The Case for Transient Magnetopause Reconnection

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Recent studies indicate that magnetopause reconnection can, at times, occur exclusively as a series of separated, short bursts. Reconnection generates "open" magnetic flux that threads the magnetospheric boundary, the magnetopause, and so connects the magnetosphere with interplanetary space. The rate at which open flux is generated by a line of unit length in the magnetopause is called the reconnection rate. By Faraday's induction law, the reconnection rate is a boundary-tangential electric field, E_t, along that line (called an X-line).

Observations at the magnetopause of what has been termed "quasi-steady" reconnection do not show that E_t is constant, and other measurements show that the reconnection rate may be pulsed. Questions then arise as to the behavior of the total voltage obtained by integrating E_t along the one or several X-lines that are active at any one time. Is this voltage also pulsed or are the phases of the pulses at different locations such that the total voltage remains roughly constant? Either way, the reconnection rate pulses appear to be major contributors to the average of the total reconnection voltage.

Since 1978, when they were first reported in ISEE and HEOS satellite observations, certain particle and field signatures near the Earth's magnetopause have been explained as resulting from bursts of reconnection. Not all scientists agree with this interpretation; nevertheless, from it the name "flux transfer events" (FTEs) was derived. The initial interpretation was in terms of localized bursts, meaning that reconnection is both patchy and sporadic [*Russell and Elphic*, 1978]. This is certainly a reasonable concept, but the question is, what are the dominant temporal and spatial scales?

In addressing this question, Mark Smith and I noted three points. First, the terms patchy and sporadic were frequently grouped together, but new concepts, analytic theories, and two-dimensional simulations predicted that FTE signatures were due to sporadic, not necessarily patchy, reconnection [*Southwood et al.*, 1988]. Because an FTE signature is the result of newly opened flux being dragged past a satellite at the magnetopause, the observations can give no indication of the event's dimensions perpendicular to that motion, nor of other events on other flow streamlines [see *Lockwood et al.*, 1995b]. In other words, no information can be obtained about the length of the X-line and the patchiness of the reconnection.

Second, we noted that the term "quasi-steady" reconnection was often used to describe observations of accelerated flows and other (non-FTE) reconnection signatures at the magnetopause, but they gave no information about the reconnection rate. This is because increases in E_t cause almost proportional increases in the boundary-normal magnetic field, B_n, such that the outflow speed of plasma and magnetic field lines along the boundary (E_t/B_n) is constant to a very good approximation (see review by *Lockwood and Smith* [1994]). Thus the observations of accelerated flows reveal that reconnection is ongoing, but they do not tell us how steady in rate it is.

The third point that we noted was that, because "patchy and sporadic" reconnection was conceived as being different from the "quasi-steady" form, FTE signatures in the ionosphere were generally thought to be small diameter flux tubes embedded within the cusp region. There, solar wind plasma has direct access to the ionosphere by flowing across the dayside magnetopause, along the newly opened field lines produced by reconnection.

We argued that these two forms of reconnection were not distinct and proposed the "pulsating cusp" model in which the reconnection rate (at any one local time) displayed pulses over a background level. In one limit of this general behavior, the background E_t could fall to zero, and the cusp would then be made up of either one FTE signature, or several abutted together. In the other limit, reconnection at a steady rate, the model yielded the pre-existing concept of the cusp. There was no need to invoke patchiness in the reconnection, although this could be introduced in the form of longitudinal (that is, local time) variations if so required.

The importance of the low-altitude observations in the cusp lies in the fact that the ionosphere is incompressible, in the sense that the magnetic field strength there, B_i, is dominated by currents in the Earth's interior and so is almost constant at 5×10^{-5} T. Thus a reconnection burst produces newly opened magnetic flux F, which maps to an expanding area A in the ionosphere. By Faraday's law, the reconnection voltage $V = \int E_t \cdot dl$ is equal to (dF/dt), which in the ionosphere is B_i(dA/dt). Thus, for example, an E_t of 4 mV m^{-1} active over an X-line of length L = 4 R_E (a mean Earth radius, 1 R_E = 6370 km), is an instantaneous voltage of $V = E_t L = 100$ kV, which causes an ionospheric patch of newly opened flux to grow at (dA/dt) = $2 \times 10^9 m^2 s^{-1}$. A pulse in E_t lasting $\Delta t = 1$ min produces a patch of area $A_P = \Delta t$(dA/dt), equivalent to 600 km × 200 km. If such pulses repeat every T = 5 min., they make a contribution of $B_i A_P/T$ = 20 kV to the average reconnection voltage. For a longer/shorter X-line, or a higher/lower E_t, the area and the voltages are proportionally higher/lower. Observed poleward-moving transients of 630-nm-dominant dayside aurora with associated longitudinal flow bursts were shown to be consistent with the precipitation and forces expected for such patches of newly opened flux.

