Ion pickup observed at comet 67P with the Rosetta Plasma Consortium (RPC) particle sensors: similarities with previous observations and AMPTE releases, and effects of increasing activity

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Ion pickup observed at comet 67P with the Rosetta Plasma Consortium (RPC) particle sensors: similarities with previous observations and AMPTE releases, and effects of increasing activity

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Abstract. Rosetta's unique trajectory is allowing exciting measurements of the development of cometary activity between ~3.6 and 1.2 AU for the first time. For a few months following Rosetta's arrival at comet 67P in August 2014, data from the Rosetta Plasma Consortium (RPC) particle instruments (the Ion and Electron Spectrometer (IES) and the Ion Composition Analyser (ICA)), have shown that the low activity cometary environment was initially dominated by the solar wind. This was expected in the early stages of the mission. In addition to the solar wind and related He^+ populations, a low energy pickup ion population is seen intermittently in the early phase of the mission near the comet. The population is very time dependent, but at times reaches higher energy approaching the solar wind energy. During these intervals, ICA data indicate that the composition is mainly water group ions. The rising energy signatures of these ions observed at times indicate that they are in the early phases of the pickup process, initially accelerated by the electric field ('early phase pickup'). Here, we compare these exciting pickup ion measurements with Giotto measurements at the relatively weak (compared to Halley) comet Grigg-Skjellerup, where early phase pickup was seen including non-gyrotropic cometary ions, and with the AMPTE lithium and barium releases. Our results reveal some striking similarities with the AMPTE releases, particularly the rising energy signature related to early pickup, and a momentum balance between the pickup ions and the deflected solar wind. There is also evidence for momentum transfer between the pickup ions and the solar wind, with less velocity change seen in the solar wind alpha particles compared to the protons; this was also observed in an AMPTE lithium release. We discuss the effects of increasing activity observed between 3.6 to 1.8 AU, including the increasing dominance and energisation of pickup ions, increasing ionospheric effects and the decreasing effect of the solar wind.

1. Introduction

As Rosetta accompanies its comet from ~3.6 AU to perihelion (~1.2 AU), it provides an unique opportunity to follow the solar wind-comet interaction from relatively dormant to well-developed (e.g. [4]). Initial pickup ion measurements from Rosetta at comet 67P indicate the importance of the solar wind in the early measurements [1,2], as had been expected before the mission [3,4]. Pickup ions in the early stages of the pickup process, accelerated along the electric field, were seen. Here, we will compare the early Rosetta results with pickup ion measurements from earlier cometary missions, pointing out the likely importance of non-gyrotropic ion distributions [5] and comparing with the AMPTE lithium [6,8] and Barium [7] releases.

The solar wind interaction with a comet has been observed at comets Giacobini-Zinner (GZ, e.g. [9]), Halley (e.g. [10]), Grigg-Skjellerup (GS, e,g.[11]), Borrelly (e.g.12) and now Churyumov-Gerasimenko (CG, 67P, e.g. [1,2]). In addition, before the 'Halley Armada' in the mid-1980s, relevant processes were studied by the US-German-UK AMPTE mission [13,14] that released neutral lithium and barium atoms in the solar wind in the vicinity of the Earth, giving an early chance to study cometary plasma physics and processes [6,15,16,17].

Unlike the earlier missions, the Rosetta orbiter stays with 67P as the comet nears the Sun, and observations were made starting at ~3.6 AU and are planned until perihelion (1.2 AU) which the comet will reach in August 2015, with some post-perihelion measurements until December 2015 in the nominal mission; this has recently been extended to the end of September 2016 when the spacecraft will be at 3.8 AU.

