 0° in latitude). This illumination occurred during equinox. The red cross corresponds to the subsolar point These pictures are available through the VESPA portal.

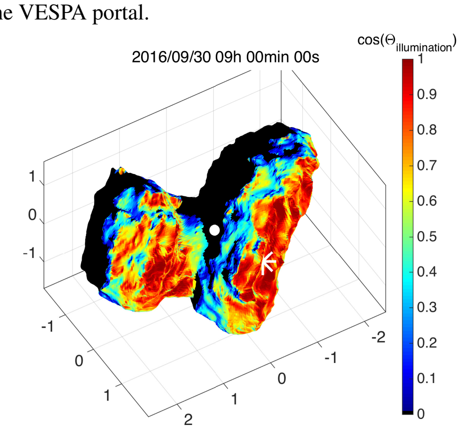

Figure 2: Reconstitution of the illumination of 67P in 3D for the last day of Rosetta at 9:00 UT from the files available through the VESPA portal. The white dot represents where the spacecraft is pointing on the surface and the white cross is the subsolar point.

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Towards a high-accuracy geological model of the 67P comet

M. Franceschi (1), L. Penasa (2), M. Massironi(1,2), S. Ferrari (2), G. Naletto (2,3,4), I. Bertini (5), G. Cremonese (6), F. Ferri (2), E. Frattin (5,6), F. La Forgia (5), M. Lazzarin (5), A. Lucchetti (6), F. Marzari (5), M. Pajola (7), E. Simioni (4,6), and the OSIRIS team. (1) Geosciences Department, University of Padova, Padova, Italy (marco.franceschi79@gmail.com) (2) Center of Studies and Activities for Space, CISAS, 'G. Colombo', University of Padova, Italy (3) Department of Information Engineering, University of Padova, Italy (4) CNR-IFN UOS Padova LUXOR, Padova, Italy (5) Department of Physics and Astronomy "G. Galilei", University of Padova, Italy (6) INAF - OAPD Astronomical Observatory of Padova, Padova, Italy (7) NASA Ames Research Center, Moffett Field, California, USA

Abstract

It was recently shown that the layered structure of each of the two lobes of comet 67P/Churyumov-Gerasimenko (67P) can be modelled as a set of concentric ellipsoidal shells. The ellipsoidal model is able to correctly predict the major layering-related features on the comet surface; however, the ellipsoidal model is a first order approximation of a more complex internal structure. A better description of this latter requires an improved model. In this contribution preliminary results in building a refined three-dimensional model of the comet are presented with focus on the Small Lobe. The model is realized using a 3D geo-modeling technique that embeds linear and planar features (layer joints and terraces) as well as other geometric characteristics (e.g. vectorial fields) as constraints, influencing the reconstruction of the comet layered structure. Results allow accounting for features that are not predicted by the ellipsoidal model, therefore such refined 3D model is a step towards a model of the comet nucleus that may clues useful in unraveling the complex history that shaped it to its present configuration.

1. Introduction

After the recognition of sets of ordered terraces and mesas on the surface of the comet 67P/Churyumov-Gerasimenko [1], evidences were provided that the two lobes of the comet are characterized by large-scale internal layering [1]. The recognition of the layered structure opened to efforts aimed at modelling in three dimensions the structure of the cometary nucleus. Recently, a 3D model made up of two independent sets of concentric ellipsoidal shells was proposed [2]. These shells (Fig.1A and 2A), characterized by a fixed aspect ratio, are obtained from non-linear optimization of the orientations of the terraces on the lobes. The ellipsoidal model is able to predict orientation of cliffs and terraces in several regions of the comet (e.g. Wosret and Hathor of the Big Lobe). However, in other regions, and in particular on the Small Lobe, discrepancies between the model-predicted layers and the visible layering and terraces are locally visible (Fig.1A) and suggest that a refinement of the 3D model would be needed to account for a structure that in specific areas appears to be more complex than expected.

Preliminary results of a refined modelling by using SKUA-Gocad geomodeling software [3] are here presented and provide a further step towards the realization of a 3D stratigraphic model of the 67P comet.

2. 3D modelling in SKUA-Gocad

The 3D model of the Small Lobe of the 67P has realized using SKUA-Gocad geomodeling suite and in particular the StructuralLab plugin. The procedure applies an implicit modeling approach in which layers are modeled as iso-surfaces within a 3D scalar field interpolated within a tetrahedral mesh [4]. A key-point of this modeling procedure is that a large number of constraints can be used to influence the shape of the iso-surfaces. This makes the modeling more flexible and able to reproduce complex and irregular geometries. In the here presented preliminary model, the center of the ellipsoidal shells [2] was kept as center of the layered envelopes, and the vectorial field made of the normals to the identified terraces was used as orientation constraint. In addition, linear features, recognized on the comet surface and interpreted as bedding joints of the

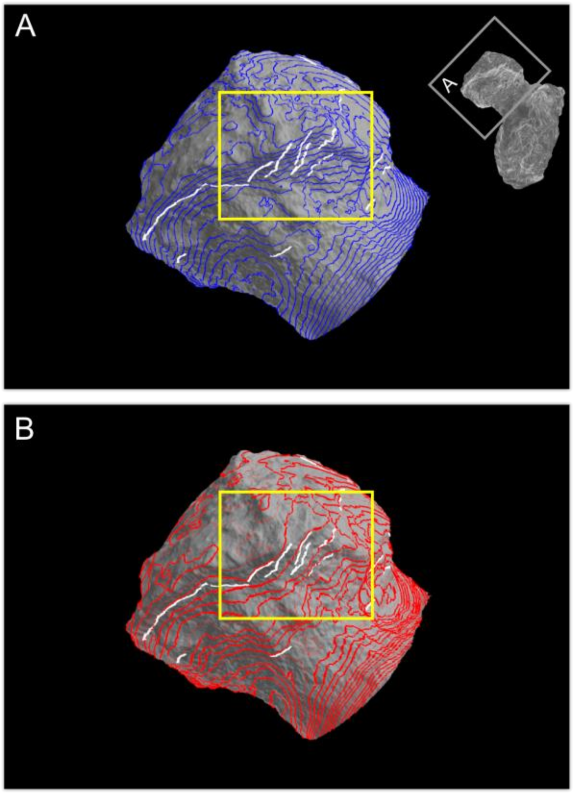

Figure 1 View of the Small Lobe of comet 67P with highlighted some observed layering traces (white) and A) the traces of layering from the ellipsoidal model (blue) and B) the traces of layering calculated from the SKUA model (red). Note (within the yellow rectangle) that discrepancies in A) are resolved in B).

layered structure, were traced and fixed as linear constraints so that in the new model each line lays on an iso-surface [4].

3. Results and Conclusions

In the new model the overall shape of the concentric shells results more irregular than that of the ellipsoidal model (Fig.2A and 2B). Since the linear features are used as constraints, a better correspondence between the modeled shells and the visible layers is obtained (Fig.1B. These preliminary results show that a modeling approach embedding a larger number of constraints (e.g. stratigraphic joints) may provide significant support for a more comprehensive 3D representation of the cometary body. The refined model may allow for resolving the actual geometry and highlighting thickness variations of the. This could help shedding light on its origin. For instance, the geometry of the layering may

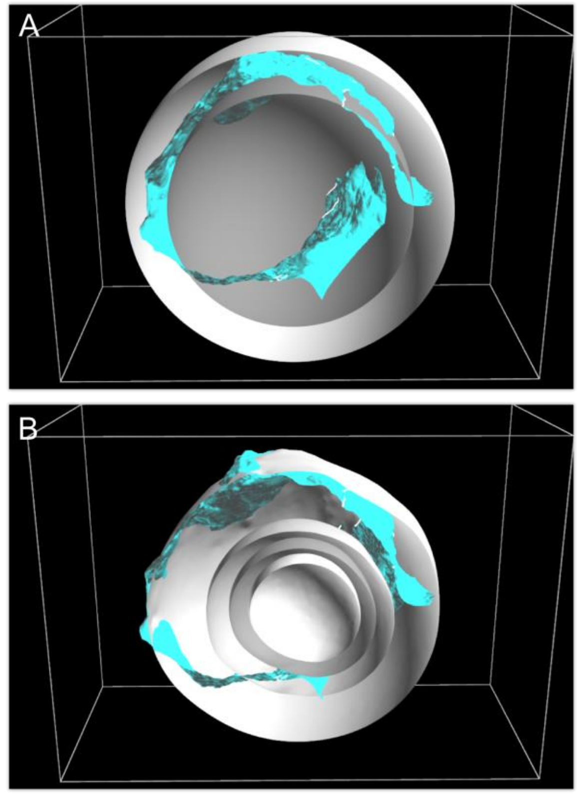

Figure 2 A) cross-section of the Small Lobe (surface painted in light blue) showing concentric shells of the ellipsoidal model. B) same cross-section showing envelopes of the model realized in this work.

provide clues on the dynamics of the collision between the two lobes whereas thickness variations within layers on the mechanisms of cometary accretion.

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The Near-Nucleus Dusty Gas Coma of Comet 67P Prior to the Descent of PHILAE

V.V. Zakharov (1,2), F. Marzari (3), J.-F.Crifo (4), I. Bertini (5), A.V. Rodionov (6) and M. Fulle (7)
(1) Laboratoire de Météorologie Dynamique/IPSL/CNRS, UPMC Univ. Paris 06, Sorbonne Universités, Paris, France, (vladimir.zakharov@lmd.jussieu.fr) (2) LEISA, Observatoire de Paris, CNRS, UPMC, Université Paris-Diderot, 5 place Jules Janssen, F-92195 Meudon, France, (3) Department of Physics, University of Padova, I-35131 Padova, Italy, (4) LATMOS/IPSL, UPMC Univ. Paris 06 Sorbonne Universités, UVSQ, CNRS, Guyancourt, France, (5) Centro di Ateneo di Studi ed Attivitá Spaziali `Giuseppe Colombo' (CISAS), University of Padova, Via Venezia 15, I-35131 Padova, Italy, (6) Federal State Unitary Enterprise Russian Federal Nuclear Center All-Russian Research Institute of Experimental Physics (FSUE RFNC-VNIIEF), Sarov, Nizhny Novgorod Region, 607188, Russia, (7) INAF - Osservatorio Astronomico di Trieste, Via Tiepolo 11, 34143 Trieste Italy

Abstract

We describe the RZC model developed to predict the gas environment of the comet 67P (it was used for estimation of the aerodynamic forces on the Rosetta lander in November 2014) and the results of adjustment of this model to the observational data obtained by the Rosetta probe before landing.

