Low-altitude signatures of magnetotail reconnection

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Abstract. Precipitating ions on the poleward edge of the nightside auroral oval sometimes exhibit sharp low-energy cutoffs in their energy spectra. These truncated spectra are interpreted as signatures of magnetic reconnection in the magnetotail. The energy cutoff is frequently smoothly dispersed in latitude, allowing an interpretation in terms of quasi-steady reconnection. These events are designated velocity-dispersed ion structures (VDIS) type 2. Roughly one third of type 2 VDIS are accompanied by a sharp transition in the polar rain near the open-closed boundary that aids in their analysis. From 886 nightside open-closed boundary crossings by DMSP spacecraft, 148 type 2 VDIS were identified. They were found most frequently within 2–3 hours of midnight and for 40% of the open-closed boundary crossings between 2200 and 0100 magnetic local time. Minimum variance fits to the cutoff energies and polar rain transition are performed on 49 of these events. For four of them the information from the minimum variance fit and observed convection velocities are used to infer distances to the reconnection site that varied from 30 to 80 R_E. In two of these four cases a sharp transition in the convection velocity is observed, coincident with the arrival of ions from the reconnection site. If the reconnection region is viewed as a voltage source, lobe field lines can be insufficiently populated to carry the current necessary to impose the required voltage on the ionosphere. This explains the coincidence between the arrival of ions and a discontinuity in convection, that is, that an electric field from the reconnection site is imposed on the ionosphere but only after sufficient density populates the field lines that connect the regions.

1. Introduction

Beams of ions and electrons have been observed in the plasma sheet boundary layer (PSBL) for some time now [see Takahashi and Hones, 1988, and references therein]. At the outer edge of the PSBL, counterstreaming electrons are observed with the more energetic electrons headed tailward [Onsager et al., 1990]. They are dispersed in energy with depth into the PSBL, the more energetic electrons being outermost. Farther in, counterstreaming ions are observed, again dispersed in energy with depth into the PSBL and with the more energetic ions headed tailward. These observations are interpreted as the result of hot plasma streaming from a tailward reconnection site toward Earth (where it mirrors), as field lines connect from the lobe toward the plasma sheet (Figure 1). The observed structures are formed by the velocity filter effect: faster particles make it to the spacecraft before the field line has moved very deeply into the PSBL. Tailward traveling particles, having mirrored at Earth, have gone farther in the same time than those that are still headed earthward; hence the tailward component of a counterstreaming beam is more energetic.

These effects can also be seen where the PSBL impinges on the ionosphere. The velocity filter effect results in a sharp low-energy cutoff in the ion spectra, since only ions with sufficient velocity will have been able to travel the intervening distance in the time since the field line was reconnected and populated. If reconnection remains steady for at least several minutes, then convection can effect a smooth dispersion of the cutoff energy with latitude. The events are called velocity-dispersed ion structures (VDIS) type 2 (type 2 to distinguish from a velocity dispersion of upwelling ionospheric plasma seen near the equatorward edge of the oval). Type 2 VDIS events are the subject of this study, and we will not discuss type 1 further. These type 2 VDIS events have been the subject of several previous studies.

Zelenyi et al. [1990] observed 80 such events with AUREOL 3 in the 2–20 keV range. They interpreted many of them as originating at a stationary X line 50 to 100 R_E down the tail, though some events were interpreted as being due to nearer substorm-related reconnection sites; they also observed some anomalous events that displayed either no dispersion or reverse dispersion. Sergeev and Bosinger [1993] studied an event with NOAA 6 and 7 using 30–800 keV ions and also inferred a reconnection region 50 to 100 R_E down the tail. Onsager and Mukai [1995] successfully modeled a similar event observed with Akebono with a reconnection site at x_GSM = −60 R_E. Shirai et al. [1997] found that the X line is
Figure 1. A conceptual depiction of the mechanism that produces velocity dispersion in the plasma sheet boundary layer (PSBL). Plasma is introduced onto former lobe field lines at the reconnection site. Ions and electrons stream along field lines as the field lines connect through the PSBL toward the plasma sheet, resulting in a segregation by velocity.

usually located in the $-50 R_E < x < -150 R_E$ range using Geotail observations of unidirectional polar rain, just inside the PSBL.