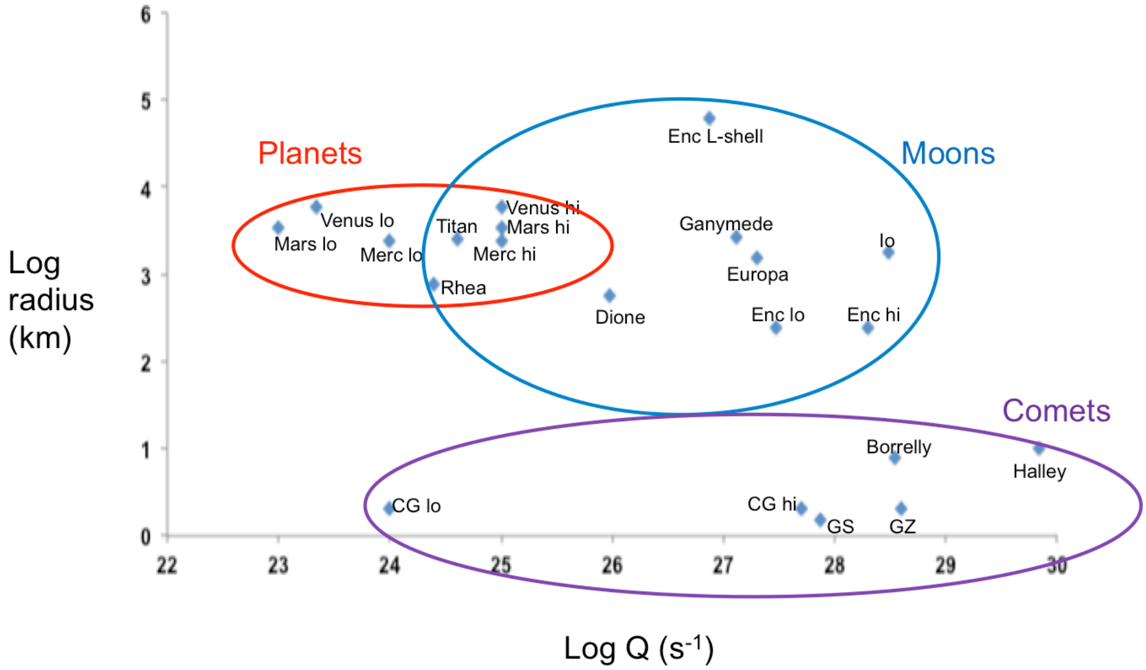

Figure 1 - Outgassing rates, Q for comets, planets and moons (adapted from [20])

As a comet nears the Sun, the nucleus warms and water molecules and other neutrals sublimate producing the neutral coma. The outflow of neutrals also brings dust. The neutral atoms and molecules ionize in sunlight and via charge exchange. On ionization the ions feel the effect of the solar wind electric field given by **E** = -$\mathbf{v}_{sw}$ x **B**. They are then initially accelerated along the electric field, and then spiral around the magnetic field, to form a cycloidal trajectory in real space. This corresponds to a ring in velocity space, which is unstable and plasma waves are formed. Far from the Sun, the comet-solar wind interaction starts relatively simply as an inert body with relatively few pickup ions, but closer to the Sun boundaries such as the bow shock and contact surface are present in a 'developed' interaction [e.g. 4]. At a developed comet-solar wind interaction such as Halley, ring distributions of pickup ions are seen upstream [e.g. 30] while a bispherical shell is observed upstream of the bow shock [32]. The maximum energy available (in the frame of the neutral particles) is $E_{max,\,shell} = 4m_{amu}E_{sw}$, corresponding to up to ~70keV for a water group ion in the solar wind [e.g. 30]. In the case of the moon, neutral reflection can give an extra 'kick' to the pickup process, giving an energy up to $9m_{amu}E_{sw}$ [18,19].

Comet 67P is of lower activity than any of the other comets visited so far (see Figure 1, from [20]). Consequently, a developed solar wind interaction is not expected except near perihelion, at the closest distances between 67P and the Sun (see also simulations by Koenders [21] and Rubin [22]). The Rosetta Plasma Consortium (RPC) of 5 sensors and electronics is designed to follow this interaction [3,23]. RPC includes two particle instruments, the Ion Composition Analyser (ICA, [24]) and the Ion and Electron Sensor (IES, Burch et al., [25]) that measure suprathermal ions up to 22 keV. In addition, the Rosina instrument is designed to study the neutral particle environment and thermal ions [26].