Also, we present the results of our attempts to fit the dust coma images obtained by the Optical, Spectroscopic, and Infrared Remote Imaging System (OSIRIS).

1. Introduction

On November 12, 2014 the ESA Rosetta probe deposited the Philae lander on the nucleus of the comet 67P located at 3.00 AU from the Sun. Within the Rosetta project, the responsibility of the aerodynamic and gravitational force assessments on the lander was delegated to the French National Space Center CNES, who delegated the assessment of the gas outflow structure to a so-called **"**RZC" team gathering the three of present authors.

The RZC model includes two differing tools: (1) a set of gasdynamic/gaskinetic codes to compute the vacuum outflow of a rarefied gas mixture from a central, highly anisotropic and rotating source; (2) a specially developed code to derive the central source parameters from data on the nucleus provided by the observations from the orbiter probe.

Ideally speaking, the optimization of the gas model would have resulted from a succession of predictions of the local gas parameters along optimal probe trajectories, as well as of the gas parameters inside the field-of-view of the remote sensing instruments, followed by comparison with the in-situ sampling and remote sensing instrument data. This turned out however impossible for many reasons. Instead, preset trajectories and instrument view directions were defined which then may not have been optimal for adjusting the model parameters. Therefore we are limiting our efforts to fitting the Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA). Also, since cometary dust has been shown to be an accurate tracer of the gas flow discontinuities, we made attempts to fit the dust coma images of the Optical, Spectroscopic, and Infrared Remote Imaging System (OSIRIS).

2. The model

The observational nucleus data for the model were (a) a nucleus rotation model, and (b) a nucleus surface shape model. From the latter we constructed an "effective surface model" to be used by the gas code. This procedure evidently erases small-scale details but also creates a surface slightly different from the "real" one, having, for instance a different shadow pattern under oblique solar illumination.

The gas production model assumes that the less volatile molecules of H_2O are produced from the surface of the nucleus by sublimation of surface ice inclusions and the more volatile molecules (CO and CO_2) are produced by diffusion to the surface after having been sublimated at variable depths inside the nucleus. The emission has two components one is modulated by the Sun, while the other is permanent. In addition, we introduce position dependent factors f_{H2O}, f_{CO}, f_{CO2} of surface inhomogeneity (separately for each gas species) which linearly adjust surface fluxes.

A multi-species 3D+t gas solver is based on: (1) gas-dynamic approach – the numerical integration of the Euler/Navier–Stokes equations combined with a locally plane-parallel solution of the collisional Boltzmann equation for the nonequilibrium near-surface Knudsen layer (BE-NSE) [1]; and (2) kinetic approach - the direct simulation Monte–Carlo (DSMC) method. Since the radial size of the region of interest is usually less than 150 km we use quasi-steady approximation for the gas simulations. For the dust coma we use the stochastic approach - the Dust Monte-Carlo (DMC) [2]. We assume that dust grains are spherical moving under influence of three forces: the nucleus gravitational force, gas coma aerodynamic force, and solar radiation pressure force, and consider the full mass range of ejectable grains. The dust grains move slower than the gas, therefor for the dust coma we perform fully time dependent simulations. At each surface point, the dust mass flux (of a given size) is proportional to the gas mass flux. This proportion may be variable over the surface.

3. The adjustment of the gas production

The adjustment of the model to the in-situ observational data is separated on two consecutive stages. On the first stage we adjust the integral parameters: the total production rates and the proportion of solar modulated and permanent diffusion. On the second stage we adjust the distribution of surface inhomogeneity factors. From positions of the orbiter we traceback the flowlines down to the corresponding surface elements. For the surface elements we collect statistics on the ratio of measured and simulated density and composition. The currently used factors f_{H2O}, f_{CO}, f_{CO2} are corrected (multiplied) by the averaged ratio. Since variation of the flux affect the flow in general it is necessary to repeat iteratively simulations for the whole rotational period with the new flux distribution. The observational data are limited and some of the surface elements may have no data, for them we apply the algorithm of flooding from adjacent cells.

4. Comparison with the dust coma images

To compare the outcome of the dust models to OSIRIS images have generated synthetic column densities from the outcomes of the dust simulations. The light scattered by the dust towards the pixel of the WAC/NAC camera is computed by using Mie theory for spherical particles. The total flux scattered back by the coma on each pixel is finally reduced taking properly into account the efficiency of the CCD and optics. For the dust particles we adopt an average density of 800 kg/m^3 and a composition typical of organic material modelling interstellar dust under the assumption that such material is also representative of cometary dust. The synthetic images are compared to observations via direct comparison with 2D images or using polar plots. These last ones are obtained by fixing a given radial distance R from the center of the comet and comparing the flux computed along the circle of radius R surrounding the comet for both the observed and synthetic image.

5. Results

We have tried to best fit the data acquired in August-November 2014 by the pressure gauge COPS on the orbiter. Fig.1 shows an example of surface inhomogeneity distribution after adjustment.

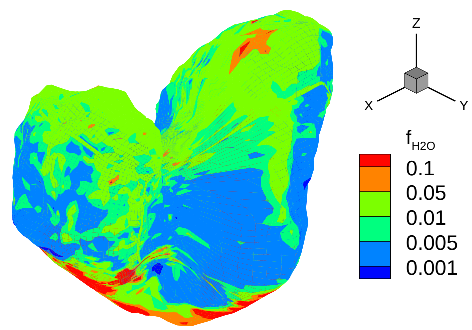

Figure 1: f_{H2O} distribution over the surface.

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Cometary activity described by chain dust modeling applied to the VIRTIS and GIADA data in the coma of 67P/Churyumov-Gerasimenko

S. L. Ivanovski (1), M. T. Capria (1), V. Della Corte (1,2), F. Capaccioni (1), G. Filacchione (1), A. Rotundi (1,2), G. Rinaldi (1), F. Tosi (1), M. C. De Sanctis (1), S. Erard (3), A. Longobardo (1), M. Ciarniello (1), A. Raponi (1), A. Zinzi (4,5), E. Palomba (1), L. Colangeli (6), D. Bockelee-Morvan (3), C. Leyrat (3), and the International VIRTIS and GIADA teams;
(1) INAF- Istituto di Astrofisica e Planetologia Spaziali, Rome, Italy (stavro.ivanovski@iaps.inaf.it), (2) Università Parthenope, Naples, Italy, (3) Observatoire de Paris, Paris, France, (4) ASI Science Data Center, c/o ASI, Rome, Italy, (5) INAF-OAR, Monte Porzio Catone (RM), Italy, (6) ESA, Noordwijk, Netherlands

Abstract

The unprecedented close-to-a-comet observations of dust particles in the circumnuclear coma of comet 67P/Churyumov-Gerasimenko opened room for new data fusion studies in cometary science. Here we use observations performed by two of the instruments onboard Rosetta, Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) and Grain Impact Analyser and Dust Accumulator (GIADA). On one hand, VIRTIS, coupling high spectral and spatial resolution in the VIS (0.25-1.07 micron) and IR (0.95-5.1 micron) ranges, provides information on the composition and temperature (derived from the 4.5-5.1 μm portion of the spectrum) of the surface. On the other hand, GIADA measures the speed, momentum and optical cross section of individual particles detected in situ, deriving their mass and geometrical cross-section. We study the dust dynamical properties in dependence on the surface illumination conditions and on the hidden under-near-surface activity, using two models calibrated by the observational data of the two instruments. The first model, a 2D nucleus thermal model(TMP) computes the dust fluxes for given dust grain size bins assuming a dust particle size distribution on the surface. The second model, an aspherical dust dynamical model computes the trajectories and dynamical properties (grain velocity, rotational frequencies and dust velocity dispersion) of ejected dust from different locations of the nucleus surface. Based on chain modeling, i.e. using the output of the thermal nucleus model as input for the dynamical model we obtain complementary information on the dynamics of dust particles having masses and sizes for which there is no observational dynamical data or are beyond of the instruments detectable sensitivity. The TMP model provided surface temperatures and gas production rates as input to the aspherical dust model that in turn provided rotational frequencies and dust speed distribution. Our models were applied to observational data acquired before 67P/C-G perihelion. We obtained grain speeds ranging from $\sim$ 1 m/s to $\sim$ 150 m/s for grain masses of 10^{-6} kg and 10^{-16} kg, respectively. The number of rotations per seconds for ellipsoidal isothermal grains varies from 1 per hundred seconds up to 10 per second.

Acknowledgements

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Parthenope. INAF-Oss. Astr. Capodimonte, in collaboration with the Inst. de Astrofisica de Andalucia, Selex-ES, FI and SENER. GIADA is presently managed & operated by Ist. di Astrofisica e Planetologia Spaziali-INAF, IT. GIADA was funded and managed by the Agenzia Spaziale Italiana, IT, with the support of the Spanish Ministry of Education and Science MEC, ES. GIADA was developed from a PI proposal from the University of Kent; sci. & tech. contribution were provided by CISAS, IT, Lab. d?Astr. Spat., FR, and Institutions from UK, IT, FR, DE and USA. We thank the RSGS/ESAC, RMOC/ESOC & Rosetta Project/ESTEC for their outstanding work. Science support provided by NASA through the US Rosetta Project managed by the Jet Propulsion Laboratory/California Institute of Technology. GIADA calibrated data will be available through ESA?s PSA web site. Thanks Angioletta. This research was supported by the Italian Space Agency (ASI) within the ASI-INAF agreements I/032/05/0 and I/024/12/0. Rosetta is an ESA mission with contributions from its member states and NASA. Rosetta?s Philae lander is provided by a consortium led by DLR, MPS, CNES and ASI. Additional computational resources used in this research have been partly supplied by INAF-IAPS through the DataWell project.

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Comet 67P/Churyumov-Gerasimenko surface changes triggered by amorphous ice transformation

D. Laufer, A. Bar-Nun[1], A. Ninio-Greenberg
Department of Geophysics, Tel-Aviv University, Israel
(dianal@post.tau.ac.il, Fax +97236409282)

Abstract

Instruments on board the Rosetta spacecraft monitored the comet 67P/Churyumov-Gerasimenko (67P) during its last two-year journey through the inner solar system and mapped the surface of the nucleus at high resolution. Upon approaching the Sun, the nucleus heats up, frozen volatiles sublimate together with water and dust into the tail region. The 67P Comet activity was observed from the whole surface combined with jets from distinct sources. Our experimental study of gas-laden amorphous ice can explain gas release and jets during the heating process of the ice and the changes on the surface.

