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Observations of Reconnected Flux Tubes Within the Midaltitude Cusp

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Dynamics Explorer 1 observations within the midaltitude polar cusp provide indirect evidence of reconnected flux tubes (RFT) envisioned to be extensions of the flux transfer events reportedly found near the magnetopause. In this study, low-energy plasma, high-energy plasma, magnetic fields, and electric fields were used to identify the signatures of reconnected flux tubes in the midaltitude cusp. Inside isolated flux tubes, low-energy plasma was observed to be transferred from the magnetosheath to the magnetosphere, and relatively hot plasma was observed to be transferred from the magnetosphere to the magnetosheath. The cool magnetosheath plasma and the relatively hot magnetospheric plasma shared the same magnetic flux tube. The RFT signature is most easily identified in electron and ion energy fluxes plotted versus time for all pitch angles. The electron signature of an RFT is characterized by a drop in energy at the upper side of the energy band. The ion energy signature is similar to the electron signature except the ions form distinct Vs within the RFTs which differ from Vs outside the RFTs by the fact that the thickness of the lines forming the sides of the Vs is thinner inside the RFTs in comparison to that outside, and the height of these Vs is shorter inside the RFTs. The characteristics of spatial scale, time duration, and frequency of occurrence between flux transfer events and midaltitude cusp reconnected flux tubes are consistent, although they differ in the direction of motion. However, the merging cell topology and the interplanetary magnetic field B_Y effect can explain this difference. Larger-scale (space and time) events can be explained by motion of the cusp resulting from a quasi-steady reconnection process. The field-aligned currents associated with reconnected flux tubes at midaltitudes within the cusp are consistent with twisting of magnetic field lines and with closure by Pedersen currents. It is possible that what appear to be field-aligned currents closing by Pedersen ionospheric currents may also be interpreted as currents carried by Alfvén waves.

INTRODUCTION

The process of magnetic flux transfer from the dayside magnetosphere to the nightside and back is very important in understanding magnetic storms and polar magnetic substorms. However, there is continuous controversy regarding the spatial and temporal nature of this process. *Dungey* [1961] applied the idea of magnetic field line reconnection to geomagnetic phenomena, while *Alfvén* [1976] has implied that steady state reconnection is misleading. *Haerendel et al.* [1978] have proposed merging in the polar cusp and envisioned a process taking place on a small spatiotemporal scale. Presently, the entry of magnetosheath plasma into the Earth's dayside magnetosphere via reconnection can be classified into three categories: (1) quasi-steady reconnection (QSR) [(*Paschmann et al.*, 1979; *Sonnerup et al.*, 1981; *Aggson et al.*, 1983], which is thought to be initiated near the subsolar point on the magnetopause; (2) flux transfer events (FTEs) [*Russell and Elphic*, 1978, 1979; *Rijnbeek et al.*, 1984*a*, *b*; *Saunders et al.*, 1984], which have been observed in the magnetosheath, magnetopause, and magnetosphere up to magnetic latitudes of 45°; and (3) merging in the polar cusp (MPC) [*Haerendel et al.*, 1978; *Burch et al.*, 1982; *Carlson and Torbert*, 1980].

Burch et al. [1982] have observed and modeled signatures of hot plasma in the midaltitude polar cusp which are consistent with a latitudinally narrow source region or a plasma injection of short duration taking place at a geocentric distance of about 8 R_E. *Torbert and Carlson* [1976] presented observations of energetic ions obtained from two separate rocket flights over Greenland in the morningside cleft during the years 1974 and 1975. They interpreted their data in ion spectrogram form to be consistent with sudden injection (at large distances) of ions of all energies, at the same time, with the high-speed ions preceding low-speed ions along the flux tube. *Carlson and Torbert* [1980] placed a transient source at a distance of 12 R_E within the polar cusp and estimated that the injection occurs simultaneously over a flux tube with 1000 km diameter at the source. Such flux tubes were repeated with spacing of minutes.

Maynard and Johnstone [1974] reported particle and electric field measurements in the polar cusp region from rocket 18.127, launched during relatively quiet magnetic conditions. Bursts of intense magnetosheath-type electron fluxes and variable large-amplitude electric fields were compared with results obtained by other types of spacecraft and were interpreted in the light of those data. We find one of their interpretations particularly illuminating in our effort to understand the data in the present paper. Perhaps for the first time they explained the variable nature of electron intensities as direct particle access occurring in small regions within a larger polar cusp region. In their Figure 12 one finds an insert at the left that illustrates the concept of a multiplicity of small, direct access regions within the observed wider cusp region. At that time, flux transfer events had not yet been discovered. After the fact, we are able to see now that they may have been reporting signatures of flux transfer events at ionospheric altitudes.

Most recently, *Smith et al.* [1986] have used high time resolution (5 s) three-dimensional ion distributions and magnetic field measurements from the Active Magnetospheric Particle Tracer Explorers (AMPTE) UKS spacecraft in order to study the structure and scale of flux transfer events. They presented instances where accelerated plasma is found

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in regions with magnetic field components normal to the magnetopause with amplitudes less that 10 nT and time scales shorter than 1 min.

A potential candidate site for reconnection in the polar cusp is the entry layer [*Paschmann et al.*, 1978, 1979]. As a result of field line interconnection, other boundary layers are formed, such as the low-latitude boundary layer [*Hones et al.*, 1972; *Eastman and Hones*, 1979], and the plasma mantle [*Rosenbauer et al.*, 1975]. In all cases the entering plasmas form a relatively thin layer adjacent to and on the earthward side of the magnetopause, and *Schindler* [1979] has proposed the term plasma boundary layer to refer collectively to all the different boundary layers. The convergence of the plasma boundary layer into the polar cusp region needs further study. For instance, electron beams observed in the low-latitude boundary layer (LLBL) [*Ogilvie et al.*, 1984] and near the equatorward side of the midaltitude cusp [*Burch*, 1983] should be correlated. Time coincident observations in the LLBL and the equatorward side of the cusp exist from DE and ISEE and may provide some clues as to the magnetic connection between these two regions (R. J. Fitzenreiter et al., unpublished manuscript, 1986).

Sibeck and Siscoe [1984] have considered theoretically the downstream evolution of reconnected flux tubes (RFTs). They proposed that following dayside merging, magnetosheath plasma expands into the magnetospheric part of the FTE, filling it in time. They further suggested that most multiple crossings of the tail boundary layer by spacecraft are encounters with tailward moving FTEs. Magnetosheath plasma expanding earthward in the reconnected flux tube and encountering hot magnetospheric plasma streaming outward within the same RFT was reported by *Paschmann et al.* [1982].

Two attempts have been made to associate discrete localized high-speed flows in the ionosphere with possible reconnected flux tubes. *Goertz et al.* [1985] have observed possible signatures of FTEs at ionospheric altitudes which last somewhat less than 1 min in the morning sector and recur with a periodicity of about 2 min. *Sandholt et al.* [1986] have used ground optical and ground magnetic observations to identify signatures of flux transfer events at ionospheric altitudes.

To our knowledge, no features in the midaltitude polar cusp have yet been identified by others as definitely corresponding to flux transfer events. It is important to note that FTEs at these altitudes have spatial scales which can be estimated by magnetic flux conservation and are found to be detectable by satellites. We present here three events interpreted as reconnected flux tubes that correspond to the extensions of FTEs which have penetrated deep into the magnetosphere down to the midaltitudes of the polar cusp.

OBSERVATIONS

The information to be used in this section comes from the satellites Dynamics Explorer 1 and 2 (DE 1 and DE 2). Descriptions of the instruments involved can be found in the work by *Burch et al.* [1981], *Chappell et al.* [1981], *Shawhan et al.* [1981], *Farthing et al.* [1981], and *Maynard et al.* [1981]. Data from the above instruments were obtained and analyzed with the goal of identifying possible signatures of flux transfer events within the midaltitude cusp. FTE magnetospheric segments, for distinction, are called RFTs (reconnected flux tubes).

Plate 1 presents spin-modulated energy fluxes of ions and electrons, separately, in energy versus time spectrogram form. (Plates 1–5 are shown here in black and white. The color versions can be found in the special color section in this issue.) Plate 1 covers the period from 0248:06 to 0254:24 UT of day 287, 1981. Clearly, the polar cusp is present following 0253:00 UT, judging only by the electron signature. Plate 2*a* shows energy-time spectrograms at pitch angles 0°–30° of high-altitude plasma instrument (HAPI) electrons (upper panel) and frequency-time spectrograms of plasma wave instrument (PWI) ac electric field spectral density (lower panel). We note that the electric spectral density increases dramatically at frequencies below 1 kHz shortly after 0253 UT. These frequencies are nearly simultaneous with "holes" in the electron energy-time spectrograms above 200-eV energies but cover wider regions. Note that the spectral densities are 96-s averages, so one should be cautious in comparing electron "holes" to enhancements of spectral densities.

Plate 2*b*'s top panel is the same as that of Plate 2*a*. Plate 2*b*'s bottom panel shows the magnetic field spectral densities versus time. Following 0253:00 UT the magnetic spectral density below 100 Hz increases, reaching peak values between 1 and 10 Hz. There are weaker spectral density values at frequencies greater than 100 Hz as indicated by the blue and green color. The spectral density in this spectrogram is also averaged over 96 s; therefore one should be cautious when comparing with features of finer detail such as the holes mentioned above. The electric and the magnetic spectrograms do not distinguish between RFTs and other types of reconnected flux tubes in the polar cusp.

Plates 3*a*–3*d* show energy-time spectrograms of HAPI energy fluxes at single pitch angles in various combinations of downward and upward moving ions and electrons. The spectrograms cover the time interval from 0249 to 0306 UT of day 287, 1981. Plate 3*a* shows that the downward electron energy flux holes are correlated with downward ion energy flux holes at the exact same times mentioned for Plates 2*a* and 2*b*. Plate 3*b*, however, shows that the upward ion energy fluxes do not exhibit flux tube depletions at the above times. Plate 3*c* shows upward electrons and downward ions, and the correlations of holes are again good at 0255:30, 0257:30, and 0300:30 UT as mentioned previously. Plate 3*d* shows upward electrons and upward ions, but the correlations in the respective holes again are not good.

Plate 4 shows RIMS H^+ count rates plotted in energy-time (upper panel) and spin-time (lower panel) spectrogram form. Plate 4 shows that beyond 0253 UT the H^+ cold plasma possesses some pitch angle dependent discrete characteristics. In the UT interval 0254:30–0255:30 the intensities are low. From 0255:30 to 0256:30, relatively intense ions are coming downward preferably in the second half of the interval. In the UT interval 0256:30–0257:30 the H^+ intensities are very low. However, relatively more intense H^+ downward intensities appear on the poleward side in the interval 0257:30–0259:30 UT for day 287, 1981. Clearly, the downcoming H^+ ions are found partly poleward of the presumed FTE tubes at the holes with significant time delays. This is probably so because convection affects the low-energy ions more severely.

Plates 5*a* and 5*b* are color-coded energy-time spectrograms of electron and ion energy fluxes. They cover the UT periods 0252:30–0259:30 and 0259:00–0305:00, respectively.

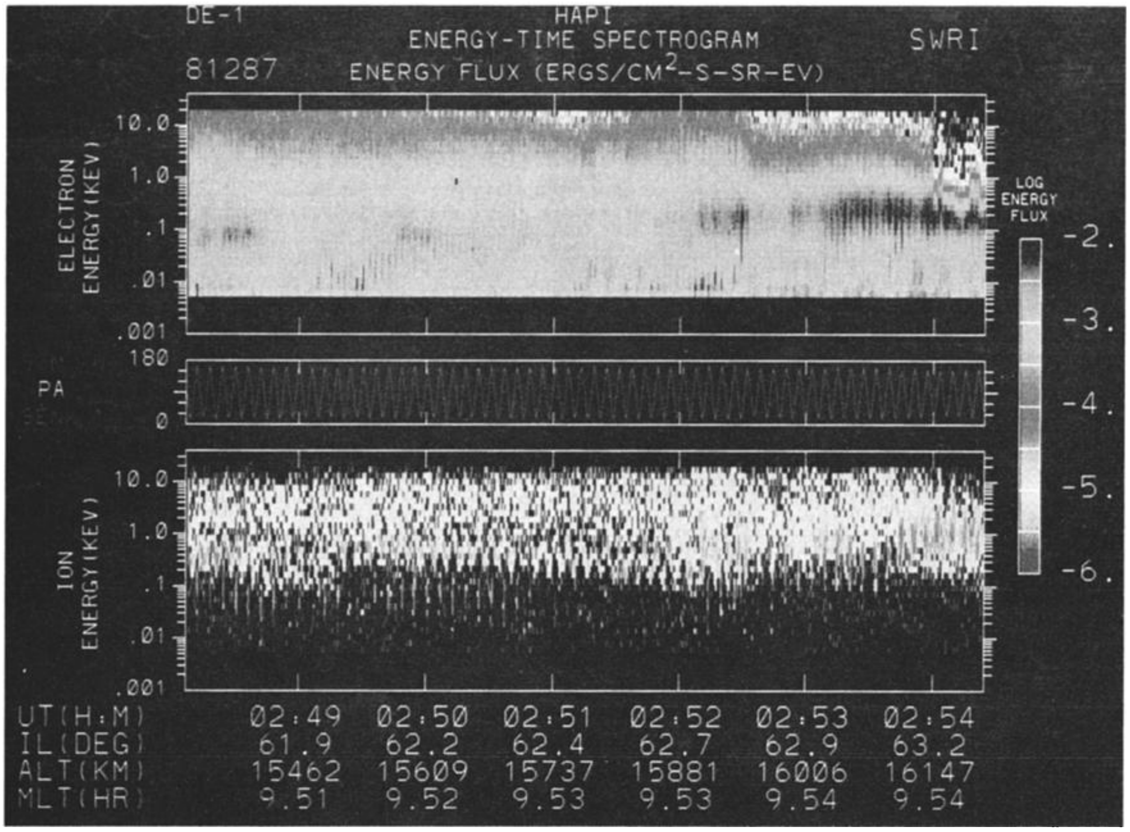

Plate 1. DE 1 HAPI *E-t* color spectrogram for 0248:06–0254:24 UT of day 287, 1981. Top panel is electron energy flux, middle panel is pitch angle, and bottom panel is ion energy flux. The color version of this figure can be found in the special color section in this issue.

