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Abstract

Electrons are needed to maintain quasineutrality in a case where positive ions are injected across the magnetic field into a limited volume in a magnetized plasma. In the absence of collisions, a positive potential builds up and traps the electrons which enter the region along the magnetic field. If the added density of ions exceeds the ambient density, large potential differences along the magnetic field can be maintained this way. The process explains several features of the Porcupine xenon ion beam injection experiment, where strong magnetic-field-aligned electric fields were measured in the vicinity of a xenon ion beam which was injected into the ambient ionosphere from a spinning sub-payload.

1. Introduction

The natural occurrence of magnetic-field-aligned electric fields in the ionosphere was originally suggested by Alfvén in the late fifties and later confirmed when *in situ* observations in space became possible (see Brenning *et al.*, 1989, and references therein). More recently structures with magnetic-field-aligned electric fields have also been observed in active injection experiments in the ionosphere (Brenning *et al.*, 1989, Potelette *et al.*, 1988).

In the ionosphere and magnetosphere there can exist three categories of magnetic-field aligned electric fields, corresponding to the only three forces that can provide the necessary momentum balance (Fälthammar, 1978). The forces are: (1) the magnetic mirror force, (2) the net force from ac electric fields, and (3) inertia of the charged particles. Electric double layers are an example of the last category. In this paper we use the newly proposed mechanism of *dynamic trapping* (Brenning *et al.*, 1989; Bohm *et al.*, 1990), which belongs to this category but has properties that are in important aspects different from those of double layers. For example, dynamic trapping can support electric potentials much larger than kT_e/e even without any net current, and the spatial scale of the potential distribution is independent of the Debye length.

The mechanism is described elsewhere (Brenning *et al.*, 1989; Bohm *et al.*, 1990) and is here only briefly summarized. It applies where there is ion motion across the magnetic field in such a geometry that the cross-field ion current has to be neutralized by magnetic-field-aligned electron currents. We here disregard the mechanisms which drive the ions across the field and focus on the electron response along a field line where the ion density grows locally over a limited length L_{inj} , and where an electron current along the magnetic field is needed to maintain quasineutrality. We have studied the process in a one-dimensional computer simulation where heavy ions are injected in the centre of the simulation region and the response along the magnetic field of the plasma is calculated. The length of the system is 100 Debye lengths. At the start of the simulation it is filled with a uniform Maxwellian background plasma made up by electrons and oxygen, with the density n_e and the temperature $T_e = T_i = 0.1$ eV. The plasma is limited at $z = 0$ and $z = L$ by two endplates with boundary conditions chosen to simulate a surrounding homogeneous plasma: particles which hit the end plates are lost, and half-Maxwellians are injected at both end-plates with the same temperature and density as the background plasma. The external circuit is chosen with the same potential $\Phi(0) = \Phi(L)$ on both end plates. In the *injection region* which has a length of $L_{inj} = 30\lambda_d$ centred in the middle of the simulation region the heavy ions are injected with a smoothly varying spatial distribution. The injected un-neutralized ion density grows from zero in the simulation. The

total number of injected ions per time unit is determined by the parameter R_0 . A crucial value is the injection rate $R_0 = R_{max}$ at which neutralization requires saturation electron current along the magnetic field.

The simulation uses the correct charge/mass ratios for electrons, oxygen ions and barium ions. Barium was used in the CRIT I ionospheric experiment which was the original reason for the simulation (Brenning *et al.*, 1989). By a coincidence the barium mass ($m = 137$ amu) is close to the xenon mass ($m = 131$ amu), which was used in the Porcupine ion beam experiment which we will discuss here. In the following we use the normalized parameters: time $\tau = t\omega_{pe}$, potential $U = e\phi/kT_e$, and distance $Z = z/\lambda_d$. Simulations with different injection rates show that the result is largely insensitive to the value of R_0 as long as $R_0/R_{max} < 1$. Fig. 1 shows the spatial and temporal evolution of the potential in the simulation for $R_0/R_{max} = 0.31$. Between successive panels there is a constant increase in the injected ion density in the centre of the injection region by approximately $\Delta n_i = 1.7n_{e0}$. High potentials are contained in the injection region and show no sign of propagating into the ambient plasma. Consequently there are very strong magnetic-field-aligned electric fields that surround the injected ions. Fig. 2 shows the potential in the centre of the injection region versus the density n_e/n_{e0} . The thin solid line shows the result of the analytical theory (Brenning *et al.*, 1989; Bohm *et al.*, 1990), and the relation between the density and the potential according to the Boltzmann relation $n_e = n_{e0}\exp(eU/kT)$ is shown as a thick solid line. The computer simulation is shown by dots. There is generally fair agreement between the simulation and the analytic theory, which gives:

$$U = \frac{\pi kT_e}{4e} \left(\frac{n_{e,tr.}}{n_{e0}} \right)^2. \quad (1)$$

Here $n_{e,tr.}$ is the density of trapped electrons and T_e and n_{e0} are the electron temperature and the density of the ambient plasma. Our physical understanding of the process is that if the ion density increases by an amount Δn_i then, in order to maintain quasineutrality, a closely equal number of electrons must be trapped from the flow along the magnetic field. The positive potential required to contain these electrons is given by Eq. 1. Notice that neither the length L_{inj} along the magnetic field line nor the rate at which the density increases appear in Eq. 1. This result is confirmed by the computer simulations. The only conditions for applicability of Eq. 1 are that the plasma is collisionless, that the density increase Δn_i ($\approx n_{e,tr.}$) is larger than the ambient plasma density, and that the magnetic-field-aligned electron current density during the trapping process is below the electron saturation current. There is no lower limit to the current density. The electrons' magnetic-field aligned velocity distribution in the centre of the injection region is shown in Fig. 3 (from Bohm *et al.*, 1990). There is approximately a plateau in velocity space up to the velocity

where the electrons have the energy eU . Thus, with U given by Eq. 1, both the potential and the electron distribution are determined by one single parameter, the density increase.

2. Application to the Porcupine experiment

In the Porcupine Xe^+ beam injection experiment (Haerendel and Sagdeev, 1981; Häusler *et al.*, 1982; Häusler *et al.*, 1986) a charge-neutralized Xe^+ beam was injected into the ambient ionosphere from a spinning sub-payload. A sequence of observations at increasing distances were made at the main payload while the sub payload moved away across the magnetic field. We will here use results from intermediate distances, 35 - 172 meters, and will focus on the magnetic-field-aligned electric fields and the variations in the payload potential which were observed associated with the recurring density maxima as the Xe^+ plasma beam swept by the main payload.

Fig. 4 gives data for one second starting at 131 seconds after launch (from Häusler *et al.*, 1986). The top panel shows three and a half successive plasma density maxima as the xenon beam swept past the payload. Panel 2 from the bottom shows the magnetic-field-aligned electric field, which reached typically 50 mV/m in the rising flank of the density. For comparison, we estimate the density increase which would give such a magnetic-field-aligned electric field in the dynamic trapping process by rewriting Eq. 1 into

$$\frac{n_{e,tr.}}{n_{e0}} = \left(\frac{4 e U}{\pi k T_e} \right)^{1/2}. \quad (2)$$

Taking $E_{||} \approx 50$ mV/m and the half-width of the beam to be 37 m, we get a potential $U \approx E_{||} L_{||} \approx 1.8$ V. The ambient electron density was $n_{e0} = 2 \times 10^{11} \text{ m}^{-3}$, and the electron temperature $kT_e = 0.14$ eV (Potelette *et al.*, 1988). With these values, Eq. 2 gives a density of the trapped electrons $n_{e,tr.} = 8 \times 10^{11} \text{ m}^{-3}$ ($8 \times 10^5 \text{ cm}^{-3}$). The agreement between this level and the measured density maxima in the top panel of Fig. 2 is quite good; thus the density increase and the strength of the magnetic-field-aligned electric field are in agreement with the dynamic trapping process. There is however a difference in timing: the electric fields occur mainly in the leading flank of the density maxima. We will discuss this below.