1. Introduction

The Rosetta mission findings on comet 67P/Churyumov-Gerasimenko (67P) provided the most accurate information on the composition and morphology of the nucleus. For the first time in comet research, the ROSINA instrument on board the Rosetta spacecraft, detected O_2, N_2 [2], [9] and also noble gases: Ar, Kr and Xe [7]. Our experimental studies on cometary gas-laden amorphous ice fit the direct measurements of gas release upon heating.

2. Experimental

The experiments presented in this study were performed using the experimental set-up described in [6]. The test chamber and its pump consisted of two 10 in. cryogenic pumps. The water-vapor and gas mixtures were prepared in a 2-L glass bulb. The mixtures were flowed onto a 17 cm^2 cold plate at a pressure of 10^{-6} torr and temperatures between 30-60 K. Ice layers about 50-100 μm thick were deposited during time periods of 45 min. The ice sample was warmed at a rate of 1 K min^{-1} and the gases were monitored by a quadrupole mass spectrometer.

3. Results

In this experimental study of gas-laden amorphous ice containing O_2, N_2 and Ar, were formed. Upon heating, all the gases are released from the ice together, in several temperature ranges: during the annealing process (60-100 K), the transformation to cubic ice (~140 K), the transformation to hexagonal ice (~160 K) and together with water sublimation (>160 K), (Fig. 1), as observed with gas mixtures of CO, CH_4 and Ar [1]. Two types of gas release from the ice were observed depending on the gas content in the mixture and the formation pressure: constant gas flow and jets forming "craters" and cracks in the ice layer [5]. The gas release in different temperature ranges can explain the measured heterogeneity in the coma of comet 67P [4].
Exothermic crystallization of amorphous ices could have triggered higher rates of activity on the surface of the nucleus in the past [3], [8].

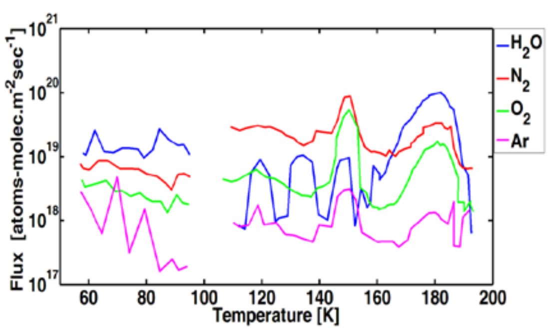

Figure 1: Gas release upon heating of O_2, N_2 and Ar from amorphous ice. Most of the gas is released during the transformation of the ice to cubic form at 140 K.

[1] Deceased, Jerusalem, 25 January 2017

4. Summary and Conclusions

Gas release form the ice rules the comet activity and surface morphology depending on the illumination conditions. The gases are released from the ice continuously and also as jets changing the nucleus surface. The gas release from amorphous ice can explain the heterogeneous coma of comet 67P/Churyumov-Gerasimenko and the surface activity as measured by ROSINA.

Acknowledgements

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Mean ions speeds in the inner coma of 67P

E. Vigren (1), A.I. Eriksson (1), E. Odelstad (1), F. Johansson (1), G. Stenberg-Wieser (2), H. Nilsson (2), P. Henri (3) and X. Vallières (3)

(1) Swedish Institute of Space Physics, Uppsala, Sweden, (2) Swedish Institute of Space Physics, Kiruna, Sweden, (3) Laboratoire de Physique et Chimie de l'Environment et de l'Espace, Orleans, France (erik.vigren@irfu.se)

Abstract

The ESA Rosetta mission followed comet 67P/Churyumov-Gerasimenko for more than two years witnessing how the cometary activity changed over distances >3.5 AU to 1.24 AU pre- and post-perihelion. Cometary ions generated by photoionization and electron-impact ionization are subject to electromagnetic fields and can be accelerated, deflected (have their trajectories confined) and can also have an oscillatory motion associated with plasma waves. At the same time, ion-neutral interactions act to interrupt ion acceleration along electric fields and to move the guiding centre of the ion's gyromotion. Knowing the mean ion velocity is relevant to test our understanding of the various processes at play in the cometary coma. Deriving the mean ion velocity from observations is, however, not straightforward with a highly negativity charged spacecraft that causes acceleration of ions towards the spacecraft. Here we combine data from three instruments within the Rosetta Plasma Consortium (RPC) - the dual Langmuir Probe (LAP), the Mutual Impedance Probe (MIP) and the Ion Composition Analyzer (ICA) - to set constraints on the mean ion velocity at the Rosetta location for different heliocentric- and cometocentric distances. From the present analysis we cannot distinguish ion drift motion from thermal/oscillatory motion.

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Evidences of Shear Deformations on Comet 67P/Churyumov-Gerasimenko: probing the internal structure of the nucleus

C. Matonti (1), N. Attree (1), O. Groussin (1), L. Jorda (1), S. Viseur (2), D. Nebouy (1), A-T. Auger (1), P. Lamy (1) and the OSIRIS team
(1) Aix Marseille Univ, CNRS, LAM, Laboratoire d'Astrophysique de Marseille, Marseille, France (matonti.christophe@free.fr), (2) Aix-Marseille Université, GEREGE, IRD, CNRS, Planétologie et Terre interne, Marseille, France.

Abstract

In this work we emphasize the occurrence of structures that can be explained by shear deformation on the nucleus of comet 67P. For supporting our interpretations we digitalized about 3000 lineaments from 11 OSIRIS-NAC images. We first show that the majority of the lineaments correspond to fractures arranged in a network characteristic of shear deformation. These deformations are preferentially located in or near the neck regions. They have likely participated in the mechanical breakdown and the erosion of the nucleus. These results may have implication for deciphering the nucleus internal structural down to hundreds of meters and for inferring the nucleus material mechanical properties.

1. Introduction

Fractures and faults are widespread and pervasive in Earth crustal and sedimentary rocks. They result from deviatoric stresses applied on brittle materials. The Rosetta spacecraft orbited comet 67P for two years and acquired images of the nucleus surface with a spatial resolution down to 20 cm/pixel.

On 67P, most of the observed fractures have been interpreted as relating to current tensile stress at the lobes boundary or to thermal stress creating isotropic meter scale polygonal fracture networks. In this work, we provide new structural interpretations of the decameter to hectometer scale lineaments observed on the surface from the OSIRIS NAC Camera images.

2. Preliminary results

Our analysis mainly focused on the Southern hemisphere of the nucleus. It is characterized by less to no dust deposits compared to the Northern hemisphere, thus exhibiting more continuous outcrops of brittle material, prone to fracturing. Lineaments were digitalized as polylines in 2D using vectorial drawing software and then projected onto the 3D surface of 67P's shape model (Fig.1).

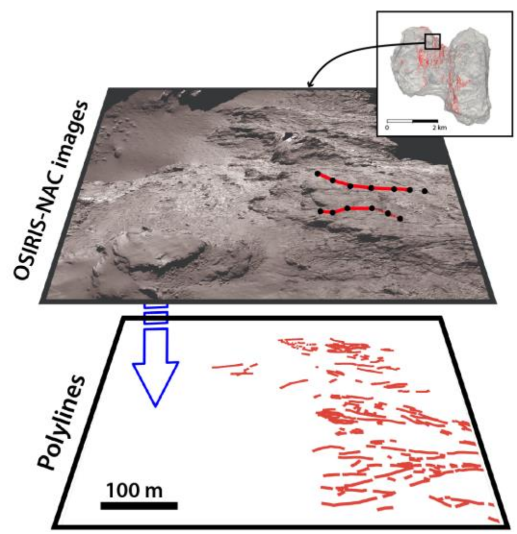

Figure 1: Example of OSIRIS-NAC image with digitalized fractures lineaments (in red).

We emphasized first that, close to the neck center, decameter to hectometer long lineaments are structural discontinuities. Indeed, they crosscut – therefore postdate– highly parallel lineaments that have been interpreted as layers (e.g. [1]). Moreover, they are arranged in patterns that nicely fit classical sheared zones structures known on Earth and telluric planets as duplexes blocks, anastomosing network or "*en-échelon*" array. These fractures are mainly composed of two sets showing two principal directions, forming an angle of about 30°, and oriented at low angle with respect to the neck middle plane. These two fracture sets directions are characteristic of Riedel P and R shear fractures [2] and are representative of mechanical parameters of the nucleus material, such as the internal friction angle. The fractures trace lengths follow a power law distribution with a slope coefficient comparable to the length distributions usually found on Earth [3].

Images of the neck borders or neck deepest point allowed the observation of these fractures along their vertical direction and to assess their occurrence to at least a depth equal to the maximum neck depth. It appears that individual fractures develop height up to 190 m and that fracture networks propagate at least down to 500 m below the surface (Fig. 2). The fracture aspect ratios (Length/Height) on the comet seem to fit of what exist on earth for unrestricted/non strata bounded fracture and faults ($2 < L/H < 3$).

Finally, in the northern hemisphere fractures seem to exhibit two principal directions, similar to those observed in the Southern hemisphere, although the fractures are less visible due to dust cover in the central neck area. The fact that all these structures are principally located near (less than 1 km from) the neck and are sub-parallel to it is consistent with an increased shear stress at the boundary between the two nucleus lobes (e.g. [4]). This could possibly be induced by torque/differential rotation forces.

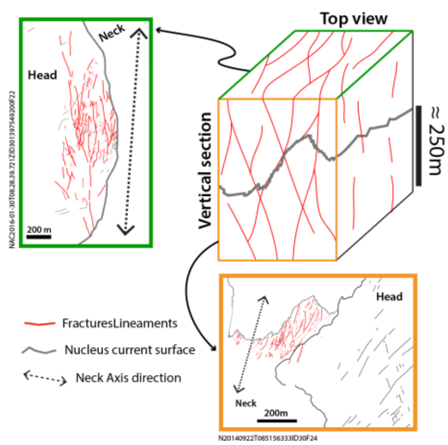

Figure 2: Conceptual scheme of the nucleus internal fractured structure.

3. Discussion on nucleus internal structure and evolution

The existence of the shear structures observed here in 3D implies the following interpretations about the nucleus structure. These are: (i) the nucleus interior is structured by decameter to hectometer fractures network; (ii) the nucleus material apparently remains sufficiently brittle below the surface to allow fracturing, even at depths of several 100's of meters; and (iii) although the nucleus material exhibits layering, it is mechanically homogenous enough for fractures to propagate freely at depth, without being stopped by mechanical boundaries.