The top panels are electrons, the middle panels are pitch angles (1°–180°), and the bottom panels are ions. The data are plotted with higher temporal resolution in order to study detailed characteristics of spin-modulated energy fluxes of ions and electrons in the UT intervals of interest (0255:00–0256:00, 0257:00–0258:00, and 0300:00–0302:00). The top panel of Plates 5*a* and 5*b* shows a greatly diminished intensity of electrons above 1 keV and a significant reduction of the energy flux above about 300 eV in the above three intervals. We call the softening of the spectra in these intervals "holes" as we did before. The more intense energy fluxes reach down to 50 eV in all three holes. These electrons appear to be of magnetosheath origin, having been injected into localized flux tubes of the polar cusp, possibly connected to FTEs, and subsequently having been reflected by magnetic mirrors at lower altitudes. As one moves away from the center of each hole, one encounters more energetic electrons on the outside. This pattern of lower energies in the middle and higher energies at the edges is reminiscent of the electron distributions reported by *Scudder et al.* [1984], which are explainable by the *Lee and Fu* [1985] theory whereby one employs the concept of connection between exterior field lines of an FTE and the region where reconnection is occurring. *Southwood et al.* [1988] and *Wright* [1987] explain the Scudder et al. data in the same way that *Lee and Fu* [1985] do except the *Southwood et al.* [1988] model does not involve multiple X line reconnection (MXR).

The bottom panels of Plates 5*a* and 5*b* show the energy versus pitch angle distribution of the ion energy flux. In the same intervals where electron holes appear, the ions have energies between 200 eV and 4 keV. The first interval (0255:00–0256:00 UT) shows lower-energy ions coming down and higher-energy ions going up. The spin period of DE 1 is 6 s, and the modulation of the pitch angle is shown in the middle panel. Clearly, the envelope of the higher energies for the ions indicates lower energies in the center of the localized flux tube and progressively increasing energies toward the edges of the tube. This may be a consequence of the local convection. All three cases are good examples of fresh injection events with characteristic V signatures. It is interesting to note that at a fixed pitch angle the energy band of a V side is narrower inside the fresh injection regions than outside [see *Menietti and Burch*, 1988]. The present set of data differs from those of Menietti and Burch due to the much greater planetary magnetic disturbance involved during this cusp crossing. The higher-energy flux in these distinct ion Vs corresponds to upgoing ions. The bottom envelope of the ion energy band varies to a lesser extent in comparison to the upper envelope. The two envelopes create the impression that the Vs are shorter near the middle of the flux tube and taller at the edges of the RFT. We believe that the narrowness of the flux tubes at the polar cusp-magnetosheath interface causes the discrete and thin energy bands of the Vs at fixed pitch angles as discussed by *Burch et al.* [1982]. The nondiscreteness of Vs outside the holes does not imply that the flux tubes are not reconnected; instead it means the injection regions have much greater cross-sectional areas as discussed by *Menietti and Burch* [1988].

Figures 1 and 2 show the moments of the electron and ion

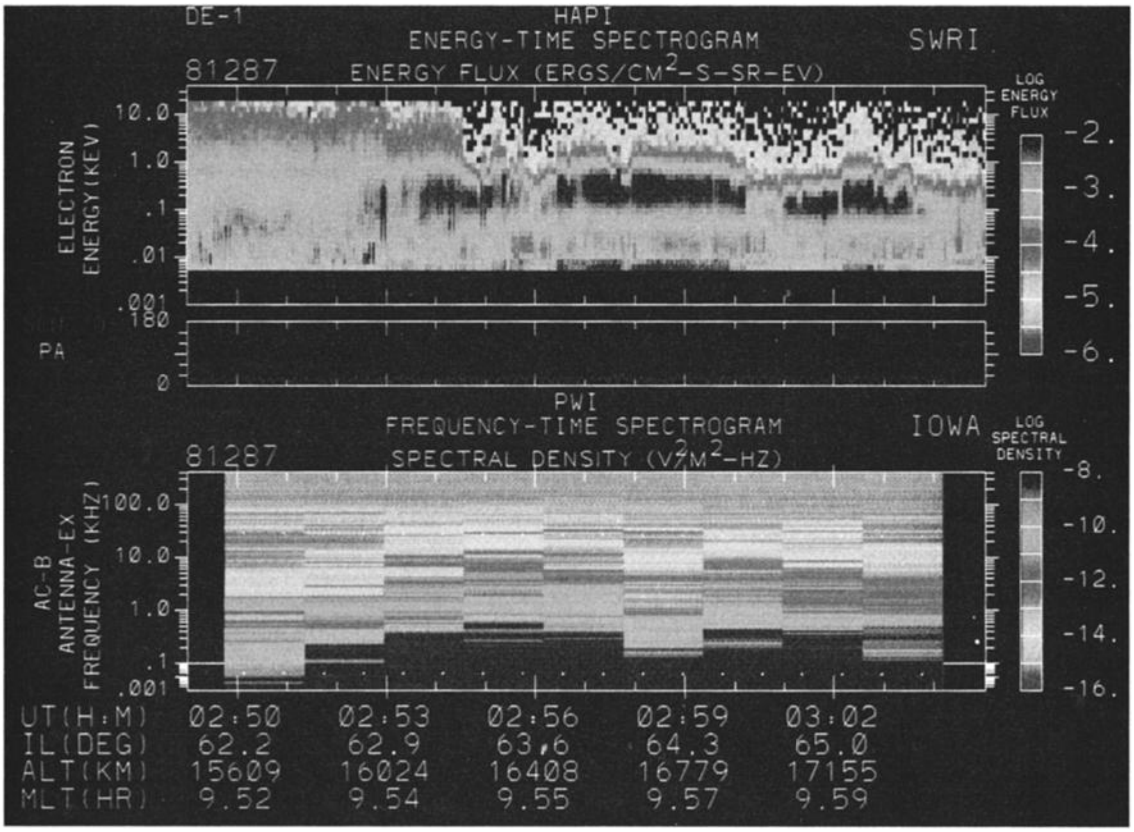

Plate 2*a*

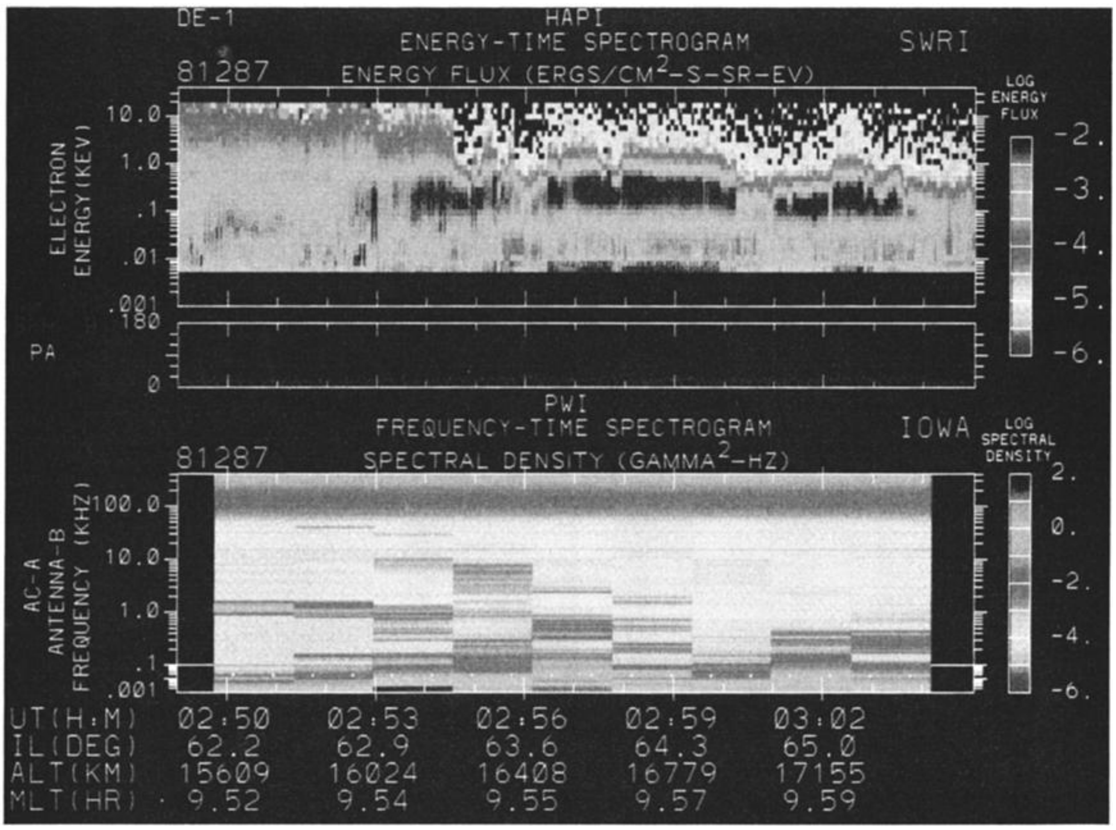

Plate 2*b*

Plate 2. DE 1 spectrograms covering the interval 0249–0306 UT of day 287, 1981. (*a*) Top panel is electron energy flux plotted in energy versus time. Middle panel is pitch angle (selected as 0° ± 30°) versus time. Bottom panel is ac electric power spectral density plotted in frequency versus time. (*b*) The same as Plate 2*a* except the bottom panel is ac magnetic power spectral density plotted in frequency versus time. The color version of this figure can be found in the special color section in this issue.

