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Two years of Solar Wind and Pickup Ion Measurements at Comet 67P/Churyumov-Gerasimenko

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ABSTRACT

The Ion and Electron Sensor (IES), as well as other members of the Rosetta Plasma Consortium (RPC) on board the Rosetta spacecraft have been measuring the characteristics of the solar wind almost continuously since arrival at 67P/Churyumov-Gerasimenko (CG) in August 2014. An important process at a comet is the so-called pickup process in which a newly ionized atom or molecule begins gyrating about the interplanetary magnetic field, is accelerated in the process and carried along with the solar wind. Within a month after comet arrival, while Rosetta was <100 km from CG, we began to observe low-energy (<20 eV) positive ions. We believe that these are newly formed from cometary neutrals near Rosetta and attracted to the negative spacecraft (S/C) potential. These ions were in the early phase of pickup and had not yet reached the energy they would after at least one full gyration about the magnetic field. As CG increased its activity the flux and energy of the measured pickup ions increased intermittently while the solar wind appeared intermittently as well. By about the end of April 2015 the solar wind had become very faint until it eventually disappeared from the IES field of view. We then began to see ions at the highest energy levels of IES, >10 keV for a few days then intermittently through the remainder of the mission, but lower energy (few keV) pickup ions were also observed. As of early February 2016 the solar wind reappeared more consistently. We believe that the disappearance of the solar wind in the IES field of view is the result of interaction with the pickup ions and the eventual formation of a cavity that excluded the solar wind.

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

1 INTRODUCTION

Previous missions to comets that included plasma payloads, such as Giotto to Halley (Reinhard 1988), ICE to comet Giacobini-Zinner (GZ) (von Rosenvinge et al. 1986), and Deep Space 1 (DS-1) to comet Borrelly (Nelson et al. 2004) were fast flybys, allowing only snapshots at instants of time over broad regions of space (but with no repeating of measurements possible) of the plasma properties. The flybys in each of these missions occurred at distances from the nucleus much greater than the distances sampled by Rosetta at CG. These missions however did provide us with important information about how comets work and allowed comparison of measurements with predictions of models. For example, Johnstone et al. (1987) and Neugebauer et al. (1987) described the results of measurements of plasma structure and characteristics during the Giotto flyby of Halley. The structure of the tail of GZ was described by Bame et al. (1986). Richter et al. (2011) have discussed measurements of the magnetic field and plasma during the DS-1 flyby of Borrelly.

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The European Space Agency's Rosetta (Glassmeier et al. 2007a) spacecraft (S/C) was launched from Kourou, French Guiana March 2, 2004, arrived at comet 67P/Churyumov-Gerasimenko (CG) in August 2014, and was orbiting or otherwise mostly within a few hundred km of CG since arrival and until the end of mission 30 September 2016. The Rosetta Plasma Consortium (RPC) (Carr et al. 2007) consists of five plasma instruments on board Rosetta: the Ion Composition Analyzer (ICA) (Nilsson et al. 2007), the Ion and Electron Sensor (IES) (Burch et al. 2007), the Langmuir Probe (LAP) (Eriksson et al. 2007), the Mutual Impedance Probe (MIP) (Trotignon et al. 2007), the magnetometer (MAG) (Glassmeier et al. 2007b), and the Plasma Interface Unit (PIU) (Carr et al. 2007). We have previously reported on the results of plasma measurements by RPC instruments: Goldstein et al. (2015), Broiles et al. (2015), Broiles et al. (2016), Clark et al. (2015), Burch et al. (2015b), Burch et al. (2015a), Nilsson et al. (2015a), and Nilsson et al. (2015b) as the comet began its activity. This report is a summary of some of the results of RPC-IES measurements of the solar wind (SW) (or its absence) as well as the characteristics of pickup ions over the course of the mission's two years in the vicinity of CG.

