Cite as: S. Fornasier *et al.*, *Science* 10.1126/science.aag2671 (2016).

Rosetta's comet 67P/Churyumov-Gerasimenko sheds its dusty mantle to reveal its icy nature

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The Rosetta spacecraft has investigated comet 67P/Churyumov-Gerasimenko from large heliocentric distances to its perihelion passage and beyond. We trace the seasonal and diurnal evolution of the colors of the 67P nucleus, finding changes driven by sublimation and recondensation of water ice. The whole nucleus became relatively bluer near perihelion, as increasing activity removed the surface dust, implying that water ice is widespread underneath the surface. We identified large (1500 m^2) ice-rich patches appearing and then vanishing in about 10 days, indicating small-scale heterogeneities on the nucleus. Thin frosts sublimating in a few minutes are observed close to receding shadows, and rapid variations in color seen on extended areas close to the terminator. These cyclic processes are widespread and lead to continuously, slightly varying surface properties.

All cometary nuclei observed to date have appeared to be dark, with only a limited amount of water ice detected in small patches (*1*, *2*), although water is the dominant volatile observed in their coma.

The Rosetta spacecraft has been orbiting comet 67P/Churyumov-Gerasimenko since August 2014, providing the opportunity to continuously investigate its nucleus. The comet has a distinct bi-lobate shape and a complex morphology (*3*–*5*), with a surface dominated by anhydrous and organic-rich refractory materials (*6*). Small amounts of water ice have been identified by the VIRTIS (Visible, Infrared and Thermal Imaging System) spectrometer in different regions (*7*–*9*), and several isolated or clustered bright spots were observed in OSIRIS (Optical, Spectroscopic, and Infrared Remote Imaging System) images and interpreted as exposures of dirty water ice (*9*, *10*).

Here we report on seasonal and diurnal color variations of the surface of 67P's nucleus from observations with the Narrow Angle Camera (NAC) of the OSIRIS imaging system (*11*) onboard Rosetta as caused by the evolution of the dust mantle and exposures of water ice.

We monitored the color evolution of the nucleus from 3.6 AU to perihelion (1.24 AU) and beyond by measuring changes in the spectral slope in the 535-882 nm range.

Comparing the spectral slopes obtained in late August 2015, shortly after perihelion passage, with those obtained in early August 2014 after phase reddening correction (*12*) (Fig. 1, figs. S1 to S3, and table S1), clearly indicates that the nucleus has become relatively bluer, i.e., the spectral slope has decreased as the comet approached perihelion.

Even though only the equatorial regions such as Imhotep (*13*) are common for both datasets (Figs. 1 and fig. S4), due to different seasonal insolation conditions, a decrease of about 30% in the mean spectral slope (*12*) from 3.6 AU to the perihelion passage is measured in the common areas. A decrease of the visible spectral slope was also reported from VIRTIS observations in the August-November 2014 timeframe (*14*). In a water-ice/refractory-material mixture, regions with bluer colors indicate a higher abundance of water ice (*15*, *16*), as demonstrated by VIRTIS observations (*8*, *9*), and as previously observed for 9P/Tempel 1 and 103P/Hartley 2 comets (1, 2).

In addition to the change of color, the amount of phase reddening (the increase of spectral slope with phase angle) decreased by a factor of two when the comet approached perihelion in the 2015 observations compared to those from August 2014 (*12*, *15*), indicating a change in the physical properties of the outermost layer of the nucleus. The relatively blue color of the surface and the decreased phase reddening effect observed at small heliocentric distances suggest that the increasing level of activity has thinned the surface dust coating, partially exposing the underlying ice-rich layer. This result is in agreement with the variation of the sublimation rate with heliocentric distance r reported by (*17*), considerably steeper ($\propto r^{-4.2}$) than the one obtained from modeling considering the shape of the nucleus and seasonal effects (*18*). This steepness can be explained by the observed thinning of the surface dust layer that facilitates the sublimation during the approach to perihelion. Observations at 2.2 AU outbound (fig. S3) show that the comet's colors redden again as the activity decreases and is no longer capable of sustained removal of dust.

The increase in water ice visibility is observed on the whole surface indicating that the composition in terms of dust to ice ratio must be similar at large scales all over the nucleus. This means that even the smooth areas commonly thought to be covered with material that fell back on the surface (18) must be water ice-rich.