At the Neck border, the cliff directions that follow the two main fracture directions indicate that these deformations very likely contributed to the mechanical breakdown and erosion of the nucleus and its current shape acquisition. This process might have amplified the initial neck topography through time, allowing significant erosion even in the regions exposed to less insolation, and explaining the neck asymmetry, i.e the depth difference between the Northern and Southern hemispheres.

In this work, we may thus underline the competition between two erosion processes; the local mechanical breakdown, and the broader erosion from sublimation.

Acknowledgements

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Seasonal variations of the source regions of the dust jets of comet 67P/Churyumov-Gerasimenko

I.-L. Lai (1), W.-H. Ip (1,2,3), J.-C. Lee (4), Z.-Y. Lin (2), J.-B. Vincent (5), N. Oklay (5), and the OSIRIS team
(1) Graduate Institute of Space Sciences, National Central University, Taiwan, (2) Institute of Astronomy, National Central University, Taiwan, (3) Space Science Institute, Macau University of Science and Technology, Macau,(4) Institute of Geophysics, National Central University, Taiwan, (5) DLR Institute of Planetary Research, Berlin, Germany
(ianlai@g.ncu.edu.tw)

Abstract

Because of the gas drag effect, dust grains usually accompany the outgassing process of cometary nuclei. The close-up imaging observations of comet 67P/Churyumov-Gerasimenko showed that the dust coma was filled by numerous narrow jets emanating from the nucleus surface. This means that they can be used to trace the time variation of the gas sublimation regions as the comet moved around the perihelion. Making use of the comprehensive imaging data set provided by the OSIRIS scientific camera, we show in detail how the foot points of the dust jets and hence the outgassing zone would move in consonance with the sunlit belt. Furthermore, a number of source regions characterized by frequent jet activity could be identified which might be the result of local topographical variations or chemical heterogeneities.

1. Introduction

The detailed imaging observations of comet 67P/Churyumov-Gerasimenko showed that its solar radiation driven outgassing behavior was controlled by the its bi-lobate structure of the comertary nucleus and the obliquity of 52° [1]. During the early part of the inbound orbit, only the northern hemisphere was illuminated. The subsolar point gradually shifted from north to south until the equinox on May 10, 2015. Since then the southern hemisphere became more and more active. Even though the time interval of the southern surface heating is short in comparison to the orbital period, the corresponding sublimation process has major effect on the evolution of the geomorphology of the comet itself. This means that the time evolution of the dust coma structure as traced by the total brightness and the fine structures could provide important information to this key process. During the monitoring phase of the Rosetta mission in 2014, the formation and source regions of collimated dust jets from the Hapi region were documented [5],[6],[7]. The OSIRIS observations afterwards until the end of mission in September, 2016 provide a very rich data set to examine the global phenomenon of jet formation and the corresponding time evolution.

2. Method

The standard technique used to identify the narrow dust jets and their footpoints has been applied to the characterization of the jet source distribution in several comets including comet 67P [6],[8]. After finding a jet in an OSIRIS image, the 2D image plane can be transferred to the 3D cometary rotating frame by using SPICE. The jet source should be in the plane perpendicular to the image plane containing the jet. If the same jet was observed in two sequential images taken at different viewing angles, the intersection of the two perpendicular planes to the surface defined by the SHAP5 shape model [9] will give the 3D orientation of the jet and the location of its source region.

3. Result

Figure 1 shows a surface density map of the 1584 jet sources produced by summing up all the data points by assigning a facet to be active if it is within 200 m of a jet foot point. What we see is that the northern part is less active except for the Hapi region and that a number of localized hot spots in the southern part suggesting the higher frequency of dust jet formation. In order to examine the dependence of gas sublimation rate (Z) on the local time (LT) and solar zenith angle (SZA), we have extracted numerically the LT and SZA value of the facets with jet activity. Figure 2 illustrates the LT and SZA distribution of the jet source regions. It is clear that Z follows closely the trends of the local time and solar zenith angle.

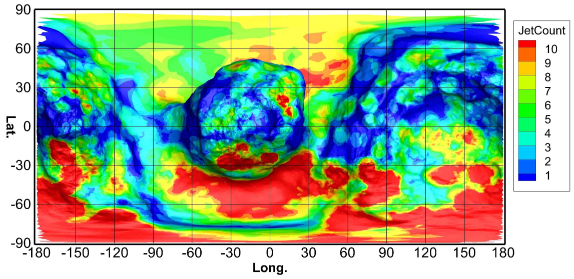

Figure 1: The surface density distribution of the 1584 jet source locations identified in our image analysis and ray-tracing calculation.

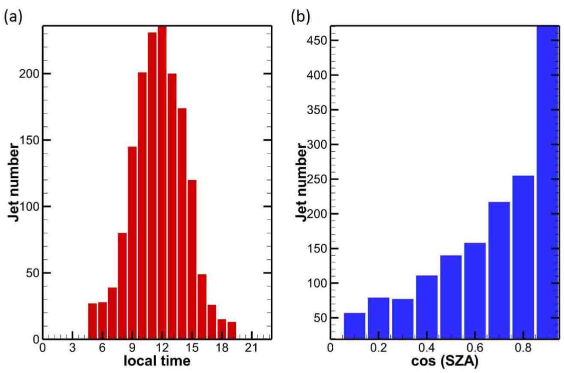

Figure 2: (a) The local time distribution of the jet sources, and (b) solar zenith angle distribution of the jet sources in our study.

4. Conclusions

We have examined the time evolution of the spatial distribution of the dust jet sources from September, 2014, to March, 2016. The observational results are very much in agreement with the idea that the surface sublimation process of comet 67P depended mainly on the local time and, alternatively, the solar zenith angle. It is reasonable to assume that the dust jet activity tracked closely the gas emission. The surface of comet 67P appears to be devoid of intrinsically inactive regions from this point of view. The shape, however, is the main driver for dust jets, as once the gas is released, the flow will be focused by the local topography. This is the main reason why jets footprints tend to fall on cliffs/pits/alcoves.

Acknowledgements

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The temporal evolution of exposed water ice-rich areas on the surface of 67P/Churyumov–Gerasimenko: thermal analysis

A. Raponi[1], G. Filacchione[1], F. Capaccioni[1], F. Tosi[1], M. Ciarniello[1], M. Formisano[1], M. C. De Sanctis[1], M. T. Capria[1], M. A. Barucci[2], A. Longobardo[1], E. Palomba[1], S. Erard[2], D. Bockelee-Morvan[2], and C. Leyrat[2]
[1]IAPS-INAF, via del Fosso del Cavaliere 100, I-Rome 00133, Italy
[2]LESIA, Observatoire de Paris/CNRS/Université Pierre et Marie Curie/Universit´e Paris-Diderot, Meudon, 75013 Paris, France

1. Introduction

Water ice-rich patches have been detected on the surface of comet 67P/Churyumov– Gerasimenko by the VIRTIS (Visible InfraRed and Thermal Imaging Spectrometer) hyperspectral imager on board the Rosetta spacecraft [1], since the orbital insertion in late 2014 August. Among these, three icy patches have been selected, and VIRTIS data are used to analyse their properties and their temporal evolution while the comet was moving towards the Sun. An extensive analysis of the spectral parameters has been performed by [2], by applying the Hapke radiative transfer model [3] to retrieve the abundance of water ice, and type of mixing. In all three cases, after the first detections at about 3.5-au heliocentric distance, the spatial extension and intensity of the water ice spectral features increased, it reached a maximum after 60–100 d at about 3.0 au, and was followed by an approximately equally timed decrease and disappearance at about 2.2 au, before perihelion (Figure 1). The behaviour of the analysed patches can be assimilated to a seasonal cycle. The similar life cycle of the three icy regions indicates that water ice is uniformly distributed in the subsurface layers, and no large water ice reservoirs are present [2].
Here we perform a thermal analysis in order to derive the total mass of water ice sublimated, and the thickness of the ice-rich layer.

2. Dataset

In the present work we take into account three large patches: the 'BAPs' (bright albedo patches) discussed by [4]: BAP1 (longitude: 118°E, latitude: 13°N), BAP2 (longitude: 180°E, latitude: −4°N), and the 'SPOT 6' (longitude: 72°E, latitude: 3°N) discussed by [5]. The surface portions that are related to patches are covered by ∼50 to ∼5000 pixels, respectively, from the least to the highest resolved acquisitions.

3. Method

We perform a thermal analysis similar to [6]: to determine the sublimated mass of the water ice we have used a latent heat of sublimation in the vacuum $h_s(T)$ as derived by solving the Clausius-Clapeyron equation as discussed in [7]:
$h_s(T) = (E + FT + GT^2)\, R_0/(10^{-3}M)$
where E, F, G, M are the water ice parameters reported by [7] and R_0 is the universal gas constant.

4. Results

We obtained an upper limit of mass of ice sublimated by assuming that i) the ice starts to sublimate from the patches at the first detection of water ice signatures, ii) the sublimation lasts until the first detection without any ice signature, iii) instantaneous sublimation rate per surface unit = solar flux / $h_s(T)$, and iv) average surface temperature derived from VIRTIS measurement. The obtained total water ice sublimeted from BAP1 is ~200 kg / m^2 (average surface temperature T=175 K for BAP 1) (Figure 2). Similar values are derived for the other two icy patches. The mass sublimated expressed as thickness of a pure water ice layer is ~20 cm.
A more accurate evaluation of the sublimating mass is in progress and shall need a full thermophysical model to describe the surface temperature variation on a daily and seasonal basis.

Acknowledgements

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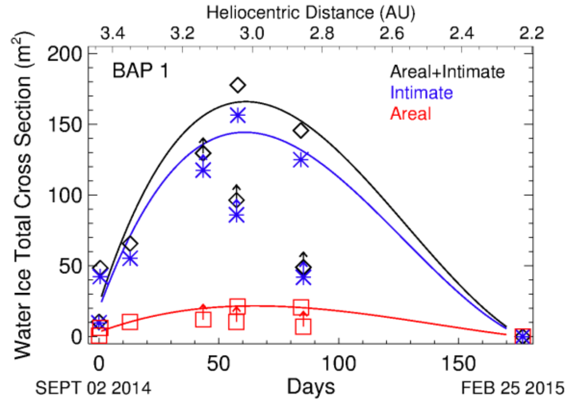

Figure 1. (extracted from [1]) total cross-section of water ice (upper right panel) is plotted as a function of time for the two types of mixtures modelled.

