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

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Abstract: 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: H_2O, CO, and CO_2. These results indicate a complex coma-nucleus relationship where seasonal variations may be driven by temperature differences just below the comet surface.

One Sentence Summary: ROSINA/DFMS shows that 67P/Churyumov-Gerasimenko has a highly heterogeneous coma with large diurnal and possibly seasonal variations.

Main Text: Initially, comets were classified depending on the location where they formed in the protoplanetary disc (*1, 2*). This classification assumed a similar composition of the nucleus within a given formation region. No cometary nucleus composition has been sampled *in situ*. Rather, it is implicitly assumed that measurements of the outgassing of comets reveal the composition of the volatile components of the nucleus. However, compositional homogeneity of at least one comet was confirmed by studying outgassing from the fragments of the broken up comet Schwassmann-Wachmann 3 (*3*). Detailed observations of other cometary comae indicated that there is evidence of heterogeneity. Missions to comet Halley detected release of volatiles in multiple jet-like features that were dominantly seen on the sunlit side of the nucleus (*4, 5*). The Deep Impact mission detected asymmetries in composition in the coma of Tempel 1 (*6*). In particular, these remote sensing observations at Tempel 1 indicated an absence of correlation between H_2O and CO_2 in the coma.

Detailed, close up cometary images have also showed visible differences between different areas of cometary nuclei. These images suggested that heterogeneity in the coma of a comet may be related to heterogeneity of the nucleus. Observations by EPOXI at Hartley 2 in 2010 near perihelion indicated that the nucleus is complex, with two different sized lobes separated by a middle waist region that is smoother and lighter in color (*7*). Outgassing from sunlit surfaces of the nucleus revealed that the waist and one of the lobes were very active. A CO_2 source was detected at the small lobe of the comet, while the waist was more active in H_2O and had a significantly lower CO_2 content. Based on these coma observations, it has been tentatively suggested that the heterogeneity in the comet's nucleus was primordial (*7*). Seasonal effects could not be ruled out because the observations also showed a complex rotational state for the comet (*7*). The smaller of the two lobes may have been illuminated differently because of this complex rotation (*7*). In support of the findings at Hartley 2, there are indications of a heterogeneous nucleus for comet Tuttle and a heterogeneous coma (*7, 8*).

The Stardust mission to comet P81/Wild 2, on the other hand, showed a large mixing of materials on the scale of grains and therefore a homogenized mix of the refractory material in the comet (*9*). The results at Hartley 2 and at P81/Wild 2 raise the larger question of whether heterogeneity in the coma is a common feature in comets and whether this reveals an underlying heterogeneity in the composition of the nucleus, which would point to general transport of cometesimals in the early Solar System.

In August, the European Space Agency's mission Rosetta arrived at its target comet 67P/Churyumov-Gerasimenko (67P) after a ten-year journey (*10*). Rosetta provides an excellent opportunity for long-term study during the comet's sunward approach to perihelion. The observations presented here are from a two-month period beginning near the initial encounter at about 3.5 AU from the Sun.
Like Hartley 2, the nucleus of 67P appears complex in shape. 67P consists of two lobes of different sizes, connected by a neck region. The lobes are much larger, more rugged, and darker than the neck region and the overall shape has been compared to a rubber duck (*11*). The structural similarities of 67P and Hartley 2 suggest the possibility of another heterogeneous comet and, by virtue of the extended observations at 67P, a chance to determine whether heterogeneity in the coma and nucleus are related.

Here we show compositional variations in H_2O, CO, and CO_2 at comet 67P observed with ROSINA/DFMS (Rosetta Orbiter Spectrometer for Ion and Neutral Analysis / Double Focusing Mass Spectrometer) (*12*). ROSINA/DFMS is a mass spectrometer that measures the in situ neutral and plasma coma composition at the position of the spacecraft [see Supplementary material]. During Rosetta's approach to 67P, ROSINA/DFMS measured the neutral coma composition with a time resolution (>10 measurements per rotation) much finer than the rotation period of the comet of ~12.4 hours (*13*). In August, the spacecraft scanned the comet at northern summer hemisphere (positive latitudes) from about 10º up to almost 90º (Coordinates: Cheops System (*14*)). In September, the spacecraft made a similar scan at southern winter hemisphere (negative latitudes) down to about -50º. Two data sets are shown in Fig. 1 and 2 to illustrate the diurnal and latitudinal variations and heterogeneity of the cometary coma.

