The organic-rich surface of comet 67P/Churyumov-Gerasimenko as seen by VIRTIS/Rosetta

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The VIRTIS (Visible, Infrared and Thermal Imaging Spectrometer) instrument on board the Rosetta spacecraft has provided evidence of carbon-bearing compounds on the nucleus of the comet 67P/Churyumov-Gerasimenko. The very low reflectance of the nucleus (normal albedo of 0.060 ± 0.003 at 0.55 micrometers), the spectral slopes in visible and infrared ranges (5 to 25 and 1.5 to 5% kÅ), and the broad absorption feature in the 2.9-3.6-micrometer range present across the entire illuminated surface are compatible with opaque minerals associated with nonvolatile organic macromolecular materials: a complex mixture of various types of carbon-hydrogen and/or oxygen-hydrogen chemical groups, with little contribution of nitrogen-hydrogen groups. In active areas, the changes in spectral slope and absorption feature width may suggest small amounts of water-ice. However, no ice-rich patches are observed, indicating a generally dehydrated nature for the surface currently illuminated by the Sun.

Comets are probably the least-altered objects that survive from the origin of the solar system, and they therefore carry the record of the physical processes that have led to their formation. The solid components we observe on the nucleus may have existed before the solar system formed, as interstellar grains, or they could be materials that condensed in the early protosolar nebula (7). Previous information on the nucleus composition was mainly derived from measurements of the coma gas and dust components, either from ground-based observations, from in situ measurements (2-4) or from analysis of grains of cometary origin (5) or presumed cometary origin, as stratospheric interplanetary dust particles and Antarctic micrometeorites (6-8). Unfortunately, only a few direct observations of comet nuclei have been carried out, limiting the amount of information known about their surface composition (9, 10).

With the arrival, in early August 2014, of the Rosetta spacecraft at 67P/Churyumov-Gerasimenko (hereafter 67P), the Visible, Infrared and Thermal Imaging Spectrometer (VIRTIS) (10) began a mapping campaign to provide direct measurements of the surface composition of the nucleus. VIRTIS is a dual channel spectrometer. VIRTIS-M (M for mapper) is a hyper-spectral imager covering a wide spectral range with two detectors: a charge-coupled device detector [visible (VIS)] ranging from 0.25 through 1.0 μm and an HgCdTe detector [infrared (IR)] covering the 1.0- to 5-μm region. VIRTIS-M uses a slit and a scan mirror to generate images with spatial resolution of 250 μrad over a field of view of 3.7°. The second channel is VIRTIS-H (H for high resolution), a point spectrometer with high spectral resolution (λ/Δλ = 9000 at 3 μm) in the range 2 to 5 μm (17).

The VIRTIS observations described in this paper were obtained from August to September 2014 (3.6 to 3.3 astronomical units from the Sun), with a surface spatial resolution varying between 15 and 30 m per pixel, over the instrument spectral range 0.5 to 5.0 μm. The three major regions of the nucleus—the “head,” “neck,” and “body”—are presented in Fig. 1, with spectra representative of the composition of the three areas. The spectra show several common features: a very low albedo, clear absorption in the range 2.9 to 3.6 μm, and a slightly reddish spectral slope with a slope change around 1.0 μm. The reflectance spectra also show definite evidence of thermal emission at 3.5 to 5.0 μm; once the temperature is calculated from the radiance data (22), we obtain surface temperatures in the range 180 to 230 K during daytime. A notable feature of all spectra is the absence of water-ice absorption bands (at 1.5, 2.0, and 3.0 μm). This indicates that no water-ice-rich patches are present, across the nucleus surface, at a scale larger than ~10 m, with an upper limit on the water-ice abundance of ~1%. The lack of ice absorption features in our spectra, along with the relatively high surface temperature mentioned above, indicate that the top layers of the surface (estimated up to few hundred micrometers), which are probed by the reflected light, are composed mainly of dark dehydrated refractory materials.

