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# POLEWARD LEAPING AURORAS, THE SUBSTORM EXPANSIVE AND RECOVERY PHASES AND THE RECOVERY OF THE PLASMA SHEET

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## ABSTRACT

The auroral motions and geomagnetic changes that characterize the substorm's expansive phase, maximum epoch, and recovery phase are discussed in the context of their possible associations with the dropout and, especially, the recovery of the magnetotail plasma sheet. The evidence that there may be an inordinately sudden large poleward excursion or displacement (a poleward leap) of the electrojet and the auroras at the expansive phase-recovery phase transition is described. The close temporal association of these signatures with the recovery of the plasma sheet, observed on many occasions, suggests a causal relationship between substorm maximum epoch and recovery phase on the one hand and plasma sheet recovery on the other.

## 1. INTRODUCTION

In an auroral substorm the auroras move poleward during the expansive phase, reach their highest latitude at the substorm's maximum epoch and then retreat equatorward during the recovery phase. In the accompanying magnetic substorm auroral zone negative magnetic bays (or the AL index) deepen during the expansive phase, reach a maximum depth, and then subside during their recovery phase. In the magnetotail beyond about 15 $R_E$ the plasma sheet suddenly thins near the onset of the auroral or magnetic substorm, remains thin through the auroral or magnetic expansion phase, and then thickens (recovers) near the peak of the auroral zone bay (near the maximum epoch of the auroral substorm). What are the causal relations among these various aspects of a substorm? The near-earth neutral line (NENL) model of substorms describes the expansive phase as a set of consequences of a release of stored magnetotail energy by magnetic reconnection at a near-earth neutral line (the substorm neutral line) formed in the plasma sheet at expansive phase onset. But the model provides no description of how the expansive phase should end nor of how (or if) the magnetosphere regains its non-substorm configuration during the recovery phase. Observationally we known that the plasma sheet refills with plasma flowing rapidly earthward from a down-tail source and an interpretation of those observations has the substorm's neutral line retreating down tail and acting as a site of earthward acceleration of lobe plasma.

The apparent near coincidence between the recovery of the plasma sheet, the peak of auroral zone bays, and the maximum epoch of the auroral substorm suggests that they are causally related, all playing some sort of cooperative role in returning the magnetosphere to its non substorm state. This paper reviews some of the research that led to the recognition of these relationships and mentions some opposing views.

## 2. THE SUBSTORM'S EXPANSIVE PHASE, MAXIMUM EPOCH AND RECOVERY PHASE

A primary feature of the auroral substorm is the dynamics of the auroral arcs which is manifested particularly in the fast poleward motions of the arcs during the expansive phase as they create the auroral bulge that can reach poleward to 80 degrees latitude in times of 30 minutes or so. These numbers imply an average poleward speed of about 1 km/sec, but instantaneous speeds ranging up to 10 km/sec have been inferred, e.g., from short-lived spikes of auroral ionospheric absorption measured with narrow-beam antennas (Ref. 1). These fast poleward motions of the auroras during the expansive phase are not $\bar{E} \times \bar{B}/B^2$ drift motions (which would require an eastward electric field, $\bar{E}$, in the ionosphere) but occur even as the ionospheric field, which is westward during the growth phase preceding the expansive phase, remains westward (Ref. 2, Ref. 3). That is, the arcs advance poleward through an ionosphere plasma which is flowing equatorward. It is hypothesized in Ref. 4 that the poleward surging arc may be connected to an acceleration region in the plasma sheet, e.g., a magnetic neutral line, that is moving tailward and thus connecting magnetically with increasingly higher latitudes. (Note that the neutral line need not be moving tailward. The presently more acceptable picture, as we shall see, has the neutral line nearly stationary some distance tailward from Earth throughout the expansive phase and field lines from increasing latitudes being convected into the neutral line by the very electric field that is convecting their feet equatorward through the ionospheric plasma.)

Figure 1 is the classical schematic representation of the evolution of the auroral substorm (Ref. 5). Starting with brightening of the most equatorward of pre-existing arcs (B), the bulge of bright auroras spreads poleward rapidly (C and D) during the expansive phase. The poleward advance does not proceed smoothly, as one might infer from Figure 1, but rather proceeds as a sequence of impulsive electrojet intensifications, each intensified electrojet element lying typically to the northwest of the previous one (Ref. 6). After completion of the expansive phase the recovery phase begins (E and F) during which auroral structures move back equatorward. The end of the expansive phase (D), when auroras have reached farthest poleward, has been called the maximum epoch of the substorm (Ref. 7) and it is sometimes characterized by the presence of a bright auroral ribbon at high latitude, separated from the main body of auroral emission by a non luminous region that can be quite wide. An example of such a maximum epoch pattern is shown in Figure 2, taken from Ref. 7. It is an image from a DMSP satellite. Also shown are superposed auroral zone magnetograms (H or X component) showing the geomagnetic signature of the substorm that started at about 2050 UT. Note: The AU and AL indices are determined from the upper and lower envelopes of such

