

Comet 67P/Churyumov-Gerasimenko surface composition as a playground for radiative transfer modeling and laboratory measurements

1 Abstract

Remote sensing observations at visible-infrared (VIS-IR) wavelengths of the nucleus of comet 67P/Churyumov-Gerasimenko performed by the Rosetta mission have revealed a surface ubiquitously covered by low-albedo material (Capaccioni et al., 2015; Ciarniello et al., 2015; Fornasier et al., 2015), characterized by the presence of refractory and semi-volatile organics and dark opaque phases (Capaccioni et al., 2015; Quirico et al., 2016). However, a quantitative determination of the physical properties (grain size, porosity) and composition of the surface regolith is still missing. As comets are considered the most primitive objects in the Solar System (Weidenschilling, 2004; Mumma & Charnley, 2011; Davidsson et al., 2016), assessing these properties is of paramount importance to constrain the physical conditions of the early solar nebula. The characterization of the regolith is also crucial to investigate the physical processes active on the surface, such as sublimation of volatiles, dust deposition and transport, and thermal stresses. In this perspective, the comparison of nucleus multi- and hyper-spectral data with spectra derived from radiative transfer models and spectra measured in the laboratory is fundamental for an accurate assessment of the properties of the material. While laboratory reflectance spectra for samples with known composition provide a direct input for comparison with remote sensing observations for a limited set of available materials and mixtures, spectral inversion based on radiative transfer models (Hapke, 2012; Shkuratov et al., 1999) allows us exploring a wide range of combinations simultaneously. However, the latter method relies on the capability of the theoretical approach to account for and correctly describe the physical properties of the investigated materials.

Based on this rationale the aim of the research project we propose is twofold:

- Investigation of 67P/Churyumov-Gerasimenko surface composition from the convergence of results from dedicated laboratory measurements of cometary analogues (by means of deriving the optical constants/reflectances/absorbances/ of minerals, organics and ices) and radiative transfer models (analytical and numerical), applied to Rosetta spectrophotometric observations of the nucleus.
- Test and improvement of widely used radiative transfer models needed for spectral inversion (Hapke, 2012; Shkuratov et al., 1999), by comparing their output with laboratory spectrophotometric measurements of materials with known compositions made available for 67P/Churyumov-Gerasimenko spectral unmixing. In this context, the main objectives of the study will concern the capability of the models to constrain *composition* (endmember abundances and mixing modalities) and *physical properties* (material grain size distribution and porosity).

Such an effort will be addressed within an international team hosted by ISSI, composed of experts on radiative transfer models in particulate media, visible-infrared laboratory spectrophotometry and remote sensing imaging spectroscopy. The presence within the team of members directly involved in the Rosetta mission, and/or having direct access to spectroscopy laboratories and measurements, represents an important asset for the maximization of the scientific outcome of the collaboration.

2 Scientific Rationale and Goals

The Rosetta mission escorted the Jupiter family comet 67P/Churyumov-Gerasimenko (hereafter 67P/C-G) from 6 August 2014 to 30 September 2016, providing unprecedented information about a cometary nucleus composition and evolution along its orbit around the Sun. Recent results from Davidsson et al. (2016), supported by Rosetta data, indicate that comets are "primordial rubble piles" that did not undergo a significant collisional processing. Conversely, alternative studies by Jutzi et al. (2017); Jutzi & Benz (2017) suggest that comets may have experienced several low-energy collisions. Such sub-catastrophic impacts, although producing a re-shaping of the nuclei, should not have led to major heating and compaction, preserving the pristine composition and porosity of comets (Jutzi & Benz, 2017). These results imply that the composition of cometary nuclei is representative of the composition of the outer regions of the early solar nebula, where volatiles (H₂O, CO₂, CO and minor species) and refractory materials (organics and minerals) condensed into solid grains that, along with presolar materials, grew by accretion or gravitational instability to form comets (Ehrenfreund et al., 2004; Johansen et al., 2007). In this perspective, the surface rejuvenation processes driven by cometary activity contribute to preserve the pristine composition of the refractory component of the nucleus, limiting the modifications induced by space weathering (Quirico et al., 2016). The surface composition of cometary nuclei is then a direct proxy to constrain the physical conditions of the early phases of the Solar System.

The extensive observation campaign performed by the two imaging experiments VIRTIS - Visible and Infrared Thermal Imaging Spectrometer, operating in the 0.2-5.2 μm range (Coradini et al., 2007) - and OSIRIS - Optical, Spectroscopic, and Infrared Remote Imaging System, 0.2-1 μm (Keller et al., 2007) - onboard Rosetta provided fundamental clues on

the spectrophotometric properties of 67P/C-G. Apart from few areas where the presence of water and carbon dioxide ices has been detected (De Sanctis et al., 2015; Filacchione et al., 2016a,b), pre-perihelion observations of the two instruments revealed a dark de-hydrated surface - geometric albedo of 0.06 at 0.55 μm (Ciarniello et al., 2015; Fornasier et al., 2015) - characterized by a reddish spectrum across the VIS-IR wavelength range (0.4-3.6 μm) and a broad absorption feature centered at 3.2 μm (Capaccioni et al., 2015; Quirico et al., 2016) (Fig. 1a,1b). In situ measurements obtained by CIVA - Comet Infrared and Visible Analyser, Bibring et al. (2007) - confirmed the low albedo of the surface down to the centimeter scale, though some heterogeneity could be observed (Bibring et al. 2015).

