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Key Point:
- IES observed low-energy ions in August 2014, at an 80 km distance from the comet

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The Rosetta Ion and Electron Sensor (IES) measurement of the development of pickup ions from comet 67P/Churyumov-Gerasimenko

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Abstract The Rosetta Ion and Electron Sensor (IES) has been measuring solar wind ions intermittently since exiting from hibernation in May 2014. On 19 August, when Rosetta was ~80 km from the comet 67P/Churyumov-Gerasimenko, which was ~3.5 AU from the Sun, IES began to see ions at its lowest energy range, ~4–10 eV. We identify these as ions created from neutral species emitted by the comet nucleus, photoionized by solar UV radiation in the neighborhood of the Rosetta spacecraft (S/C), and attracted by the small negative potential of the S/C resulting from the population of thermal electrons. Later, IES began to see higher-energy ions that we identify as having been picked up and accelerated by the solar wind. IES continues to measure changes in the solar wind and the development of the pickup ion structure.

1. Introduction

The Rosetta spacecraft (S/C), launched from Kourou, French Guiana, in March 2004, rendezvoused with the comet 67P/Churyumov-Gerasimenko (C-G) in August 2014. We describe here the results of measurements of pickup ions produced by the outgassing of C-G by the Ion and Electron Sensor (IES) [*Burch et al.*, 2007] on board the S/C early in its escort of C-G in its orbit around the Sun [*Glassmeier et al.*, 2009]. IES is a part of the five-instrument Rosetta Plasma Consortium [*Carr et al.*, 2007].

One of the most important plasma phenomena at a comet is the ion pickup process, involving the interaction of gas evolved from the comet nucleus and the solar wind plasma and magnetic field. Although we are concerned here with the process at a comet, it can occur throughout the plasma universe, such as in a planetary magnetosphere or in interstellar clouds where we cannot study it directly. Our present case at a comet allows a direct, in situ measurement of the details of the process, which we now describe. A neutral atom or molecule emitted by the nucleus does not experience any effects of the interplanetary electric and magnetic fields until it is ionized by solar UV, undergoes charge exchange with an ion, or becomes ionized by some other process. Then it is affected by electromagnetic forces, begins to gyrate about the interplanetary magnetic field (IMF), and becomes incorporated into or is "picked up" by the solar wind flow [see, e.g., *Neugebauer et al.*, 1987; *Coates et al.*, 1989]. Also, as these pickup ions are added to the solar wind plasma, the flow slows down as a result of energy conservation and is heated.

The maximum velocity of these ions occurs at the peak of the cycloidal path around the IMF and is $V_{max} = (2V_{sw} \sin \Phi)$, where V_{sw} is the solar wind velocity and Φ is the angle between the IMF and V_{sw}, so the maximum velocity is twice the solar wind velocity and for an ion of mass m_i, the maximum energy is 4 times the solar wind energy times the picked up ion mass: $E_{max} = 4\ m_i\ E_{sw}$. For a proton picked up when $E_{sw} = 1$ keV/e, this maximum would be 4 keV/e, well within the IES energy range but for a water ion ($m_i = 18$), the maximum would be 72 keV/e, outside the IES range. So IES can see water pickup ions only if the angle Φ is small enough and/or if the field of view (FOV = 90°×360°) was pointed in the appropriate direction.

2. Low-Energy Pickup Ions

There are two special cases, first, when the ions have been newly formed and are still in the process of increasing their energy, IES is able to see them. A second situation occurs when the comet becomes very