During this approach and latitude scan, the H_2O, CO, and CO_2 signals from the comet increased by more than an order of magnitude, roughly in agreement with a $1/R^2$ dependence on the coma density, where R is the distance from comet center. Overall, the H_2O signal is the strongest; however, there are clearly periods when the CO or CO_2 signals rival that of H_2O.
Superposed on this general increase in signal are large, diurnal variations for all three neutral species. For H_2O, these variations are periodic, initially with half the rotation rate of the comet (~6.2 hours) and then, after August 6, at the rotation rate (~12.4 hours). This change in periodicity in the signal is interpreted as a latitudinal effect of the sampling position. Peaks occur at ±90º longitude. For the most part, the CO signal follows the H_2O signal, but the variations are smaller. CO_2 shows a different periodicity. Initially, a CO_2 peak is observed in association with an H_2O peak and a second CO_2 peak occurs approximately 3 hours later. After August 6, a single CO_2 peak is observed; however, this peak is not exactly coincident with the H_2O peak. The two CO_2 peaks merge, resulting in a shoulder on the main peak and a slight shift of the main CO_2 peak relative to that of H_2O (~45 min or one measurement point). Statistical uncertainties

(√#particles) in the signal detected by ROSINA/DFMS are smaller than dots in Figures 1-3 and contributions to the signal due to spacecraft outgassing (*15*) are subtracted.

The diurnal variations at half the rotation rate of the comet that are seen in August are also observed at southern latitudes in the September timeframe (Fig. 2). The H_2O peaks in Fig. 3 are nearly equal and there is a deep minimum between the two peaks. As in the first dataset, CO follows H_2O. However, there is much less variation in CO than in H_2O, resulting in times when the CO signal is greater than that for H_2O. The best example of the differences between H_2O and CO_2 are seen just after September 18 (Figs. 2 and 3). The nearly equal H_2O peaks and the deep minimum in the H_2O signal are evident as is the clear offset between the second CO_2 and H_2O peaks.

We have combined the signal and the spacecraft perspective over the September 18 to 19, 2014 window to illustrate which side of the comet is in view when the peaks occur (Fig. 3). The peaks in H_2O signal are observed when the neck of the comet is in view of the spacecraft. The deep minimum in H_2O signal is observed when the spacecraft views the southern hemisphere of the larger of the two lobes. This large lobe blocks a direct view of the neck of the comet. The separate, second CO_2 enhancement is observed when the spacecraft views the underside of the body of the larger of the two lobes of the comet. The CO signal in the second rotation of the comet follows the CO_2 profile, and CO and CO_2 have very similar intensities.

We see from this data (Figs. 1-3) that the coma composition of 67P is highly heterogeneous. H_2O, CO, and CO_2 variations are strongly tied to the rotation period of the comet and to the observing latitude. At large negative latitudes, the H_2O signal varies by at least two orders of magnitude (Fig. 3). Also, the H_2O minima are not as deep when the spacecraft is at mid and high positive latitudes because there is a view of the neck region over the edge of the larger lobe (see Fig. 1 and the observations on Sept 15 in Fig. 2).

The separate CO_2 peak also occurs when the spacecraft views the bottom of the larger of the two lobes of the comet (see Fig. 3 at 5 hours). CO follows H_2O at positive latitudes and follows both H_2O and CO_2 at negative latitudes.

The separate CO_2 peak, the large variations in the H_2O signal, and the weaker variations in CO result in large changes in the relative concentration of H_2O, CO, and CO_2 in the heterogeneous coma of 67P [see Supplementary Material]. For example, the CO/H_2O number density ratio is 0.13 ± 0.07 and the CO_2/H_2O ratio is 0.08 ± 0.05 in the last H_2O peak on August 7 at 18 hours in Fig. 1 (measured high in the northern summer hemisphere). However, The CO/H_2O ratio changes from 0.56 ± 0.15 to 4 ± 1 and back to 0.38 ± 0.15 within the second cometary rotation Fig. 3, between 12 and 24 h on September 18, measured low in the southern winter hemisphere. Similarly, the CO_2/H_2O ratio changes from 0.67 ± 0.15 to 8 ± 2 and back to 0.39 ± 0.15 over the same rotation. These are large changes within a short amount of time, which indicate a strongly heterogeneous and time variable coma.