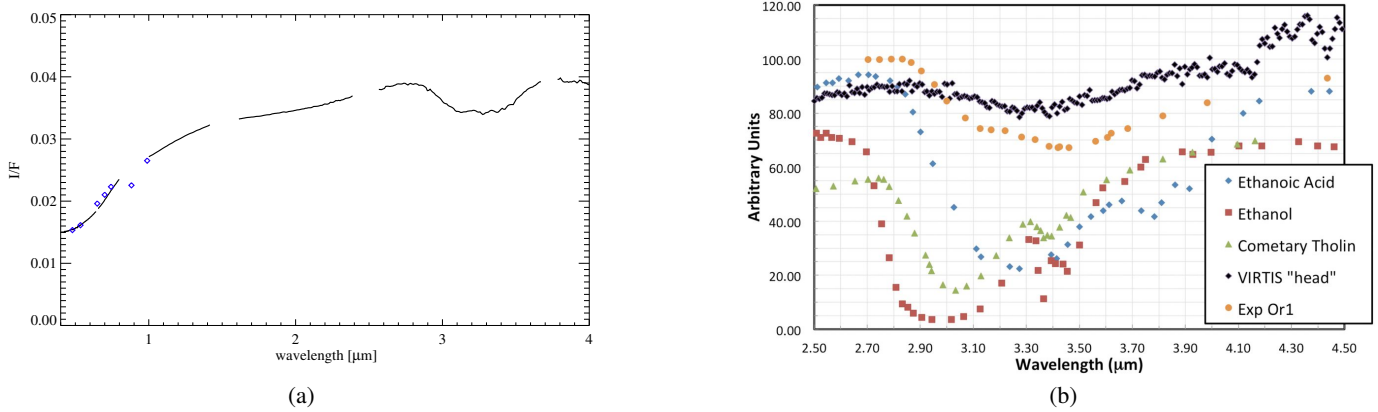


Figure 1: a) Average radiance factor (I/F) of 67P/C-G referred to the standard observation geometry (incidence angle = 30° , emission angle = 0° and phase angle = 30°) as derived from VIRTIS (Ciarniello et al., 2015, black curve) and OSIRIS observations (Fornasier et al., 2015, blue symbols). Missing parts in the VIRTIS curve correspond to instrumental order sorting filters. OSIRIS data are scaled to match VIRTIS observations at 0.55 μm . b) VIRTIS spectrum of the small lobe ("head") of comet 67P/C-G in the spectral range 2.5 to 4.5 μm , compared to spectra of different organic compounds: ethanol and ethanoic (acetic) acid spectra (from AIST-SDBS spectral database, http://sdb.sdb.aist.go.jp/sdb/cgi-bin/cre_index.cgi), a cometary tholin (McDonald et al., 1996), and a refractory residue (Exp Or1) obtained after UV irradiation of a mixture of $\text{H}_2\text{O}:\text{CH}_3\text{OH}:\text{NH}_3:\text{CO}:\text{CO}_2$ (Muñoz Caro & Schutte, 2003). Figure from Capaccioni et al. (2015).

These spectrophotometric properties have been interpreted in terms of composition by Capaccioni et al. (2015) and Quirico et al. (2016) as a mixture of refractory polyaromatic and aliphatic organic materials, fine-grained opaque materials (Fe-sulfides, Fe-Ni alloys) and a semivolatile component (ammonium-bearing species and carboxylic acids). Complementary compositional information of the surface has been determined from in situ measurements of the coma. While the GIADA (Colangeli et al., 2007) experiment has inferred different grain compositions (ices, silicates, hydrocarbons and Fe-sulfides) (Fulle et al., 2016), ROSINA (Balsiger et al., 2007) has provided an inventory of many volatile species (Le Roy et al., 2015), including prebiotic glycine and phosphorus (Altwegg et al., 2016). However, a precise identification of these endmembers and a quantitative characterization of their relative abundances as well as the physical properties of the regolith covering the surface of 67P/C-G (grain size and porosity), from spectrophotometric data analysis, are still open points.

In order to address these questions we propose an ISSI international team, that will investigate the detailed composition of 67P/C-G, taking advantage of the collaboration of experts on radiative transfer modeling in particulate media, laboratory spectroscopy and remote sensing imaging spectroscopy. The recent conclusion of the Rosetta mission (30 September 2016) and the intense ongoing work within the scientific community for the interpretation of the large amount of data produced, provide an optimal context for pursuing this study.

The synergy of radiative transfer modeling and laboratory spectroscopy applied to remote sensing data analysis maximizes the number of explored compositional scenarios providing a more thorough characterization of the 67P/C-G surface. In particular, Rosetta hyper-spectral (VIRTIS) and multi-spectral (OSIRIS) data can be directly compared with laboratory spectral reflectance measurements of cometary analogue materials and their mixtures. At the same time, these measurements provide the input for radiative transfer models - both analytical (Hapke, 2012; Shkuratov et al., 1999) and Monte Carlo ray-tracing (Pilorget et al., 2013; Ciarniello et al., 2014) - that allow us to simulate reflectance spectra of mixtures for any combination of physical and compositional properties (endmembers abundances, grain sizes, porosity). In addition, radiative transfer simulations are able to predict the spectral behavior of a given material, helping to select the compounds to be investigated in laboratory.

The interplay among remote sensing measurements, radiative transfer simulations and laboratory measurements, as shown in Fig. 2, is essential for surface composition interpretation. In fact, laboratory measurements of

analogue materials with known physical properties will be crucial to improve our understanding of the physical processes acting within the regolith layer and treated by the radiative transfer models. **The accurate description of those physical processes will be one of the goals of this ISSI International Team.**

This approach, however, partly relies on the capability of the models to correctly describe the medium and the light scattering process, and on their sensitivity to the physical properties of the investigated materials, which is yet a matter of investigation (Shkuratov & Grynko, 2005; Denevi et al., 2008; Lucey & Noble, 2008; Carli et al., 2014; Ciarniello et al., 2014). For example, one important point in this context is that many widely used spectral simulation models assume that the scattering process can be described under the geometric optics approximation; that means these approaches are only valid for particle sizes much larger than the wavelength. However the very low reflectance of 67P/C-G likely requires the presence of sub-micron-sized highly absorbing materials such as Fe-sulfides and Fe-Ni alloys (Capaccioni et al., 2015; Quirico et al., 2016). Moreover, small particles (from sub-micron to few-micron sizes) can develop diffraction and scattering effects, e.g. Rayleigh scattering (Clark et al., 2012), which are neglected for materials made of large grains in close contact (Hapke et al., 2009) and are not generally considered in many of the radiative transfer modeling applications.

