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THE NATURE AND FREQUENCY OF THE GAS OUTBURSTS IN COMET 67P/CHURYUMOV-GERASIMENKO OBSERVED BY THE ALICE FAR-ULTRAVIOLET SPECTROGRAPH ON ROSETTA

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ABSTRACT

Alice is a far-ultraviolet imaging spectrograph onboard *Rosetta* that, amongst multiple objectives, is designed to observe emissions from various atomic and molecular species from within the coma of comet 67P/Churyumov-Gerasimenko. The initial observations, made following orbit insertion in August 2014, showed emissions of atomic hydrogen and oxygen spatially localized close to the nucleus and attributed to photoelectron impact dissociation of H₂O vapor. Weaker emissions from atomic carbon were subsequently detected and also attributed to electron impact dissociation, of CO₂, the relative H I and C I line intensities reflecting the variation of CO₂ to H₂O column abundance along the line-of-sight through the coma. Beginning in mid-April 2015, Alice sporadically observed a number of outbursts above the sunward limb characterized by sudden increases in the atomic emissions, particularly the semi-forbidden O I λ 1356 multiplet, over a period of 10-30 minutes, without a corresponding enhancement in long wavelength solar reflected light characteristic of dust production. A large increase in the brightness ratio O I λ 1356/O I λ 1304 suggests O₂ as the principal source of the additional gas. These outbursts do not correlate with any of the visible images of outbursts taken with either OSIRIS or the navigation camera. Beginning in June 2015 the nature of the Alice spectrum changed considerably with CO Fourth Positive band emission observed continuously, varying with pointing but otherwise fairly constant in time. However, CO does not appear to be a major driver of any of the observed outbursts.

Keywords: comets: individual (67P) — ultraviolet: planetary systems

1. INTRODUCTION

We have previously (Feldman et al. 2015) described the initial observations of the near-nucleus coma of comet 67P/Churyumov-Gerasimenko made by the Alice far-ultraviolet imaging spectrograph onboard *Rosetta* made in

the first few months following orbit insertion in August 2014. These observations of the sunward limb, made from distances between 10 and 30 km from the comet's nucleus, showed emissions of atomic hydrogen, oxygen, and carbon, spatially localized close to the nucleus and attributed to photoelectron impact dissociation of H₂O and CO₂ vapor. This interpretation is supported by measurements of suprathermal electrons by the Ion and Electron Sensor (IES) instrument on *Rosetta* (Clark et al. 2015). Beginning in February 2015,

as the activity of the comet increased, the orbit of *Rosetta* was adjusted to increasing distance from the nucleus due to concerns for spacecraft safety. At distances ≥ 50 km, when pointed towards the nadir, the spatial extent along the Alice 5.5° long slit (Stern et al. 2007) allows the coma, both sunward and anti-sunward, to be resolved from the nucleus and observed nearly continuously.

This geometry allowed Alice, beginning in mid-April 2015, to observe a number of outbursts above the sunward limb. These outbursts are characterized by sudden increases in the atomic emissions, particularly the semi-forbidden O I $\lambda 1356$ multiplet, over a period of 10-30 minutes, without a corresponding enhancement in long wavelength solar reflected light characteristic of dust production. The corresponding increase in the brightness ratio O I $\lambda 1356$ /O I $\lambda 1304$ suggests that O₂, detected for the first time in a comet by Bieler et al. (2015), is the primary source of the additional gas. This is the same spectroscopic diagnostic used to determine that O₂ is the dominant species in the exospheres of Europa and Ganymede (Hall et al. 1995, 1998). As the comet rotates the Alice slit samples different regions above the comet’s limb, but the magnitude of the increase on the short time scale as well as the spatial distribution along the slit makes it very unlikely that it is due to a spatial gradient or a collimated “jet”.

Although C I $\lambda 1657$ is also seen to increase, the variation in the brightness ratio O I $\lambda 1356$ /C I $\lambda 1657$ indicates that it cannot be CO₂ alone, nor can the effects be due to an increase in photoelectron flux. These outbursts do not correlate with any of the visible images of outbursts taken with either OSIRIS (Lin et al. 2016; Vincent et al. 2016) or the navigation camera. We also find that CO does not appear to be driving any of the observed outbursts.