The similarities in the structure of the nuclei and the heterogeneous comae of 67P and Hartley 2 are striking. The behavior in terms of the H_2O dominant outgassing at the neck versus CO_2 outgassing at one of the lobes described here was also found for Hartley 2 (*7*).

The compositional differences in the Hartley 2 coma were interpreted as evidence for a heterogeneous cometary nucleus (*7*). However, seasonal effects could not be ruled out. With observations over a wide range of latitudes at 67P, we can distinguish between compositional differences and seasonal effects; to do so, we have mapped the CO_2/H_2O density ratio from August 17 through September 22 onto the shape model (Fig. 4).

Although a direct mapping of the signal observed in the coma onto the comet surface is oversimplified, a generalized interpretation reveals features of the outgassing of the comet. Seasonal effects on the CO_2/H_2O ratio are clearly evident (Fig. 4). On the upper half of the comet, the CO_2/H_2O ratio is less than 1, indicating a higher sublimation of H_2O from positive latitude regions that receive more illumination during northern hemisphere summer on the comet. A broad region of high CO_2/H_2O ratio occurs at negative latitudes in the winter hemisphere, likely the result of deep minima in the H_2O signal (such as the one shown in Fig. 3 on September 18 at 4 hours). This winter hemisphere of the comet is poorly illuminated by the Sun. With limited illumination, this region of the comet nucleus may be significantly colder than other regions, including the neck and smaller lobe. The temperature at and below the surface of the nucleus may be sufficient to sublimate CO and CO_2, but not sufficient to sublimate water. The weak, periodic illumination of this region may be sufficient to drive CO and CO_2 sublimation, producing the separate CO and CO_2 peak (Fig. 3 at 18 hours). However, the compositional asymmetry in the two H_2O peaks can't be explained in a similar way and might be the strongest indication for heterogeneity in the comet nucleus. The strong heterogeneity in the coma of comet 67P is likely driven by seasonal effects on the comet nucleus. However, the smaller variation of CO and CO_2 compared to H_2O might indicate that CO and CO_2 ices sublimate from a greater depth, while H_2O ice sublimates closer to the surface and experiences more direct temperature differences due to sunlight. Furthermore, that lack of overall correlation between H_2O, CO and CO_2 implies that the outgassing from the nucleus is not correlated, or that CO and CO_2 are not strictly embedded in H_2O. For Temple 1, material was found in layers and supports the above idea (*16*).

In summary, the coma composition has been measured over many rotational periods of the comet and a wide range of latitudes with high time resolution and compositional detail. Concentrations of the three molecules change over the rotational period of the comet and indicate a strongly heterogeneous coma. For the most part, H_2O dominates, but CO and CO_2 can at times dominate in the coma. These observations also indicate that there are substantial diurnal and latitudinal variations in the coma. Peaks in the H_2O signal are observed, along with deep minima at high negative latitudes when the neck region of the nucleus is blocked from view of the spacecraft. A separate peak in CO_2 signal occurs when the winter hemisphere of the larger lobe of the comet faces the spacecraft. The diurnal and latitudinal variations suggest that compositional differences in the coma may be a seasonal and may indicate different sub-surface temperatures in the nucleus.

Further observations may distinguish seasonal effect from nucleus heterogeneity. As the comet approaches the Sun, the overall temperature of the nucleus will increase, and as the seasons change, there may be significant changes in the H_2O, CO, and CO_2 outgassing, with the current high CO_2/H_2O ratio region shown in Fig. 4. In addition, differences in the sublimation of species similar in sublimation temperatures could demonstrate the extend of heterogeneity in the nucleus independent of seasonal changes.