These issues can be naturally investigated by comparing the theoretical simulations with laboratory measurements made already available for the unmixing of 67P/C-G spectral data, where the physical properties of the investigated samples are known. For these reasons, **we include as an aim of this ISSI international team the testing and possible improvement of widely used models for radiative transfer in regoliths**, focusing in particular on Hapke's (Hapke, 2012) and Shkuratov's theories (Shkuratov et al., 1999). We stress that, apart from the specific application to the case of 67P/C-G's surface, **these aspects are of general interest for the interpretation of remote sensing reflectance measurements in planetary science. The results and the methodology of this study will be shared among the community and should significantly contribute to a better characterization of any planetary surface.**

3 Planned program

Below we synthetically describe the program to achieve the aims of this project, that can be divided in two main topics: **a) Retrieval of 67P/C-G surface composition** and **b) Test and improvement of radiative transfer models in particulate media.**

3.1 Retrieval of 67P/C-G surface composition

- Retrieval of typical 67P/C-G surface VIS-IR reflectance spectra over specific regions of interest across the surface. Preprocessing of the data (calibration, photometric-thermal correction) for comparison with theoretical models.
- Collection of existing spectral reflectance measurements of cometary analogue materials already available from team members and public spectral libraries.
- Measurements of spectral reflectance and optical constants of single endmembers of cometary analogue materials such as relevant minerals, refractory and semi-volatile organic compounds and H₂O and CO₂ ices with various grain sizes (from sub-micron to hundred-of-microns particles) and porosities.
- Measurements of spectral reflectance of mixtures of cometary analogue materials with controlled grain size distribution, endmembers abundances and porosities.
- Spectral simulation of mixtures by means of radiative transfer models. (Hapke, 2012; Shkuratov et al., 1999): endmembers optical properties will be computed from available optical constants and/or determined from laboratory measurements (Carli et al., 2014; Hiroi & Pieters, 1994; Lucey, 1998).
- Best-fitting of 67P/C-G nucleus spectra with those of laboratory mixtures and/or from radiative transfer simulations.

3.2 Test and improvement of radiative transfer models in particulate media

- Compare the measured spectral reflectance of single endmembers and mixtures with known composition, grain size distribution and porosity (Sec. 3.1), with simulated spectral reflectance. Validate models results by checking

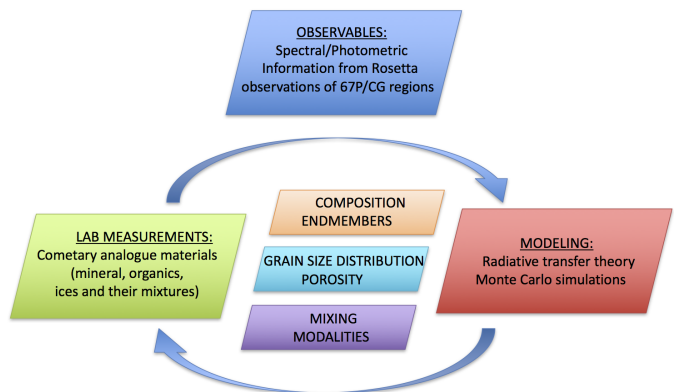


Figure 2: Scheme of the proposal workflow.

their capability to infer grain size, endmember abundances, optical properties and porosities.

- Model the contribution from small particles (sub-micron and micron-sized grains) in materials with multidisperse size distributions. Compare simulated reflectances with laboratory measurements of samples with known size distribution.

3.3 Laboratories

Laboratory measurements will be performed at the following facilities: 1) PEL (IR Spectroscopy/Planetary Emissivity Laboratory) at the DLR Institute of Planetary Research, Berlin Germany; 2) Laboratory for Outflow Studies of Sublimating icy materials (LOSSy) of the Bern University, Switzerland; 3) Laboratory for Cold Surfaces Spectroscopy, Institut de Planétologie et d'Astrophysique de Grenoble, France.

4 ISSI added value

ISSI logistic and financial support is considered a very important asset for the project. It enables the team members to interact in effective face-to-face meetings in an easily accessible venue. In particular, this speeds up the sharing of knowledge and expertise among groups from different countries, which is a fundamental aspect, given the multidisciplinary nature of the proposed investigation. Along with this, ISSI sponsorship is considered an added value for the impact of the present investigation within the scientific community.

5 Schedule

We propose the team to join for three meetings at ISSI Bern, each three days long, approximately every six months, for a total of 90 man-days (18 man-weeks). The date of the first meeting will be scheduled between July and December 2017. The draft agendas of the meetings are reported below.

Pre-meeting activities. 1) Selection of young scientists to be associated to the team. 2) Preparation of a spectral library of cometary analogue materials. 3) Refinement of the roles of the team members.

First meeting

- Review talks: state of art of radiative transfer models in regoliths; state of art of 67P/C-G spectral unmixing from laboratory measurements and radiative transfer modeling.
- Description of the laboratory facilities available to the team members for reflectance spectroscopy measurements.
- Planning of reflectance spectroscopy measurements: focus on materials composition (endmembers and mixtures), grain size distribution and porosity.
- Discuss strategy for testing radiative transfer modeling using available and planned spectral reflectance measurements.
- 67P/C-G data selection for specific regions of interest to be investigated.
- Discuss strategy for 67P/C-G spectral modeling.

Between first and second meeting: distribution of measured reflectance spectra to the team as input for spectral modeling activities; distribution of modeled spectra.

Second meeting

- Discussion of the results from laboratory measurements.
- Discussion of the results from spectral modeling tests: limits of the models and possible improvements.
- Discussion of the results from spectral modeling of 67P/C-G surface.
- Identification of 67P/C-G best-fit surface composition from spectral modeling and planning for reproduction in laboratory.
- Discussion of peer-review papers from the team and planning of future work.

Third meeting

- Wrap up of simulations and laboratory measurements: what we learned about 67P/C-G surface composition.
- Wrap up of simulations and laboratory measurements: spectral modeling capability to constrain physical properties of the investigated material and theoretical improvement of the current models.
- Preparation of databases containing produced spectral data (measured and modeled).

- Discussion of peer-review papers from the team.

For each meeting we require standard ISSI support: meeting room, internet access, teleconference facilities, projector and white board. Standard financial support (per diem for living expenses of the core team and team coordinator travel support) are also required.

In the time lapse between the meetings, team members will work individually on the assigned tasks. Progress teleconferences will be organized to update the team on the members' activity.

6 Output from the ISSI team

An overview paper about the main achievements of the ISSI team will be produced. Along with this, team members will publish independent papers in peer-reviewed literature on specific topics. We will make every effort to make spectral databases and codes developed within this project publicly available. A final report about the activity of the team will be provided to ISSI.