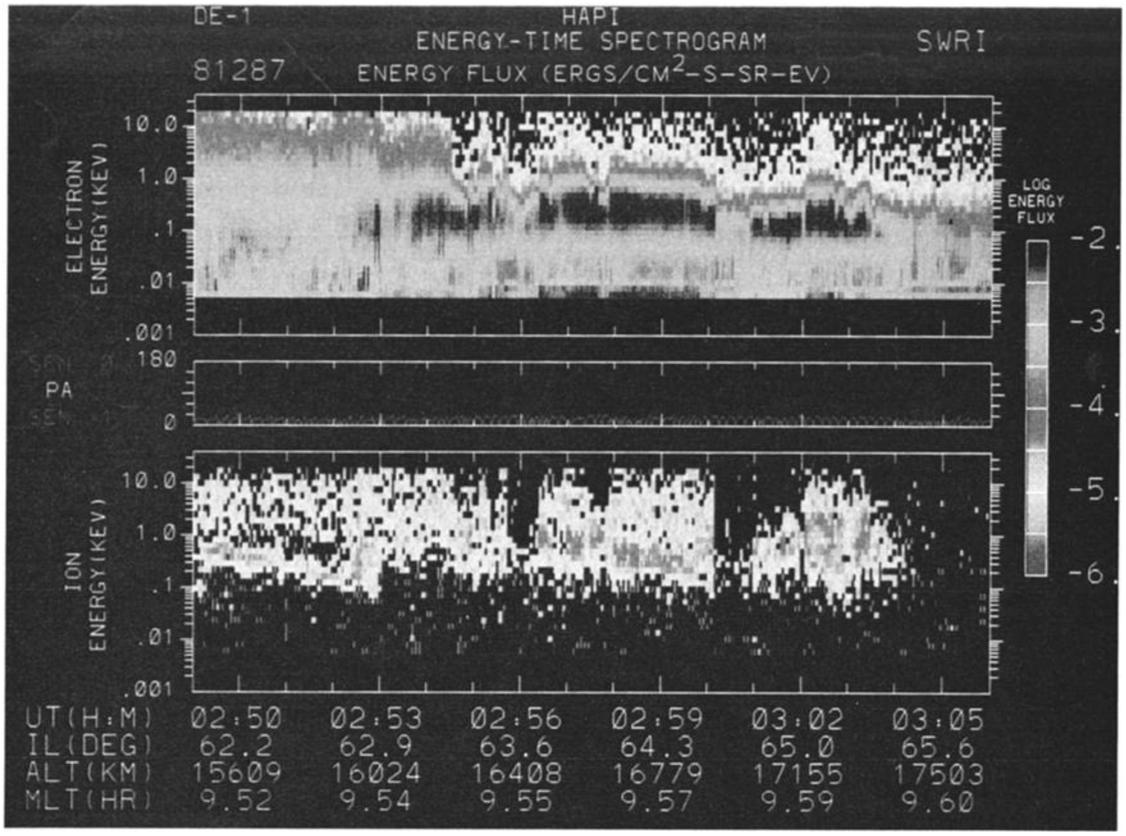

Plate 3*a*

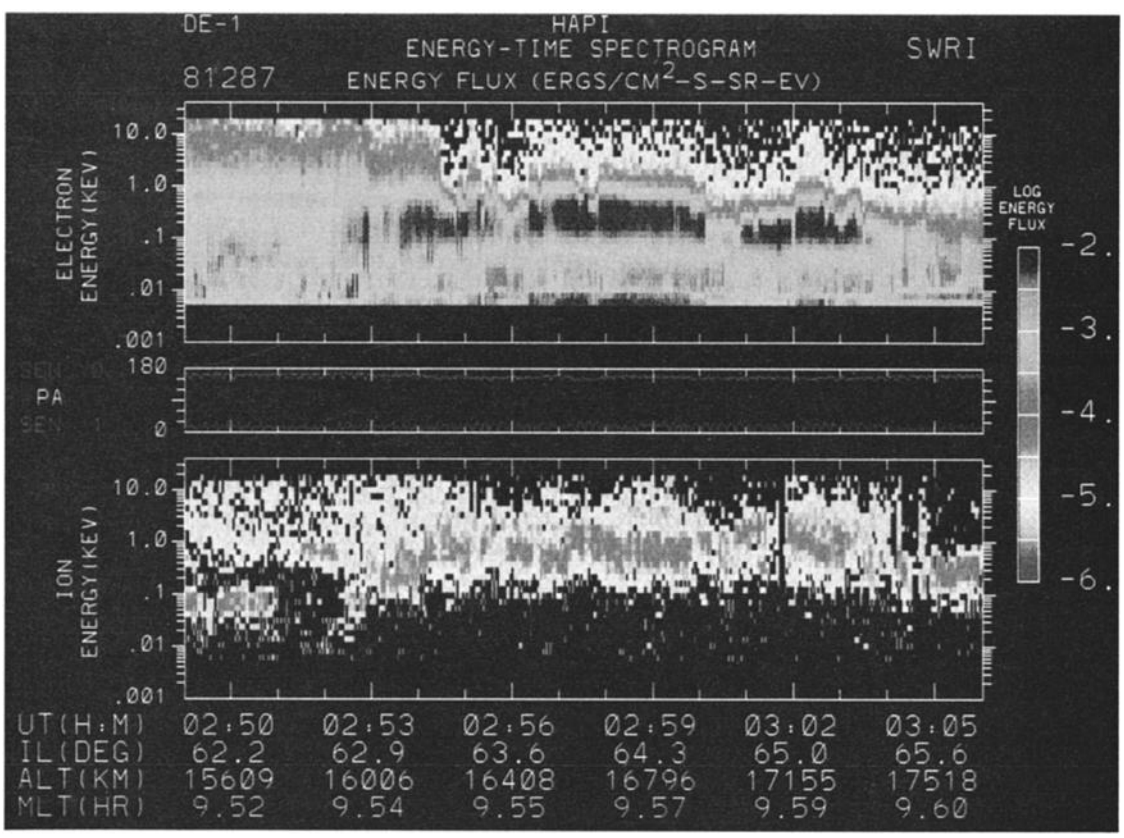

Plate 3*b*

Plate 3. DE 1 HAPI *E-t* spectrograms covering the interval 0249–0306 UT of day 287, 1981. (*a*) Top panel is electron energy flux. Bottom panel is ion energy flux. Middle panel is pitch angles of ions and electrons lying in the range 0° ± 30°. (*b*) The same as Plate 3*a* except the range of ion pitch angles is 180° ± 30°. (*c*) The same as Plate 3*b* except the pitch angles of ions and electrons are reversed. (*d*) Same as Plate 3*a* except the ranges of ion and electron pitch angles are 180° ± 30°. The color version of this figure can be found in the special color section in this issue.

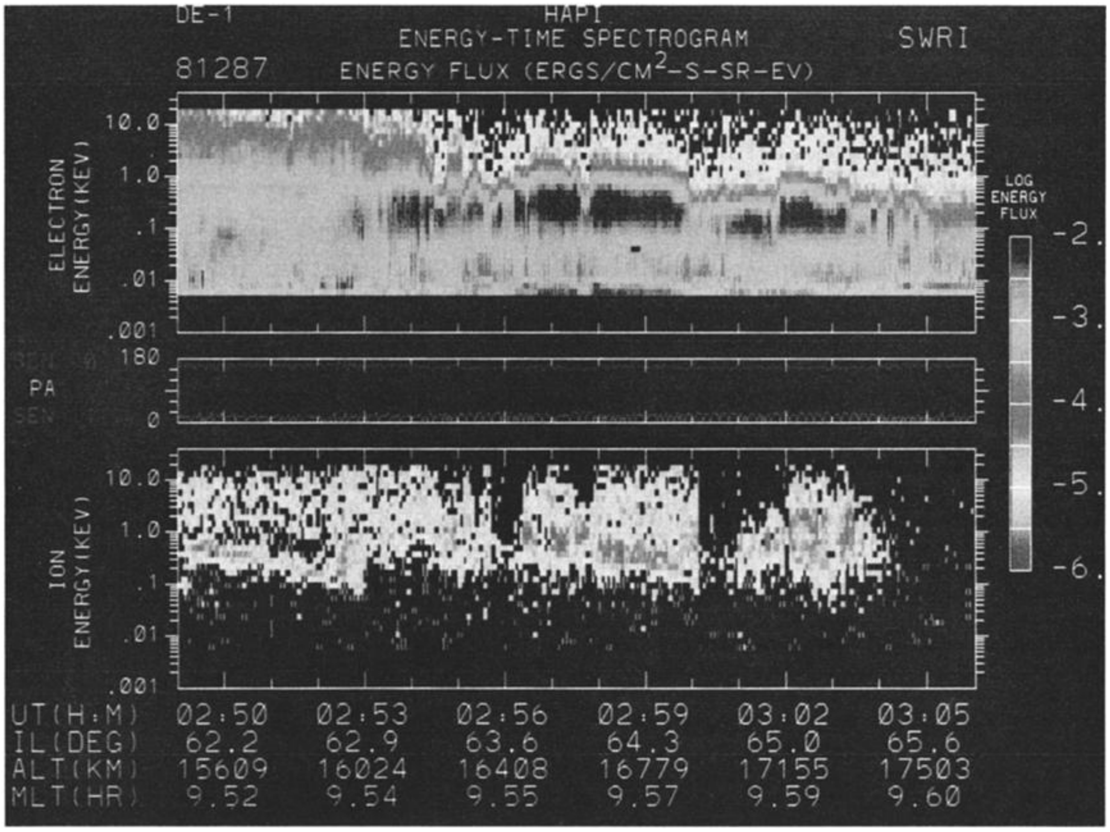

Plate 3*c*

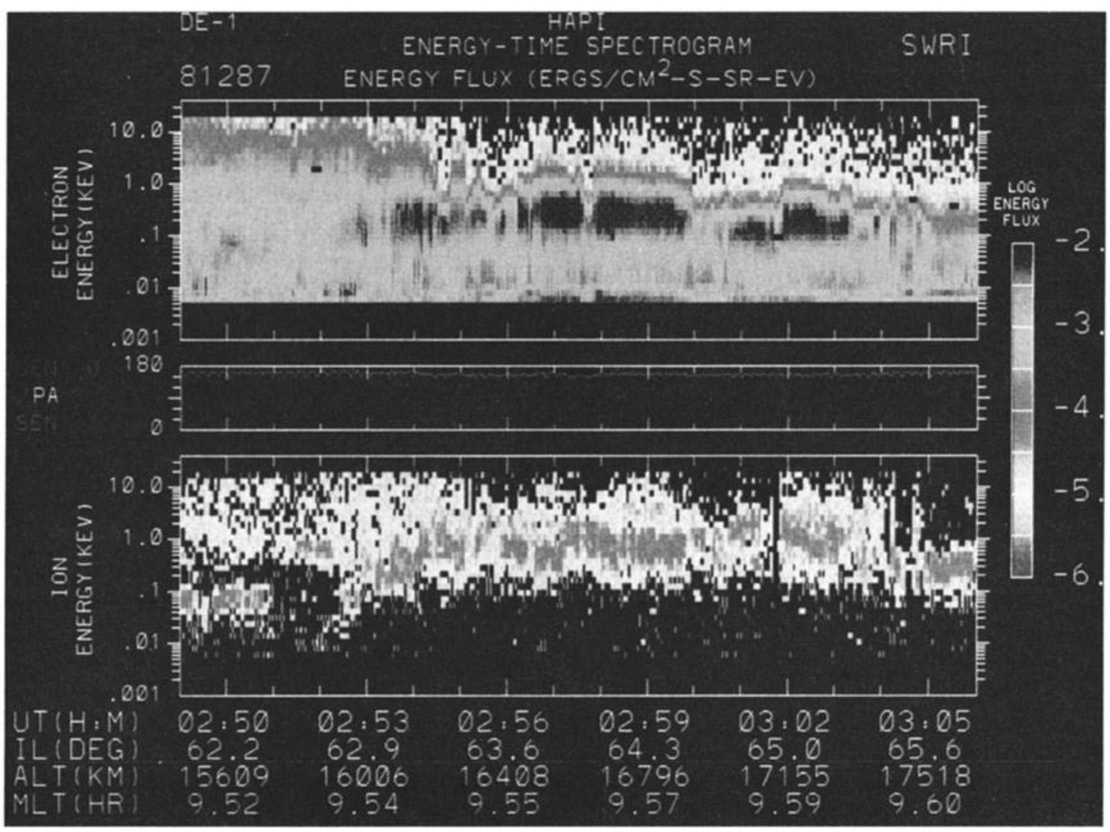

Plate 3*d*

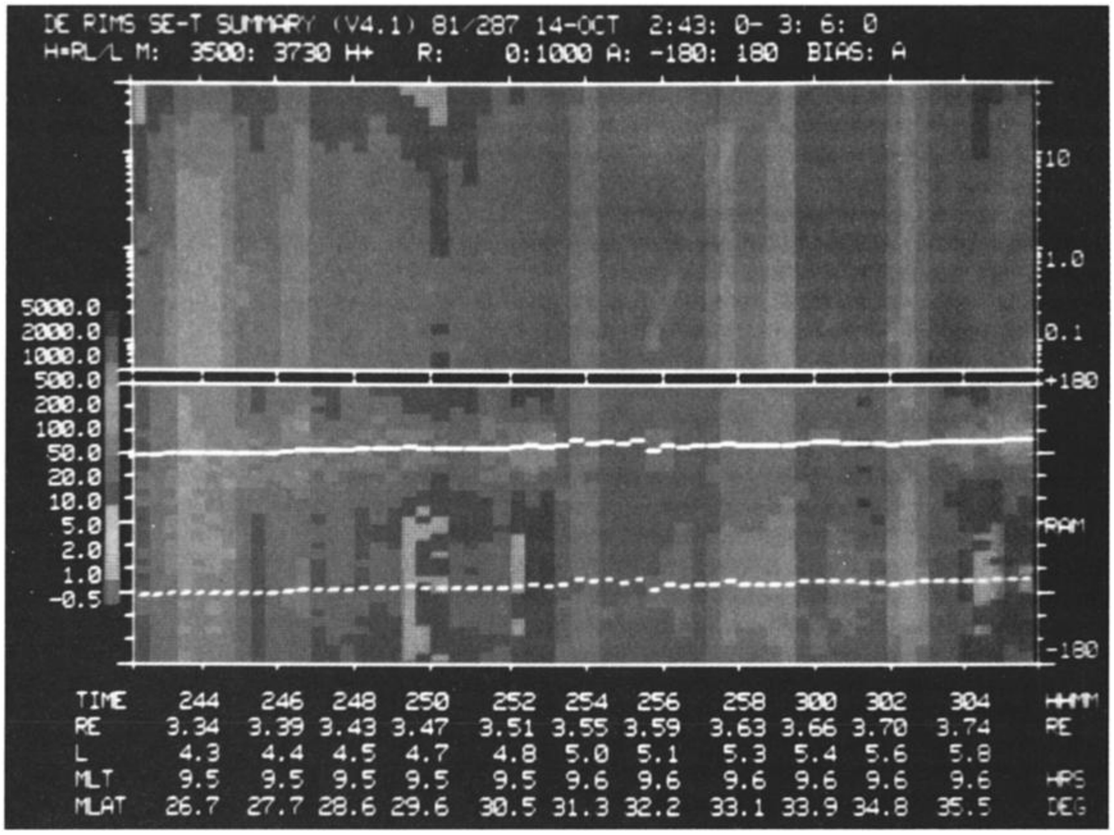

Plate 4. DE 1 RIMS spectrograms covering the period 0243–0305 UT of day 287, 1981. Three-dimensional plots of H^+ ions. Top panel *E-t*, bottom panel spin angle–time spectrograms. The dashed lines in the bottom panel are the upward (upper) and the downward (lower) field-aligned flow directions. Downward H^+ flow is present at 0256, 0257, and 0301 UT. The color version of this figure can be found in the special color section in this issue.

distribution functions in the energy range 23–13,206 eV. The integration was performed over 12 s of data (2 spin periods). Both figures cover the interval 0240–0310 UT as the satellite moves poleward. Heavy traces correspond to labels on the right, and light traces to labels on the left. The times of interest are 0255:30, 0257:30, and 0300:30 UT. Generally, all the computed parameters are different around the above times of FTE signatures in comparison to the neighboring regions on both sides.

From top to bottom the first panel of Figure 1 shows the Pedersen and Hall conductivities in units of mhos. Both types of conductivities show a reduction inside the flux tubes (at the vertical lines) that may be connected to an FTE at the magnetopause. The second panel shows the electron velocities parallel to the magnetic field (heavy trace). Near the vertical lines the spin-averaged parallel velocity is downward, and tens of seconds away from the vertical lines the parallel velocities of the electrons are upward. At time 0257:30 the parallel velocities do not have a strong downward component but have upward components on either side of the vertical line. The light trace in the second panel represents the average energy of the downcoming electrons with pitch angles in the range 0°–90°. The scale is logarithmic; therefore the shallow reductions in energy around the FTE connected flux tubes are significant as they amount to reductions of the order of 100 eV downward from 400 eV outside the RFTs, especially on the equatorward side of each RFT. The heavy trace of the third panel shows the logarithm of the downward electron energy flux (0°–90° pitch angle range) versus time. Clearly inside the FTE connected flux tube the downward energy flux shows the greatest drops, at least 1 order of magnitude, while outside the flux tube the energy flux remains at relatively higher levels. The light trace of the third panel shows the logarithm of the electron number density computed from the downward distribution function (0°–90° pitch angle). Again the dips of the electron density at the vertical lines are significant as they represent 25–50% decreases inside the FTE connected flux tubes in comparison to regions outside the RFT. The heavy trace in the bottom panel shows the logarithm of the number flux in particles/(cm^2 s) computed from the downward distribution functions. Inside the RFTs the integral intensity shows half an order of magnitude decreases. The light trace in the bottom panel shows the current density derived from the electron distribution functions. The current densities behave quite similarly to the average parallel velocities. Near the first and last vertical lines the field-aligned current is upward on either side of an RFT and downward at the center. Near the middle vertical line in Figure 1 the field-aligned current is reduced upward at the center but enhanced upward on the sides. Along the horizontal axis the time dependent parameters are the invariant latitude in degrees, ILAT(D); the magnetic local time in hours, MLT(HR); the altitude in kilometers, ALT(KM); the geodetic latitude in degrees, GLAT(D); and the geodetic longitude in degrees, GLONG(D).

