**Primitive bodies: highlights of the 67P/CG nucleus as observed by ESA Rosetta mission.** S. Fornasier[1,2], M. A. Barucci[1], and M. Fulchignoni[1] , [1] LESIA, Observatoire de Paris, Université PSL, CNRS, Université de Paris, Sorbonne Université, 5 place Jules Janssen, 92195 Meudon, France (sonia.fornasier@obspm.fr, antonella.barucci@obspm.fr, marcello.fulchignoni@obspm.fr), [2] Institut Universitaire de France.

**Introduction:** Comets are primitive small bodies witness of the Solar System formation. Together with asteroids, their study provides important insights on our Solar System formation, composition, and evolution processes. Moreover, comets and primordial asteroids like the B, C and D types, whose composition experienced small changes since their formation, have a high biological importance because they may have enriched our planet of organic and volatile materials favoring the appearance of life.

The deepest investigation of a comet nucleus was recently performed thanks to the Rosetta mission. Launched on 2 March 2004, Rosetta arrived on August 2014 at its target, the comet 67P/Churyumov-Gerasimenko (67P hereafter), and had orbited around it for more than 2 years from 4 AU inbound, to the perihelion passage (1.37 AU) and up to 3.6 AU outbound.

We will present an overview of the main results achieved by the Rosetta mission on the surface, activity, and evolution of comet 67P [1]. These results, coupled with those obtained on Bennu and Ryugu, currently under study by the sample return missions OSIRIS-REx and HAYABUSA2, will cast light on the interpretation of our Solar System formation and evolution, and on the contribution of the small bodies to the appearance of life on the Earth.

**Geomorphology and physical properties:** The 67P's nucleus has a peculiar bilobated shape (Fig. 1) with a surface characterized by a variety of astounding morphological regions including both fragile and consolidated terrains, dusty areas, depressions, pits, boulders, talus, fractures and extensive layering, with layers up to 1 km in length long and having a depth up to 650 m (2, 3). Twenty-six regions were defined (3, 4). The nucleus bulk density is 537.8±0.7 kg $m^{-3}$ and the rotational period is 12.4043±0.0007 h (1, 5). The low density implies a large value of porosity of 70–80%.

The study of the extensive layering revealed that the layers of the main lobe are independent from those of the small lobe, indicating that the comet is a binary objet resulting from the collision at low velocity (1m/s) of two bodies in the primordial Solar System.

The comet surface is dark, with a geometric albedo of 5.9 % at 535 nm (6). Important phase angle reddening effects, i.e. the increase of spectral slope with phase angle, were observed since the first resolved images of the comet, and attributed to the increased contribution of the multiple scattering at large phase angles as the

**Fig. 1**:*The bi-lobated shape of 67P nucleus from images acquired on 3 August 2014 with the OSIRIS instrument, resolution 7 m/px (credits ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA)*

wavelength and albedo increase, plus a contribution of surface roughness effects. The phase reddening effects were observed to change and evolve, together with the surface color, with the heliocentric distances, reaching a minimum at perihelion, where the high activity removed part of the dust mantle.

A number of localized morphological changes were reported for several regions of 67P during the mission. A region with extensive changes is Imhotep, which showed exhumation of structures (boulders and roundish features) by the removal of 4 m dust coating and the appearance of two roundish structures with a diameter of ~240 and 140 m and a height of 5±2 m (7, 8). Extensive changes were also observed in the Aswan site, with a cliff collapse originated from an outburst producing a mass loss of ~$10^6$ kg and exposing water-ice (9). Cliff collapses with exposure of water ice were also observe in the Anhur region (10). Other morphological changes include the sublimation of some thick dust layers (up to 10-15 m in depth) in Anhur, Khonsu and Imhotep (10, 11), and boulder displacements in Khonsu and Anhur region (7, 10, 11). However, even though numerous localized changes were reported, they did not substantially change the cometary landscape, which was very probably shaped much earlier in its history (7).

Boulders of various sizes have been observed on the nucleus, with a cumulative size-frequency distribution represented by a power-law with index of -3.6

globally on the nucleus [12]. Differences in the boulders cumulative size distribution are observed in some areas, notably the smooth Hapi region. The southern hemisphere has a larger number of boulders per $km^2$ than the northern one, consistent with stronger activity, erosion and thermal processes in this hemisphere, which is illuminated during the perihelion passage.

**The 67P'nucleus surface composition:** The OSIRIS cameras and VIRTIS spectrometer have shown that the 67P nucleus has a red spectral behavior with spectral properties similar to those of bare cometary nuclei, of primitive D-type asteroids like the Jupiter Trojans, and of the moderately red transneptunians population (2, 13). The surface is globally dominated by dehydrated and organic-rich refractory materials (13) showing a broad signature in the 2.8-3.6 micron region, and shows some color heterogeneities at different spatial scales. Three kind of terrains, from the spectrally bluer and water ice enriched terrains to the redder ones, associated mostly to dusty regions, have been identified by visible spectrophotometry (6).

Although water is the dominant volatile observed in the coma, exposed water ice on the cometary surface has been detected in relatively small amounts (a few percent) in several regions of the comet (14, 15), and in higher amounts (> 20%) in localized fresh ice patches (16, 9). In the Anhur region there was also the first and unique detection of exposed $CO_2$ ice (17).

Water frost was observed close to the morning shadows in several regions, putting in evidence the diurnal cycle of water (14, 16). Seasonal color and spectral variations have also been observed when the comet approached perihelion, indicating that the increasing activity had progressively shed the surface dust, partially showing the underlying ice-rich layer (16).

The comet nucleus is largely dominated by the refractory material. In fact, the average dust/ice mass ratio is 7.5 inside 67P. Fulle et al. [18] deduced that the nucleus is composed of a mixture of (20 ± 8) % of ices, (4 ± 1) % of Fe sulphides, (22 ± 2) % of silicates and (54 ± 5) % of hydrocarbons, on average volume abundances.

The 67P/CG dark terrains are interpreted as made of a complex mixture of dark disordered poly-aromatic compounds, opaque minerals and several chemical species containing -COOH, $NH_4^+$, $CH_2$ / $CH_3$, -OH (19). The organic rich nature of the 67P nucleus was confirmed also by the results of ROSINA mass spectrometer and COSIMA dust grain analyzer [20, 21, 22]. In fact, more than 60 molecules were detected by Rosina, including complex organics compounds and glycine, the simplest amino acid. Rosina also determined a D/H ratio of 67P three times higher than that of the Earth water (19).

The fact that the 3.2 micron band is ubiquitous (13) on the surface of 67P/CG, and that the erosion rate is important and estimated to be of 1.0±0.5 meters per orbit, globally averaged (23), and even higher locally (~15 m in places) is a clear evidence that the composition of the material at the surface is representative of the non-volatile component of the bulk material and not the result of surface alteration due to space weathering.

**Summary :** We will present the main results on the 67P nucleus obtained by the Rosetta mission, and we will compare them to those of the 2 primitive NEA Bennu and Ryugu, under investigation by the OSIRIS-REx and HAYABUSA2 missions.

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