Surface localization of gas sources on comet 67P/Churyumov–Gerasimenko based on DFMS/COPS data

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ABSTRACT
We reconstruct the temporal evolution of the source distribution for the four major gas species H2O, CO2, CO, and O2 on the surface of comet 67P/Churyumov–Gerasimenko during its 2015 apparition. The analysis applies an inverse coma model and fits to data between 2014 August 6 and 2016 September 5 measured with the Double Focusing Mass Spectrometer (DFMS) of the Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA) and the COmet Pressure Sensor (COPS). The spatial distribution of gas sources with their temporal variation allows one to construct surface maps for gas emissions and to evaluate integrated production rates. For all species peak production rates and integrated production rates per orbit are evaluated separately for the Northern and Southern hemisphere. The nine most active emitting areas on the comet’s surface are defined and their correlation to emissions for each of the species is discussed.

Key words: methods: data analysis – comets: individual: 67P/Churyumov–Gerasimenko.

1 INTRODUCTION
Solar radiation triggers the activity of comets as they approach the inner Solar system and start to release a mixture of different volatiles and solid dust grains. The Rosetta mission has studied the nucleus and the environment of the comet 67P/Churyumov–Gerasimenko (67P/C–G). The suite of instruments examining volatiles and dust onboard the spacecraft incorporates ROSINA, VIRTIS, MIRO, GIADA, COSIMA, and OSIRIS (Schulz 2009). Optical instruments probe the integrated intensity of dust and gas along the line of sight, while the mass spectrometers and pressure sensors measure the local composition and density in the coma at the momentary spacecraft position. All measurement data must be embedded in a global coma model for interpretation and reconstruction of the three-dimensional volume density.

Analytical coma models starting with Haser (1957) are complemented by computational models reflecting the flow dynamics, illumination conditions, and complex non-spherical shape of the nucleus on various levels of complexity. The reproduction of measurements necessitates the determination of unknown surface parameters from observations. Marshall et al. (2017) incorporate MIRO data into a local effective Haser model based on projections into the nadir direction to attribute production rates to separated surface regions in their fig. 6. Based on three-dimensional shape models, Bieler et al. (2015), Marschall et al. (2016), and Marschall et al. (2017) introduce gaskinetic models (direct simulation Monte Carlo codes, DSMC). Bieler et al. (2015) apply a parameter fit for a latitudinal dependence of the gas activity. Fougere et al. (2016b), Fougere et al. (2016a), and later Hansen et al. (2016) apply an inverse approach to an analytical gas model (Fougere et al. 2016b, equation 3) and assimilate Double Focusing Mass Spectrometer (DFMS) data to 25 coefficients of spherical harmonics. These local inhomogeneities define the inner boundary condition of their DSMC model. Kramer et al. (2017) introduce a different simplified gas model and fit surface production rates on 10^4 surface elements to COmet Pressure Sensor (COPS) density data.

Here, we analyse the species-resolved coma of 67P/C–G and trace the evolution of ~4000 gas emitters on the nucleus every 14 d for more than ±350 d around perihelion. This corresponds to heliocentric distances in the range of 3.5–1.24 au. Our model connects individual gas density observations with limited spatial/temporal resolution to the surface activity across the entire nucleus. The input data to the model is the combined ROSINA COPS and DFMS data set. The data processing is detailed in Section 2. By parametrizing the measured density in terms of surface emitters following Kramer et al. (2017), we reconstruct the temporal evolution of the gas emission rates of the four major volatiles H2O, CO2, CO, and O2 (Section 3). In addition, our method determines the spatial distribution of the species on the surface and reveals different production rates and ice distributions on the Northern and Southern hemispheres (Section 4). The production rates are compared to the MIRO data presented by Marshall et al. (2017), to the Reflectron-type Time Of Flight (RTOF) data by Hoang et al. (2017), and with the COPS
analysis by Hansen et al. (2016). The localization of the most active emitting areas in Section 5 is in good agreement with Hoang et al. (2017) and Kramer et al. (2017). This activity pattern shows a high correlation (0.7) to active gas emitters with short-living dust locations derived from OSIRIS and NAVCAM images by Vincent et al. (2016). We recover ice-rich spots for H$_2$O and CO$_2$ found by Filacchione et al. (2016) and Fornasier et al. (2016). Section 6 provides a summary of our findings and describes possible contributions to first-principle modelling of cometary activity.

