CLUSTER OBSERVATIONS OF THE ELECTRON EDGE OF THE LOW-LATITUDE BOUNDARY LAYER AT MID-ALTITUDES.

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ABSTRACT

The nature of the particle precipitations at dayside mid-altitudes can be interpreted in terms of evolution of reconnected field lines. Due to the difference between electron and ion parallel velocities, two distinctive boundary layers should be observed at mid-altitudes between the open-closed boundary and the injections in the cusp proper. The first layer, the electron-dominated boundary layer, named the electron edge of the Low-Latitude Boundary Layer (LLBL), consists of soft magnetosheath electrons and high-energy plasma sheet ions. The second layer, the LLBL proper, is a mixture of both ions and electrons with magnetosheath energies. The Cluster spacecraft frequently observe these boundary layers. We present one example of a mid-altitude cusp crossing with an extended electron edge of the LLBL. This electron edge contains 10-200 eV low-density isotropic electrons presumably from the halo solar wind source and parallel and/or anti-parallel electron beams with higher fluxes accelerated presumably near the magnetopause X-line. We have used 3 years of data of mid-altitude cusp crossings to carry out a statistical study of the location and size of this electron edge of the LLBL. The electron edge size has been estimated using new multi-spacecraft techniques. The Cluster tetrahedron crossed electron and ion boundaries of the LLBL/cusp with time delays of 1-40 minutes, so we can reconstruct the motion of the electron boundary between different spacecraft observations and improve the accuracy of the estimation of the boundary layer size. Our study shows that the electron edge was observed in 87% of mid-altitude cusp crossings by Cluster. The size of this region varied between 0°-2° Invariant Latitude (ILAT) with a median value of 0.2° ILAT. Generally the size of the electron edge depends on the combination of many parameters, but we have found anti-correlation between the size of this region and the magnitude of the IMF and solar wind dynamic pressure, as expected from a simple reconnection model.

1. INTRODUCTION

Reconnection between terrestrial magnetic field lines and the interplanetary magnetic field (IMF) is responsible for the penetration of the solar wind plasma into the magnetosphere [e.g. 1, 2]. Under southward B_Z, IMF field lines will reconnect at the sub-solar point and will convect anti-sunward, forming a cusp region. At mid-altitudes (5-7 R_E) time-of-flight effects for particles injected by sub-solar reconnection will define typical cusp signatures [3] such as energy-latitude dispersion and low-energy cut-off in the energy-time ion spectrogram.

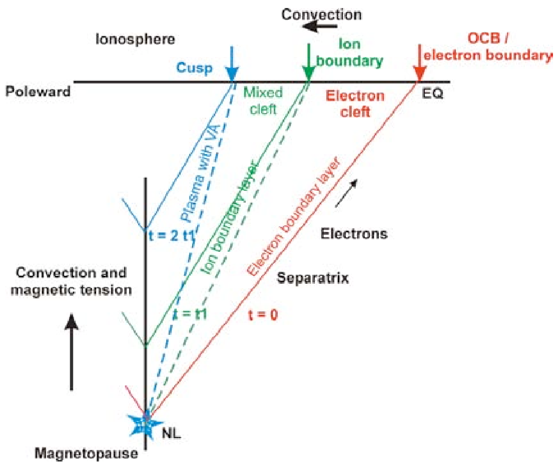

Fig.1. Sketch of the different regions of plasma injections from dayside reconnection (see discussion in the text).

However, before crossing the cusp proper, any low- or mid-altitude satellite should cross two boundary layers with different plasma properties, both originated from the magnetic dayside reconnection [4, 5]. Figure 1 shows a simplified sketch of the evolution of magnetic field lines following reconnection and the corresponding plasma regions in the mid-altitudes or ionosphere. The most recent reconnected field line (red line on fig. 1) corresponds to the separatrix or Open-Closed Boundary (OCB) between closed terrestrial field lines and magnetosheath field lines. Along this field line (or

Proceedings Cluster and Double Star Symposium – 5th Anniversary of Cluster in Space, Noordwijk, The Netherlands, 19 - 23 September 2005 (ESA SP-598, January 2006)

OCB) electrons will move with very high velocity [4] and arrive into the ionosphere almost immediately after the field lines become open. Arrival of magnetosheath-like electrons will therefore mark the electron boundary of the Low-Latitude Boundary Layer (LLBL) [5, 6]. Due to the difference between ion and electron velocities, the most energetic ions will arrive at mid-altitudes with significant delay (estimated to be up to 12 minutes in [7]). The part of the LLBL containing magnetosheath-like electrons and only magnetospheric-type ions is named the electron edge of the LLBL [5, 7, 8]. Arrival of energetic ions at low altitudes will mark the ion boundary of the LLBL [5]. Ions observed inside the LLBL proper are more energetic and less dense than ions observed in the cusp proper [9]. Finally, the plasma bulk flow moving with Alfvén velocity will arrive at the mid- and low-altitudes and form the cusp region. While the plasma properties inside the LLBL and the cusp proper as well as statistical properties of the LLBL and cusp regions have been extensively studied [3, 9-20], the electron edge of the LLBL containing only magnetosheath-like electrons is not a very well-studied region.

