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## Birth of a comet magnetosphere: a spring of water ions

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**Abstract:** The Rosetta mission has been designed to rendezvous with and escort comet 67P/Churyumov-Gerasimenko from a heliocentric distance of >3.6 AU, when the comet still has a low activity level, until perihelion passage at 1.25 AU where the comet reaches the maximum

of its activity. Initially, the solar wind permeates the thin comet atmosphere that has just begun to form from sublimation of the surface material. Eventually the size and plasma pressure of the ionized atmosphere leads to the formation of plasma boundaries: a magnetosphere is born. Using the Rosetta Plasma Consortium Ion Composition Analyzer, we study the gradual evolution from the first detectable traces of water ions to the stage where the comet atmosphere starts to repel the solar wind at a distance from the sun of about 3.3 AU. We have observed the spatial structure of this early interaction between the comet atmosphere and the solar wind. The near-comet water ion population is composed of accelerated ions of energy up to 800 eV, produced upstream of the observation point, and lower energy locally produced ions. We provide quantitative estimates of fluxes of different ion species and energetic neutral atoms in the near-comet environment.

**One Sentence Summary:** Characterization of the energetic ion environment near a low activity comet nucleus resulting from solar wind – comet atmosphere interaction

**Main Text:**

An active comet emits gas and dust that expand into the surrounding space and form the comet atmosphere or coma. Its neutral component, mainly composed of H<sub>2</sub>O, CO and CO<sub>2</sub>, is thought to result from the sublimation of surface ice or icy grains when the comet draws closer to the Sun (1). Interplanetary space is permeated by the solar wind: a stream of charged particles (plasma) emitted from the sun. The electromagnetic forces of the solar wind act on the charged particles in the environment of the comet. Charged particles are created as the atmosphere is ionized by extreme ultraviolet light as well as through collisions between the solar wind and the comet atmosphere. The partially ionized and collisional atmosphere of a well-developed comet is electrically conductive. The conductive part of the atmosphere acts as an obstacle to the solar wind. When the solar wind meets this obstacle, plasma boundaries such as a bow shock and an ionopause (contact surface) form, separating the solar wind domain from the atmospheric plasma (2-4). This resembles the interaction between the solar wind and the unmagnetized planets Mars and Venus. The sun distance where the comet–solar wind interaction changes to this more “active” stage depends on the comet. For comet 67P/Churyumov-Gerasimenko at the time of the Rosetta rendezvous the nucleus outgassing rate is low (of the order of 10<sup>26</sup> molecules/s). The resulting comet atmosphere is thin enough that the ion – neutral collision frequency is negligible. The solar wind should be largely unaffected by the comet atmosphere, and the plasma boundaries will not yet have formed (5,6).

Due to weak gravity, the neutral atmosphere of a comet extends well into the solar wind, beyond the plasma boundaries once formed. If a constituent of an atmosphere is ionized within the solar wind domain, the newborn ion is accelerated by the solar wind electric field: the ion is “picked up” by the solar wind. Newly picked-up ions may form ring distributions in velocity space, if the source region is large compared to the ion gyro radius. This is not the situation we expect at a comet with a low outgassing rate (6). The accelerated ion gains energy provided by the solar wind. If the energy taken from the solar wind becomes significant, the solar wind is slowed down noticeably and deflected in a process known as mass loading (7). Mass loading is believed to be important for planets around young stars, where the solar extreme ultraviolet radiation heating the upper part of an atmosphere is generally more intense than for an older star such as the sun (8), causing a higher temperature and an extended scale height of the upper atmosphere. More of the upper atmosphere may thus reach into the solar wind domain. Another possible situation is that the dynamic pressure of a stellar wind is significantly higher than the ionospheric plasma

pressure of a planet (9), leading to a situation where the solar wind magnetic field permeates the entire atmosphere of the planet. A weak comet represents an example of the situation when the local plasma pressure cannot balance the solar wind dynamic pressure. The solar wind itself, as well as ion and neutral fluxes resulting from the interaction of the atmosphere and solar wind, may affect atmospheric and surface chemistry at a comet or a planet with a very thin atmosphere.

