Characterization of cometary activity of 67P/Churyumov-Gerasimenko comet

Abstract

After 2.5 years from the end of the mission, the data provided by the ESA/Rosetta mission still leads to important results about 67P/Churyumov-Gerasimenko (hereafter 67P), belonging to the Jupiter Family Comets. Since comets are among the most primitive bodies of the Solar System, the understanding of their formation and evolution gives important clues about the early stages of our planetary system, including the scenarios of water delivery to Earth.

At the present state of knowledge, 67P's activity has been characterized by measuring the physical properties of the gas and dust coma, by detecting water ice patches on the nucleus surface and by analyzing some peculiar events, such as outbursts.

We propose an ISSI International Team to build a more complete scenario of the 67P activity during different stages of its orbit. The retrieved results in terms of dust emission, morphology and composition will be linked together in order to offer new insights about 67P formation and evolution.

In particular the main goals of the project are:

1. Retrieval of the activity degree of different 67P geomorphological nucleus regions in different time periods, by reconstructing the motion of the dust particles revealed in the coma;
2. Identification of the main drivers of cometary activity, by studying the link between cometary activity and illumination/local time, dust morphology, surface geomorphology, dust composition.

The project will shed light on how (and if) cometary activity is related to surface geology and/or composition or is just driven by local illumination. The physical and compositional properties of the emitted dust give information about the state and the exposition time (i.e., on the evolution) of the surface and sub-surface layers where it is originated, and how they change during the comet orbit.

The Team will exploit the great amount of data provided by the ESA/Rosetta orbiter, in particular the GIADA dust detector, the VIRTIS imaging spectrometer, the OSIRIS camera, the MIDAS atomic force microscope and the COSIMA and ROSINA dust and gas mass spectrometers, respectively. Cross-correlation among these data will allow combining different pieces of information (dust composition and morphology, nucleus composition, emission rate, geology), which, thanks to the support of dust models and laboratory measurements of cometary analogs, will lead to our goals.

The proposing team is composed of members from teams of the above listed instruments and is strongly skilled in the analysis of Rosetta data.

The first four months of activity are dedicated to goal #1 and will end with a summary meeting at ISSI facilities and an overview paper. A similar schedule is foreseen in the following 20 months for goal #2, for which two meetings are planned.

The ISSI support will be necessary and fundamental to organize meetings at ISSI facilities, which will allow a quick and effective interaction among the team members. The project goals are well in line with the ISSI scientific activities.

1. Scientific rationale and goals

Comets are among the most primitive bodies in the Solar System still containing records of physical processes which led to the early Solar System formation. In particular, according to formation scenarios (e.g. Hartogh et al., 2011) they are supposed to have delivered to Earth's surface, atmosphere, and oceans (Marty et al.; 2016) the ingredients (water and organics) essential for the emergence of life.

The ESA/Rosetta mission was launched in 2004 and orbited the Jupiter Family comet 67P/Churyumov-Gerasimenko (hereafter 67P) from August 2014 until September 2016. After 2.5 years from the end of the mission, the data provided by the 21 instruments on board the Rosetta orbiter and its lander Philae are still giving important clues about 67P formation and evolution.

Rosetta escorted the comet along three stages of its orbit: 1) *pre-perihelion*: 67P was poorly active and its surface properties were mostly influenced by processes that occurred at the previous perihelion passage then modified far from the Sun (e.g., collisions and space weathering); 2) *perihelion*: approaching the Sun, the 67P activity led to rejuvenation of its surface, exposing underlying and most primordial material; 3) *post-perihelion*: nucleus and coma were partially renewed from the occurred activity.

The suite of instruments on board Rosetta observed both the nucleus and the coma. The VIRTIS (Visible and Infrared Thermal Imaging Spectrometer) imaging spectrometer provided composition of the nucleus by acquiring visible and near-infrared spectra. It revealed the ubiquitous occurrence of the 3.2 μm absorption

band, ascribed to organics (Capaccioni et al., 2015) but also affected by water ice (De Sanctis et al., 2015). Spectral modifications were observed after perihelion, i.e. flattening of the visible spectral slope, ascribed to the recent exposition of subsurface water ice caused by cometary emissions (Ciarniello et al., 2016). VIRTIS also studied the coma, finding a spatial correlation between the emission of the dust and H_2O in the pre-perihelion period (Rinaldi et al. 2016), suggesting that at this stage water vapour is the only gas pushing the dust. VIRTIS also detected some transient events as outburst, i.e. sudden increase of the dust emission, characterized by a change of the dust colour from red to blue, revealing the presence of very small grains (≤100 nm). The measured bolometric albedos indicate bright grains in the ejecta, which could be either silicatic or icy (Rinaldi et al. 2018).
The OSIRIS (Optical, Spectroscopic, and Infrared Remote Imaging System) camera allowed the geological and morphological mapping of the nucleus surface (El Maary et al., 2015; 2016). It identified regions and periods of higher cometary activity by means of brightness variations (Tubiana et al., 2015) and surface changes (Hu et al., 2017).
Gas and dust ejected have been analysed in situ by the GIADA (Grain Impact Analyser and Dust Accumulator) dust detector, the MIDAS (Micro-Imaging Dust Analysis System) atomic force microscope, and the COSIMA (Cometary Secondary Ion Mass Analyser) and ROSINA (Rosetta Orbiter Spectrometer for Ion and Neutral Analysis) dust and gas mass spectrometers.
GIADA detected mm-sized dust particles belonging to two families, i.e. compact particles and fluffy agglomerates. Della Corte et al. (2016) mapped the spatial distributions of the fluffy and compact particles in the coma, finding a lack of correlation among them. Longobardo et al. (2019) developed an empirical approach to trace back the dust particles detected by GIADA in the coma down to the surface, finding that, in the first part of the pre-perihelion stage, fluffy and compact particles are generated from the same source and then are spread in the coma due to their different speed. This procedure has to be extended to the entire dataset, characterized by different spacecraft altitudes and illumination conditions, also with the help of dust dynamical numerical simulations (Ivanovski et al., 2017). Provided that the Rosetta data revealed seasonal changes of some dust properties (Fulle et al., 2016; Merouane et al., 2017), we could obtain different results with respect to the first part of the mission.
MIDAS collected μm-sized dust particles and investigated their 3D surface structure (Bentley et al., 2016a). All particles were found to be agglomerates (Bentley et al., 2016b). Additionally, one extremely porous particle with a fractal structure similar to GIADA's fluffy particles was imaged (Mannel et al., 2016). A particle catalogue (Boakes et al., 2018) is now giving the opportunity to access the whole MIDAS collection in a sophisticated way and allows the calculation of particle properties for the whole mission time.
The μm-sized particles studied by COSIMA are almost equally divided in compact and porous (Merouane et al., 2016). However, most of the compact particles are also aggregates of smaller units probably collected at low velocity, as was shown during charging experiments using the ion beam of COSIMA that lead to the fragmentation of the compact particles into their smaller constituents (Hilchenbach et al., 2017). Bardyn et al. (2017) reported elemental composition of some dust particles analyzed by COSIMA, suggesting a composition of ~50% organic matter (Fray et al, 2016) and ~50% of other anhydrous mineral phases. Occurrence of CAIs (calcium aluminum rich inclusions) was also suggested (Paquette et al., 2016).
ROSINA monitored the gas activity from which gas production rates and activity distributions of different volatile species were derived (Kramer et al., 2017; Läuter et al. 2018). The comparison between coma and surface in-situ measurements performed by the Rosetta lander revealed an interesting link between the organics detected in the coma and the nucleus composition (Altwegg et al., 2017).

