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Oxygen Isotopes in Water in the Coma of Comet 67P / Churyumov-Gerasimenko as measured with the Rosetta / ROSINA Double Focusing Mass Spectrometer

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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, 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 494 ± 8, which is consistent within 1σ uncertainty with the terrestrial value of 499 calculated by Lodders (2003) [4], but not with the ratio of 530 ± 2 measured for the solar wind by McKeegan et al. (2011) [5].

In this study, the ^{16}O **/** ^{18}O ratio of H_2O in the coma of the comet 67P, as measured by the Rosetta **/** ROSINA DFMS, was found from the ratio of H_2O **/** $H_2{}^{18}O$ to be 445 ± 35, which represents a 12% enrichment of ^{18}O compared with the terrestrial value [4] of 499 and would be consistent with the comet containing primordial water, in accordance with leading self-shielding models, which hypothesise primordial water to be between 5% to 20% more enriched in the heavier oxygen isotopes than terrestrial water [6].

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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Exploring the Compositional Heterogeneity of Dust Particles of 67P/Churyumov-Gerasimenko

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Abstract

Dust particles in the inner coma were collected in-situ by dust instruments onboard ROSETTA, the ESA mission orbiting and traveling along comet 67P/Churyumov-Gerasimenko from August 2014 to September 2016. One in-situ dust instrument, the COmetary Secondary Ion Mass Analyser (COSIMA), had applied the laboratory techniques of optical microscopy and secondary ion mass spectrometry (SIMS) to in-situ measurements of cometary particles collected between 1.25 and 3.8 AU. These particle agglomerates were captured on metal targets and imaged and identified in-situ with the COSIMA microscope COSISCOPE. Collected secondary ions reflect the composition of the elements and molecules on the surface particle area bombarded by the primary ion beam. The interpretation of the spectra requires knowledge of the stable molecular ions as well as statistical methods analyzing and comparing mass spectra. Within the inner coma, particles were captured at low velocities and the optical images and SIMS revealed particle agglomerates of various morphologies and compositions. We will present particle compositions in view of the particle population heterogeneity and will discuss their impact on selected comet evolution 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 1801), France (CNES), Austria and Finland. Rosetta is an ESA mission with contributions from its Member States and NASA.

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On the dust properties and dynamical evolution of the near-Earth Jupiter family comet 41P/Tuttle-Giacobini-Kresak

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Abstract

We present a study of the evolution of the dust environment of the near-Earth Jupiter family comet (hereafter NEJFC) 41P/Tuttle-Giacobini-Kresak, based on observational data obtained using TRAPPIST telescopes from January to July, 2017. In addition, we performed numerical simulations to constrain its origin and dynamical nature. These results have been recently accepted for publication in [1].

1. Introduction

Thanks to the Rosetta mission, our understanding of comets has greatly improved. A very good opportunity to apply this knowledge appeared in early 2017 with the near-Earth Jupiter family comet 41P, which during its perihelion passage was only 0.15 au from the Earth. It was then that it attracted international attention and many observatories started to monitor its behaviour. We performed long-term monitoring of 41P using the TRAPPIST telescopes [2]. For our dust modelling purposes, we used the broad-band R Johnson-Cousin filter. The observational campaign lasted from January 20 to July 27, 2017. During that period we obtained 30 photometric nights of observations that were used in our analysis.

2. Results

2.1 Dust model

To model the observational data set we used a Monte Carlo dust tail model [3], which allowed us to derive the time-evolution of the dust parameters: dust production rate, the size distribution and ejection velocities of the dust particles, and its emission pattern. Our main result was that it is not possible to explain the complete set of observations using a full isotropic ejection model. In fact, we found that a complex ejection pattern which switched from full isotropic to anisotropic (February 24-March 14), and then back from anisotropic to full isotropic again on June 7-28 provides the best description of the observations (Fig 1), we called this model *hybrid model*. During the anisotropic period, we found that $\sim$ 90% of the ejected particles came from two strongly active areas, one located in the northern hemisphere and the other in the southern. This model is in agreement with the recent discovery of the fast rotational period variation reported by [4] from March to May, 2017, in the sense that the two powerful active areas could have acted as brakes, increasing the nucleus rotation period. In general terms, from the dust model we obtained that the total dust mass ejected is $\sim 7.5 \times 10^8$ kg. This quantity is roughly the total dust ejected by the comet during the whole orbit. This amount of dust is low compared to other comets of the same family; however, 41P is a small comet, and this quantity represents a non-negligible fraction of its total mass. This implies that 41P suffered a substantial amount of erosion during its last incursion to perihelion. From observations of gases also performed with TRAPPIST telescopes we found that the dust-to-water mass ratio was low ranging from 0.25 to 1.5.

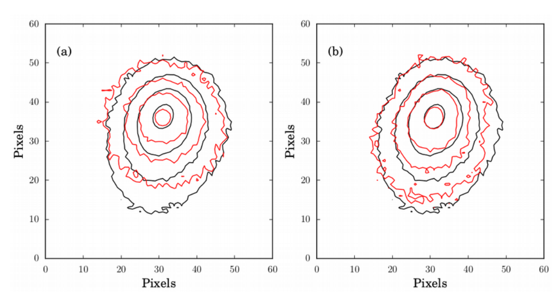

Figure 1: Comparison between full isotropic model (a), and hybrid model (b).

2.2 Dynamical analysis

The main reason for studying the dynamical evolution of comet 41P is to understand how long this comet has been suffering its current rate of erosion, and for how long it will continue. Comet 41P is a NEJFC, that is, a JFC with a perihelion distance of q < 1.3 au. The recent work by [5] revealed a subgroup among NEJFCs that reside in highly stable orbits, with a likely origin in the main asteroid belt. This new class of objects could be the counterparts to the Main Belt Comets, that is, they may be asteroids disguised as comets. In order to clarify the dynamical nature of 41P, we performed numerical integrations following the same steps given by [5], where a likely dynamical path is defined as the average of the set of results obtained for a given object and its clones, characterised by the f_q index, f_a index, the capture time, t_{cap} ,and the closest approach to Jupiter, d_{min}. To perform this analysis we made use of the numerical package MERCURY6, where the Sun and the eight planets were included in the simulation. We obtained that $f_q \sim 0.02$, $f_a \sim 0.005$, $t_{cap} \sim 10^4$ yr and $d_{min} \sim 0.20$ au. This indicates that 41P is more stable in its orbit than typical a JFC, and it belongs to the Moderately Asteroidal category defined in [5]. With two extra experiments we obtained that 3600 yr is the period of time during which 41P will belong to NEJFCs (Fig 2.).

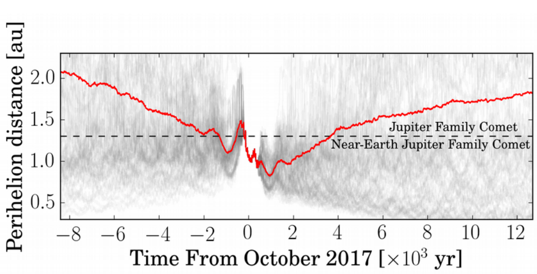

Figure 2: Evolution of the perihelion distance of 41P.

3. Summary and Conclusions

From our dust analysis we found that 41P is a dust-poor comet compared with other JFCs, with a complex ejection pattern which switched from full isotropic to anisotropic sometime during February 24-March 14 in 2017, and then back from anisotropic to full isotropic again between June 7-28. During the anisotropic period, the emission was controlled by two strong active areas, where one was located in the southern hemisphere and the other in the northern hemisphere of the nucleus. The total dust mass loss is estimated to be roughly 7.5×10^8 kg. From the dynamical simulations we estimated that about 3600 yr is the period of time during which 41P will remain in a similar orbit. Taking into account the estimated mass loss per orbit, after 3600 yr, the nucleus may lose about 30% of its mass. However, based on its dust-to-water mass ratio and its propensity to outbursts, the lifetime of this comet could be much shorter.

Acknowledgements

This work is supported by a Marie Curie CO-FUND fellowship, co-founded by the University of Liège and the European Union. TRAPPIST-South is funded by the Belgian Fund for Scientific Research (Fond National de la Recherche Scientifique, FNRS) under the grant FRFC 2.5.594.09.F, with the participation of the Swiss FNS. TRAPPIST-North is a project funded by the University of Liège, and performed in collaboration with Cadi Ayyad University of Marrakesh.

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Modelling the inner coma of comet 67P/Churyumov-Gerasimenko

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Abstract

Based on about 1 million of pressure measurements around comet 67P/Churyumov-Gerasimenko we reconstruct the gas emission across the entire nucleus. Dust particles are seeded in the gas model and the resulting dust distribution follows a daily pattern which agrees with observations if a uniform dust release across the entire sunlit surface is assumed.

1. Introduction

The long-term evolution of the cometary coma from in-situ measurements by ROSINA on-board of the Rosetta spacecraft provided a unique opportunity to retrieve the gas and dust emission from an active cometary nucleus. We have taken a collisionless gas model, which incorporates the detailed bi-lobed shape of the nucleus and serves as the starting point for a simulation of the dust emission from the surface.

2. Distribution of gas sources on the surface

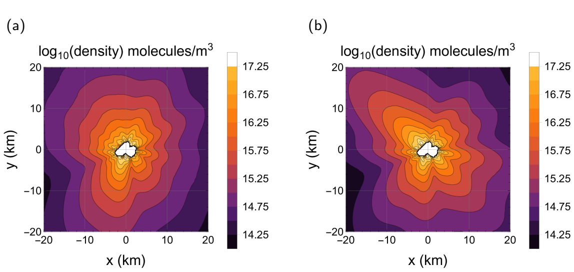

Figure 1: Gas number density N_{gas} for water around comet 67P/C-G (slice at $z = 0$) for (a) a best fit coma model for April 2015 to the COPS data set [1] and for (b) homogeneous gas emission.

The reconstruction of the three-dimensional gas density around the nucleus is done by fitting the Comet Pressure Sensor (COPS) data to uniformly distributed surface sources [1]. The resulting gas coma is shown in Fig. 1, before the fit (b) and with adjusted emission rates (a) [3]. The fit reduces the gas emission above the big lobe, but the homogeneous case already shows the influence of the concave neck area on the gas distribution. In addition to more broadly distributed sources, some gas emission areas are concentrated on the southern hemisphere. These areas are correlated with short-lived gas outbursts occurring around perihelion [5]. Already several months before the eventual outburst, the localized emitters release CO2 and their elevated activity lasts until the end of the Rosetta mission [4].

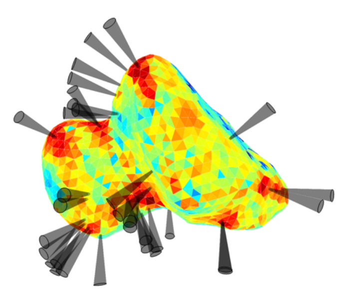

Figure 2: Reconstruction of localized gas sources (highest emission rate colored red) on the surface of 67P/C-G [1, 4] and locations of observed dust outbreaks [5].

3. Dust release from the surface

Two distinct dust release processes are observed by Rosetta. Short lived, eruptive outbursts and dust "jets" observed at any instance in the inner coma. The latter inner coma structures are highly dependent on the perspective and relative position of observer (Rosettas cameras) with respect to the nucleus. They are faith-

fully reproduces by assuming a uniform seeding of the gas emitters with dust particles [2, 3].
The observed bending of the dust coma provides an independent measurement of the dust velocity based on the Coriolis effect. We find that the dust particles are quickly accelerated close to the surface and at distances of a few kilometers reach velocities around 3 m/s [3].

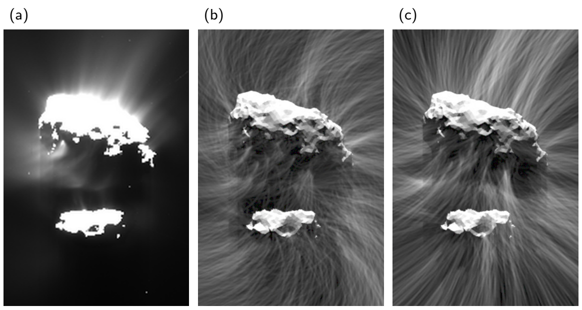

Figure 3: Parametric study of varying dust-gas interactions (α = 0.5-1,8) for the Rosetta viewpoint on 2015-04-24 09:30 UTC (see [3] for more details). (a) contrast enhanced WAC image (id: W20150424T092929750ID30F13, filters: empty+UV375, exposure: 36.45 s, direction to Sun upwards) to emphasize the dust in the shadowed neck area. Best agreement of the OSIRIS image with the simulation is obtained for small $\alpha = 0.5$-1 in the shadowed area (b), while outside the nucleus dust from sunlit areas fits better with higher $\alpha = 8$ (c). The parameter $\alpha = 3/(4\rho_{\rm dust} R_{\rm dust})$ is related to the dust particle radius $R_{\rm dust}$ and density $\rho_{\rm dust}$.

4. Summary and Conclusions

The gas emission of 67P/C-G has been determined from in-situ gas pressure measurements and reveals the gas sources across the entire nucleus, with CO2 at all times predominantly released in the southern hemisphere [4]. The observed dust and jet-like structures near the nucleus are determined by the perspective of the observer with respect to the nucleus. Concave surface areas lead to a focusing of dust densities, causing a ray-like structure emerging from the surface for certain alignments [2]. The Coriolis has been used to constrain the dust velocity.

Acknowledgements

The work was supported by the North-German Supercomputing Alliance (HLRN). We acknowledge joint work on dust models with M. Noack published in [2, 3], and on gas models with K. Altwegg, and M. Rubin in [1, 4]. Rosetta is an ESA mission with contributions from its member states and NASA and we acknowledge herewith the work of the whole ESA Rosetta team. Work on ROSINA at the University of Bern was funded by the State of Bern, the Swiss National Science Foundation, and by the European Space Agency PRODEX program. The authors acknowledge the OSIRIS Principal Investigator Holger Sierks (MPS, Göttingen, Germany) and the OSIRIS Team for providing images and related data-sets. The shown OSIRIS image is part of the ESA Planetary Science Archive and NASA Planetary Data System, data-set identifier: ROSETTA-ORBITER COMET ESCORT OSIWAC 3 RDR MTP 015 V1.0, RO-C-OSIWAC-3-ESC2-67PCHURYUMOV-M15-V1.0.

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A ROSINA Perspective on the Organics in Comet 67P/Churyumov-Gerasimenko

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I. Abstract

The Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA) was sent onboard the Rosetta spacecraft to determine the chemical composition of comet 67P/Churyumov-Gerasimenko. ROSINA consists of three different instruments: the Comet Pressure Sensor (COPS), the Reflectron-type Time-Of-Flight mass spectrometer (RTOF), and Double Focusing Mass Spectrometer (DFMS).[1] The ROSINA instruments have investigated the coma of comet 67P for more than two years, performing measurements at various distances and angles between comet, Sun, and spacecraft. Thereby they proved the existence of a surprising amount of organics in the comet.[2] Some of these molecules were detected for the first time ever in comets. These results have been revealing an unexpected chemical complexity of comets and led to a more profound understanding of the origin of our Solar System.[3]

The study here presented is based on laboratory and space data from the ROSINA-DFMS. The instrument has the advantage of a high mass resolution (3000 at 1% peak height on mass/charge 28 u/e) and a high sensitivity. Furthermore, it allows measurements up till mass 180 u/e and can be operated in neutral gas- and ion mode.[1] Thus, the instrument is predestined to decipher the variety of organic molecules in the coma of comet 67P. The complexity of the study is increased by the unique DFMS ionization energy of 45 eV, leading to fragmentation different from databases like NIST. On the one hand this leads to potentially very complex fragmentation patterns, on the other hand it allows a clear identification of the molecules in the DFMS space data.

Thus, the results of the identification and quantification campaign of various organic compounds such as aliphatic and aromatic hydrocarbons, and alcohols in the cometary bulk will be shown. The presentation also focusses on the relative abundances of these compounds during various mission phases and conditions.

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TRAPPIST monitoring of the activity and composition of the small near-Earth Jupiter Family Comets : 41P and 252P

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Abstract

We report on photometry and imaging of the Jupiter Family Comets (hereafter JFC) 252P/LINEAR (hereafter 252P) and 41P/Tuttle-Giacobini-Kresak (hereafter 41P) with TRAPPIST telescopes [1]. We observed 252P with TRAPPIST-South from February 4 to June 8, 2016, while we collected the data for 41P with TRAPPIST-North from February 16 to July 27, 2017. We monitored the evolution of the gaseous species OH, NH, CN, C_3 and C_2 production rates as well as the evolution of the dust proxy, A(θ)fρ parameter. The peak of the water production rate of 41P reached $(3.5\pm0.2)\times10^{27}$ molecules/s on April 3, 2017 when the comet was at 1.05 au from the Sun. 41P is a unique comet that showed a rapid slow down of its rotation period during this recent apparition from 20 hrs to 50 hrs in 2 months [2, 3]. The peak of the water production rate of comet 252P reached $(8.5\pm0.08)\times10^{27}$ molecules/s on April 10, 2016 two weeks after perihelion. The similarity of the orbit of 252P and the asteroidal object P/2016 BA14 may indicate that the later could be a fragment of the comet[4]. The comparison of the coma morphologies exhibited by the gas species and the dust will be discussed for both comets.

1. Introduction

JFCs are defined as comets with Tisserand parameter between 2 and 3, which is a measure of the influence of Jupiter on the dynamics of the comets.

41P is a near-Earth Jupiter family comet (5.42 yr), discovered by Horace Parnell Tuttle on May 3, 1858. 41P has a small nucleus (0.7-1 km) [5], this radius is less than 70% of all measured radii of JFCs [6]. This comet was observed with TN (and 2 nights with TS) over 5 months. Its perihelion was on April 12, 2017 at 1.0 au from the Sun and the comet was at its closest distance to Earth on April 1 at only 0.14 au.

252P is a near-Earth Jupiter family comet (5.32 yr), discovered by the LINEAR survey on April 7, 2000. The nucleus size of 252P is also very small, about 0.3-0.5 km [7]. We monitored 252P over 4 months, its perihelion was on March 15, 2016 when the comet was at 0.996 au from the Sun and did a very close approach 0.053 au from the Earth.

2. Production rates and dust (Afρ)

In order to derive the production rates, we converted the flux for different gas species (OH, NH, CN, C_3 and C_2), through the HB narrow band cometary filters [8], to column densities and we have adjusted their profiles with a Haser model [9]. The model adjustment is performed around a physical distance of 10000 km from the nucleus. We computed a vectorial-equivalent water production rate (Figure 1) from our Haser-model OH production rates using Q(H_2O)=1.36 $\times r^{-0.5}\times$ Q(OH) [10].

We derived the Afρ parameter, proxy of dust production [11], from the dust profiles using the HB cometary narrow-band BC, GC and RC filters [8] and the broad-band Rc filter. We corrected the A(θ)fρ from the phase angle effect to obtain A(0)fρ.

3. Coma morphology

The morphological analysis revealed several features in the coma of both comets. Using a simple rotational filter which takes the difference between two oppositely-rotated copies of the image, we enhanced the CN narrow-band images of 41P and 252P. Two jets are detected like partial spirals in a counter-clockwise rotation in 41P images. This technique has been used to measure the rotation period of 41P which shows an increase from 30 hrs at the end of March to 50 hrs at the end of April.

4. Figures

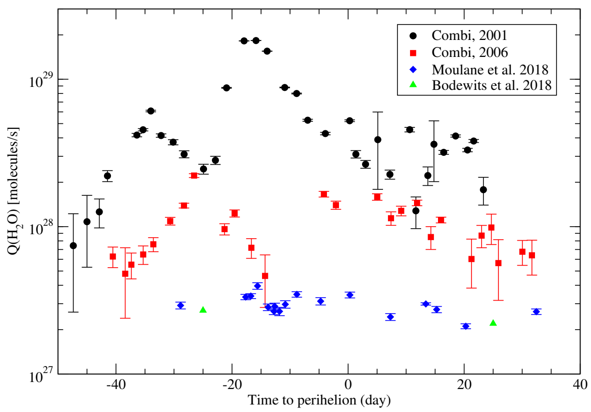

Figure 1: The logarithm of the water production rate for different apparitions of comet 41P in 2001, 2006 and 2017 as a function of time to perihelion.

5. Summary and Conclusions

We monitored 41P and 252P on both sides of perihelion with the TRAPPIST telescopes. The gas species production rates were computed as well as the Afρ parameter for both comets. Our results have shown that the two JFCs have a *typical* composition according to the $Q(C_2)/Q(CN)$ and $Q(C_3)/Q(CN)$ ratios but have a low gas and dust activity compared to other JFCs. We found that the activity of 41P is decreasing by about 30% to 40% from one apparition to the next. We confirmed rotation period derived from coma features slowed down by 20 hours in 2 months [2]. 252P has shown an increase in production rates and dust production after perihelion which is believed to be associated with thermal processing of the nucleus surface.

Acknowledgements

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EPSC Abstracts
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Agglomeration of 67P/Churyumov-Gerasimenko from clathrates and crystalline ices

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Abstract

The origin of cometary volatiles remains a major open question in planetary science. Comets may have either agglomerated from crystalline ices condensed in the protosolar nebula (PSN) or from amorphous ice originating from the molecular cloud and interstellar medium (Klinger 1980; Bar-Nun and Laufer 2003; Bar-Nun et al. 2007; Mumma & Charnley 2011; Rubin et al. 2015; Mousis et al. 2016a; Marty et al. 2017). Here, based on the recent argon, krypton and xenon measurements performed by the ROSINA instrument aboard the European Space Agency's *Rosetta* spacecraft in the coma of 67P/Churyumov-Gerasimenko (67P/C-G), we show that these noble gas relative abundances can be explained if the comet's building blocks formed from a mixture of gas and H_2O grains resulting from the annealing of pristine amorphous ice (i.e., originating from the presolar cloud) in the PSN. In this scenario, the different volatiles released during the amorphous-to-crystalline ice phase transition would have been subsequently trapped at lower temperatures in hydrate or clathrate forms by the crystalline water ice generated by the transition (see Figure 1). Once crystalline water completely consumed by clathration in the ~25–80 K range, the volatiles remaining in the gas phase would have formed pure condensates at lower temperatures. The formation of clathrates and pure condensates to explain the noble gas relative abundances is consistent with an interstellar origin for the molecular oxygen detected in 67P/C-G (Bieler et al. 2015; Mousis et al. 2016b; Mousis et al. 2018), and with the measured molecular nitrogen depletion in comets (Rubin et al. 2015).

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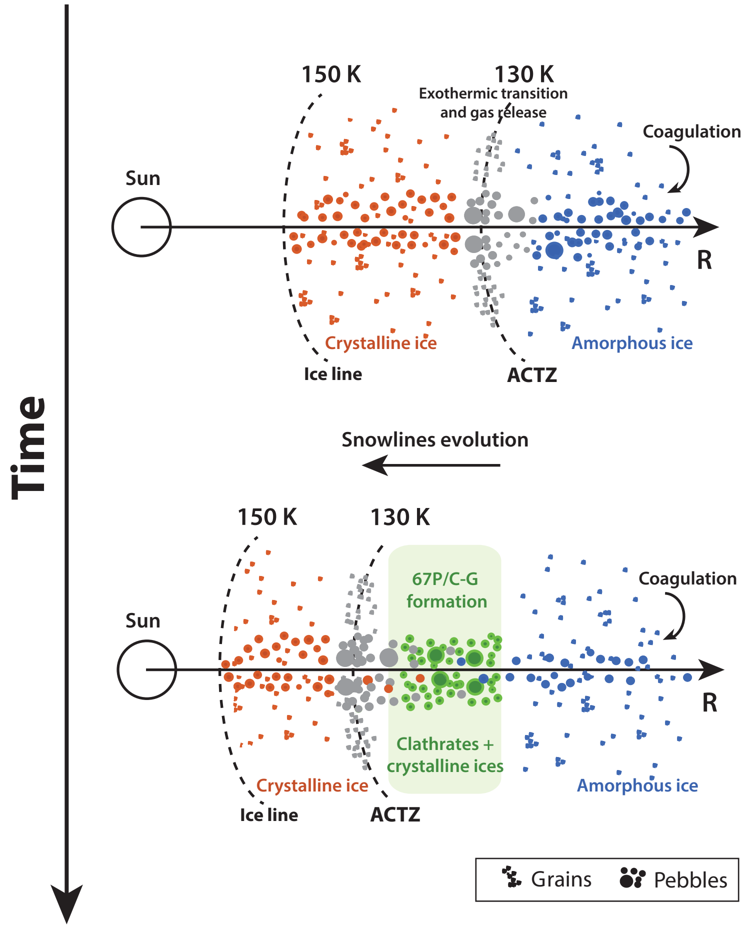

Figure 1: Illustration of the formation conditions of the ice grains precursors of 67P/C-G beyond the ice line during the cooling of the PSN. *Blue particles:* grains/pebbles made from pristine amorphous ice coming from ISM. *Red particles:* grains/pebbles made exclusively from crystalline ice condensed at the location of the ice line in the PSN. *Grey particles:* grains/pebbles made from crystalline ice resulting from the amorphous-to-crystalline transition at the location of the ACTZ line. *Green particles:* grains/pebbles incorporating clathrates and crystalline ices. *Top panel*: Snapshot of the distribution of grains/pebbles around the different snowlines at a given epoch of the PSN evolution. Small grains coagulate into pebbles which rapidly settle to the midplane and drift inward, thereby allowing pristine material originating from the outer portions of the PSN to be processed in the inner regions. Pebbles made of amorphous water ice crystallize at the ACTZ line and release the adsorbed volatiles as vapors during their inward motion. Crystalline ice also forms from the condensation of water vapor at the ice line which moves inward as the PSN cools down. *Bottom panel*: Snapshot of the distribution of grains/pebbles around the different snowlines at a later epoch of the PSN evolution. The snowlines have continued their drift inwards the PSN and clathrates formed at the surface of grains/pebbles that crystallized from pristine amorphous material at earlier times when the ACTZ line was present at these now cooler locations. With time, these regions of the disk cooled enough to favor the condensation of the most volatile species because the water budget was insufficient to form clathrates. 67P/C-G agglomerated from a mixture of clathrates and pure condensates formed in these regions.

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Modelling the trapping of noble gases in comets ices

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Abstract

Among the information impatiently awaited from the observation of comet 67P/Churyumov-Gerasimenko were those concerning noble gases. From these observations, it is surmised that there is a relation between abundances in the nucleus and volatiles in the coma. However, their origin is still under debate. We consider a scenario according which the noble gases have been integrated in an early time to the icy grains precursors of comets in the interstellar medium, and this strongly enough to persist till now through the comet formation and aging. In this contribution we report theoretical investigations focusing on two key parameters of this scenario, i.e. the ability of noble gases to adsorb onto ices surfaces (first step of the process in the ISM) and their stability within cavities of the icy bulk.

1. Observational background

The recent observations of comet 67P/Churyumov-Gerasimenko brought valuable information concerning noble gases; as a matter of fact, the nature of their source in different space bodies was still unknown and their relative abundances subject to debate. Analysis of the data delivered by the ROSINA instrument showed depletion of Xe with respect to Kr, and of Kr itself with respect to Ar. These relative abundances were found consistent, within observational errors, with solar relative abundances [1, 2, 3].

2. A primordial scenario

We might assume that the noble gases have been integrated to the icy grains precursors of comets in the interstellar medium, first stuck on the surfaces by adsorption, then covered by the successive layers of ices. Thus, they could have been kept embedded in the voids of the compact ices till they desorbed with ices and other volatiles by sputtering or sublimation of the surface ice layers. Such a scenario implies that Ar, Kr and Xe were trapped as a function of their solar abundances and strongly enough into ices holes not to migrate efficiently to the surface. It is most probably the reason why we are still able to observe them to day.

