

DETERMINATIONS OF RELATIVE TIMING OF NEAR-EARTH SUBSTORM ONSET
AND TAIL RECONNECTION

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ABSTRACT

Several studies have recently been performed that are directed towards determining the timing of near-Earth neutral line (NENL) formation in the tail relative to substorm onset. These studies are reviewed here. It is found that they are all consistent with each other and that they show that NENL formation does not occur prior to substorm onset in the inner plasma sheet. This result is inconsistent with the fundamental premise of the new NENL substorm model that flows from a NENL lead to substorm onset in the inner plasma sheet well earthward of the NENL. Despite not occurring prior to substorm onset, NENL formation is clearly an important aspect of substorms. It is suggested that consideration be given to the possibility that NENL formation may be a result of, rather than a cause of, current wedge initiation in the inner plasma sheet. It is also suggested that understanding is needed of why signatures of NENL formation are often not observed within the plasma sheet, even when spacecraft are located within the longitude range of current wedge formation.

INTRODUCTION

I was asked to discuss what the incorporation of ionospheric observations into substorm studies can tell us about the relative timing between tail reconnection and substorm onset. This question is of critical importance to one of the major current substorm models, the “new Near-Earth Neutral Line (new NENL)” model, which attributes substorm expansion phase onset to formation of a neutral-line in the plasma sheet well earthward of the distant tail magnetic x-line. This model requires that neutral line formation occur a few minutes prior to substorm onset [e.g., *Birn and Hesse*, 1996]. While this has been a highly controversial subject of magnetospheric research, there have been several recent studies which directly address this issue. I will show here that the results from these studies are consistent with each other, and that when taken together, these studies give a clear answer to the question of whether a NENL forms a few minutes prior to substorm onset.

Significant progress has been made on the substorm problem since the time of the First International Conference on Substorms (ICS-1) in 1992. At that time, two descriptions of substorm onset received the most attention. These were the NENL model, which

attributed onset and auroral breakup to the formation of a neutral line within the central plasma sheet at $r \sim 15 R_E$ [e.g., *McPherron*, 1992], and the boundary layer model, which attributed onset to processes associated with the plasma sheet boundary layer [e.g., *Eastman et al.*, 1988]. However, at the same time a number of researchers felt that observational evidence indicated that substorm onset occurred within the inner plasma sheet at $r \sim 6-10 R_E$ [*Feldstein and Galperin*, 1985; *Lopez et al.*, 1990, *Jacquey et al.*, 1991, *Lui*, 1991; *McIlwain*, 1992], which was far closer to the Earth than required by the above two ideas.

Soon after ICS-1, ground based measurements from the CANOPUS array of meridian scanning photometers in central Canada lead to a major breakthrough in substorm physics. These measurements provided convincing evidence that the auroral brightening that initiates the substorm expansion phase lies on magnetic field lines that are several degrees equatorward of the nightside boundary between open and closed field lines and cross the equator within the inner plasma sheet at $r \sim 6-10 R_E$ [*Samson et al.*, 1992]. This led to renewed interest in ideas for substorm onset within the inner plasma sheet such as turbulence-driven current disruption [*Lui et al.*, 1990], ballooning instability [*Roux et al.*, 1991; *Samson et al.*, 1996], drift of plasma sheet particles following an interplanetary magnetic field (IMF) change that leads to a reduction in convection [*Lyons*, 1995; *Lyons et al.*, 2000], and the new-NENL.

The new NENL requires that an X-line form in the tail plasma sheet well beyond the inner plasma sheet region where onset phenomena initiate. Reconnection at the X-line then “ejects (magnetic flux) earthward ... initiating phenomena closer to the Earth” [*McPherron and Fairfield*, 1998] such as the substorm current wedge, magnetic field dipolarization, and auroral brightening [*Birn and Hesse*, 1996; *McPherron and Fairfield*, 1998]. A second significant breakthrough was achieved by *Nagai et al.* [1998], who presented convincing evidence using Geotail spacecraft data that an X-line and associated reconnection occurs between $x \sim -20$ to $-30 R_E$ in the tail plasma sheet in association with some substorms. X-line formation was observed up to $\sim 2-3$ min prior to low-latitude Pi2 onsets that were observed between 10 to 18 UT at one station (Kakioka, 26.6° latitude, 24 MLT at 15 UT). This *Nagai et al.* [1998] study has been responsible for a surge in popularity of the new NENL, and has led to statements such as “all

key elements in the substorm sequence through the expansion phase are now rather well understood --- work has systematically addressed and answered the key outstanding question about the substorm expansion phase onset: It favors the ‘modified’ NENL picture with an X-line at $X_{\text{GSM}} \sim -25 R_E$ [Baker *et al.*, 1998].