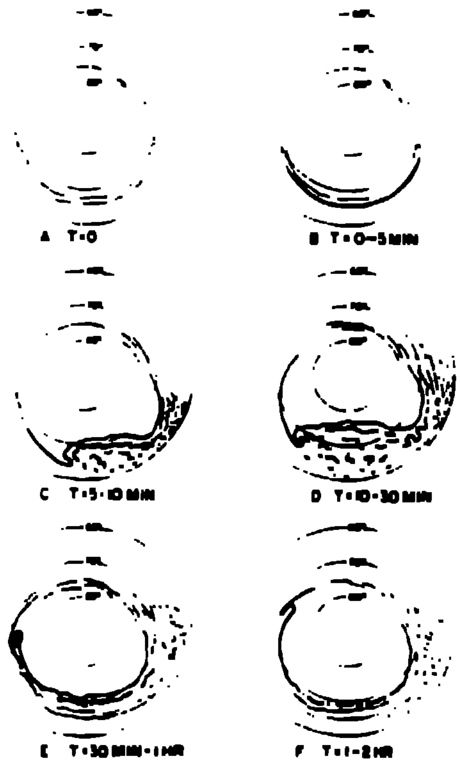


**Figure 1.** Schematic diagram to show the development of the auroral substorm (from Ref. 5).

indicated by the arrow with the orbit number 1100. Note that the magnetic signature of the substorm comprised negative bays at some stations (those near magnetic midnight) which deepened rather rapidly and then began to subside about 30 minutes later, shortly before the image was recorded. In substorm research it is usually necessary to use geomagnetic records such as those in Figure 2 to identify the occurrence of substorms and their phases because the global array of magnetic stations is quite dense and their records are continuous; images of auroras from the ground or from satellites, on the other hand, are much less readily available. Thus it is customary to identify the expansive phase of a substorm with the deepening of the negative bays at midnight auroral zone stations and to refer to the subsidence of the bays as the recovery phase of the substorm. Figure 2 illustrates that there is uncertainty in this procedure of identifying auroral substorm phases from their auroral zone magnetic signatures alone (often the only recourse one has). For example, does the beginning of auroral zone bay subsidence really correspond to the maximum epoch of the auroral substorm and the beginning of its recovery phase, or does the beginning of auroral zone bay subsidence signify, instead, that the auroral bulge and its associated ionospheric currents are advancing poleward beyond the range of the auroral zone magnetometers? What is the history of the bright poleward arc? Did it move poleward suddenly (i.e., leap poleward) from lower latitude? Did it just appear there? Or is it the residual of the poleward border of the auroral bulge that has remained bright or that has brightened recently? Does it carry much current, perhaps current that has been diverted poleward from the auroral zone?

## 3. THE MAGNETIC SUBSTORM AND THE PLASMA SHEET

The above concerns about the detailed associations between the auroral substorm development and that of the magnetic substorm may seem trivial or pedantic, but they are not. A fundamental change of magnetotail structure seems to be initiated at about the time of transition from the substorm's expansive phase to its recovery phase (i.e., near the substorm's maximum epoch). This temporal association has been made principally using the magnetic substorm signatures for the reasons mentioned above. This change is the refilling or "recovery" of the plasma sheet — a change which represents the termination of the substorm and which returns the magnetosphere essentially to its pre-substorm state. It is likely that the features of the substorm's recovery at earth are directly attributable to the plasma sheet's recovery in the magnetotail.