We observed and monitored 2 bright patches, of about 1500 m^2 each (Table S2), located in a smooth area of the Anhur/Bes (*13*) regions (Fig. 2, and fig. S4), on images acquired on 27 April-2 May 2015. One of the two patches, B in Fig. 2, was still present in an image acquired on 7 May, yielding a survival time of at least 5-10 days. These features are considerably larger than the meter-scale bright spots previously detected on 67P comet (*10*). The VIRTIS spectrometer detected the presence of CO_2 ice in region A on 21-23 March 2015 that had sublimated in less than 3 weeks (*19*). On 12 April the bright patches were not present yet but these regions were spectrally bluer than the surrounding ones, indicating a higher water ice abundance (Fig. 2). On 27 April and 2 May the bright patches were clearly visible, and showed a relatively flat spectrum, with a maximum reflectance 4 to 6 times brighter than the surrounding regions. A water ice surface abundance of ~25% linearly mixed with the comet dark terrain is needed to match the patches reflectance (*12*). Subsequent images covering the Anhur region were acquired on 4-5 June, revealing that the water ice had fully sublimated from the surface, leaving a layer spectrally indistinguishable from the average nucleus (Fig. 2).

We compute the sublimation rate for this period by applying the thermal model described in (*18*) for both intimate and areal mixtures of refractory material and ice (*12*). The estimated ice loss rate ranged from 1.4 to 2.5 kg day^{-1} m^{-2} for the intimate mixture, and from 0.14 to 0.38 kg day^{-1} m^{-2} for the areal mixture cases. By noting that the permanence of the ice patches was about 10 days, we estimate a solid-ice equivalent thickness between 1.5 and 27 mm for the ice patches. The actual thickness of this layer will be up to a factor 10 higher due to porosity of the dust/ice mixture.

The appearance and disappearance of water ice patches shows that the level of activity is varying on time scales that are short compared to seasonal changes of the illumination. These ice-rich patches indicate a variation of the water ice content in the uppermost layers pointing to local compositional heterogeneities with scales of 10s of meters on 67P's nucleus. The huge width-to-depth ratio observed in the ice patches would suggest a near-surface solar-driven processing being responsible for enhancement of local ice abundance, resulting from the recondensation of volatiles and sintering of the subsurface material during previous perihelion passages. Laboratory results from KOSI (KOmetenSImulation) experiments had shown that a considerable fraction of sublimating ice can be redeposited instead of being released through the dust mantle (*20*). Numerical simulations show that a hardened layer may form beneath a fine dust mantle (*21*), hard layer that was detected by the Philae lander in the Abydos site (*22*). The composition of the icy patches may be representative of the comet's near-surface. Occasional local removal of the overlying mantling material could expose the underlying layer, leading to an icy surface for limited periods of time.

Approaching perihelion, the nucleus has shown considerable diurnal color variations on extended areas and the occurrence of water frost close to morning shadows. This is evident on the Imhotep region, where morphological changes were observed (*23*). Areas just emerging from the shadows are spectrally bluer than their surroundings (Fig. 3A), while 40 min later, once fully illuminated, their spectral slope has increased (Fig. 3B). This phenomenon, observed during other color sequences acquired in June-July 2015, and seen at dawn on different areas on both lobes of the comet (*12*) (fig. S5 and movie S1), is periodic. We interpret the relatively blue surface at dawn as the presence of additional water frost that condensed during the previous night.

We also observe the presence of fronts of bright material in the illuminated regions close to rapidly traveling shadows cast by local topography (Fig. 3). A water rich fringe near shadows at the Hapi/Hathor transition was also observed by VIRTIS (*7*). The bright fronts move with the shadows. Modeling of the illumination (fig. S6 and movie S2) shows that the extent of these bright features directly correlates with the shadow travel speed, being wider where the shadow speed is faster, and narrower where the shadow speed is slower.