Despite its popularity, key aspects of the new-NENL have not been shown to be consistent with observations. Specifically, NENL formation prior to near-Earth onset has not been demonstrated. Also the lack of NENL signatures within the plasma sheet for many substorms (signatures not seen within ± 10 min of onset for 183/243 cases in Nagai *et al.* [1998]), even when Geotail is within the typical onset region, has not been given serious attention. Recent studies have addressed the timing issue, and the implications of these studies is addressed in the following.

TIMING ISSUES

There are several timing issues which must be considered in order to interpret studies of the relative timing between NENL formation and substorm onset. First, the new NENL requires that flow from the NENL carry magnetic flux to the onset region prior to the initiation of expansion-phase phenomena (dipolarization, particle injections, current wedge formation) in the inner plasma sheet. It is straightforward to obtain an estimate for the time delay ΔT between NENL formation and inner plasma sheet onset required by the new NENL. For an earthward speed of ~ 500 km/s (an upper limit for sustained earthward flow perpendicular to \mathbf{B}), NENL formation at $x \sim -25 R_E$, inner plasma sheet onset at $x \sim -8 R_E$, we get $\Delta T \sim 3.5$ min. MHD simulations of the new-NENL can also be used to estimate ΔT . B_z versus t in the equatorial plane at $x \sim -7.5$ from the simulation of Birn and Hesse [1996] is shown in Figure 1. With distance units in R_E , the unit of time in Figure 1 is 6s. Reconnection initiated at $t \approx 100-105$ in the simulation, and as shown by the increase in B_z , dipolarization at $x \sim -7.5 R_E$ initiated a few time units after $t = 140$. This gives $\Delta T \approx 4$ min, essentially equal to the simple estimate obtained above.

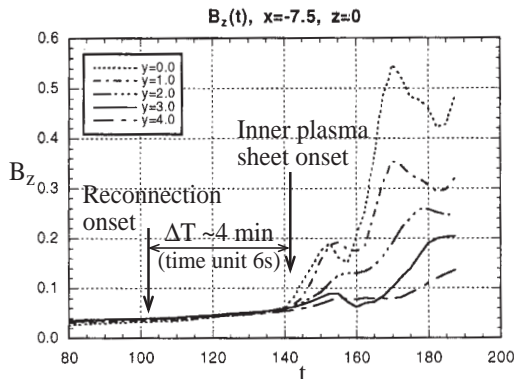


Figure 1: Temporal evolution of B_z in the equatorial plane for various y locations in normalized units [Birn and Hesse, 1996].

Since most studies of substorm timing use ground observations to identify substorms and to determine the time of their onset, we must also consider the propagation delay from inner plasma sheet onset to the ionosphere. Several studies have shown this delay to be $\sim 1-2.5$ min to the auroral ionosphere [Ohtani *et al.*, 1992; Angelopoulos *et al.*, 1996; Nagai *et al.*, 1998; Erickson *et al.*, 2000; Lyons *et al.*, 2000; Slavin *et al.*, 2000]. Note that determination of this delay requires spacecraft observations from within the inner plasma sheet region where onset occurs. This region is generally, though not always, somewhat beyond synchronous orbit, and the inward propagation time to synchronous orbit is often $\sim 1-2$ min [Ohtani, 1998].

For studies, such as that of Nagai *et al.* [1998] which used low-latitude Pi2 pulsation to determine the substorm onset time, we must also include the time delay from auroral onset to low-latitude Pi2 onset. This delay has been found to be $\sim 0.5-2$ min, the delay typically increasing with increasing longitudinal separation between the Pi2 observatory and the auroral onset [Liou *et al.*, 2000].

Based on the above estimates, we have the testable prediction that the minimum time delay from NENL formation to inner plasma sheet, auroral zone, and low-latitude Pi2 onset must be ~ 3 , ~ 4 , and ~ 5 min, respectively.