References and Notes:

1. M. F. A'Hearn, R. C. Millis, D. O. Schleicher, D. J. Osip, R. V. Birch, The Ensemble Properties of Comets- Results from Narrowband Photometry of 85 Comets, 1976-1992, *Icarus* **118**, 223-270 (1995).
2. M. J. Mumma and S. B. Starnely, The Chemical Composition of Comets - Emerging Taxonomies and Natal Heritage, *Annu Rev. Astron. Astrophys* **49**, 471-524 (2011).
3. N. Dello Russo *et al.,* Compositional homogeneity in the fragmented comet 73P-

Schwassmann–Wachmann 3, *Nature* **448**, 172-175 (2007).
4. H. U. Keller *et al.,* First Halley Multicolour Camera imaging results from Giotto., *Nature* **321**, 320–326 (1986).
5. H. A. Weaver, M. J. Mumma, H. P. Larson, D. S. Davis, Postperihelion observations of water in comet Halley., *Nature* **324**, 441-444 (1986).
6. L. M. Feaga, M. F. A'Hearn, J. M. Sunshine, O. Groussin, T. L. Farnham, Asymmetreis in the distribution of H2O cann CO2 in the inner coma of Comet Tempel 1 as observed by Deep Impact, *Icarus* **190**, 345-356 (2007).
7. M. F. A'Hearn *et al.,* EPOXI at Hartley 2, *Science* **332**, 1396-1400 (2011).
8. B. P. Bonev *et al.,* The peculiar volatile composition of comet 8P/Tuttle: a contact binary of chemically distinct cometesimals?, *The Astrophysical Journal* **680**, 61-64 (2008).
9. M. F. A'Hearn, Whence Comets?, *Science* **314**, 1708-1709 (2006).
10. K.-H. Glassmeier *et al.,* The Rosetta Mission: Flying Towards the Origin of the Solar System, *Space Science Reviews* **128**, 745-801 (2007).
11. N. Thomas *et al.*, *Science, submitted* (2014).
12. H. Balsiger *et al.,* ROSINA-ROSETTA-orbiter-spectrometer-for-ion-and-neutral-analysis, *Space Science Reviews* **128**, 745-801 (2007).
13. S. Mottola *et al.*, The rotation state of 67P/Churyumov-Gerasimenko from approach observations with the OSIRIS cameras on Rosetta, *Astron. Astrophys* **569**, L2 (2014).
14. L. Jorda *et al.,* Shape models of 67P/Churyumov-Gerasimenko. RO-C-OSINAC/OSIWAC-5-67P-SHAPE-V1.0, *NASA Planetary Data System and ESA Planetary Science Archive*. In preparation (2015)
15. B. Schläppi *et al.,* Influence of spacecraft outgassing on the exploration of tenuous atmospheres with in situ mass spectrometry, *Journal of Geophysical Research (Space Physics)* **115**, 12313 (2010).
16. M. F. A'Hearn *et al.,* Deep Impact Excavating Comet Tempel 1, *Science* **310**, 258-264 (2005).

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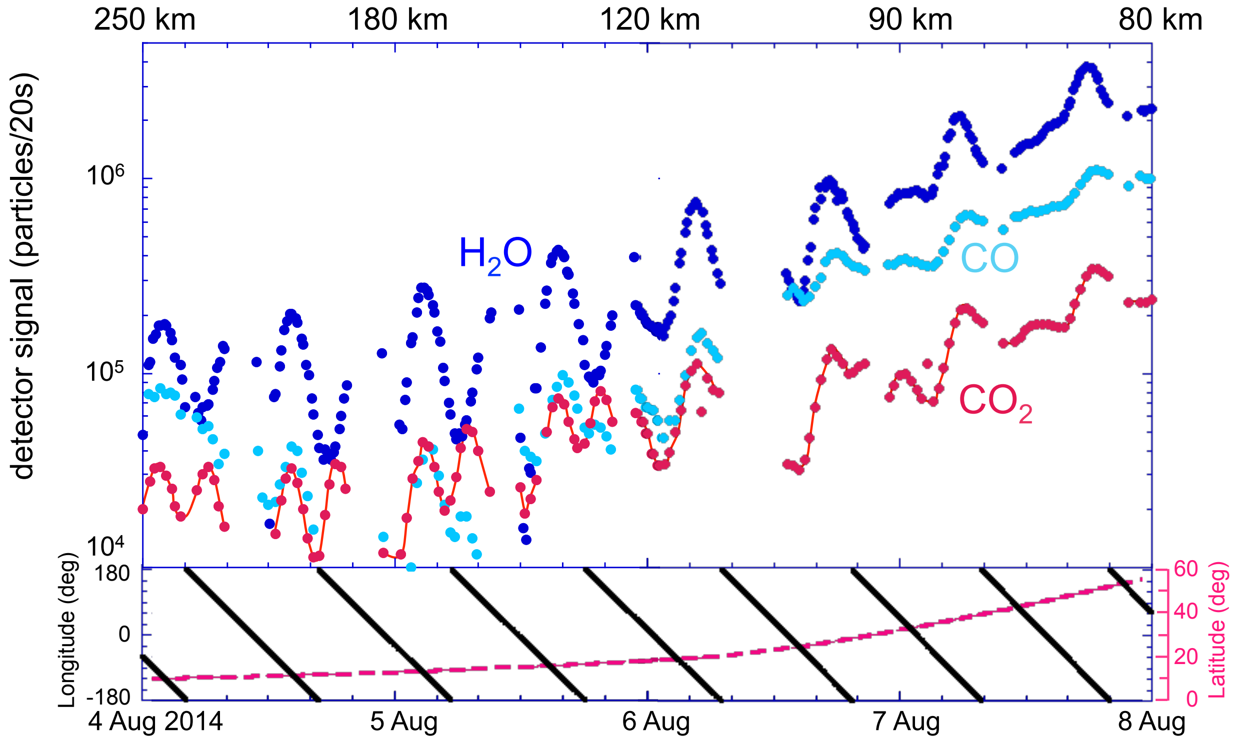