An in depth characterization of cometary activity would shed light on the processes occurred during the evolution of the comet. In particular:

a) the identification of the most and the least active regions would allow:
    i. the understanding of the main drivers of the activity, i.e. if it is related to the illumination only, or if it is also affected by other properties, such as surface composition, morphology, layering or physical properties (as supposed, e.g., by Fornasier et al., 2017);
    ii. to analyze the influence of the cometary activity on the surface geomorphology;
b) the morphology of the emitted dust could be related to the exposition period and physical state of terrains (Schultz et al., 2015);
c) the composition of the emitted gas and dust could be related to:
    i. the composition of the surface;

ii. the composition of the subsurface, i.e. the most pristine layers (e.g., Altwegg et al., 2017), which can be related to cometary formation.

In order to answer the issues above, it is necessary to merge the different pieces of information provided by the Rosetta instruments. This process is needed also in perspective of future missions to comets, such as the planned JAXA/DESTINY+ (Toyota et al., 2017) or the studied NASA/CAESAR (Squyres et al., 2018), which will highly benefit by complementing the planned future measurements with results obtained by Rosetta. This is particularly true for NASA/CAESAR that going back to comet 67P will particularly take advantage of the combined dust/gas activity investigation proposed here.

To analyze in detail the identified issues, we propose an ISSI International Team with complementary expertise, including team members of the Rosetta instruments listed above and experts of 3D dusty gas models and numerical simulations. Many Team members already started a collaboration to study the cometary dust properties (Güttler et al., 2019).

This project proposes to go beyond the state of art, by addressing the following key-goals:

1. Retrieval of the activity degree of different regions of 67P surface in different time periods, by reconstructing the motion of the dust particles revealed in the coma;
2. Identification of the main drivers and the effects of cometary activity, by studying the link between cometary activity and illumination/local time, dust morphology and composition, surface geomorphology

The goal #1 requires the development of an appropriate algorithm to reconstruct the motion of the dust particles ejected from the nucleus. This algorithm has been developed by Longobardo et al. (2019) and combines the velocity of compact and fluffy particles measured by GIADA, the spacecraft altitude and the rotation of the comet, in order to obtain the geomorphological regions on the nucleus, from where each coma dust particle detected by GIADA was ejected. The algorithm has been applied and validated for the first part of the pre-perihelion GIADA dataset. We will extend its application to the entire GIADA dataset, characterized by different spacecraft altitudes, and we will validate it by using a dust model (Ivanovski et al., 2017), currently applied to a couple of periods along the mission. The model describes the cometary environment in terms of dust velocity and acceleration regions, which will serve to relate the measured dust space distribution with probable ejection locations on the nucleus for the full duration of the mission, in order to identify more and less active regions, in terms of dust emission, in different seasons and local times. Since cometary activity causes the exposition of water ice on the surface, with a subsequent shortward shift of the 3.2 μm band and a spectral slope flattening (Longobardo et al., 2017), the comparison between cometary activity maps and VIRTIS spectral maps (e.g., distribution of 3.2 μm band center and spectral slopes) will further reinforce the identification of the most active regions.

The goal #2 will relate the cometary activity maps obtained from goal #1 with Rosetta geometric information (coordinates, illumination and viewing angles) and with the data provided by the VIRTIS, OSIRIS, MIDAS COSIMA and ROSINA instruments. Most of these data are publicly available, including gas activity maps derived from ROSINA data (Kramer et al. 2018; Läuter et al. 2019). However, with our Team composed of instrument team members, we will have access to proprietary data, too.

The cometary activity maps will be firstly related with maps of illumination and with local time, in order to study the link between illumination and activity. In the regions where this link would not arise, or would deviate from the comet average, we will study cometary activity as possibly triggered also by other surface or dust properties, e.g. a) morphology and/or b) composition.

a) A link with dust morphology could be expected: it is in fact believed that fluffy particles are more abundant in more pristine - less processed terrains (e.g., Shultz et al., 2015). We will analyse the cometary activity maps and the fluffy/compact particles ratio in each nucleus region, as revealed by GIADA, supported by the morphological maps provided by OSIRIS, to observe a possible correlation between emission of fluffy agglomerates and surface physical state (e.g, rough/smooth terrains). The events revealed by both GIADA and MIDAS instruments will give us information on the physical properties of dust particles ejected by different terrains.

b) The link between activity degree and coma dust composition can be analysed by searching for possible events revealed by both GIADA and COSIMA, and associate dust composition with source region activity. COSIMA data would be also used to produce dust analog mixtures reproducing the comet composition. Spectra of these mixtures will be acquired and compared with the VIRTIS spectra, giving new constraints about the dust composition and its possible daily and seasonal variability, due to cometary activity.

The comparison of cometary activity maps with ROSINA and VIRTIS data would allow relating the peaks of dust cometary activity as revealed by goal #1 with the gas density peaks observed by ROSINA. This could reveal which gases are correlated with dust emission during the different stages of the comet's orbit.