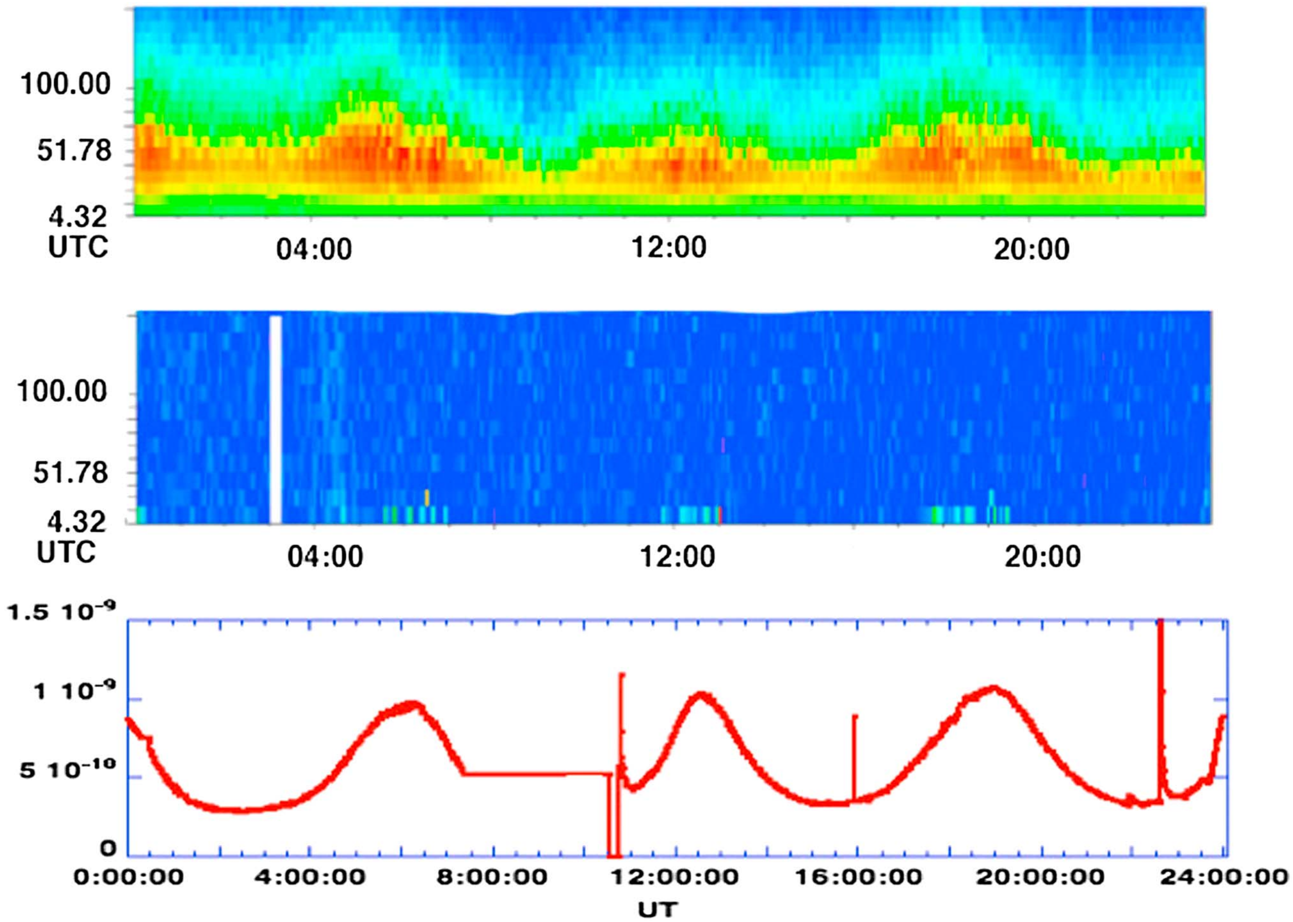

Figure 1. Comparison of (top) IES electron, (middle) ion, and (bottom) ROSINA neutral gas pressure (in mbar) measurements on 10 September 2014. The low-energy pickup ions occur when the electron count rate and neutral pressure are high. Rosetta is at a distance of ~28 km to C-G.

active. If enough ions have been created and picked up far from the comet, they will mass load the solar wind and slow it sufficiently to bring the energy into the IES energy range and FOV.