2. OBSERVATIONS

2.1. Instrument Description

Alice is a lightweight, low-power, imaging spectrograph designed for in situ far-ultraviolet imaging spectroscopy of comet 67P in the spectral range 700-2050 Å. The slit is in the shape of a dog bone, 5.5° long, with a width of 0.05° in the central 2.0° , while the ends are 0.10° wide, giving a spectral resolution between 8 and 12 Å for extended sources that fill its field-of-view. Each spatial pixel or row along the slit is 0.30° long. Details of the instrument have been given by Stern et al. (2007).

2.2. Gas Outbursts

The strongest of the outbursts, from the period May-July 2015, are listed in Table 1. The table includes the heliocentric distance of the comet, r_h , the distance of *Rosetta* from the center of the comet, d , the sub-spacecraft longitude and latitude, and the solar phase angle at the time of observation. With the exception of the June 18 and June 23 outbursts, the

sub-spacecraft positions of the tabulated outburst are uncorrelated, attesting to their random nature. As an example we will consider in detail the outburst of May 23 since the pointing was constant over two rotations of the comet enabling us to obtain nearly continuous light curves except for gaps in the data due to a lack of observations during spacecraft maintenance activities. Light curves for the strongest coma emissions are shown in Fig. 1. Note that prior to the outburst the relative intensities of H I Lyman- β , O I $\lambda 1304$, and O I $\lambda 1356$, are consistent with the earlier observations that attributed the emissions primarily to electron dissociative excitation of H₂O (Feldman et al. 2015). One rotation period (~ 12 h) later both the absolute and relative brightnesses have returned to their pre-outburst values, in strong contrast to the persistent diurnal variability seen in mass spectrometer data (Hässig et al. 2015; Mall et al. 2016; Fougere et al. 2016).

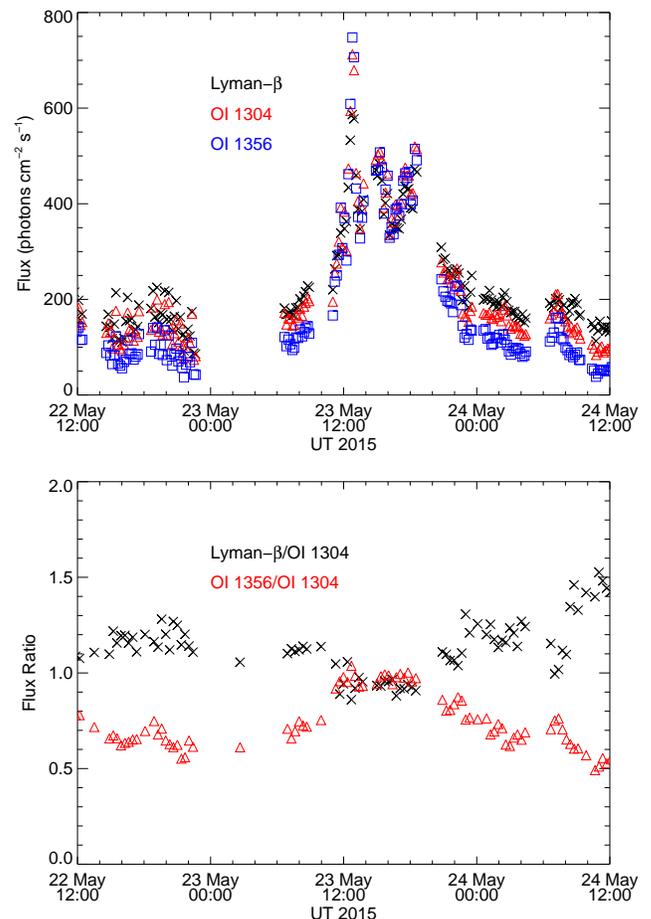


Figure 1. Temporal variation of the atomic hydrogen and oxygen emissions above the limb on 2015 May 22–24 (top). Individual error bars are not shown but the $1-\sigma$ statistical uncertainty for all points is $<5\%$. The bottom panel shows the variation in relative intensities of these emissions.