The first particle data from 67P were published by Nilsson et al. [1] and Goldstein et al. [2] from the ICA and IES instruments respectively.

In this paper, we briefly review the ICA and IES data available so far from the Rosetta mission, and compare these with measurements from the Giotto mission at GS and the AMPTE lithium and barium releases. We find that several results from 67P have some similar features to those found from earlier missions, but are more complete; we also note that the increasing activity is already affecting the data (see Figure 6 and related discussion).

2. Pickup ions previously observed at comets

From the earlier encounters at active ($Q > 5\text{x}10^{27}$ s^{-1}) comets, observations showed that:

(a) Pickup ions produce mass loading (a decrease in the solar wind speed) [e.g. 9,10,12].

(b) Bow shocks are eventually formed, that under exceptionally high Q ($> 5\text{x}10^{28}$ s^{-1}) may become 'mass loading shocks'.

(c) Upstream of the shock, nongyrotropic rings [5], rings [30,31] and bispherical shells [32] are commonly observed.

(d) Pickup ion acceleration (formation of suprathermal tails) takes place. Such acceleration was observed at comets Giacobini-Zinner (e.g. [9,33]), Halley (e.g. [10,34,30,32]) and Grigg-Skjellerup (e.g. [11,35,5,36]) and reviewed [45,46,4].

(e) Pickup ions play a key role in cometary bow shocks [27,28]. During some of the observed shock crossings, particularly the wide, quasi-parallel outbound shock observed by Giotto at comet Halley, additional ion pickup was observed within the shock structure; this is described as a 'mass loading shock' [29].

At 67P, much less developed interactions are expected, with perihelion and immediate post perihelion interactions at a production rate approaching that of comet GS.

3. Early results from 67P[1]

Initial results after achieving orbit showed the early appearance of low fluxes of low energy (~10s of eV) water group pickup ions 100 km from 67P, with the comet at 3.6 AU from the Sun, on 7 August 2014, (Fig 1a of [1]]). This was expected since, with 67P at 3.5 AU, its outgassing rate was $<10^{25}$ s^{-1} (see Figure 1, also [48]). Water group ions were seen moving at ~90° to the solar wind direction. Additional observations from 11 August showed some acceleration up to ~100eV (Fig 1b of [1])..

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[1] The first particle data from 67P were published by Nilsson et al. [1] and Goldstein et al. [2] from the ICA and IES sensors respectively.

