Observations of Modulation of Ion flux in the Coma of Comet 67P/Churyumov-Gerasimenko

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Key Points:

- In early June 2015 troughs appeared in measurements of ion flux when Rosetta was about 200 km from the comet and about 1.5 au from the sun.
- These troughs correspond to the peaks in the neutral density produced by the nucleus.
- We believe that the troughs are the result of charge exchange reactions between the cometary ions and the neutrals, reducing the flux of water ions at the peaks of neutrals.

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Abstract

In early June 2015 the Ion and Electron Sensor (IES) on board the Rosetta spacecraft (SC) observed troughs in the ion measurements at about 200 km from the comet and about 1.5 au from the sun. These troughs had a periodicity of about 6 hrs, one half the rotation period of the comet. The troughs coincided with measurement results of two other instruments on board Rosetta: the peaks of the neutral gas density measured by the Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA) and the peaks of the electron density measured by the Langmuir and Mutual Impedence Probe Instruments, (LAP and MIP) and the most negative levels of the Spacecraft potential also measured by LAP. We propose that the dips in the ion measurements are the result of charge exchange reactions between the ions and the neutral population emitted by the comet nucleus. This interaction converts the $\leq$ keV ions to neutrals near that energy, and ions of the higher energy to neutrals of higher energy. Measurements from the Ion Composition Analyzer (ICA) on board Rosetta show that these ions are mostly water ions.

Plain Language Summary

The Rosetta spacecraft (SC) carried a number of instruments to measure the properties of the gas surrounding the nucleus. Included in these were plasma instruments to measure the characteristics of the charged particles. The Ion and Electron Sensor (IES) was one of them. Also on board were the Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA), the Ion Composition Analyzer (ICA) and the Langmuir and Mutual Impedence Probe instruments (LAP and MIP). This paper discusses some of the results of measurements by these instruments and their relation to each other. It was found that the neutral gas emitted by the comet nucleus and the resulting positively charged ions interact in such a way to produce dips in the ion density as a result of what is called ”charge exchange”, in which an electric charge is transferred from one ion to another or to a neutral particle.

1 Introduction

The Rosetta spacecraft (SC) arrived at comet Churyumov-Gerasimenko (CG) in August 2014 and remained in its vicinity until September 2016, when it landed on the comet and terminated the mission. Perihelion occurred in September 2015 at 1.24 au from the sun. Early measurement of plasma at CG showed primarily low energy H_2O^+, such as reported by Nilsson et al. (2015), Broiles et al. (2015), and Goldstein et al. (2015). These ions are the result of a combination of solar UV photoionization and electron impact collisions (see Galand et al. (2016)). At this early period in the mission, the energy of the ions produced was near that of the neutrals emitted by the nucleus, that is, the order of 1 eV (Gulkis et al., 2015). This energy was too low to be detected by either ICA (Nilsson et al., 2015) or IES, but because the SC potential was normally negative near CG (as much as -20V) these low energy positive ions were attracted to the SC and appeared at the lowest end of the energy scale of these instruments.

As the comet increased its activity the coma became more complex (Galand et al., 2016). A feature of a comet coma is the ion-neutral interaction known as charge exchange. Charge exchange reactions at comets have been studied at least as far back as the Giotto mission to comet Halley (Fuselier et al., 1991). Studies of charge exchange between solar wind and CG coma species include Burch et al. (2015), Mandt et al. (2019), and Wedlund et al. (2019). Note that there are no traces of the solar wind over the period of approximately from the middle of March to the middle of December 2015 because the density of the CG coma had grown sufficiently to deflect the solar wind away from the comet, forming a cavity (Behar et al., 2017), (Williamson et al., 2020), (Nilsson et al., 2020).