Wing et al [21, 22] modelled the penetration of the magnetosheath electrons into the low altitudes and compared results from models with the DMSP observations. It was shown that the parallel electric field between the magnetopause and the low-altitudes should exist in order to model the observed population. This electric field prevents penetration of the solar wind electrons ahead of ions and conserves the quasi-neutrality of plasma. However, the suprathermal halo part of the solar wind will not be stopped by this parallel electric field and may penetrate into the low-altitudes, and therefore should be detected by low- and mid-altitude satellites on open field lines inside the LLBL, the mantle and the polar cap.

So far there has been only one attempt to study the electron edge of the LLBL existing near the equatorward boundary of the cusp and containing the halo part of the solar wind population [7]. However, Topliss et al. found only 6 events with a clear electron edge out of 200 cusp crossings by the Polar spacecraft. The Cluster spacecraft cross the mid-altitude cusp region of the Northern hemisphere from the dayside to nightside and often detect such an electron edge of the LLBL. The aim of this work is to perform a statistical study of this part of the LLBL and to examine how the size of this region depends on different external parameters.

The manuscript is organised as follow: section 2 gives a description of instruments, section 3 presents an example of Cluster observations of typical mid-altitude cusp crossings with an electron edge, section 4 contains description of the data set and methodology for the statistical study, section 5 presents the results of this study and section 6 contains a discussion of these results. Finally we present our conclusions in section 7.

2. INSTRUMENT DESCRIPTION

The Cluster polar orbit has a perigee of ~4 R_E and an apogee of ~19.7 R_E, an inclination of 90°, and an orbital period of ~58 hours. Such an orbit is very favourable to study the cusp region, particular the mid-altitude cusp. The observations reported here were acquired by the PEACE [23] and CIS-CODIF [24] instruments on the Cluster satellites. The Plasma Electron and Current Experiment (PEACE) on board the Cluster spacecraft consist of two sensors, HEEA (High Energy Electron Analyser) and LEAA (Low Energy Electron Analyser) mounted on diametrically opposite sides of the spacecraft. They are designed to measure the three dimensional velocity distributions of electrons in the range of 0.6 eV to ~ 26 keV with a time resolution of 4 seconds. The ion data used in this study comes from the time-of-flight ion Composition and Distribution Function (CODIF) sensor experiment, which is a part of the Cluster Ion Spectrometry (CIS) experiment. The CODIF sensor combines a top-hat analyser with an instantaneous 360° field of view with a time of flight section to measure complete 3D distribution functions of the major ion species, H^+, He^{++}, He^+, O^+. The sensor covers the energy range between 0.02 and 38 keV/q and the time resolution of the sensor is 4 seconds.

3. EXAMPLE OF MID-ALTITUDE CUSP WITH ELECTRON EDGE OF THE LLBL

Figure 2 presents observations of the mid-altitude cusp crossing with electron edge near the equatorward boundary of the LLBL/cusp on 23rd August 2001, 1240-1305 UT. The three top panels present data from the PEACE instrument: energy-time spectrograms for differential energy flux in antiparallel (a), perpendicular (b) and parallel (c) directions. The black line around 10-12 eV shows the spacecraft potential measured by the EFW instrument. The part of the electron distribution with energies lower than the spacecraft potential consists of photoelectrons. The five bottom panels show the CIS/CODIF data: energy-time spectrogram of protons H^+ (d), pitch-angle (0°-360°) spectrograms for low-energy E = 40-200 eV (e) and mid-energy E = 200-1000 eV (f) protons, time-energy spectrograms of oxygen O^+ ions (g) and pitch-angle spectrogram of O^+ ions with energies E = 200-1000 eV. The differential energy flux is colour-coded according to colour bars on the right.

At the beginning of the time of interest, at 1240 UT, Cluster SC4 was inside the dayside plasma sheet, characterised by high energy, E = 1-30 keV, electrons with fluxes perpendicular to the magnetic field higher than those parallel, which is typical of trapped particles on closed field lines. At ~1246 UT (the first dashed line) a dramatic change in the observed electron distribution occurs: the high energy population disappears and low-energy, E = 40-500 eV, magnetosheath-like electrons become evident. This marks the electron boundary of the LLBL/cusp. However, magnetosheath-like ions do not arrive until two minutes later, at 1248 UT (the second dashed line), as can be seen in the pitch-angle spectrogram panel. Appearance of magnetosheath-like H^+ ions with 0° pitch-angles marks the ion boundary of