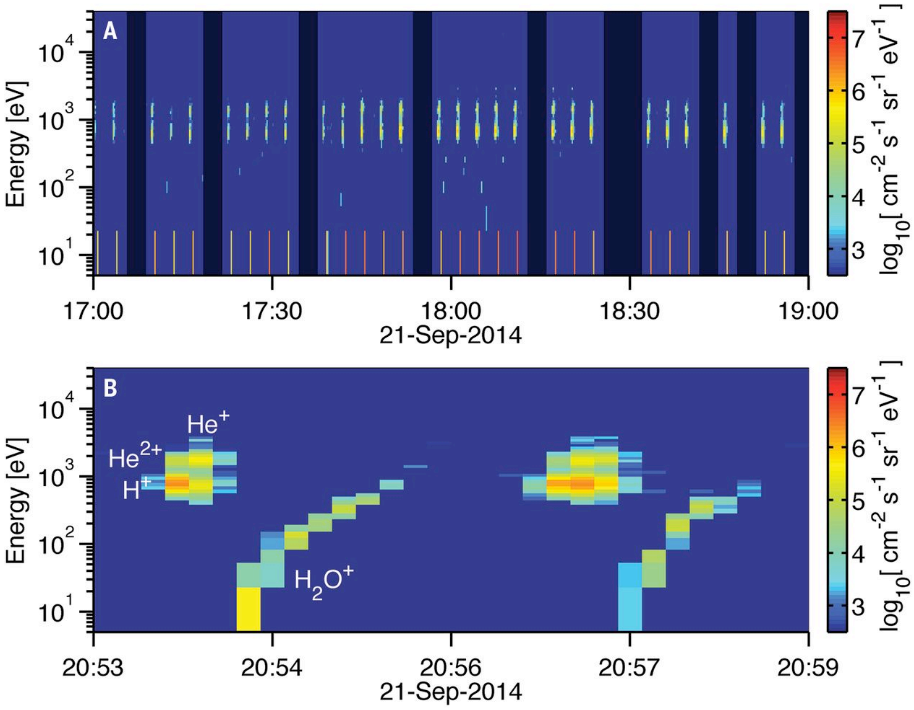

Figure 2 - Rosetta ICA data from 21 September 2014 at ~3.3 AU (Figure 2 from [1]). Panel A shows the solar wind at ~1keV and pickup ions at ~10eV Panel B shows solar wind ions H^+ and He^{++}, and He^+ created from charge exchange between He^{++} and H_2O [1]. The rising energy signature of H_2O^+ in the lower panel is caused by internal instrument stepping of the elevation angle, resulting in sampling of pickup ions from different parts of the comet's coma [1].

On 21 September 2014 Rosetta was at 28km from 67P and ~3.3 AU from the Sun, and the solar wind was seen to be deflected [1]. The deflection was ~20° for H^+, 10° for He^{++}. Rising energy signatures were noted at up to ~800eV (see Figure 2) – these water group ions were accelerated along the electric field in the early phase of pickup. The different energies were interpreted as coming from different polar deflection angles in the instrument sequence – due to the instrument field of view this corresponds to different locations in the comet's atmosphere [1] and different points on the early part of the cycloidal trajectory of pickup ions. The rising energy signatures, which were identified as water group ions in the ICA composition data, are shown in Figure 2.

The IES data on 10 September 2014, when Rosetta was 28km from the comet and 3.4 AU from the Sun, also showed early pickup ions at ~10eV [2]. These were correlated with enhancements in the IES electron fluxes up to ~200 eV, interpreted as electrons from the photoionization of neutrals, and with pressure data from the Rosina COmetary Pressure Sensor (COPS) (Fig 1 of [2]).

At 28km from the comet on 21 September 2014 and at a comet –Sun distance of ~3.3 AU, pickup ions were seen by IES at higher energies up to ~1keV, at 90° to the solar wind direction [2].

On 6 Jan 2015, the data showed a clear deflection of the solar wind protons, and it was shown that these were more deflected than He^{++}) (see Figures 4 and 5 of [2]). On this day the pickup ions were at 45° to solar wind. A month later on 6 Feb. 2015, the pickup ions (PU) and solar wind (SW) directions are shown in the top panel of Figure 3, and an anti-correlation in their deflection was seen(bottom panel). When the pickup ions have moved to right, the solar wind ions moved to the left – indicative of possible effects resulting from momentum conservation.

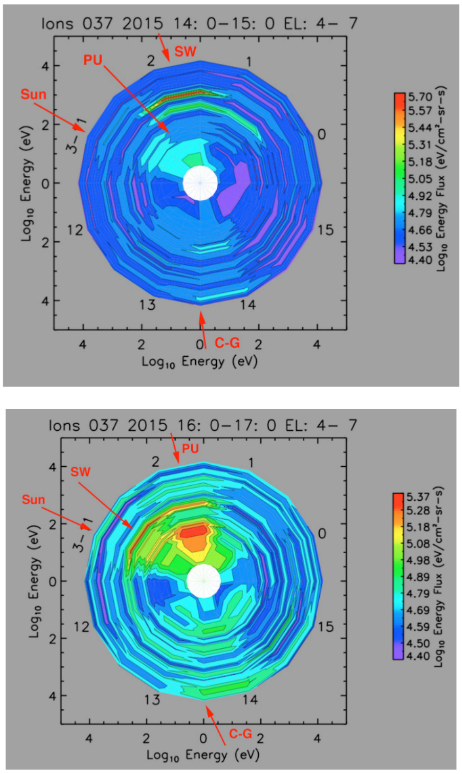

Figure 3 - Rosetta IES sectored spectrograms recorded on 6 February 2015 (14:00-15:00 top, 16:00-17:00 bottom) showing deflection of the solar wind (Figure 6 from [2]). Directions of motion of the solar wind (SW), pickup ions (PU) and the comet (C-G) are indicated. Note that between the plots, while the pickup ions move to the right, the solar wind ions move to the left.