We will improve on the analysis of Zelenyi et al. [1990], some elements of which were flawed. They assumed a specific acceleration mechanism [Speiser, 1967], which presents ion beams whose energy depends on distance from an x line, as input to the velocity filter. In their treatment this dispersion of peak energy with distance from an x line is modified by the velocity filter and realized as dispersion with latitude at low altitude. This is not correct since a velocity filter does not simply shift the peak energy of an input distribution but mixes particles originating at the different locations visited by a moving field line in a very specific way. A velocity filter does pick a particular energy at which to truncate the resulting distribution, and this cutoff energy does not depend on the peak energy of the source distribution. Furthermore, assuming an acceleration mechanism that depends on $B_z$ in the neutral sheet makes the results model dependent.

In this study we emphasize the low-energy cutoffs in the ion energy spectra, as this is the principal consequence of the velocity filter effect. Onsager et al. [1990] and Lockwood and Smith [1992] have previously advocated using low-energy cutoffs in the analysis of velocity filters in the PSBL and in the cusp, respectively. We find VDIS more frequently than Zelenyi et al. [1990], probably because of greater sensitivity. After consideration of some examples we focus on the four events depicted in Plate 1. We are able to determine the distance to the reconnection site more accurately and with greater confidence by taking into account transitions in the electron precipitation in our minimum variance analyses. The distances to the reconnection sites for the four events in Plate 1 are estimated. In addition, it appears that the convection reversal boundary lies significantly closer to the VDIS than expected from the transit time of the Alfvén wave from the reconnection site.

2. Observations and Interpretation

The defining feature of interest to us is the presence of truncated ion spectra at the poleward edge of the oval. Such a feature is the expected result of simple time-of-flight segregation of ions that have recently been introduced to newly reconnected lobe field lines [Onsager et al., 1991]. Only ions above a particular energy have sufficient velocity to have reached Earth since the field line was first populated at the reconnection site. Frequently, the energy at which the spectra drop off is smoothly dispersed with latitude hence the VDIS of Zelenyi et al. [1990]. This is an indication that reconnection has been steady for at least the time it takes to form such a structure. For example, the travel times for field-aligned H+ along a 50 $R_E$ long field line at 3 keV and 20 keV would be 7 min and 3 min, respectively. A smooth VDIS extending between these energies and mapping to such a distance would imply that starting before 7 min in the past, reconnection had proceeded in a somewhat steady fashion for at least 4 min. Since we see many of these events, they probably last for much longer than 4 min, though we do not estimate their persistence. We describe such events as being quasi-steady. Some structures are not as smooth as others are, this may indicate small-scale transient behavior in the reconnection process for these cases.

Plate 2 shows two DMSP passes for which many truncated ion spectra are observed. Four examples of such spectra were selected from these and two other VDIS and are shown in Figure 2. Note the dramatic drop to very low fluxes, a distinctive signature of the velocity filter effect combined with recent merging. For the events in Plate 1 and Plate 2a, there is a clear cutoff of the polar rain poleward of the VDIS. Only about one third of VDIS exhibit such a transition from polar rain to either higher-energy electrons or no electrons. Polar rain streams in on open field lines from the solar wind [Fairfield and Scudder, 1985; Sotirelis et al., 1997] (the open field lines closest to the plasma sheet, such as those being considered here, first go very far down the tail). The field line associated with the sudden disappearance of polar rain is interpreted as having very recently reconnected, picking up the flow of electrons. Hence the gap between the VDIS and the polar rain transition is interpreted as a region of newly closed field lines on which ions have not yet had time to reach the ionosphere. In some cases the last few seconds of polar rain spectra are cut off at high energies that are dispersed with latitude (e.g., Plate 1c). This feature is easily understood in terms of time-of-flight effects: when the field line is pinched off, the faster electrons are ejected from the field line first. Since this feature is usually latitudinally small compared to our instrument resolution, it is only sometimes resolved. Shirai et al. [1997] see this feature more clearly in Akebono observations because of differences in location and instrumentation. The intensity of polar rain depends primarily on the presence of suprathermal electrons in the solar wind and on which hemisphere is connected toward the Sun [Vasyliunas and Frank, 1976; Gussenhoven et al., 1984]. For most VDIS not accompanied by a clear polar rain transition, the polar rain is too weak; in other cases the transition may be unclear because the polar rain blends smoothly into auroral electrons (e.g., Plate 2b).