2. Timeliness and project program

The project is divided in *Work Package 1 (Trace-back)* and *Work Package 2 (Data Fusion)*. WP1 will last four months, whereas WP2 will start from the end of WP1 until the end of the project, for a total duration of 20 months. The main topics of each WP are summarized below.

2.1 WP1: Trace-back

- Review of developed dust models and extension of their application to the entire mission period
- Review of the developed trace-back algorithm, validation by means of the dust model, extension to the entire GIADA dataset and retrieval of geomorphological regions from where detected dust particles (fluffy and compact) are emitted in different time periods
- Determination of the activity degree of different comet regions in the three mission stages (pre-perihelion, perihelion, post-perihelion), as inferred by VIRTIS data (e.g., distribution of spectral features or changes, relatives to exposition of water ice), and comparison with results obtained by GIADA
- Production of dust activity maps, one for each mission stage
- Collect published gas activity maps for later comparison

2.2 WP2: Data Fusion

- Comparison between dust activity maps and geometric information (illumination maps, local time)
- Review of the geomorphological maps obtained by OSIRIS
- Analysis of the relation between emitted fluffy/compact particles and the physical state of comet terrains, by combining GIADA, MIDAS and OSIRIS data
- Analysis of the COSIMA dataset (retrieval of the elemental composition of the dust particles measured)
- COSIMA-GIADA cross-correlation, to search for possible events detected by both instruments and to associate dust composition (COSIMA) with source region activity (GIADA, WP1)
- Preparation of dust analog mixtures reproducing the comet dust composition suggested by COSIMA data
- Acquisition of spectra of laboratory mixtures and comparison with VIRTIS spectra
- Comparison between dust activity maps obtained in WP1 with ROSINA data (density peaks of water vapour and other gases)
- Review and interpretation of all the results obtained by data fusion activities

3. Expected output

Two peer-reviewed overview papers, one for each WP, will be produced by the Team. The papers will include appropriate acknowledgements of ISSI's support. Team members will also produce independent papers related to the topics of the project. A final report will be provided to ISSI.

4. ISSI added values

The logistic support (meeting rooms, projection facilities, Internet connection, facilities for teleconferences) and funding provided by ISSI are necessary and fundamental to carry on the proposed research activity, since they will allow a quick and effective interaction among the team members. A web page of the project will be maintained on the ISSI's server, giving to the scientific community the possibility to be informed about the ongoing research activities and the obtained results, as well as to consider the latter in perspective on future studies on comets. The presented research concerns Planetary Science, which is among the research fields covered by ISSI, and the ISSI sponsorship will increase the impact of our results.

5. Schedule

Three meetings are planned (hereafter **M1, M2** and **M3**) at ISSI premises. Each meeting will last three days, for a total of 99 person-days, i.e. almost 20 person-weeks.
The project will start presumably between July and November 2019. The kick off (KO) meeting will consist in a teleconference organized by the Team Leader. The first four months will be devoted to WP1activities.

The preliminary agenda of **M1** meeting (KO+4 months) will include: review and interpretation of WP1 results, discussion of the paper concerning the WP1 activity, identification of high-priority activities of WP2 (on the basis of WP1 results), discussion of data fusion strategies, scheduling of WP2 activities.
The WP2 timeline will be definitively determined during the **M1** meeting. However, we propose here a preliminary schedule.
The first nine months of WP2 activity (from KO+4 to KO+13 months) will be focused on comparison of WP1 results with geometric information, with OSIRIS (geomorphological maps) and MIDAS data (dust's physical properties) and on review of COSIMA data. At the **M2** meeting (planned at KO+13 months) the outputs of all these activities will be presented and discussed. Then, a discussion of strategies for the remaining activities will be held, and the project schedule will be updated on the basis of the results obtained thus far. Finally, a preliminary draft of the WP2 scientific paper will be discussed.
The following nine months (from KO+13 to KO+22 months) will be dedicated, on one side, to preparation of laboratory mixtures (on the basis of COSIMA results), acquisition of their spectra at INAF FTIR facility, and comparison with VIRTIS spectra, and, on the other side, to the comparison between GIADA and ROSINA activity maps. All the results will be discussed and interpreted at **M3** meeting (planned at KO+22 months), where a final wrap-up will also take place, and the WP2 paper and the final report will be discussed. The latter will be finalized, submitted and delivered in the last two months (from KO+22 to KO+24).

6. Facilities

The Team requires from ISSI computer equipment and Internet connection for each scheduled meeting.
Preparation of analogs and acquisition of their visible and near-infrared spectra will be performed at FTIR spectrometer facility (which covers the VIRTIS spectral range), available at INAF-IAPS laboratories.

7. Team and financial support

We require the standard financial support for each meeting at ISSI: per-diem rate for all the team members (+ 1 young scientist member), and travel reimbursement for the Team Leader. One team member is from Bern and does not require funding. All team members are available to participate in the activities and meetings of the project.

Andrea Longobardo (INAF-IAPS, Rome, Italy, Team Leader)
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Carsten Güttler (Max Planck Institute, Göttingen, Germany)
Stavro Ivanovski (INAF-Osservatorio Astronomico di Trieste, Trieste, Italy)
Thurid Mannel (Space Research Institute Austrian Academy of Sciences, Graz, Austria)
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Altwegg, K. et al. (2017), MNRAS, 492, 2, S130-S141; Bardyn, A. et al. (2017), MNRAS, 469, 2, S712-S722; Bentley, M.S. et al. (2016a), Acta Astronautica 125; Bentley, M.S. et al. (2016b), Nature 537; Boakes, P. et al. (2018), EGU 2018-7134; Capaccioni, F. et al. (2015), Science, 347, 6220; De Sanctis, M.C. et al. (2015), Nature, 525, 500-503; Della Corte, V. et al. (2016), MNRAS, 462, 1, S210-S219; El-Maarry, M.R. et al. (2015), A&A, 583, A26, 28pp.; El-Maarry, M.R. et al. (2016), A&A, 593, A110, 20 pp.; Fornasier, S.et al., (2017), DPS abstract; Fray, N. et al. (2016), Nature 538, 72-74; Güttler, C., et al. (2019). A&A, doi: 10.1051/0004-6361/201834751; Hartogh, P. et al. (2011), Nature, 478, 7368, 218-220; Hu, X. et al. (2017), A&A, 604, A114, 31 pp.; Ivanovski, S. et al. (2017), MNRAS, 492, 2, S774-S786; Läuter, M. et al. (2019), MNRAS. 483, 852-861; Kramer, T. et al. (2017), MNRAS, 469, S20-S28; Longobardo, A. et al. (2017), MNRAS, 469, 2, S346-S356; Longobardo, A. et al. (2019), 483, 2165-2176; Mannel, T. et al. (2016), MNRAS 462; Marty, B. et al. (2016), Science, 356, 1069; Merouane, S. et al. (2016), A&A, 596, A87, 12 pp.; Merouane, S. et al. (2017), MNRAS, 469, 2, S459-S474; Paquette, J.A. et al. (2016), M&PS, 51, 7, 1340-1352; Rinaldi, G. et al. (2016), MNRAS, 462, 1, S547-S561; Rinaldi, G. et al. (2018), MNRAS, 481, 1235; Schultz, R. et al. (2015), Nature, 518; Squyres, S. (2018), 18th NASA-SBAG Meeting; Toyota, H. et al. (2017), LCPM abstract; Tubiana, C. et al. (2015), A&A, 573, A62, 11pp.