These fronts are about 6 times brighter than the mean comet reflectance. Their spectrum is globally flat with a flux enhancement in the ultraviolet (Fig. 4 and fig. S7), similar to what observed on blue regions of comet Tempel 1 (*1*). An abundance of about 17% water frost linearly mixed with the comet dark terrain is needed to match the reflectance of the bright fronts (*12*). We interpret these bright features as surface frost, formed when water vapor released from the subsurface recondenses after sunset, that rapidly sublimates when exposed to the Sun. Molecules in the inner coma may also be back-scattered to the nucleus surface and recondense, contributing to the frost formation (*24*, *25*). From the shadow travel speed and the extent of the frost fronts we calculate an ice permanence time of about 3 min (*12*). From thermal modeling using intimate mixture we estimate a water-ice sublimation rate of about 4 g m^{-2} min^{-1}, from which we infer a total ice content of about 12 g m^{-2} for the frost layer, which is extremely thin (thickness ~10-15 μm of equivalent solid ice, Table S3). If we assume an areal mixing, the sublimation rate and total ice content are 8 times lower. In the absence of direct temperature measurements of the frost it is impossible to discriminate whether areal or intimate mixture represent the correct thermal model (*1*). In either case, the exposed ice is depleted on short time scales. In the case of geographical mixing, however, sublimation rates at the time of the observations would be so low, that a frost permanence time of 3 min would imply a frost layer of the order of ~1 μm solid-ice equivalent. Since it is questionable whether such a thin layer would be optically thick, it appears more likely that the frost patches are intimately mixed with the refractory material. Similarly to the observed diurnal color variations, the recondensation of frosts is also a periodic phenomenon that takes place close to topographic shadows, as indicated in Figs. 3 and 4.

The long term observations of 67P provide information on the composition of the outermost layers of the nucleus. They reveal that ice is abundant just beneath the surface on the whole nucleus, which, most of the time, is covered by a thin layer of dust. Hence the apparent surface composition is globally dominated by anhydrous refractory materials (*6*). The increasing cometary activity while approaching the Sun progressively thins the dust surface layer partially exposing the ice-richer sub-surface, yielding nucleus's colors that are bluer relative to those at large heliocentric distances.

OSIRIS observations show that mixtures having high abundance (up to ~30%) of water ice are occasionally locally present on the nucleus and that the lifetime of exposed ice is short, of the order of few minutes to few days. However, no dust-free ice patches were observed even during the peak of activity near perihelion, indicating that water ice and dust are well mixed within the resolution limit of the images (~2 m $pixel^{-1}$). Most of the bright features are observable only at high spatial resolution and under particular insolation conditions, i.e., close to the morning shadows. Similar phenomena presumably take place on other comets, explaining why cometary nuclei are so dark even if they have significant water ice abundance. The extended bright patches observed in the Anhur/Bes regions indicate a local enrichment of water ice, pointing to compositional heterogeneities in the uppermost layers of comet 67P.

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ACKNOWLEDGMENTS

OSIRIS was built by a consortium led by the Max-Planck-Institut für Sonnensystemforschung, Göttingen, Germany, in collaboration with CISAS, University of Padova, Italy, the Laboratoire d'Astrophysique de Marseille, France, the Instituto de Astrofísica de Andalucia, CSIC, Granada, Spain, the Scientific Support Office of the European Space Agency, Noordwijk, The Netherlands, the Instituto Nacional de Técnica Aeroespacial, Madrid, Spain, the Universidad Politéchnica de Madrid, Spain, the Department of Physics and Astronomy of Uppsala University, Sweden, and the Institut für Datentechnik und Kommunikationsnetze der Technischen Universität Braunschweig, Germany. The support of the contributing research institutes of the OSIRIS consortium and of the national funding agencies of Germany (DLR), France (CNES), Italy (ASI), Spain (MEC), Sweden (SNSB), and the ESA Technical Directorate is gratefully acknowledged. M.F.A. acknowledges NASA funding through Jet Propulsion Laboratory contract no. 1267923 and from the Akademie der Wissenschaften zu Göttingen. W.-H.I acknowledges the Ministry of Science and Technology, Taiwan (grant no. NSC 102-2112-M-008) and Macau university of Science and Technology (grant no. FDCT 017/2014/A1). We thank the ESA teams at European Space Astronomy Centre, European Space Operations Centre, and European Space Research and Technology Centre for their work in support of the Rosetta mission. P. H. Hasselmann and D. Perna are acknowledged for helpful discussion. Rosetta/OSIRIS data are available through the ESA's Planetary Science Archive (PSA) http://www.cosmos.esa.int/web/psa/rosetta. Some images used in this paper which are not yet available at PSA can be downloaded from the MPS OSIRIS website at https://planetgate.mps.mpg.de/WebFileShare/Released_Images/Fornasier+Science.