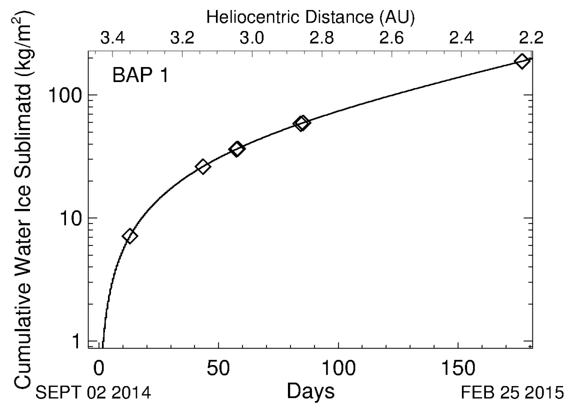

Figure 2. Cumulative water ice mass sublimated, calculated as discussed in the text. Points on the solid line represent the observation times, and correspond to the points in Figure 1.

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Physical process in the coma of comet 67P derived from narrowband imaging of fragment species

F. Pérez-López, M. Küppers, J. Marín-Yaseli de la Parra, S. Besse, R. Moissl, and the OSIRIS team.

Operations Department, Directorate of Science, European Space Astronomy Center (ESAC), European Space Agency, Camino bajo del Castillo s/n, Urb. Villafranca del Castillo P.O. Box 78 - 28691 Villanueva de la Cañada, Madrid, Spain (fperez@sciops.esa.int / T: +34-91-8131203)

Abstract

During the rendezvous of the Rosetta spacecraft with comet 67P/Churyumov-Gerasimenko, the OSIRIS scientific cameras monitored the near-nucleus gas environment in various narrow-band filters, observing various fragment species. It turned out that the excitation processes in the innermost coma are significantly different from the overall coma, as observed from the ground [1]. In particular, some of the observed emissions of fragments (daughter molecules) are created by direct dissociation of parent molecules, and in those cases the spatial distribution of the emission directly maps the distribution of parent molecules. We investigate the evolution of the brightness and distribution of the emissions over time to improve our understanding of the underlying emission mechanisms and to derive the spatial distribution of H_2O and CO_2. The outcome will provide constraints on the homogeneity of the cometary nucleus.

1. Introduction

For many decades, the observation of fragment species in the visible spectral range has been a tool to study the gas coma of comets (e.g. [2]). The creation and destruction of those molecules through fluorescence and through collisions with water molecules is now well understood for some species (e.g. H_2O -> OH or HCN -> CN). A special case are the OI lines in the green and red spectral range that are known to be largely created by prompt emission after dissociation of parent molecules into an excited state of oxygen. Their distribution therefore maps that of their parent molecules.

When Rosetta spent more than 2 years at comet 67P, the Wide Angle Camera (WAC), one of the OSIRIS scientific cameras, observed the gas coma from the onset of detectable gas activity through perihelion until the end of mission at 3.8 AU outbound. WAC observations were performed in 7 narrow band filters, targeting emissions of the daughter molecules CS (created from CS_2), OH (created from H_2O), NH and NH_2 (the parent molecule of both is NH_3) CN (a daughter molecule of HCN), Na (created from dust or a sodium bearing molecule) and OI (a product of H_2O, CO_2 and O_2). While ground-based observations typically cover the coma at spatial scales of 10000s to 100000s of km with a resolution of a few 100 km, Rosetta was most of the time between 10 km and a few hundred km from the nucleus, providing a resolution of decimetre o metre scale, at a field of view of between less than 10 km and 100 km.

2. A new emission process: Prompt emission from electron impact dissociation

Gas emission from the OSIRIS narrow band filters was detected early on, and at substantially higher intensities than expected. As the corresponding gas production rates would have been unrealistic high (compared to measurements by other instruments on Rosetta, a new process acting in the inner coma had to be found to explain the observations. Indeed, *Bodewits et al.* [1] were able to explain most of the emissions with electron impact excitation by low energy electrons in the inner coma. Notably, the emissions in some of the filters were not from the species that were expected to be seen (see Table 1). Closer to the sun, generally the known processes took over in dominating the observed emissions.

Table 1: The emissions targeted by the 7 narrow band filters of the OSIRIS WAC, the processes known from ground-based observations at those wavelengths, and the additional processes detected by OSIRIS in the very inner coma (from ref. [1]). F = Fluorescence, PD = Photodissociation followed by prompt emission, EID = Electron Impact Dissociation followed by prompt emission, RS = Resonance Scattering. In brackets: the parent and daughter molecules involved in the emission.

Emission	Known processes	Additional processes [1]
CS 257 nm	F (CS_2, CS)	-
OH 308 nm	F (H_2O, OH) PD (H_2O,OH)?	EID (H_2O, OH)
NH 335 nm	F (NH_3, NH_2 NH)	EID (H_2O, OH^+)
CN 388 nm	F (HCN, CN)	EID (CO_2, CO_2^+)
NH_2 570 nm	F (NH_3, NH_2)	?
Na 589 nm	RS (dust or Na-bearing molecule, Na)	-
O I 630 nm	PD (H_2O, O)	EID (H_2O, O) EID (CO_2, O)

3. Nucleus homogeneity from gas emissions in the very inner coma

At large heliocentric distance the newly found processes listed in Table 1 dominate the emissions seen by OSIRIS. This allows to map both, the spatial distribution of H_2O (through prompt emission of OH and OH^+ after electron impact dissociation of H_2O), and that of CO_2 (through prompt emission of CO_2^+ after electron impact dissociation of CO_2). In this way we compare the spatial distribution of the two major ices of the nucleus through the gas immediately above it. We will present those distributions and their implications on the homogeneity of the cometary nucleus.

4. Conclusions

The Rosetta mission allows for the first time to monitor gas emissions directly at the cometary nucleus. In addition to observing the physical processes in the nucleus-coma interaction region, we can deduce the localized production of various molecules as a function of position on the nucleus, providing constraints on the homogeneity of the nucleus and on its evolution over time.

Acknowledgements

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Stellar Occultations in the Coma of Comet 67/P Churyumov –Gerasimenko Observerd by the OSIRIS Camera System

R. Moissl and M.Kueppers for the OSIRIS Team

ESAC, ESA, Villanueva de la Canada, Madrid, SPAIN

Abstract

In this paper we will present the results of an analysis on a large part of the existing Image data from the OSIRIS camera system onboard the Rosetta Spacecraft, in which stars of sufficient brightness (down to a limiting magnitude of 6) have been observed through the coma of Comet 67/P Churyumov- Gerasimenko ("C-G"). Over the course of the Rosetta main mission the Coma of the comet underwent large changes in density and structure, owed to the changing insolation along the orbit of C-G. We report on the changes of the stellar signals in the wavelength ranges, covered by the filters of the OSIRIS Narrow-Angle (NAC) and Wide-Angle (WAC) cameras.

Acknowledgements

OSIRIS was built by a consortium led by the Max-Planck-Institut für Sonnensystemforschung, Göttingen, Germany, in collaboration with CISAS, University of Padova, Italy, the Laboratoire d'Astrophysique de Marseille, France, the Instituto de Astrofísica de Andalucia, CSIC, Granada, Spain, the Scientific Support Office of the European Space Agency, Noordwijk, The Netherlands, the Instituto Nacional de Técnica Aeroespacial, Madrid, Spain, the Universidad Politéchnica de Madrid, Spain, the Department of Physics and Astronomy of Uppsala University, Sweden, and the Institut für Datentechnik und Kommunikationsnetze der Technischen Universität Braunschweig, Germany.

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Water and carbon dioxide production in 67P/Churyumov-Gerasimenko: comparison with VIRTIS-M observations

M. T. Capria[1], F. Capaccioni[1], G. Filacchione[1], A. Migliorini[1], M. C. De Sanctis[1], M. Ciarniello[1], M. Formisano[1], A. Longobardo[1], G. Piccioni[1], A. Raponi[1], F. Tosi[1], D. Bockelée-Morvan[2], S. Erard[2], C. Leyrat[2]
(1) Istituto di Astrofisica e Planetologia Spaziali, INAF, Rome, Italy (mariateresa.capria@iaps.inaf.it)
(2) LESIA/Observatoire de Paris/CNRS/UPMC/Université Paris–Diderot, 75013 Meudon, France

Abstract

The VIRTIS spectrometer (1) on the Rosetta mission performed infrared observations of the coma of the comet 67P/Churyumov-Gerasimenko, detecting water and carbon dioxide emission (2). Using a thermopysical model, we compare the results of the observations with the theoretical gas production. Preliminary results show that the interior composition is probably quite homogeneous and that illumination conditions and topography can explain observations.

1. Introduction

The VIRTIS-M imaging channel detected and mapped water vapour and carbon dioxide emissions in the comet's coma from 8 to 14 April 2015 when 67P was at a heliocentric distance of 1.9 AU.
The maximum H2O emission was mainly concentrated above two active regions, Aten-Babi and Seth-Hapi, while the CO2 distribution appeared more uniform with significant emissions coming from both the "head" and southern latitude regions.
Through the use of a thermophysical model, we are willing to see if the different behaviour of water and carbon dioxide outgassing above the surface, seen in the VIRTIS-M data, might be indicative of a different thermal history of the northern and southern hemispheres of 67P or reflects instead a primordial compositional difference.

2. The method

We are using the Rome model for the thermal evolution and differentiation of nuclei in order to analyze the gas emission from the comet during the period of the VIRTIS observations in April 2015. Different hypotheses on the internal composition (abundance, homogeneity and status of the ices, layering) are considered. The code is solving the coupled heat transport and gas diffusion equations in a porous body, composed by ices and a refractory component. The illumination history of the comet and the surface topography of the nucleus are taken into account. Studying a number of different cases, we try to reproduce the observations and we derive which set of initial assumptions is giving the best match with the observations.

3. Summary and Conclusions

Preliminary analysis, restricted to this set of data, suggest that internal composition is probably quite be interpreted and reproduced by considering the thermal and illumination history of the comet along its orbit. A key element that we derive is the depth at which the active layers are to be found.

Acknowledgements

VIRTIS was built by a consortium from Italy, France, and Germany under the scientific responsibility of the Istituto di Astrofisica e Planetologia Spaziali of INAF, Rome (IT), which also led the scientific operations. The VIRTIS instrument development for ESA has been funded and managed by ASI, with contributions from Observatoire de Meudon financed by CNES and from DLR. The instrument's industrial prime contractor was former Officine Galileo, now Selex ES (Finmeccanica Group) in Campi Bisenzio, Florence, IT.

