CLUSTER observations of electrostatic acceleration structures above the polar cap and implications for their origin in the magnetopause boundary layer

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Abstract

During quiet periods of Northward IMF, CLUSTER observed electron acceleration structures at high altitudes along magnetic field lines connected to the polar and extended along the magnetopause boundary layers. The electrons are observed to be successively earthward and outward accelerated, forming current sheets of opposite polarities. The precipitating electrons are accelerated to keV-energies in relatively stable and broad structures. The outflowing electron beams, accelerated to weaker energies (tens of eV), form structures at much smaller scales. These acceleration structures are suggested to result from electrostatic structures generated at the interface between the magnetopause boundary layers and the lobes.

1. Introduction

First statistics of polar cap arcs from observations at low altitude revealed their occurrence mostly during periods of northward Interplanetary Magnetic Field (IMF) [1-2]. Polar cap arcs are formed by electron precipitations at energies of the order of 1 keV, organized in narrow structures often extended near the sun-aligned direction. There is no consensus on their origin and several assumptions are considered. For some authors, polar cap arcs could be considered as a polar extension of the auroral oval, due to the precipitation of plasmasheet electrons accelerated by electrostatic structures as auroral arcs [3-4]. For others, the origin region is suggested to be the plasmasheet boundary layer or the magnetopause boundary layers, connected to the polar cap by open or closed magnetic field lines, which is another debated issue. Finally, the acceleration processes involve different acceleration processes from quasi-steady electrostatic potential structures to wave-particle interactions [5].

In this paper, we present electron precipitation events observed by CLUSTER at high altitudes, 5 to 10 Earth's radii above the polar cap, and we discuss the implications concerning their source region and the acceleration processes.

2. Observations

During periods of northward Interplanetary Magnetic field (IMF), CLUSTER observes precipitating electron structures accelerated at energies of the order of 200 – 300 eV. An example from the experiment PEACE onboard CLUSTER is given in Figure 1: the bottom panel presents the precipitating fluxes (i.e. in the downward direction) of such electron precipitation structures, observed around 11:10 - 11:15 UT and 11:30 – 11:35 UT on May 18th, 2003, at about 7 terrestrial radii above the polar cap. The 3rd panel shows that the fluxes in the upward direction cancel out.

The electron precipitation structures are accompanied by ions beams observed by the experiment CIS onboard CLUSTER, accelerated at energies of the order of 200 eV to 1 keV, and forming energy structures with typical inverted-V shapes as already observed in auroral zone (see second panel). The first panel shows that these beams are directed in the upward direction, thus escaping the ionosphere, and some of them are embedded in an isotropic background plasma as for instance for the structure at 11:30 – 11:35 UT. As shown in [6], the ion acceleration is correlated with the presence of a bipolar structure in the observed electric field. Moreover they found that the ion energy gain is consistent with the potential drop inferred by integration of the electric field along the orbit, which suggested that the ions were accelerated upward by electrostatic electric fields located below the spacecraft, similarly to the auroral zone.

The precipitating electron acceleration in the downward direction, mentioned above, is interpreted similarly, as the acceleration by a field-aligned potential drop located this time above the spacecraft. The simultaneous acceleration of the ions in the upward direction and of the electrons in the downward direction gives an order of magnitude of the total quasi-static potential drop along polar cap magnetic field lines, estimated

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to vary between 600 V and 1 kV for this structure. This potential structure is not localized near the topside of the ionosphere as generally inferred in auroral zone from observations by low-altitude satellites. It rather extends to higher altitudes than Cluster orbit (more than 7 Earth radii for the considered events). Its life time may exceed half an hour which suggests a quasi-stationary structure [7].