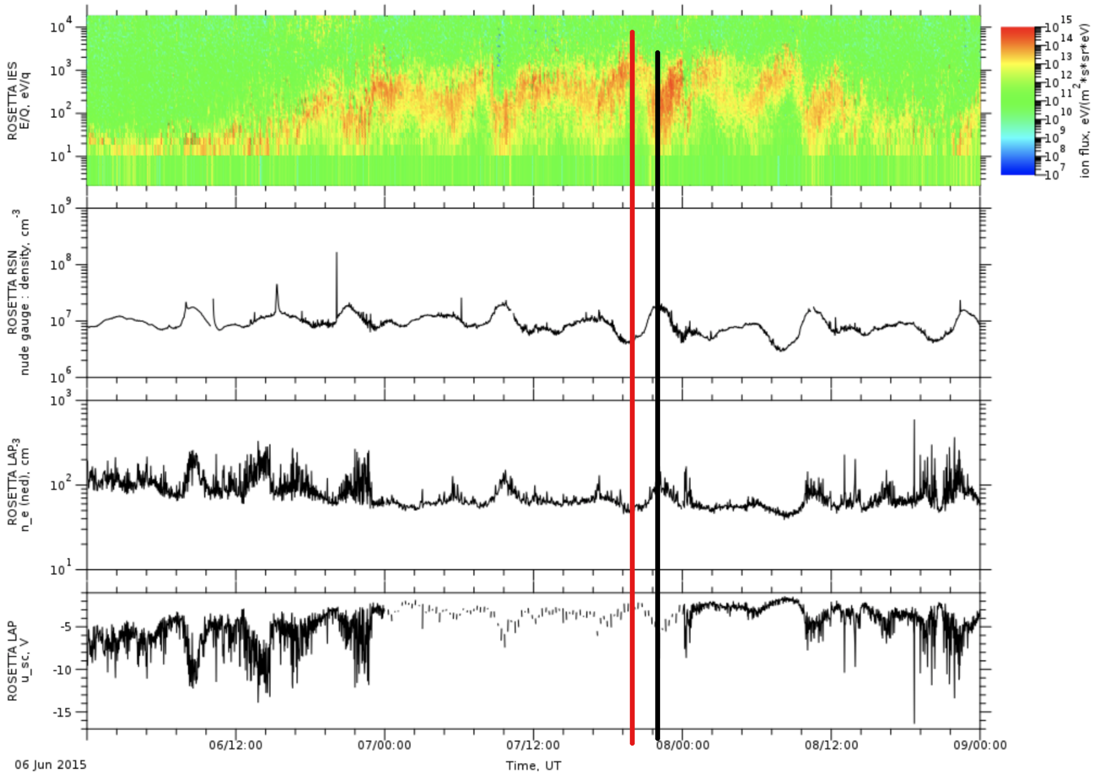

Figure 1. Comparison of results of measurements of IES ion flux, ROSINA neutral density, and LAP-MIP electron density and spacecraft potential during the period 6-8 June 2015. The vertical black line indicates the correspondence of the features of all data sets at one trough, as example. The vertical red line indicates a similar correspondence for the peak preceding the black line (approximately 22:12:25 UT on 7 June 2015). Due to the operational modes used, the time resolution in the two lower panels is much lower during June 7 than in the adjacent days. (Data are from AMDA.)

2 Analysis

The present paper discusses analysis of data for the period 6-8 June 2015, shown in Fig. 1, at about 200 km from CG and 1.5 au from the sun. This period is part of the solar wind exclusion period so the ion interactions to be described do not include solar wind but only coma ingredients, although picked up ions are important. Reading from top to bottom in Fig. 1 are the ion flux measured by the Ion and Electron Sensor, IES (Burch et al., 2007), the neutral density from the Rosetta Orbiter Spectrometer for Ion and Neutral Analysis, COmet Pressure Sensor ROSINA COPS (Balsiger et al., 2007), and the cross-calibrated electron density and SC potential from the Langmuir probe, LAP (Eriksson et al., 2007) and the Mutual Impedence Probe, MIP (Trotignon et al., 2020). (Data for this Figure were provided by the AMDA Science and Analysis online System. See the Acknowledgement Section for more details.) The notable features of Fig. 1 are the periodic troughs in the ion flux measurements, with a period near half the Rosetta rotation rate, the coincidence of those troughs with the peaks of the neutral and electron density, and with the dips in the SC potential. A vertical black line is superimposed on the plots at approximately 22:12:25 on 7 June to indicate for one case the coincidence of an IES trough and the extrema of the other data. We believe that the troughs in the IES ions are a result of charge exchange between the ions and neutrals, changing the ions to energetic neutrals and the neutrals to low energy ions. A vertical red line is superimposed on the peak preceding the trough previously mentioned.