TESTS OF NEW NENL

With Geotail plasma sheet data

An ideal test of the new NENL would be a comparison of plasma sheet onset timing at $r \sim 20-30 R_E$ with that at $r \sim 8 R_E$. Unfortunately, spacecraft orbits have not yet allowed for such as test. However, Slavin *et al.* [2000] have recently looked at a few cases when Geotail was at $x = -8.8 R_E$ and IMP 8 was at $x = -30 R_E$ in the tail lobes. An example of their observations is shown in Figure 2. In this example, Geotail observed three closely spaced flow and dipolarization onsets that are identified by vertical dashed lines in the figure. The CANOPUS magnetometer chain gave good coverage of these onsets. Pi2 pulsation data from one CANOPUS auroral station, Ft. Smith, is shown in the figure and nicely illustrates the delay (~ 2 min in this case) that can occur between inner plasma sheet and auroral zone onset. This delay to auroral onset is confirmed by the auroral kilometric radiation (AKR) data shown in the upper panel. (Note the darkening soon after each of the onsets in the emissions spectrogram; this darkening indicates significant emission enhancement and shows more clearly in the original color spectrograms.)

The arrows above the IMP-8 lobe magnetic field data in Figure 2 indicate times that Slavin *et al.* [2000] identified as times of compressional responses to plasmoid formation. Note that these responses initiated ~ 4 min after inner plasma sheet onset, and that

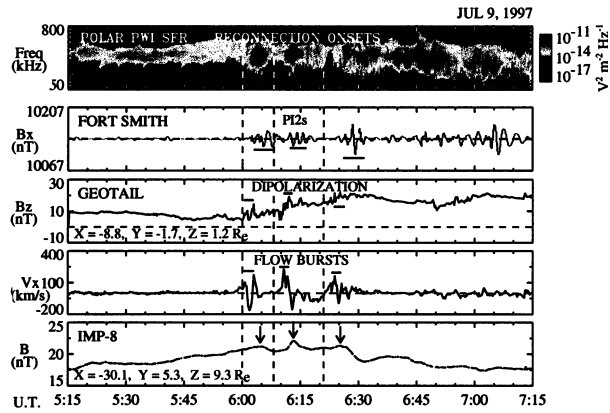


Figure 2: From top to bottom are POLAR AKR emissions, auroral zone Pi2, Geotail B_z and V_x , and IMP-8 lobe B [based on Slavin et al., 2000].

signatures of NENL formation a few minutes prior to inner plasma sheet onset, as required by the new NENL, are absent. This example gives a nice illustration of substorm onset in the inner plasma sheet, and suggests that NENL effects did not initiate prior to inner plasma sheet onset. However, the observations do not give direct evidence that neutral line formation did not occur a few min prior to onset.

Superposed epoch studies have given quite accurate information on the timing of NENL formation. The first comprehensive study is that of Machida et al. [1998, 1999]. They performed a superposed epoch study of tail onset phenomena using Geotail data and onset times obtained from low latitude Pi2 pulsations. Their results for flow in the x,y plane are shown in Figure 3. Each panel shows flow at the time of maximum flow speed (12 s samples) during the 1 min interval centered on the indicated times relative to the low-latitude Pi2 onsets.

The -5 and -3 min panels in Figure 3 show the occasional flows which are believed to be small scale and are a general feature of the tail plasma sheet [e.g., Angelopoulos et al., 1996]. Neutral line signatures in V_x and B_z (not shown) are first seen in the -1 min panel. At this and later times, a sign change in V_x (and ΔB_z) shows neutral line formation at $x \sim -26 R_E$. These results were confirmed in a more in depth analysis by the same research group [Miyashita et al., 2000], where the signature of NENL formation was first observed at 0 min, indicating NENL formation is within the 2 min interval prior to Pi2 onset [Miyashita et al., 2000]. Figure 4 from Miyashita et al. [2000] shows 2-min averages of V_x and of B_z changes for onsets where a maximum average tailward flow speed exceeding 300 km/s was observed. Figure 4 shows that consistent changes first occur at $t = 0$, implying that neutral line formation initiates between $t = -2$ and $t = 0$ min. These results place NENL formation 0-2 min following inner plasma sheet onset, and give strong evidence that NENL formation does not occur a few minutes prior to inner plasma sheet onset.

