Transient ion beamlet injections into spatially separated PSBL flux tubes observed by Cluster-CIS

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[1] Ion measurements from Cluster-CIS were used to characterize and interpret the signatures of PSBL energy-dispersed ions and their fine structure. On 14 February 2001, several ion injections were encountered by SC 1 and SC 3, separated by ~530 km, during an outbound orbit at 4.5 R_E. Both satellites recorded the same ion structures. The energy dispersion of each ion structure was dominated by the time-of-flight effect (TDIS). In addition, we show evidence for spatial properties of the ion injections: (1) SC 1 and SC 3 encountered the same ion structures with a time delay of ~30 s, which indicates their spatial extent. (2) The peak energy of each injection increased with increasing latitude. We propose a scenario in which both temporal and spatial effects are incorporated: Ion beamlets are impulsively and recurrently injected from separated regions distributed along the tail current sheet (ranging from X ~70 to 110 R_E) into latitudinally narrow (~600 km to 1800 km) and convecting (at ~10 km/s) flux tubes of the PSBL. Beamlets injected closer to the X line gain higher energies as a result of the intrinsic dispersion effect. *INDEX TERMS:* 2716 Magnetospheric Physics: Energetic particles, precipitating; 2731 Magnetospheric Physics: Magnetosphere—outer; 2748 Magnetospheric Physics: Magnetotail boundary layers. **Citation:** Keiling, A., et al. (2004), Transient ion beamlet injections into spatially separated PSBL flux tubes observed by Cluster-CIS, *Geophys. Res. Lett.*, *31*, L12804, doi:10.1029/2004GL020192.

1. Introduction

[2] With every new spacecraft traversing the plasma sheet boundary layer (PSBL) new properties of ion beams are identified. In a recent study [*Keiling et al.*, 2004] (hereinafter referred to as K1) the phenomenon of energy-dispersed ion structures (EDIS) in the PSBL was revisited using the multipoint measurement capability of Cluster. This study focused on the beamlet substructure that accompanied the EDIS for one particular PSBL crossing (Figure 1b). Two scenarios were proposed to explain the observations. The main difference was whether the beamlet structure was created at the source or during the flight. We refer the reader to this study for an introduction on EDIS and the various types that have been proposed in the literature: velocity-dispersed (VDIS), time-dispersed (TDIS), and intrinsically dispersed (IDIS) ion structures. It is important for this paper that the reader is familiar with these types.

[3] The study presented here complements the work by K1. About 2.5 hours after their event, the Cluster satellites crossed the opposite (northern) edge of the plasma sheet, at about the same radial distance and local time (Figure 1a). Geomagnetic activity was similar during both PSBL crossings, such as auroral double ovals, indicating that a substorm recovery phase prevailed each time, and a negative IMF Bz (time-shifted to account for solar wind speed) as recorded by the ACE satellite, suggesting similar global magnetospheric convections. At first glance, the ion signatures during the inbound and outbound crossings on the same day show stark differences. Here we report an analysis of the ion signatures during the outbound crossing (Figure 1a) and contrast the observations to those of K1. We will reconcile our observations with those of K1 by proposing a scenario that combines both temporal and spatial properties to explain the ion signatures encountered during both PSBL crossings.

2. Observations

[4] The Cluster satellites were in "string-of-pearls" configuration during the PSBL crossing on 14 February 2001 and the separation between SC 1 and SC 3 was (178, 219, 448) km in x, y, and z (GSE). Data came from the Cluster Ion Spectrometry (CIS) instruments [*Rème et al.*, 2001]. Figures 2a and 2c show ion energy-time spectrograms of SC 1 and SC 3, respectively. Both satellites recorded similar large-scale ion structures. The most characteristic ion features are the zigzag shaped low-energy cutoff (LEC) (dashed orange line) and the energy-dispersed ion beams (some of which are marked by dashed black lines) immediately above this cutoff. Repeatedly, the LEC decreases with increasing latitude followed by a more rapid jump to an energy value that is higher than the previous jump.