7 Team

The team is composed of experts on radiative transfer modeling in particulate media, laboratory spectroscopy and remote sensing spectral imaging. This ensures the coverage of the areas of expertise needed for the proposed investigation. The majority of the team members are directly involved in experiments onboard the Rosetta mission, providing an added value in terms of collection and analysis of 67P/C-G remote sensing data. Direct access to the laboratory facilities described in Sec. 3.3 for some of the team members ensures the feasibility of reflectance spectroscopy measurements.

Core Team

Pierre Beck	IPAG, Grenoble	France
Mauro Ciarniello (team leader)	Istituto di Astrofisica e Planetologia Spaziali-INAF	Italy
Gianrico Filacchione	Istituto di Astrofisica e Planetologia Spaziali-INAF	Italy
Lyuba Moroz	Institute of Earth and Environmental Science, University of Potsdam	Germany
Cedric Pilorget	IAS - Institut d'Astrophysique Spatiale	France
Antoine Pommerol	Physics Institute, University of Bern	Switzerland
Eric Quirico	IPAG, Grenoble	France
Andrea Raponi	Istituto di Astrofisica e Planetologia Spaziali-INAF	Italy
Stefan Schröder	Deutsches Zentrum für Luft- und Raumfahrt (DLR)	Germany
Katrin Stephan	Deutsches Zentrum für Luft- und Raumfahrt (DLR)	Germany

External collaborator

David Kappel	Deutsches Zentrum für Luft- und Raumfahrt (DLR)	Germany
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NAME, First Name: Ciarniello, Mauro

Affiliation: INAF-IAPS, Istituto di Astrofisica e Planetologia Spaziali, via del Fosso del Cavaliere, 100, 00133, Rome, Italy.

Role in the project: team leader. Coordination of team activities; analysis of Rosetta data relevant to the proposal, spectrophotometric modelling of regoliths and interpretation of the results.

Current position: research associate on the subject “Investigation of the composition and of photometric properties of the surfaces of Solar System bodies, focusing on water ice rich surfaces, from spectrophotometric data in the visible and infrared range”, at INAF-IAPS, Rome, Italy.

Former Position(s):

1 March 2013 to 1 November 2015: Research fellow on the subject “Theoretical models of the spectrophotometric properties of solid surfaces of Solar System bodies, focusing on the Saturn’s system”, at INAF-IAPS, Rome, Italy.

1 August 2009 to 28 February 2013: Research fellow on the subject “Theoretical models of the spectrophotometric properties of the surfaces of atmosphereless bodies in the Solar System”, at INAF-IAPS, Rome, Italy.

Education:

- 2012: PhD in Astronomy from “Università degli Studi di Roma La Sapienza”, Italy. Thesis: “Theoretical models of the spectrophotometric properties of atmosphereless bodies surfaces in the Solar System”.
- 2008: Master’s degree in Astronomy and Astrophysics from “Università degli Studi di Roma La Sapienza”. Thesis: Spectrophotometric analysis of the opposition effect of Saturn’s rings: observations from Vims-Cassini. Score:110/110 cum laude.
- Specialization schools: Spice training class (2011); International School of Astrophysics “F. Lucchin”, Vulcano (ME), Italy.

Services in National and/or International Committees (last ones): VIRTIS/Rosetta team member; VIR/Dawn team member; MAJIS/Juice associated scientist; SOC member for the Rosetta Science Working Team #45, 6-8, June 2016, Open University, Milton Keynes; member of the hiring committee (2016-05-AR grant, INAF-IAPS).

Honors: Dawn Group Achievement Award.

Selected Publications: author of 28 publications in peer-reviewed journals.

1. M. Ciarniello, et al. *Hapke modeling of Rhea surface properties through Cassini-VIMS spectra*. *Icarus*, 214:541–555, 2011.
2. C. Carli et al. *Spectral variability of plagioclase-mafic mixtures (2): Investigation of the optical constant and retrieved mineral abundance dependence on particle size distribution*. *Icarus*, 235:207–219, June 2014.

3. M. Ciarniello, et al. *A test of Hapke's model by means of Monte Carlo ray-tracing*. *Icarus*, 237:293–305, July 2014.
4. F. Capaccioni, et al. *The organic-rich surface of comet 67P/Churyumov-Gerasimenko as seen by VIRTIS/Rosetta*. *Science*, 347:628, January 2015.
5. M. Ciarniello, et al. *Photometric properties of comet 67P/Churyumov-Gerasimenko from VIRTIS-M onboard Rosetta*. *Astronomy and Astrophysics*, 583, 2015.
6. M. C. De Sanctis et al. *The diurnal cycle of water ice on comet 67P/Churyumov-Gerasimenko*. *Nature*, 525:500–503, September 2015.
7. G. Filacchione, et al. *Exposed water ice on the nucleus of comet 67P/Churyumov-Gerasimenko*. *Nature*, 529:368–372, January 2016.
8. G. Filacchione, et al. *The global surface composition of 67P/CG nucleus by Rosetta/VIRTIS. (I) Prelanding mission phase*. *Icarus*, 274:334–349, August 2016.
9. E. Quirico, et al. *Refractory and semi-volatile organics at the surface of comet 67P/Churyumov-Gerasimenko: Insights from the VIRTIS/Rosetta imaging spectrometer*. *Icarus*, 272:32–47, July 2016
10. M. C. De Sanctis, et al. *Bright carbonate deposits as evidence of aqueous alteration on (1) Ceres*. *Nature*, 536(7614):54–57, 08 2016.
11. Filacchione, G. et al., *Seasonal exposure of carbon dioxide ice on the nucleus of comet 67P/Churyumov-Gerasimenko*, *Science*, 354, 1563-1566, 2016.
12. M. Ciarniello, et al. *The global surface composition of 67P/Churyumov–Gerasimenko nucleus by Rosetta/VIRTIS. II) Diurnal and seasonal variability*. *Mon. Not. R. Astron. Soc.* 2016; 462 (Suppl_1): S443-S458. doi: 10.1093/mnras/stw3177.
13. A. Raponi, et al. *The temporal evolution of exposed water ice-rich areas on the surface of 67P/Churyumov–Gerasimenko: spectral analysis*. *Mon. Not. R. Astron. Soc.* 2016; 462 (Suppl_1): S476-S490. doi: 10.1093/mnras/stw3281.
14. M. Ciarniello, et al. *Spectrophotometric properties of dwarf planet Ceres from the VIR spectrometer on board the Dawn mission*. *A&A* 598, A130 (2017).
15. De Sanctis, et al. *Localized aliphatic organic material on the surface of Ceres*. *Science*, Volume 355, Issue 6326, pp. 719-722.