The normal albedo derived from VIRTIS data is 0.060 ± 0.003 at 0.55 μm, in excellent agreement with the value obtained by the Optical, Spectroscopic, and Infrared Remote Imaging System (OSIRIS) team (19). The reflectance spectra in the VIS range display a peak at 0.5 μm (“red”) over the range 0.5 to 0.8 μm with a coefficient of 5 to 25% kÅ⁻¹, which is also in good agreement with the OSIRIS results. The spectrum has a knee at ~1.0 μm and displays a more neutral (1.5 to 5% kÅ⁻¹) spectral slope in the range 1.0 to 2.0 μm. If compared to the reflectance of trans-Neptunian objects, 67P would be associated, according to the present taxonomy described in (14), with the two slightly red classes (denoted BR and IR) being substantially different from the extreme cases of the very red objects (RR) or the neutral slopes objects (BB).

To take full advantage of the mapping capability of VIRTIS, we mapped the spectral slopes over the ranges 0.5 to 0.8 μm and 1.0 to 2.0 μm, onto the shape model (Fig. 2). The region located in the neck, which is also the region associated with the first sign of activity in August to September 2014 (13), displays a less steep slope than the rest of the surface in both VIS and IR ranges. Moving into the IR region, the most prominent feature observed is a wide absorption band extending from 2.9 to 3.6 μm. The band is fairly asymmetric with a steeper slope toward the shorter-wavelength region, a band depth (relative

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Fig. 1. Examples of images acquired by VIRTIS-M and representative spectra. (Left) VIRTIS-M VIS RGB images of the nucleus acquired on the neck (top panel, acquisition V1_00366693519 taken on 15 August 2014 from 03:20 to 03:54, spatial resolution 25 m per pixel) and on the head and body regions (bottom panel, acquisition V1_00368219081 taken on 1 September 2014 from 19:05 to 20:30, spatial resolution 12.5 m per pixel). (Right) Representative reflectance spectra (thermal emission removed) of the three regions in the 0.5-to-4.0-μm range by VIRTIS-M (red, black, and blue curves) and in the 2-to-4-μm range by VIRTIS-H (light blue curve). The color code corresponds to the location of the crosses reported in the images. The vertical scale is given in radiance factor (I/F), and offsets are added for clarity: black and blue spectra shifted by 0.01, light blue spectrum shifted by −0.02. Vertical light gray bars indicate instrumental bridging zones and order sorting filters gaps (11). The spectra extend to 5.0 μm but their analysis is limited to 4.0 μm, where the spectral interpretation is unaffected by the emissivity of the surface. Error bars associated with the measurements are also reported.

Fig. 2. Spectral slopes, sampled at 1° by 1° spatial resolution, are shown projected on the nucleus shape model for different viewing orientations. The spectral slopes in the VIS (0.5 to 0.8 μm, left column) and IR (1 to 2.0 μm, right column) are reported in units of percent per kiloangstrom (%/kÅ). Slopes have been calculated from 160 observations acquired from 7 August 2014 to 2 September 2014, limiting the samples to the pixels having incidence and emission angles less than 80°. Projections of VIRTIS data on the shape model were performed using the MATISSE software developed by A. Zinzi and collaborators at the ASI Science Data Center (ASDC, Rome). [Credit for nucleus shape model: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA]
Fig. 3. The spectrum of the head shown in Fig. 1 is compared (in the spectral range 0.5 to 2.5 \(\mu m\)) to the spectra of several other compounds described in the text. Enstatite, pyrothite, and troilite spectra are scaled down by 100, 75, and 50%, respectively. The Murchison IOM is from (16), enstatite spectrum from (29), troilite and carbon black spectra from (30), and pyrothite spectrum from (31).

Fig. 4. The spectrum of the head in the spectral range 2.5 to 4.5 \(\mu m\) is compared to several other organic compounds described in the text. The VIRTIS spectrum is rescaled in arbitrary units to compare the X-H stretch region with ethanol and ethanoic (acetic) acid spectra (32), a cometary tholins (obtained after ion irradiation of a mixture of 80% H\(_2\)O, 16% CH\(_3\)OH, 3.2% CO\(_2\), and 0.8% C\(_2\)H\(_2\)) (33), and a refractory residue (labeled “Exp Or1”) obtained after UV irradiation of a mixture of H\(_2\)O:CH\(_3\)OH:NH\(_2\)CO:CO\(_2\) in the ratio 2:1:1:1 (34).

