POLAR CAP PARTICLE ACCELERATION : ELECTRON DYNAMICS ASSOCIATED WITH ION OUTFLOWS

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ABSTRACT

During periods of northward Interplanetary Magnetic field (IMF), Cluster observed outflowing ion beams at altitudes of 5-7 terrestrial radii above the polar cap. These ions, accelerated at energies of the order of 200 eV to 1 keV, form energy structures with typical inverted-V shapes as already observed in auroral zone. The associated electron distribution shows two different behaviours.

During ion outflow events, downgoing electrons are accelerated at energies of the order of 200 – 300 eV. The simultaneous acceleration of the ions in the upward direction and of the electrons in the downward direction is interpreted as the effect of a quasi-static potential drop along polar cap magnetic field lines. This potential structure is not localized near the topside of the ionosphere as generally inferred in auroral zone from lower altitude satellites. It rather extends to higher altitudes than Cluster orbit (more than 5 Earth radii for the considered events). Its life time may exceed half an hour which implies that the polar ionosphere represents a significant particle source for the magnetosphere.

Between the ion outflow structures, upward electron beams are accelerated at low energies (30-100 eV). These low-energy beams carry current densities of the order 10 nA/m², corresponding to a few µA/m² at ionospheric altitudes, which balance the currents carried by the surrounding regions involving ion outflows. During northward IMF periods, the polar cap current system appears to be structured in successive current sheets of opposite polarities.

1. INTRODUCTION

Since the first observations of ionospheric ions accelerated at plasma sheet energies in the magnetosphere [1], the ionosphere has been recognized as a major plasma source for the magnetosphere. Various processes have been identified at high latitudes leading to the polar wind, the cleft ion fountain, ion conics and beams above the auroral regions ([2], [3]).

On another hand, other studies focused on the high-latitude electron characteristics and mostly on the various types of auroral precipitation. The presence of electron precipitation inside the polar cap was first reported in [4]. Subsequent statistical studies exhibited various classes of polar precipitations and outline their dependence on the orientation of the interplanetary magnetic field (IMF): polar rain with weak and nearly isotropic fluxes, polar shower with structured, localized and intense fluxes, stable structures of polar cap arcs. These polar precipitations strongly depend on the orientation of the magnetic field and in particular the northward component of Interplanetary Magnetic field (IMF) plays an important role ([5], [6], [7]).

The polar cap ion outflows also depend on the IMF orientation. The local presence of outflowing ion beams has recently been reported from Cluster observations at several Earth radii above the polar cap and during periods of northward IMF [8]. In the present paper, we use Cluster observations to investigate the electron dynamics correlated to these polar cap events of outflowing ion beams during northward IMF conditions.

2. OBSERVATIONS

The Cluster mission has been launched in 2000 on a polar orbit around the Earth with a perigee and apogee respectively at 4 and 19 Earth radii [9]. It consists of 4 satellites designed to form a regular tetrahedron in key regions along the orbit such as the magnetotail current sheet, the cusps, the magnetopause crossing, ..

We mainly use particle data. The Plasma Electron And Current Experiment (PEACE) consists of 2 instruments, the Low-Energy Electron Analyser (LEEA) and the High-Energy Electron Analyser (HEEA), located on opposite sides onboard the spacecraft. A detailed description can be found in [10]. The Cluster Ion Spectrometers (CIS) also consist of two instruments, one devoted to the mass spectrometry (CODIF) and the other one to high angular and energy resolutions (HIA) [11].