2 PROCESSING AND INTERPOLATION OF DFMS DATA

The Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA) consisted of the two mass spectrometers DFMS and RTOF and COPS, the COrnet Pressure Sensor (see Balsiger et al. 2007). COPS measured the total gas density at the location of the Rosetta spacecraft whereas the two mass spectrometers obtain the relative abundances of the volatiles including the major parent species H$_2$O, CO$_2$, CO, and O$_2$. Combining COPS with the DFMS mass spectrometer, total abundances at Rosetta can be derived (for details see Gasc et al. 2017). Our measured data considers the latest detector ageing model as described by Schroeder et al. (2018).

Rosetta moved rather slowly with respect to the comet (typically $<1$ m s$^{-1}$). However, the comet rotates once per $\sim$12 h and the combination of the comet’s shape and tilt in the rotation axis led to a complex variation of the measured abundances, in both relative and absolute numbers (see Fougere et al. 2016b).

The total gas density at Rosetta’s location is monitored by the COPS instrument throughout most of the mission with a time resolution of 1 min. The times of measurements are denoted by $T_{\text{COPS}}$. Our data set includes 949 381 COPS measurements and is depicted in Fig. 1. The measurements are taken between 2014 August 6 and 2016 September 5, (−372, 390) d from perihelion on 2015 August 13. Negative values denote times before perihelion. In addition to COPS, the DFMS instrument determines the relative abundances of H$_2$O, CO$_2$, CO, and O$_2$ at a lower time resolution ($T_{\text{DFMS}}$ denotes all times of measurements). The DFMS data set contains 32 700 points (see Fig. 1). Fig. 2(a) shows both data sets in the exemplary time interval (−330, −310) d. To increase the number of data points entering our DFMS coma model, we linearly interpolate the species-resolved DFMS densities to the COPS times $T_{\text{COPS}}$. Spurious extrapolation artefacts are avoided by restricting the interpolation to a 4 h sized window around each point in $T_{\text{DFMS}}$, namely $T_k = \{ t \in T_{\text{COPS}} | t \in (t_l, t_r), |t_l - t| < 4\text{ h}, t_l, t_r \in T_{\text{DFMS}} \}$. The resulting 489 009 interpolated densities are denoted by $\rho_{\text{H}_2\text{O}}(t), \rho_{\text{CO}_2}(t), \rho_{\text{CO}}(t), \rho_{\text{O}_2}(t)$, for $t \in T_k$. (1)

The different densities at the times $T_{\text{COPS}}, T_{\text{DFMS}},$ and $T_k$ are depicted in Fig. 2(a).

3 RECONSTRUCTION OF THE COMA FROM LOCAL MEASUREMENTS

The global reconstruction of the entire three-dimensional coma around 67P/C-G proceeds as a two-step process from the time-series of COPS and DFMS measurements along the trajectory of Rosetta and is based on the assignment of surface emission rates as described by Kramer et al. (2017). First we run a forward model on a surface shape to build a global coma model by assuming equally strong emitting gas sources on each of the surface elements. In the second step we apply the inverse model and adjust the emission rates of each source to obtain the best match with the actually measured DFMS/COPS data. Systematic model uncertainties (insufficient observational sampling in space or/and time) are discussed below.

The whole surface of the nucleus is approximated by a triangular mesh with $N_E = 3996$ equidistantly spaced surface elements, leading to a spatial resolution of 110 m on average. The original shape model (SPC-ESA 2016) is remeshed using the ACDVQ tracing tool by Valette, Chassery & Prost (2008) and smoothed. We have validated the method by performing the model inversion for more and less detailed shape models. The surface reconstructions from
higher resolution models are slightly more scattered (see Kramer et al. 2017 for COPS data), but do not change the regional results discussed here.

To follow the evolution of the emission rates as the comet orbits the sun, we divide the complete time interval \((-372, 390)\) d into \(N_I = 58\) subintervals.

\[ -372 = t_0, t_1, \ldots, t_{N_I} = 390, \]
\[ I_j = (t_{j-1}, t_j), \quad \text{for} \quad j = 1, \ldots, N_I. \]

Each subinterval \(I_j\) includes 8600 values from \(T_{\text{obs}}\) on average and comprises typically 14 d. As an example, Fig. 2(b) shows four subintervals, each enclosing extremal subspacecraft latitudes and five or more comet rotations. Because the data points need to constrain the parameters, the complete determination of the \(N_E\) model parameters (here, the surface emission rate) requires to have more data points available (here, DFMS/COPS measurements). The intervals \(I_j\) are chosen such that the spacecraft positions in \(I_j\) result in an almost complete coverage of the nucleus surface. Surface sources with no flyover within the interval \(I_j\) are set to zero emission for the lower bound estimate of the activity.