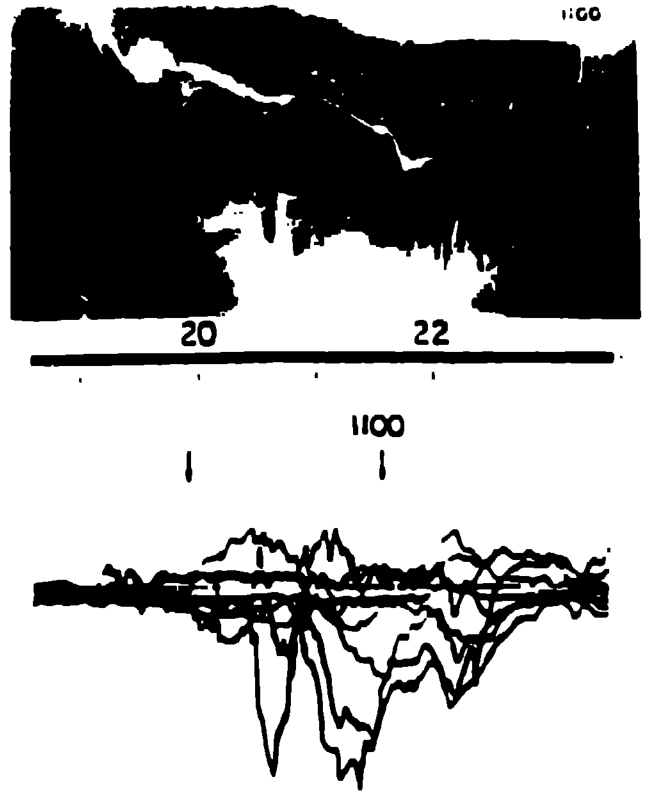


**Figure 2.** An auroral arc at the maximum epoch of a substorm and concurrent auroral zone magnetic records (from Ref. 7)

Figure 3 (from Ref. 8) is presented to remind the reader of the behavior of the plasma sheet beyond about 15 $R_E$ during a substorm. This substorm began with a sudden onset of a negative bay at 1112 UT (top). The bay reached maximum depth at 1142 UT and subsided thereafter. Within about 4 minutes after bay onset the plasma sheet at $X = -20 R_E$ dropped out showing tailward plasma flow and southward $B_Z$ as it disappeared. At 1142 UT the plasma sheet reappeared showing earthward flow and northward $B_Z$. Note the close coincidence between the substorm's maximum epoch, defined here as the peak of the magnetic bay, and the reappearance of the plasma sheet. Such coincidences are not rare but could more nearly be described as the norm, as was shown in a statistical study of the association of plasma sheet recovery at the Vela satellite orbit (circular, 18 $R_E$ radius) with the geomagnetic signatures of substorms. Hones *et al.* (Ref. 9) did a superposed epoch analysis of the AL index using the instant of plasma sheet recovery at a Vela satellite as the fiducial time. Figure 4 shows results obtained for events that occurred when the Vela satellite was in one of four different ranges of distance from the neutral sheet. One recognizes the magnetic signatures of expansive phase and recovery phase, each lasting an hour or more and notes that the maximum epoch of the average magnetic substorm coincides very closely with the time of plasma sheet recovery, independent of $dZ_{NM}$ for $0 < |dZ_{NM}| < 6R_E$. These results imply that the expansive phase-recovery phase transition of the magnetic substorm is causally related to plasma sheet recovery and that the plasma sheet expands very rapidly to half thickness ≲6$R_E$. The subsidence of the auroral zone negative bay is thought to be due to a sudden poleward displacement (poleward leap) of the auroral electrojet current.

In the context of the near earth neutral line (NENL) model of substorms (e.g., Ref. 10), individual events like shown in Figure 3

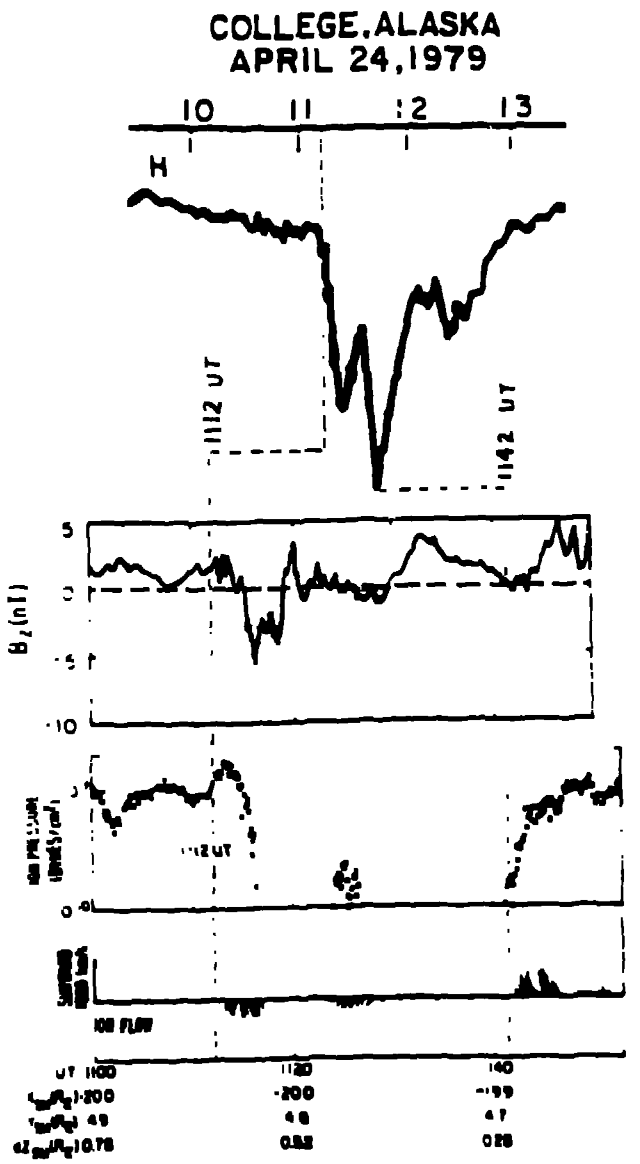


Figure 3. College, Alaska geomagnetic record and data from ISEE 2 during a substorm on April 24, 1979. The ISEE 2 data include $B_z$, the plasma ion pressure and plasma ion flow vectors. The ISEE 2 location is given at the bottom (from Ref. 8).