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Distributed sources for the hydrogen halides in the coma of comet 67P/Churyumov-Gerasimenko

Johan De Keyser (1,2), **Frederik Dhooghe** (1), Kathrin Altwegg (3,4), Hans Balsiger (3), Jean-Jacques Berthelier (5), Christelle Briois (6), Ursina Calmonte (3), Gaël Cessateur (1), Michael R. Combi (7), Eddy Equeter (1), Björn Fiethe (8), Stephen Fuselier (9,10), Sébastien Gasc (3), Andrew Gibbons (1,11), Tamas Gombosi (7), Herbert Gunell (1), Myrtha Hässig (3,9), Léna Le Roy (4), Romain Maggiolo (1), Urs Mall (12), Bernard Marty (13), Eddy Neefs (1), Henri Rème (14,15), Martin Rubin (3), Thierry Sémon (3), Chia-Yu Tzou (3) and Peter Wurz (3,4)
(1) Royal Belgian Institute for Space Aeronomy, BIRA-IASB, Brussels, Belgium,
(2) Center for mathematical Plasma Astrophysics, KULeuven, Belgium,
(3) Physikalisches Institut, University of Bern, Switzerland,
(4) Center for Space and Habitability, University of Bern, Switzerland,
(5) LATMOS/IPSL-CNRS-UPMC-UVSQ, France,
(6) LPC2E, Université d'Orléans, France,
(7) Department of Climate and Space Sciences and Engineering, University of Michigan, Michigan, USA,
(8) Institute of Computer and Network Engineering, TU Braunschweig, Germany,
(9) Space Science Directorate, Southwest Research Institute, Texas, USA,
(10) University of Texas at San Antonio, Texas, USA,
(11) Service de Chimie Quantique et Photophysique, Université Libre de Bruxelles, Belgium,
(12) Max-Planck-Institut für Sonnensystemforschung, Germany,
(13) Centre de Rech. Pétrographiques et Géochimiques, Univ. Lorraine, France,
(14) Université de Toulouse, UPS-OMP, France,
(15) Institut de Recherches en Astrophysique et Planétologie, CNRS-IRAP, France.
(frederik.dhooghe@aeronomie.be)

Abstract

Rosetta has detected the presence of the hydrogen halides HF, HCl, and HBr in the coma of comet 67P/Churyumov-Gerasimenko. Analysis of the abundances of HF and HCl as a function of cometocentric distance suggests that these hydrogen halides are released both from the nucleus surface and off dust grains in the inner coma. We present three lines of evidence. First, the abundances of HF and HCl relative to the overall neutral gas in the coma appear to increase with distance, out to ∼200 km, indicating that a net source must be present; since there is no hint at any possible parent species for HF and HCl with sufficient abundance, dust grains are the likely origin. Second, the amplitude of the daily modulation of the halide density due to the rotation and geometry of 67P's nucleus and the corresponding surface illumination is observed to progressively diminish with distance; this can be understood from the roughly omnidirectional outgassing from grains as well as from the range of grain speeds well below the neutral gas expansion speed, which both tend to smooth the coma density profiles. Third, strong halogen abundance changes detected locally in the coma cannot be easily explained from composition changes at the surface, while they can be understood from differences in local gas production from the grains near the spacecraft.

1. Introduction

Rosetta has provided the in situ detection of halogens in a cometary coma, that of 67P/Churyumov-Gerasimenko. Neutral gas mass spectra collected by the ROSINA/DFMS mass spectrometer on the European Space Agency's Rosetta spacecraft indicate that the main halogen-bearing compounds are HF, HCl and HBr. The bulk elemental abundances relative to oxygen are typical of those of the protosolar nebula. The observations point to an origin of the hydrogen halides in molecular cloud chemistry, with frozen hydrogen halides on dust grains, and a subsequent incorporation into comets as the cloud condensed and the solar system formed.

2. Evidence for distributed sources

A detailed analysis of the abundances of the hydrogen halides detected in the coma has been performed.

These abundances depend on the total gas production rate, the comet-Sun distance, the spacecraft-comet distance, the phase angle, and the latitude and longitude of the spacecraft relative to the nucleus. The effects of all these parameters have been disentangled and lead to three important findings.

A first result is that the halogen abundance relative to the total gas production tends to increase with distance within roughly 200 km from the nucleus. This points to the existence of an additional source of neutral hydrogen halides in the inner coma. Note that photo-dissociation and/or other loss processes can be neglected in this region. Since no other halogen-bearing species have been detected by DFMS in sufficient quantities, the plausible conclusion is that these hydrogen halides are progressively released from grains in the inner coma.

A second observation is that the daily abundance variations seen in the overall neutral gas production are also present for the hydrogen halides in measurements close to the nucleus, but they disappear at larger distances. This suggests that part of the hydrogen halides sublimates from the nucleus, but the major part is released from the grains which are distributed more evenly in the coma.

Finally, we occasionally observe strong local changes in composition, which are hard to explain in terms of inhomogeneities on the nucleus surface since DFMS at any instant observes material originating from all over the illuminated surface of the comet. An explanation in terms of a local source from dust jets, however, seems plausible.

3. Summary and Conclusions

A careful analysis of hydrogen halide abundance measurements by Rosetta/ROSINA provides several lines of evidence that suggest that a distributed source for the hydrogen halides exists in the inner coma.

Thermal desorption of the hydrogen halides apparently occurs at higher temperatures than the bulk of the neutral coma gas (especially H_2O, CO, CO_2). This is in line with the observed depletion of the halogen content in molecular clouds, where they are believed to be frozen out on the grains even when H_2O, CO, CO_2 are still present in the gas phase. The precise nature of the hydrogen halide reservoir on the grains is still unknown at present.

Acknowledgments

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Summer outbursts in the coma of 67P/Churyumov-Gerasimenko as observed by VIRTIS-M

G. Rinaldi[1], D. Bockelee-Morvan[2], M. Ciarniello[1], G. P. Tozzi[3], F. Capaccioni[1], , G. Filacchione[1], U. Fink[4], L. Doose[4], A. Raponi[1], M. T. Capria[1] , S. Erard[2], C. Leyrat[2], A. Longobardo[1] , F. Taylor[5] ,

[1] INAF-IAPS Istituto di Astrofisica e Planetologia Spaziali, Rome, Italy.
[2] LESIA, Observatoire de Paris, LESIA/CNRS, UPMC, Université Paris-Diderot, 92195, Meudon, France;
[3]INAF - Osservatorio Astrofisico di Arcetri, Firenze, Italy;
[4] Lunar Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA;
[5] Departement of Physics, Oxford University, Oxford, UK;

1- Introduction

The Rosetta/ESA spacecraft followed the comet 67P/Churyumov-Gerasimenko (hereafter 67P/CG) from 2014 August (3.6 au pre-perihelion) to 2016 September (3.6 au post-perihelion). This offered a unique opportunity to follow closely a comet during the most active part of its nucleus. Onboard Rosetta, the Visual Infrared and Thermal Imaging Spectrometer (VIRTIS-M, Coradini et al. 2007) in the spectral range 0.25 to 5µm, acquired a relevant amount of dust coma measurements. In this work, we present an analysis of the outbursts observed by VIRTIS-M for the dates of August 10, September 13 and 14 2015, when the comet was at heliocentric distances of -1.2 AU (inbound) to 1.3 AU (outbound), 2 day before and one month after the perihelion passage respectively. The dust properties of the outbursts are discussed in terms of spatial distribution, temporal evolution and surface location. We also analyze dust physical properties such as total dust mass loss, reflectance and color.

2- Outburst properties

The outbursts on 67P/CG occur at typically rate of one every 2.4 cometary rotation in the daylight side of the nucleus (Vincent at al. 2016). They are characterized by a sudden and short increase of the dust emission, from localized areas with variable degree of collimation, followed by a sweet decrease of activity. The lifetime is between 5 and 15 minutes and the corresponding radiance at 0.55 µm is typically of the order of 10^{-2} – 1 Watt/m^2/str/µm, i.e. 10-20 times larger than the surrounding coma. VIRTIS-M identified 2 main dust plumes morphologies associated to these events: a narrow jet (September 13, Fig.1) and a broad plumes (August 10 and September 14, Fig.2). On Sept. 13 and 14 the comet produced 3 and 2 consecutive outbursts, respectively.

On September 13 the spatial and temporal distribution of the dust indicates a complex pattern for each event showing internal structures (Fig.1, first panel).

We analysed the map locations of these events and we found that broad emission are likely from the Imhotep region and the collimated ones originate from the neck region. It seems that the spatial distribution of outbursts locations on the nucleus correlates well with local topography.

In Fig.3 we report a color image corresponding to the 2015 September 13 (upper panel) and 14 (lower panel) events. We found clear evidence of different colour values in the ouburst with respect to the surrounding coma. In the range of 0.45-0.75 µm, the spectral slope shows a lower value for the outburst material in the range 10-12 % per 100 nm, than the values in the background, in the range 15-16 % per 100 nm (Fig.3 upper panel). A peculiar case is the September 14 large outburst. In the color map (Fig.3 lower panel), the front of the outburst is bluer than the rest of the coma, with values of 4.0-7.0 %/100nm. The color corresponding to peak of the maximum intensity is around 7 %/100nm, while at smaller levels of the radiance it is of the order of 10.0 – 14.0 %/100nm. The same color behavior has been observed by VIRTIS-H on the IR channel. Bockelee-Morvan et al. (2017, submitted) found that the evolution of the color in the IR channel reaches the extreme value of -10 %/100nm at the peak of intensity, returning to the pre-outburst value of about 2.5 %/100nm. The color variation can be explained as a change of size distribution, with the front part dominated by smallest particles which are accelerated faster from the gas drag. This implies that we observed dust with different physical characteristics both in the structures and in the coma.

The comparison between IR (VIRTIS-H) and VIS (VIRTISM) observations allows to derive the projected velocity of the small dust grain obtaining 23 -40 m/s.

It is also possible to estimate the total mass loss in the outburst, by converting the radiance over an image to a dust cross section, and then to mass assuming a dust size distribution with a power law index of -3. For September 14 large event we estimated a total ejected dust mass of few tens tons as found by Vincent et al. 2016.

Further analysis will be presented during the congress.