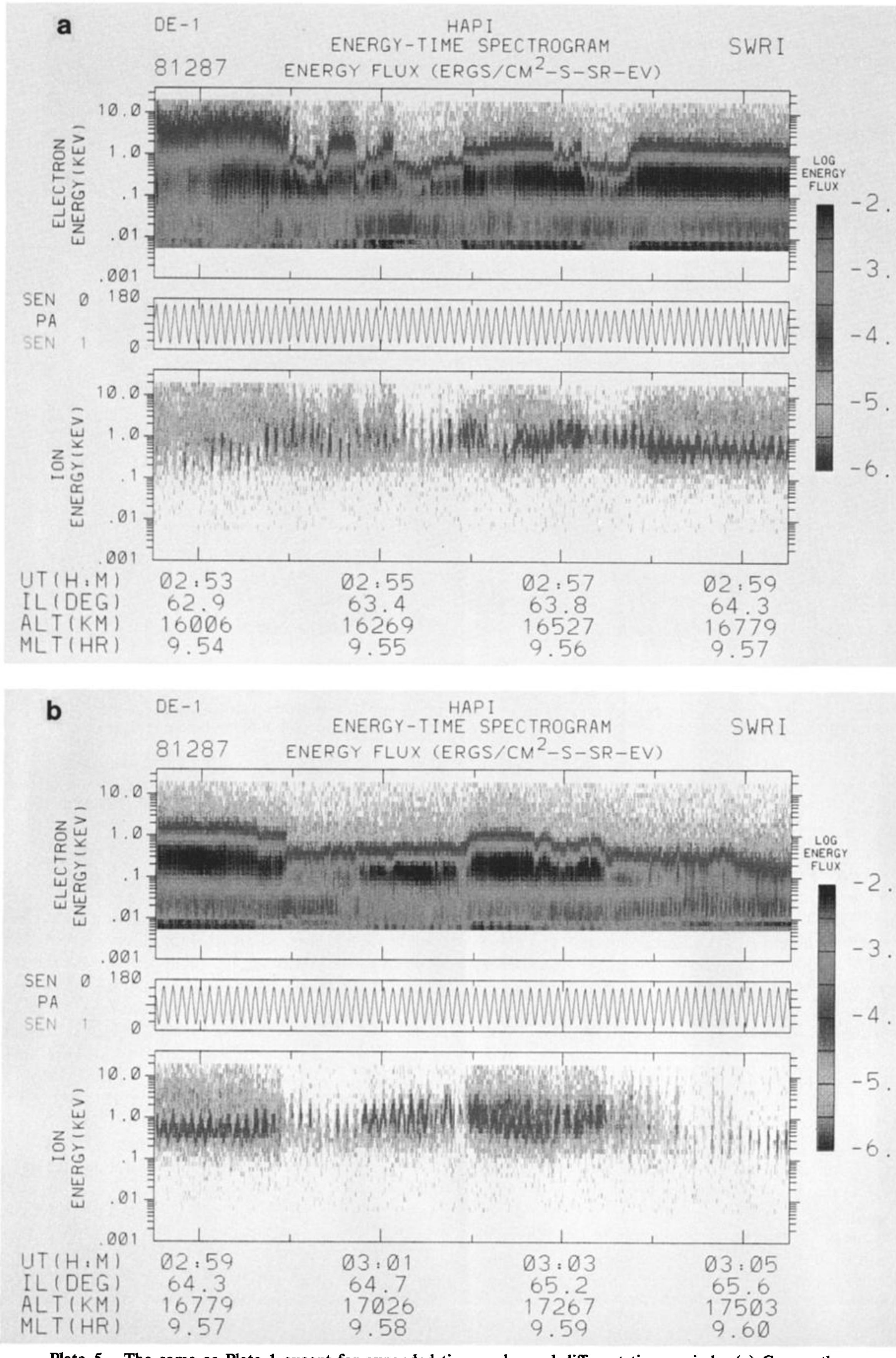

Plate 5. The same as Plate 1 except for expanded time scales and different time periods. (*a*) Covers the range 0252:30–0259:30 UT. (*b*) Covers the range 0259–0305 UT. The color version of this figure can be found in the special color section in this issue.

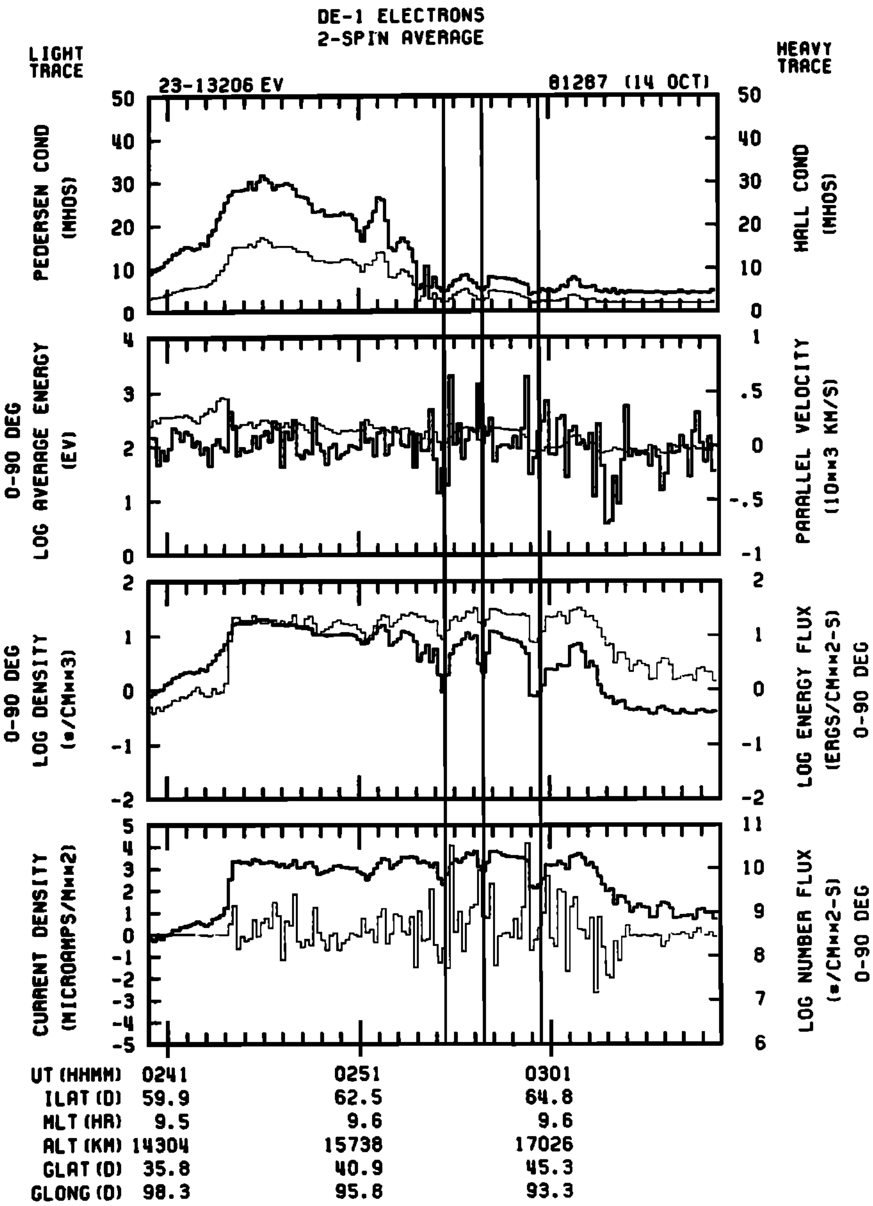

Fig. 1. Parameters computed from the hot-electron velocity distributions measured with the DE 1 HAPI instrument. Heavy traces have scales and labels on the right-hand side of the figure, and light traces on the left. The vertical lines mark the approximate central regions of the three reconnected flux tubes.

From top to bottom the first panel of Figure 2 shows that east/west and the parallel velocity of ions measured in kilometers per second. The heavy trace shows the westward (positive) and eastward (negative) ion velocity. This quantity is fluctuating about zero but shows eastward directed convection at all three vertical lines positioned at 0255:30, 0257:30, and 0300:30 UT of the centers flux tubes presumed to be connected magnetically to FTEs. The direction of this velocity would be qualitatively consistent with a southward convection electric field. If this electric field were very strong, there would be a lack of optimally positioned ion detectors relative to the spin axis of HAPI in order to measure such a flow mostly along the spin axis of DE 1. The light trace shows the parallel velocities which are predominantly away from the ionosphere but with large absolute values near the center of flux tubes, possibly connected to FTEs at the magnetopause. The heavy trace in the second panel of Figure 2 shows the logarithm of the downcoming energy flux in the pitch angle interval 0°–90°. Clearly, the precipitating ion energy flux has deep minima near the center of RFTs. The light trace in the second panel shows the logarithm of the ion density. This also shows reductions near the center of RFTs. In fact, the ion and electron densities shown in Figures 1 and 2 are about 10 cm^{-3} inside RFTs and about 30 cm^{-3} outside. The light trace of the bottom panel of Figure 2 is a line plot of 12-s averaged current points connected by straight-line segments. Again, the currents at the central part of the holes are either reduced in intensity or are of reverse polarity in comparison to the edge currents, which are directed away from the ionosphere. Thus currents carried by ions and electrons are parallel to each other on the same field lines, which implies that some field-aligned potential is distributed along the current carrying flux tubes.

Figure 3 shows spin-plane electric field components per-

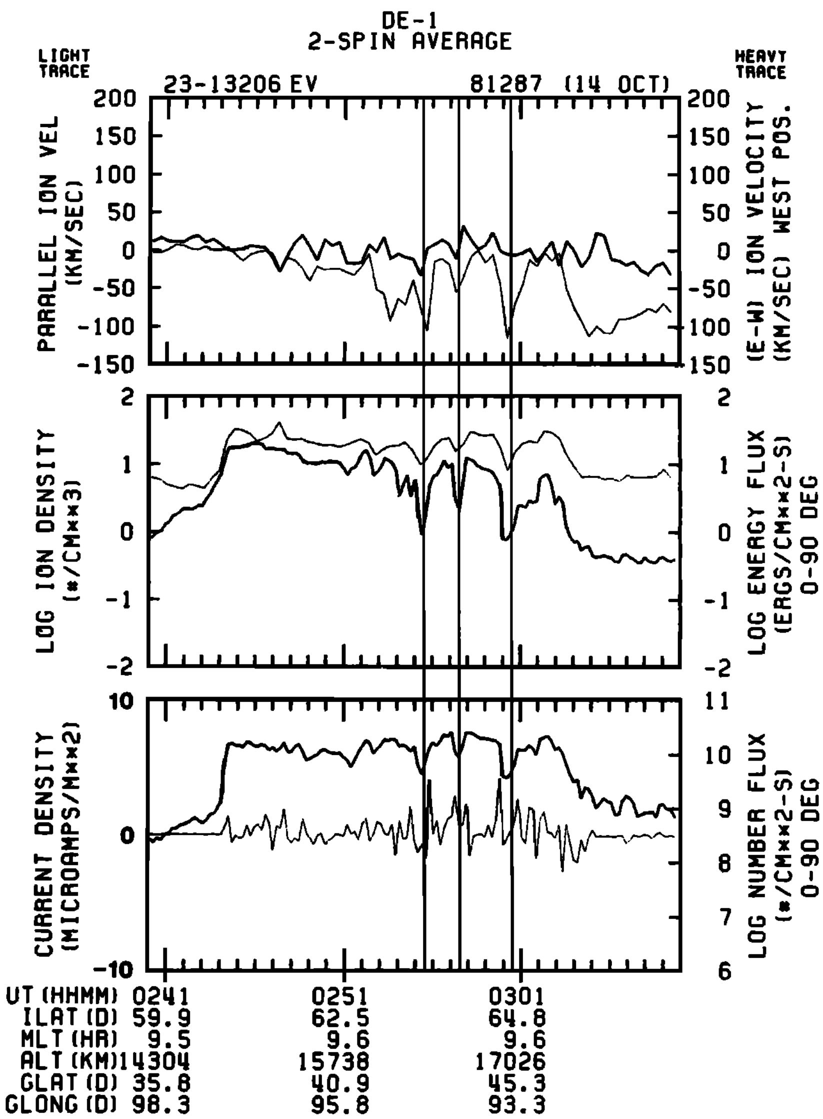

Fig. 2. Parameters computed from the hot-ion velocity distributions measured with the DE 1 HAPI instrument. Heavy traces have scales and labels on the right-hand side of the figure, and light traces on the left. The vertical lines mark the approximate central regions of the three reconnected flux tubes.

pendicular and parallel to the projection of **B** in the spin plane. These are derived from a least squares fit of a sine wave to the spin-plane data, with the spin-plane component of $\mathbf{V}_{SC} \times \mathbf{B}$ subtracted, where $\mathbf{V}_{SC}$ is the satellite velocity. The computations were performed with segments of data over one spin period (6 s), which were centered on times 4 s apart so there was a 2-s overlap between segments. In Figure 3, positive $E_\perp$ is poleward and positive $E_\parallel$ is downward, and these directions are applied to the fields in the RFT-related intervals (0253:30–0256:00, 0256:42–0258:00, and 0259:42–0301:36 UT). In the first and second intervals the peak perpendicular electric field value is about 88 mV/m. The ambient magnetic field value is 865 nT at the satellite position for the time 0255 UT. The eastward convection velocity V_C is given by the expression E(V/m)/B(T) which for the above values of E and B yields V_C = 101 km/s.