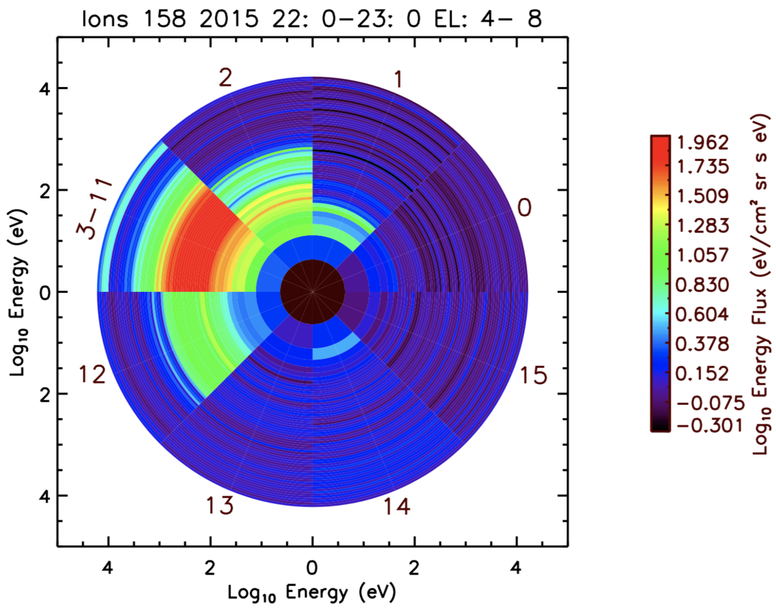

Figure 2. Color contour plot of the IES ion flux in the region around the trough indicated by the vertical black line in Fig. 1. The sun is in the direction of azimuth bins 3-11 and CG is in the direction of the boundary between bins 13 and 14. The elevation range of the data is steps 4-8 (25° to -5°).

Figs. 4 and 5 of Galand et al. (2016) for early October 2014 at 20 km from CG are analogous to Fig. 1 here except the latter data are at 200 km from CG and in the solar wind-free cavity so solar wind does not appear. The solar wind protons were the most evident ions in 2014, in contrast to the water ions appearing in Fig. 1 in 2015. But in both cases ionization of the neutrals from the comet increases the local electron density (also shown in Galand et al. (2016)) which in turn drives the SC potential more negative (Johansson et al., 2020).

Figs. 2 and 3 are color polar plots of the IES ion flux shown at the trough and peak, resp., in the region of the vertical black and red lines, resp., in Fig. 1. The time and IES elevation ranges (25° to -5°) are given in the titles. The specific elevation range (was chosen based on the IES elevation measurements for the period of interest (not shown here). The azimuth bin is numbered around the circumference and the Log_{10} energy (eV) is given along the sides of the Fig. In each of these Figs. the sun is toward azimuth bins 3-11 and CG is in the direction from the dividing line between azimuths 13 an 14. In each case there is a high flux of keV ions from the solar direction as well as a more directionally distributed contribution. The highest energy signature may be the result of charged nanograins ((Burch et al., 2015) that are heavier than the ions and would appear with a higher energy signature. But there is also a low flux over a wide energy range from the CG direction. These may be ions produced locally from the neutrals emitted from the nucleus. Since solar wind does not appear in the IES measurements, as noted, we do not expect an actual solar contribution but the interplanetary magnetic field is present (see e.g., Goetz et al. (2019)) so pickup ions may be part of the IES measurements. The recent papers by Williamson et al. (2020) and Nilsson et al. (2020) explain how ion pickup is possible when the solar wind is absent, because, in part, of the magnetic pressure. Another explanation of this is that in the solar wind-free region the pickup ions take over the role of the solar wind ions in terms of carrying the momentum from the solar wind into the solar wind cavity. Thus there are similarities to the case shown by Galand et al. (2016), with protons replaced by pickup ions.

