COMETARY SCIENCE

67P/Churyumov-Gerasimenko surface properties as derived from CIVA panoramic images

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The structure and composition of cometary constituents, down to their microscopic scale, are critical witnesses of the processes and ingredients that drove the formation and evolution of planetary bodies toward their present diversity. On board Rosetta's lander Philae, the Comet Infrared and Visible Analyser (CIVA) experiment took a series of images to characterize the surface materials surrounding the lander on comet 67P/Churyumov-Gerasimenko. Images were collected twice: just after touchdown, and after Philae finally came to rest, where it acquired a full panorama. These images reveal a fractured surface with complex structure and a variety of grain scales and albedos, possibly constituting pristine cometary material.

Cometary nuclei preserve the initial conditions of the evolution of the solar system and of its resulting planets, satellites, and small bodies. Although their distribution has been modified by gravitational effects over solar system history, comets have likely never undergone global thermal resets, thus maintaining their original volatiles and icy contents up to now.

Part of these initial conditions is recorded in the microscopic and macroscopic properties of the surface of the nucleus: size and shape of individual grains and matrix components, from micrometer- to meter-sized crustal features and boulders, and molecular and mineralogical composition of their constituent materials. The combination of OSIRIS (Optical, Spectroscopic, and Infrared Remote Imaging System) remote imaging and in situ imaging performed by CIVA (Comet Infrared and Visible Analyser) and ROLIS (Rosetta Lander Imaging System) (*1*) on board Philae offers an unprecedented potential for deciphering these properties on comet 67P/Churyumov-Gerasimenko (67P).

Here, we focus on the set of CIVA-P (CIVA-Panorama) images acquired in situ. CIVA-P is a set of seven identical miniaturized microcameras (*2*), implemented as five single cameras and one stereoscopic pair of two coaligned cameras with their optical axes separated by 10 cm; CIVA-P acquires a ~360° panoramic field of view (FOV) by six adjacent FOVs of 60° each (figs. S1 and S2). The angular sampling of CIVA-P is ~1.02 mrad, which corresponds to ~1 mm at 1 m, the distance of the landing feet, and up to a few centimeters at the local horizon. The spectral response of each broadband camera, integrating the properties of both the detector and the optics, extends from 400 to 1100 nm. CIVA shares a common Imaging Main Electronics (IME) with ROLIS.

The sequence of operations was loaded in the Philae on-board Command and Data Management System to be run automatedly during descent, landing, and just after touchdown. It included a CIVA-P panorama to be performed ~5 min after touchdown. The first image, received from camera 6 (fig. S3), indicated unambiguously that Philae was not at rest when it was acquired, at 15:38:52 UT on 12 November, less than 5 min after the nominal touchdown (15.34.06 UT on-board time). Coupled to other measurements [from MUPUS (Multipurpose Sensors for Surface and Sub-Surface Science), ROMAP (Rosetta Magnetometer and Plasma Monitor), and the solar panels], it confirmed that Philae had bounced; the lander eventually came to rest ~2 hours later.

A new set of commands was then uploaded so as to obtain a subsequent CIVA-P panorama, to be run during the next visibility window between the Orbiter and the Lander. The goal was to confirm that Philae had indeed landed and to characterize its environment and attitude, in order to enable reshuffling and adapting, accordingly, the First Science Sequence (FSS), for which the available energy was expected to support up to another ~50 hours of scientific operations. The upload was successful, and this second CIVA-P panorama was performed on 13 November, at 06:13:46 UT on-board time.

All seven images were nominally acquired, compressed on board as planned (at a rate of 1.5 bits/pixel), transmitted, and received, with no error. After decompression, they were processed by the CIVA team and at CNES's Science, Operation, and Navigation Center (SONC): Images were bias-subtracted, corrected for optical distortion, linearity, readout smear, and flat-fielded.