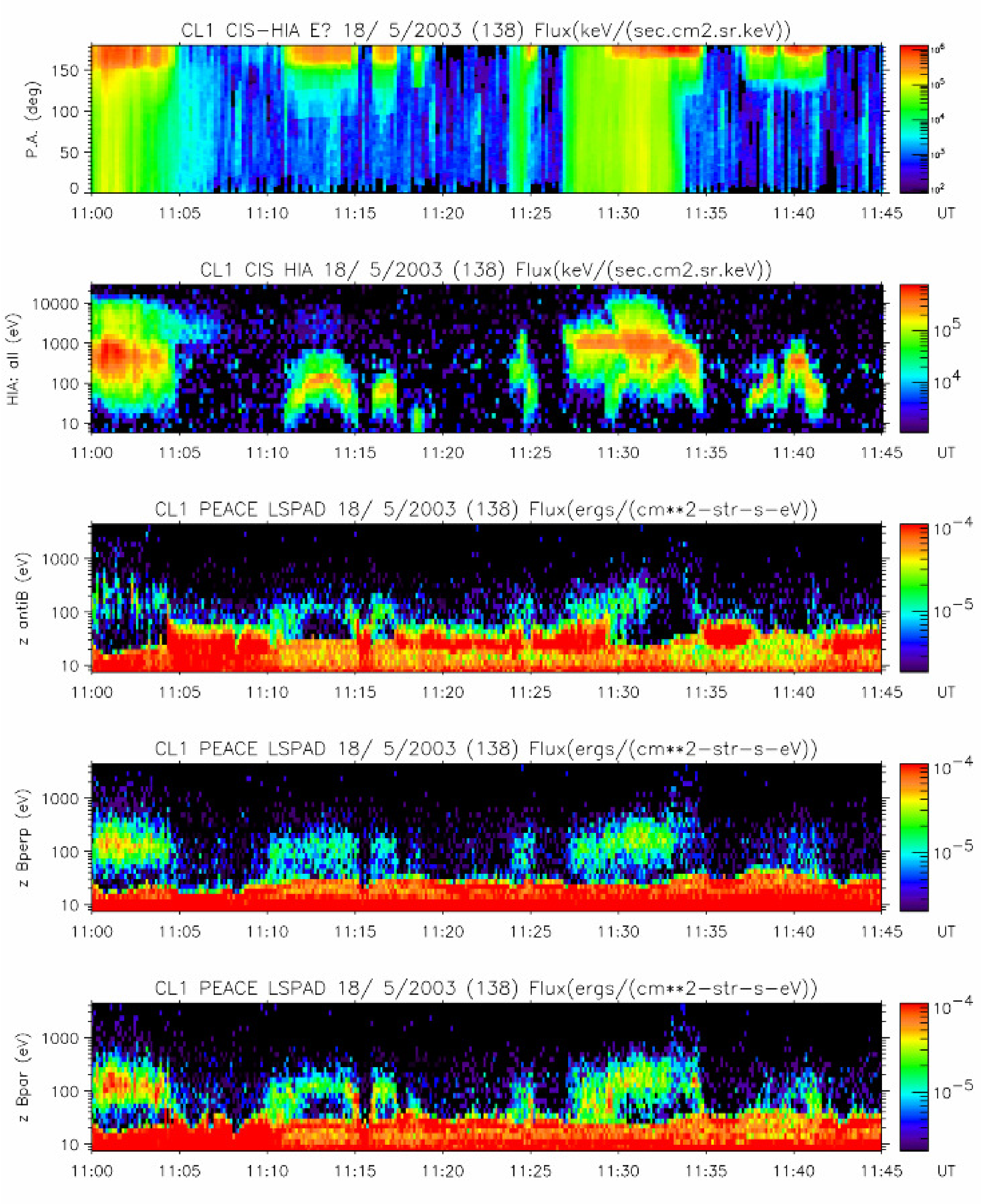

Figure 1: Top panel: pitch-angle distribution of outflowing ion fluxes observed on May 18th, 2003 and their energy distribution (2nd panel). Electron fluxes observed : in the upward direction (3rd panel), perpendicular direction (4th panel) and downward direction (precipitations) (bottom panel).

Between these accelerated structures of electron precipitation and of ion outflow structures, upward electron beams are observed accelerated at low energies (30-100 eV). Their fluxes are both very large and variable, and extremely well collimated along magnetic field lines. In the case of examples shown in Figure 1 (middle panel), they appear just at the top of the photoelectron strip. The outflowing low-energy beams presented in these examples cannot be properly studied because they are not well separated from the photoelectron energies. A statistical study preformed on better identified cases showed that these outflowing low-energy electron beams are extremely well correlated with broadband electrostatic emissions (0-6 kHz) simultaneously observed by the wave experiment WHISPER onboard CLUSTER [8]. It concluded that these electron beams are likely to destabilize Langmuir waves and, by the non-linear evolution of the electron bump-on-tail instability, could be responsible for the appearance of electrostatic solitary waves above the polar cap.

Finally, the electric current estimations by showed that these low-energy beams carry current densities of the order 10 nA/m², corresponding to a few µA/m² at ionospheric altitudes [9]. They also showed that they balance the currents carried by the surrounding regions involving electron precipitation and ion outflows. Finally, during northward IMF periods, the polar cap current system appears to be structured in successive current sheets of opposite polarities. A quasi-steady current sheet is formed by precipitating electrons (at keV-energies when they reach the ionosphere) and outflowing ion beams. This current closes through the ionosphere through a small-scale return current, very variable and intense, mostly carried by outflowing low-energy electron beams, correlated with small-scale electrostatic structures.

3. Implications for the origin of the precipitating keV -electrons

Polar cap arcs appear predominantly during periods of quiet and northward IMF. In such situations, Tsyganenko's magnetic field model provides good estimates for the geometry of the magnetic field lines. In the case of our electron acceleration structures, it predicts that the magnetic field lines are open and that they extend through the tail at the vicinity of the magnetopause. In addition, following [Chiu and Schulz (1978)], we have developed a model of transport along the magnetic field lines conserving the adiabatic invariants in order to estimate the initial characteristics of the plasma before its acceleration and detection by CLUSTER. We proceeded backward from the observed distribution functions of precipitating electrons and using CLUSTER potential drop estimations above the spacecraft, to determine the distribution function of these electrons beyond the acceleration region. We found that they came from a source with densities of the order of 0.1 cm^{-3} and temperatures of the order of 100 eV. These orders of magnitudes are typical of the boundary layers at high-latitude along the magnetopause flanks, which meets the predicted configuration along the magnetopause for the magnetic field lines [10-11].

4. Discussions and conclusion

During quiet periods of Northward IMF, CLUSTER observed electron acceleration structures at high altitudes above the polar cap. The electrons are observed to be successively earthward and outward accelerated, forming current sheets of opposite polarities. The precipitating electrons are accelerated to keV-energies in relatively stable and broad structures. The outflowing electron beams, accelerated to weaker energies (tens of eV), form structures at much smaller scales and contribute to close the current carried by the precipitation flux. They are well correlated with broadband electrostatic emissions, and it is suggested that they are accelerated by small-scale electrostatic structures. The source of the precipitating electron is expected to be in the high-altitude boundary layers, as predicted from a transport model along magnetic field lines. Finally, it is suggested that these acceleration structures could result from electrostatic potentials generated at the interface between the magnetopause boundary layers and the lobes [12-13].

5. References

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