

# Rosetta begins its COMET TALE

By M. G. G. T. Taylor,<sup>1\*</sup> C. Alexander,<sup>2</sup> N. Altobelli,<sup>3</sup> M. Fulle,<sup>4</sup> M. Fulchignoni,<sup>5</sup> E. Grün,<sup>6</sup> P. Weissman<sup>2</sup>

Comets are the best sample of primitive solar nebula material presently available to us, dating back 4.57 billion years to the origin of our planetary system. Past missions to comets have all been “fast flybys”: They provided only a snapshot view of the dust and ice nucleus, the nebulous coma surrounding it, and how the solar wind interacts with both of these components. Such space-based investigations of comets began in the 1980s with a flotilla of spacecraft: the European Space Agency’s (ESA’s) first deep space mission, Giotto, which pursued comet 1P/Halley; Deep Space 1 at 19P/Borrelly; Stardust at 81P/Wild 2; Deep Impact and Stardust NeXT at 9P/Tempel; and EPOXI at 103P/Hartley 2.

Rosetta is now taking a more prolonged look. The spacecraft is an ESA mission, with contributions from member states and from NASA, and it currently orbits the Jupiter family comet 67P/Churyumov-Gerasimenko (67P). Rosetta met the comet nucleus on 6 August 2014, at 3.7 astronomical units (AU) from the Sun, and delivered the Philae lander to the nucleus surface on 12 November 2014, when the comet was 3.0 AU from the Sun.

Rosetta is uniquely positioned to further the understanding of these primitive bodies, having revealed an unusual and fascinating object. After rendezvous, the Rosetta spacecraft moved from 100 km above the comet to a bound orbit only ~10 km away. This early period of the mission has revealed previously unseen details of a comet nucleus, as Rosetta’s instruments recorded measurements that were once impossible. This issue of *Science* contains the first published scientific results from Rosetta at comet 67P.

The surface of the comet shows evidence of many active processes and is highly complex. The solid nucleus is an object for which neither horizontal nor vertical variations are modest (Thomas *et al.*, this issue). The current comet shape model suggests that the mass is  $10^{13}$  kg (about 100 million times the mass of the international space station), with a bulk density of ~470 kg/m<sup>3</sup> (similar to cork, wood, or aerogel). The low mass and density values strongly constrain the composition and internal structure of the nucleus, implying a relatively fluffy nature, with a porosity of 70 to 80% (Sierks *et al.*, this issue). The nucleus surface itself appears rich in organic materials, with little sign of water ice (Capaccioni *et al.*, this issue).

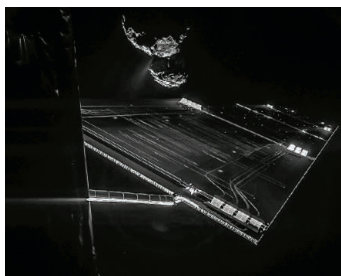
The coma produced by ices sublimating from the nucleus is highly variable, displaying large diurnal and possibly seasonal changes. For example, both atomic H and O have been detected close to the nucleus and vary with time, probably stemming from electron impact

dissociation of venting H<sub>2</sub>O vapor. The total H<sub>2</sub>O gas production rates varied from  $1 \times 10^{25}$  molecules per second in early June 2014 to  $4 \times 10^{25}$  molecules per second in early August, broadly consistent with predictions. In August, water outflow from the surface varied by a factor of at least 5, owing to the effects of terrain, comet shape, and daily illumination changes and possibly other factors (Gulkis *et al.*, this issue). The science team reports the detection of several molecules, including H<sub>2</sub><sup>17</sup>O, H<sub>2</sub><sup>18</sup>O, CO, and CO<sub>2</sub>, and assessed their time variability and heterogeneous distribution (Hässig *et al.*, this issue). A high D/H ratio in water,  $5.3 \times 10^{-4}$ , was measured, which precludes the idea that Jupiter family comets contain solely Earth ocean-like water (Altwegg *et al.*, this issue). As observed at 3.6 AU from the Sun, a cloud of about  $10^5$  grains (larger than 5 cm) surrounds the nucleus in bound orbits, likely from the previous perihelion passage. The nucleus currently emits dust grains up to 2 cm in size, giving a dust/gas mass ratio of  $4 \pm 2$  averaged over the sunlit nucleus surface (Rotundi *et al.*, this issue). This is higher than generally accepted for comets. In a progressive series of observations, Rosetta observed the emergence of an energetic ion environment from a low-activity comet nucleus under the influence of the solar wind (Nilsson *et al.*, this issue).