Figure 4 shows traces of the perturbation magnetic field in geomagnetic dipole spherical coordinates. Positive directions correspond to radially outward (DBR(nT)), magnetically southward (DBTHETA(nT), and magnetically eastward (DBPHI(nT)). The figure covers the time interval 0240–0310 UT, and the data are all 1-s averages. The three regions associated with RFTs are the same as those for the PWI dc measurements. The DBR deviations are small in comparison to the other two, and the DBTHETA components show increasing values of magnetic field disturbance at the equatorward side of the flux tube and decreasing values at the poleward side. The DBPHI deviations show a magnetic field increasing in the westward direction on the equatorward side of the flux tubes and decreasing in the westward direction on the poleward side of the flux tube. This is consistent with twisted magnetic field lines. Such a reversal is possible if two curved current sheets oriented mostly from southwest (SW) to northeast (NE) are separated by a distance measured along the NW to SE diameter and have current directions which are upward on the SE side and downward on the NW side. If the currents close by Pedersen currents, then another component of the electric field along the eastward direction is needed for which we did not have measurements.

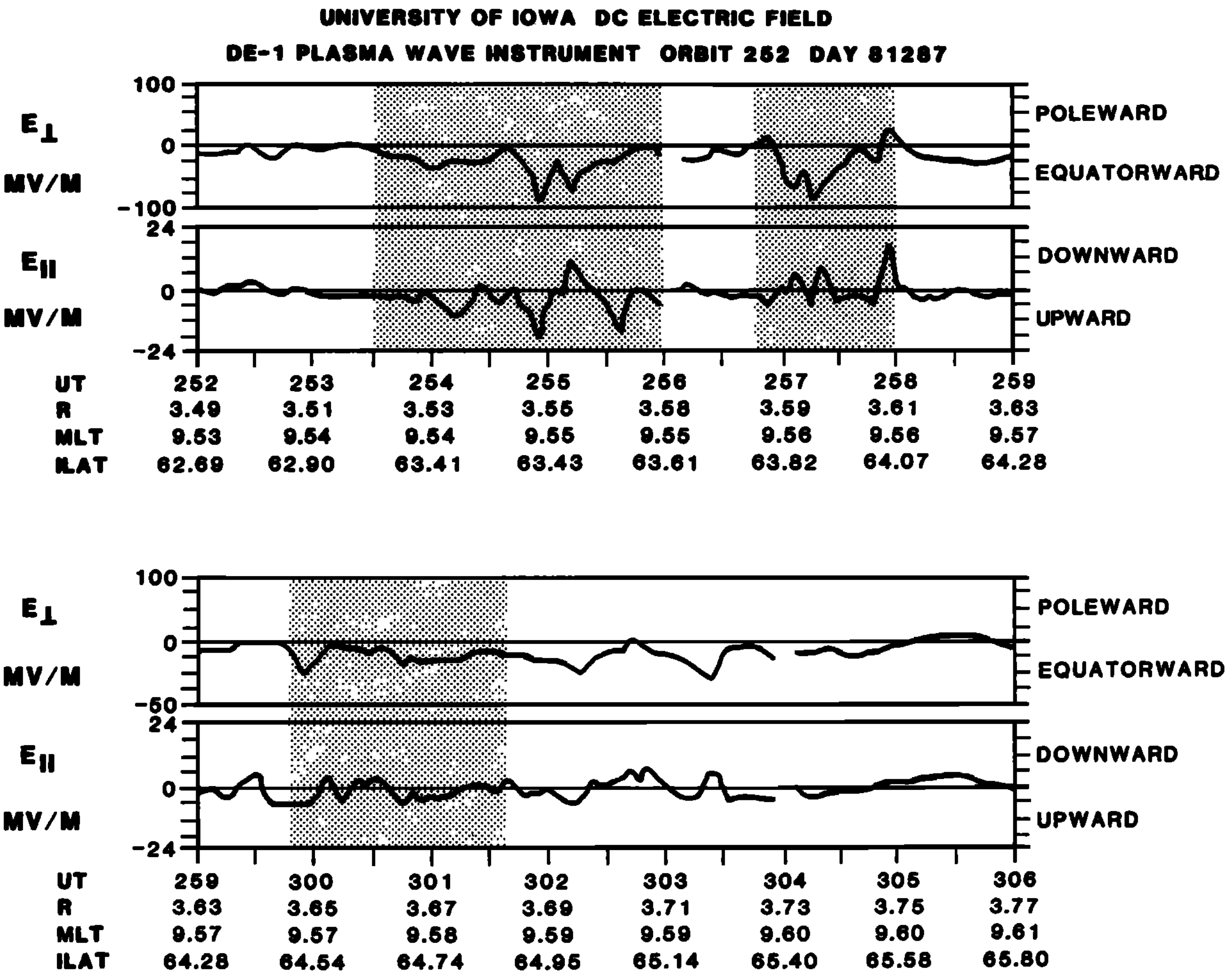

Fig. 3. PWI dc electric field data ($E_\perp$) perpendicular to and ($E_\parallel$) parallel to the projection of B in the satellite spin plane. These were derived from a least squares fit of data to a sine wave. The spin plane component of the satellite motion induced electric field was subtracted before the fitting process. Five sets of 6-s measurements obtained over a 22-s interval with 2 s overlap between successive sets of measurements were properly merged in order to perform the computations.

It is interesting to note that the DE 1 and DE 2 subsatellite tracks intersect at 0243:30 UT on day 287, 1981. Figure 5 shows the invariant latitude versus UT at 0930 MLT. The cusp at DE 2 was less than 2° wide, inferred from electric field measurements to be shown below. We repeat that judging from the twisting of magnetic field lines, we envision the RFT to resemble approximately an elliptical cylinder with its major axis oriented from SW to NE as mentioned above. Its NW side carries a downward current, and its SE side carries an upward current. The RFTs under consideration were moving in the NE direction, which is consistent with the poleward motion of the polar cusp as observed by the DE 1 and DE 2 satellites, which is not discussed in this paper.

Figure 6 shows ac and dc electric field data from DE 2 for the transition through the polar cusp. Two features are rather interesting at DE 2: (1) spiky increases and decreases of the north-south dc electric field, and (2) intense increases of ELF signals at the regions of steep gradients of the dc electric fields. Recall that similar enhancements of ac electric field spectral densities were observed at DE 1 near the identified RFTs up to frequencies of 1000 Hz. Though we do not claim a perfect time coincidence for this magnetic conjunction, we do see corresponding similar features at the two altitudes within similar plasma regimes.

Most likely, the RFTs are temporal in nature, occur spontaneously at various locations, last for a period from 1 to 3 min, and initiate an ion mass analysis process in the magnetosphere that lasts about 10 min. It is entirely possible that the downward field-aligned current on the poleward side of an eastward moving RFT contains information relevant to the onset of dynamic reconnection, and the upward current on the equatorward side contains information regarding the turning off of such reconnection. The time required to establish this current loop is equal to the bounce period of Alfvén waves, which is about 2 min and thus is consistent with the observation of currents from 1 to 3 min apart. The low-frequency waves, especially below 100 Hz, contain frequency components corresponding to ion gyrofrequencies and to Alfvén waves capable of interacting with these ions. These Alfvén waves should be associated with the RFT field-aligned currents, and their pressure should provide prompt information regarding the status of reconnection on the magnetopause. However, they also exist in regions outside RFTs.

The geomagnetic conditions around hour 0300 UT were

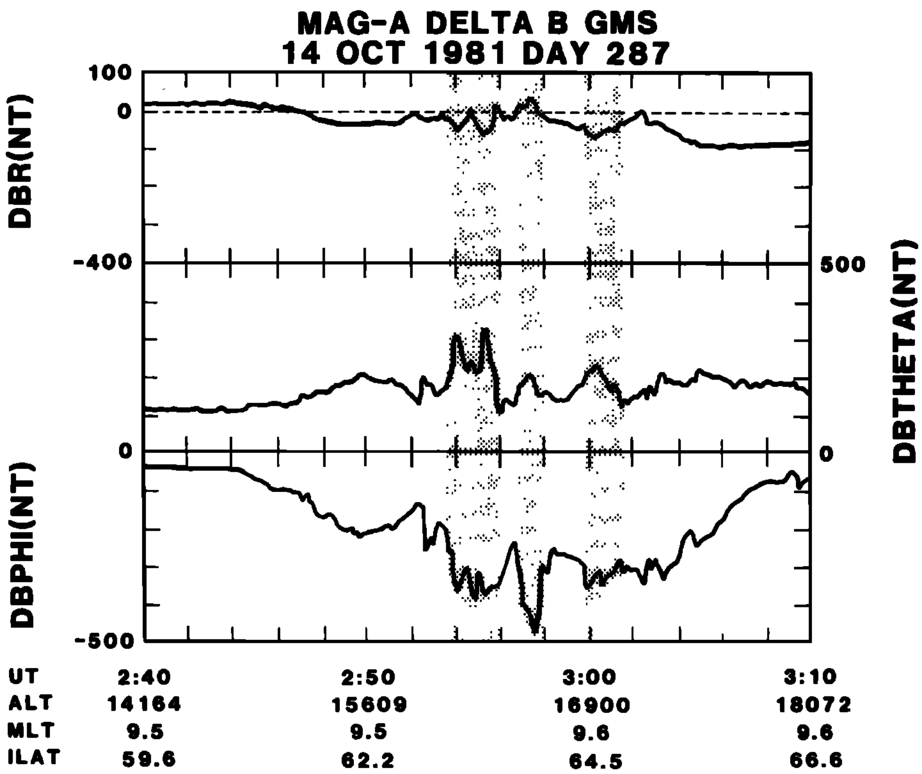

Fig. 4. Plots of the DE 1 magnetometer data for the interval 0240–0310 UT of day 287, 1981. The vertical labels and scales are for the residuals of the magnetic field DB (nT) in geocentric magnetic spherical (GMS) coordinate system. Positive signals are radially outward for DBR, magnetically southward for DBTHETA, and magnetically eastward for DBPHI.

Kp of 8 and *AE* of 1150 nT. A polar magnetic substorm had already started at 0220 UT, and the *AL* value reached −1500 nT by 0240 UT. The interplanetary magnetic field, measured by the ISEE 1 satellite in GSM coordinates, had a B_Z component of −35 nT in the interval 0247–0300 UT, a B_Y component of −5 to −35 nT in the interval 0247–0354 UT, and a B_X of 0 to −20 nT in the interval 0247–0300 UT.

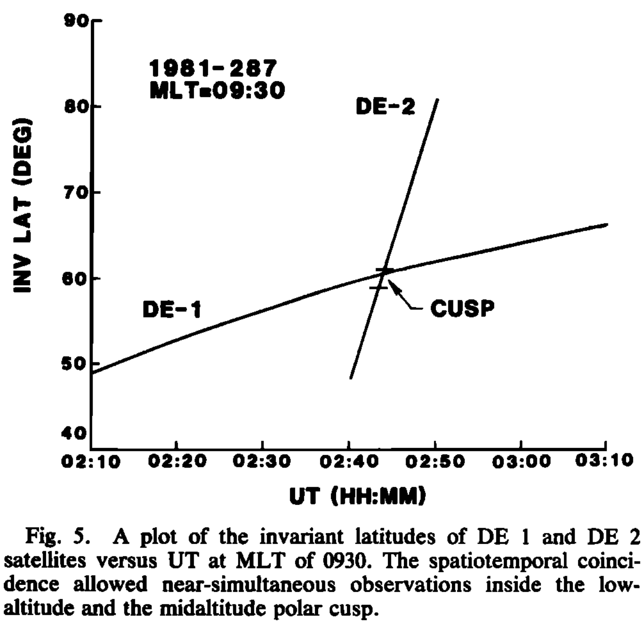

Fig. 5. A plot of the invariant latitudes of DE 1 and DE 2 satellites versus UT at MLT of 0930. The spatiotemporal coincidence allowed near-simultaneous observations inside the low-altitude and the midaltitude polar cusp.

DISCUSSION

The injection region of magnetosheath plasma into the polar cusp appears not to be only uniform and steady but rather to include localized and possibly varying in time injections. Observations of ions and electrons (in energy versus time and energy versus pitch angle spectrograms) show energy dispersion and V-shaped signatures consistent with a localized source region positioned at the magnetopause [*Burch et al.*, 1982; *Carlson and Torbert*, 1980]. The V-shaped signatures of the ions in RFTs are characterized by thin V sides and narrow energy bands from the top to the bottom of a V. In addition, there is a distinct distance of separation between Vs inside an RFT in comparison to Vs outside an RFT (see Plates 5*a* and 5*b*). One factor that influences the localized injection region at the magnetopause is the GSM B_Z component of the interplanetary magnetic field (IMF), which is reflected in the change of the cusp location [*Burch*, 1972]. The combined contributions of vigorous quasi-steady reconnection and flux transfer events in the cusp lead to lowering of the latitudinal position of the cusp [*Saflekos et al.*, 1985]. If the scale size and the frequency of occurrence of FTEs increase, then the day to night flux transfer rate exceeds the night to day transfer rate. Thus the probability of detecting RFTs within the midaltitude cusp increases when the cusp is encountered at lower latitudes or alternatively when the IMF is strongly southward and the *AE* index is very large, as was the case for the 1-hour interval between 0200 and 0300 UT on day 287, 1981.

