VIRTIS on Rosetta: a unique technique to observe comet 67P/Churyumov-Gerasimenko - first results and prospects

Gabriele E. Arnold*[a], Fabrizio Capaccioni[b], Gianrico Filacchione[b], Stéphane Erard[c], Dominique Bockelee-Morvan[c], Maria Antonietta Barucci[c], Maria Cristina De Sanctis[b], Ernesto Palomba[b], Maria Teresa Capria[b], Priscilla Cerroni[b], Pierre Drossart[c], Cedric Leyrat[c], Giuseppe Piccioni[b], Bernard Schmitt[d], Federico Tosi[b], Gian Paolo Tozzi[e], David Kappel[a], Kathrin Markus[a], Alessandra Migliorini[b], and the Rosetta-VIRTIS Team

[a]Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Institute of Planetary Research, Rutherfordstrasse 2, 12489 Berlin, Germany;
[b]Istituto di Astrofisica e Planetologia Spaziali (IAPS), INAF, Via Fosso del Cavaliere 100, 00133, Roma, Italy;
[c]Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique (LESIA), Observatoire de Paris, 5 Place Jules Janssen, 92195, Meudon, France;
[d]Université Grenoble Alpes, CNRS, Institut de Planétologie et d'Astrophysique de Grenoble, Grenoble, France;
[e]Osservatorio Astrofisico di Arcetri, INAF, Firenze, Italy.

*Gabriele.Arnold@dlr.de; phone +49-3067055370; fax + 49-3067055303

ABSTRACT

VIRTIS aboard ESA's Rosetta mission is a complex imaging spectrometer that combines three unique data channels in one compact instrument to study nucleus and coma of comet 67P/Churyumov-Gerasimenko. Two of the spectral channels are dedicated to spectral mapping (-M) at moderate spectral resolution in the range from 0.25 to 5.1 µm. The third channel is devoted to high resolution spectroscopy (-H) between 2 and 5 µm. The VIRTIS-H field of view is approximately centered in the middle of the -M image. The spectral sampling of VIRTIS-M is 1.8 nm/band below 1 µm and 9.7 nm/band between 1-5 µm, while for VIRTIS-H $\lambda/\Delta\lambda$= 1300-3000 in the 2-5 µm range.

This paper describes selected findings during the pre-landing phase of Philae's robotic subsystem and the comet's escort phase as well as prospects of further observations. The preliminary results include studies of surface composition, coma analyses, and temperature retrieval for the nucleus surface-coma system demonstrating the capability of the instrument.

Keywords: Planetary remote sensing, comets, Rosetta, spectroscopy.

1. INTRODUCTION

Comets can be considered as some of the remaining original elements in our 4.6 billion-years-old solar system. These minor bodies were formed in the outer and cold regions of the planetary system, and thus they are less altered containing information about the early solar nebula's state of matter[1, 2]. Spectroscopic observations in the UV, VIS, IR, and millimeter wave region have revealed many molecular species in comets including ices of water, hydrocarbons, alcohols, and acids. The presence of CO and CH_4 ices demonstrate that the material is pristine and may has preserved from the early solar system[3, 4]. Water ice is the major bulk component with abundances up to 90% [4]. Depending on the condensation temperature, water ice can exist either in amorphous (≤30 K) or crystalline phases. Amorphous water ice can trap large amounts of gases, which are going to be released with increasing temperature when the ice transits to its

Infrared Remote Sensing and Instrumentation XXIII, edited by Marija Strojnik Scholl,
Gonzalo Páez, Proc. of SPIE Vol. 9608, 960803 · © 2015 SPIE
CCC code: 0277-786X/15/$18 · doi: 10.1117/12.2187208

crystalline form[5]. The precursor cometary material may be a combination of unaltered interstellar grains and volatiles that would be subsequently condensed in the protoplanetary disk.[1]