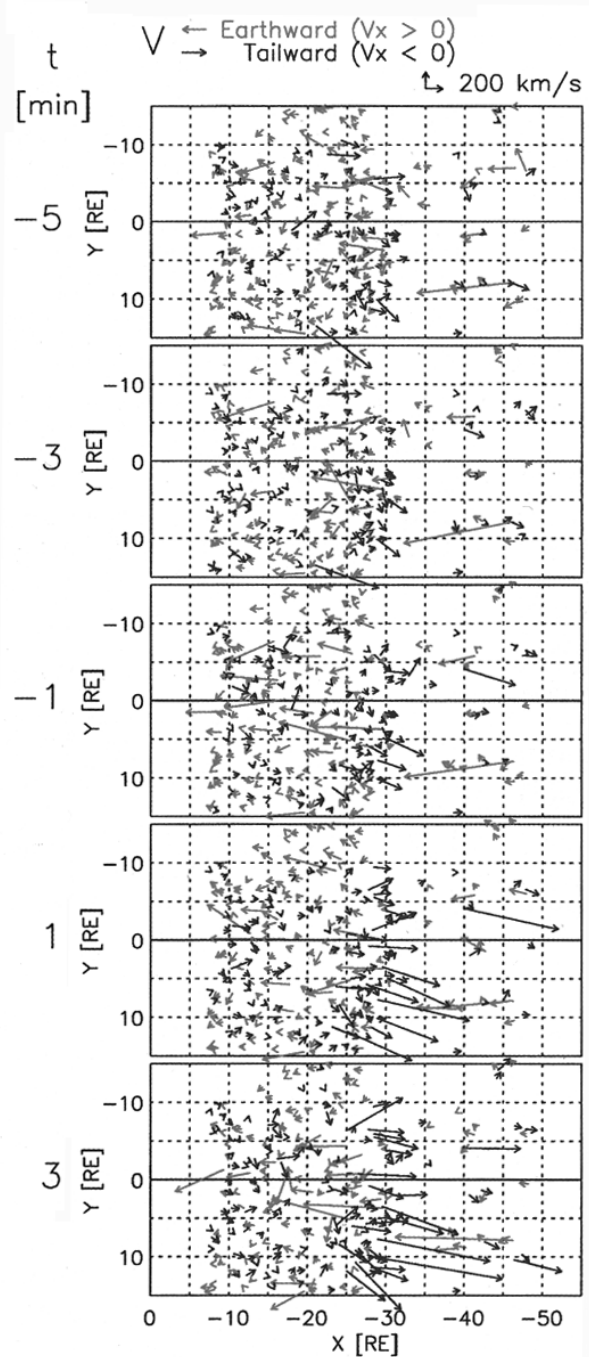


Figure 3: Flows in x,y plane for 12 s samples having the maximum $|V_x|$ during 1 min intervals centered on times indicated, which are relative to low-latitude Pi2 onset [Machida et al., 1999].

Lui et al. [1998] used Geotail plasma sheet data to perform a study similar to that of Machida et al. [1998, 1999] but using global auroral images from the POLAR spacecraft to determine substorm onset. Using 1 min averages of flow vectors and ΔB_z , Lui et al. [1998] found that NENL signatures initiate $2 (\pm 1)$ min after auroral onset, and their results also place the NENL at $x \sim -25 R_E$. These results agree with the implication from Machida et al.'s results that NENL formation

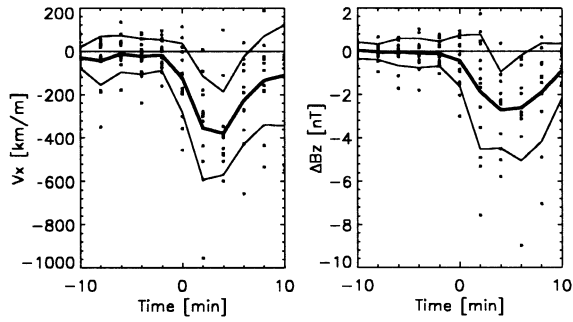


Figure 4: Two-minute averages of V_x and B_z changes for onsets where the maximum tailward flow speed exceeded 300 km/s. Thick and thin lines give, respectively, averages and ± 1 standard deviation [Miyashita et al., 2000].

occurs after inner plasma sheet onset. Lui et al.'s results suggest formation occurs ~ 3 min after onset rather than 0-2 min after onset; however, this small disagreement is not relevant to the fundamental timing question.