We review a typical example of polar cap ion outflows, discussed in [8]. The two top panels in Fig. 1 represent the ion pitch-angle distribution and energy fluxes for a time period of 45 min on May 18, 2003. Two main structures of nearly field-aligned outflowing ion beams (pitch-angles around 180°) are observed with typical inverted-V energy signatures around 11:10 - 11:15 UT

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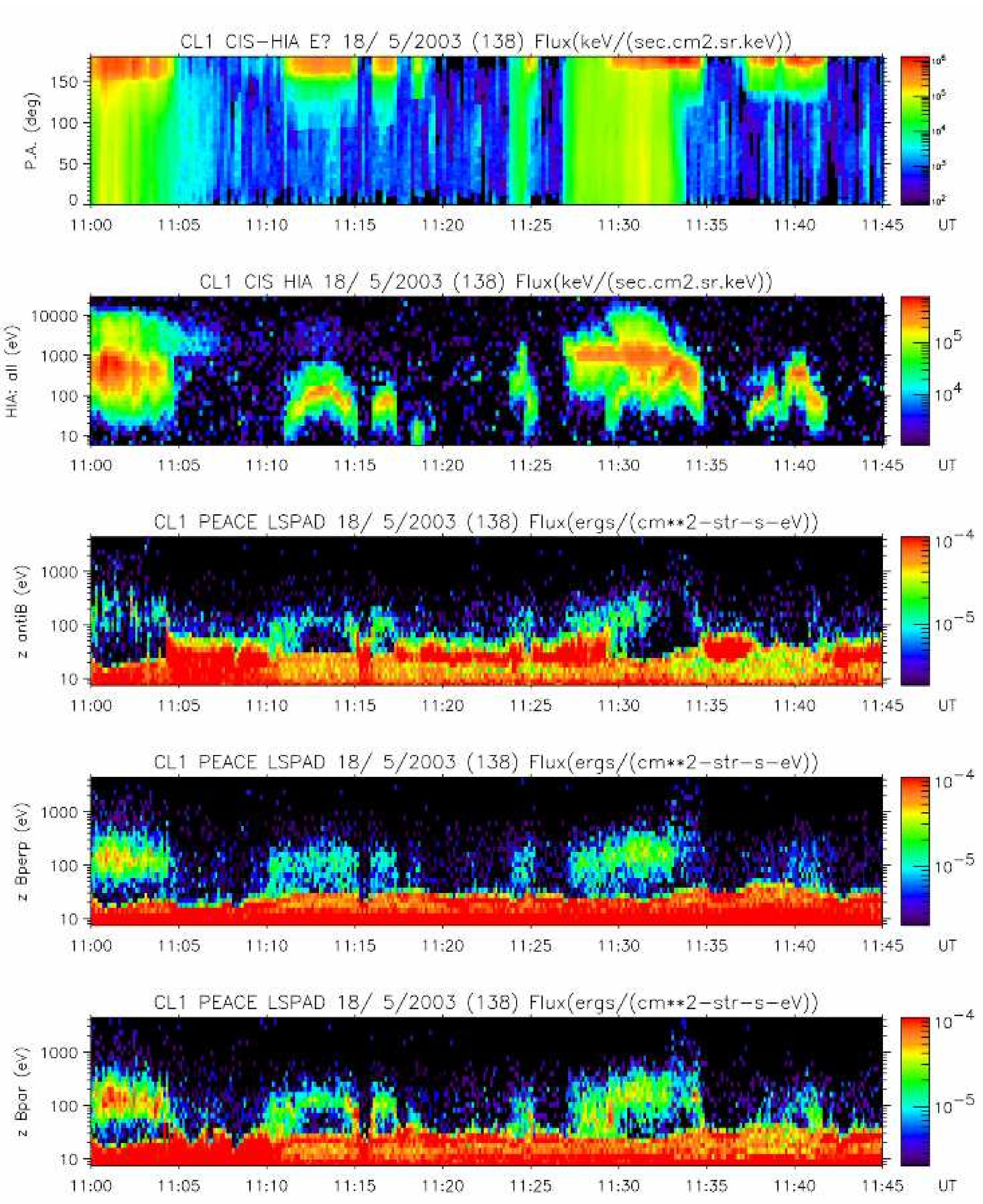

Fig. 1. Panels 1 and 2 represent the ion pitch-angle distribution and energy fluxes. Panels 3, 4, 5 represent the electron energy fluxes in three directions, parallel to the magnetic field lines in the upward direction (labelled antiB), perpendicular to them and parallel to the magnetic field lines in the downward direction (labelled Bpar).