[5] The energy dispersion associated with the ion beams cannot be caused by the velocity-filter effect of drifting plasma as is the case for VDIS, because the systematic decrease in energy is with increasing latitude. Instead, the TDIS model offers a simple explanation for this energy dispersion. Because the energy dispersion is due to the time-of-flight effect, we can use the dispersion slope to estimate the injection location. This is done in Figures 2b and 2d by

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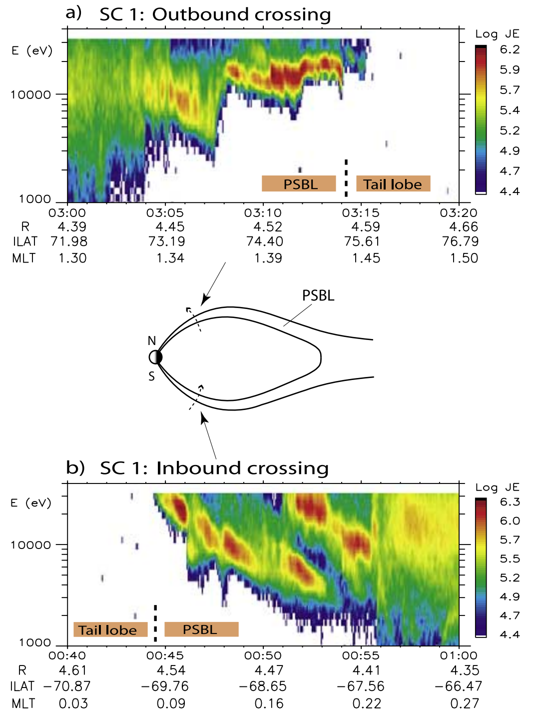

Figure 1. Cluster crossings of the PSBL in both hemispheres on 14 February 2001. Ion energy-time spectrograms (CIS-HIA) for (a) the outbound crossing and (b) for the inbound crossing [from *Keiling et al.*, 2004].

plotting the inverse velocity versus time. The inverse of the slope is an estimate of the travel distance. The key observations are: (1) Each ion structure was injected at different times, and (2) as a general trend, the ion structures on field lines with larger L value (closer to the lobe-PSBL interface) have larger travel distances, bearing in mind the relatively large uncertainty in fitting lines through the ion structures. Note that the ion structures poleward of the lobe-PSBL interface for both satellites (first dashed line from the right in Figure 2) do not follow this trend. It is possible that these ion beams are located on tail lobe field lines. We thus believe that they are of different origin than the PSBL ion beams and will be analyzed elsewhere.

[6] We now draw the attention to the dashed white line in Figures 2a and 2c. This line follows the highest energies of each TDIS. It is apparent that the closer the TDIS was to the lobe-PSBL interface, the more energetic (higher velocity) it was. This ion velocity profile as a function of L value has been observed before [*Takahashi and Hones*, 1988] and was attributed to intrinsic dispersion (IDIS) [*Zelenyi et al.*, 1990], although individual ion beams were not reported to be TDIS.

[7] Figure 3 shows an expanded interval for further analysis. We note first that the temporal energy dispersion is again clearly visible. Several vertical and horizontal dashed lines are drawn as a visual aid. The data from SC 1 (Figure 3a) are shifted by ~30 s with respect to the data from SC 3 (Figure 3b). This shift brings similar ion features recorded by both satellites to line up with the vertical dashed lines (labeled '1' through '5'). In particular, we point out that the zigzag LEC of both satellites line up well (see, e.g., vertical line '2'). Furthermore, both satellites observed ion injections at '3' and abrupt energy steps (discontinuities) at '4' and at '5'. Also note that after '4' the energy range of the ion injections broadened suddenly. Since both satellites were spatially separated in the direction of motion and the same (or similar) ion structures were encountered with a 30-s time delay, this suggests that spatial structures in the PSBL were crossed by the two satellites.

[8] At each vertical dashed line, the ion structures of SC 1 (leading satellite) consistently show higher energies compared to those of SC 3 while the dispersion slopes are the same. For example, the energy difference of the ion beams at '3' is a few keV, and at '2' the LEC extends to lower energies for SC 3 compared to SC 1. It is also noted that the extension of the dispersion slope of the ion structure at '1' (lower dotted line in Figure 3b) intercepts the horizontal dashed line about 30 s earlier. For comparison, we also drew the time-shifted dispersion slope of the ion structure recorded by SC 1 (Figure 3a) in Figure 3b (upper dotted line). Similar comparisons can be made with other ion structures (e.g. at '4'). Remembering that Figure 3b is shifted by ~30 s, we conclude that SC 3 recorded the same ion structure (same dispersion slope) as SC 1 but with lower energies since the higher energy ions had already passed. This is additional evidence for the temporal nature of these ion injections.