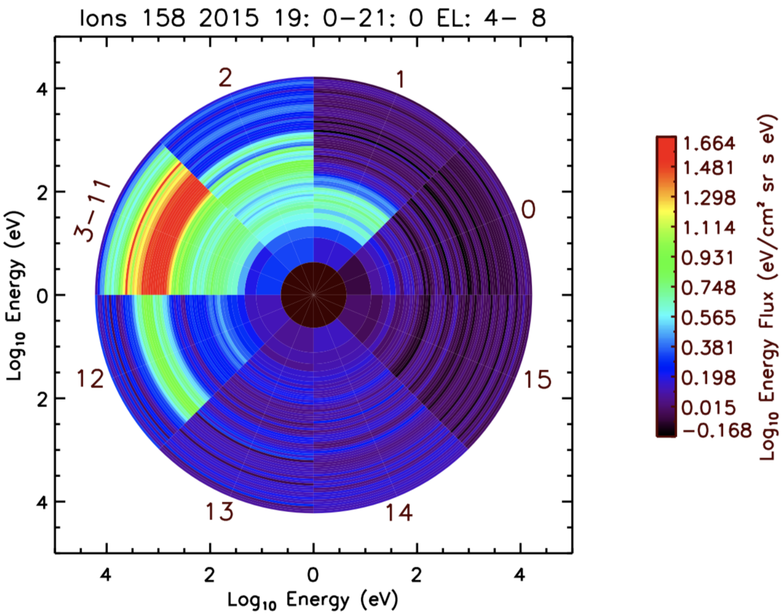

Figure 3. Color contour plot of the IES ion flux around the peak, indicated by the vertical red line, earlier than the vertical black line in Fig. 1. The directions of the sun and CG and elevation range are as in Fig.2.

Results of ion density measurements on 7 June 2015 by the Ion Composition Analyzer (ICA) (Nilsson et al., 2015) on board Rosetta are shown in Fig. 4. Ions of energy $\geq$ 60 eV (pickup ions) are plotted in the nC curve and those of energy $<$ 60 eV are in the nClow curve. These ions have been identified as primarily H_2O^+.

For the current case we assume that the charge exchange interaction is mostly between neutral water molecules and H_2O^+, so we have simply

$$H_2O_{Lo}+H_2O^+{}_{Hi}\rightarrow H_2O^+{}_{Lo}+H_2O_{Hi}.$$

where the subscripts "Hi" and "Lo" refer to high ($\approx$ 1 keV) or low ($\leq$ 1 eV) energies, resp. On the left side, the "Low" neutral molecules are the newly emitted molecules from the nucleus, while the "High" ions are existing ions in the coma (the peaks). On the right side, the "Low" ions are the converted neutral water molecules and the "High" are the neutralized energetic ions. In other words, in this symmetric collision the high and low energy molecules exchange places. The cross section σ for this reaction is energy dependent and has been measured by Lishawa et al. (1990). Unfortunately the highest collision energy for which data are reported is about 57 eV. However, the cross section data appear to asymptote to about 8x10^{-16}cm^2 at 1 keV and we have used this value in the analysis.

Figures 5 and 6 show the data of Figs. 2 and 3, resp., as line-plotted energy spectra. The integrated flux from these figures (see e.g. (Burch et al., 2015)) are 2.54x10^5 cm^{-2}s^{-1} and 3.3x10^4 cm^{-2} s^{-1}, resp. The "missing" water ions at the location of the black line have presumably been converted by the charge exchange reaction given above to neutral water molecules. These are lost to IES. We can model the reaction by

$$W_r = \mathrm{W}(1\text{-}W_n\ \mathrm{D}\ \sigma), (1)$$

where W_r is the flux of the remainder of the water ions that have not been neutralized (at the trough), W is the original water ion flux (from Fig. 1), W_n is the flux of neutral wa-