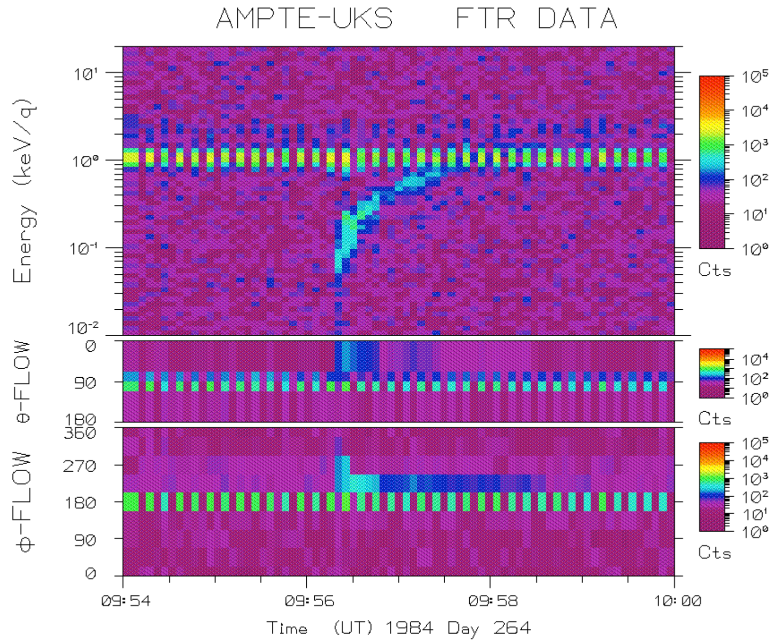

Figure 4 - AMPTE-UKS ion data from 11 September 1984 showing a solar wind lithium release (from [6]). Note the rising energy signature of lithium pickup ions.

4. Results from AMPTE

The Active Magnetospheric Particle Tracer Explorers (AMPTE) mission was a joint US-German-UK mission involving 3 satellites – the Charge Composition Explorer (CCE), Ion Release Module (IRM) and UK subsatellite (UKS). The latter two were in an 18.7 R_E apogee orbit that placed them in the solar wind for some portions of their orbits. On September 11 and December 26 1984, ~10^{25} neutral lithium and ~$5x10^{24}$ barium atoms respectively were released [14].

The lithium release (see Figure 4) as was recorded by UKS and IRM, showing the formation of the early part of a ring distribution as the cloud of neutral atoms receded from the spacecraft, while being ionized by sunlight [6,17]. These observations were used to measure the speed at which the neutral cloud expanded. The spectrogram shown in Figure 4 is very reminiscent of the early Rosetta results.

In addition, it was possible to measure the change in solar wind and pickup ion velocities [6,8], see Figure 5. These were used to calculate the momentum interchange in the interaction between the solar wind and lithium ions [8].