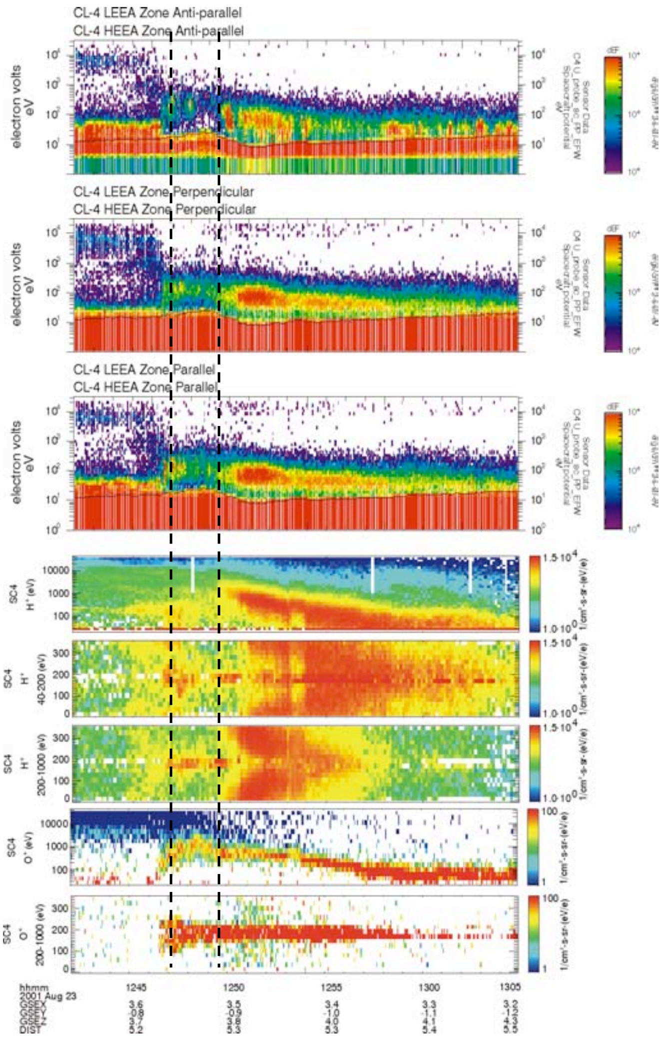

Fig.2. Example of the mid-altitude cusp crossing with the prominent electron edge of the LLBL. See text for details.

the LLBL/cusp. After 1248 UT, Cluster crossed a small LLBL with both magnetosheath-like low-density ions and electrons and entered the cusp proper, characterised by the dense magnetosheath-like plasma with energy-latitude dispersion and a low-energy cut-off of the ions, which are typical signatures of the cusp proper [e.g. 3].

Between the electron and ion boundaries of the LLBL/cusp, between 1246 and 1248 UT, Cluster was inside the boundary layer which we have defined as the electron edge of the LLBL. This layer contains fairly isotropic low density (~ 20 % of the density inside the cusp proper) electrons and uni- or bi-directional short-duration electron beams with higher fluxes. The energy range of the observed electrons suggests that this boundary layer is on open field lines, recently reconnected somewhere on the dayside magnetopause. However, this boundary layer still contains high-energy trapped protons of plasma sheet origin and also heated and outflowing H^+ ions with low-energies, E = 40-300 eV, probably of ionospheric origin. The electron edge of the LLBL also coincides with the appearance of oxygen outflow from the ionosphere. Bogdanova et al. [25] show that broad-band extra-low frequency (BBELF) waves simultaneously appeared with the arrival of magnetosheath-like electrons and that electron beams inside this boundary layer correlate with enhancements of the magnetic component of the BBELF wave power and with local O^+ and H^+ heating.

4. DATA SET FOR STATISTICAL STUDY AND METHODOLOGY

As described in the previous section, the boundary layer is frequently observed by Cluster near the equatorward boundary of the LLBL/cusp. A systematic statistical study of the position and size of such boundary layers as observed at mid-altitudes, and how these depend on different external parameters, has been performed. In this statistical study we have used 3 years of data from the Northern hemisphere mid-altitude cusp crossings, July-October 2001-2003. For every event the electron boundary of the LLBL/cusp has been defined by the simultaneous disappearance of the high-energy trapped electron population and the arrival of the low-energy low-density magnetosheath-like electrons based on energy-time spectrograms. We exclude events with a smooth transition between these two regions, when there are still some significant fluxes of high-energy electrons in the cusp, or when there is an obvious LLBL on closed field lines. The ion boundary has been defined by arrival of magnetosheath-like ions with energies up to 4-6 keV and with pitch-angles of 0°, based on pitch-angle spectrograms of the protons. We selected events only with clear ion boundaries.

As we wish to concentrate on the boundary layer near the equatorward edge of the cusp, which is formed due to reconnection at the dayside magnetopause, events with long-lasting Northward IMF have been excluded from the study. For this IMF orientation lobe reconnection is preferable [2, 26] and any boundary layer should form near the poleward boundary of the cusp. For events with highly variable IMF B_Z-component, the energy-time and pitch-angle spectrograms have been studied in more detail. We include events under temporarily northward IMF if there are combined observations of 'normal' energy-latitude dispersion with low-energy ion cut-offs near the equatorward boundary of the cusp and arrival of the protons with 0° pitch-angles at the equatorward boundary of the cusp. Any of these observations are signatures of reconnection at the dayside magnetopause [e.g. 3].