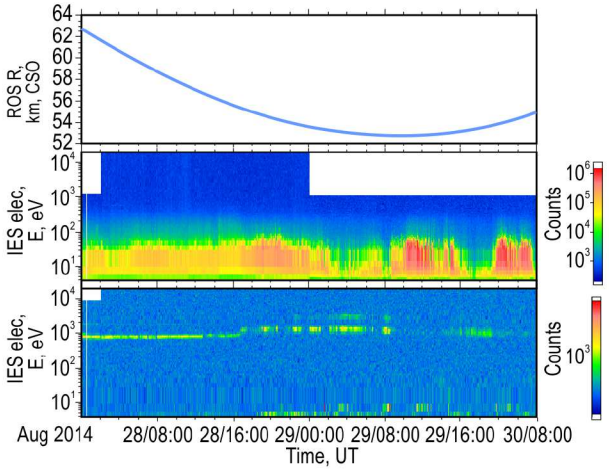


Figure 1. Energy-time spectrograms of the solar wind: electron (middle) and ion (lower) IES measurements for August 28-29, 2014. Note the shock at 16:00 UT. Distance to CG is shown in the top panel. The white areas are the result of changes in operating mode.

2 INSTRUMENTATION AND EARLY OBSERVATIONS

The RPC-IES instrument measured ion and electron flux as function of energy (4.3 eV to 17.7 keV) and direction (360°azimuth on 16 anodes and +/- 45°elevation stepped over 16 bins). See Burch et al. (2007) for details. Figure 1 is an example of an energy-time spectrogram of solar wind electrons (middle panel) and ions (protons and intermittently, alpha particles, lower panel) measured by IES during August 28 and 29, 2014, within a month of Rosetta's arrival at CG. (The white areas in the electron portion is the result of changes in IES operating mode using different energy ranges.) The upper panel shows the distance of Rosetta to CG during this period.

During this period Rosetta was 3.47 AU from the Sun, moving toward perihelion at 1.24 AU in August 2015. Note what appears to be a solar wind shock around 16:00 UT on the 28th We estimate the velocity jump to have been approximately from 360 km/s to 400 km/s, accompanied by a factor of 2 increase in density in front of the discontinuity. In addition to the jump in proton energy, the electron flux has also increased. Further, there is a sudden appearance of low energy (<20 eV) ions shortly after the increase in electron flux. We believe that these are newly formed from cometary neutral molecules or atoms near Rosetta and attracted to the negative spacecraft (S/C) potential due to the increase in electron density [(Goldstein et al. 2015) and (Broiles et al. 2015)]. Rosetta was 50 km to CG so ions created locally were in the early phase of pickup and had not yet reached the energy they would attain after at least one full gyration about the magnetic field, hence could be drawn to the S/C by its weak electric field. Ions created far enough away (see Section 3, below) would have been accelerated to much higher energies. (See Fig. 6 of Rubin et al. (2014) for a discussion of the beginning of the pickup process and Fig. 1 of Goldstein et al. (2015), which also shows the relation

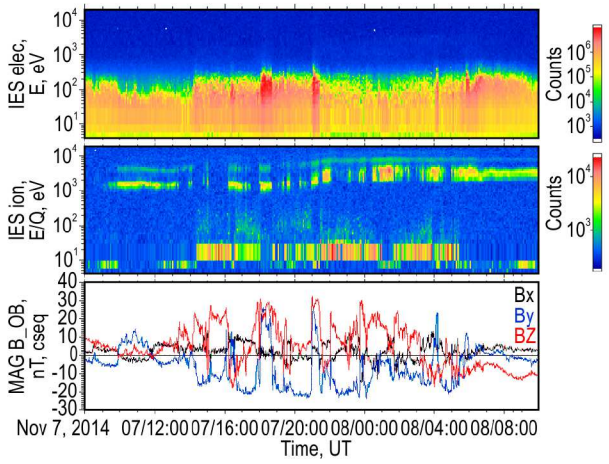


Figure 2. Energy-time spectrogram of electrons (upper) and ions (middle) measured on 7-8 November 2014. Solar wind protons and alphas are at 1 and 2 keV, resp., while the few hundred eV signal is from pickup ions. Components of the magnetic field measured by the outboard magnetometer are shown in the lower panel.

of these ions to the local neutral density.) We observed such low energy ions almost continuously since then until the end of the mission.