The orientation of the Alice slit projected onto the comet is shown in Fig. 2 (left) in an image from the navigation cam-

era (NAVCAM) taken ~ 45 minutes after the peak brightness. The Sun is towards the top of the image and the comet's rotation axis is roughly perpendicular to the slit. We attribute the secondary peaks seen in the light curve (top panel of Fig. 1) to geometric effects of the rotation, as visualized in the three-dimensional coma models of Fougere et al. (2016). Similar effects are seen in the light curves of the other outbursts listed

in Table 1.

The spectral image in Fig. 2 (right) shows the clearly separated coma emissions together with the reflected solar spectrum from the nucleus in rows 11 to 17 of the slit. Again, the Sun is towards the top of the image. Note that the O I emissions are seen against the solar reflected radiation from the nucleus and into the anti-sunward coma.

Table 1. Major Gaseous Outbursts Observed by Alice in May - July 2015.

Date	Peak Time (UT) ^a	r_h (AU)	d (km)	Sub-spacecraft		Phase Angle (°)	$B_{max}(1356)$ (rayleighs) ^b
				Longitude (°)	Latitude (°)		
2015 May 23	12:42	1.58	143	151.2	-17.1	61.1	223
2015 June 18	03:43	1.42	202	214.8	51.3	89.9	173
2015 June 20	15:26	1.40	181	269.3	19.9	89.9	60
2015 June 23	20:39	1.39	196	215.0	53.3	89.7	113
2015 July 04	08:56	1.34	179	111.6	53.8	89.9	83
2015 July 13	01:16	1.30	155	149.3	15.6	88.8	78

^a start time of histogram integration

^b maximum O I $\lambda 1356$ brightness above the sunward limb in a 0.3° spatial pixel.

2.3. Spectra

To study the evolution of the gas content during the outburst we present four successive spectra of the sunward coma taken from 10-minute histograms beginning 2015 May 23 UT12:10:07 in the left panel of Fig. 3. These correspond to rows 18 to 21 of the spectral image in Fig. 2. The difference between the spectra at the peak of the outburst and the prior spectra is then indicative of the erupting gas. The difference spectrum, shown in the right panel, is characterized by an enhancement in the atomic emissions, particularly atomic oxygen, without a corresponding enhancement in long wavelength solar reflected light characteristic of dust production. The large increase in O I $\lambda 1356$ /O I $\lambda 1304$ (intensity ratio $\geq 1:1$) suggests O₂, now known to be present in the cometary ice of 67P (Bieler et al. 2015), as the primary source of the additional gas.

However, laboratory data on the electron impact dissociative excitation of O₂ (Kanik et al. 2003) suggests that this ratio should be ~ 2 , as seen in the exospheric spectra of Europa (Hall et al. 1995) and Ganymede (Hall et al. 1998). The observed ratio varies in the other outbursts listed in Table 1 and likely reflects additional sources of O I $\lambda 1304$ such as photodissociation of O₂ (Beyer & Welge 1969; Lee et al. 1974) or electron impact on O (if present). The dramatic change in relative intensities implies that the outburst cannot be due to a sudden increase in photoelectron flux or change in the electron energy distribution. For May 23 this is borne out by data

from RPC/IES (Clark et al. 2015) that shows only a modest uniform increase in electron flux beginning about two hours before the outburst observed by Alice and lasting for 12 hours (K. Mandt, private communication).

A significant amount of H₂O is also released as evidenced by the presence of H I Lyman- α and Lyman- β in the difference spectrum. If we ignore the blending of Lyman- β with O I $\lambda 1027$, also produced by e+O₂ (Ajello & Franklin 1985), and assume that all of the emission at 1026 Å is Lyman- β , then we can use the e+H₂O cross section for Lyman- β at 100 eV from Makarov et al. (2004) relative to the e+O₂ cross section for O I $\lambda 1356$ from Kanik et al. (2003) to estimate the relative O₂/H₂O abundance in the outburst. From the relative fluxes in the difference spectrum (Fig. 3) we find O₂/H₂O ≥ 0.5 , considerably greater than the mean quiescent value of 0.038 reported by Bieler et al. (2015). The presence of H₂O in the outburst is confirmed by concurrent sub-mm measurements of the H₂O column density by MIRO (Lee et al. 2015) along a line-of-sight contiguous with the central row of the Alice slit that showed a threefold increase at the same time (P. von Allmen, private communication), consistent with the increase in Lyman- β seen in the top panel of Fig. 1.