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Role in the project: Team Leader, analysis of the GIADA dataset, spectral analysis of VIRTIS and laboratory spectra, contribution to mixture preparation and laboratory spectra acquisition

Current position: Researcher

Former Position(s):

- 2018-in progress: Researcher at INAF-IAPS (Rome)
- 2016-2018: Contract Researcher at INAF-IAPS (Rome)
- 2012-2016: Research Fellow (post-doc) at INAF-IAPS (Rome)
- 2008-2012: Research Fellow at INAF-IFSI (Rome)

Education:

- 2012: Phd in Remote Sensing (Università La Sapienza, Rome)
- 2008: Master Degree in Physics (Università "Federico II", Naples)
- 2005: Bachelor's Degree in Physics (Università "Federico II", Naples)

Services in National and/or International Committees (last ones):

- Associated scientist of GIADA-Rosetta dust detector
- Associated scientist of VIRTIS-Rosetta and VIR-Dawn imaging spectrometers
- Database Manager of the COmetary, MEteoroids, Dust and Analogs (COMEDA) database in the SSHADE project
- Work Package Leader of ESA projects CAM and CAMLAB (development of crystal microbalance for space and laboratory applications)
- Task Leader in the Horizon2020 project EUROCARES (development of facility for returned samples from missions)
- Deputy PI of the VISTA instrument
- Task Leader of Solar System Working Group (SSWG) of WFIRST-NASA observatory
- SOC member of COSPAR event (small bodies) and National Planetary Science Congress, Convener at National Planetary Science Congress (sample return and astrobiology), EPSC (sample return) and EGU (small bodies)
- Member of NASA Panel Review "Cassini and New Frontiers Data Analysis Program"

Honors:

- ESA Innovation Award for the activity concerning development of CAM sensor
- ESA Group Achievement Awards (Venus Express and Rosetta missions)
- NASA Group Achievement Award (Dawn mission)
- 1st Prize Science Flash Contest, for the best 3-minutes presentation at EPSC 2017

Selected Publications:

1. A. Longobardo et al. (2019), *67P/Churyumov-Gerasimenko active areas before perihelion identified by GIADA and VIRTIS data fusion*, MNRAS, 483, 2, 2165-2176

2. A. Longobardo et al. (2017), *Photometric behaviour of 67P/Churyumov-Gerasimenko and analysis of its pre-perihelion diurnal variations*, MNRAS, 469, 2, S346-S356
3. A. Longobardo et al. (2019), *Photometry of Ceres and Occator faculae as inferred from VIR/Dawn data*, Icarus, 320, 97-109
4. A. Longobardo et al. (2019), *Mineralogy of the Urvara-Yalode region on Ceres*, Icarus, 318, 241-250
5. A. Longobardo et al. (2019), *Mineralogy of the Occator Quadrangle*, Icarus, 318, 241-250
6. A. Longobardo et al. (2018), *Production and 3D visualization of high-level data of minor bodies: the MATISSE tool in the framework of VESPA-Europlanet 2020 activity*, Advances in Space Research, 62, 8, 2317-2325
7. A. Longobardo et al. (2016), *Disk-Resolved Photometry of Vesta and Lutetia and Comparison with Other Asteroids*, Icarus, 267, 204-216
8. A. Longobardo et al. (2015), *Mineralogical and spectral analysis of Vesta's Gegania and Lucaria quadrangles and comparative analysis of their key features*, Icarus, 259, 72-90
9. A. Longobardo et al. (2014), *Photometric behaviour of spectral parameters in Vesta dark and bright regions as inferred by the Dawn VIR spectrometer*, Icarus, 240, 20-35
10. A. Longobardo et al. (2012), *Limb darkening study using Venus night side infrared spectra from VIRTIS-Venus Express data*, PSS, 69, 1, 62-75
11. D. Bockelee-Morvan, … A. Longobardo (2019), *VIRTIS-H observations of comet 67P's dust coma: spectral properties and color temperature variability with phase and elevation*, A&A, in press, doi: 10.1051/0004-6361/201834764
12. G. Rinaldi, … A. Longobardo et al. (2018), *Summer outburts in the coma of comet 67P/Churyumov-Gerasimenko as observed by Rosetta-VIRTIS*, MNRAS, 481, 1, 1235-1250
13. G. Rinaldi, … A. Longobardo et al. (2017), *Cometary coma dust size distribution from in-situ IR spectra*, MNRAS, 469, 2, S598-S605
14. M. Ciarniello, … A.Longobardo et al. (2016), *The global surface composition of 67P/Churyumov-Gerasimenko nucleus by Rosetta/VIRTIS. II) Diurnal and seasonal variability*, MNRAS, 462, S443-S459
15. A. Raponi, … A. Longobardo et al. (2016), *The temporal evolution of exposed water ice-rich areas on the surface of 67P/Churyumov-Gerasimenko: spectral analysis*, MNRAS, 462, S467-S490
16. E. Quirico, … A. Longobardo et al. (2016), *Refractory and semi-volatile organics at the surface of comet 67P/Churyumov-Gerasimenko: insights from the VIRTIS/Rosetta imaging spectrometer*, Icarus, 272, 32-47
17. G. Filacchione, … A.Longobardo et al. (2016), *The global surface composition of 67P/CG nucleus by Rosetta/VIRTIS. I) Prelanding mission phase*, Icarus, 274, 334-349
18. G. Filacchione, … A. Longobardo et al. (2016), *Exposed water ice on the nucleus of comet 67P/Churyumov-Gerasimenko*, Nature, 529, 368-372
19. F. Capaccioni, … A. Longobardo et al. (2015), *The organic-rich surface of comet 67P/Churyumov-Gerasimenko as seen by VIRTIS/Rosetta*, Science, 347, 6220, doi: 10.1126/science.aaa0628
20. De Sanctis, M.C., … A. Longobardo et al. (2015), *The diurnal cycle of water ice on comet 67P/Churyumov-Gerasimenko*, Nature, 525, 500-503