Because these events form, propagate in one direction, and then fade, this is further evidence of reconnection pulses (see discussion by *Lockwood et al.* [1995a]). They also provide our first opportunities to separate the

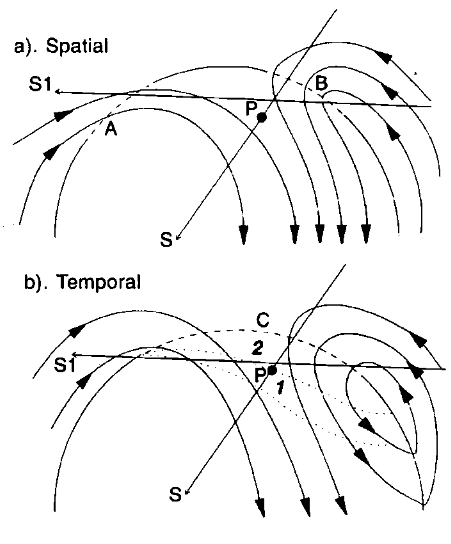

Fig. 1. Cusp ion steps are discontinuous changes in the dispersion ramp of ion energies with latitude (examples are given in Figure 2). This figure illustrates how they may be produced by a) spatial and b) temporal reconnection variations. Here they would be seen by satellite S at the point P. In both cases the ionospheric polar cap (here meaning the region of open flux) is viewed from above, with noon to the top, dawn to the right, and dusk to the left. The dashed lines are "merging gaps," mapping to active reconnection X-lines on the magnetopause. The solid lines are "adiaroic" polar cap boundary segments, mapping to nonreconnecting sectors of the magnetopause. Flow streamlines are marked with arrows. Dotted lines in b) separate patches of newly opened flux (1 and 2) produced by sequential reconnection pulses at a single X-line C. S1 is the path of a longitudinally moving satellite.

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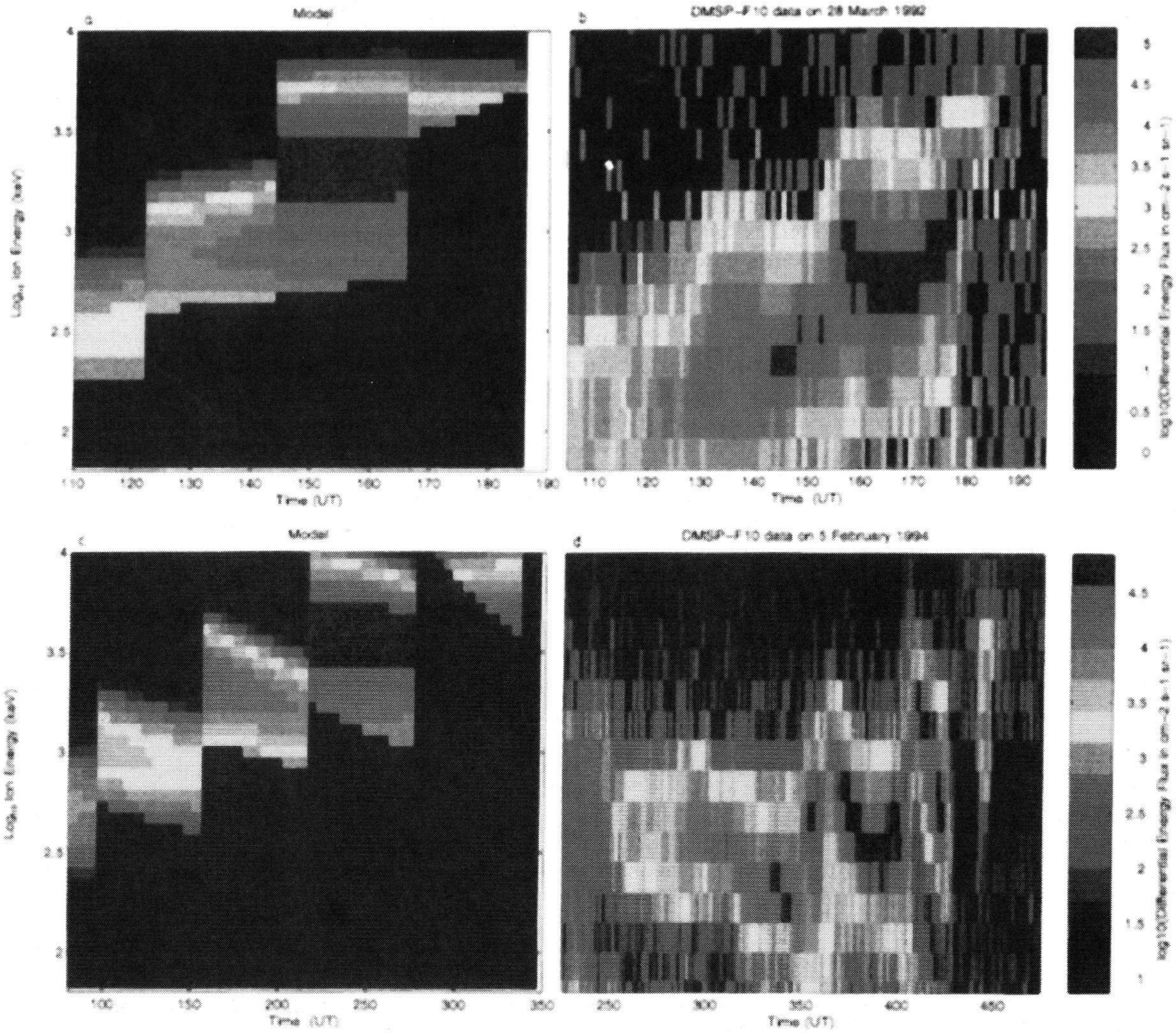