The mechanism of current closure in the xenon beam has been discussed in detail by Häusler *et al* (1986). They conclude that the ions are largely unaffected by the ambient plasma, so that they move as individual test particles with gyro radii of several hundred meters. The xenon ion beam therefore constitutes a region of positive space charge which sweeps around the ion source like a light-house

beacon. In the near zone, closer than 20 m from the source, the azimuthal motion of this positive space charge can be neutralized by azimuthal Bohm diffusion or by Hall drift of the electrons inside the beam (Häusler *et al.*, 1986). Further away from the source, magnetic-field-aligned electron currents from the surrounding ionosphere are required.

There are two main current systems. The first current system is associated with the outwards ion current in the stream: the electrons from the source are stripped off the xenon beam in the near zone and flow out along the magnetic field. The current carried by the xenon ions in the radial direction eventually has to close by attracting electrons from the ionosphere. This current system would probably keep its characteristics even if the source were not rotating. The rotation introduces another current system in the azimuthal direction, which is of primary interest for the discussion here. It is schematically illustrated in Fig. 5: the leading front of the rotating xenon ion beam attracts electrons along the magnetic field lines, which constitute a current sheet extending along the xenon beam. The magnetic field at the passage of the beam (Fig. 4) shows this current. The magnetic signature is that of an upward current sheet corresponding to downward electron fluxes, which agrees with a picture where the main payload is in the upper half of the beam and electrons from the top flow into the beam to charge neutralize the ions (Häusler *et al.*, 1986).

Consider the situation along a magnetic field line which sees the arrival of the rotating xenon beam, e. g. at the time interval 100-150 ms in Fig. 4. During this time the ion density increases by a factor 4 and ambient electrons flow in along the magnetic field to maintain space charge neutrality. As shown above, the magnetic-field-aligned electric field has a strength which is consistent with the dynamic trapping mechanism. Also the direction of the field is correct: according to Potelette *et al.* (1988) it corresponds to an excess positive charge in the region in the front of the xenon beam. Thus, all the requirements for the dynamic trapping mechanism are here. Ion motion across the magnetic field builds up a density much exceeding the ambient density, charge neutrality is maintained by electron flow along the magnetic field, and the magnetic-field-aligned electric field has the correct strength and direction. In fact, the dynamic trapping mechanism could help to explain the observations: Häusler *et al.* (1986) point out that there is a problem to trap the electrons at the positive space charge since the classical cross section for these ionospheric electrons is too small to trap them effectively in a narrow beam such as the near zone xenon ion beam.

If the dynamic trapping mechanism really is operating here, it should be associated with the characteristic parallel electron distribution of Fig. 3, with high magnetic-field-aligned fluxes $F_{e//}$ up to energies $W_e \approx U/e$. Unfortunately, the measurements of $F_{e//}$ in the Xe^+ beam by RPA:s (Retarding Potential Analyzers) are uncertain because the interpretation requires knowledge of

the payload potential U_p which was measured only sporadically as can be seen in the bottom panel of Fig. 4. Furthermore, U_p varied rapidly when the xenon beam hit the payload, *i.e.* precisely at the time when the RPA:s should measure the enhanced electron fluxes. However, the payload potential U_p gives indirect evidence concerning the electron distribution which can be extracted by the following argument. The payload has a floating potential $U_{p0} \approx -1.3$ V in the undisturbed plasma. In the presence of the electron distribution of the dynamic trapping process, the floating payload has to take on an additional negative potential so that $U_p \approx U_{p0} - U$ in order to repel all except the most energetic electrons. With U calculated from Eq. 1, this potential becomes

$$U_p = U_{p0} - \frac{\pi k T_e}{4 e} \left(\frac{n_e - n_{e0}}{n_{e0}} \right)^2 \quad (3)$$

where we have approximated the trapped electron density with $n_e - n_{e0}$. The value from Eq. 3 is in Porcupine completely determined by the measured density increase. It is compared to the measured values in Figures 6a, 6b and 6c. The top panel in each figure shows the measured density n_e and the second panel the floating potential during the sporadic times it was measured. The dotted line in the third panel shows the potential U_p from Eq. 3 calculated using the measured density in the top panel. The measured U_p is repeated for reference. There is quite good agreement, particularly with respect to the amplitude of the U_p variations. Notice particularly that U_p is almost constant in Fig. 6c where the xenon ion beam density is smallest, which can be understood from the quadratic dependence of U_p on $(n_e - n_{e0})$ in Eq. 3. It is also worth noting that Eq. 3 explains the negative sign of $(U_p - U_{p0})$, which is a somewhat surprising result since the payload is hit by an energetic (200 eV) ion beam. If the electron energy distribution were unchanged, $(U_p - U_{p0})$ would become more positive in response to the enhanced ion current.