Lui et al. [1998] also noted that it is only the perpendicular flow that contributes to flux transport. They found that for earthward directed flows, the x, y component of the perpendicular flow is considerably smaller than the total flow vector and is very much smaller than the ~ 500 km/s which would be needed to carry significant magnetic flux to the inner plasma sheet

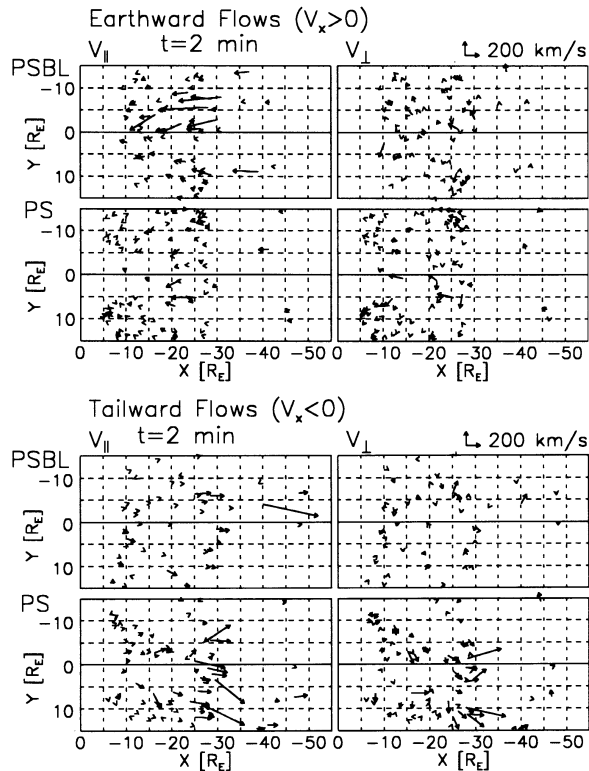


Figure 5: 2 min averages of parallel and perpendicular flows in x, y plane at time 2-min after low-latitude Pi_2 onset. Tailward and earthward flows, central plasma sheet (PS) and plasma sheet boundary layer (PSBL) cases shown separately [Miyashita et al., 2000].

in a reasonable amount of time.

[Miyashita et al., 2000] have confirmed Lui et al.'s [1998] finding with regard to the earthward directed perpendicular flows. Figure 5 shows 2-min averages of the x, y component of parallel and perpendicular flows at a time centered 2-min after onset, when Figure 4 shows that NENL flows are near their maximum. Plots are shown separately for tailward and for earthward directed flows and for cases when Geotail was within the central plasma sheet and within the plasma sheet boundary layer. Notice that all the earthward directed perpendicular flow speeds are < 200 km/s and that the vast majority of the speeds are $\ll 200$ km/s. This indicates that not only do NENL flows not initiate until after inner plasma sheet onset, but they are also unable to convect significant magnetic flux to the inner plasma sheet in times < 10 min.

The above analyses of plasma sheet flows also confirm Nagai et al.'s [1998] results that NENL signatures within the plasma sheet are not seen for many substorms, even when Geotail is within typical onset region.

Ieda et al. [2000] examined Geotail observations of NENL effects in a somewhat different way than in the above studies. They first identified 24 well-defined

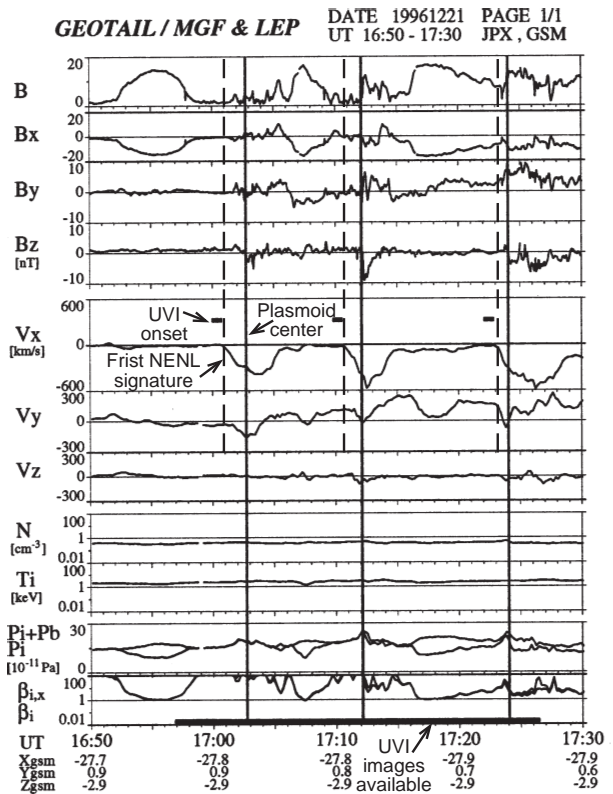


Figure 6: Geotail magnetic field and ion parameters during an interval when three plasmoids were identified. Short horizontal bars indicate time of auroral onset as determined from POLAR ultraviolet imager images [Ieda et al., 2000].