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Role in the project: Insight on dust composition

Current position: Professeur des Universités (Full Professor), 1st class, UPEC, LISA

Former Position(s):

- October 2010 – August 2015: Professeur des Universités (Full Professor), 2nd class, UPEC, LISA.
- February 2002 - September 2010: Maître de Conférences (Assistant professor) Chemistry/Astrochemistry, Université Paris 12, LISA
- February 2001 - January 2002 National Research Council (NRC) Associate /NASA - Goddard Space Flight Center, Astrochemistry Branch Cosmic Ice Laboratory / Greenbelt, MD, 20771, USA

Education:

- **Habilitation à Diriger les Recherches** (December 9th 2008)

Formation and evolution of the organic matter of comets and small bodies of the solar system

- **Thèse de doctorat (PhD)** (November 10th 1999)

Organic chemistry of the cometary environment: experimental study of the contribution of the refractory organic component to the gas phase

Services in National and/or International Committees (last ones):

- Co-Chair of ESA Astrobiology Topical Team (2011-2018)
- Member of the CNES Solar System Working group
- Member of the board of the Science Committee of Ile de France Astrophysics and Life Apparition Conditions fund.

Selected Publications:

- Cottin, H., et al. 2004. Origin of cometary extended sources from degradation of refractory organics on grains: polyoxymethylene as formaldehyde parent molecule. Icarus 167, 397–416.
- Cottin, H., Fray, N., 2008. Distributed Sources in Comets. Space Science Reviews 138 179-197
- Cottin, H., et al. (2012) The PROCESS experiment: an astrochemistry laboratory for solid and gaseous organic samples in low Earth orbit. Astrobiology 12, 412-425.
- Cottin, et al., (2015) Photochemical studies in low Earth orbit for organic compounds related to small bodies, Titan and Mars. Current and future facilities. Bulletin de la Société Royale des Sciences de Liège 84, 60-73.
- Cottin, H., et al. (2017) Astrobiology and the Possibility of Life on Earth and Elsewhere…. Space Science Reviews 209, 1-42.
- Cottin, H., et al. (2017) Space as a Tool for Astrobiology: Review and Recommendations for Experimentations in Earth Orbit and Beyond. Space Science Reviews 209, 83-181.

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Role in the project: Analysis of OSIRIS data

Current position: Scientist and Co-Investigator of Rosetta/OSIRIS

Former Position(s):

- 07/2013–12/2013 Post doctoral research fellow, University of Braunschweig
- 07/2011–06/2013 Post doctoral research fellow, Kobe University (Japan)
- 12/2009–06/2011 Post doctoral research fellow, University of Braunschweig.
- 02/2007–12/2009 PhD student, University of Braunschweig

Education:

- 02/2007–12/2009 Dr. rer. nat., University of Braunschweig, Braunschweig, Germany.
- 09/2001–01/2007 Dipl.-Phys., University of Braunschweig, Braunschweig, Germany

Services in National and/or International Committees (last ones):

Honors:

Fellowship of the Japan Society for the Promotion of Science (JSPS)

Humboldt Fellow

Selected Publications (out of > 90 in the last 5 years)**:**

Güttler, C., et al. (2019). Synthesis of the morphological description of cometary dust at comet 67P/Churyumov-Gerasimenko. Astronomy & Astrophysics, DOI 10.1051/0004-6361/201834751.

Güttler, C., et al. (2017). Characterization of dust aggregates in the vicinity of the Rosetta spacecraft. *The Monthly Notices of the Royal Astronomical Society*, 469:S312-S320.

Ott, T., Drolshagen, E., Koschny, D., **Güttler, C.**, et al. (2017). Dust mass distribution around comet 67P/Churyumov-Gerasimenko determined via parallax measurements using Rosetta's OSIRIS cameras. *The Monthly Notices of the Royal Astronomical Society*, 469:S276-S284.

Schmitt, M. I., Tubiana, C., **Güttler, C.**, et al.. (2017). Long-term monitoring of comet 67P/Churyumov-Gerasimenko's jets with OSIRIS onboard Rosetta. *The Monthly Notices of the Royal Astronomical Society*, 469:S380-S385.

Davidsson, B. J. R., Sierks, H., **Güttler, C.**, et al. (2016). The primordial nucleus of comet 67P/Churyumov-Gerasimenko. *Astronomy and Astrophysics*, 592:A63.

Sierks, H., … **Güttler, C.**, et al. (2015). On the nucleus structure and activity of comet 67P/Churyumov-Gerasimenko. *Science*, 347(6220):1044.

NAME, First Name: IVANOVSKI Stavro Lambrov

Affiliation: National Institute for Astrophysics - Osservatorio Astronomico di Trieste, Via G.B. Tiepolo, 11 I-34143 Trieste, Italy; stavro.ivanovski@inaf.it

Role in the project: Non-spherical dust dynamics expert, analysis of the GIADA data

Current position: Researcher at INAF- Osservatorio Astronomico di Trieste

Former Position(s):
2017-2019 Researcher (fixed-term position) at INAF-IAPS, Rome, Italy; 2011-2014-2017 Postdoc at INAF – Oss. Astron. di Capodimonte, Naples and IAPS-INAF; 2010 - 2011 Research Fellow (RF) at the University of Parthenope; 2007 - 2008 RF at Astr. Obs. of Catania; 2005 - 2006 RF at MHD Group, Astroph. Inst. of Potsdam, Germany; 2004 - 2005 External Colaborator at Geospace Hydrodynamics Lab, Inst. of Mechanics, BAS