By early November 2014 IES began to detect pickup ions of energies up to several hundred eV. Fig. 2 shows plots of data measured on 7-8 Nov. 2014. The upper panel is an energy-time spectrogram of electrons measured by IES, the second panel is a similar spectrogram for ions, and the bottom panel plots the magnetic field components measured by the magnetometer (Glassmeier et al. 2007b). Rosetta was 3 AU from the Sun and 30 km from CG at that time. Solar

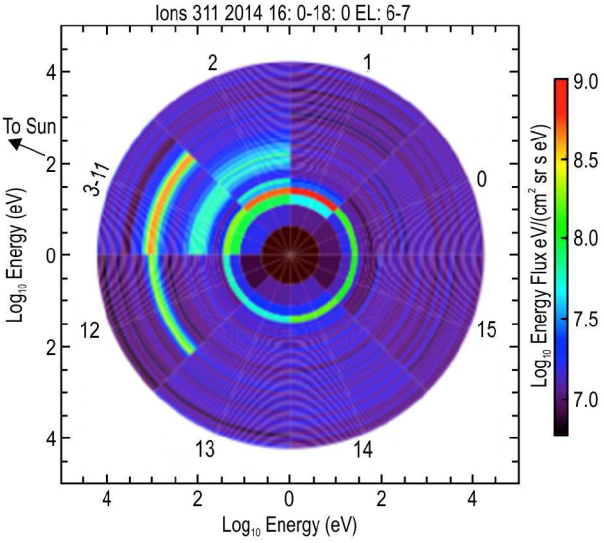


Figure 3. Polar plot of ion data between 16:00 to 18:00 UT 7 Nov 2014. The 16 anodes in the IES azimuth plane are numbered. The anti-solar direction is toward anodes 3-11 and the comet nucleus points between anodes 13 and14.

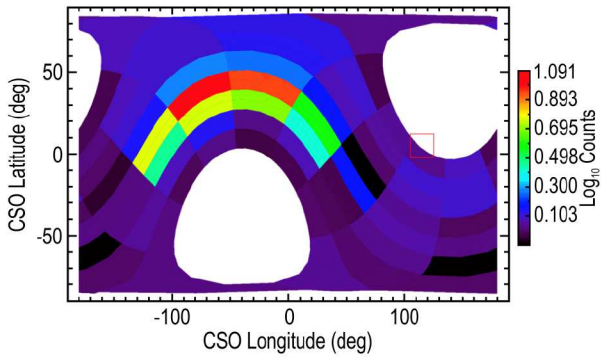


Figure 4. .Plot in the CSO coordinate system of a portion of the ion data used for Fig. 3. The Sun is at (0,0) and the location of the comet in the IES FOV is given by the red square. Each colored element is an IES azimuth-elevation pixel.

wind ions are seen intermittently, protons at 1kev and He^{++} at 2 keV, although these energies begin to increase at 18:00 UT. The 20 eV ions described in the previous figure appear here as well, but also, very diffusely, ions of energy up to about several hundred eV appear. The magnetic field shows considerable variation during the period from about 13:00 UT on 7 Feb to 07:00 on the 8th, coinciding approximately with the increases in the electron and pickup ion flux. Most striking are the (in phase) pulse structures of the y and z field components at 18:00 and 22:00 on Nov 7, while the x component remains relatively constant. This means that there are two linearly polarized (45°in the yz plane) structures occurring at those times. These structures could be caused by a tilted current sheet passing the S/C.