If data only from one spacecraft were available (for example, during seasons 2001 and 2002, SC3 was far away from the other spacecraft), the size of the electron edge of the LLBL was defined as the difference between invariant latitudes of the electron and ion boundaries observed by this spacecraft, i.e., Size = $ILAT_{ions}$ - $ILAT_{el}$. Such 'one-spacecraft' estimation will be accurate providing the boundaries do not move much between observations of the ion and electron boundaries by the single spacecraft. However, the boundaries in the LLBL/cusp can be highly dynamic and respond quickly to any changes of the reconnection geometry and IMF/solar wind conditions. For example, for stable southward IMF magnetopause erosion has been frequently observed [27], meaning that the OCB and electron boundary are constantly drifting equatorward. Moreover, variations in the IMF B_Y-component could change the position of the cusp proper and the surrounding boundary layers in MLT [3, 13, 19, 28] while changes in the IMF B_Z-component may shift the latitudinal position [17, 19, 28]. In this situation the one-spacecraft estimation of this boundary size is likely to be inaccurate, as the ion and electron boundaries are observed by one spacecraft at different times. Note that this also depends on the time between the detection of the electron and ion boundaries: if the time is small, the uncertainty of the estimation is small. However, the accuracy of size estimation would decrease with increasing time difference between observations.

With Cluster we have the advantage of using multi-spacecraft observations to estimate the motion of the OCB and electron/ion boundaries with time. Figure 3 illustrates this idea. If all four Cluster spacecraft enter the cusp and the surrounding boundary layers, we will have 4 measurements of the magnetic local time (MLT) and invariant latitude (ILAT) of the electron boundary of the LLBL/cusp at four different times. These points are marked as 1e, 2e, 3e, and 4e in fig. 3. We also will have 3 measurements of the MLT and ILAT of the ion boundary of the LLBL/cusp (CIS is not working on SC2) at three different times. These points are marked as 1i, 3i, and 4i in fig. 3. Based on 4 measurements of the invariant latitude of the electron boundary by different spacecraft we are able to reconstruct the electron boundary motion (ILAT versus time) using a linear least squares fit (the red line in fig. 3). Using the reconstructed electron boundary, we could find the invariant latitudes of this boundary at the times when the Cluster satellites detect the ion boundaries. These reconstructed invariant latitudes are marked as 1e_new, 3e_new, and 4e_new in fig. 3. Therefore, in the 'multi-spacecraft' method, the size of the electron edge

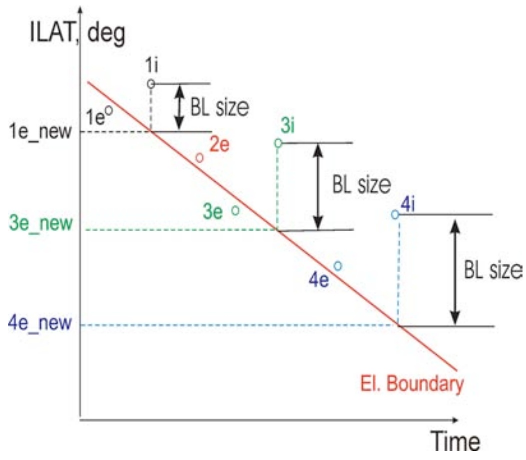

Fig. 3. The illustration of the multi-spacecraft method of the boundary layer size estimation.

of the LLBL is calculated as the difference between the invariant latitude of the observed ion boundary and the invariant latitude of the reconstructed electron boundary at the same time: Size = $ILAT_{ions}$ – $ILAT_{el\_rec.}$. For the example presented in fig. 3, it is evident that the size of the electron edge estimated from the multi-spacecraft method will be larger than that estimated from the one-spacecraft method. This will typically be the case for events during which magnetopause erosion is occurring.

The multi-spacecraft method can be used with high accuracy under two assumptions: (1) the OCB and electron boundary are aligned along latitude at small MLT scales; (2) The motion of the OCB and electron boundary between observations by different spacecraft is linear. In the former case, we note that the typical spacecraft separation in MLT in the mid-altitude cusp varied between 0.1h-0.5h MLT, so we assumed that differences in ILAT observations by different spacecraft due to MLT separation could be neglected. The multi-spacecraft method was based on 4-point measurements during the 2003 season and on 3-point measurements of the electron boundary for events from 2001 and 2002, as SC3 was very far away from the other three spacecraft (30-40 minutes). We do not believe that the assumption of linear motion of the OCB can realistically be applied over such a long time interval. The time of crossings of the electron boundary by the closely separated spacecraft varied between 20 seconds and ~ 10 minutes, so the accuracy of the electron boundary motion reconstruction could vary between events. However, we assume that the error of the size estimation is not higher than 0.1° ILAT. For the example discussed above (23rd August 2001) the SC crossed 1° ILAT in 5 minutes, corresponding to 30s for 0.1° ILAT. The PEACE and CIS data have a time resolution of 4 seconds, while the orbits of the SC are reconstructed from orbit files with a 5-minute resolution. Taking these points together with the linear fits to the observed data, the error of 0.1° ILAT seems reasonable. However, if the multi-spacecraft method returned an unrealistically large size estimation which was very different from the one-spacecraft method, we used size estimated from the latter method in the statistical study (relevant to 10 events).

We have 129 events with clear electron and ion equatorward boundaries of the LLBL/cusp. In 83 events multi-spacecraft estimation of the electron edge size was performed. We have determined how the size of this boundary layer depends on the IMF components, magnitude and clock-angle; on the solar wind dynamic pressure, velocity and density; on the invariant latitude, magnetic local time and level of the geomagnetic activity K_p. For IMF and solar wind estimations we have used ACE data taking into account the time delay based on the average velocity of the solar wind over a time period of 40-70 minutes before the Cluster observations.