Earth-based optical spectroscopy has been intensely used to analyze dissociation products (daughter molecules) in cometary comas. However, it is often only possible to a limited extent to deduce their parent molecules. Moreover, it is even more difficult to study the solid nucleus of the comets as direct source of the coma's products. Previous space missions targeted to comets significantly increased our knowledge about cometary nuclei. Mass spectroscopic measurements aboard Giotto to comet 1P/Halley in 1986 detected inorganic minerals and organic refractory materials consisting of C, H, N, O, P, and S[6, 7, 8]. The analyses of particles ejected from comet 81P/Wild 2 and collected by the Stardust spacecraft have shown the presence of a wide range of organic material and inorganic components like sulfides and silicates[9, 10]. The comet's organic material was similar to the insoluble organic matter (IOM) found in meteorites[11, 12] with lower aromaticity and longer or less branched aliphatic components and with higher O, N contents. The detection of D and ^{15}N suggest that some particles may be of presolar origin[9]. Spacecraft observations with Giotto (1P/Halley), Stardust (81P/Wild 2)[13], Deep Impact (9P/Tempel 1)[14], and EPOXI (103P/Hartley 2)[15] have shown that all cometary surfaces are extremely dark exhibiting bright and active areas in only a few, often sharply limited areas. Thus, the cometary surfaces might be depleted in volatiles caused by an erosion process, which is driven by sublimation and thermal stress.

All previous cometary space missions have flown by their targets, and thus they took only time-limited snapshots within their orbital evolution. ESA's cornerstone Rosetta to comet 67P/Churyumov-Gerasimenko is the first mission escorting a comet during its passage through the inner solar system. Additionally, a robotic device, "Philae", which landed on the cometary surface in November 2014, provided important *in situ* data. ESA's Rosetta mission was launched on 2 March 2004 on an Ariane 5 G+ rocket. It rendezvoused with comet 67P/Churyumov-Gerasimenko, henceforth shortly called 67P, in August 2014.

Among the lander Philae and eleven orbiter experiments, the Visible and InfraRed Thermal Imaging Spectrometer, "VIRTIS", onboard ESA's Rosetta mission began observing the comet 67P within two steps: the Philae pre-landing and the ongoing cometary escorting phase. Starting from early observations of the less active comet at heliocentric distances > 3 AU (August 2014) until its perihelion approach (August 2015, 1.242 AU), VIRTIS measured UV-VIS-IR spectra enabling to record spectral image cubes from 0.25 to 5.1 µm and high resolution IR spectra in in the 2-5 µm range. This paper offers a brief overview of the first results of these measurements demonstrating the capability of space-based UV-VIS-IR spectroscopic techniques exploring solar system objects.

2. VIRTIS ON ROSETTA

The Visible and InfraRed Thermal Imaging Spectrometer (VIRTIS) aims to study the nucleus surface composition, its temperature, and the gaseous and dust components in the coma of comet 67P. For this purpose, the reflected and emitted radiance of the comet in the spectral range 0.25-5.0 µm are measured with a Mapping Spectrometer (VIRTIS-M) and a High Resolution Spectrometer (VIRTIS-H). The UV-IR spectrum offers the opportunity to extract compositional and physical information. This includes the measurement of temperature and thermal inertia basing on IR brightness detection. Compositional data of the cometary nucleus, coma, and dust can be gained on the basis of diagnostic features in the UV-VIS-IR range spectra.

2.1 Rosetta Mission and comet 67P/Churyumov-Gerasimenko

The Rosetta mission is a cooperative project between ESA, various European national space agencies, and NASA, and is comprised of eleven orbital and ten lander experiments, making it unprecedented in scale. Rosetta rendezvoused the comet 67P in May 2014 at 4 AU from the Sun and entered a 30-km bound orbit around the comet on 9 September 2014. It will accompany the comet's journey towards perihelion (13 August 2015, 1.24 AU). ESA's cornerstone Rosetta is the first spacecraft to orbit a comet and was the first to land a robotic device on the surface of a comet. Therefore, Rosetta combines remote sensing and *in situ* investigations. The mission aims at a global characterization of the cometary nucleus, the determination of dynamic properties, the surface morphology and composition, chemical /mineralogical

/isotopic compositions of volatiles and refractories, physical properties, studies of cometary activity and evolution of interaction with the solar wind[16].