and the average results in Figure 4 imply that the plasma sheet's recovery is a consequence of a suddenly initiated rapid tailward retreat of the substorm neutral line. At the expansive phase onset the substorm neutral line, $N'$ forms in the near-earth plasma sheet (Figure 5). An azimuthal segment of the plasma sheet is severed within a few minutes (panels 2-5), generating the large plasmoid that departs down-tail (panels 6-9), leaving only a very thin plasma sheet in its place. This accounts for the plasma sheet dropout just after substorm onset. About an hour later the substorm neutral line suddenly rushes down tail (panel 10) and magnetic reconnection at the tailward moving neutral line creates a new body of plasma filled closed flux tubes that reconstitute the plasma sheet.

## 4. THE AURORAL SUBSTORM AND THE PLASMA SHEET

It is naturally of great interest to learn how auroral aspects of a substorm are related to plasma sheet recovery. One expects from our discussions thus far, that the plasma sheet reappearance might coincide with the maximum epoch of the auroral substorm

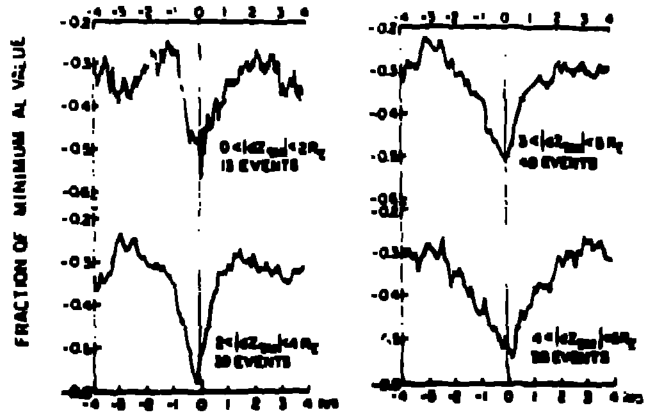


Figure 4. Averaged records of normalized AL index for 8-hour intervals centered on times when plasma sheet expansions were observed with Vela satellites in 18 $R_E$ circular, 60° inclination orbits (from Ref. 9).

from an aircraft flying a constant local time path over Canada and Alaska while a Vela satellite, 15 $R_E$ in the magnetotail, crossed the plasma sheet at the same local time. Two substorms occurred during the experiment and, in each one, a rapid poleward excursion of auroras from $\Lambda_m \approx 68°$ to $\Lambda_m \geq 76°$ coincided with plasma sheet recovery. Also, negative magnetic bays began at the high latitude station Baker Lake ($\Lambda_m = 74°$) coincident with the two plasma sheet recoveries. Thus both the auroras and the electrojet experienced suddenly-initiated rapid poleward motions (poleward leaps!) in association with plasma sheet recovery. The results of Wolcott *et al.* also tell us something about the nature of the auroral substorm's maximum epoch and how it is reached. The initial brightening of the auroras in their first substorm occurred in the latitude range $\Lambda_m = 62°$ to 65° and within 10 minutes bright auroras had spread to $\Lambda_m = 70°$. Thereafter, for about 75 minutes bright auroras prevailed over the latitude range $\Lambda_m = 62°$ to 68°. Then, within one or two minutes, coincident with plasma sheet recovery, the bright auroras appeared poleward of the airplane, extending from $\Lambda_m = 69°$ to > 75°. Thus, this maximum epoch was not attained by steady poleward progression of the auroral bulge, but by a sudden "appearance" of auroras at high poleward latitudes, i.e., by a poleward leap of the auroras.

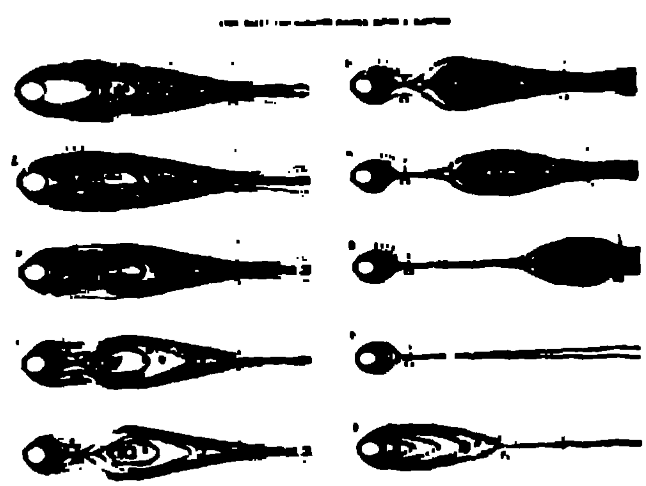

Figure 5. Schematic representation of the variations of the magnetotail plasma sheet during a substorm (from Ref. 10).