Fig. 1. H_2O, CO, and CO_2 measurements for August 4 to 8, 2014. The upper panel shows the signal on the DFMS detector for H_2O, CO, and CO_2 and the lower panel shows the latitude and longitude of the nadir view of the spacecraft. At the top is the distance from the spacecraft to the comet. The signal increases with decreasing distance to the comet, while diurnal variations are also visible. CO_2 has a different periodicity than H_2O as seen around August 4 to 6.

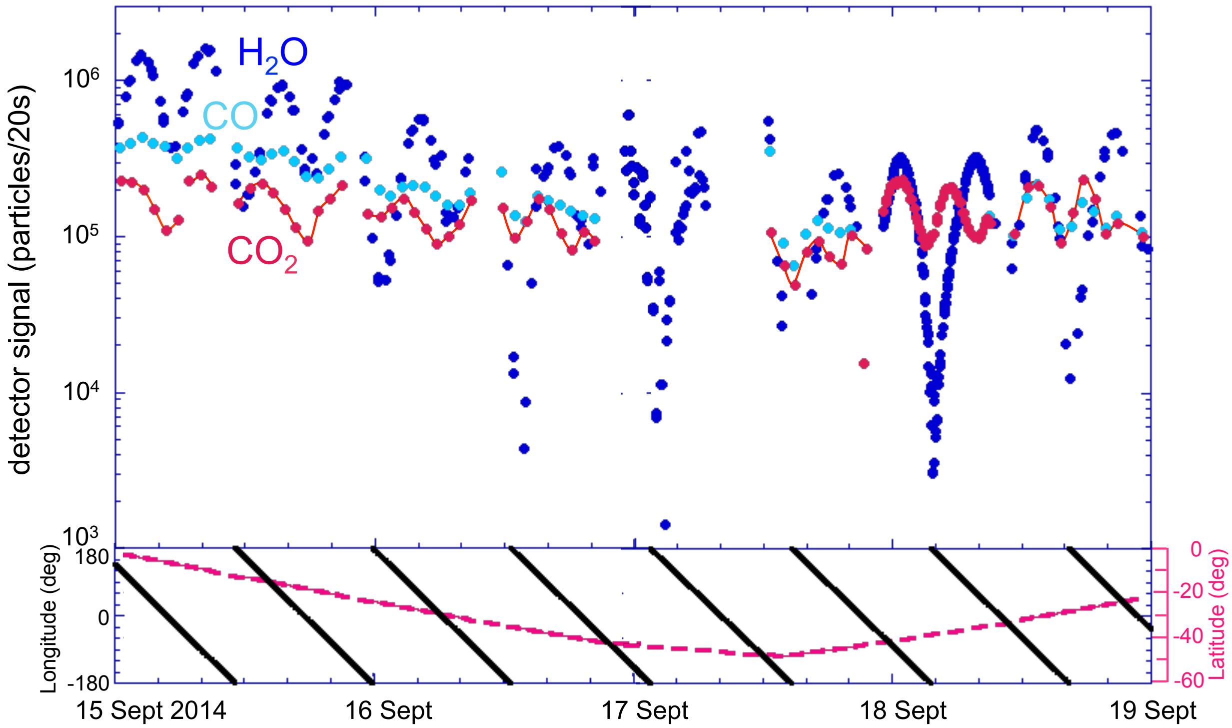

Fig. 2. H_2O, CO, and CO_2 measurements for September 15 to 19, 2014. Over this 4-day period, the spacecraft remained at a nearly fixed distance from the comet and executed a southern latitude scan from about 0º to -45º latitude. H_2O and CO_2 have different periodicities and there are deep minima in the H_2O signal. CO follows the CO_2 profile with less variation.