and 11:30 - 11:35 UT. Smaller structures also exist during the whole period. The peak energy of the ion outflows vary between about 100 eV for the first main beam and up to 800 eV for the second main one. Such beams are also observed in the auroral zone; they are generally interpreted as the acceleration of ionospheric ions by a quasi-static potential drop below the spacecraft [12, 13]. Onboard Cluster, the Electron Drift Instrument (EDI) provides the electric field component perpendicular to the magnetic field [14]. Reference [8] has demonstrated that the ion energy gain was consistent with the potential drop below the spacecraft inferred from EDI observations of converging electric fields along the spacecraft path.

We now turn to the electron distribution. In a first approach, the presence of an electric field below the spacecraft in the upward direction should prevent the outflowing electrons from reaching the spacecraft, except if they have a larger energy than the energy corresponding to the potential drop. The distribution of the downgoing electrons should remain unchanged because they have not yet experienced the potential drop below the spacecraft.

The three bottom panels represent the electron energy fluxes observed during the ion outflow events in three directions, successively parallel to the magnetic field B in the upward direction, perpendicular and parallel to B in the downward direction. The low energy strip (below about 30 eV) should be discarded because it is contaminated by the photoelectrons surrounding the satellite body. The upward fluxes present holes at low energy levels, below 100 eV for the first main event and below 800 eV for the second one, i.e. over a large part of the energy range. This absence of upgoing electrons at low energy confirms the existence below the spacecraft of a potential drop that accelerates the ions and prevents the electrons from reaching the spacecraft. Moreover, the downgoing distribution (bottom panel) exhibits enhanced fluxes around 100 to 300 eV for all events. This can be simply explained by an extension of the already mentioned potential drop below the spacecraft to higher altitudes than the spacecraft orbit. This additional potential drop can then accelerate the electrons coming from a distant source above the spacecraft. Fig. 2 shows the potential drop above Cluster inferred from the downgoing electrons (red line) by comparison to the potential below the spacecraft inferred from the upflowing ions (black line). Its values vary smoothly and remain in the same range between 100 V and 300 V; they can be comparable to the potential below Cluster (first main structure) or much weaker (second one). Both potential estimates give access to the total potential drop along the magnetic field line. It ranges between about 300 V up to 800 V, remain constant during the structure crossing (first structure) or not (second one).

In summary, over the polar cap during northward IMF conditions, we observed outflowing ion beams of ionospheric origin which are accelerated by an upward electric field aligned along the magnetic field lines, similarly to the auroral zone. The simultaneous observation of electron beams accelerated in the downward direction suggests that the acceleration region extends to larger altitudes than CLUSER orbit, up to more than 5 Earth radii in this case. This differs from the ion auroral acceleration which is generally predicted to be localized at low altitudes above the ionosphere. Finally, the energy gain of the upflowing ions due to the acceleration region below the spacecraft and of the downgoing electrons above the spacecraft allow to estimate a total potential drop along polar cap magnetic field lines. For all studied events, as for the one illustrated in Fig. 2, the total potential drop generally ranges between a few hundreds of eV up to 1 keV [8].

3. DYNAMICS OF THE ACCELERATION STRUCTURES

These acceleration structures involve field-aligned processes along the whole magnetic field line or at least over a large part of it. The spatial and temporal scales in the parallel direction are respectively much larger and faster than in the perpendicular one. The global dynamics in the direction perpendicular to B and the life time of these structures can be inferred from observations onboard the 4 satellites.