An energy polar plot of the ion data of this figure from 16:00 to 18:00 UT on 7 Nov is shown in Fig. 3. The 22.5°divisions in azimuth of the detector are numbered in order to identify and orient the look directions. The log of the energy is given by the radius and the color bar shows the measured energy flux. The anti-Sun direction is to the anode 3-11 group although the solar wind appears also to be spread toward anode 12, 22.5°away from that direction. Perhaps that accounts for its "smeary" appearance in Fig. 2. The several hundred eV ions appear to come mostly on anode 2, within 22.5°from the anti-solar direction, which would be expected for ions picked up and carried along with the solar wind. Figure 3 is in an IES-centric coordinate system. Instead, in order to more directly relate to the comet and Sun, we will use the comet solar orbital (CSO) system for plotting IES data. In this system the origin is at the comet, 0°longitude is toward the Sun, and latitude is measured northward from the comet orbital plane. Figure 4 is an example of the data plotted in Fig. 3 as it appears in the CSO system. This plot explicitly shows both the elevation as well as azimuth, i.e. the IES FOV for the time and energy given. The colored elements are azimuth-elevation pixels. The Sun is at coordinates (0,0) and the location of the comet in the IES FOV is given by the red square. The odd-shaped holes in the FOV are a result of the elevation angle limit of +/- 45°and the location and attitude of Rosetta at the time of the data. Two MP4 videos are included in the Additional Information section that show, in one case a time-stepped series and the other an energy-stepped series of the data for Fig. 4. These correspond to a portion of the data in the spectrogram of Fig. 2 and a portion of the data used for Fig. 3. The videos show that for a given energy range, the location of the count rate peak in the IES FOV moves around during the period of the video although the S/C pointing was relatively steady during this period.

3 OBSERVATION OF HIGH ENERGY PICKUP IONS

During mid-April 2015 the Rosetta S/C was traveling in an approximately triangular (about 100 km per side) trajectory about CG, 20 km sunward of it. Rosetta's speed was about 0.5 m/s relative to CG. The ion data for 17 April 2015, for several days following and intermittently during the following month, began to show the presence of ions of energy at the highest level of the IES capability ($\gtrsim$17 keV), which we had previously never seen in IES or ICA data. The evolution of the ICA data was shown in Nilsson et al. (2015a), with water ion energies typically not reaching much above a few keV. The IES electron data show an increase in flux by a factor of about 2 in the energy range up to 100 eV during this time period, but it is not clear whether that is related to the appearance of the high-energy ions. Rosetta was 100 km from CG, which was 1.8 AU from the sun at that time. Figure 5 is an IES ion energy-time spectrogram for 19 April 2015 showing the appearance of these newly observed very high-energy ions appearing in anode 2 (Sun pointing) at an elevation angle of 45°. We believe these ions to be the result of neutral water molecules that have moved far from the nucleus as the coma expands, becoming ionized by solar UV or other processes, picked up by the solar wind,

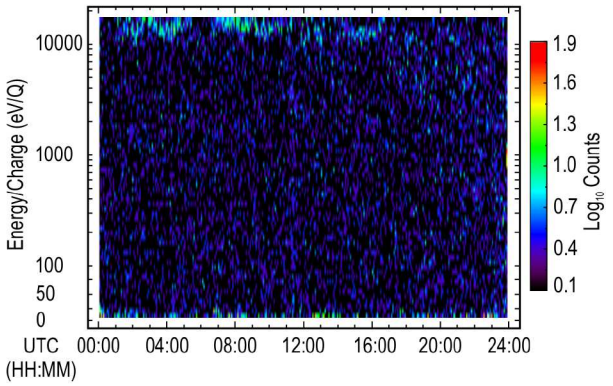


Figure 5. Ion energy-time spectrogram for 19 April 2015 from IES measurements, showing the appearance of high-energy ions. The very low energy ions were created locally and attracted by the negative S/C potential. The high-energy ion counts correspond to the IES anode 2 (solar direction) and elevation channels 0-1 (45°in the IES frame). Rosetta was 105 km from CG, which was 1.8 AU from the Sun at this time. The color bar shows the measured ion count level.)