After a 10-years cruise, the Rosetta spacecraft began a close exploration of its main target, comet 67P in July 2014. The Jupiter Family Comet 67P discovered in 1969 is characterized by an eccentricity of 0.64102, an inclination of 7.0405°, a perihelion distance of 1.2432 AU, and a semi-major axis of 3.4630 AU resulting in a period of 6.44 years. In 1959 67P had a close encounter with Jupiter which changed its perihelion distance from 2.74 AU to its present value[17]. The current rotation period is about 12.4 h[18].

Rosetta's OSIRIS camera mapped the comet disclosing a structure of two lobes connected by a neck (see figure 1)[19]. The cometary surface displays different morphologies including dust covered terrains, brittle material, large scale depressions, smooth terrains, and exposed consolidated surfaces (see figure 1)[20].

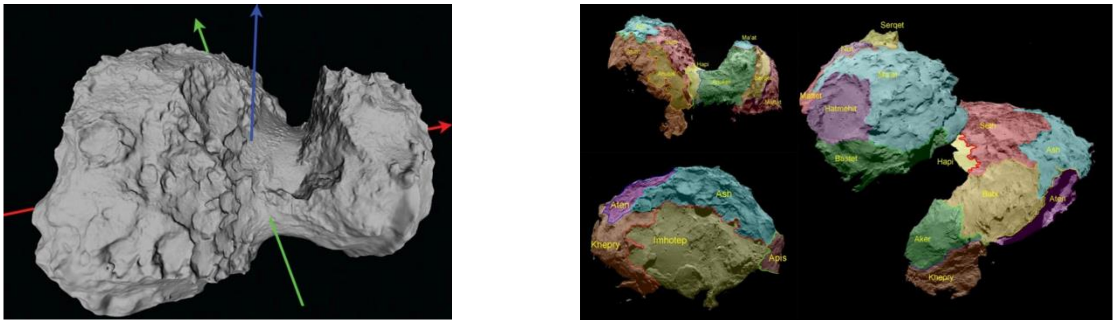

Figure 1. OSIRIS results. Left: shape model of 67P with rotation axis (blue) and (red, green) equatorial x and y axis [19].
Right: examples of naming and morphological units [20].
Shape model credit: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA.

During the pre-landing (before 12 Nov 2014) and escort phase (after 12 Nov 2014), the orbiter instruments collected data to characterize the comet with remote sensing optical systems, with a microwave device, with radar sounding, gas and dust analyses, plasma and magnetic field studies, and radio sounding [19, 20, 21, 22, 23, 24]. Among the optical systems, the VIRTIS instrument has completed extensive UV – IR measurement campaigns from which compositional maps[25], temperatures, and photometric properties of the cometary nucleus were derived and coma studies were performed.

2.2 Visible and InfraRed Thermal Imaging Spectrometer (VIRTIS)

VIRTIS[26, 27, 28, 29] stands for Visible and InfraRed Thermal Imaging Spectrometer. VIRTIS combines a two-channel imaging spectrometer (VIRTIS-M) for mapping with a high spectral resolution Echelle spectrometer (VIRTIS-H). The VIRTIS-M (Mapper optical subsystem) covers the spectral range between 0.28 to 5.13 µm. It is devoted to spectral mapping of the comet's nucleus and coma at moderate spectral resolution.

The VIRTIS-H Echelle spectrometer is devoted to high resolution spectroscopy in the range between 1.84 and 5 µm. Figure 2 shows the Optics Module of VIRTIS Rosetta, and table 1 summarizes the main instrument parameters and performances.