Fig. 4 The spectrum of the head in the spectral range 2.5 to 4.5 \(\mu m\) is compared to several other organic compounds described in the text. The VIRTIS spectrum is rescaled in arbitrary units to compare the X-H stretch region with ethanol and ethanoic (acetic) acid spectra (32), a cometary tholins (obtained after ion irradiation of a mixture of 80% H\(_2\)O, 16% CH\(_3\)OH, 3.2% CO\(_2\), and 0.8% C\(_2\)H\(_2\)) (33), and a refractory residue (labeled “Exp Or1”) obtained after UV irradiation of a mixture of H\(_2\)O:CH\(_3\)OH:NH\(_2\)CO:CO\(_2\) in the ratio 2:1:1:1 (34).

to the local continuum) on the order of 20%, and a band center located at 3.2 to 3.3 \(\mu m\). The band is observed in both VIRTIS-M and VIRTIS-H spectra, independently calibrated, with similar band depth and shape.

When this band is mapped over the surface of 67P, the data taken so far indicate a limited variability across the observable nucleus, mainly localized in the neck region. The absorption band of spectra taken in the neck region is deeper, broader, and shifted toward shorter wavelengths (2.8 to 3.6 \(\mu m\)) with respect to the other regions. The short-wavelength shoulder of the neck band is most likely due to the addition, in this region, of a small percentage of water-ice mixed with the dark material responsible for the overall appearance of the spectrum. This is in agreement with the slight increase in the reflectance (on the order of a few percent), the increase in band depth (Fig. 1), and the previously mentioned decrease of the VIS spectral slope for this same region (Fig. 2, left column top projection). Furthermore, it is consistent with localized activity driven by volatiles (including water) in the uppermost few millimeters of the nucleus surface. This process is quite distinct from the diffuse activity observed by OSIRIS (15) in regions where VIRTIS observations indicate a dehydrated crust. We note that the increase of the amount of organic matter may also contribute to part of the band-depth increase in the neck. In contrast to the neck region, the spectral features observed on the head and body (Fig. 1) are markedly similar and indicate a compositionally homogeneous surface at the present spatial resolution.

Comparison with laboratory spectra of carbonaceous chondrites of the CI, CM, and CR types reveals that none of the typical features of their spectra are compatible with the spectra of 67P [for a thorough analysis of carbonaceous chondrites spectra, see (15–17)]. Spectra of bulk carbonaceous chondrites display a change of slope at \(\sim 0.6 \mu m\) and are basically flat in the near-IR range and thus do not match the red slope seen on 67P. Furthermore, carbonaceous chondrites’ broad 3-\(\mu m\) band due to structural hydroxyl or water is shifted substantially toward shorter wavelengths. Thus, the material that composes the surface of 67P is not identical to the main groups of primitive carbonaceous chondrites. The reflectance spectra of the insoluble organic matter (IOM) extracted from the Murchison chondrite are indeed dark and flat in both the visible and IR ranges (15), but the absolute abundance of IOM in primitive chondrites is limited to a few percent and cannot account for the overall appearance of the 67P spectra.

Numerous asteroidal bodies have an absorption feature around 2.7 to 2.8 \(\mu m\) (18) associated with the presence of hydrated minerals. In the case of small bodies such as 24 Themis, 65 Cybele, and a few other objects (18–20), the absorption-band maxima are shifted toward higher wavelength (\(\sim 3.1 \mu m\)). For these observations, the absorption feature is explained by the presence of water-ice, with a possible contribution of organic compounds (~3.4 \(\mu m\)). Still, the band shape and position of the maximum of absorption measured by VIRTIS for 67P is substantially different from these objects and, at present, distinct across the observed small bodies.