Fig. 2. Energy-time spectrograms of ion differential energy flux for satellites moving meridionally (top) and longitudinally (bottom). The left-hand plots are the results of an illustrative model with pulsed, longitudinally extensive reconnection; the right-hand plots are examples observed by DMSP satellites in close conjunction with poleward moving events seen by ground-based radars. The model and inputs have not been fine-tuned to give close agreement with the data, but nevertheless they illustrate how the data in d) are consistent with longitudinally extensive (>1100 km) events produced by pulsed reconnection. Original color image appears at the back of this volume.

spatial and the temporal variations of the reconnection rate because event sizes and repeat periods can be continuously monitored.

Out of this work has emerged another method that reveals the temporal variations of the reconnection rate, using the precipitation of cusp ions. These are accelerated as they cross the dayside magnetopause, but then precipitate into the ionosphere without any significant further acceleration, heating, or scattering. The reconnection theory predicts that there will be a low-energy cut-off in the precipitating spectrum: these minimum velocity ions have the longest flight time and were thus the first to be injected across the magnetopause. That is, they and only they were injected in the immediate vicinity of the reconnection site and at the time when the field line was first opened. Thus the cut-off energy, along with the other main features of the ion spectrum, depend on the time elapsed since the field line was reconnected.

Periods or regions of low or zero reconnection rate produce discontinuous "steps" in the cusp ion precipitation dispersion [*Lockwood and Smith*, 1994]. Figure 1 illustrates how cusp ion steps can be produced by either spatial or temporal variations in the reconnection rate. Both yield discontinuous changes in the time elapsed since those field lines that are monitored by a satellite S were reconnected. In Figure 1a, a step at P is produced because S crosses from field lines reconnected at one X-line, which maps to an ionospheric "merging gap" B, to those emerging from a more distant one, A. As a result there is a discontinuous change in the time elapsed since reconnection, giving a "spatial" cusp ion step. However, in Figure 1b, the same step has a temporal cause as the satellite crosses from patch 1 to patch 2, which were produced at the same X-line (which maps to C), but at different times.

Some observations show that the reconnection can have spatial structure, as in Figure 1a. However, a key difference between the two cases is that Figure 1a does not predict poleward moving events whereas Figure 1b does, as each patch of newly opened flux evolves away from C. The temporal cusp ion steps will lie between such poleward moving events. Observations of this situation by *Lockwood et al.* [1993a] (for the cusp data in Figure 2b) are important evidence that the ion steps and the poleward moving events are indeed linked; that is, they share the temporal rather than the spatial cause in this case and the reconnection only occurred in short pulses. However, these data do not answer all of the questions about how longitudinally extensive the events (and the reconnection pulses generating them) were, because the poleward-moving events were seen by the two EISCAT radars, used with quasi-meridional beams that were separated by only about 200 km in longitude.