For building the forward model, we consider the approach of Kramer et al. (2017) and introduce a model for a collisionless gas regime in the coma. Around perihelion and close to the nucleus, estimated gas densities of up to \(10^{18} \text{ molecules m}^{-3}\) result in mean free paths of about 3 m. This value is considerably larger than the mean free paths considered by Gombosi, Nagy & Cravens (1986) (0.1–1 m), Crifo et al. (2004) (<1 m), and Tenishev, Combi & Davidsson (2008) (<1 m) and results in higher Knudsen numbers >0.003. Away from perihelion and farther away from the nucleus, the fast \(\sim 1/r^2\) drop in gas density quickly leads to intermediate and collisionless flow regimes. From fig. 2 in Finklenburg et al. (2011), we estimate the uncertainties due to collisions at observational spacecraft distances to be less than 25 per cent around perihelion, resulting in smaller contributions to the model uncertainties compared to coverage and fitting errors.

On every surface element the model assumes a point source, which emits gas with a displaced Maxwellian velocity distribution shifted by a given mean velocity. This leads to the analytical expression (1) in Kramer et al. (2017) for the density derived by Narasimha (1962). The lateral expansion of the gas column perpendicular to the surface normal is taken into account. The modelled gas density at every space point around the nucleus arises from a superposition of all surface emitters. The accurate incorporation of the nucleus shape and the possibility to assign multiple surface locations to a single gas measurement set our model apart from a
simple nadir mapping of data points. The nadir method projects each spacecraft measurement on to a single point on the surface of the nucleus.

Within each subinterval $I_j$ and for every species $s = \text{H}_2\text{O}, \text{CO}_2, \text{CO},$ and $\text{O}_2$, the gas is emitted constantly in time. This results in an assimilation of the time-averaged surface emission rates, with a bias towards the local time of observation. A discussion of density variations due to changing subspacecraft longitudes follows below.

The surface emission rate for each species $s$ on the surface element $i = 1, \ldots, N_s$ is given by equation (4) in Kramer et al. (2017), namely

$$\dot{\rho}_s \left( I_j \right) = \frac{\dot{u}_{s,0}}{U_0} q_s \left( I_j \right),$$

for $t \in I_j$ and $j = 1, \ldots, N_1$, with the speed $u_{s,0}$ of the outflow velocity into the surface normal direction and the source strength $q_s$. The emission rates are expressed in units molecules m$^{-2}$ s$^{-1}$, or alternatively rescaled to kg m$^{-2}$ s$^{-1}$ with the respective molecular mass. The parameter $U_0$ denotes the speed ratio between the outflow velocities along the surface normal $u_{s,n}$ and into the lateral direction. We treat $U_0$ as an unknown parameter to be determined by a fit and set the speed into the normal direction as given in equations (2) and (3). Within the exemplary test interval $(-330, -310)$ d, we have compared model densities to DFMS/COPS data for different values of $U_0$, ranging from $U_0 = 1$ to $U_0 = 4$. A larger value $U_0 \geq 4$ exaggerates the density variations at the sampling points, while a smaller value $U_0 < 2$ diminishes the fluctuations. We have selected $U_0 = 3$, which gives the best agreement between the model and observations.

The transformation of the DFMS/COPS density data to flux quantities $\dot{\rho}_s \left( I_j \right)$ requires us to assign an outflow speed $u_{s,0}$ to the density for each interval $I_j$. At distances $r = 10-1000$ km from the nucleus, Bockelée-Morvan & Crovisier (1987) show that the radiative equilibrium conditions in the coma lead to speeds around 850 m s$^{-1}$. Lämmertzahl et al. (1988) measured 800 m s$^{-1}$ at $r = 1000-4000$ km for comet Halley. DSMC computations by Tenishiev et al. (2008) (fig. 7) and Davidson et al. (2010) (figs 2, 4, 5) yield speeds of water of 900–450 m s$^{-1}$ at heliocentric distances $r_h = 1.3–3.5$ au. For the choice of the speed of water we follow the approach of Hansen et al. (2016) (table 1, equation 7, fig. 4) and assume a function of heliocentric distance