VIRTIS-M design relies on a single optical head in which a Shafer telescope is joined to an Offner imaging spectrometer and two focal plane arrays (FPA). A dual zone convex grating is used as dispersive element. VIRTIS-H is a high spectral resolution infrared cross-dispersed spectrometer using prism and grating for dispersion. VIRTIS-H spectral resolving power is >1000. The VIRTIS experiment consists of four modules: the Optics Module containing the -M and -H Optical Heads, the two Proximity Electronics Modules (PEM), and the Main Electronics (ME). The Optics Module is externally mounted on the –X panel of the spacecraft with the Optical Heads co-aligned in +Z direction.[26, 27]

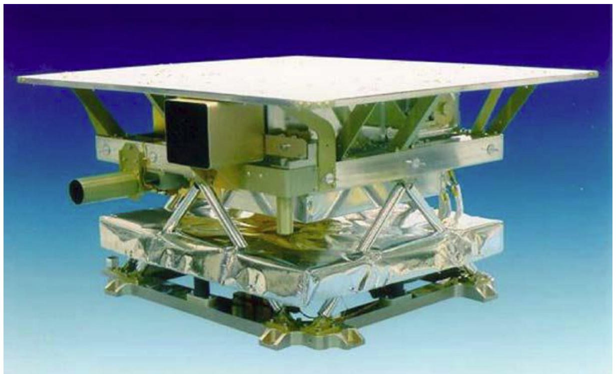

Figure 2. VIRTIS-Rosetta: Optics Module, credits: Officini Galileo, Italy, 2001.

	VITRIS-M Visible	*VIRTIS-M Infrared*	*VIRTIS-H*
Spectral range (µm)	0.28-1.10	1.02-5.13	1.84-5.00
Spectral resolution $\lambda/\Delta\lambda$	~200	~200	~1200
Spectral sampling (nm)$^{1)}$	1.9	9.7	0.6-1.6
Field of view (mrad ×mrad)	64 (slit) × 64 (scan)	64 (slit) × 64 (scan)	0.44 × 1.34
Image size, full FOV	256 × 256	256 × 256	-
IFOV (µrad)	250	250	-
Noise equivalent spectral radiance (central band, W m^{-2} sr^{-1} µm^{-1})	2.5×10^{-2}	5.0×10^{-4}	5.0×10^{-4}
Spectrometer type	Offner Relay	Offner Relay	Echelle
Detectors	CCD	MCT (HgCdTe)$^{2)}$	MCT (HgCdTe)$^{2)}$

$^{1)}$ Depends on selected mode of operation; the finer value is shown here. $^{2)}$ Actively cooled.

Table 1. Instrumental parameters of the tree VIRTIS channels[26, 27, 29].

The slits of both optical systems are parallel to the Y axis. VIRTIS-M and -H channel telescopes have a cover to protect the instrument from direct solar illumination, comet's dust particles, and to preserve the cold environment inside the spectrometer. The focal planes with state of the art CCD and infrared detectors achieve high sensitivity. VIRTIS-M-VIS uses a Si CCD (Thomson TH7896) for the range between 0.28- 1.1 µm. The IR FPA of -M and -H are housed on bi-dimensional HgCdTe arrays of 270 x 438-pixel detectors (256 of them used for spatial and 432 for spectral sampling) designed to provide high sensitivity and low dark current (1 fA at 80K). Both are cooled to 85 K by an active cooler. VIRTIS-M and -H spectrometers themselves are cooled down to 135 K by means of an external radiator reducing the background level of thermal radiation[26, 27, 28, 29]. The same radiator is used to maintain the VIS channel CCD at an operative temperature of 135 K.