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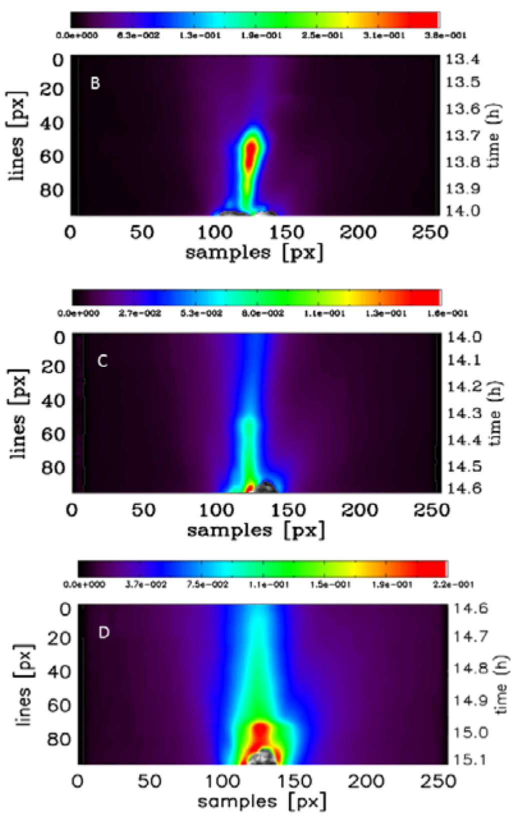

Fig. 1. The distribution of dust radiance at 0.55 µm. for the images acquired on 2015 September 13, showing the nucleus, the surrounding coma and outburst (collimated jet). Color bars have units of Watt/m2/str/µm.

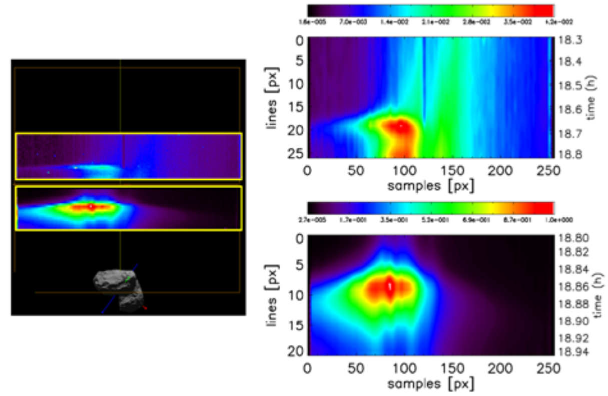

Fig. 2. Spatial distribution of dust continuum at 0.5µm for 2015 September 14. The image on the left shows the configuration of the nucleus of the comet with respect to the VIRTIS-M frames (yellow rectangle). The images on the right show the spatial distribution of dust radiance at 0.5µm.

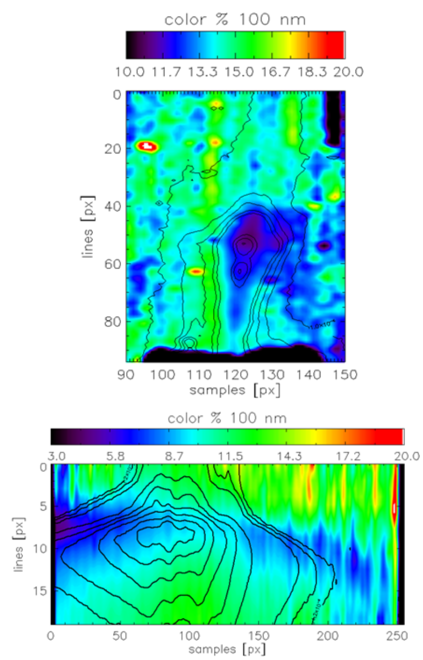

Fig.3 Color image corresponding to the September 13 (upper panel) and 14 (lower panel) 2015. The black contour levels are the radiance at 0.55 µm.

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V. Della Corte (1,2), A. Rotundi (1,2), M. Fulle (3), S. Ivanovski (2), J. Agarwal(4), E. Gruen(5) and The International GIADA Team
(1) Dip. Scienze e Tecnologie, Universitá deli Studi di Napoli "Parthenope", Napoli, Italy, (2) IAPS-INAF, Roma, Italy, (3) OAT-INAF, Trieste, Italy, (4) Max Planck Institute for Solar System Research, Justus-von-Liebig-Weg 3, 37077 Göttingen, Germany, (5) Max Planck Institute for Nuclear Physics, Saupfercheckweg 1, 69117 Heidelberg, Germany; (vincenzo.dellacorte@uniparthenope.it)

Abstract

GIADA (Grain Impact Analyzer and Dust Accumulator), an in-situ instrument onboard Rosetta [1], monitored the dust environment of comet 67P/Churyumov-Gerasimenko. GIADA is composed of 3 sub-systems: 1) the Grain Detection System (GDS), based on particle detection through light scattering; 2) the Impact Sensor (IS), measuring particles momentum; 3) the Micro-Balances System (MBS), constituted of 5 Quartz Crystal Microbalances (QCMs), giving cumulative deposited dust. The combination of the measurements performed by these 3 subsystems provides: number, mass, momentum and speed distribution of dust particles ejected from the comet nucleus. We present the coma dust environment as observed by GIADA during the outburst event occurred on the 5th of September 2016, few days before Rosetta landing on comet 67P/Churyumov-Gerasimenko. GIADA observed dust density temporal and spatial variation from a very close distance (<5km from the comet surface) during this brief and intense event. The three GIADA subsystems, MBS, GDS and IS recorded data with relevant statistics. In few hours, a very large number of dust particle detections allowed to characterize the dust environment in the size ranges from few microns to millimeters.

1. Introduction

One of the Rosetta mission target was to disentangle the normal cometary activity from specific active areas inducing peculiar high activity features in order to understand their origin. Rosetta observed sudden and transitory features characterized by high dust and gas loss defined as "outbursts" [2] [4]. Morning outbursts have been explained by thermal stresses while afternoon events have been associated to heat wave reaching buried volatiles, some events can result from the collapse of cliffs [4]. Additional stored energies prompting the outbursts are suggested to be pressurised sub-surface gas reservoirs or the crystallisation of amorphous water ice [2].

2. Data

At the end of the ROSETTA mission GIADA recorded a very low particle detection rate with the exception of the 5th September 2016 spike. From 17:40 to 20:30 UT, GIADA experienced an exceptional increase in the dust counts. The detected dust events and the MBS frequency shifts, convertible in dust mass deposited on the sensors, are reported in Table 1.

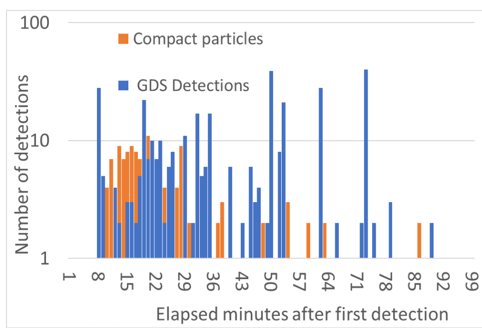

Figure 1: Dust particle detections per minute recorded by GIADA during the 2016 September 5 outburst. Compact (orange) and fluffy (blue) particle detections show different detection rates with respect to time: the compacts are present with high counts at the beginning of the event while the fluffy particle detections are spread along the whole event.

3. Results

GIADA observed two different types of particles in the 67P coma: compact particles [5] and fluffy porous aggregates [6]. During the outburst, GIADA detected both particle types but differently distributed in time, as shown in Fig. 1. The plot shows the number of detection per type as a function of the elapsed time since the initial GIADA detection of the outburst, which was at first detected by the MBS: as expected, the small particles reached GIADA before the larger ones, detected by the GDS and IS. Compact particles show a high rate during the first 30 minutes of the event. The GDS-only multiple detections ("dust showers" – [6]), i.e. fluffy aggregates, with isolated GDS detections, i.e. particles characterised by a highly non-radial velocity or with a momentum below the IS sensitivity, are spread over the outburst duration. The geometry of the detections shows that dust emitted during the outburst cover an angle of about 60 deg and are not correlated with the nucleus rotation. The masses and speeds of the compact particles show a clear temporal evolution after a rapid increase in the first minutes of the outburst both particle masses and speeds decrease. The smallest particles (<10 microns diameter) measured by the MBS show higher speeds and extremely collimated trajectories: the mass accumulated on the MBS during the first 10 minutes of the event.

Table 1: Dust counts obtained for each subsystem measurement.

GDS-only	IS-only	GDS-IS	QCM4	QCM5
759(*)	136	74	25Hz(**)	10Hz(**)

4. Summary and Conclusions

The GIADA dust environment continuous monitoring allowed us to detect an outburst at the end of the Rosetta mission, when the dust activity was very low as 67P was at heliocentric distances greater than 3.5 au. Thanks to the close distance to the comet surface GIADA, providing the most complete dataset of the entire mission, allowed a complete physical and dynamical characterization of this peculiar dust event.

Acknowledgements

GIADA was built by a consortium led by the Univ. Napoli "Parthenope" & INAF- Oss. Astr. Capodimonte, IT, in collaboration with the Inst. de Astrofisica de Andalucia, ES, Selex-ES s.p.a. and SENER. GIADA is presently managed & operated by Ist. di Astrofisica e Planetologia Spaziali-INAF, IT. GIADA was funded and managed by the Agenzia Spaziale Italiana, IT, with a support of the Spanish Ministry of Education and Science MEC, ES. GIADA was developed from a PI proposal supported by the University of Kent; sci. & tech. contribution given by CISAS, IT, Lab. d'Astr. Spat., FR, and Institutions from UK, IT, FR, DE and USA. We thank the RSGS/ESAC, RMOC/ESOC & Rosetta Project/ESTEC for their outstanding work. Science support provided by NASA through the US Rosetta Project managed by JPL/California Institute of Technology. GIADA calibrated data will be available through the ESA's PSA web site.

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Temporal evolution of comet 67P/Churyumov-Gerasimenko's surface as observed by VIRTIS-M

M. Ciarniello (1), G. Filacchione (1), F. Capaccioni (1), A. Raponi (1), M. C. De Sanctis (1), F. Tosi (1), M. T. Capria (1), M. Formisano (1), S. Erard (2), D. Bockelee-Morvan (2), C. Leyrat (2), G. Arnold (3), M. A. Barucci (2), E. Quirico (4), S. Fornasier (2), D. Kappel (3), A. Longobardo (1), B. Rousseau (2), S. Mottola (3) and the VIRTIS-Rosetta Team

(1) INAF-IAPS, Rome, Italy (mauro.ciarniello@iaps.inaf.it), (2) LESIA, Meudon, France, (3) DLR Institute for Planetary Research, Berlin, Germany, (4) Universitè Grenoble Alpes, CNRS, IPAG, France.