Figure 2 shows predicted (left) and observed (right) cusp ion steps for low-altitude satellites moving meridionally (top) or longitudinally (bottom), (see S and S1 in Figure 1) respectively [*Lockwood and Davis*, 1996]. The model plots differ only in the direction of satellite motion: the ion precipitation results from purely temporal variations of the reconnection rate (all the reconnection takes place in square-wave pulses 1 min long and 4 min apart), with no longitudinal variations. Reconnection is sporadic but not patchy.

The steps shown in Figure 1d, recently reported by *Pinnock et al.* [1995] (also in association with poleward-moving events seen by a ground-based radar) throw interesting new light on the extent of the reconnection rate increases. The general behavior is as predicted by *Lockwood and Smith* [1994] and is well reproduced by the model, which does not allow for any longitudinal variations, despite the fact that the satellite in Figure 2d covers roughly 1100 km of longitude during this cusp intersection.

Pinnock et al. [1995] believe that the reconnection is probably both sporadic and patchy. However, Davis and I argue that there are severe problems with this view because an additional mechanism must be found that causes isolated magnetopause X-line segments to produce reconnection pulses in set sequence. Without such a mechanism, the phases of the pulses would be random, downward cusp ion steps would be as likely as upward steps, and the coherent sawtooth structure in Figure 1d (with only upward steps) would not result. Similarly, the survey by *Newell and Meng* [1995] found that steps during southward IMF were almost all in the same sense (respectively up/down with decreasing/increasing latitude) consistent with sporadic reconnection but inconsistent with patchy and with patchy-and-sporadic reconnection.

As mentioned above, the cusp particles also give rise to aurora dominated by 630-nm atomic oxygen emissions, in which poleward-moving events are also detected. These, like FTE signatures, are seen over a wide range of local times on the dayside and are strongly correlated with southward IMF. Their distribution of repetition periods is similar to the FTEs [*Fasel*, 1995] and during the only set of combined observations to date an association was indeed found [*Elphic et al.*, 1990]. These transients can be imaged using all-sky cameras, although to be seen in full often requires a longitudinal chain of such instruments. There are, however, problems in quantifying their area A_p (and thus the voltage V of the reconnection pulses) because the altitude of emission is not well known, because the long radiative lifetimes allow neutral winds to smear the images, and because the observations are integrations along slant paths through the ionosphere.

Newell and Sibeck [1993] argue that these limitations have caused substantial overestimation of the longitudinal extent of these events and thus of their area A and of the associated voltage pulses. However, the latitudinal dimensions would be similarly affected, but these were shown to agree well with radar data, which are subject to none of the above effects [*Lockwood et al.*, 1995b]. The radar measurements also reveal transient longitudinal flow channels (when the IMF B_y is large), usually without strong flow in the opposite direction outside the event. This is significant because an object moving in an incompressible fluid like the ionosphere must push fluid out of the way. If the patch were small we would see such return flow on its flanks. However, these return flows become more extensive but weaken as the object's dimension in the direction of motion is increased. Thus the weak return flows indicate that the events have large local time extent. The flow bursts typically last $T \sim 10$ min at a meridian, through which the longitudinal flow speeds are $v \sim 2$ km s^{-1}, giving longitudinal event dimensions of $vT \sim 1200$ km.

Newell and Sibeck [1993] also proposed a theoretical limit to how big the voltage produced by a reconnection pulse may be. They argued that in a pulse of duration Δt, the enhanced reconnection rate, E_t, can only spread over the magnetopause at the fast mode speed, V_A, giving a maximum X-line of length of $L = V_A\Delta t$, and a peak instantaneous voltage of $E_tV_A\Delta t$. However, *Lockwood et al.* [1995b] do not accept that this limit is real. For example, the enhanced E_t can be triggered externally by the interplanetary boundary conditions at a range of locations, placing no such limit on X-line length. Even if the events are not externally triggered, Newell and Sibeck's argument requires that all of the event, at different longitudes, be reconnected in the same interval Δt long. This overlooks the concept, introduced by *Lockwood et al.* [1993b] to explain observations of dayside auroral and ionospheric flow transients, that events may grow as traveling enhancements of E_t propagate over the magnetopause, such that, although the reconnection at each location lasts for just Δt, the reconnection intervals at different locations are not the same. Lastly, there is no theoretical limit to the value of E_t.