Regarding the first case, beginning in mid-August 2014, at a S/C distance to C-G about 80 km, IES began to observe positive ions in its lowest few energy bins (4.32–21.58 eV/e). These ions appeared quite frequently and often in groups that corresponded in time to the ~6 h period of increases in the measured electron flux, which also usually corresponded with peaks in the neutral gas pressure measured by the Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA) instrument on the S/C [*Hässig et al*., 2015]. An example of a comparison between IES electrons and low-energy ions and ROSINA gas pressure (in mbars) is shown in Figure 1 for measurements on 10 September 2014. (The spikes in the pressure measurements are a result of S/C interference.) Rosetta was at a distance of 28 km from C-G and 3.4 AU from the Sun at that time. We conjecture that the electrons are the result of photoionization by solar ultraviolet (UV) of the neutral plume from the nucleus. Based on other measurements [*Nilsson et al*., 2015], we assume that these ions are water molecule ions. The electrons cause a negative potential of the S/C (in this case ~−10 to −20 V), attracting the low-energy ions. So it is plausible that these ions have just been recently ionized in the vicinity of the S/C and have not had sufficient time to be accelerated by the IMF. Assuming that the ions have about the same velocity (~0.7 km/s) [*Gulkis et al*., 2015] as the neutral water vapor emitted by the nucleus, a singly charged water molecule ion would have an energy of ~0.05 eV. When first ionized, these ions would not be measureable by IES until they were accelerated by the S/C potential. To the best of our knowledge, this represents the first reported observation of newly created and picked up ions from

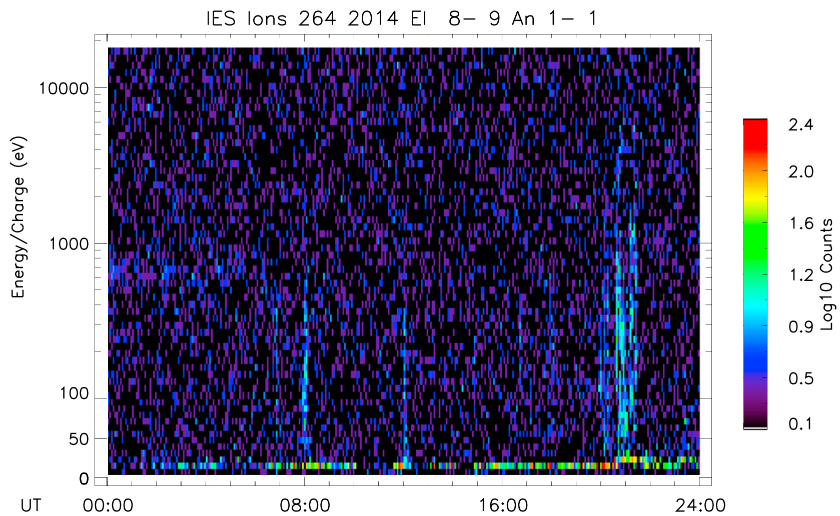

Figure 2. Ion energy spectrogram for 21 September 2014 for the IES look direction in elevation +10° and azimuth 25° in the IES reference frame. The pickup ion signatures appear as vertical streaks. The low-energy pickup ions discussed previously also appear in the figure. Rosetta is at a distance of ~28 km to C-G. See also Figure 3 for further analysis of the ion signature at ~20:30.

a weakly outgassing comet far from the Sun. In the case of the flybys of comet Halley by several S/C, such as Giotto [*Reinhard*, 1987], the pickup ions reported [e.g., *Neugebauer et al.*, 1987] were measured near comet perihelion when the comet was very active and had been producing pickup ions for a considerable amount of time. These ions had been produced far from the nucleus and carried to the S/C by the solar wind, resulting in their reported high-energy values in contrast to the newly created ions discussed above. Our measurements agree with the results of the model calculations by *Rubin et al.* [2014], who show the H_2O^+ density and velocity during the beginning of their gyrations just after pickup. It is slow at first, but at their fully picked up energy, these ions would have a gyroradius ~36,000 km, very distant from C-G and Rosetta.