3. Two key points checked

In this contribution we report theoretical investigations of two key parameters of this scenario, i.e. the ability of noble gases to adsorb onto ices surfaces (first step of the process in the ISM) and their stability in cavities. In all situations we assume that the surrounding ice is made of H_2O (testing different shapes and sizes of cavities). For this purpose, we have used quantum numerical simulations based on first principle periodic density functional theory (DFT) [4, 5, 6]. These methods have shown to be well adapted to the description of compact and porous ices and are capable to describe the trapping of volatiles in the ice matrix [7, 8]. Our theoretical results were checked against the adsorption and inclusion energies obtained by the Bertin team using technics of Temperature Programmed Desorption (TPD) [9, 10].

3.1 Adsorption step

The three noble gases are found able to adsorb on icy surfaces in different locations with averaged energies going from 0.10 eV for Ar to 0.13 eV for Kr and 0.16 eV for Xe (Table 1).

Table 1: Adsorption energies of NG on water ices (eV)

NG	max	min	aver.	exp.[11]
Ar	0.12	0.07	0.10	0.08
Kr	0.15	0.10	0.13	0.13
Xe	0.19	0.10	0.16	0.17

Concerning the adsorption process, the specificity of crystalline versus amorphous ices is found irrelevant, giving no energetic differences [11].

3.2 Inclusion step

Voids of different shapes and sizes have been created within the crystalline structure in order to simulate irregular compact water ices. We found that Ar, Kr and Xe could stabilize in such voids (Table 2) with energies close enough to H_2O ice binding energy, implying that they can be trapped without disturbing the ice matrix.

Table 2: Stabilization energies of NG in holes (size of 2/4 water molecules) within the bulk of water ices (eV)

NG	hole 2	hole 4
Ar	0.2	0.22
Kr	0.2	0.27
Xe	0.2	0.34

In fine, these noble gases should leave the icy matrix only when this latter sublimates.

4. Summary and Conclusions

Noble gases detected in the coma of 67P/C-G might issue from the icy bulk where they might have been trapped in the constitutive planetesimals at the time of their formation in the interstellar medium. Using computational chemistry models based on first principle periodic density functional theory (DFT), we have evaluated their adsorption energies on top of ices, checking the possibility of their trapping, and then, the stability of these species in the irregular cavities of the compact ices, revealing a stabilisation efficient enough to keep them trapped until the ices sublimate.

Acknowledgements

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High resolution spectroscopy of the unusual comet C/2016 R2 (PanSTARRS)

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Abstract

We report on high spectral resolution observations of the peculiar comet C/2016 R2 (Pan-STARRS). This comet was found to have a highly unusual composition, with a very high abundance of CO, and is only the third comet in which the N_2^+ ion is clearly detected. Our observations allowed us to measure the $N_2^+/CO^{+}/CO_2^+$ ratios. Among other things, we also put an upper limit to the $^{14}N/^{15}N$ isotopic ratio, measured for the first time directly from N_2^+, and detected the [NI] lines for the first time in a comet.

1. Introduction

The long period comet C/2016 R2 (Pan-STARRS) was discovered on September 7, 2016 at 6.3 au from the Sun. In December 2017, it was found that the coma emission of the comet was surprisingly dominated by CO^+ and N_2^+ [1], while most of the emission bands usually detected in the optical spectrum of comets were hardly visible. Prior to this detection, the presence of the N_2^+ molecule has only been confirmed in the coma of three comets: C/2002 VQ94 (LINEAR) [3], 67P/Churyumov-Gerasimenko [5], and 29P/Schwassmann-Wachmann 1 [2]. From the N_2/CO abundance ratio measured in 67P, it appears that molecular nitrogen is highly depleted in comets compared to the proto-solar value, which has implications on their formation. The detection of bright N_2^+ emission lines in the coma of comet C/2016 R2 represented a rare opportunity to enlarge the sample of comets for which we have a measurement of the N_2^+/CO^+ ratio, but also to determine for the first time the $^{14}N/^{15}N$ isotopic ratio directly from N_2^+. We thus decided to observe comet C/2016 R2 with the UVES instrument at the VLT, in order to obtain a high-resolution spectrum of the comet over the full optical range.

2. Observations and data reduction

We obtained a total of 6h of observations of comet C/2016 R2 (Pan-STARRS) with the VLT UVES high resolution spectrograph, between February 11 and February 16, 2018. We used two different UVES standard settings to cover the whole optical spectrum. The 390+580 setting (ranging from 326 to 454 nm in the blue and from 476 to 684 nm in the red) allowed us to secure a high SNR ratio measurement of the N_2^+ and CO^+ emissions while the rest of the optical range and, among others, NH_2 and H_2O^+ emissions, were covered using the 437+860 setting (ranging from 373 to 499 nm in the blue and from 660 to 1060 nm in the red). For both setups, we used a 0.44" slit, providing a resolving power of R~80000.

The basic data reduction was made using the ESO UVES pipeline in combination with IRAF routines. More details regarding data reduction procedures can be found in [4]

3. Data analysis and Results

As reported in [1], we detect strong emissions of N_2^+ and CO^+. In addition to those two ions, we report the clear detection of CO_2^+, fainter emissions of CH^+, CN, C_2, C_3, and a possible detection of CH. From those high-resolution spectra of C/2016 R2 (Pan-STARRS) we are thus able to measure the

$N_2^+/CO^+/CO_2^+$ ratios in the coma of the comet, and compare its N_2^+/CO^+ ratio to the ratio in other comets. The forbidden oxygen lines at 5577.339, 6300.304, and 6363.776 Å are detected, allowing us to measure the ratio between the green line and the red doublet. The so-called G/R ratio provides a way to determine the abundance of CO and CO_2 relative to H_2O in the coma of comets. Such a measurement is particularly interesting in the case of C/2016 R2, which has strong CO^+ and CO_2^+ emissions, but no detected H_2O^+ emission.

We do not detect individual $^{14}N^{15}N^+$, and derive an upper limit on the $^{14}N/^{15}N$ isotopic ratio in the coma of comet C/2016 R2 (Pan-STARRS).

Finally, we also report the first detection of the [NI] lines at 5197.900 and 5200.256Å in the coma of a comet.

Acknowledgements

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Colours, albedos and spectral properties of the Khepry-Imhotep region of comet 67P as observed by Rosetta/OSIRIS during the April 2016 flyby

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Abstract

The ROSETTA mission was the ESA cornerstone mission for the study of the small bodies of the solar system in the Horizon 2000 perspective. Between July 2014 and September 2016, the Rosetta spacecraft rendez-vous'ed with the comet 67P/Churyumov-Gerasimenko (hereafter 67P/CG) and followed it closely along its orbit, before, during and after its passage at perihelion. During this period, the observations performed by the instruments on-board the Rosetta spacecraft, and the Philae lander, have allowed to observe, measure and constrain many of the physical and chemical properties of the nucleus and inner coma of 67P/CG. Additionally, during those 26 months, the Rosetta spacecraft also performed 3 flyby manoeuvres at small phase angles, which have allowed the on-board scientific imaging system to obtain highly detailled images of the nucleus' surface, and in two cases, to observe the opposition effect as well. We present here the results of the spectrophotometric and photometric analyses of the area of the comet 67P/CG's nucleus, over which the Rosetta spacecraft flew-by in April 2016. During this manoeuvre, the OSIRIS instruments [6] collected 256 high-resolution images of the surface using different filters in the 250-1000 nm domain.

Between the 9th and 10th of April 2016, the Rosetta spacecraft flew by the nucleus at an altitude of ~29 km, thus allowing the OSIRIS instrument to map the boundary between the Khepry and Imhotep morphological regions [1] with, at best, a resolution of 0.53 cm/px and several other surface of the comet with a resolution of at least 5 m/pxl. From those observations, we have assembled the phase curve of the flyby area for phase angles ranging from 0.1° to 62°.

The boundary between the Khepry and Imhotep regions presents a large diversity of morphological features (such as fine material deposits, boulder fields, megaclasts, scarps, outcropping consolidated material, or diamictons). Similarly, this area also presents some diversity in terms of colours and albedos: while the average reflectance of the area is similar to that the whole nucleus (~ 6.8% at 649 nm), some particular features present systematically a reflectance around 15% lower than the average, while the brightest features observed display a reflectance up to 3 times higher than this average. While the former tend to present a spectral slope steeper than that of the average featureless surface, the latter present lower spectral slopes. Such bright features with a neutral or low spectral slope display properties similar to surface features proven to be water-ice enriched material [3], and as such stands as candidates for water-ice exposure on the nucleus at the time of the flyby.
Such features were not observed in the area flown-by the Rosetta spacecraft in February 2015 [2]. Photometric modeling of the data shows the absence of a strong increase of the reflectance at phase angle lower than 2°. Furthermore, for all of the wavelengths investigated (480, 649, 743 nm), the computed FHWMs using the linear exponential model [5,7] range between 5.0° and 6.3° and indicate that the opposition effect is dominated by the shadow-hiding mechanism. This result concurs with initial modeling results [4].

We will present the results of our global and local spectrophotometric analysis of the flyby area, and those of the phase curve modeling using different photometric models, and we will compare them to those previously obtained for the comet nucleus at different heliocentric distances as well as for other primitive Solar System bodies.

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New constraints on the chemical composition and outgassing of 67P/Churyumov-Gerasimenko

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Abstract

Constraining the composition and the internal structure of the cometary nuclei of 67P/Churyumov-Gerasimenko (hereafter 67P) is challenging as we mainly dispose of remote measurements. The ROSINA/DFMS mass spectrometer has measured the production rates of various species in the coma of 67P. Results display strong variations of volatile abundances [1]. Several studies proposed that the complex shape of the nucleus and the large tilt of the rotation axis of 67P would imply large seasonal effects driving the species outgassing [2,3] while others suggested that the diversity of surface morphologies of 67P results from non-uniform sub-surface composition [4,5]. Here we brings some constraints on the composition and internal structure of the nucleus of comet 67P by comparing the data provided by the ROSINA/DFMS instrument and a thermochemical numerical model designed to depict the evolution of the stratigraphy of cometary nuclei.

1. Data and comet nucleus numerical modelling

The production rates of the species coming out from the nucleus have been investigated via a numerical model depicted in [6]. This model is designed to compute the thermal and chemical evolution of a single spot at a given cometary latitude on the surface of the nucleus along the comet's orbit around the Sun. The nucleus is considered to be a porous sphere with an initially defined radius R and made of a mixture of ices and dust in specified proportions. The model solves the conservation of energy and conservation of mass equations via the finite volume method, in spherical coordinates and in one dimension along the radial axis. Errors in the mass conservation do not exceed 0.1% for the global error and 1% for the local error (at a given time t).

Our model outputs are compared with the ROSINA/DFMS data, which correspond to the bulk composition of the coma. We focus on H_2O, CO and CO_2, namely the three major species detected in the coma [1,7]. As the data were collected at different sub-spacecraft latitudes and distances from the nucleus, following the spacecraft orbit, we ran simulations for different latitudes explored by the spacecraft and extracted the results at the corresponding epochs. We performed numerical simulation for latitudes between 60°S to 60°N, with a 10 ± 2° increment. We used the characteristic properties of 67P as input of the model. The nucleus is considered as a mixture of dust and crystalline ice. The initial abundances of the three studied species were modified until we found the best combination to fit the measurements. The dust mantle thickness at the surface is a parameter that has also been varied.

2. Results

Our simulations match fairly well the CO/CO_2 ratio measured by ROSINA/DFMS at different epochs of the comet orbital evolution (Fig. 1). At epochs before perihelion (*i.e.*13th August 2015), the data are fitted with the same initial configuration, *i.e.* a CO/CO_2 abundance ratio of ~0.6 and a dust mantle of 5 mm (composed of silicates) corresponding to the top layer of the nucleus. This latter modifies the thermal inertia and the heat wave propagation. The initial conditions differ at epochs after perihelion. The fits are satisfied assuming i) an initial CO/CO_2 ratio of ~0.1 and ii) the absence of a dust mantle. Agreements of CO/H_2O and CO_2/H_2O ratios with those measured by the ROSINA/DFMS instrument are less striking than the previous ones (Fig. 1). The global trend is reproduced but the order of magnitude sometimes differs. This could be explained by the fact that H_2O outgassing present larger variation than CO and CO_2 over time and is sensitive to the complex topography of the nucleus, redistribution of dust containing H_2O ice and/or the presence of active areas at the surface of 67P [8,9].

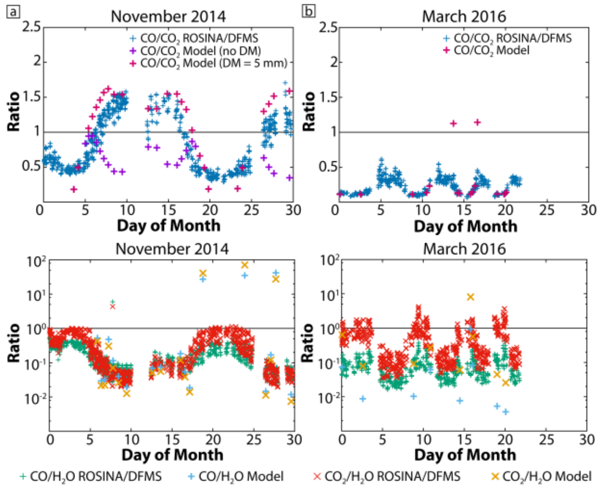

Figure 1: Comparison of the CO/CO_2 (top) and CO/H_2O and CO_2/H_2O (bottom) ratios computed by the model (pink, blue and orange crosses respectively) with the data measured by ROSINA/DFMS (blue, green and red crosses respectively) for (a) before perihelion (November 2014, initial molar abundance: 90% H_2O, 4% CO and 6% CO_2) and (b) after perihelion (March 2015, initial molar abundance: 90% H_2O, 1% CO and 9% CO_2). Results obtained with no initial dust mantle (DM) are also show in (a, top) (purple crosses).

3. Conclusion

Our study suggests that the nucleus volatiles composition is likely to be dominated by H_2O ice with a relative molar abundance ratio of CO/CO_2 ranging between 0.1 and 0.6. As we fit the data at different times and latitudes for a given composition for pre-perihelion data and another composition for post-perihelion data, 67P's nucleus is thought to be rather homogenous. Still, it results that a heterogeneous coma, as it has been observed for 67P by ROSINA/DFMS, does not necessary result from heterogeneous composition of the nucleus. Therefore the outgassing seems to be mainly insolation-driven leading to an internal structure defined by the sublimation front of each ice. Further investigations need to be performed to provide hints on the absolute H_2O abundance, the influence of the dust mantle and the dichotomy between the CO/CO_2 ratios needed to match the measurements before and after perihelion.

Acknowledgements

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The global composition of comet 67P's dust as measured *in situ* by the COSIMA mass spectrometer

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Abstract

We report here the global composition of the dust particles released from the Jupiter family comet 67P/Churyumov-Gerasimenko, as deduced from the COSIMA instrument measurements during the two years of Rosetta mission. We will particularly focus on the high carbon content found [1] and discuss its astrophysical significance and implications.

1. Introduction

COSIMA (COmetary Secondary Ion Mass Analyzer) was a Time-Of-Flight Secondary Ion Mass Spectrometer (TOF-SIMS) on board the Rosetta spacecraft [2, 3]. During two years, the instrument allowed *in situ* analysis of the dust particles released from 67P/Churyumov-Gerasimenko before and after the comet's perihelion. Compared to the previous space missions targeting a comet, COSIMA collected the cometary dust at a lower impact velocity (<10 m.s^{-1} [4]) that largely preserved the dust chemical properties and part of its physical structure such as the particle porosity [5, 6]. More than 35,000 particles were collected during the mission [7] and about 250, ranging from ~50 to ~1000 µm in size (Figure 1), were analyzed by TOF-SIMS.

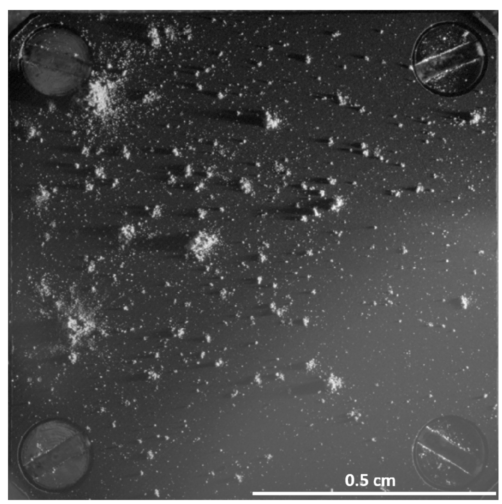

Figure 1: A collecting target (1 cm x 1 cm) of the COSIMA instrument showing cometary dust particles (up to a millimetre in size) that impacted it. Credit: ESA / Rosetta / MPS for COSIMA MPS / CSNSM Team / UNIBW / TUORLA / IWF / IAS / ESA / BUW / MPE / LPC2E / LCM / IMF / UTU / LISA / UOFC / vH & S.

2. Results and discussion

We will present the elemental composition of the cometary dust as deduced from COSIMA measurements [1, 8, 9]. The average elemental composition measured for 67P's dust will be compared to previous results obtained from the Giotto and Vega missions for comet 1P/Halley and the Stardust mission for comet 81P/Wild 2, to the composition of Chondritic Porous Interplanetary Dust Particles (CP-IDPs), and to the CI chondrite composition.

According to the mass spectra measurements, 67P's dust has a high carbon content (atomic $\mathrm{C/Si} = 5.5\,^{+1.4}_{-1.2}$ on average) [1] close to the solar value and comparable to comet 1P/Halley's value. Based on their elemental composition, the cometary particles collected by COSIMA are estimated to be made of nearly 50% organic matter in mass mixed with minerals that are mostly anhydrous (Figure 2).

The dust collected and analyzed by COSIMA is representative of 67P's non-volatile composition. The average minerals to organics mass ratio deduced from the TOF-SIMS measurements (Figure 2) gives constraints on the comet's surface and nucleus characteristics. The astrochemical implications of COSIMA results will be discussed with a focus on the high carbon content found in the cometary dust [1].

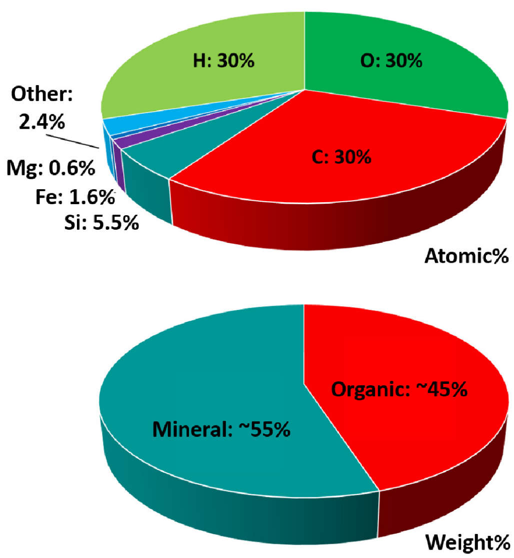

Figure 2: Top panel: the average elemental composition of the dust particles of comet 67P. Lower panel: the average mass distribution of minerals and organic material in these particles [1].

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 (FWF, P26871-N20), and Finland. Rosetta is an ESA mission with contributions from its Member States and NASA.

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Constraining activity models of comet 67P/Churyumov-Gerasimenko with Rosetta data

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1. Introduction

Comet outgassing produces a reaction force on the nucleus which changes its rotation and trajectory. Using measurements made by the Rosetta spacecraft, we can constrain outgassing models to better understand this activity.

Here, we use the measured total water production rate [1], as well as nucleus torque and ranging curves, derived from optical and radio navigation, to constrain a thermal outgassing/non-gravitational force model of 67P/Churyumov-Gerasimenko.

2. Modelling

We use a comet thermal model [2] including: varying solar insolation, water sublimation, self-shadowing and heating, but zero thermal inertia, in order to calculate the surface temperature and water sublimation rate of each facet of a shape model with time. The reaction force per facet can then be calculated, assuming a momentum coupling factor, η, and an effective active fraction (relative to a pure water ice surface). The thermal model is run at a number of points over a comet rotation and the relevant quantities averaged over the day. This is then repeated over the comet's orbit to produce time varying curves for comparison with the measured water production and torque. For the trajectory, a full N-body integration must be performed and the resulting comet position compared at each time. We use the open-source $REBOUND$ code, complete with full general relativistic corrections and gravity of all major solar system objects. 67P is initialised with its position given by the SPICE kernels and the system is then integrated forward in time, using the IAS15 integrator, with the addition of an extra acceleration term provided by our model. We then directly compare the modelled and observed magnitudes of the comet-to-Earth range (the most accurate part of the trajectory).

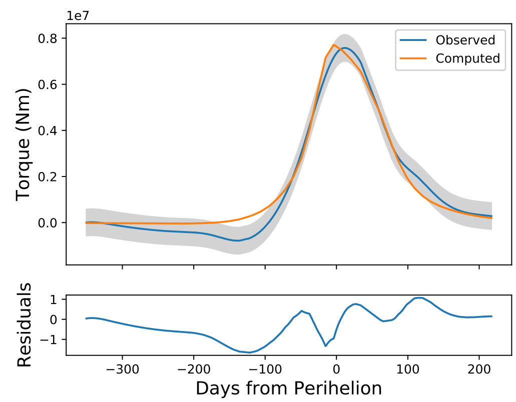

Figure 1: Observed and computed torques and residuals for our best-fit solution.

We perform a bounded least-squares fit to the residuals (linearly scaling the three datasets to roughly the same magnitude), optimising for the effective active fraction of a number of regions across the comet's surface.

3. Results

Optimisations with 5 regions, as used by [3], or the full 26 regions defined by [4] fail to adequately reproduce the data. In order to fit the positive torque peak at perihelion (Fig. 1) we had to split the southern hemisphere region of [3] by torque efficiency (a geometric factor; see Fig. 2), while to fit the production rate and trajectory curves (Figs. 3, 4) a time-varying active fraction was needed (see Fig. 5).

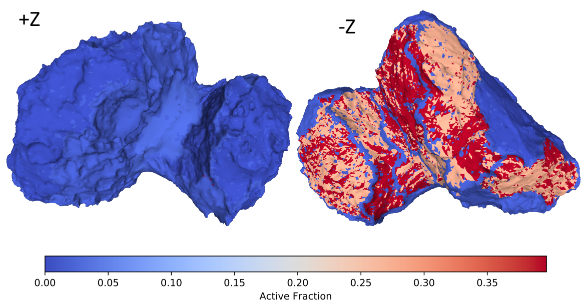

Figure 2: Mapped peak active fraction for our best-fit solution.

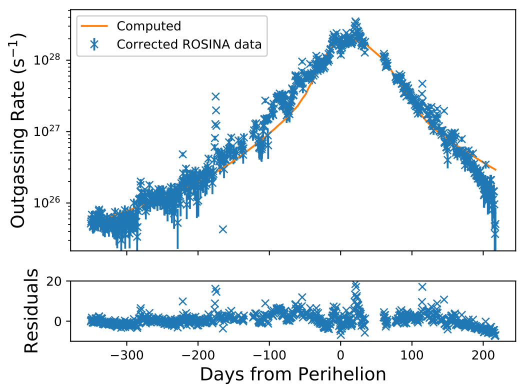

Figure 3: Observed and computed water production rates and residuals for our best-fit solution.

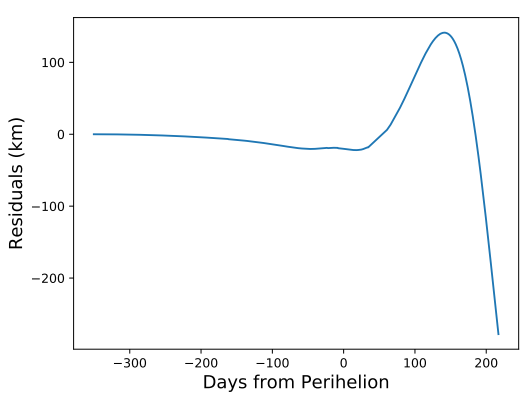

Figure 4: Observed minus computed range for our best-fit solution.

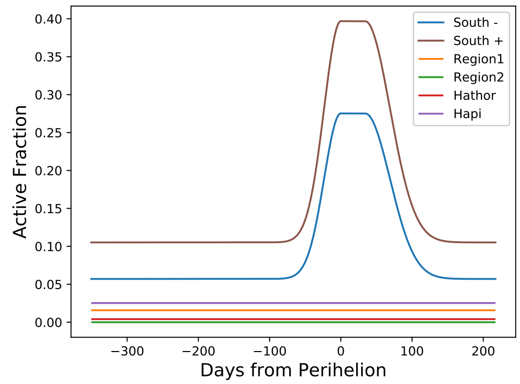

Figure 5: Active fraction with time for our best-fit solution.

4. Summary and Conclusions

Our best-fit solution suggests that: the southern hemisphere has a high active fraction compared to the north; active fraction varies significantly, both spatially and temporally; the data cannot be explained by purely seasonal solar variations and active fractions must increase near perihelion.

A time-varying active fraction could be explained by changing dust cover, which would generally stifle activity, except where it is lifted by intense perihelion outgassing, exposing more of the surface. Additonal work will be done to constrain η.

Acknowledgements

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The inner coma of 67P/Churyumov-Gerasimenko as seen from OSIRIS and VIRTIS on board Rosetta

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Abstract

The Rosetta spacecraft had the unique opportunity to follow comet 67P/Churyumov-Gerasimenko (hereafter 67P/C-G) for 2.5 years, examining how the comet evolved while moving along its orbit. On 27 April 2015, when 67P/C-G was at an heliocentric distance of 1.76 au moving towards perihelion, the Visible InfraRed Thermal Imaging Spectrometer (VIRTIS-M) [1] and the Optical, Spectroscopic, and Infrared Remote Imaging System (OSIRIS) [2] onboard Rosetta monitored the inner coma, observing the evolving dust and gas during a complete comet rotation. Given the spacecraft – to – comet distance of 125 – 142 km at the time of the observation, 67P/C-G was entirely contained in all OSIRIS WAC images and in 7 out of 9 VIRTIS-M images.

In this work we want to take advantage of the capabilities of the two instruments to analyze, in a more comprehensive way, the dust and gas behavior during a complete comet rotation. We have analyzed the diurnal behavior of the dust at about 630 nm. The comparison between the diurnal curve obtained from the OSIRIS and VIRTIS-M datasets allow inter–instrument cross–calibrations to be able then to directly compare OSIRIS and VIRTIS-M measurements at different wavelengths. We also studied the evolution of the emission due to CO_2 at 4200 nm and water vapor at 2700 nm over the comet day, and we compared the observed water production rate with the one computed by a thermo-physical model.

The diurnal variations of dust, H_2O and CO_2 will be presented, compared and discussed.

Acknowledgements

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A closed self-organizing map of Chury

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Abstract

Standard global map projections cannot display the complete surface of a highly irregular body like Rosetta's target comet 67P/Churyumov-Gerasimenko. A self-organizing Kohonen map can be used to sample the surface of any three-dimensional shape, however, the unrolled map misses some area beyond its edges. Here, we combine two square grids into an inherently closed structure that really maps the complete surface of the comet. While this closed self-organizing map is neither exactly shape nor area preserving, it is generally well behaved. The projection has been implemented in the widely used shapeViewer software.

1. Introduction

The highly irregular shape of Rosetta's target comet 67P/Churyumov-Gerasimenko (or "Chury" for short) poses some challenges for mapping, in particular for displaying the complete comet in one map. Global map projections for the Earth (and other — more or less — spherical solar system bodies) rely on the requirement that a surface point can uniquely be identified by longitude and latitude. However, because of the large overhanging areas, there are ranges of longitude and latitude for which there are three different surface points. Therefore, a significant area of Chury — about 5 % — is not visible in a map resultant from the naive application of any standard global projection. We present an approach from the area of machine learning and self-organizing neural networks. It is based on the well known Kohonen map, but extends it by introducing a closed, limitless structure.

2. The Kohonen self adative map

A so called Kohonen map [2] is a self-organizing artificial neural network that allows it to fit a rectangular grid to any kind of data, including a closed three-dimensional surface. While this approach is straight forward, there is a shortcoming: the grid wraps itself around the shape, trying to cover it as evenly as possible with all its grid points, but there is always an uncovered gap where the edges of the grid approach each other. This gap gets narrower with increasing grid resolution, but it never closes completely.