Another factor possibly controlling the behavior of RFTs is the IMF B_Y component. Merging of magnetosheath field

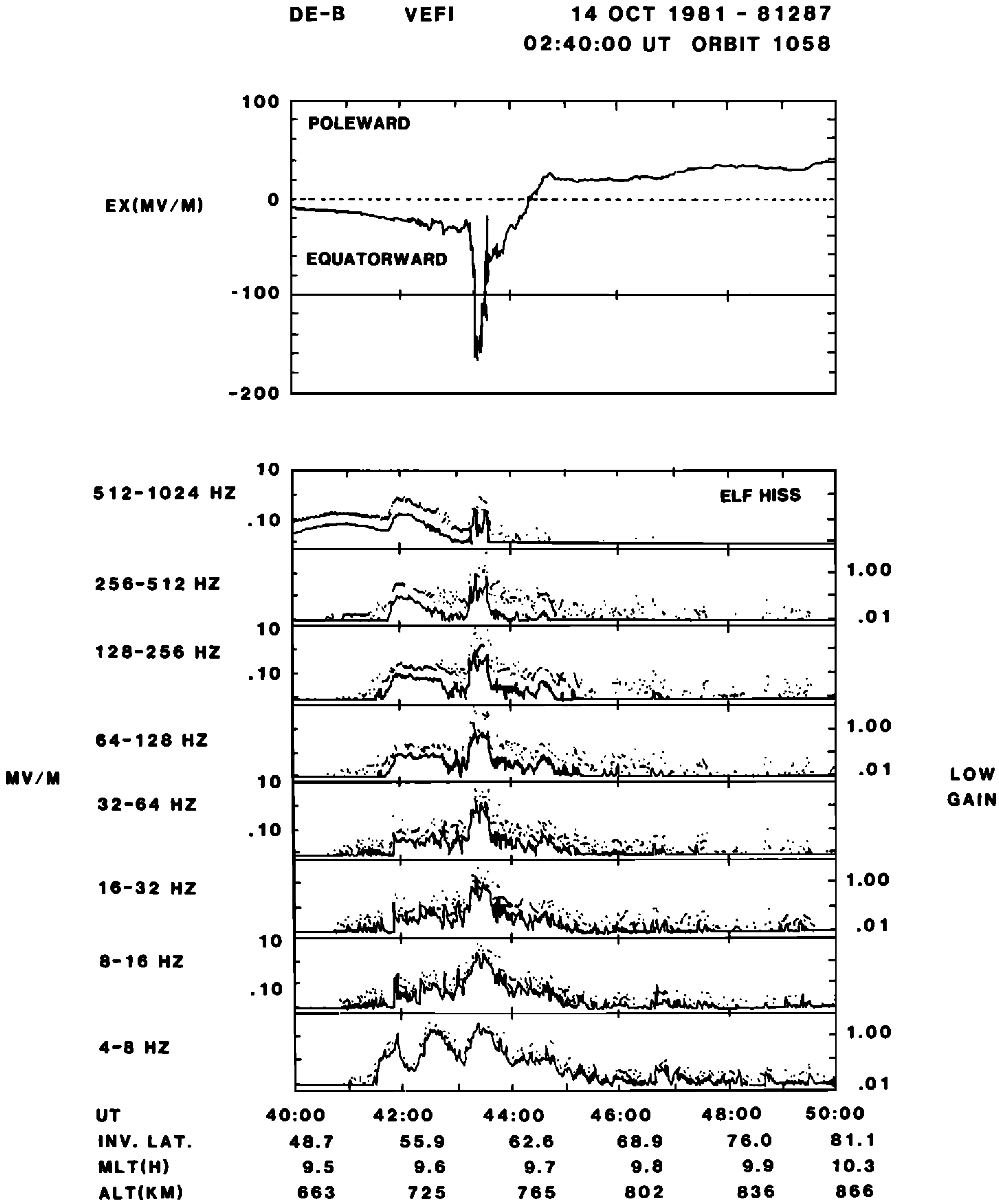

Fig. 6. A plot of dc and ac electric field measurements from DE 2 for 0240–0250 UT of day 287, 1981. Top panel is the poleward-equatorward component of the dc electric field in the ELF hiss frequency range, 4–1024 Hz.

lines with field lines threading the cusp/magnetopause interface near 1000 MLT has been supported by indirect evidence obtained in the cusp at low altitudes and midaltitudes [*Saflekos et al.*, 1979; *Burch et al.*, 1985]. If the FTEs have counterparts down to the ionosphere, then a consequence of their motion is the expectation of isolated moving RFTs within the midaltitude cusp [*Goertz et al.*, 1985; *Sandholt et al.*, 1986]. For IMF $B_Y < 0$ the foot of an RFT at prenoon ionospheric altitudes would be expected to move mainly eastward at the outset, eventually changing direction toward the pole as it passes through the narrow flow region called the "throat" [*Heelis et al.*, 1976] where flow is diverted toward the duskside of the polar cap. Figure 7 is a sketch describing the evolution of the convection of an RFT based on the convection model of *Burch et al.* [1985, Figure 6*b*]. A negative B_Y causes stresses which can accelerate the flux tube in the eastward direction poleward of the electric field reversal associated with the equatorward boundary of the polar cusp [*Cowley*, 1976, 1982; *Crooker*, 1979]. *Russell* [1984] expressed the belief that the magnetosheath flow field determines the direction of motion. However, he indicated that sometimes the field line tensions can overcome the magnetosheath flow and pull the FTE against the flow. Our DE 1 observations of RFTs comply with the last scenario proposed by *Russell* [1984].

In the past the reason that FTEs moving eastward on the magnetopause have not been observed is because a systematic search for such phenomena above a magnetic latitude (λ_M) of 45° on the magnetopause has not been conducted. It should be instructive to take another look at HEOS 2 and Hawkeye magnetometer data with the IMF B_Y control of RFTs in mind, as both of these satellites shared the mission of high-altitude polar cusp exploration. In the rest of this section, various aspects of FTEs will be compared to those of RFTs, and the interrelationships of the different properties of the measurements within the RFTs will be pointed out.

A model of the FTEs was constructed by *Russell and Elphic* [1978]. They used magnetic field data from the ISEE 1 and 2 satellites for a large number of magnetopause crossings and found a magnetopause normal (*N*) oriented coordinate system which ordered the data well. The components orthogonal to *N* are *L* and *M*, where *L* is along the projection of the magnetospheric *Z* unit vector onto the magnetopause and *M* completes the right-handed coordinate system (*L*, *M*, *N*). The major signature of FTEs is a relatively large magnetic deviation in the *N* direction, which is first positive and then negative. This signature is attributed mainly to the draping of the ambient field around the reconnected flux tube and to a lesser extent to an axial current flowing toward the ionosphere within the RFT. The DE 1 observations at midaltitudes are not expected to show the B_N equivalent signature of FTEs. However, they show DBTHETA and DBPHI signatures which are consistent with encounters of a discrete eastward moving filamentary flux tube carrying field-aligned currents (downward along the NW side and upward along the SE side). This pattern is consistent with twisting of magnetic field lines and current closure in the ionosphere by Pedersen current driven by at least an observed equatorward electric field inside the RFT. The pair may be consistent with Alfvén waves as suggested by *Goertz et al.* [1985].

Saunders et al. [1984] have looked at the relationship of the *X* and *Y* GSE components of the magnetic field $\mathbf{b}_\perp$ and the flow perturbations $\mathbf{u}_\perp$. They claim that these quantities satisfy the properties of Alfvén waves propagating antiparallel to the ambient magnetic field $\mathbf{B}_0$. The fluid velocity ($u_\perp$) is given by the expression $u_\perp = V_A b_\perp / B_0$. The DE 1 satellite determined a plasma density n of 3×10^7 m^{-3} and a magnetic induction B_0 of 8.65×10^{-7} wb/m^2 at the edge of the holes, yielding an Alfvén velocity ($V_A = B_0/(\mu_0 \rho)^{1/2}$) of about 1100 km/s. The fluid velocity $u_\perp$ parallel to DBPHI ($\simeq 1.50 \times 10^{-7}$ Wb/m^2) is given by setting $b_\perp$ approximately equal to DBPHI. The resulting fluid velocity is about 191 km/s. This value is nearly double the eastward convection velocity of 100 km/s measured by using the dc electric and magnetic field experimental techniques. Thus the field-aligned currents which are downward on the poleward side and upward on the equatorward side of an RFT can be best understood as being due to the divergence of ionospheric Pedersen currents. If a factor of 2 is set aside, the currents may also originate in Alfvén waves.

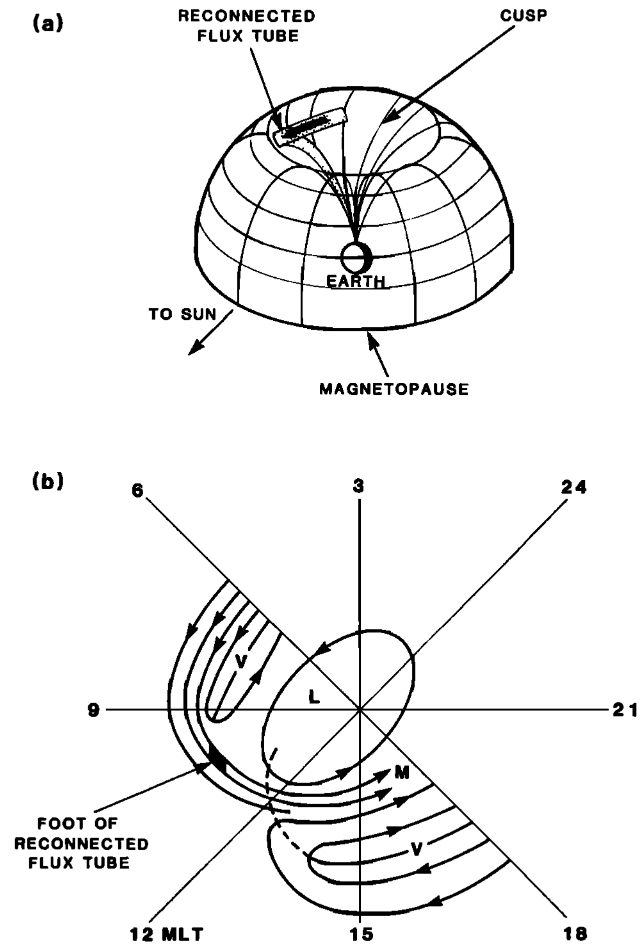

Fig. 7. (*a*) A sketch illustrating the reconnection of a flux tube in the dawnside polar cusp. The distant kink in the magnetic field provides the tension that pulls the reconnected flux tube eastward. The heavy arrow inside the shaded reconnected flux tube represents an earthward field-aligned current. (*b*) A sketch of a simplified convection model with three cells (viscous (V), merging (M), and lobe (L)), under negative IMF B_Z and B_Y conditions. The solid area represents the foot of the reconnected flux tube around 9030 MLT.

A study of electric fields associated with FTEs has been made by *Daily et al.* [1985]. The convection velocities they found were independent of IMF B_Y. The ISEE 1 ($\lambda_M < 45°$) events were selected on the basis of prominence of features ($B_N \geq 10$ nT peak to peak, and time scale >1 min). There is evidence that a spectrum of smaller-sized FTE dimensions exists at the magnetopause [e.g., *Saunders et al.*, 1984, Figures 1 and 3; *Russell and Elphic*, 1978; *Rijnbeek et al.*, 1984*a*, *b*; *Berchem and Russell*, 1984]. *Sonnerup* [1984] has investigated the cross-sectional dimensions of FTEs and found them to be of diameter about 1 R_E with $B_N < B$. He speculated that in reality there may be a continuum of sizes ranging from dimensions comparable to the ion gyroradius up to the scale of quasi-steady reconnection, which may be several Earth radii. Similarly, *Russell* [1984] finds the typical diameter of an RFT to be about 1 R_E. These dimensions are consistent with the RFT dimensions inferred from DE 1 measurements.

The convection velocities derived by *Daily et al.* [1985]

from electric and magnetic field measurements were in agreement with ion flow velocities near the magnetopause. The direction of motion was perpendicular to the reconnected field lines and was mainly directed northward (V_L = 87 km/s) as well as northwestward (V_{LM} = 125 km/s). Daily et al. also found some events with reverse (i.e., southward) convection of $V_L = -131$ km/s. The northward (southward) motion was interpreted by interconnection of the reconnected flux tube to the north (south) ionosphere. The magnitudes of the FTE convection velocities are comparable to the DE 1 observations of midaltitude inferred RFT motion of 100 km/s. Of course, the major velocity component of the DE 1 observations is directed eastward, and we attribute the nature of this phenomenon to IMF B_Y control of RFTs (see Figure 7). *Daily et al.* [1985] looked at one more problem. They compared the ambient magnetic field direction and the FTE convection and found no correlation between the L component of the magnetic field and the L component of $(E \times B)/B^2$ velocity. This result is inconsistent with the prediction of *Cowley* [1982]. Our higher λ_M observations are consistent with RFT motion in the L and M direction at the magnetopause.

Russell [1984] observed that there is internal structure to the flux transfer events, i.e., the magnetic field inside an RFT is twisted. The twist implies inward current in the northern hemisphere, which obviously would continue into the magnetosphere. If we let B_N = 15 nT and let the diameter be 1 R_E for an RFT, we obtain an inward current of 2.4×10^5 A. At the DE 1 altitude the typical magnetic deviation associated with RFTs is 150 nT. Using this fact and current continuity, we obtain a diameter of 0.1 R_E for the tube at DE 1 altitude. Therefore the typical dimension of RFTs at ionospheric altitudes where values of ΔB are less than 450 nT (see Figure 8) is 213 km. This mapping of the RFTs to ionospheric altitudes predicts scales large enough and interesting enough to be studied by radars, rockets, and satellites. The temporal resolution of particle spectra, electric fields, and magnetic fields measured by low-altitude satellites is much better than 0.5 s, which translates to a spatial resolution better than 3.5 km. Therefore the structure of RFTs should now be studied further using multiple techniques.

The recurrence rate of the RFTs within the midaltitude polar cusp was observed with DE 1 to be about 2–3 min apart. This rate is consistent with the time spacings reported by the following researchers: *Berchem and Russell* [1984], *Sibeck and Siscoe* [1984], *Daily et al.* [1985], *Goertz et al.* [1985], and *Sandholt et al.* [1986].