3. High-Energy Pickup Ions

Late in September 2014, IES began to see evidence of higher-energy pickup ions, appearing as a number of approximately vertical traces at several times in the energy-time spectrogram plots, indicating the acceleration of several pickup ions at each of those times (in addition to the low-energy ions discussed above), such as in the energy-time spectrogram in Figure 2 for 21 September 2014. During this period, Rosetta was in an approximately terminator orbit at a distance of 28 km to C-G and about 3.3 AU from the Sun. The spectrogram includes only the elevation channel at +10° in the IES coordinate system and anode number 1, which is 25° in the azimuth plane. We identify these traces as populations of higher-energy pickup ions. The particular FOV for this figure does not include either the Sun, solar wind ions, or C-G. The contour plot of Figure 3 shows the energy flux (eV/(cm^2 sr s)) for the period of 20:00–22:00 UT, plotted as energy (radius of the plot, 4.32 to 10^4 eV/e) versus azimuth angle. Energy and flux are given by log10 scales. The low-energy pickup ions shown in Figures 1 and 2 are seen as the light green ring near the center of Figure 3. The high-energy pickup ions that occur at ~21:00 UT in Figure 3 appear in the azimuth anode labeled “PU.” Although neither the Sun nor solar wind ions appear in this particular FOV, we show the direction from the Sun for reference. So these pickup ions are about 90° from the solar direction. We do not yet know the IMF direction, but models of the nominal Parker spiral [*Forsyth et al.*, 2001] give an angle of ~90° to the solar wind at 3.3 AU. IES measured two shocks in the solar wind on this day, one in fact, just at the time of the appearance of the high-energy pickup ions. The solar wind did abruptly change direction in both elevation and azimuth plane just after this shock. The IES resolution in azimuth was 45° (two adjacent anodes averaged together), so that is an upper bound for the solar wind change. If we assume that the IMF remained ~90° to the solar wind direction, that change would have taken the IMF to ~45° of the pickup ions rather than 90°. It is possible then that the IMF changed direction and caused the high-energy pickup ions to deflect into the IES FOV at that time.

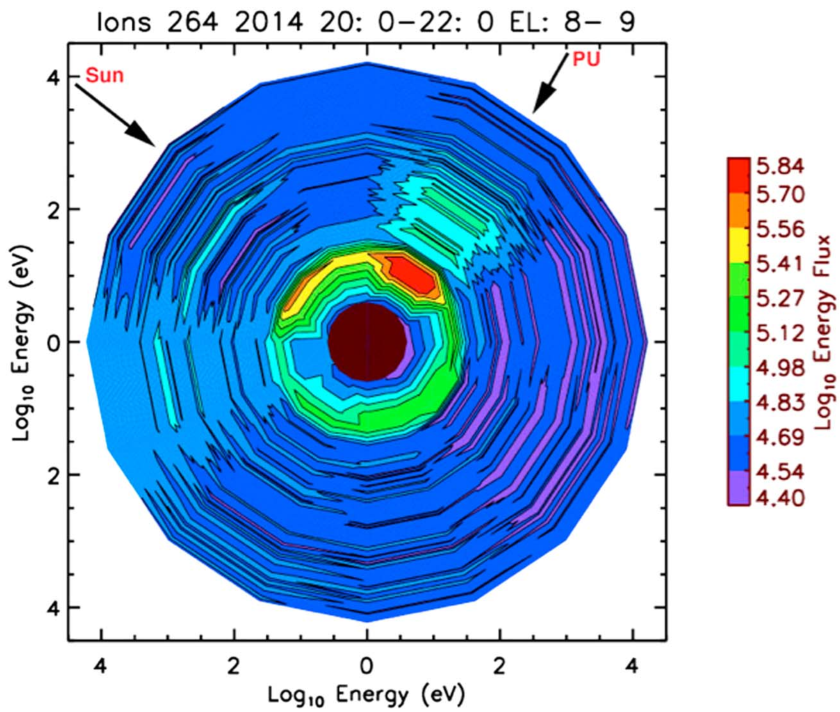

Figure 3. An ion energy-angle contour plot for 21 September 2014 for the period of 20:00–22:00 UT, plotted as energy (radius of the plot, 4.32 to 10^4 eV) versus azimuth angle. Flux is in units of eV/(cm^2 sr s). The directions from the Sun and C-G and the high-energy pickup ions (PU) are indicated. The low-energy pickup ions shown in Figures 1 and 2 are seen as the light green ring near the center. See the text for detailed explanation.