$$u_{\text{H}_2\text{O},0} \left( r_h \right) = u_{\text{Hansen}} \left( r_h \right)$$

resulting in speeds between 820 m s$^{-1}$ and 560 m s$^{-1}$. To facilitate comparisons with other models, we also consider a simplified model with a fixed water outflow speed

$$u_{\text{H}_2\text{O},0} = 755 \mathrm{~m} \mathrm{~s}^{-1}.$$

If not stated otherwise, the results in this article are based on equation (2). The speeds of the other species are derived from the water speed weighted by the square root of the molecular mass ratio with water

$$u_{s,0} = u_{\text{H}_2\text{O},0} \sqrt{\frac{\mu_{s}}{\mu_{\text{H}_2\text{O}}}}.$$
lists the integrated productions $P_s$ compared to that, the model with constant speed (equation 3) results in only one-tenth of the water mass production. Com- perihelion and is clearly dominated by $\text{H}_2\text{O}$, whereas $\text{CO}_2$ con- distributed source of e.g. icy grains that evaporate before reaching the Sun. One possible reason for the higher value is the asymmetric mass production ratios from $\text{H}_2\text{O}$, $\text{CO}_2$, $\text{CO}$, and $\text{O}_2$ at almost 1.46 $\pm$ 0.41. This value presents a lower limit for the dust-to-gas ratio. The escaping material may still contain volatiles that affect the dust-to-gas ratio (see e.g. Altwegg et al. 2016; De Keyser et al. 2017). In addition, the dust-to-gas ratio may differ from the dust-to-ice ratio in the nucleus as backfall of dry or almost dry dust would contribute to the amount of dust ejected, but would not lead to mass loss of the nucleus.

The sufficient temporal coverage of DFMS/COPS data allows us to integrate the production per orbit by summing all interval contributions (see equation 4). Another possibility sometimes used in the literature is to approximate the integral from the power-law fit $r_\alpha$. Fig. 4 shows that the production rate $Q_{\text{H}_2\text{O}}$ follows power laws with exponents $r_\text{H}_2\text{O} = 1.8$ and $r_\text{CO}_2 = -6.5$ for the inbound and outbound orbits, respectively. The exponents given by Hansen et al. (2016) ($-5.1 \pm 0.05$ and $-7.15 \pm 0.08$) and Shinnaka et al. (2017) ($-6.0 \pm 0.5$ and $-5.22 \pm 0.41$) are in a similar range. The data analysis of Marshall et al. (2017) yields considerably lower exponents ($-3.8 \pm 0.2$ inbound, $-4.3 \pm 0.2$ outbound). This is one consequence of the smaller peak production rates derived from MIRO versus ROSINA as discussed above in the context of the peak production. Although not as steep as for $\text{H}_2\text{O}$, the $\text{O}_2$ curves are fitted by exponents of $-5.5$ and $-6$. The inbound production of $\text{CO}_2$ and $\text{CO}$ is not well reproduced by a power law since 150 d before perihelion and even earlier the production rate stagnates. Outbound, the $\text{CO}_2$ production drops down with $r_\text{CO}_2 = 4.5$, slower than for $\text{H}_2\text{O}$. This difference leads to a crossover from a water-dominated coma to a carbon-dioxide-dominated one at 2.75 au (250 d after perihelion). CO partially resembles the $\text{CO}_2$ trend with a similar exponent $r_\text{CO} = -6.0$.

Fig. 4 and Table 1 show production contributions separated for the Northern (N) and Southern (S) hemispheres. All species are released in higher quantities from the Southern hemisphere compared to the Northern one. This is caused by the stronger illumination of the southern latitudes during perihelion, with summer solstice occurring only 23 d after perihelion. The asymmetric mass production ratios $P_{s,N}/P_{s,S}$ for $\text{H}_2\text{O}$, $\text{CO}$, and $\text{O}_2$ range between 1.7:1 and 2.0:1. In contrast to that, the S/N ratio for $\text{CO}_2$ becomes 4.9:1. This indicates a predominant $\text{CO}_2$ production from southern sources. In agreement with the southward-shifted integrated productions, the ratios $Q_{s,N}(t)/Q_{s,S}(t)$ around perihelion are close to the S/N ratios in Table 1 for $P_s$. For CO, the S/N ratio remains elevated also on the outbound cometary orbit after perihelion and for $\text{CO}_2$ at almost all times. For $\text{CO}_2$, only the first interval is an exception, where the subspacecraft latitude leads to a poor southern coverage.