A typical cross-sectional area of an RFT mapped to ionospheric altitudes is about 3×10^{10} m^2. At auroral altitudes the magnetic field strength is about 5×10^{-5} Wb/m^2. Given the fact that RFTs are observed to last about 2 min, one obtains a potential drop across an RFT equal to 10 kV. If one allows three RFTs in one front crossing the noon "throat" simultaneously, they would account for 30 kV of potential applied across the polar cap. These RFTs thus become a viable candidate for transferring magnetic flux from dayside to nightside at a rate consistent with what is needed to power the auroral processes.

Regarding the electromagnetic waves observed in association with flux transfer events, we point out that *Gurnett et al.* [1979] reported plasma wave electric and magnetic fields near current layers close to the magnetopause. The electric turbulence spanned the frequency range from a few hertz to 100 kHz, while the magnetic field turbulence spanned the range from a few hertz to 1 kHz. These observations may be related to the turbulence (1–100 Hz) observed at DE 1 and DE 2 altitudes. In the first and second case of presented RFTs the frequency was of the order of 100 Hz. The common thread in all these observations is the presence of field-aligned currents. The currents described above may originate in Alfvén waves and may play an important role by accelerating magnetosheath ions into the RFTs, here proposed to be associated with FTEs.

The last set of properties of FTEs and RFTs that needs to be compared and contrasted is the particle observations associated with them. *Daly et al.* [1981] have observed magnetospheric energetic ions ($E > 25$ keV) moving antiparallel to the magnetic field inside FTEs found outside the magnetopause. These ions filled the pitch angle space from 90° to 180°. Furthermore, *Daly and Keppler* [1983] have shown that an FTE appears as a flux tube filled with streaming particles (primarily ions) moving northward on the surface of the magnetopause with speeds from 50 to 100 km/s. Their interpretation is that magnetospheric ions are escaping along freshly opened magnetic field lines. Observations of upward ions in the DE 1 HAPI (Plates 5*a* and 5*b*) showed the absence of ions with energies greater than about 4 keV. This absence of energetic ions can be understood in terms of a recently reconnected flux tube that allowed the energetic ions to escape from the magnetosphere.

Figure 9 is a road map of the DE 1 multiexperiment observations versus time for the interval 0253:30–0302:30 UT. Three events identified as RFTs are shown by the shaded areas which we have diagnosed as signatures of FTEs using the various instruments. The nature of the measurement is coded by an open or solid horizontal bar. Within RFTs we expect to find mixing of magnetosheath and magnetospheric plasmas. The top row shows the time intervals during which HAPI observed downcoming magnetosheath-type electrons and ions. The second row from the top shows the RIMS observed low-energy ions ($E < 50$ eV) coming down along the magnetic field direction. In all three RFTs the downward low-energy H^+ ions arrived with a time delay of 1–1.5 min. Since particles of small pitch angles seen at DE 1 had smaller pitch angles at the injection point (say, 8 R_E away), the shift in time is consistent with energy dispersion. However, the H^+ travel times along an 8-R_E field line segment corresponding to energies 50, 100, and 1000 eV are 9.6, 6.8, and 2.0 min, respectively. Obviously, the difference between any two is greater than 1.5 min. Thus at least for the lower-energy ions some other process is responsible for their injection. Following the suggestion of *Haerendel et al.* [1978] that a diffusive entry creates an entry layer which penetrates deep in the equatorward boundary of the polar cusp, it is reasonable also to assume that the earthward edge of the entry layer provides an injection source region for lower-energy ions at lower altitudes, which may reconcile the above mentioned time delay differences. During the first half of an RFT, RIMS measurements show the absence of H^+ and He^+ (not shown here) at any pitch angle, which is again consistent with the energy dispersion idea. We therefore conclude that mixing of magnetosheath and magnetosphere plasmas within RFTs is possible.

Southwood [1987] has treated theoretically the ionospheric signature of flux transfer events. His Figure 3 bears a remarkable resemblance to the empirical model that we

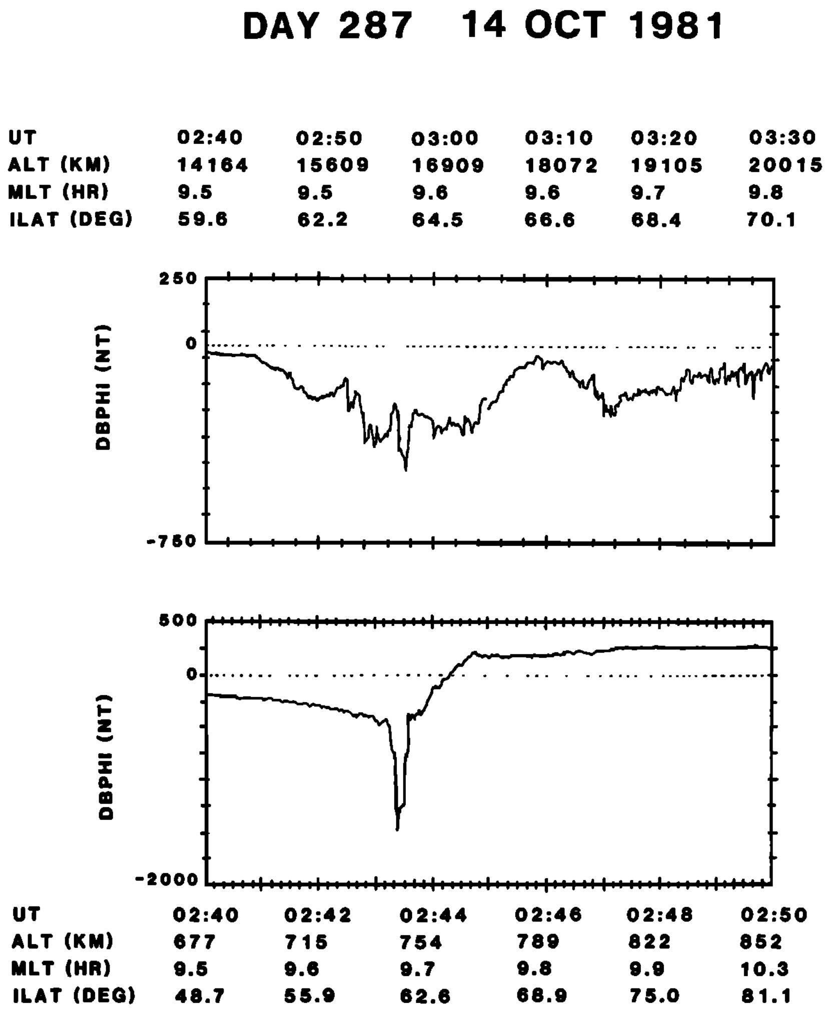

Fig. 8. A plot of transverse magnetic field disturbances for 0240 UT, day 287, 1981. Top panel from the DE 1 magnetometer covers 50 min, and bottom panel from the DE 2 magnetometer covers 10 min. The positive (negative) DBPHI values indicate eastward (westward) magnetic field components. Positive (negative) slopes of DBPHI indicate downward (upward) field-aligned current directions.

presented herein (see Figure 7). Empirically, the widths of regions with RFT signatures due to ac/dc electric and magnetic fields are broader than the widths of the measured RFT hot-plasma signatures. Therefore ac fields may correspond to these and other regions carrying field-aligned currents. The observations presented here deal with the finer scale of midaltitude cusp structures and provide urgently needed evidence in support of FTE signatures being presented in a region far removed from the magnetopause and the ionosphere. The RFTs are short-lived, spatially confined, fresh individual injections of plasma that power the polar cusp, which may also be a manifestation of a temporal phenomenon owing its existence to the reappearance of FTEs.

SUMMARY AND CONCLUSIONS

A reconnected flux tube is a bundle of magnetic field lines with one end in the Earth and the other in the solar wind. To prove the existence of an RFT, one must be able to trace its magnetic field lines from the Earth to the solar wind. This is very difficult to do. The process of reconnection takes place at the magnetopause where antiparallel terrestrial and solar wind magnetic field lines merge. There are two observable consequences of reconnection at the dayside magnetopause: magnetic field components normal to the magnetopause (B_n) and high-speed plasma flows. To show that merging is actually taking place at any one point in time, one needs to show measurements of B_n and of electric fields parallel to the magnetopause (E_t). The B_n must exist over distances greater than the thickness of the magnetopause. Difficulties are introduced by experimentation which reveals that signatures of open magnetosphere are not observed as often as predicted by quasi-steady reconnection. Apparently, direct evidence for continuous existence of E_t and B_n at the magnetopause does not exist. So one looks at consequences of reconnection as a last resort. For instance, if one studies possible RFT candidates near the magnetopause or within the magnetosphere, one would expect to find (1) accelerated magnetosheath plasma entering the flux tube, (2) escaping magnetospheric hot plasma, (3) appearance of a measurable component of B normal to the magnetopause surface, (4) observations of accelerated magnetosheath ions at low altitudes in the dayside polar cusp, and (5) observations of field-aligned currents (FACs) flowing inside an RFT which

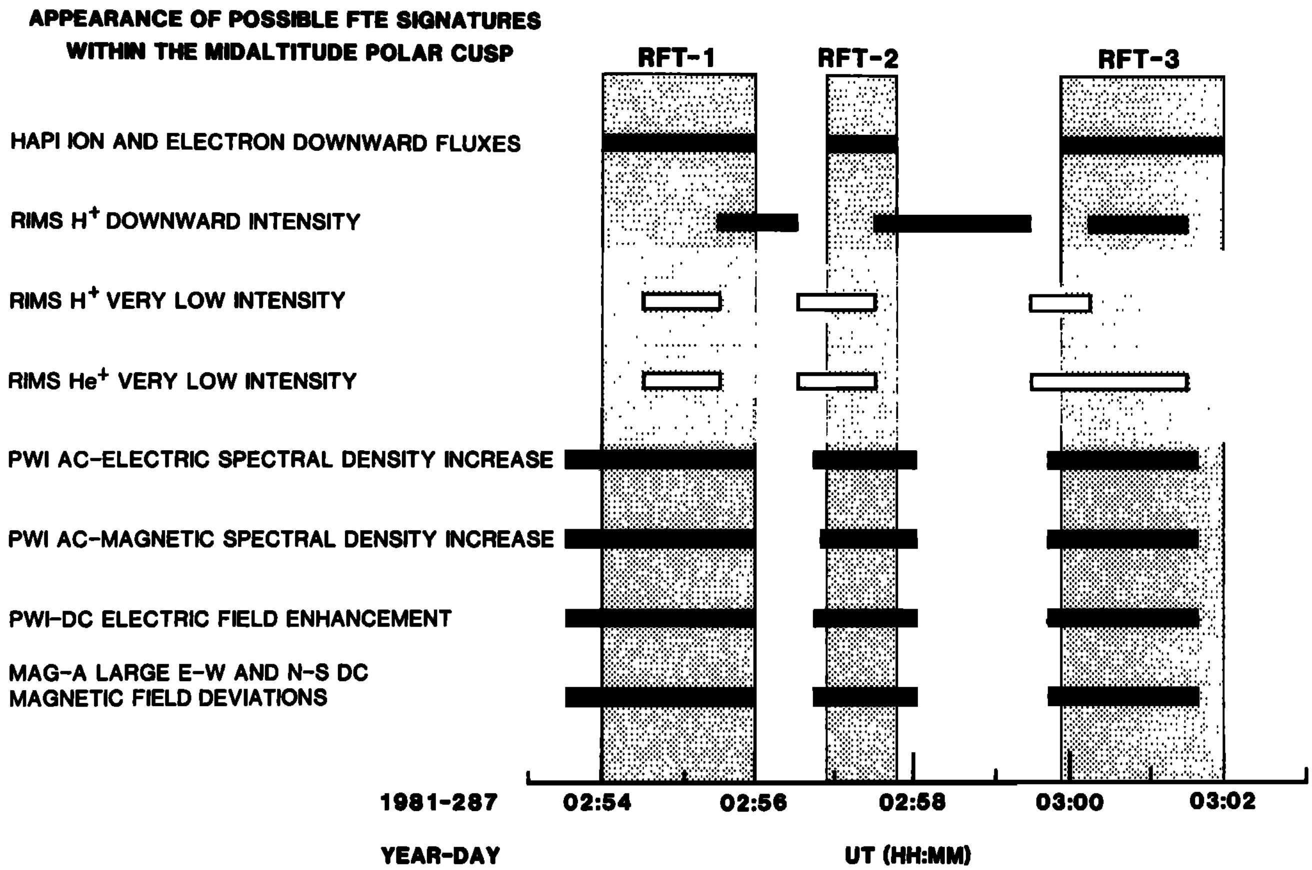

Fig. 9. A road map of the appearance of possible FTE signatures (RFTs) within the midaltitude polar cusp on its dawnside. Eight types of measurements show effects attributable to characteristics of reconnected flux tubes. The duration and recurrence of the three RFTs are obtainable from the linear time scale covering the interval 0253–0303 UT of day 287, 1981.

cause N/S as well as E/W magnetic perturbations, most likely due to twisted flux tubes. In this paper we do not raise the question whether the cusp field lines are open or closed. Rather we point out that RFT lines are identifiable within the polar cusp by virtue of their dynamic nature in comparison to other cusp field lines. We envision the steady cusp lines to be driven by quasi-steady reconnection and RFT lines by FTEs which are time dependent reconnection. Our goal in this paper is to present data that concern the behavior of reconnected flux tubes as observed within the midaltitude cusp region. We believe that we introduced new observations regarding the nature of the low-altitude to midaltitude polar cusp.

We have presented evidence supporting the contention that observations of signatures of magnetic flux transfer events in the midaltitude polar cusp are possible. On the prenoon side of the polar cusp, and near its equatorward boundary, localized discrete flux tubes are observed to be convected rapidly in the northeastward direction. The interplanetary conditions under which these events had occurred were strong IMF B with negative B_Z and B_Y GSM components. The reconnected flux tubes presumed to be associated with FTEs contain a mixture of magnetosheath and magnetosphere plasma. The plasma below 50 eV occurs on the poleward side of the RFTs at midaltitudes. The hot plasma differs from the rest of the polar cusp plasma in that it is intense in a narrower energy band. Energetic ions ($E > 4000$ eV) with velocities antiparallel to the ambient magnetic field are absent within the RFTs.