Observations from the high latitude station South Pole ($\Lambda_m = 75°$) have provided more information regarding the relation of auroral development to plasma sheet recovery (Ref. 12). Riometer measurements at South Pole frequently revealed suddenly occur

...s moving very rapidly poleward from lower latitude and passing over the station. A superposed epoch analysis of the AL index for many of these events, using the onset of auroral absorption as the fiducial time, gave the results shown in Figure 6. The auroras arrived over South Pole very near the peak of the average AL bay. This is very reminiscent of the correlation of plasma sheet recovery and the AL index shown in Figure 4 and suggests, of course, that the surge of auroras to very high latitude is a feature of the expansive phase-recovery phase transition and is related to the recovery of the plasma sheet and to the retreat of the substorm neutral line. Fortunately there were magnetotail data available from ISEE 1 during part of the period of the South Pole measurements. Figure 7 shows concurrent data from the South Pole riometer and from a plasma instrument on ISEE 1, both compared to the magnetic field measured by a midnight auroral zone station. Substorm onset times determined from mid-latitude Pi2 pulsations are indicated by large dots. The plasma sheet recovery always occurs very late in the substorm, often at the time the negative bay begins its final recovery. And in many cases the South Pole riometer onset coincides closely with the plasma sheet recovery.

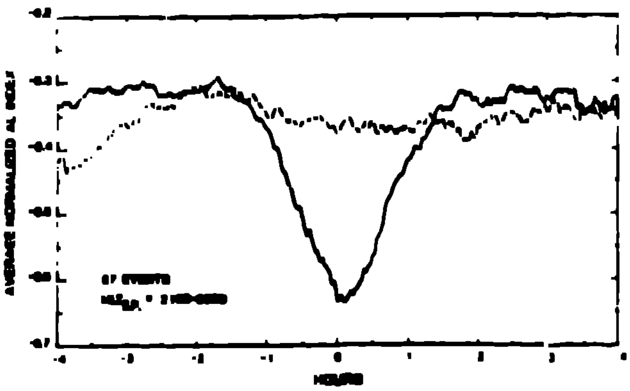


Figure 6. Average normalized AL index for 8-hour intervals centered on the onset times of 87 South Pole riometer events (solid curve) and for 8-hour intervals centered on the same times minus 24 hours (dashed curve). South Pole was in the 2100-0300 MLT range for all events (from Ref. 12).

## 5 THE VIEW PROVIDED BY GLOBAL AURORAL IMAGERY

The advent of time resolved global images of the auroras such as those from DE 1 and Viking brings a new opportunity to study the auroral substorm evolution, to relate it (a) to the substorm's magnetic signatures and, most important, to relate it (b) to behavior of the plasma sheet when satellite measurements in the plasma sheet are made concurrently with the recording of auroral images. Application of this new capability to the matters surrounding substorm recovery, which are the principal theme of this paper, has been limited. Here we shall review briefly some results relevant to (a) the matter simply of the behavior of the auroras around the time of the maximum epoch of the magnetic substorm, i.e., the peak of AE or AL index, with no regard for outer magnetosphere measurements. Is there an inordinately fast poleward surge of the auroras near this time as the ground observations (e.g., Figures 6 and 7) would suggest? This matter can best be addressed using DE 1 images because although their time resolution (12 minutes) is longer than those of Viking (1 minute), their imaging intervals are longer (because of the higher altitude orbit) and thus the full history of a substorm is often encompassed in an image set. Several substorm image sets have been published and there are conflicting opinions as to whether these display a poleward leap of the auroras near maximum AE.