The data presented here allow us to build a detailed portrait of comet 67P. These initial observations provide a reference description of the global shape, the surface morphology and composition, and the bulk physical properties of the nucleus. Subsequent measurements with the orbiter and with the Philae lander will further describe the comet over time. Rosetta will follow the comet at close range through its closest approach to the Sun, perihelion, in August 2015, and then as the comet moves away from the Sun. The spacecraft will perform many flybys that will allow the onboard instruments to measure the evolution of the nucleus and coma with respect to the comet’s initial state, defined by the data presented here.

The Rosetta mission has begun to explore our origins, thanks to the efforts of thousands of people at ESA, NASA, industrial partners, and space agencies and to engineers and scientists from around the world. For more than 25 years, they dreamed of these moments when they designed, developed, and launched the Rosetta spacecraft and then followed its interplanetary journey, watched over its long sleep, and woke it from hibernation. These first papers are dedicated to all of them.

10.1126/science.aaa4542



<sup>1</sup>European Space Research and Technology Centre, Science and Robotic Exploration Directorate, European Space Agency, Noordwijk, Netherlands. <sup>2</sup>Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA. <sup>3</sup>European Space Astronomy Centre, Science and Robotic Exploration Directorate, European Space Agency, Madrid, Spain. <sup>4</sup>INAF-Osservatorio Astronomico, Trieste, Italy. <sup>5</sup>Laboratoire d'Etudes Spatiales et d'Instrumentation en Astrophysique, Observatoire de Paris, France. <sup>6</sup>Max-Planck-Institut für Kernphysik, Heidelberg, Germany. \*Corresponding author. E-mail: mtaylor@cosmos.esa.int

## On the nucleus structure and activity of comet 67P/Churyumov-Gerasimenko

H. Sierks,\* C. Barbieri, P. L. Lamy, R. Rodrigo, D. Koschny, H. Rickman, H. U. Keller, J. Agarwal, M. F. A'Hearn, F. Angrilli, A.-T. Auger, M. A. Barucci, J.-L. Bertaux, I. Bertini, S. Besse, D. Bodewits, C. Capanna, G. Cremonese, V. Da Deppo, B. Davidsson, S. Debei, M. De Cecco, F. Ferri, S. Fornasier, M. Fulle, R. Gaskell, L. Giacomini, O. Groussin, P. Gutierrez-Marques, P. J. Gutiérrez, C. Güttler, N. Hoekzema, S. F. Hviid, W.-H. Ip, L. Jorda, J. Knollenberg, G. Kovacs, J.-R. Kramm, E. Kührt, M. Küppers, F. La Forgia, L. M. Lara, M. Lazzarin, C. Leyrat, J. J. Lopez Moreno, S. Magrin, S. Marchi, F. Marzari, M. Massironi, H. Michalik, R. Moissl, S. Mottola, G. Naletto, N. Oklay, M. Pajola, M. Pertile, F. Preusker, L. Sabau, F. Scholten, C. Snodgrass, N. Thomas, C. Tubiana, J.-B. Vincent, K.-P. Wenzel, M. Zaccariotto, M. Pätzold

Images from the OSIRIS scientific imaging system onboard Rosetta show that the nucleus of 67P/Churyumov-Gerasimenko consists of two lobes connected by a short neck. The nucleus has a bulk density less than half that of water. Activity at a distance from the Sun of  $>3$  astronomical units is predominantly from the neck, where jets have been seen consistently. The nucleus rotates about the principal axis of momentum. The surface morphology suggests that the removal of larger volumes of material, possibly via explosive release of subsurface pressure or via creation of overhangs by sublimation, may be a major mass loss process. The shape raises the question of whether the two lobes represent a contact binary formed 4.5 billion years ago, or a single body where a gap has evolved via mass loss.