5 Localized Surface Sources

It has been recognized (see e.g. Bieler et al. 2015) that a homogeneous distribution of the activity cannot explain the coma gas distribution. Consequently advanced models use different heterogeneous distributions of active areas. For example, Fougere et al. (2016a) use an inverse approach for spherical harmonics in the neck region to introduce heterogeneity and Marschall et al. (2017) use specific surface morphology (cliffs, plains) to attribute activities to different areas. Our inverse model allows one to trace back in situ DFMS/COPS measurements in the coma to localized emission rates. It
Figure 4. Production rates $Q_s(r_h)$ (split into Northern, Southern hemisphere and total) for the species $s = \text{H}_2\text{O}, \text{CO}_2, \text{CO}, \text{and} \text{O}_2$ as a function of heliocentric distance $r_h$, power-law fits $Q_s(r_h) \sim r_h^{\alpha(s)}$.

Figure 5. Surface emission rate $\dot{\rho}_{\text{H}_2\text{O}}$ averaged over the intervals $A = (-330, -280)$, $B = (-50, 50)$, and $C = (340, 390)$ d after perihelion. The colours correspond to the colour bars in Fig. 7 for water and the intervals $A$, $B$, and $C$, respectively.
incorporates the complex shape of the nucleus with two lobes, large concave areas, and additional valleys, cliffs, and plains. No assumptions for the active areas on the surface of 67P/C–G enter our model.

The surface is shown from different viewing directions in Fig. 5 and coloured by the surface emission rate $\dot{\rho}_{H_2O}$ temporally averaged over three intervals, respectively. The first interval $A = (-330, -280)$ ends months before perihelion, the second interval $B = (-50, 50)$ covers the time around perihelion, and the last interval $C = (340, 390)$ begins months after perihelion. According to Fig. 4 the dominating hemisphere for the H$_2$O emissions changes from north in interval $A$ to south in interval $B$ and back to north in interval $C$.

The integrated H$_2$O production over the complete interval ($-372, 390$) amounts to 780 $\pm$ 250 kg m$^{-2}$ in the most active source regions and to 110 $\pm$ 30 kg m$^{-2}$ on average. Assuming a pure water ice surface with a density of 470 kg m$^{-3}$, this corresponds to a maximum ice erosion of 1.7 m. The average ice erosion across the entire nucleus and orbit is then 0.23 m. With increasing dust-to-gas ratio the erosion height increases correspondingly.

To focus the discussion to regions of highest activity, Fig. 6 shows the most abundant volatile H$_2$O around perihelion in the latitude/longitude Cheops frame defined by Preusker et al. (2015). Only those surface elements are depicted that contribute 50 per cent of the total water loss during the time interval $B$. Based on this set nine oval activity areas are marked. Area 1 covers parts of the regions Apis and Khonsu, area 3 parts of the region Anuket, area 6 parts of the region Bastet, area 7 parts of the region Bes and Khepyr, area 8 parts of the region Bes, and area 9 parts of the region Ash (see fig. 11 of El-Maarry et al. 2016 for the definition of regions). Our activity areas contain 23 out of 34 locations of short-living outbursts around perihelion (small circles) reported by Vincent et al. (2016). Based on this we incorporate the complex shape of the nucleus with two lobes, large concave areas, and additional valleys, cliffs, and plains. No assumptions for the active areas on the surface of 67P/C–G enter our model.

Activity in area 1 is going up first (Fig. 5). Area 1 is the only one where a significant increase in the emission rate starts well before perihelion (Fig. 5). This remarkable correlation is even more pronounced and longer lasting (including months before and after perihelion) in the CO$_2$ data discussed below.