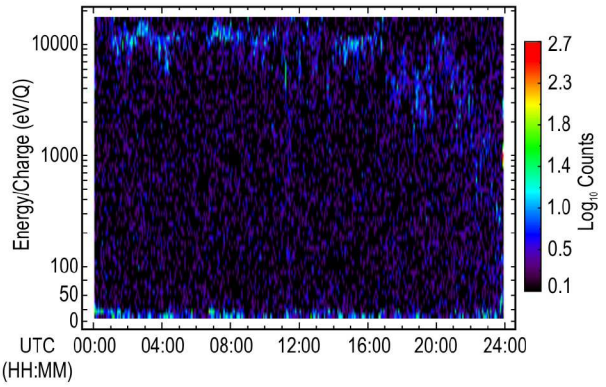


Figure 6. Ion energy-time spectrogram for the same conditions as those for Fig. 5 except that the elevation channels were 4-5 (30°in the IES frame).

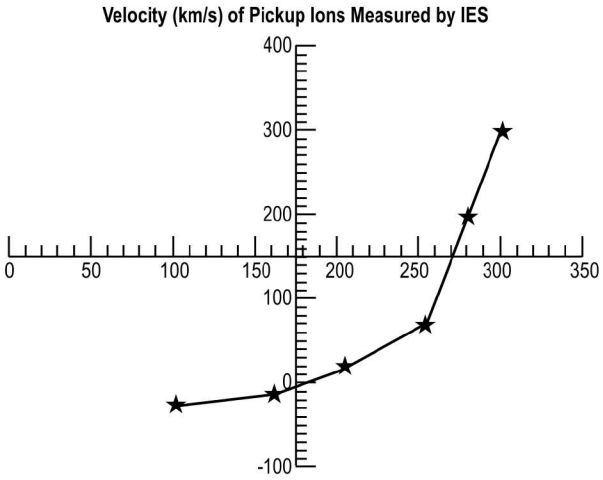


Figure 7. Ion energy measured by IES at different IES elevation angles for 19 Apr 2015, suggesting the formation of a pickup ion shell. See also Figs. 5 and 6.

and accelerated by the pickup process as they are carried back toward the comet. Such an anti-sunward flow is typical for the water ions observed with ICA (Nilsson et al. 2015b), though normally at much lower energy. Also seen in Fig. 5 are the very low energy ions locally formed and attracted to the S/C by its negative potential (Goldstein et al. 2015).

The maximum velocity of an ion picked up by the solar wind is twice the solar wind speed. Hence the maximum energy for pickup protons would be four times the solar wind proton energy, or, typically, 4 keV. We believe, therefore, that the $\gtrsim$17 keV ions must be more massive than protons, and we assume that they are water molecule ions (based on the ICA measurements), which would have a maximum pickup energy of 4*18 = 72 keV. The mean density and velocity of these high-energy ions, assumed to be water, from a moment calculation on the measured count rates are 33 cm^{-3} and 420 km/s, respectively.

Figure 6 shows the IES ion data at an elevation angle of 30°, and an energy of 6 keV from 0:00 to about 16:00 UT on this day, and decreasing in energy after that. Comparison of Figs. 5 and 6 suggest an energy distribution as function of angle and in fact, the apparent ion energy did decrease further with additional elevation angle steps. Figure 7 is a plot of the measured ion velocity between 0:00 and 8:00 UT as function of the IES elevation angle for 19 Apr 2015 (with arbitrary axes). The dependence on energy suggests that these ions form a ring or shell, typical geometries for a developed pickup ion distribution (e.g., Fig. 1 in (Neugebauer et al. 1987).