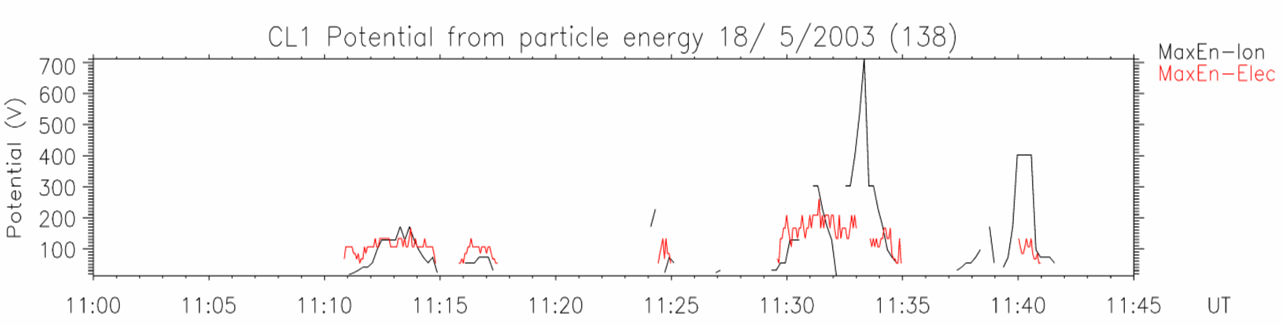

Fig. 2. Estimate of the potential drop below the spacecraft from the accelerated ions in the upward direction (black line) and of the potential drop above the spacecraft electron accelerated electrons in the downward direction (red lone).

Fig. 3 shows the electron spectrograms in the downward direction observed onboard the 4 spacecraft between 10:30 UT and 12:10 UT on May 18, 2003. At the beginning of the time period, all spacecraft detect first electrons from the plasmasheet boundary layer with large fluxes around 100 eV. Then they come over the polar cap and the fluxes become very weak except when they cross acceleration structures. Cluster 3 spectrogram looks different from the others for 2 reasons. The experiment of Active Spacecraft Potential Control (ASPOC) is operating on Cluster-3 [15] and cancels out the contribution of the photoelectrons detected onboard the other satellites up to 30 eV over the polar cap. Secondly, the configuration of the 4 satellites is distorted relative to a regular tetrahedron. Cluster 3 is separated by a larger distance from the other ones (~ 1.4 Earth radii) which are closer to each other (0.4 Earth radii) and thus crosses the same regions with a delay of about half an hour. For example, the last acceleration structure encountered by Cluster-3 just before 12:00 UT (red arrow) is first detected more than half an hour earlier by Cluster-2 at 11:24 UT, by Cluster-4 near 11:26 UT and by Cluster-1 after 11:30 UT. This leads to conclude that such acceleration structures can persist for time periods of the order of half an hour.

