COMETARY SCIENCE

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

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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.

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 (Extrasolar Planet Observation and Deep Impact Extended Investigation) 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, whereas the waist was more active in H_2O and had a considerably 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

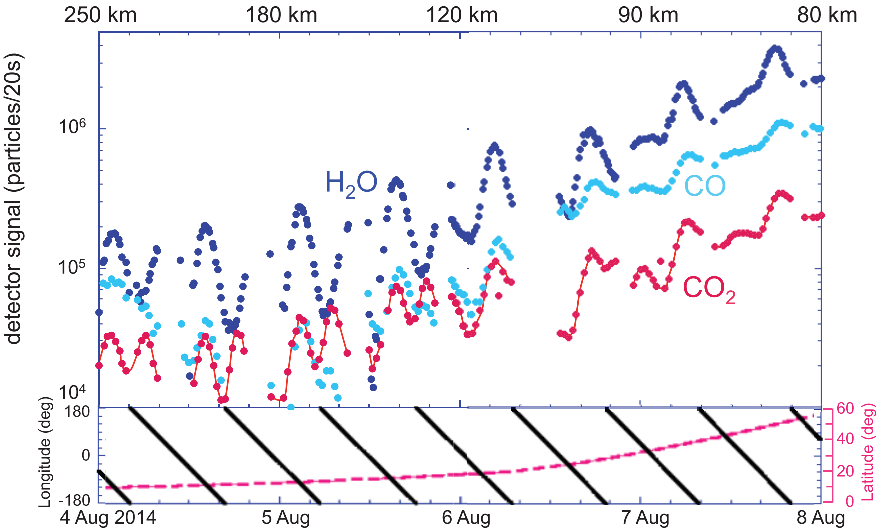

Fig. 1. H_2O, CO, and CO_2 measurements for 4 to 8 August 2014. The upper panel shows the signal on the DFMS detector for H_2O, CO, and CO_2, and the lower panel shows the latitude and longitude of the nadir view of the spacecraft. At the top is the distance from the spacecraft to the comet. The signal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

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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 10-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 2-month period beginning near the initial encounter at about 3.5 astronomical units from the Sun.

Like Hartley 2, the nucleus of 67P appears complex in shape. The comet 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 the supplementary materials). 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 10° up to almost 90° (Coordinates: Cheops System). In September, the spacecraft made a similar scan at southern winter hemisphere (negative latitudes) down to about –50°. Two data sets are shown in Figs. 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 the comet's 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 6 August, 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 ±90° 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 ($\sqrt{\#\text{particles}}$) in the signal detected by ROSINA/DFMS are smaller than the dots in Figs. 1 to 3, and contributions to the signal due to spacecraft outgassing (*14*) are subtracted.

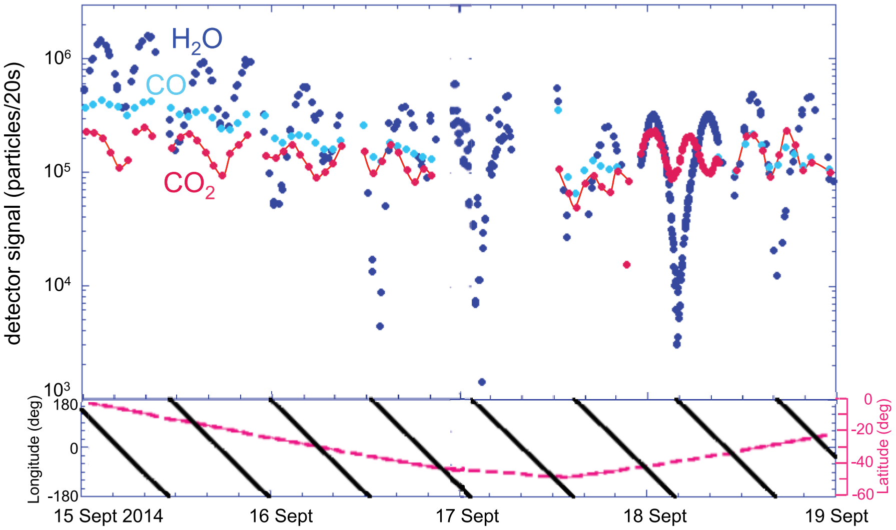

Fig. 2. H_2O, CO, and CO_2 measurements for 15 to 19 September 2014. Over this 4-day period, the spacecraft remained at a nearly fixed distance from the comet and executed a southern latitude scan from about 0° to –45° latitude. H_2O and CO_2 have different periodicities, and there are deep minima in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