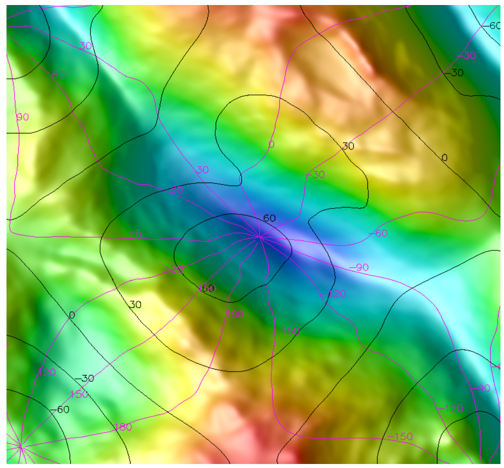

Figure 1: The closed self-organizining map of comet 67P/Churyumov-Gerasimenko in quincuncial layout. The color encodes (just to provide some example data) the distance of the surface point from the center of the comet. Latitudes are depicted black, longitudes magenta.

3. Closing the grid

Here, we create an inherently closed structure by taking two square grids and "sewing" them together at all four edges. This closed Kohonen map is then fitted to the SHAP5 shape model [1] of Chury in a similar way as the simple open map, yielding a complete map of the whole surface, see Fig. 1. Because of its construction from two squares, it exhibits the same tessellation

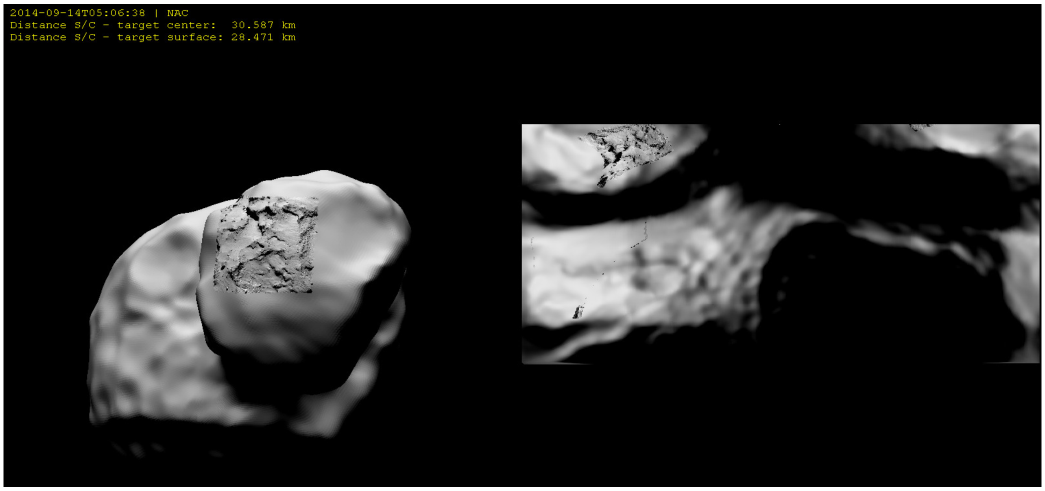

Figure 2: An example image projected onto the comet shape with shapeViewer.. *Left:* rendered 3D view. *Right:* projected onto our closed self-organizing map, here — differently from Fig. 1 — in hemispheres side by side layout.

properties as the Peirce quincuncial map projection of the Earth, which maps (in a first step) each hemisphere conformally to a square. This tessellation allows various different map layouts, e. g., in order to center a particular region of interest or for personal taste. Two of the possibilities — quincuncial and hemispheres side by side — are shown in Figs. 1 and 2, respectively.

4. The resultant map

The projection implied by the closed self-organizing map cannot be described analytically. It is neither exactly conformal (shape preserving) nor exactly area preserving, but behaves quite well over most of the surface. The projection is described by a very special shape model, which is not made of triangles — as all other shape models of Chury — but of quadrangles. It has the additional property that the vertices of the quadrangles are ordered along the lines of a two-dimensional grid, so that there is a unique relation between any point on the surface of the three-dimensional shape model and a position on the map defined by the grid.

The application of the projection given by our closed self-organizing map is more complicated than applying any of the standard global projections given by an analytic expression, however, the map projection has been implemented in the widely used shapeViewer software.[1] Fig. 2 shows the example of an actual image projected onto the comet shape and our closed self-organizing map.

5. Summary and Conclusions

We have extended the algorithm of the self-organizing Kohonen map by creating an inherently closed structure out of two rectangular grids. The resultant projection allows to display the complete surface of the highly irregular shaped comet 67P/Churyumov-Gerasimenko in one single map. The projection has been implemented in the shapeViewer software for convenient application.

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Strength of cometary particles on the nano- to micrometer scale. Force-curve analysis of MIDAS data

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Abstract

The MIDAS atomic force microscope on board the Rosetta orbiter studied dust particles which provide an insight into cometary properties and cometary formation in the early Solar System. Here the first results of a special measurement mode which allows the strength of the collected dust to be probed at the nano- to micrometer scale will be presented. This technique enabled us to generate the first force-displacement curves ever measured for cometary material.

1. Micro-Imaging Dust Analysis System

To achieve a better knowledge about the properties of the early solar nebula, untouched dust particles which are assumed to be found on comets need to be analysed. The purpose of MIDAS is to study the size, shape, morphology and physical parameters of these cometary dust particles emitted from the nucleus.

MIDAS runs in two different operation modes. Primarily, it operates as an amplitude modulated atomic force microscope in the so called dynamic mode [1].

Furthermore, MIDAS can be used to analyse the physical properties of a dust sample by recording the force-displacement curve throughout an image in the contact mode. The contact mode is especially important for the calculations carried out in this project. In the contact mode the cantilever is statically lowered towards the target and its physical deflection is measured as a value of voltage. As the cantilever hits a dust particle and starts to bend, it exerts a pressure on the dust particle which is proportional to the deflection. The cantilever is further lowered until the dust particle breaks, rolls or gets maximally compacted. These different types of interaction between tip and dust correlate with different shapes of the force curves. To validate the results, scans from before and after the measurement are generated by using the dynamic mode.

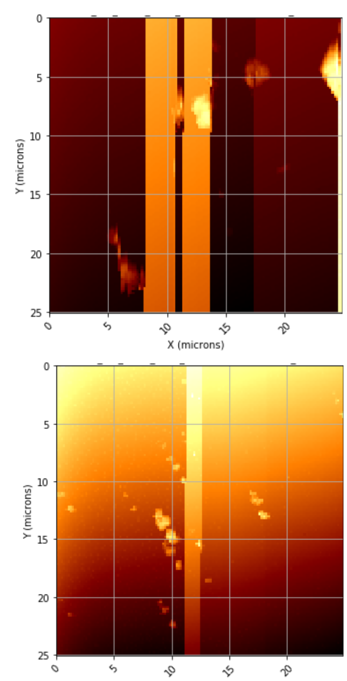

Figure 1: MIDAS scans generated with the dynamic mode immediately before (on top) and after (below) a contact mode scan. The grid has a step size of 5 micrometers in x and y direction.

2. Force measurements

To generate a force curve from the voltage values the Hooke's law is applied [4].

$$F = kx$$

Therefore, the spring constant k and the deflection of the cantilever as a distance x have to be known. The spring constant depends on the used cantilever. In this case the spring constant was derived by using the geometry and the input of the resonance frequency.

3. Interpretation and future goals

A few of the significant force curves are displayed in figure 2. It is possible to divide the force curves into various families which are based on different formation processes. For instance, the red curve, family A, indicates a process of compacting and, at a maximum force, the breaking of a particle. The blue curve, family B, suggests a rather different process. Here the particle most probably rolled away or the tip of the cantilever hit the particle at the edge and pushed it away.

The goal is to derive the physical properties of the dust samples from the force curves we can generate. Therefore, the forces between the subunits of a dust particle must be described. Two models which can be considered for the characterization of the contact between two solid spheres are the JKR model [3] and the DMT model [2]. As a result, the tensile strength, which is needed to separate two adhering subunits of a particle, shall be obtained.

Acknowledgements

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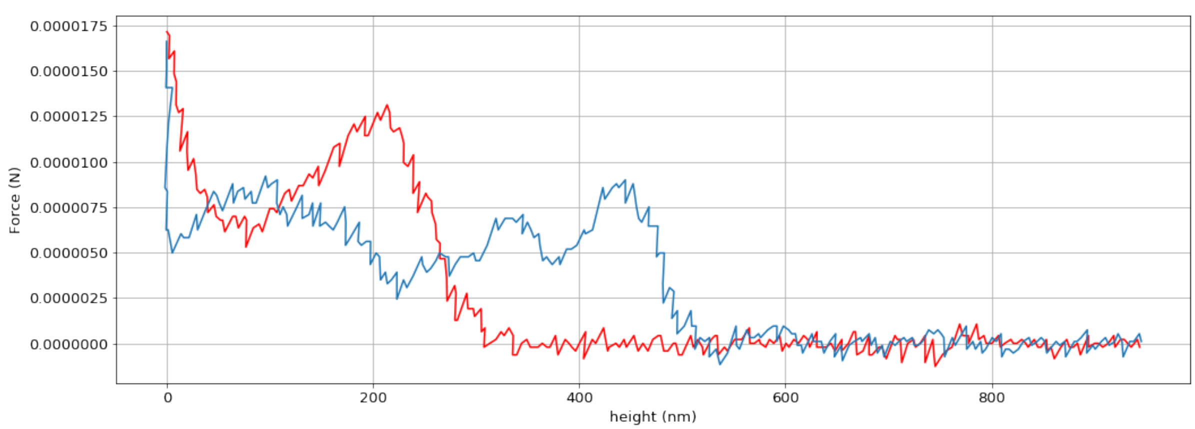

Figure 2: Two Force curves generated from a contact mode scan by MIDAS. The curves display different processes of tip-dust interaction and can be used to obtain a better knowledge about the physical properties of the cometary dust.

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The “Memory” of the Oort cloud

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Abstract

Long term simulations of two proto-Oort clouds have been performed. The first shape was initially isotropic and fully thermalized and the second one was a disk-like shape. The aim of our study was to investigate how a memory of these initial shapes can be identified in the sample of observable long period comets. Our main result is that considering the orbital elements of the observable comets at the perihelion preceding the observable perihelion, some features are clearly related to a memory of the initial disk-like shape since they are no present for the isotropic case. Future works will be devoted to the extraction of these hidden informations from the sample of known long period comets.

1. Introduction

The formation of the Oort cloud is still an open question. Two main scenarios are proposed: a cloud formed by the stellar scattering while the Sun was still in the cluster where it was born (e.g. [3, 1, 5]), and a Oort cloud formed by planetary scattering (e.g., [7, 2]). The former kind of scenarios would preferentially built a proto-Oort cloud that is fully thermalized, whereas the second one built a proto-Oort cloud with a disk-like shape. Two such simplified proto-Oort clouds were thus considered for the present study.

In Sec. 2 a brief description of our simulations is made. Section 3 is devoted to our main results and the conclusions are made in Sec. 4.

2. Simulations

Our first proto-Oort (isotropic model) cloud has fully thermalized shape with semi-major axis between 500 and 50 000 au and perihelion distance greater than 15 au; and the second one (disk model) has a disk like shape with semi-major axis between 500 and 20 000 AU, perihelion distances between 3 and 45 au from the Sun and ecliptic inclinations between 0 and 20°. In both cases the orbital energy and other distribution are uniform (except for q for the thermalized shape).

Each sample contains more than 10^7 comets. Each comet is propagated during a maximum time of 5 Gyr, or impact the Sun or a planet, goes at more than 400 000 au from the Sun or has a semi-major axis smaller than 100 au. The effect of galactic tides, passing stars and giant planets are taken into account.

Five final snapshots regularly spaced between 3.75 and 4.75 Gyr are made. After each snapshot a quiescent period of 30 Myr where we take care that no comets shower arises is performed. Then for each comet, the first perihelion passage after the quiescent period is considered. If this passage is made at less than 5 au from the Sun and the “original” semi-major axis, i.e. the barycentric semi-major axis at 200 au from the Sun before perihelion, is greater than 10^4 au, then the comet is counted as a “new” observable comets.

Four class of observable comets are considered: if the previous perihelion distance was beyond 10 au the the comet is a *Jumper*, otherwise it is a *creeper*. In addition, in the case where the original orbital energy $z = -1/a$ has increased for more than 10^{-5} au^{-1} from just before the previous perihelion passage, then the comet is also called a Kaib-Quinn comet (jumper or creeper) [6].

3. Results

Statistical results are shown on Tab 1. The main differences are: (i) the flux is four times greater for the disk model rather than for the isotropic model, (ii) the KQ-creeper are more numerous for the istropic model rahter than for the disk model, which is caused by the fact that such class of comet prefers retrograde orbit [4], and (iii), related to the previous point, the isotropic model produces more retrograde orbit than the disk model, mainly for the moderated original semi-major axis where KQ-creepers are creepers are coming from.

mod	set	p-f	ret (%)	$a_{0_{\min}}$	$a_{\rm med}$	$a_{0_{\max}}$
D	total	3.8	49.6	10.2	28.9	-235.6
	j	38,1	49.5	20.1	36.5	-235.6
	kqj	23.2	33.6	26.4	30.2	65.7
	c	11.3	67.9	10.2	18.5	46.6
	kqc	27.4	55.7	10.6	22.5	74.5
I	total	1.0	58.6	10.9	26.9	-144.0
	j	25.3	52.1	20.1	37.0	-144.0
	kqj	21.1	41.7	21.4	29.4	83.1
	c	9.7	71.6	10.9	15.7	35.3
	kqc	43.8	67.6	11.0	22.0	48.1

Table 1: Column “p-f" gives the flux per year considering a initial population of 10^{12} comets for the “total" line (given by the “set" column), otherwise it gives the proportion of the observable class (given by the “set" column) . Column “ret" gives the proportion (in percent) of retrograde orbits for each set. Columns $a_{0_{\min}}$, $a_{\rm med}$ and $a_{0_{\max}}$ gives respectively the minimal, median and maximal values of the original semi-major axis for each set of observable comets (unit is 1000 au).

On Fig. 1 an additional fundamental difference is observed on the distribution obtained from the KQ-jumpers. Indeed for the disk model this class of comets are concentrated toward the ecliptic plane (max. of $\cos i$ in 1 and max. of Ω close to $180°$) whereas such a concentration is not observed for the isotropic model. This is the class of comets for which the memory of the initial shape is stronger.

4. Conclusions

We have show that some characteristics of observable “new” long period comets are directly related to the initial shape of the Oort cloud. Future work will be devoted to the identification of such fingerprint in the sample of known long period comets.

Acknowledgements

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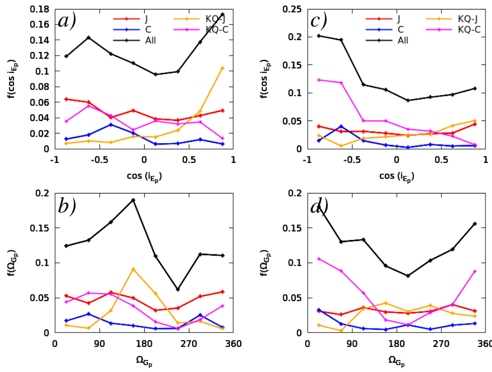

Figure 1: Distributions of $\cos i$ (where i is the ecliptic inclination) for the disk (panel a) and the isotropic (panel c) models and distributions of galactic longitude of the ascending node Ω for the disk (panel b) and the isotropic (panel d) models. All elements are original element for the perihelion preceeding the observable one. Black line is for all the comets, red, orange, blue and magenta are for jumpers, KQ-jumpers, creepers and KQ-creepers respectively.

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The challenge of fitting dust coma pattern in simulation images compared to Rosetta OSIRIS image data

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Abstract

We studied the differences of artificial simulation images of the inner gas and dust coma of comet 67P/Churyumov-Gerasimenko (hereafter 67P) compared to Rosetta OSIRIS images (Fig. 1). We used the identified differences to improve our simulation model (e.g. include night-side shadowing) and simultaneously gain more insight in the physical processes possibly ongoing in the innermost coma, such as fragmentation or sublimation of particles, that are not included in our simulations. We briefly describe our simulation method and our methods of image comparison.

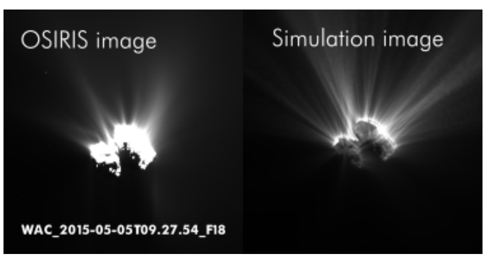

Figure 1: Example of a comparison of an OSIRIS image with the corresponding simulation image.

1. Introduction

The OSIRIS (Optical, Spectroscopic, and Infrared Remote Imaging System) camera system onboard the Rosetta spacecraft acquired image data of the comet nucleus and the innermost dust coma of comet 67P. While approaching the sun, ices on the comet surface sublimate and form the gas coma around the nucleus. Dust particles get accelerated away from the surface by gas drag and scatter sunlight which is caught on the images of the OSIRIS cameras. The visible dust coma on the images therefore contains information about the gas outflow, the surface source regions of the emitted gas and dust and effects of the complex shape of the nucleus. 3D numerical simulations are a powerful tool to study the behaviour of gas and dust in the inner coma of comets [1, 2]. The image data of the dust coma can be used to better constrain parameters in the simulation models. To compare OSIRIS images to artificial simulation images we found two methods to be especially suitable: We use (i) polar plots to compare the azimuthal dust distribution in the coma and (ii) azimuthal average profiles with distance to study the more general dust outflow behaviour [3].

2. The simulation model

We use the Direct Simulation Monte Carlo (DSMC) method for simulating a steady state gas flow field around comet 67P. We take into account the complex nucleus shape and simulate the gas flow to a distance of 10 km from the nucleus centre. Local surface temperatures and gas production rates are computed by solving the thermal balance equation for the different insolation angles of every surface facet. To match real production rates of 67P, we scale them by setting the effective active fraction (EAF) at the surface. The EAF can be understood as the local ice content of the surface and is a free parameter in our simulations.
To simulate the dust coma an equation of motion including gas drag and gravity from the nucleus is solved for a statistically representative number of test particles. Artificial images are computed by integrating the number densities in the simulated dust coma along the camera line-of-sight. We apply Mie scattering theory for spherical particles to calculate images in reflectance units that can be compared directly to OSIRIS images. To account for the particle size distribution we assume a power law function of the form $n(r) \propto r^{-\beta}$, with n the number of particles per dust size of radius r. A more detailed description of the model is given in [2].

3. Comparing simulation images to OSIRIS data

To compare the artificial simulation images to OSIRIS image data we use two different methods. In polar plots we analyse the reflectance values along a circle with a fixed radius around the centre of the comet nucleus in both the simulation and the OSIRIS image (Fig. 2). This allows us to check whether we are simulating the correct azimuthal dust distribution around the nucleus. It offers valuable information about the distribution of sources for gas and dust on the comet surface which is a free parameter in our simulations. To study the dynamics of dust outflow behaviour we compare profiles of azimuthal average of the simulation and the OSIRIS image. These profiles are obtained by averaging the reflectance in the images around circles with radius b and plotting the averaged reflectance R_{dust} multiplied by the distance b against distance. We found considerable deviations of the azimuthal average profiles of simulation images compared to observation data. This indicates that physical processes that are not included in the simulation model, such as fragmentation or sublimation of dust particles, might be important in the innermost coma .

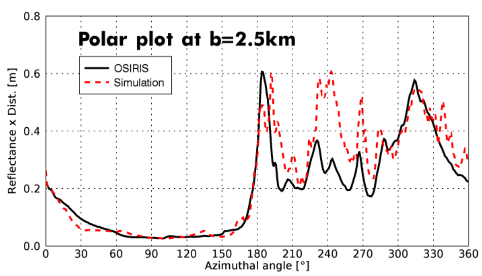

Figure 2: Comparison of the azimuthal dust distribution for the OSIRIS and simulation images in Fig. 1.

4. Results and perspectives

We have identified significant deviations in our dust simulation images compared to the OSIRIS data. The azimuthal average plots of OSIRIS images over a whole comet rotation show stronger profile variations in the dust acceleration region than the model predicts. This indicates that effects like night-side shadowing of the coma or physical processes like fragmentation or sublimation of particles might play an important role in the dust dynamics right above the comet surface. We will show the deviations between simulation and data images and focus on the most probable explanations thereof. We also discuss possible improvements of our simulation model on that basis.

Acknowledgements

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The change of the comet's shape by sublimation

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Abstract

The excellent imagery of the Rosetta mission revealed that 67P/Churyumov-Gerasimenko features a bi-lobed nucleus [1]. In fact, five out of the seven comets that have been imaged so far are bi-lobed [2], i.e. they consist of two lobes connected by a 'neck'. It has long been surmised that sublimation of the cometary material caused by incident sunlight is capable of changing the nucleus shape over the course of its existence [4].

Our hypothesis suggests that the peculiar shape of those comets is indeed caused by the interplay between an inhomogenous nucleus and the consequent differential sublimation of material exposed to sunlight.

We show that even initially spherical comets with a symmetric density distribution that decreases towards the center of the nucleus can end up having non-convex shapes. The timescale on which this shape transformation occurs is a function of the comets orbit. However, apart from its orbit, a comet's spin evolution greatly affects local sublimation rates leading to the broad range of both convex and non-convex shapes that were observe in cometary nuclei today.

1. Introduction

Short period comets that venture into the inner Solar System are known to experience significant mass loss by sublimation and outgassing. Such a loss of material can make up a significant fraction of the nucleus mass. It is, therefore, not surprising that sublimation caused by solar irradiation has been proposed as a mechanaism to modify the shape of the nucleus itself over time [4]. In this work we address how sublimation modifies the shape of cometary nuclei.

2. A simple model

In order to investigate how the shape of cometary nuclei evolve under sublimation we considered the following model.

- Comets are considered to be roughly spherical initially.
- All comets investigated in this work spin rapidly enough so that changes in the shape of the nucleus can be averaged over one spin period.
- All orbit pericenters are at a large enough distance from the Sun so that the changes in nucleus shapes can be safely averaged over one orbital period.
- The density distribution in the nucleus, $\rho(R)$, is spherically symmetric and given by:

$$\rho(r) = \begin{cases} 1, & R \in [0.6, 1] \\ -5R + 3.5 & R \in [0.5, 0.6] \\ 0.5, & R < 0.5 \end{cases} \tag{1}$$

  where R is a distance from the center of the comet in terms of comet radius.

The rate of material sublimating from a unit area perpendicular to the incident sunlight per unit time at a distance of r from the Sun is described by a sublimation function. In this work we consider the sublimation function of water ice derived in Marsden et al. [3]:

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

where $\alpha = 0.111262$, $m = 2.15$, $n = 5.093$, $k = -4.6142$.

Changes in the shape of the comet are then calculated by numerically solving the corresponding set of nonlinear partial differential equations.

2.1. Spin history of the nucleus

As the spin history affects the shape of a nucleus in a significant way, we consider it in our model. We divide the evolution of the rotation of the comet's nucleus into two phases. In phase 1 the nucleus spin axis is tilted with respect to the orbital plane by an angle α_1. Over time, sublimation in this configuration deforms the comet's nucleus into a more elongated shape. This, in turn, reduces the moment of inertia around the spin axis. Perturbations such as close approaches with planets, collisions with interplanetary debris, or the sudden onset of jets, would then lead to a destabilization of the rotation state. In our model we define the rotation state after such a perturbation as phase 2. In this phase the comet attains a second spin axis (axis of precession) and it is perpendicular to the former spin axis. The angle between the second spin axis and the orbital plane is named α_2.

3. Results

Sampling the angles α_1 and α_2 we see a variety of shapes. In this work

$$\alpha_1, \alpha_2 \in \{0^\circ, 30^\circ, 60^\circ, 90^\circ\}.$$

Some of the resulting nuclei are displayed in Fig. 1. All the resulting shapes are axially symmetric (as it follows from the model). We can see that some of them are elongated and/or bi-lobed, but some are convex.

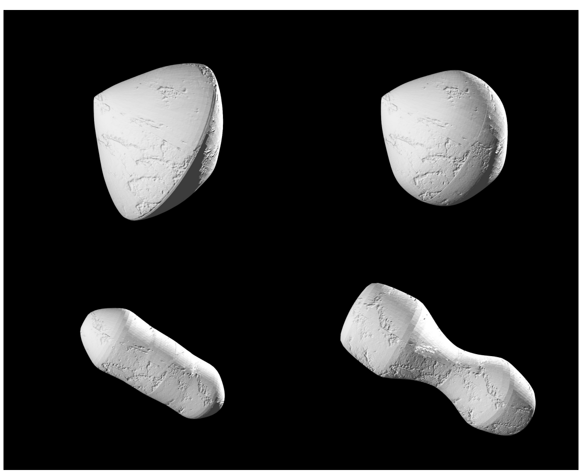

Figure 1: The resulting comets shapes for pairs of α_1 and α_2 $(30^\circ, 30^\circ)$, $(30^\circ, 90^\circ)$, $(60^\circ, 30^\circ)$, $(90^\circ, 90^\circ)$

4. Summary

We have shown that continous sublimation can cause initially spherical, rotating comet nuclei to evolve into more complex shapes. This process occurs very naturally as a consequence of the exposure of a rotating nucleus with non-uniform density to sunlight. Depending on the spin history of the nucleus, both convex and non-convex shapes can evolve. The here proposed mechanism can explain both, the bi-lobed structure of the majority of imaged comets and the convex shape of the remaining nuclei.

Acknowledgements

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The Rosetta Science Archive: Enhancing the Science Archive Content.

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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 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 ongoing, with the instrument teams updating their science data in response to recent scientific reviews and delivering them for ingestion into ESA's Planetary Science Archive (PSA) [1]. In addition, ESA is working with some instrument teams to produce new, enhanced data products, with the aim of providing the best long-term archive possible for the Rosetta mission.

2. Rosetta Data in the PSA

All science data from the Rosetta mission are hosted jointly by the Planetary Science Archive (PSA) at ESA (http://psa.esa.int) [1], 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 [2]. A number of independent data reviews have taken place over the 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 took place in October 2017, and had a focus on the science return from the comet phase of the mission. The outcome of the review was generally very positive, indicating that the data from most instrument teams are in excellent scientific shape and the Rosetta science archive is already an extremely powerful scientific resource. There were nevertheless several issues raised, and the instrument teams and the PSA are now implementing the fixes requested. In many cases this work is ongoing, and the review process has understandably resulted in a slow down of the standard delivery schedule. Nevertheless, the majority of teams have delivered all of their data from the entire mission. The aim is to complete the updates requested from the review and to work on delivering samples from the enhanced archiving activities by the end of this summer in preparation for another scientific review in autumn. This final review will assess the complete data holdings from Rosetta, and will review the outputs from the enhanced archiving activities discussed in the following section. This will ensure that the archive is ready for the long-term.

With the updates being made to the data pipelines as a result of the last review, teams have also been asked to re-run 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.

3. Rosetta Enhanced Archiving

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.

With the resources from the operational mission now at an end, ESA has established a number of activities with the Rosetta instrument teams to allow them to continue working on enhancing their archive content. The planned updates focus on key aspects of an instrument's calibration or the production of higher-level data, and are therefore specific to each instrument's needs. Several activities have already been running in 2017, while others are in the process of being kicked off, with their duration varying depending upon the activities to be undertaken. The full 'archive enhancement' process will end September 2019, when the post operations activities for Rosetta come to a close. This presentation will highlight just a few of the archive enhancement activities to give a flavour of the updates being made.

Most instrument teams will be providing a *Science User Guide*, as well as updating calibrations for their data. Several teams will also be delivering higher-level processed and derived products. For example, the VIRTIS team are updating both their spectral and geometrical calibrations, and aim to deliver mapping products to the final archive in the coming year.