4 DISAPPEARANCE AND RE-APPEARANCE OF THE SOLAR WIND

Around the time that these high-energy pickup ions appeared the solar wind gradually disappeared from the IES field of view. Figure 8 shows this decline over the period from early March 2015 to the end of April. The solar wind eventually reappeared in the IES FOV in early 2016, as shown in Fig. 9. We believe that this disappearance and re-appearance is the result of the interaction of the solar wind with the pickup ions, causing a deflection of the solar wind out of the IES FOV. Such a deflection was first discussed by Chapman & Dunlop (1986) in connection with the AMPTE plasma releases, and was described previously for CG [(Broiles et al. 2015)and (Goldstein et al. 2015)]. The deflection over the period from September 2014 to the end of the mission in September 2016 was measured by the Ion Composition Analyzer (ICA) component of RPC and discussed in Behar et al. (2016), and Behar et al., (MNRAS 000, 1-7 (2017), in press) as the result of the exclusion of the solar wind, forming a cavity.

Also during this period Rosetta moved sunward to about 1500 km (on 30 Sep 2015) to explore the plasma in this region and in the hopes of encountering a bow shock.

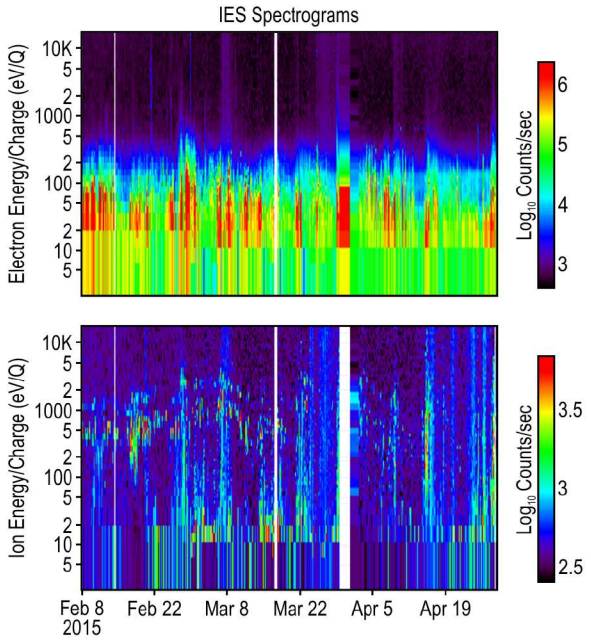


Figure 8. Ion and electron count rate measured by IES showing the gradual disappearance of the solar wind ions in the IES FOV during approximately early March 2015 to the middle of April.

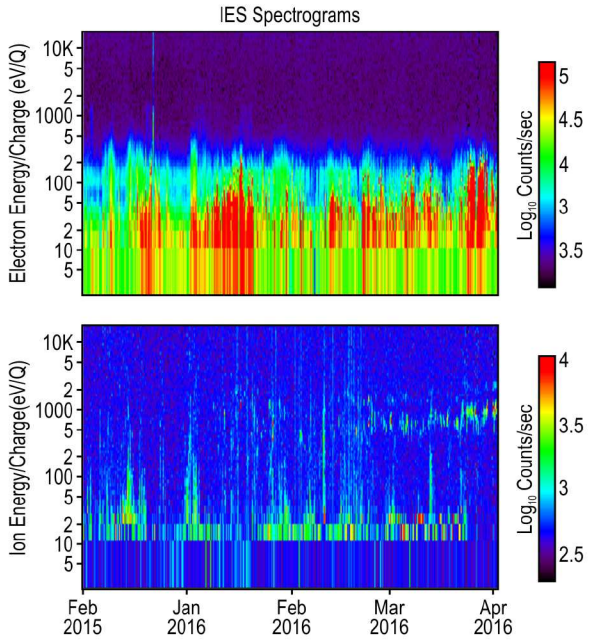


Figure 9. Ion and electron count rate measured by IES showing the gradual return of the solar wind in the IES FOV during approximately mid-January 2016 to the middle of March.

No indication of a shock was observed but a number of other boundaries of interest were seen (Mandt et al. 2016). A second (tail) excursion from CG was performed in the anti-sunward direction, reaching 1000 km from the comet on 30 March 2016.