3. VIRTIS' OBSERVATION RESULTS

3.1 Cometary nucleus surface

Compositional studies: Nucleus observations at high spatial resolution down to 7.5 m/pixel[30] have been performed by VIRTIS-M in the pre-landing phase from August to September 2014 (3.6 to 3.3 AU from the Sun). After calibration and geometrical projection to the shape model, the VIRTIS-M data have been processed using spectral slopes and band depths as indicators to map the surface composition of the illuminated northern part of the comet[25, 30]. VIRTIS spectra reveal an overall very low normal albedo of 0.060 ± 0.003 at 550 nm[25]. Figure 3a shows normalized spectra collected in the 0.4 to 4 µm range. The spectra show common features: a reddish spectral slope, which changes at about 1µm, and a broad, shallow absorption band between 2.9 and 3.6 µm[25, 30, 31]. The spectral slopes in the VIS and IR range have been determined to be 5 to 25 and 1.5 to 5% kÅ^{-1}, respectively[25]. The 4 to 5 µm range is affected by the surface thermal emission and not shown in Figure 3a. Figure 3b displays the spectral slopes sampled at 1° by 1° spatial resolution and projected on an early nucleus shape model for different viewing orientations[25]. The lowest slopes apparently are observed over the neck region, which is associated with early activity of the comet.

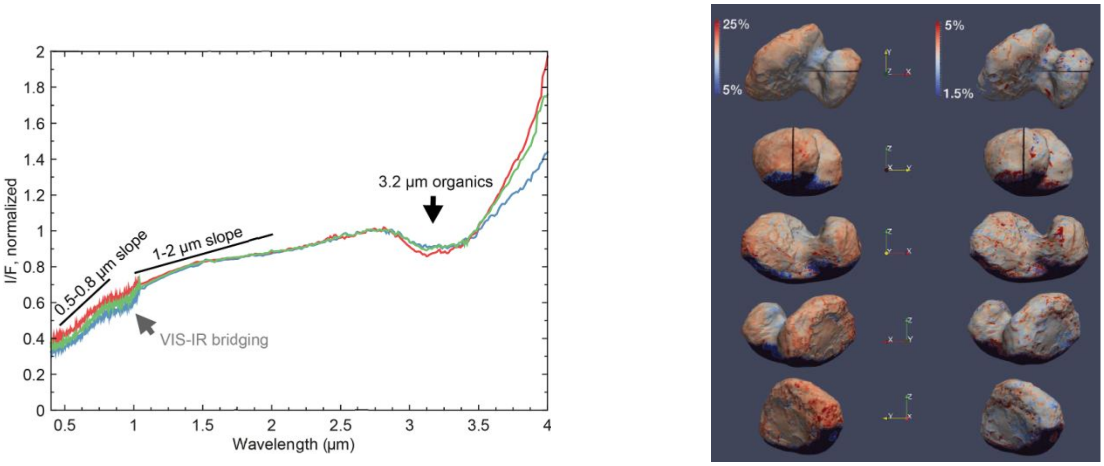

Figure 3. a: Left: Nucleus I/F spectra normalized at 2.7 µm (MTP006, STP 015; heliocentric distance: 3.46093 AU; distance to comet: 54.69 km; IR cube: I1_00367986514; VIS cube: V1_00367986521; 30 AUG 2014). b: Right: Spectral slopes (VIS-left; IR-right) calculated from 160 observations acquired in August and September 2014[25]. Shape model courtesy by OSIRIS team: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA.

The lack of significant ice absorptions at 1.5, 2.0, and 3.0 µm indicates that the crust is enriched in dehydrated refractory materials. However, close up observations of the cometary nucleus have revealed very limited amount of small water ice patches and water ice cyclically appearing and disappearing[32]. The broad 3.2 µm band appears across the entire illuminated surface. It is compatible with nonvolatile organic macromolecular material[25]. This band can be assigned to OH, COOH, CH, and NH chemical groups, molecules, or ions[31]. The very low reflectance of the cometary surface requires additional dark components to be present in the crust. Candidate materials are Fe-bearing agents found in 81P/Wild 2 grains by Stardust, stratospheric dust particles, and Antarctic micrometeorites[33, 34, 35]. Although the broad organic band is a common feature to all spectra observed, it displays several spatial variations of its fine structure, which are currently under evaluation. The larger abundance of complex organic materials at the surface of 67P compared to other Jupiter Family Comets suggests a formation at larger heliocentric distances[25].