[9] Examples of velocity space distribution functions for SC 1 are shown at the top of Figure 3. The three distributions are nearly isotropic which suggests that the ion injections

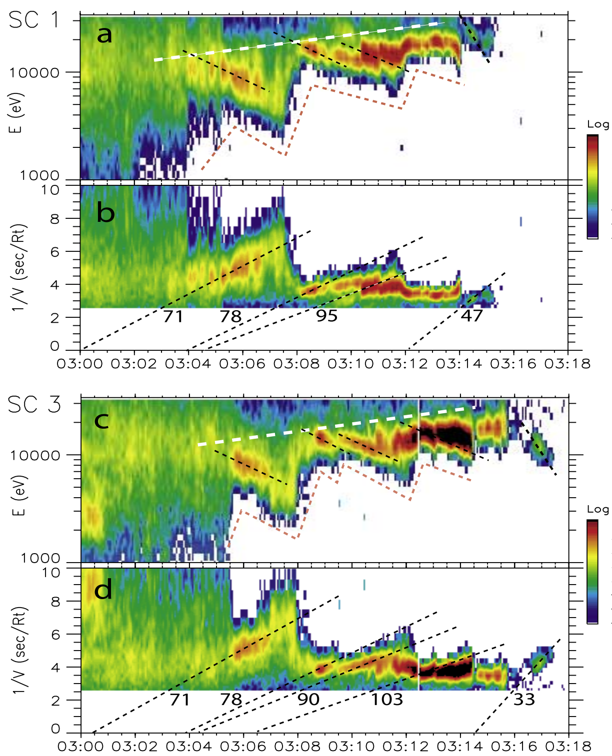

Figure 2. Time-dispersed ion structures (TDIS) recorded by CIS-HIA (omnidirectional) during the outbound PSBL crossing on 14 February 2001. (a) Ion energy-time spectrogram for SC 1. (b) Inverse velocity versus time spectrogram for SC 1. Values in R_E next to the dashed lines are estimated travel distances. (c) and (d) are the same as the first two panels but for SC 3.

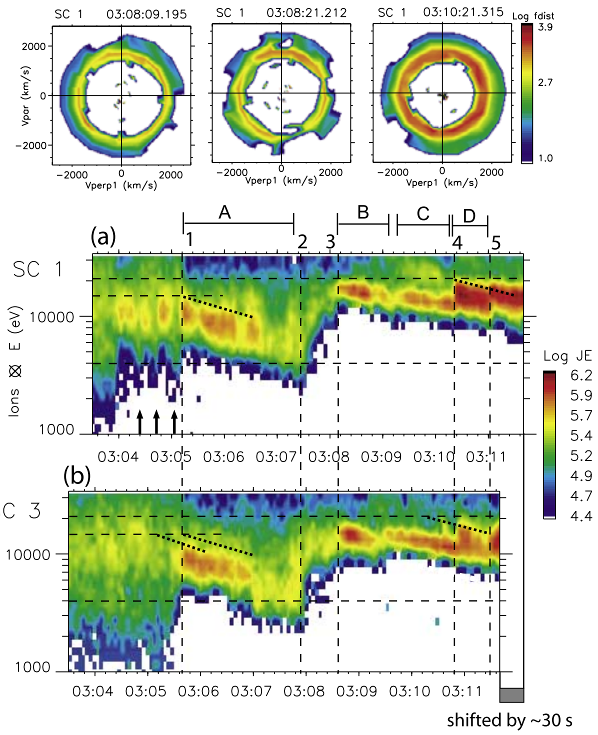

Figure 3. Velocity space distribution functions and expanded views of ion energy-time spectrograms for SC 1 and SC 3 (CIS-HIA, omnidirectional). See text for description of dashed lines and arrows.

started before SC 1 entered the ion beamlet flux tubes (see Section 3 for more discussion). Also note that an isotropic distribution allows for beamlike injections at the source region, which was very far away and occurred under much smaller ambient magnetic field. Furthermore, the circle of nearly uniform density is slightly shifted towards negative (tailward) velocities, which allows for the possibility that the tailward-moving ions are the reflected ions of an earlier, more energetic Earthward-moving ion population.