SUPPLEMENTARY MATERIALS

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1 June 2016; accepted 27 October 2016
Published online 17 November 2016

10.1126/science.aag2671

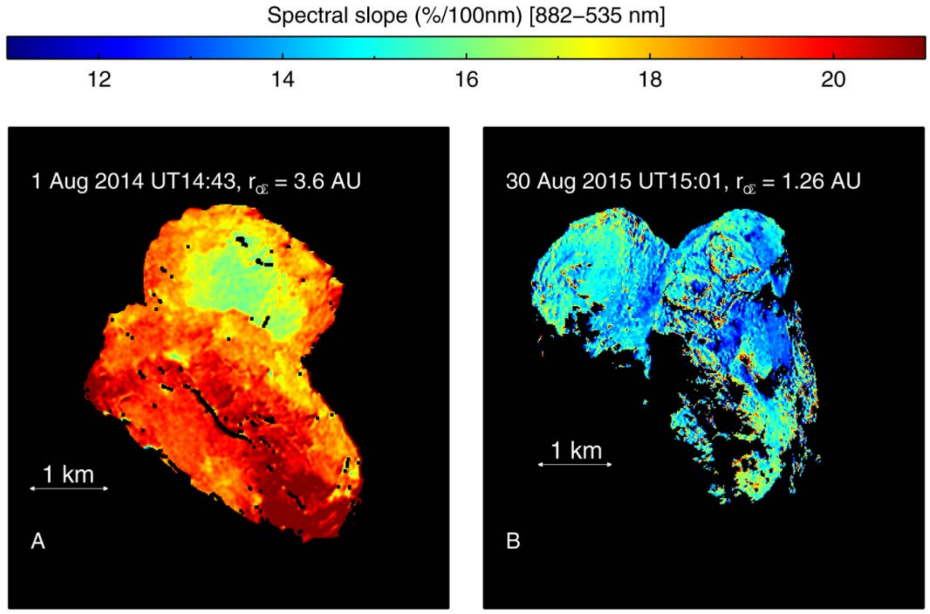

Fig. 1. Spectral slope evolution with heliocentric distance. The August 2014 image was corrected for the phase reddening from 10° to 70° using the coefficients published in (*15*) to match the viewing geometry on the right. See fig. S4 for the morphological regions context.