The list of author affiliations is available in the full article online.

\*Corresponding author. E-mail: sierks@mps.mpg.de Cite as H. Sierks *et al.*, *Science* **347**, aaa1044 (2015).

Read the full article at <http://dx.doi.org/10.1126/science.aaa1044>

## Dust measurements in the coma of comet 67P/Churyumov-Gerasimenko inbound to the Sun

A. Rotundi,\* H. Sierks, V. Della Corte, M. Fulle, P. J. Gutierrez, L. Lara, C. Barbieri, P. L. Lamy, R. Rodrigo, D. Koschny, H. Rickman, H. U. Keller, J. J. López-Moreno, M. Accolla, J. Agarwal, M. F. A'Hearn, N. Altobelli, F. Angrilli, M. A. Barucci, J.-L. Bertaux, I. Bertini, D. Bodewits, E. Bussoletti, L. Colangeli, M. Cosi, G. Cremonese, J.-F. Crifo, V. Da Deppo, B. Davidsson, S. Debei, M. De Cecco, F. Esposito, M. Ferrari, S. Fornasier, F. Giovane, B. Gustafson, S. F. Green, O. Groussin, E. Grün, C. Güttler, M. L. Herranz, S. F. Hviid, W. Ip, S. Ivanovski, J. M. Jerónimo, L. Jorda, J. Knollenberg, R. Kramm, E. Kührt, M. Küppers, M. Lazzarin, M. R. Leese, A. C. López-Jiménez, F. Lucarelli, S. C. Lowry, F. Marzari, E. Mazzotta Epifani, J. A. M. McDonnell, V. Mennella, H. Michalik, A. Molina, R. Morales, F. Moreno, S. Mottola, G. Naletto, N. Oklay, J. L. Ortiz, E. Palomba, P. Palumbo, J.-M. Perrin, J. Rodríguez, L. Sabau, C. Snodgrass, R. Sordini, N. Thomas, C. Tubiana, J.-B. Vincent, P. Weissman, K.-P. Wenzel, V. Zakharov, J. C. Zarnecki

Critical measurements for understanding accretion and the dust/gas ratio in the solar nebula, where planets were forming 4.5 billion years ago, are being obtained by the GIADA (Grain Impact Analyser and Dust Accumulator) experiment on the European Space Agency's Rosetta spacecraft orbiting comet 67P/Churyumov-Gerasimenko. Between 3.6 and 3.4 astronomical units inbound, GIADA and OSIRIS (Optical, Spectroscopic, and Infrared Remote Imaging System) detected 35 outflowing grains of mass  $10^{-10}$  to  $10^{-7}$  kilograms, and 48 grains of mass  $10^{-5}$  to  $10^{-2}$  kilograms, respectively. Combined with gas data from the MIRO (Microwave Instrument for the Rosetta Orbiter) and ROSINA



(Rosetta Orbiter Spectrometer for Ion and Neutral Analysis) instruments, we find a dust/gas mass ratio of  $4 \pm 2$  averaged over the sunlit nucleus surface. A cloud of larger grains also encircles the nucleus in bound orbits from the previous perihelion. The largest orbiting clumps are meter-sized, confirming the dust/gas ratio of 3 inferred at perihelion from models of dust comae and trails.

The list of author affiliations is available in the full article online.

\*Corresponding author. E-mail: [rotundi@uniparthenope.it](mailto:rotundi@uniparthenope.it) Cite as A. Rotundi *et al.*, *Science* **347**, aaa3905 (2015). Read the full article at <http://dx.doi.org/10.1126/science.aaa3905>