Similarly, in addition to their standard PDS3 IMG format science products, the OSIRIS team have recently started delivering data in both FITs and JPG formats, allowing an end-user to more easily view and select the images they may be interested in. Future updates will include the delivery of distortion corrected, straylight corrected and three-dimensional geo-referenced data products.

The Rosetta Plasma Consortium (RPC) instrument suite is 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). An illumination map of the comet has also been produced to help with their cross-calibration work.

The MIDAS team is also working on instrument cross-calibrations and the production of a dust particle catalog from the comet coma, while the GIADA team has started to produce higher-level products in the form of dust environment maps, developed in 3D plus time. Initial samples have already been delivered and are in preparation for inclusion in the PSA.

The NASA-funded ALICE, RPC-IES and MIRO instruments also have some limited enhanced archiving activities, which will wrap-up in Spring 2018, to allow the teams some funded time to respond to a review of their final submissions before the funding runs out at the end of this year.

A separate activity has also been established to produce 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. Initial samples of some of these products were included in the recent scientific review, and the feedback has been extremely helpful in ensuring the development is on the right track.

In addition to these activities, the Rosetta ESA archiving team will internally 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.

4. Final Reviews

The enhanced data deliveries from the 3 US funded instruments will be reviewed in late Spring 2018. For the remainder of instruments, a final 'mission archive review' will be held with independent reviewers to assess the complete Rosetta data holdings towards the end of 2018.

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 Rosetta archive enhancement activities will be provided. With the support of the instrument teams and the completion of the archive enhancement, the Rosetta archive will remain 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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Experiments on cometary activity: ejection of dust aggregates from an evaporating water-ice surface

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Abstract

For a better understanding of cometary activity, comet-simulation experiments are necessary. In our experiments we study the ejection of dust aggregates caused by the sublimation of water ice under cometary-like conditions. We find that dust ejection exactly occurs when the pressure of the water vapor in the ice-dust interface exceeds the tensile strength plus the gravitational load of the covering dust layer. Furthermore, we analyzed the trajectories of emitted dust and the size of ejected aggregate clusters depending on the dust layer thickness.

1. Introduction

The gas-driven dust activity of comets is still an unresolved question in cometary science. In the past, it was believed that comets are dirty snowballs and that the dust is ejected when the ice retreats. However, thanks to various space missions to comets, it has become evident that comets have a much higher dust-to-ice ratio than previously thought and that most of the dust mass is ejected in large particles. Because of the very low albedo of comets [1], they are among the darkest objects in the Solar System. Hence, the solar radiation can effectively heat the surface of the cometary nucleus, which leads to the evaporation of the volatile constituents and, therewith, to the ejection of the surface material. Dust-aggregate release from the surface is possible, if the gas pressure underneath the dust cover is sufficient to overcome the sum of the gravitational stress exerted by and the tensile strength of the dust-aggregate layer. The gas pressure can be approximated by the sublimation pressure and by taking the influence of the dust layer on the diffusing molecules into account [4].

With this work, we intend to establish a new series of comet simulation experiments, focusing on the investigation of the gas-driven dust activity by starting as simple as possible. Thus, we use a solid block of water ice and dust aggregates placed on top of this ice block.

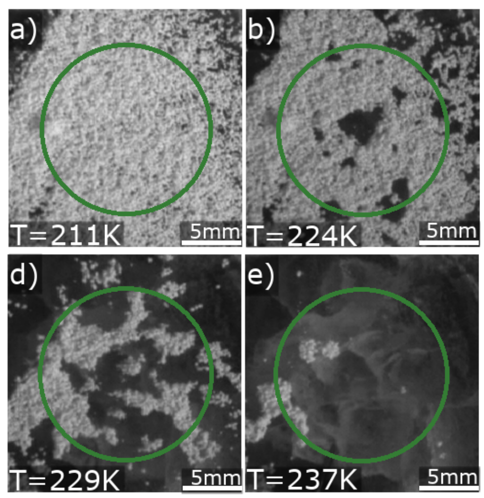

Figure 1: Temperature-dependent evolution of an ice-dust sample from a top view. The dust aggregates appear white and the water ice black. The green circle shows the area in which the fractional dust-cover data was acquired.

2. Experimental

The experiments were performed inside a vacuum chamber to ensure cometary-like conditions. Two cameras were used to monitor the surface evolution of the dust-covered water ice from top and from the side. The samples were produced inside the sample holder, a cylindrical copper block. A heater was inserted in order to heat the sample from $\sim 180\,\mathrm{K}$ to $\sim$

$250\,\mathrm{K}$. As cometary dust analogues, we chose aggregates, consisting of irregular silica (SiO_2) monomers, which were sieved into different size ranges, between $\sim 50\ \mu\mathrm{m}$ and $\sim 500\ \mu\mathrm{m}$ in diameter onto the water ice.

3. Results

When the surface of the ice had reached a certain temperature, the dust layer visibly began to erode, due to the ejection of dust aggregates. The temperature-dependent evolution is shown in Figure 1). We define the activity temperature T_A as the temperature at which $50\,\%$ of the dust layer within the green circle in Figure 1 was ejected. From this temperature and from the estimated layer thickness, we derived the water-vapor pressure below the dust cover. The water-vapor pressure has to exceed the tensile strength of the material plus the gravitational load of the dust layers to be able to eject the dust aggregates. For the derivation of the tensile strength, we used the model developed in Ref. [6] and the data show a good match to the predictions. This means that our approach is a reasonable approximation for the ice-evaporation-driven dust activity.

Additionally, we observed that mostly clusters of dust aggregates were ejected by the outgassing water-ice surface. Those sizes we determined for different layer thicknesses, but for a fixed dust-aggregate diameter. From this analysis, we derived the median value of the cluster size as a function of the layer thickness. This means: the thicker the layer, the lager the clusters are.

The side view of the samples allowed us to observe the trajectories of single aggregates or clusters when ejected by the outflowing water molecules. In total, the trajectories of eight particles were recorded and fitted by parabolic functions to derive the initial velocity and mean accelerations of the aggregates.

4. Implications for comets and summary

With this work, we will present our first comet-simulation experiments on the ejection of dust aggregates from an evaporating water-ice surface. The experimental results provide three major implications for our understanding of cometary activity, namely, the observed emission of dust aggregates can be explained by our assumptions, the dust layer thickness has an important influence on the size of ejected clusters and most of the ejected dust aggregates have an initial starting velocity exceeding zero. Details can be found in our upcoming paper [2].

Acknowledgements

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Global and Local Color Mapping of 67P/Churyumov-Gerasimenko using Rosetta-OSIRIS images

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Abstract

During the 2 year of Rosetta mission in August 2014 to September 2016, from arrival to the comet to end of mission, OSIRIS [1], the scientific imaging system onboard Rosetta acquired high resolution images of the comet surface in different filters in the visible wavelength range. OSIRIS contains two cameras: the Wide Angle Camera (WAC) and the Narrow Angle Camera (NAC). Surface images have been acquired at varying resolution in the different phases of the mission. For this work we have selected NAC images acquired when the spacecraft was at distance lower than 30 km from the comet's surface, thus providing resolution higher than 0.52 m/pix.

Based on OSIRIS NAC images, the global shape model of 67P has been constructed using either the stereo-photogrammetric analysis technique (SPG) [2, 3] or the stereo-photoclinometric method (SPC) [4]. From the shape model a coordinate system can be extracted and the surface can in theory be mapped into any map projection. However, for very irregular shapes such as the bi-lobed shape of 67P, the map projection can be problematic. Other approaches to map comet 67P, such as 3-D visualizations, are also under developed [5].

We use the OSIRIS NAC images acquired in the F24 filter (480.7 nm), F22 filter (649.2 nm) and F41 filter (882.1) in order to generate the color images. The color images (RGB images) are created assigning the filters F41, F22, and F24 to the color channels red (R), green (G), blue (B), respectively. Further, the images are co-registered, photometrically corrected using the Lommel-Seelinger (LS) disk function and then projected into a two dimensional coordinate map. We use the simple cylindrical projection, which is the most common used global map in literature and easy to understand.

The map projected images can be stitched together (mosaicked) to create local or global maps. All procedures are performed using the Integrated Software for Imagers and Spectrometers (USGS ISIS3) software [6].

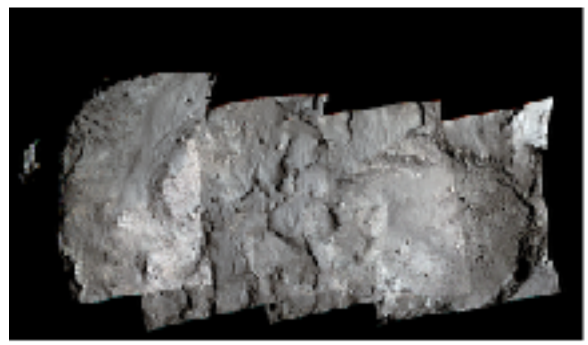

Figure 1: Local color map of the surface of 67P in simple cylindrical projection with 2.18 meters/pixel resolution.

Figure 1 shows an example of a local color map from the region covering the Hatmehit depression, and the Ma'at and Nut regions. As can be seen in the color map, the map-projected images show brightness mismatches even though they are already corrected using the LS photometric function. This suggests that the LS function does not adjust the brightness in a way that the resulting images appear as if they were obtained under uniform observation and illumination conditions. We aim to implement more photometric functions such as Minnaert's model and Akimov function to address the brightness mismatches.

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Intense Morphological Changes in a dust bank situated at the Khonsu region of 67P/Churyumov-Gerasimenko

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Abstract

Situated along a latitude band of -11 to -30 degrees, the dust bank in the Khonsu Region is an area that experienced dramatic morphological changes during the 67P/Churyumov-Gerasimenko's perihelion passage of July to September 2015 [1], the maximum period of activity [2]. Through the colors sequences obtained by the OSIRIS Narrow-Angle Camera (NAC) on-board the Rosetta/ESA mission, Deshapriya et al. [3] showed many ice-enriched spots appearing and surviving several months after and before perihelion. Using same instrument, Vincent et al. [4] detected two bright outbursts rising from the bank during same period.

Therefore, to study the relationship among the location, ejected mass and morphological changes, we further analysed the full rotational NAC color sequences of August 1st 2015 and December 13th 2015 that shows an impressive amount of outgassing happening on the dust bank and proximities. In total, it revealed 33 events of varied intensity. Most of them are clustered on the equatorial reach of the bank (Fig. 1). In particular, two bright events, one rotation apart, released an instantaneous mass of 3-4 tons during cometary night from same area in August 1st 2015. Finally, in December 13th 2015, we detected the strongest outburst, 23-30 tons were released from a ice-enriched terrain (8-9%/100 nm) very close to the origin of "jumping boulder" detected by El-Maarry et al. [5]. All mass were calculated applying the grain-size distribution estimated by Agarwal et al. [6].

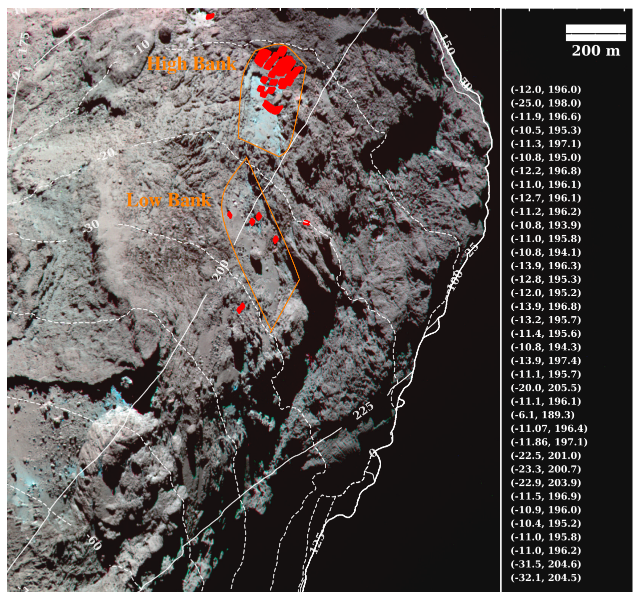

Figure 1: **All jet sources projected onto NAC image of January 28th 2016, 01:48.** Positions for events #7 $(-12, 196)$ & #33 $(-25, 198)$ of Vincent et al., 2016 are also included there. Most of the documented events cluster on the equatorial outskirts of Khonsu cliff, with sparse sources located in the southern reach.

Once these mass ejection events were located and identified, we searched through OSIRIS database to look for morphological and/or spectrophotometric counterparts. After perihelion passage, the spacecraft went to inscursion of low altitude and obtained the highest-resolution images during the "Target of Opportunity observations" between June and July 2016. Conversely, before perihelion, only a couple of images were taken at low altitude on January 16th 2015 01:27 (30 km). Comparing both sets, we identified 8 features related to mass loss and a new displaced boulder of 50-meter size El-Maarry et al. [5]. Among these features we have 6 shallow cavities of 1.6 to 16.4 meters depth and 20 to 100 meters length, one retreating scarp of 25 meters height and 100 meters length and one mound of 16 meters height and 30 meters length. After the perihelion passage, the mound gave space to a 2.6-meter depth cavity and two cavities appeared, of 2.7 and 5-to-16 meters depth each. Looking precisely on the location of the previously identified events, we unveil an evident heterogeneity, the source points cluster in 5 morphological changes: the new "jumping boulder", the retreating scarp of $8.8 \cdot 10^7$ kg, a thick dust missing layer of $3 \cdot 10^7$ kg and one cavity in an extended bright patch. The 50-meters "jumping boulder", in particular, had escavated a mass of $2.8 \cdot 10^7$ kg, and corresponds to the two bright events and several other smaller ejections of August 1st 2015.

Except for the one bright patch and the few parts of the scarp borders, all mass ejection sources are apparently dry after 9 months of southern "summer fireworks" in late 2015. This is different from January 16th 2015 when the equatorial reach of the bank was fully ice-enriched, probably by recondensation, due to large casting shadows from Apis wall.

To conclude, we estimate an ejected mass for a single perihelion passage, in respect to the global density of 533 kg/m3 (7; 8), of $1.7 \cdot 10^8$ kg, which correspond to 1.7-3.4% of the total ejected mass estimated by Paetzold et al. [9] or Thomas et al. [10], respectively. The minimum gas flux to lift the new "jumping boulder" is estimated at $2.85 \cdot 10^{24}\ m^{-2}s^{-1}$ according to El-Maarry et al. [5] (Supp. Mat.) formulation. The characteristic features' depth and apparent violence of several events advocates for very energetic sub-surface storage mechanism [6] instead of a predominance of cliff collapses as raised by Vincent et al. [4] and exemplified in Pajola et al. [11].

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Cometary dust, present understanding and open questions after the Rosetta mission

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Abstract

In-situ observation of several comets by spacecraft, the collection and delivery to Earth of dust from a cometary coma, remote sensing of comets, and comparison with the properties of interplanetary dust, some of which is cometary, collected at Earth, have provided many new insights to the composition and structure of cometary dust. These investigations have raised new, more detailed questions, suggesting future directions for comet research.

1. Introduction

Our present understanding of cometary dust has significantly progressed in the last years. It was mostly derived from the results of ten flyby missions to comets, e.g., Giotto, Vega, Stardust (with samples collected in 81P/Wild 2 coma), Deep Impact, and of the 26-months long Rosetta rendezvous mission with comet 67P/Churyumov-Gerasimenko (thereafter 67P). Numerous remote observations and technical achievements, together with elaborate theoretical studies, laboratory experiments and analytical capabilities, made such missions possible and contributed to the interpretation of their results.

Our purpose is to summarize our understanding on cometary dust, as given in [1], and to update it as much as possible.

2. Cometary dust Present understanding

It is now recognized that, at least for Jupiter Family Comets (JFCs) such as 67P, the relative proportion of minerals and organics within the dust is quite comparable, and that the refractory-organic phase appears to be dominated by organics of high molecular-mass [e.g., 2, 3]. The elementary composition of the particles for 67P is chondritic for most major elements (within a factor of 3), except for C and N, which are enriched with respect to the chondritic value [3]. It is also understood that dust particles within such comets are built up of aggregates of sub-micrometer grains, with morphologies of the particles ranging from extremely porous particles to almost compact ones; their hierarchical structure has been imaged during the Rosetta mission [e.g., 4, 5, 6].

Such properties suggest that cometary dust particles consist of material from the outer regions of the Solar System, mixed with material reprocessed in the inner protosolar nebula and transported to the outer regions. The existence of both fractal and more compact aggregates is consistent with dust growth starting by low-velocity hierarchical accretion forming low-porosity fractal particles, followed by a compaction phase creating aggregates with a range of higher densities. The preserved fractal particles are quite likely the most pristine solid matter available from the early stages of the Solar System formation [7].

It may be added that cometary dust particles, mainly subjected to gravitational and radiative forces, progressively become parts of the interplanetary dust cloud. Recent independent studies indicate that most interplanetary dust particles reaching the Earth could originate from JFCs [e.g., 8]. They might have delivered a huge amount of complex organics to the Earth, during the heavy bombardment epoch.

3. Cometary dust
Some open questions

As anticipated by Mike A'Hearn in 2017, "As we have dramatically increased our knowledge, we have also opened up many new questions" [9]. The results already obtained about composition and physical properties of dust in comets are indeed opening new questions.

1. Does the (elementary and isotopic) composition of the dust vary between comets?
2. Is the composition of the dust released by the nucleus representative of the bulk composition of the dust in its interior, or has it been reprocessed? At which scale are organic and mineral phases mixed in dust? How is ice mixed with the mineral and organic components? Is the organic refractory component totally or only partly of pre-solar, i.e., interstellar origin?
3. What are the smallest grains or monomers building cometary dust aggregates? What are their individual properties? Are they of interstellar origin, or did they form within the early Solar System?
4. Were dust particles revealed from studies within 67P's coma altered during the formation and evolution of the nucleus? Or during the processes leading to dust ejection from the nucleus? Or during the collection on-board Rosetta?
5. While clear similarities appear between cometary dust and CP-IDPs (Chondritic Porous Interplanetary Dust Particles collected in the Earth's stratosphere) [10] or even UCAMMs (Ultra Carbonaceous Antarctica Micro-Meteorites) [11], could further developments in collection and analyses of such particles provide more information on various types of comets and main-belt primitive objects?

4. Perspectives

Missions Hayabusa 2 and OSIRIS-REx to primitive main belt asteroids should soon offer the opportunity to compare cometary dust to primitive asteroid material, a study that will further advance our understanding of the early Solar System. The Lucy mission to Jupiter Trojans could later provide links between comets and other primitive objects. Meanwhile, some of the above-mentioned open questions could hopefully be solved by further studies of the enormous amount of data provided by Rosetta and comparisons with interplanetary dust particles collected at Earth.

Further progress requires sophisticated cross-platform analysis combining more insight into past space missions, elaborate remote observations of comets from Earth and near-Earth based telescopes, as well as improved numerical and experimental simulations. The development of the technological steps allowing sample returns of fragile cometary material in a not too distant future would be of major importance. NASA has preselected in late 2017 two proposals as possible New Frontiers 4 missions. One of them (CAESAR) would return a sample from 67. A final selection between the two missions is expected in 2019, for a launch sometime in 2025.

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Activity in the Imphotep region on comet 67P/Churyumov – Gerasimenko: dynamics of slow ejecta and landslides

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Abstract

In this work we investigate slow ejecta from comet 67P/Churyumov–Gerasimenko. We calculated trajectories of the ejecta from the Imhotep region, the locations of their deposition and stability of the deposited material. For initial velocity ~0.6 m s^{-1} the ejecta are deposited mainly on the Northern Hemisphere contrary to the ejecta from depression Hatmehit that are deposited mainly on the Southern Hemisphere.

1. Introduction:

Rosetta mission has indicated the activity in several sites of nucleus of comet 67P/Churyumov–Gerasimenko [1]. In present research we investigate trajectories of ejecta from depression Imhotep.

Comets and other small celestial bodies have very weak gravity field, so it was believed that probability of slope instability is low there. Even low cohesion could prevent instability. However, data from space missions to comets 9P/Tempe 1 and 67P/CG revealed existence of such instabilities. Large inclination of slopes in respect to the gravity makes instability more probable.

According to our best knowledge it is the first paper which treats about: (a) trajectories of slow ejecta from the Imhotep region, (b) places of their deposition, and (c) stability of these deposits.

2. Endogenic activity and ejecta

According to [2] an endogenic activity is responsible for formation of depression Hatmehit. Transformation of amorphous ice into crystalloid hexagonal ice could provide some heat that leads to vaporization of volatiles. Eventually a cavity is formed where the pressure of gas could reach a few dozens of Pa. If the pressure exceeds a critical value the upper crust could be crushed and its parts could be ejected into space. Their velocity could be lower than the escape velocity (therefore we use the term slow ejecta for them). Note also that initial velocity vector tends to be approximately perpendicular to the surface of the comet (the pressure force is perpendicular to the surface).

The flow of gas in cracks is another possible mechanism of grains' acceleration [3]. The gas can flow with the sound velocity (i.e. ~300 m s^{-1}). The velocity of grains in such jet depends on their size. Very small particles (dust) can reach high velocity but large grains cannot reach high velocity as a result of this mechanism. Both considered mechanisms of acceleration lead to segregation of the grains (the larger ones are usually slower). The details of the mechanism responsible for origin of ejecta is not critical for the present considerations.

3. Gravity field of the model

Model of gravity developed by [4] is used. It is based on the shape model published by ESA (given by 45994 faces and 24997 vertices). The distribution of mass is approximated with the use of 21890 spherical masses. Fig. 1 presents the distribution of masses (enveloped in the green surface). It should be noted that the shape of the nucleus does not resemble the shape of any surface with a constant value of the gravitational potential.

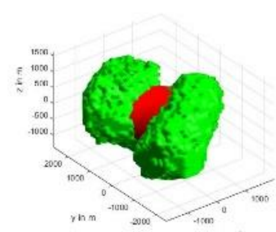

Fig. 1. The assumed mass distribution in the comet (the green volume) and the surface of the constant gravitational potential value: (red) for -0.45 m^2 s^{-2}. Note non-spherical shape of the red surface. After [4].

On the highly asymmetric comet determination of the slope of the surface is not a trivial problem – e.g., [5]. [3] found that the most of the surface (~74%) has the slope in the range $0 < \alpha < 40^o$. The slope in the range $40^o < \alpha < 70^o$ is found on ~17% of the surface and on ~6% of the surface the slope is $70^o < \alpha < 90^o$.

4. Equation of motion

To investigate the motion of ejecta we use Newton equation for motion in a non-inertial frame of reference in the form:

$$\frac{d\boldsymbol{v}}{dt} = \boldsymbol{g} - 2\boldsymbol{\omega}\times\boldsymbol{v} - \boldsymbol{\omega}\times(\boldsymbol{\omega}\times\boldsymbol{r}), \qquad (1)$$

where $\boldsymbol{v}$ is the velocity, $\boldsymbol{g}$ is the local gravity, $\boldsymbol{\omega}$ is the angular velocity of comet and $\boldsymbol{r}$ is the position of the ejecta. The equation is solved numerically using the standard Runge-Kutta method.

5. Results and conclusions

We performed calculations for the following velocities of ejecta: 0.3, 0.4, 0.5, 0.6, 0.7 m s^{-1}. Fig. 2 shows the trajectories of the grains ejected vertically (relative to the local physical surface) from 15 points inside the Imhotep region at the speed of 0.6 m s^{-1}. Please note that the most landing sites are situated on the large lobe (Body) of the comet.

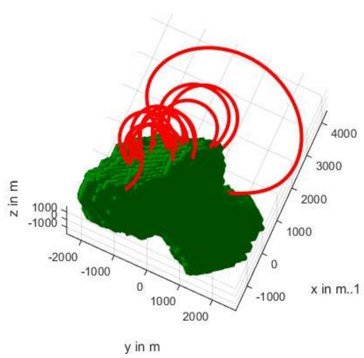

Fig. 2. The trajectories of matter (red lines) ejected vertically (relative to the physical surface) from chosen 15 sites inside the Imhotep region at the speed of 0.6 m s^{-1}.

Fig. 3 presents 145 starting points (red points) and the corresponding distribution of landing points for the speed 0.6 m s^{-1}. Moreover, landing sites are supplemented with information about the angle of fall (see the caption). Low angles (yellow marks) indicate stable position of deposits. Large angles (cyan marks) indicate that ejecta after landing are unstable and they could give rise to a landslide.

Note that the neck of the comet is a region of low gravitational potential, so it is a natural place for stable deposits (independent of discussed angles).

[6] performed similar calculations for ejecta from depression Hatmehit. Comparison of both calculations enables us for a few interesting conclusions:

(1) At the same speed, ejecta from the Imhotep region fell closer than from the depression Hatmehit, which is due to the higher mass of lobe Body compared to Head.

(2) Ejecta from the Imhotep region move on a trajectory directed towards the Northern Hemisphere and they are deposited there. Therefore, probably the ejecta from the Imhotep region are not substantially responsible for depositions in the Southern Hemisphere.

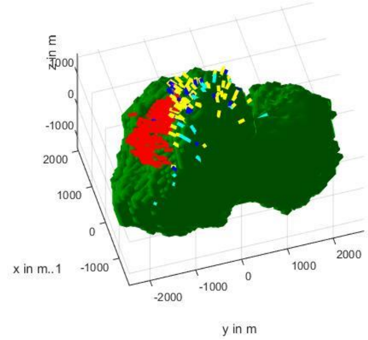

Fig. 3. The starting 145 sites inside the Imhotep region (red marks) and landing sites for ejectas (with the speed 0.6 m s^{-1}). Colors give information about the angles of the fall (i.e. angle between the velocity vector and normal to the surface) and inclination of the ground at the site of landing. The ranges of angles are given by the colors: 0^o - 30^o (yellow marks), 30^o - 45^o (blue marks), 45^o - 80^o (cyan marks), and other (magenta marks).

(3) Depositions of ejecta from the Imhotep region are generally less stable than depositions from Hatmehit.

We hope that determination of the place of origin of the surface deposits could be useful for choosing the objectives of the research goals of the CAESAR mission.

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Gas production of comet 67P/Churyumov-Gerasimenko reconstructed from DFMS/COPS data

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Abstract

We reconstruct the temporal evolution of surface emissions for the four major gas species H_2O, CO_2, CO, and O_2 emitted during the 2015 apparition of comet 67P/Churyumov-Gerasimenko (67P/C-G). Measurements from the Double Focusing Mass Spectrometer (DFMS) of the Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA) and the COmet Pressure Sensor (COPS) are used to determine the gas sources on the surface with an inverse gas model for the entire coma. For all species, peak production rates and integrated production rates per orbit are evaluated separately for the northern and the southern hemisphere. Complemented with the total mass production, this allows us to estimate the dust-to-gas ratio of the emitted material.

1. Introduction

The ROSINA instrument, a part of the Rosetta mission, has studied the gas environment of the comet 67P/C-G with mass spectrometers and pressure sensors. With an inverse gas model we analyze the species resolved evolution of the coma of 67P/C-G for ±350 days around perihelion, August 13th 2015, which corresponds to heliocentric distances in the range $3.5 - 1.24$ au.

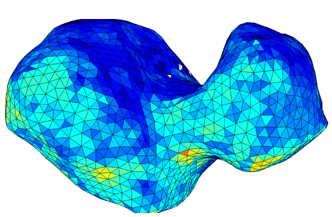

Figure 1: Surface shape approximation of comet 67P/C-G with triangular elements. The colors describe H_2O emission rates around perihelion, see [3].

2. Analysis of DFMS/COPS

For the global reconstruction of the three-dimensional gas atmosphere around comet 67P/C-G we run a numerically efficient gas model based on equations neglecting collisions in the tenuous atmosphere, see [2]. Each of the 3996 triangular elements approximating the surface shape, see Fig 1, possesses an emitting gas source with normal and lateral velocity components, see [5]. Applying an inverse model approach, the emission rates are determined as the best fit to the actually measured DFMS/COPS data at the spacecraft position.