Photometric properties: VIRTIS observed the nucleus of 67P at various phase angles[30] enabling to study the influence of photometric effects on the reflected solar radiance (I/F). Integrated fluxes from full-disk acquisitions were used to derive light curves, and disk-resolved observations enabled to deduce the single scattering albedo (SSA) and geometric albedo $A_{geo} = 0.062 \pm 0.002$ at 550 nm[37] from VIRTIS-M observations by applying Hapke's model[38]. The values obtained for SSA and opposition effect function are compatible with other cometary observations. These studies will be used for photometric corrections and for physical characterization of the surface roughness[37].

Surface temperature: The comet's thermal emission at longer VIRTIS wavelengths can be used to derive temperatures of the cometary surface. First surface temperature studies revealed daytime temperatures in the range between 180 and 220 K at heliocentric distances from 3.59 to 2.74 AU. In very few places the maximum surface temperature was determined to be 230 K. The observed temperature is primarily correlated to small incidence and phase angles[36], and thus to insolation.

3.2 Cometary coma and dust

Observations of H_2O and CO_2: VIRTIS-H measurements were undertaken in limb geometry with tangent altitudes from the cometary surface up to 1.5 km in various line-of-sight orientations, which were related to geomorphologic positions and their illumination properties. They have been used to study the productions and distributions of water (2.67 µm) and carbon dioxide (4.27 µm) in the cometary coma, when the comet was between 2.47 and 2.91 AU from the Sun[39]. Until now, VIRTIS has not revealed carbon monoxide emission. These components are key species of cometary ices having different volatility. High water column densities are observed above the active areas located in the illuminated neck region. The water vapor production rate decreases for low solar illumination, whereas CO_2 is outgassing from both illuminated and non-illuminated areas[40]. This distribution of the two species results in variable CO_2/H_2O column density ratios between 2 and 30%[39]. Rotational temperatures have been used to determine coma temperatures of typically 100 K above 1 km from the nucleus[39].

4. CONCLUSION AND OUTLOOK

The VIRTIS observations on ESA's cornerstone mission Rosetta have provided important information about 67P's surface albedo, composition, photometric properties, and temperatures. First near-nucleus coma studies revealed information about distribution and levels of gas production for the two major species, water vapor and carbon dioxide. As 67P approaches its perihelion passage in August 2015 it becomes more and more active enabling to study details of the cometary gases and dust emissions. At the same time the southern hemisphere of 67P will be illuminated progressively disclosing the yet not known part of the comet. VIRTIS studies of temporal and spatial dynamic processes regarding the nucleus and coma will contribute to understand the sources and effects of cometary activity, while monitoring the nucleus/coma composition will enable to trace the comet's evolutionary path.

5. ACKNOWLEDGEMENTS

We thank the following institutions and agencies for support of this work: Italian Space Agency (ASI, Italy), Centre National d'Etudes Spatiales CNES, France), DLR (Germany), NASA (USA) Rosetta Program, and Science and Technology Facilities Council (UK). VIRTIS was built by a consortium, which includes Italy, France, and Germany, under the scientific responsibility of the Istituto di Astrofisica e Planetologia Spaziali of INAF, Italy, which also guides the scientific operations. The VIRTIS instrument development has been funded and managed by ASI, with contributions from Observatoire de Meudon financed by CNES, and from DLR. We thank the Rosetta Science Ground Segment and the Rosetta Mission Operations Centre for their support throughout the early phases of the mission.

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