Subsequently, these high-energy pickup ions began appearing more frequently and occasionally filling most of a day. As an example, the case for 6 January 2015 is shown in Figure 4, as an energy-time spectrogram. The IES data for this plot were summed over all angles. The solar wind ions appear intermittently, protons at several hundred eV, He^{++} at ~2 keV/e, and very faintly, He^{+} at ~4 keV/e. The He^{+} is the result of charge

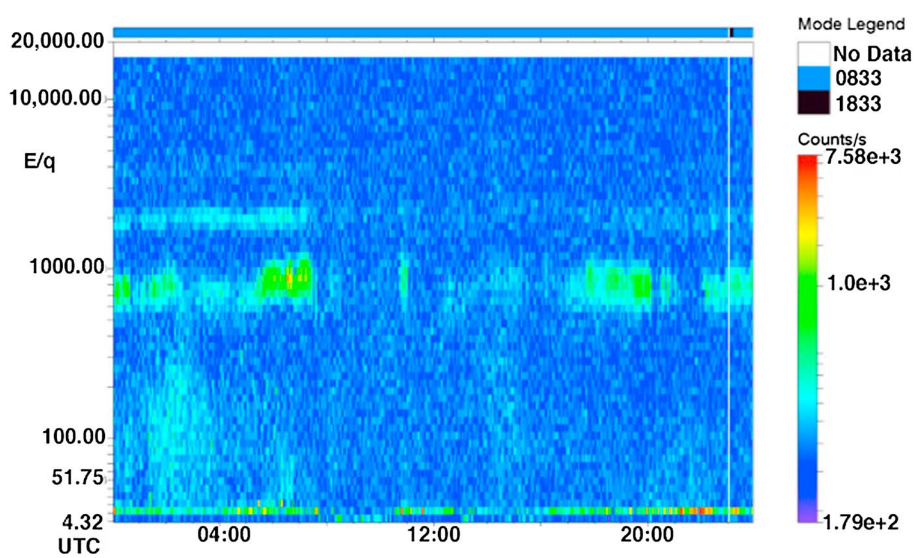

Figure 4. Ion energy-time spectrogram for 6 January 2015, summed over all angles. Solar wind is seen intermittently, protons at approximately several hundred eV/e, He^{++} at ~2 keV/e, and He^{+} faintly at ~4 keV/e. Pickup ions are seen intermittently up to approximately several hundred eV/e.