The observed midaltitude RFTs have a duration of 1–2 min and recur every 2–3 min. They occur when the polar cusp is found at low magnetic latitudes corresponding to an expanded auroral oval. The magnetic residual signatures play an important role in identifying the RFTs by virtue of the interpretation that they correspond to effects of filamentary field-aligned current distributions. Twisting of field lines around RFTs is observed at DE-1 altitudes near the equatorward boundary of the cusp. The field-aligned currents associated with the set of three RFTs are consistent with strong localized electric fields causing their closure in the ionosphere via Pedersen currents. Measured appropriate quantities do not argue strongly against Alfvén waves carrying any measured RFT-related pairs of field-aligned currents closing in the ionosphere. Alternating current electric and magnetic field turbulence inside and outside these RFTs is correlated with the field-aligned currents found there. The major convection of RFTs is consistent with the global convection model of *Burch et al.* [1985].

Our most important conclusion is that the data of particles, electric and magnetic fields, and low-energy plasma argue in favor of a cusp structure that is extremely variable during disturbed times and allows direct magnetosheath plasma entry via flux transfer events at discontinuous locations. Apparently, the entry layer contributes to the injection of lower-energy plasma as a source region located at lower altitudes in comparison to the cusp magnetopause intersection. The quasi-steady reconnection process appears not to switch off during the absence of RFTs. Thus the combination of FTE and QSR processes suffices to power the auroral phenomena in the polar cusp.

We recognize that this is a case study and that the generality of our conclusions is limited. A statistical study may confirm our results and shed more light on the spatial evolution of the polar cusp, which may be powered by FTEs or RFTs in addition to the QSR process.

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REFERENCES

Aggson, T. L., P. J. Gambardella, and N. C. Maynard, Electric field measurements at the magnetopause, 1, Observation of large convective velocities at rotational magnetopause discontinuities, *J. Geophys. Res., 88,* 10,000, 1983.

Alfvén, H., On frozen-in field lines and field line reconnection, *J. Geophys. Res., 81,* 4019, 1976.

Berchem, J., and C. T. Russell, Flux transfer events at the magnetopause: Spatial distribution and controlling factors, *J. Geophys. Res., 89,* 6689, 1984.

Burch, J. L., Precipitation of low-energy electrons at high latitudes: Effects of interplanetary magnetic field and dipole tilt angle, *J. Geophys. Res., 77,* 6696, 1972.

Burch, J. L., Energy transfer in the quiet and disturbed magnetosphere, *Rev. Geophys., 21,* 463, 1983.

Burch, J. L., J. D. Winningham, V. A. Blevins, N. Eaker, W. C. Gibson, and R. A. Hoffman, High-altitude plasma instrument for Dynamic Explorer-A, *Space Sci. Instrum., 5,* 455, 1981.

Burch, J. L., P. H. Reiff, R. A. Heelis, J. D. Winningham, W. B. Hanson, C. Gurgiolo, J. D. Menietti, R. A. Hoffman, and J. N. Barfield, Plasma injection and transport in the mid-altitude polar cusp, *Geophys. Res. Lett., 9,* 921, 1982.

Burch, J. L., P. H. Reiff, and M. Sugiura, Upward electron beams measured by DE-1; A primary source of dayside region 1 Birkeland currents, *Geophys. Res. Lett., 10,* 753, 1983.

Burch, J. L., P. H. Reiff, J. D. Menietti, R. A. Heelis, W. B. Hanson, S. D. Shawhan, E. G. Shelley, M. Sugiura, D. R. Weimer, and J. D. Winningham, IMF B_y-dependent plasma flow and Birkeland currents in the dayside magnetosphere, 1, Dynamics Explorer observations, *J. Geophys. Res., 90,* 1577, 1985.

Carlson, C. W., and R. B. Torbert, Solar wind ion injections in the morning auroral oval, *J. Geophys. Res., 85,* 2903, 1980.

Chappell, C. R., S. A. Fields, C. R. Baugher, J. H. Hoffman, W. B. Hanson, W. W. Right, H. D. Hammack, G. R. Carignan, and A. F. Nagy, The retarding ion mass spectrometer on Dynamics Explorer-A, *Space Sci. Instrum., 5,* 477, 1981.

Cowley, S. W. H., Comments on the merging of nonantiparallel magnetic fields, *J. Geophys. Res., 81,* 3455, 1976.

Cowley, S. W. H., The causes of convection in the earth's magnetosphere: A review of developments during the IMS, *Rev. Geophys., 20,* 531, 1982.

Crooker, N. O., Dayside merging and cusp geometry, *J. Geophys. Res., 84,* 951, 1979.

Daily, R., C. A. Cattell, and F. S. Mozer, Electric fields and convection velocities associated with flux transfer events, *Geophys. Res. Lett., 12,* 843, 1985.

Daly, P. W., and E. Keppler, Remote sensing of a flux transfer event with energetic particles, *J. Geophys. Res., 88,* 3971, 1983.

Daly, P. W., D. J. Williams, C. T. Russell, and E. Keppler, Particle signature of magnetic flux transfer events at the magnetopause, *J. Geophys. Res., 86,* 1628, 1981.

Dungey, J. W., Interplanetary magnetic field and the auroral zones, *Phys. Rev. Lett., 6,* 47, 1961.

Eastman, T. E., and E. W. Hones, Jr., Characteristics of the magnetospheric boundary layer and magnetopause layer as observed by IMP 6, *J. Geophys. Res., 84,* 2019, 1979.

Farthing, W. H., M. Sugiura, B. G. Ledley, and L. J. Cahill, Jr., Magnetic field observations on DE-A and -B, *Space Sci. Instrum., 5,* 369, 1981.

Goertz, C. K., E. Nielsen, A. Korth, K. H. Glassmeier, C. Haldoupis, P. Hoeg, and D. Hayward, Observations of a possible ground signature of flux transfer events, *J. Geophys. Res., 90,* 4069, 1985.

Gurnett, D. A., R. R. Anderson, B. T. Tsurutani, E. J. Smith, G. Paschmann, G. Haerendel, S. J. Bame, and C. T. Russell, Plasma wave turbulence at the magnetopause: Observations from ISEE 1 and 2, *J. Geophys. Res., 84,* 7043, 1979.

Haerendel, G., G. Paschmann, N. Sckopke, H. Rosenbauer, and P. C. Hedgecock, The frontside boundary layer of the magnetosphere and the problem of reconnection, *J. Geophys. Res., 83,* 3195, 1978.

Heelis, R. A., W. B. Hanson, and J. L. Burch, Ion convection velocity reversals in the dayside cleft, *J. Geophys. Res., 81,* 3803, 1976.

Hones, E. W., Jr., J. R. Asbridge, S. J. Bame, M. D. Montgomery, S. Singer, and S.-I. Akasofu, Measurements of magnetotail plasma flow made with VELA 4B, *J. Geophys. Res., 77,* 5503, 1972.

Lee, L. C., and Z. F. Fu, A theory of magnetic flux transfer at the Earth's magnetopause, *Geophys. Res. Lett., 12,* 105, 1985.

Maynard, N. C., and A. D. Johnstone, High-latitude dayside electric field and particle measurements, *J. Geophys. Res., 79,* 3111, 1974.

Maynard, N. C., E. A. Bielecki, and H. F. Burdick, Instrumentation for vector electric field measurements from DE-B, *Space Sci. Instrum., 5,* 523, 1981.

Menietti, J. D., and J. L. Burch, Spatial extent of the plasma injection region in the cusp-magnetosheath interface, *J. Geophys. Res., 93,* 105, 1988.

Ogilvie, K. W., R. J. Fitzenreiter, and J. D. Scudder, Observations of electron beams in the low-latitude boundary layer, *J. Geophys. Res., 89,* 10,723, 1984.

Paschmann, G., N. Sckopke, G. Haerendel, I. Papamastorakis, S. J. Bame, J. R. Asbridge, J. T. Gosling, E. W. Hones, Jr., and E. R. Tech, ISEE plasma observations near the subsolar magnetopause, *Space Sci. Rev., 22,* 717, 1978.

Paschmann, G., B. U. Ö. Sonnerup, I. Papamastorakis, N. Sckopke, G. Haerendel, S. J. Bame, J. R. Asbridge, J. T. Gosling, C. T. Russell, and R. C. Elphic, Plasma acceleration at the Earth's magnetopause: Evidence for reconnection, *Nature, 282,* 243, 1979.

Paschmann, G., G. Haerendel, I. Papamastorakis, N. Sckopke, S. J. Bame, J. T. Gosling, and C. T. Russell, Plasma magnetic field characteristics of magnetic flux transfer events, *J. Geophys. Res., 87,* 2159, 1982.

Rijnbeek, R. P., S. W. H. Cowley, D. J. Southwood, and C. T. Russell, A survey of dayside flux transfer events observed by ISEE 1 and 2 magnetometers, *J. Geophys. Res., 89,* 786, 1984*a*.

Rijnbeek, R. P., S. W. H. Cowley, D. J. Southwood, and C. T. Russell, Recent investigations of flux transfer events observed at the dayside magnetopause, in *Magnetic Reconnection in Space and Laboratory Plasmas, Geophys. Monogr. Ser.,* vol. 30, edited by E. W. Hones, Jr., p. 139, AGU, Washington, D. C., 1984*b*.

Rosenbauer, H., H. Grunwaldt, M. D. Montgomery, G. Paschmann, and N. Sckopke, HEOS 2 plasma observations in the distant polar magnetosphere: The plasma mantle, *J. Geophys. Res., 80,* 2723, 1975.

Russell, C. T., Reconnection at the Earth's magnetopause: Magnetic field observations and flux transfer events, in *Magnetic Reconnection in Space and Laboratory Plasmas, Geophys. Monogr. Ser.,* vol. 30, edited by E. W. Hones, Jr., p. 124, AGU, Washington, D. C., 1984.

Russell, C. T., and R. C. Elphic, Initial ISEE magnetometer results: Magnetopause observations, *Space Sci. Rev., 22,* 681, 1978.

Russell, C. T., and R. C. Elphic, ISEE observations of flux transfer events at the dayside magnetopause, *Geophys. Res. Lett.*, *6*, 33, 1979.

Saflekos, N. A., T. A. Potemra, P. M. Kintner, Jr., and J. L. Green, Field-aligned currents, convection electric fields, and ULF-ELF waves in the cusp, *J. Geophys. Res.*, *84*, 1391, 1979.

Saflekos, N. A., J. L. Burch, J. D. Winningham, J. D. Craven, and L. A. Frank, Dynamics of the polar cusp during a strong magnetic substorm, *Eos Trans. AGU*, *66*, 1034, 1985.

Sandholt, P. E., C. S. Deehr, A. Egeland, B. Lybekk, R. Viereck, and G. J. Romick, Signatures in the dayside aurora of plasma transfer from the magnetosheath, *J. Geophys. Res.*, *91*, 10,063, 1986.

Saunders, M. A., C. T. Russell, and N. Sckopke, Flux transfer events: Scale size and interior structure, *Geophys. Res. Lett.*, *11*, 131, 1984.

Schindler, K., On the role of irregularities in plasma entry into the magnetosphere, *J. Geophys. Res.*, *84*, 7257, 1979.

Scudder, J. D., K. W. Ogilvie, and C. T. Russell, The relation of flux transfer events to magnetic reconnection, in *Magnetic Reconnection in Space and Laboratory Plasmas, Geophys. Monogr. Ser.*, vol. 30, edited by E. W. Hones, Jr., p. 151, AGU, Washington, D. C., 1984.

Shawhan, S. D., D. A. Gurnett, D. L. Odem, R. A. Helliwell, and C. G. Park, The plasma wave and quasi-static electric field instrument (PWI) for Dynamics Explorer-A, *Space Sci. Instrum.*, *5*, 535, 1981.

Sibeck, D. G., and G. L. Siscoe, Downstream properties of magnetic flux transfer events, *J. Geophys. Res.*, *89*, 10,709, 1984.

Smith, M. F., D. J. Rodgers, R. P. Rijnbeek, D. J. Southwood, A. J. Coates, and A. D. Johnstone, Plasma and field observations with high time resolution in flux transfer events, in *Solar Wind–Magnetosphere Coupling*, edited by Y. Kamide and J. A. Slavin, pp. 321–329, Terra Scientific, Tokyo, 1986.

Sonnerup, B. U. Ö., Magnetic field reconnection at the magnetopause: An overview, in *Magnetic Reconnection in Space and Laboratory Plasmas*, *Geophys. Monogr. Ser.*, vol. 30, edited by E. W. Hones, Jr., p. 92, AGU, Washington, D. C., 1984.

Sonnerup, B. U. Ö., G. Paschmann, I. Papamastorakis, N. Sckopke, G. Haerendel, S. J. Bame, J. R. Asbridge, J. T. Gosling, and C. T. Russell, Evidence for magnetic field reconnection at the Earth's magnetopause, *J. Geophys. Res.*, *86*, 10,049, 1981.

Southwood, D. J., The ionospheric signature of flux transfer events, *J. Geophys. Res.*, *92*, 3207, 1987.

Southwood, D. J., C. J. Farrugia, and M. A. Saunders, What are flux transfer events?, *Planet. Space Sci.*, *36*, 503, 1988.

Torbert, R. B., and C. W. Carlson, Impulsive ion injection into the polar cusp, in *Magnetospheric Particles and Fields*, edited by B. M. McCormac, pp. 47–53, D. Reidel, Hingham, Mass., 1976.

Wright, A. N., The evolution of an isolated reconnected flux tube, *Planet. Space Sci.*, *35*, 813, 1987.

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