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

**F. Capaccioni,\* A. Coradini, G. Filacchione, S. Erard, G. Arnold, P. Drossart, M. C. De Sanctis, D. Bockelee-Morvan, M. T. Capria, F. Tosi, C. Leyrat, B. Schmitt, E. Quirico, P. Cerroni, V. Mennella, A. Raponi, M. Ciarniello, T. McCord, L. Moroz, E. Palomba, E. Ammannito, M. A. Barucci, G. Bellucci, J. Benkhoff, J. P. Bibring, A. Blanco, M. Blecka, R. Carlson, U. Carsenty, L. Colangeli, M. Combes, M. Combi, J. Crovisier, T. Encrenaz, C. Federico, U. Fink, S. Fonti, W. H. Ip, P. Irwin, R. Jaumann, E. Kuehrt, Y. Langevin, G. Magni, S. Mottola, V. Orofino, P. Palumbo, G. Piccioni, U. Schade, F. Taylor, D. Tiphene, G. P. Tozzi, P. Beck, N. Biver, L. Bonal, J.-Ph. Combe, D. Despan, E. Flamini, S. Fornasier, A. Frigeri, D. Grassi, M. Gudipati, A. Longobardo, K. Markus, F. Merlin, R. Orosei, G. Rinaldi, K. Stephan, M. Cartacci, A. Cicchetti, S. Giuppi, Y. Hello, F. Henry, S. Jacquino, R. Noschese, G. Peter, R. Politi, J. M. Reess, A. Semery**

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  $0.060 \pm 0.003$  at 0.55 micrometers), the spectral slopes in visible and infrared ranges (5 to 25 and 1.5 to 5%  $\text{k}\text{\AA}^{-1}$ ), and the broad absorption feature in the 2.9- to 3.6- $\mu\text{m}$  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.

The list of author affiliations is available in the full article online.

\*Corresponding author. E-mail: [fabrizio.capaccioni@iaps.inaf.it](mailto:fabrizio.capaccioni@iaps.inaf.it) Cite as F. Capaccioni *et al.*, *Science* **347**, aaa0628 (2015). Read the full article at <http://dx.doi.org/10.1126/science.aaa0628>

## Birth of a comet magnetosphere: A spring of water ions

**H. Nilsson,\* G. Stenberg-Wieser, E. Behar, C. S. Wedlund, H. Gunell, M. Yamauchi, R. Lundin, S. Barabash, M. Wieser, C. Carr, E. Cupido, J. Burch, A. Fedorov, J.-A. Sauvaud, H. Koskinen, E. Kallio, J.-P. LEBRETON, A. Eriksson, N. Edberg, R. Goldstein, P. Henri, C. Koenders, P. Mokashi, Z. Nemeth, I. Richter, K. Szego, M. Volwerk, C. Vallat, M. Rubin**

The Rosetta mission shall accompany comet 67P/Churyumov-Gerasimenko from a heliocentric distance of  $>3.6$  astronomical units through perihelion passage at 1.25 astronomical units, spanning low and maximum activity levels. Initially, the solar wind permeated the thin comet atmosphere formed from sublimation, until the size and plasma pressure of the ionized atmosphere

PHOTO: ESA/ROSETTA/MPS FOR OSIRIS TEAM, MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA

defined its boundaries: A magnetosphere is born. Using the Rosetta Plasma Consortium Ion Composition Analyzer, we traced the evolution from the first detection of water ions to when the atmosphere begins repelling the solar wind (~3.3 astronomical units), and we report the spatial structure of this early interaction. The near-comet water population comprises accelerated ions (<800 electron volts), produced upstream of Rosetta, and lower-energy locally produced ions; we estimate the fluxes of both ion species and energetic neutral atoms.

The list of author affiliations is available in the full article online.

\*Corresponding author. E-mail: [hans.nilsson@irf.se](mailto:hans.nilsson@irf.se) Cite as H. Nilsson *et al.*, *Science* **347**, aaa0571 (2015).