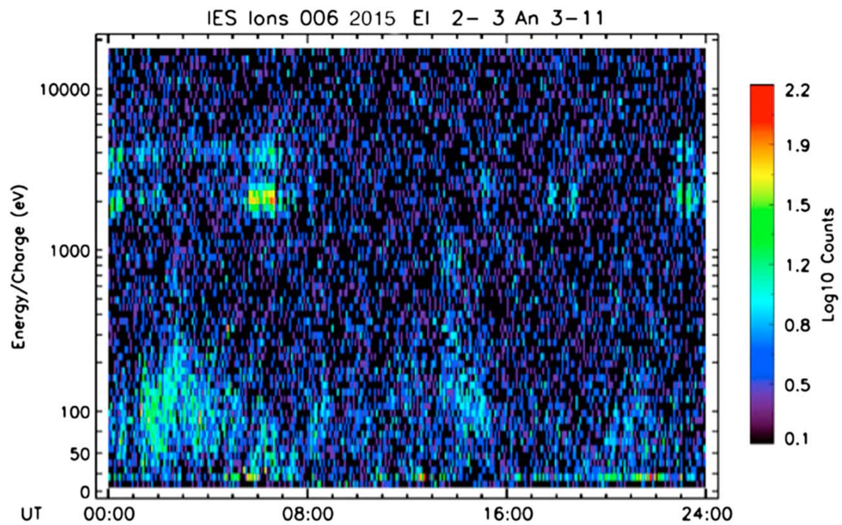

Figure 5. Energy-time spectrogram for the same day as in Figure 4 but including only elevation angle 75° and azimuth angles 270°–315° (both of which included the solar direction). Solar wind protons are not seen in this view but both helium ion species are. Pickup ions are present at the lowest energies as well as up to several hundred eV/e.

exchange between the doubly charged species and the ambient neutral cloud [*Shelley et al*., 1987; *Fuselier et al*., 1991]. These variations in the solar wind appearance are a result of the momentum conserving interaction between the solar wind and the pickup ions [*Chapman and Dunlop*, 1986]. If we assume that the solar wind protons originally had an energy of ~1 keV/e (corresponding to the ~2 keV alphas), the momentum of each would have been (~437 km s^{-1} D). In order to reduce their speed to 366 km s^{-1} (700 eV/e), ~23 H_2O^+ pickup ions would have had to be added per solar wind proton to maintain the same momentum as before the pickup occurred. In these interactions, the protons are affected more than the heavier helium ions. See also the discussion below. Pickup ions appear throughout the day in this plot but have a strong dependence on time and angle as shown in Figure 5, which includes only elevation channels 2 and 3 (75°) and azimuth anodes 3–11 (300°). For this view, the pickup ions appear as irregular traces at different times, such as between 00:00 and 07:00 UT. Also, although the angles chosen for this figure include the solar direction, the solar wind protons do not appear (they do appear in elevation angles ~5° to 20°), but both He ion species are present. Figure 5 is a good example of the frequent direction and characteristic changes of the solar wind ion components.

4. Discussion and Conclusions

The IES instrument has been measuring solar wind (SW) electrons, protons, and doubly and singly charged helium ions while in the vicinity of C-G. The He^+, normally infrequently seen in the solar wind, is a result of the alpha particle charge exchanging with the cometary neutrals. The pickup ions described above appear to have a distribution that is random in time. We have not seen an expected ring-like distribution [*Neugebauer et al*., 1987] and the reason may be that these ions are created locally and have only sufficient time to accelerate to several hundred eV/e and are still on a relatively linear trajectory. These observations are thus very different from those measured previously during relatively fast flybys of very active comets such as the case for the Giotto mission to comet Halley and represent a view of the beginning of plasma processes at a comet.

The interaction between the SW and the increasing clouds of electrons and neutrals is probably partly the cause of the observed SW speed, direction, and intensity changes. At times, the SW seems either to disappear or to move completely out of the IES FOV without any significant change in the Rosetta attitude. Usually, the proton beam changes significantly while the helium components do not. As described by *Chapman and Dunlop* [1986] for the case of measurements at the Active Magnetospheric Particle Tracer Explorer releases, to conserve momentum, the solar wind protons are deflected in the opposite direction from the initial motion of the pickup ions. The result of our measurements at C-G in Figure 6 show indeed