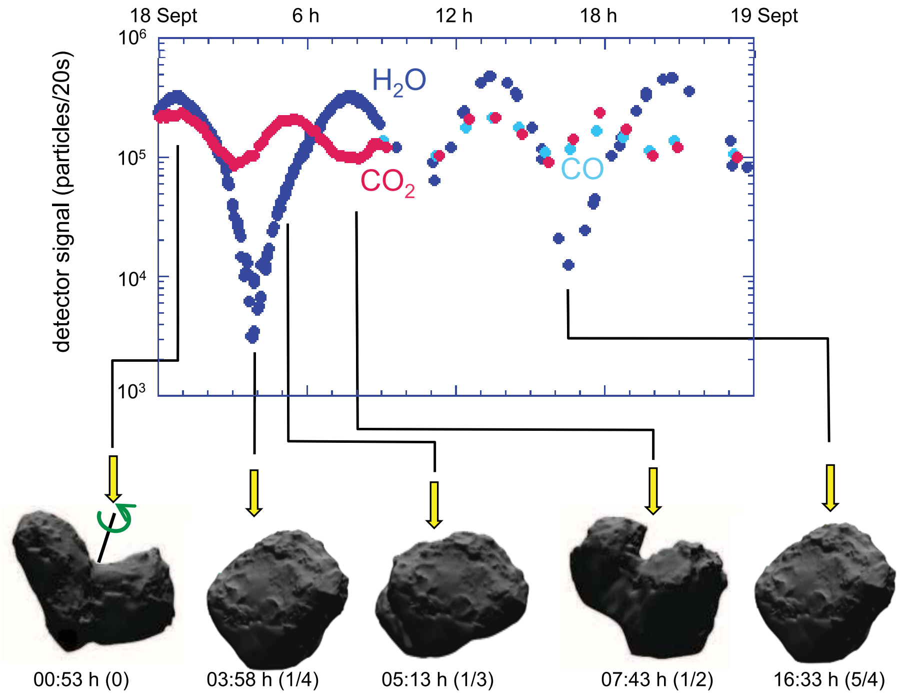

Fig. 3. H_2O, CO, and CO_2 profiles for 18 September 2014. The Sun is shining on the comet from the top middle of the pictures. The snapshots of the spacecraft view of the comet show that H_2O peaks are observed when the neck region is in view. The separate CO_2 peak and the deep minimum in H_2O occur 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].

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 time frame (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 data set, 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 18 September (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 18 to 19 September 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 to 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 15 September 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 the supplementary materials). 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 7 August 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 hours on 18 September, 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 17 August through 22 September 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 18 September 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 considerably 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 cannot 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 with H_2O might indicate that CO and CO_2 ices sublimate from a greater depth, whereas 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 Tempel 1, material was found in layers and supports the above idea (*15*).

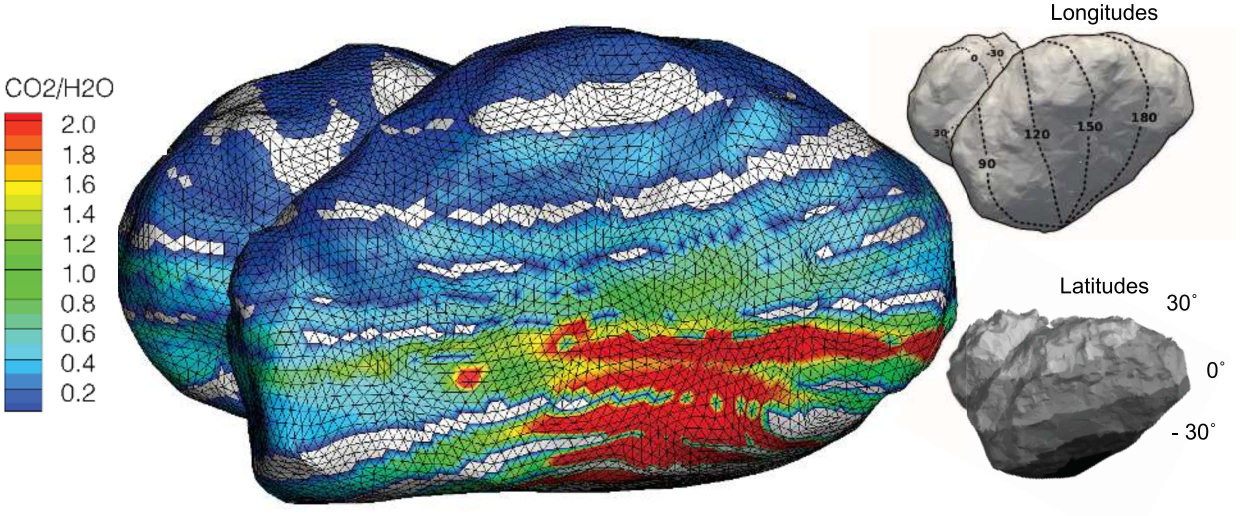

Fig. 4. The nadir point for each pair of CO_2/H_2O measurements over the time period from 17 August through 22 September was mapped to the model surface. The mapping is shown for the bottom side of the larger of the two lobes of the comet, and cometary latitudes run approximately vertically in this. 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 southern hemisphere winter. [Shape model credit: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA].

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 seasonal and may indicate different subsurface 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 considerable 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.

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SUPPLEMENTARY MATERIALS

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