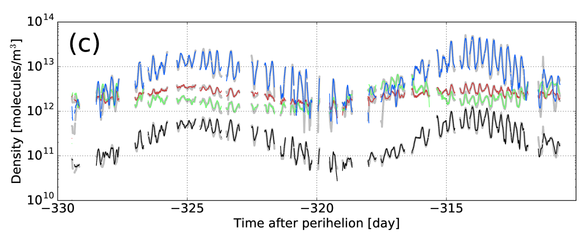

Figure 2: Modeled gas densities at the spacecraft position, 330 days to 310 days before perihelion. H_2O – blue, CO_2 – green, CO – red, and O_2 – black. DFMS/COPS data – gray lines.

Density measurements are available for the four major gas species H_2O, CO_2, CO, and O_2 from DFMS/COPS at the spacecraft location. The mission time is divided into subintervals with an average length of 14 Earth days. Each subinterval is chosen such that the spacecraft trajectory provides a good coverage of the comet surface. A typical, species-resolved density reconstruction between 330 days and 310 days before perihelion is shown in Fig. 2. A detailed analysis of gas source localization is given in [3].

3. Gas production

The integration of spatially and temporally resolved emission rates leads to integrated production rates for each of the gas species, see Fig. 3.

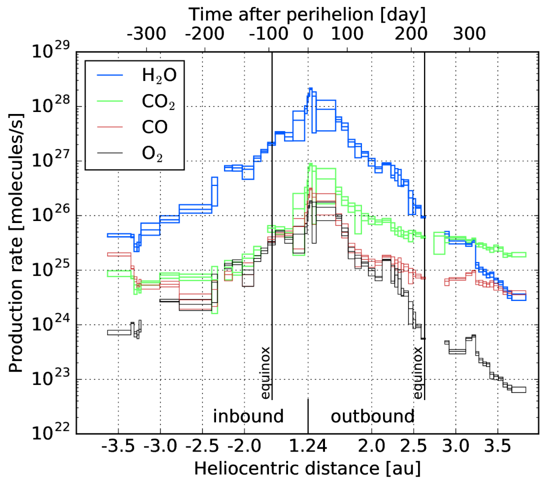

Figure 3: Gas production rates over time and heliocentric distance, The boxes denote error estimates due to varying spacecraft surface coverage.

H_2O production dominates the gas production up to the outbound equinox. A crossover from a water dominated to a carbon dioxide dominated coma happens at 2.75 au. The peak production is reached three weeks after perihelion and is dominated by H_2O. CO_2 adds only one tenth, the CO and O_2 contributions are below 5%. With respect to H_2O, our results are lower than the gas productions in [1], but higher than the analysis of [4] and [6].

The orbital losses allow us to constrain the dust-to-gas ratio of the emitted material from 67P/C-G. With the total gas loss including contributions from the four gas species investigated here and further 5% volatiles, we obtain a dust-to-gas ratio of below than 1.5.

Exponents appearing in power law fits ($\sim r_h^\alpha$ with the heliocentric distance r_h) of the production rates are characteristic for cometary activity. We provide exponents α for all species ranging from -7 to -4.5.

We analyze the gas production separated to the regional origin, from the northern and southern comet hemispheres. Caused by the stronger illumination of the southern latitudes during perihelion (summer solstice is 23 days after perihelion), all species are released in higher quantities from the southern hemisphere. For CO_2 we observe southwards shifted production rates for almost the whole mission time.

4. Summary and Conclusions

Based on the inverse gas model in [2] and DFMS/COPS measurements in the coma, gas emissions rates are reconstructed for the major gas species H_2O, CO_2, CO, and O_2 spatially resolved on the surface of comet 67P/C-G and temporally resolved during the mission time, see [3]. Derived from that, we present the temporal evolution of cometary gas production rates, the peak production and the total production over one orbit. We indicate the dust-to-gas ratio for the emitted material. The power laws (functions of heliocentric distance) for the gas production is analyzed and different gas activities from northern and southern hemispheres can be reported.

Acknowledgements

The work was supported by the North-German Supercomputing Alliance (HLRN). Rosetta is an ESA mission with contributions from its member states and NASA. We acknowledge herewith the work of the whole ESA Rosetta team. Work on ROSINA at the University of Bern was funded by the State of Bern, the Swiss National Science Foundation, and by the European Space Agency PRODEX program.

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Sublimation of cometary ice and mobilization of the dust mantle.

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Abstract

1. Introduction

Most of the surface of comet 67P/Churyumov-Gerasimenko is covered by dust. Patches of exposed ice-rich material were identified, but they lasted only about 10 days [1]. Thus, the dominating way of outgassing is the sub-dust sublimation. The rate of this process depends on the properties of the dust mantle, and of the underlying ice. Thus, it should be calculated taking into account the temperature dependent sublimation coefficient (e.g. [2]).

In this work direct measurements of the recession of the surface of ice covered by sand are presented, when ice covered by a sand of different granulation sublimes into vacuum. The experimental results are compared with the theoretical ones obtained using the Hertz-Knudsen equation with the sublimation coefficient and the Clausing formula for the gas permeability of granular media.

2. Measurements

The experimental is the same as described in [3], but the investigated samples had larger diameters. During experiments the evolving positions $z(t)$ of the surfaces of the samples and the temperature within the samples were recorded. In the experiments three types of sand were used: coarse ($r_g = 0.5 - 1$ mm), medium ($r_g = 0.25 - 0.5$ mm) and fine ($r_g = 0.125 - 0.25$ mm).

The profiles $z(t)$ split into sections. Subsequently, the average recession rate $(\frac{dz}{dt})_{av}$, the average temperature T_{av}, and the average pressure p_{av} were calculated. They were used to compute the values of the sublimation coefficient.

3. Results

The measured rate of erosion is in agreement with the theoretical one, calculated taking into account the temperature dependent sublimation coefficient. The agreement requires using correct value of the characteristic radius r_p of pores. We have found, that for coarse and medium sand $r_p \simeq 0.5(r_{max} + r_{min})$. However, for fine sand $r_p > 0.5(r_{max} + r_{min})$.

Another result is that at high temperature ice covered by fine, or medium sand sublimes faster than it is predicted for a stable layer of sand. This can be due to vibration of grains due to the flow of vapor.

Full description of the results is described in [4].

Acknowledgments

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Meter scale changes on comet 67P. J.-B. Vincent[1], E. Kührt[1], and the OSIRIS team, [1]DLR Institute of Planetary Research, Berlin, Germany, jean-baptiste.vincent@dlr.de

Cometary surface evolution is assumed to be mostly driven by the sublimation of volatiles in the subsurface when the nucleus is in the inner Solar System. Rosetta at 67P has shown a more complex picture, with the nucleus changing through many different processes, epochs, time scales [1,2,3].

During its two years around comet 67P, Rosetta observed only a handful of large scale changes, with most modifications being very localized, sporadic events: cliff retreat, deflation of smooth terrains, transport of a decameter-size blocks [1].

These large scale changes are impressive, but do not account for all the material being lost due to activity. Distributing the orbital mass loss (0.1% comet mass [5]) evenly over the nucleus would lead to surface modifications of at least ~50 cm. However, due to the seasonal variations of insolation [6] and the resulting heterogeneous distribution of active sources, we expect most small scale changes to be below the OSIRIS NAC [7] typical resolution (60cm/px) in the least active areas, and reach several meters elsewhere.

Up to now, tracking these changes has been difficult, due the complexity of Rosetta observation, never quite having a real mapping orbit with consistent viewing geometry. To overcome this challenge, we have developed dedicated mapping tool and a new algorithm designed for automating the detection of surface changes [6], we are now able to extend our coverage of surface changes to the smallest scale (<1m) on the whole nucleus.

After processing OSIRIS-NAC images acquired before and after perihelion, we detected several thousands changes, ranging from the redistribution of dust in local ponds, to the possibly thermally induced breaking of blocks, or the opening of small pits (10 m diameter) in conjunction with fracture expansion and/or outbursts.

This presentation will review the different types of small scale changes thus detected, and their distribution on the nucleus. We will discuss how we use these changes to retrieve important physical parameters. For instance: the survival or destruction of boulders being transported across the surface sets a lower limit for the material strength; or the opening of small pits associated to outbursts can be related to the thermal inertial of the upper surface.

Among all changes, we will focus primarily on the reorganization of regolith in smooth terrains. It is the dominant type of surface changes and is particularly interesting as such terrains will be the preferred target of future sample return missions like NASA's CAESAR. We will present a numerical model of dust transport under shear (aeolian or saltation), aiming at assessing whether those changes are primarily due to dust deposition or to sublimation of volatile material below the dust cover.

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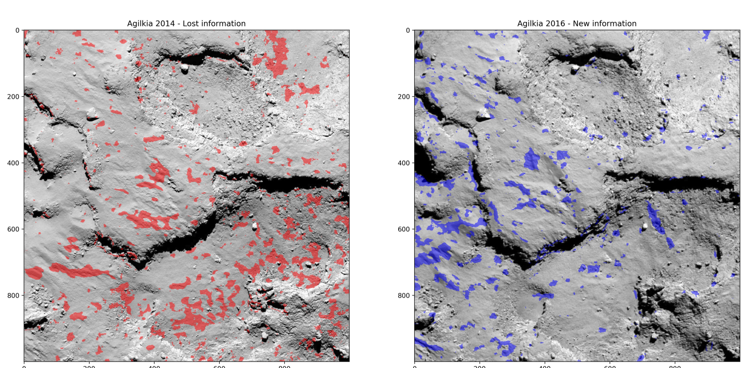

Automatic change detection on nucleus-referenced images of Agilkia region (comet 67P)

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Bowl shaped features on comet 67P/Churyumov-Gerasimenko as a test of cometary material properties

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Abstract

1. Introduction

Comet 67P/Churyumov-Gerasimenko shows a large variety of circular structures such as pits [1], elevated roundish features in Imhotep [2], and a single bowl shaped feature in the Ash region [3]. Analyzing images of the OSIRIS camera gives a set of characteristics of these features that need to be explained by models for cometary formation and evolution. Using the iSALE code [4, 5], simulations of impact experiments into a cometary analogue material have been performed to investigate the plausibility of an impact origin of these features.

An additional impact experiment has been performed by the touchdown of the Philae lander in Agilkia. The depressions left by the impact give an opportunity to test our understanding of the material parameters at the very surface of the comet.

1.1 Modelling impacts into cometary material

Parameterizing the cometary material is the principle challenge of impact simulations. A number of material properties have already been derived from observations, as e.g. an extremely low tensile strength of only a few Pa [6, 7] for boulders as well as the consolidated material in cliffs, and a shear strength of a few tens of Pa [7]. The least constrained at the moment is the compressive strength: While Groussin et al. [7] derived a value of 30 to 150 Pa for the compressive strength on large scales such as cliffs, on the local scale the Philae lander experiment SESAME/CASSE finds a much higher compressive strength in the MPa regime [8]

Exploring the parameter space of strength and impact velocity, we found that only the bowl shaped depression in the Ash region can be directly linked to impact processes. Other features, such as the prominent pit structures and the elevated circular features found in Imhotep can in principle be explained by impactors, but only if additional evolutionary processes are considered, making it complicated to infer cometary material properties using these events.

The bowl shaped features, on the other hand, can be linked directly to impact processes. In this work, in a series of numerical impact experiments we try to recreate the shape and size of these features. This can be used to narrow down the range of plausible strength values and the compaction curve of the highly porous cometary material. Additionally, these values are cross checked by recreating the depressions left by the Philae lander on its touchdown, using the Philae lander as a validation experiment.

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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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A Comet Active Beyond the Crystallization Zone

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Abstract

We discuss activity of the in-bound long-period comet C/2017 K2 (PANSTARRS) at record heliocentric distances of 16 and 24 AU [1, 2, 3]. At these distances, nucleus temperatures are too low either for water ice to sublimate or for amorphous ice to crystallize, requiring another source for the observed activity. Using the Hubble Space Telescope we find a sharply-bounded, circularly symmetric dust coma 10^5 km in radius, with a total scattering cross section of $\sim 10^5$ km^2. The coma has a logarithmic surface brightness gradient -1 over much of its surface, indicating sustained, steady-state dust production. A lack of clear evidence for the action of solar radiation pressure suggests that the dust particles are large, with a mean size $>$ 0.5 mm. Using a coma convolution model, we find a limit to the apparent magnitude of the nucleus $V > 25.2$ (absolute magnitude $H > 12.9$). With assumed geometric albedo p_V = 0.04, the limit to the nucleus circular equivalent radius is $<$ 9 km. While neither water ice sublimation nor exothermic crystallization can account for the observed distant activity, the measured properties are consistent with activity driven by sublimating supervolatile ices such as CO_2, CO, and N_2. Survival of supervolatiles at the nucleus surface is likely a result of the comet's recent arrival from the frigid Oort cloud.

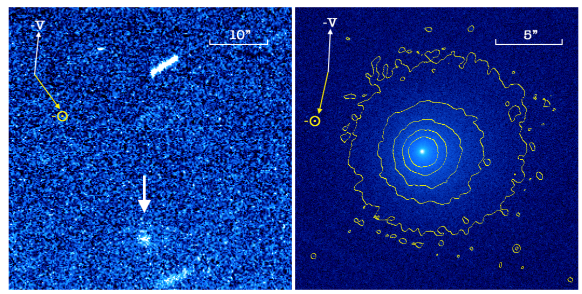

Figure 1: Left: Prediscovery CFHT image of C/2017 K2 (arrow) from UT 2013 May 12 at 23.765 AU. Right: HST image from UT 2017 Jun 27 at 15.874 AU. The antisolar (-⊙) and negative velocity ($-V$) vectors are marked. Both images have North to the top, East to the Left).

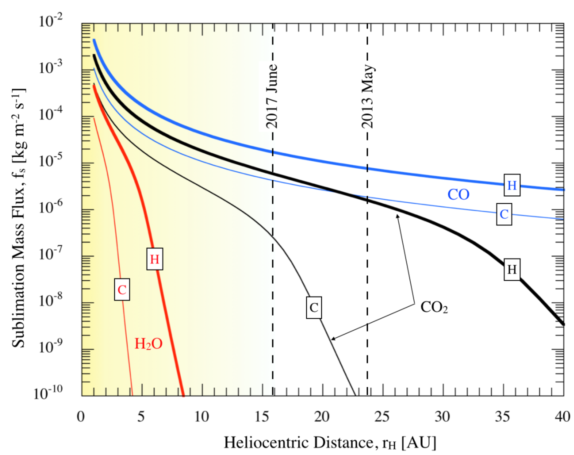

Figure 2: Specific sublimation rates as a function of heliocentric distance for three ices: (red) H_2O, (black) CO_2 and (blue) CO. Sublimation rates for the minimum (labeled C for “cold”) and maximum (H for “hot”) possible temperatures are indicated by thin and thick lines. The shaded region shows the heliocentric distances where crystallization is possible.

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Analysis of phase curve of 67P/Churyumov-Gerasimenko at small phase angles using Rosetta-OSIRIS images

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Abstract

The Rosetta spacecraft reached its target 67P/Churyumov-Gerasimenko (hereafter 67P) in August 2014 and orbited around the comet until 30th September 2016. During the 2.5 years of mission, two zero-phase-angle fly-bys were performed by Rosetta. During these, OSIRIS, the Optical, Spectroscopic, and Infrared Remote Imaging System [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 at 6 km 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 images with the Wide Angle Camera (WAC) and the Narrow Angle Camera (NAC).

For our study we analyze a set of NAC images, acquired on 09-10th April 2016, in the F84 (480.7 nm), F82 (649.2 nm), and F88 (743.7 nm) filters, spanning the phase angle range from 0.2° to 8.0°. The NAC images cover an area in the Ash-Khepry-Imhotep region [4].

At small phase angle range, the opposition effect (OE) manifests itself as a rapid increase in the surface reflectance with decreasing phase angle. The reflectance dependence on the phase angle (known as surface phase function) contains information about photometric and structural properties of the surface.

We built a surface phase function for the Ash-Khepry-Imhotep region. In order to separate the surface phase function and disk function contributions to the measured reflectance, we evaluate the images with different disk functions, such as Lommel-Seelinger, Minnaert and Akimov. Our goal is to explore the photometric properties of the comet's surface together with the physical mechanisms that play a role in the OE.

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.

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Dielectric properties of comet 67P/CG and implications for the 2021 radar observations of its next closest approach

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Abstract

In November 2021, comet 67P/Churyumov-Gerasimenko (67P/CG) will make its next closest approach to Earth at a distance of 0.418 AU, presenting an opportunity for radar detection by the Arecibo Observatory. We report on the most up-to-date 3D dielectric model of the comet surface and interior as constrained by Rosetta mission observations primarily by the CONSERT 90-MHz radar investigation and OSIRIS optical imager. Our results suggest that any observed changes in the comet's radar backscatter reflectivity will be the result of changes in the nucleus' structure, such as surface smoothening associated with increased coverage by fine-grained material, or potential nucleus breakup.

1. Introduction

Due to comets' infrequent passes by Earth—in addition to having characteristically small diameters and low radar albedo—only a few tens of comets have been observed by Earth-based radar to date [1]. Less than half of these cometary nuclei have both (1) independent constraints on their shape and size (e.g., from lightcurve analysis); as well as (2) a detectable radar backscatter echo, which together permit reliable interpretation of the comet's physical properties [2].

Physical properties nominally inferred from radar backscatter measurements include the shape, size and spin of the comet nucleus (e.g., [3]). In addition, the power and polarization of the radar return constrain the characteristics of (1) the surface roughness at the scale of the radar wavelength (cm to m), and (2) the complex relative permittivity or dielectric constant ε_r of the material that comprises the upper meters of the shallow subsurface (e.g., [3,4])—where ε_r depends primarily on the mineralogy, bulk density, volatile content and temperature of the material at a given radar frequency (e.g., [5,6]).

Herein, we present the updated 3D dielectric model of comet 67P/CG after the Rosetta rendezvous, and assess the radar detectability of the nucleus using Earth-based radar during its next closest approach in 2021.

2. Post-rendezvous 3D dielectric model of comet 67P/CG

Table 1 lists the post-rendezvous geophysical and dielectric constraints on comet 67P/CG established by Rosetta and Arecibo observations of the nucleus, which we use to construct our updated 3D dielectric model. We define the nucleus in terms of three primary layers: (1) ~1-2 m thick fine-grained dust-ice deposits that cover about 30% of the surface—where 'fine-grained' refers to blocks ≤1 m in size—(2) ~1-5 m thick consolidated dust-ice material that is exposed over about 70% of the surface, and (3) the dust-ice bulk interior of the nucleus—considering the hypothesis of a structurally and dielectrically homogeneous interior [7,8]. We calculate the parametric range of possible $\varepsilon_r'_{eff}$ for each surface terrain type using the Maxwell-Garnett dielectric mixing law and using Hérique et al.'s [6] constraints on the density and dielectric properties of the constituent cometary dust and cometary ice materials.

Table 1: Geophysical and dielectric constraints for three primary layers of the comet 67P/CG nucleus.

Layer	Porosity	Dust-ice mass ratio [13]	ε_r'
Fine-grained deposits [9]	~85% [10]	> (4 ± 2)	≤ 1.9-2.1*
Consolidated material [9]	< 50% [11]; 30-65% [12]	(4 ± 2)	≤ 1.9-2.1*; >2.45 ± 0.20**
Dust-ice interior	75-85% [8]	(4 ± 2)	1.27 ± 0.05***

*at 2.4 GHz, averaged over the surface [14]; **at 10 Hz-10 kHz at the final Philae landing site [11]; ***at 90 MHz in the comet head interior [8]

Our resulting 3D dielectric model is shown in Fig. 1. We find that $\varepsilon_r{}'_{deposits} \lesssim \varepsilon_r{}'_{interior}$ and $\varepsilon_r{}'_{consolidated} > \varepsilon_r{}'_{deposits}$, where $\varepsilon_r{}'_{deposits} \approx$ 1.2-1.3 and $\varepsilon_r{}'_{consolidated} \approx$ 1.9-2.7 (where higher $\varepsilon_r{}'$ correspond to the upper limit of possible $\varepsilon_r{}'$ values for the pure cometary dust component used in the mixing law formula [6]). Unlike asteroids, which have thick, well-gardened desiccated regoliths with homogeneous dielectric properties [15], our results suggest that comet 67P/CG has an actively reworked surface with a subsequently dielectrically heterogeneous surface due to the uneven distribution of regolith material.

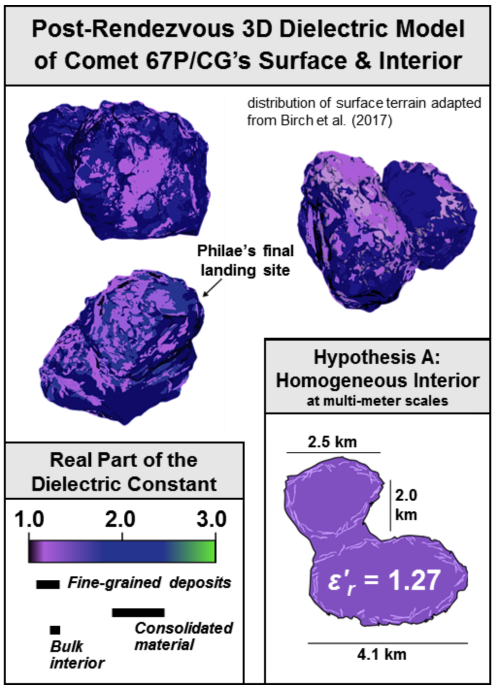

Figure 1: Three-dimensional dielectric model of comet 67P/CG's surface and interior at different perspectives. ~30% of the surface has $\varepsilon_r{}' \leq 1.3$ due to thick deposits of loose fine-grained dust and ice, while 70% has a higher $\varepsilon_r{}' \leq 1.9\text{-}2.7$ where consolidated material is exposed.

3. Implications for future Earth-based radar observations of comet 67P/CG

The only Earth-based radar observations of comet 67P/CG were conducted by the Arecibo Observatory in 1982 [14]. While the nucleus' radar echo was not detected, Kamoun et al. [14] recently reanalyzed the 1982 data after 67P/CG's diameter was constrained using optical data (pre-Rosetta). This enabled the estimation of an upper limit on 67P/CG's surface radar cross section (by approximating 67P/CG as a sphere with a simple cosine angular scattering law) such that σ_{max} = 0.7 km^2 and $\varepsilon_r{}'_{surface} \approx$ 1.9-2.1 [14].

Our post-rendezvous dielectric model, however, suggests that ~70% of the surface has a dielectric constant of $\varepsilon_r{}' \approx$ 1.9-2.7, which at its upper limit corresponds to $\sigma_{max} \approx$ 1.17 km^2 (using the same scattering-law assumptions as Kamoun et al. [14]). Moreover, the Arecibo antenna was upgraded in 1997, including a gain increase of ~5 dB, and a decrease in system temperature by ~20 K (e.g., [16]). Using the latest Arecibo Observatory's antenna parameters for S-band radar observations [17], we calculate that during comet 67P/CG's next closest approach at ~0.418 AU throughout the month of November 2021, the comet will be detectable by Arecibo S-band with an SNR_{max} of ~7.6 dB above noise level.

Future work will incorporate the latest 67P/CG nucleus shape model derived from Rosetta observations to accurately simulate S-band radar scattering from the comet's surface.

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Layering-Related Linear Features on Comet 67P

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Abstract

We studied the three-dimensional orientation of layerings in the nucleus of comet 67P/Churyumov-Gerasimenko ('67P'). Using high-resolution 2D images from the OSIRIS Camera system onboard the Rosetta spacecraft in combination with a 3D shape model of the nucleus, we mapped presumably layering-related linear features on the comet's surface, then applied methods of structural geology to predict their subsurface orientation. Our results independently confirm the internal structure proposed by preceding works [1,2] of a nucleus whose two lobes are independently concentrically layered to a depth of at least several hundred meters below the nucleus surface.

1. Introduction

Photographic images of the nucleus surface of 67P suggest that the comet may have a layered internal structure, which would hold clues to the comet's formation and evolution in the early Solar System.

Previous works concluded that the two lobes of the nucleus of 67P are individually wrapped in 'onion-like' stratification that formed through accretion before the bodies merged in a gentle collision in the early Solar System [1]. The layerings and internal structure were later modelled by fitting ellipsoidal shells to "terraces" on both lobes [2]. Both of these approaches are based on planar terrace features, whereas our method relies exclusively on linear surface features.

2. Methods

We identified and mapped linear layering structures on the nucleus surface, determined their normal vectors, and analysed their orientation relative to each other.

We focused our study on morphological edges between terraces and the steep cliff faces below them ("edges"), as well as linear discontinuities visible on hill slopes and cliff faces ("strata heads").

We aligned high-resolution 2D images from the OSIRIS Narrow Angle Camera on the lower-resolution SHAP5 shape model on the nucleus. We

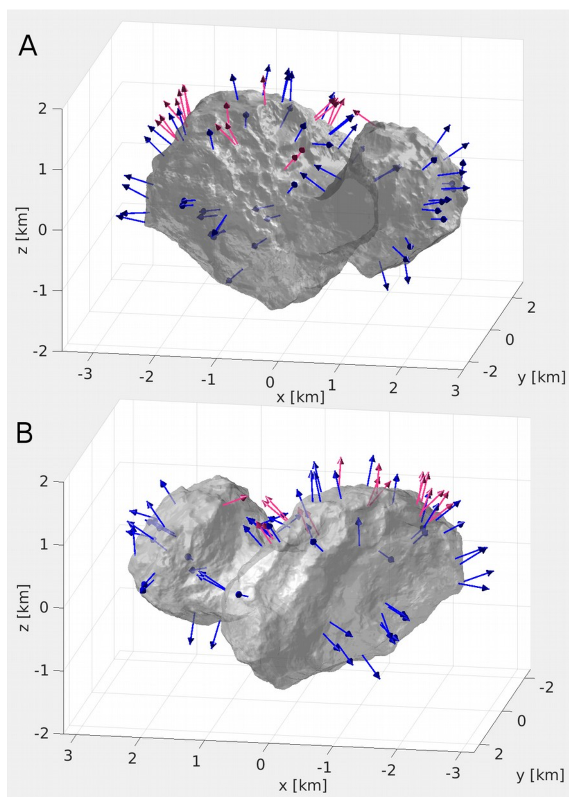

Figure 1: Shape model of comet 67P showing the normal vectors of the best-fitting planes to the mapped terrain edges (blue arrows) and strata heads (pink arrows). Coordinates are in the Cheops reference frame. A: ‘Front’ view towards positive y-values; B: ‘Back’ view rotated around the z-axis by 180°.

then mapped the linear features on these aligned images, fitted planes through all features with sufficient curvature, and analysed the orientation of the plane-normals.

3. Results

We mapped 74 linear features on a total of 30 aligned OSIRIS images. 56 of the features are classified as terrace edges and 18 as strata heads. The plane-normals fitted to these features are illustrated in Figure 1.

4. Interpretation and Conclusions

Our proposed layering-normals are close to perpendicular to the nucleus surface, independent of their location on the nucleus or their distance to the gravitational centre of the respective lobe (Figure 1). In terms of structural geology, this means that the layerings are in a centroclinal configuration, i.e. they are concentric. The majority of layering-normals are furthermore parallel with, or at small angles (< 20°) to the normals of a set of concentric ellipsoids inscribed to the lobes (see [2]).

Concentric layerings have previously been proposed through the analysis of planar terraces [1,2]. The terrace surfaces on 67P are, however, visibly and extensively covered in deposits of fine-grained material and larger debris [3], such that the orientation of these surfaces might not be equal to the orientation of the underlying layerings. This limitation is acknowledged [2] and the authors estimate that this might introduce errors of up to 20° on the estimated orientation of the terraces. By focusing on the edges of terraces and outcropping strata, we avoided the effect of sedimentary deposition upon our measurements. In turn, our terrace edges are somewhat influenced by erosional processes.

In conclusion, we found that normals, fitted to layering planes at various distances from the respective lobes' centres across most of the nucleus surface of comet 67P, are approximately perpendicular to the nucleus surface. Furthermore, fitting our measurements with concentric ellipsoidal shells yields a result similar to [2] and supports that the comet is enveloped in numerous concentric layerings to a depth of at least several hundred metres. Our results, especially the orientations of the layering normals adjacent to the comet's neck, add to the large body of evidence that 67P consists of two independently formed bodies that were joined together in a gentle collision (e.g. [4,5,6]).