Education:
2007 - 2010 Ph.D. in Applied Mathematics (University of Catania, Catania, Italy); 1995 - 2003 M. Sc. in Mathematics Sofia University "St. Kl. Ohridski", FMI, Bulgaria

Services in National and/or International Committees (last ones):

- 2017 **SOC member** of "Comet formation paradigm after Rosetta. What is the hallmark of cometary nuclei formation in protoplanetary discs inherited from Rosetta?" Worskhop , 19-23 June 2017, Sofia Bulgaria
- 2012-2014 **Member of two ISSI Teams** 1)"Analysis of the circumnuclear gas and dust coma of comet 67P, the Rosetta target, on the basis of 3D and 3D+t model fits to data collected from part of the orbiter payload" and 2)"Modeling cometary environments in the context of the heritage of the Giotto mission to comet Halley and of forthcoming new observations at Comet 67P/Churyumov-Gerasimenko"
- 2018 **Co-I of GIADA/Rosetta** mission. A member of the scientific teams of **SERENA/BepiColombo** and **LICIACube/DART** missions.

Honors

- **Rosetta Group Achievement Awards,** ESA (2004/2017).
- Main-belt Asteroid (1981 EP12) was renamed "**11802 Ivanovski**" by the IAU for the contributions to the exploration of comets, particularly on the dynamics of aspherical dust grains in cometary atmospheres (2017).
- **Young Scientist prize** 2003, Inst. of Mechanics, Bulgarian Academy of Sciences

Selected Publications:
1) Ivanovski S. et al. (2017) Dynamics of aspherical dust grains in a cometary atmosphere: I. Axially symmetric grains in an spherically symmetric atmosphere. Icarus 282 333–350
2) Ivanovski S. et al. (2017) Dynamics of non-spherical dust in the coma of 67P/Churyumov–Gerasimenko constrained by GIADA and ROSINA data, MNRAS 469, S774–S786 (2017)
3) Fulle* M., *Ivanovski* S.*, et al. (2015), Rotating dust particles in the coma of comet 67P/ Churyumov–Gerasimenko, A&A, 583, A14
4) V. Della Corte, S. Ivanovski et al. (2014) Simulated measurements of 67P/Churyumov–Gerasimenko dust coma at 3 AU by the Rosetta GIADA instrument using the GIPSI tool, Astronomy and Computing, 5, 57-59
5) Rotundi A., … Ivanovski, S., et al. (2015), Dust measurements in the coma of comet 67P/Churyumov-Gerasimenko inbound to the Sun, Science, 347, 6220, aaa3905

NAME, First Name: MANNEL, Thurid

Affiliation Space Research Institute (IWF) of the Austrian Academy of Sciences (OEAW), Schmiedlstr. 6, 8042 Graz, Austria

Role in the project: Particle morphology, Analysis of MIDAS data

Current position: Scientist and PI of MIDAS

Former Position(s):
2016 – 2018 Research Fellow at the Space Research Institute Graz
2015 – 2016 Scholarship holder at the Space Research Institute Graz

Education:
2014 – 2018 Dr. rer. nat in physics at the University Graz, Graz, Austria
2011 – 2013 Master of Science in physics at the Technical University Munich, Munich, Germany
2008 – 2011 Bachelor of Science in physics at the Technical University Munich, Munich, Germany

Services in National and/or International Committees (last ones):

- 2017 Member of the Scientific Organising Committee of "Comet formation paradigm after Rosetta. What is the hallmark of cometary nuclei formation in protoplanetary discs inherited from Rosetta?" Worskhop , 19-23 June 2017, Sofia Bulgaria
- Member of the ISSI Workshop on Cosmic Dust from the Lab to the Stars in 2016
- 2015 – 2017 Co-I of the MIDAS instrument, 2017 – present PI of MIDAS

Honors:

- Grant of the JungforscherInnenfonds in 2015, a fellowship for excellent research projects at the University of Graz

Selected Publications:

- 2018: A. Levasseur-Regourd, J. Agarwal, H. Cottin, C. Engrand, G. Flynn, M. Fulle, T. Gombosi, Y. Langevin, J. Lasue, **T. Mannel**, S. Merouane, O. Poch, N. Thomas, and A. Westphal. **Cometary dust**. Space Science Reviews, 214. doi: 10.1007/s11214-018-0496-3.
- 2017: L. E. Ellerbroek, B. Gundlach, A. Landeck, C. Dominik, J. Blum, S. Merouane, M. Hilchenbach, M. S. Bentley, **T. Mannel**, H. John, and H. A. van Veen. **The footprint of cometary dust analogues - I. Laboratory experiments of low-velocity impacts and comparison with Rosetta data**. Monthly Notices of the Royal Astronomical Society, 469:S204–S216. doi: 10.1093/mnras/stx1257.
- 2016: **T. Mannel**, M. S. Bentley, R. Schmied, H. Jeszenszky, A. C. Levasseur–Regourd, J. Romstedt, and K. Torkar, **Fractal cometary dust - a window into the early Solar system**, Monthly Notices of the Royal Astronomical Society, vol. 462.
- 2016: M. S. Bentley, R. Schmied, **T. Mannel**, et al. **Aggregate dust particles at comet 67P/Churyumov-Gerasimenko**. Nature, 537:73–75. doi: 10.1038/nature19091.
- 2016: M. S. Bentley, H. Arends, B. Butler, J. Gavira, H. Jeszenszky, **T. Mannel**, J. Romstedt, R. Schmied, and K. Torkar. **MIDAS: Lessons learned from the first spaceborne atomic force microscope**. Acta Astronautica, 125:11–21. doi:10.1016/j.actaastro.2016.01.012.

CURRICULUM VITAE of Dr. Sihane MEROUANE

Affiliation:
Max-Planck Institute for Solar System Research
Justus-von-Liebig-Weg 3
37073, Göttingen
Germany

Role in the project: Team member providing data and data interpretation from the Rosetta/COSIMA instrument.

Current position: Postdoctoral Researcher, CoI of the instrument COSIMA (COmetary Secondary Ion Mass Analyzer) on Rosetta

Former Position(s):
Dec 2013 – Mar. 2014: Research Associate. The Open University, Milton Keynes, UK.
Oct. 2010 – Nov. 2013: PhD student, IAS, Université Paris Sud 11, Orsay, France.