During the period of absence of the SW in the IES FOV, the instrument continued to see pickup ions intermittently over a range of energies, such as described for Figs. 5 to 7.

An example of the coma plasma measured during 6 through 9 June 2015 is shown in Fig. 10. Rosetta was about 200 km from CG and both were about 1.5 AU from the Sun during this period. The top panel in the figure is an energy-time spectrogram of ions measured by IES. The lower panel shows the local neutral gas density, assumed to be primarily water molecules, measured by the onboard COPS (Comet Pressure Sensor) portion of the ROSINA (Rosetta Orbiter Spectrometer for Ion and Neutral Analysis) sensor (Balsiger et al. 2007). There appear to be at least 2 sets of periodic peaks of the neutral gas, each with a period of 12 hrs, but shifted 6 hrs from each other. The periodicity is presumably related to the 12 hr nucleus rotation period. The stronger gas peaks are mostly closely coincident with the deeper dips in the ion peaks, while the weaker gas peaks tend to be closely coincident with the weaker ion dips. These ions were flowing within 20°in the anti-sunward direction and we conclude that they are pickup ions traveling with the solar wind although the solar wind itself was not within the IES FOV at that time. Figure 11 is a contour plot in CSO coordinates of the ion count rate for the period 9:00 to 17:00 UT of 7 June 2015, that shows the direction from which the ions are flowing. The Sun is at 0°in this coordinate system so the ions are coming within 20°of anti-sunward, consistent with our suggestion that these ions have been energized by their pickup by the solar wind. Similar to the measurements for April 2015, the June 2015 data also show the presence of ions at $\gtrsim$17 keV energy. There may be other mechanisms responsible for the high energy (such as excitation by waves), but we believe that the most plausible is by the pickup process since that tends to be ubiquitous at comets. Aside from the presence of very high-energy ions, of note is the apparent periodicity of the ion peaks, with a period 12 hours, close to the nucleus rotation period, suggesting a connection with gas production from a specific location on the nucleus. This relationship had previously been observed with the IES-measured electron density in 2014 (Goldstein et al. 2015), although at $\gtrsim$6 hrs, half the period seen here. That was thought to be the result of seeing the same source twice in one rotation of the nucleus. In that observation, increases in the electron flux coincided with the neutral gas peaks. We estimate that the average density of the ions shown in Fig. 10 is 33 cm^{-3}, about several orders of magnitude lower than the ambient neutral density shown in the same figure. We suggest that the neutral gas interacts with the flow of the much less dense ions, possibly by charge exchange, producing the pattern seen in Fig. 10. We estimate the ion average speed to be 15 km/s, in contrast to the neutral speed 0.7 km/s measured by the MIRO instrument (Gulkis et al. 2007) on board Rosetta.

When the solar wind began reappearing in the IES FOV in early 2016 it was at an unusually low energy: 400 eV for the protons, and very variable. There were also not very many pickup ion observations during 2016 presumably as a result of the decreasing activity of the comet. Although the S/C orientation during Rosetta's final descent was not

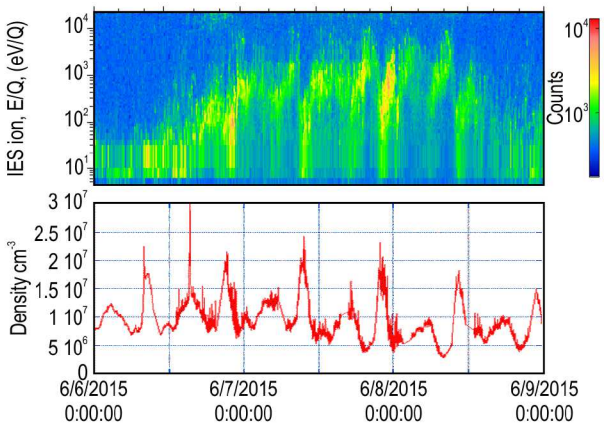


Figure 10. Energy-time spectrogram for 6-9 June 2015. Upper panel: Pickup ions flowing anti-sunward measured by IES. Lower panel: Neutral density measured by the ROSINA-COPS instrument.