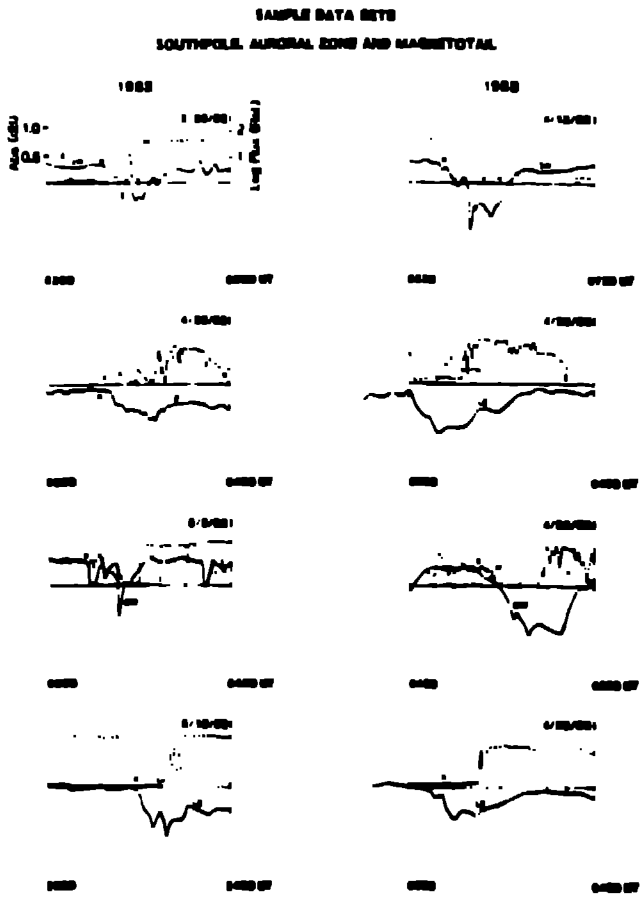


Figure 7. Plots of geomagnetic H or X component (solid curves), South Pole 30-MHz riometer signal (dotted curves), and plasma sheet 6-keV electron flux (dashed curves) for 4-hour intervals encompassing eight of the South Pole riometer events. Black dots indicate times of Pi2 pulsations at mid-latitude stations (from Ref. 12).

November 8, 1981. The late-evening station, Meanook showed negative bay development starting about 0700. Bays began at Sitka, College, and Great Whale at about 0800 UT signaling onset of a substorm's expansive phase. At about 0848 UT bays began suddenly at Fort Churchill (68°) and at the higher-latitude stations Baker Lake and Cambridge Bay, signifying that the electrojet had suddenly moved poleward substantially. (The positive Z bays at Baker Lake and Cambridge Bay show that the main electrojet current did not reach those high latitudes however.) Shortly afterward, at 0900 UT, the bays at the auroral zone stations began to recover rapidly. Here, then, is another example of a sudden poleward surge of the electrojet (a poleward leap?) closely coincident with the peak and beginning of recovery of auroral zone bays. The DE-1 satellite recorded the set of images of this substorm that is presented in Figure 9 (taken from Ref. 14). How can the global view that they provide augment our understanding of this particular example of a poleward leap of the electrojet? (This event was earlier discussed in this context by Hones (Ref. 13).)

Some auroral brightening is seen in the first image which was started at 0711 UT. Thereafter, increasing intensity and structure is seen in each succeeding image. Then, in the ninth image (accumulation interval 0851-0903 UT) a large enhancement of the width of the auroral band took place, and this coincides with the peak of the AL index, which is shown below the images. Figure 4 of Ref. 14 shows that the poleward boundary of the auroras advanced poleward by about 6 degrees of magnetic latitude. Thus, in this instance it seems appropriate to speak of a poleward leap of the auroras accompanying the poleward leap of the electrojet. This, of course, is not completely surprising since it is known that the

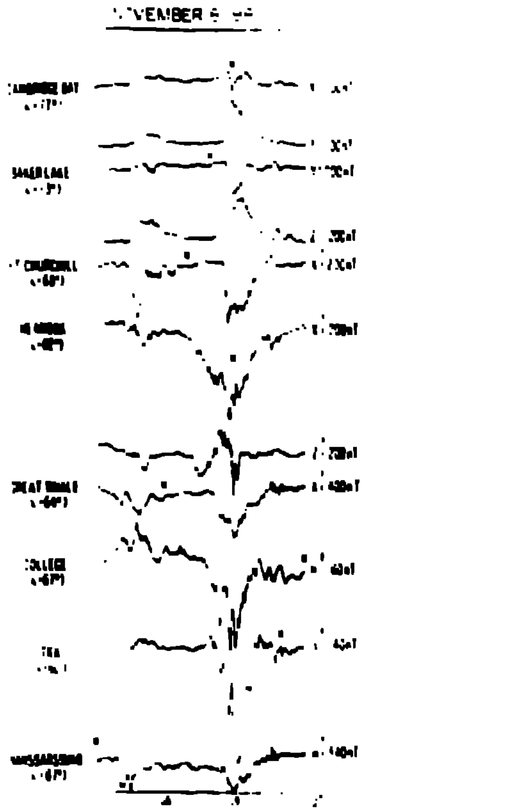

Figure 8. Magnetic records from auroral zone and polar cap stations for November 8, 1981. Local magnetic midnight at each station is indicated by M (from Ref. 13).