The electrons precipitating immediately equatorward of the polar rain dropoff are interpreted as originating at the reconnection site. Such electrons have been observed at high altitude, where they form the outer edge of the plasma sheet boundary layer (PSBL) [Onsager et al., 1990]. At low altitude the flux of PSBL electrons tends to ramp up slowly as the main part of the oval is approached. This suggests that the gap that is sometimes present between the disappearance of polar
Plate 1. Four velocity-dispersed ion structure (VDIS) events indicated by the red boxes, with polar rain transitions marked by a red arrow. Within the VDIS, ion spectra are cut off at low energy, indicative of ion injection onto newly merged field lines under the influence of the velocity filter effect. The top two panels of each plot show log energy flux (eV cm\(^{-2}\) sr\(^{-1}\) s\(^{-1}\)) and log average energy (eV), respectively. The bottom two panels are energy-time spectrograms of the differential energy flux in cm\(^{-2}\) sr\(^{-1}\) s\(^{-1}\).

rain and precipitating PSBL electrons is due to the instrument's detection threshold. This is consistent with the hypothesis that the PSBL electron flux is sometimes restrained by the field-aligned potential that can result from the need to maintain quasi-neutrality on field lines poleward of the VDIS when ion densities are low. The PSBL electrons that do arrive do not seem to exhibit low-energy cutoffs. We list three possible reasons for this. First, the dispersion of the electron cutoff energy with latitude would be very fast, spanning several energy channels during the 1-s integration time of the instrument; the resulting signature may be impossible to resolve with 1-s measurements. Second, the flux of electrons at the polar rain dropoff where this signature would be expected is frequently below detection threshold. Third, the energy spectrum of PSBL electrons may be blurred by the large-amplitude, kilohertz range, parallelly polarized electrostatic waves associated with the outer electron layer of the PSBL [Onsager et al., 1993]. The peak differential energy flux of the precipitating PSBL electrons described above is usually between 0.4 keV and 2 keV. The flux of electrons more than a few channels below the
peak is usually suppressed, giving the appearance of an overhang (e.g., as seen between the open-closed boundary and the VDIS in the middle panel of Plate 2a). Such overhanging poleward extensions of the main oval have been noted elsewhere [Newell et al., 1996]. They are associated with the vast majority of our VDIS events.

Plate 3 shows two passes wherein DMSP F11 skims the nightside oval, observing truncated ion spectra at each encounter. These events appear to extend across 2.5 and 5 hours of local time, respectively. In Plate 3a, VDIS are observed when the spacecraft first enters the cap and during its final departure. In between a small fragment of plasma sheet (PS) precipitation is seen. It appears to be sandwiched between two and three truncated ion spectra, though the indications are not entirely clear. The appearance of such an isolated PS fragment raises the possibility of an association with theta aurora [Newell et al., 1997]. An F8 pass 55 min later finds a PS fragment surrounded by two to three clearly truncated spectra on each side.
Figure 2. Examples of clearly truncated ion energy spectra, that is, spectra that cut off at low energies. Such spectra are produced by time-of-flight effects when newly introduced ions stream along recently reconnected field lines. The one count level is shown with dashed lines, and the error bars are ±√n, except for zero count points for which they are not very meaningful.

at 0300 magnetic local time and 80° magnetic latitude (MLAT) quite close to the main oval. This indicates the possibility that there was a cross-polar incursion of the PS (the bar of the theta) into the cap that has moved toward dawn in the inter-vening 55 min. It could easily be the case that the PS fragment in Plate 3a is just a small bump in the nightside oval. Regardless, it seems clear from the presence of truncated ion spectra that field lines on both sides of these PS fragments are either open or very recently closed.

In contrast, the reentry into the oval in the middle of Plate 3b, which occurs almost 4 hours later, is very likely not associated with theta aurora. First of all, it consists entirely of PSBL-like very clearly truncated spectra. In addition, dawn-dusk DMSP F6 passes 1 hour before and 40 min later sec no isolated PS fragments. This brief reentry into the PSBL is probably due to an irregularity in the shape of the oval. Regardless of any association with theta aurora the examples in Plate 3 demonstrate that, at times, quasi-steady reconnection occurs simultaneously across much of the tail.