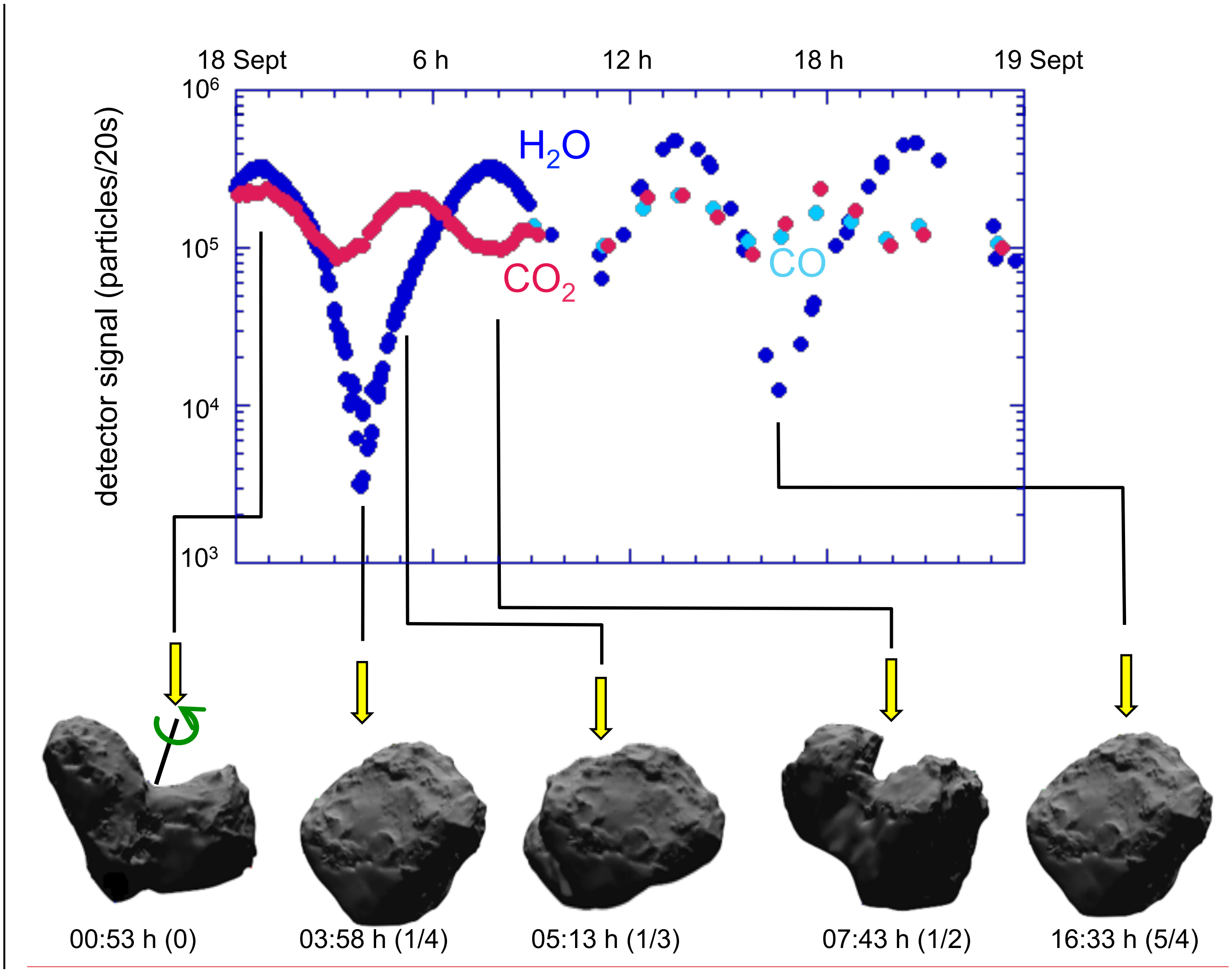

Fig. 3. H_2O, CO, CO_2 profiles for September 18, 2014. The Sun is shining on the comet from the top middle of the pictures. The snap shots of the spacecraft view of the comet show that H_2O peaks are observed when the neck region is in view. The separate CO_2 peak and the deep minimum in H_2O occur when the spacecraft views the larger of the two lobes and the neck region is blocked. (Shape model credit: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA, OSINAC/OSIWAC SHAP1 (*14*)).

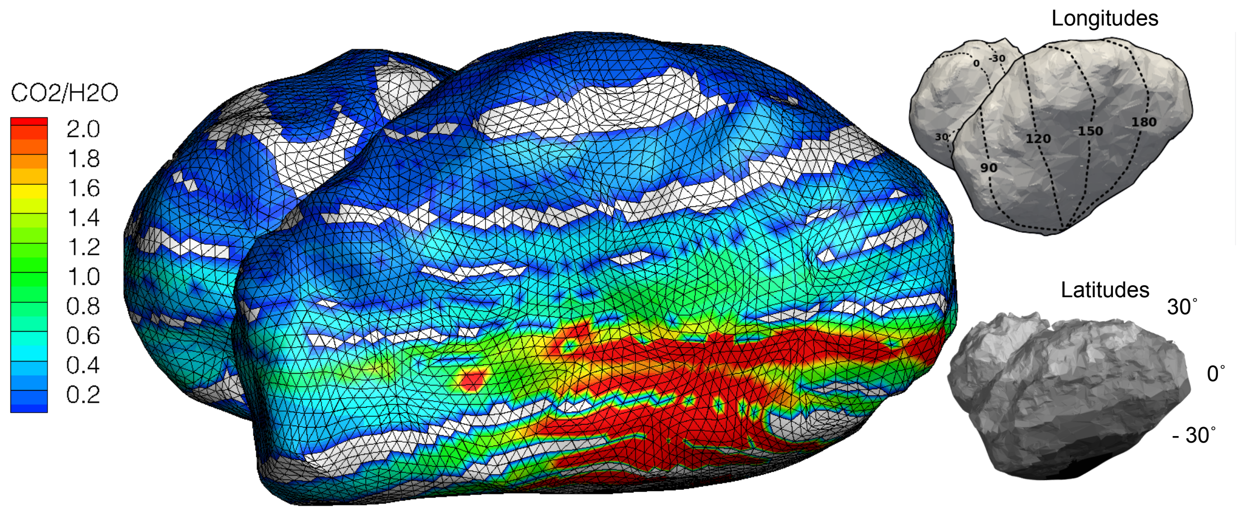

Fig. 4. The nadir point for each pair of CO_2/H_2O measurements over the time period from August 17 through September 22 was mapped to the model surface. The mapping is shown for the bottom side of the larger of the two lobes of the comet and cometary latitudes run approximately vertically in this. The layering is due to spacecraft rastering above the comet nucleus. A high ratio is measured for the lower part that is poorly sunlit in northern hemisphere summer. (Shape model credit: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA, OSINAC/OSIWAC SHAP1 (*14*)).