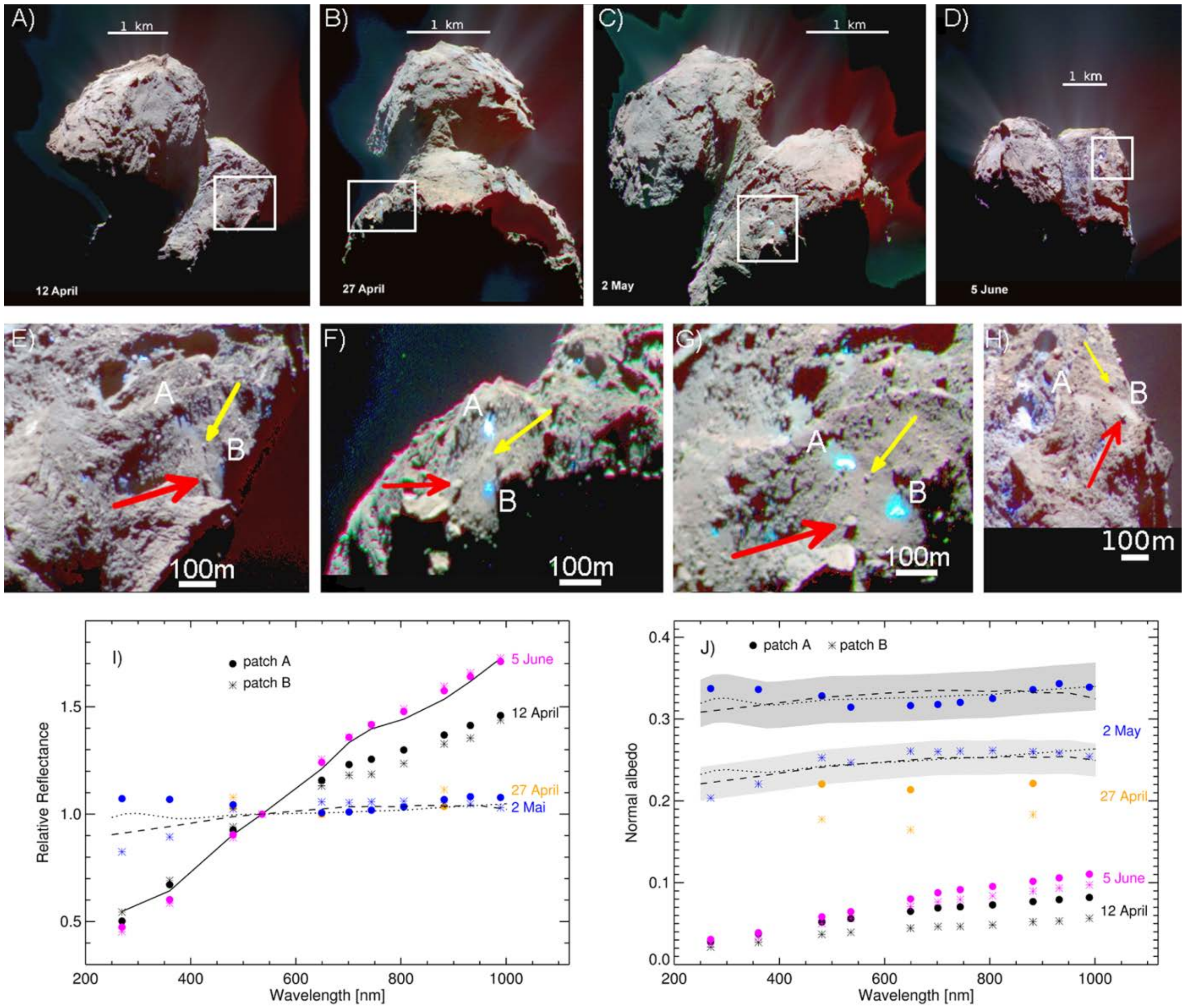

Fig. 2. Anhur/Bes ice-rich patches. Composite images (882 nm, 649 nm and 480nm filters) showing the appearance of the bright patches in the Anhur/Bes regions (**A** to **D** panels), and associated zooms (**E** to **H** panels, the arrows indicate two common boulders). The reflectance relative to 535 nm and the normal albedo are represented in the (**I**) and (**J**) panels. The black line represents the mean spectrum of the comet from a region close to the patches. Dashed and dotted lines (J) show the best fit spectral models to the patches (in gray the associated uncertainty), produced by the linear mixture of the comet dark terrain (12) enriched with 21 ± 3% of water ice (dashed line), or 23 ± 3% of water frost (dotted line) for patch B, and with 29 ± 3% of water ice (dashed line), or 32 ± 3% of water frost (dotted line) for patch A.