signatures of plasmoids in the tail at $x = -21$ to -28 R_E . They then found that that all 24 were associated with auroral brightenings, though not all the brightenings were associated with global substorms, and they found that in 21/24 cases the brightenings occurred 0-3 min before the first plasmoid signature was seen. An example from *Ieda et al.* [2000] where three plasmoid signatures were observed and longitudinal conjunction with the auroral brightenings was excellent is shown in Figure 6. Figure 6 shows that the first signatures of each plasmoid were seen at Geotail at or after the initiation of each of the auroral brightenings.

The timing of the flows in Figure 6 and those in the remainder of the 21 cases where plasmoid signatures were first seen after auroral onset are consistent with the superposed epoch studies discussed above. Given the tailward flow speeds in these events, which reached ~ 500 - 600 km/s, it is unreasonable to expect that NENL formation occurred within the $x \sim -20$ to -30 R_E a few minutes before onset. *Ieda et al.* [2000] did find 3 events where plasmoid signatures were seen 1-2 min prior to auroral onset. However, the auroral images for two of those are shown in their paper, and both showed brief, longitudinally localized brightenings of the type that is associated with auroral poleward boundary intensifications, an auroral disturbance (discussed later) that is fundamentally different from substorms.

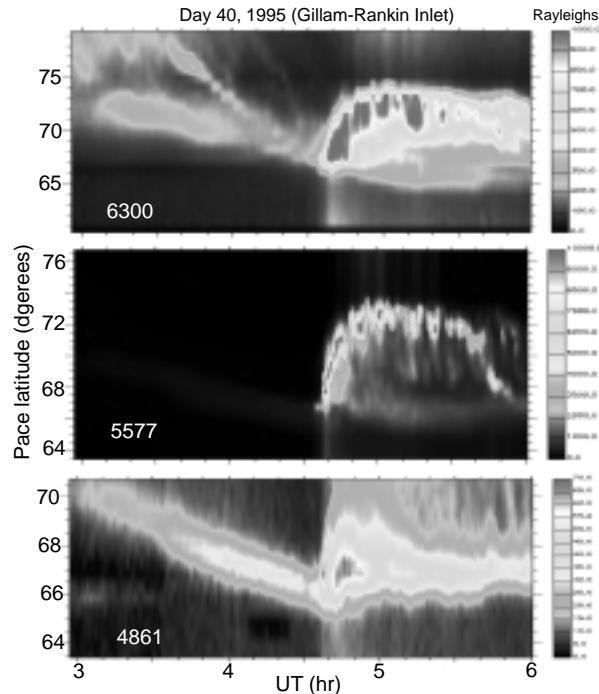


Figure 7: CANOPUS MSP observations obtained from a merging of data from Gillam and Rankin Inlet. Intensities are shown as a function of latitude under the assumption that each emission comes from a fixed altitude. Small dark regions within the brightest white areas indicate emission intensities that are higher than within the white areas [*Friedrich et al.*, 1999].

With other data

CANOPUS ground meridian scanning photometer (MSP) observations of auroral emissions give excellent monitoring of auroral onset and the location and motion of the magnetic separatrix as mapped to the auroral ionosphere. *Friedrich et al.* [1999] examined in detail the MSP observations during 15 substorm onsets and found that poleward motion of the separatrix associated with the substorm initiated 2-4 min after auroral onset in all cases.

An example of their MSP observations from within the longitude range of substorm onset is shown in Figure 7. The substorm onset is identified by the strong brightening of 5577\AA and 6300\AA emissions that starts near 67° latitude soon after 0435 UT and then moves poleward. The separatrix is obtained from the observed location of the poleward boundary of 6300\AA emissions [*Samson et al.*, 1992; *Blanchard et al.*, 1997], which can be seen to have moved equatorward during the substorm growth phase prior to onset and to have moved rapidly poleward starting soon after onset. The substorm growth phase is also indicated by the equatorward motion of the 4861\AA emissions, which result from precipitation of plasma sheet protons.