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Supplementary Materials for

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This PDF file includes:

Materials and Methods
Supplementary Text

Materials and Methods

Instrumentation and Data Analysis

The Rosetta orbiter caries an instrument package, ROSINA (*12*) designed for in situ measurements of the cometary coma composition. In the instrument package is a high resolution, high sensitivity mass spectrometer, the Double Focusing Mass Spectrometer (DFMS). ROSINA/DFMS measures the neutral and plasma coma composition. ROSINA/DFMS steps through a mass spectrum m/z 13-100 in ~ 45 min, the integration time per mass is 20 s, and ROSINA/DFMS can detect neutral particle densities down to 1 cm^{-3}. However, the spacecraft background (*15*) is around 10^6 cm^{-3} depending on mass. In this paper, we focus exclusively on the measurement of neutral molecules. The radial outflow of molecules from the cometary nucleus enters the instruments field of view of 20˚ x 20˚, when pointing generally in the direction of the comet. A neutral entering the instrument is ionized by electron impact and then analyzed by a combination of and electro static analyzer focusing in energy and angle. The electrostatic analyzer is followed by a magnet resulting in a mass per charge separation and finally detected. This mass spectrometer is operated in a variety of modes covering a wide range of masses, but typically measures the major neutral species including H_2O, CO, and CO_2. ROSINA detected and characterized a gaseous background due to spacecraft outgassing from the Rosetta spacecraft (*15*), which is present even after ten years of cruise in space including nearly two years in hibernation. For the following measurements described in this paper, this background was determined from a time period when the spacecraft was far (>800 km) from the comet and subtracted from the total signal.

Derivation of relative concentrations

The number densities for these three species considered are related to the signals in Figure 1 after different sensitivities for the different molecules are taken into account. The sensitivities for H_2O and CO are nearly the same, but the sensitivity for CO_2 is 30% lower. These sensitivities were determined through calibration of the instrument and the nearly identical flight spare in the laboratory. Uncertainties are due to statistical uncertainties in the detection, calibration uncertainties for relative sensitivities (~17%), and calibration uncertainties (~10%) such as the detector gain. The instrument specific signal contribution of CO2 due to fragmentation in the ion source for CO was taken into account. The contributions of the spacecraft background for those three species due to spacecraft outgassing were derived earlier in the mission, when no cometary signal was detected and subtracted from the total signal. The relative concentrations of CO, and CO_2 to H_2O that are derived from these data are discussed in the main text.

Supplementary Text

Additional description of Figure 1

The instrument is bore sighted with the nadir direction. The latitude and longitude of the sub-spacecraft point on the comet are derived from the OSIRIS shape model. Over the 4-day period in Figure 1, the spacecraft approached the comet as the comet rotated beneath it (as seen by the longitude changes). During the last 2 days, the latitude of the nadir point increased from about 20º to 60º. Low mass resolution data are used here because they provide the highest instrument sensitivity and show the best evidence of the comet at these relatively far distances. Nearly continuous measurements of all three molecules were made over this 4-day period with data gaps mainly due to times when the instrument was off because of spacecraft reaction-wheel offloading.

Additional description of Figure 2

During this period, the instrument was almost exclusively in high mass resolution mode with a factor of approximately 10 reduction in sensitivity when compared to low resolution mode. After 18 September, the instrument was operated in a special water species and CO_2 mode for about 12 hours. Although there are no CO measurements at that time, there are many more measurements of H_2O and CO_2, and the two species have nearly the same overall signal.

Additional description of Figure 3

The upper part shows the counts on the DFMS detector for H_2O and CO_2 for a timespan of two rotations of the comet. CO is only measured during the second rotation. The lower part of Figure 3 shows spacecraft views of the comet (using the OSIRIS shape model) for different times within the first rotational period. Because the neck of the comet is also in view, the H_2O signal is higher than its minimum when the neck region is completely blocked. Although there are no CO measurements in this first comet rotation, the CO signal in the second rotation of the comet follows the CO_2 profile and, in this case the CO and CO_2 have very similar intensities. This effect seen at Hartley 2 with a high outgassing of H_2O at the waist and CO_2 at one of the lobes was interpreted as an evolutionary effect associated with re-deposition and sublimation of ice in the waist region (*7*). 'Chunks' of nearly pure water ice are drag out by super volatiles (mainly CO_2) from the lobe; fall in onto the waist, where it resublimes driven by heat absorption of the dark nucleus surface *(7*). However, the overall CO_2 activity that drives this mechanism for Hartley 2 is much higher than the water/ice driver at the current position of 67P. The observations at Hartley 2 were conducted when the comet was one week past perihelion at 1.06 AU, hence at the comet's most active time. In contrast, 67P is currently at 3.5 AU, far away from the Sun. The CO_2 activity is much lower at this distance from the Sun and there must be far fewer ice chunks that are dragged out by the CO_2 gas.