The attached side panels to Figs 7 and 8 show the longitutinately averaged emission (zonial mean) and in addition indicate the range of subsolar latitudes during the considered interval. Around perihelion and southern solstice (in interval $B$), all emission peaks are concentrated on the Southern hemisphere close to the subsolar latitude at that time. Months before inbound equinox (in interval $A$), the peaks for H$_2$O and O$_2$ are also linked to the subsolar latitude in the north. Months after outbound equinox (in interval $C$), H$_2$O and O$_2$ features peak near the northern subsolar latitude but still have contributions from the Southern hemisphere. In contrast to H$_2$O and O$_2$, the peaks for the volatiles CO$_2$ and CO are decoupled from the subsolar latitude in the intervals $A$ and $C$. Substantial emissions originate from the Southern hemisphere. The strongest CO$_2$ sources remain localized on the Southern hemisphere for all intervals independent to the corresponding subsolar latitude.

Figs 7 and 8 show the overall surface emissions averaged within the time intervals $A$, $B$, and $C$ for all species H$_2$O, CO$_2$, CO, and O$_2$. For H$_2$O this corresponds to the three-dimensional representation in Fig. 5. The seasonally changing solar illumination leads to latitudinal shifts in the source distribution, but with different patterns for H$_2$O, CO$_2$, CO, and O$_2$. Peak sources for H$_2$O, CO$_2$, CO, and O$_2$ appear roughly at places in agreement to Hoang et al. (2017), who projected the RTOF density measurements to a 10 km surface. This agreement becomes even better when comparing the RTOF data for H$_2$O with Fig. 4 in Kramer et al. (2017), which shows our inverse model data on a 100 km surface. As suggested by VIRTIS-H observations in Bockelée-Morvan et al. (2016), by modelling results in Fougere et al. (2016b) and Hoang et al. (2017), CO$_2$ and CO are decoupled from H$_2$O at the time before inbound equinox. This matches our observation in interval $A$, that CO$_2$ and CO are mainly located in the Southern hemisphere, while H$_2$O originates from the Northern hemisphere.

Around perihelion (in interval $B$) the H$_2$O emissions are not limited to the nine activity areas but occur to some extent around the entire nucleus. CO and O$_2$ are predominantly active in all water areas, but CO$_2$ coincides with water only for the southern areas 1–2, 4–8. On the Northern hemisphere, the CO$_2$ emission is almost absent from area 3, close to the Anuket fracture described in El-Maarry et al. (2015), and area 9 in the Ash region. Area 7 covers the patches reported by Filacchione et al. (2016) and Fornasier et al. (2016), including high-CO$_2$ ice and H$_2$O ice concentrations around day $-145$ and around day $-105$, respectively. Although their observations are made before our interval $B$, the agreement for this source localization is still remarkable.

During the inbound northern summer (in interval $A$) H$_2$O and O$_2$ activity is located along a northern belt including the areas 3, 6, and 9. This repeats in the outbound northern summer (in interval $C$) and is complemented by activity in southern areas 1, 4, and 6 for H$_2$O and in 1–2, 4–5, 7–8 for O$_2$. Thus, O$_2$ source locations correlate to H$_2$O source locations during all intervals $A$, $B$, and $C$. For the inbound northern summer (in interval $A$) CO$_2$ and CO activity is widely spread over the whole surface; CO$_2$ exhibits important contributions from the southern areas 1–2, 4–8, and almost all activity areas (except area 8) show CO emissions. Comparing this pattern to H$_2$O sources, CO sources seem to correlate to a linear combination of H$_2$O and CO$_2$ sources. At the same time despite the low emission from area 8, CO$_2$ emissions in area 8 and surroundings in region Imhotep are still higher than the H$_2$O emissions. This shows a good agreement with the area of high ratio $p_{CO_2}/p_{H_2O}$ described in Hässig et al. (2015). During the outbound northern summer, when $H_2O$ is almost vanished, the pattern of CO sources seems to correlate to CO$_2$ sources only. Both source patterns focus to the southern areas 1–2, 4–8.

The CO$_2$ sources are pinned to the south throughout the whole Rosetta mission at the marked active areas: For all intervals $A$, $B$, and $C$ the southern CO$_2$ sources (areas 1–2, 4–8) remain active. This shows the consistent retrieval and assignment of CO$_2$ sources for the intervals $A$ and $C$, long before and after perihelion, respectively. Because these surface locations are reconstructed from completely disjoint data sets and widely varying spacecraft trajectories, this
validates our inverse model approach. Furthermore, the location of 
CO₂ sources on the Southern hemisphere is in agreement with the 
COPS data analysis for the month 2016 May performed in Kramer 
et al. (2017).