5. STATISTICAL RESULTS

5.1 Size of the electron edge of the LLBL

Figure 4 presents two histograms showing the distribution of sizes of the electron edge, for all events (left) and for events in which we obtained a multi-

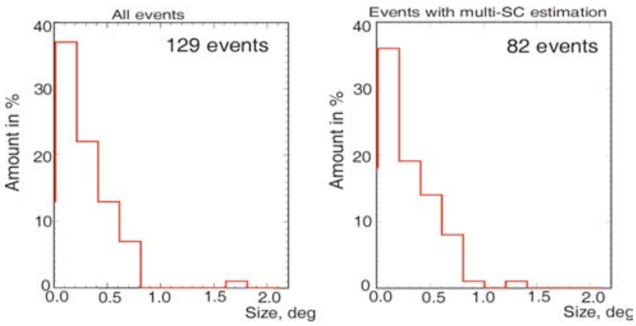

Fig. 4. The electron edge size histogram.

-spacecraft estimation of the size (right). Our study shows that only 13% of all events do not show a distinct electron edge, i.e. for these events the ion and electron boundaries were observed simultaneously. The size of the electron edge of the LLBL varies between 0° and 2° ILAT, with a mean value of 0.3° ILAT and a median value of 0.2° ILAT. The median value is more meaningful as it excludes the influence of a few extreme points. There are seven events where the electron edge size is > 1° ILAT. However, five of these relied on an estimation of size from the one spacecraft method. Hence, in these cases the accuracy could be low, as discussed above. The majority of events have size 0.05-0.2° ILAT with monotonically decreasing number of events with increasing size.

5.2 Dependence of the electron edge size on different parameters

Figure 5 shows how the size of the electron edge of the LLBL depends on the magnitude of the IMF (top left), the dynamical pressure of the solar wind (top right), the Magnetic Local Time (MLT) of the observation (bottom left) and the solar wind velocity (bottom right). These are 4 examples of the dependencies tested in our study. In each panel, the red points represent events where the size was estimated from the multi-spacecraft method, while the black points represent events where the size was estimated from the one-spacecraft method. The green line shows a linear least squares fit to these data,

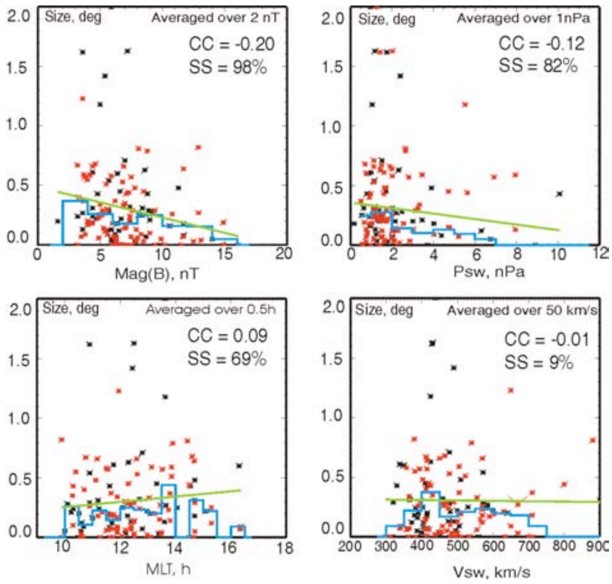

Fig. 5. Examples of the LLBL electron edge dependencies on external parameters. See text for details.

while the blue line shows the median value of the size in each bin, for cases where there are more than 3 points in the bin. For these calculations, we have combined events with the size estimated from either multi-spacecraft (if available) or one-spacecraft methods to increase statistics. We estimated the Pearson correlation coefficient CC [29] and statistical significance of the result SS. The statistical significance was calculated based on Student's t-test [30]. Both values are indicated in the top right of each panel. Following other statistical studies [31], we consider that correlation with SS > 95% is a statistically significant result. This means that the probability of two random sets of data of the same size as our dataset showing the same correlation coefficient as we had in a statistical study is only 5 percent.

The two top panels of fig. 5 show examples of relatively good dependencies between the size of the electron edge and external parameters. The anti-correlation between the electron edge size and the IMF magnitude is evident. The correlation coefficient between these values was

CC = -0.20. This means that 20% of variations in the electron edge size correspond to variations in the IMF magnitude. This result has high statistical significance, SS = 98%. Similar anti-correlation also has been seen in the median values. Correlation between the electron edge size and the solar wind dynamic pressure is smaller, CC = -0.12, as well as statistical significance of the result, SS = 82%. This result in general should not be considered as statistically significant. However, there is a pronounced dependency between median values of the size and the solar wind dynamic pressure. We consider such dependency in the median values as an important result, as (1) the Pearson correlation corresponds to the simplest situation of a linear least squares fit and for our data we probably need to use more sophisticated analysis; (2) the size of the electron edge depends on a combination of many parameters, so a very high correlation coefficient between the electron edge size and one of the parameters is not likely.

The bottom left panel of the fig. 5 shows how size of the electron edge depends on the magnetic local time of observation. There is no clear correlation or dependency between these two data sets. However, it seems possible that the number of events with a smaller size, 0-0.3° ILAT, is higher near the 12 MLT sector, although further investigation is needed to confirm this. For MLT dependency, the linear least squares fit and Pearson correlation coefficient are not the best way to analyse the data as we would expect some symmetrical changes in the boundary layer size from the noon sector in both the dusk and dawn directions.