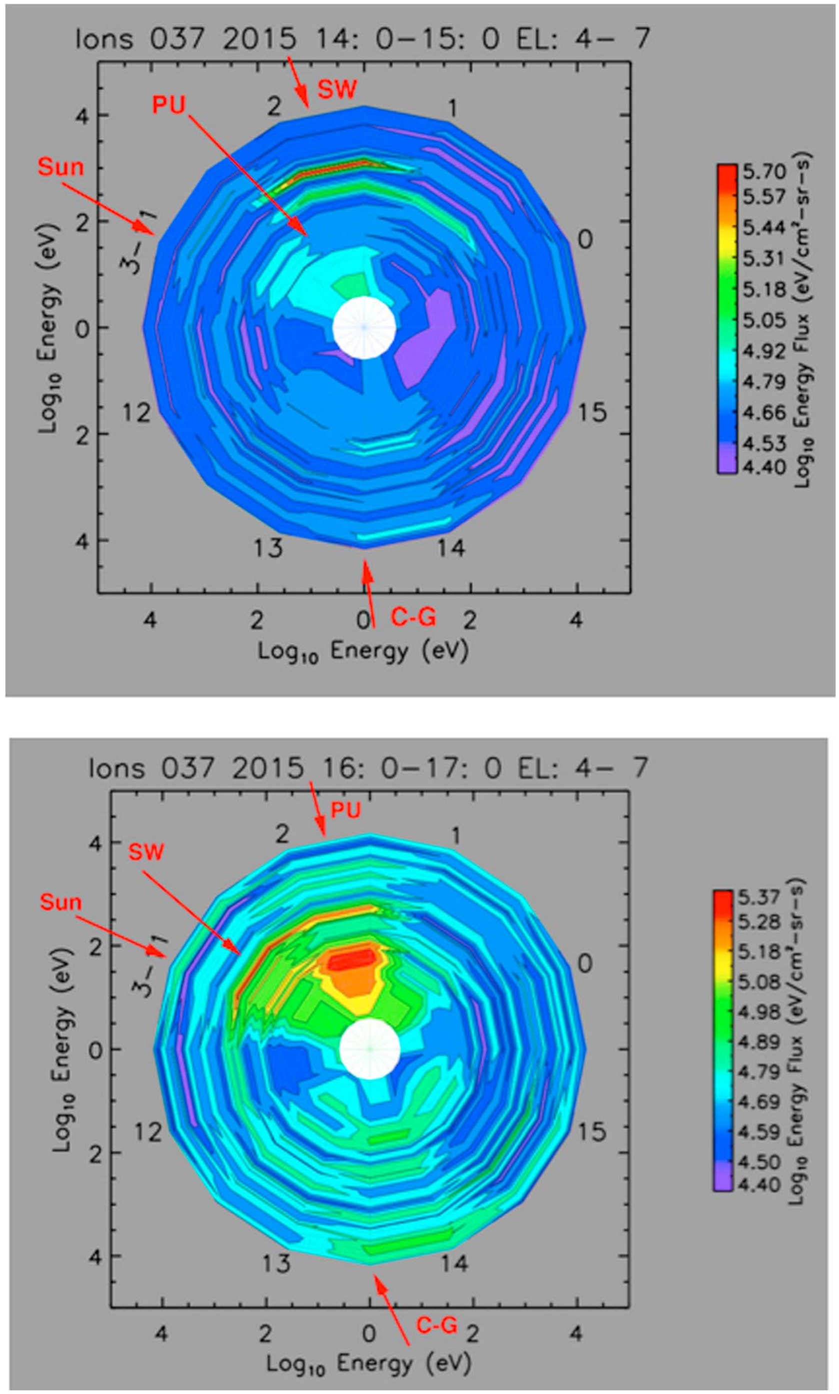

Figure 6. Comparison of ion energy-angle contour plots for 6 February 2015 for the periods of (top) 14:00–15:00 and (bottom) 16:00–17:00. The directions of the pickup ions (PU) and solar wind (SW) are indicated. Comparison of these two images show that when the pickup ions have moved to the right, the solar wind ions moved to the left as a result of momentum conservation in their interaction.

that when the H_2O^+ pickup ions (PU) are deflected clockwise in the figure, the solar wind (SW) is deflected in the opposite direction (counterclockwise). (The relative positions of the Sun and C-G are also indicated.) To the best of our knowledge, this is the first reported measurement of such an interaction of pickup ions and solar wind at a comet. The heavier ions have higher momentum than the protons and would be more resistant to change in direction than the protons would be. Also, we see no obvious effect on the electrons during such events.

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