The very low reflectance of 67P surface material throughout VIRTIS spectral ranges requires the presence of a darkening agent in the refractory component. Fe-bearing opaque minerals are known to absorb visible and near-IR light, and their presence in cometary grains is established from the analysis of grains from the comet 8P/Wild2 collected by the STARDUST mission, stratospheric dust particles, and Antarctic micrometeorites (6–8). IOM also contains some insoluble opaque minerals (e.g., sulfides, iron oxides) that are not dissolved by the chemical procedure of extraction from the bulk chondrites. Sulfides (troilite, pyrrhotite, pentlandite), Fe-Ni alloys, Fe-bearing crystalline, and amorphous silicates have been identified in those dust grains. In particular, the
analysis of the comet dust samples indicates the presence of amorphous silicates associated with Fe-Ni inclusions and of crystalline silicates, mainly Mg-rich olivines and low-Ca pyroxenes ($\text{FeO}_{0.8-1.00}$ and $\text{En}_{0.6-1.00}$). Similar compositions ($\text{FeO}_{0.8-1.00}$ and $\text{En}_{0.6-1.00}$) have been measured for Antarctic micrometeorites of presumed cometary origin (7, 8). Iron sulfides (e.g., troilite, pyrrhotite) are common in meteorites, interplanetary dust particles, and cometary dust; they are highly absorbing opaque phases and may play an important role in darkening and reducing spectral contrasts of diagnostic absorption bands if these minerals are fine-grained (21) and references therein. In addition to darkening the IR range, sulfides display a reflectance spectra slope over the 0.5-1.0-μm range that may approximate the slope seen in VIRTIS spectra (Fig. 3).

In many previous studies, the reddish surfaces of outer solar system bodies, such as Kuiper belt objects, have been modeled using tholins produced from $\text{N}_2\text{NH}_3$ gas mixtures (22). Although the reflectance spectra of these tholins may qualitatively account for the reddish slope of VIRTIS data, they are definitely too bright in the IR to be considered as viable materials present at the surface of 67P. The broad absorption band observed at ~3.3 μm in all VIRTIS spectra is a congested spectral region that results from the contribution of X-H vibrations in different chemical groups. CH and OH groups can be reasonably suspected (23). On the other hand, a major contribution of NH or NH$_2$ is less likely, as nitrogen-rich carbonaceous materials devoid of oxygen are not representative of the bulk macromolecular fraction of Jupiter family comets (JFCs) (24). The absorption bands of water-ice, structural water, and hydroxyl trapped in silicates and iron oxides or oxy-hydroxides occur at shorter wavelengths compared with VIRTIS spectra, and their contribution should be low, if any, except in the neck active area where slightly wider and stronger bands are observed. The substructure in the observed absorption band points to a complex mixture of both aromatic and aliphatic C-H bonds (25) (but their presence cannot yet be firmly established); in addition, the broad feature may also be consistent with the presence of OH groups, either as carbonic acid groups or alcohols, inserted in a macromolecular organic solid (20). These chemical groups are known to account for the faint and broad feature in the IR spectra of IOM extracted from primordial meteorites (26, 27). The position and width of the band may depend on the alcohol/carbonic acid ratio and on the groups onto which they are branched. They may account for some of the observed variability of the band shape (Fig. 4).

VIRTIS clearly observed a comet that is different from the other JFCs encountered so far. Previous spectroscopic observations of the surfaces of JFCs indicated the presence of water-ice (20) and tentatively identified a weak band near 2.39 μm that is possibly compatible with hydrocarbons (9). Mass spectrometry of solid grains ejected from comet nuclei showed various species of organic materials ranging from aliphatic and aromatic compounds to carboxylic acids and alcohols (28), but these compounds have not been observed in absorption on comet nuclei. From this point of view, 67P represents a different species in the comet zoo.

The compositional homogeneity of the surface observed by VIRTIS, despite the rejuvenating processes acting on the nucleus (at least on the active portion of it) at every passage close to the Sun, indicates that space weathering plays only a minor role in determining the observed composition. The refractory compounds so widespread on the surface of 67P are then representative of the material that must have been readily available at the time of the formation of the solid materials that ended up forming the nucleus of 67P in the early phases of the protosolar nebula. This suggests that the larger abundance of organics on the surface of 67P, with respect to other JFCs, could be correlated with a formation scenario in which most of the material that constitutes the nucleus of 67P is produced in a low-temperature environment consistent with large distances from the Sun, such as the Kuiper belt region.

REFERENCES AND NOTES


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