Education:
2013 – PhD in Physics
2010 – Master's degree in Astronomy and Astrophysics
2008 – Bachelor's degree in Earth, Environment and Planetary Sciences

Selected Publications:

1) Bardyn A., Baklouti D., Cottin H., Fray N., Briois C., Paquette J., Stenzel O., Engrand C., Fischer H., Hornung K., Isnard R., Langevin Y., Lehto H., Le Roy L., Ligier N., **Merouane S.**, Modica P., Orthous-Daunay F.-R., Rynö J., Schulz R., Silén J., Thirkell L., Varmuza K., Zaprudin B., Kissel J., Hilchenbach M. (2017). *Carbon-rich dust in comet 67P/Churyumov-Gerasimenko measured by COSIMA/Rosetta*. Monthly Notices of the Royal Astronomical Society, Volume 469, Issue Suppl. 2, p.S712-S722.
2) Merouane S., Stenzel O., Hilchenbach M., Schulz R., Altobelli N., Fischer H., Hornung K., Kissel J., Langevin Y., Mellado E., Rynö J., Zaprudin B. (2017). *Evolution of the physical properties of dust and cometary dust activity from 67P/Churyumov-Gerasimenko measured in situ by Rosetta/COSIMA*. Monthly Notices of the Royal Astronomical Society, Volume 469, Issue Suppl. 2, p.S459-S474.
3) Rotundi A., Rietmeijer F.J.M., Ferrari M., Della Corte V., Baratta G.A., Brunetto R., Dartois E., Djouadi Z., **Merouane S.**, Borg J., Brucato J.R., Le Sergeant D'Hendecourt L., Mennella V., Palumbo M.E., Palumbo P. (2014). *Two refractory Wild2 terminal particles from a carrotshaped track characterized combining MIR/FIR/Raman micro-spectroscopy and FE-SEM/EDS analyses.* Meteoritics and Planetary Sciences, 49, 550.
4) Merouane S., Djouadi Z., Le Sergeant D'Hendcourt L. (2014). *Relationship Between Aliphatics and Silicate Components In Twelve Stratospheric Particles Deduced From Vibrational Spectroscopy*. The Astrophysical Journal, 780, 174.
5) Merouane S., Djouadi Z., Le Sergeant D'Hendcourt L., Zanda B., Borg J. (2012). *Hydrocarbon Materials Of Likely Interstellar Origin From The Paris Meteorite*. The Astrophysical Journal, 756, 154-160.

NAME, First Name: RINALDI Giovanna

Affiliation: IAPS-INAF

Role in the project: Analysis of coma dust by suing VIRTIS and GIADA data

Current position: Researcher at IAPS- INAF in Rome.

Former Position(s):

- **Decembre 2018 – present:** Researcher at IAPS- INAF
- **June 2017 – Novembre 2018** : Fellow Researcher at IAPS - INAF
- **June 2012 - June 2017**: Research grant at IAPS - INAF
- **January 2004 - March 2011**: Research Grants at IAPS- INAF

Education:

- **2002**: M.D. in Astronomy, Univ. of Padua.
- **2003**: Master in Applied Optics, Univ. Of Padua
  2007: Ph.D. in Space Sciences & Technologies, Univ. of Padua,.

Honors:

- **Rosetta Group Achievement Awards,** ESA (2004/2017).
- **Mars-Express Group Achievement Awards,** ESA (2004/2008).
- **Venus-Express Group Achievement Awards,** ESA (2006/2008).

Selected Publications:

1. **Summer outbursts in the coma of comet 67P/Churyumov-Gerasimenko as observed by Rosetta-VIRTIS G. Rinaldi** et al. DOI: 10.1093/mnras/sty2266
2. "**Cometary coma dust size distribution from in-situ IR spectra**" **G. Rinaldi** et al. 'DOI:https://doi.org/10.1093/mnras/stx1873
3. **Properties of the dust in the coma of 67P/Churyumov-Gerasimenko observed with VIRTIS- M" Rinaldi, G** et al. MNRAS, 462, 1, S547-S561 http://adsabs.harvard.edu/abs/2016MNRAS.462S.547R
4. **Comet 67P outbursts and quiescent coma at 1.3 au from the Sun: dust properties from Rosetta/VIRTIS-H observations.** Bockelée-Morvan, D.; **Rinaldi, G** et al. DOI 10.1093/mnras/stx1950
5. **Investigation into the disparate origin of CO2 and H2O outgassing for Comet 67/P** Fink, U; Doose, L.; **Rinaldi, G.** et al. Icarus, 277, 78-97. http://adsabs.harvard.edu/abs/2016Icar..277...78F
6. **Coma dust scattering concepts applied to the Rosetta mission** Fink, Uwe; **Rinaldi, Giovanna,** Icarus, 257, 9-22. http://adsabs.harvard.edu/abs/2015Icar..257....9F

RUBIN Martin
Space Research and Planetary Sciences, Physikalisches Institut, Univ. of Bern, Switzerland.
Email: martin.rubin@space.unibe.ch

Role in the project: I will support the team with relevant Rosetta/ROSINA measurements and associated interpretation.

Current Position: **Lecturer/Docent,** Physikalisches Institut, University of Bern, Switzerland

Former Positions:

09/2012 – 12/2016 **Adjunct Research Scientist**, Department of Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, United States.

05/2015 – 05/2017 **Oberassistent**, Physikalisches Institut, University of Bern, Bern, Switzerland.

Education:

Habilitation treatise, University of Bern, Bern, Switzerland, 2015.
Ph.D. in Physics, University of Bern, Bern, Switzerland, 2006.

Honors:

Rosetta Group Achievement Awards, ESA (2004/2017).
Main-belt Asteroid (1981 EH19) was renamed "11811 Martinrubin" by the IAU for the contributions to the exploration of comets (2017)

Selected Peer-Reviewed Publications (out of 100+):

Läuter et al., [et al., including **Rubin, M.**], Surface localization of gas sources on comet 67P/Churyumov–Gerasimenko based on DFMS/COPS data. Monthly Notices of the Royal Astronomical Society. 483, 852-861, 01/2019.

Shou, Y., [et al., including **Rubin, M.**], A New 3D Multi-fluid Dust Model: A Study of the Effects of Activity and Nucleus Rotation on Dust Grain Behavior at Comet 67P/Churyumov-Gerasimenko, Astrophys. J., 850:72, 11/2017.