[10] There are some differences in the ion fine structures between both satellites. For example, the ion structures of SC 1 before '1' are not observed by SC 3 (Figure 3), but note that each of these injections was shorter than 30 s in the spacecraft frame (See Section 3 for more discussion). This and other differences could be due to the temporal character of the ion injections or the azimuthal satellite separation of ~220 km. K1 showed that even for azimuthal separations of only 100 km, ion signatures can vary drastically.

3. Discussion

[11] We reported ion injections in the PSBL that showed both temporal and spatial features and that showed systematic differences between two Cluster satellites. First, the closer the ion injections were to the lobe-PSBL interface, the more energetic they were. Second, the energy dispersion associated with individual injections was due to the time-of-flight effect. Third, the two Cluster satellites recorded several similar ion structures with a time delay of ~30 s throughout the PSBL crossing, suggesting that spatial structures were crossed. Fourth, the leading satellite (SC 1) consistently recorded higher energies than the following satellite (SC 3) when encountering the same ion structures. Fifth, most ion injections showed abrupt energy steps over a range of energies.

[12] To reconcile these observations, we propose the following scenario, which is illustrated in Figure 4. Ions are impulsively injected from a broad region along the current sheet (ranging from X ~70 to ~110 R_E). Ions that are closer to the X line are accelerated to higher energies. The underlying mechanism could be neutral sheet acceleration along Speiser orbits. *Zelenyi et al.* [1990] showed by using a tail magnetic field that falls off with distance that this mechanism can lead to an intrinsic dispersion effect along the neutral sheet, i.e., the maximum speeds of accelerated ions varies with the distance from the X line.

[13] Furthermore, we propose that the injections occurred in regions that were separated from one another (Figure 4). This injection pattern has been found in particle simulations [*Ashour-Abdalla et al.*, 1993], and it was interpreted based on the theoretical analysis by *Büchner and Zelenyi* [1989]. The particle simulation assumed static field conditions and as a consequence the ion beamlet injections were continuous. Instead, here we show evidence that the ion beamlet injections were transient and recurrent. Later, *Peroomian et al.* [2000] extended the simulation to include time variations. Temporal fluctuations of the location of the X line of the order of 3.5–5 min were simulated, resulting from the escape of accelerated current sheet ions via the magnetotail flanks. This time scale is comparable to the recurrence rate of the beamlets reported here, and it is thus possible that this mechanism is associated with the recurrent ion beamlet injections into the PSBL, although *Peroomian et al.* [2000] did not show an ion escape into the PSBL.

[14] The injection islands in the current sheet map towards the Earth along PSBL flux tubes that are spatially separated. These flux tubes are thus the spatial structures that were consecutively crossed with a constant time delay (~30 s) by the two satellites (Figure 4b). Even though the injections were temporal and one could argue that they should have been observed simultaneously by the two

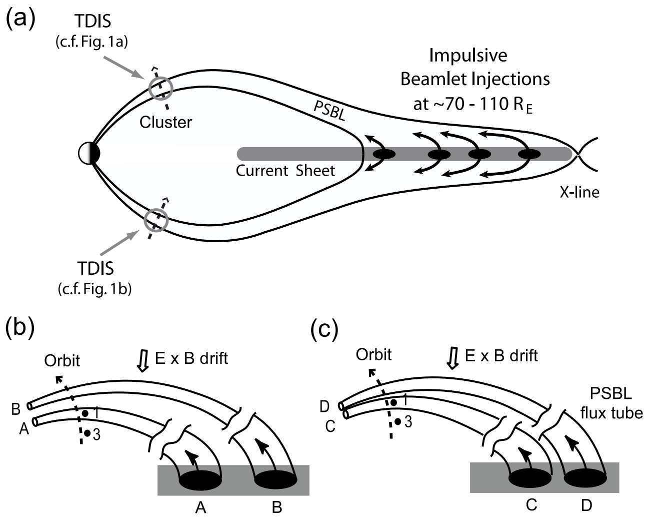

Figure 4. Scenario to explain the observations reported here and those reported by *Keiling et al.* [2004]. The length of the solid arrows indicates beamlet speeds.

satellites, their limited spatial extent led to the spatial signature. However, we note that this time delay between SC 1 and SC 3 cannot be explained by their spatial separation ($\Delta z \sim 440$ km) alone. Each satellite, moving nearly perpendicular to the nominal magnetic field at ~4.7 km/s, covers only about ~140 km in 30 s. Consequently, the additional distance of ~300 km is obtained by additional $\mathbf{E} \times \mathbf{B}$ drift motion of the beamlet-carrying flux tubes towards the equatorial plane (i.e., in the expected sense of the large-scale magnetospheric convection) at ~10 km/s (= 300 km/30 s). Satellite speed and plasma drift speed can be used to estimate the thickness of the beamlet flux tubes. For this event, the durations of separated ion structures were in the range from ~40 s to 120 s, which yields a perpendicular thickness from ~600 km to 1800 km at the satellite's location.