The poleward boundaries of the 6300\AA and of the bright 5577\AA and 4861\AA emissions during the time surrounding the substorm onset is shown in Figure 8. This plot clearly shows that significant closing of open lobe flux initiated when the bright 5577\AA emissions from the poleward expanding auroral bulge reached the separatrix ~ 2 min after the substorm onset. Since such a delay was seen in all 15 cases, the delay between closing of lobe flux and auroral-zone onset must be a general feature of substorms and not the result of longitudinal localization of a region where closing of lobe flux initiates earlier. This implies that a closing of lobe flux initiates ~ 2 - 4 min after auroral onset. Lobe magnetic flux is required for NENL flows to carry significant flux to the inner plasma sheet, since there is very little flux within the thin growth-phase tail plasma sheet. Thus, *Friedrich et al.*'s [1999] results imply that significant flux transfer by the NENL begins a few min after inner plasma sheet onset, consistent with all the Geotail results discussed in the previous section.

Maynard et al. [1998] and *Erickson et al.* [2000] have performed an interesting study of substorm onsets using observations from the CRRES spacecraft when it was located within the inner plasma-sheet region of substorm onset. They examined the Poynting flux and plasma flow coming from tailward of the spacecraft for 20 onsets identified with ground instrumentation. For 19/20 events, they could not find an enhancement in Poynting flux or bulk plasma flow coming into the region of inner plasma sheet onset prior to or at the time of onset. This implies that energy flux from NENL does not reach the inner plasma sheet prior to or at onset, consistent with all the studies addressed above. They found that

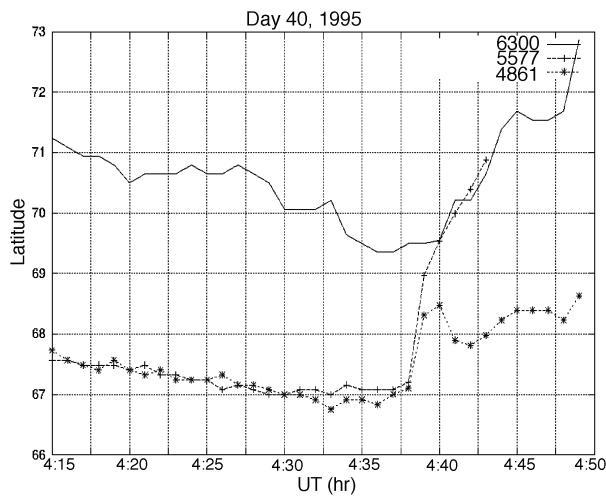


Figure 8: Poleward boundary of 6300 Å and of the bright 5577 and 4861 Å emissions during the time surrounding the substorm onset shown in Figure 7 [Friedrich et al., 2000].

$j \cdot E < 0$ within the plasma sheet at onset, implying that electromagnetic energy for substorm development near the time of onset comes from the energy of the inner plasma sheet particles themselves, rather than from energy stored in the tail lobes.

IONOSPHERIC SIGNATURE OF TAIL FLOW BURSTS

Auroral intensifications referred to as poleward boundary intensifications (PBIs) are often seen initiating on the poleward boundary of the auroral oval [Lyons et al., 1998]. They often occur repetitively with an ~ 10 min period, and several can be seen in the 5577 Å emissions in Figure 7 starting at ~ 0450 UT. Some PBIs extend equatorward as north-south structures (also known as auroral streamers) through the plasma sheet [e.g., Henderson et al., 1998; Zesta et al., 2000], and equatorward extension from $\sim 73^\circ$ latitude to $\sim 68^\circ$ latitude can be seen for several of the PBIs in Figure 7.

PBIs occur on the dusk side of ionospheric flow bursts [de la Beaujardière et al., 1994] that have the characteristics expected from the ionospheric mapping of tail flow bursts, and PBIs have recently been shown to be an ionospheric signature of the tail flow bursts [Henderson et al., 1998; Sergeev et al., 1999, 2000; Lyons et al., 1999; Kauristie et al., 2000]. Zesta et al. [2000] in particular showed that a series of PBIs which extended equatorward in the MSP observations appeared as north-south structures in the all-sky imager data and had a one-to-one association with tail flow bursts.

North-south structures are often seen extending to the inner plasma sheet without leading to substorm onset [e.g., Henderson et al., 1998; Henderson, 1999], and Sergeev et al. [2000] showed that tail flow bursts can reach synchronous orbit without leading to a substorm.