For many external parameters we did not find good correlations or an obvious dependency between them and the LLBL electron edge size. One example of poor correlation is presented in the bottom right panel of the fig. 5: the correlation coefficient between the electron edge size and the solar wind velocity was very low, CC = -0.01 as well as the statistical significance, SS = 9%. We did not find any simple dependency in the median values of the size for this parameter.

Table 1 summarizes our results. It shows the external parameter tested for correlation with the electron edge size, the Pearson correlation coefficient, the statistical significance of the correlation and whether we have dependency in the median values or not. Results are sorted according to the correlation coefficient.

There is only one result with SS > 95% (correlation between the electron edge size and magnitude of the IMF, marked in blue in the table 1) which is considered as statistically significant. Moreover, there are three distinct trends between median values of the electron edge size and the invariant latitude, ILAT, of observation, the level of geomagnetic activity K_p and the solar wind dynamic pressure P_{sw} (marked by red colour in the Table 1). Such trends in the median values could suggest a link between the electron edge size and these three external parameters (e.g. trends in the median values have been used before in the statistical cusp studies [19], [28]). For other parameters we did not find any good statistically significant correlations or any valid dependencies in the median values. A similar analysis has been performed for events using only the multi-spacecraft estimation of the boundary layer size and a small distance between spacecraft (to increase accuracy). For these events (38 events) the correlation coefficients between the electron edge size and different external parameters slightly increased, but the statistical significance of results decreased due to the smaller data set.

Table 1. Correlation coefficients and statistical significances between the electron edge size and external parameters.

Parameter	CC	SS	Median values
IMF mag(B)	-0.20	98%	Yes
IMF B_X	0.15	91%	No
ILAT	0.14	89%	Yes
K_p	-0.14	89%	Yes
P_{sw}	-0.12	82%	Yes
MLT	0.09	69%	No
N_{sw}	-0.09	69%	No
IMF B_Y	-0.05	43%	No
IMF B_Z	0.05	43%	No
Mag(CA)	-0.03	27%	No
V_A	-0.04	35%	No
V_{sw}	-0.01	9%	No

6. DISCUSSION

6.1 Discussion of the plasma population inside the electron edge of the LLBL

In section 3 we presented plasma data for a typical mid-altitude cusp crossing with a distinct electron edge near the equatorward boundary of the LLBL/cusp. This electron boundary layer consists of ‘background’ fairly isotropic electrons with low flux and density. The density is around 20% of that observed later in the cusp proper. We suppose therefore that this electron distribution corresponds to the suprathermal halo part of the solar wind electrons, as suggested and modelled by Wing et al [21, 22]. With the multi-point measurements from Cluster we have a unique opportunity to check the efficiency of the parallel electric field which may exist between the magnetopause and low-altitudes and which prevents the core population of electrons penetrating to low-altitudes. The existence of such a parallel electric field was also discussed by Topliss et al [7]. They suggested that the ion conics observed inside the electron edge is indirect evidence of the existence of such a parallel electric field. In the future we intend to study further events inside the mid-altitude LLBL/cusp with significant altitude difference between two or more Cluster spacecraft. Study of the electron and ion distribution functions as observed simultaneously at different altitudes will provide new information on the existence of such parallel potential drop and probably help in the estimation of the parallel electric field. Another possibility for such type of study could provide events with close conjunction between Cluster and Double Star TC2 spacecraft inside the cusp region.

In addition to the background low-density electrons, the uni- or bi-directional electron beams (suprathermal electron bursts) have often been detected in this region. Downgoing electron beams could originate near the dayside X-line during the reconnection process as predicted by the reconnection theory [e.g. 20] and have been observed near the magnetopause [e.g. 4]. The most likely source of the upgoing short duration electron beams inside the electron edge is a wave-particle interaction process. For example, it was suggested that electrons could be trapped in the parallel electric fields associated with kinetic Alfven waves and propagate with these waves [32]. The parallel electric field existing below the spacecraft and accelerating electrons is also possible explanation [33].

Inside the electron edge the observed ions are still of magnetospheric origin and usually consist of two distinct populations. The first population consists of high-energy protons H^+ from the dayside plasma sheet, and the second population consists of low-energy protons locally heated and outflowing presumably from the ionospheric origin. Another often observed feature of this electron edge region is the beginning of the oxygen O^+ outflow, as well as local heating of oxygen ions. In events studied so far (see [7] and [25] for details) good correlation between suprathermal electron bursts, ULF wave activity and local ion heating has been found. However more events need to be studied in order to make more precise conclusions. So far we have not considered the question of quasi-neutrality of the plasma inside the electron edge, but close correlation between dense electron beams and the appearance of the ion outflow suggests that the local heating of ions and ion outflow could be a quick reaction of the ionosphere-magnetosphere system to the electron injections. Study of the quasi-neutrality question has been postponed for the future when a good cross-calibration between the PEACE and CIS plasma instruments can be done.