Kramer, T., Läuter, M., **Rubin, M**., and Altwegg, K., Seasonal changes of the volatile density in the coma and on the surface of comet 67P/Churyumov-Gerasimenko, Mon. Not. R. Astron. Soc., 469, S20 – S28, 04/2017.

Fougere, N., [et al., including **Rubin, M.**], Direct Simulation Monte-Carlo modeling of the Major Species in the Coma of Comet 67P/Churyumov-Gerasimenko, Mon. Not. R. Astron. Soc., 462, S156–S169, 09/2016.

Marschall, R., [et al., including **Rubin, M.**], Modelling of observations of the inner gas and dust coma of comet 67P/Churyumov-Gerasimenko – First results, Astron. Astrophys., 589, A90, 04/2016.

Rubin, **M.**, Fougere, N., Altwegg, K., Combi, M. R., Le Roy, L., Tenishev, V. M., and Thomas, N., Mass transport around comets and its impact on the seasonal difference in water production rate, Astrophys. J., 788:168, 06/2014.

Rubin, **M.**, Tenishev, V. M., Combi M. R., Hansen, K. C., Gombosi, T. I., Altwegg, K., and Balsiger, H., Monte Carlo modeling of neutral gas and dust in the coma of Comet 1P/Halley, Icarus, Vol. 213, Issue 2, pp. 655-677, 04/2011.

NAME, First Name: TUBIANA, Cecilia

Affiliation: Max-Planck-Institute for Solar System Research, Göttingen, Germany

Role in the project: Co-investigator of the OSIRIS instrument.

Current position: Research scientist, Max-Planck-Institute for Solar System Research, Göttingen, Germany

Education:

- 10/2008 – present: Scientist, Max Planck Institute for Solar System Research, Göttingen (Germany)
- 2/2005 – 8/2008: PhD in Natural Science, Technischen Universität Braunschweig, Braunschweig (Germany)
- 9/2002 – 7/2004 Master in Environmental and Biomedical Physics, Università degli Studi di Torino, Torino (Italy)
- 9/1999 – 9/2002 Bachelor in Physics, Università degli Studi di Torino, Torino (Italy)

Selected Publications:

Tubiana et al. (2015), Scientific assessment of the quality of OSIRIS images, A&A, 583, id.A46.

Tubiana et al. (2015), 67P/Churyumov-Gerasimenko: Activity between March and June 2014 as observed from Rosetta/OSIRIS, A&A, 573, id.A62.

Tubiana et al. (2011), 67P/Churyumov-Gerasimenko at large heliocentric distance, A&A, 527, id.A113.

Bertini, I., La Forgia, F., Fulle, M., Tubiana, C., Güttler, C., et al. (2019), The backscattering ratio of comet 67P/Churyumov-Gerasimenko dust coma as seen by OSIRIS onboard Rosetta, A&A, 482, 2924.

Moreno, F., Guirado, D., Muñoz, O., Bertini, I., Tubiana, C., Güttler, C., et al. (2018), Models of Rosetta/OSIRIS 67P Dust Coma Phase Function, The Astronomical Journal, 156, id. 237.

Bertini, I., La Forgia, F., Tubiana, C., Güttler, C., et al. (2017), The scattering phase function of comet 67P/Churyumov-Gerasimenko coma as seen from the Rosetta/OSIRIS instrument, MNRAS, 469, Suppl_2.

Schmitt, M. I., Tubiana, C., Güttler, C., et al. (2017), Long-term monitoring of comet 67P/Churyumov-Gerasimenko's jets with OSIRIS onboard Rosetta, MNRAS, 469, Suppl_2.

NAME, First Name: ZAKHAROV Vladimir

Affiliation: Laboratoire de Meteorologie Dynamique, Universite Pierre et Marie Curie, BP99, 4 place Jussieu, Paris, 75252, France

Role in the project: team member, development of radiative transfer model

Current position: Research engineer

Former Position(s): Research engineer

Education: Baltic State Technical University 'Voenmeh', ul. 1-ja Krasnoarmejskaja, 1, St-Petersburg, 190005, Russia

Selected Publications:

Radiative transfer:

1. Zakharov, V., Bockelée-Morvan, D., Biver, N., Crovisier, J., and Lecacheux, A., Radiative transfer simulation of water rotational excitation in comets. Comparison of the Monte Carlo and escape probability methods. Astronomy & Astrophysics, 473, 303–310, (2007)
2. Debout, V., Bockelée-Morvan, D., Zakharov, V., A radiative transfer model to treat infrared molecular excitation in cometary atmospheres. Icarus 265, pp. 110–124, (2016).

Gaseous atmosphere:

3. Zakharov, V.V., Crifo, J.F., Loukianov, G.A., Rodionov, A.V., On modeling of complex nonequilibrium gas flows in broad range of Knudsen numbers on example of inner commentary atmosphere. Journal Mathematical Modelling, vol. 14, N8, p.91, (2002) (in russian).
4. Crifo, J.F., Lukyanov, G.A., Zakharov, V.V., Rodionov, A.V., Physical Model of the coma of Comet 67P/Churyumov-Gerasimenko. in: Colangeli, L., Epifani, E.M., Palumbo, P. (Eds.), The new Rosetta targets - observation, simulations and instrument performances. Kluwer Academic Publishers, Dordrecht, NL, pp. 119-130, (2004).
5. Kuppers, M., O'Rourke, L., Bockelee-Morvan, D., Zakharov, V., Lee, S., von Allmen, P., Carry, B., Teyssier, D., Marston, A., Muller, T., Crovisier, J., Barucci, M.A., Moreno, R., Localized sources of water vapour on the dwarf planet (1) Ceres. Nature vol.505, January 2014.

Dust coma:

6. Zakharov, V.V., Rodionov, A.V., Lukianov, G.A., Crifo, J.F., Monte-Carlo and multifluid modelling of the circumnuclear dust coma. II. Aspherical-homogeneous, and spherical-inhomogeneous nuclei. Icarus 201, pp. 358–380, (2009)
7. Zakharov, V.V., Rodionov, A.V., Lukyanov, G.A., Crifo, J.F., Navier–Stokes and direct Monte-Carlo simulations of the circumnuclear gas coma. III. Spherical, inhomogeneous sources. Icarus 194, pp. 327–346, (2008)

Core team member contacts

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