The Rosetta mission reached comet 67P/Churyumov-Gerasimenko at a heliocentric distance of about 3.6 AU when the comet was still in a low activity state. For all previous in-situ spacecraft comet encounters, the targeted comet had high activity, with an enormous atmosphere extending millions of km into space, and well-formed plasma boundaries with a bow shock and ionopause. On 13 March 1986 the Giotto spacecraft flew by comet Halley at a sun distance of 0.89 AU. The relative velocity was a few tens of km/s, with a closest approach distance of about 600 km. The outgassing rate of Halley at that time was estimated to be of the order of  $10^{30}$  molecules/s. The bow shock was observed at  $\sim 1$  million km from the nucleus, and the ionopause at  $\sim 5000$  km (10,11). Rosetta thus enters a wholly different domain, approaching a low activity comet as close as 10 km from the nucleus and remaining in its close vicinity at a walking pace. We study this environment using the Ion Composition Analyzer, part of the Rosetta Plasma Consortium (RPC-ICA) (12,13). RPC-ICA can distinguish between different mass groups of ions with a mass per charge ratio of about 1, 2, 4, 8, 16 and 32 amu/e and covers an energy range per charge of 10 eV/e to 40 keV/e in 12 s. The basic field-of-view is near  $2.8 \pi$  sr, with an electrostatic entrance elevation sweep providing a  $\pm 45^\circ$  view away from a central  $360^\circ$  viewing plane divided into 16 sectors of  $22.5^\circ$ . Due to spacecraft blocking, the actual field-of-view is closer to  $2\pi$  sr or half the sky. A complete angular scan is performed in 16 steps taking 192 s to complete. Due to instrument limitations the elevation field of view is restricted to only small elevation angles in the lowest energy bins. Water ions are expected to be one of the most common ions in the near vicinity of the comet [1-5,14]. RPC-ICA cannot distinguish water ions from  $O^+$  or  $H_3O^+$  ions, but for convenience we will call ions in the mass group in the vicinity of mass 16 amu/e "water ions" throughout this paper (the mass of water molecules is 18 amu). Similarly, for convenience we will express energy as eV, which is really eV/e, energy per charge.

The first detectable traces of water ions were observed on 7 August 2014, at a distance of 100 km from the nucleus of comet 67P/Churyumov-Gerasimenko (Fig. 1A). The sun-comet distance was 3.6 AU. The cyclical nature of the data is due to the entrance angle sweep. The solar wind ions are only seen when the instrument probes the solar wind direction. Inspection of the full data set reveals that the ions at  $\sim 650$  eV are protons ( $H^+$ ), those at  $\sim 1300$  eV are alpha particles ( $He^{2+}$ ) and the ions in the lower energy bins are water ions. The water ions are coming from a direction  $90^\circ$  from that of the solar wind direction. This is consistent with the ions moving in the direction of the solar wind electric field. The water ions and the solar wind are for this event seen for the same elevation angle (same time in Fig. 1A). The lowest energy ions can only be seen for small elevation angles due to instrument limitations. The sun is always seen at low elevation angles due to constraints on spacecraft orientation imposed by the solar panels. The water ion flux for this first event was up to  $3 \times 10^8$   $m^{-2}s^{-1}$ . With a drift velocity in the range 10 to 20 km/s (the latter corresponding to a drift energy of about 40 eV), the water ion density is  $\sim 10^4 - 10^5$   $m^{-3}$ . The data from 7 August are typical for the early observations, with an undisturbed solar wind. The weak water ion flux of a few  $10^8$  ions  $m^{-2} s^{-1}$  does not yet influence the solar wind.

By 11 August 2014, the water ions are accelerated to nearly 100 eV (Fig. 1B). The fact that no or few ions are seen at the lower energies indicates that there is some distance between the spacecraft and the strongest water ion source. The energy of the ion directly corresponds to the travel distance along the solar wind electric field, which is expected to be of the order of 1 V/km or less. The ions thus appear to have traveled several tens of km from a main source to the observation points.

We observed enhanced activity on 21 September 2014 (Fig. 2A). The distance to the comet center was just below 28 km and Rosetta was over the northern hemisphere of the comet. The sun distance was 3.3 AU. The repeating pattern of ions in the 700 to 800 eV range is solar wind  $H^+$ , at 1400-1600 eV it is  $He^{2+}$ , while at 3000 eV a weak signal from  $He^+$  can occasionally be seen. On this day, RPC-ICA detected solar wind fluxes about an order of magnitude higher than average, up to  $10^{12} m^{-2} s^{-1}$  for  $H^+$  and  $10^{11} m^{-2} s^{-1}$  for  $He^{2+}$ .

At around 18 UT we see a significant flux of water ions at the lowest energy we can measure. The observed water ion flux is  $10^{10} m^{-2} s^{-1}$ . The ions are accelerated into the instrument by a negative spacecraft potential, determined using the RPC-LAP instrument (15) to be  $-5$  to  $-10$  V. Fig. 3 shows the geometry of the observations and flow directions of all observed populations in the detector central plane. The solar wind is now slightly deflected due to interaction with the comet atmosphere and has a component of flow away from the comet.  $H^+$  is somewhat more deflected than  $He^{2+}$ . The coarse sector resolution makes a precise angle difficult to determine. The deflection is also seen in the higher angular resolution elevation scans: protons are typically deflected by  $\pm 25^\circ$  in elevation angle from the sun line and  $He^{2+}$  by about half that angle. The elevation angle is the angle out of the plane depicted in Fig. 3.