Plate 4 shows two examples of VDIS that are interrupted by accelerated electrons. Such events imply that significant field-aligned currents can flow out of VDIS. The electric field that accelerates electrons downward seems to decelerate ions in the VDIS to the point where the cutoff energy is reduced below to near or below zero. It may strike the reader as odd that 5-keV ions are being excluded by an electric field that accelerates electrons to only 1 keV, but this is a commonly observed occurrence regardless of the presence of VDIS and may reflect time dependence in the acceleration process. There are many examples where VDIS are terminated on their equatorward edge by such accelerations, but examples such as these where they are merely interrupted are rare. Such interruptions raise the possibility that some potential VDIS are never seen because of concurrent accelerations.

Ten days in March 1992 were visually surveyed for truncated ion spectra on the poleward edge of the oval. During this time, there were four DMSP spacecraft operational, F8–F11. The DMSP spacecraft are in polar orbits at ~850-km altitude and carry the S3I4 detector [Hardy et al., 1984]. The S3I4 measures downward fluxes of field-aligned (within ~3° of vertical) ions and electrons from 32 eV to 30 keV in 19 channels, once per second. Our primary identification criterion was the occurrence of more than about five spectra with visible low-energy cutoffs in the polewardmost precipitating ions. Borderline cases were decided by secondary criteria: dispersion of the cutoff energy with latitude and the presence of electron “overhanging.” These criteria were applied manually, but the number of borderline cases was a small percentage of the total. We will continue to call these events VDIS even though dispersion with latitude is not the primary identifying criterion. In 886 nightside crossings, 147 such signatures were found. Their locations are shown in Figure 3. Note that no VDIS were found on the dayside though a similar number of dayside crossings were examined (we exclude the truncated spectra sometimes associated with cusp precipitation and interpreted as a signature of dayside reconnection [Lockwood and Smith, 1992; Newell and Meng, 1995]).

Plate 5 shows the percentage of crossings with VDIS as a function of position, together with the total number of boundary crossings in each bin. Clearly, there is some noise due to the small numbers of events. Regardless, we can conclude that VDIS are present roughly 40% of the time between 2200 and 0100 MLT. Excepting noise, the percentages in Plate 5 may be viewed as a lower bound since weak borderline events were discarded. It is possible that a more sensitive instrument would permit the reliable identification of events with fluxes lower than even our borderline cases.

If VDIS do extend to flux lev-
Plate 5. The percent of open-closed boundary crossings for which VDIS are observed as a function of location. The total number of boundary crossings in each 5° by 1 hour bin is indicated by the number within.

The extent of the dispersion with latitude of low-energy cutoffs depends on the product of the convection velocity and the length of the field line. In order to disentangle the two, one of them must be independently determined. We make use of data from the retarding potential analyzer and the drift meter from the SSEIS instrument package on the DMSP spacecraft [Greenspan et al., 1986] to measure the convection velocity so that the length of the field line can be determined. The plasma velocity measurements have 4-s resolution. For only nine of the 49 selected events were three-dimensional plasma velocity data available. Of the nine VDIS, for only four was the convection
direction sufficiently parallel to the satellite trajectory for the distance to the reconnection site to be well approximated. These are the energy-time spectrograms shown in Plate 1.

3. Minimum Variance Analysis

Individual events are modeled by minimum variance analyses of the cutoff energy of the ion spectra and polar rain transitions. We consider only field-aligned particles as these are what the DMSP SSII+ measures. The model consists of a simple time-of-flight calculation, under the assumption of steady convection, a stationary reconnection site and constant reconnection rate. Deviations from these assumptions will be indicated by large variances in our fits. An excellent discussion of the physical mechanism behind the velocity filter effect, on which such time-of-flight calculations are based, is given by Onsager et al. [1990, 1991].

We digress briefly in order to discuss the analysis of Zelenyi et al. [1990]. This pioneering work makes an important contribution, but some elements of the analysis are flawed. They viewed the dispersion of the peak energy of ion spectra with latitude in terms of a combination of differential acceleration from an extended source and the velocity filter effect. They were able to produce many different profiles of energy versus latitude, based on a variety of magnetic field models. While the acceleration model they use [Lyons and Speiser, 1982] may or may not apply to these types of events, there is no need to consider an acceleration model. Their view seems to be that there is a characteristic energy to which ions are accelerated that depends on distance from an X line. The resulting variation with distance from the X line would map to a variation of peak energy with latitude in the ionosphere, as modulated by the velocity filter effect. This is not correct since a velocity filter does not simply modulate the peak energy of a source distribution.