The image acquired by camera 1 (fig. S4) exhibits the +Y Philae foot (see fig. S2), largely sunlit, with the brightest parts near saturation [820 analog-to-digital units (ADU)]. No illuminated cometary surface is seen in contact, indicating that Philae is likely not resting on this foot, as would be the nominal configuration. Essentially no features can be identified at first sight in the background. However, thanks to the very high dynamic range of CIVA-P microcameras, combined with the very low electronic noise (0.4 ADU), it was possible to substantially stretch the signal, which covers the dynamical range 0 to 8 ADU (Fig. 1). A large fractured

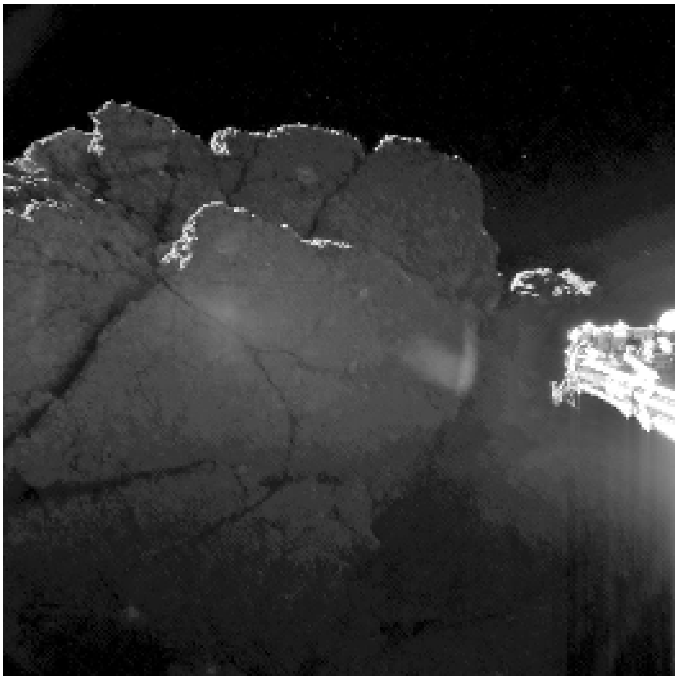

Fig. 1. Image acquired by camera 1. The dynamics have been highly stretched and custom flat-fielding has been applied, so as to exhibit the backlit fractured cliff, shadowing part of the lander. The image is further processed to mitigate detector electronic noise and low dynamics quantification error. The +Y foot is well illuminated and partly reflects on the shadowed surface facing Philae (see also fig. S5).

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boulder can then be observed, backlit: The shadowed part of the boulder is weakly illuminated by sunlight likely reflected by the lander itself (fig. S5).

The image acquired by camera 2 (fig. S6) indicates that this camera is exposed to open sky, with direct sunlight illumination of the front lens (glare). The only structure visible on this image is one of the two CONSERT (Comet Nucleus Sounding Experiment by Radiowave Transmission) antennas, which seems nominally deployed. The image acquired by camera 3 (fig. S7) displays a scene that would be expected for a landing in nominal configuration, with one Philae foot (later identified as the +X foot; see fig. S2) most likely in contact with the nucleus surface (red circle).

The image acquired by camera 4 (fig. S8) also exhibits a scene that would be expected for a successful landing on the nucleus, with good sunlight illumination conditions. The other CONSERT antenna is visible (red circle), in contact with the surface. The images acquired by cameras 3 and 4 have been mosaicked (fig. S9) to show the sunlit part of the nucleus surrounding Philae at the time the images were acquired. The dimensions of the CONSERT antenna (5 mm in diameter, 693 mm long), apparently in contact with the nucleus, enable us to estimate the distance of this cometary material, and the scale of the structures that we identify.

In contrast with the images acquired by cameras 3 and 4, the image acquired by the camera 5 (fig. S10) covers a part of the surface that is entirely in shadow, with a dynamic range limited to 7 ADU only. The –Y foot (fig. S2) is identified on the lower right of the image. The stereo cameras 6 and 7 also face an entirely shadowed part of the local cometary environment (fig. S11), with a dynamic limited to 5 ADU.

The attitude of Philae at the landing site can be in part reconstructed from the CIVA-P images, given the location and geometry of the relevant cameras. Indeed, Philae legs and feet, as well as the CONSERT antennas, can be identified on specific images, the close-ups of which exhibit, through shadows, the direction of illumination. Philae was far from the near-"horizontal" three-legs-resting that was targeted and assumed for the sequence of scientific operations. Philae seems to rest in a hole about its own size, partially shadowed by nearby boulders or cliffs, with the –Y foot pointing downward (most likely stuck in a local cavity), the +X foot resting on the Sun-lighted surface and the +Y foot pointing upward. The landing site is dominated by meter-scale blocks, with a large elongated cliff, starting ~1 m away. These large structures are responsible for Philae being partially shadowed at the time of the FSS, drastically limiting its energy intake for both warming up the internal compartment and supplying the solar panels.