Acknowledgements

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Seasonal colors cycling on 67P/CG nucleus and coma

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Abstract

Understanding how comets work is one of the more compelling questions to which Rosetta mission is trying to answer to. In this perspective, we investigate the temporal evolution of 67P/CG nucleus surface and dust particles with the scope to quantify the spectral changes occurring at different heliocentric distances, to search for possible correlations among them and to verify their dependence with activity. A quantitative analysis of seasonal color changes occurring in the coma and nucleus of 67P/CG has been conducted by means of a systematic processing of the entire Rosetta-VIRTIS-M-VIS [1] channel dataset. Specific spectral indicators have been separately computed for the coma and the nucleus and then ordered in time-series spanning from January 2015 (in-bound orbit, heliocentric distance 2.55 AU), encompassing perihelion passage (August 2015, 1.24 AU) up to May 2016 (outbound orbit, 2.92 AU).

1. How does the coma changes?

For VIRTIS coma data, spectral analysis is performed considering all pixels inside an annulus defined by tangent altitudes between 1 and 2.5 km above the limb. The following four spectral indicators are computed for each observation: 1) integrated radiance (I) across the VIS spectral range; 2) wavelength of maximum emission of the radiance (λ_{max}); 3) 0.4-0.5 μm I/F spectral slope; 4) 0.5-0.8 μm I/F spectral slope. The *integrated radiance (I)* of the coma emission (dust and gas) is computed by averaging the integral of the spectral radiance in the 0.25-1 μm spectral range on the annulus:

$$I = \frac{\sum_{n=1}^{N} \int_{0.25\mu m}^{1\mu m} R(n,\lambda) d\lambda}{N} \quad (1)$$

where $R(n,\lambda)$ is the spectral radiance measured on the n-th pixel of the annulus at wavelength λ and N is the total number of pixels within the annulus area. The *wavelength of maximum emission of the radiance (λ_{max})* is determined from a 4th degree quadratic fit on the average spectral radiance computed on the annulus ($\sum_{n=1}^{N} R(n,\lambda)/N$). *Spectral slopes* are computed following the method discussed in [2, 3]. On average, both dust colors and integrated radiance changed significantly approaching the perihelion passage (Fig. 1). The spectral radiance from 67P coma is largely dominated by scattered light from grains at visible wavelengths. Monitoring the integrated intensity in an annulus around the nucleus allows to trace the temporal activity changes as a function of the heliocentric distance. The general trend of the integrated radiance as a function of the heliocentric distance shown in Fig 1 top left panel, is characterized by an asymmetric, or cusp-like, profile similar to the water production rate measured by other Rosetta instruments [4]. The maximum is reached in MTP020, with a delay of less than a month with respect to the perihelion passage (MTP019). Two intense integrated radiance peaks of about 50 W/(m^2 sr), occurred around the perihelion period when the spacecraft was performing dayside excursions orbiting at great distances (up to 1400 km) from the nucleus. The increased optical depth along the line of sight during these two periods and the intense cometary activity (outbursts occurred in September 2015) are the cause of the integrated radiance rapid increment. The wavelength (λ_{max}) of maximum emission increases from about 0.45 μm in January 2015 to 0.55 μm around perihelion to decrease again to 0.45 μm in May 2016 (Fig 1, bottom left panel). A similar trend is observed also on the two spectral slopes (0.4-0.5 and 0.5-0.8 μm) profiles calculated on I/F spectra which show a reddening around perihelion passage (Fig 1, right column panels). All these parameters show how the spectral behavior of the coma is changing with the heliocentric distance, becoming more red towards perihelion.

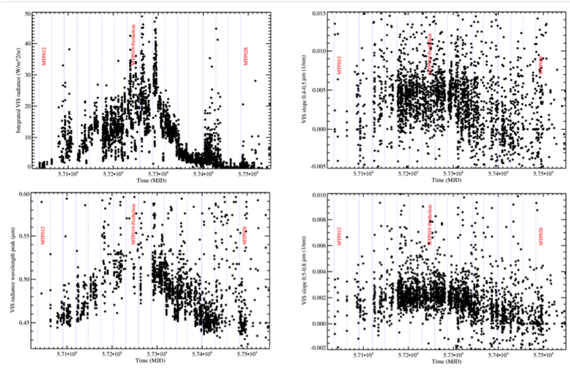

Figure 1: Time-series showing the evolution of coma spectral indicators: integrated radiance (top left panel), λ_{max} (bottom left), 0.4-0.5 μm slope (top right), 0.5-0.8 μm slope (bottom right).

2. How does the nucleus changes?

The color of the nucleus is mainly driven by the abundance of the water ice on the surface regolith [5, 6]. VIRTIS data show that the nucleus surface is progressively becoming bluer while the comet was approaching the sun [2, 3, 7]. The analysis performed on several locations across the nucleus for which a continuous coverage across the entire mission is available (Fig. 2) indicate that the minimum reddening is reached in September 2015, about one month after perihelion. On the next months the reddening increases again returning to pre-perihelion values towards the end of the Rosetta mission

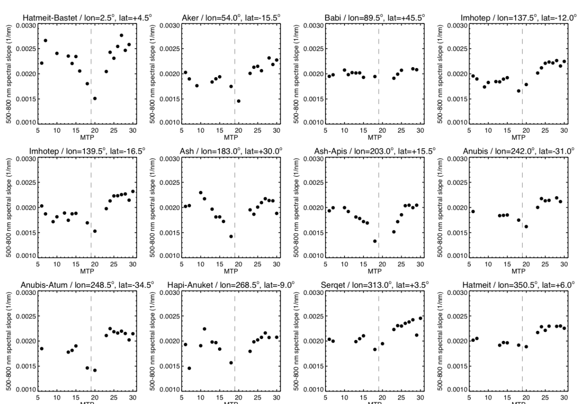

Figure 2: Time-series showing the evolution of visible spectral slope on 12 test equatorial areas. The minimum reddening is observed in MTP020 (September 2015).

3. Summary and Conclusions

By comparing coma and nucleus spectral slopes, two opposite trends with heliocentric distance are observed: while the I/F spectra of the coma becomes more red when the comet approaches perihelion, on 12 equatorial areas of the nucleus, for which we have continuous time-coverage during the entire Rosetta mission, we observe a systematic bluening of the surface, with a reduction of the spectral slope up to 50%. During the pre-perihelion period we interpret the coma color changes as a consequence of the progressive loss of the ice fraction in the dust grains ejected from the nucleus which makes them more red. At the same time the nucleus' surface becomes bluer following the exposure of more pristine subsurface layers and the removal of surface dust caused by the gaseous activity. After perihelion, as soon as activity begins to settle, the progressive accumulation of dehydrated dust on the surface makes it redder again. The study of coma's and surface's color time-series observed by VIRTIS indicate that a similar seasonal cycle is developing during the orbital phase close to the sun.

4. Acknowledgments

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EPSC Abstracts
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Evidence for a Surface Evolution Trend in Jupiter-Family Comets

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Abstract

We studied the rotation-rate changes and surface properties of comets 14P/Wolf, 143P/Kowal-Mrkos, and 162P/Siding Spring. We derived upper limits for the spin changes which occurred during their latest perihelion passages, and confirmed that large comet nuclei experience small rotation rate changes. This finding adds to a growing list of evidence suggesting that large comets are expected to survive more perihelion passages than smaller ones. We added 143P to the small group of Jupiter-family comets (JFCs) for which both the albedo and the phase-function slope have been measured. These comets indicate a possible correlation between the albedo and the phase-function slope [1]. In the light of recent findings from the Rosetta mission, we propose a hypothesis which interprets this trend as a result of the sublimation-driven erosion of JFC nuclei.

1. Introduction

Ground photometric observations of bare Jupiter-family comet nuclei can be used to study their rotations and surface characteristics. We have developed a method for absolute photometric calibration using the Pan-STARRS catalogue. This has allowed us to derive precise lightcurves and phase functions of comets using sparsely-sampled observations from various ground-based telescopes. Combining our observations with quasi-simultaneous thermal infrared observations from the SEPPCoN program [2] enables us to derive the albedos of the comet nuclei.

2. Enhanced survivability of large JFC nuclei

We collected photometric data for 3 comets. The data enabled us to derive the current rotation periods and to compare them with the known rotation rates of the comets from previous orbits. None of the three comets had detectable period changes, and we set conservative upper limits of 4.2 (14P), 6.6 (143P) and 25 (162P) minutes per orbit.

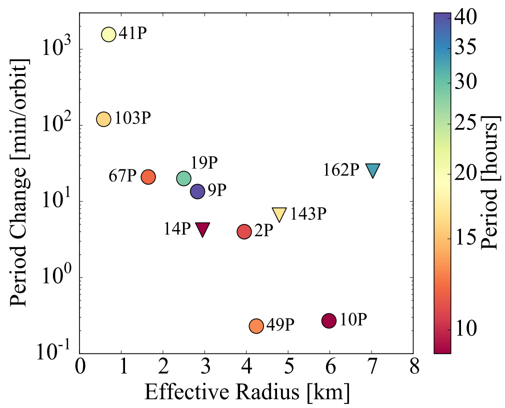

Figure 1: Properties of the JFC nuclei with measured rotation changes. The circles correspond to comets from the literature. The triangles indicate the upper limits of the spin changes measured for the comets from this work. The symbol colours correspond to the rotation rates of the comets. The largest period changes were measured for the smallest comets, 41P and 103P, while the smallest period changes were detected for the biggest nuclei.

We compared the upper limits from this study to all previously measured period changes of JFCs (Fig. 1). It is evident that, in agreement with theoretical predictions [3], the smallest comets experience the largest period changes, while the large nuclei change their periods the least. Large comets are therefore less likely to experience significant spin-up over their lifetimes. This conclusion agrees with the observation from [1] that no large comets lie close to the rotational-instability limit. The small period changes of large

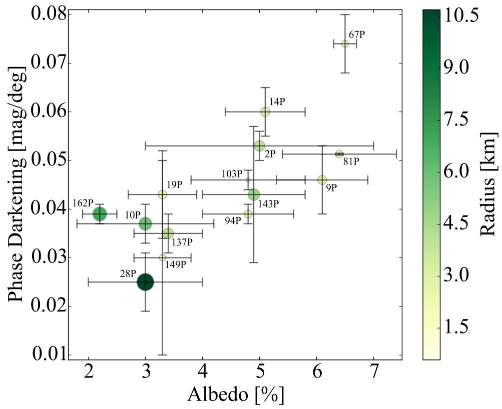

Figure 2: Linear phase-function slope β versus geometric albedo in R-band for JFCs. The colours and the sizes of the points correspond to the effective radii of the nuclei. The distribution of the points on the plot suggests a trend for increasing albedos wih increasing β. The largest and least active nuclei are at the lower left corner of the plot, with small albedos and β values.

comet nuclei can be added to the factors which contribute to the excess of large objects in the cumulative size distributions of JFCs [2] and asteroids on cometary orbits [4, 5].

3. Surface evolution of JFC nuclei

In [1] we identified a possible correlation between the phase-function slope and the albedos of JFC nuclei. Interestingly, the largest and least active comets are observed to have low albedos and shallow phase functions. In this work we added comet 143P to this sample and attempted to understand the physical parameters behind the correlation (Fig. 2). Based on the conclusions from recent detailed studies of the surfaces of JFCs visited by spacecraft [6, 7], we hypothesise that the albedo-phase function correlation corresponds to the evolutionary path of comet surfaces. According to this scenario, dynamically young JFCs have relatively high albedos and steeper phase functions. As their sublimation-driven erosion progresses, their surfaces become smoother and their phase-function slopes decrease. As the the dust layers gradually cover larger portions of the surfaces, the comets transition to dormancy, their surfaces lose the remaining volatiles, and therefore their albedos decrease even further.

4. Conclusions

We found evidence that the sublimation-driven evolution of the surfaces of JFCs might be observable through a correlation between their phase-function slopes and albedos. This hypothesis needs to be validated with further observations. If confirmed, it provides an exciting prospect to characterise the surfaces of an extended number of comets with telescope observations. The details of this work can be found in [8].

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Nano-to-micro dust environment monitored by GIADA during the entire ROSETTA scientific phase

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Abstract

Among the measurement subsystem of the GIADA instrument the MBBS is devoted to monitor the mass fluence and flux of the nano to micro meter size dust particles. This subsystem continuously operated along the whole scientific phase of the Rosetta mission, allowing a complete characterization of the finest part of the dust environment.

Introduction

The Micro Balance System (MBS) [1] is the GIADA [2,3] subsystem devoted to the flux and fluence of nano to micro dust particles measurement. The cumulative flux of particles/grains with diameters <10 µm is measured by a net of five Quartz Crystal Microbalances (QCMs) pointing towards different directions in order to characterize the dust flux within a solid angle of 180 deg.

Each QCM has an acceptance angle of about 40 deg, a collection area of about 12 mm2 and consists of a matched pair of quartz crystals resonating at ∼15MHz. Each QCM is equipped with a heating device to: (1) check the frequency vs. temperature dependence, (2) perform thermo-gravimetric measurements on the accumulated dust, at temperatures < 100 °C, and (3) remove volatile materials from the sensitive surface. Starting from the July 2014, i.e. during the Rosetta/ESA space probe approach to comet 67P/Churyumov-Gerasimenko, the MBS was continuously operating to monitor the dust coma environment.

The QCMs' high sensitivity (0.2 [Hz ng−1]) allowed to detect nano-micron-sized dust dust flux variation events well constrained in time. Otherwise, the nano-to-micron-sized particle flux was constant over the entire Rosetta mission scientific phase.

1. Data

The MBS data analysis allowed us to characterize the nano-to-micron sized dust particles flux identifying: (1) the preferred dust flux directions [4]; (2) the flux time variation for particles with sizes smaller than 10 microns; 3) the presence of fine dust in dust "outbursts"; in Figure 1 are reported the data collected for the QCM1 (pointing to the solar direction for almost the whole scientific phase) and QCM5 (pointing the Nadir direction).

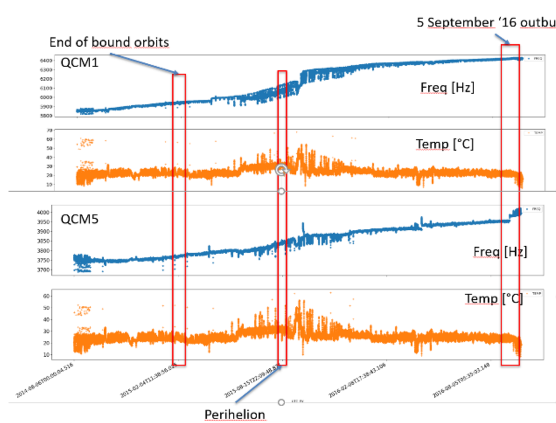

Figure 1: Raw data collected during the whole scientific phase by the QCM5 (nadir pointing) and QCM1 (roughly solar direction for most of the scientific phase).

2. Results

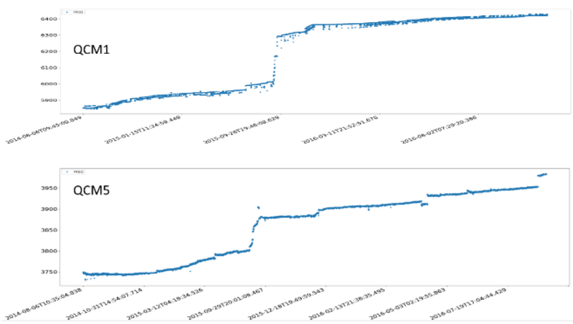

Figure 2: QCM1 (roughly solar direction for most of the scientific phase) QCM5 (nadir pointing) data, after removing the thermal effects.

In Figure 2 are reported the QCM1 and QCM5 measurements after removing the thermal effects. For both is evident the high enhancement of the nano to micro dust size flux during 67P perihelion passage. Despite the large distance from the comet (>300 km) a strong change in the trend of the data testifies a great increase of the dust mass cumulated on the QCM1 and QCM5 sensitive surfaces. The dust fluxes seem uncorrelated with respect to the comet surface illumination conditions. It is not trivial to identify a scaling factor that takes into account the detection distance from the comet. A simple $1/r^2$ scaling factor does not fit, probably because the nano to micron size fluxes are affected by the perihelion outburst activity.

Acknowledgements

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Mass loss during outbursts on comet 67P

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Abstract

During its 2.5-year mission at comet 67P/Churyumov-Gerasimenko, instruments on board the European Space Agency's Rosetta spacecraft frequently observed outbursts of activity on various scales. The events typically lasted for less than a few hours and were characterised by the emission of gas and/or dust in quantities higher than typical for the given region and local time. The vast majority of these outbursts was too small to be detectable by Earth-based telescopes, and seemed to originate from confined small areas on the surface [1]. Possible causes of cometary outbursts include collapsing cliffs [2], exposure of supervolatiles to sunlight in expanding fractures [3], cryovolcanism driven by the crystallisation of amorphous ice [4], and the collapse of sub-surface cavities [5, 6].

The amount of dust produced during an outburst can be constrained both from the measurements of in situ dust instruments (GIADA and COSIMA) and from the light scattered by the dust (as observed e.g. with the cameras OSIRIS and NAVCAM). The gas production rate can be constrained from measurements of the gas instrument (ROSINA), and indirectly from the area on the surface affected by an outburst [7, 8].

We here study a sample of outbursts on 67P for which at least two complementary measurements are available, to address whether a given event can have been driven by the free sublimation of H_2O, CO_2 or CO ice, or whether energy stored in the cometary (sub-)surface must have played a role.

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Seasonal evolution of comet 67P's near-nucleus coma: a model interpretation of Rosetta/OSIRIS observations

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Abstract

The near-nucleus coma of a comet, formed by its volatile and dust activities, provides key information for understanding how comets work. Data collected by European Space Agency's Rosetta spacecraft during over two years' rendezvous with 67P/Churyumov-Gerasimenko has revealed the highly complex nature of the comet's coma, with its structure and composition varying both spatially and temporally [1, 2, 3].

Studies have shown the existence of cyclic dust activities driven by water ice sublimation on diurnal and orbital time scales [4, 5]. Correlations are found between the distribution of water gas and dust in the coma [6]. However, it is not straightforward to determine how water and dust activities are distributed over the nucleus and how this distribution is affected by nucleus properties. Inversions using different methods and datasets often lead to different patterns for the distribution of activity [7, 8].

In this work, we combine imaging data with realistic modeling to investigate the changing morphology and intensity of 67P's inner-most coma and its link to the seasonal variation of water activity. We select observations taken by OSIRIS cameras when 67P was at different positions in its orbit. A thermo-physical model is applied to derive the distribution of temperature and water sublimation rate over the nucleus at the epochs of observations [9]. The three-dimensional gas field is then developed using the method of Direct Simulation Monte Carlo. By applying actual observing geometries, we develop synthesized images to be compared with actual observations.

Preliminary results show that, when 67P was at a heliocentric distance of around 2.5 au before perihelion, the column density of water coma modeled with a homogeneous distribution of activity presents similar pattern as that of the observed dust coma. Further analyses will reveal the consistency or variance of this correlation when different areas of the nucleus became illuminated as the comet approached and passed through perihelion.

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 Astrofisica 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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Inbound to perihelion dust activity of 67P/Churyumov-Gerasimenko's Northern hemisphere

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Abstract

We studied dust activity of comet 67P/Churyumov-Gerasimenko (67P) inbound to perihelion, from August 2014 to January 2015, by means of the GIADA dust detector and the VIRTIS imaging spectrometer, on board the ESA Rosetta spacecraft. We found that illumination is the main driver for both fluffy and compact dust particles ejection and leads to exposition of water ice on 67P surface. We derive a spatial correlation between fluffy and compact particles that we derive on the nucleus, which is not observed in the coma, where the two types of particles disperse due to their different velocity.

1. Introduction

The ESA/Rosetta spacecraft orbited comet 67P/Churyumov-Gerasimenko (hereafter 67P) from August 2014 until September 2016, escorting it through perihelion, occurred on 13th August 2015. The VIRTIS (Visual InfraRed and Thermal Imaging Spectrometer) imaging spectrometer [1] revealed a dark surface, composed mainly of a opaque, spectrally featureless material, and organics, producing the absorption band at about 3.2 μm [2]. Water ice is also observed as the result of a water diurnal cycle [3], and can be detected by deepening and shortward shift of the 3.2 μm band [3], as well as flattening of the infrared spectral slope between 1.1 and 1.9 μm (e.g. [4]). These spectral signatures are more evident in regions at high temperature, supposing that increasing temperature leads to cometary activity and consequent water ice exposition on the surface [5].
The GIADA (Grain Impact Analyser and Dust Accumulator) dust detector [6] detected compact particles (high density) and fluffy aggregates (high porosity), which distribute differently in the coma [7]. the association with the type of particle was based on results obtained by previous instrument calibrations.
This work combines GIADA and VIRTIS datasets to give further insights on 67P's cometary activity inbound to perihelion (from August 2014 to January 2015). We studied a possible correlation between dust emission and nucleus compositional variations in each geomorphological region (as defined by [8]) of 67P's Northern hemisphere, i.e. the hemisphere observed during the inbound orbit.

2. Method

We defined and retrieved for each geomorphological region the following indicators of cometary activity:
- for VIRTIS, the decrease of the 3.2 μm band centre (BC) and of the spectral infrared slope (S) between the lowest and the highest temperature;
- for GIADA, the number of fluffy and compact particles ejected.

To retrieve the latter, we defined an algorithm to trace the motion of each dust particle detected by GIADA in the coma back to the nucleus. The algorithm combines the velocities measured by GIADA, the rotation of the comet, as well as assumptions derived from dust models [9], i.e. a radial trajectory with a constant acceleration up to 11 km from the nucleus surface and then a constant velocity.

3. Results and conclusions

VIRTIS. We observed a strong correlation between BC and S shifts with temperature, suggesting that the reason of the two shifts is the same, i.e. exposition of water ice.

GIADA. Whereas the correlation between fluffy (parent) and compact particles is low in the coma, we found a strong correlation on the nucleus, after the application of the traceback procedure, (Figure 1). This indicates that the two types of particles are emitted together and then spread in the coma due to their different velocity.

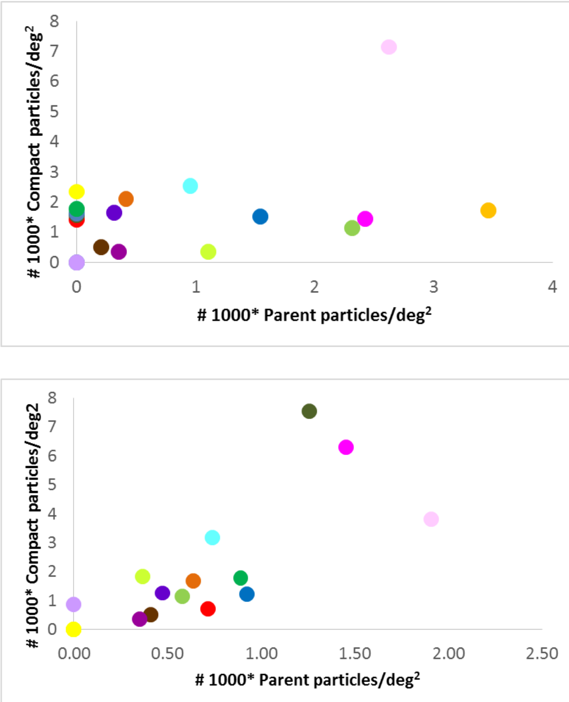

Figure 1. Number of compact and fluffy parent particles in the coma (top) and on the nucleus (bottom). Each dot corresponds to a geomorphological region.

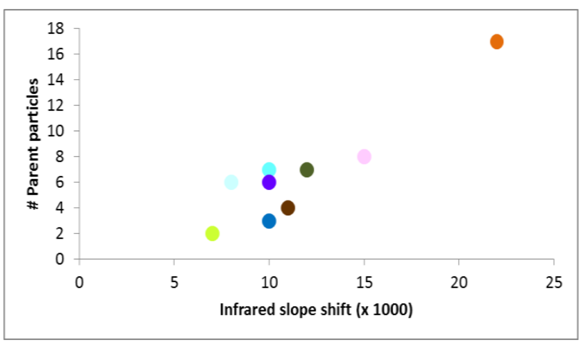

Figure 2. Correlation between number of fluffy parent particles measured by GIADA and spectral slope with temperature observed by VIRTIS. Each dot corresponds to a geomorphological region.

GIADA-VIRTIS data fusion. The VIRTIS and GIADA indicators correlate, indicating that dust ejection leads to water ice exposition on the nucleus surface (Figure 2). In addition, we related the number of dust particles emitted with the insolation period of each region, finding again a strong correlation (Figure 3). This lead to the conclusion that illumination is the main, if not the only, driver for dust cometary activity.

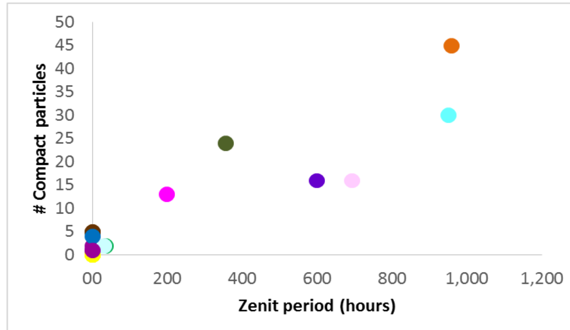

Figure 3. Number of compact particles emitted as a function of insolation time. Each dot corresponds to a geomorphological region.

Acknowledgements

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Implications of Rosetta data on cometary dust stream dynamics and their risk for interplanetary space crafts

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Abstract

From August 2014 to September 2016 ESA's Rosetta spacecraft escorted comet 67P/Churyumov-Gerasimenko (hereafter 67P) on its journey into the inner solar system and out again. The mission provides, via various dust and gas instruments, unprecedented data on the nature of cometary activity.

By using state of the art models for the inner gas and dust comae dynamics for the interpretations of Rosetta data sets (e.g. [1], [2], and [3]) we are now able to extend our understanding of the dust emission direction and speed distribution of cometary dust particles. Furthermore the in-situ dust experiments provide data point to determine the dust size distribution (e.g. [4], and [5]). This expands our knowledge of the dust size distribution we have from other comets (e.g. [6] for 1P/Halley). These results are the basis to determine the trajectories of dust streams within the solar system (e.g. [7]). Such models can predict the number densities of interplanetary dust particles originating from comets. In this work we will present the effects of our updated input parameters which are informed by Rosetta measurements on the dynamics of these dust stream. Understanding the dynamics of dust streams is of great importance for our assessment of the risk for interplanetary space craft posed by cometary dust particles. The results of or model can be directly used to estimate this risk by calculating dust impact probabilities.

Acknowledgements

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Colors and morphology of sources of activity on 67P/Churyumov-Gerasimenko nucleus from OSIRIS/ROSETTA observations

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Abstract

The European Space Agency (ESA) Rosetta mission was launched on 2 Mars 2004 to perform the most detailed study ever attemped of a comet. After ten years of interplanetary cruise, Rosetta enter in orbit around its primary target, the short period comet 67P/Churyumov-Gerasimenko, on August 2014, and followed the comet for more than 2 years until 30 September 2016, when it gently landed on the nucleus surface.
Rosetta had a complex instrumentation, including the Optical, Spectroscopic, and Infrared Remote Imaging System (OSIRIS) which acquired more than 80000 images of the comet during the mission. OSIRIS is composed of two cameras: a Narrow Angle Camera (NAC) for nucleus surface and dust studies, and a Wide Angle Camera (WAC) for the wide-field coma investigations.
OSIRIS has enabled extensive studies at high resolution (down to 10 cm/pixel, and even lower during the Rosetta final descent phase) of the nucleus, and it has monitored the cometary activity and its evolution from 4 AU inbound to 3.6 AU outbound, including the perihelion passage at 1.25 AU.

