**COMETARY SCIENCE**

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


Comets contain the best-preserved material of 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 comet 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 H₂O and CO₂ 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 CO₂ source was detected at the small lobe of the comet, whereas the waist was more active in H₂O and had a considerably lower CO₂ 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

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**Fig. 1.** H₂O, CO, and CO₂ measurements for 4 to 8 August 2014. The upper panel shows the signal on the DFMS detector for H₂O, CO, and CO₂, 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. CO₂ has a different periodicity than H₂O, as seen around 4 to 6 August.
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 cometary nuclei 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 (30). 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 H₂O, CO, and CO₂ 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 H₂O, CO, and CO₂ signals from the comet increased by more than an order of magnitude, roughly in agreement with a 1/R² dependence on the coma density, where R is the distance from the comet’s center. Overall, the H₂O signal is the strongest; however, there are clearly periods when the CO or CO₂ signals rival that of H₂O. Superposed on this general increase in signal are large, diurnal variations for all three neutral species. For H₂O, 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 H₂O signal, but the variations are smaller. CO₂ shows a different periodicity. Initially, a CO₂ peak is observed in association with an H₂O peak, and a second CO₂ peak occurs approximately 3 hours later. After August 6, a single CO₂ peak is observed; however, this peak is not exactly coincident with the H₂O peak. The two CO₂ peaks merge, resulting in a shoulder on the main peak and a slight shift of the main CO₂ peak relative to that of H₂O (~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.
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 \( CO \) is the large variation in the relative concentration of \( H_2O \), \( CO \), and \( CO_2 \) in the heterogeneous coma of 67P (see the supplementary materials). For example, the \( CO/H_2O \) ratio number density ratio is \( 0.15 \pm 0.07 \), and the \( CO_2/H_2O \) ratio is \( 0.08 \pm 0.05 \) in the \( H_2O \) profile on 7 August at 18 hours in Fig. 4 (measured high in the northern summer hemisphere). However, the \( CO/H_2O \) ratio changes from \( 0.56 \pm 0.15 \) to \( 4 \pm 1 \) and back to \( 0.38 \pm 0.15 \) within the second comet rotation (Fig. 3), between 12 and 24 hours on 18 September, measured low in the southern winter hemisphere. Similarly, the \( CO/H_2O \) ratio changes from \( 0.67 \pm 0.15 \) to \( 8 \pm 2 \) and back to \( 0.39 \pm 0.15 \) over the same rotation. These are large changes within a short amount of time, which indicate a strongly heterogeneous and time-variable coma.

The 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. Also, the \( CO_2/H_2O \) ratio is less than 1, indicating a higher sublimation of \( CO_2 \) 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 at 18 September at 4 hours). The winter hemisphere of the comet is poorly illuminated by the Sun. With limited illumination, this region of the comet nucleus may be considerably older 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 peak, 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 (25).

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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 \( CO \) 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).
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, H₂O dominates, but CO and CO₂ 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 H₂O 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 CO₂ signal occurs when the nucleus is blocked from view of the spacecraft.

REFERENCES AND NOTES


ACKNOWLEDGMENTS

The authors thank the following institutions and agencies, which supported this work: Work at the University of Bern was funded by the State of Bern, the Swiss National Science Foundation, and the European Space Agency (ESA) PRODEX Program. Work at the Max-Planck-Institut für Sonnensystemforschung (MPS) was funded by the Max-Planck-Gesellschaft (MPG) and Bundesministerium für Wirtschaft und Energie (BMWi) under contract 500P1302. Work at Southwest Research institute (SwRI) was supported by subcontract 149654 from the Jet Propulsion Laboratory (JPL) and under NASA prime contract NNX14AF71G. Work at BIRA-IASB was supported by the Belgian Science Policy Office via PRODEX/ROSINA PEA 90020. Work at Imperial College London has been partially funded by the Science and Technology Facilities Council (STFC). This work has been carried out thanks to the support of the A*MIDEX project (ANR-11-IDEX-0001-02) funded by the Investissements d’Avenir French Government program, managed by the French National Research Agency (ANR). This work was supported by CNES grants at IRAP, LATMOS, LPC2E, Laboratoire d’Astrophysique de Marseille (LAM) and CRPG and by the European Research Council (grant 267255). A.B.-N. thanks the Ministry of Science and the Israel Space Agency. Work at the University of Michigan was funded by NASA under contract JPL-1266313. Work by J.H.W. at SwRI was supported by NASA JPL subcontract NAS703001TOM71089. ROSINA would not give such outstanding results without the work of the many engineers, technicians, and scientists involved in the mission, in the Rosetta spacecraft, and in the ROSINA instrument over the past 20 years whose contributions are gratefully acknowledged. Rosetta is an ESA mission with contributions from its member states and NASA. We thank the OSIRIS team for giving permission to use the shape model. We acknowledge herewith the work of the ESA Rosetta team. All ROSINA data are available on request until it is released to the PSA archive of ESA and to the PDS archive of NASA.

SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/347/6220/aaa0276/suppl/DC1
Materials and Methods
Supplementary Text
References

10 October 2014; accepted 31 December 2014
10.1126/science.aaa0276
Time variability and heterogeneity in the coma of 67P/Churyumov-Gerasimenko
M. Hässig et al.
Science 347, (2015);
DOI: 10.1126/science.aaa0276