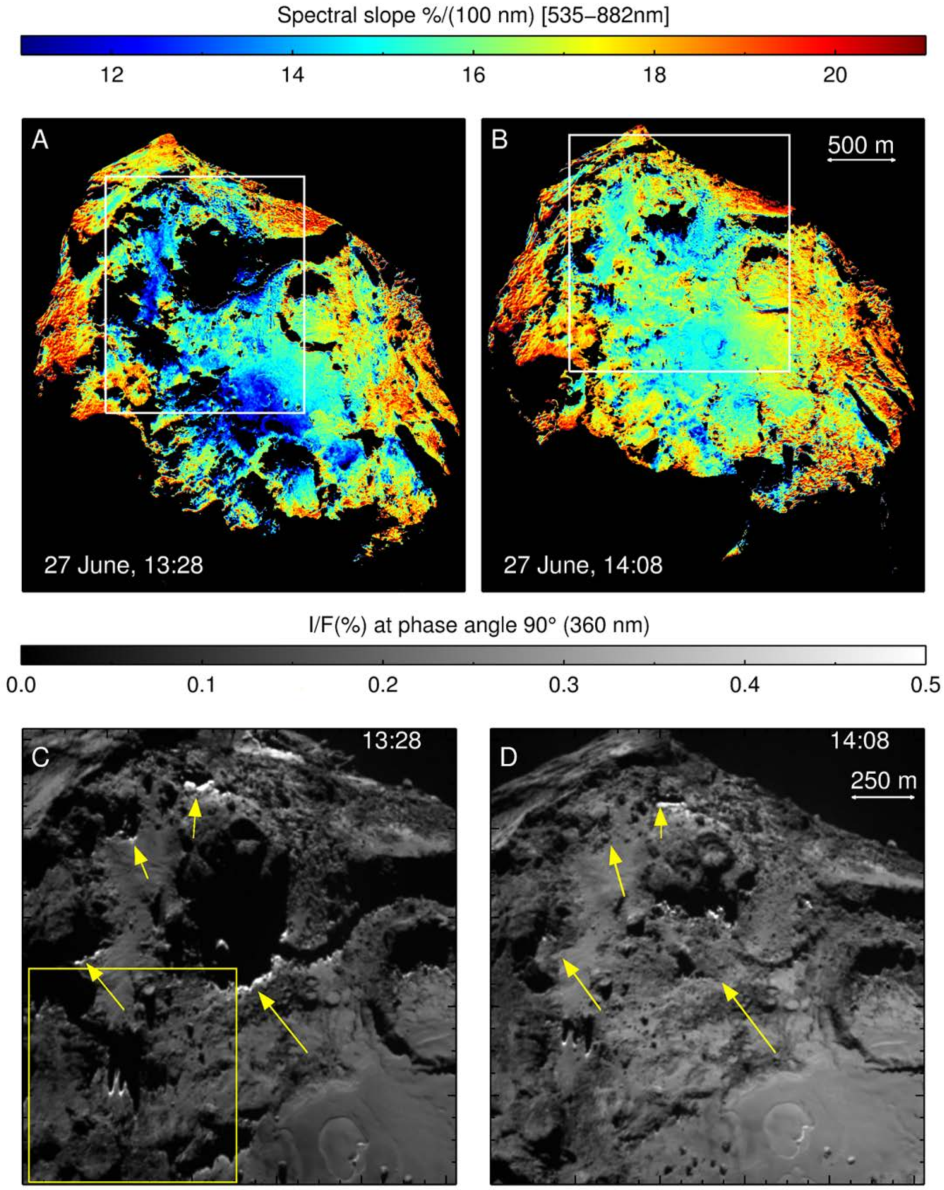

Fig. 3. Spectral slope changes and frost sublimation. (**A** and **B**) Spectral slope maps of Imhotep region taken 40 min apart. The Sun is toward the top. (**C** and **D**) Zoom in radiance factor (I/F) of the regions indicated by the white rectangle on A-B panels showing morning frosts (evidenced by the yellow arrows), disappearing and moving with shadows. The yellow rectangular region in the C panel indicates the area where the same frost structures are seen 2 weeks later, and analyzed in Fig. 4.

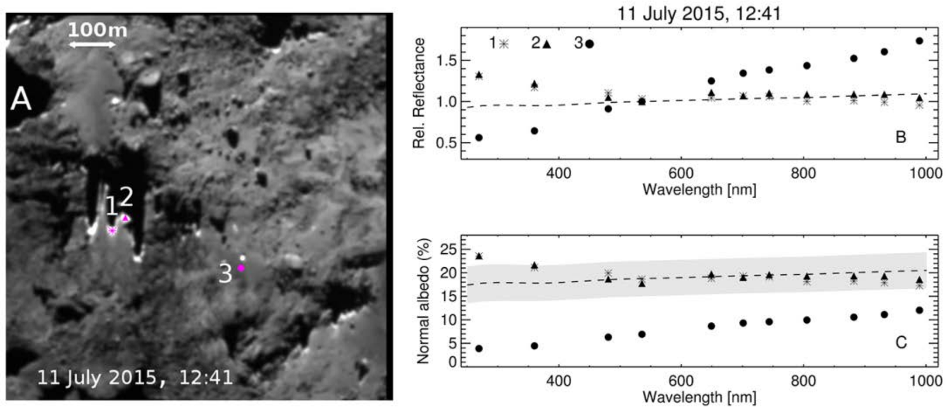

Fig. 4. Reflectance of frost fronts. (**A**) Bright fronts seen close to shadows on Imhotep region (see Fig. 3 for the context). (**B** and **C**) Reflectance normalized at 535 nm and normal albedo of 3 selected regions (magenta points in A). The dashed line represents the best fit model, with uncertainties in gray, including 17 ± 4% of water frost linearly mixed to the comet dark terrain.

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Rosetta's comet 67P/Churyumov-Gerasimenko sheds its dusty mantle to reveal its icy nature

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published online November 17, 2016

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