NAME, First Name: BECK Pierre

Affiliation: Institut de Planetologie de Grenoble

Role in the project: I will provide my expertise on the composition of extra-terrestrial materials (meteorites and IDPs) and will be involved in laboratory measurements using a suite of unique set-up at IPAG.

Current position: Maître de Conférence

Former Position(s): Postdoctoral fellow, Carnegie Institution of Washington

Education: Master Earth Sciences, Ecole Normale Supérieure de Lyon, 2002, PhD Earth and Planetary Sciences, Ecole Normale Supérieure de Lyon, 2005.

Services in National and/or International Committees:

- 2015 - Scientific Advisory Board, Labex ESEP, Observatoire de Paris (4.1 M€)
- 2015 Review Board, Laboratoire de Planétologie et de Géodynamique de Nantes
- 2014 Review panel member, NASA « Emerging Worlds »
- 2010-2016 Member of the hiring committee for the positions MCF1336 (Grenoble), MCF0237 (Grenoble), MCF0357(Paris/Orsay), MCF 0351 (Paris/IPGP), MCF (Museum, Paris), MCF0313 (LPG Nantes)
- 2015- Associate Editor, *Geochimica et Cosmochimica Acta***
- 2017- Editorial Board, *Earth & Planetary Science Letters***

Honors:

2011 and 2015: Prime d'Excellence Scientifique, Université Joseph Fourier.

2014-2017: Titulaire de la Chaire Université Grenoble Alpes

2015 Alfred O. Nier Prize of the *Meteoritical Society*

2015 Bronze medal, CNRS, Earth Sciences

2016 Institut Universitaire de France *Junior member, 2016-2021.*

Selected Publications:

- P. Vernazza and **P. Beck** (2017) Composition of solar system small bodies. In *Planetesimals*, Cambridge University
- A Garenne*, **P. Beck**, G. Montes-Hernandez, O. Brissaud, B. Schmitt, E. Quirico, L. Bonal, K.T. Howard (2016). Bidirectional reflectance study on carbonaceous chondrites : implications for water quantification and primary composition. *Icarus* 264, 172-183.
- P. Beck**, B. Schmitt, E.A. Cloutis and P. Vernazza (2015). Low-T reflectance spectra of brucite and the primitive surface of 1-Ceres? *Icarus*, 257, 471-476.
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- P. Beck**, A. Pommerol, N. Thomas, B. Schmitt and F. Moynier (2012). Photometry of meteorites. *Icarus* 218, 364-377

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Affiliation: *INAF-IAPS, Istituto di Astrofisica e Planetologia Spaziali, via del fosso del cavaliere, 100, 00133, Rome, IT*

Role in the project: *Analysis of Rosetta data relevant to the proposal, spectral modeling and interpretation of the results*

Current position: *Staff Researcher*

Former Position(s): *INAF-IAPS Associate Researcher*

Education: *(2006) PhD in Aerospace Engineering, Naples University "Federico II"; (2001) degree in Physics, Rome University "La Sapienza"*

Services in National and/or International Committees (last ones): *deputy PI of VIRTIS/Rosetta; team member of VIMS/Cassini and Cassini mission participating scientist; co-I of JIRAM/Juno and SIMBIO-SYS/BepiColombo; instrument scientist of MAJIS/Juice experiments.*

Honors:

- (2005) ESA award, Venus Express mission launch.*
- (2008) NASA Group Achievement Award to Dawn payload team.*
- (2009) NASA Group Achievement Award to Cassini-VIMS team.*
- (2012) NASA Certificate of Appreciation to JIRAM team.*
- (2012) NASA Group Achievement Award to JIRAM instrument team.*
- (2014) NASA Group Achievement Award to Juno Earth Flyby Operations team.*
- (2015) ESA award, Venus Express end of science mission.*

Selected Publications:

- 1. Filacchione, G. et al., Seasonal exposure of carbon dioxide ice on the nucleus of comet 67P/Churyumov-Gerasimenko, Science, 354, 1563-1566, 2016.*
- 2. Filacchione, G. et al., Exposed water ice on the nucleus of comet 67P/Churyumov-Gerasimenko, Nature, 529, 368-372, 2016.*
- 3. Filacchione, G. et al., The global surface composition of 67P/CG nucleus by Rosetta/VIRTIS. (I) Prelanding mission phase, Icarus, 274, 334-349.*
- 4. De Sanctis, M. C. et al., The diurnal cycle of water ice on comet 67P/Churyumov-Gerasimenko, Nature, 525, 500-503, 2015.*
- 5. Ciarniello, M. et al. Photometric properties of comet 67P/Churyumov-Gerasimenko from VIRTIS-M onboard Rosetta, A&A, 583, A31, 2015.*
- 6. Ciarniello, M. et al., The global surface composition of 67P/Churyumov-Gerasimenko nucleus by Rosetta/VIRTIS. II) Diurnal and seasonal variability, MNRAS, doi: 10.1093/mnras/stw3177, 2016*
- 7. Barucci, et al., Detection of exposed H₂O ice on the nucleus of comet 67P/Churyumov-Gerasimenko as observed by Rosetta OSIRIS and VIRTIS instruments, A&A, 595, id.A102, 13 pp., 2016.*

MEMBERS TEAM CV

NAME, First Name: MOROZ, Lyuba

Affiliation: (1) Institute of Earth and Environmental Sciences, University of Potsdam, Potsdam, Germany; (2) Institute of Planetary Research, German Aerospace Center (DLR), Berlin, Germany.

Role in the project: Spectral reflectance measurements of well-characterized cometary analogue materials and their mixtures as an input for theoretical models; discussion of modeling strategies/results.