This work focuses on the identification of the regions sources of faint jets and outbursts, and on the study of their spectrophotometric properties, from observations acquired with the OSIRIS/NAC camera during the July-October 2015 period, i.e. close to perihelion.
More than 200 jets of different intensities were identified directly on the nucleus from NAC color sequences acquired in 7-11 filters covering the 250-1000 nm wavelength range, and their spectrophotometric properties studied.
Some spectacular outbursts appear spectrally blue, due to the presence of grains having very small size and possibly water ice enriched.
Some jets have an extremely short lifetime, appearing on the cometary surface during the color sequence observations, reaching their peak in flux and then vanishing in less than a couple of minutes. These short lived events were observable thanks to the unprecedented spatial and temporal resolution of the ROSETTA/OSIRIS observations.

The observed jets are mainly localized close to boundaries between different morphological regions. Some of this active areas were observed and investigated in higher resolution (up to few dm per pixel) during the last months of Rosetta mission operations. These observations allow us to investigate the link between morphology, composition, and activity on cometary nuclei.

This study indicates that a number of faint outbursts feed continuosly the cometary activity close to perihelion. If some bright events were connected to cliff collapse [1, 2], more in general the faint jets and dust plumes here investigated are originated from different terrains' morphologies: consolidated terrains, active pits, scarps, dust deposits, jumping stones, and cavities.
The main driver of activity is local insolation, with areas close to regional morphological boundaries, under cliff or inside cavities, being the most active ones. These terrains cast shadows thus favorizing volatiles recondensation mostly from the subsurface, during the cometary night, and partially from inner coma molecules back-scattered to the nucleus surface. Approacing perihelion, the cometary dust mantle got thinner [3], and several evidence of diurnal color changes and frost formation close to shadows has been observed and attributed to volatiles condensation during the cometary night [3, 4].
Moreover, several of the jets/outburst sources are lo-

cated in, or close to, areas being brighter and having colors relatively bluer than the comet dark terrain, indicating a local enrichement in volatiles that, once illuminated, sublimate and give rise to the observed jets. A clear example is the Anhur region in the big lobe of the comet, which is the source of several jets, including the spectacular perihelion outburst, and which show several exposure of volatiles at the surface, including the first and unique detection of CO_2 ice [3, 5, 6].

Acknowledgements

OSIRIS was built by a consortium led by the Max-Planck-Institut für Sonnensystemforschung, Goettingen, 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 Universitat 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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On understanding multi-instrument Rosetta data of the innermost dust and gas coma of comet 67P/Churyumov-Gerasimenko - results, strengths, and limitations of models

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Abstract

Numerical models are powerful tools for understanding the connection between the emitted gas and dust from the surface of comets and the subsequent expansion into space where remote sensing instruments can perform measurements. We will present such a predictive model which can provide synthetic measurements for multiple instruments on board ESA's Rosetta mission to comet 67P/Churyumov-Gerasimenko (hereafter 67P). We will demonstrate why a multi instrument approach is essential and how models can be used to constrain the gas and dust source distribution on the surface.

1 Introduction & problem

From August 2014 to September 2016 ESA's Rosetta spacecraft escorted comet 67P on its journey into the inner solar system and out again. The mission provided, via various instruments for dust and gas measurements, unprecedented data on the nature of cometary activity. The determination of the activity distribution on the surface of a comet is a key goal of Rosetta to investigate the interaction of the comet with the Sun.

As the cometary ice sublimates the gas expands into space and fills the near-nucleus environment. Individual sources of activity have been observed on the surface but it remains uncertain where the bulk of the mass is lost and how the processes that are involved work in detail. There are several reasons for this. First, optical imaging experiment use the dust coma as a proxy for the gas activity. Because the optical depth of the dust is orders of magnitude below 1 in all but a few cases, it is not possible to trace dust filaments back to the source against the backdrop of the illuminated surface. Second, remote sensing instruments detecting gas emission (i.e. infrared and sub-mm spectrometers) may suffer from limited spatial and temporal resolution. In addition, the spectral lines may be optically thick and the line-of-sight direction usually cuts through the inhomogeneous coma (in density or temperature) which further complicates their interpretation considerably. However, as we will show, with good a-priori estimates of coma structures spectral lines can be accurately inverted to provide constraints of the gas coma down to a few hundreds of meters above the surface (e.g. MIRO). The in-situ instruments (e.g. ROSINA or GIADA) must consider possible biases due to the spacecraft position relative to the nucleus and respective illumination conditions on the surface. For instance, the frequent use of terminator orbits by Rosetta introduced a significant problem because the measured local densities were at points remote from what we assume to be the main direction of outflow, namely near the sunward direction. In addition, the possible inhomogeneities of the outgassing at the surface cannot be detected due to the fact that the rapid gas expansion smoothens the coma. Therefore, measurements taken tens of kilometers above the nucleus surface are rather insensitive to emission inhomogeneities at the surface and provide only ambiguous results.

2 Multi-instrument approach

The difficulties described above show the need for predictive models that can reproduce multiple measurements in one self-consistent framework. The starting point of all our models is the SPG shape model SHAP7 [1]. We then use a Direct Simulation Monte Carlo (DSMC)[2] code to model the expanding rarefied gas, and a test particle code [3, 4] to simulate the dynamics of dust particles of different sizes. Each program provides us with the physical properties of the gas/dust coma within 10 km from the nucleus center. This allows the generation of synthetic measurements of multiple Rosetta instruments and compared to the actual measurements. We will present results from our study of diverse Rosetta data sets (including OSIRIS, VIRTIS, MIRO, and ROSINA), constraining the gas emission into the coma and establish whether the data enable us to reach appropriate conclusions on the activity distribution on the nucleus surface. We focus here on the time around May 2015 (equinox). While this period is a few months prior to perihelion, the spacecraft was close to the comet, providing a relatively high spatial resolution of the remote sensing observations such that, in principle, they can be more easily linked with the in-situ measurements.

On the one hand, models can be used to constrain certain properties of the activity such as the emission distribution of the surface. On the other hand, they provide strong constraints on the limits of the interpretations of some of the available datasets. Due to the use of physical models we can test a variety of initial conditions that result in identical predicted measurements. We will present such limitations rooted in the physical dynamical processes of the expanding gas and dust flows from the surface.

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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), France (CNES), Italy (ASI), Spain (MEC), Sweden (SNSB), and the ESA Technical Directorate is gratefully acknowledged.
Work on ROSINA at the University of Bern was funded by the State of Bern, the Swiss National Science Foundation, and the ESA PRODEX Programme.
VIRTIS was built by a consortium, which includes Italy, France, and Germany, under the scientific responsibility of the Istituto di Astrofisica e Planetologia Spaziali of INAF, Italy, which also led the scientific operations. The VIRTIS instrument development, led by the prime contractor Selex-ES (Florence, Italy), has been funded and managed by ASI, with contributions from Observatoire de Meudon financed by CNES, and from DLR.
The authors acknowledge the entire MIRO team contributing to the data calibration and archiving, and the PI, Mark Hofstadter.

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Thermophysical analysis of the Imhotep region

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Abstract

Using a thermophsical model and comparing the theoretical results with the data on the comet 67P/Churyumov-Gerasimenko (hereafter 67P) it is possible to determine the composition and properties of the surface and how they change with time.
In this talk the results will be shown of the analysis, performed on VIRTIS [2] and OSIRIS [4] data, of the surface thermophysical properties of the Imhotep region related to the presence/absence of ice.

1. Introduction

The huge amount of data on the comet 67P gave us the opportunity to test and improve in an unprecedented way the models describing the thermophysical properties of cometary nuclei and their evolution. Using this kind of models and comparing their results with the available observations, it is possible to determine the composition and properties of the surface and how they change with time. As far as regards the observations, we are using the temperature images, derived from the VIRTIS data, and the OSIRIS images, that with their better pixel resolution provide the context to interpret the results. The area on which this analysis has been performed is the Imhotep region [3], selected for its variety of different terrains and structures and the good and continuous coverage along the time of the mission from both instruments.

2. Method and results

The thermophysical model [1] is used in a feedback process, i.e. when the comparison of its results with the VIRTIS temperature data is satisfied we can assume that the description of the surface properties and composition given in the model through the input parameters is close to reality. In this way it is possible, for example, to interpret the temperatures derived from VIRTIS spectra in order to determine the amount of ice that is present in the surface layers and its variation along the orbit. The results are then checked on the OSIRIS images.
The first results are encouraging. We are finding that it is possible to determine the amount of ice on the surface necessary to match the theoretical temperatures with the observed ones, when available, and the composition information extracted from VIRTIS spectra, confirmed also by the OSIRIS images that clearly show the presence and evolution of various ice patches.

3. Summary and conclusions

With the help of a thermal evolution model we are trying to determine the thermophysical and compositional properties of the surface of the Imhotep region on the comet 67P. We are finding a good match between the results of this analysis and the composition information extracted from VIRTIS spectra, confirmed also by the OSIRIS images that clearly show the presence and evolution of the ice patches.

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.

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 Reseach 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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Organic features in the spectrum of 67P/ Churyumov-Gerasimenko from the improved calibration of VIRTIS-M-IR

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1. Introduction

The VIRTIS spectra of 67P/CG in the region between 2.9 and 3.5µm display a wide absorption band, which has been associated to the presence of organic compounds [1, 2]. However, several instrumental effects have hindered, so far, the detailed interpretation of the molecules and compounds contributing to this band. In this work we revised the in-flight calibration of the VIRTIS-M-IR instrument onboard Rosetta spacecraft [3, 4] with the aim to improve: a) the detection of low-contrast spectral features and b) the radiometric accuracy. This updated calibration involves all 432 spectral channels (λ) and 256 spatial samples. It includes: 1) the removal of artifacts associated to calibration residuals and/or incomplete flat field correction; 2) the reduction of the non-poissonian noise introduced by the readout electronics of the instrument; 3) a newer version of the radiometric calibration using stellar sources. Furthermore, we have modeled the thermal emission to remove the nucleus contribution at wavelengths in excess of 3.0 µm and we have also modeled and removed, by means of the Hapke [5] model, the contribution of water ice absorption to isolate the organic features within the spectral region 2.9 – 3.5 µm. These spectral features have been compared with laboratory measurements and observations of diffuse interstellar medium to provide indications on the relative contribution of the Aromatic and Aliphatic components.

2. Artifacts Removal

Spectral artifacts, caused by calibration residuals, are superimposed on the real spectral features preventing the detection of small features. A comparison of the 67P/CG and 21 Lutetia spectra revealed that these artifacts are ubiquitous and they depend linearly on the signal level. In order to remove these effects, for each spatial sample we take into account an average signal of the comet nucleus acquired during the first mapping phase of the Rosetta mission in August-September 2014, and of the Lutetia asteroid. Spectra are processed sample (s) by sample to trace the variability of the artifacts across the focal plane. The ratio between 67P/CG and 21 Lutetia spectra allows removing all the spectral artifacts while keeping information of the ratio of the real features. Assuming the spectrum of Lutetia is devoid of small (few spectral channels-wide) real features, we model it with a polynomial interpolation representing the absolute reference, which is then used to isolate an artefact-removed spectrum of 67P (see Eq. 1):

1)
$$\frac{\frac{I}{F}(\lambda,s)_{67P/CG}}{\frac{I}{F}(\lambda,s)_{Lutetia}}\cdot\frac{I}{F}(\lambda,s)^{interp}_{Lutetia}=\frac{I}{F}(\lambda,s)^{AR}_{67P/CG}$$

3. Reduction of the noise

The average spectrum of the comet, cleaned from artifacts, still presents a source of non-poissonian noise introduced by the electronics of the instrument. Due to the detector's architecture, the even spectral channels response is affected by the temperature of the instrument, which introduces spurious offset along the wavelengths especially at low fluxes. Thus, we replaced the even channels by an average of the contiguous odd spectral channels.

4. Absolute calibration with star observations

Both VIRTIS-Rosetta and VIMS-Cassini observed stars during the cruise phase of the mission. This gives the possibility to compare the flux observed by both instruments to perform an inter-calibration. In particular, we compared two acquisitions of Arcturus performed by VIRTIS-M-IR with six observations performed by VIMS onboard Cassini [6]. The ratio of the average fluxes observed by the two instruments provides a correction factor as a function of the wavelength, which can be applied over the whole VIRTIS-M dataset.

5. Modeling: thermal emission and water ice removal

Thermal emission is subtracted from the average 67P spectrum as discussed in [7].

Previous works [8, 9, 10] showed that the surface of the comet presents spatial and temporal variations of the band depth and shape of the absorption at 2.9-3.5 µm due to variation of water ice content. Following this argument, we can reasonably expect that the entire nucleus surface contains a small amount of water ice, in depths accessible to VIRTIS. By means of Hapke model [5] and using the optical constants of [11, 12] we inferred an anhydrous spectral albedo of the comet removing from the average spectrum of the nucleus a modeled spectrum of 1.8% (p_w) of water ice, with a grain diameter of 0.6 microns, according to equation (2).

2) $(\text{Anhydrous } 67P)_\lambda = (67P)_\lambda - p_w\,(\text{water ice})_\lambda\,/(1.-p_w)$

When water ice is removed additional small spectral features stand out, which are discussed below.

6. Interpretation of the spectral features

The elaboration of the average spectrum of the comet by means of the improved calibration and the modeling resulted in a revised shape of the whole spectrum and the isolation of spectral features, which can be attributed to specific organic materials. In particular we identified small features centered at: 3.28 µm, which are consistent with aromatic C-H stretching; 3.38, 3.42, 3.48 µm which can be attributed to aliphatic (CH_3 asymmetric, CH_2 asymmetric, and CH_3 symmetric stretching, respectively) [13], previously reported in [14]; other small features are present at 2.85, 3.0, 3.1 µm. They can be attributed to C-H overtones, OH-stretches, and/or N-H stretching, according to spectral comparison with analog materials. Finally, the organic features on the spectrum of the comet present similarities with observations of interstellar diffuse material [15], with Ceres [16] and Saturn rings [17]. Their significance in the framework of the comet origin and evolution will be discussed.

Acknowledgements

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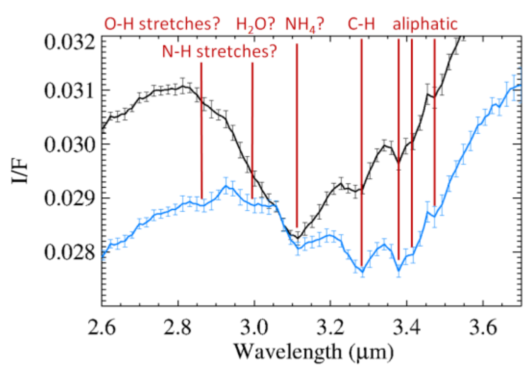

Figure 1. Black line: average spectrum of 67P after the new calibration process, and thermal removal. Blue line: 67P spectrum after water ice removal. Error bars indicate the uncertainties of the calibration.

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VIRTIS and GIADA observations of summer outbursts on 67P/CG

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1.Introduction

During the period between July and September 2015, the Rosetta spacecraft had the opportunity to monitor the inner coma of comet 67P/Churyumov-Gerasimenko (67P/CG) along the most active part of its orbit. The Visible InfraRed Thermal Imaging Spectrometer (VIRTIS) [1] and the Grain Impact Analyzer and Dust Accumulator (GIADA) [2] onboard Rosetta observed and detected a series of transient events. Cometary outbursts are well-known but still poorly understood phenomena. GIADA is an in-situ instrument and detects outbursts pointing nadir, i.e. towards the nucleus. VIRTIS is a remote-sensing instrument and detects outbursts mainly during limb/off-nadir pointing, because the nucleus is always brighter than the coma events as jets and outbursts. Thus, the two instruments observed outburst material in remote-sensing mode (VIRTIS) or at the spacecraft location (GIADA) producing two independent but complementary outburst datasets. (Fig. 1 and 2). In this perspective, we combined the VIRTIS and GIADA outburst detections to fix some constraints for the physical properties of the outbursts.

2.Preliminary Results

Outburst lifetime: The two instruments observe different outburst lifetimes. For VIRTIS the outbursts are characteristically of short duration, the outbursts appear to decay away typically in tens of minutes, rarely lasting as much as an hour. For GIADA the outbursts are characterized by a slower decay ~~more slowly~~, being sometimes ~~being~~ observable for more than an hour.

Outburst locations: The GIADA and VIRTIS observations suggest that there are localized regions on the comet surface that are more prone to outbursts than the rest of the nucleus. All outburst sources are located in the main lobe, within the latitude range +30° to -60° and in ~~the~~ the eastern side of the body, around longitude 210° to 280° and latitude -20° to -55°, in areas characterized by steep scarps, cliffs, and pits with considerable talus deposits [4,6].

Dust outburst spectral properties. The outburst colour maps in the VIS show a colour gradient which seems to be associated to the level of the dust radiance within the outburst (Fig. 3) [6]. The same colour behaviour has been observed in the IR channel reaching the bluer values of -9.1±1.4 % /100 nm and returning to the pre-outburst value of about 2.5 % /100 nm [5]. The IR continuum emission is also characterised by high colour temperatures of about 600 K and a bolometric albedo of 0.6 [5]. The combination of VIS and IR dust properties thus reveals the presence of very small grains (less than 100 nm) in the outburst material. The bright grains in the ejecta could be silicate grains, implying the thermal degradation of the carbonaceous material, or icy grains. The rapid increase in radiance at the start of an outburst event is not due primarily to an increase in the number of existing dust particles, but rather to the release of small and bright icy particles with a high geometric albedo and a filling factor between 1.3 and 5.0 % [5,6].

Outburst particle dynamics: The dust particle velocities measured by GIADA during the outbursts are not different with respect to the velocities associated to the regular dust activity around perihelion, with values ranging between 10 to 60 m/s (Fig.1). VIRTIS found that the small particles in the dust ejecta expanded at speeds between 22.2 ±2.2 and 64.9 ±10.6 m/s [6].

Total dust mass ejected Assuming a typical size distribution taken from the 67P/CG literature, with indexes between -2.5 and -3, the observed total mass of ejected dust is estimated to be between 500 to 10000 kg [6].

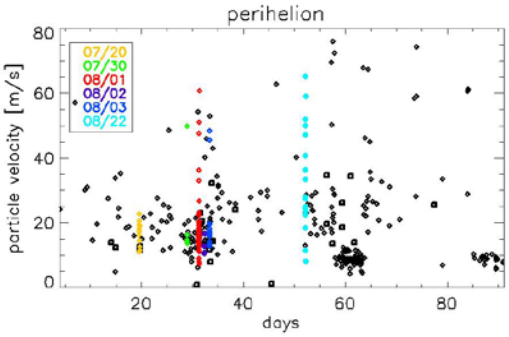

Figure 1: GIADA dataset of summer outburst. The outburst observed by GIADA are the result of a high dust particle detection rate (multicolor points).

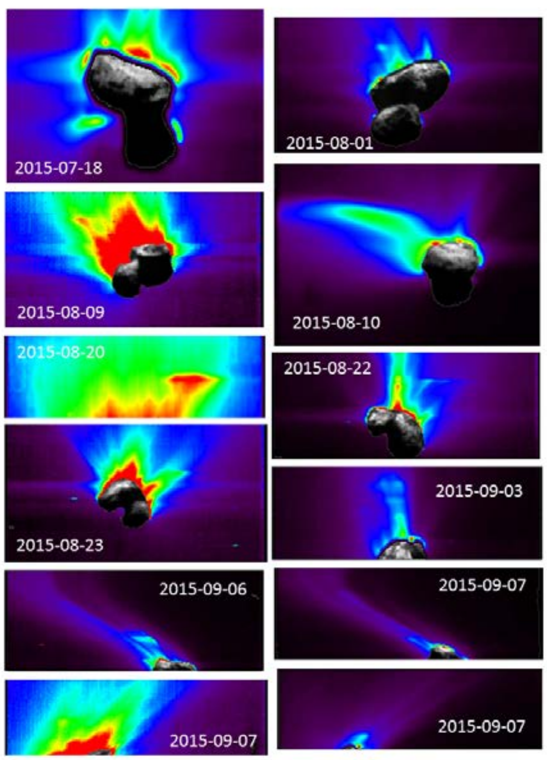

Fig. 2 VIRTIS dataset of some summer outbursts. Each image is an image at 0.55 µm, showing the nucleus, dust coma and outburst ejecta (collimated ejecta). A VIRTIS-M image of the nucleus at 0.55 µm is superimposed for better visualisation. The radiance has units of W/ m2/ sr/µm

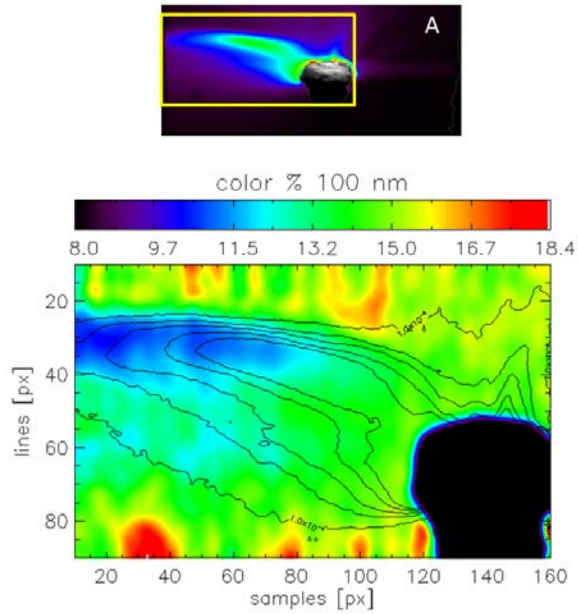

Figure 3: Dust continuum image of the 10 August 2015 outburst at 0.55 µm (upper plot) and the spatial distribution of the colour (lower plot) calculated in the yellow square of the dust image. The black contours are the radiance levels at 0.55 µm. The outburst ejecta display colours bluer than the background coma.

Acknowledgements

GIADA was built by a consortium led by the Universitá degli Studi di Napoli 'Parthenope' and INAF – Osservatorio Astronomico di Capodimonte, in collaboration with the Instituto de Astrofisica de Andalucia, Selex-ES, FI and SENER. GIADA was managed and operated by IAPS-INAF. VIRTIS was built by a consortium formed by IAPS-INAF (Italy), which guides also the scientific operations. LESIA (France) and DLR (Germany).
This research was supported by the Italian Space Agency (ASI) within the ASI-INAF agreements I/032/05/0 and I/024/12/0.

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Alkali metals and other light elements in the dust of comet 67P/Churyumov-Gerasimenko

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Abstract

During the ESA Rosetta mission to 67P/Churyumov-Gerasimenko (67P hereafter), the COSIMA instrument onboard the space craft collected about 35,000 particles in the inner coma between August 2014 and September 2016 [1–3]. The time-of-flight secondary ion mass spectrometer (ToF-SIMS) subcomponent of COSIMA was used to analyze many of these particles. It was found among other results that the dust contains high levels of Na and to a lesser degree K when compared to chondrites and solar system abundances [4,5].

Since Na shows a higher overabundance than K, we look into possible differences of chemical context in which the alkali metals and other rock forming elements are present in the cometary particles. Figure 1 shows an example for Na distribution at particle Jean-Baptiste on the COSIMA dust collection target 2CF. Figure 2 shows the same particle but the K distribution. The maxima of both distributions are in different places. The ion image for Al in Fig. 3 is noisier than for the alkali metals but tentatively shows its higher values where the K is also high.

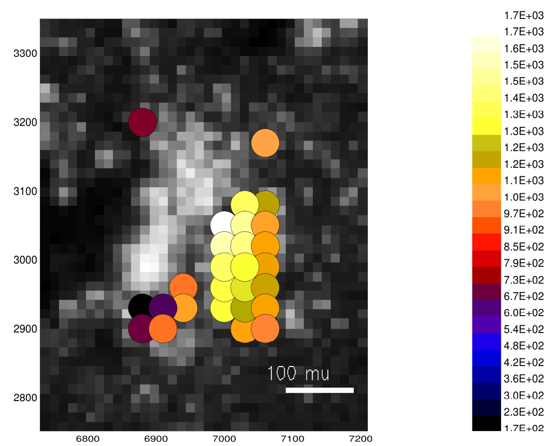

Figure 1: Integrated and normalized Na peaks from COSIMA ToF-SIMS spectra at various positions on the particle Jean-Baptiste on target 2CF.

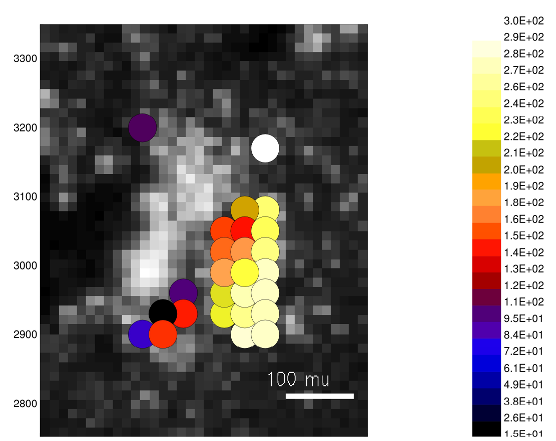

Figure 2: Integrated and normalized K peaks from COSIMA ToF-SIMS spectra at various positions on the particle Jean-Baptiste on target 2CF.

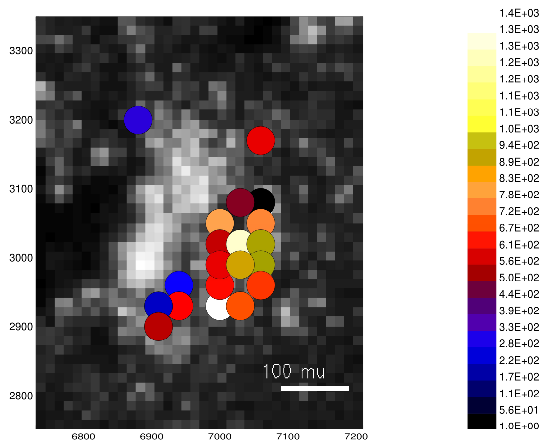

Figure 3: Integrated and normalized Al peaks from COSIMA ToF-SIMS spectra at various positions on the particle Jean-Baptiste on target 2CF.

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 1801), France (CNES), Austria and Finland. Rosetta is an ESA mission with contributions from its Member States and NASA.

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Experimental simulation to analyse geomorphological properties of cometary surfaces with outgassing volatiles

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Abstract

We want to study the development of cometary and other outgassing surfaces of airless planetary objects with analog laboratory experiments on Earth. The focus is on the evolution of different morphologies, taking into account the composition of the sample material and variable insolation flux. Our aim is to understand how different cometary materials interact and how the appearance of cracks and boulders develop during insolation and outgassing.

1. Introduction

A vast amount of image data with previously unknown surface features have recently become available through the Rosetta mission and will be complemented by the Hayabusa2 and Osiris-Rex Missions arriving at their target asteroids this year. The characterization of these features and the understanding how they evolve are tasks that are not completed until now.

The relation of surface features with the volatile content of the host body and the evolution of these features under outgassing conditions is the aim of a set of experiments suggested in this abstract [1].

Here, we present the set-up and parameters of a number of experiments related to the evolution of volatile-rich planetary surfaces. We aim to investigate boulders, crater-like depressions and cliffs composed of volatile rich material. Of particular interest is the formation of new structures and their relations to previous morphological features.

2. Methods

The Simulation Chamber for Imaging the Temporal Evolution of Analogue Samples (SCITEAS) facility is a small thermal vacuum chamber and provides spectral analyses of analogue materials in the visible and near infrared range [2]. In addition to in-situ and remote studies, a direct interaction with the sample material and its residuals is possible. The chamber allows investigations how water ice on small bodies sublimates with respect to the presence of various other materials.

During the analogue experiments we will investigate the influence of the sample composition to the evolving morphology. Here, the content of silicate dust will be considered as well as the distribution of these materials within water ice samples. Previous studies revealed different surface evolutions during sublimation if non-volatile materials are distributed as inclusions within water ice particles (intra-mixture) or if they fill the space between particles of pure water ice (inter-mixture) [3]. Combined with a predetermined morphology (Figure 1), the alterations of the surface during the sublimation process will be characterized.