CO began to appear regularly in Alice coma spectra in June 2015 and continues to be present through early 2016. While not detected in the May 23 spectrum the CO Fourth Positive system is seen in several other spectra listed in Table 1. However, it does not appear in any of the difference spectra and thus is unlikely to be the major driver in any of the outbursts

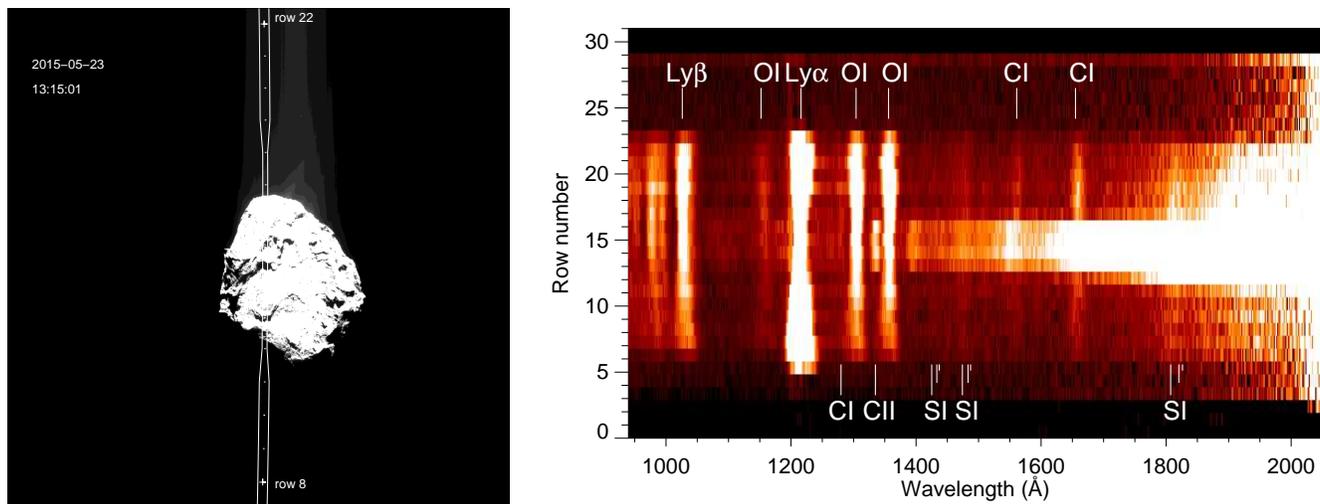


Figure 2. Left: NAVCAM context image obtained 2015 May 23 UT 13:15, shortly after the peak emission was observed. Right: Spectral image beginning UT 12:31, 1589 s exposure, three co-added histograms from the time of peak emission. The sunlit nucleus appears in rows 12–17. The distance to the comet was 143 km, the heliocentric distance was 1.58 AU, and the solar phase angle was 61.1° . For both images the direction of the Sun is towards the top of the image.