Current position: Academic employee (“akademische Mitarbeiterin”)

Former Position(s): Since 1996 until now: Guest Scientist, Research Fellow, German Aerospace Center, Berlin, Germany. 2004-2013: Research Fellow, Institute of Planetology, University of Münster, Münster, Germany. 1999-2001; Research Fellow, Free University, Berlin, Germany. 1988-1998; Ph.D. Student, then Junior Scientist, Vernadsky Institute, Russian Academy of Sciences (RAS), Moscow, Russia

Education: 1996: Ph.D. in Geology and Mineralogy, Vernadsky Institute, Moscow. 1988: Diploma (M.Sc.) in Geology/Geochemistry, M.V. Lomonosov Moscow State University, Moscow, USSR

Honors: 2015-2018: DFG Research Grant (PI) MO 3007/1-1; 2002: Asteroid 6203 *Lyubamoroz*; 1994-1996: Russian President’s State Fellowship for Talented Young Scientists of Russia.

Selected Publications:

Moroz, L., Arnold, G., Korochantsev, A., Wäsch, R. 1998. Natural solid bitumens as possible analogs for cometary and asteroid organics: 1. Reflectance spectroscopy of pure bitumens. *Icarus*, 134, 253-268.

Moroz, L.V., Arnold, G., 1999. Influence of spectrally neutral components on relative band contrasts in intimate mixtures: Implication for remote sensing. 1. Nonlinear mixing modeling. *J. Geophys. Res.* 104, E6, 14,109-14,122.

Moroz, L.V., Starukhina, L.V., Rout, S.S., et al., 2014. Space weathering of silicate regoliths with various FeO contents: New insights from laser irradiation experiments and theoretical spectral simulations. *Icarus*, 235, 187-206.

Quirico, E., Moroz, L.V., Schmitt, B. 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.

PILORGET Cedric

Affiliation: Institut d'Astrophysique Spatiale (IAS, France)

Role in the project: Core team member with emphasis on radiative transfer methodology and lab measurements analysis.

Current position: Assistant Professor at the Université Paris-Sud (IAS, France)

Former Position(s):

2013-2014: Postdoctoral fellow at Caltech (USA)

2014-2016: Postdoctoral fellow at IAS (France)

Education: PhD in Astrophysics from the Université Paris-Sud (2012)

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

Honors:

- 2009-2012: 3-year grant from the French Ministry of Research
- 2014-2016: 2-year postdoctoral fellowship for the French Space Agency (CNES)

Selected Publications:

Pilorget C., Fernando J., Ehlmann B.L., Schmidt F., Wavelength dependence of scattering properties in the VIS-NIR and links with grain-scale physical and compositional properties, *Icarus*, 2016 , 267, 296-314.
DOI:10.1016/j.icarus.2015.12.029

Bibring J.-P., Langevin Y., Carter J., Eng P., Gondet B., Jorda L., Le Mouélic S., Mottola S., **Pilorget C.**, Poulet F., Vincendon M., 67P/Churyumov-Gerasimenko surface properties as derived from CIVA panoramic images, *Science*, 2015, Volume 349, Issue 6247. DOI: 10.1126/science.aab0671

Fernando J., Schmidt F., **Pilorget C.**, Pinet P., Ceamanos X., Douté S., Daydou Y., Costard F., Characterization and mapping of surface physical properties of Mars from CRISM multi-angular data : Application to Gusev Crater and Meridiani Planum, *Icarus*, 2015, Volume 253, 271-295. DOI: 10.1016/j.icarus.2015.03.012

Pilorget C., Fernando J., Ehlmann B.L., Douté S., Photometry of particulate mixtures: what controls the phase curve?, *Icarus*, 2015, Volume 250, 188-203
DOI: 10.1016/j.icarus.2014.11.036

Pilorget C., Vincendon M., Poulet F., A radiative transfer model to simulate light scattering in a compact granular medium using a Monte-Carlo approach: validation and first applications, *Journal of Geophysical Research: Planets*, 2013, Volume 118, 1-14. DOI: 10.1002/2013JE004465

NAME, First Name: POMMEROL, Antoine

Affiliation: Physikalisches Institut, Universität Bern.

Role in the project: I will provide to the project a number of laboratory measurements of icy analogues and the expertise to analyze them and compare to with remote-sensing data from the comet's nucleus.

Current position: Postdoc

Former Position(s):

Education: Bachelor and Master degree in Earth and Planetary Sciences, Ecole Normale Supérieure de Lyon, France. PhD Thesis, Université de Grenoble, France.

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

Honors:

Selected Publications:

Poch, O., **A. Pommerol**, B. Jost, N. Carrasco, C. Szopa, and N. Thomas, Sublimation of water ice mixed with silicates and tholins: evolution of surface texture and reflectance spectra, with implications for comets, *Icarus*, 267, p. 154-173, doi: 10.1016/j.icarus.2015.12.017, 2016.

Jost, B., **A. Pommerol**, O. Poch, B. Gundlach, M. Leboeuf, M. Dadras, J. Blum, and N. Thomas, Experimental characterization of the opposition surge in fine-grained water-ice and high albedo analogs, *Icarus*, 264, p. 109-131, doi: 10.1016/j.icarus.2015.09.020, 2016.

Yoldi, Z., **A. Pommerol**, B. Jost, O. Poch, J. Gouman, and N. Thomas, VIS-NIR reflectance of water ice/regolith analogue mixtures and implications for the detectability of ice mixed within planetary regoliths, *Geophys. Res. Lett.*, 42, Issue 15, p. 6205-6212, doi: 10.1002/2015GL064780, 2015.

Pommerol, A., et al., OSIRIS observations of meter-size exposures of H₂O ice at the surface of 67P/Churyumov-Gerasimenko and interpretation using laboratory experiments, *A&A*, 583, id.A25, doi: 10.1051/0004-6361/201525977, 2015.

Pommerol, A., B. Jost, O. Poch, M. R. El-Maarry, B. Vuitel, and N. Thomas, The SCITEAS experiment: optical characterizations of sublimating icy planetary analogues, *PSS*, 109-110, p. 106-122, doi: 10.1016/j.pss.2015.02.004, 2015.