Despite the very low signal level, the three-dimensional (3D) reconstruction of the pair of stereo images illustrates the nucleus topography facing the Philae balcony (figs. S12 to S15). A large fraction of the FOV is at distances close to 1 m (Fig. 2, zone 1). However, distant regions, as far as ~7 m, are observed in other parts of the images (Fig. 2, zone 3). They likely correspond to the continuation of the backlit cliff observed with camera 1 (Fig. 1). The pebbles, blocks, and cliffs observed by CIVA-P at centimeter-to-meter scale can be linked to the rugged terrain and boulders observed by OSIRIS (*3*) at a 20-cm to 20-m scale in the rougher regions of the nucleus.

The surface material imaged by CIVA-P in the immediate vicinity of Philae exhibits a diversity of structures and brightnesses, with two end-members (Fig. 3A). The first are agglomerates of dark granular material, with grain size in the millimeter-to-centimeter range, as evaluated with reference to the diameter (5 mm) of the CONSERT antenna, imaged by camera 4. Several pebble-like grains seem loosely attached to the surface, possibly resulting from a redeposition process. This material, by its texture, looks similar to the "regolith-type" material identified by the ROLIS descent images of the nominal landing site where touchdown took place (*1*); however, this rough morphology could correspond to consolidated terrains rather than dust-covered smooth terrains as revealed by OSIRIS (*4*). Representing the

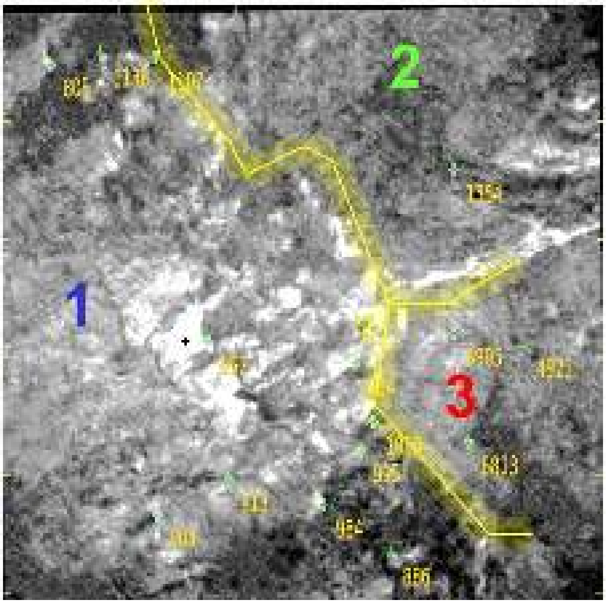

Fig. 2. Three-dimensional reconstruction of the stereo pair. The numbers (yellow) indicate the distance (in millimeters) of the points marked by green crosses. With Philae on its side, the right side of the image (where the most distant regions are observed) is facing up.

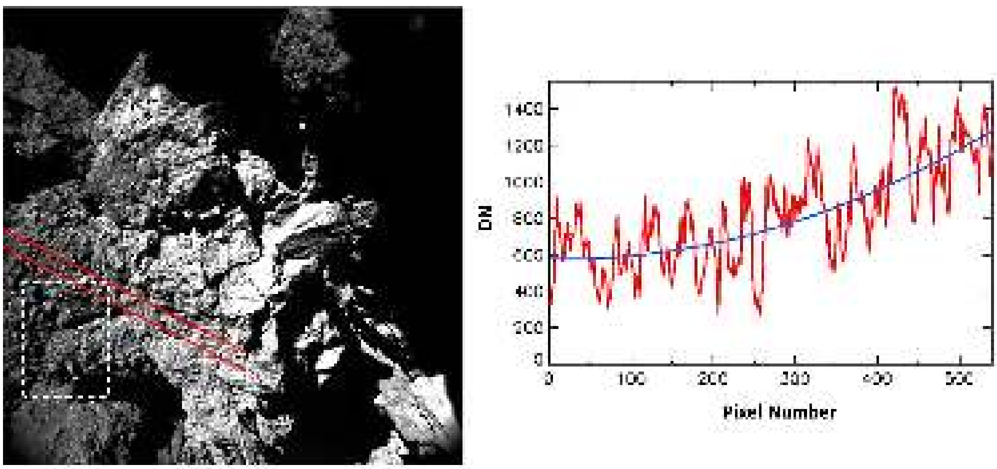

Fig. 3. Surface reflectance. Left: profile (red) along which the signal intensity has been measured on the image corrected for flat-field. Right: signal intensity (in ADU) along the profile and polynomial adjustment (blue). The CONSERT antenna reflectance is ~1200.