However, it is important not to confuse this debate about the size of individual events with debate about the overall contribution of events to the total reconnection voltage. The latter can be estimated from the occurrence probability of magnetopause FTE signatures as a function of local time, independent of the extent of the individual events. However, the results do depend on the FTE signature model adopted. For the new two-dimensional models, for which the length of the FTE signature, L', equals the length of the X-line generating it, L, FTEs can easily explain all of the observed reconnection voltage [*Lockwood et al.*, 1995b]. However, there are other three-dimensional models (such as the original by Russell and Elphic) for which the FTE signatures can extend beyond the X-line that generated them (that is, L' > L). This reduces the estimated total contribution by a factor of (L/L'). Thus FTEs could supply all of the reconnection voltage, provided L is a sizeable fraction of L' (roughly > 0.5) for each event.

The poleward moving events and cusp ion steps provide powerful new evidence for temporal variations in the magnetopause reconnection rate. To fully define the spatial scales of events, longitudinal measurements (like those shown in Figure 2d) are required, along with more multipoint observations, like those recently presented by *Moen et al.* [1995]. These authors have shown poleward moving transients at two stations more than 800 km apart in longitude. They also report associated and large fluctuations of the ionospheric convection in both the dawn and the dusk cells, consistent with large-scale variations in the total reconnection voltage. In addition, the discussion has tended to concentrate on what can sometimes happen, rather than on what usually happens. For example, the cusp ion steps in Figure 2 show that the reconnection rate E_t can, at least sometimes, come only in isolated pulses at any one local time.

Newell and Meng [1995] have begun to evaluate the statistics of cusp ion steps and conclude that fully pulsed reconnection like this is not common in that E_t fell to zero for only short periods of time, at least in their survey of a limited number of satellite passes through the cusp. On the other hand, *Lockwood et al.* [1994] showed that even apparently steady-state, step-free cusp ion dispersions reveal large (of a factor of 2 and greater) variations in the reconnection rate when studied in detail. In addition, poleward moving auroral transients are exceedingly common when the IMF points southward, repeating every 8 min on average at any one local time [*Fasel*, 1995].

The early observations tend to select the biggest and clearest events, but I believe that they demonstrate that events can sometimes cover large (>1000 km) longitude ranges (and so contribute significantly to the total average voltage individually as well as collectively). In addition, there are other, less obvious selection effects. For example, optical observations can only be made at winter solstice. Thus at this stage, any statements about what is typical would be premature. However, we do now have a better understanding of the range of possibilities and the exciting new data we will acquire in the next few years will tell us much about how the reconnection occurs. This is an important goal because reconnection is a fundamental and important process in astrophysical, solar system, and laboratory plasmas.

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Latest 1997 Budget Forecast: Still Cloudy, but Milder

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In the past three weeks, the U.S. Congress has taken action on three sets of bills that affect funding for science research: a science authorization bill, a 6-year balanced budget plan, and a set of appropriations bills for the 1997 fiscal year (FY '97). Only one of them, however, is likely to prove relevant to federally supported scientists this year.

Science Act of 1996

On May 31, the U.S. House of Representatives approved H.R. 3322, the Omnibus Civilian Science Act of 1996, by a voice vote. The bill, which was drafted and passed by the House Science Committee on April 24 (*Eos*, May 14), suggests a federal science budget of $19.4 billion (the Clinton Administration has requested $20.9 billion) and provides a road map for how congressional appropriators ought to fund federal science programs in FY '97. The version of the bill passed by the House of Representatives on May 31 closely resembled the one passed by the committee in April. However, some of the less popular provisions—such as changing the name of the National Science Foundation to include engineering, and a ban on indoor air research at the Environmental Protection Agency (EPA)—were deleted from the final draft. Also, the final bill included $41 million more for university basic research grants at NSF than was recommended by the committee.

"With H.R. 3322, the House of Representatives has sent a message to the science community, the Senate, and the nation that science policy is a crucial part of a potent economic blueprint for our future," House Science Committee Chairman Robert Walker (R-Pa.) noted. "The House has approved policies that replace the status quo with an activist formula for economic growth, sound fundamental science, and a safe, healthy environment." The chairman added that his authorization bill would provide 5% more funding for basic research than the budget presented by the Clinton Administration.

George Brown (D-Calif.), ranking Democratic member of the Science Committee, rejected Walker's interpretation. "I remain appalled at the lack of understanding my Republican colleagues show on the role of science and technology for this nation's future," Brown said in a written statement. "However, I do want to give credit where credit is due. By freeing up resources in both public and private sector laboratories across the country, the Republican majority is taking a brave step towards filling high-demand, service industry jobs in burger and taco stands around the country."