6 DISCUSSION

In this manuscript, we have presented emission rates for the gas 
species H₂O, CO₂, CO, and O₂ with high spatial resolution on 
the surface of 67P/C-G and also temporally resolved in the time 
between 2014 August 6 and 2016 September 5. Previous surface 
maps were derived from lower resolution expansions with 25 pa-
rameters by Fougere et al. (2016b) and did not localize gas sources 
due to the inherent averaging over longitudes. The coma model 
by Marschall et al. (2017) considers various topographical features 
as gas sources, does not employ an inversion process, and leads 
to a non-unique source attribution. The lower longitudinal reso-
lution of the inversion models by Hansen et al. (2016) (fig. 10) 
and Fougere et al. (2016b) (fig. 5) results in striped activity pat-
ters and concentric fringes around the poles, respectively. With 
the hundred-fold increase of resolution shown here, we obtain a 
more accurate determination of local gas emitters on the surface, 
validated by matching with independent optical observations of 
outbreaks and spectroscopy of icy patches. Another internal consis-
tency check of the model is the assignment of identical gas sources 
across completely distinct time-periods with vastly varying solar 
radiation and spacecraft orbits. In contrast to previous inversions, 
which work with single data sets covering a long interval (300 d 
by Fougere et al. 2016a), the combined COPS/DFMS data set al-
ows us to trace the coma evolution in 14 d intervals. We also 
introduced a systematic uncertainty quantification due to missing 
visibility of surface areas. The reconstruction was based on the in-
verse gas model in Kramer et al. (2017) and in situ DFMS/COPS 
measurements in the coma. Based on the speed assumption in 
Hansen et al. (2016) for each of the species, peak production rates 
(integrated over space) and integrated (over space and time) pro-
duction rates are evaluated. The summation over all gas species 
yields a peak production rate $2.2 \pm 0.1 \times 10^{28}$ molecules s$^{-1}$, 
an integrated production rate $5.8 \pm 1.8 \times 10^{9}$ kg, and a max-
imum (averaged) water ice erosion of $1.7$ m (0.23 m). Incor-
porating the total mass loss, for the dust-to-gas ratio this 
yields $0.5^{+1.0}_{-0.5}$.

Nine activity areas are defined by H₂O emissions around peri-
helion and these correlate well with short-living outbursts reported 
by Vincent et al. (2016). The examination of the nine areas before, 
around, and after perihelion shows that the source locations of H₂O 
and O₂ follow the subsolar latitude and correlate to each other. In 
contrast to that, CO₂ sources are mainly located in southern areas 
throughout the whole mission. CO correlates to a linear combina-
tion of H₂O and CO₂ months before inbound equinox; months after 
outbound equinox it correlates to CO₂ only.

By comparing optical observations with dust-coma models 
(Kramer & Noack 2015; Kramer et al. 2018) it is known that the 
dust coma is best explained by uniform activity across the entire 
sunlit nucleus, which points to a rather homogeneous surface com-
position.
Figure 8. Surface emission rates $\dot{\rho}_{O_2,i}$ and $\dot{\rho}_{CO,i}$ in the intervals $A = (−330, −280)$, $B = (−50, 50)$, and $C = (340, 390)$ d after perihelion. The side panels show the longitudinally averaged rate (zonal mean) and the grey bar indicates the subsolar latitude.

The surface localization of emissions for different gas species, also described by A’Hearn et al. (2011) for comet Hartley 2, is a first step to connect observational data to the reconstruction with first-principle modelling of cometary activity such as that suggested by Keller et al. (2015). The fast drop of the water production rates with increasing heliocentric distance rules out the simplest sublimation models from Keller et al. (2015) taking a uniformly covered icy body with $Q_{H_2O} \sim r^{-2.8}$ in model A. One way to accommodate higher exponents in the power law is to consider a time-varying dust cover on the surface, leading to a transition from Keller model A to models with a larger dust cover. In addition, the peak water production of $\sim 3200$ kg s$^{-1}$ in model A (a completely water-ice-covered surface) is about five times as high as our peak production. A detailed comparison with first-principle thermal and compositional models of the surface is planned for future work.