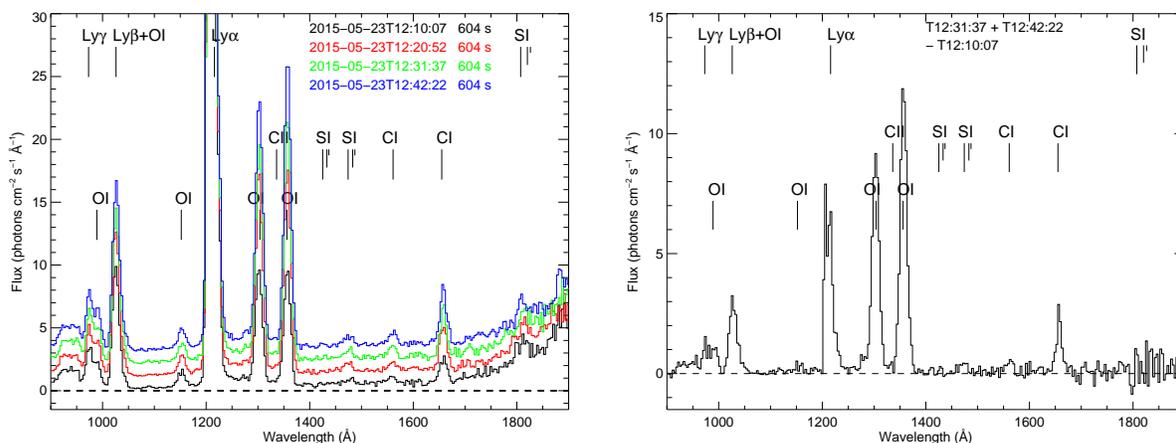


Figure 3. Left: Sequence of four 10-minute histogram spectra above the sunlit limb. The spectra are offset from one another for clarity. The upturn at long wavelengths is due to scattered solar radiation from dust in the coma. Right: The difference between the average of the final two and the first of the spectra shown at left. The difference represents the spectrum of the material ejected into the coma in a ~ 30 minute period.

presented here. The origin of the C I $\lambda 1657$ emission in the difference spectrum is not clear. Electron impact on CO_2 would produce emission at 1561 \AA with an intensity about half that of C I $\lambda 1657$ (Mumma et al. 1972) as well as CO Cameron band emission at longer wavelengths which is not observed. Other carbon bearing molecules are not precluded as a source (Le Roy et al. 2015).

We note that N_2 , also discovered for the first time in 67P (Rubin et al. 2015), also has a rich electron excited spectrum of N_2 bands and atomic and ionic N multiplets within the Alice spectral range (Heays et al. 2014). None of these are detected in the outburst spectrum so that N_2 , whose mean abundance relative to CO is found by Rubin et al. to be less than 1%, also plays no role in the gas outbursts.

2.4. Spatial Profiles

Additional information about the outburst can be obtained from the profiles of the O I emissions along the slit. Fig. 4 shows the profiles of O I $\lambda 1304$ and O I $\lambda 1356$ for the four spectra shown in Fig. 3. Both profiles peak just above the sunward limb and decrease radially outward. The brightness increases nearly uniformly in each successive 10 minute integration. With an outflow velocity of 0.5 km s^{-1} the escaping O_2 molecules will exit the Alice field-of-view in ~ 10 seconds, so the ejection is continuous. From the light curve we see that one rotation later ($\sim 12 \text{ h}$), at the same sub-spacecraft longitude, the emission has returned to its quiescent level. Emission is seen against the nucleus and off the anti-sunward limb, indicating that the outburst is not in the form of a col-