At press time, the House's omnibus authorization seemed to be having a relatively minor effect on what congressional appropriators have in mind for 1997. In 1995, Walker's committee and the House passed a similar omnibus authorization bill, but the Senate never considered it, and House appropriators appeared to ignore it.

Budget Plan

With regard to the congressional plan to balance the federal budget, Republicans in the Senate have taken the lead in the budget debate for FY '97 and have moderated the party's stance on spending in this election year. The House of Representatives (June 12) and the Senate (June 13) passed a

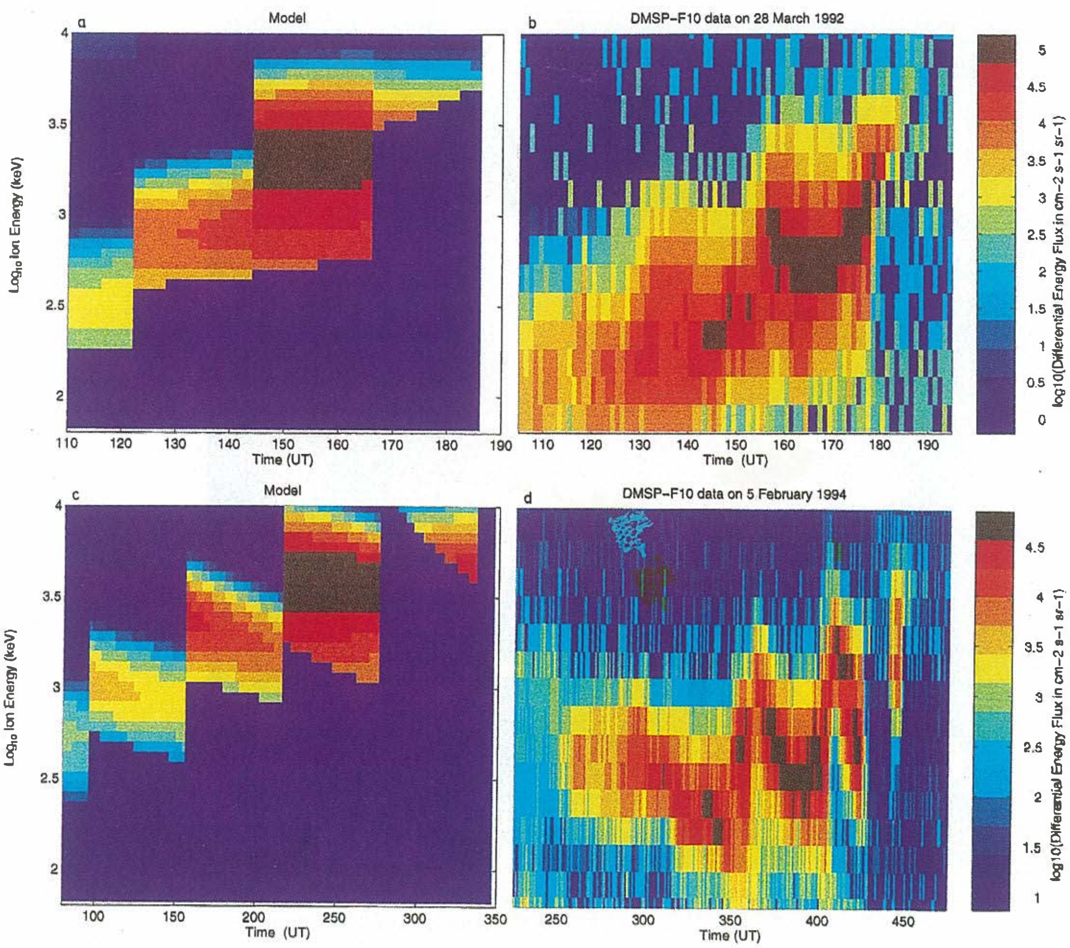

Fig. 2. Energy-time spectrograms of ion differential energy flux for satellites moving meridionally (top) and longitudinally (bottom). The left-hand plots are the results of an illustrative model with pulsed, longitudinally extensive reconnection; the right-hand plots are examples observed by DMSP satellites in close conjunction with poleward moving events seen by ground-based radars. The model and inputs have not been fine-tuned to give close agreement with the data, but nevertheless they illustrate how the data in d) are consistent with longitudinally extensive (>1100 km) events produced by pulsed reconnection.