Pommerol, A., N. Thomas, M. Affolter, G. Portyankina, K. Seiferlin, and K.-M. Aye, Photometry and bulk physical properties of Solar System surfaces icy analogs: the Planetary Ice Laboratory at University of Bern, *Planet. Space Sci.*, 59, p. 1601-1612, doi: 10.1016/j.pss.2011.07.009, 2011.

QUIRICO, Eric

Affiliation: University Grenoble Alpes - Institut de Planétologie et Astrophysique de Grenoble (IPAG UMR 5274)

Role in the project: Laboratory experiments: optical measurements, analogs production, cosmomaterials analysis. VIRTIS/Rosetta spectral data analysis.

Current position: Professor at Université Grenoble Alpe, IPAG

Former Position(s): Associate Professor at Université Paris-Sud, IAS (1997-2001). 2002-... : University Grenoble Alpes, IPAG - 1997-01 : University Paris XI, Institut d'Astrophysique Spatiale. 1996-97 : Laboratoire de Planétologie et Géodynamique, University of Nantes - France

Education: 1995: Ph. D. Thesis : A spectroscopic study of the surfaces of Triton and Pluto. (University Grenoble 1). 1991 : Master Degree in Material Sciences (Université Grenoble 1). 1990: Ecole Nationale Supérieure de Physique de Marseille (Ecole Centrale Marseille)

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

2014 : Associate Editor for *Geochimica Cosmochimica Acta*. 2014-...: Member of the Working Group "Exo- biology" - CNES (Centre National d'Etudes Spatiales). 2012-...: Member of the Scientific Council of Labex LIO (University of Lyon). 2011-15: Elected member of the National Council of Universities (Astronomy and Planetary Sciences department). 2010-14: Deputy Director of Observatoire des Sciences de l'Univers de Grenoble (OSUG).

Selected Publications: 82 publications in peer-reviewed international journals; 4 book chapters; 11 Invited conferences, 12 seminars. ISI-WOK : 2385 citations ; h-index=29

[1] Quirico E., L. V. Moroz, B. Schmitt, G. Arnold, M. Faure, P. Beck, L. Bonal, M. Ciarniello, A. Zinzi, E. Palomba, and the Rosetta VIRTIS team. Refractory and semi-volatiles organics at the surface of comet 67P/Churyumov-Gerasimenko : insights from the VIRTIS/ROSETTA imaging spectrometer. *Icarus* 272, 32-47.

[2] Quirico E., F-R Orthous-Daunay, P. Beck, L. Bonal, R. Brunetto, E. Dartois, T. Pino, G. Montagnac, J-N Rouzaud, C. Engrand and J. Duprat Origin of insoluble organic matter in type 1 and 2 chondrites : new clues, new questions. *Geochimica Cosmochimica Acta*, 136, 80-99

[3] Quirico, E., G. Montagnac, J-N Rouzaud, L. Bonal, M. Bourot-Denise, S. Duber, B. Reynard 2009. Precursor and metamorphic conditions effects on Raman spectra of poorly ordered carbonaceous matter in chondrites and coals. *Earth and Planetary Sciences Letters* 287, 185-193

[4] Quirico, E., S. Douté, B. Schmitt, C. de Bergh, D. P. Cruikshank, T. Owen, T. Roush 1999. Composition, physical state and distribution of ices on the surface of Triton. *Icarus*. 139,159-178

NAME, First Name: Raponi, Andrea

Affiliation: IAPS – INAF via del Fosso del Cavaliere 100, Rome 00133, Italy

Role in the project: radiative transfer modeling of regoliths; spectral analysis from imaging spectrometer data; in-flight calibration and performance analysis of imaging spectrometers.

Current position: Fellow Researcher

Former Position(s): PhD student at IAPS-INAF (Italy)

Education:

- PhD in Astronomy, University “Tor Vergata”, Rome, 2014. Thesis title: Spectrophotometric analysis of Cometary Nuclei from in situ observations
- Master Degree in Astronomy and Astrophysics, University “La Sapienza”, Rome, 2011. Score:110/110 cum laude.

Services in National and/or International Committees (last ones): VIRTIS/Rosetta Team member; VIR/Dawn Team member

Honors: NASA Group Achievement Award to Dawn VIR Team; Honored invited speakers for the Dawn Special Session at AOGS 2017.

Selected Publications:

- A. Raponi et al., The temporal evolution of exposed water ice-rich areas on the surface of 67P/Churyumov–Gerasimenko: spectral analysis, *MNRAS* 462, 2016
- M.C. De Sanctis et al., Localized aliphatic organic material on the surface of Ceres. *Science* 355, 2017
- G. Filacchione et al., Seasonal exposure of carbon dioxide ice on the nucleus of comet 67P/Churyumov-Gerasimenko. *Science* 354, 2016
- A. Barucci et al., Detection of exposed H₂O ice on the nucleus of comet 67P/Churyumov-Gerasimenko. as observed by Rosetta OSIRIS and VIRTIS instruments. *A&A* 595, 2016
- M. C. De Sanctis et al., Bright carbonate deposits as evidence of aqueous alteration on (1) Ceres, *Nature* 536, 2016.
- G. Filacchione et al., The global surface composition of 67P/CG nucleus by Rosetta/VIRTIS. (I) Prelanding mission phase. *Icarus*, 274, 2016.
- G. Filacchione et al., Exposed water ice on the nucleus of comet 67P/Churyumov-Gerasimenko, *Nature* 529, 2016.
- M. Ciarniello et al., Photometric properties of comet 67P/Churyumov Gerasimenko from VIRTIS-M onboard Rosetta. *A&A*, 583, 2015.
- M.C. De Sanctis et al., The diurnal cycle of water ice on comet 67P/Churyumov-Gerasimenko, *Nature*, 525, 2015.
- F. Capaccioni et al., The organic-rich surface of comet 67P/Churyumov-Gerasimenko as seen by VIRTIS/Rosetta. *Science* 347, 2015.

NAME, First Name: Schröder, Stefan.

Affiliation: Deutsches Zentrum für Luft- und Raumfahrt (DLR), Berlin, Germany.

Role in the project: Photometric modeling support

Current position: Project scientist

Former Position(s): Project scientist at Max-Planck-Institut für Sonnensystemforschung (MPS), Lindau, Germany.