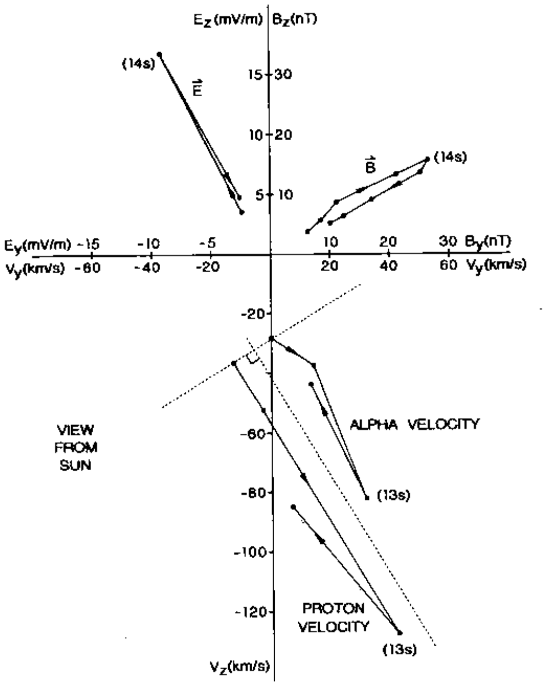

Figure 5 - B and E directions, and observed solar wind deflection (from [8]) 13-14s after the AMPTE lithium release on 11 September 1984. The pickup ions move along E and the solar wind deflection is in the opposite direction showing momentum conservation. The solar wind alpha deflection is less than that of the protons.

The barium release also showed that the momentum of the deflected barium ions was opposite to that of the deflected solar wind [7]. The momentum transfer was also modeled and calculated theoretically [37].

5. Non-gyrotropic ions at Grigg-Skjellerup

The Giotto encounter with comet Grigg-Skjellerup provided the closest comet production rate conditions (~$7.5x10^{27}$ s^{-1} [11])) to the most active phase of 67P (see Figure 1). One of the interesting results was the observation that near to the comet the pickup ion distributions were nongyrotropic. This was interpreted to be the result of the variation of the density gradient of the injected ions over a cycloid, between cusp and cusp [5]. This causes additional instabilities (e.g. [38,39,40]). It is possible that a similar effect was measured at 67P, which may contribute to the observed magnetic fluctuations from related plasma instabilities; these magnetic fluctuations have been called a 'singing comet' [see also 41].