The velocity filter mixes particles originating from different locations in the vicinity of the reconnection site in a specific manner. In principle, to find the peak energy of the near-Earth distribution we need nearly complete knowledge of the source distribution and how it varies as the high-altitude extreme of a field line samples points farther and farther from the reconnection site. However, the energy at which the spectrum cuts off depends only on the velocity filter, characterized by the geometry, the convection rate, and the reconnection rate. In point of fact, the cutoff energy of the near-Earth distribution is frequently the same as its peak energy (but unrelated to the peak energy of the source): it is the interpretation that is simpler when we focus on the cutoff energy. Said differently, it is unnecessary to consider variations of the source distribution with distance from the reconnection site because the source for the lowest energy ions is always the most recently closed field line (see the bottom panel of Figure 1 of Onsager and Mukai [1995]). The additional complexity introduced by Zelenyi et al. [1990] appears to be motivated by a desire to accommodate anomalous events exhibiting either reverse dispersion or no dispersion, for which we suspect there are different interpretations.

Our analysis of VDIS is based on a simple time-of-flight calculation wherein events are located in the ionosphere in altitude-adjusted corrected geomagnetic coordinates [Baker and Wing, 1989]. For the ith cutoff ion spectra we find the velocity

\[ v_i = \sqrt{2E_i/m} \]

of the lowest-energy ions and set it equal to the distance to the reconnection site divided by the time since the field line reconnect (\( t_i - t_a \)). The time since the field line reconnected is equal to the ratio of the separation in magnetic latitude from the open-closed boundary to the convection speed multiplied by several geometric factors

\[ v_i = s/(t_i - t_a) = sf/(\mu_i - \mu_0) \]  

where the corrected magnetic latitude of the open-closed boundary is \( \mu_0 \) and the corrected magnetic latitude of the ith ion spectra is \( \mu_i \). The factor \( f \) is the rate of change of latitude of the field line projected into the ionosphere. There is also an implied geometric factor related to any local time structure of the open-closed boundary. The velocities \( v_i \) map from the MLATs \( \mu_i \) back through the velocity filter to a single location, the reconnection site. A similar equation applies to polar rain transitions.

An automated search of the visually identified VDIS time interval (indicated by a red box in Plate 1) is made for truncated ion spectra and their cutoff energies. The criterion is a sharp transition from large energy fluxes at high energies to almost no counts at lower energies (with the exception of the lowest-energy channel, which is sometimes contaminated by spacecraft charging effects). The polar rain transition is determined visually, tagged either by the first electrons to arrive from the reconnection site (Plates 1a and 1d) or the dropoff of polar rain (Plates 1a and 1b), whichever seems to be the most immediate indicator of a transition. Using these velocities in (1) and rearranging, we obtain a system of \( N \) equations in two unknowns \( \mu_0 \) and \( sf \)

\[
\begin{align*}
    v_1 \mu_0 + sf &= v_1 \mu_1 \\
    v_2 \mu_0 + sf &= v_2 \mu_2 \\
    &\vdots \\
    v_N \mu_0 + sf &= v_N \mu_N
\end{align*}
\]  

(2)
Minimum variance solutions for \( \mu_0 \) and \( \sigma \) are then obtained numerically. The quality of the fits is verified by substituting the solutions for \( \mu_0 \) and \( \sigma \) back into (2) and plotting the implied energy cutoffs together with the actual cutoffs. Such plots for the events in Plate 1 appear in Figure 4.

Including polar rain transitions (the isolated points on the right of Figure 4) improves the fits since they lie much closer to the open-closed boundary. They reduce the sensitivity to small-scale irregularities, permitting a more accurate fit based on the events' grosser features. It is clear that the event shown in Figure 4c best fits the assumption of steady reconnection at a stationary site. While Figures 4a and 4d show some small-scale structure, their gross features, nonetheless, conform to this assumption. For the event shown in Figure 4b, however, the slope derived from the electron–ion spacing does not seem to fit the ion structure at all. The disagreement is not as bad as it might seem since one can see evidence for stronger ion dispersion in Plate 1b (the plus signs in Figure 4 are determined automatically and the polewardmost ion counts in Plate 1b are below threshold). However, we suspect that assuming a retreating reconnection site might better fit events like this where the dispersion flattens out near the equatorward edge of the structure. (A correctly varying reconnection rate could also produce such an effect; unfortunately, distinguishing between these two possibilities would require additional observations and analysis.)