We observe the low-energy water ions in the lowest energy bin only. An upper limit to the drift energy is thus 10 eV or a velocity of about 10 km/s, corresponding to a water ion density of  $10^6 m^{-3}$ . The RPC-LAP Langmuir probes (15) indicate a total plasma density of  $10^7 m^{-3}$ , which is consistent with our observations if the drift velocity is 1 km/s. The neutral density determined using Rosetta Orbiter Spectrometer for Ion and Neutral Analysis Cometary Pressure Sensor (ROSINA COPS) (16) was a few times  $10^{13} m^{-3}$ . The ionization time for water molecules at 3.3 AU is about  $10^7$  s. Thus the observed ion density would be produced in 1 to 10 s over a distance of 10 km, the order of magnitude of the distances involved. A water ion density of  $10^7 m^{-3}$  would correspond to about the same particle density as that of the solar wind  $H^+$  and the mass density would be an order of magnitude higher than that of the solar wind. The kinetic energy density of water ions is still tiny compared to that of the solar wind, with a kinetic energy ratio of  $10^{-4}$  to  $10^{-3}$  for 1 and 10 km/s water ions, respectively.

We also examined the narrower time period 20:53 to 20:59 UT on 21 September 2014 (Fig. 2B). Due to instrument angular scans we see repetitive structures of accelerated ions forming curves from the lowest energy up to that of solar wind  $H^+$  at 800 eV (the ions are seen in sector 12; see Fig. 3 for a schematic overview). The ions appear to follow an angular dispersion, with higher energy ions seen for larger elevation deflection angles (seen as a time series in the energy spectrogram). Careful analysis reveals that this is an artifact caused by an offset in our energy table. All these ions are seen just at the limit of observable angles for that energy. The ions come from a small range of angles of  $20^\circ$  to  $30^\circ$ . The ions reach energies of 800 eV, which implies acceleration over a distance of a few 100 km assuming that the solar wind electric field is the underlying acceleration mechanism. The integrated flux of the accelerated cometary ions is  $10^9 m^{-2} s^{-1}$ , an order of magnitude less than the cold water ions.

By constructing an energy mass matrix from the time period when accelerated cometary ions were observed on 21 September 2014, we see that the different ion populations are seen where they are expected, i.e.  $\text{H}^+$  at mass per charge 1, alpha particles at 2 amu/e,  $\text{He}^+$  at 4 amu/e and the accelerated ions around 16 amu/e (Fig. 4). The highest and lowest energy bins with significant fluxes of cometary ions appear also to include ions with mass of well above 16 amu/e. This indicates the presence of some heavier ions ( $\text{CO}^+$ ,  $\text{CO}_2^+$ ) for this occasion.

The observed  $\text{He}^+$  are created by charge exchange between  $\text{He}^{2+}$  and  $\text{H}_2\text{O}$  and allow us to make an estimate of the total  $\text{H}_2\text{O}$  atmosphere the ions have passed through, i.e.,  $2.5 \times 10^{17} \text{ m}^{-2}$  (17). This corresponds to an in-situ neutral  $\text{H}_2\text{O}$  density of about  $1 \times 10^{13} \text{ m}^{-3}$ , in good agreement with ROSINA COPS measurements (16). The charge exchange of  $\text{H}^+$  into H is more important for the near-comet environment, as this constitutes a much larger flux. It has commonly been observed at other solar system objects such as Mars (18). RPC-ICA cannot measure these energetic neutral atoms, but we can infer the approximate flux of H by comparing with the effect of the charge exchange product that we can observe, i.e.,  $\text{He}^+$ . The flux ratio of  $\text{He}^+$  to  $\text{He}^{2+}$  for 30 September 2014, the day when we observed the clearest  $\text{He}^+$  signal, was 2.1% (17). Using models of charge exchange, we then estimate that at the same point in space we should have a H to  $\text{H}^+$  ratio of 4.4%. Scaling this value with a model of the comet atmosphere density, we find that the H to  $\text{H}^+$  ratio close to the nucleus reaches up to 33% at the terminator, i.e., a large fraction of the impinging solar wind will have charge-exchanged with water molecules close to the nucleus, leading to the formation of a relatively dense cloud of energetic neutral hydrogen atoms.