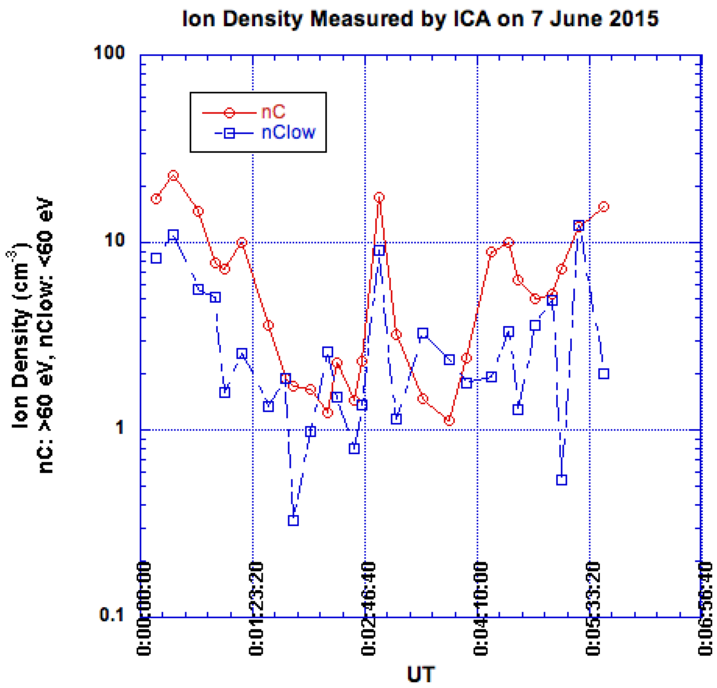

Figure 4. Results of the Ion Composition Analyzer (ICA) measurements of ion density on 7 June 2015. nC are ions $\geq$ 60 eV (pickup ions) and nClow are ions $<$ 60 eV. The ions have been identified as primarily H_2O^+.

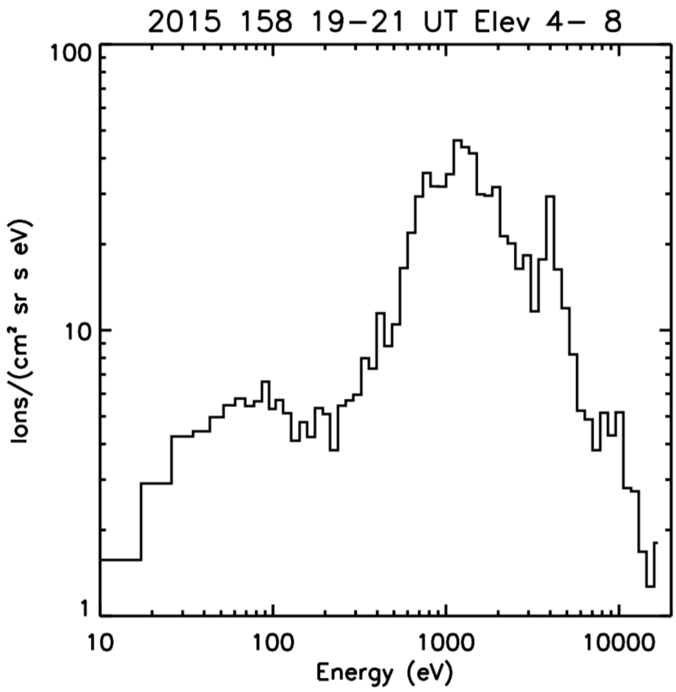

Figure 5. IES Ion Energy Spectrum for 19-21 UT, Day 158 2015, for elevation range 4-8 (25° to -5°). This time interval corresponds to the peak in the flux indicated by the vertical red line in Fig. 1, shortly before the trough indicated by the vertical black line in Fig. 1.