3. Discussion

The magnetic-field-aligned electric field in the Porcupine experiment has earlier been analyzed by Potelette *et al.* (1988). Although they discuss the Porcupine flight F3 and the data here was taken from flight F4, these two flights show the same overall results and the same processes should have been operating. Potelette *et al.* (1988) have concentrated on the features around a plasma density minimum which develops ahead of the rotating xenon beam at distances such that the azimuthal xenon beam velocity becomes comparable to the ion acoustic velocity of the background plasma. They interpret this feature and the wave activity around it as the result of an ion acoustic electrostatic shock. We have no argument against this interpretation, but rather feel that the two explanations support each other. For example, the ion acoustic shock model cannot explain all the magnetic-field-aligned electric fields because these are observed also where the rotation velocity

does not match the ion acoustic velocity, at these distances without the ion acoustic shock. Possibly the potential structure is maintained by the dynamic trapping process, and excites the shock only where the velocities match. This interpretation is actually quite close to the description of the phenomenon by Potelette *et al* (1988) who describe the beam region as a region of enhanced electrostatic potential which accelerates and reflects the background ions in all directions so that a reflected ion beam is created, and argue that the shock is formed when the velocity of the beam is of the same order of magnitude as the phase velocity of the background oxygen ion acoustic waves.

The magnetic-field-aligned electric fields in Fig. 4 are seen mainly in the rising flank of the ion density, while the dynamic trapping mechanism as treated here would predict that these two quantities follow each other both in the rising and in the falling flank. We can see two possible reasons for this. One is that collisions would scatter in pitch angle both the trapped electrons and the electrons in the magnetic-field-aligned flow from the ambient ionosphere. Both types of scattering would tend to decrease the positive potential which has been build up by the dynamic trapping process during the time of density increase. The situation is analogous to blowing up a balloon with a leak: by blowing fast enough one can inflate the balloon in spite of the leak, but as soon as one stops blowing it begins to shrink. The electron-neutral collision time at the altitude of Fig. 4, 220 km, is about 10 ms for 1 eV electrons and longer for lower energies. Although this is far too long to trap an ambient electron during a single transit through the xenon ion beam along the magnetic field (0.1 - 0.4 ms), the trapped electrons would stay inside the xenon beam for 50-100 ms and would be affected. The other possible reason for the time shift between the density and the potential has to do with the ion acoustic shock of Potelette *et al.* (1988). In the F3 flight which they study, the magnetic-field-aligned electric fields actually sometimes coincide with a density minimum ahead of the xenon beam. This is very difficult to reconcile with the dynamic trapping mechanism alone, where the strongest magnetic-field-aligned electric fields should fall at the density maximum. However it could be the result if an ion acoustic shock wave mixes with the dynamic trapping process.

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Fig. 1. The potential in the simulation region at different time steps, in normalized units: time $\tau = t\omega_{pe}$, potential $U = e\phi/kT_e$, and distance $Z = z/\lambda_d$.

Fig. 2. The potential $U = e\Phi/kT_e$ versus n_e/n_{e0} , in the centre of the injection region.

Fig. 3. The magnetic-field aligned velocity distribution of the electrons in the centre of the injection region.

Fig. 4. Data from one second of the Porcupine xenon beam injection experiment (from Häusler *et al.*, 1986).

Fig. 5. The current sheath to the positive space charge at the leading flank of the rotating xenon beam in Porcupine.

Fig. 6. A comparison between the observed floating payload potential U_P in Porcupine and that expected from the dynamic trapping mechanism. (a) Time After Launch (TAL) = 127 sec. (b) TAL = 131 sec. (c) TAL = 164 sec. In each figure the upper panel shows the measured density, the second panel shows the measured U_P , and the third panel shows the value of U_P according to Eq. 3.

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Key words: Electron Trapping, Non-Neutral Plasmas, Magnetic-Field-Aligned Electric Fields.