Education: Ph.D. Geophysics, Georg-August-Universität, Göttingen, Germany.
Master's Astrophysics, Universiteit van Amsterdam (UvA), Amsterdam, The Netherlands. Master's Biology, Vrije Universiteit (VU), Amsterdam, The Netherlands.

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

Honors: N/A.

Selected Publications:

Schröder *et al.* (2017) "Resolved spectrophotometric properties of the Ceres surface from Dawn Framing Camera images", *Icarus* **288**, 201-225.

Schröder *et al.* (2017) "Close-up images of the final Philae landing site on comet 67P/Churyumov-Gerasimenko acquired by the ROLIS camera", *Icarus* **285**, 263-274.

Schröder *et al.* (2014) "Laboratory observations and simulations of phase reddening", *Icarus* **239**, 201-216.

Schröder *et al.* (2013) "Resolved photometry of Vesta reveals physical properties of crater regolith", *P&SS* **85**, 198-213.

Stephan, Katrin

Institute of Planetary Research (DLR) (Rutherfordstrasse 2, 12489 Berlin, Germany, phone: +49 30 67055422, email: Katrin.Stephan@dlr.de)

Role in the Project:

Spectral mapping of the comet's surface composition with the scientific background of outer planet's icy satellites

Current Position:

Since 2006 Staff Scientist Institute of Planetary Research (German Aerospace Center, DLR)
Since 2015 Associate Editor (Earth Moon Planets / Springer)

Former Position(s)

Postdoc Dept. Planetary Geology, Institute of Planetary Research (DLR), Berlin, Germany

Education:

1994 - 2000 Diploma, Geology (Institute of Geoinformatics, Remote Sensing, Department of Geoscience, Free University Berlin)
2001 - 2006 PhD (German Aerospace Center, DLR, Institute of Planetary Research)

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

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Honors/Awards

Dawn Group Achievement Award

Selected Publications

Stephan, K., et al. (2017), An investigation of the bluish material on Ceres, *Geophysical Research Letters*, 44, doi:10.1002/2016GL071652.

Stephan, K., et al. (2016), Cassini's geological and compositional view of Tethys, *Icarus*, 274, 1-22.

Stephan, K., et al. (2014), Small fresh impact craters on asteroid 4 Vesta: A compositional and geological fingerprint, *Journal of Geophysical Research (Planets)*, 119, 771-797.

Stephan, K., et al. (2015), The Sextilia-region on Asteroid 4Vesta - Stratigraphy and variegation, *Icarus*, 259, 162-180.

Stephan, K., Jaumann, R., Wagner, R. "Geology of Icy Bodies" In: Science of the Solar System Ices (Gutpati, M., Castillo-Rogez, J.), Springer, 2013.

J. B. Dalton, D. P. Cruikshank, K. Stephan et al., "Chemical Composition of Icy Satellite Surfaces", In: Satellites of the Outer Solar System: Exchange Processes Involving the Interiors, [Space Science Reviews, Vol. 153, No 1-4](#), p. 113-154, 2010.

Stephan, K., et al., "Dione's spectral and geological properties": *Icarus* 206, p. 631-652, 2010.

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Team members (alphabetical order)

<p>Pierre Beck</p> <p>Institut de Planétologie et d'Astrophysique de Grenoble, Institut Universitaire de France <i>Bat. Physique D, 414 rue de la piscine, BP53 38041 Grenoble cedex 09, France</i> Phone: +33(0)476635277 Email: pierre.beck@univ-grenoble-alpes.fr</p>	<p>Mauro Ciarniello (team leader)</p> <p>INAF-IAPS Institute for Space Astrophysics and Planetology <i>via del Fosso del Cavaliere, 100, 00133 Rome, Italy</i> Phone: +39-0649934689 Email: mauro.ciarniello@iaps.inaf.it Fax: +39-0646488168</p>
<p>Gianrico Filacchione</p> <p>INAF-IAPS Institute for Space Astrophysics and Planetology <i>via del Fosso del Cavaliere, 100, 00133 Rome, Italy</i> Phone: +39-0649934454 Email: gianrico.filacchione@iaps.inaf.it Fax: +39-0646488168</p>	<p>Lyuba Moroz</p> <p>Institute of Planetary Research, DLR-German Aerospace Center <i>Rutherfordstrasse 2, D-12489 Berlin, Germany</i> Phone: +49-30-67055-9143 Email: Liubov.Moroz@dlr.de Fax: +49-30-67055-303</p>
<p>Cedric Pilorget</p> <p>IAS - Institut d'Astrophysique Spatiale Centre Universitaire d'Orsay <i>Bat 121, 91405 Orsay cedex, France</i> Phone: +33(0)169858732 Email: cedric.pilorget@ias.u-psud.fr</p>	<p>Antoine Pommerol</p> <p>Space and Planetary Science Department Physikalisches Institut, University of Bern <i>Sidlerstrasse 5, CH-3012 Bern, Switzerland</i> Phone: +41-31-631-3998 Email: antoine.pommerol@space.unibe.ch</p>
<p>Eric Quirico</p> <p>Institut de Planétologie et d'Astrophysique de Grenoble, Université Grenoble Alpes <i>414, Rue de la Piscine, 38058 Grenoble Cédex 9, France</i> Phone: + 33(0)476514156 Email: eric.quirico@univ-grenoble-alpes.fr Fax: +33476514146</p>	<p>Andrea Raponi</p> <p>INAF-IAPS Institute for Space Astrophysics and Planetology <i>via del Fosso del Cavaliere, 100, 00133 Rome, Italy</i> Phone: +39-0649934696 Email: andrea.raponi@iaps.inaf.it Fax: +39-0646488168</p>
<p>Stefan Schroeder</p> <p>Institute of Planetary Research Planetary Geology Department DLR - German Aerospace Center, <i>Rutherfordstrasse 2, D-12489 Berlin, Germany</i> Phone: +49-30-67055-104 Email: Stefanus.Schroeder@dlr.de</p>	<p>Katrin Stephan</p> <p>Institute of Planetary Research Planetary Geology Department DLR - German Aerospace Center, <i>Rutherfordstrasse 2, D-12489 Berlin, Germany</i> Phone: +49-30-67055-422 Email: Katrin.Stephan@dlr.de Fax: +49-30-67055-402</p>