ter molecules (also from Fig. 1), D is the distance of Rosetta to CG (200 km), and σ is the charge exchange cross section. We will compare the results of equation (1) with the direct measurement from Fig. 6. So

$$W_r = 2.54\text{x}10^5\text{cm}^{-2}\ \text{s}^{-1}(1 - 2\text{x}10^7\text{cm}^{-3}\text{x}2\text{x}10^7\text{cm}^{-1}\text{x}8\text{x}10^{-16}\text{cm}^{-2}) = 1.93\text{x}10^5\text{cm}^{-2}\text{s}^{-1}.$$

This quantity should be close to the ion flux at the trough location indicated by the vertical black line in Fig. 1, which we have estimated from Fig. 6 as $1.6\text{x}10^5\ cm^{-2}\text{s}^{-1}$. This is 15 percent less than the value calculated from Eq. (1). We consider this a reasonable agreement. This analysis is comparable to that of Eq. 4 in Burch et al. (2015).

3 Summary and Conclusions

We have identified a series of troughs in the IES measurements during the period 6-8 June 2015 of ions in the CG coma, with a periodicity of about 6 hrs while the Rosetta SC was about 200 km from the nucleus. These troughs coincide in time with peaks in the neutral gas measurements by the COPS (Comet Pressure Sensor) component of the ROSINA instrument on board Rosetta and are thus approximately at one half the rotation period of the nucleus. Measurements earlier in the mission by IES (Goldstein et al., 2015) and others (Galand et al., 2016) had observed peaks in the ion flux coincident with neutral gas peaks, which was understood to be the result of solar UV or electron impact ionization producing ion peaks correlated with the neutral peaks. We have interpreted the surprising correlation of neutral peaks with decreases in ion flux as the result of a charge exchange reaction between the newly generated neutral molecules and the existing coma. This reaction converts the low energy neutrals to low energy ions (which are too low in energy to be detected by IES) and the higher energy ions to neutrals of similar energy.

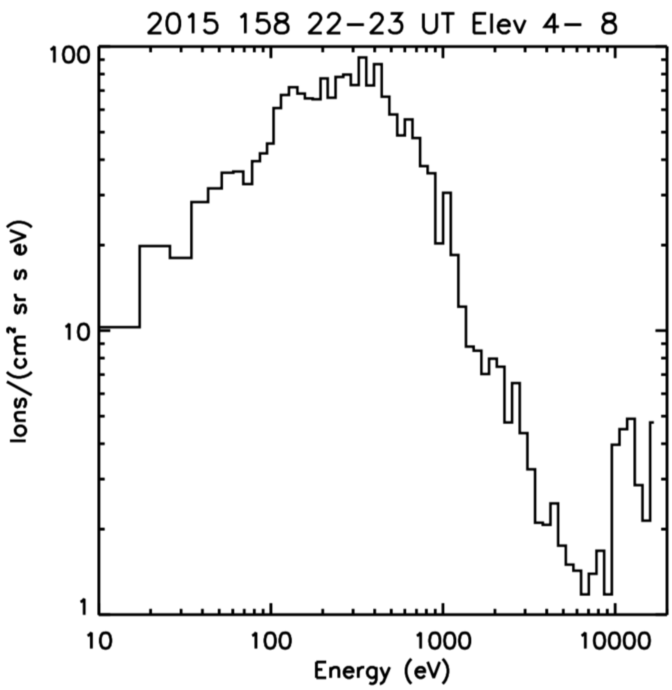

Figure 6. IES Ion Energy Spectrum for 22-23 UT, Day 158 2015, for elevations 4-8 (25° to -5°). This time interval corresponds to the trough indicated by the vertical black line in Fig. 1.

Although there have been many reports of the observation of charge exchange between cometary products and the solar wind, we believe that this is the first report of observations of charge exchange reactions between different components of a comet's coma. See also Mandt et al. (2019). However, we do not understand why these reactions occurred only particularly during a few days in June 2015 at 200 km from the nucleus and 1.5 au from the sun. The presence of energetic ($\geq$1 keV) ions indicates a pickup process by the solar wind outside the cavity, with the ions frozen into the IMF that then caries them to the coma, even in the absence of solar wind at the comet. (See Williamson et al. (2020) and Nilsson et al. (2020).)

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