6.2 Comparison with previous studies

Our statistical study shows that the electron edge of the LLBL is often observed during mid-altitude cusp crossings by Cluster. It is interesting to compare our results with statistical results from Newell and Meng [9, 14, 15, 16] who performed a large statistical survey and created the well-known map of the different magnetospheric regions as seen at low-altitudes [16]. The boundary layer described here was not included in their statistical study. However, they discussed a region named 'void' which was observed between the Central Plasma Sheet (CPS) and the LLBL and consists of low-flux plasma. Another region existing in their classification was named Boundary Plasma Sheet (BPS) which is a region with soft (magnetosheath-like) electrons in the dawn and dusk sectors. As discussed by Lockwood [5] and Onsager and Lockwood [6], the identification and classification of the void region partially depends on the sensitivity of instruments. Therefore it was suggested [5, 6] that the void region represents the BPS in cases where the flux falls below the one-count level.

The plasma properties inside the Newell and Meng 'void' region and the Lockwood 'BPS' region are somehow similar to those observed by Cluster inside the electron edge of the LLBL. We therefore suggest that at least part of the void region seen in the Newell and Meng statistics and the BPS region discussed by Lockwood corresponds to the electron edge of the LLBL seen in the Cluster data. The magnetosheath-like electrons suggest that this boundary layer is on open field lines and places poleward from the Open Closed Boundary. In this case, the name of electron edge of the LLBL is a more topologically appropriate than Boundary Plasma Sheet as it shows connection to the dayside processes.

Topliss et al. [7] studied a similar electron edge observed in Polar data. Their statistical study shows the existence of such a boundary layer in only 6 events out of 200 events of mid-altitude cusp crossings. This result is very different from our result where we observed an electron edge of the LLBL in 87% of the mid-altitude cusp crossings. We suggest that a number of possible reasons could explain such a difference: (1) in their paper Topliss et al. did not describe the criteria which were used for the definitions of the electron and ion boundaries. It is possible that they used different definitions for clear electron and ion boundaries, which could give a slightly different result. (2) Topliss et al. did not mention how many events they have with clear ion and electron boundaries. In Cluster data we have only ~50% events out of all crossings in which boundaries could be clearly defined. (3) As discussed above, since the sensitivity of instruments is essential in the detection of the electron edge, it is possible that the Polar spacecraft has a lower sensitivity. (4) Time resolution of the Polar particle instrument is 12 seconds compared to 4 seconds for Cluster, so it is possible that events with a time difference between two boundaries less than 12 seconds were not recognisable in the Polar data. (5) Polar sampled mostly in the noon sector. Cluster observations also show that near noon there are many events with simultaneous electron and ion boundaries. Another possible explanation is that during the Polar observations the parallel electric field was stronger and the suprathermal part of the solar wind electrons also has been stopped, as suggested in [7]. However, further consideration is needed to understand why the Cluster result is so different to the Polar result.

6.3 The LLBL electron edge statistical properties – expectations and results

As discussed above, the size of the electron edge varies between 0° and 2° ILAT with a median value of 0.2° ILAT. These values correspond very well to expectations from simple calculations based on plasma convection and distance to the magnetopause. Thus, Topliss et al. [7] noticed that for Polar observations assuming the distance to the magnetopause reconnection of 10 R_E and poleward convection speed inside the cusp of 10-50 km/s, the time difference between encountering electron and ion boundaries should be 3-10 minutes. In our data the time difference between observations of these two boundaries varied between 10 seconds and 5 minutes.

Based on Polar observations it was not possible to find factors defining the size of the electron edge [7]. Based on Cluster data we have found some dependencies as we have a larger data set. However, we note that the size of this boundary layer most likely depends on the combination of many external parameters. Indeed, the size of the electron edge as observed at mid-altitudes depends on (1) the relative position of the reconnection point and observation point, (2) the velocity of the ions and (3) convection of the reconnected field lines.

The relative position of the reconnection point and observation point depends on the location of the magnetopause and the location of the X-line at the magnetopause. The location of the magnetopause depends on the solar wind dynamic pressure [34] and IMF B_Z-component [35]. The location of the site of anti-parallel sub-solar reconnection could be shifted into the Southern or Northern hemispheres according to sign of the B_X-component of the IMF [e.g. 20]. The location of the anti-parallel merging site also will be shifted into the dusk or dawn sectors according to the sign of the B_Y-component of IMF [e.g. 3]. Based on these assumptions, we would expect that the size of the electron edge will anti-correlate with the solar wind dynamic pressure and the B_Z-component of the IMF. Observed in the northern hemisphere, the electron edge size should be bigger for a negative IMF B_X-component, and, when observed in the dusk(dawn) sector, the electron boundary layer size should be bigger for the dawnward(duskward) IMF.