[15] SC 1 consistently recorded higher energies than SC 3 when encountering the same ion structures. These energy differences can be explained by the transient nature of the TDIS that were impulsively injected into the spatially separated flux tubes (Figure 4b). For example, SC 1 is inside such a flux tube and records the TDIS, while SC 3 is still outside. As soon as SC 3 moves inside, it records the same structure same dispersion slope starting with a lower energy because the higher energy ions have already passed.

[16] The separation of neighboring beamlet flux tubes varies and can lead to observable variations. For example, if the beamlet flux tubes are close together, the satellite quickly crosses from one flux tube to the next (Figure 4c). If the injection properties are different in each flux tube, the satellite will record a sudden change. An example of this is the sudden change at '4' (Figures 3a and 3b) as the satellites move from flux tube 'C' to 'D' with 'D' covering a broader energy range than 'C'. We note that the abrupt change over many energy values, as also observed for other flux tubes, implies a steep spatial gradient at the edges of the flux tubes, which could be due to a broad-energy ion source that is itself convecting [*Lennartsson et al.*, 2001].

[17] If, on the other hand, the flux tubes are farther separated (Figure 4b), then the spacecraft might cross a gap in which no injection occurs and the next ion injection occurs at considerably higher energies because of the intrinsic dispersion of the neutral sheet acceleration as described above. The signature could be the one that is seen in Figures 3a and 3b (flux tubes 'A' and 'B').

[18] Our observations can be compared with those of K1. We note the following similarities. The entire crossing of the ion beamlets took about 10 min in the spacecraft frames. Four to six beamlets were recorded lasting each for ~1–2 min and covering each a similar energy range. The slopes of the beamlets were similar. If we also interpret the energy slopes of beamlets in the K1 event as due to temporal dispersion, it follows that the ions were also injected at different times and different locations. Beamlets showed additional fine structures. For example, K1 pointed out low energy extensions that were attached to some beamlets. It appears that similar structures were also present for our event (see arrows in Figure 3a and also compare Figures 1a and 1b). An important difference is that K1 recorded echoes (bouncing ions) of the ion beamlets (appearing after ~0051 UT in Figure 1b). However, we note that in the case of TDIS it is far more likely to see bouncing ions for a satellite that moves with the plasma drift as was the case for K1. We conclude that it is possible that the ion signatures reported by K1 are the result of the same magnetotail acceleration processes that are illustrated in Figure 4.

4. Conclusions

[19] Polar-orbiting satellites cross the PSBL twice per orbit; one encounter is while coming from the tail lobes (inbound leg) and the other one while coming from the CPS (outbound leg). The relative motion of the large-scale plasma convection with respect to the satellites is in opposite direction during these two types of crossings, provided the global magnetospheric convection is the same. In this study we have shown that, at first glance, the ion signatures can be very different during similar global geomagnetic conditions because of this relative motion. We proposed a scenario that can account for the satellite observations made during both an inbound and an outbound crossing of the PSBL. This scenario is based on transient ion beamlet injections (TDIS) in the neutral sheet into narrow, spatially separated and convecting PSBL flux tubes.

[20] This is the first report of TDIS injections in association with an ion velocity profile (for peak values) in the PSBL as reported by *Takahashi and Hones* [1988] which has commonly been explained by intrinsic dispersion and quasi-static structures. Here, however, we reported that the ion injections were of temporal nature, i.e. TDIS. We emphasize that the TDIS reported here must be distinguished from those reported by *Sauvaud et al.* [1999] which occur on auroral bulge field lines during the substorm expansion phase and which do not show a peak-velocity dependence on L value. Some ion structures reported by *Lennartsson et al.* [2001], using the Polar satellite, show similarities to the presented data. Finally, we emphasize that the local ion measurements at ~4.5 R_E allowed us to infer the topology and properties of neutral sheet injections in the magnetotail.

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