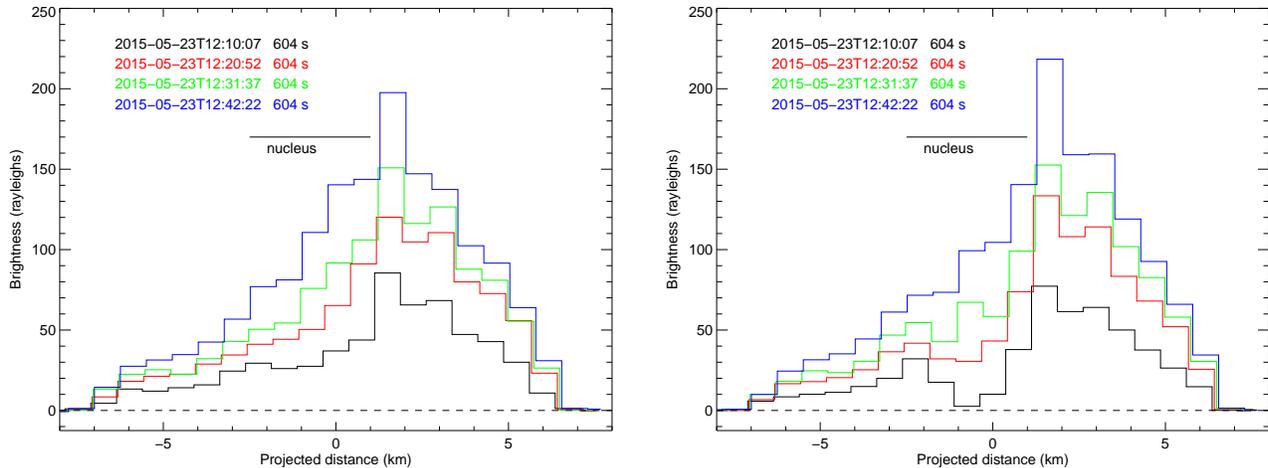


Figure 4. Spatial profiles of O I λ 1304 (left) and O I λ 1356 (right) corresponding to the spectra shown in Fig. 3. The Sun is to the right. The position of the nucleus is indicated. The ends of the projected slit are at -6.5 and $+6.0$ km, respectively.

limited jet but is rather diffuse. As noted above, any dust produced would have been detected by an increase at long wavelengths of reflected solar radiation.

2.5. Additional Events

For the other dates in Table 1, the light curves, difference spectra, and spatial profiles are all similar to those of the May 23 event. A search through the Alice database for earlier events reveals multiple outbursts with similar spectra on 2015 April 15 and April 29/30. Prior to April, the geometry for observing outbursts (closer distance to the nucleus) was less favorable. In April the spacecraft was at southern latitudes but the longitudes of the outbursts was also random. The rate of detected gas outburst events decreased after perihelion on 2015 August 13. Post-perihelion observations, through the present, continue to show variable O I λ 1356/O I λ 1304 intensity ratios although these measurements are not always confined to the short time scales of the “outburst” events described above. These observations provide a means of monitoring the O₂/H₂O abundance in the coma even when *Rosetta* is at large distances (≥ 100 km) from the nucleus, complementing ROSINA measurements closer to the comet.

3. DISCUSSION

A likely source of gas outbursts is the warming of sub-surface volatile reservoirs as the comet approaches perihelion. Water ice containing frozen O₂, as has been proposed for the surface of Ganymede (Spencer et al. 1995), would reside below the dust mantle. Sublimated O₂, together with some H₂O, would then percolate through the porous mantle and diffuse into the coma taking some of the dust with it. The coupling of dust to gas sublimated from sub-surface ice has been studied by many authors (e.g., Blum et al. 2014) For 67P, Gundlach et al. (2015) consider only CO, CO₂, and H₂O ices. O₂ has a sublimation temperature and pressure comparable to those for CO (Fray & Schmitt 2009) so that the CO

models should similarly apply. The absence of dust in the outbursts observed by Alice suggests a different scenario.

Skorov et al. (2016), seeking to explain a narrow, short-lived dust outburst observed by the OSIRIS imager, has proposed a deepening of a pre-existing fracture that would lead to the exposure of a sub-surface ice layer and a subsequent rapid ejection of gas and dust. Although Skorov et al. considered a model with CO ice, their calculations should also be valid for O₂. A narrow very short-lived dust jet would be missed by the Alice slit, while the high density of the escaping gas would collisionally be distributed throughout the coma.

4. SUMMARY

We report here the detection by the Alice far-ultraviolet spectrograph on *Rosetta* of a number of sporadic gas outbursts above the sunward limb. These outbursts are characterized by sudden increases in the emissions of atomic H and O over a period of 10-30 minutes, without a corresponding enhancement in long wavelength solar reflected light characteristic of dust production. The emissions are seen to decay over a period of several hours, returning to their quiescent level after a complete rotation of the comet. Spectroscopic analysis of the ejected gas suggests O₂ as the principal driver of the additional gas. These outbursts do not correlate with any of the visible images of outbursts taken with either OSIRIS or the navigation camera. A complete accounting of both pre- and post-perihelion events will be presented in a future publication.

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Facility: Rosetta

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