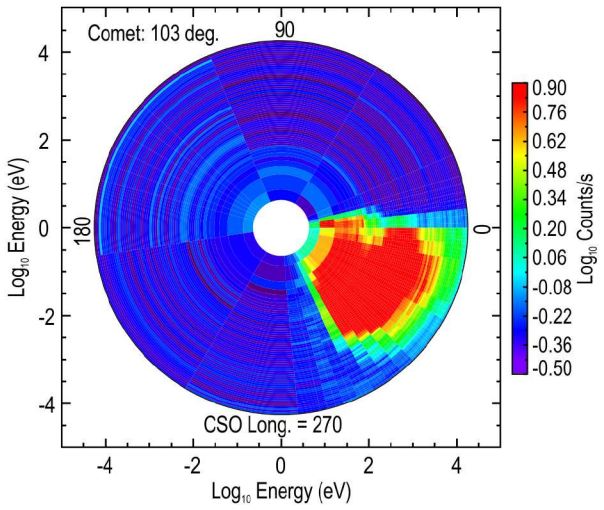


Figure 11. Ion energy-angle contour plot in the CSO system, from IES measurements during 9:00 to 17:00 UT on 7 June 2015, in the energy/charge range 10 to 17600 eV/Q. In this coordinate system the Sun is at 0°longitude and CG at 103°. Most of the ions are coming from within 20°of the solar direction.

ideal for IES, we were able to catch a final glimpse of the SW during the last 3 days, as shown in the ion energy-time spectrogram of Fig. 12. Note that in order to obtain this farewell image it was necessary to choose very limited look directions in the data, specifically pointing only to the Sun.

5 SUMMARY AND CONCLUSION

The RPC-IES instrument studied the solar wind, cometary plasma, and pickup ions in the vicinity of comet 67P/Churyumov-Gerasimenko during the approximately 2 years that the Rosetta S/C was in the vicinity of the comet.

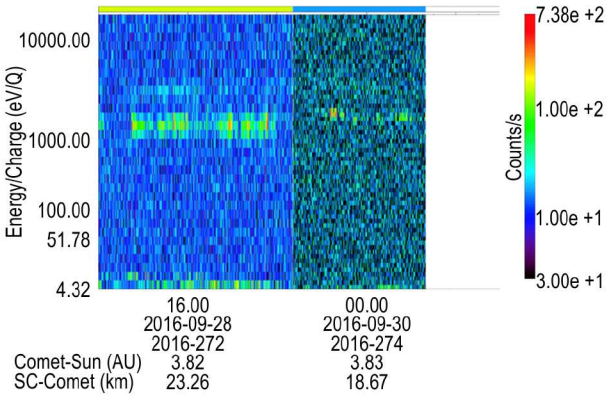


Figure 12. IES ion energy-time spectrogram during the last 2 days of the Rosetta mission, 28-30 Sept. 2016. The S/C impacted the nucleus just after the last data were received. Note that the IES operation mode changed at about 0800 UT on 29 Sept.

The solar wind interacted strongly with the pickup ions, turning away significantly from its normal ant-sunward direction for much of 2015 and part of 2016. High-energy ($\gtrsim$17 keV) pickup ions (presumably water) have been measured intermittently beginning in 2015. The neutral coma gas appears to interact with the flow of the anti-sunward moving pickup ions at times, possibly as a result of charge exchange reactions between the two. Since the neutral gas density is often quasi-periodic as a result of the nucleus rotation, this sometimes introduces a quasi-periodic character to the pickup ion flux.

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APPENDIX

The IES data used for preparation of this report are available from both the NASA PDS (https://pds.nasa.gov/) as well as the ESA PSA (https://archives.esac.esa.int/psa/) archive web sites. Level 3 IES data (differential energy flux) have also been submitted and are currently under review. Questions about the use of these resources may be sent to the author.

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