Of particular interest are the formation of cracks and pits and the conditions under which they would occur on a surface of a comet or an asteroid. To simulate processes that correspond to the local conditions on a rotating body, the insolation should be realized in intervals and from different angles to the surface.

Following direct observations on small bodies and previous analogue experiments with SCITEAS and the KOSI project [4], a number of parameters were selected and predetermined most realistic before the experiments start (Table 1). During the experiments these parameters will be monitored and analyzed in detail after the experiment has ended.

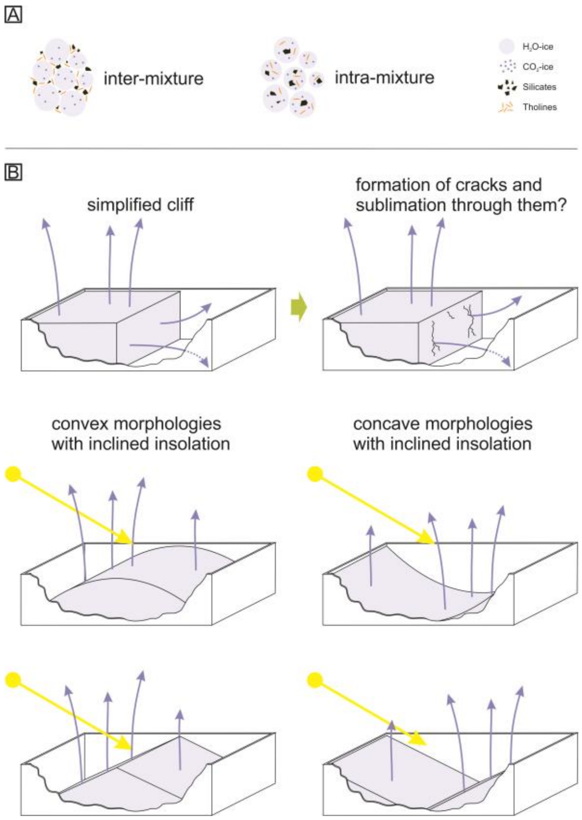

Figure 1: A) A schematic view of different mixtures of water ice and accessory materials. B) Some simple morphological features in the sublimation chamber as analogue to the surface of a volatile rich body.

Table 1: Predetermined variables with initial values.

Parameter	Initial Value
Material composition	
H_2O content	40-90 %
Dust content	10-60 %
Org. content	0.1-0.5 %
Material properties	
Porosity	70-80 %
Grain size	5-67 µm
Insolation properties	
Insolation period	6-13 h
Insolation flux	200-900 W/m^2
Background temperature	180-210 K

3. Objectives

To achieve a better understanding of the evolution of cometary surfaces the planned analogue experiments will help to answer the question what the influence of initially different morphologies to their development is and how long initial structures are stable until they disappear under given volatile content. Furthermore, it is of interest what new structures form during the sublimation of volatiles and if the formation of fractures or cracks is related to specific morphologic features. Also the periodicity of insolation may have an influence to the surface evolution.

To achieve these objectives a subsequent analysis of the residual material is essential. It has to be clarified to what extent the bonding forces of the residuals change and up to what static stress they form stable structures. The gained results will finally help to generate a vertical profile in dependence of material composition, insolation, and initially morphology.

Acknowledgements

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Geomorphological units of Khepry and Imhotep regions of comet 67P/Churyumov-Gerasimenko

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Abstract

During the two-years mission, ESA's Rosetta spacecraft provided countless images of the cometary nucleus. The two cameras of the Optical, Spectroscopic, and Infrared Remote Imaging System (OSIRIS) were equipped with broad-band filters ranging from ultraviolet to near-infrared wavelengths (250-1000 nm). Thanks to such imagery, the identification of morphological features and units [1,2,3] has been followed by detailed geomorphological maps [4,5] and complemented by studies of the spectrophotometric behaviour of the global surface [6]. Several terrains deviate from the average reflectance of the nucleus (∼6.8% at 649 nm), generally displaying lower values as part of the outcropping consolidated materials and relative deposits, or being notably brighter when associated with water-ice rich material [7].

Images provided by the last Rosetta's flyby, in April 2016, allowed the spectrophotometric comparison of specific features of the nucleus at the boundary between Khepry and Imhotep regions [8], confirming that the brightest patches located on overhangs and alcoves tend to have lower spectral slope than the rest of the terrains. Therefore, those patches are interpreted as water-ice exposures of the nucleus at the time of the flyby. Similarly, bright terraces and proximal deposits that surround those patches (e.g., case A, Fig. 1) and display low spectral slopes are considered rich in water ice.

Consolidated materials of this area are characterised by an additional sort of bright terrains, which conversely show steep red slopes usually attributed to volatile-depleted materials. Those bright terrains appear with a yellow hue in false-colour multispectral images (e.g., case B in Fig. 1) and contrast with low- and medium-spectral slope grey-hue terraces associated with bright patches and high-spectral slope darker outcrops and megaclasts. That yellow hue results from a value drop of the shorter wavelengths, which provides as well the steep spectral slopes.

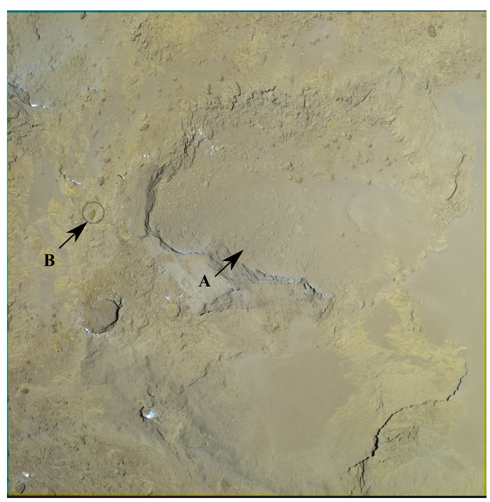

Figure 1: False-color image of the 2016-04-09 flyby sequence (red: F88, green: F82, blue: F84). Letter A labels a bright outcrop associated with water ice, and the relative arrow points to the proximal deposit. Letter B labels a bright yellow outcrop, and the relative arrow points to a dark yellow megaclast.

We therefore propose an analysis of the spectral properties of the discernible geomorphological units of the 2016 flyby area, associating materials of different maturity (i.e. consolidated materials and clasts deposits) depending on those properties and discussing possible explanations of their nature.

Acknowledgements

OSIRIS was built by a consortium of the Max-Planck-Institut für Sonnensystemforschung, in Göottingen, 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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Spectrophotometric investigation of the layered structure of comet 67P/Churyumov-Gerasimenko

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Abstract

ESA's Rosetta OSIRIS cameras [1] acquired high resolution images in the NUV-VIS-NIR wavelengths range that allowed the definition of a pervasive layered structure for comet 67P/Churyumov-Gerasimenko [2]. The measurement of the different orientation of the morphological terraces allowed the construction of a three-dimensional ellipsoid-based model (Ellipsoidal Model, EM) defining the structural level of any point of the 67P nucleus in terms of elevation [3]. The model highlights thus that different regions are exposed at different structural elevation. Therefore, a spectrophotometric investigation has been performed on outcropping consolidated materials in order to define possible differences between stacks of layers.

1. Introduction

The images acquired by the OSIRIS cameras allowed to describe a cometary body with a bi-lobed shape [4] characterized by several morphological features [5-6-7-8]. In particular, the morphological terraces, present in ordered sets, can be interpreted as the surface expression of over-imposed layers characterized by discontinuity surfaces and defining an inner stratification. The different orientation of the terraces and cuestas has been derived and used by [2] to obtain geological cross-sections that allowed to define the presence of a nearly continuous stratification. The calculation of the angular deviations, namely the differences between the perpendicular to the fitting planes and the local gravity vector fields, both for the entire comet as well as for the two distinct lobes, unequivocally confirms the presence of an onion-like stratification that independently envelopes each lobe. Furthermore, by measuring the orientation of a large number of terraces and mesas scattered on both lobes, [3] reconstructed a three-dimensional geometrical model (EM) based on a number of concentric ellipsoidal shells. That model can reproduce the inner layering of the cometary nucleus and accurately predict the intersection of layers with the topography. Therefore, the EM can be used to define the position, namely the structural elevation, of any point on the cometary surface as a distance from the structural centre of the reference lobe. Concerning the two distinct lobes, it is thus possible to identify regions, or areas, localized at different structural elevations relatively to the EM. This is the starting point of the spectrophotometric analysis performed.

2. Methods

For the spectrophotometric investigation of the two lobes, two OSIRIS-NAC sequences of post-perihelion images per lobe were selected. Those sequences cover the maximum number of available filters and have similar spatial resolutions and phase angles. According to the EM, the framed regions are located at different structural elevations, with the innermost and outermost layers corresponding respectively to Imhotep and Apis regions for the big lobe (BL) and to Wosret and Bastet regions for the small lobe (SL). The sequences were then converted to reflectance and photometrically corrected using the Akimov photometric model [9, and reference therein] in order to obtain multispectral images. For each dataset, a geomorphological map was realized in order to easily distinguish outcropping consolidated materials from deposits. A two-classes supervised classification was firstly used to mask the fine material deposits, obtaining datasets constituted exclusively by outcropping materials and relative coarse deposits, which can be considered autochthonous materials. On masked multispectral images a supervised classification was then applied on the basis of the structural elevation in order to verify if layers located at different elevations display different spectral characteristics.

3. Results

The spatial distribution of the obtained classes highlights a dependence on the structural elevation defined by the EM. In particular, outcropping materials located at different elevations are characterized by a different brightness, with the outermost classes that result darker than the innermost ones. On the contrary, once normalized to the green wavelength (535.7 nm), reflectance values of all the classes display no substantial differences.

4. Conclusions

The obtained results are congruent between the BL and SL: the spectral dichotomy observed between layers located at different structural elevations can be mainly due to differences in the composition and/or textural properties of the cometary nucleus [10].

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Modelling the H_2O outgassing from the southern hemisphere of comet 67P/Churyumov-Gerasimenko constrained by ROSINA

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Abstract

The purpose of this work is to investigate the distribution of H_2O emissions at the surface of comet 67P/Churyumov-Gerasimenko (hereafter 67P) using ROSINA's data. We therefore use direct simulation Monte Carlo (DSMC) to test different gas source distributions on the nucleus surface in order to model the coma of 67P. We then validate our surface boundary condition by comparing the simulation results for the number density to the measurements obtained by ROSINA.

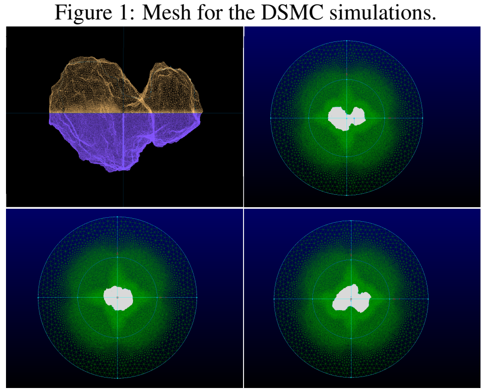
1. Introduction

Previous studies have successfully explained the H_2O activity distribution in the coma of comet 67P at the early stages of the ROSETTA mission, during summer in the northern hemisphere of the comet [1, 2, 3, 4]. These studies found that the outgassing of H_2O is driven to a large extend by insolation and the inhomogeneous distribution of H_2O on the cometary surface, with strong sources localized in the Hapi region. Cometary activity close to the perihelion has been studied by Fougere et al.[5]. Their model reproduces the evolution of the densities observed by ROSINA, which suggests a seasonal variation in the activity of the major cometary species with differences in their distribution mainly given by the illumination conditions at the surface. Based on these studies, we will utilize DSMC to link the measurements by ROSINA during July 2015 to the emission distribution at the surface and the corresponding surface morphology.

2. Modelling Approach

The inner-gas coma of comet 67P is modeled using a DSMC code, called PDSC++ [6], which numerically simulates 3D flow-fields of rarefied gas. This code requires a simulation mesh based on the shape model SHAP7 [7] and fully covers the cometary surface and its inner-coma up to 10 km with high precision as can be seen in Figure 1.

Figure 1: Mesh for the DSMC simulations.



As a first step, we use purely insolation-driven conditions for the H_2O sublimation and assume an homogeneous distribution of H_2O-ice at the surface (M1). For the second model (M2), we use the H_2O the model introduced by Marschall et al.[2] to account for the distribution of H_2O activity, which is in good agreement with the observations made by ROSINA/COPS in August and September 2014. We then add regional complexity to the input parameters in the third model (M3) in order to obtain DSMC simulations for July 2015. A description of the boundary parameters used in this work is listed in Table 1. In all our models, the temperature of H_2O-ice (T_{H2O}) is driven by solar illumination. However, the spatial distribution of the ice on the surface of 67P is given by the Effective Active Fraction (EAF), which defines the activity strength of each surface facet of the nucleus and is chosen regionally based on the observations.

Table 1: Boundary conditions for each model.

Model	T_{H2O}	EAF_{H2O}
M1	Iso-Dr	Homogeneous
M2	Iso-Dr	Active Neck
M3	Iso-Dr	Regional Distribution

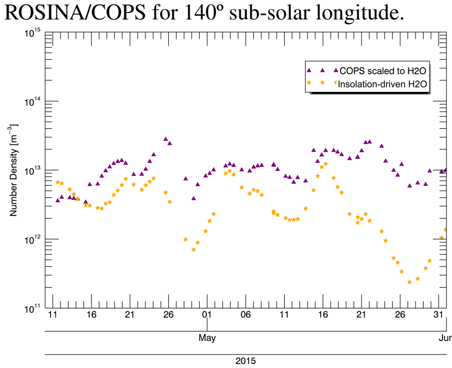
3. Comparison with ROSINA

For the comparison with ROSINA data, we perform a series of DSMC simulations for the corresponding heliocentric distance and sub-solar latitude, such that each model is run for 8 different sub-solar longitudes that sample a whole rotation of the cometary nucleus. We use SPICE to calculate the geometry of each measurement made by ROSINA in time ranges close to our simulated time periods. Then, we extract the DSMC-derived value of the number density of the cell which is closer to the spacecraft location and extrapolate this value to the cometocentric distance of Rosetta. In this manner, the result of each model can be directly compared with the measurements.

4. Preliminary results

We have simulated the inner-gas coma of 67P for the spring equinox. Our DSMC results for this time period have suggested that a purely insolation-driven surface at southern latitudes is not a sufficient condition to explain the observations by ROSINA/COPS. This is shown in Figure 2, where the extrapolated DSMC-values of H_2O outgassing do not follow the behavior of the ROSINA/COPS measurements. This can be due to the contribution of the H_2O outgassing from the southern hemisphere, for which the ice sources were assumed to be equally distributed at negative latitudes on the comet. We therefore focus on the study of the key parameters that drive the H_2O outgassing at southern latitudes of the comet for a time period where most of this region is highly active.

Figure 2: DSMC results for the spring equinox compared with the 10 minute average measurements by ROSINA/COPS for 140º sub-solar longitude.



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A revised theory of the diamagnetic cavity of comets

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Abstract

The physics of the diamagnetic cavity of a comet is governed by a set of three coupled partial differential equations. The classical description of the cavity – although surprisingly successful in explaining many aspects of the observations – concentrates only on solving a single equation in the long distance and zero resistivity limit. Recent observations of the Rosetta mission provide comprehensive plasma data about a multitude of cavity crossing events and reveal the cavity as a dynamic object with many new and interesting features. Here we show that exact analytical solutions of the equations exist for a much more general case, which provide new insight into the properties and dynamics of the phenomenon. For the most general case the system of equations can be integrated numerically. The generalized solutions show that the magnetic field does not drop to zero immediately inside the cavity, but rather features a rapid exponential decay. Outside the cavity, for longer distances the field approaches the classical solution. The plasma velocity first drops rapidly as the plasma enters the cavity boundary; for larger distances it decreases as 1/r towards its asymptotic value in the infinity. In general, the velocity does not necessarily approach zero in the infinity, there are inward and outward moving solutions as well, explaining the dynamic nature of the cavity. Interestingly, these moving solutions imply a small, but finite field value inside the cavity. Thus, in contrast with prevailing belief, the magnetic field inside the cavity is in general not zero, but small. The shape of the magnetic field solution also depends on the asymptotic plasma velocity, consequently, the field gradient is different for inward and outward moving boundary crossings. The ion density has a strong peak in the boundary layer of the cavity. Away from the boundary – both inside and far outside – the density shows a 1/r dependence, but with different coefficients. The sharp density increase in the boundary layer affects the size of the cavity: the size scales as the square root of the density ratio at the jump. Thus the cavity size is larger than that predicted by the classical theory.

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Mapping and changes of exposed bright features on the comet 67P/Churyumov-Gerasimenko

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Abstract

The Optical, Spectroscopic and Infrared Remote Imaging System (OSIRIS) [10], studied the Jupiter-family comet, 67P/Churyumov-Gerasimenko (67P), embarked on the Rosetta spacecraft from August 2014 to September 2016. Consisting of two scientific cameras: Narrow Angle Camera (NAC) and Wide Angle Camera (WAC), respectively optimised to observe the coma and the nucleus, OSIRIS contributed immensely to further the scientific know-how of comets. In this context, our study [5] focusses on the exposed features of volatile ices on the nucleus of the comet 67P.

Several studies [4],[8],[11],[12] have investigated the exposed bright features using OSIRIS data where, based on the spectrophotometric characteristics of the features, it was concluded that H_2O was present in those exposures. Apart from this, local exposures of H_2O [1],[3],[6] and CO_2 [7] have been spectroscopically identified on the nucleus by the spectro-imaging instrument VIRTIS-M [2] on-board ROSETTA. All these results indicate the presence of volatile ices on the nucleus of the comet, as predicted by the theories and they correspond to a restricted period of time (in-bound phase of the orbit as the comet was approaching its perihelion) throughout the orbit of the comet around the sun. In this study, we attempt to investigate data spanning in a wider time frame, which is from Rosetta's arrival near the comet in August 2014 up to the end of the extended mission in September 2016, which encompases more than two years, including a year of the in-bound orbit and a period more than a year in the out-bound orbit, as we explore the exposed bright features on the nucleus. As such, it is possible to constrain the evolution and morphologies of such features as the comet moves through its orbit.

We report the identification of 57 exposed bright features which are preferably located in the equatorial latitudes. Analysing the available spectrophotometric data for 51 of them, we are confident to interpret them to be exposures of H_2O ice. This is based on the flat reflectance curve of these features, which mimics the visible spectra of H_2O ice and the fact that their lifetimes are consistent with the sublimation rates of H_2O ice, unlike the other super-volatile ices like CO, CO_2 , SO_2, NH_3, etc that also share the flat visible spectra. We also show that the studied features can be morphologically categorised under 4 types :1) isolated patches on smooth terrains, 2) isolated patches close to irregular structures, 3) patches resting on boulders, 4) clusters of patches. Using the linear-exponential phase curve of bright features published by Hasselmann et al. [9], albedos are calculated for these features, which we interpret to have a correlation with the type of the feature as shown in the Fig. 1.

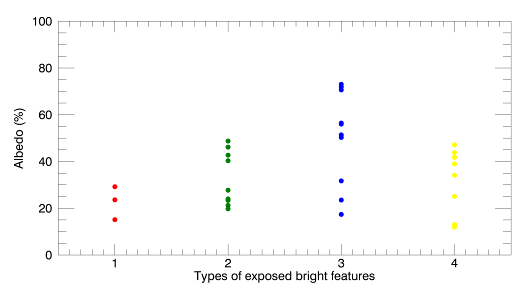

Figure 1: Albedos calculated for the explosed bright features, grouped according to their respective types.

Furthermore, we highlight the link with potential activity sources, responsible for resulting in the formation of two exposed bright features, belonging to the type 2. As such, the Fig. 2 illustrates a displacement of a boulder in the Bes region of the comet, that resulted in the appearance of an exposed bright patch on top of it, that was observed to stay for about 6 months with gradual decrease of its area due to sublimation.

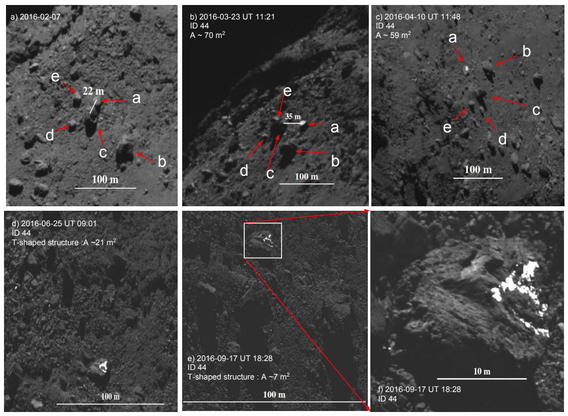

Figure 2: The field of boulders in Bes region, where a displacement of a boulder was observed, leading to the appearing of an exposed bright patch on it between February and March 2016. Its sublimation-driven evolution can be characterised by means of the diminution of its effective size calculated from pixels resolutions.

The results of the detected exposed bright features and their albedo distribution will be presented and discussed.

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Results from two unusual comets C/2016 R2 (Pan-STARRS) and C/2015 V2 (Johnson)

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Abstract

A typical optical spectrum of a comet with well developed coma shows molecular emissions dominated by carbon chain molecules. The Oort cloud comets C/2015 V2 (Johnson) and C/2016 R2 (Pan-STARRS) were spectroscopically followed and observed using a low resolution spectrograph (LISA) mounted on the 1.2m telescope at the Mount Abu Infrared Observatory (Mount Abu, India) during the period of December 2016 to Feb 2016 and in January 2018 respectively. Our observations and studies revealed that the optical spectra of these two comets are quite unusual as compared to general cometary spectra. Most of the major cometary emissions like C2, C3 and CN were absent in comet C/2016 R2. However, the comet spectrum showed very strong emission bands from ionic species like CO+ and N2+. The N2/CO ratio was determined from the spectra and an extremely low depletion factor of 1.6 has been estimated. In comparison, the optical spectrum of comet C/2015 V2 was also devoid of any kind of molecular emissions and the major cometary species were absent when the comet was observed at a heliocentric distance of 2.83 AU. However, no other emissions were detected (like that of the ions detected in R2). Regular cometary emissions in comet V2 were detected after 2.3 AU, although the productions rates remained much lower as compared to other active Oort cloud comets. The unusual spectra of these comets may be the consequence of their distinctive processing at the location of formation in the early solar nebula.

1 Introduction

In general molecular emissions in a comet start appearing sequentially when the comet comes closer than 3 AU [Krishna Swamy, 2010] to the Sun. The most likely emission to appear first is that of CN molecule at around 3 AU, followed by the rest of the emissions. There are very few comets in which emissions are reported beyond 3 AU and even fewer beyond 5 AU. Ionic emissions like CO^+ and N_2^+ are rarely seen in the coma of a comet. They are however abundantly found in the plasma tail of comets. One such comet, from which CO^+ emissions were detected in its coma was 1962 VIII [Arpigny, 1964], also known as comet Humason. Lot of work [e.g. Voelzke et al., 1997; Guineva et al., 1999, 2000; Jockers et al., 1987] has been carried out based on the CO^+ emissions that were found in the coma and tail of Comet 1P/Halley.

In this work, we have obtained and analysed the optical spectrum of two Oort cloud comets C/2016 R2 (PanSTARRS) ('R2') and comet C/2015 V2 (Johnson) ('V2'). R2 was discovered by PanSTARRS on September 7^{th} 2016, whereas V2 was discoverd by Jess Johnson on 03^{rd} November 2015. The comet R2 brightened to a magnitude of 13 in visual band in January 2018. It has an orbital eccentricity of 0.996, semi-major axis of 738 AU, orbital inclination of 58 deg to the ecliptic and a total orbital period of 20084 years and a perihelion distance of 2.6 AU (may 2018). Comet V2 has an eccentricity of 1.001, semi-major axis of 976 AU, orbital inclination of 50 deg to the ecliptic.

2 Observations and Reductions

The observations were carried out with LISA spectrograph mounted on the 1.2 m(f/13) telescope (PlaneWave Instruments CDK20) at the Mount Abu Infra-red observatory (MIRO), Mount Abu, India. The sky conditions were photometric during the observing period.

Details of the comet observations are given in table 1. The exposure times mentioned in the table are for each individual frame. A more detailed description of the instrument LISA is given in Kumar et al. [2016]. The slit was placed at the photo-center of the comet and was manually tracked through the guiding CCD throughout the exposure time. The observations were

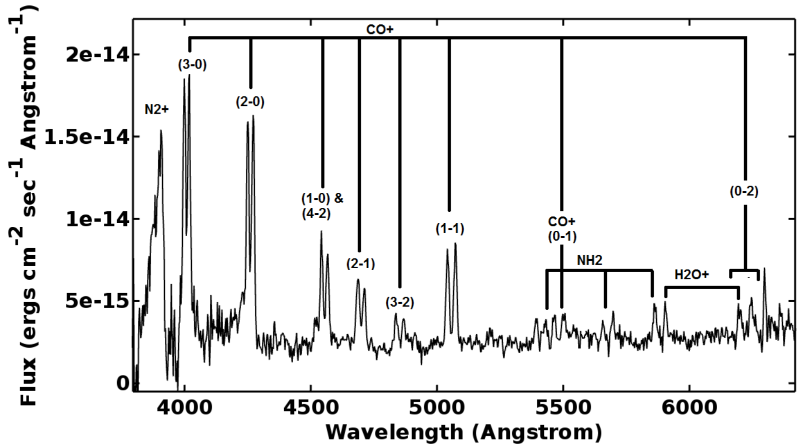

Figure 1: The optical spectrum of comet C/2016 R2 (Kumar et al.2018, submitted to A&A) taken on 25th January 2018 using LISA spectrograph on 1.2m telescope at the Mount Abu Infra-red observatory, Ahmedabad. All the major emission lines are marked

Table 1: Observational Log

Comet	Date	Heliocentric Distance r_h (AU)	Solar Phase (degrees)	Exposure (Seconds)
R2	25/01/2018	2.87	15	1800
V2	10/12/2016	2.83	130	1200

made using the scheme, sky-object-sky, for the proper background sky subtraction.

3 Results and Conclusion

Our observations and studies revealed that the optical spectrua of comets R2 and V2 are quite unusual as compared to general cometary spectra. Most of the major cometary emissions like C_2, C_3 and CN were absent in comet R2. However, the comet spectrum showed very strong emission bands from ionic species like CO^+ and N_2^+. The N_2/CO ratio was determined from the spectra and an extremely low depletion factor (with respect to the solar nebula value) of 1.6 $\pm$ 0.4 has been estimated. This depletion factor is much lower than Our estimation of the N_2/CO ratio obtained with the low resolution spectra (Kumar V et al., 2018, submitted to A&A) is well in agreement with those reported by Cochran & McKay [2018] using high resolution spectra. The column densities and production rates of CO^+ and NH_2 were calculated from their emission bands which were of the order of 10^{24} molecules sec^{-1}.

The major cometary species were also absent in comet V2, when it was observed at a heliocentric distance of 2.83 AU. However, no other emissions were detected (like that of the ions detected in R2). The optical spectra of this comet was obtained at various epochs using LISA on the 1.2m telescope at Mount abu. The regular cometary emissions were detected after 2.3 AU. The extremely low activity of comet V2 suggests a resemblence with comets like C/2014 S2 [Meech et al., 2016] which are classified as Manx objects (Inactive objects in comet like orbits).

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Comet 67P/Churyumov-Gerasimenko mass estimation from CONSERT ranging data

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Abstract

The Philae lander on the surface of comet 67P/C-G was finally imaged by the OSIRIS camera onboard the Rosetta spacecraft on September 2, 2016. In this study, we derive an estimate of the mass of the comet from the three CONSERT measurement sequences taken in direct visibility from the lander to the orbiter, and compare it with the mass estimate derived from radio-tracking data of the Rosetta spacecraft from the Earth[1][2]. We also derive updated 3D coordinates for the lander, by taking into account the shape of the comet as a constraint and the 2D a priori coordinates from the OSIRIS images[3].

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