The source of the energetic LLBL ions is still under discussion. According to Lockwood et al [36, 37], ions forming the LLBL region can be generated on open field lines by reflection of the pre-existing magnetosphere population by the interior Alfvén wave. This wave is launched from the reconnection site into the inflow region, on the magnetospheric side of the boundary and propagates faster from the reconnection site than the exterior Alfvén wave due to the smaller plasma density and the higher magnetic field inside the magnetosphere in comparison with the magnetosheath parameters. In this model, the cusp proper is formed by ions accelerated on the exterior Alfvén wave which stands in the magnetosheath and contains major rotation in the magnetic field. However, Fuselier et al [38] suggested an alternative explanation of the energetic LLBL ions, based on the solar wind and magnetosheath ion distribution functions. They show that the distribution of the magnetosheath ions already has ~20% higher energy (hotter) ions and suggest that LLBL forms due to the arrival of this high energy part of the magnetosheath distribution. In our data, the proper LLBL, containing a mixture of both high-energy low-density electrons and ions, was sometimes missing or it was hard to distinguish between the cusp proper and the LLBL. We therefore thought that the ion boundary in many cases corresponds to the arrival of ions in the cusp proper, which accelerated by exterior Alfvén wave with parameters calculated based on magnetosheath values of magnetic field and density [36, 37]. If our suggestion is valid, then the size of the boundary layer should anti-correlate with the magnitude of the IMF and correlate with the square root of the solar wind density.

The convection of the reconnected field lines depends on the solar wind electric field (reconnection rate) [3, 11, 12, 20]. In this case, the size of the electron edge will correlate with the velocity of the solar wind and magnitude of the IMF. As one can see, there are at least six external parameters which could influence the size of the LLBL electron edge. Probably there are more parameters (for example, the strength of the potential drop above the spacecraft) which could also influence the size of this boundary layer. Note that there is also a temporal factor in the electron edge size determination. If a spacecraft crosses into the cusp/boundary layer region, which has formed due to a reconnection pulse but some time after the reconnection has ceased, it is possible that the spacecraft would not detect newly-reconnected field lines with only magnetosheath-like electrons, but would directly cross onto older reconnected field lines with both magnetosheath-like ions and electrons.

Our statistical study shows that the size of the electron edge anti-correlates with the magnitude of the IMF. One possible explanation of such a dependency could be based on the suggestion that ions which mark the ion boundary in our events propagates with an Alfvén velocity calculated with the magnetosheath parameters. However, anti-correlation with the IMF magnitude contradicts expectations based on the motion of the reconnected field lines. In the trend of median values we have found some anti-correlation between solar wind dynamic pressure and the size of the electron edge, which was expected on the basis of the discussion above. We did not find any obvious dependencies in the electron edge size on any IMF components nor any dependency on the solar wind density or velocity. The slight dependency of the electron edge size on ILAT and the index of the geomagnetic activity K_p seen in the median values trend appears to be a 'secondary effect', as both of these parameters depend in turn on the solar wind and IMF conditions. In general we conclude that while some parameters (IMF magnitude and solar wind dynamic pressure P_{sw}) influence the size of the electron edge as expected from the simple reconnection model [e.g. 3], any other anticipated correlations have not been found in this study. We suggest that the combination of at least six different factors make such statistical study very complicated. For more careful analysis, we need to fix some of the external parameters and study how the electron edge size depends on the variation on free parameters. This study must be postponed for the future, as we need to extend our database to do it. However, our main conclusion so far is that the magnitude of the IMF and the solar wind dynamic pressure are the main factors influencing the size of this boundary layer.

7. CONCLUSION

We present results of a statistical study of the electron edge of the LLBL observed by Cluster during mid-altitude cusp crossings:

(1) The electron edge consists of low density fairly isotropic electrons presumably from the halo population of the solar wind and uni- or bi-directional electron beams. Inside this boundary layer there are ions of magnetospheric origin.

(2) The wave activity correlates with the arrival of boundary layer electrons, and local oxygen O^+ ions heating and ion outflow correlate with the appearance of the electron beams.

(3) This electron edge has been observed in 87% of the mid-altitude cusp crossings by Cluster, which is different from the previous Polar result.

(4) With Cluster 4-point measurements we have introduced a multi-spacecraft technique of estimation of the size of this boundary layer to increase accuracy of this estimation.

(5) The size of the electron edge varies between 0° and 2.0° ILAT with a median value of 0.2° ILAT.

(6) The size of the electron edge depends on the combination of many external parameters. We found statistically significant anti-correlation between the electron edge size and the magnitude of the IMF. The distinct trends between median values of the electron edge size and the solar wind dynamic pressure, the invariant latitude, and the level of geomagnetic activity Kp have been also found. We did not find any dependencies on other parameters.

There are three interesting potential studies based on this work which will be pursued in the future:

(1) As the electron boundary is very close to the Open-Closed Boundary, it could be a good proxy for the OCB. Based on the multi-spacecraft technique introduced here, it is possible to do a quantitative estimation of the OCB motion in response to variation in the solar wind and in the IMF parameters.

(2) Using the 4 sets of Cluster observations with significant differences in altitude, it is possible to test for the existence of the parallel electric field and to estimate the value of potential drop retarding the core solar wind electron distribution from reaching low altitudes.

(3) As the electron edge size depends on the combination of many parameters, ideally we have to fix some of them and study how size of this boundary layer reacts on changes of other parameters. To do so, the number of events has to be increased and mid-altitude cusp crossing from 2004 and 2005 need to be included.

8. Acknowledgements

This work is supported in the UK by the UCL/MSSL Particle Physics and Astronomy Research Council Rolling Grant. We would like to thank the CDAWeb team for providing the level 2 ACE MAG and ACE Solar Wind Experiment data.

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