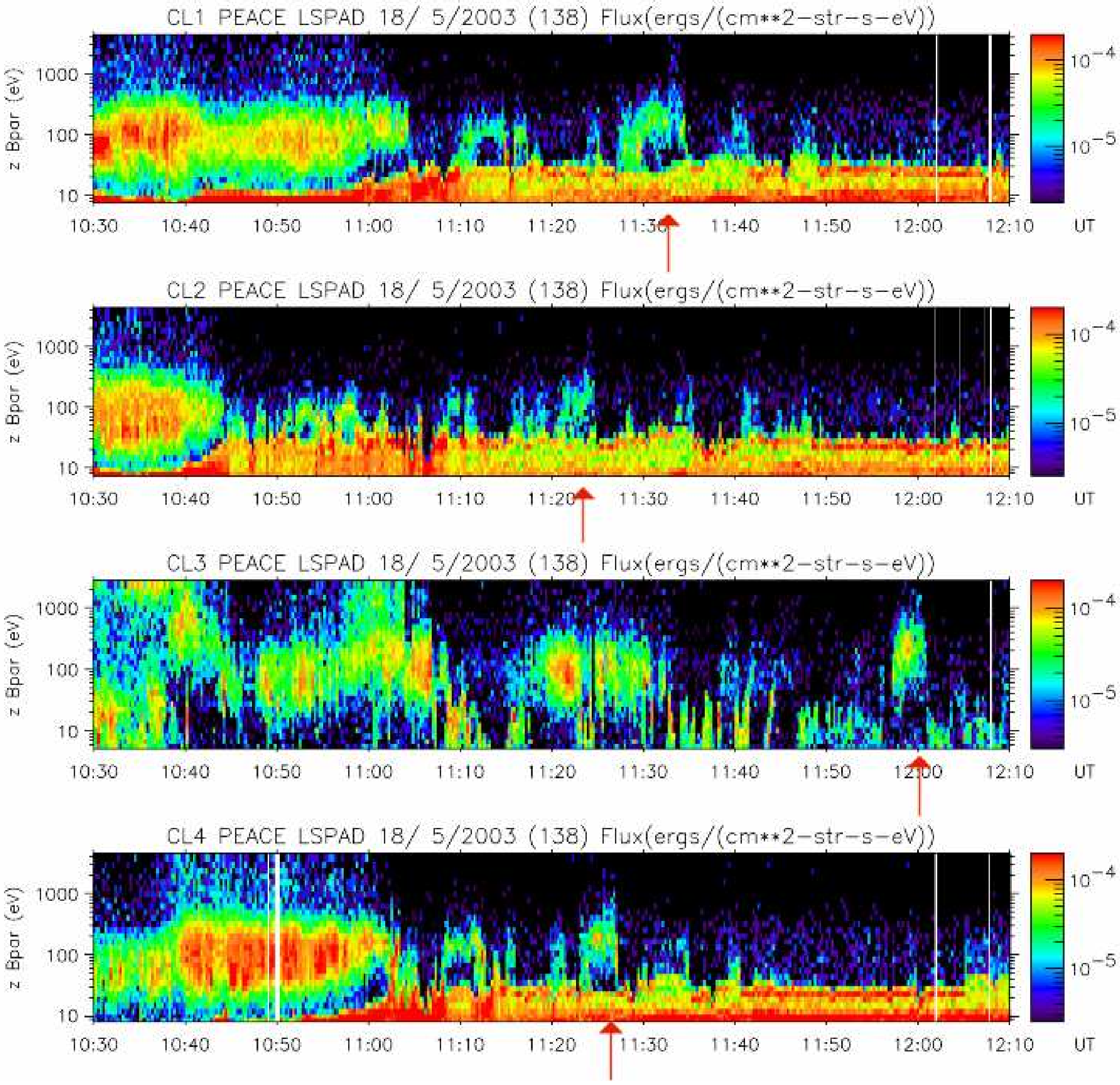

Fig. 3. Electron spectrograms in the downward direction observed onboard the 4 spacecraft between 10:30 UT and 12:10 UT on May 18th, 2003.

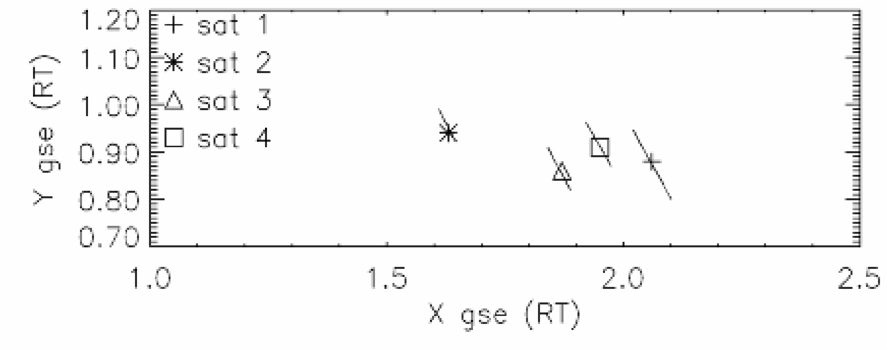

Fig. 4. : Mapping of the structure crossing by each satellite in the GSE plane (X,Y) (approximately perpendicular the magnetic field).