Read the full article at <http://dx.doi.org/10.1126/science.aaa0571>

## The morphological diversity of comet 67P/Churyumov-Gerasimenko

N. Thomas,\* H. Sierks, C. Barbieri, P. L. Lamy, R. Rodrigo, H. Rickman, D. Koschny, H. U. Keller, J. Agarwal, M. F. A'Hearn, F. Angrilli, A.-T. Auger, M. A. Barucci, J.-L. Bertaux, I. Bertini, S. Besse, D. Bodewits, G. Cremonese, V. Da Deppo, B. Davidsson, M. De Cecco, S. Debei, M. R. El-Maarry, F. Ferri, S. Fornasier, M. Fulle, L. Giacomini, O. Groussin, P. J. Gutierrez, C. Güttler, S. F. Hviid, W.-H. Ip, L. Jorda, J. Knollenberg, J.-R. Kramm, E. Kührt, M. Küppers, F. La Forgia, L. M. Lara, M. Lazzarin, J. J. Lopez Moreno, S. Magrin, S. Marchi, F. Marzari, M. Massironi, H. Michalik, R. Moissl, S. Mottola, G. Naletto, N. Oklay, M. Pajola, A. Pommerol, F. Preusker, L. Sabau, F. Scholten, C. Snodgrass, C. Tubiana, J.-B. Vincent, K.-P. Wenzel

Images of comet 67P/Churyumov-Gerasimenko acquired by the OSIRIS (Optical, Spectroscopic and Infrared Remote Imaging System) imaging system onboard the European Space Agency's Rosetta spacecraft at scales of better than 0.8 meter per pixel show a wide variety of different structures and textures. The data show the importance of airfall, surface dust transport, mass wasting, and insolation weathering for cometary surface evolution, and they offer some support for subsurface fluidization models and mass loss through the ejection of large chunks of material.

The list of author affiliations is available in the full article online.

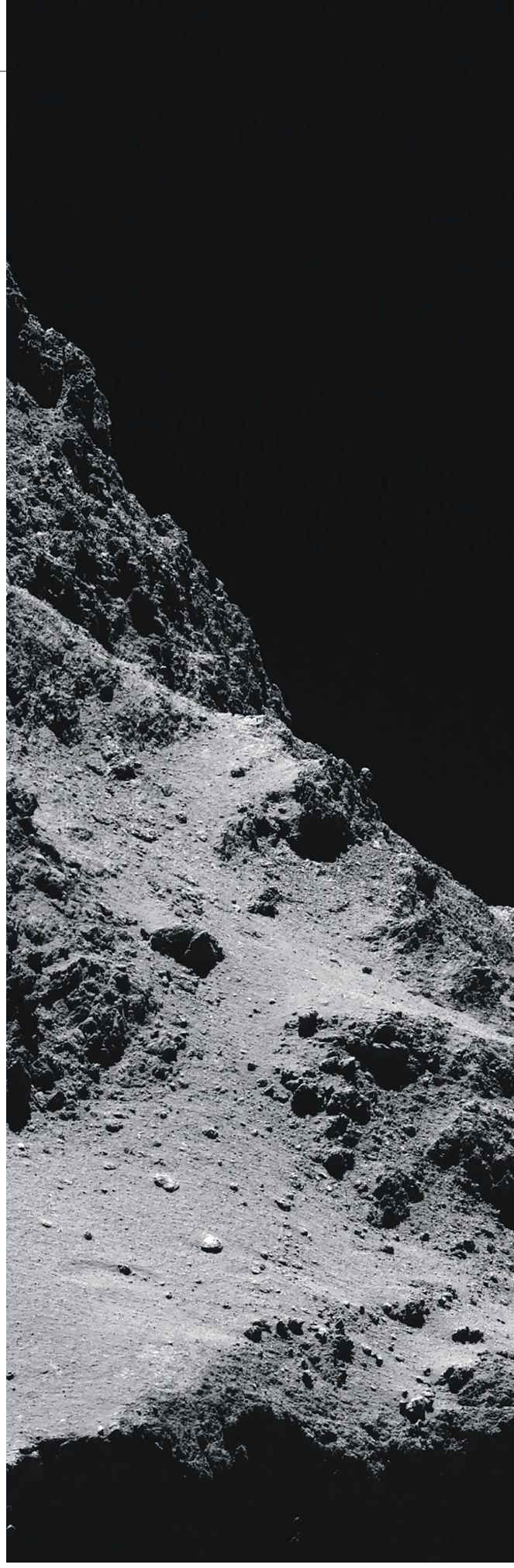
\*Corresponding author. E-mail: [nicolas.thomas@space.unibe.ch](mailto:nicolas.thomas@space.unibe.ch) Cite as N. Thomas *et al.*, *Science* **347**,

aaa0440 (2015). Read the full article at <http://dx.doi.org/10.1126/science.aaa0440>