Abstract

We report about the seasonal evolution of 67P/Churyumov-Gerasimenko's (hereafter 67P) surface as inferred from VIRTIS-Rosetta measurements. We analyze observations performed from August 2014, when the comet was at a heliocentric distance of ~3.5 AU along the inbound part of the orbit, up to the end of the Rosetta mission in September 2016, when 67P was at ~3.8 AU outbound.

1. Introduction

The Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) [1] on board the Rosetta spacecraft acquired disk-resolved images of the nucleus of comet 67P for more than two years from August 2014 to September 2016. The observation campaigns took advantage of both the visible (VIS) and infrared (IR) channels of the instrument covering the 0.25-5.1 μm spectral range up to early May 2015 and by means of solely the VIS channel (0.25-1 μm) for the remaining part of the mission. We were able to investigate the spectral properties of 67P's surface as a function of the heliocentric distance following the comet approaching the Sun from ~3.5 AU to perihelion (~1.2 AU) and then along the outbound part of the orbit up to ~3.8 AU. Throughout this period, the surface evolution was further complicated by the combination of the relatively large orbital eccentricity, of the irregular shape of 67P's nucleus and of the inclination of its rotational axis (52° [2]), which amplify the seasonal effects.

2. Method

The long-term spectral variability of 67P's nucleus is described by means of spectral indicators as defined in [3,4]. These are computed after thermal emission removal at infrared wavelengths and reduction of reflectance spectra to single scattering albedo (SSA) [5], which minimizes observation and illumination geometry effects (Fig. 1). The spectral indicators are represented by the spectral slopes in the VIS (0.55-0.8 μm) and IR (1.2-2.0 μm) wavelength ranges, the single scattering albedo at 0.55 μm and the band area and band center of the 3.2 μm absorption feature. These quantities are projected onto latitude-longitude maps at different mission times, in order to monitor both spatial and temporal variations (Fig. 2). In parallel, the evolution of selected areas on 67P's surface is followed to monitor local variability.

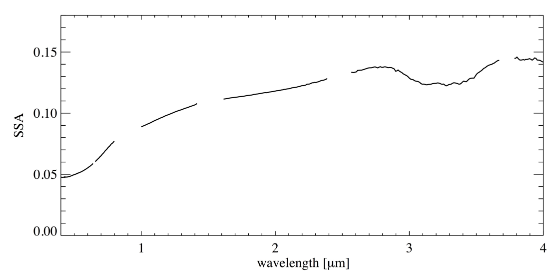

Figure. 1. Average SSA spectrum of 67P's surface. Missing parts in the curve correspond to instrumental order sorting filters and to the VIS-IR channels junction at ~1μm. 67P's spectrum has been interpreted as a mixture of refractory organics, fine-grained opaque materials (Fe-sulfides, Fe-Ni alloys) and a semi-volatile component (ammonium-bearing species and carboxylic acids) [6].

3. Preliminary results

The analysis of the VIS slope from observations taken from August 2014 to August 2016, corresponding to the Rosetta mission Medium Term Planning (MTP) observation phases from MTP006 to MTP035, indicates a progressive reduction (blueing) while the comet was approaching the Sun during the inbound orbit leg. The maximum blueing is reached in September 2015 (MTP20) just after perihelion passage (13 August 2015), followed by a slope increase (reddening) along the outbound leg. This is in agreement with the seasonal color variations reported by OSIRIS [7]. During the outbound leg of the orbit the reddening of the surface reached its maximum approximately around March-April 2016 (MTP027-MTP028), exceeding the largest values measured during the early observations on the inbound leg. Then, the VIS slope progressively decreases across the surface until the last available measurements (MTP035, ~3.8 AU outbound) to the values derived at the beginning of the observations (MTP006, ~3.5 AU, inbound).

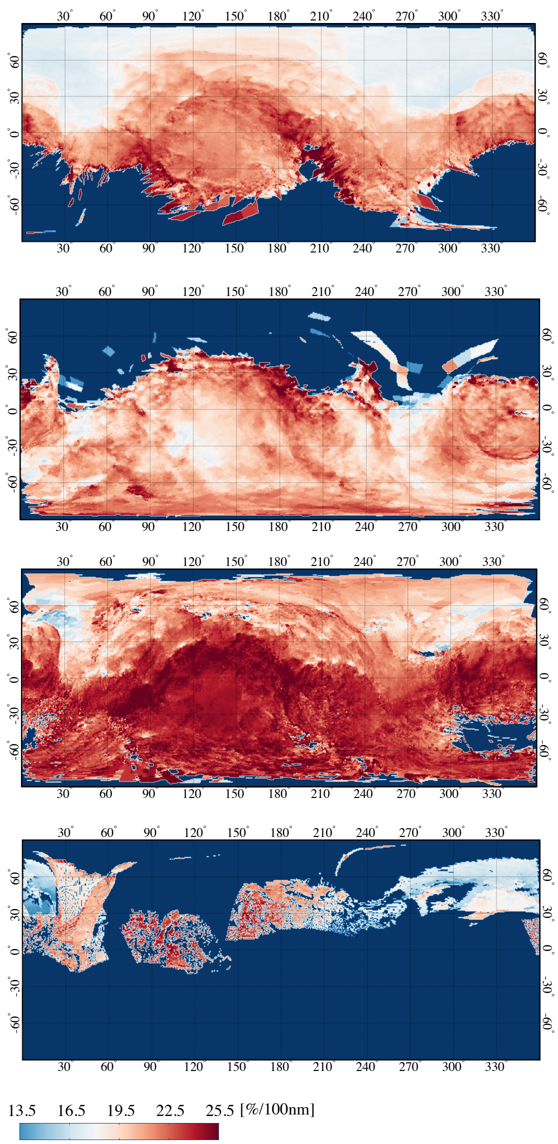

Figure 1. VIS slope maps at different observation phases from top to bottom: MTP006 (August 2014, ~3.5 AU inbound), MTP019 (August 2015, ~1.25 AU), MTP028 (April 2016, ~2.8 AU) and MTP035 (September 2016, ~3.8 AU).

These observations suggest that 67P's surface spectral properties follow a seasonal cycle related to the surface variability of the water ice content. While approaching the Sun the increasing activity removes dust from the top layers exposing the former sub-surface, which contains larger amounts of ice, and the spectra exhibit smaller VIS spectral slopes [3,4,7]. This is corroborated by the accompanying variation of the IR spectral indicators, when available [3,4]. The spectral reddening after perihelion, following the reduction of the activity, can be explained by a deposition of dust grains expelled from the Southern Hemisphere which is experiencing summer at this time, thus mantling the nucleus. Along with this, another possible mechanism, which has yet to be validated by thermophysical modeling, can be represented by a progressive depletion of the surface water ice content due to sublimation, if the timescale of replenishment from the deeper layers is larger than the sublimation rate. In this case, when the comet is at relatively large heliocentric distances (September 2016, ~3.8 AU) and the sublimation rate decreases, water ice from the interior becomes newly available on the top layers, blueing the surface again.

4. Acknowledgements

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CHARACTERISTICS OF CIRCULAR FEATURES ON COMET 67P/CHURYUMOV-GERASIMENKO

J. F. Deller (1*), C. Güttler (1), C. Tubiana (1), M. Hofmann (1), H. Sierks (1) and the OSIRIS team(2)

(1) Max Planck Institute for Solar System Research (Justus-von-Liebig-Weg 3, D-37077 Göttingen),
(2) MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA; (*Email:deller@mps.mpg.de)

Abstract

Comet 67P/Churyumov-Gerasimenko shows a large variety of circular structures such as pits [5], elevated roundish features in Imhotep [1], and even a single occurrence of a plausible fresh impact crater [4]. Imaging the pits in the Ma'at region, aiming to understand their structure and origin drove the design of the final descent trajectory of the Rosetta spacecraft. The high-resolution images obtained during the last mission phase allow us to study these pits as exemplary circular features. A complete catalogue of circular features gives us the possibility to compare and classify these structures systematically.

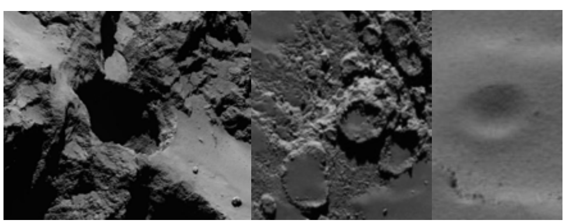

Figure 1 Pit in Seth region (left). Elevated roundish features in Imhotep (centre). Potential fresh impact crater in the Ash region (right).

1. Classes of circular features on comet 67P/Churyumov-Gerasimenko

The comet shows a large variety of circular features. While the pits are certainly the most prominent ones (Fig. 1 left, Fig. 2), with sizes ranging from 50 to 310 m [5], there are also intriguing elevated circular structures found in the Imhotep region (Fig. 1, centre). Their sizes range between 2 and 59 m, without any characteristic size dominating [1]. The fact that all these features seem to be confined to specific regions on the comet [2] poses questions about their origin. We will present a full inventory of all circular features found on the comet to test which of these features could be a different occurrence of the same morphological process.

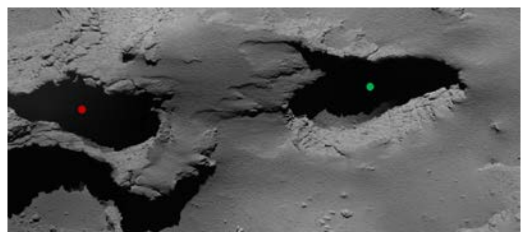

Figure 2 Composite image of Ma'at pit 'E' (red dot) and the Deir el-Medina pit (green dot) in the Ma'at Region imaged during Rosetta's final descent.

2. Possible origin and evolution of pits, at the example of the Ma'at pits

Both pits imaged during final descent in the Ma'at region have been observed as sources of activity early in the mission [5]. In the 2.5 years of the Rosetta mission, no major morphological changes to pits have been observed, and jet activity is found not to be primarily originating from specific features. We will reassess the available observational evidence to test the plausibility of pit formation scenarios proposed as a sinkhole collapse mechanism [5] or a sinkhole collapse mechanism followed by mass wasting of the surrounding material [3]. Using numerical impact experiments we will assess a possible impact origin of the pits as well as the elevated features in Imhotep.

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