On the other hand, equatorward extensions of PBIs have never been identified in association with substorm onset. Examples of MSP data where substorm onset occurs without being associated with an equatorward extending PBI can be seen in Figure 7, in Samson et al. [1992], and in Lyons et al. [1998]. While north-south structures are expected to be longitudinally localized, they should be seen in some cases if tail flow bursts lead to substorm onset. However numerous cases have been examined without such a structure being identified. Also north-south structures have not been identified just prior to or at onset in spacecraft global auroral images, for which longitudinal localization is not a problem [Henderson et al., 1998; Henderson, 1999]. These observations contradict the central assertion of the new NENL model that tail flow bursts extending to the inner plasma sheet lead to substorm onset.

In addition to the above recent studies, the classic study of auroral displays during substorms as observed from ground-based all-sky imagers [Akasofu, 1964] indicates that the plasma sheet region lying tailward of the onset region is not disturbed prior to substorm onset. In that study, Akasofu found that east-west arcs lying poleward of the arc which brightens at onset are not disturbed until the auroral bulge moves poleward to the location of individual poleward arcs. These arcs, which lie along field lines that map to the plasma sheet region where flow bursts from a NENL would have to traverse, should be disturbed prior to onset by a longitudinal localized earthward flow prior to onset. However, such a disturbance was not observed.

CONCLUSIONS

The above observations are all consistent with each other and imply that a NENL does not form prior to substorm onset as would be required if flow from a NENL were to carry magnetic flux to the inner plasma sheet and lead to substorm onset. For the new NENL to be correct, the minimum time delay from NENL formation to inner plasma sheet, auroral zone, and low-latitude and Pi2 onset, must be ~ 3 , ~ 4 , and ~ 5 min, respectively. However, such an early NENL formation is not seen in any of the studies considered here.

Signatures of NENL formation are seen well after inner plasma sheet and auroral zone onset in the study of Slavin et al. [2000]. Statistical studies using low-latitude Pi2 onset [Nagai et al., 1998, Machida et al., 1998, 1999, Miyashita et al., 2000] place NENL formation ~ 0 -2 min after inner-plasma sheet onset, and a statistical study using auroral onset [Lui et al., 1998] places NENL formation ~ 3 min after inner plasma sheet onset. Ieda et al.'s [2000] study based on identified tail plasmoid signature confirms the above results.

In addition to the above timing inconsistency, Lui et al. [1998] and Miyashita et al. [2000] have found that the perpendicular component of earthward flows associated with NENL formation are < 200 km/s and generally

«200 km/s, so that the NENL does not lead to perpendicular flows that could bring flux to the inner plasma sheet in a reasonable time scale.

The above conclusions regarding the timing of NENL formation are supported by the study of MSP data showing that significant closing of open lobe flux initiates ~2-4 min after auroral onset when bright 5577 Å emissions from the poleward expanding auroral bulge reaches the separatrix [Friedrich *et al.*, 1999]. The conclusions are also supported by the studies using CRRES data showing no enhanced Poynting flux or inward flow to the inner plasma sheet region of substorm onset prior to or at the time of onset [Maynard *et al.*, 1998, Erickson *et al.*, 2000]. Additional support comes from studies showing that bursty flows often reach the inner plasma sheet without leading to substorm onset and that the auroral signature of such flows is not seen in association with substorm onset [e.g., Henderson *et al.*, 1998; Henderson, 1999]. In addition, the substorm auroral morphology study of Akasofu [1964] shows that the plasma sheet is not disrupted along field lines that map to the plasma sheet poleward of the arc which brightens at substorm onset.

All the above studies are consistent with NENL formation occurring at or after the time of substorm onset in the inner plasma sheet. This suggests that consideration should be given to the possibility that NENL formation may be a result of current wedge initiation in the inner plasma sheet, as has been suggested by Lui [1991] and Erickson *et al.*, [2000], rather than being a cause of current wedge formation as required by the new-NENL. Despite NENL formation not being the cause of substorms, the NENL is clearly an important aspect of many substorms, strongly affecting tail dynamics and energy and mass transfer. However, the fact that signatures of NENL formation are not always seen, even when satellites are within the longitude range of current wedge formation, needs to be understood. It could mean that the NENL can be quite localized in longitude and located at longitudes away from the current wedge, or it could mean that the NENL is not a necessary part of the substorm expansion phase and that some substorms can proceed without NENL formation. Both of these possibilities warrant consideration.

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