The fits to these four events are fairly representative of the fits to the remaining 45 events, some relying on the polar rain transition more strongly than others and a few that violate our assumptions and/or exhibit local time structure. (When the spacecraft trajectory does not parallel the direction of convection, local time structure can be expected to yield unusual VDIS.)

In these fits we assume steady reconnection at a stationary site. One could go beyond these assumptions on a case-by-case basis. To account for a reconnection site that is retreating down the tail, for instance, one would have to modify (1) by replacing \( s \) with \( s = s_0 + u(t_0 - t) \), where \( u \) is the velocity of the retreating reconnection site. One would then solve for \( s_0, \mu_0 \), and \( u \), though in this case the minimum variance calculation would be nonlinear. By allowing for local time structure, time-dependent reconnection, and an unsteadily moving reconnection site, we likely have more freedom than we need to reproduce any unusual VDIS we might encounter, but such contortions will not likely be very revealing.

![Figure 4](image)

**Figure 4.** Fits to velocity-dispersed ion structures. Low-energy cutoffs in the ion spectra and polar rain transitions for the four events depicted in Plate 1 are shown in energy versus time (seconds from the beginning of the hour). The plus signs are the data, and the crosses are the values obtained from two-parameter fits. The cluster of points to the left of each plot corresponds to ion cutoffs, and the isolated points on the right correspond to polar rain transitions. The dashed vertical line is the ionospheric footprint of the inferred open-closed boundary.
4. Distance Determination

Minimum variance fits provide numerical values for the quantity $s$. In order to find the distance $s$ to a reconnection site, we need to know $s$, which is a function of the convection velocity and several factors of a geometric nature. Of the several geometric factors to be taken into account, only one is unknown, the local time dependence of the latitude of the open-closed boundary. This factor contributes only when the convection flow and the satellite motion are not in the same direction, so we have discarded five such events. Velocity measurements for the four remaining events are shown in Figure 5; these are the same four events shown in Plate 1 and Figure 4.

Examination of these velocity data reveals an unexpected feature. Velocities corresponding to equatorward convection tend to appear where the ion precipitation structure is present but not always poleward between the ion structure and the open-closed boundary as indicated by the polar rain transition (Figures 5a, 5c, and 5d). Since these events appear to be somewhat steady for at least several minutes, one might expect the convection of open field lines poleward of the polar rain transition to slowly turn equatorward as their high-altitude portion in the lobe is drawn into the reconnection site. The Alfvén speed on lobe field lines $v_A \sim 0.5 R_e/s$ for $B_L = 1.5$ nT and $n = 0.01$/cm$^3$ appears to be too fast to account for the observed delay, especially since the reconnection electric field should begin propagating earthward on magnetic field lines poleward of the open-closed boundary.

Another possible explanation is that in order for the reconnection site to impose an electric field on the ionosphere, a current must flow between them. The density available to carry the current could limit this imposition (the density of electrons cannot exceed that of ions, which should resemble lobe densities until ions streaming along the field line from the reconnection site arrive). As a crude estimate, we wish to consider an imposed velocity of 1000 m/s at DMSP altitude where $B = 40,000$ nT, which requires $E_L = 40$ mV/m. If we take $\Sigma_p = 2$ mho and a characteristic length of 100 km in $J_b = \Sigma_p V \cdot E_L$, we estimate a field-aligned current density of $J_b \sim 0.8$ $\mu$A/m$^2$. Using 100-eV electrons to carry the current and taking the density in the lobe to be 0.01/cm$^3$, we find an upper limit of

![Diagram](image_url)

**Figure 5.** Plasma velocity measurements from the retarding potential analyzer and drift meter aboard the DMSP spacecraft: (a) $s = 50 \text{ to } -80 R_E$, (b) $s = -30 R_E$, (c) $s = -38 R_E$, and (d) $s = -80 R_E$. These four second measurements are shown in bold when coincident with VDIS; the thinner vectors are for between the VDIS and the polar rain transition.
Taking the density in the PSBL to be 0.1/cm³, we obtain an upper limit of

\[ J_{\text{PSBL}} \approx 100 \text{ nA/m}^2 \]