## 67P/Churyumov-Gerasimenko, a Jupiter family comet with a high D/H ratio

K. Altwegg,\* H. Balsiger, A. Bar-Nun, J. J. Berthelier, A. Bieler, P. Bochsler, C. Briois, U. Calmonte, M. Combi, J. De Keyser, P. Eberhardt, B. Fiethe, S. Fuselier, S. Gasc, T. I. Gombosi, K.C. Hansen, M. Hässig, A. Jäckel, E. Kopp, A. Korth, L. LeRoy, U. Mall, B. Marty, O. Mousis, E. Neefs, T. Owen, H. Rème, M. Rubin, T. Sémon, C.-Y. Tzou, H. Waite, P. Wurz

The provenance of water and organic compounds on Earth and other terrestrial planets has been discussed for a long time without reaching a consensus. One of the best means to distinguish between different scenarios is by determining the deuterium-to-hydrogen (D/H) ratios in the reservoirs for comets and Earth's oceans. Here, we report the direct in situ measurement of the D/H ratio in the Jupiter family comet 67P/Churyumov-Gerasimenko by the ROSINA mass spectrometer aboard the European Space Agency's Rosetta spacecraft, which is found to be  $(5.3 \pm 0.7) \times 10^{-4}$ —that is, approximately three times the terrestrial value. Previous cometary measurements and our new finding suggest a wide range of D/H ratios in the



water within Jupiter family objects and preclude the idea that this reservoir is solely composed of Earth ocean-like water.

The list of author affiliations is available in the full article online.

\*Corresponding author. E-mail: [altwegg@space.unibe.ch](mailto:altwegg@space.unibe.ch) Cite as K. Altwegg *et al.*, *Science* **347**, 1261952 (2015).

Read the full article at <http://dx.doi.org/10.1126/science.1261952>

## Time variability and heterogeneity in the coma of 67P/Churyumov-Gerasimenko

M. Hässig, \* K. Altwegg, H. Balsiger, A. Bar-Nun, J. J. Berthelier, A. Bieler, P. Bochler, C. Briois, U. Calmonte, M. Combi, J. De Keyser, P. Eberhardt, B. Fiethe, S. A. Fuselier, M. Galand, S. Gasc, T. I. Gombosi, K. C. Hansen, A. Jäckel, H. U. Keller, E. Kopp, A. Korth, E. Kührt, L. Le Roy, U. Mall, B. Marty, O. Mousis, E. Neefs, T. Owen, H. Rème, M. Rubin, T. Sémon, C. Tornow, C.-Y. Tzou, J. H. Waite, P. Wurz

Comets contain the best-preserved material from the beginning of our planetary system. Their nuclei and comae composition reveal clues about physical and chemical conditions during the early solar system when comets formed. ROSINA (Rosetta Orbiter Spectrometer for Ion and Neutral Analysis) onboard the Rosetta spacecraft has measured the coma composition of comet 67P/Churyumov-Gerasimenko with well-sampled time resolution per rotation. Measurements were made over many comet rotation periods and a wide range of latitudes. These measurements show large fluctuations in composition in a heterogeneous coma that has diurnal and possibly seasonal variations in the major outgassing species: water, carbon monoxide, and carbon dioxide. These results indicate a complex coma-nucleus relationship where seasonal variations may be driven by temperature differences just below the comet surface.

The list of author affiliations is available in the full article online.

\*Corresponding author. E-mail: [myrtha.haessig@swri.org](mailto:myrtha.haessig@swri.org) Cite as M. Hässig *et al.*, *Science* **347**, aaa0276 (2015).