At this time, the magnetic field measured onboard the spacecraft is approximately aligned along the Z-axis in the GSE coordinate system. In order to investigate the global dynamics of the acceleration structure perpendicularly to the magnetic field, we map its crossing by each spacecraft into the GSE (X,Y) plane which is approximately the plane perpendicular to B. This is illustrated in Fig. 4. Although the time delay between Cluster 3 and Cluster 4 exceeds half an hour, they cross the structure at a very close location. This suggests that the acceleration structure has persisted at a quasi-steady location for more than half an hour. Considering all 4 spacecraft, the locations of their respective crossing suggest that the structure has a narrow perpendicular size in the Y-direction and an elongated one in the X-direction (at least more than 0.5 Earth radii).

The orientation and life time of these electron precipitation structures detected at high altitudes (~5 Earth radii) are comparable to the characteristics of stable sun-aligned arcs observed in the polar cap ionosphere and precisely during northward IMF conditions [7].

4. ELECTRON OUTFLOWS AND CURRENTS

The lowest energy range of the electron spectrograms in Fig. 1 is polluted by photoelectrons. However, a detailed analysis of the fluxes reveals large fluxes exactly between the outflowing ion structures and only in the upward direction (anti-parallel to B) in the range 30-50 eV just at the top of the photoelectron level. It should be mentioned that the energy corresponding to these high fluxes exceeds the spacecraft potential (not shown here). Usually quite large over the polar cap due to low plasma densities, the spacecraft potential precisely decreases in presence of these larges fluxes. The presence of large upward fluxes between the ion acceleration structures is quite systematic over the polar cap during northward IMF conditions. Such large upward fluxes at low energy carry significant downward currents. Finally, the polar cap appears structured with successive sheets of upflowing ions and electrons, carrying successive currents of opposite polarities.

A quantitative estimate of the current densities requires either the acceleration of electron fluxes at higher energies in order to properly separate the electron outflows from the photoelectron range, or the operation of the instrument ASPOC which controls the spacecraft potential and reduces the photoelectron effects. From the analysis of several cases, the current density carried by the upward electron fluxes is typically estimated to about 10 nA/m² at 5 – 7 Re altitude above the polar cap, which corresponds to a few µA/m² at ionospheric altitudes [16]. These values exceed by more than one order of magnitude the current carried by the adjacent regions of ions outflows and electron precipitation, but conversely, their width is much more narrow. Both effects almost compensate each other. Finally, the current intensities estimated by integration over the width of each sheet balance each other at values of the order of 1. mA/m [16].

5. CONCLUSION

During periods of northward IMF, at 5-7 Re altitude above the polar cap, Cluster observed structures of outflowing ion beams. These structures have a typical energy shape in inverted-V. Similarly to the auroral zone, this energy structure has been found to be consistent with the energy gained by ionospheric ions in presence of an upward electric field resulting from a quasi-static field-aligned potential drop below the spacecraft. We have then investigated the electron dynamics during these events. They have two types of behaviours.

The first one concerns accelerated electrons at energies of the order of 200 – 300 eV simultaneously observed during the events of accelerated outflowing ions, but in the downward direction. This electron downward acceleration is suggested to result from the presence of a potential drop located above the spacecraft. This leads to conclude that, along polar cap magnetic field lines, the potential drop accelerating the ionospheric ions is not restricted to a localized region at the top of the ionosphere, as expected above the auroral zone. On the contrary, it should extend to large distances along magnetic field lines exceeding the spacecraft altitude (5-7 Re).

In addition, these acceleration structures may persist at the same location over time periods exceeding half an hour, which represents a significant particle supply from the ionosphere toward the magnetosphere. Their size estimated from the 4 spacecraft observations is narrow in the Y-direction and elongated in the X-direction in the GSE coordinate system. These are the characteristics expected for sun-aligned arcs observed in the ionosphere for periods of northward IMF.

The second effect is the presence of electron beams, accelerated in the upward direction up to typical energies of the order of 30 – 100 eV and located just between the ion outflowing structures. During northward IMF conditions successive ion and electron outflows escape from the polar cap ionosphere. These electron outflowing beams carry current densities much larger than the ion outflows. However, when integrated over their respective sheet width, both contributions are comparable. During periods of northward IMF, the polar current system appears to be structured in current sheets of opposite polarities, carried by outflowing particles, either ions or electrons.

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