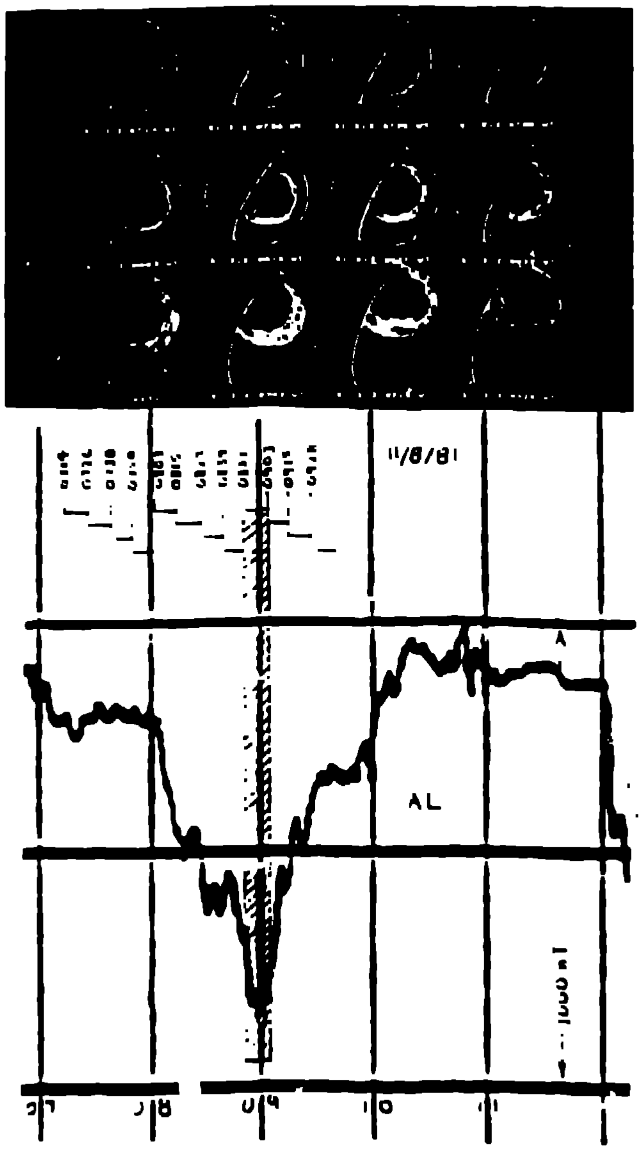


Figure 9. Sequence of 12 consecutive false color auroral images of the 557.7-nm emission line of OI during 0714-0940 UT on November 8, 1981. Universal time for the beginning of the 12 min telemetering period for each image is provided. At the bottom is the AL index with lines indicating the onset times and telemetering periods of all the images (adapted from Ref. 11).

The great value of the DE-1 images is that they reveal the large scale of this change. That is, the poleward leap was seen to occur simultaneously over at least two hours of local time (see Figure 4 of Ref. 11).

Craven and Frank (Ref. 11) examined IMF data obtained during this event and related variations of IMF $B_z$ to variations in polar cap size indicated by the DE-1 images. They suggested that the temporal sequence of events displayed in this auroral substorm was unusual and causally related to systematic variations of the IMF direction. They expressed doubt that observations in this unusual period of auroral activity support the concept of a poleward leap, suggesting that the large poleward motions are more readily interpreted as the latitudinal motions in an expansion phase.

Three other image sequences were published showing substorms on November 4, November 28, and December 2, 1981 (Ref. 11 and 15). In two of these (November 28 and December 2) the images suggest that enhanced poleward motion of the auroras occurred during the image taken at the peak of the auroral zone bay development. In one of these cases (December 2) the Z-component magnetogram from the midnight station, Tromso, indicated that poleward displacement of the overhead electrojet began just a few minutes after the peak of the H bay. Craven and Frank (Refs. 11 and 15) argued that the poleward auroral motions seen in those instances were normal expansion phase latitudinal motion. Unfortunately there was no satellite in the magnetotail during this 1981 period that might have been able to determine whether plasma sheet thinning and recovery accompanied these events.

## 6. WHAT INFLUENCES PLASMA SHEET AND SUBSTORM RECOVERY?

Many people would agree that the growth phase and expansive phase of substorms are fairly well understood under the general elements of the NENL model, that is, a coupling of energy into the stored energy by reconnection at a near-earth neutral line formed in the plasma sheet. But the model does not complete the story by telling us how the magnetosphere returns to its non-substorm state. There are only the observations which suggest that the substorm cycle is closed by the substorm neutral line's retreat to a distant location. The retreat could be instigated by a configurational instability internal to the magnetotail or by a change in the external environment; northward turning of the IMF has been considered as a cause. To test the latter suggestion we have extended our analyses of the South Pole data discussed earlier. We found 21 South Pole riometer events for which there were concurrent IMP 8 measurements of the IMF and we conducted superposed epoch analyses of the AL index and of the IMF Z component, again using the sudden onset of riometer absorption at South Pole as the fiducial time. The results are shown in Figures 10 and 11.