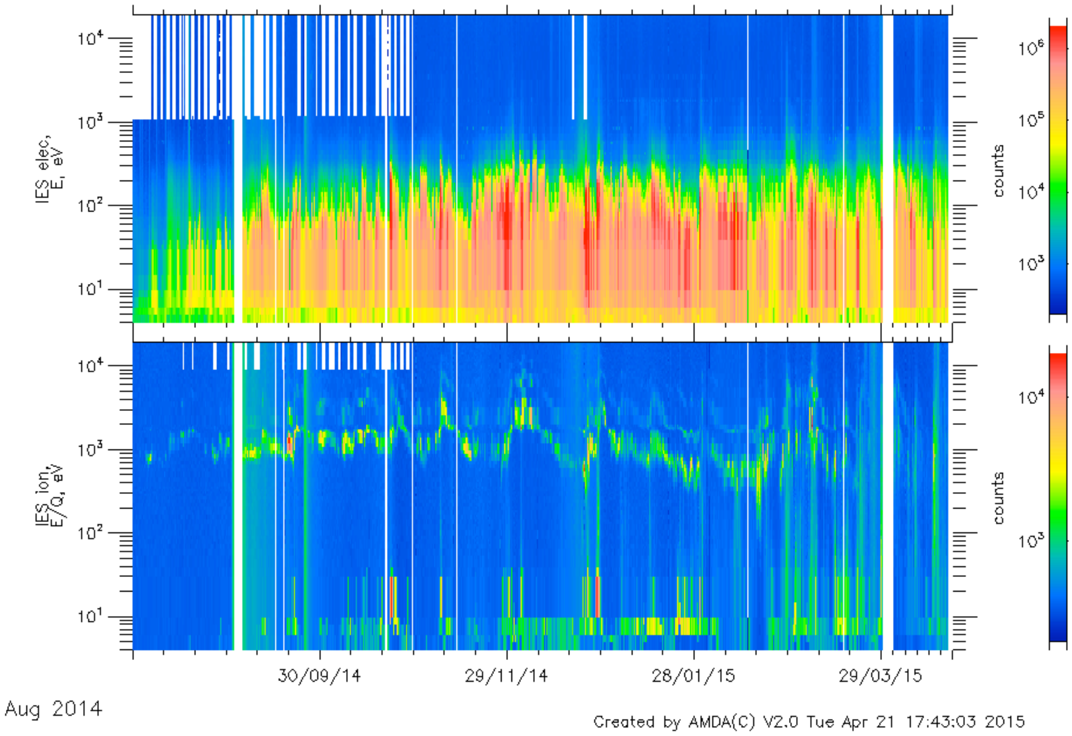

Figure 6 - Rosetta IES data from a few days before orbit insertion at 67P (1 August 2014, comet-sun distance 3.62 AU) to 21 April 2015 (comet-sun distance 1.81 AU). During this time, the Rosetta orbiter has been between ~10-300 km from the nucleus of 67P. The top panel shows electrons, the bottom panel ions. The electron data show a general increase with time indicating higher activity. The ion data show the variable solar wind protons (~1 keV), also the alpha particles at 2x solar wind proton energy/q and He^+ at 4x solar wind proton E/q. The increasing pickup ion population is seen at ~10eV, with variable intensity that increases during the plot. The pickup ion energy also increases towards the right of the plot, indicating additional acceleration (see also [47]).

6. Discussion and new results

There are several similarities between the early Rosetta results and the AMPTE lithium and barium releases discussed above. In particular:

1. Rising energy spectrograms associated with varying neutral densities with distance from the observation point (see Figures 2 and 4)
2. Deflection of the solar wind in an opposite direction from the pickup ion deflection, indicating momentum conservation
3. A more enhanced deflection for solar wind protons than for alpha particles.

These are all features of the early stage of the pickup process.

As the comet nears the Sun, a more developed solar wind interaction is expected. RPC is beginning to see this in the raw data (see Figure 6). Increased numbers and energies of pickup ions, as well as less prominent solar wind, are seen in the plot. In addition, electron fluxes are prominent indicating ionospheric effects. A diamagnetic cavity may be expected near to the nucleus [21,22], and if operations at ~10^3 km away from the nucleus occur, it may be possible to distinguish features such as a Mach cone and formation of a bow shock (e.g. [21,22]).

Regarding bow shock identification, previous cometary missions confirmed the presence of a weak cometary bow shock (e.g. [27,28,42]) using several features. These included calculations of the Mach number (*M*) [43], conditions where the ion implantation rate exceeds a critical value (e.g. [44]), and thermalisation of the key species. Heavy ions played a key role in the shock structure: mass loading causes the shock to be low M~1-2 [43,27,28]. The shock position was observed close to the predicted point in the flow (a 3d version of 1d critical point [44]). The shock structure was complex, and cometary ions dominated the pressure. Speed dips, similar to a subshock, were observed, with scale lengths varying from H^+ to O^+ gyroradii (for perpendicular shocks), and wider (for parallel shocks). In some cases 'shocklets' were seen. Also observed was a wide, parallel 'mass-loading shock' structure seen in the Halley outbound data [29]. Thermalisation was seen for different species at different times, with an indication that the thermalisation begins in the shock foot (associated with a density increase for heavy ions). Rosetta may enable the first studies of bow shock onset at a weak comet [42].

7. Conclusions

Rosetta is producing unique measurements of the solar wind-comet interaction between ~3.6 AU and 1.2 AU. The early results from Rosetta RPC shows pickup ions at an early phase as they start their gyration following acceleration along the electric field. During this early phase, momentum balance between the new ions (propagating along **E**) and the deflected solar wind is seen [1,2]. We have seen that the AMPTE lithium and barium releases saw the effects of similar physics (e.g.[6,8,7]). The Giotto measurements at GS showed non-gyrotropic ions [5] that may be relevant at 67P. This non-gyrotropy may cause plasma instabilities and additional waves.

Rosetta is also observing the evolution of the comet-solar wind interaction between relatively dormant and developed interactions (see Figure 6, and ICA measurements reported in [47]). The pickup ions are intensifying and becoming more energetic, and the cometary electrons related to the ionosphere have become more prominent.

Observations of a diamagnetic cavity and a cometary bow shock are anticipated – these will be identified by examining the Mach number, the point in the flow, and the thermalisation of all species. It is also important to note that kinetic effects will be important, particularly pickup ion gyration. We look forward to the next few months of unprecedented measurements near the heart of a comet approaching the activity level of GS.

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