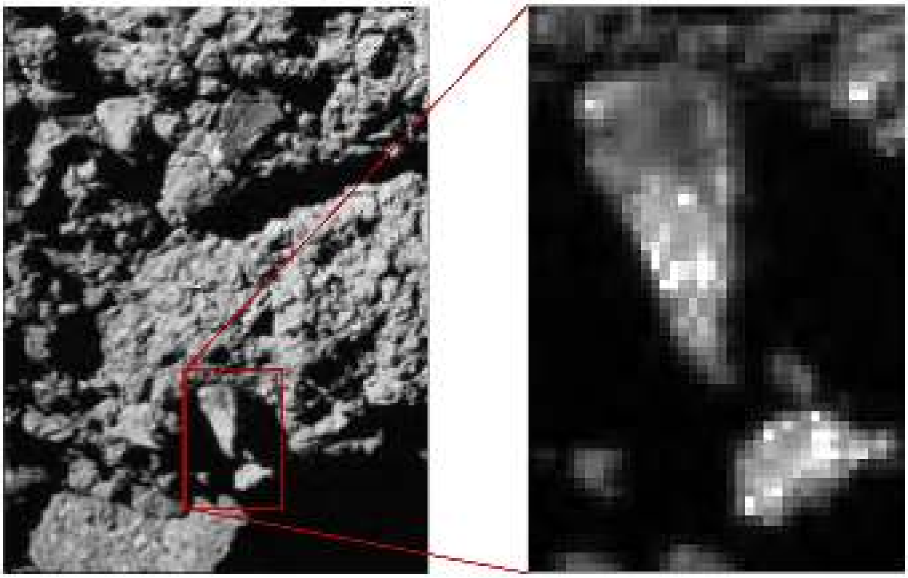

Fig. 4. Enlargement of the white rectangular zone in Fig. 3 (left). The image exhibits reflectance variations at centimeter down to millimeter scale.

second end-member are brighter grains and decametric-scale areas with smoother texture, imaged as saturated pixels on CIVA-P charge-coupled devices.

To obtain a quantitative evaluation of the reflectance of this surface material (Figs. 3 and 4), we used the CONSERT antenna, imaged by camera 4 as a reference, after having performed laboratory imaging of a spare model of the flight antenna using an identical microcamera, from the spare CIVA set. The antenna reflectance varies from 4.5 to 5.9%, for phase angles varying from 50° to 20° (fig. S9). Using the reference to the CONSERT antenna, the absolute reflectance of the nucleus material along the profile varies typically from 3 to 5%. It is in agreement with the OSIRIS and VIRTIS measurements (*3*, *5*), with the illumination geometry accounting for at least part of the variation. The similarity of the reflectance of this material, and of that of the soil mobilized by the touchdown and analyzed by PTOLEMY (*6*) and COSAC (*7*) while bouncing, would indicate its being dominated by carbon-rich species, agglomerated into grains, possibly constituting pristine accreted material.

In contrast to the low-albedo materials that dominate the granular agglomerates, a few brighter spots, as well as larger blocks (mid to bottom right of Fig. 3, left), appear saturated, corresponding to a reflectance of 10% or higher. They could either be mineral grains, with intrinsic reflectance >10%, facets observed with a geometry favoring specular reflection, or icy-rich phases; indeed, fractures, mostly linear, observed both in Fig. 3 (left) and on the cliff (Fig. 1 and fig. S5), are interpreted as resulting from thermal stress driven by the comet trajectory around the Sun. Fractures and cracks are ubiquitous at both grain scale and block scale; they are likely responsible for the fragmentation and the erosion of the nucleus surface.

CIVA-P extends, at a subcentimeter scale, structures observed in the 10-cm to 10-m scale both from the Orbiter (OSIRIS) and the ROLIS descent camera (*3*). CIVA-P indicates that, when observing the nucleus material at a subcentimeter scale, large heterogeneities also appear in texture and/or albedo. Although it is not possible, at this point, to correlate these inhomogeneities with compositional variations, Philae's landing site exhibits a variety of materials translating the cometary diversity and likely preserving their pristine properties.

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SUPPLEMENTARY MATERIALS

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Figs. S1 to S15

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