At 100 km from a low-activity comet nucleus, where we first detected the traces of cometary water ions, the source of the observed ions is already spatially structured. This is revealed through the absence of ion populations at the lowest energies. Thus at 100 km from the nucleus, the number of locally produced ions was below the measurement threshold of the instrument. This view is supported by time variations of the local neutral density as measured by the ROSINA instrument which measures significant variations related to the comet nucleus rotation period (19).

At a distance of 28 km from the nucleus, we observe a comet plasma of similar number density to that of the solar wind. The neutral atmosphere had a density of  $10^{13} \text{ m}^{-3}$ , similar to the F region in Earth's ionosphere (20). This atmosphere is still essentially collision-less, but charge-exchange collisions are already noticeable. We are witnessing the initial stages of an ionosphere being born.

In this nascent stage, before the plasma boundaries are formed, the comet nucleus and near-comet atmosphere are affected by a relatively direct flux of solar wind. However at this stage, the solar wind is already somewhat deflected by the comet atmosphere. The deflection is about  $20^\circ$  from the sun-comet line for  $\text{H}^+$  and about half of that for  $\text{He}^{2+}$ . Simple calculations indicate that a large fraction of the solar wind impinging on the nucleus and lowest part of the atmosphere will undergo charge exchange: 30% for our example day of 30 September 2014. Energetic cometary ions were observed at 28 km from the nucleus. The continuous presence of ions throughout the

energy interval from near 0 to 800 eV indicates a continuous source extending over a few 100 km. Thus similar fluxes can be expected to hit the nucleus. Based on our observations, the nucleus is consequently [?] hit by the solar wind, by charge-exchanged H and a flux of  $10^9 \text{ m}^{-2} \text{ s}^{-1}$  of accelerated ions with a cometary origin, with an energy of up to 800 eV per charge. The neutral hydrogen flux will not be affected by the enhanced magnetic field caused by the solar wind slowing down and by associated magnetic field line draping. The important role of a heterogeneous and dynamic comet atmosphere, the deflection of the solar wind at an early stage, and the presence of accelerated ions — these present challenges for comet–solar wind interaction models (6,21). This energetic ion environment represents the first stage of the birth of the comet magnetosphere.

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**Figure 1.** Energy-time ion spectrograms: (A) Data obtained on 7 August 2014 showing the first detection by RPC-ICA of water ions from the comet. The color scale shows differential flux summed over all azimuthal sectors and all masses. The water ions are the signal at just above 10 eV. Solar wind proton and alpha particles are visible at higher energies (650 eV, 1300 eV). The black patches indicate times of decoder errors; (B) Energy-time spectrogram from 11 August 2014. The water ions are accelerated to nearly 100 eV.

**Figure 2** Energy-time ion spectrograms: (A) Data from 21 September 2014. The color scale is differential flux. The solar wind ions are visible at the 700-800 eV ( $H^+$ ) and 1400-1600 eV ( $He^{2+}$ ). At even higher energies (3000 eV) a weak signal from  $He^+$  is sometimes seen. In the lowest energy bin we see water ions; (B) Details of the time period 20:53 to 20:59 on 21 September. The solar wind components are clearly seen at different energies with a faint  $He^+$  signal at higher energy. The ions seen in the energy range 100-1000 eV, forming curves, are comet origin water ions with an elevation angle of  $20^\circ$  to  $30^\circ$ .

**Figure 3.** The geometry of the RPC-ICA observations made on 21 September 2014. The cold ions were mainly observed between 17 and 19 UT. The accelerated ions were observed between 21:00 and 21:30 UT. Sector numbers identify the field-of-view of the corresponding instrument sector. Comet shape model credit: ESA/Rosetta/NAVCAM.

**Figure 4.** Energy-mass matrix from 21 September 2014. . The observed counts are integrated over a time period including the data shown in Fig 2(B). The white lines show the position of the peak of the signal for ions with mass 1 amu/e (dotted), 2 amu/e (dashed), 4 amu/e (solid) and 16 amu/e (dash-dotted), respectively.  $H^+$ ,  $He^{2+}$  and  $He^+$  are seen at about 750, 1500 and 3000 eV. Cometary ions are seen at 10 eV. Grey lines show extrapolation beyond 300 eV, the lowest energy available from laboratory calibration. The line at mass about 16 amu/e has been determined through in-flight calibration. The signal at 16 amu/e has an asymmetric shape with the peak to the right and a rather sharp cut-off towards higher mass channels. This is observed both in the laboratory and in flight.

## Supplementary Materials:

### Instrument Operations

### Basic Theory

### Field of View of the Instrument

### Calculation of ENA fluxes

Figures S1

Table S1

References (22-24)