The events were analyzed in two randomly selected groups, events 1-11 and 12-21. The AL analysis in Figure 10 reveals that the riometer events showed the same relationship to auroral zone activity as was found in the earlier South Pole event study (Fig-

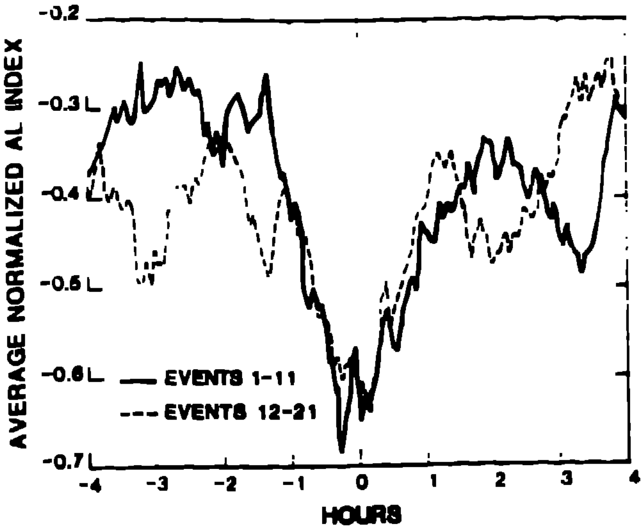


Figure 10. Average normalized AL index for 8-hour intervals centered on the onset times of eleven South Pole riometer events (solid curve) and of ten further such events (dashed curve).

average South Pole riometer event, reached its peak near the time of the event and then subsided during the next hour. Both groups (1-11 and 12-21) displayed the same behavior. The superposed epoch analyses of IMF $B_Z$, shown separately for the two groups in Figure 11, exhibit somewhat different behavior, but neither offers a clear indication of a causative influence of the IMF. This preliminary investigation does not seem to support the idea, for example, that a sudden northward turning of the IMF reduces the input of energy to the magnetosphere, causing the magnetosphere suddenly to relax to its non-substorm state.

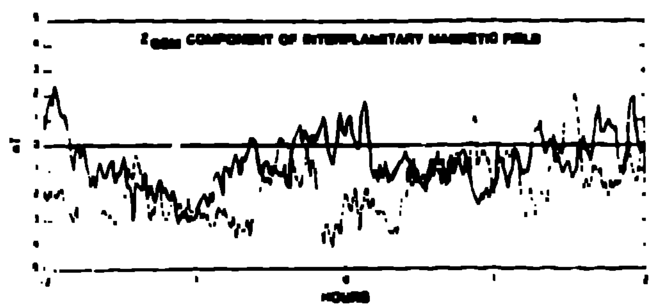


Figure 11. Average normalized $Z_{GSM}$ component of the interplanetary magnetic field for 4-hour intervals centered on the onset times of eleven South Pole riometer events (solid curve) and of ten further such events (dashed curve).

## 7 SUMMARY AND CONCLUSIONS

Throughout a substorm's expansion phase and into its maximum epoch auroras execute motion that can be of irregular speed but that are almost always poleward. The recovery phase brings a reversal of auroral motions, turning them equatorward. The associated geomagnetic signature is a suddenly initiated rapid deepening of auroral zone negative bays which reach a peak (often a sharp peak) at a time that seems to be roughly coincident with the maximum epoch of the auroras. The negative bays subside roughly in concert with the auroral substorm's recovery phase. In the magnetotail beyond about 15 $R_E$ the plasma sheet thins suddenly within a few minutes after expansive phase onset and later thickens (recovers) near the time of the peak of the auroral zone bays. The subsidence of the auroral zone bays seems to be associated with a sudden poleward excursion of the electrojet which has expect that the auroras should undergo a poleward leap also and various observations described in this paper indicate that they do. It seems likely that this poleward leap of the auroras carries the auroral substorm to its maximum epoch.

It has been argued by many people (e.g., Ref. 10) that the normal motion of the auroras throughout the expansive phase is poleward and that the so-called poleward leap is just more of the same. But that argument ignores the truly remarkable fact that the initial poleward motion at expansive phase onset is accompanied by a drop-out of the plasma sheet, while the final poleward motion, the poleward leap, is accompanied by a recovery of the plasma sheet. The recovery of the plasma sheet is believed to be due to tailward retreat of the substorm neutral line. Why this phenomenon is accompanied, at the earth, by sudden further poleward motion of the auroral substorm phenomenon is not fully understood. It probably has to do with an imbalance of convection rates of lobe field lines into the retreating reconnection region and of their feet through the ionosphere.

## ACKNOWLEDGMENT


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