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REFERENCES

A’Hearn M. F. et al., 2011, Science, 332, 1396
Altwegg K. et al., 2016, Sci. Adv., 2, e1600285
Balsiger H. et al., 2007, Space Sci. Rev., 128, 745
Bailer A. et al., 2015, A&A, 593, A7
Bockelée-Morvan D., Crovisier J., 1987, Proceedings of the International Symposium on the Diversity and Similarity of Comets, 6-9 April 1987, Brussels, Belgium, p. 235, Available at: http://adsabs.harvard.edu/abs/1987ESASP.278..235B
Bockelée-Morvan D. et al., 2016, MNRAS, 462, S170
Calmonte U. et al., 2016, MNRAS, 462, S253
Crifo J., Fulle M., Kömle N. I., Szego K., 2004, in Festou M., Keller H.U., Weaver H.A., eds, Comets II. University of Arizona Press, Tucson, p. 471
Davidsson B. J., Gulkis S., Alexander C., von Allmen P., Kamp L., Lee S., Warell J., 2010, Icarus, 210, 455
De Keyser J. et al., 2017, MNRAS, 469, S695
El-Maarry M. R. et al., 2015, Geophys. Res. Lett., 42, 5170
El-Maarry M. R. et al., 2016, A&A, 593, A110
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Gasca S. et al., 2017, Planet. Space Sci., 135, 64

Filacchione G. et al., 2016, Science, 354, 1563

Finkenburg S., Thomas N., Knollenberg J., Kührt E., 2011, AIP Conference Proceedings, 1333, 1151

Fornasier S. et al., 2016, Science, 354, 1566

Fougere N. et al., 2016a, MNRAS, 462, S156

Fougere N. et al., 2016b, A&A, 588, A134

Gasc S. et al., 2017, Planet. Space Sci., 135, 64

Godard B., Budnik F., Muñoz P., Morley T., Janarthanan V., 2015, in Proceedings of the 25th International Symposium on Space Flight Dynamics, Munich, Germany, Available at: http://issfd.org/2015/files/downloa ds/papers/124_Godard.pdf

Godard B., Budnik F., Bellei G., Morley T., 2017, in Proceedings of the 26th International Symposium on Space Flight Dynamics, Matsuyama, Japan, Available at: http://issfd.org/ISSFD_2017/paper/ISTS-2017-d-095_ISSFD-2017-095.pdf

Gombosi T. I., Nagy A. F., Cravens T. E., 1986, Rev. Geophys., 24, 667

Hansen K. C. et al., 2016, MNRAS, 462, S491

Hase L., 1957, Bulletin de la Class des Sciences de l’Académie Royale de Belgique, 43, 740

Hässig M. et al., 2015, Science, 347, aaa0276

Hoang M. et al., 2017, A&A, 600, A77

Keller H. U. et al., 2015, A&A, 583, A34

Kramer T., Noack M., 2015, ApJ, 813, L33

Kramer T., Lüter M., Rubin M., Altweck K., 2017, MNRAS, 469, S20

Kramer T., Noack M., Baum D., Hege H.-C., Heller E. J., 2018, Adv. Phys.: X, 3, 1404436

Lämmerzahl P. et al., 1988, in Growing M., Pradere F., Reinhard R., eds, Exploration of Halley’s Comet, Springer, Berlin, p. 169

Marschall R. et al., 2016, A&A, 589, A90

Marschall R. et al., 2017, A&A, 605, A112

Marshall D. W. et al., 2017, A&A, 603, A87

Narasimha R., 1962, J. Fluid Mech., 12, 294

Preusker F. et al., 2015, A&A, 583, A33

Schroeder I. R. et al., 2018, A&A, preprint (arXiv:1809.03798)

Shulz R., 2009, Sol. Syst. Res., 43, 343

Shinnaka Y. et al., 2017, AJ, 153, 76

SPC-ESA, 2016, ESA/RMOC, SPC-ESA MTP019 Cartesian Plate Model Low Res dsk for Comet 67P/C-G. Available at: https://pdsbsn.astro.umd.edu/holdings/ro-c-mul-5-67p-shape-v2.0/ data/spice_dsk/space_esa/mtp019/cksp_dlv_130_01_lores_bds.lbl

Tenishev V., Combi M., Davidsson B., 2008, ApJ, 685, 659

Valette S., Chassery J.-M., Prost R., 2008, IEEE Trans. Vis. Comput. Graphics, 14, 369

Vincent J.-B. et al., 2016, MNRAS, 462, S184

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