Assuming sufficient currents, the carrier density would increase as it approached the ionosphere following converging field lines, reaching 0.8 μA/m² at DMSP altitude. Its magnitude as a function of field strength would be

\[ J_e \approx 0.8 \text{ μA/m}^2 \sqrt{B/40,000 \text{ nT}} \]

This exceeds the maximum current density in the lobe at about \( r \approx 5 R_E \). The PSBL threshold is exceeded at about \( r \approx 2.3 R_E \). In this circumstance the current might jump the gap from \( r \approx 2.3 R_E \), with the aid of field-aligned acceleration if necessary. Field-aligned acceleration is not thought to occur at \( r \approx 5 R_E \), so it is unlikely that such a current could be supported in either the lobe or in the outer layer of the PSBL that has not yet been populated with ions from the reconnection site. Admittedly, the numbers used here are rough estimates, but they establish the feasibility of the proposed mechanism.

Similar velocity shears have been previously observed and sometimes associated with VDIS and the PSBL [Burke et al., 1994; Senior et al., 1994; de la Beaujardière et al., 1994], though the emphasis and interpretations are varied. It is possible that the mechanism we propose applies to some of these observations, but the situation is far from settled. This phenomenon clearly requires further study.

The convection speed is required in order to deduce the distance to a reconnection site. We will interpret the sudden change in velocity as being due to an electrostatic field propagation effect, regardless of the mechanism, and will average the velocity measurements coincident with the VDIS (the bold vectors in Figure 5). Using these velocities and taking into account various geometric factors, we were able to estimate field line lengths for our four events: \(-50-80 R_E \) (Figure 5a), \(-50 R_E \) (Figure 5b), \(-35 R_E \) (Figure 5c), \(-80 R_E \) (Figure 5d). Characterizing the uncertainty in these determinations is difficult. A large uncertainty in the distance determination is due to the unknown local time structure of the open-closed boundary in the ionosphere. Unless the convection velocity is very close to the satellite track, assuming that the boundary is either perpendicular to the satellite track or lies at constant magnetic latitude can result in very different estimates. This is the reason why a distance range is provided for the event shown in Figure 5a and would contribute uncertainties to the other three events of approximately \( \pm 2 R_E \), \( \pm 5 R_E \), and \( \pm 10 R_E \) for Figures 5b-5d, respectively. Barring violations of our assumptions, the remaining uncertainty in the distance determination is estimated to fall in the 20% to 40% range. The primary concerns here are uncertainties in the polar rain transition and the convection velocity.

Another major source of uncertainty is the degree to which our assumption of steady reconnection at a stationary reconnection site fails. This uncertainty is potentially large. The small-scale irregularities seen in Figure 4 could be due to fluctuating reconnection rates that, nonetheless, left our distance determinations relatively intact. If, however, the disagreement between the data and the fit in the event shown in Figure 5b is due to the reconnection site retreating down the tail, then a different kind of fit would need to be performed (though the distance provided here would probably be bracketed by the near and far locations that contributed precipitation to the event). Proper resolution of this issue would require multiple observations of each event in order to ascertain their time dependence. Any field-aligned potentials overlapping the VDIS in Plate I would also affect our distance determination, though we see little evidence of this.

5. Summary

Type 2 VDIS have been reexamined with an emphasis on truncated ion spectra and associated polar rain transitions. We find these VDIS mostly within 2-3 hours of midnight and for 40% of open-closed boundary crossings between 2200 and 0100 MLT. Several examples were provided to illustrate various commonly observed features. It was explained that it is unnecessary to assume a specific acceleration mechanism in order to interpret these events as all features are well explained as time-of-flight effects.

A minimum variance technique was used to model the events, and plasma velocity measurements were used to estimate the field line length for four of them. Lengths ranging from 30 R_E to 80 R_E were obtained. An interesting velocity transition was associated with three of these four events, unfield closed field lines, in close proximity to the first ions to arrive from the reconnection site. A possible explanation was put forward: that the electric field at the reconnection site was being imposed on the ionosphere but only after the field line is sufficiently populated to carry the necessary current. This hypothesis requires further study. If true, then field lines associated with quasi-steady reconnection are frequently not equipotentials.

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