Read the full article at <http://dx.doi.org/10.1126/science.aaa0276>

## Subsurface properties and early activity of comet 67P/Churyumov-Gerasimenko

S. Gulkis,\* M. Allen, P. von Allmen, G. Beaudin, N. Biver, D. Bockelée-Morvan, M. Choukroun, J. Crovisier, B. J. R. Davidsson, P. Encrenaz, T. Encrenaz, M. Frerking, P. Hartogh, M. Hofstadter, W.-H. Ip, M. Janssen, C. Jarchow, S. Keihm, S. Lee, E. Lellouch, C. Leyrat, L. Rezac, F. P. Schloerb, T. Spilker

Heat transport and ice sublimation in comets are interrelated processes reflecting properties acquired at the time of formation and during subsequent evolution. The Microwave Instrument on the Rosetta Orbiter (MIRO) acquired maps of the subsurface temperature of comet 67P/Churyumov-Gerasimenko, at 1.6 mm and 0.5 mm wavelengths, and spectra of water vapor. The total H<sub>2</sub>O production rate varied from 0.3 kg s<sup>-1</sup> in early June 2014 to 1.2 kg s<sup>-1</sup> in late August and showed periodic variations related to nucleus rotation and shape. Water outgassing was localized to the “neck” region of the comet. Subsurface temperatures showed seasonal and diurnal variations, which indicated that the submillimeter radiation originated at depths comparable to the diurnal thermal skin depth. A low thermal inertia (~10 to 50 J K<sup>-1</sup> m<sup>-2</sup> s<sup>-0.5</sup>), consistent with a thermally insulating powdered surface, is inferred.

The list of author affiliations is available in the full article online.

\*Corresponding author. E-mail: [samuel.gulkis@jpl.nasa.gov](mailto:samuel.gulkis@jpl.nasa.gov) Cite as S. Gulkis *et al.*, *Science* **347**, aaa0709 (2015).

Read the full article at <http://dx.doi.org/10.1126/science.aaa0709>

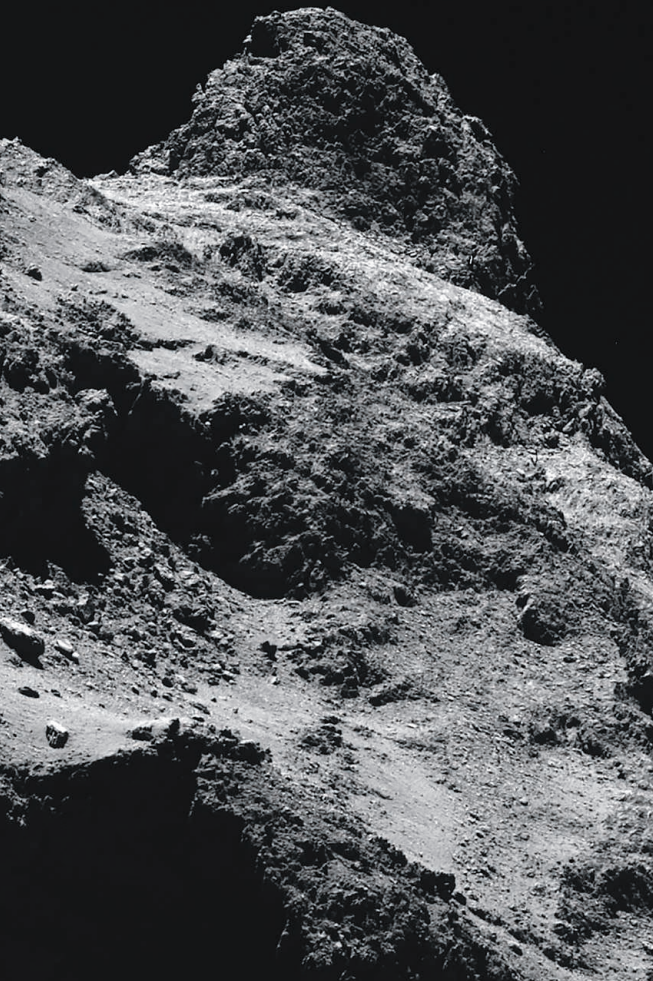


PHOTO: ESA/ROSETTA/MPS FOR OSIRIS TEAM, MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA